Beyond the Standard Model

Paul de Jong, Nikhef

BND school 2010

With pictures, slides and text from many, many sources…


THEORIES
PROOFS

The Standard Model: a HUGE success !

A) **Fermions**:   three generations of quarks and leptons
arranged in left-handed doublets and right-handed singlets

B) **Bosons**: quanta of fields, interactions between fermions
interactions based on symmetry under local gauge transformations

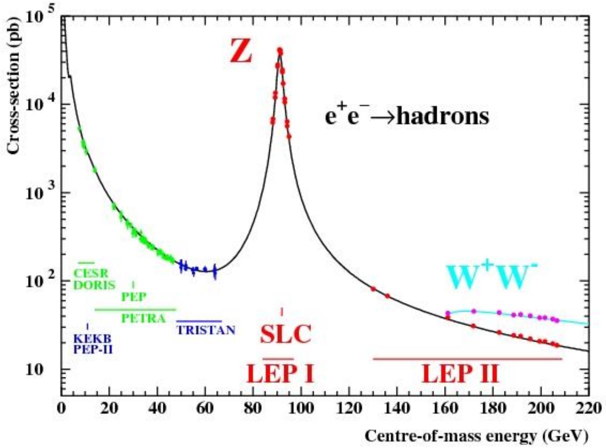
$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

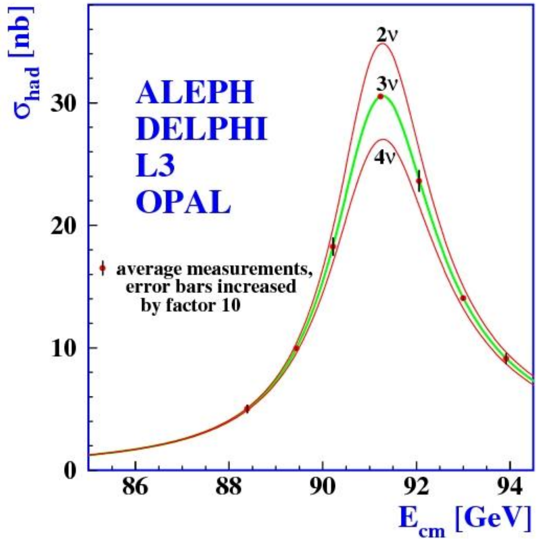
weak bosons and gluons also have self-interactions

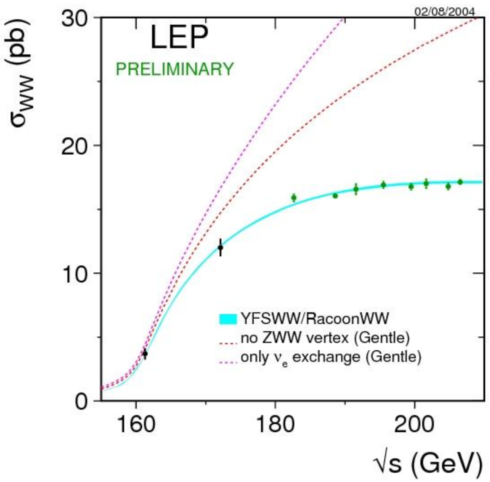
C) One **scalar** field with a non-zero vacuum expectation value breaks electroweak symmetry, and generates masses of fermions.

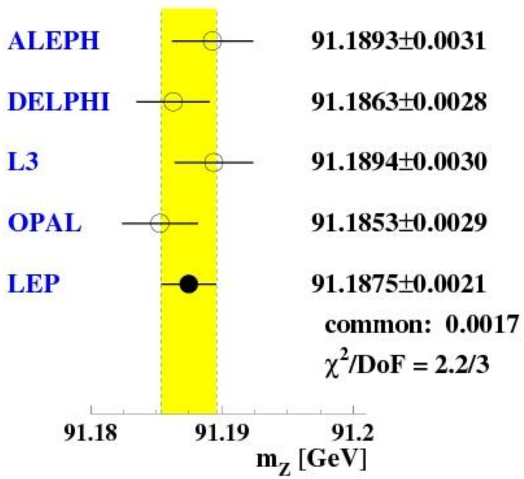
A): check! ✓
B): check! ✓
C): seems to work, final confirmation at LHC?

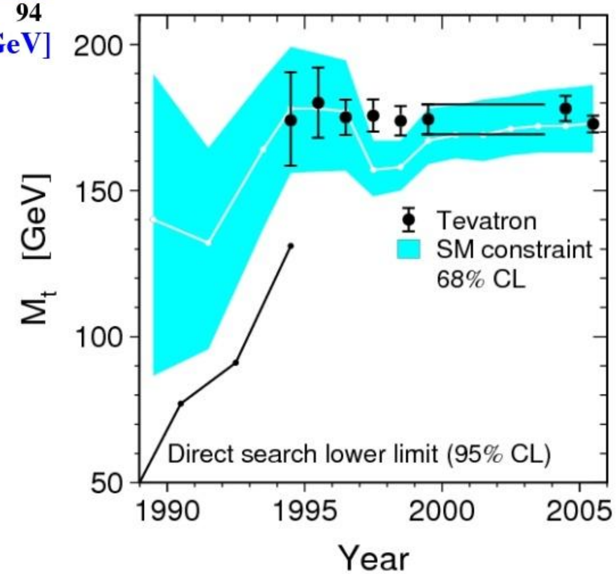
Experimental evidence





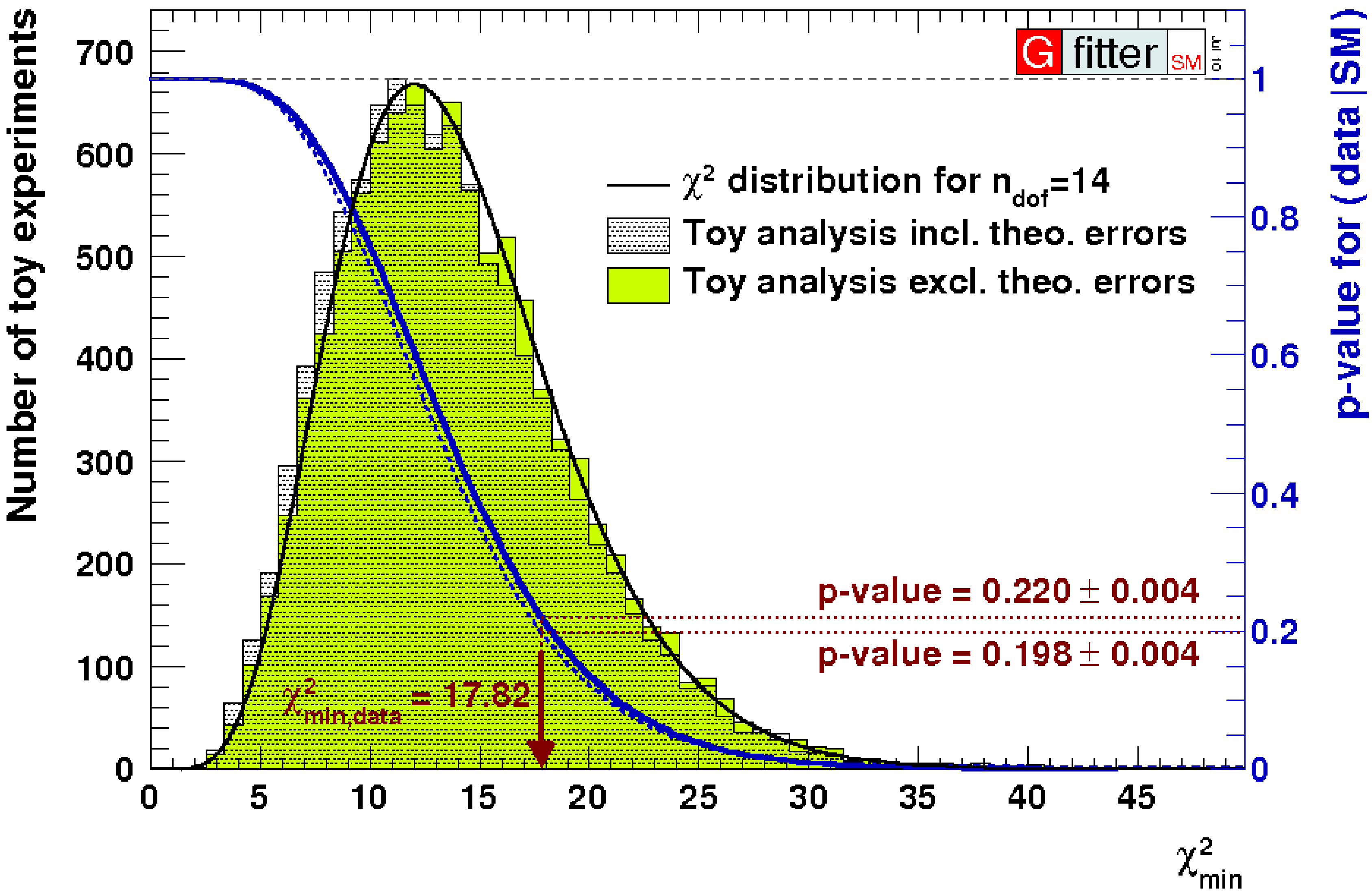






LEP + SLC + Tevatron + HERA + BaBar/Belle + neutrino scattering + low energy + …

Global fit to all data: 20% probability to do worse if model is correct



→ Standard Model fit is OK   (but not great)

Why go beyond the Standard Model ?

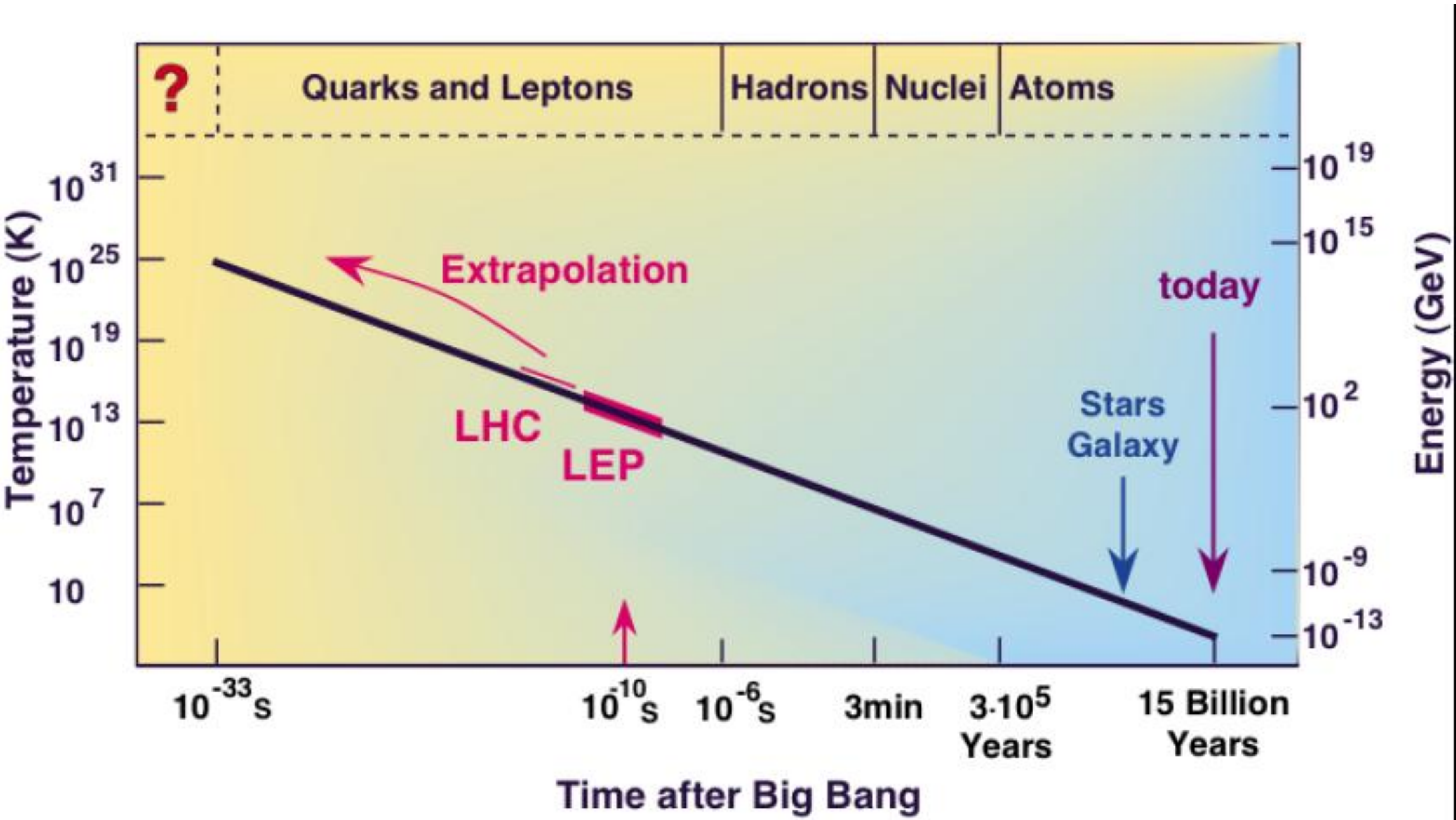
- -Experimental reasons

- -Theory reasons

- -Because we have only covered so little!

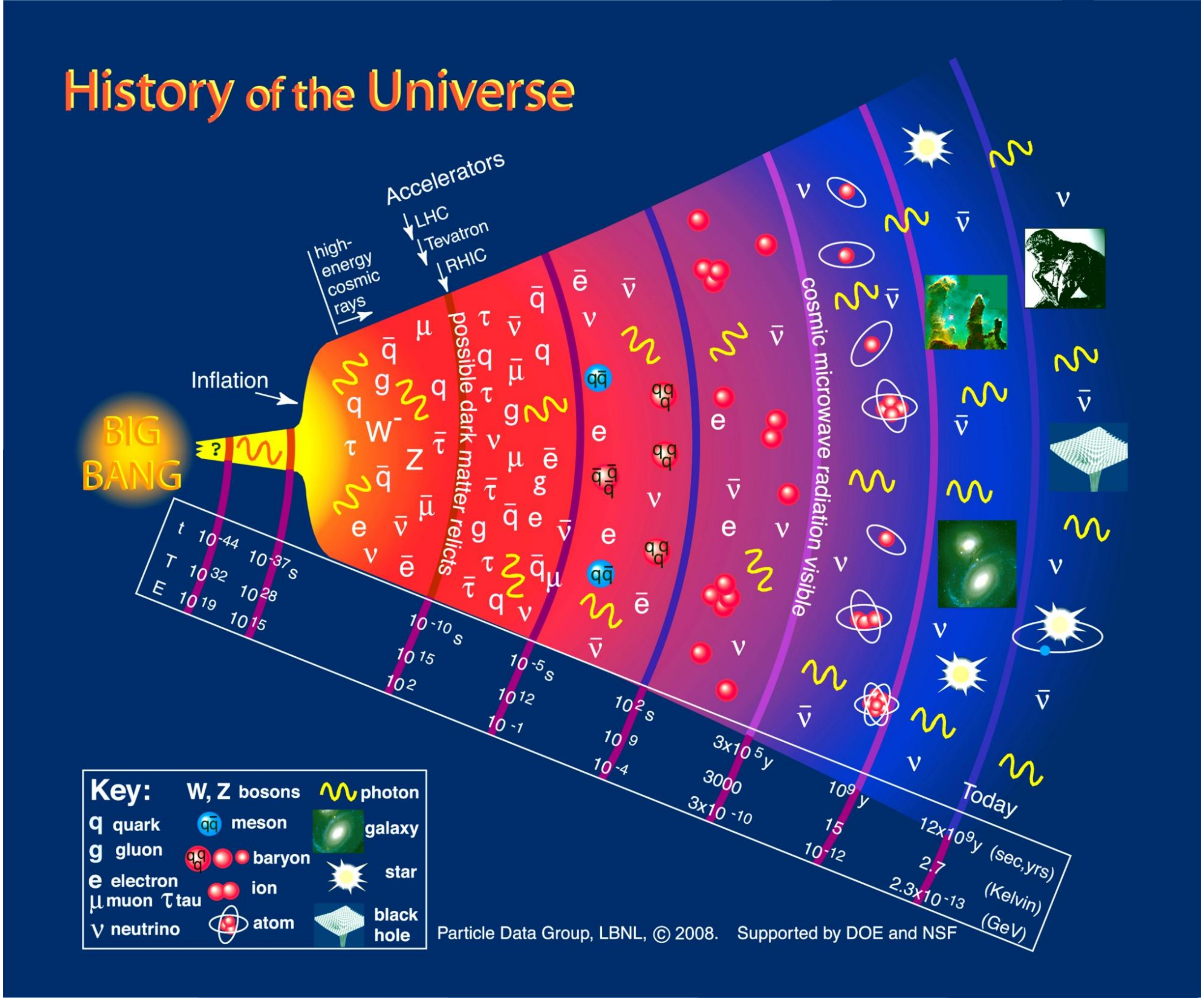
Where are we?

Temperature ←→ Energy ←→ length ← → time



1 eV ~ 10^{-6} m ~ 10^4 K ~ 10^6 years after big bang

LHC: 10^{13} eV, 10^{-19} m, 10^{17} K, 10^{-11} s after big bang


History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
?
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
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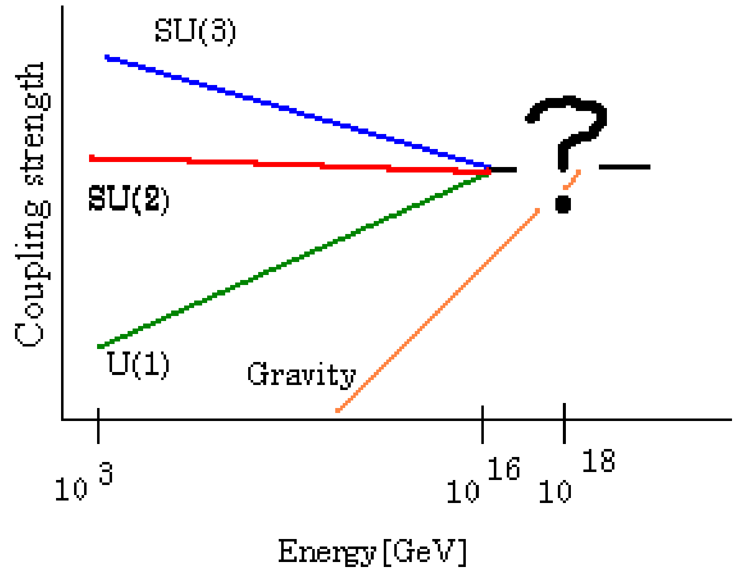
When gravity becomes strong:

Planck scale

10^{28} eV, 10^{32} K,
10^{-34} m, 10^{-42} s

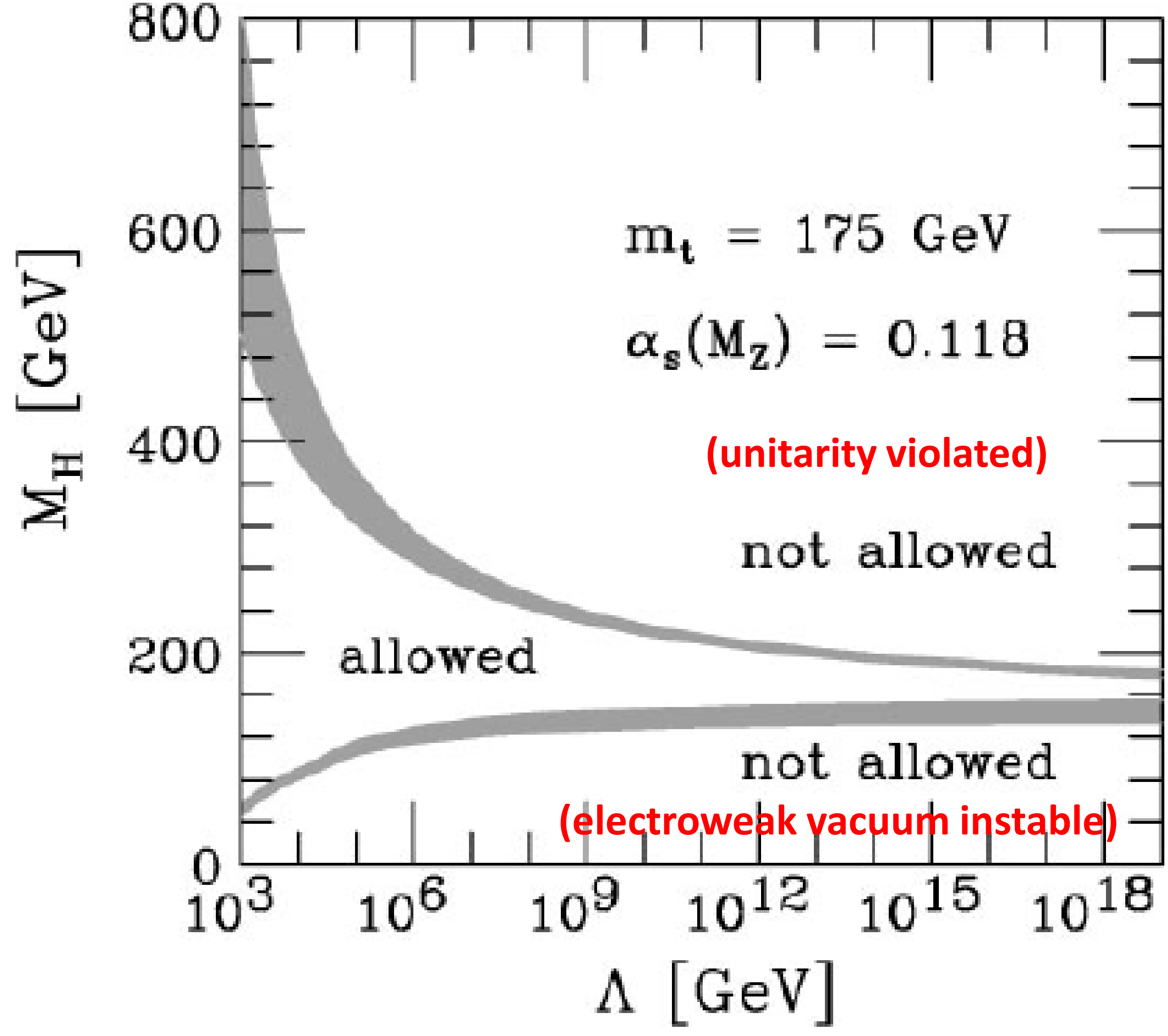


Further consequence: Schwarzschild radius of black hole with mass M_{planck} equal to Compton wavelength of such particle.

(For lower energies: $\lambda_C >> R_S$)

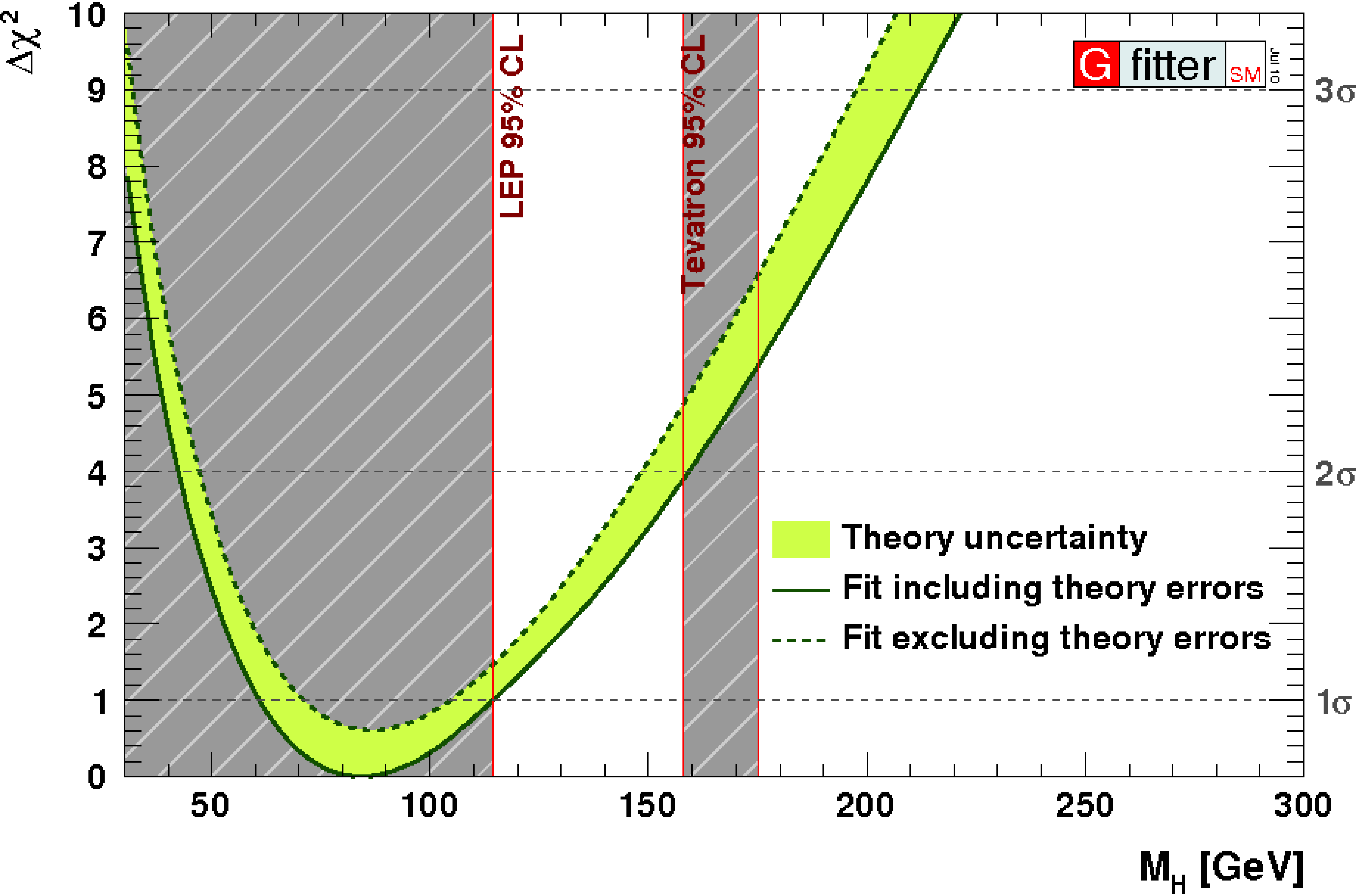
Can the Standard Model be valid up to the Planck scale?

Valid Standard Model must have valid Higgs mechanism

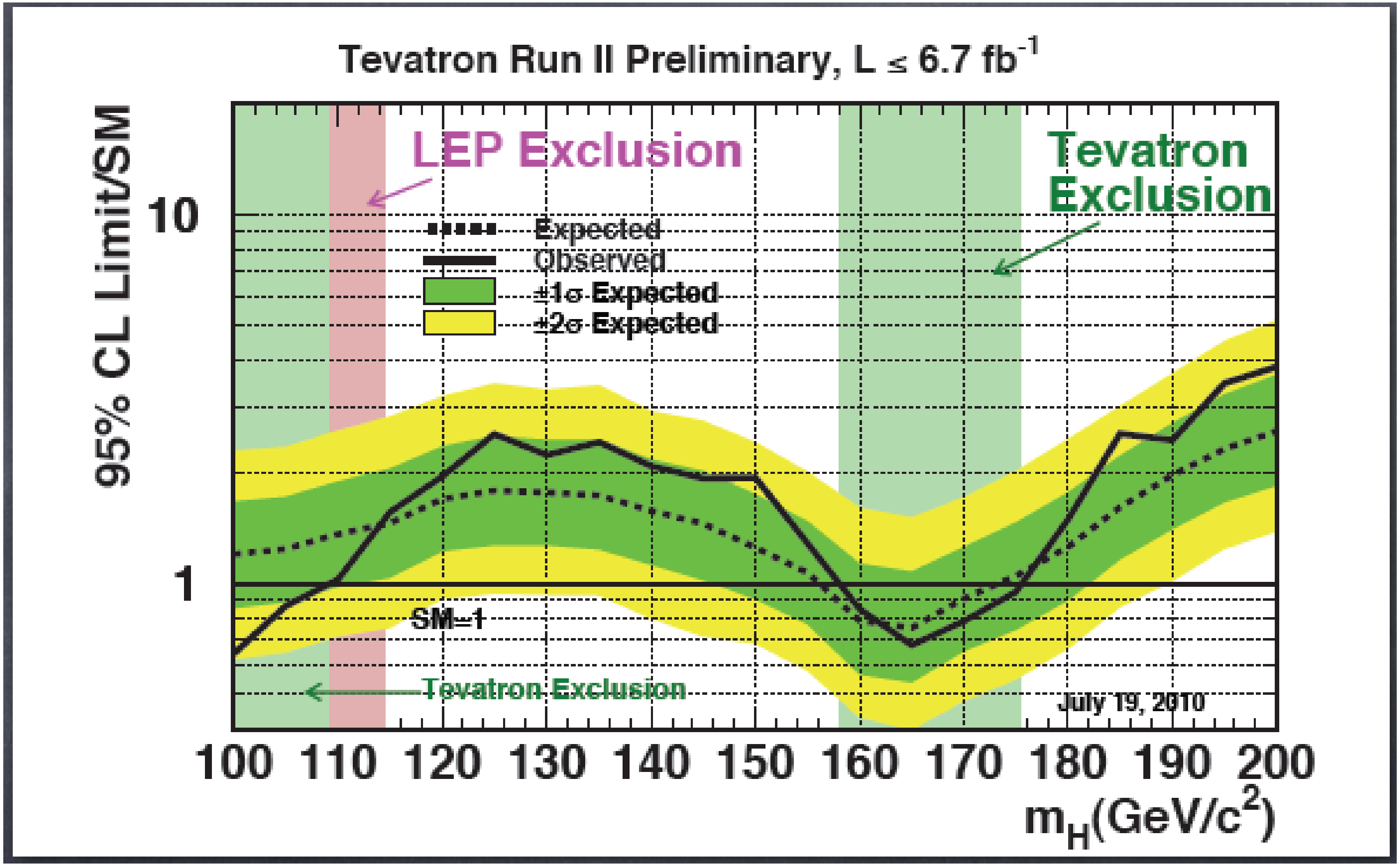


Λ: scale where SM validity stops and new physics must come in

Electroweak fit 2010

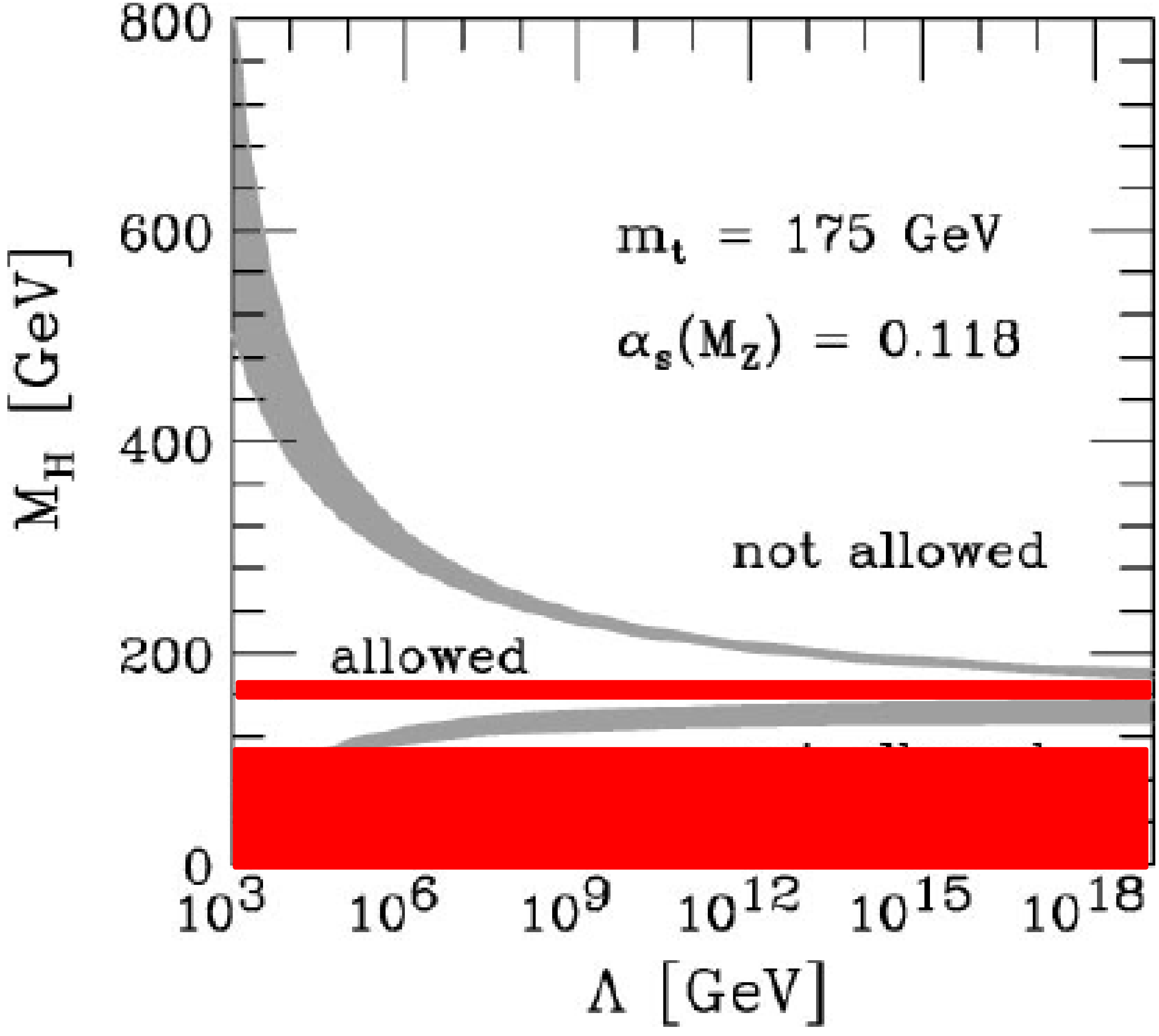


Exclusion limits

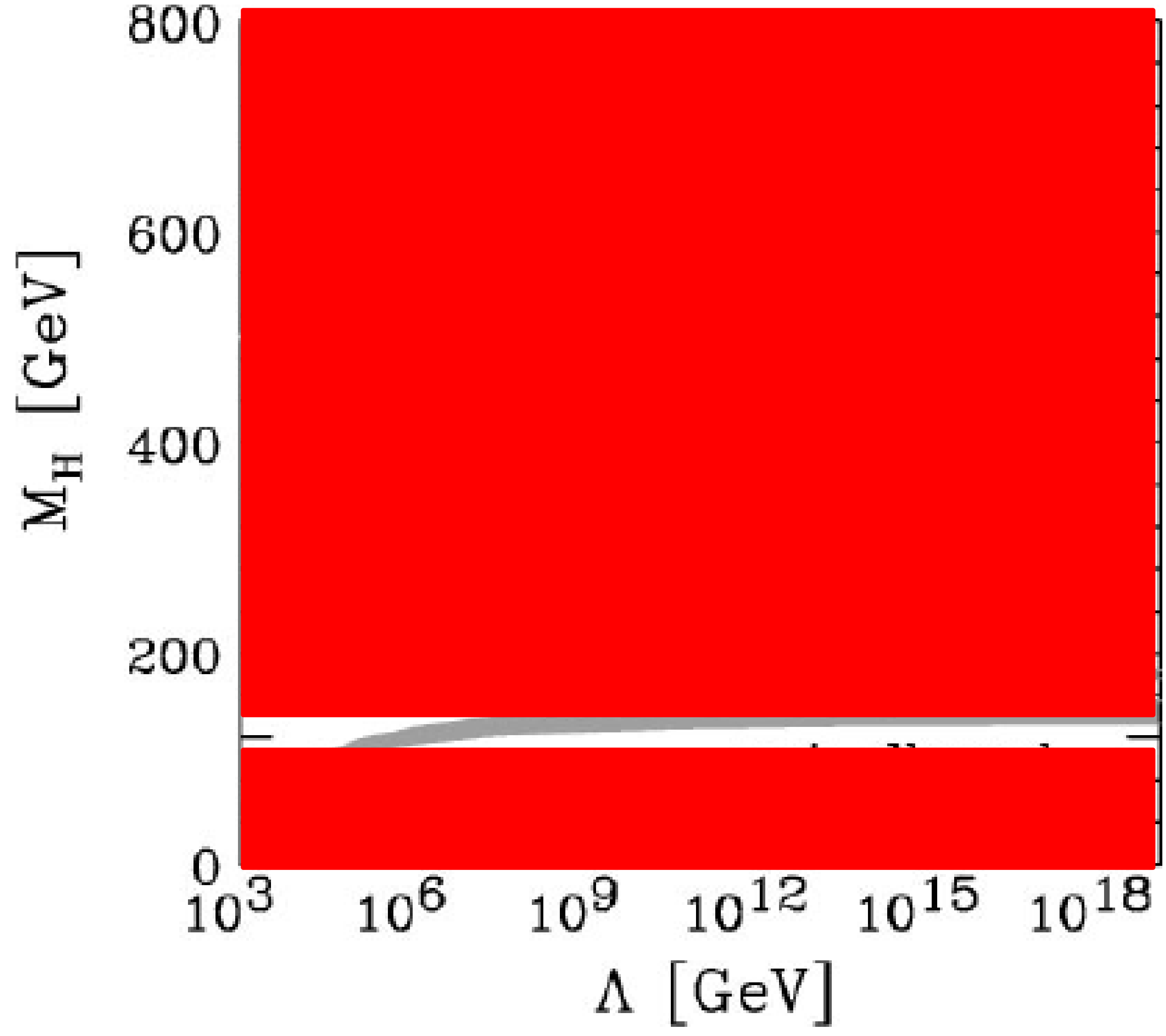


Consequences: 2010

= excluded by expt.



Soon?



Experimental issues with the Standard Model

Neutrino masses
Dark matter and dark energy
Matter-antimatter asymmetry of the universe
A few measurements in disagreement with SM at ~3σ level

Theory issues with the Standard Model

19 (28?) arbitrary parameters?
Why 3 generations, why L-R structure?
Why $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$? Can forces be unified?
Higgs field really responsible for EWSB? Why H ~ 120 GeV, not 10^{19} GeV?
Why CKM matrix?
How many dimensions of space?
Contribution of EW vacuum to cosmological constant wrong by 10^{55} or so…
Gravity?

What can we expect?
Ask an (un)baised theorist:

Murayama LP03

Hierarchy Problem

Do we understand EW symmetry breaking?

Flavour

Why 3 families?

CP violation?

Unification of forces

GUTs? Gravity?

Structure of the universe

Dark matter/energy? #dimensions?

Short tour around the compass

Hierarchy Problem

Do we understand EW symmetry breaking?

SM: electroweak symmetry breaking through Higgs mechanism. Is a hypothesis!

The origin of all the masses in the Standard Model is an isodoublet scalar Higgs field, whose kinetic term in the action is

$$\mathcal{L}_\phi = -|D_\mu \phi|^2 \tag{4}$$

and which has the magic potential:

$$\mathcal{L}_V = -V(\phi) : V(\phi) = -\mu^2 \phi^\dagger \phi + \frac{\lambda}{2}(\phi^\dagger \phi)^2 \tag{5}$$

Because of the negative sign for the quadratic term in (5), the symmetric solution $< 0|\phi|0 >= 0$ is unstable, and if $\lambda > 0$ the favoured solution has a non-zero vacuum expectation value which we may write in the form:

$$< 0|\phi|0 >=< 0|\phi^\dagger|0 >= v \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} \end{pmatrix} : v^2 = \frac{\mu^2}{2\lambda} \tag{6}$$

corresponding to spontaneous breakdown of the electroweak gauge symmetry.

Expanding around the vacuum: $\phi =< 0|\phi|0 > + \hat{\phi}$, the kinetic term (4) for the Higgs field yields mass terms for the gauge bosons:

$$\mathcal{L}_\phi \ni -\frac{g^2 v^2}{2} \; W_\mu^+ \, W^{\mu -} - g'^2 \, \frac{v^2}{2} \, B_\mu \, B^\mu + g \; g' v^2 \; B_\mu \, W^{\mu 3} - g^2 \, \frac{v^2}{2} \, W_\mu^3 \, W^{\mu 3} \tag{7}$$

$$m_{W^\pm} = \frac{gv}{2}$$

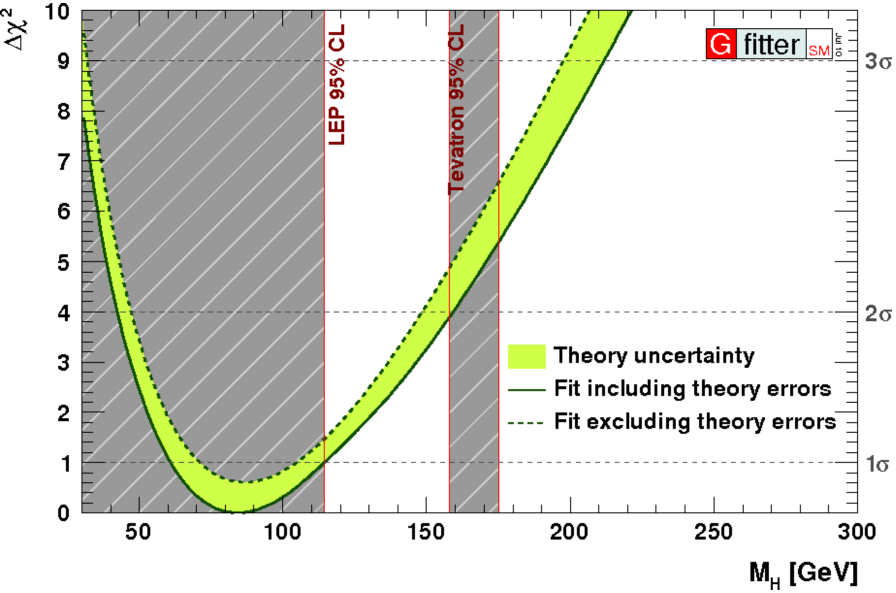
whilst the neutral gauge bosons (W_μ^3, B_μ) have a 2×2 mass-squared matrix:

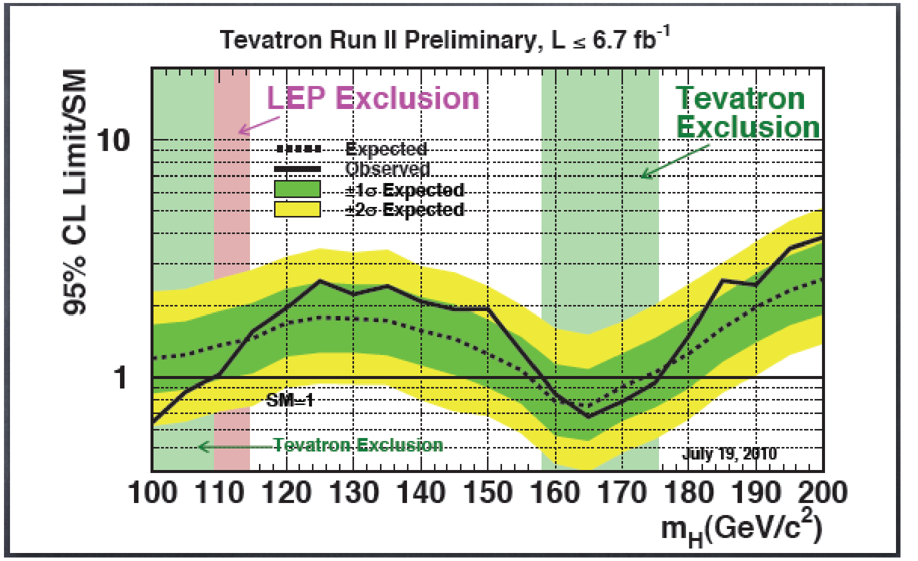
$$\begin{pmatrix} \frac{g^2}{2} & \frac{-gg'}{2} \\ \frac{-gg'}{2} & \frac{g'^2}{2} \end{pmatrix} v^2$$

This is easily diagonalized to yield the mass eigenstates:

$$Z_\mu = \frac{gW_\mu^3 - g' B_\mu}{\sqrt{g^2 + g'^2}} \; : \; m_Z = \frac{1}{2}\sqrt{g^2 + g'^2} v \; ; \; A_\mu = \frac{g' W_\mu^3 + g B_\mu}{\sqrt{g^2 + g'^2}} \; : \; m_A = 0$$

$$m_H^2 = 2\mu^2 = 4\lambda v^2 \qquad g_{H\bar{f}f} = \frac{g}{2}\frac{m_f}{m_W} \; , \; g_{HW^+W^-} = g m_W \; , \; g_{HZ^0Z^0} = g m_Z$$

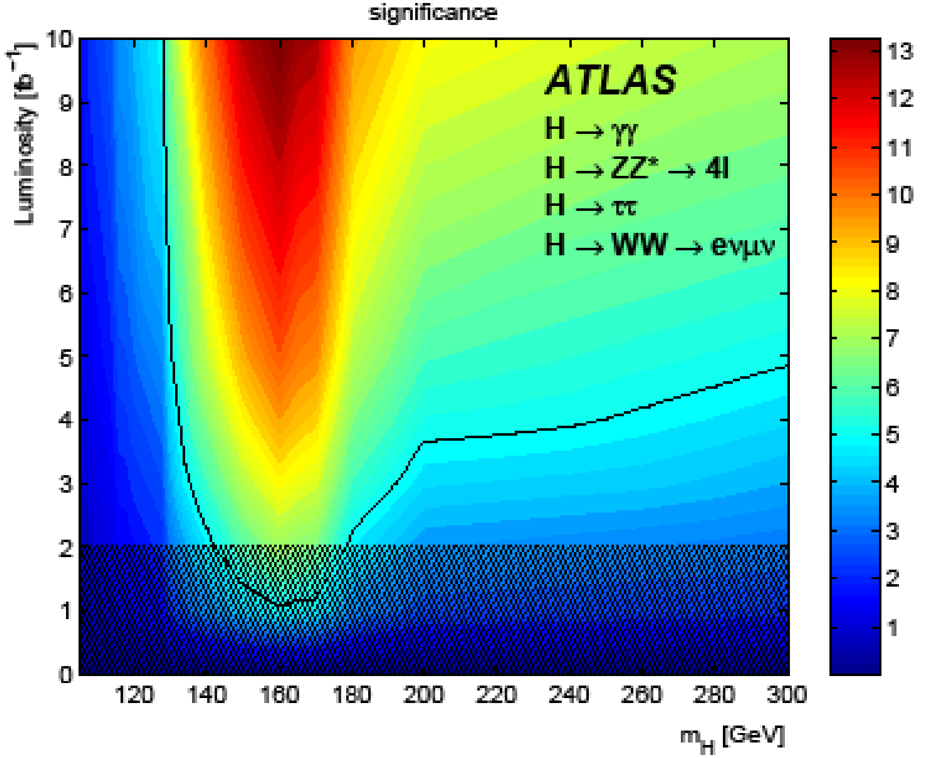




Where is it?

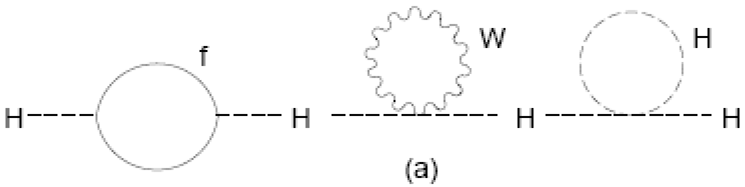
LHC will tell

(or otherwise…)



However: some dissatisfaction with the whole model.
Scalar field “deus ex machina”

Stability of the Higgs boson mass under radiative corrections



$$\delta m^2_{H,W} = \mathcal{O}\left(\frac{g^2}{16\pi^2}\right) \int^{\Lambda} d^4k \frac{1}{k^2} = \mathcal{O}\left(\frac{\alpha}{\pi}\right)\Lambda^2$$

(hierarchy problem, fine-tuning problem)

Possible answers: what, me worry?
no Higgs, something else saves unitarity
Higgs is a composite object (technicolor)
Higgs mass protected by a symmetry (little Higgs)
large extra dimensions: Λ is not so high
Supersymmetry

Unification of forces

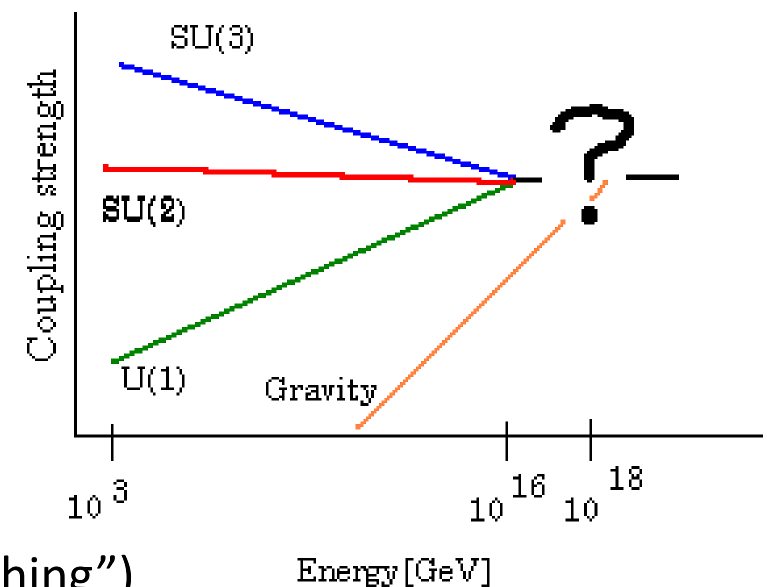
GUTs? Gravity?

Why $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$?

Electroweak = electromagnetism + weak interactions

$$Q = T^3 + \frac{Y}{2}$$

Grand Unified Theory
= QCD + Electroweak theory



(and ultimately: gravity! "theory of everything")

Is there a large symmetry group G encompassing the SM?

$$G \supset SU(3) \times SU(2) \times U(1)$$

unifying representations R that contain both quarks and leptons.

Hope to explain: family structure
charge quantization
some SM parameters (relations between parameters)
small neutrino masses

GUTs: Very interesting experimental consequences!

Proton decay: for example $p \rightarrow e^{+}\pi^{0}$

eventually all p decay and universe will only contain photons!

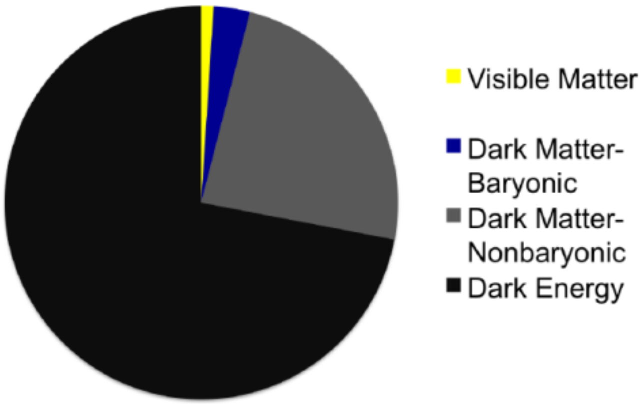
New gauge bosons (Z'): like Z and W bosons, but more massive
typically different couplings to fermions

Magnetic monopoles? No such things in Maxwell's theory!
But symmetry of equations almost demands them…

Structure of the universe

Dark matter/energy? #dimensions?

Whatever the universe is, it is very little baryonic.



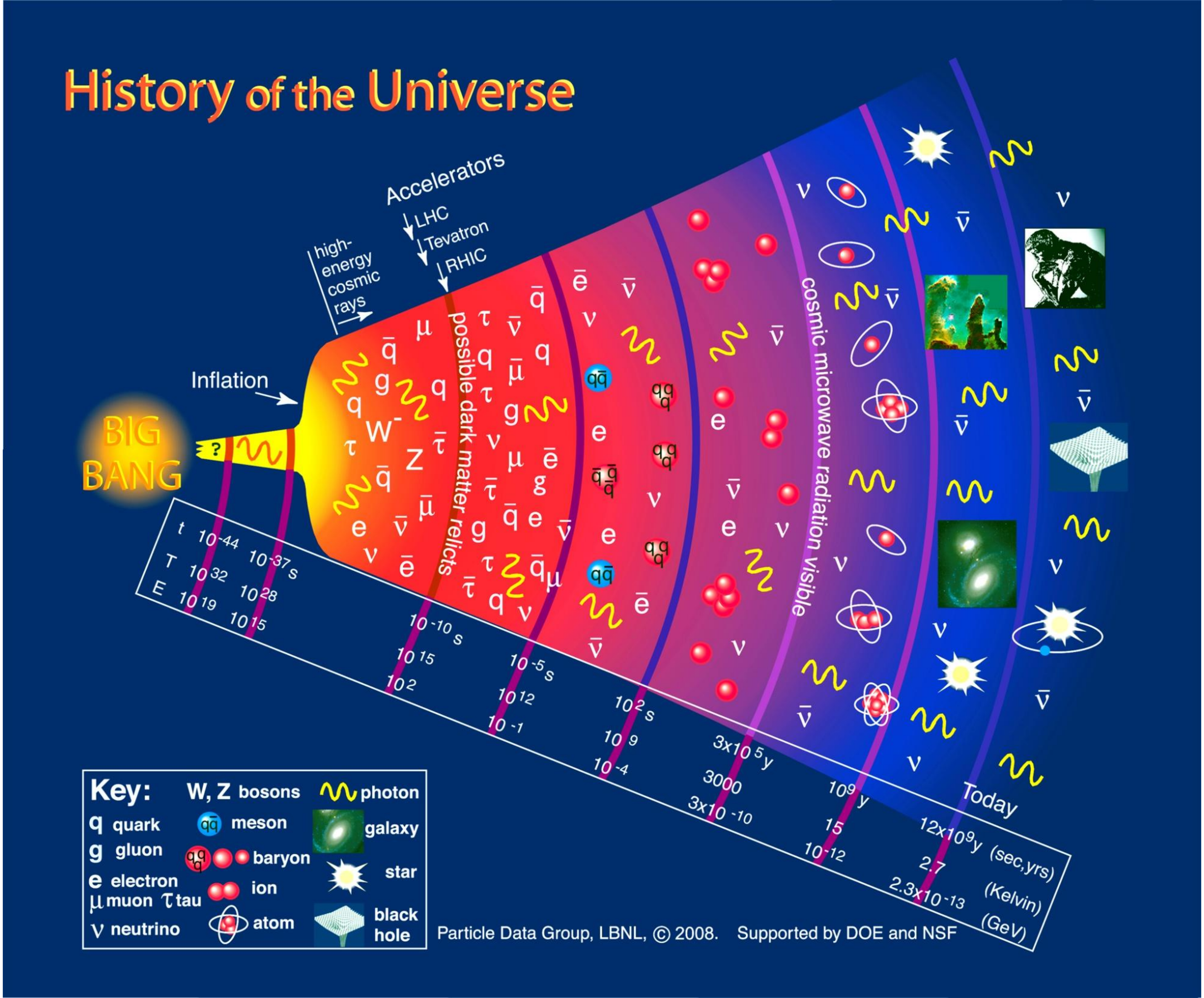
Dark matter and dark energy must eventually be explained by particle physics

Evolution of the universe: inflation → to be explained by particle physics

Space-time: flat ? Curved?

How many spatial dimensions?

Can the extra spatial dimensions be “large” ?



History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
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Experimental issues:

Dark matter formed by **new particles**: find and study them!
in the laboratory
while earth moves through DM halo
elsewhere in the universe

Cosmological / astrophysical observables: electromagnetic waves,
gravitational waves
particles!

What do these tell us about the earliest universe (inflation or earlier?)
What do they tell us about dark energy and the fate of the universe?

Deviations from **Newton's gravitational law**

Deviations from SM predications in pp collisions at the **LHC**

Micro black holes? "Trans-Planckian" physics?

Flavour

Why 3 families?

CP violation?

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Could there be a 4th generation?

Do quarks and/or leptons have substructure?

Flavour eigenstates of quarks $\neq$ mass eigenstates

CKM matrix: can the elements be explained?

In the SM: the phase in the CKM matrix is responsible for CPV
But matter-antimatter asymmetry in universe needs more!
Baryogenesis →leptogenesis?

Since ~10 years: neutrinos have masses too!
Mixing matrix: PMNS matrix
Is there a relation between CKM and PMNS matrices?

CKM elements sensitive to new physics, but SM seems to do well, why?
New physics in flavour observables?

Of course, there are many links across the compass, linking N/E/S/W together!

Examples: GUTs and neutrino mass

supersymmetry: hierarchy problem, and dark matter

proton decay experiments also measure neutrino oscillations

Z': from GUTs, but also from little Higgs, extra dimensions

First extra-dimension models were attempts for GUTs

supersymmetric GUTs : hierarchy problem, dark matter, flavour

In some more details:

Flavour

Why 3 families?

CP violation?

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

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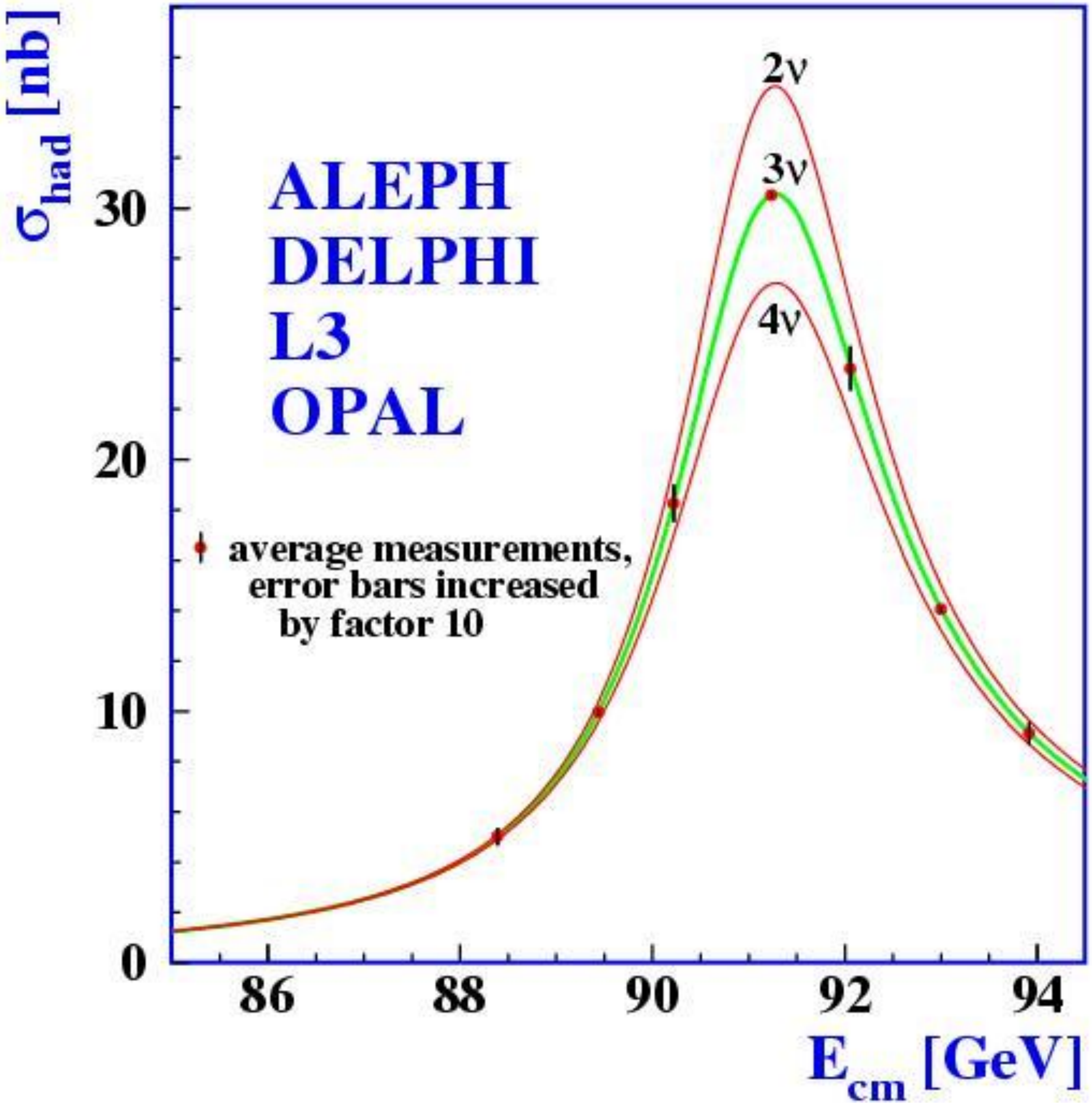
Quarks spin =1/2

Flavor	Approx. Mass GeV/c²	Electric charge	
u up	0.002	2/3	I
d down	0.005	–1/3	
c charm	1.3	2/3	II
s strange	0.1	–1/3	
t top	173	2/3	III
b bottom	4.2	–1/3	

Why 3 copies?



LEP: $N_\nu = 2.984 \pm 0.009$

More families?

-**Strong constraints on neutrinos**: $\Sigma m_\nu < 1$ eV or so
Heavy neutrinos? Non-standard neutrino couplings?

-Standard Model contains left-handed isospin doublets: (t,b) etc.
A single 4th generation quark (no doublet) gives problems!

-But otherwise, **it's largely an experimental game**:
-- Heavy charged leptons: LEP: M > 100 GeV
-- Heavy neutral leptons: LEP: M > 90-100 GeV
-- Heavy b': CDF: M > 200-270 GeV
-- Heavy t': CDF: M > 256 GeV

(Unitarity of CKM matrix could provide constraints, but not yet precise enough)

Excited leptons, excited quarks

Natural explanation for "copies" of first generation:
muon, tau are "excited" electrons

Needs electron to consist of more fundamental building blocks:
substructure

Would expect rapid $\mu \rightarrow e\, \gamma$ decay: not observed

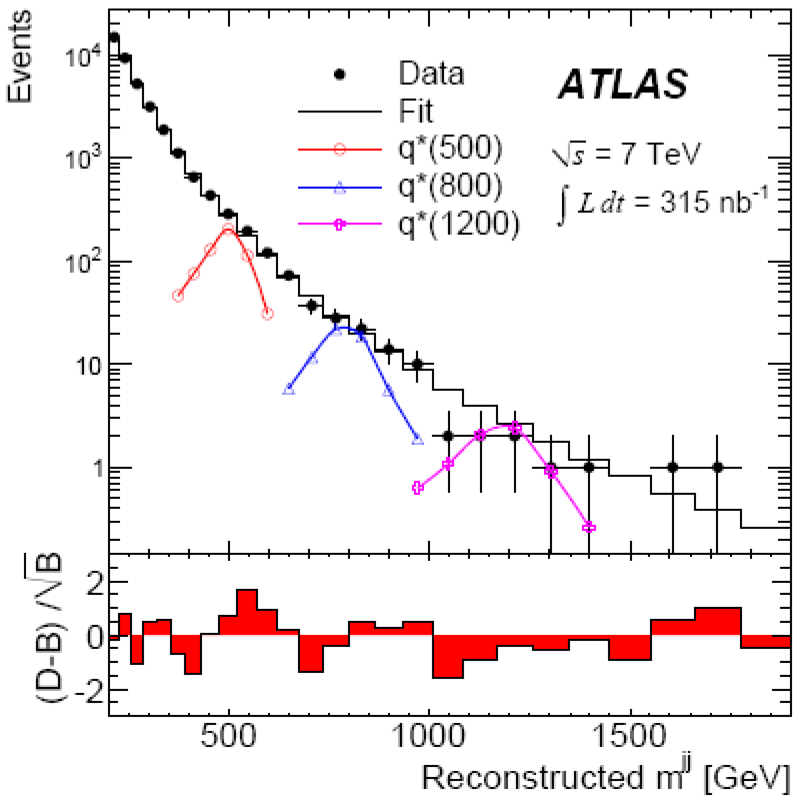
Also no other sign of $e^* \rightarrow e\, \gamma$

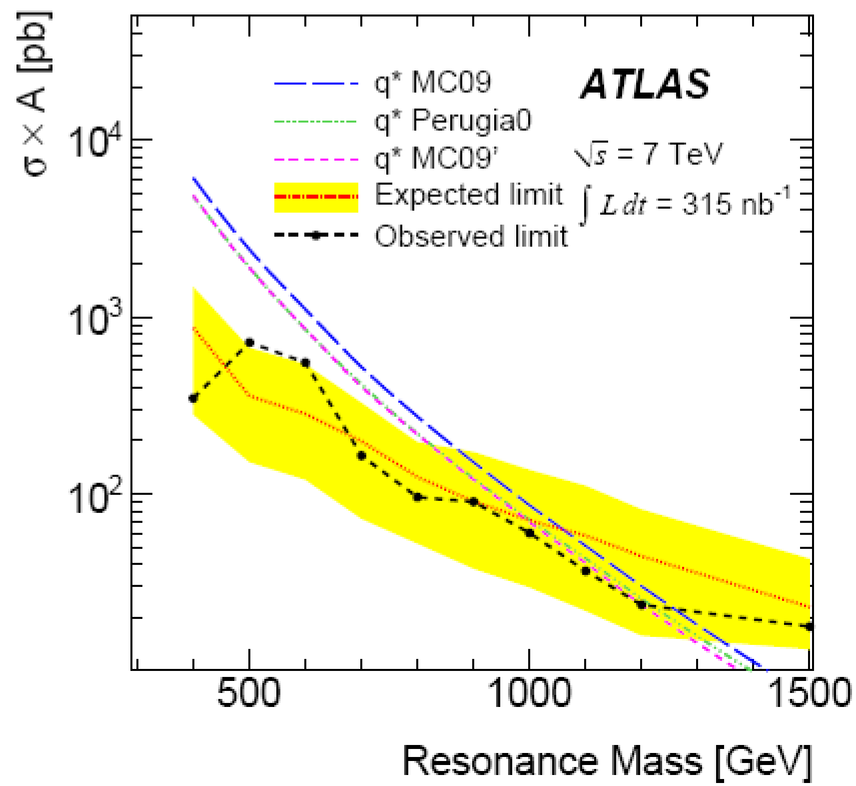
Quark substructure: hypothetical "**preons**"

Early LHC search for excited quarks: $q^* \rightarrow q\, g$

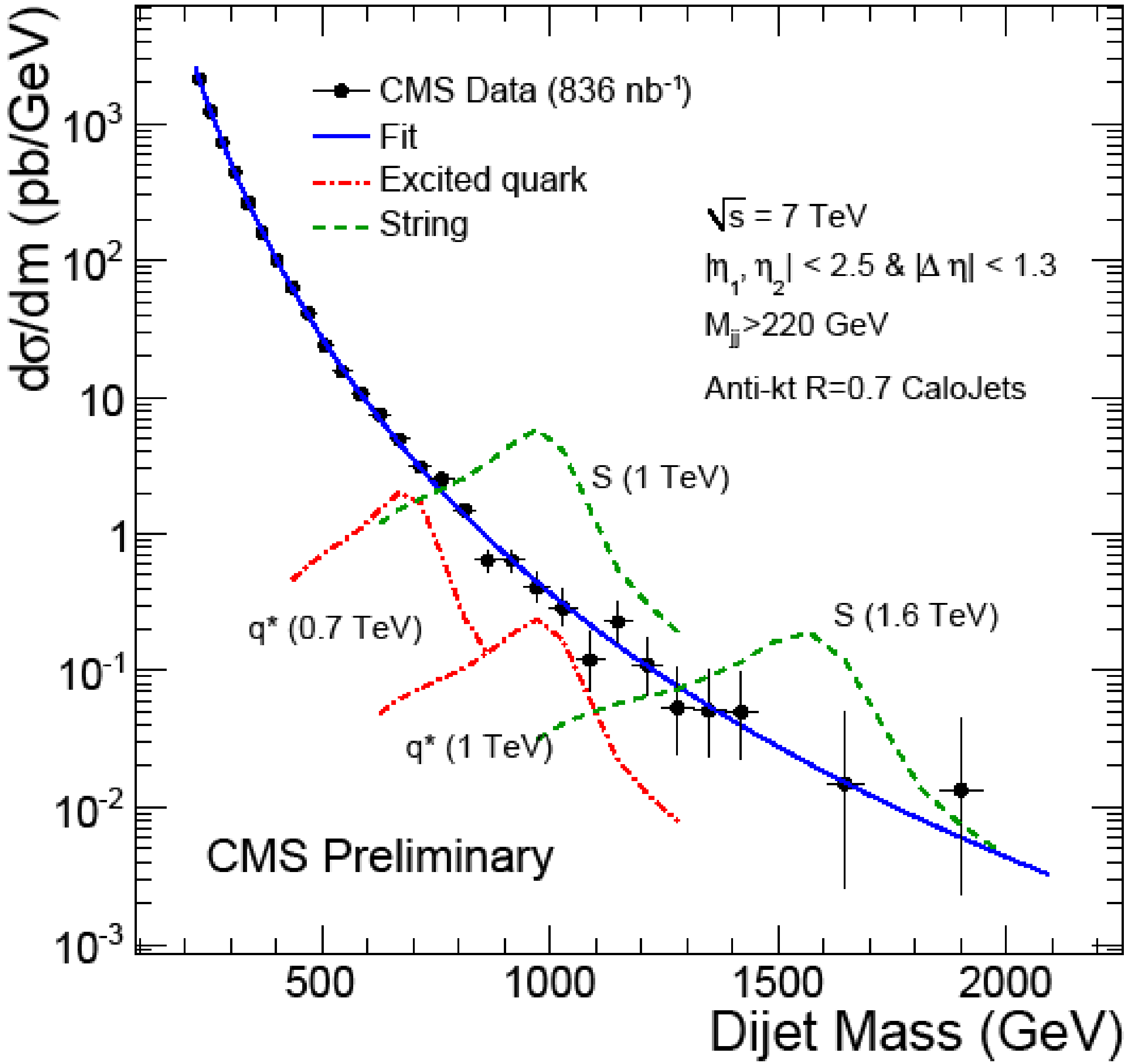
Would show up in di-jet mass spectrum: resonance at $m = m(q^*)$

Can be done very early @ LHC: cross sections large!





First new LHC limits with 7 TeV data!



dσ/dm (pb/GeV)
Dijet Mass (GeV)
CMS Data (836 nb-1)
Fit
Excited quark
String
√s = 7 TeV
|η1, η2| < 2.5 & |Δ η| < 1.3
Mjj>220 GeV
Anti-kt R=0.7 CaloJets
S (1 TeV)
S (1.6 TeV)
q* (0.7 TeV)
q* (1 TeV)
CMS Preliminary
10^3
10^2
10
1
10^-1
10^-2
10^-3
500
1000
1500
2000

Closer look at how 3 generations are implemented in Standard Model

$$\mathcal{L}_Y = -Y^d_{ij}\,\overline{Q^I_{Li}}\,\phi\, d^I_{Rj} - Y^u_{ij}\,\overline{Q^I_{Li}}\,\epsilon\,\phi^* u^I_{Rj} + \text{h.c.}$$

Right-handed singlet

Higgs field

Left-handed doublet

Yukawa couplings: a 3x3 complex matrix!

Above expression written in the interaction basis: Q^I , d^I , u^I are interacting fields

$$Q^I_{Li} = \begin{pmatrix} u^I_{Li} \\ d^I_{Li} \end{pmatrix}, \quad L^I_{Li} = \begin{pmatrix} \nu^I_{Li} \\ \ell^I_{Li} \end{pmatrix}$$

But another valid basis is the mass basis:

Electroweak symmetry breaking: $\mathcal{R}e(\phi^0) \to (v + H^0)/\sqrt{2}$

$$-\mathcal{L}_M = (M_d)_{ij}\overline{d^I_{Li}}d^I_{Rj} + (M_u)_{ij}\overline{u^I_{Li}}u^I_{Rj} + (M_\ell)_{ij}\overline{\ell^I_{Li}}\ell^I_{Rj}$$

$$M_f = \frac{v}{\sqrt{2}}Y^f$$

The mass basis corresponds, by definition, to diagonal mass matrices. We can always find unitary matrices V_{fL} and V_{fR} such that

$$V_{fL}M_fV^\dagger_{fR} = M^{\rm diag}_f, \tag{1.10}$$

with $M^{\rm diag}_f$ diagonal and real.

$$d_{Li} = (V_{dL})_{ij}d^I_{Lj}, \quad d_{Ri} = (V_{dR})_{ij}d^I_{Rj}$$

$$V_{\rm CKM} \equiv V_{uL}V^\dagger_{dL} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

After some redefinitions of arbitrary phases, a 3x3 CKM matrix is characterized by 3 angles θ_{12} , θ_{13} , θ_{23} and 1 phase δ

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$s_{12} = \sin\theta_{12}$, $c_{12} = \cos\theta_{12}$

A useful parametrization is:

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda = 0.2196 \pm 0.0023, \quad A = 0.819 \pm 0.035, \quad (\rho^2+\eta^2)^{1/2} = 0.36 \pm 0.09.$$

Why? No idea! → Standard Model flavour problem

As a result of the fact that V_{CKM} is not diagonal, the $W^{\pm}$ gauge bosons can couple to quark (mass eigenstates) of different generations. Within the Standard Model, this is the only source of *flavor changing* interactions.

Observe other sources of flavour changing interactions? → New Physics!

SM: no mixing in the lepton sector
neutral currents conserve flavour (no FCNCs)

Mixing in the lepton sector: An analysis similar to the above applies also to the left-handed leptons. The mixing matrix is $(V_{\nu L} V_{\ell L}^{\dagger})$. However, we can use the arbitrariness of $V_{\nu L}$ (related to the masslessness of neutrinos) to choose $V_{\nu L} = V_{\ell L}$, and the mixing matrix becomes a unit matrix. We conclude that the masslessness of neutrinos (if true) implies that there is no mixing in the lepton sector. If neutrinos have masses then the leptonic charged current interactions will exhibit mixing and CP violation.

W-interactions in flavour space:

$$-\mathcal{L}_W = \frac{g}{2}\overline{Q^I_{Li}}\gamma^\mu \tau^a Q^I_{Li} W^a_\mu .$$

W-interactions in mass space:

$$-\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}}\overline{u_{Li}}\gamma^\mu (V_{uL} V^\dagger_{dL})_{ij} d_{Lj} W^+_\mu + \text{h.c.}.$$

But for Z-interactions, the combination of relevant matrix elements is such that they are the same in both spaces → no flavour changes

Mixing in neutral current interactions: Defining $\tan\theta_W \equiv g'/g$, the Standard Model gives

$$Z^\mu = \cos\theta_W W_3^\mu - \sin\theta_W B^\mu. \tag{1.15}$$

(B is the gauge boson related to $U(1)_Y$.) Therefore, to study the interactions of the Z boson, we need to know the W_3-interactions (given in (1.5)) and the B interactions:

$$-\mathcal{L}_B = -g'\left[\frac{1}{6}\overline{Q^I_{Li}}\gamma^\mu \mathbf{1}_{ij} Q^I_{Lj} + \frac{2}{3}\overline{u^I_{Ri}}\gamma^\mu \mathbf{1}_{ij} u^I_{Rj} - \frac{1}{3}\overline{d^I_{Ri}}\gamma^\mu \mathbf{1}_{ij} d^I_{Rj}\right] B_\mu. \tag{1.16}$$

Let us examine, for example, the Z-interactions with d_L in the mass basis:

$$\begin{aligned} -\mathcal{L}_Z =& \frac{g}{\cos\theta_W}\left(-\frac{1}{2}+\frac{1}{3}\sin^2\theta_W\right)\overline{d_{Li}}\gamma^\mu (V^\dagger_{dL}V_{dL})_{ij} d_{Lj} Z_\mu \\ =& \frac{g}{\cos\theta_W}\left(-\frac{1}{2}+\frac{1}{3}\sin^2\theta_W\right)\overline{d_{Li}}\gamma^\mu d_{Li} Z_\mu. \end{aligned} \tag{1.17}$$

We learn that the neutral current interactions remain universal in the mass basis and there are no additional flavor parameters in their description. This situation goes beyond the Standard Model to all models where all left-handed quarks are in $SU(2)_L$ doublets and all right-handed ones in singlets. The Z-boson does have flavor changing couplings in models where this is not the case.

$$-\mathcal{L}_W = \frac{g}{2}\overline{Q^I_{Li}}\gamma^\mu\tau^a Q^I_{Li} W^a_\mu. \qquad (1.5)$$

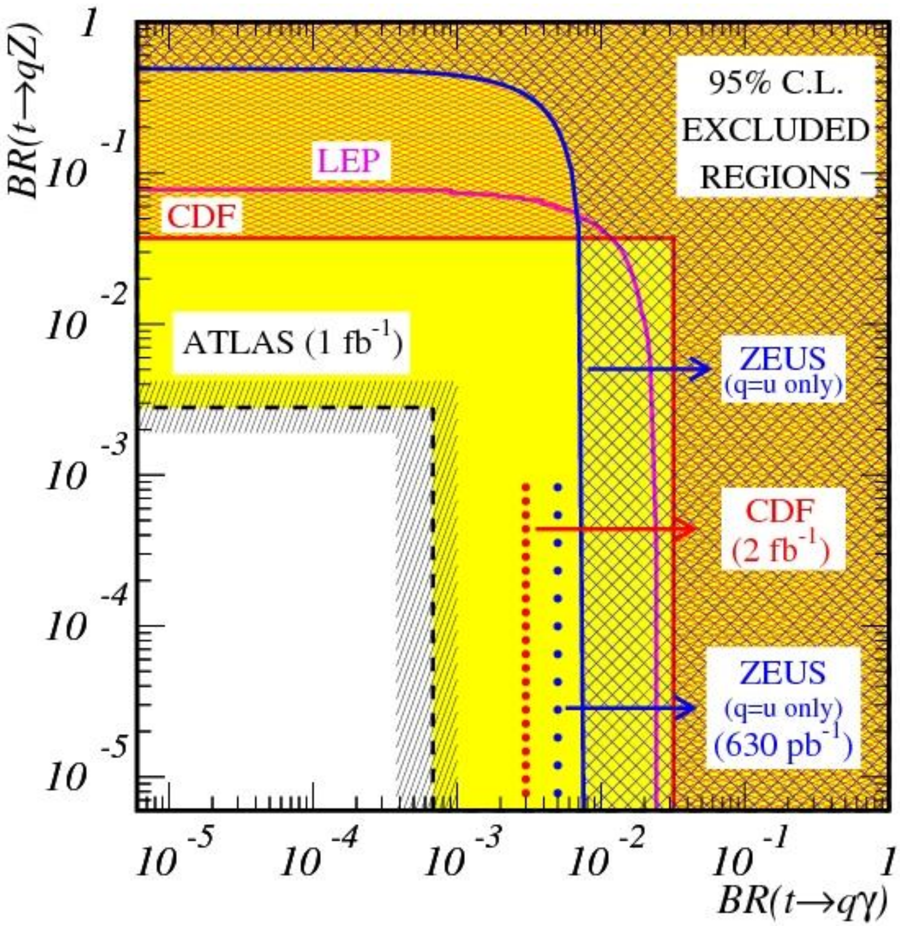
Looking for flavour-changing neutral currents is an excellent way of searching for new physics beyond the Standard Model !

Examples: $\mu \rightarrow e\,\gamma$

$Z \rightarrow \mu\tau$

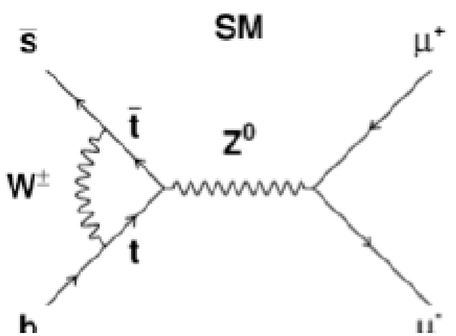
$t \rightarrow cZ,\ c\gamma,\ cg$

$B \rightarrow \mu\mu$

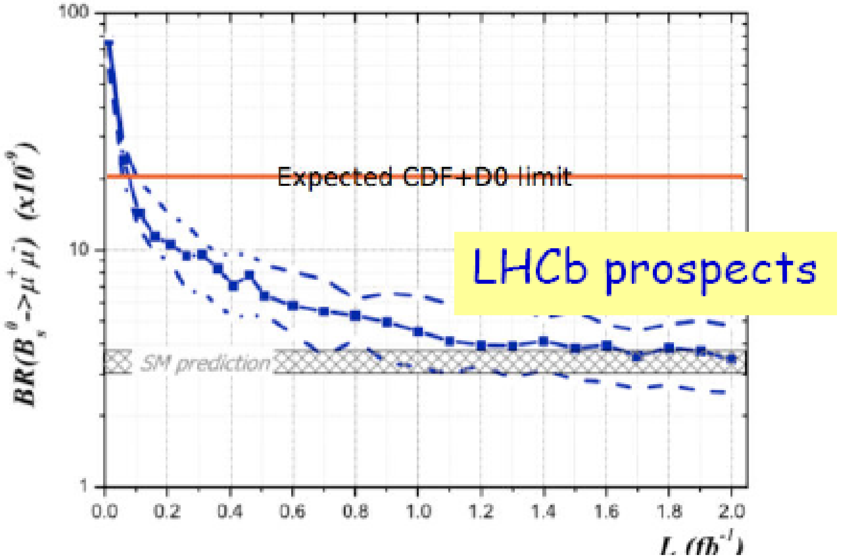


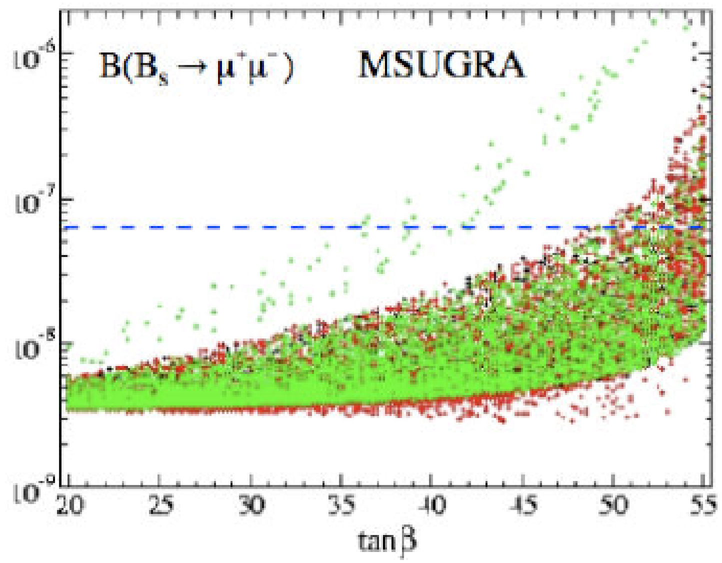
Example: The Rare Decay $B_s \to \mu\mu$

This decay is sensitive to new physics (new heavy particles)



- SM prediction: $BR(B_s \to \mu^+\mu^-) = (3.35 \pm 0.32) \times 10^{-9}$ [1]
- Current Tevatron limit at 90% CL: $< 4.7 \times 10^{-8}$ [$2\,fb^{-1}$] [2]

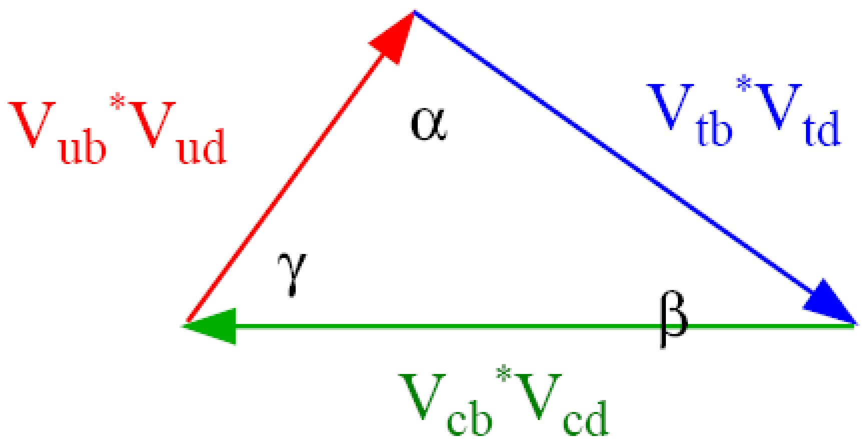


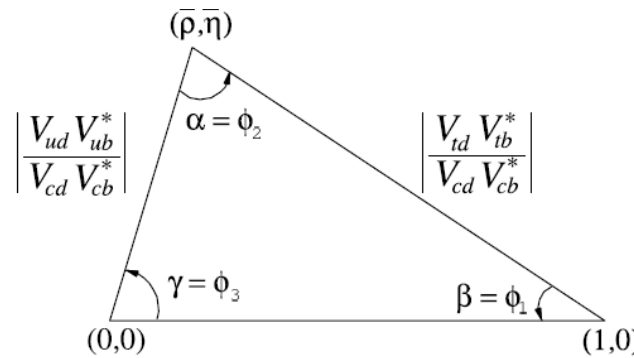


$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad V_{\rm CKM}^{\dagger} V_{\rm CKM} = 1$$

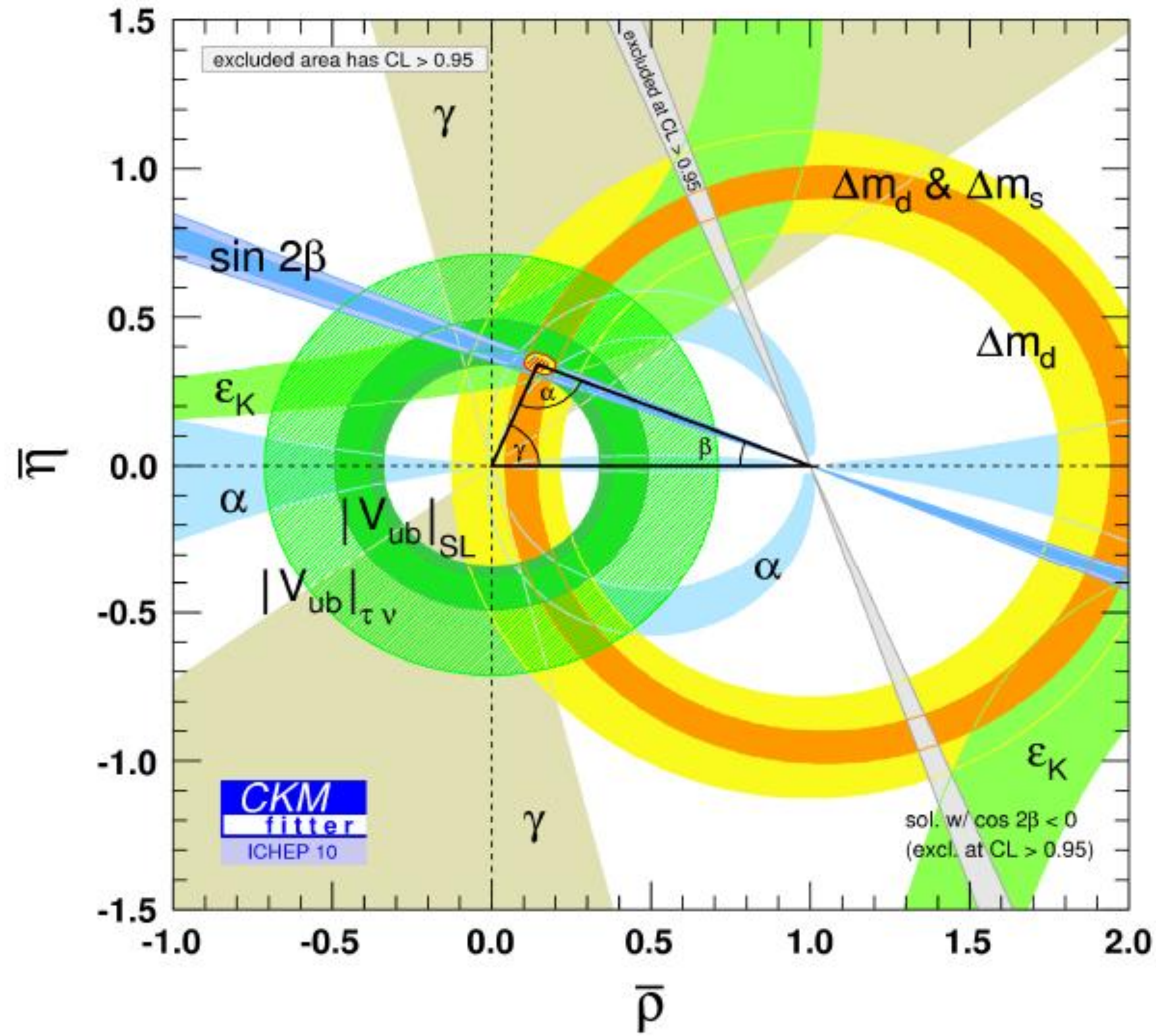
: CKM matrix unitary

$$V_{ub}^{*} V_{ud} + V_{cb}^{*} V_{cd} + V_{tb}^{*} V_{td} = 0$$





Area of triangle is a measure of $\delta \neq 0$: CP violation



Summary of 8 different measurements of unitarity triangle: impressive!

Overall fit is decent. Nevertheless: there are some tensions!

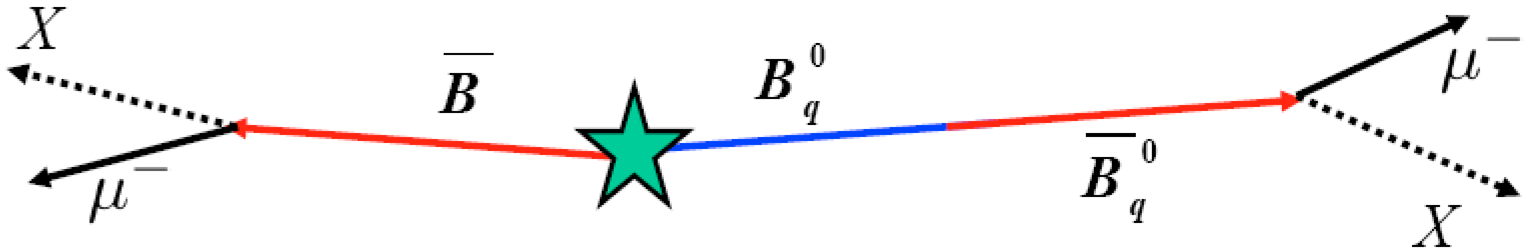
A. β measured from B → J/ψ K differs from prediction from V_{ub} by ~2.5 sigma

B. The measured branching ratio B → $\tau\nu$ differs from prediction by ~2.5 sigma

C. D0 has made 2 measurements that differ 2-3 sigma from prediction

Dimuon charge asymmetry
Phase ϕ in time-dependent B_s mixing

Dimuon charge asymmetry



$$A_{sl}^{b} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

N_b^{++} (N_b^{--}) – number of same-sign $\mu^+\mu^+$ ($\mu^-\mu^-$) events from $B \to \mu X$ decay

- Both B_d and B_s contribute in A^b_{sl} at Tevatron :

$$A_{sl}^{b} = (0.506 \pm 0.043)\, a_{sl}^{d} + (0.494 \pm 0.043)\, a_{sl}^{s}$$

B_d contribution — B_s contribution

  – a^q_{sl} is the charge asymmetry of "wrong sign" semileptonic B^0_q ($q = d,s$) decays:

$$a_{sl}^{q} \equiv \frac{\Gamma(\overline{B}_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \mu^- X)}{\Gamma(\overline{B}_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \mu^- X)}; \quad q = d, s$$

Evidence for an anomalous like-sign charge asymmetry

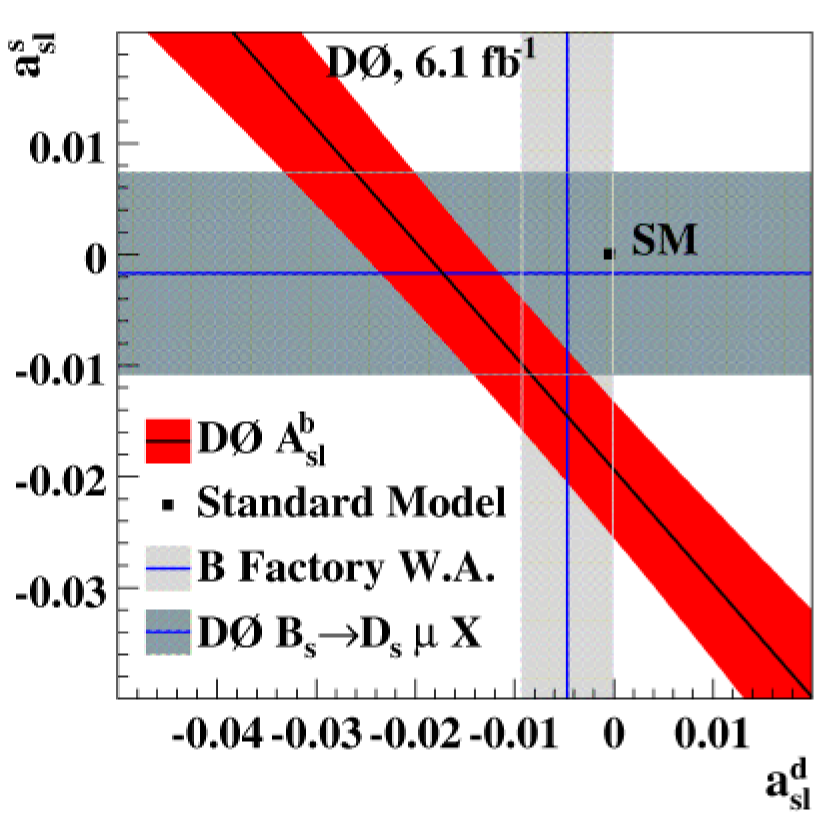
$$A_{sl}^{b} = (-0.957 \pm 0.251\ (\text{stat}) \pm 0.146\ (\text{syst}))\%$$

- This result differs from the SM prediction by ~3.2 σ
- A^{b}_{sl} produces a band in a^{d}_{sl} v.s. a^{s}_{sl} plane:

$$A_{sl}^{b} = (0.506 \pm 0.043)\, a_{sl}^{d} + (0.494 \pm 0.043)\, a_{sl}^{s}$$

- Obtained result agrees well with other measurements of a^{d}_{sl} and a^{s}_{sl}

B. Hoeneisen, ICHEP-2010,
DØ Collab., arXiv:1005.2757 accepted by PRD
DØ Collab., arXiv:1007.0395 accepted by PRL



Main conclusion: overall the SM picture works quite well!

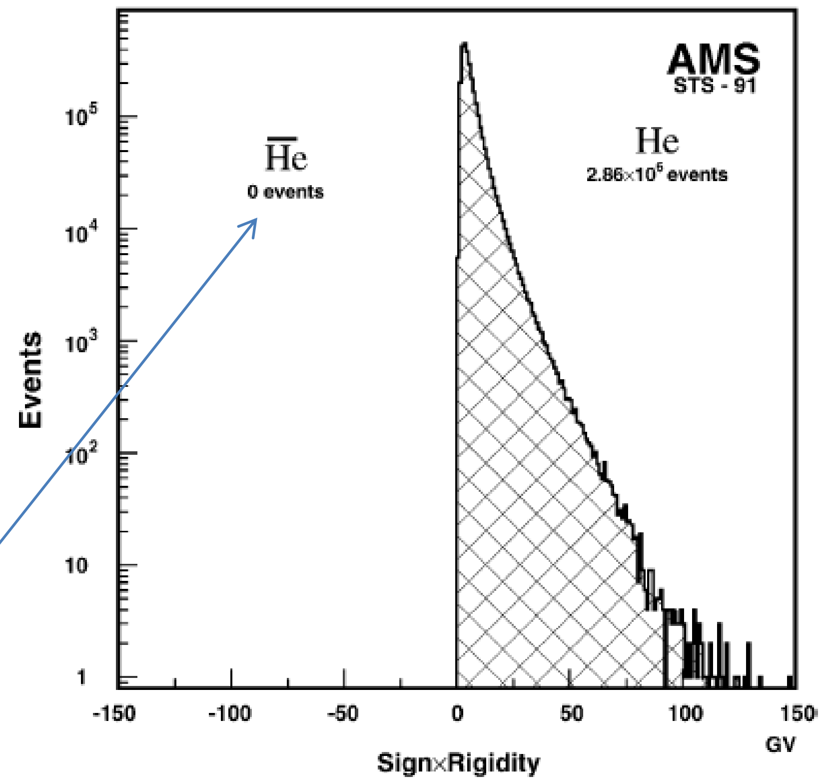
But that doesn't solve our problems!

Baryogenesis: the generation of baryonic matter after the big bang.
If equal amount of matter and antimatter: complete annihilation: nothing left!

But we exist!
We observe matter in the universe
  but very little antimatter.

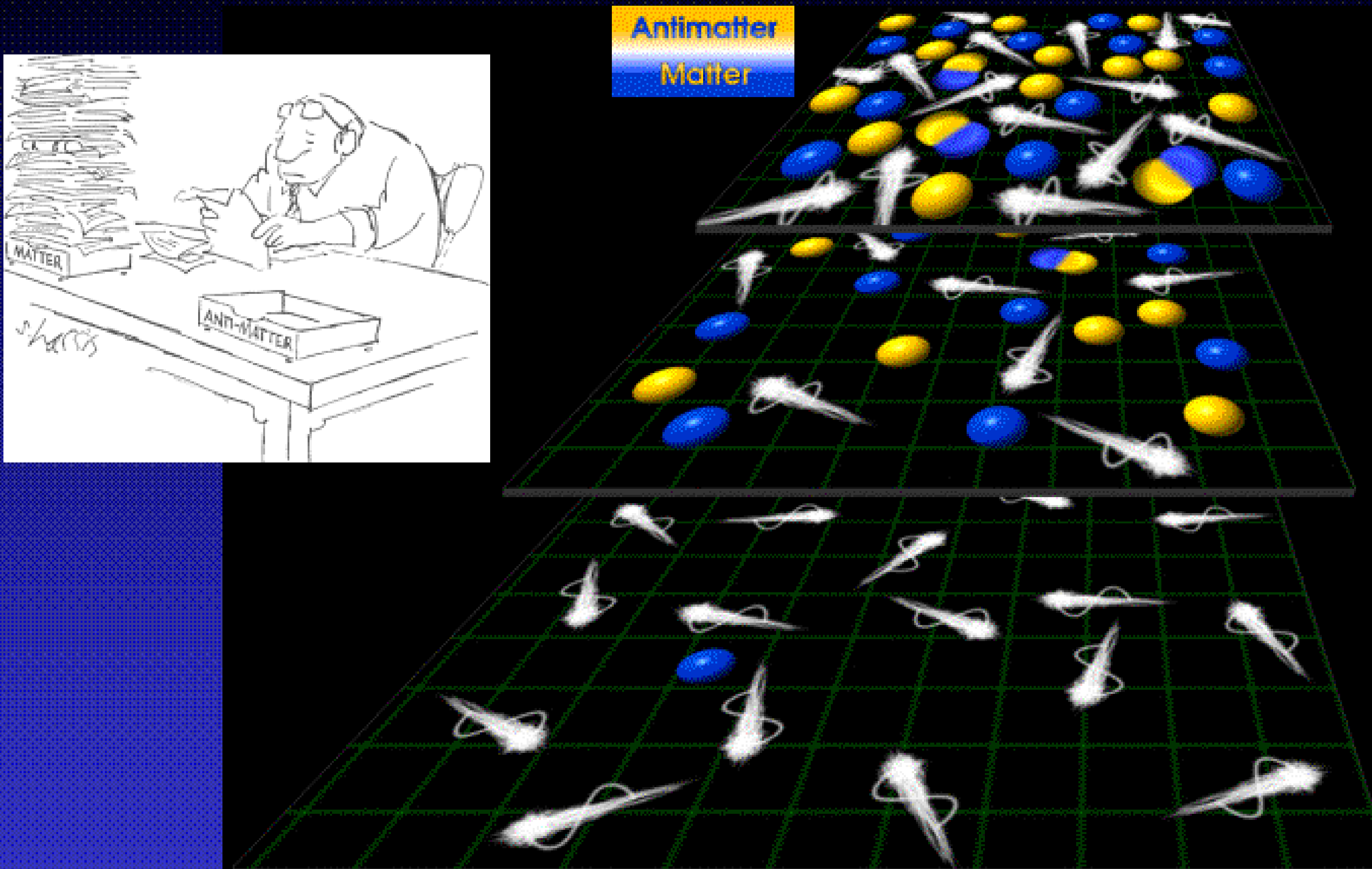
$$\eta \equiv \frac{n_B - n_B}{n_\gamma}$$

$$\eta = (6.14 \pm 0.25) \times 10^{-10}$$



No anti-stars!

Matter-Antimatter Asymmetry of the Universe



Sakharov's Conditions for Baryogenesis

1. B violation
2. Loss of thermal equilibrium
3. C, CP violation

1. Not at tree level in SM (but at higher orders in non-perturbative processes)
   Possible in GUTs and in SUSY
2. $\Gamma(Y + B \to X) = \Gamma(X \to Y + B)$: no net generation of B
3. $\Gamma(\bar{X} \to \bar{Y} + \bar{B}) = \Gamma(X \to Y + B)$ $\quad \frac{dB}{dt} \propto \Gamma(\bar{X} \to \bar{Y} + \bar{B}) - \Gamma(X \to Y + B)$ = 0

CP conservation would imply

$$\Gamma(X \to q_L q_L) = \Gamma(\bar{X} \to \bar{q}_R \bar{q}_R) \tag{2.13}$$

and also

$$\Gamma(X \to q_R q_R) = \Gamma(\bar{X} \to \bar{q}_L \bar{q}_L) \tag{2.14}$$

Then we would have

$$\Gamma(X \to q_L q_L) + \Gamma(X \to q_R q_R) = \Gamma(\bar{X} \to \bar{q}_R \bar{q}_R) + \Gamma(\bar{X} \to \bar{q}_L \bar{q}_L) \tag{2.15}$$

As long as the initial state has equal numbers of X and $\bar{X}$, we end up with no net asymmetry in quarks. The best we can get is an asymmetry between left- and right-handed quarks, but this is not a baryon asymmetry.

CP-violation through phase δ in SM alone is too small for baryogenesis!

We need **new physics** to enhance CP-violation.
Fortunately, many new physics models predict enhanced CP-violation, and related flavour phenomena (FCNCs).
For example: generic supersymmetry

→Is this an indication that there must be new physics?

But experiments see nothing yet!
Why are the many new flavour phenomena of new physics not seen?
It is in fact **quite hard to suppress** such new flavour phenomena…

→New physics flavour problem

Maybe flavour in new physics also through Yukawa matrices, just like in SM? CKM only source of flavour-changing transitions?
→ "Minimal Flavour Violation" hypothesis

Future experiments will keep looking for anomalies in flavour physics

LHCb @ LHC: detailed studies of B decays

Rare decay experiments, e.g. $\mu \rightarrow e\gamma$

B factories → "Super B factories" (Japan, Italy?)

LHCb search strategies for NP

- Measure FCNC transitions where NP may show up as a relatively large contribution, especially in $b \rightarrow s$ transitions which are poorly constrained by existing data:
  - B_s mixing phase: β_s
  - $B_s \rightarrow \phi\gamma$, $B_s \rightarrow K^*\mu^+\mu^-$, $B_s \rightarrow \mu^+\mu^-$
  - Also: CP phase in D^0 mixing

Single measurements with NP discovery potential

- Improve measurement precision of CKM elements
  - Compare two measurements of the same quantity, one which is insensitive and another one which is sensitive to NP (tree vs loop):
    - $\sin(2\beta)$ from $B^0 \rightarrow J/\psi K_S$ and $\sin(2\beta)$ from $B^0 \rightarrow \phi K_S$
    - γ from $B_{(s)} \rightarrow D_{(s)}K$ and γ from $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$
  - Measure all angles and sides in many different ways
    - any inconsistency will be a sign of new physics

Precision CKMology, including NP-free determinations of angle γ

The big discovery of ~10 years ago: neutrinos also mix!

$$|\nu_i> = \sum_\alpha U_{\alpha i} |\nu_\alpha>$$

$$|\nu_\alpha> = \sum_i U^*_{\alpha i} |\nu_i>$$

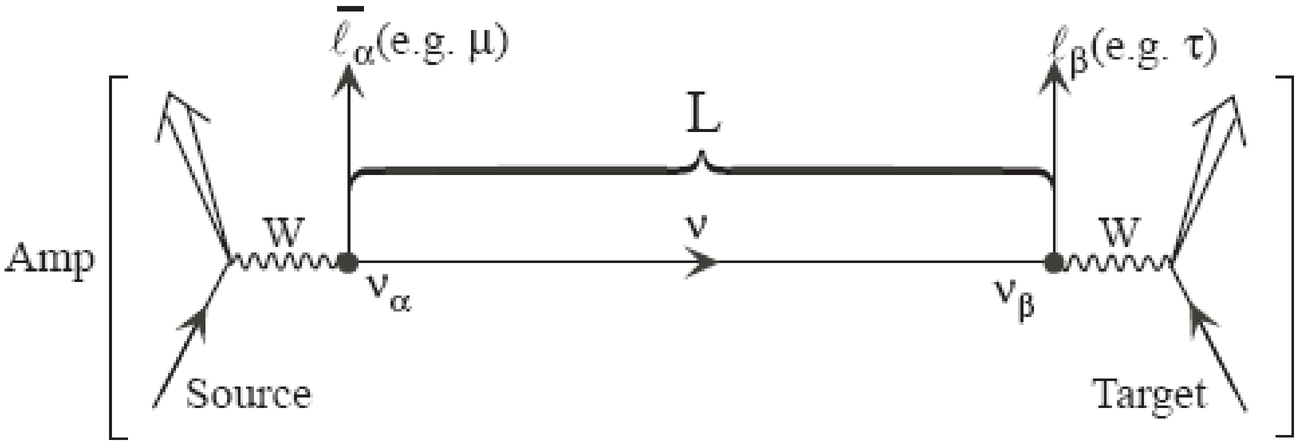
Flavour eigenstate: ν_e , ν_μ , ν_τ

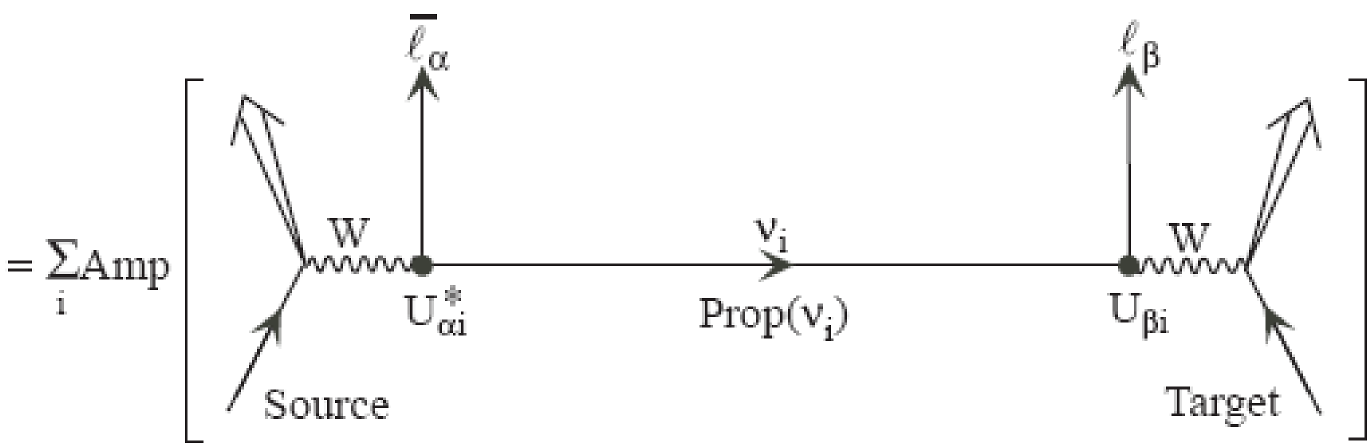
PMNS matrix

Mass eigenstate: ν_1 , ν_2 , ν_3

Charged currents: operate on flavour eigenstates → production, measurement

Propagation: mass eigenstates



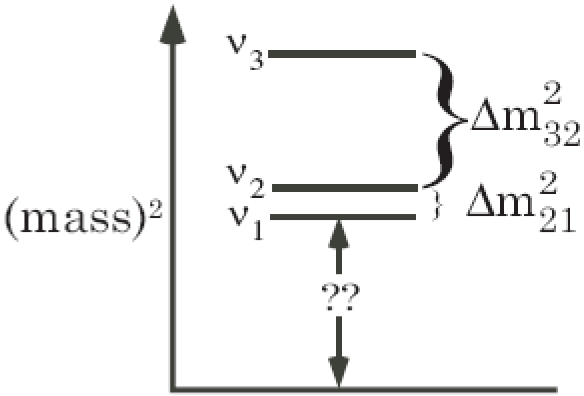


$$\mathrm{Amp}(\nu_\alpha \to \nu_\beta) = \sum_i U^*_{\alpha i} \mathrm{Prop}(\nu_i) U_{\beta i}$$

$$\mathrm{Prop}(\nu_i) = \exp[-im_i^2 \frac{L}{2E}]$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

$$\begin{aligned} \mathrm{P}(\nu_\alpha \to \nu_\beta) &= |\mathrm{Amp}(\nu_\alpha \to \nu_\beta)|^2 \\ &= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2(\Delta m_{ij}^2 \frac{L}{4E}) \\ &\quad + 2 \sum_{i>j} \Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin(\Delta m_{ij}^2 \frac{L}{2E}) \end{aligned}$$



$$\Delta m_{ij}^2 \frac{L}{4E} = 1.27\, \Delta m_{ij}^2(\mathrm{eV}^2) \frac{L\,(\mathrm{km})}{E\,(\mathrm{GeV})}$$

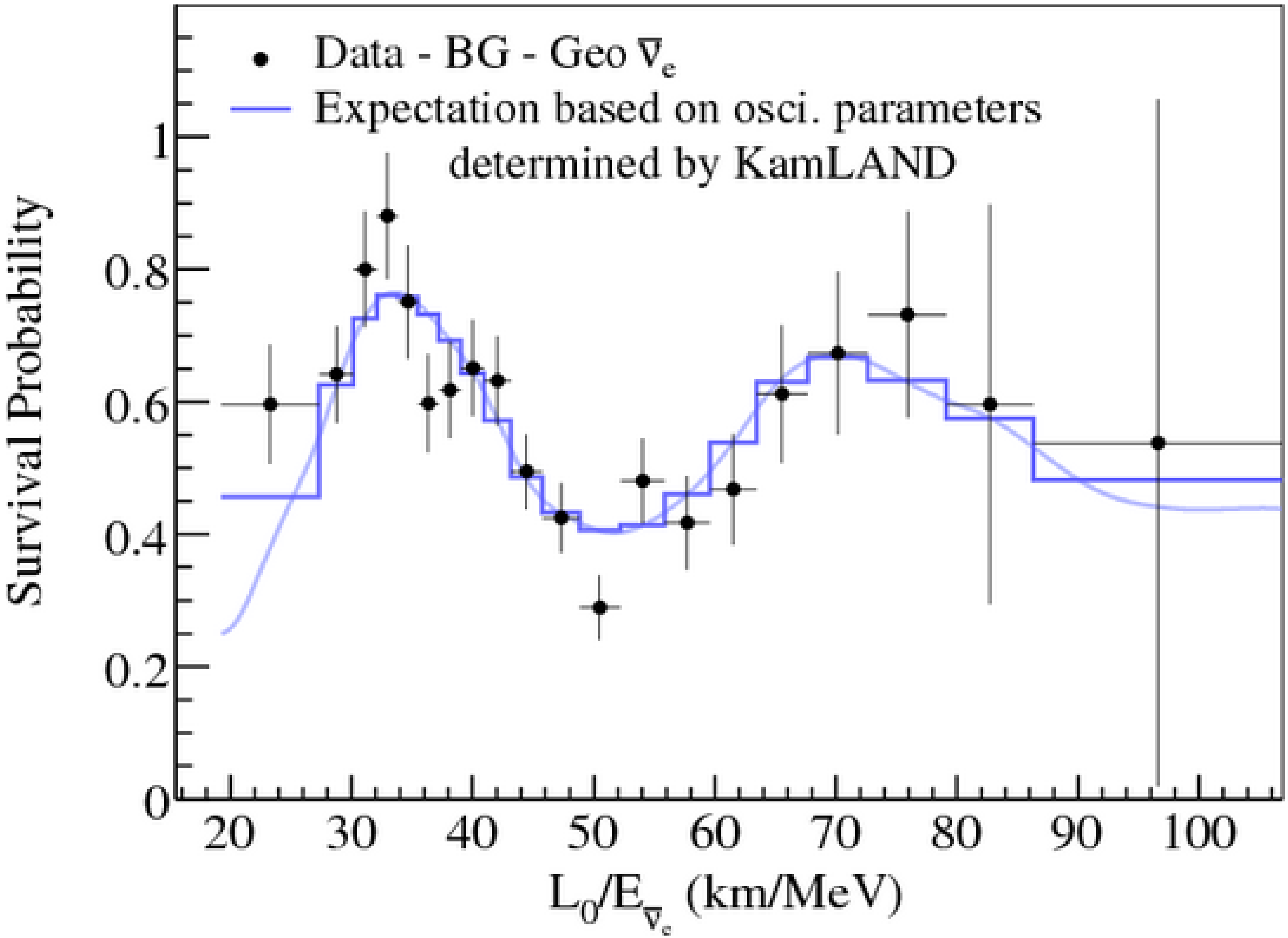
In simplified case of just 2 generations:

$$U = \begin{array}{c} \\ \nu_e \\ \nu_\mu \end{array} \begin{array}{c} \begin{array}{cc} \nu_1 & \nu_2 \end{array} \\ \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \end{array}$$

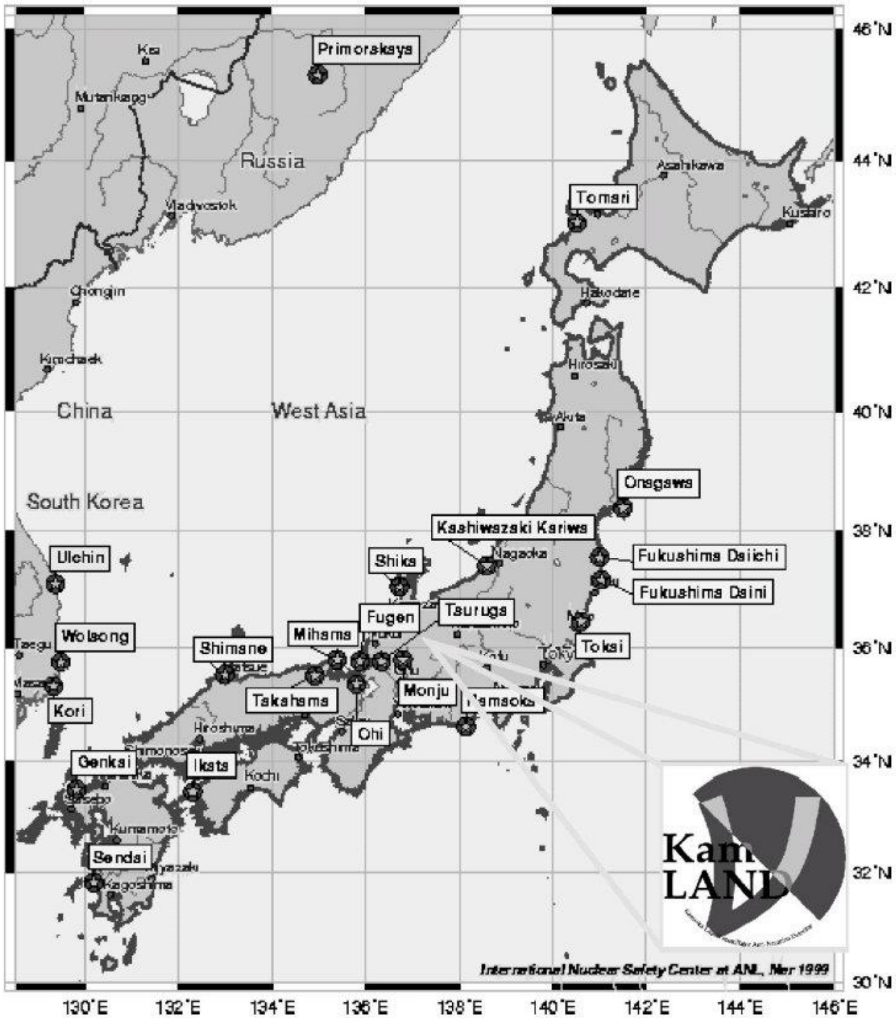
$$\mathrm{P}(\overset{(-)}{\nu_\alpha} \to \overset{(-)}{\nu_\beta}) = \sin^2 2\theta \sin^2(\Delta m^2 \frac{L}{4E})$$

oscillation

KamLand experiment, Japan



KamLAND



Site	Distance (km)	of cores	P_{th} (GW)	Flux ($\bar{\nu}_e$ cm^{-2} s^{-1})	Signal ($\bar{\nu}_e$/yr)
Japan					
Kashiwazaki	160.0	7	24.6	4.25×10^5	348.1
Ohi	179.5	4	13.7	1.88×10^5	154.0
Takahama	190.6	4	10.2	1.24×10^5	101.8
Hamaoka	214.0	4	10.6	1.03×10^5	84.1
Tsuruga	138.6	2	4.5	1.03×10^5	84.7
Shiga	80.6	1	1.6	1.08×10^5	88.8
Mihama	145.4	3	4.9	1.03×10^5	84.5
Fukushima-1	344.0	6	14.2	5.3×10^4	43.5
Fukushima-2	344.0	4	13.2	4.9×10^4	40.3
Tokai-II	294.6	1	3.3	1.7×10^4	13.7
Shimane	414.0	2	3.8	9.9×10^3	8.1
Onagawa	430.2	2	4.8	9.8×10^3	8.1
Ikata	561.2	3	6.0	8.4×10^3	6.9
Genkai	755.4	4	6.7	5.3×10^3	4.3
Sendai	824.1	2	3.3	3.5×10^3	2.8
Tomari	783.5	2	5.3	2.4×10^3	2.0
South Korea					
Ulchim	~750	4	11.2	8.8×10^3	7.2
Wolsong	~690	4	8.1	7.5×10^3	5.2
Yonggwang	~940	6	16.8	8.4×10^3	6.9
Kori	~700	4	8.9	8.0×10^3	6.6
Total		69	175.7	1.34×10^6	1101.6

Neutrinos from commercial nuclear power plants!

Experimental situation:

Solar neutrino oscillations: ν_e from the sun seem to disappear!
Actually transform into ν_μ and ν_τ

$\Delta m^2 \sim 8 \times 10^{-5}$ eV^2

Homestake, Gallex, SNO, KamLand,...

Atmospheric neutrino oscillations: ν_μ from cosmic ray interactions disappear

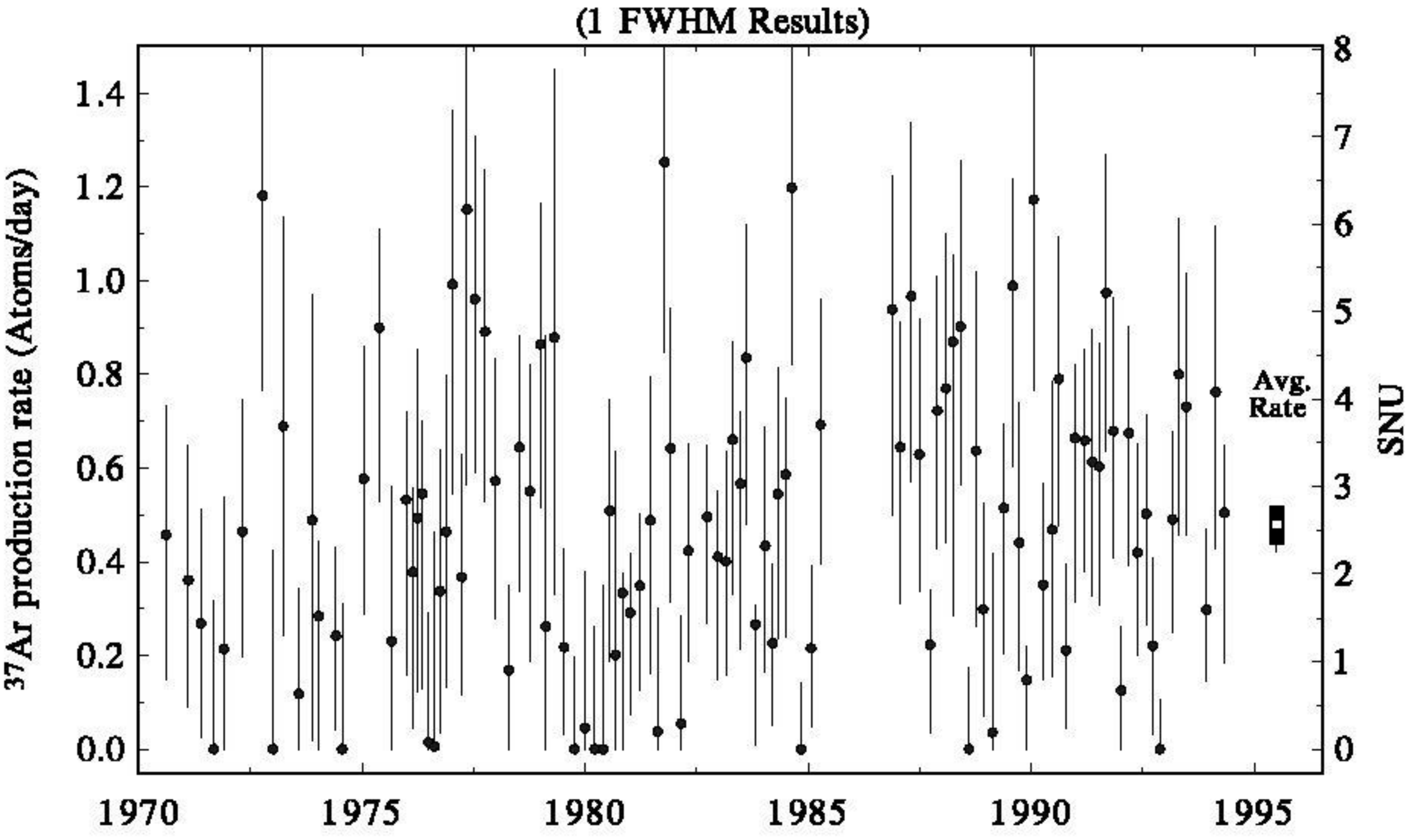
$\Delta m^2 \sim 3 \times 10^{-3}$ eV^2

Super-Kamiokande, K2K, MINOS,...

(LSND: accelerator @ Los Alamos: ν_μ transforming into ν_e with $\Delta m^2 \sim 1$ eV^2 ?
Doesn't fit into 3-neutrino picture!)

First indication: Homestake

Theory from solar model: 8.6 ± 1.2 SNU



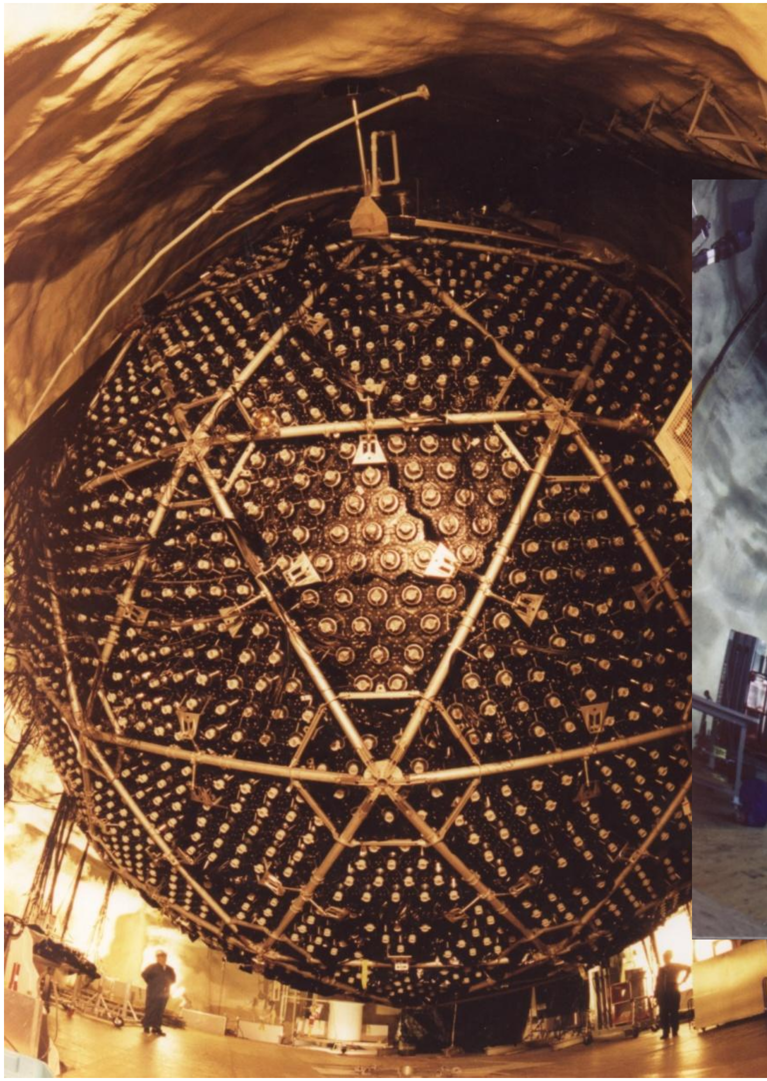
→ The sun produces neutrino's, but not nearly enough!

SNO experiment (Canada)

Measures CC as well as NC scattering

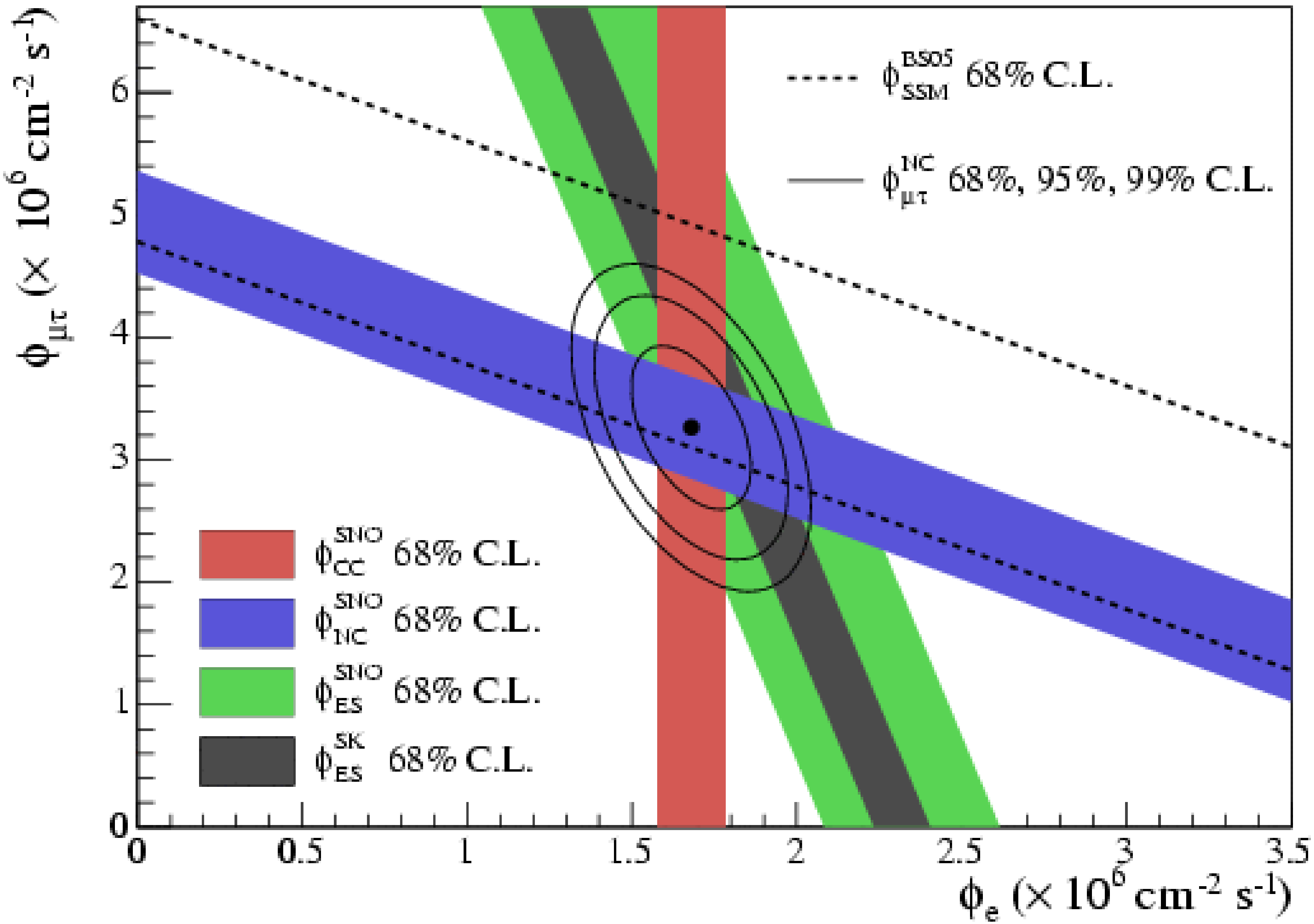
CC: only electron neutrinos

NC: all neutrino flavours



Result: neutrino flux agrees with solar models but only 1/3 are electron neutrinos

SNO result:



ϕ^{BS05}_{SSM} 68% C.L.
$\phi^{NC}_{\mu\tau}$ 68%, 95%, 99% C.L.
ϕ^{SNO}_{CC} 68% C.L.
ϕ^{SNO}_{NC} 68% C.L.
ϕ^{SNO}_{ES} 68% C.L.
ϕ^{SK}_{ES} 68% C.L.
$\phi_{\mu\tau}$ ($\times$ 10^6 cm^{-2} s^{-1})
ϕ_e ($\times$ 10^6 cm^{-2} s^{-1})
0
1
2
3
4
5
6
0.5
1.5
2.5
3.5

$$U = \overset{\text{Atmospheric}}{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}} \times \overset{\text{Cross-Mixing}}{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}} \times \overset{\text{Solar}}{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$

$\theta_{12} \sim 30^0$ $\theta_{23} \sim 45^0$ θ_{13} not yet measured, $< 5^0$

Big mixing (→ θ_{12})

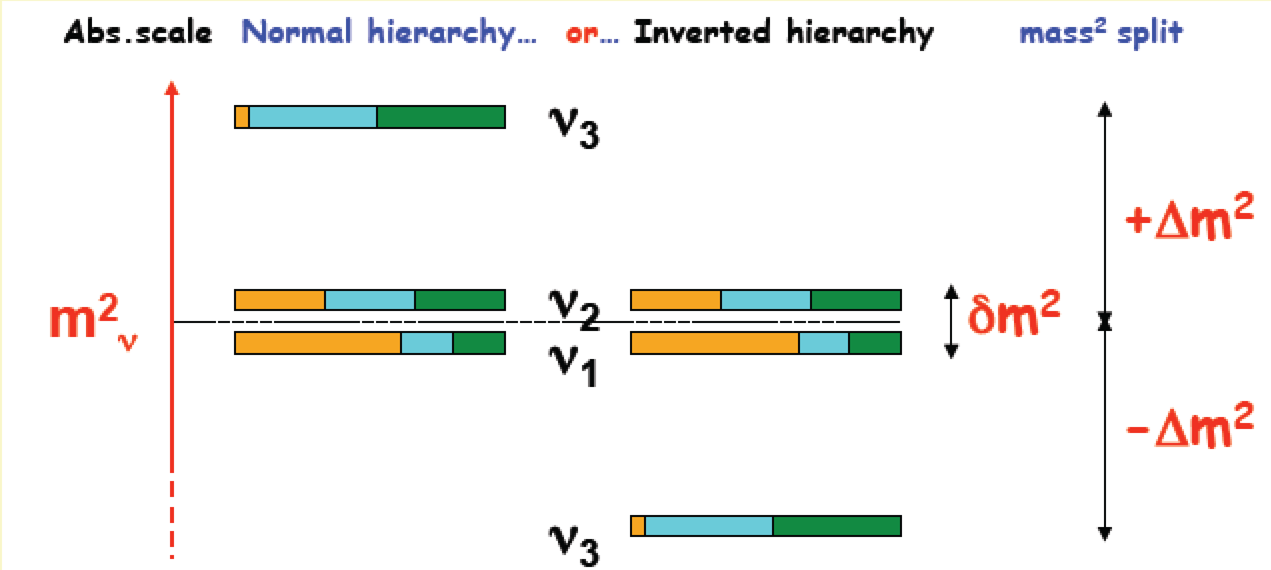
Maximal mixing! (→ θ_{23})

PMNS:

$$\begin{Bmatrix} 0.8 & 0.55 & <0.05 \\ 0.45 & 0.55 & 0.7 \\ 0.45 & 0.55 & 0.7 \end{Bmatrix}$$

CKM:

$$\begin{Bmatrix} 0.98 & 0.22 & 0.004 \\ 0.22 & 0.98 & 0.04 \\ 0.004 & 0.04 & 1 \end{Bmatrix}$$



$$\delta m^2 \sim 8 \times 10^{-5} \text{ eV}^2 \qquad \sin^2\theta_{12} \sim 0.3$$
$$\Delta m^2 \sim 3 \times 10^{-3} \text{ eV}^2 \qquad \sin^2\theta_{23} \sim 0.5$$

$$m_\nu < O(1) \text{ eV} \qquad \sin^2\theta_{13} < \text{few}\%$$

$$\text{sign}(\pm\Delta m^2) \text{ unknown} \qquad \delta \text{ (CP) unknown}$$

Absolute neutrino mass

Beta decay : $|m_\nu| = \Sigma\, |U_{ei}|\, m_i$ < 2.6 eV (90 % CL)

Double beta : $\langle m_{ee}\rangle = |\Sigma\, U^2_{ei}\, m_i|$ $< 0.3 - 0.7$ eV (95% CL)

Cosmology : $m_\nu = m_1 + m_2 + m_3$ $< 0.5 - 1$ eV (95 % CL)

This is very different from CKM matrix!   Why?   Nobody knows!

Open questions: θ_{13} ?

δ ?

Is the 3-neutrino picture correct?

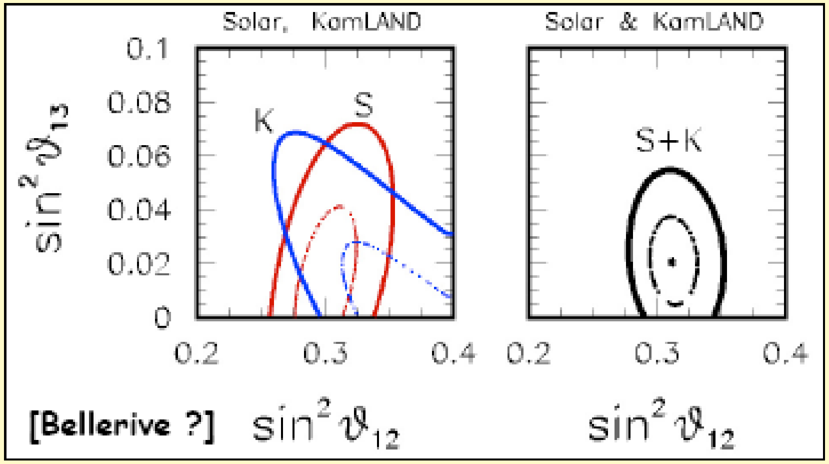
Explain the form of the PMNS matrix?

What are the neutrino masses exactly?
Why are they so small?

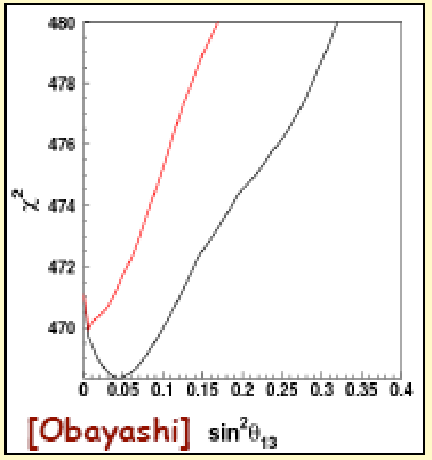
Neutrinos: Dirac or Majorana?

Hints of $\theta_{13}>0$? [Fogli, EL, Marrone, Palazzo, Rotunno.] Current status:

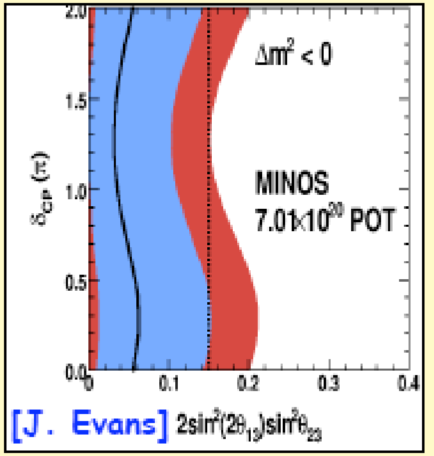
Solar & KamLAND: ~1.5σ



SK atmos.: ~1.5σ



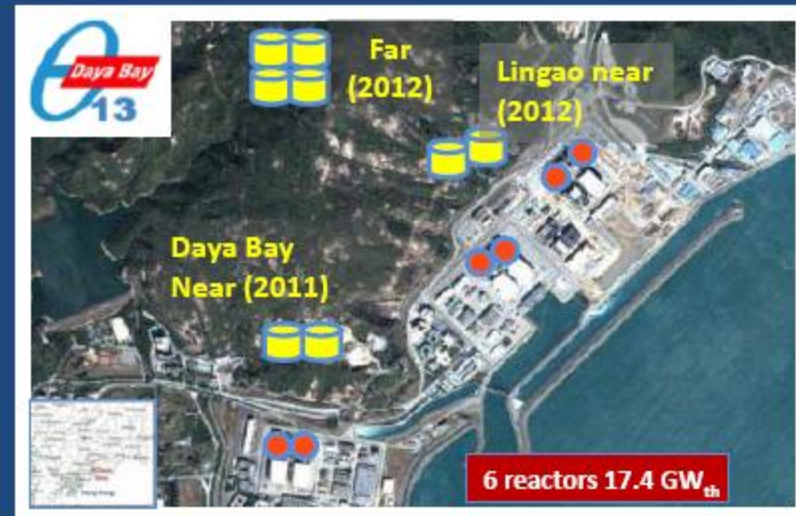
MINOS: ~0.7σ



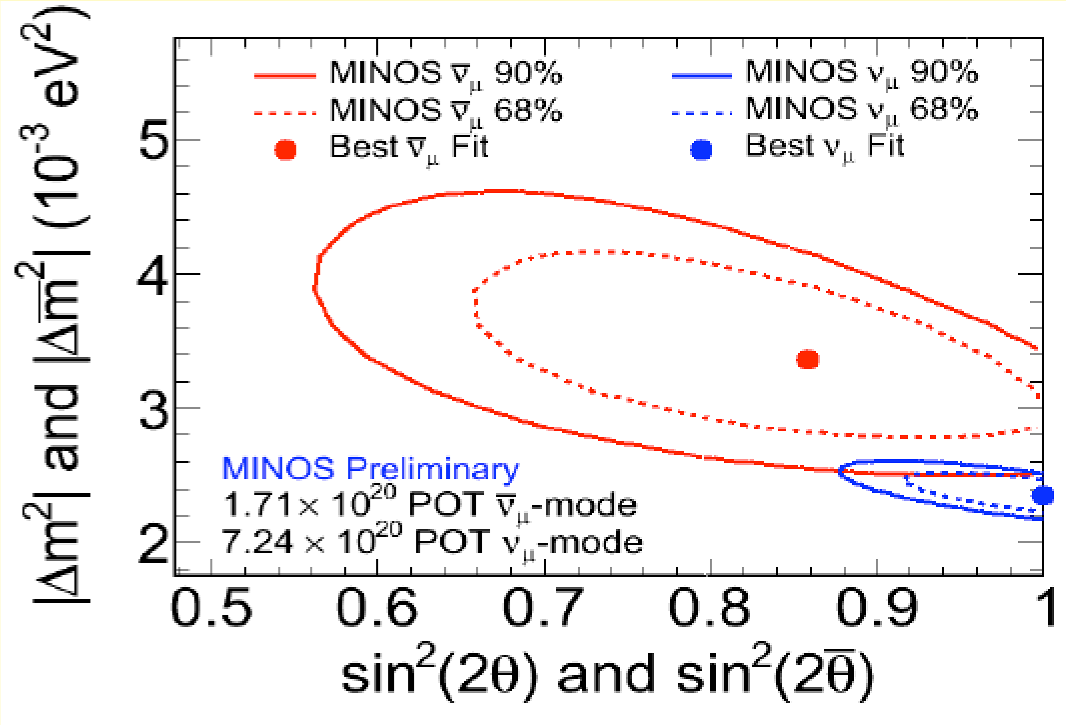
Overall significance close to ~2σ. Intriguing, but still weak.

Need direct θ_{13} searches at reactors/accelerators. Results will be decisive to plan next steps: The larger θ_{13}, the "easier" will be to probe CPV and the mass hierarchy at future accelerator facilities.

Reactor neutrinos



	Location	Thermal Power	Distance Near/far	Depth Near/far
Double Chooz	France	8.5	410/1050	120/300
RENO	South Korea	17.3	290/1380	120/450
DAYA BAY	China	17.4	360/1985 500/1613	260/910



MINOS: some tension at 2σ level

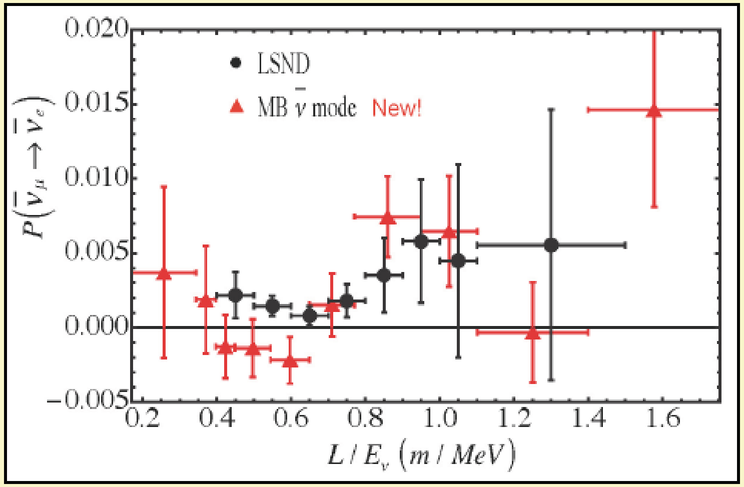
Nasty surprises 2010?

Neutrino parameters

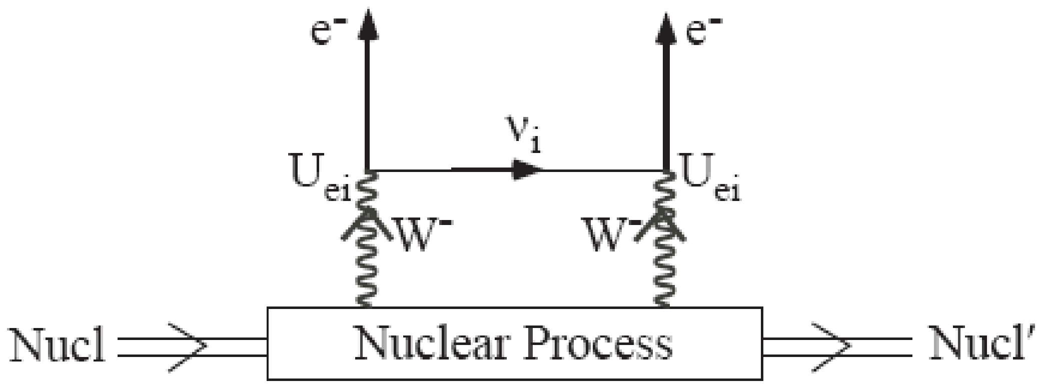
≠

Antineutrino parameters?

Minos: Fermilab → Minnesota



Mini-Boone @ Fermilab checking LSND
Results inconclusive!



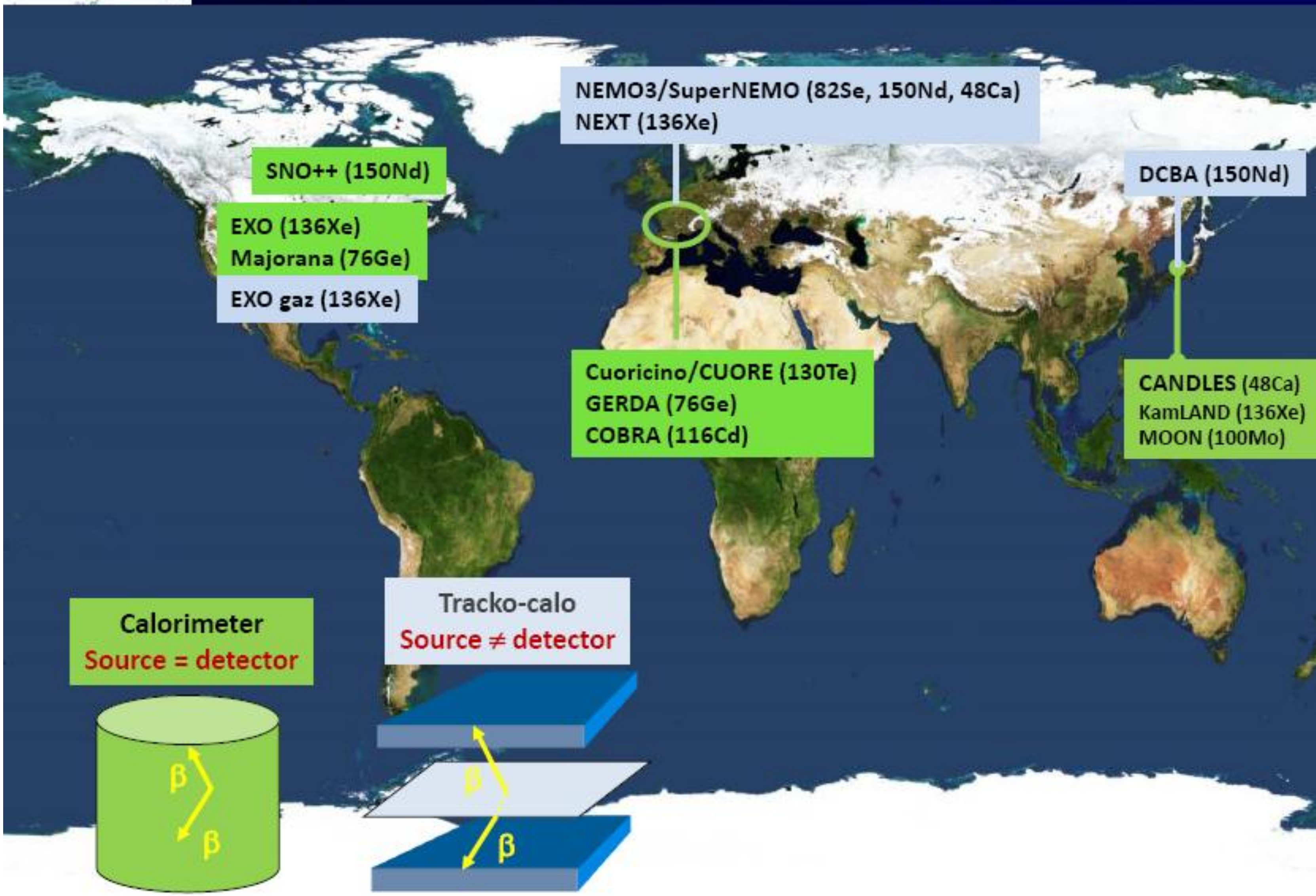
Neutrinoless double beta decay ($0\nu\beta\beta$)

Not possible if neutrino is Dirac particle: $\bar{\nu} \neq \nu$

But possible if neutrino is Majorana particle: $\bar{\nu} = \nu$
(Violation of lepton number!)

Experimental sign: double beta decay, no energy lost by neutrinos
Rare! Need low noise detectors, excellent energy resolution!

ββ(0ν) : experiments and projects



Leptonic CP violation + Majorana neutrinos ($0\nu2\beta$) would make it plausible that heavy ν_R at a new-physics scale m_R may induce:

- Matter-antimatter asymmetry (via leptogenesis, $\nu_R \rightarrow l^+ \neq \nu_R \rightarrow l^-$)
- Small Majorana ν masses (via see-saw mechanism, $m \sim m_D^2/m_R$)

Leptogenesis

Generating the matter-antimatter asymmetry via baryogenesis (Sacharov) seems to run into trouble.

Can mixing and CP-violation in the lepton sector save us?
→**Leptogenesis**

Required: $\theta_{13} \neq 0$

Sizable CP-violation in lepton sector

A mechanism to transfer lepton asymmetry to baryons
(needs lepton- and baryon number violation)

Absolute neutrino mass

Beta decay : $|m_\nu| = \Sigma\, |U_{ei}|\, m_i$ < 2.6 eV (90 % CL)

Double beta : $\langle m_{ee}\rangle = |\Sigma\, U^2_{ei}\, m_i|$ < 0.3 – 0.7 eV (95% CL)

Cosmology : $m_\nu = m_1 + m_2 + m_3$ < 0.5 – 1 eV (95 % CL)

Neutrino mass from beta decay: originally expressed as mass limit on ν_e mass

But it does not make sense to talk about ν_e mass!

Rather, one measures $\Sigma\, |U_{ei}|\, m_i$

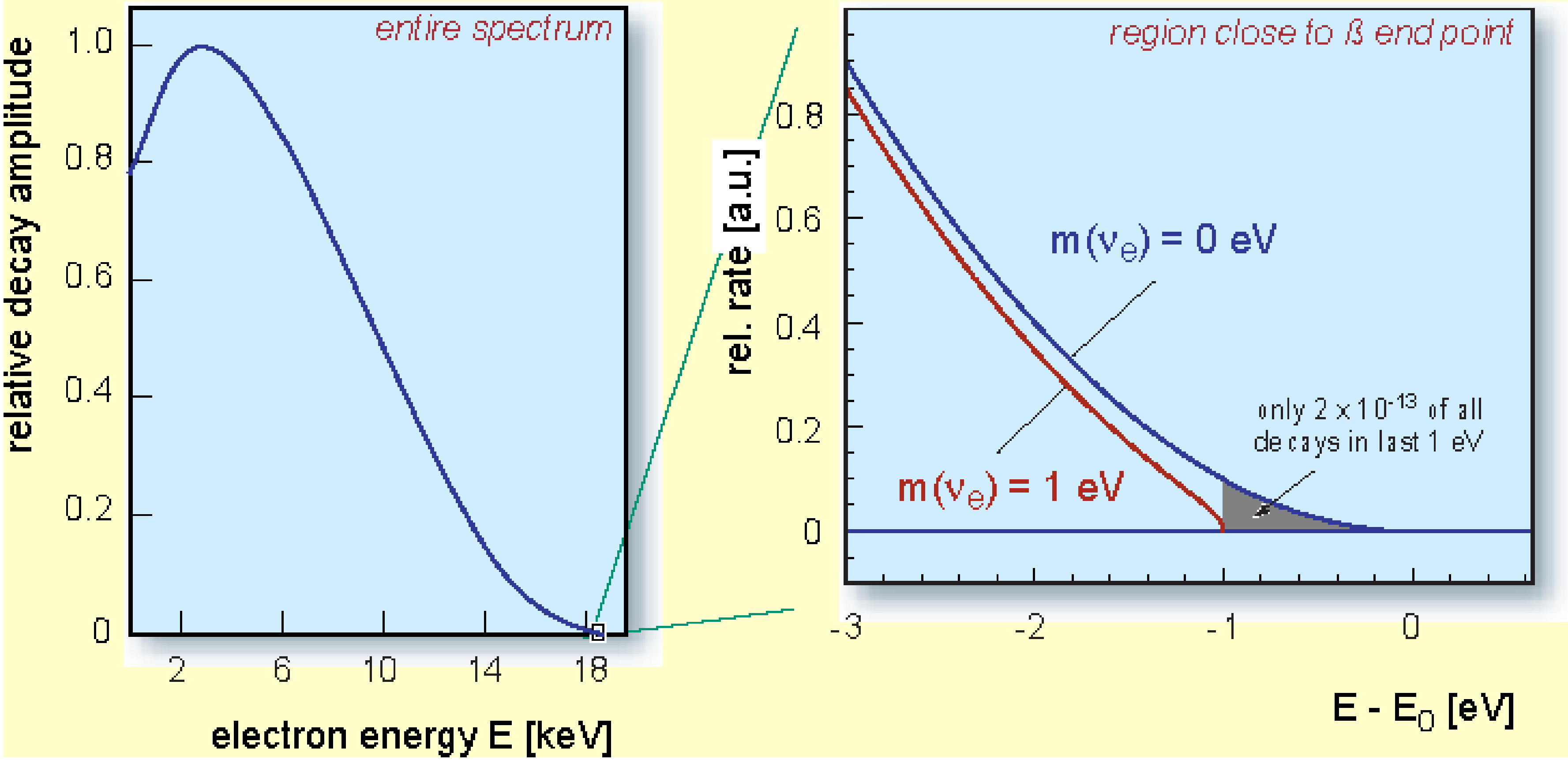
tritium ß-decay and the neutrino rest mass

$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

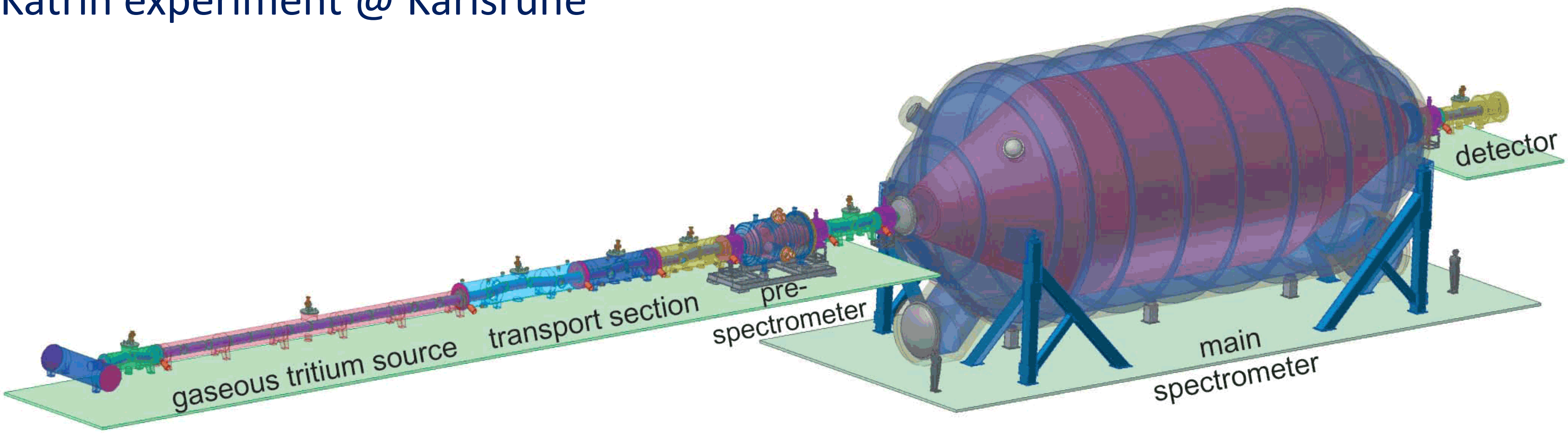
superallowed

half life : $t_{1/2}$ = 12.32 a

ß end point energy : E_0 = 18.57 keV



Katrin experiment @ Karlsruhe



Neutrino masses: the seesaw mechanism

Neutrinos can have Dirac mass term in Lagrangian: $\mathcal{L}_D = -m_D \, \overline{\nu_L} \, \nu_R + \mathrm{h.c.}$

But if they are Majorana particles, also this term: $\mathcal{L}_M = -m_M \, \overline{\nu_R^c} \, \nu_R + \mathrm{h.c.}$

ν_R^c is the charge conjugate of ν_R.

$$(\nu_L, N) \cdot \begin{pmatrix} m^M & m^D \\ m^D & M^M \end{pmatrix} \begin{pmatrix} \nu_L \\ N \end{pmatrix}$$

$m^M = 0$ $\quad\quad$ M^M could *a priori* be $\mathcal{O}(M_{GUT})$

$$\nu_L + 0\left(\frac{m_W}{m_X}\right) N \quad : \quad m = \mathcal{O}\left(\frac{m_W^2}{m_{GUT}}\right)$$

$$N + 0\left(\frac{m_W}{m_X}\right) \nu_L \quad : \quad M = \mathcal{O}(M_{GUT})$$

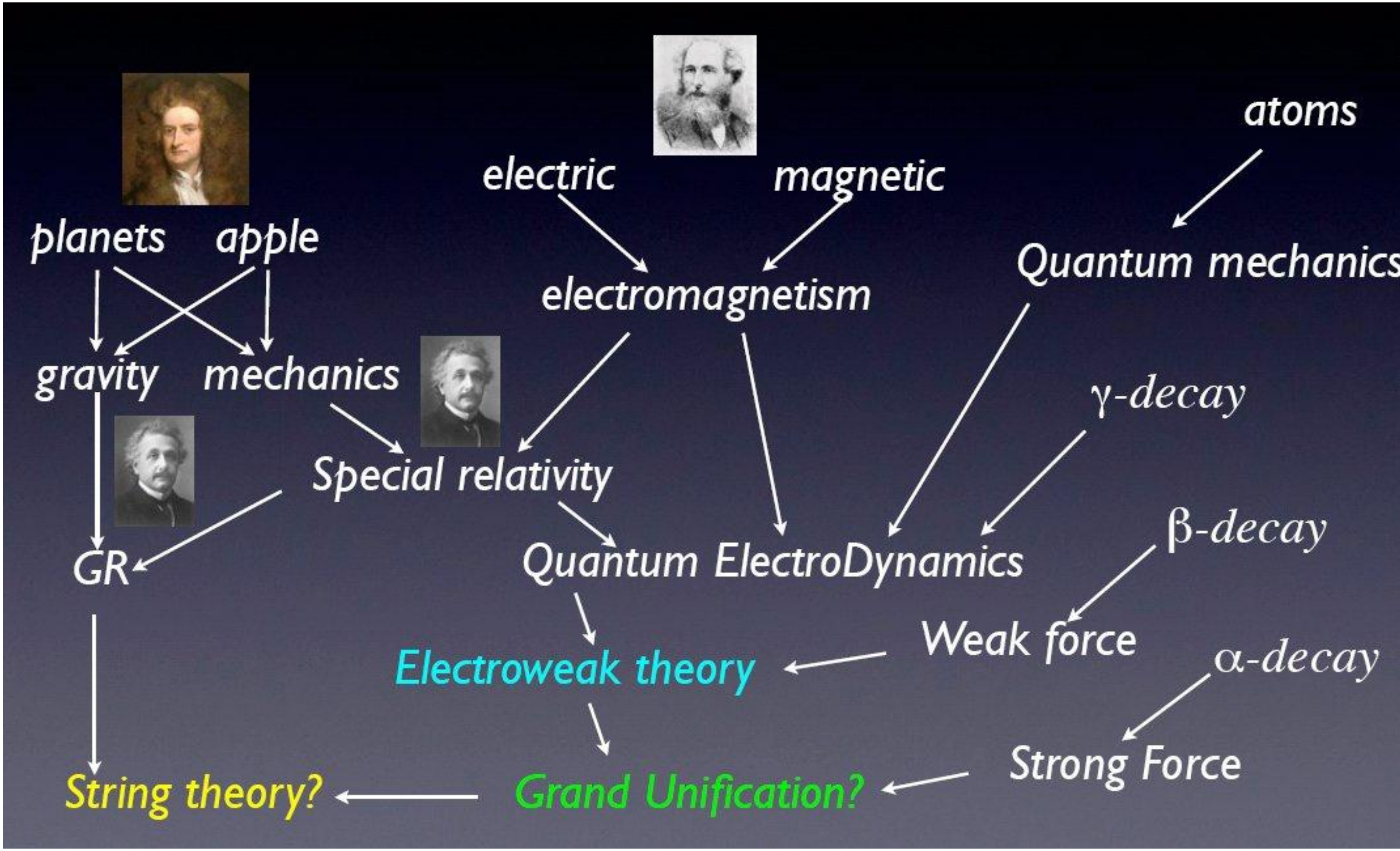
Works if $M_{GUT} \sim 10^{14} - 10^{16}$ GeV

M_{GUT} ?

Unification of forces

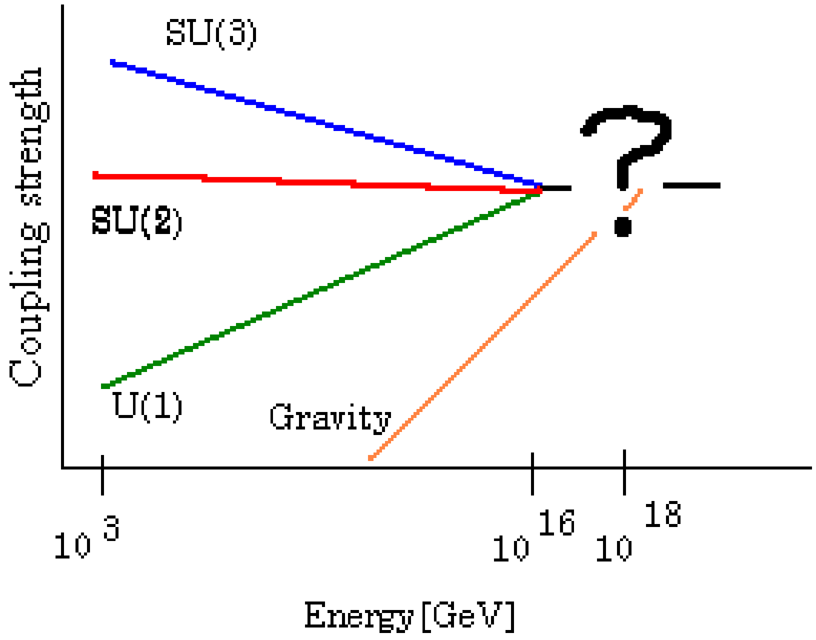
GUTs? Gravity?

Why unification? A unified theory is more than the sum of parts.

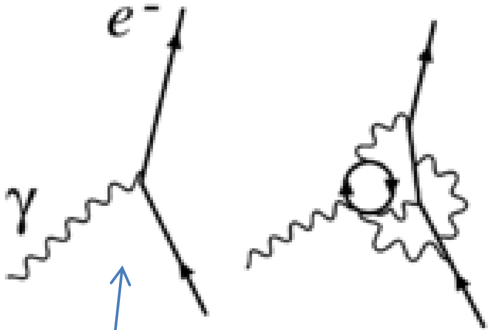


$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

Each group has a coupling constant (e.g. α_s)



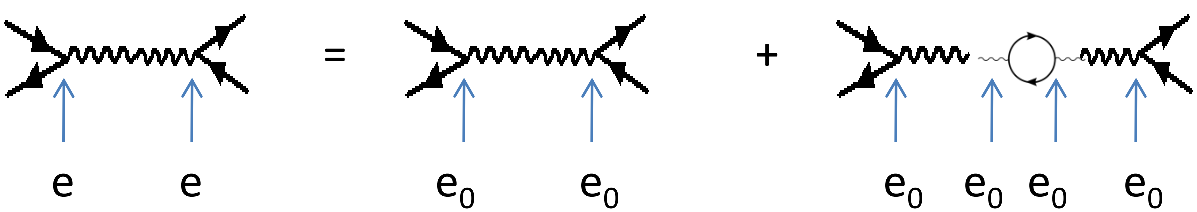
Coupling constants are NOT constant: they "run"



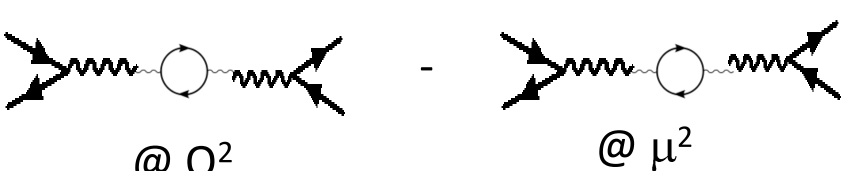
The details of a vertex depends on the scale at which you probe that vertex

Higher scale = better resolution

Lower scale = poorer resolution



+ … @ scale Q^2



$$= \frac{\alpha}{3\pi}\log\frac{\mu^2}{Q^2}$$

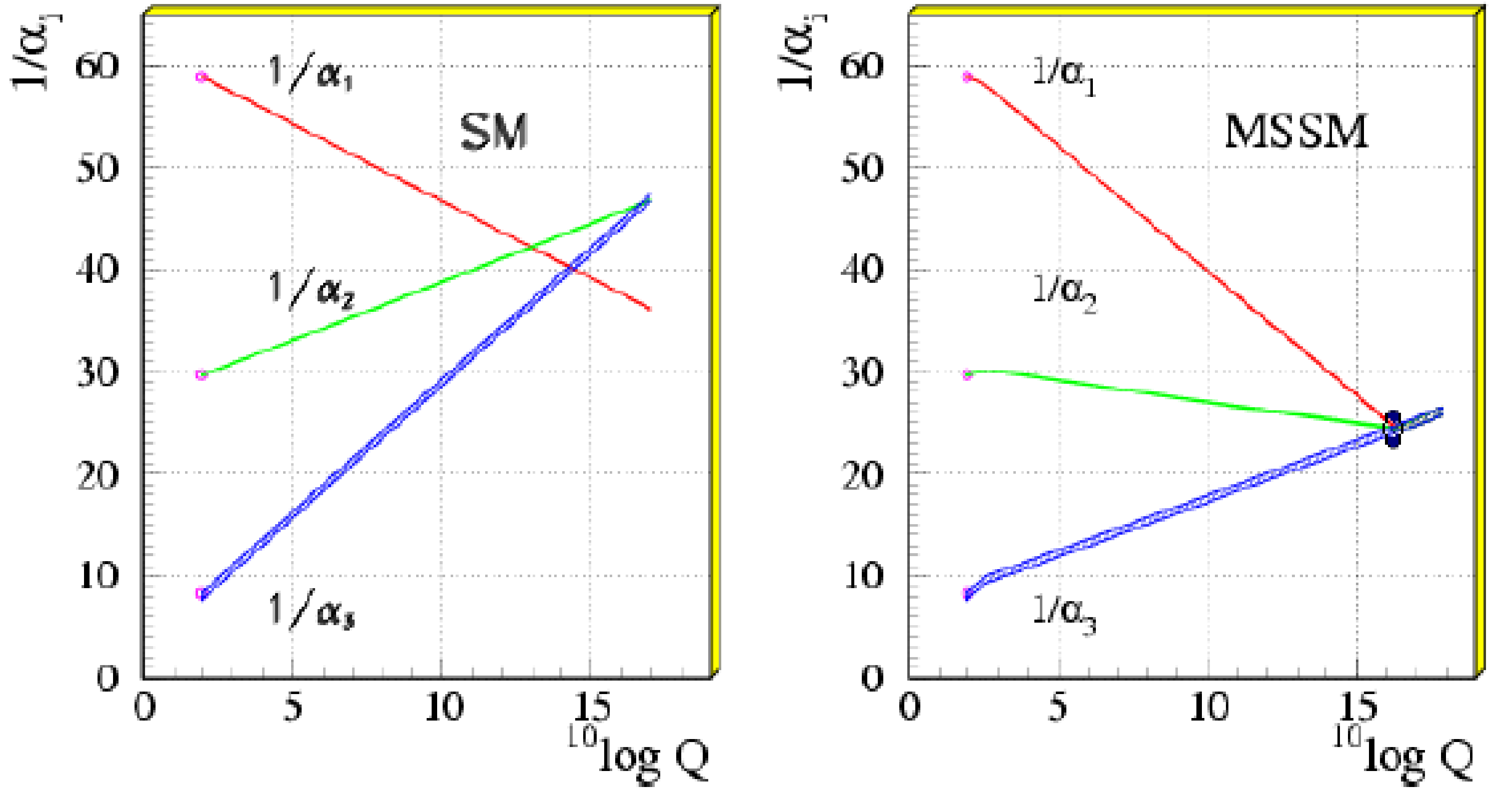
μ^2 is the renormalization scale.
The final matrix element M for any process can not depend on μ !

$$\mu \frac{dM}{d\mu} = \left(\mu \frac{\partial}{\partial \mu}\bigg|_e + \mu \frac{\partial e}{\partial \mu} \frac{\partial}{\partial e}\right) M = 0$$

→ **Renormalization Group Equation (RGE)**

In QED: $$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{3\pi} \log \frac{Q^2}{\mu^2}}$$

In QCD: $$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi} (33 - 2n_f) \log \frac{Q^2}{\mu^2}}$$



Unification: at M_{GUT} = $10^{14} - 10^{16}$ GeV!

With supersymmetry (see later) it works better.

For $Q^2 < M_{GUT}^2$: individual couplings, $SU(3)_C \times SU(2)_L \times U(1)_Y$

For $Q^2 > M_{GUT}^2$: unified coupling g_G , new gauge group G

Appropriate gauge groups

We want a group $G \supset SU(3) \times SU(2) \times U(1)$

We also want to combine the fermions:

unifying representations R that contain both quarks and leptons.

The basic rules of GUT model-building are that one must look for (a) a gauge group of rank 4 or more – to accommodate the Standard Model $SU(3) \times SU(2) \times U(1)$ gauge group – which (b) admits complex representations – to accommodate the known matter fermions.

$$Sp(8)\ ,\quad SO(8)\ ,\quad SO(9)\ ,\quad F_4\ ,\quad SU(3)\times SU(3)\ ,\quad SU(5)$$

Among these, only $SU(3) \times SU(3)$ and $SU(5)$ have complex representations. Moreover, if one tried to use $SU(3) \times SU(3)$, one would need to embed the electroweak gauge group in the second $SU(3)$ factor. This would be possible only if $\sum_q Q_q = 0 = \sum_\ell Q_\ell$, which is not the case for the known quarks and leptons. Therefore, attention has focussed on $SU(5)$ [8] as the only possible rank-4 GUT group.

Rank of a group?

The basic rules of GUT model-building are that one must look for (a) a gauge group of rank 4 or more – to accommodate the Standard Model $SU(3) \times SU(2) \times U(1)$ gauge group – which (b) admits complex representations – to accommodate the known matter fermions. The rank of a gauge group is the number of generators that can be diagonalized simultaneously, i.e., the number of quantum numbers that it admits. For example, $SU(2)$ and $U(1)_{em}$ both have rank 1 corresponding to I_3 and Q_{em}, respectively, and $SU(3)$ has rank 2 corresponding to T_3 and Y.

SU(5):

The quarks and leptons of each generation are accommodated in $\underline{5}$ and $\underline{10}$ representations of $SU(5)$:

$$\bar{F} = \begin{pmatrix} d^c_R \\ d^c_Y \\ d^c_B \\ \cdots \\ -e^- \\ \nu_e \end{pmatrix}_L , \quad T = \begin{pmatrix} 0 & u^c_B & -u^c_Y & \vdots & -u_R & -d_R \\ -u^c_B & 0 & u^c_R & \vdots & -u_Y & -d_Y \\ u^c_Y & -u^c_R & 0 & \vdots & -u_B & -d_B \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ u_R & u_Y & u_B & \vdots & 0 & -e^c \\ d_R & d_Y & d_B & \vdots & e^c & 0 \end{pmatrix}_L \qquad (104)$$

$$\underline{\bar{5}} = (\bar{3}, 1) + (1, 2) \ , \quad \underline{10} = (3, 2) + (\bar{3}, 1) + (1, 2)$$

And there are $5^2 - 1 = 24$ gauge bosons:

8 gluons, W_i (i=1..3), B

12 new gauge bosons X, Y charges 4/3, 1/3 coupling to q, l

In the SM, it is a puzzle why

$$\sum_{q,\ell} Q_i = 3Q_u + 3Q_d + Q_e = 0 \tag{100}$$

In the Standard Model, the hypercharge assignments are **a priori** independent of the $SU(3) \times SU(2)_L$ assignments, although constrained by the fact that quantum consistency requires the resulting triangle anomalies to cancel. In a simple GUT, the relation (100) is automatic: whenever Q is a generator of a simple gauge group, $\sum_R Q = 0$ for particles in any representation R (consider, e.g., the values of I_3 in any representation of $SU(2)$).

→Charge d-quark must be 1/3 of electron charge
→Charge u-quark must be -2 times d-quark charge

Another qualitative success is the prediction of the b quark mass [90, 91]. In many GUTs, such as the minimal $SU(5)$ model discussed shortly, the b quark and the τ lepton have equal Yukawa couplings when renormalized at the GUT sale. The renormalization group then tells us that

$$\frac{m_b}{m_\tau} \simeq \left[\ln \left(\frac{m_b^2}{m_X^2} \right) \right]^{\frac{12}{33-2N_q}} \tag{91}$$

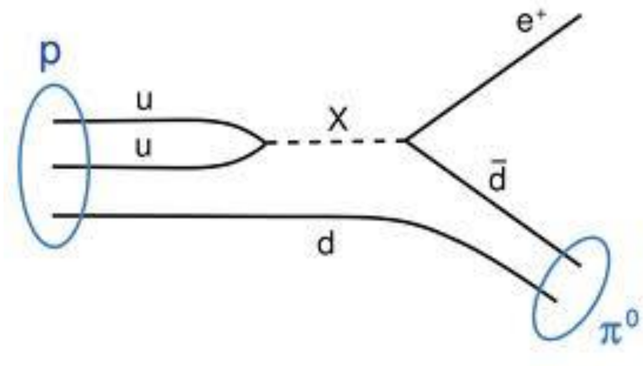
Using $m_\tau = 1.78$ GeV, we predict that $m_b \simeq 5$ GeV, in agreement with experiment[7]. Happily, this prediction remains successful if the effects of supersymmetric particles are included in the renormalization-group calculations [92].

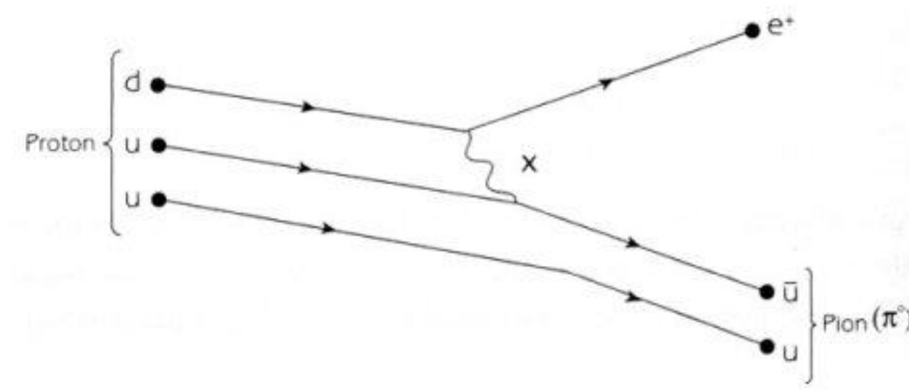
$$\sin^2 \theta_W = \frac{\alpha_{em}(m_W)}{\alpha_2(m_W)} \simeq \frac{3}{8} \quad \left[1 - \frac{\alpha_{em}}{4\pi} \quad \frac{110}{9} \ln \frac{m_X^2}{m_W^2} \right]$$

which can be evaluated to yield $\sin^2 \theta_W \sim 0.210$ to 0.220, if there are only Standard Model particles with masses $\lesssim m_X$ [7]. This is to be compared with the experimental value $\sin^2 \theta_W = 0.23155 \pm 0.00019$ shown in Fig. 2. Considering that $\sin^2 \theta_W$ could *a priori* have had any value between 0 and 1, this is an impressive qualitative success. The small discrepancy can be removed by adding some extra particles, such as the supersymmetric particles in the MSSM.

Proton decay

New gauge bosons X, Y couple to quarks and leptons, violate baryon number
→ Proton can decay



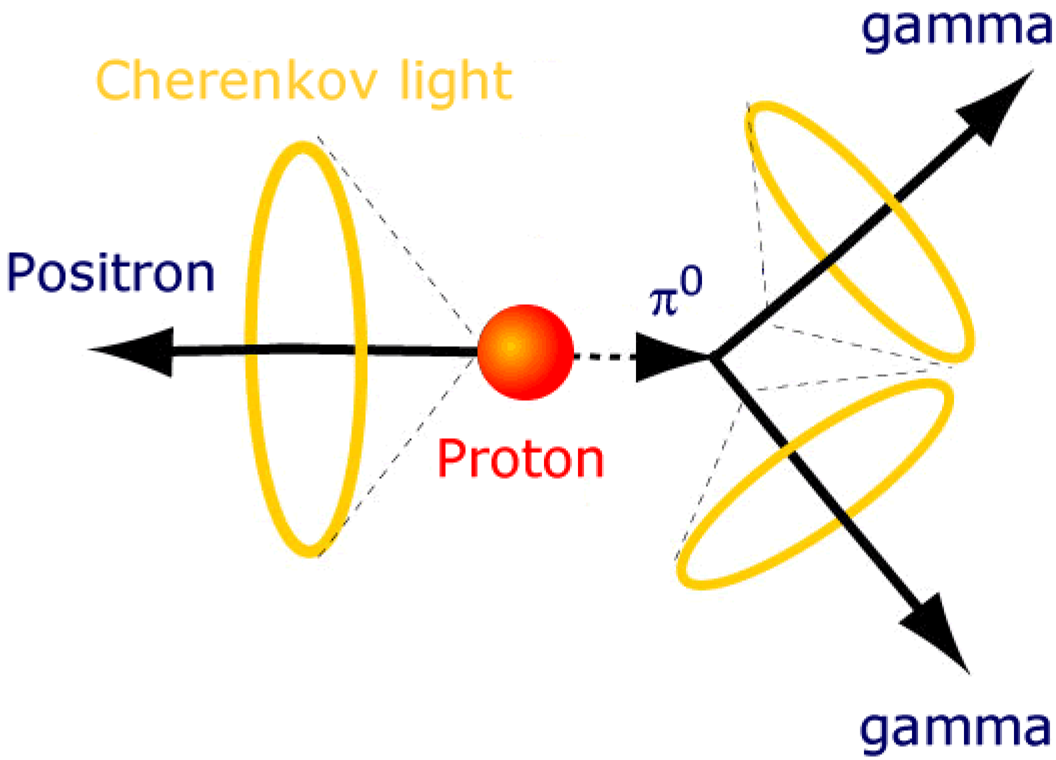


Calculate rate by comparing to muon decay (weak interaction)

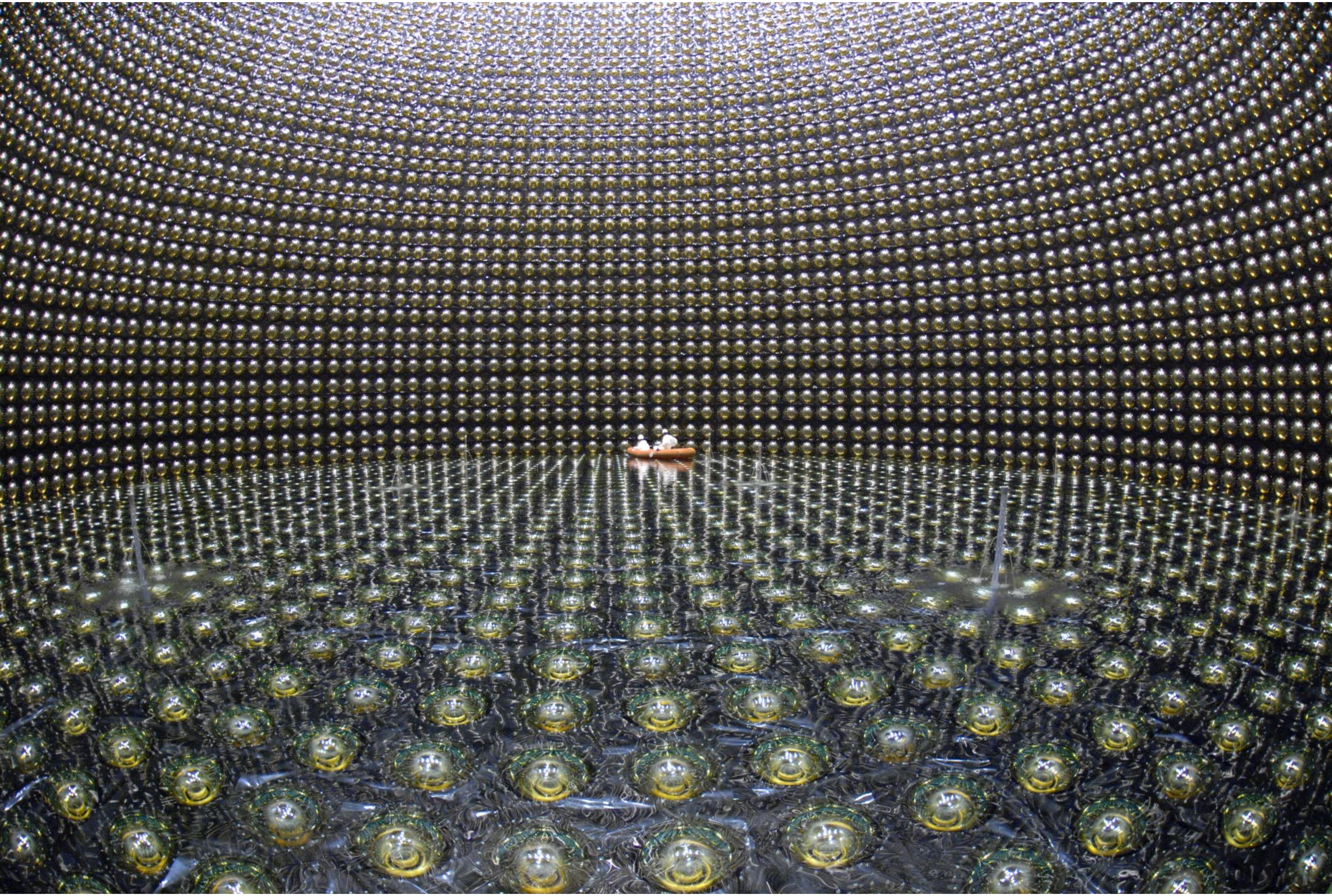
$$\Gamma(\mu \to e\nu\nu) \sim G_F^2 m_\mu^5 \sim \frac{m_\mu^5}{M_W^4} \qquad \frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

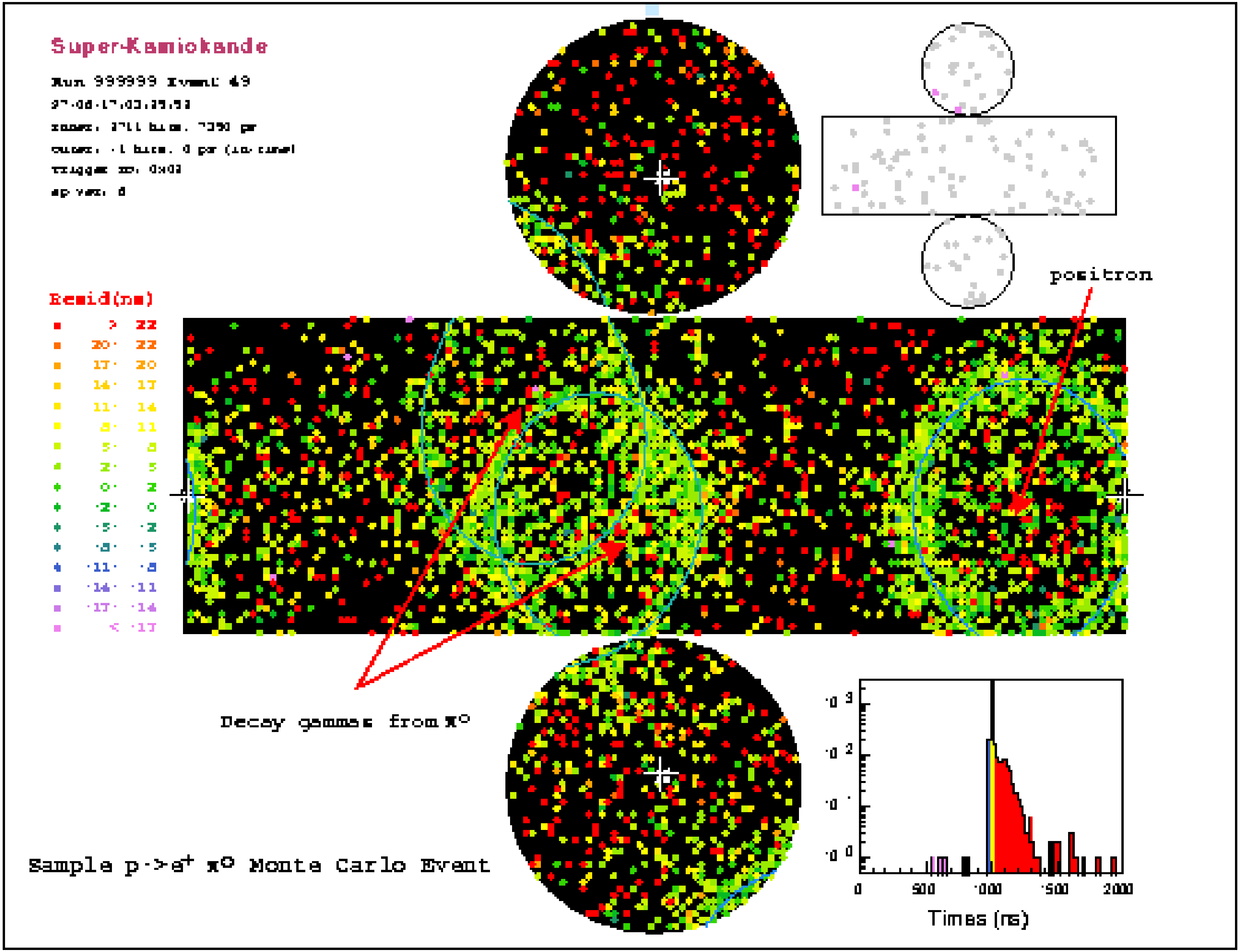
$$\Gamma(p \to e^+\pi^0) \sim \frac{m_p^5}{M_X^4}$$

For $M_X \sim 10^{15\text{-}16}$ GeV → $\tau \sim 10^{31\text{-}33}$ year


gamma
Cherenkov light
Positron
π^0
Proton
gamma

Super-Kamiokande




Super-Kamiokande
Run 999999 Event 49
Resid(ns)
> 22
20 - 22
17 - 20
14 - 17
11 - 14
8 - 11
5 - 8
2 - 5
0 - 2
-2 - 0
-5 - -2
-8 - -5
-11 - -8
-14 - -11
-17 - -14
< -17
positron
Decay gammas from π0
Sample p->e+ π0 Monte Carlo Event
0
500
1000
1500
2000
Times (ns)

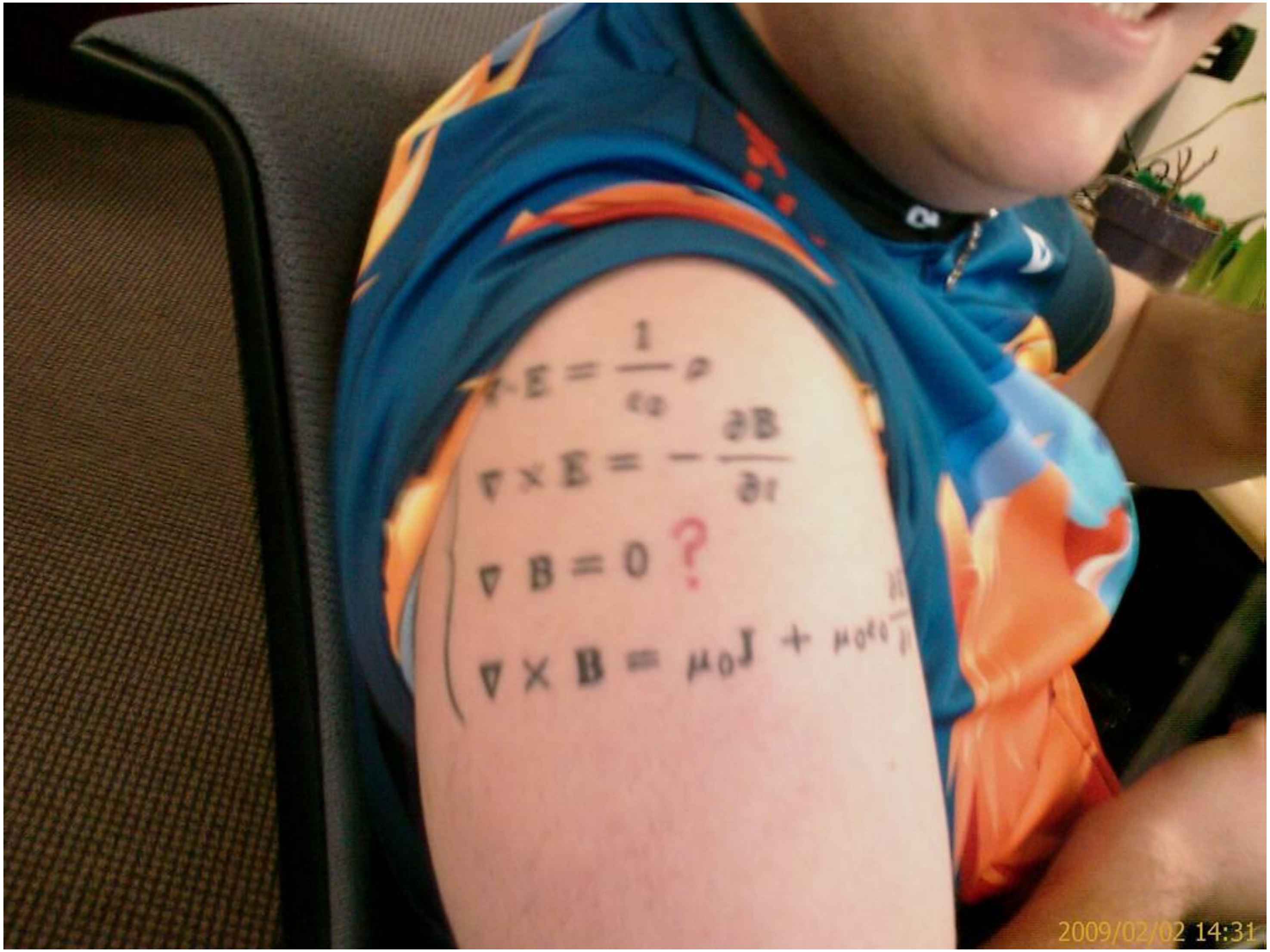
Latest Super-Kamiokande result:

τ (p $\rightarrow$ e^+ π^0) > 8.2 x 10^{33} year   at 90% CL

(0 events observed, 0.3 expected)

Compare to current age of universe: 1.4 x 10^{10} year!

GUTs typically predict the existence of magnetic monopoles
→ Make Maxwell's equations more symmetric!



GUT prediction: $Q_E^{\rm min} Q_M^{\rm min} = 2\pi$

For example, an SU(5) model with

$$\mathrm{SU}(5) \xrightarrow{M_X} \mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1) \xrightarrow{M_W} \mathrm{SU}(3) \times \mathrm{U}(1) \qquad (5)$$

has a monopole [6] with $Q_M = 2\pi/e$ and mass

$$M_{\rm mon} \sim \frac{4\pi M_{\rm X}}{g^2}\,, \qquad (6)$$

where g is the SU(5) gauge coupling. For a unification scale of 10^{16} GeV, these monopoles would have a mass $M_{\rm mon} \sim 10^{17} - 10^{18}$ GeV.

But in other models much lighter monopoles could exist

Dirac’s observation:

“ The existence of a magnetic monopole anywhere in the universe leads
to electric charge quantization everywhere in the universe”

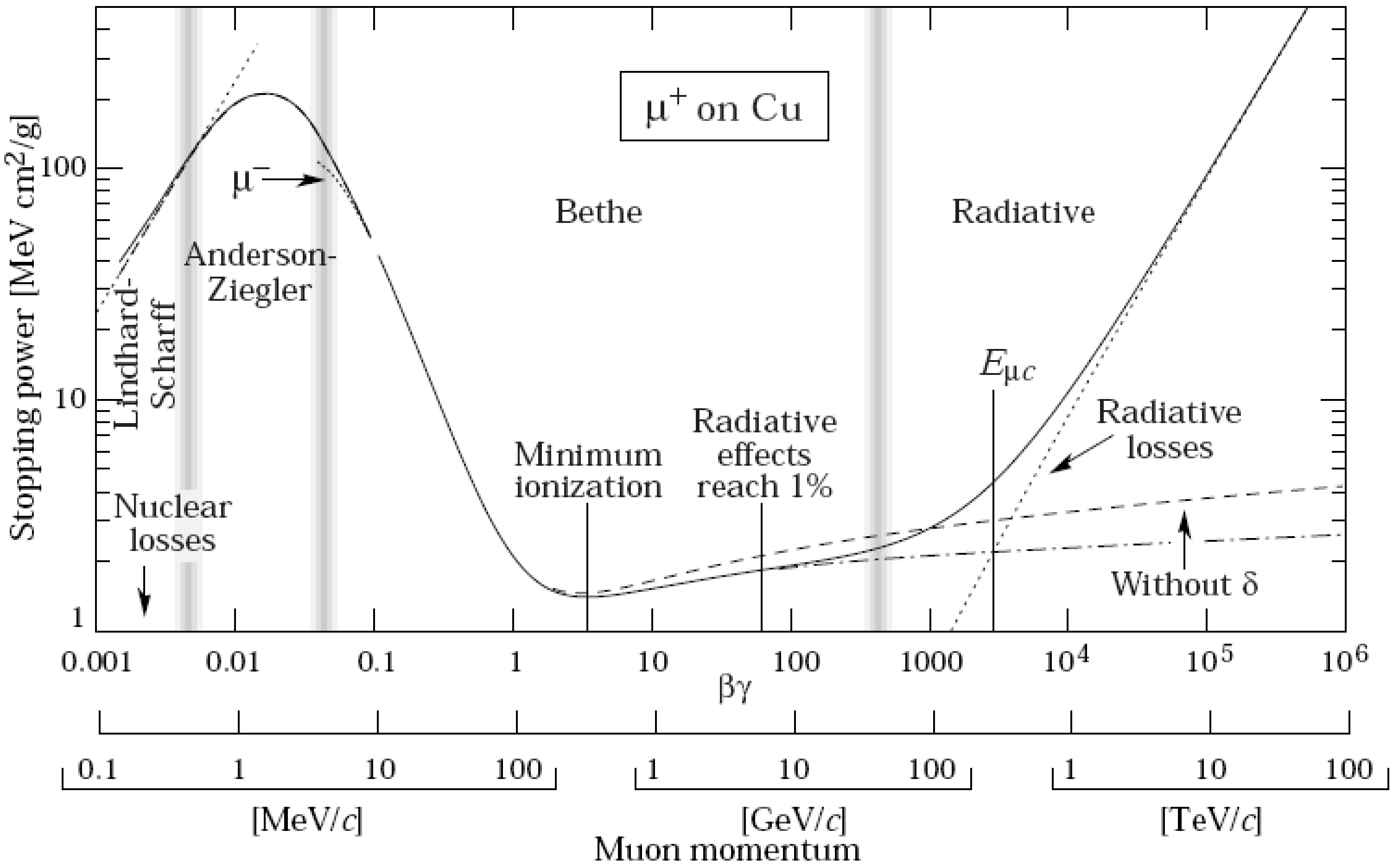
Magnetic monopole would have charge $e/2\alpha$ ~ 68.5 e

Searches: superconducting loop + SQUIDs

highly ionizing particles @ LHC

Ionization: measure dE/dx in appropriate detectors (e.g. silicon)

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



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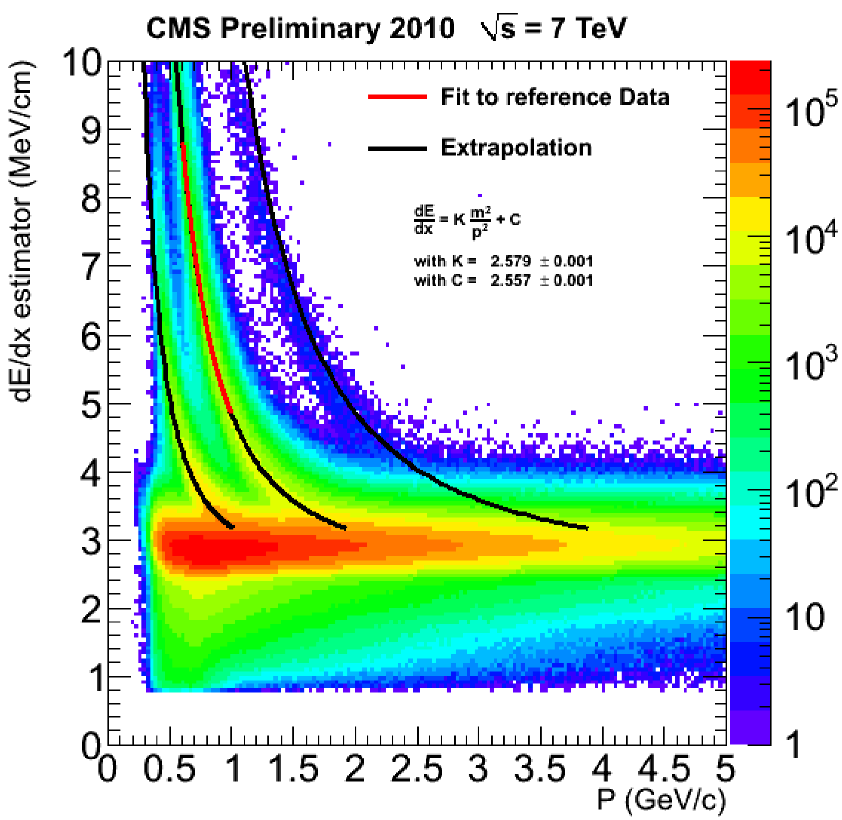
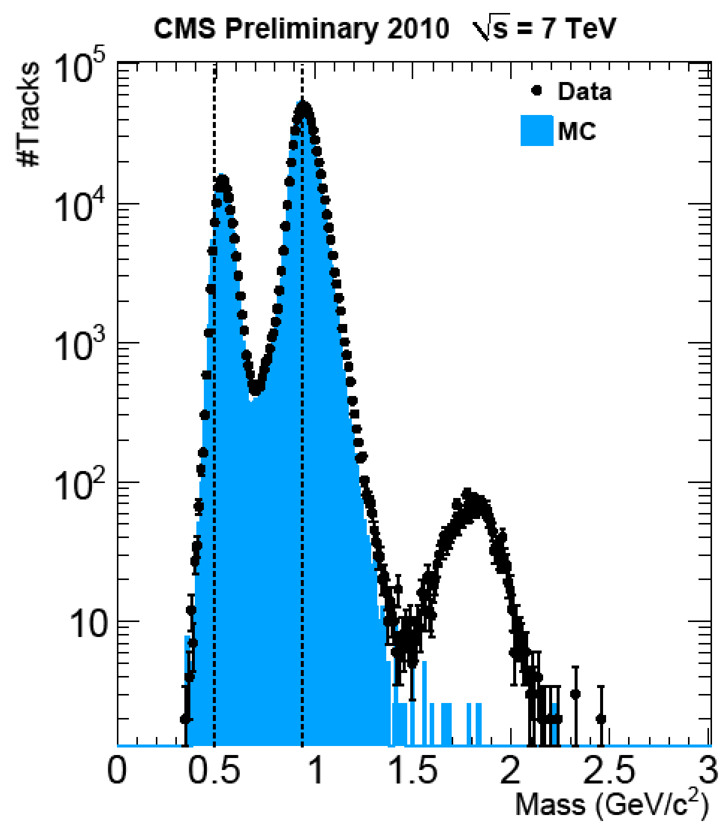




SU(5) in trouble with p lifetime limits

Look further:

- supersymmetrize spectrum

- rank 5 groups: SO(10)

SO(10) has a 16-representation

10 + 5 + 1

that fits ALL SM fermions + ν^C

Supersymmetric SO(10) probably best-studied GUT

Z'

$$E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi$$

$$Z'(\beta) = \chi \cos\beta + \psi \sin\beta$$

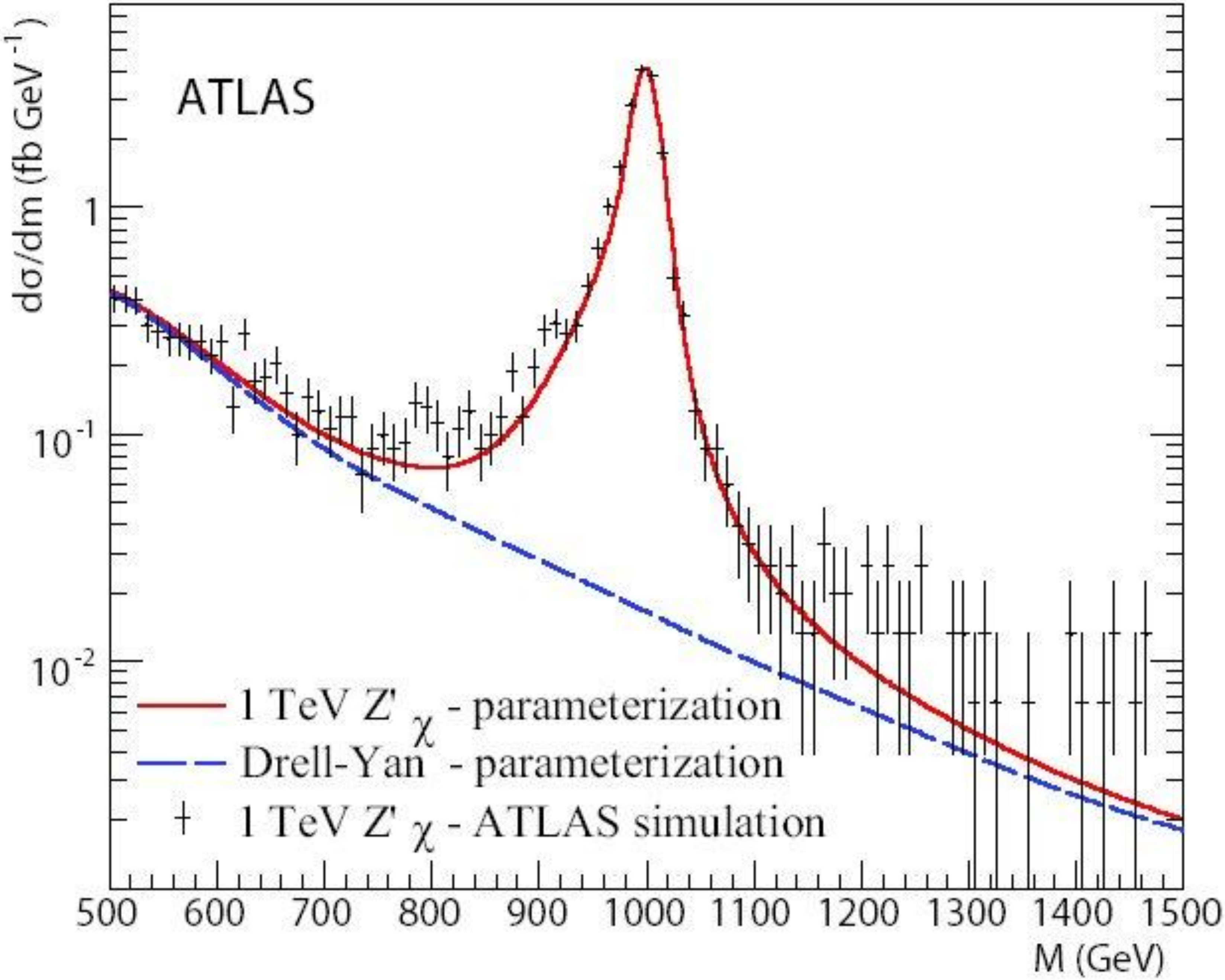
GUT symmetry breaking: → new U(1) symmetries
or alternatively Left-Right symmetric groups

$$\begin{aligned} SO(10) &\to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi \\ &\to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \end{aligned}$$

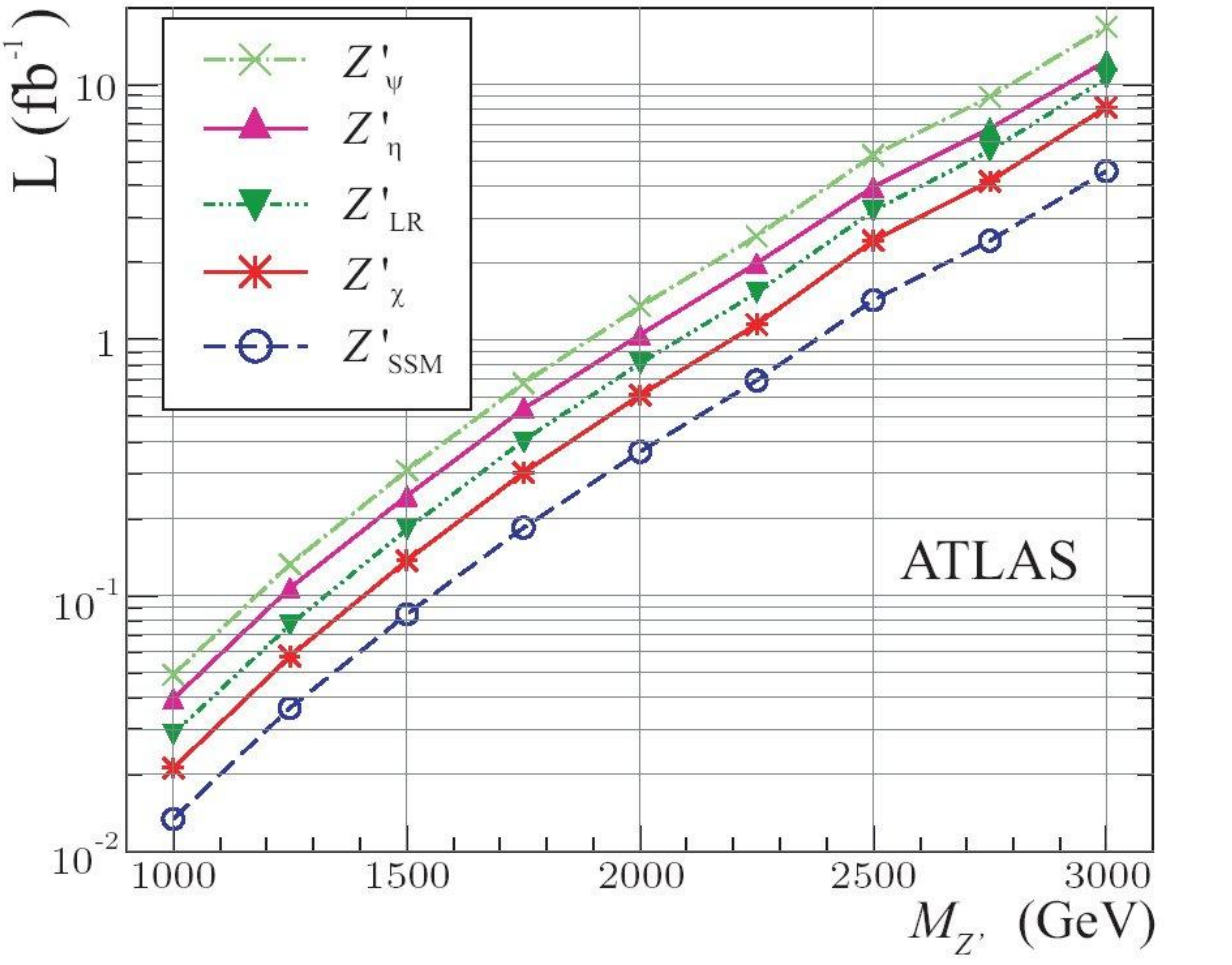
$$\begin{aligned} Z_1 &= Z' \sin\phi + Z \cos\phi \\ Z_2 &= Z' \cos\phi - Z \sin\phi \end{aligned}$$

$$M^2_{1,2} = \frac{1}{2}\left[M_Z^2 + M_{Z'}^2 \pm \sqrt{(M_Z^2 - M_{Z'}^2)^2 + 4(\delta M^2)^2}\right]$$

Consequence: heavy Z' bosons (and/or W', heavy W_R)

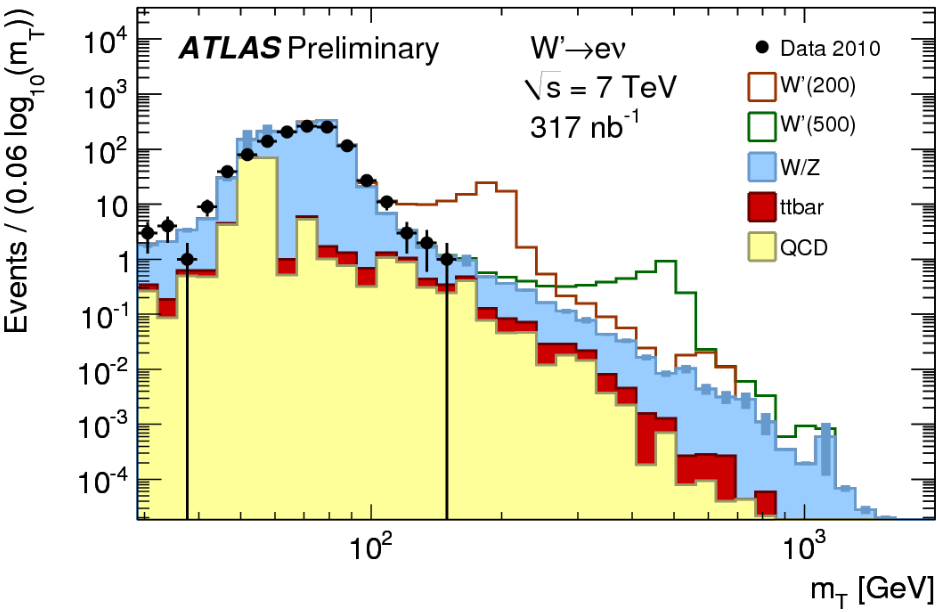


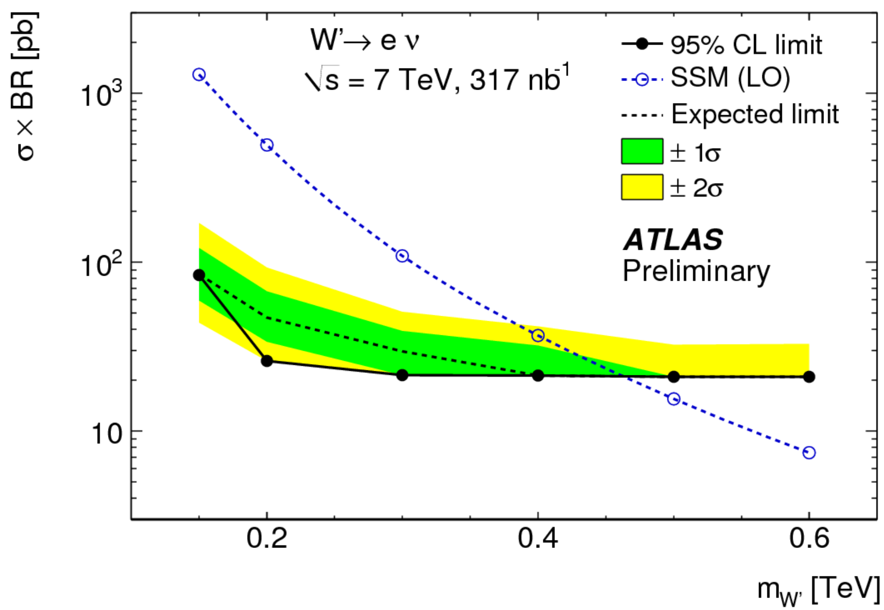
ATLAS
dσ/dm (fb GeV⁻¹)
1
10⁻¹
10⁻²
500
600
700
800
900
1000
1100
1200
1300
1400
1500
M (GeV)
1 TeV Z' χ - parameterization
Drell-Yan - parameterization
1 TeV Z' χ - ATLAS simulation



L (fb⁻¹)
10
1
10⁻¹
10⁻²
Z'ψ
Z'η
Z'LR
Z'χ
Z'SSM
ATLAS
1000
1500
2000
2500
3000
M_Z' (GeV)

And if a Z' exists, a W' might as well





Another source of narrow resonances:

Structure of the universe

Dark matter/energy? #dimensions?

What is the structure of the universe?

How many spatial dimensions?

Is space-time intrinsically flat or curved?

Gravity and space-time are closely connected.
A quantum theory of gravity = a quantum theory of spacetime
The holy grail of physics!

Remember: energy and distance are closely related: $\lambda \sim 1/E$

Gravity becomes strong at large energy ($\sim M_{planck} \sim 10^{19}$ GeV)
= very short distances ~ 10^{-34} m

Suppose we wanted to make gravity strong at much lower energy, what would we need to do?
= Equivalent to making it strong at much larger distances.

$$V(r)_{massless} \propto \frac{1}{r}$$

(massless mediator, like photon: $F \sim 1/r^2$)

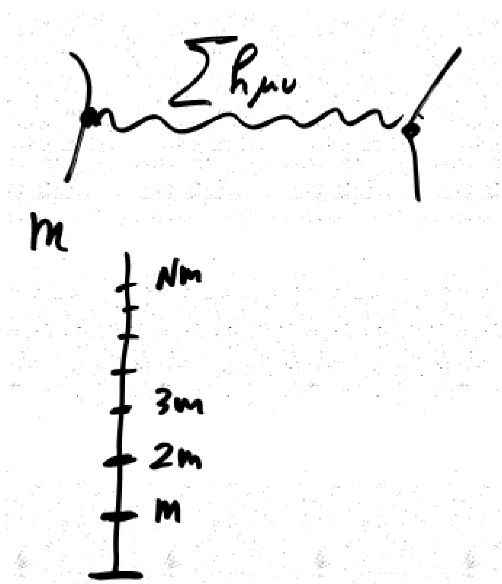
$$V(r)_{massive} \propto \frac{e^{-mr}}{r}$$

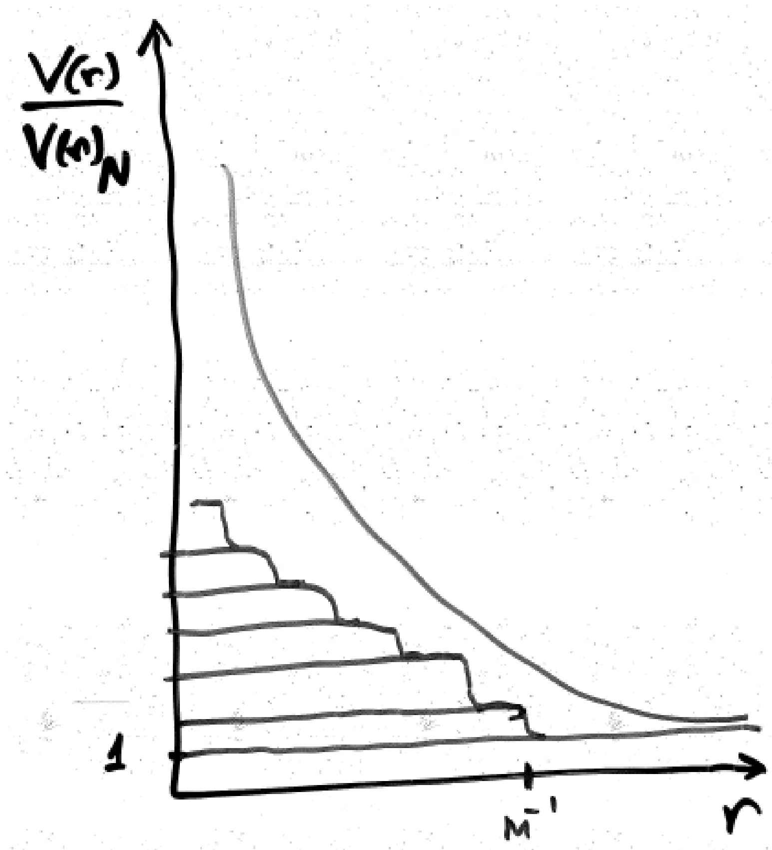
(massive mediator)

Note:

$$\frac{e^{-mr}}{r} \to \frac{1}{r} \quad \text{for } r \ll 1/m \qquad\qquad \frac{e^{-mr}}{r} \to 0 \quad \text{for } r \gg 1/m$$

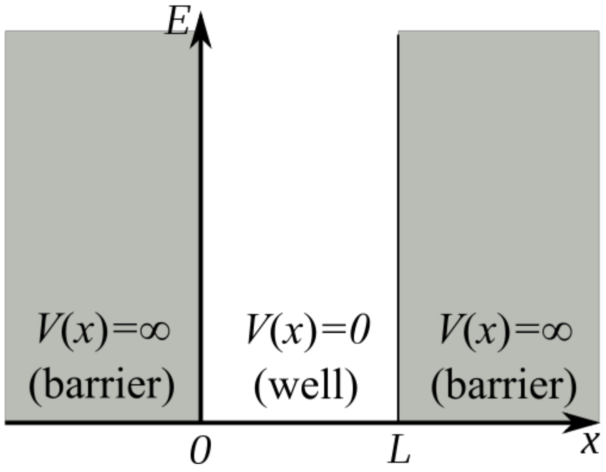
Suppose we had a large set of mediators, with different masses m_i

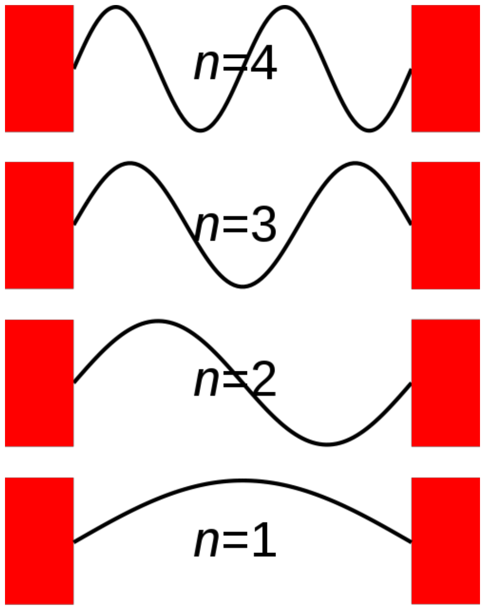




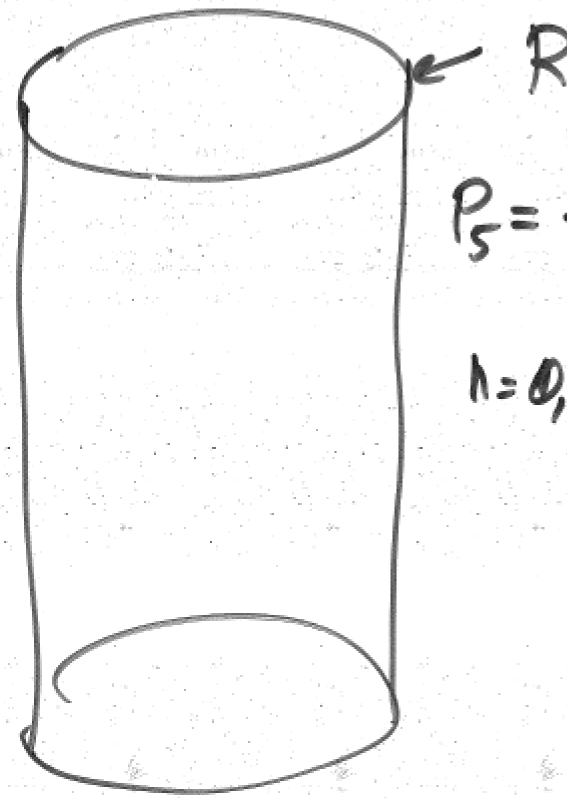
It is not so difficult to make a large set of mediators m_i

Think of the quantum mechanics of a particle in a box potential:





→Constrain wavelength of particle in a dimension with finite size
→Needs to be an extra dimension, above the 4 we already know



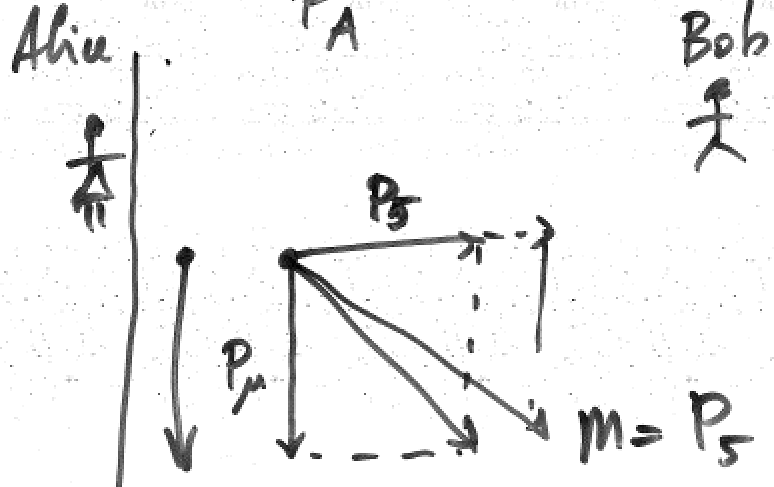
$$p_5 = \frac{n}{R}$$

$n = 0, 1 \ldots$

$$p_\mu p^\mu - \left(\frac{n}{R}\right)^2 = 0$$

5D $\quad X_A \quad A = \mu, 5$

P_A



$$P_A P^A = 0$$

$$P_\mu P^\mu - P_5^2 = 0$$

$X_5 = 0$

$$P_\mu P^\mu - m^2 = 0$$

The first extra dimension theory was an attempt to make a GUT!

Unification of electromagnetic and gravitational forces
by a 5th dimension: Kaluza and Klein, 1921-1926

Also Einstein's dream for the rest of his life.

Models with Extra Dimensions

Large Extra Dimensions   Planck scale (M_D) ~ TeV

Size: » TeV^{-1}; SM-particles on brane; gravity in bulk
KK-towers (small spacing); KK-exchange; graviton prod.
Signature: e.g. x-section deviations; jet+$E_{T,miss}$ ....

Warped Extra Dimensions

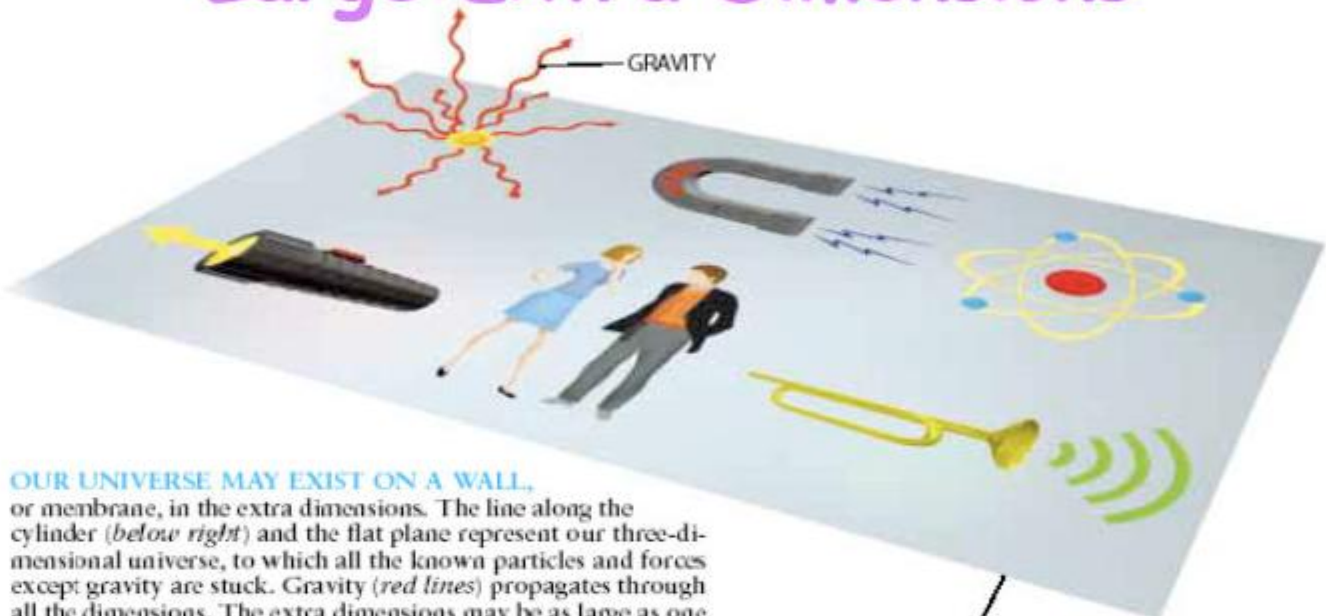
5-dimensional spacetime with warped geometry
Graviton KK-modes (large spacing); graviton resonances
Signature: e.g. resonance in ee, μμ, γγ-mass distributions ...

TeV-Scale Extra Dimensions   look-like SUSY

SM particles allowed to propagate in ED of size TeV^{-1}
[scenarios: gauge fields only (nUED) or all SM particles (UED)]

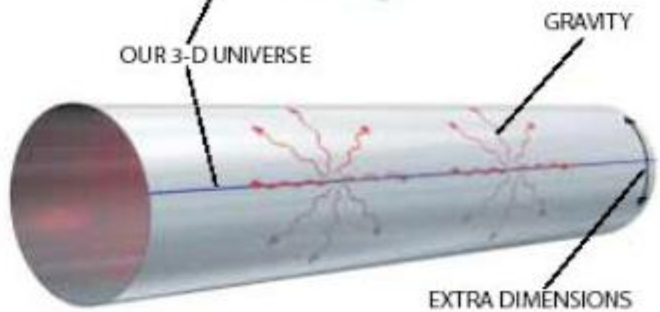
nUED : KK excitations of gauge bosons
UED : KK number conservation; KK states pair produced (at tree-level) ...
Signature: e.g. Z'/W' resonances, dijets+$E_{T,miss}$, heavy stable quarks/gluons...

Large Extra Dimensions



OUR UNIVERSE MAY EXIST ON A WALL, or membrane, in the extra dimensions. The line along the cylinder (*below right*) and the flat plane represent our three-dimensional universe, to which all the known particles and forces except gravity are stuck. Gravity (*red lines*) propagates through all the dimensions. The extra dimensions may be as large as one millimeter without violating any existing observations.

Model of Arkani-Hamed, Dvali, Dimopoulos: Standard Model particles are localized on a 3-D brane. Gravity propagates inside the bulk (a more dimensional space)



Extra dimensions formalism:

$$V_\delta = (2\pi R_c)^\delta$$

Extra dimensions compactified with radius R_C

$$M_{\rm Pl}^2 = V_\delta M_D^{2+\delta}$$

"Real" Planck scale in 4+δ D

Apparent Planck scale in 4D

Gravity diluted by extra dimensions

Suppose we want $M_D \sim 1$ TeV.
δ= 1: $R_C \sim$ solar system: ruled out
δ= 2: $R_C \sim$ mm
δ= 3: $R_C \sim$ sub mm → particle physics!

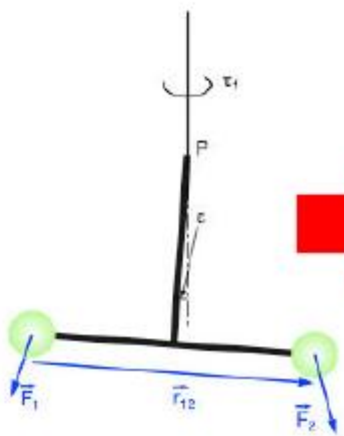
Experimental test: see any deviation from classical behaviour?

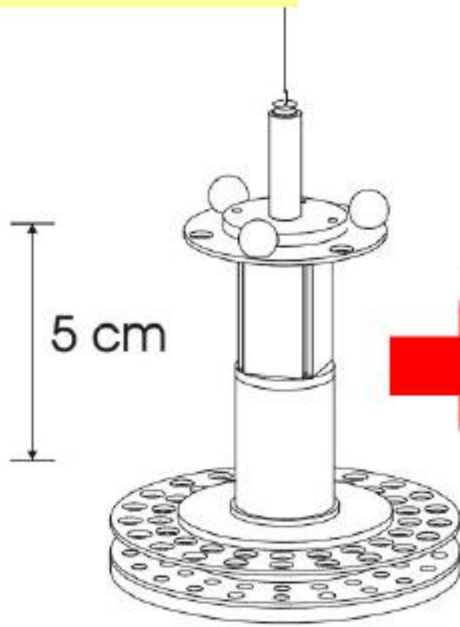
Gravity Experiments

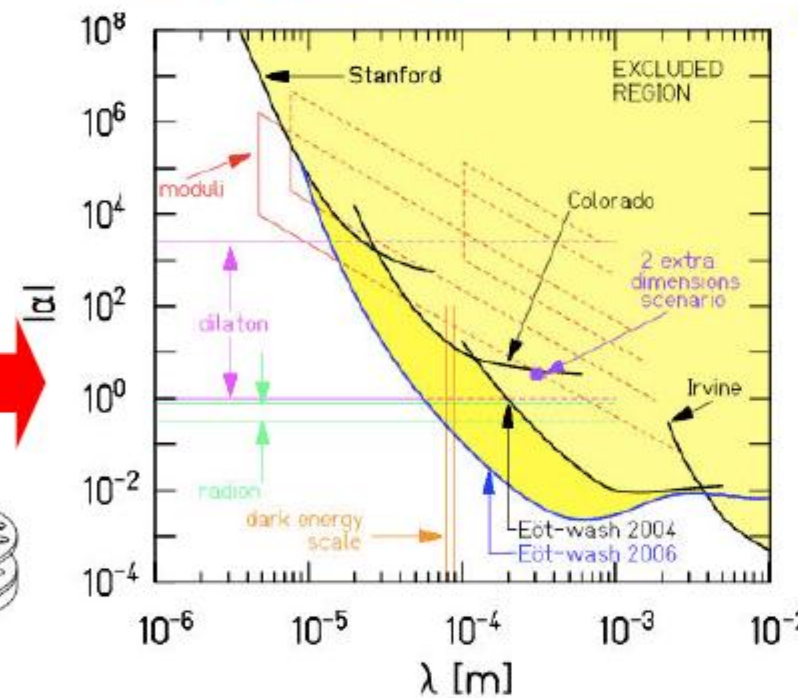
Measure the force of gravity at sub-milimeter distances with sophisticated torsion experiment

$$V(r) = -G\,\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

Adelberger et al. '06





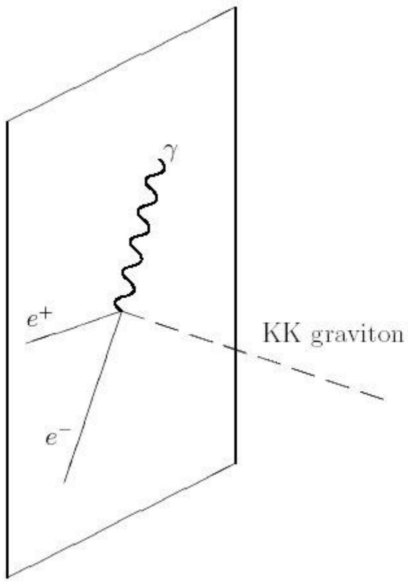


$R_\perp \lesssim 45\ \mu m$ at 95% CL

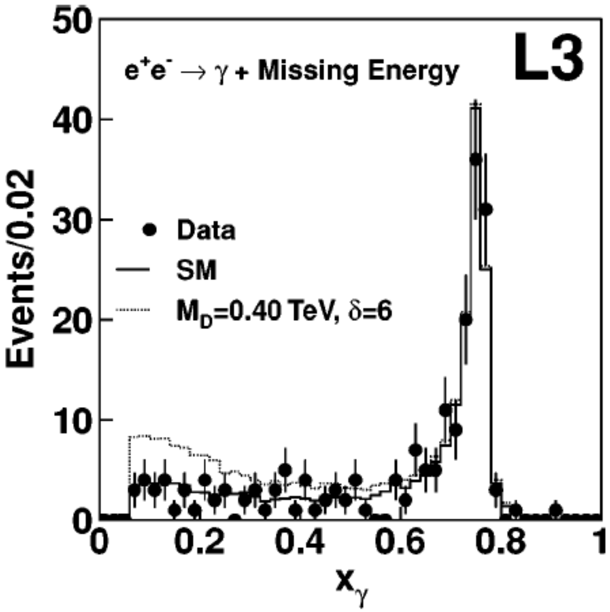
- dark-energy length scale $\approx 85\mu m$ [3] [18]

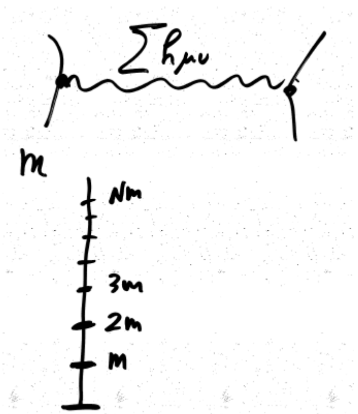
⇒ Newtonian law works down to ~ 45 μm

Experimental consequences in particle physics:

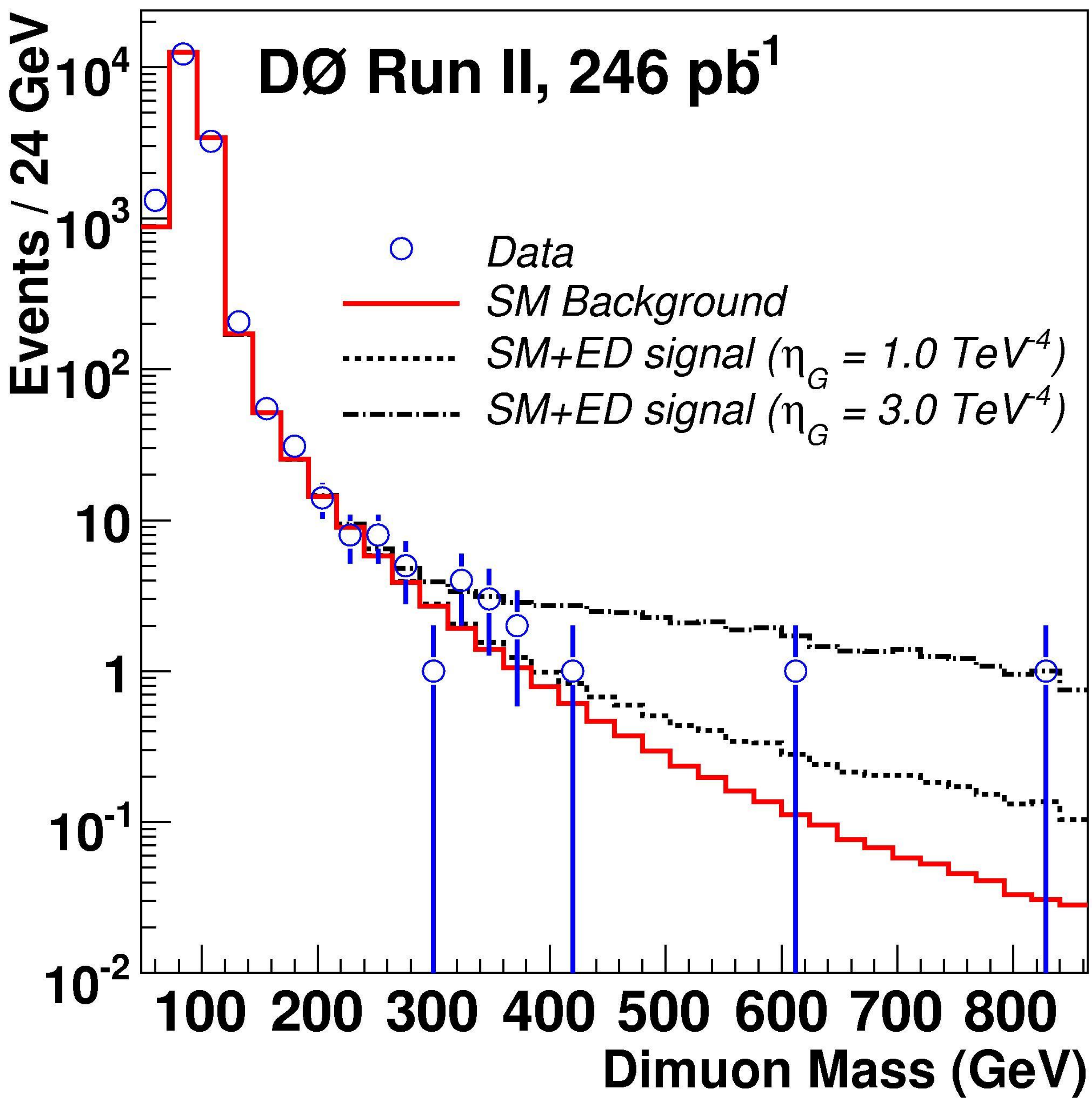


Graviton disappearing in extra dimension
→ Missing energy



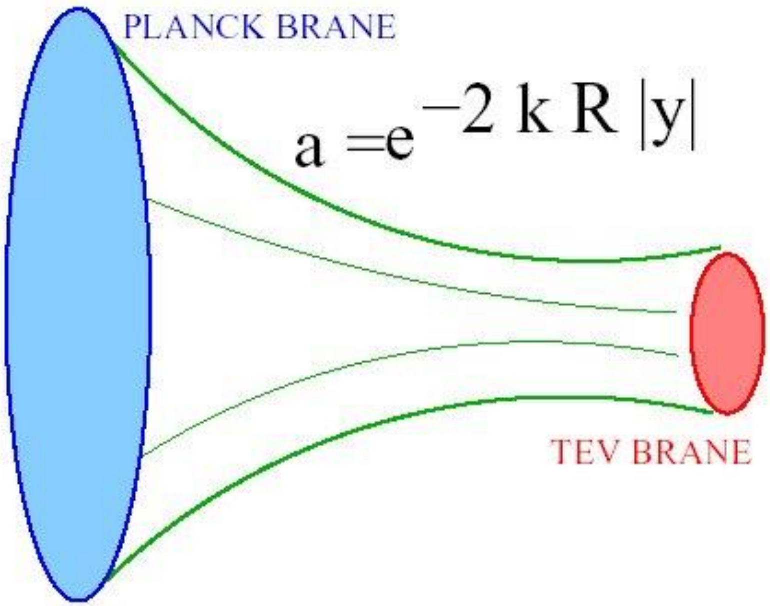


Interactions mediated by tower of graviton excitations (Δm between states ~ eV or sub-eV)
→ Cross sections changed w.r.t. SM



DØ Run II, 246 pb^{-1}
Events / 24 GeV
Dimuon Mass (GeV)
Data
SM Background
SM+ED signal (η_G = 1.0 TeV^{-4})
SM+ED signal (η_G = 3.0 TeV^{-4})
10^{-2}
10^{-1}
1
10
10^2
10^3
10^4
100
200
300
400
500
600
700
800

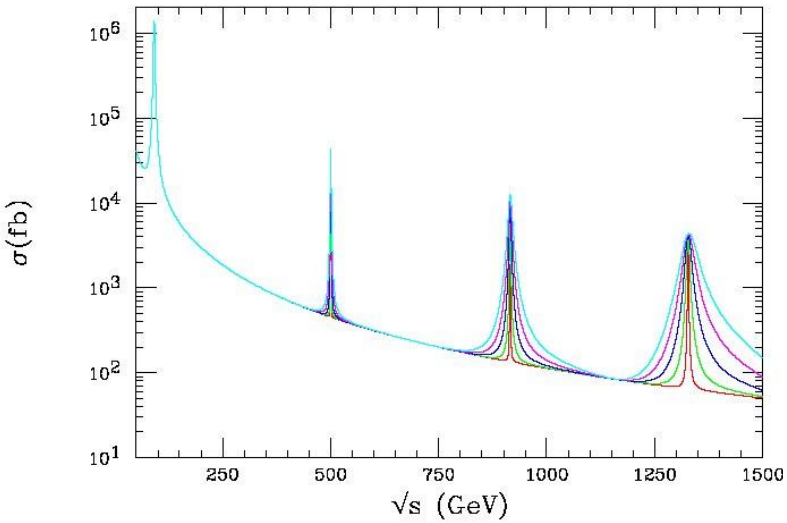
A slightly different model: 1 extra dimension, but highly curved (RS)

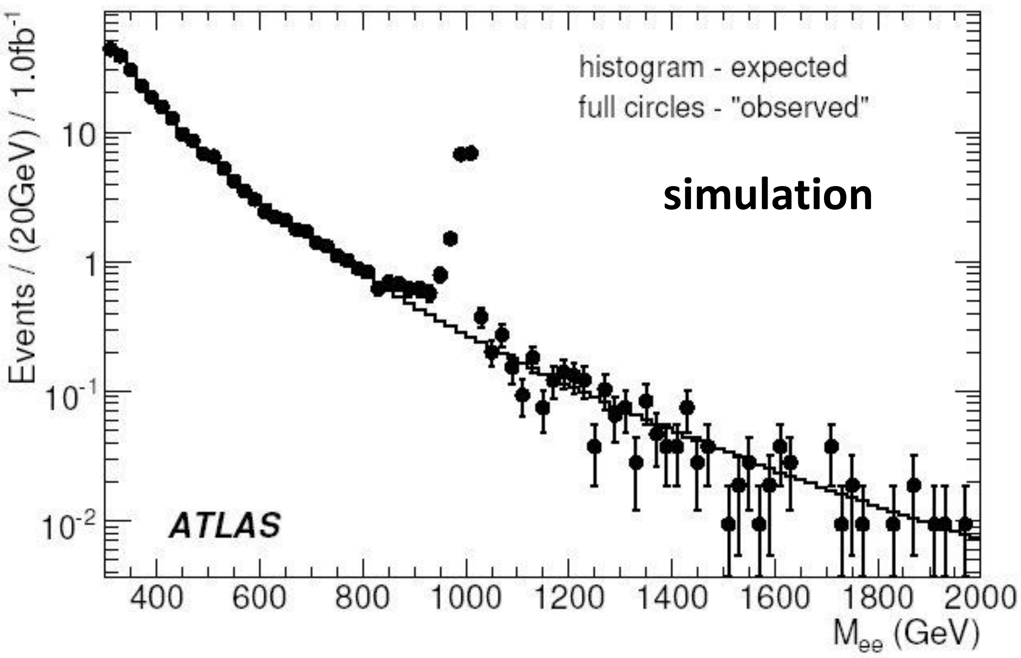


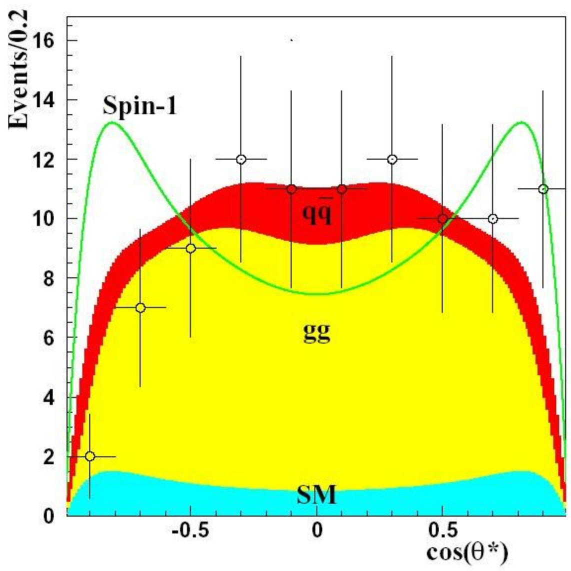
Strong curvature of space makes difference between M_D and M_{planck}

Graviton excitations, but larger mass splittings

Experimental consequences: resonances!







Spin should tell difference w.r.t. Z'

Note that there are also astrophysical/cosmological constraints (but how model-independent?)

Table 1 Current limits on the fundamental energy scale

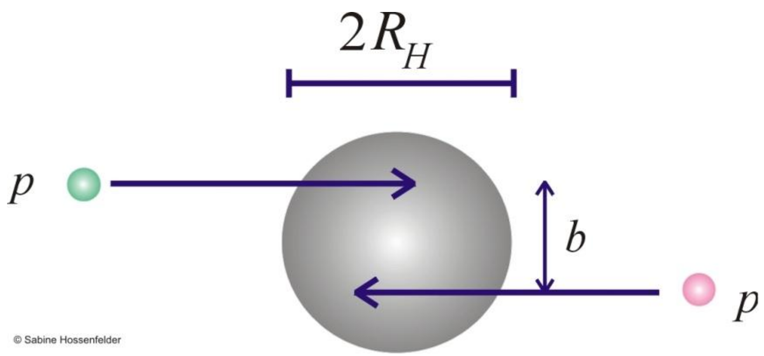
Type of Experiment/Analysis	$M_* \geq$	$M_* \geq$
Collider limits on the production of real or virtual KK gravitons [11]-[13]	1.45 TeV ($n = 2$)	0.6 TeV ($n = 6$)
Torsion-balance Experiments[14, 15]	3.2 TeV ($n = 2$)	($\mathscr{R} \leq 50\,\mu$m)
Overclosure of the Universe[16]	8 TeV ($n = 2$)	
Supernovae cooling rate [17]-[20]	30 TeV ($n = 2$)	2.5 TeV ($n = 3$)
Non-thermal production of KK modes [21]	35 TeV ($n = 2$)	3 TeV ($n = 6$)
Diffuse gamma-ray background [16, 22, 23]	110 TeV ($n = 2$)	5 TeV ($n = 3$)
Thermal production of KK modes [23]	167 TeV ($n = 2$)	1.5 TeV ($n = 5$)
Neutron star core halo [24]	500 TeV ($n = 2$)	30 TeV ($n = 3$)
Time delay in photons from GRB's [25]	620 TeV ($n = 1$)	
Neutron star surface temperature [24]	700 TeV ($n = 2$)	0.2 TeV ($n = 6$)
BH absence in neutrino cosmic rays [26]		1-1.4 TeV ($n \geq 5$)

Small E, large r: plain old 4-dimensional theory

Intermediate E, r approaching R_C : start seeing effect of extra dimensions

E > M_D : “Trans-Planckian” regime: no good theory! Gravity strong!
→ Micro-black hole production?

With extra dimensions, the Schwarzschild radius R_H can be much larger than for a classical black hole.



If $b < 2\,R_H$: black hole production?

Naieve cross section:

$\sigma \sim \pi R_H^2$

→ pb or nb: very large!

Quantum Back Holes

- Schwarzschild radius

Landsberg, Dimopoulos
Giddings, Thomas, Rizzo...

4-dim., $M_{gravity} = M_{Planck}$ (:10^{19}GeV)

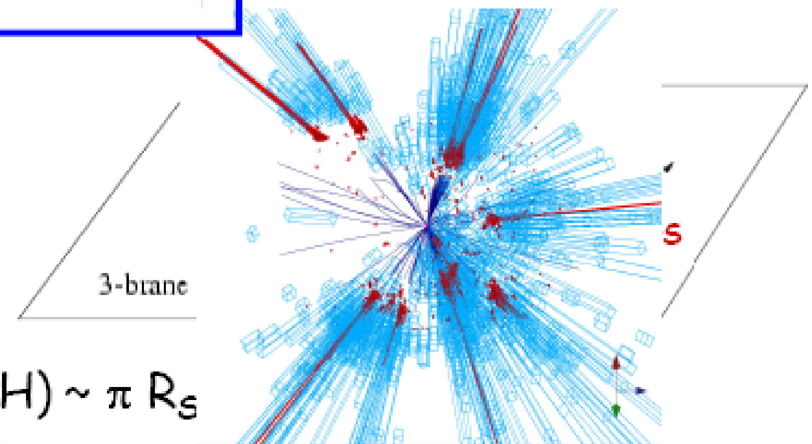
4 + n-dim., $M_{gravity} = M_D \sim$ TeV

$R_s \rightarrow \ll 10^{-35}$ m

$R_s \rightarrow \sim 10^{-19}$ m

⬇

Since M_D is low, tiny black holes of $M_{BH} \sim$ TeV can be produced if partons ij with $\sqrt{s_{ij}} = M_{BH}$ pass at a distance smaller than R_S

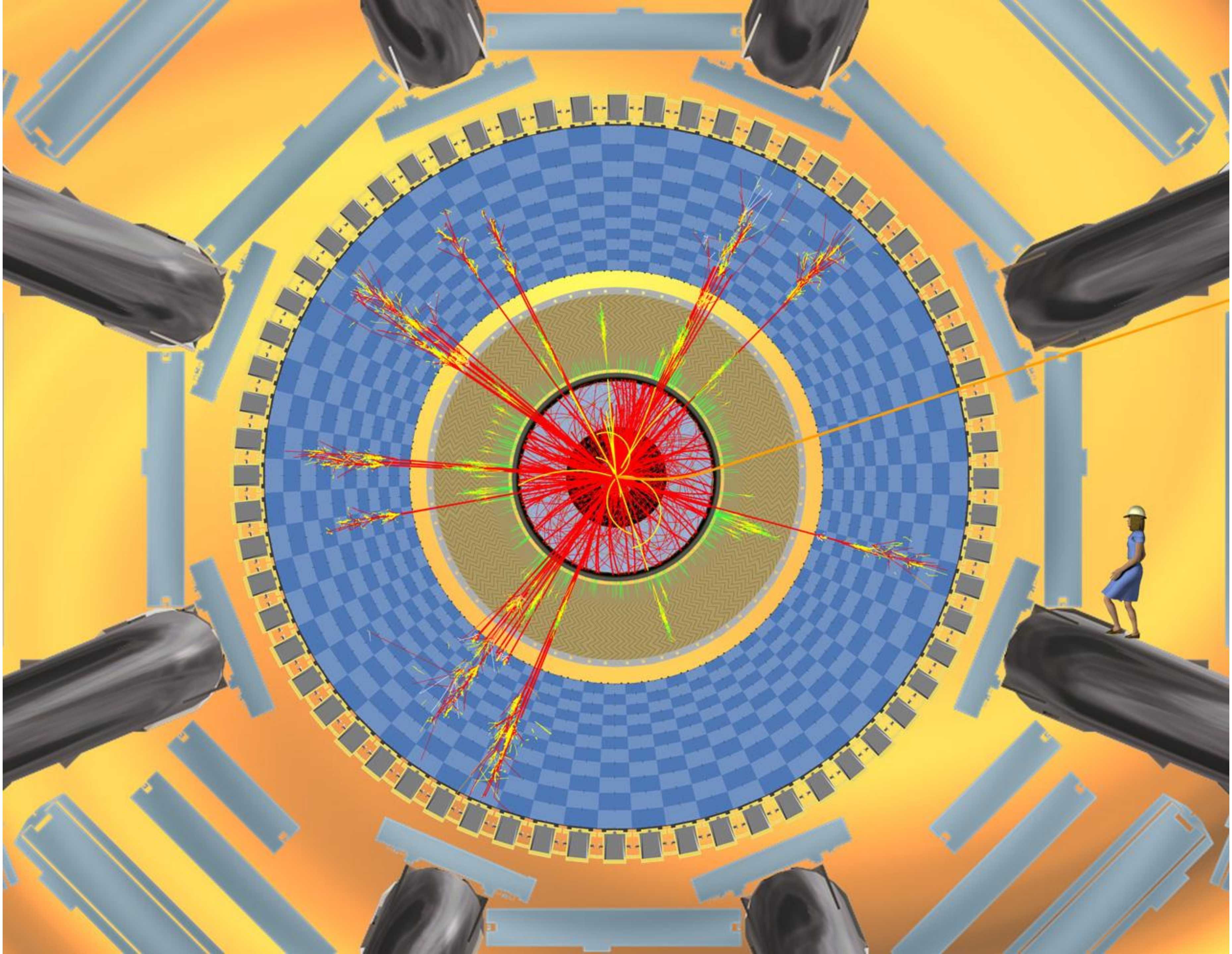


- Large partonic cross-section : $\sigma(ij \rightarrow BH) \sim \pi R_S$
- $\sigma(pp \rightarrow BH)$ is in the range of 1 nb - 1 fb

e.g. For M_D ~1 TeV and n=3, produce 1 event/second at the LHC

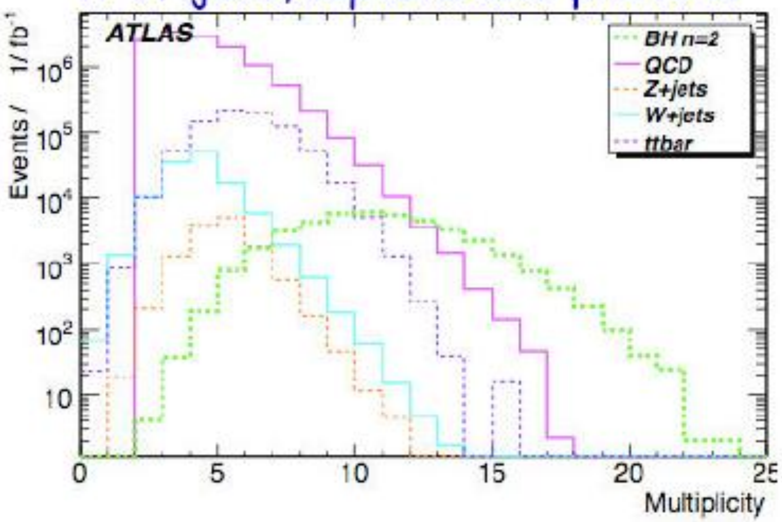
- Black holes decay immediately by Hawking radiation (democratic evaporation) :
  - -- large multiplicity
  - -- small missing E
  - -- jets/leptons ~ 5

expected signature (quite spectacular ...)

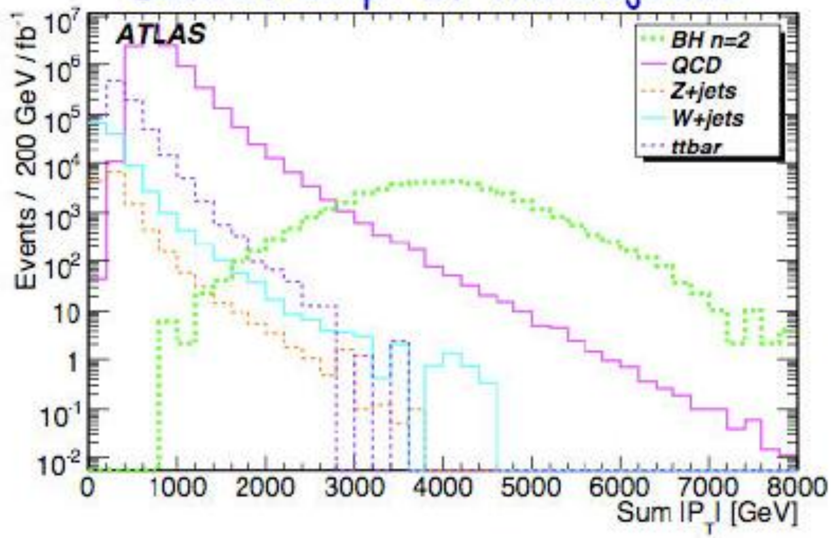


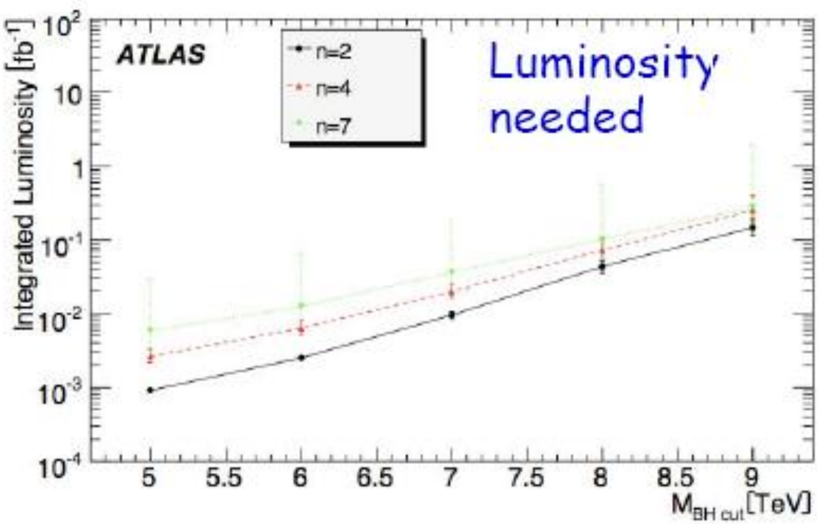
Black Hole Studies

of jets, leptons and photons



Sum of all pt of the objects





Luminosity needed

Already possible to discover with 1 pb^{-1}!!!

However cross sections largely unknown (and challenged)

Quantum Black Holes

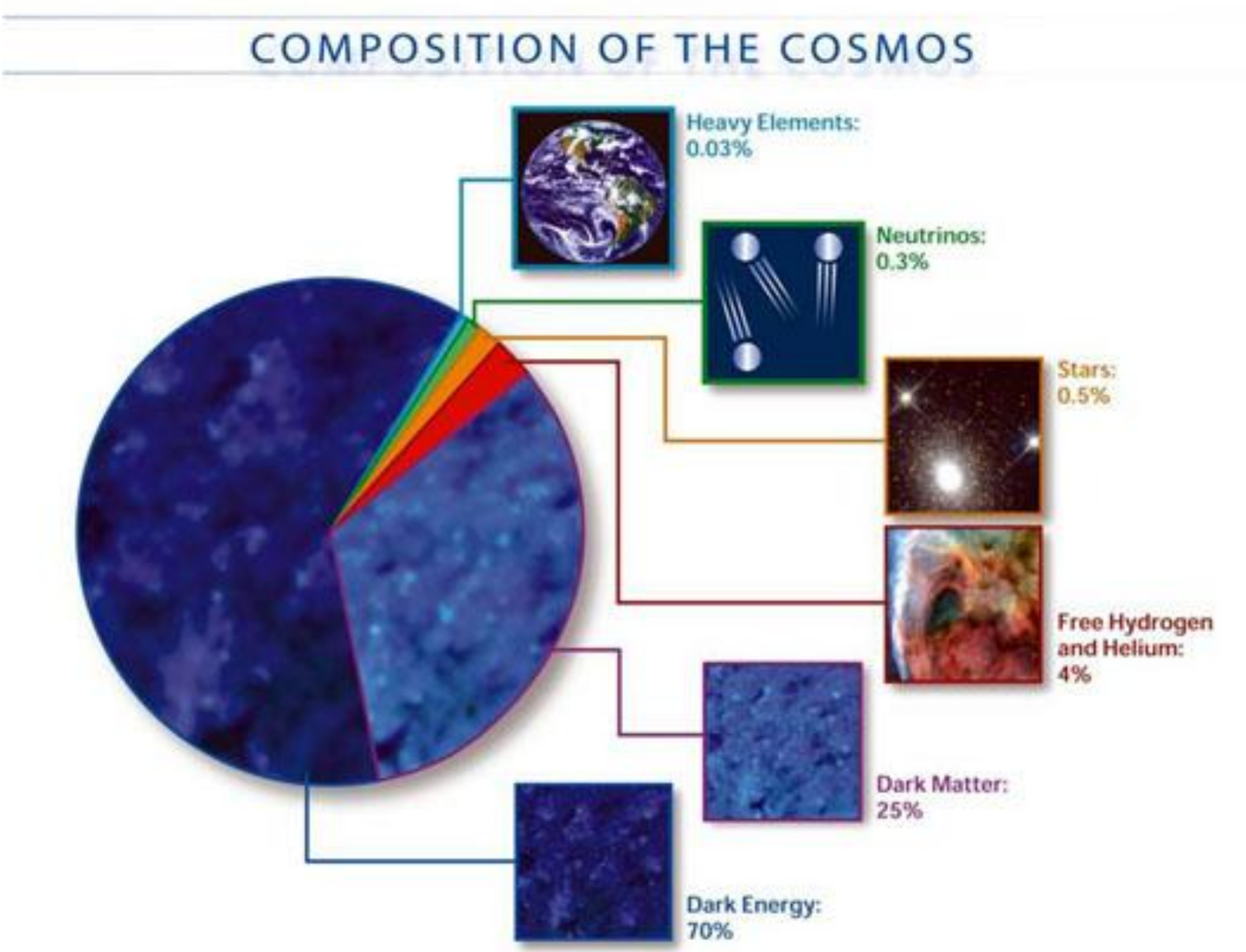
Professor Landsberg was fast regretting becoming the first man to successfully create a mini black hole in the laboratory.

- Can LHC destroy the planet?

  $\Rightarrow$ No!

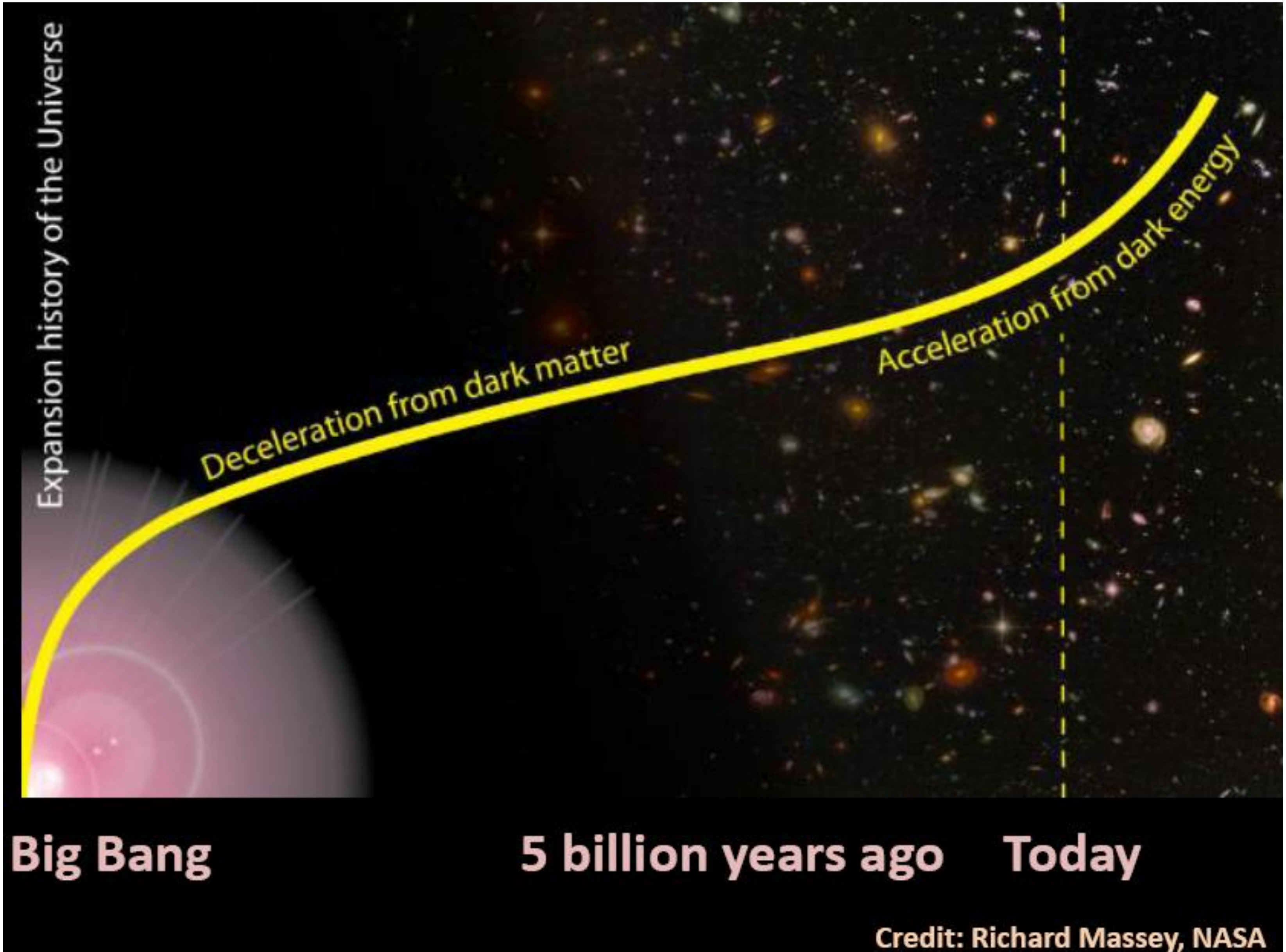
- See the report of the LHC Safety assesment group (LSAG) *http://arXiv.org/pdf/0806.3414*
- More information on
  - S.B. Giddings and M. Mangano, *http://arXiv.org/pdf/0806.3381* LSAG, http://arXiv.org/pdf/0806.3414
  - Scientific Policy Committee Review, *http://indico.cern.ch/getFile.py/access?contribId=20&resId=0&materialId=0&confId=35065*
  - CERN public web page, *http://public.web.cern.ch/public/en/LHC/Safety-en.html*

Universe carries many more surprises!



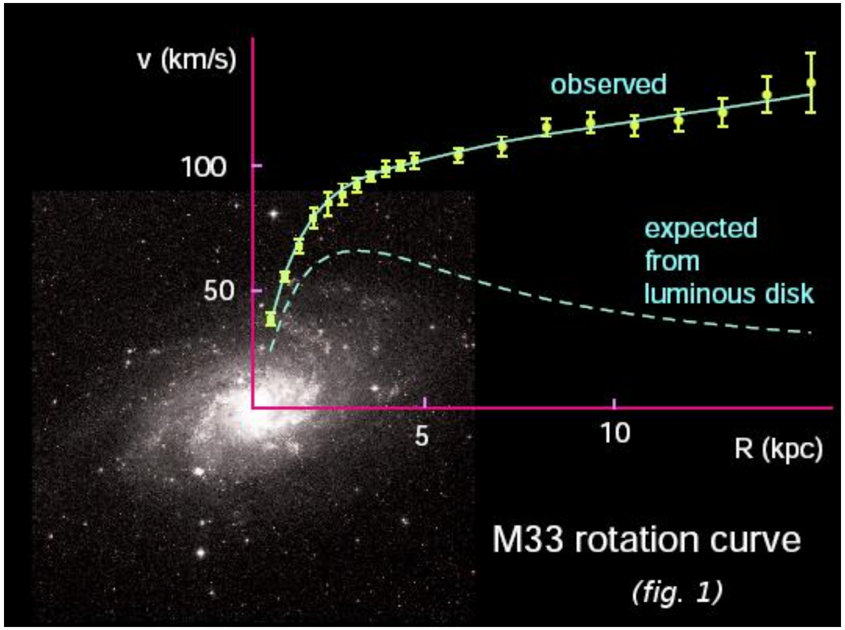
We do not know 96% of the energy-content of the universe!

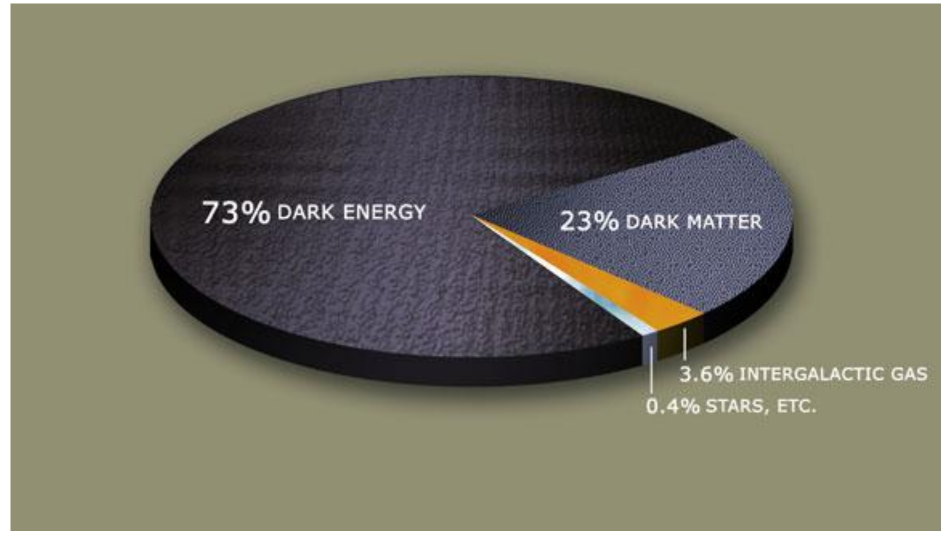
Dark energy. Universe expansion is accelerating.

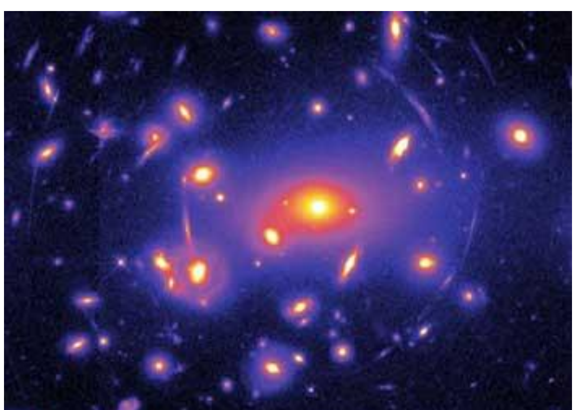


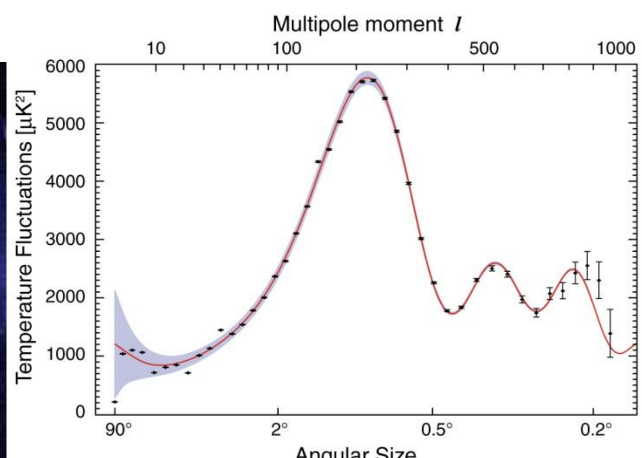
Compelling evidence for dark matter

$\Omega_M h^2 = 0.133 \pm 0.006$
$\Omega_B h^2 = 0.0227 \pm 0.0006$









Dark matter relic density

Suppose: "dark matter" particles X, SM particles Y

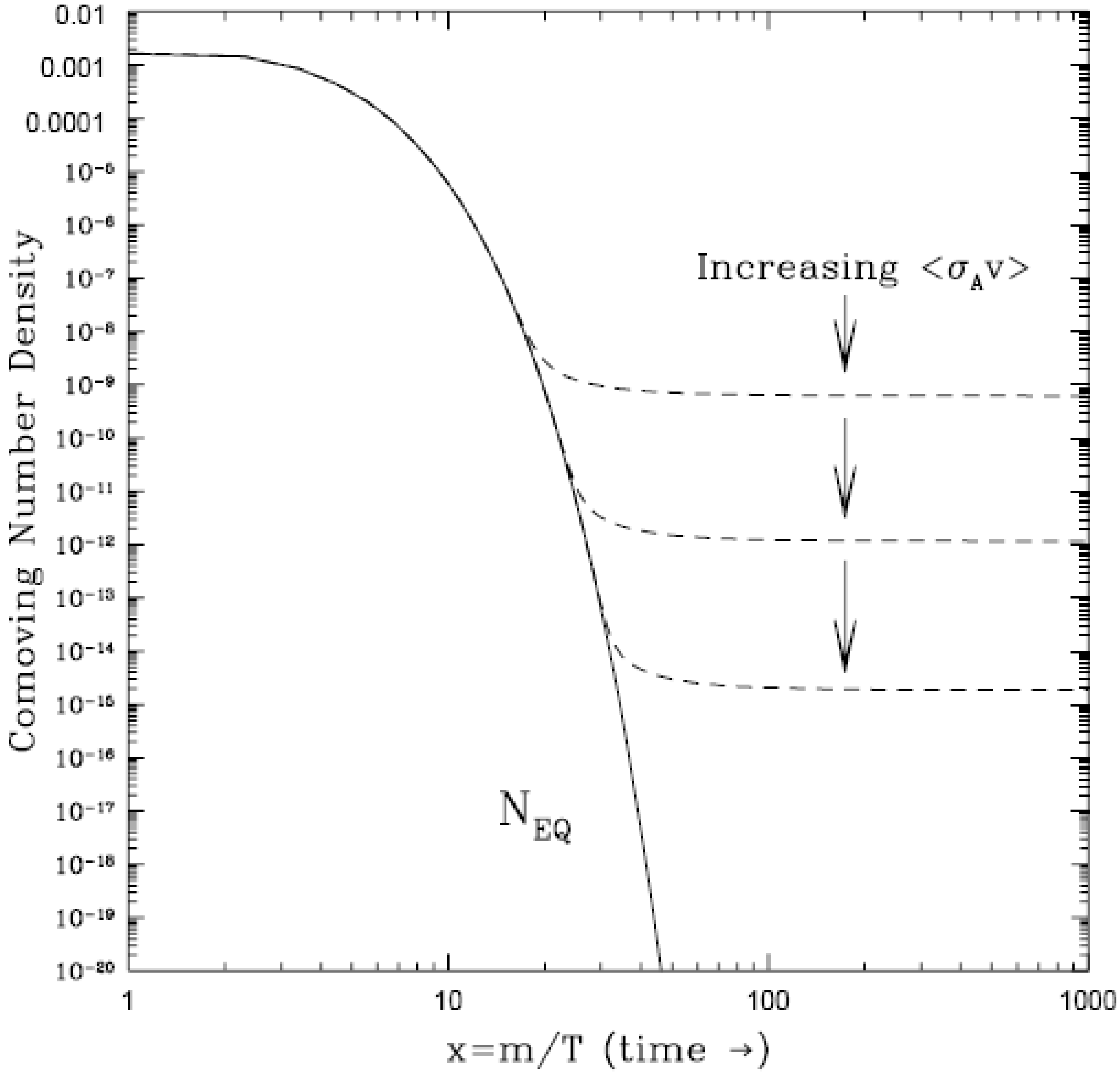
Early universe: $kT >> M_X c^2$ (M_X ~ 100 GeV: T ~ 10^{15} K, t = 10^{-10} s)

$$X\overline{X} \leftrightarrow Y\overline{Y}$$

Universe cools: $kT < M_X c^2$: $$X\overline{X} \rightarrow Y\overline{Y}$$

But universe also expands: X density drops, particles do not find each other anymore: "freeze-out"

Relevant parameter: $<\sigma_A v>$ = thermally averaged annihilation cross section times velocity



Comoving Number Density
0.01
0.001
0.0001
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
Increasing <σ_A v>
N_EQ
1
10
100
1000
x=m/T (time →)

Measured relic density: $\Omega_M h^2 = 0.133 \pm 0.006$

With a given M_X and σ_A : we can calculate Ω_M

M_X ~ 100 GeV – 1 TeV: σ_A ~ 1 pb (typical weak cross section)

“WIMP miracle”

SM neutrinos do not do the job

No other SM particle candidates.

New physics candidates:

-**Modified gravity**?
("MOND": modified Newtonian dynamics")
But: bullet cluster

-(Kaluza-Klein) particles from **extra dimensions**
if stable

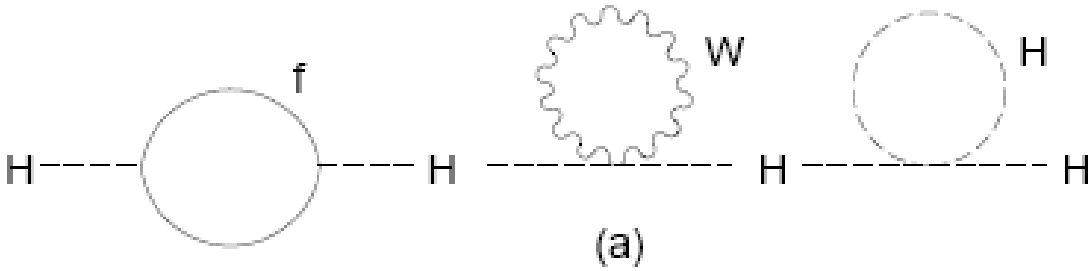
-**Axion**
hypothetical particle corresponding to a symmetry
that ensures CP conservation in QCD
"Super-WIMP": very small cross sections, difficult!

-**4^{th} generation neutrino** with non-SM couplings

-**Lightest Supersymmetric Particle**
My favourite candidate

Hierarchy Problem

Do we understand EW symmetry breaking?



$$\delta m_{H,W}^2 = \mathcal{O}\left(\frac{g^2}{16\pi^2}\right) \int^{\Lambda} d^4k \frac{1}{k^2} = \mathcal{O}\left(\frac{\alpha}{\pi}\right) \Lambda^2$$

The Higgs boson acquires a mass due to radiative corrections ~ Λ^2

(a fermion, like an electron, acquires a correction ~ ln Λ)

$$\delta m_f = \mathcal{O}\left(\frac{g^2}{16\pi^2}\right) m_f \int^{\Lambda} d^4k \frac{1}{k^4} = \mathcal{O}\left(\frac{\alpha}{\pi}\right) m_f \ln \frac{\Lambda}{m_f}$$

Possible solutions of the hierarchy problem:

what problem? why worry?

no Higgs, something else saves unitarity

Higgs is a composite object (technicolor)

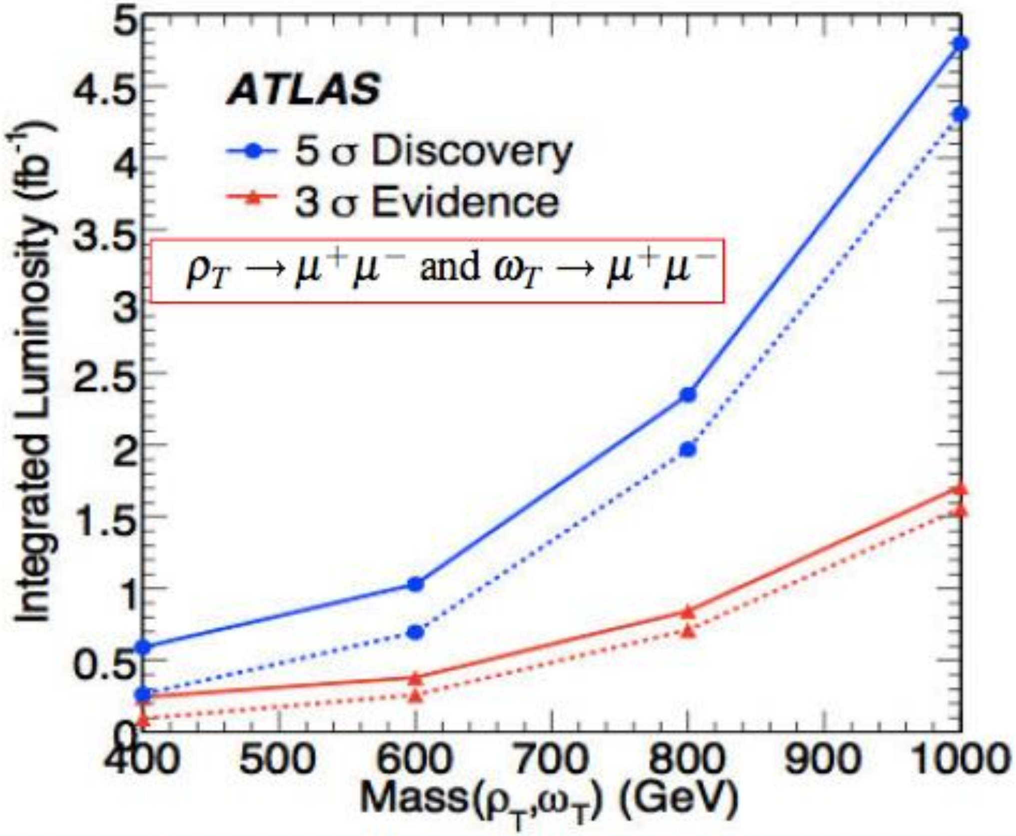
Higgs mass protected by a symmetry (little Higgs)

large extra dimensions: Λ is not so high

Supersymmetry

A new strong force: Technicolor?

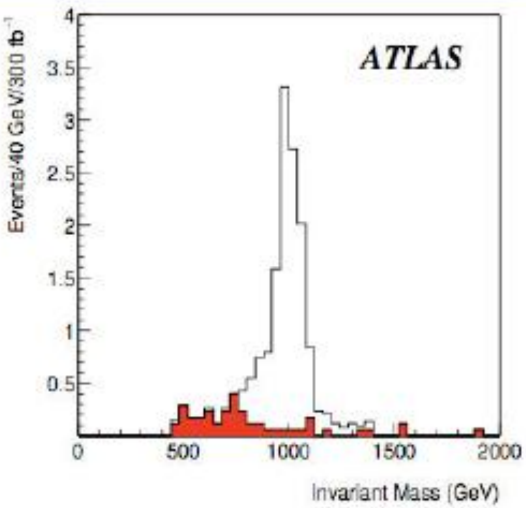
No elementary Higgs but a new type of color-like force, predicting particles called techni-pions, techni-rhos, techni-omegas…with masses ~ few 100 GeV

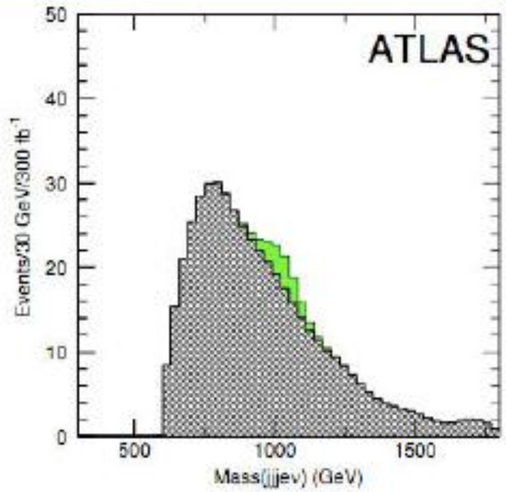


Luminosities of ~ 0.5-1 fb^{-1} or more needed

Little Higgs Models

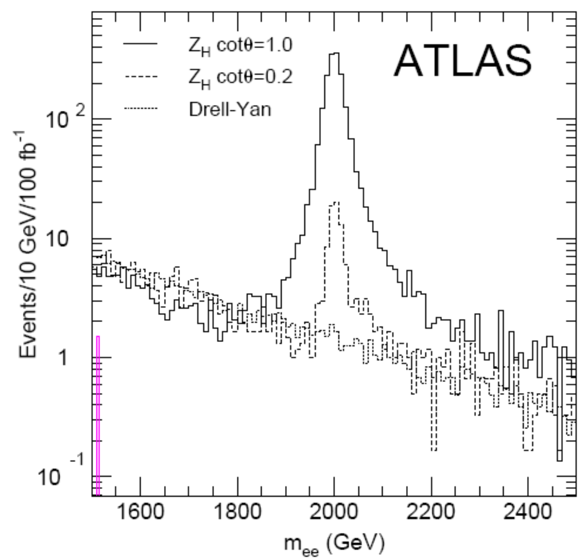
Heavy top partner around 1 TeV $\Rightarrow$ Decay eg into $T \rightarrow tZ$, $T \rightarrow tH$





Signals+BG
Needs a lot of
luminosity!!

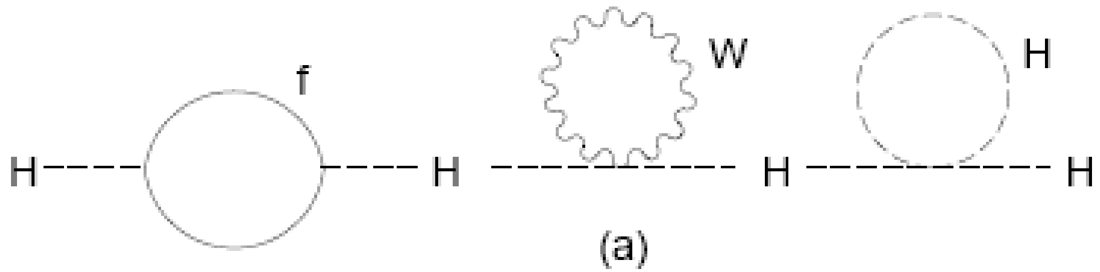
Little Higgs models also have
a heavy Z, W



Supersymmetry: fermions ←→ bosons

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle, \qquad Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$

Partners with different sign cancel loops affecting Higgs mass!
(Exactly if masses are identical)



$$\delta m^2_{H,W} = -\left(\frac{g_F^2}{16\pi^2}\right)\ (\Lambda^2 + M_F^2) + \left(\frac{g_B^2}{16\pi^2}\right)\ (\Lambda^2 + M_B^2) = \mathcal{O}\left(\frac{\alpha}{4\pi}\right)\ |m_B^2 - m_f^2|$$

$$+\text{logarithmic divergences} + \text{uninteresting terms}$$

Answer still "natural" if $|m_B^2 - m_F^2| \lesssim 1\ \text{TeV}^2$

Supersymmetry

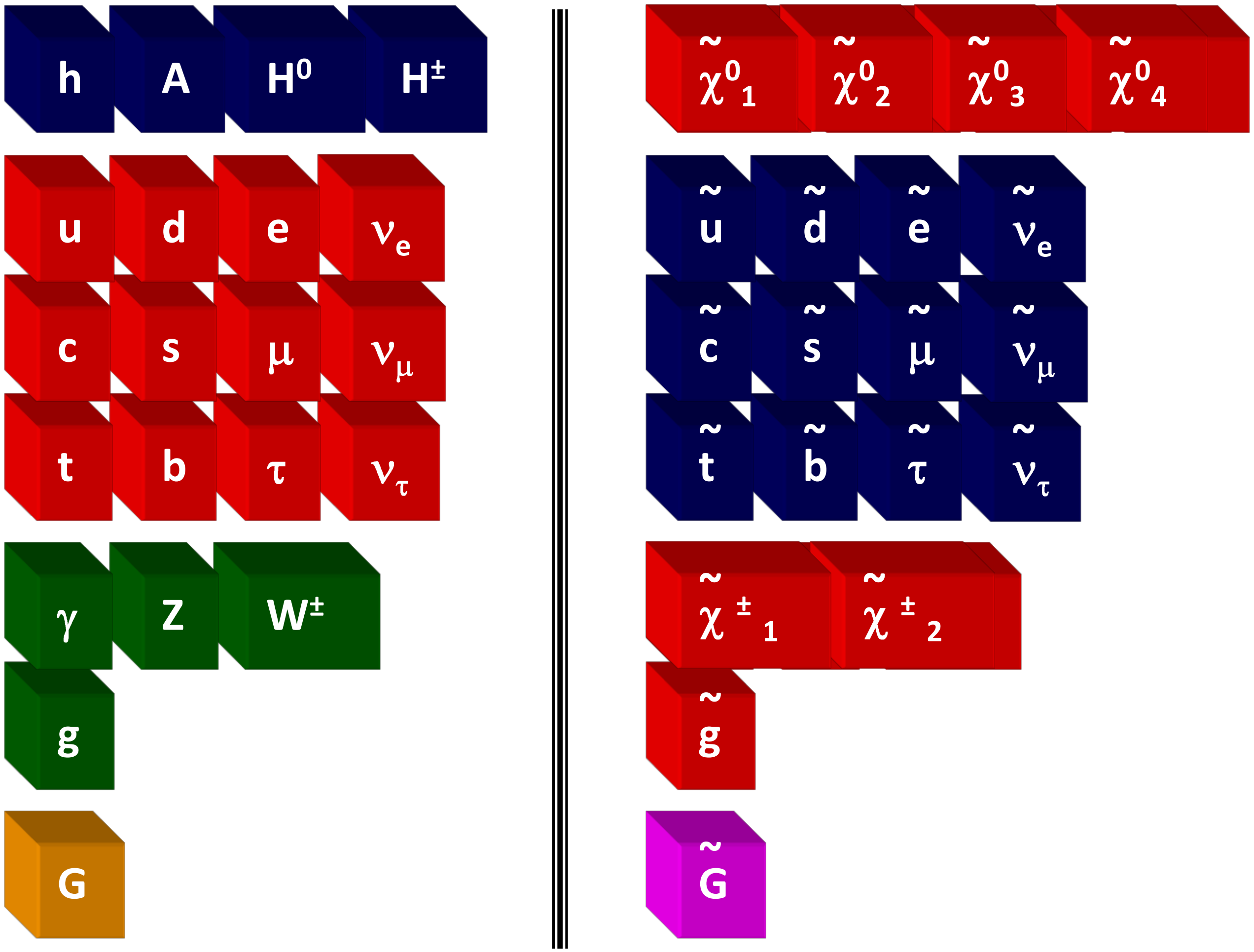
A VERY popular benchmark...

More than 8000 papers since 1990 (Kosower)

"One day all these trees will be SUSY phenomenology papers"

Considered as a benchmark for a large class of new physics models

- **SUSY gives rise to partners of SM states with opposite spin-statistics but otherwise same Quantum Numbers.**



Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \;\; \widetilde{d}_L)$	$(u_L \;\; d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \;\; \widetilde{e}_L)$	$(\nu \;\; e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H_u^+ \;\; H_u^0)$	$(\widetilde{H}_u^+ \;\; \widetilde{H}_u^0)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H_d^0 \;\; H_d^-)$	$(\widetilde{H}_d^0 \;\; \widetilde{H}_d^-)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

Supersymmetry needs a somewhat extended Higgs sector (compared to SM)
Two Higgs doublets, one for u-quarks, one for d-quarks

Higgs sector in SUSY

One complex Higgs doublet for d-type quarks and charged leptons.
Vacuum expectation value v_1

Another complex Higgs doublet for u-type quarks.
Vacuum expectation value v_2

We know $v^2 = v_1^2 + v_2^2 = (246\ \text{GeV})^2$

But we don't know $\tan\beta = v_2 / v_1$

Four complex Higgs fields = 8 free parameters
3 parameters eaten by EWSB → 5 Higgs bosons h, H, A, H^+, H^-

Four complex Higgsino fields

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8},\ \mathbf{1},\ 0)$
winos, W bosons	$\widetilde{W}^{\pm}\ \ \widetilde{W}^{0}$	$W^{\pm}\ \ W^{0}$	$(\mathbf{1},\ \mathbf{3},\ 0)$
bino, B boson	$\widetilde{B}^{0}$	B^{0}	$(\mathbf{1},\ \mathbf{1},\ 0)$

$\widetilde{W}^0\ \ \widetilde{B}^0\ \ \widetilde{H}_u^0\ \ \widetilde{H}_d^0$ mix to neutralinos $\tilde{\chi}_i^0$

$\widetilde{W}^{\pm}\ \ \widetilde{H}_u^+\ \ \widetilde{H}_d^-$ mix to charginos $\tilde{\chi}_{1,2}^{\pm}$

SUSY particles have same quantum numbers as SM partners (except spin)
→ Gauge interactions are fixed!   No freedom!

The only freedom is still present in a function called the **superpotential**

$$W = \epsilon_{ij}\mu\hat{H}_1^i\hat{H}_2^j + \epsilon_{ij}\left[\lambda_L\hat{H}_1^i\hat{L}^{cj}\hat{E}^c + \lambda_D\hat{H}_1^i\hat{Q}^j\hat{D}^c + \lambda_U\hat{H}_2^j\hat{Q}^i\hat{U}^c\right] + \epsilon_{ij}\left[\lambda_1\hat{L}^i\hat{L}^j\hat{E}^c + \lambda_2\hat{L}^i\hat{Q}^j\hat{D}^c\right] + \lambda_3\hat{U}^c\hat{D}^c\hat{D}^c,$$

$$\hat{Q} = (Q, \tilde{Q}) \quad \tilde{Q} = \begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix} \qquad \hat{L} = (L, \tilde{L}) \quad \tilde{L} = \begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}$$

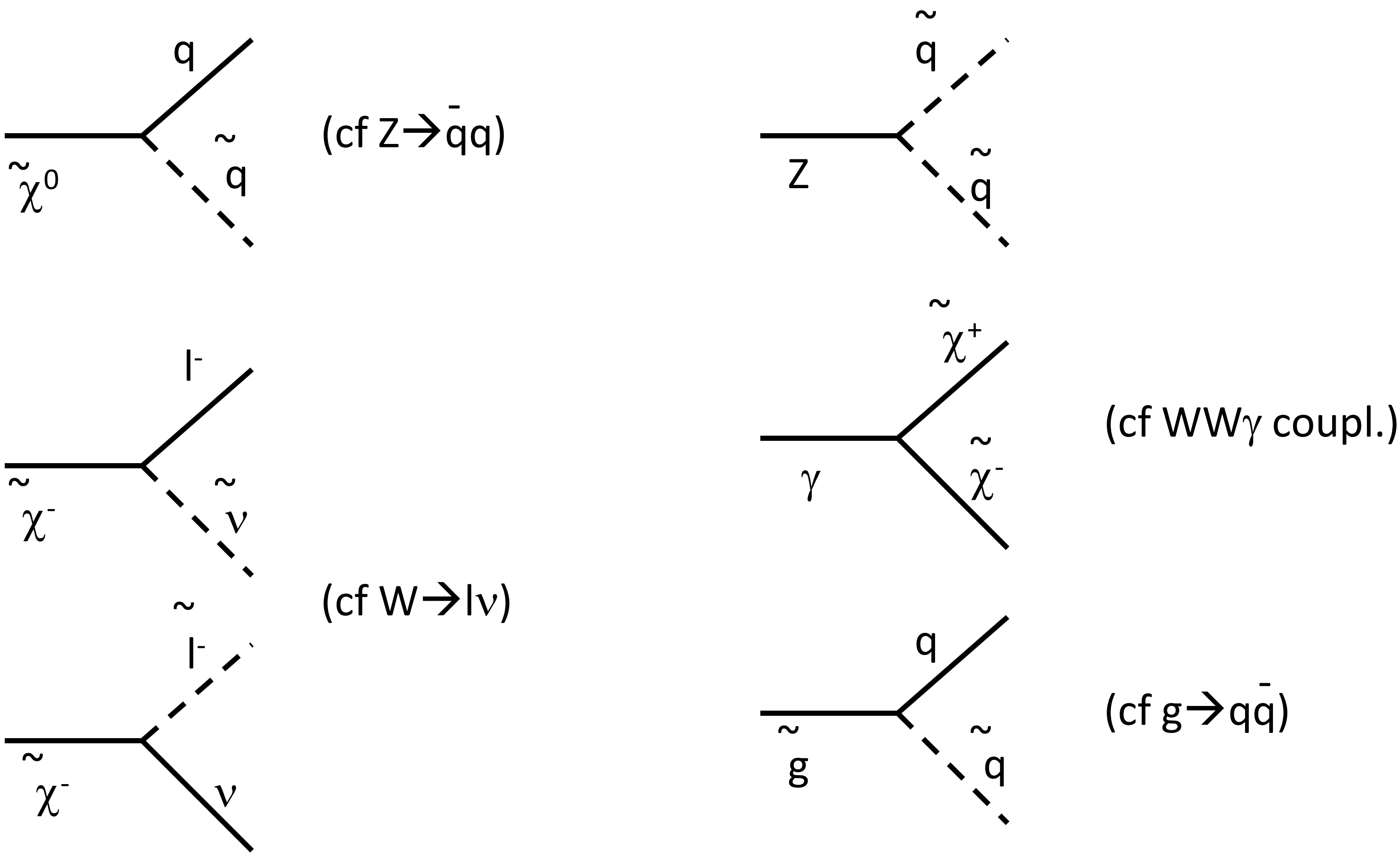
From the superpotential can be found both the scalar potential and the Yukawa interactions of the fermions with the scalars:

$$\mathcal{L}_W = -\sum_i \left| \frac{\partial W}{\partial z_i} \right|^2 - \frac{1}{2}\sum_{ij}\left[\overline{\psi}_{iL}\frac{\partial^2 W}{\partial z_i \partial z_j}\psi_j + \text{h.c.}\right], \qquad (15)$$

Interactions: General rule: take SM Feynman diagram, replace two SM particles by their superpartners → SUSY diagram.

(excepted: interactions with Higgs bosons…)

(Feynman rules complicated by mixings…)

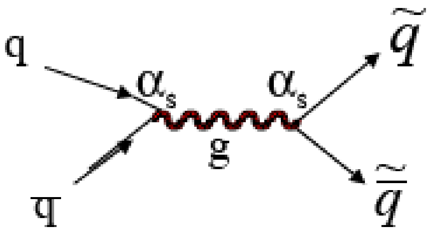


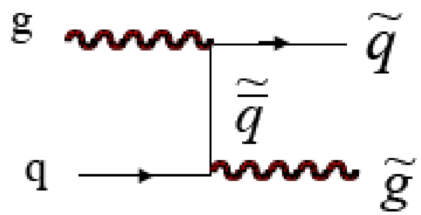
SUSY production

- The SUSY partners have the same coupling constants as the SM particles. QCD production cross sections, if available, are the largest.

	Strong	EM	Weak
Squark	X	X	X
Gluino	X	-	-
Chargino	-	X	X
Neutralino	-	-	X
Slepton	-	X	X
Sneutrino	-	-	X

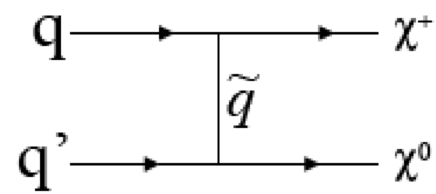
SUSY production - 2

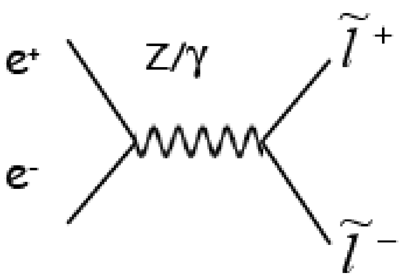


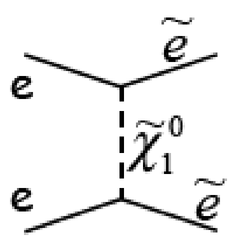


• In a hadron machine Squarks and gluinos produced via strong processes → large cross-section if kinematically allowed

• Charginos, neutralinos, sleptons produced via electroweak processes → much smaller rate







•In e+e- democratic production of everything, but smaller cross section. Good for sleptons and weak gauginos.

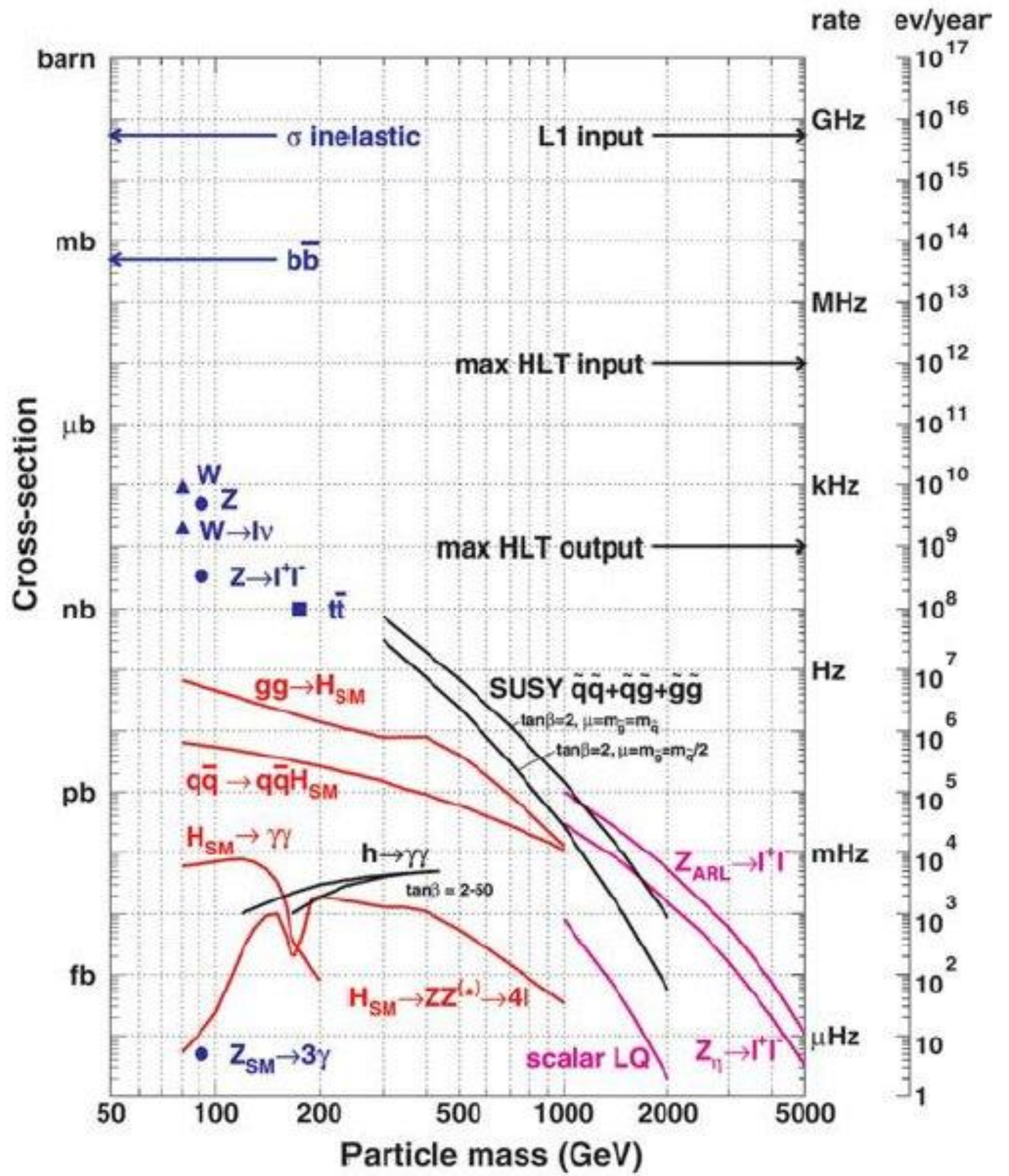
The cross section for
$gg \rightarrow qq$ at LHC is HUGE

But the cross section for
$gg \rightarrow \tilde{q}\tilde{q}$ is OF THE SAME ORDER OF MAGNITUDE

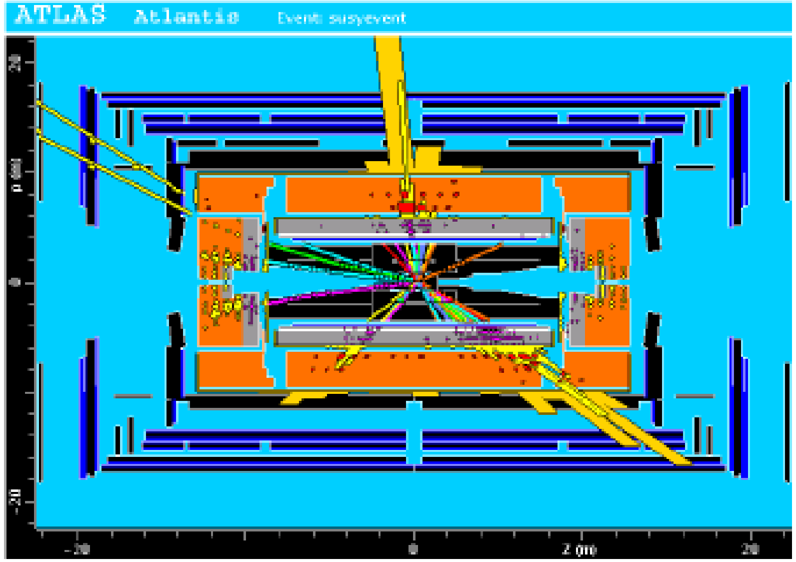
(if $m_q = m_{\tilde{q}}$)

(same order only because of spin factors, etc)

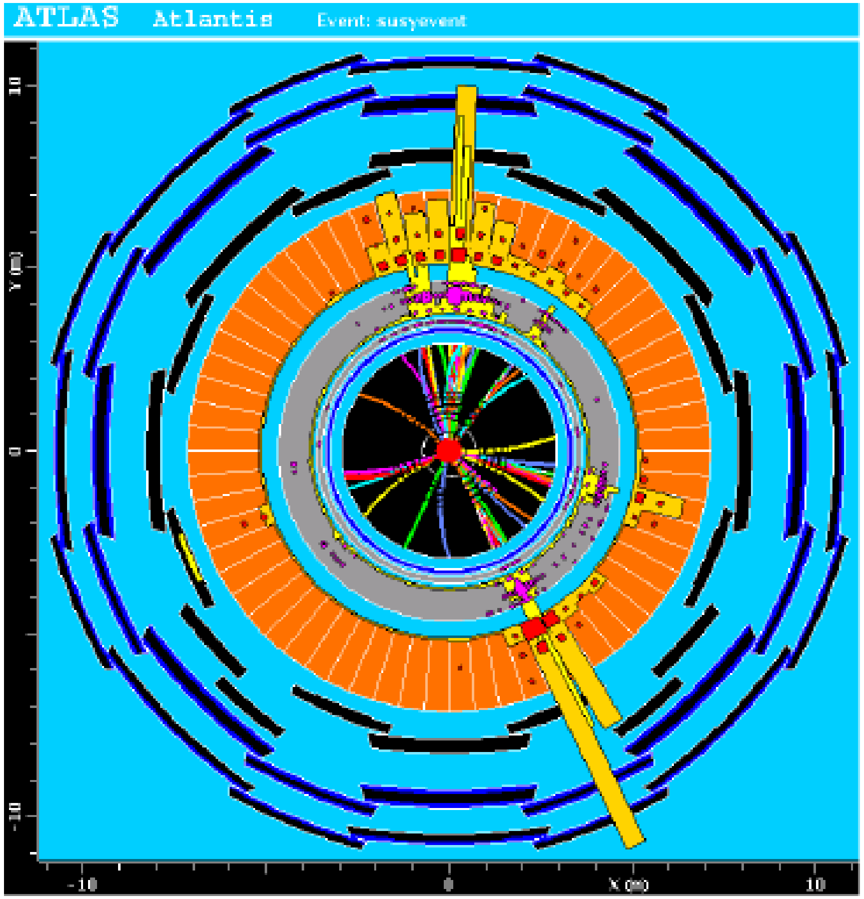
SUSY at LHC dominated by squark and gluino production. Other particles produced in decays.



A SUSY event in ATLAS



simulation!



Multi-jet event in Bulk Region

- 6 jets
- 2 high-pt muons
- Large missing E_T

R-parity

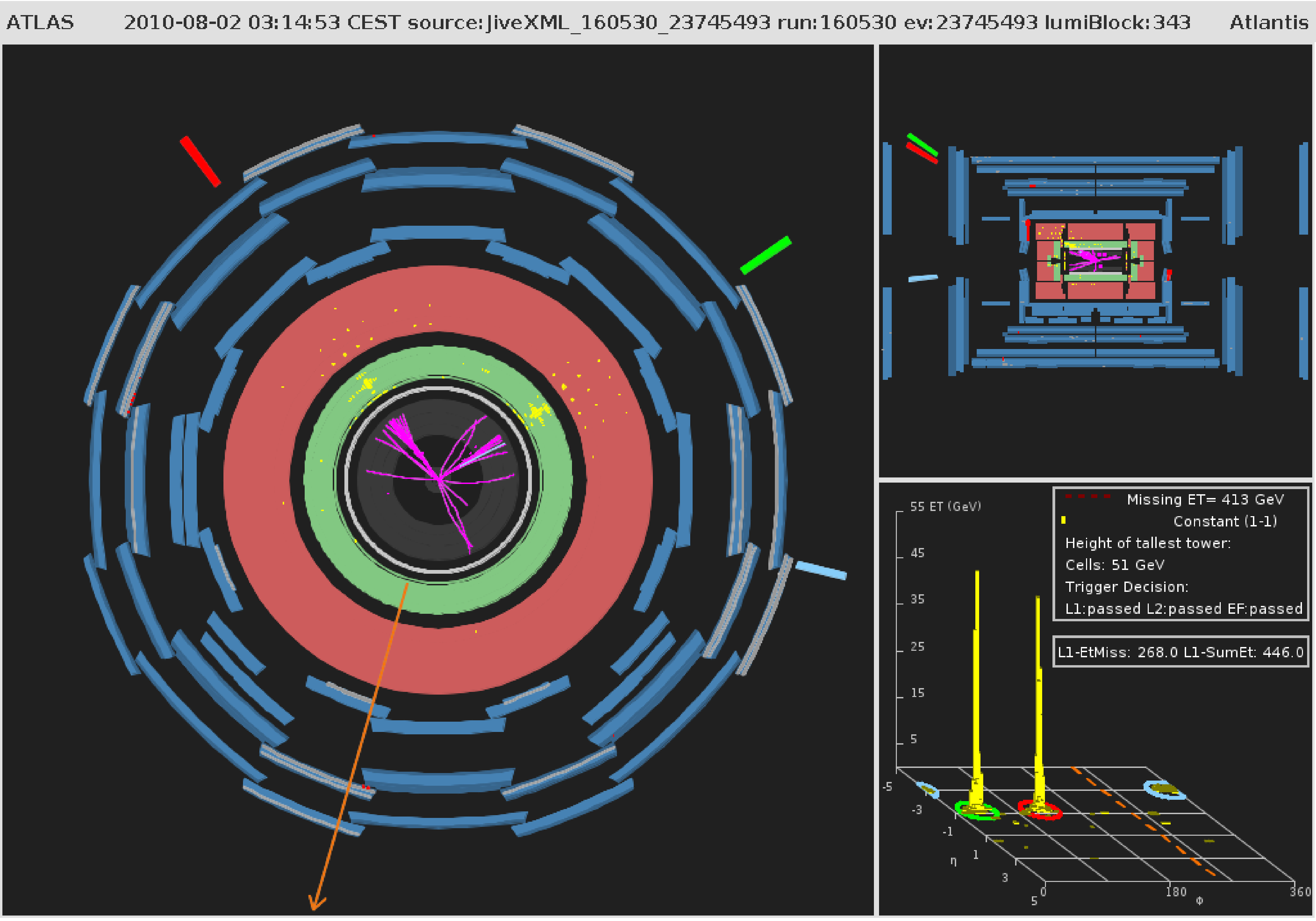
- $R = (-1)^{(L+3B+2S)}$
- Conserved:
  - SUSY particle produced in pairs
  - LSP is stable (and a dark matter candidate)
  - If neutral (neutralino, gravitino, sneutrino) it disappears from the detector undetected → missing energy

Usually $\tilde{\chi}_1^0$

(but also $\tilde{G}$, $\tilde{\nu}$)

- Violated (RPV)
  - LSP decays in the detector
  - Single particle production possible
  - Constrained by proton decay limits

    (the λ_1 , λ_2 , λ_3 terms in the superpotential are R-parity violating)



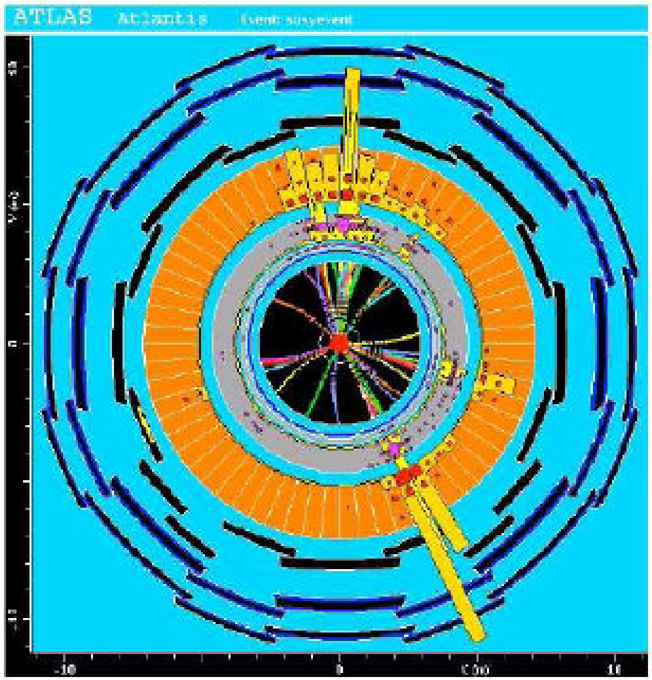
Actual ATLAS event at 7 TeV

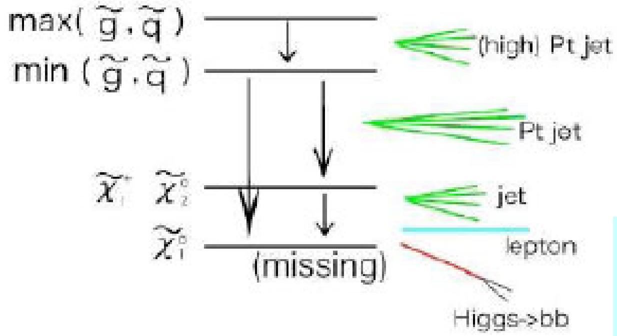
Early Supersymmetry?

SUSY could be at the rendez-vous very early on!

M_{sp}(GeV)	σ (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

$10 fb^{-1}$





event topologies of SUSY

	multi	leptons
$\not{E}_T$ +	High P_T jets +	b-jets
		τ-jets

For low mass SUSY we get O(10,000) events/year even at startup

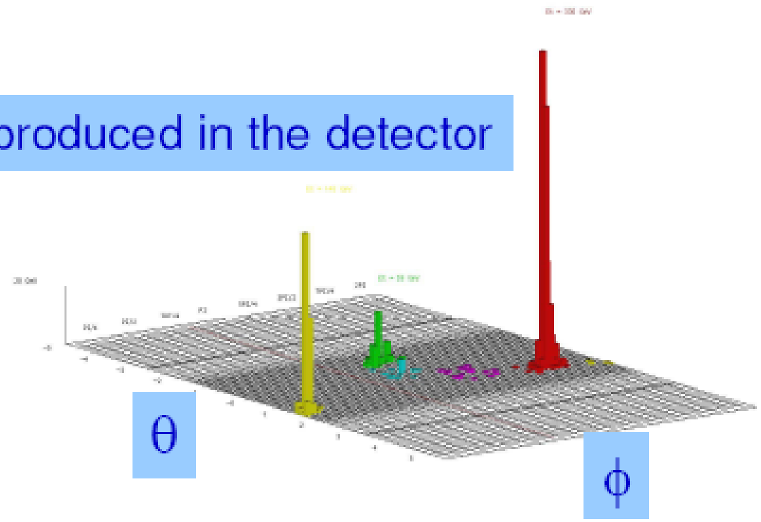
Main signal: lots of activity (jets, leptons, taus, missing E_T)

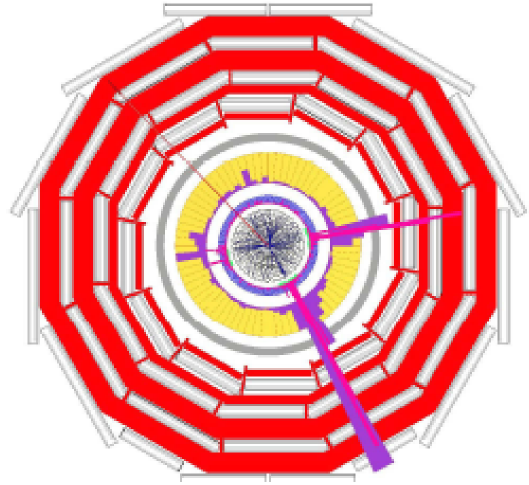
Needs an excellent understanding of the detector and SM backgrounds

Note: establishing that the new signal is SUSY will be more difficult!

Hunting for SUSY

Energy produced in the detector



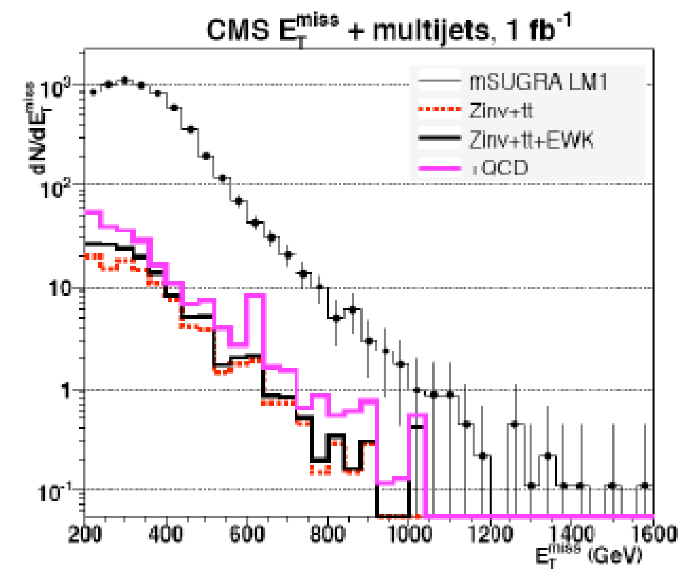


Missing E_T is a difficult measurement for the experiments

Distribution of the "Missing Transverse Momentum (Energy) "⇒

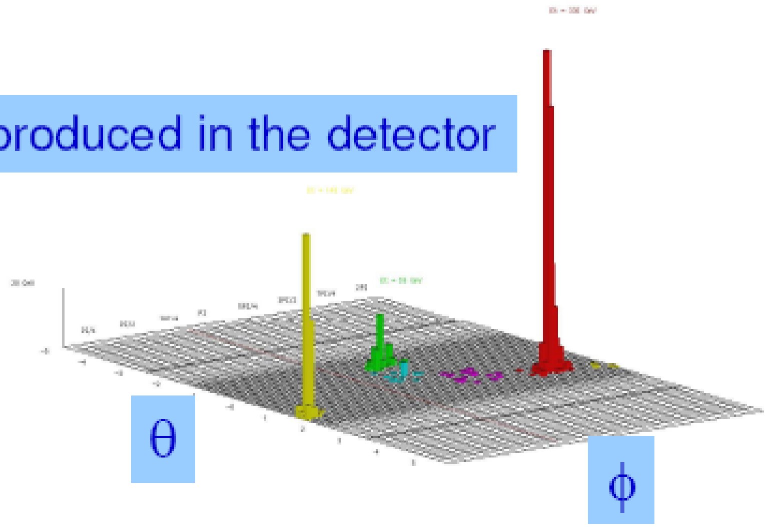
Large signal over background in E_T^{miss} for the a chosen "easy" SUSY point (LM1)

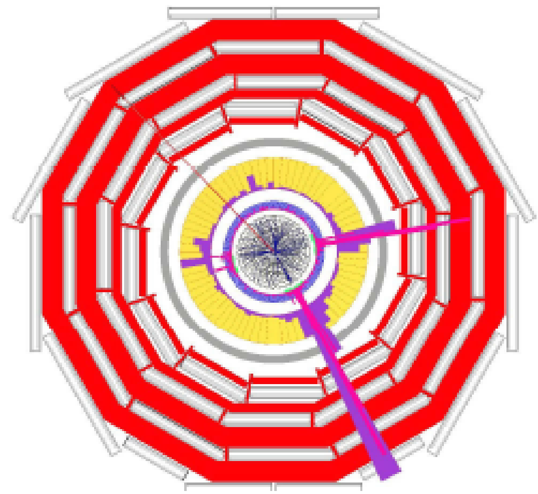
Can we thrust our background estimate?



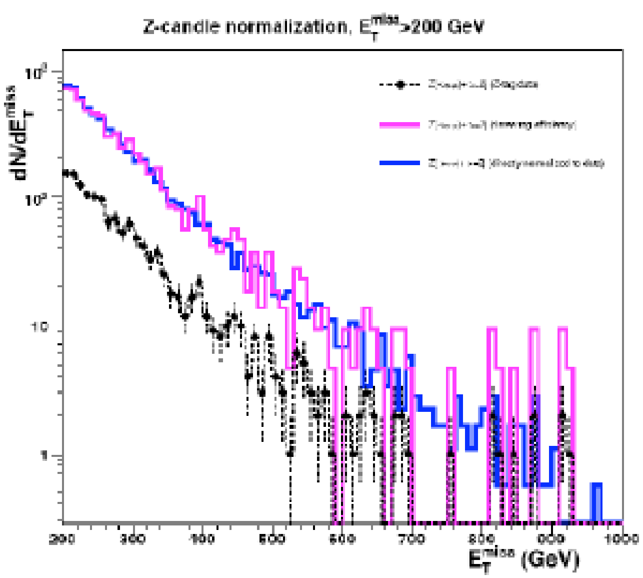
Hunting for SUSY

Energy produced in the detector





Missing E_T is a difficult measurement for the experiments



⇒ Missing E_T from the process $Z \rightarrow \nu\nu$ (+jets)

- Determine this background by the measurable process $Z \rightarrow \mu\mu$ (+ jets)
- Calculate the expected $Z \rightarrow \nu\nu$ (+jets)
  Still see more events in data? You are in business!!
- More checks $W \rightarrow \mu\nu$, $e\nu$, photon + jets, kinematic variables etc etc...

Supersymmetry cannot be exact: it must be broken

We do not know very well how: models

General MSSM: 105 new parameters.
MSSM = Minimal Supersymmetric Standard Model

Number reduced in SUSY breaking models.

Phenomenology at LHC depends on model.
(Although in general: production of squarks and gluinos
dominates → production cross section fairly well known)

MSSM: designed as the minimal most general extension of the Standard Model.

Minimal: Higgs sector as simple as possible.

Most general: → 105 new parameters.
But: most heavily constrained by data:
- flavour changing neutral currents
- CP-violation
- cosmology

In a sense, the SM could have had many more parameters as well… (e.g. most general triple gauge boson vertices: 14 new parameters. In the SM most are just zero.)

Once the SUSY breaking principle is known, parameter space will be reduced.

SUSY “broken by hand” in Lagrangian.
But we want to keep the good property that $\Delta m_H \sim \ln \Lambda$, and not $\sim \Lambda^2$!
→ **“soft SUSY breaking”**

The “soft SUSY breaking” MSSM Lagrangian:

$$
\begin{aligned}
-\mathcal{L}_{soft} \; = \; & m_1^2 \mid H_1 \mid^2 + m_2^2 \mid H_2 \mid^2 - B\mu\epsilon_{ij}(H_1^i H_2^j + \text{h.c.}) + \tilde{M}_Q^2(\tilde{u}_L^* \tilde{u}_L + \tilde{d}_L^* \tilde{d}_L) \\
& + \tilde{M}_u^2 \tilde{u}_R^* \tilde{u}_R + \tilde{M}_d^2 \tilde{d}_R^* \tilde{d}_R + \tilde{M}_L^2(\tilde{e}_L^* \tilde{e}_L + \tilde{\nu}_L^* \tilde{\nu}_L) + \tilde{M}_e^2 \tilde{e}_R^* \tilde{e}_R \\
& + \frac{1}{2}\left[M_3 \bar{\tilde{g}} \tilde{g} + M_2 \bar{\tilde{\omega}}_i \tilde{\omega}_i + M_1 \bar{\tilde{b}} \tilde{b}\right] + \frac{g}{\sqrt{2} M_W} \epsilon_{ij} \left[\frac{M_d}{\cos\beta} A_d H_1^i \tilde{Q}^j \tilde{d}_R^* \right. \\
& \left. + \frac{M_u}{\sin\beta} A_u H_2^j \tilde{Q}^i \tilde{u}_R^* + \frac{M_e}{\cos\beta} A_e H_1^i \tilde{L}^j \tilde{e}_R^* + \text{h.c.}\right] \quad .
\end{aligned}
$$

$$
\tilde{Q} = \begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix} \qquad \tilde{L} = \begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}
$$

The “soft SUSY breaking” MSSM Lagrangian:

$$
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-\mathcal{L}_{soft} = \; & m_1^2 \mid H_1 \mid^2 + m_2^2 \mid H_2 \mid^2 - B\mu\epsilon_{ij}(H_1^i H_2^j + \text{h.c.}) + \tilde{M}_Q^2(\tilde{u}_L^* \tilde{u}_L + \tilde{d}_L^* \tilde{d}_L) \\
& + \tilde{M}_u^2 \tilde{u}_R^* \tilde{u}_R + \tilde{M}_d^2 \tilde{d}_R^* \tilde{d}_R + \tilde{M}_L^2(\tilde{e}_L^* \tilde{e}_L + \tilde{\nu}_L^* \tilde{\nu}_L) + \tilde{M}_e^2 \tilde{e}_R^* \tilde{e}_R \\
& + \frac{1}{2}\left[M_3 \overline{\tilde{g}} \tilde{g} + M_2 \overline{\tilde{\omega}_i} \tilde{\omega}_i + M_1 \overline{\tilde{b}} \tilde{b}\right] + \frac{g}{\sqrt{2} M_W} \epsilon_{ij} \left[\frac{M_d}{\cos\beta} A_d H_1^i \tilde{Q}^j \tilde{d}_R^* \right. \\
& \left. + \frac{M_u}{\sin\beta} A_u H_2^j \tilde{Q}^i \tilde{u}_R^* + \frac{M_e}{\cos\beta} A_e H_1^i \tilde{L}^j \tilde{e}_R^* + \text{h.c.}\right] \quad .
\end{aligned}
$$

Gaugino’s and their masses M_3, M_2, M_1

The “soft SUSY breaking” MSSM Lagrangian:

$$
\begin{aligned}
-\mathcal{L}_{soft} \;=\;& m_1^2 \mid H_1 \mid^2 + m_2^2 \mid H_2 \mid^2 - B\mu\epsilon_{ij}(H_1^i H_2^j + \text{h.c.}) + \tilde{M}_Q^2(\tilde{u}_L^* \tilde{u}_L + \tilde{d}_L^* \tilde{d}_L) \\
& + \tilde{M}_u^2 \tilde{u}_R^* \tilde{u}_R + \tilde{M}_d^2 \tilde{d}_R^* \tilde{d}_R + \tilde{M}_L^2(\tilde{e}_L^* \tilde{e}_L + \tilde{\nu}_L^* \tilde{\nu}_L) + \tilde{M}_e^2 \tilde{e}_R^* \tilde{e}_R \\
& + \frac{1}{2}\left[M_3 \bar{\tilde{g}}\tilde{g} + M_2 \bar{\tilde{\omega}}_i \tilde{\omega}_i + M_1 \bar{\tilde{b}}\tilde{b}\right] + \frac{g}{\sqrt{2}M_W}\epsilon_{ij}\left[\frac{M_d}{\cos\beta} A_d H_1^i \tilde{Q}^j \tilde{d}_R^* \right. \\
& \left. + \frac{M_u}{\sin\beta} A_u H_2^j \tilde{Q}^i \tilde{u}_R^* + \frac{M_e}{\cos\beta} A_e H_1^i \tilde{L}^j \tilde{e}_R^* + \text{h.c.}\right] \quad .
\end{aligned}
$$

Squarks and sleptons, and their masses

The “soft SUSY breaking” MSSM Lagrangian:

$$
\begin{aligned}
-\mathcal{L}_{soft} \;=\;& m_1^2 \mid H_1 \mid^2 + m_2^2 \mid H_2 \mid^2 - B\mu\epsilon_{ij}(H_1^i H_2^j + \text{h.c.}) + \tilde{M}_Q^2(\tilde{u}_L^* \tilde{u}_L + \tilde{d}_L^* \tilde{d}_L) \\
& + \tilde{M}_u^2 \tilde{u}_R^* \tilde{u}_R + \tilde{M}_d^2 \tilde{d}_R^* \tilde{d}_R + \tilde{M}_L^2(\tilde{e}_L^* \tilde{e}_L + \tilde{\nu}_L^* \tilde{\nu}_L) + \tilde{M}_e^2 \tilde{e}_R^* \tilde{e}_R \\
& + \frac{1}{2}\left[M_3 \bar{\tilde{g}}\tilde{g} + M_2 \overline{\tilde{\omega}_i}\tilde{\omega}_i + M_1 \bar{\tilde{b}}\tilde{b}\right] + \frac{g}{\sqrt{2}M_W}\epsilon_{ij}\Big[\frac{M_d}{\cos\beta} A_d H_1^i \tilde{Q}^j \tilde{d}_R^* \\
& + \frac{M_u}{\sin\beta} A_u H_2^j \tilde{Q}^i \tilde{u}_R^* + \frac{M_e}{\cos\beta} A_e H_1^i \tilde{L}^j \tilde{e}_R^* + \text{h.c.}\Big] \quad .
\end{aligned}
$$

Tri-linear couplings A
(from the superpotential)

The “soft SUSY breaking” MSSM Lagrangian:

$$
\begin{aligned}
-\mathcal{L}_{soft} \;=\; & m_1^2 \mid H_1 \mid^2 + m_2^2 \mid H_2 \mid^2 - B\mu\epsilon_{ij}(H_1^i H_2^j + \text{h.c.}) + \tilde{M}_Q^2(\tilde{u}_L^* \tilde{u}_L + \tilde{d}_L^* \tilde{d}_L) \\
& + \tilde{M}_u^2 \tilde{u}_R^* \tilde{u}_R + \tilde{M}_d^2 \tilde{d}_R^* \tilde{d}_R + \tilde{M}_L^2(\tilde{e}_L^* \tilde{e}_L + \tilde{\nu}_L^* \tilde{\nu}_L) + \tilde{M}_e^2 \tilde{e}_R^* \tilde{e}_R \\
& + \frac{1}{2}\left[M_3 \bar{\tilde{g}}\tilde{g} + M_2 \overline{\tilde{\omega}_i}\tilde{\omega}_i + M_1 \bar{\tilde{b}}\tilde{b}\right] + \frac{g}{\sqrt{2}M_W}\epsilon_{ij}\left[\frac{M_d}{\cos\beta} A_d H_1^i \tilde{Q}^j \tilde{d}_R^* \right. \\
& \left. + \frac{M_u}{\sin\beta} A_u H_2^j \tilde{Q}^i \tilde{u}_R^* + \frac{M_e}{\cos\beta} A_e H_1^i \tilde{L}^j \tilde{e}_R^* + \text{h.c.}\right] .
\end{aligned}
$$

Higgs sector: 2 complex doublets (1 for u-type, 1 for d-type)

Higgs bosons get mass from m_i and from μ

B: bilinear interaction

Explicit models of SUSY breaking can reduce number of parameters:

For example, inspired by GUTs: let parameters unify at 10^{16} GeV:

→ Common scalar mass m_0
→ Common gaugino mass $m_{1/2}$
→ Common trilinear coupling parameter A_0

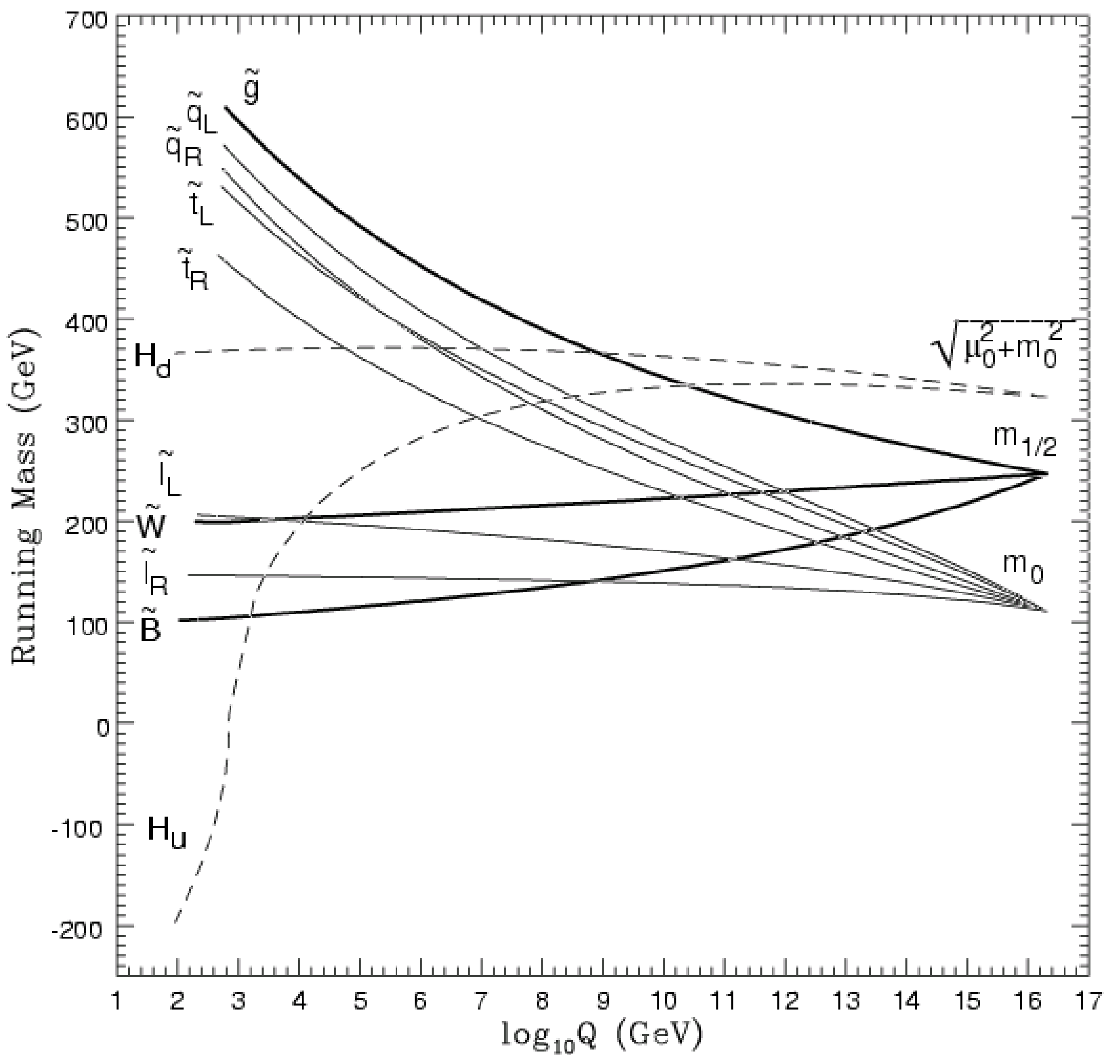
And then only parameters left: B, μ

Can be traded for tan β and sign(μ)

→ Constrained MSSM: 4 parameters plus a sign

(Variations on this theme (since case for m_0 not so strong):
- non-universal Higgs mass models
- $m_0 >> m_{1/2}$: "split supersymmetry")

Fixing parameters at 10^{16} GeV, the renormalization group equations will tell you exactly all masses at LHC!



Example:

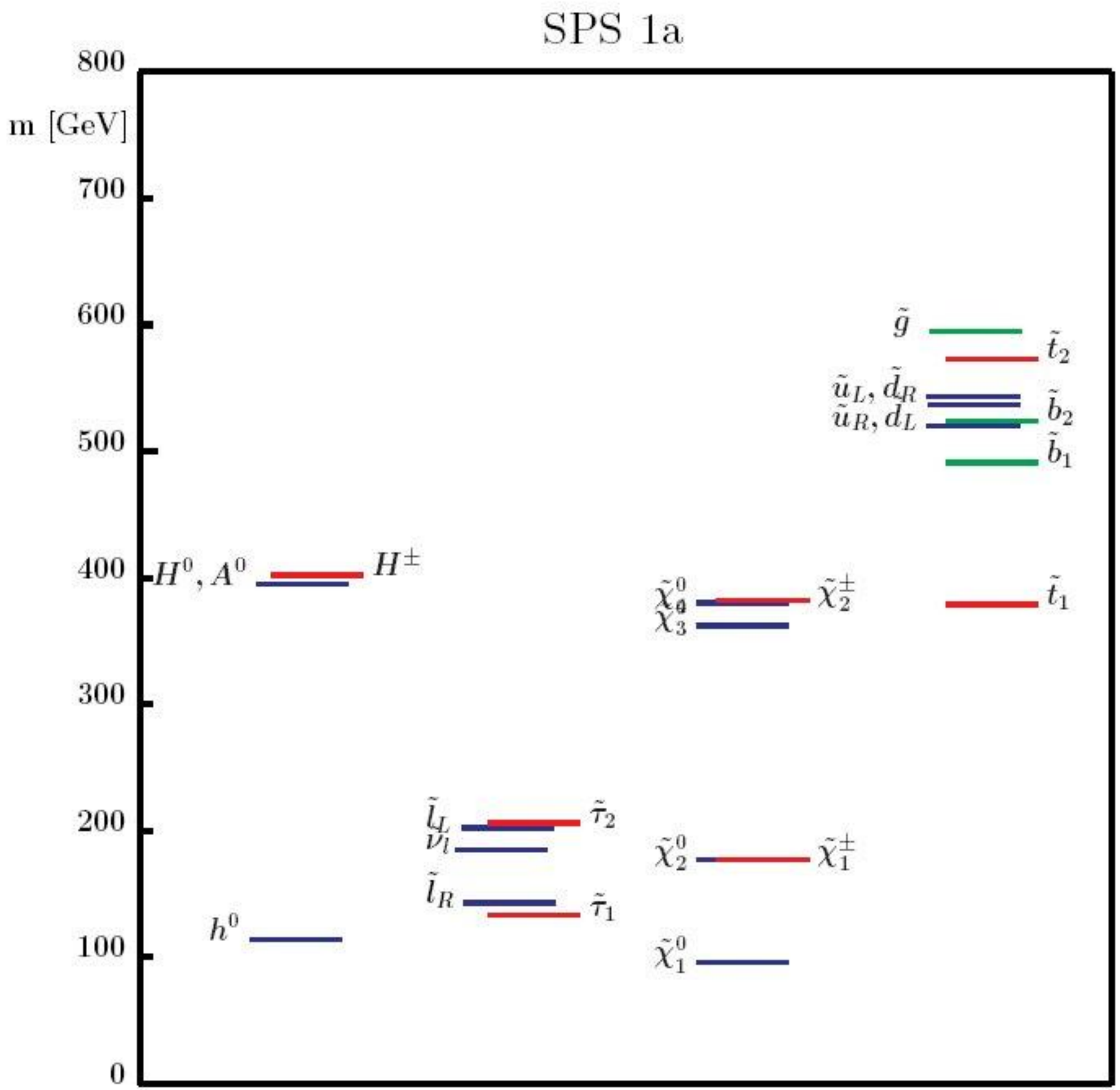
m_0 = 100 GeV

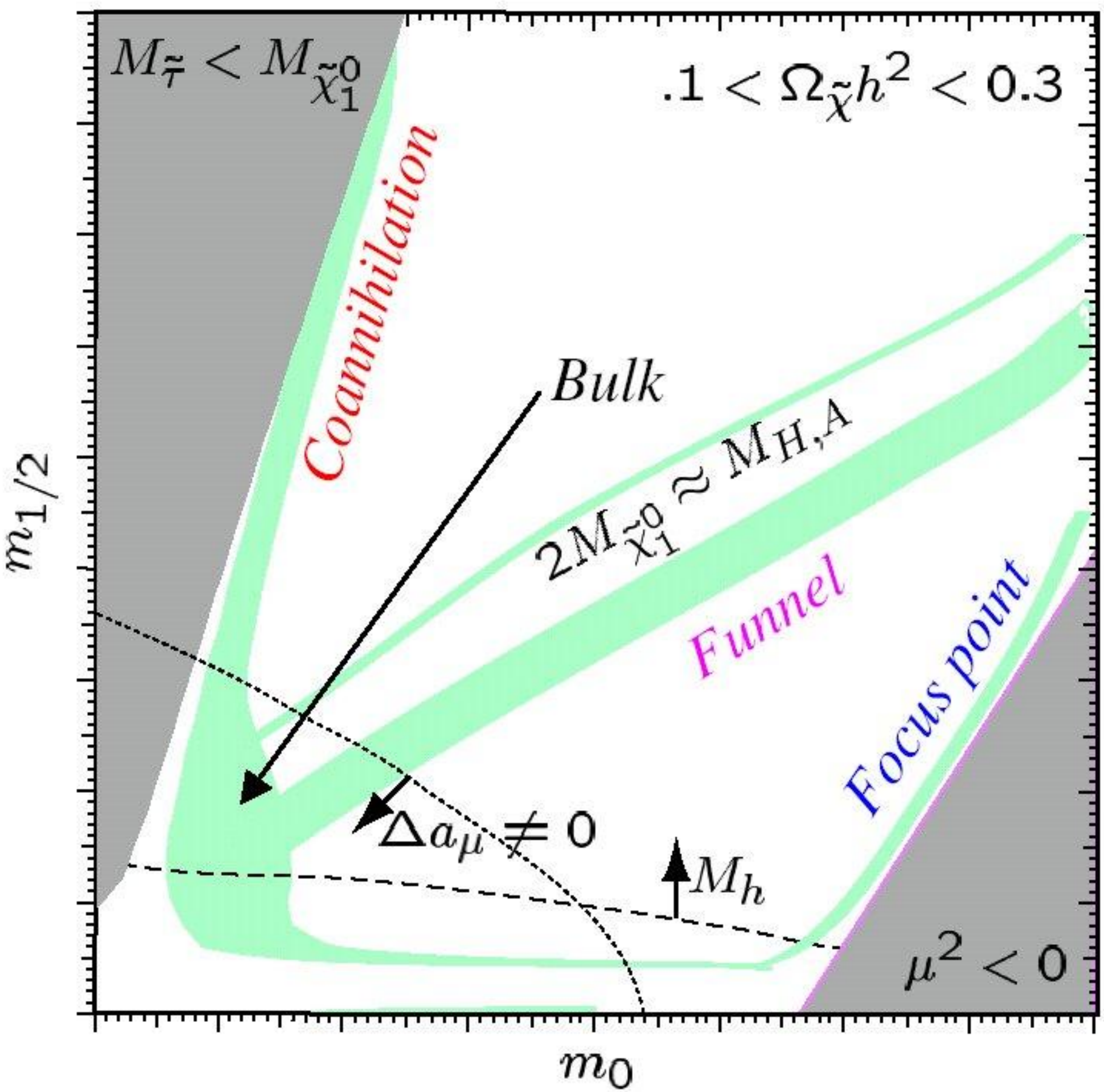
$m_{1/2}$ = 250 GeV

A_0 = -100 GeV

tan β = 10

μ > 0



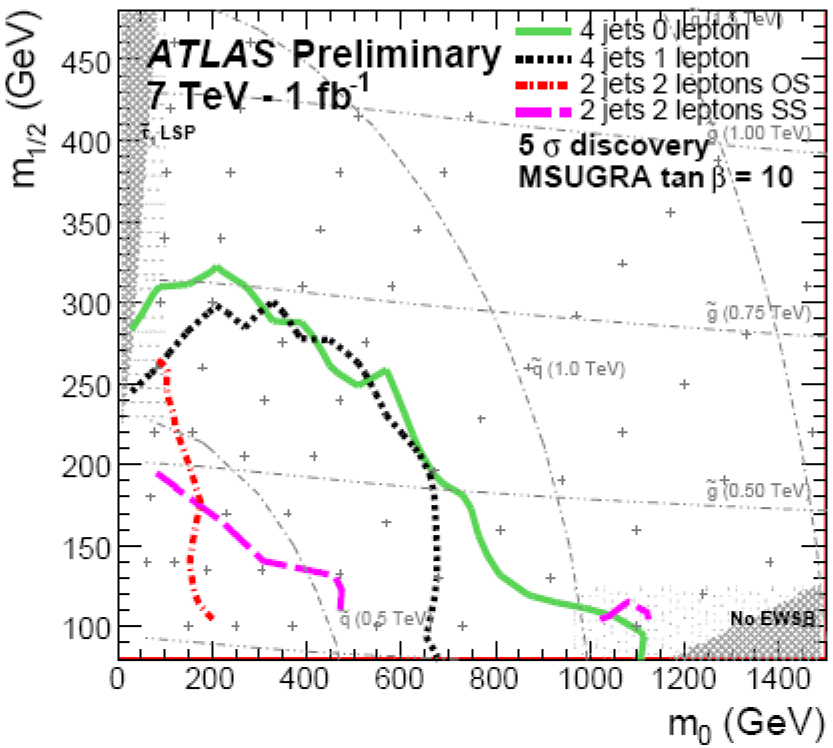


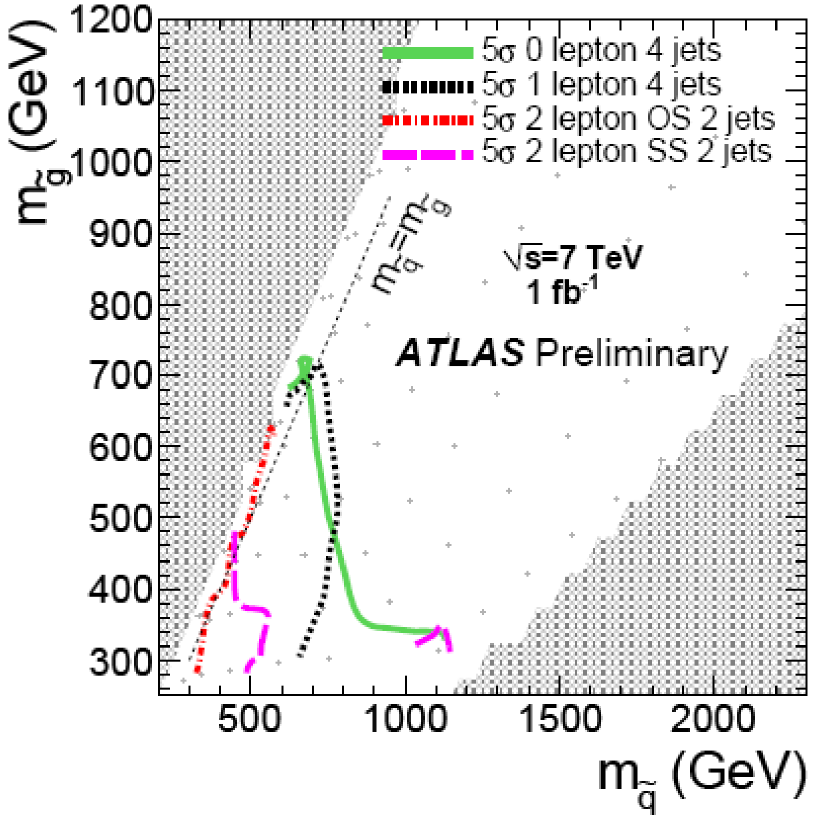
Often shown:
$m_{1/2} - m_0$ plane

(for given A_0, $\tan\beta$)

Not every combination
is allowed!

ATLAS expectation by end of 2011: 1 fb^{-1} at 7 TeV





Sensitivity up to ~700 – 800 GeV
Current Tevatron limits: ~400 GeV

Where do we expect SUSY?

O. Buchmuller et al
arXiv:0808.4128

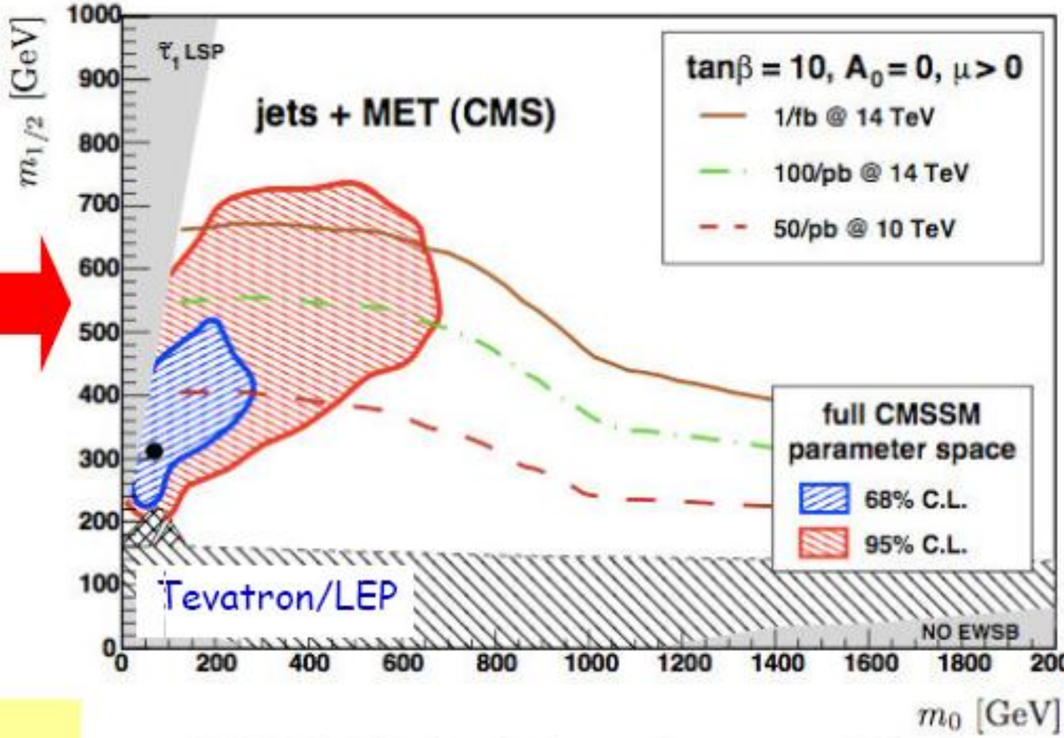
OB, R.Cavanaugh, A.De Roeck
J.R.Ellis, H.~Flaecher, S.~Heineme
G.Isidor, K.A.Olive, P.Paradisi,
F.J.Ronga, G.Weiglein

Precision measurements
Heavy flavour observables

Simultaneous fit of CMSSM parameters m_0, $m_{1/2}$, A_0, tan (μ>0) to more than 30 collide and cosmology data (e.g. M_t, M_{top}, g-2, BR(B→Xγ), relic density)

"Predict" on the basis of present data what the preferred region for SUSY is (in constrained MSSM SUSY)

"LHC Weather Forecast"



"CMSSM fit clearly favors low-mass SUSY - Evidence that a signal might show up very early?!"

Many other groups attempt to make similar predictions

Results are often expressed as limits on few parameters (e.g. m_0 , $m_{1/2}$)

But **SUSY is much richer than just those few parameters**
Simplification assumptions are often indeed simplifications, not always justified

→ Important to keep the search general

Recent study: **Supersymmetry without prejudice at the LHC**

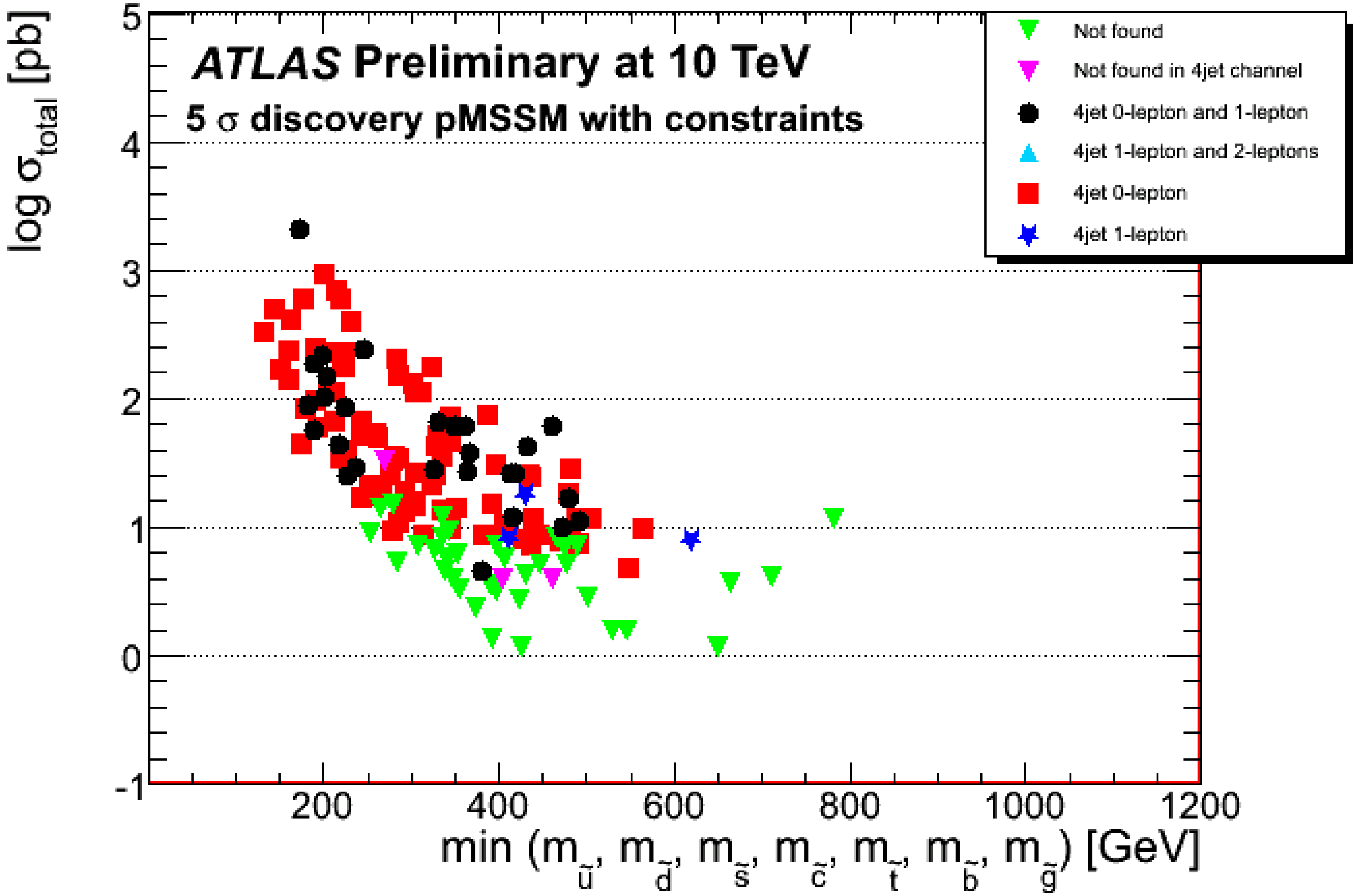
arXiv:1009.2539v1 [hep-ph] 13 Sep 2010

MSSM with 19 dimensional-parameter space (no flavour parameters)
~70000 samples generated at random points not yet ruled out

→Conclusion: ATLAS will find 99.4% of the models with sparticle masses < 1 TeV
with 1 fb^{-1} at 14 TeV

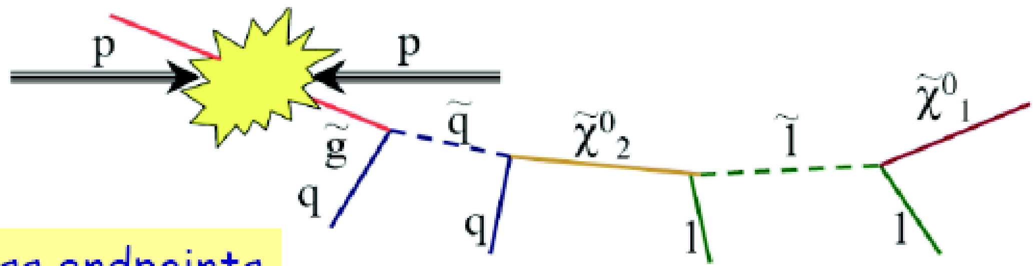
→ Need to take a further look at the models we don't find!

Expressed in 19-parameter MSSM (not mSUGRA)
Each dot is a model point; green = not detectable

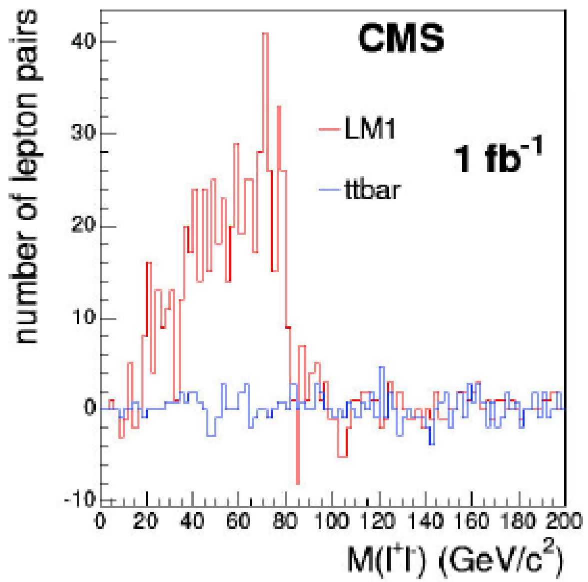


Sparticle Mass Reconstruction

First Mass Clues (dileptons)



Invariant mass endpoints



- $M_{\ell\ell}^{max} = M(\tilde{\chi}_2^0)\sqrt{1 - \frac{M^2(\tilde{\ell}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1 - \frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{\ell}_R)}}$
- $M_{\ell\ell}^{max}$(meas)= 80.42 ± 0.48 GeV/c^2, *cfr* with
- expected $M_{\ell\ell}^{max}$= 81 GeV/c^2 [given $M(\tilde{\chi}_1^0)$ = 95, $M(\tilde{\chi}_2^0)$= 180 and $M(\tilde{\ell}_R)$ = 119 GeV/c^2]

SUSY Program for an Experimentalist

- Understand the detector and the Standard Model Backgrounds
- Establish an excess ⇒ Discover a signal compatible with supersymmetry
- Measure sparticle masses
- Measure sparticle production cross sections, branching ratios, couplings
- Look for more difficult sparticle signatures hidden in the data
- Is it really SUSY? Check eg. the spin of the new particles. Compatible with present/future data on precision measurements (LHCb, B-fact…)
- Turn the pole mass measurements into MSSM Lagrangian parameters of the model
- Map the measurements to the SUSY space to select possible underlying theory at the high scale and SUSY breaking mechanism (Eg. Nature May06, "theorists try to guess what the theory is from pseudo-data")

Even for an early discovery it will take years to complete such a program

In minimal supersymmetry the lightest Higgs mass is computable:

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \log \frac{\tilde{m}_t^2}{m_t^2} + \cdots$$

$M_h < 130\ GeV.$ (or so…)

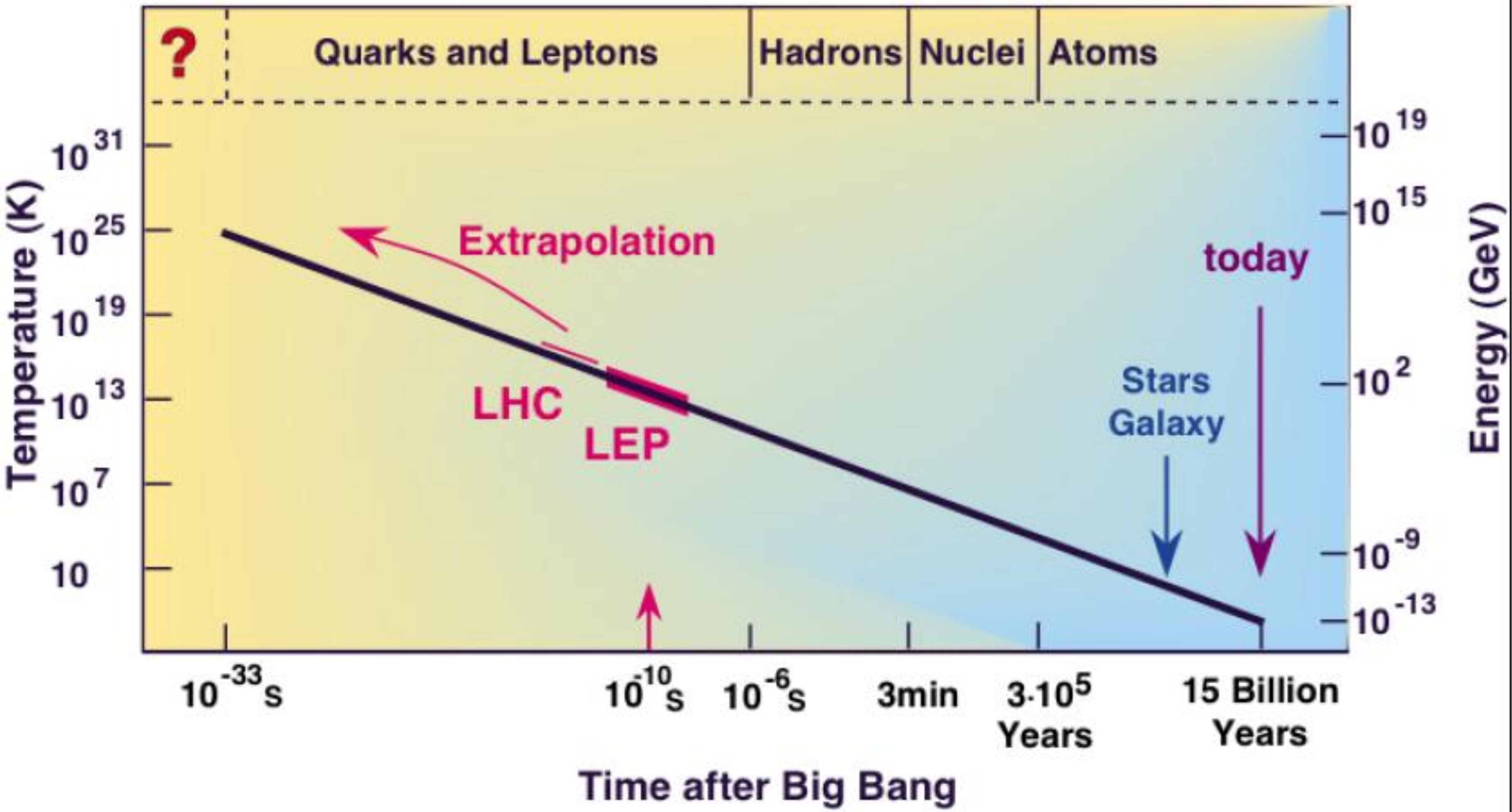
Furthermore, there must be more Higgses! H, A, H^+ , H^-

Studying the Higgs sector is crucial for establishing the new physics as supersymmetry

Final remarks:

“LHC is most powerful street lamp in history”

Are we looking under the street lamp only because that’s where the light is?



?
Quarks and Leptons
Hadrons
Nuclei
Atoms
Temperature (K)
10^{31}
10^{25}
10^{19}
10^{13}
10^{7}
10
Energy (GeV)
10^{19}
10^{15}
10^{2}
10^{-9}
10^{-13}
Extrapolation
LHC
LEP
today
Stars
Galaxy
10^{-33}s
10^{-10}s
10^{-6}s
3min
$3 \cdot 10^5$ Years
15 Billion Years
Time after Big Bang

I can guarantee nothing, but I have good hope:

Electroweak symmetry breaking: find the Higgs, or trouble…
Higgs: really SM ? We will find out at the LHC

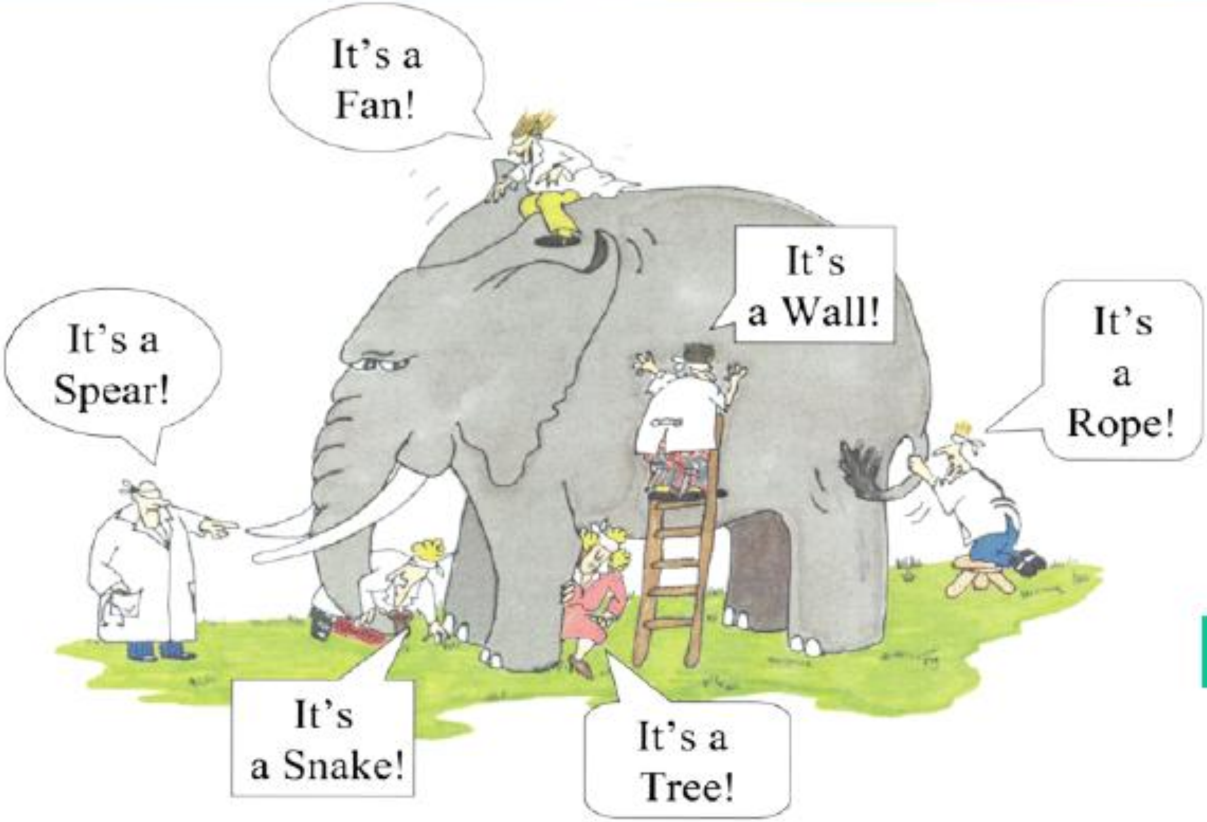
Hierarchy problem points to TeV scale

Dark matter & WIMP miracle: point to TeV scale

Plus: neutrinos
unification
matter-antimatter asymmetry
inflation, dark energy
Beyond the LHC: precision experiments, astroparticles, ILC

→ **YOU ARE PIONEERS!**

Since we do not know what we will find…



Nature.com

…we will look at it from all angles….

Close interaction between Experiment and Theory will be important


That's all Folks!

But maybe the "New World" is far more weird than what we thought sofar…

Recent developments in many models lead to the possible existence of heavy particles that have unusual long lifetimes

These can decay in the middle of the detector (nanoseconds) or live even much longer eg seconds, hours, days…

This leads to very special detector signatures!

Long Lived Particles in Supersymmetry

Split Supersymmetry

- Assumes nature is fine tuned and SUSY is broken at some high scale
- The only light particles are the Higgs and the gauginos
  - Gluino can live long: sec, min, years!
  - R-hadron formation (eg: gluino+ gluon): slow, heavy particles containing a heavy gluino.

  Unusual interactions with material

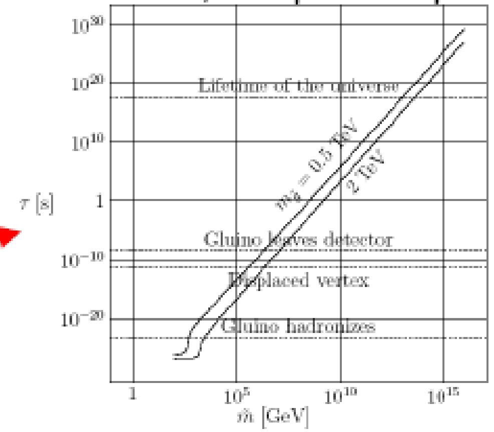
  eg. with the calorimeters of the experiments!

Gravitino Dark Matter and GMSB

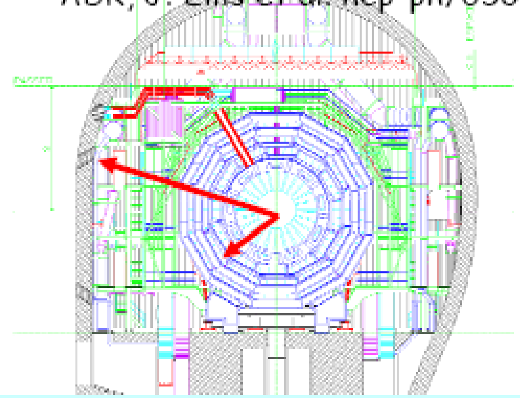
- In some models/phase space the gravitino is the LSP
- ⇒ NLSP (neutralino, stau lepton) can live 'long'
- ⇒ non-pointing photons

⇒Challenge to the experiments!

Arkani-Hamed, Dimopoulos hep-th/0405159



K. Hamaguchi,M Nijori,ADR hep-ph/0612060
ADR, J. Ellis et al. hep-ph/0508198

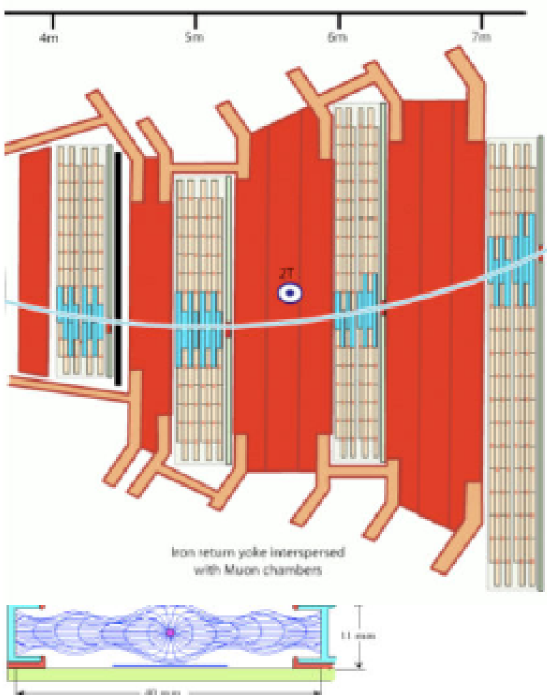


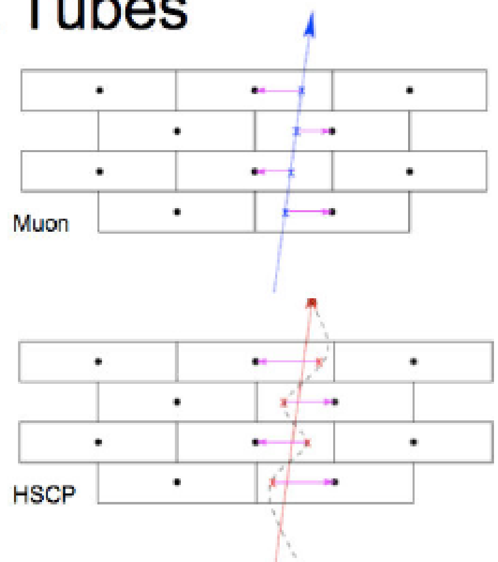
Sparticles stopped in the detector,walls of the cavern, or dense 'stopper' detector. They decay after hours---months...

Heavy Stable Charged Particles

The heavy particles are moving with less the speed of light, ie. $\beta < 1$
A particle with $\beta = 1$ reaches the muon detectors in CMS after 13 ns
A particle with $\beta < 1$ reaches the muon detectors later than 13 ns

TOF in Drift Tubes





Normally the fit assumes $\beta=1$; here δt is left as a free parameter in the fit
=> TOF measurement
(see extra slides)

8

Derive the Time-of-flight from hit pattern in the muon chambers
$\Rightarrow$ Measure β of the particle from the time-of-flight!!

Stopped R-hadrons or Gluinos!

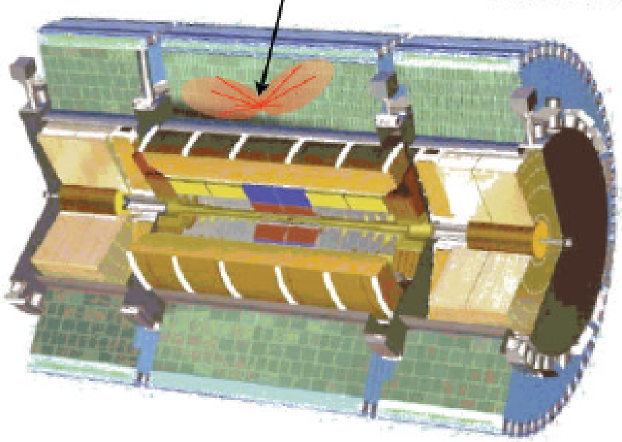
The R-hadrons may loose so much energy that they simply stop in the detector

Long Lived Gluinos

$\tau_{\tilde{g}} > 100$ ns

looking for stopped gluinos that later decay

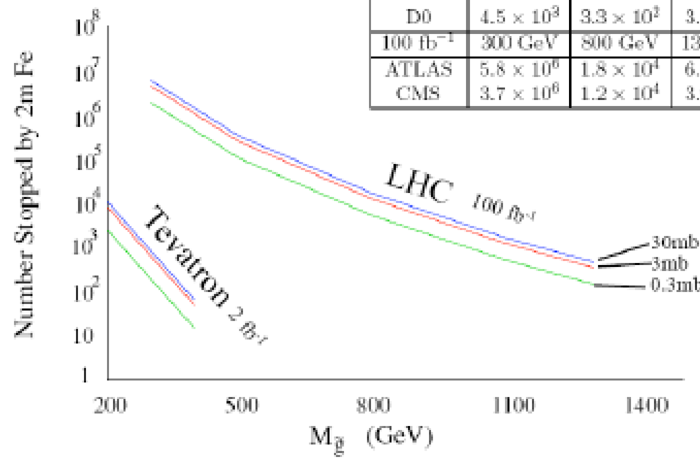
100s GeV Unbalanced $= \not{E}_T$



Uncorrelated with any beam crossing
No tracks going to or from activity

Total Number of Stopped Gluinos

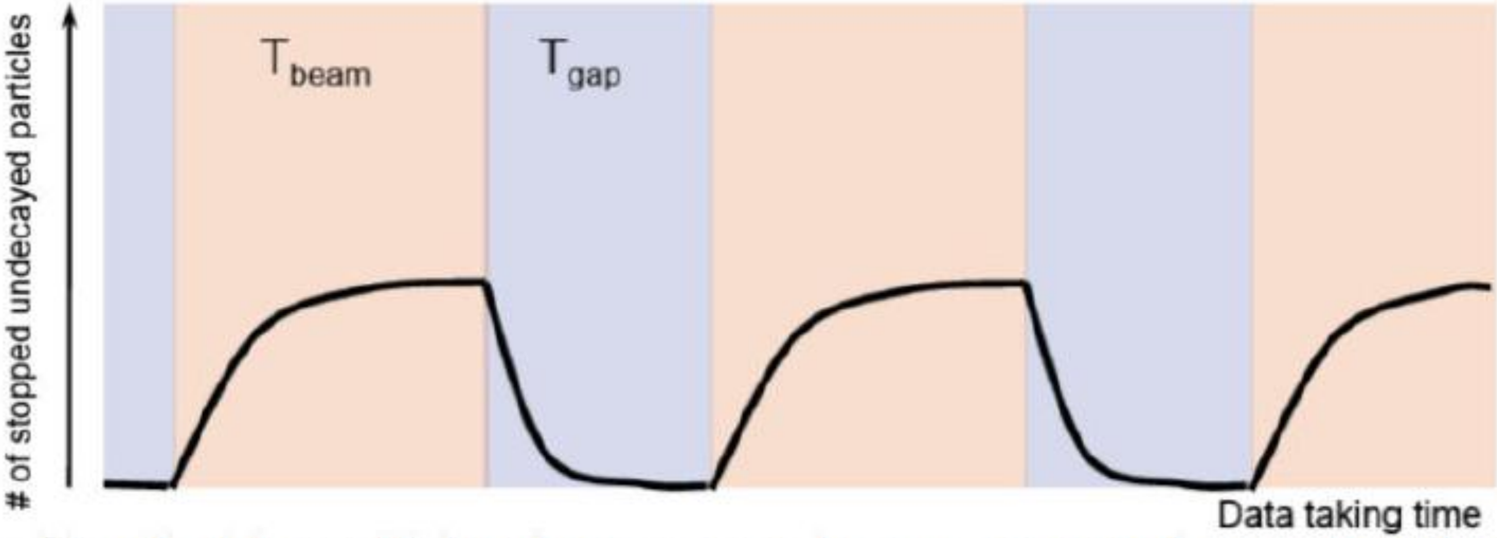
Arvanitaki, Dimopoulos, Pierce, Rajendran, JW hep-ph/0506242



$2\ fb^{-1}$	200 GeV	300 GeV	400 GeV
CDF	4.1×10^3	3.1×10^2	3.3×10^1
D0	4.5×10^3	3.3×10^2	3.4×10^1
$100\ fb^{-1}$	300 GeV	800 GeV	1300 GeV
ATLAS	5.8×10^6	1.8×10^4	6.2×10^2
CMS	3.7×10^6	1.2×10^4	3.9×10^2

⇒ Special triggers needed, asynchronous with the bunch crossing

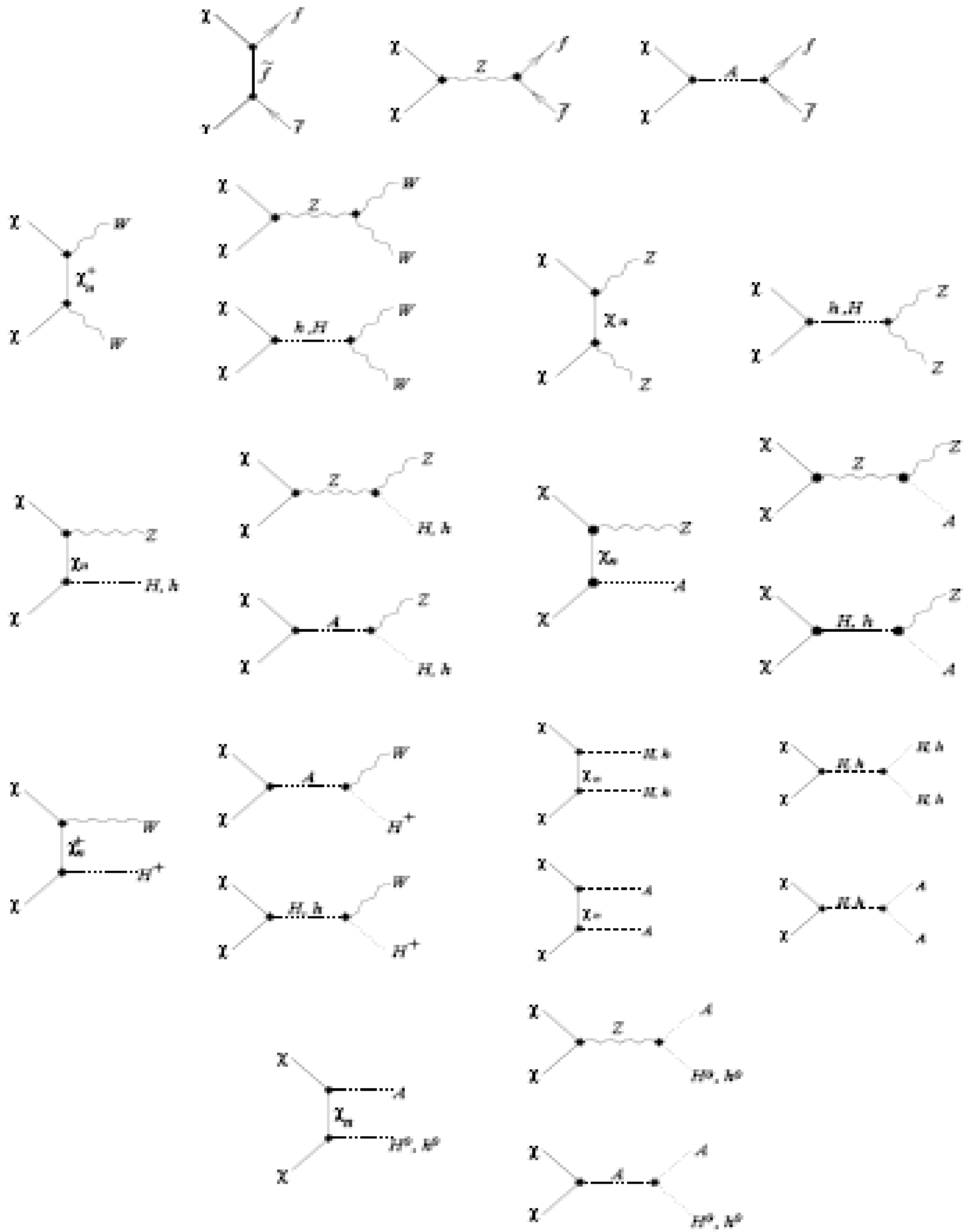
Stopped gluinos



- Basic idea: R-hadrons can loose enough energy in the detector to stop somewhere inside (usually calorimeters)
- Sooner or later they must decay Eg when there is no beam!
- Trigger: (jet) && !(beam)
- Only possible backgrounds: cosmics and noise

Can be studied in the experiments NOW with cosmic data

SUSY particles and dark matter



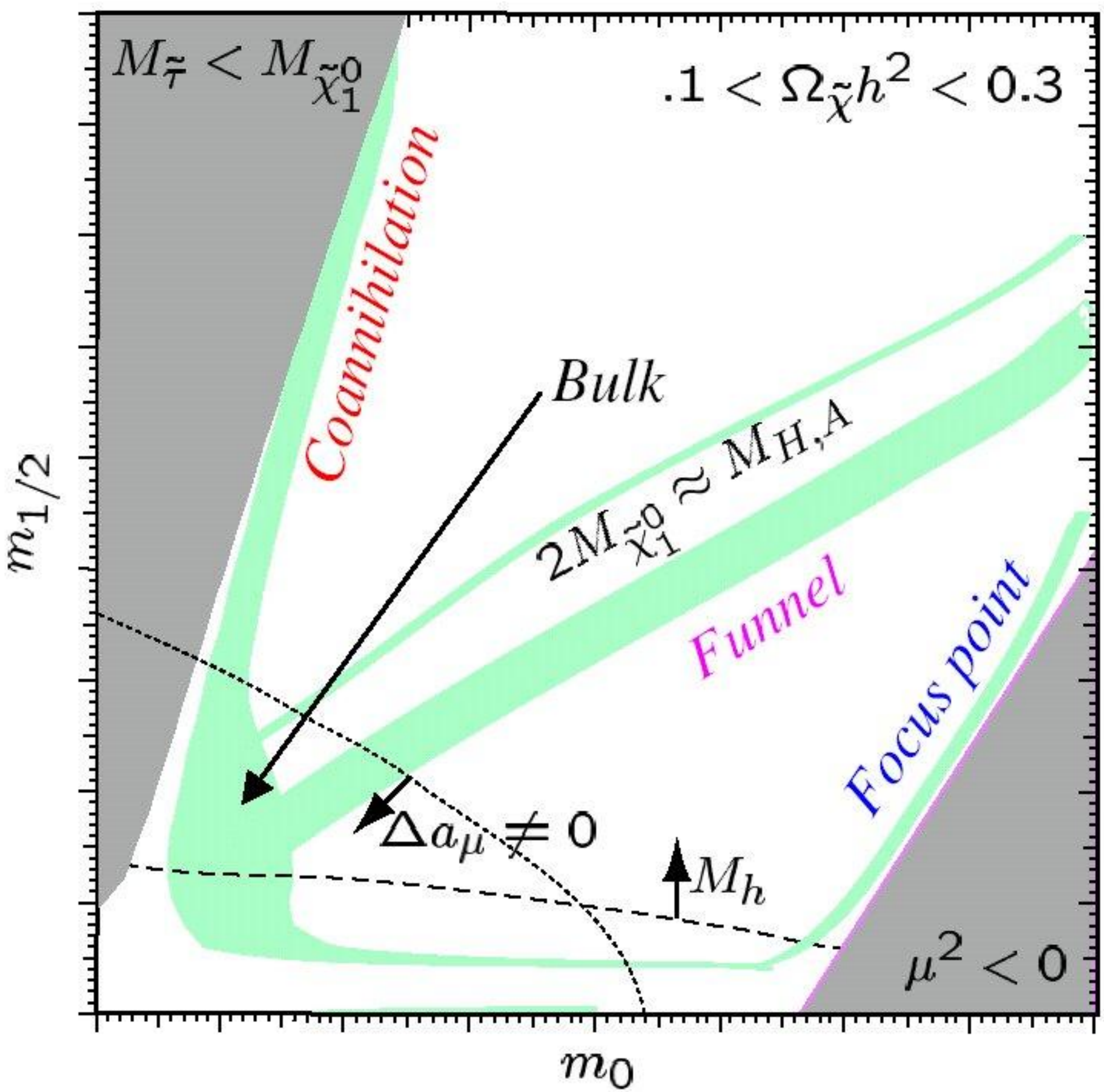
Neutralino annihilation

Note: χ is Majorana
→Particle = antiparticle
Self-annihilation

Cross sections can be calculated from M_χ and bino-wino-higgsino mixing parameters

Implemented in DarkSUSY and MicrOMEGAs

mSUGRA: only blue-green region allowed!



Bulk: light sleptons

Focus Point: large Higgsino component

Funnel: resonant annihilation via H,A

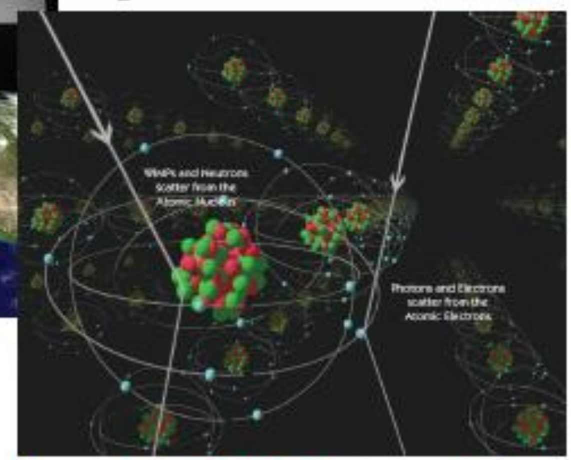
Coannihilation: stau mass almost equal to M_X

Strategies for WIMP Detection

PARTICLE COLLIDERS:
Produce and Detect WIMPs

INDIRECT DETECTION: measure gamma rays, neutrinos , positrons, antiprotons, anti-deuterons, etc. from WIMP annihilation in GC, in Sun, in MW

DIRECT DETECTION:
measure WIMP scattering off targets in detectors on Earth



Potential for Breakthrough in coming decade: WIMP models will be stringently probed by one or more method

LHC: cannot detect $\widetilde{\chi}_1^0$

Rather: measure other particles in decay chain
measure mass differences
deduce underlying model, and model parameters
deduce M_X

With 100 fb^{-1} : might calculate $\Omega_M h^2$ to a few percent
(but: always some model-dependence)

Direct and indirect detection:

Rely on presence of DM in galaxy

Interpretation needs DM density distribution

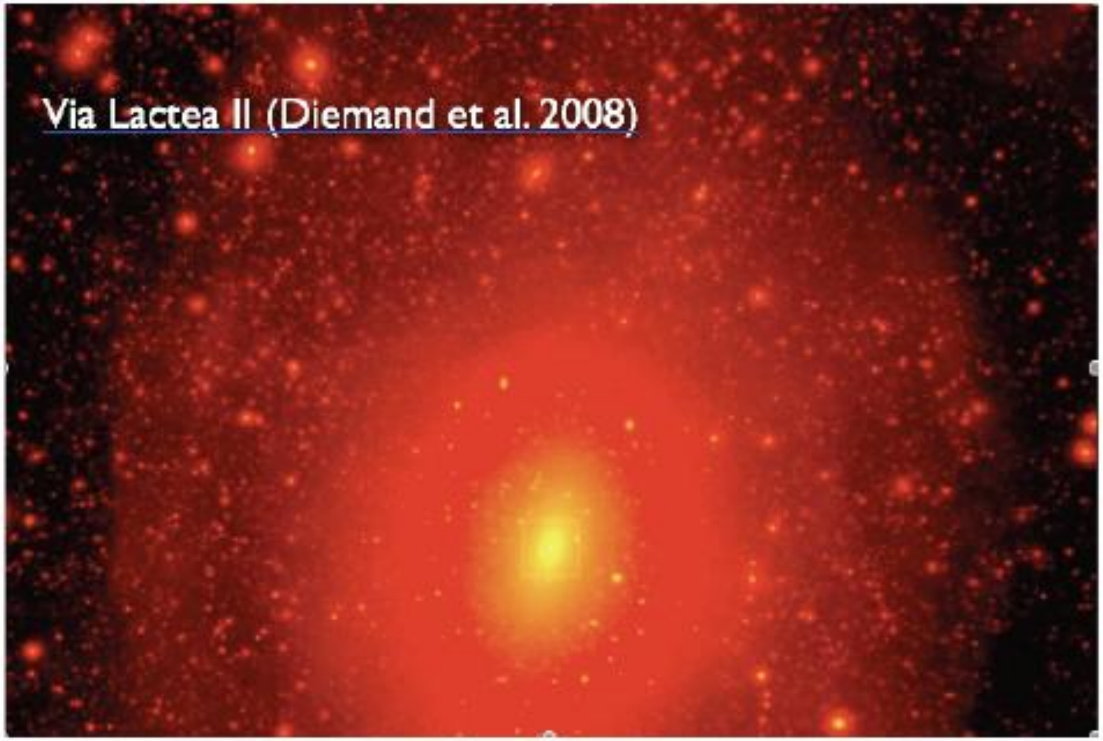
Challenge: understanding backgrounds
(astrophysics as well as detector)

DM Distribution

- Expect concentration of DM at Galactic center.
- "Traditional" Profiles (e.g. NFW) have a smooth distribution
- N-Body simulations indicate considerable clumpiness and can lead to significant boost factors.

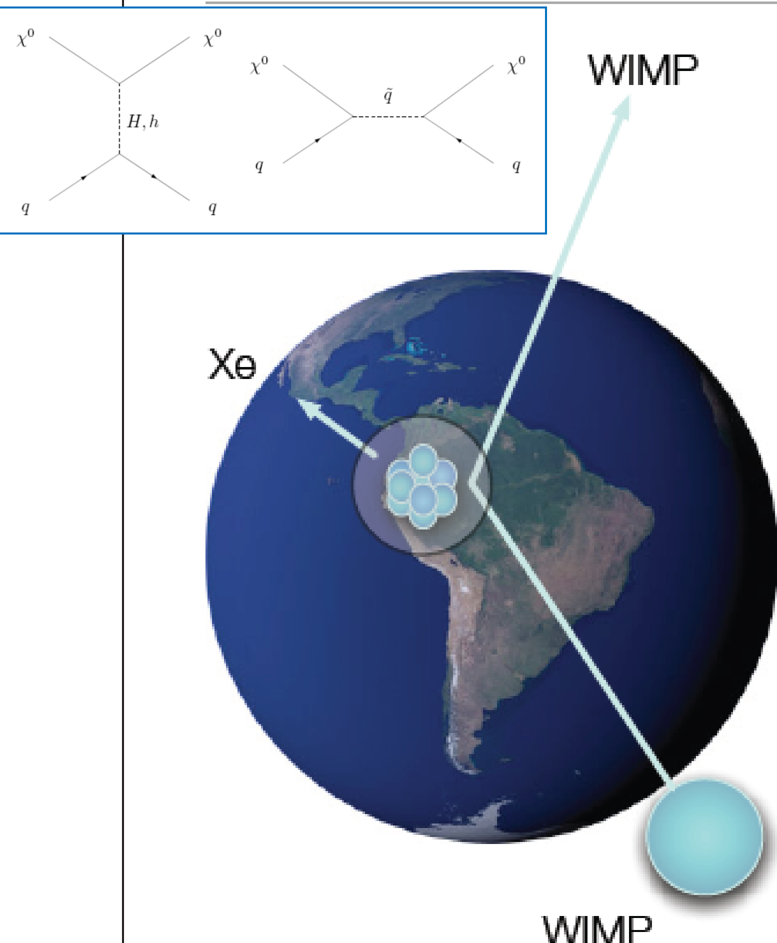
$$\rho(r)_{NFW} = \rho_0 \frac{r_0}{r} \frac{1 + (r_0/a_0)^2}{1 + (r/a_0)^2}$$

This is a model, with uncertainties!



Principle of Direct Detection

Goodman and Witten: coherent scattering of WIMPs (1985)



- Elastic collisions with nuclei
- The recoil energy is:

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) \leq 50\ keV$$

- and the expected rate:

$$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi N} \rangle \qquad \mu = \frac{m_\chi m_N}{m_\chi + m_N}$$

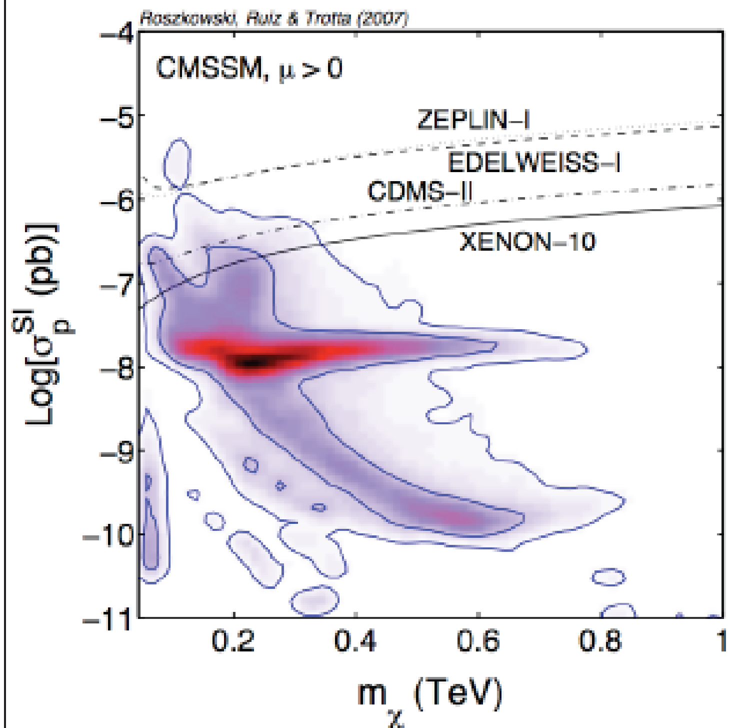
N = number of target nuclei in detector

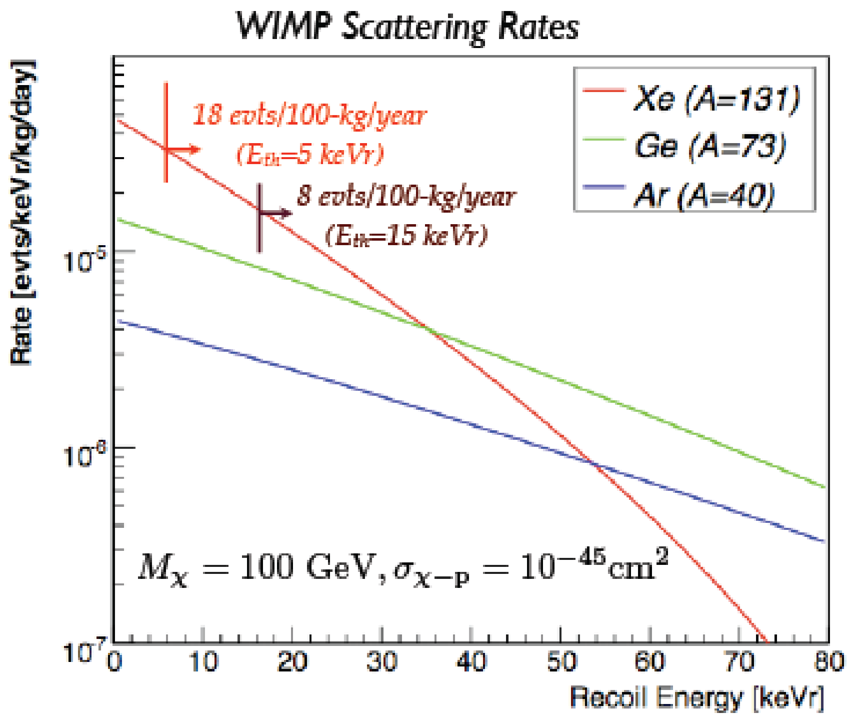
ρ_χ = local WIMP density, m_χ = WIMP mass

$\langle \sigma_{\chi N} \rangle$ = scattering cross section

Predicted Event Rates

- Constrained MSSM (mSUGRA) cross- section predictions: XENON10, CDMSII already below 10^{-7} pb!
- Rates: << 1 event/kg/month - Prospects good for some current and next generation searches

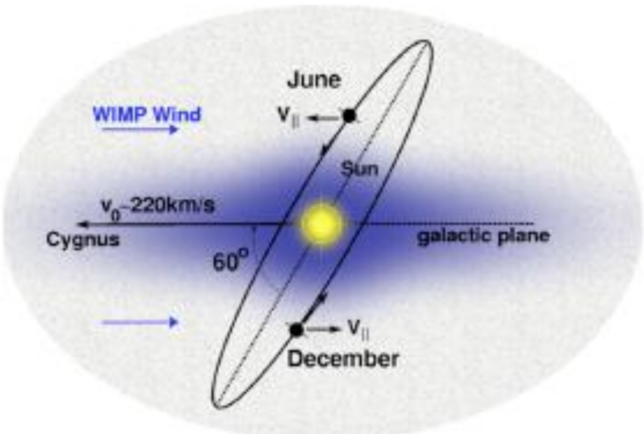


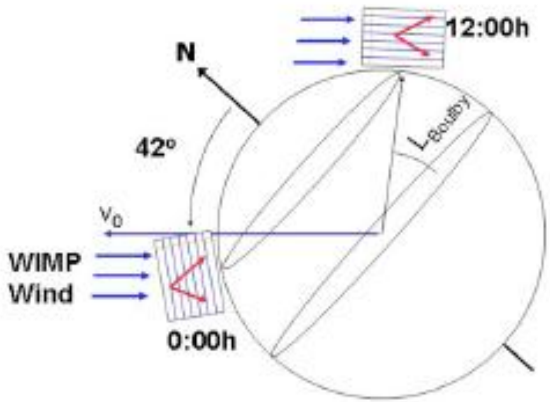


- Requirements for direct DM detectors: Large Mass + Low Background + Low Threshold

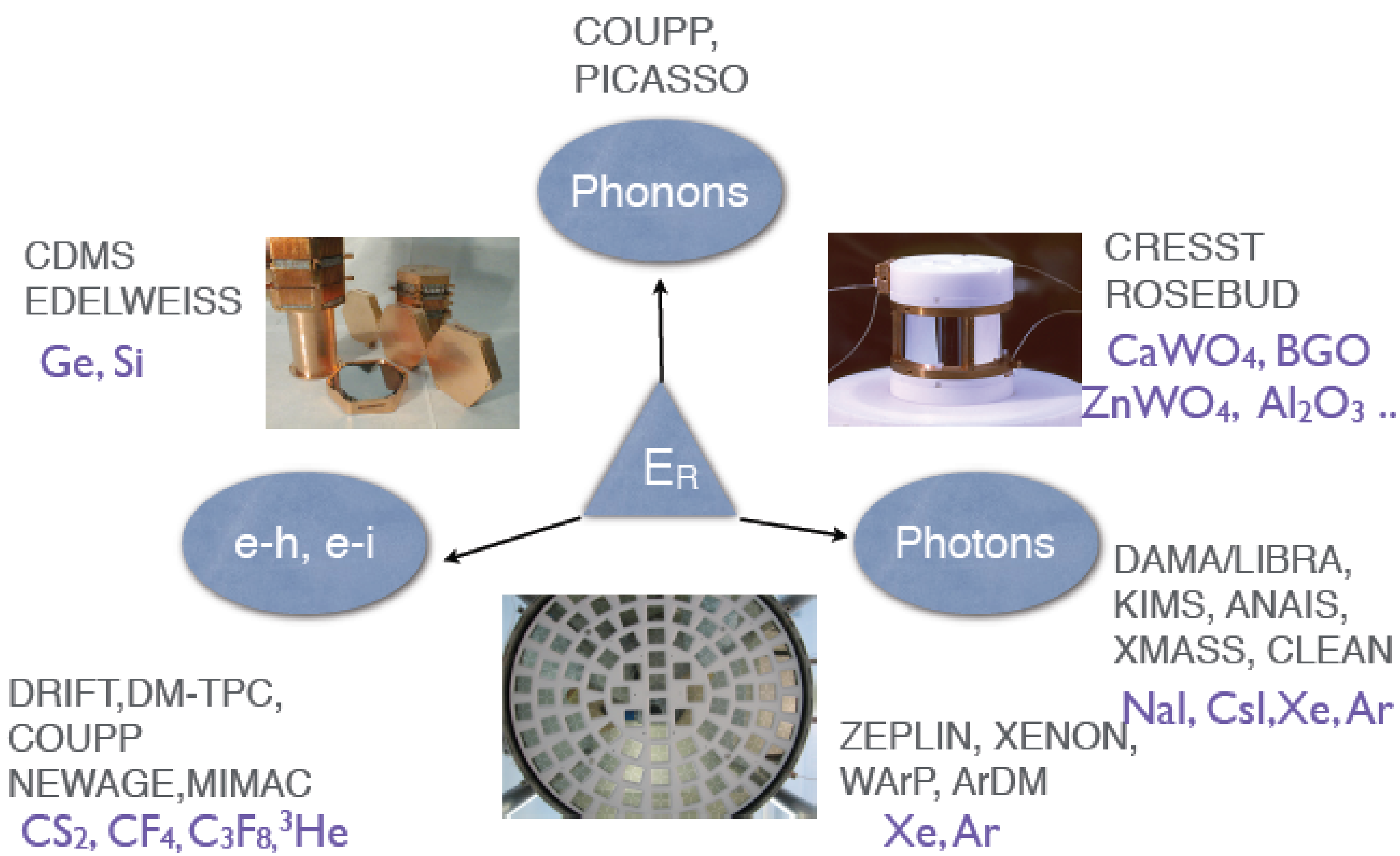
WIMP Signals

- *Nuclear recoils:* *single scatters with uniform distribution in target volume*
- *A^2 & F (Q) Dependence:* *test consistency of signal with different targets*
- *Annual Modulation:* *as a result of Earth motion relative to WIMP halo; rate modulation with a period of 1 year and phase ~2 June; large mass required (~2% effect)*
- *Diurnal Direction Modulation:* *Earth rotation about its axis, oriented at angle w/respect to WIMP "wind", change the signal direction by 90 degree every 12 hrs. ~30% effect.*

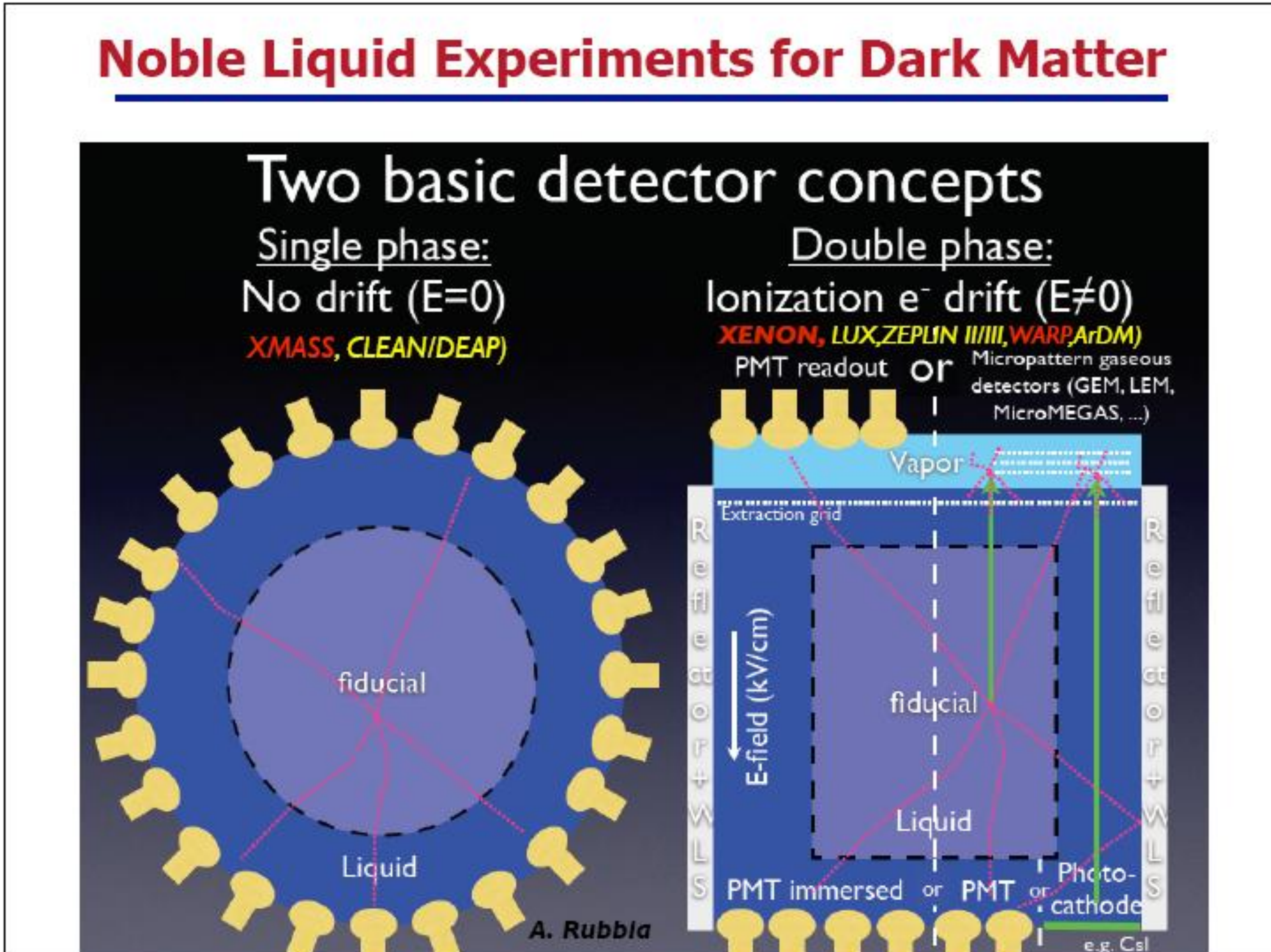




Direct Detection Experiments

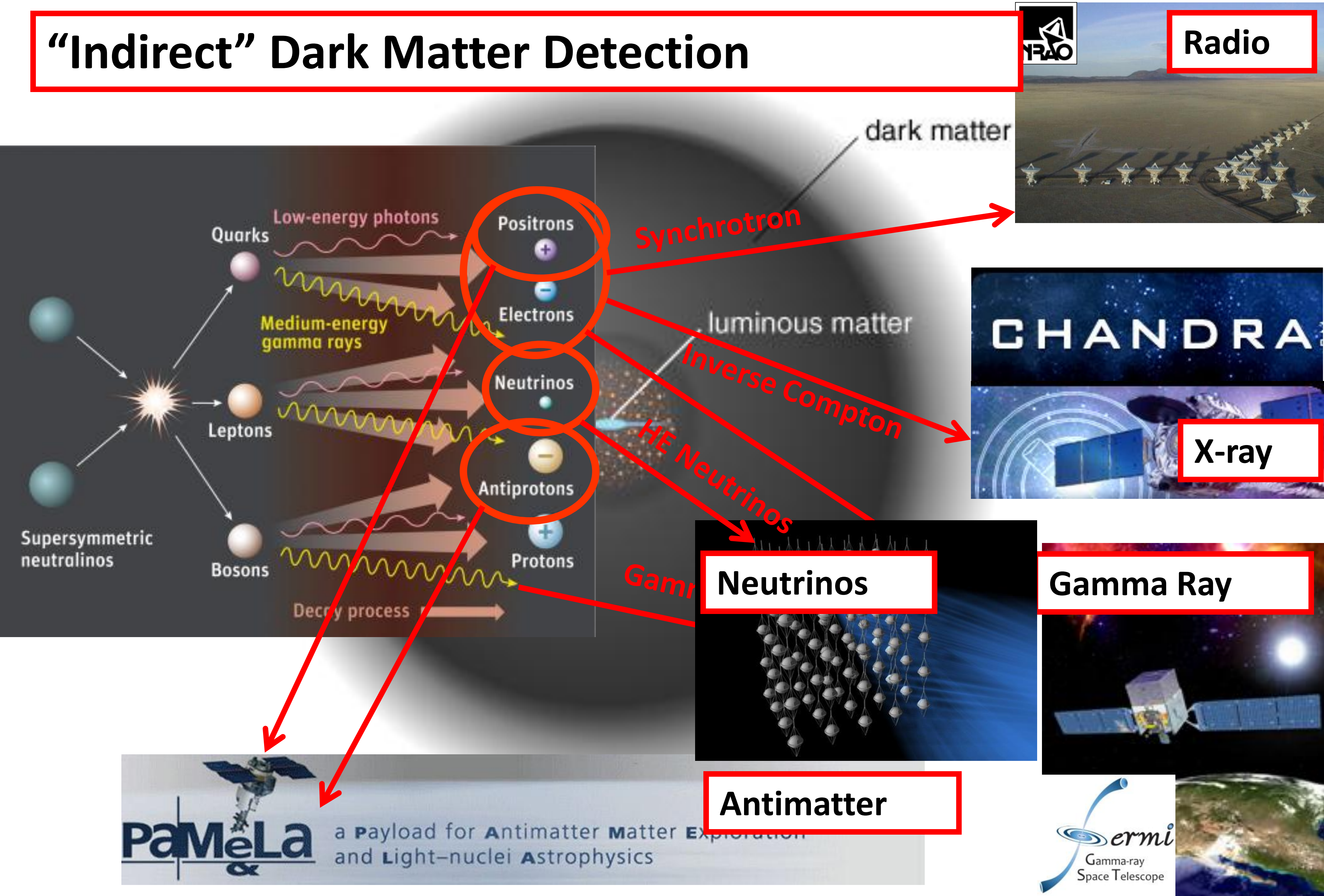


A number of new experiments planned, higher sensitivity



WIMPs pair-annihilate to stable, SM particles

"Indirect" Dark Matter Detection



Searching in gamma-rays

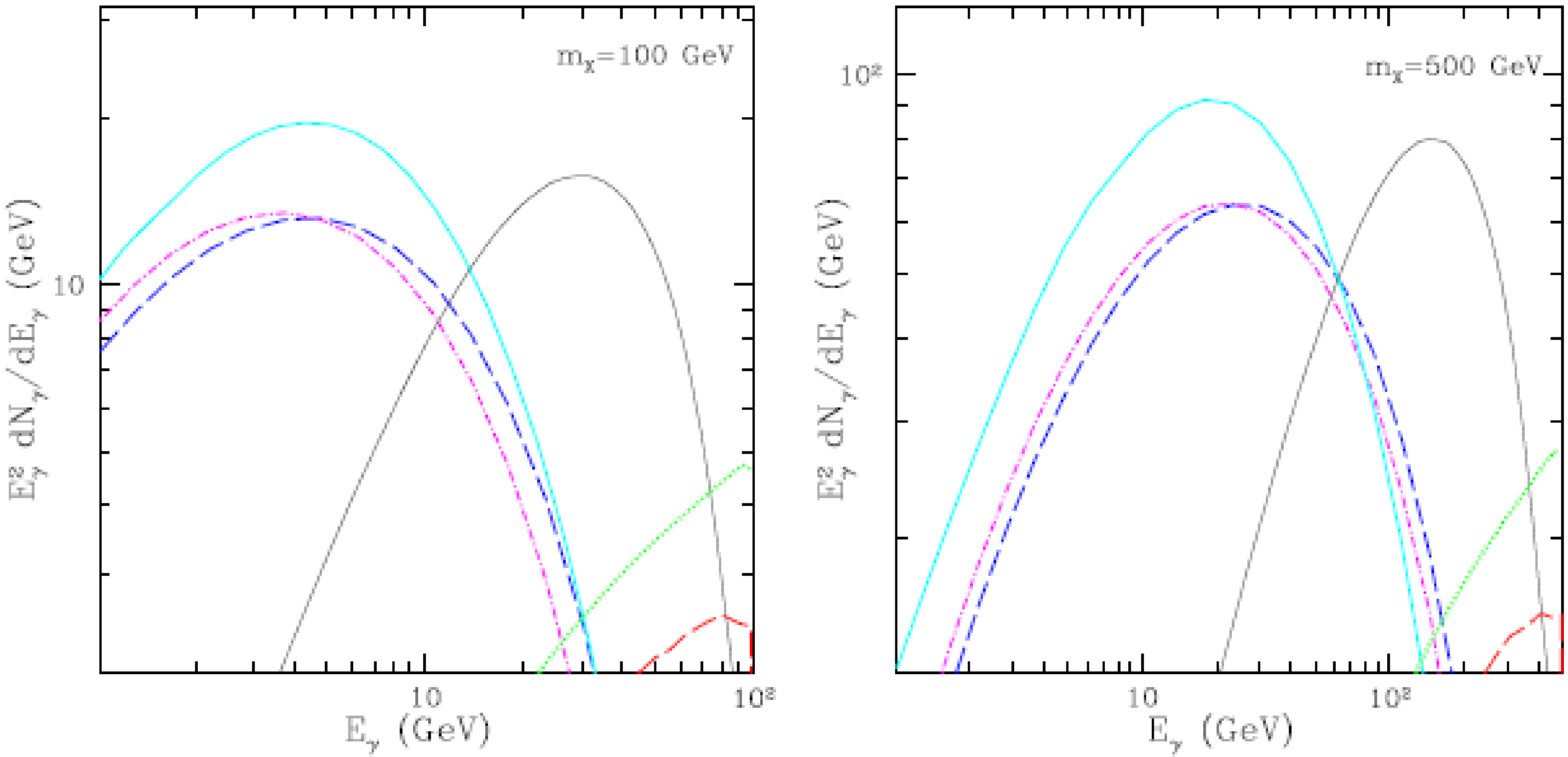
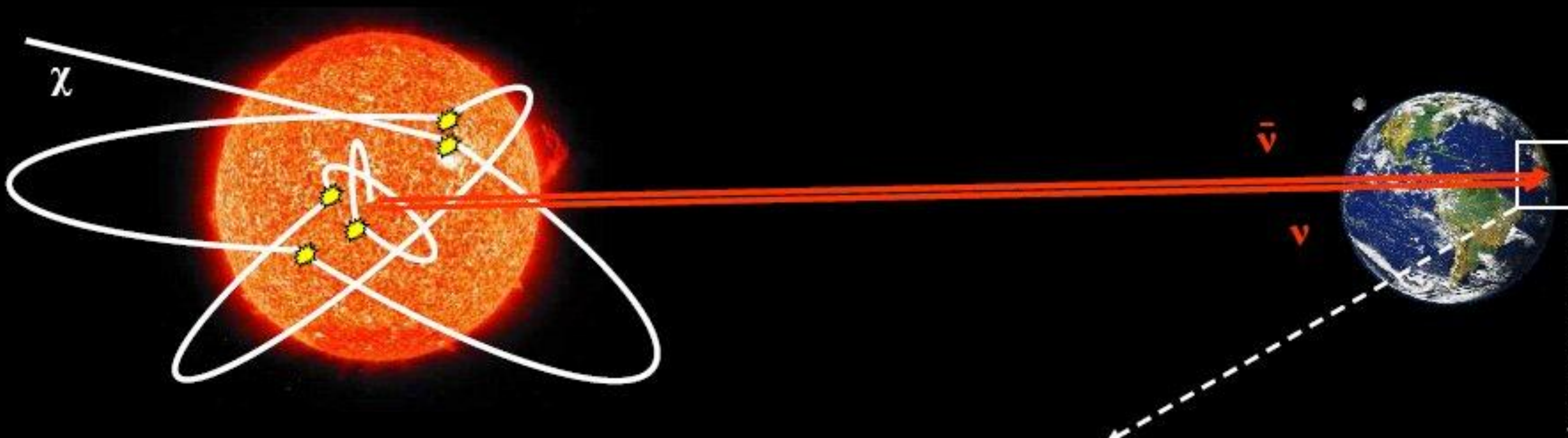


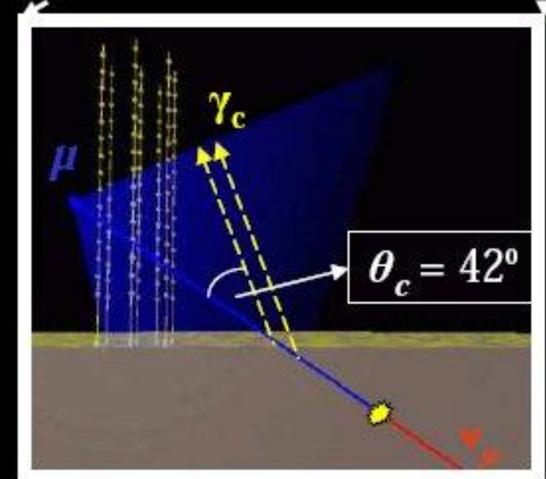
Figure 6. The gamma ray spectrum per WIMP annihilation for a 100 GeV (left) and 500 GeV (right) WIMP. Each curve denotes a different choice of the dominant annihilation mode: $b\bar{b}$ (solid cyan), ZZ (magenta dot-dashed), W^+W^- (blue dashed), $\tau^+\tau^-$ (black solid), e^+e^- (green dotted) and $\mu^+\mu^-$ (red dashed).

Searching with high-energy neutrinos

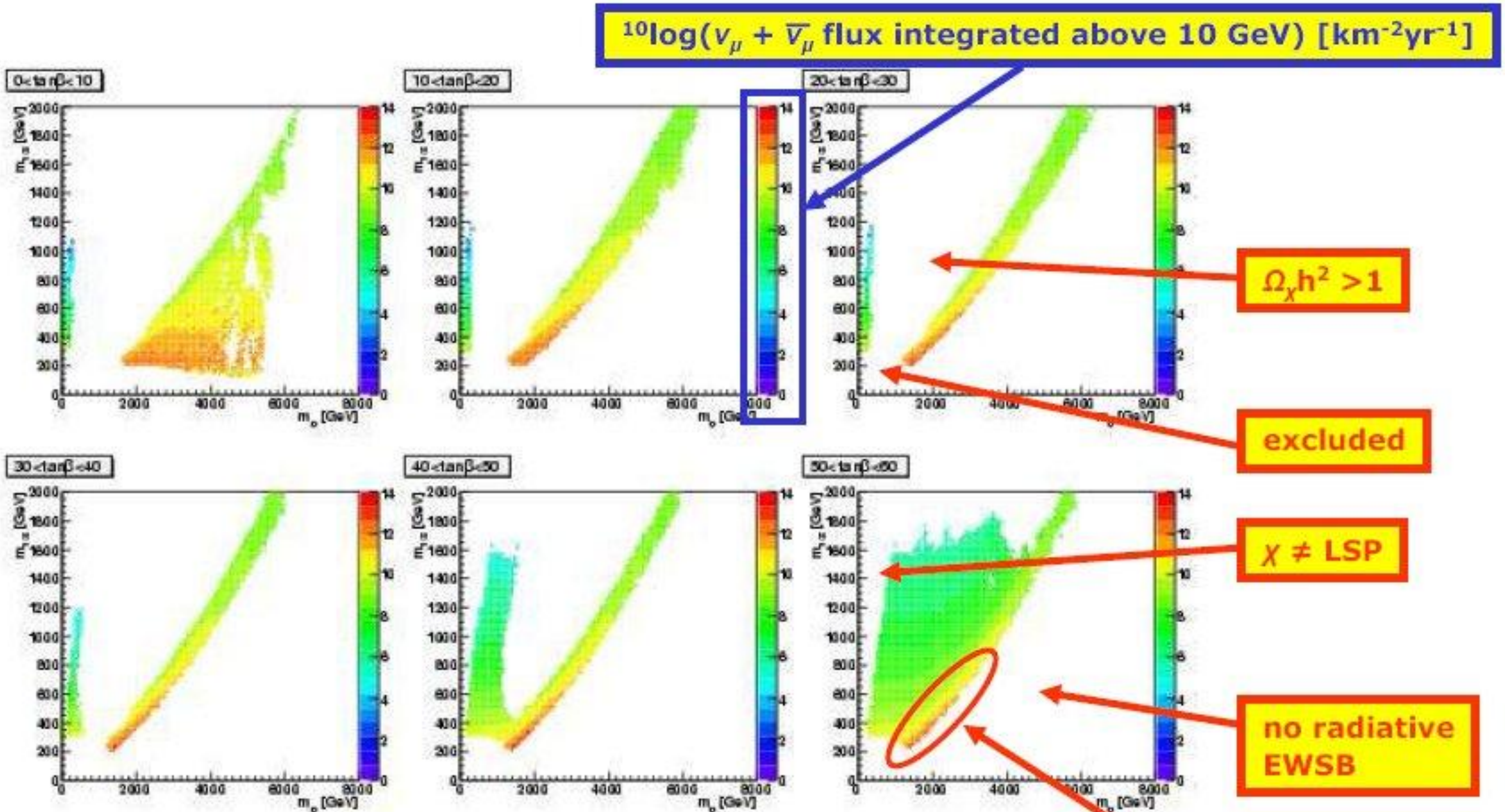


Indirect detection of WIMPs using neutrino telescopes:

- ***Relic WIMPs from the Big Bang traversing the universe undergo multiple elastic interactions with inside a massive celestial object (e.g. the Sun), lose kinetic energy and become gravitationally bound to the object.***
- ***Over time, the WIMP density in the core of the object increases. This enhances the WIMP annihilation rate significantly, resulting in a relatively high energy neutrino flux that will reach the Earth.***
- ***These neutrinos can interact through a CC interaction in the vicinity of a neutrino telescope, producing an energetic muon. When traversing the transparent medium of the telescope, the muon will emit Cherenkov light. By measuring the time & position of the photons using a 3D grid of PMTs, the neutrino track can be reconstructed.***



mSUGRA parameter space



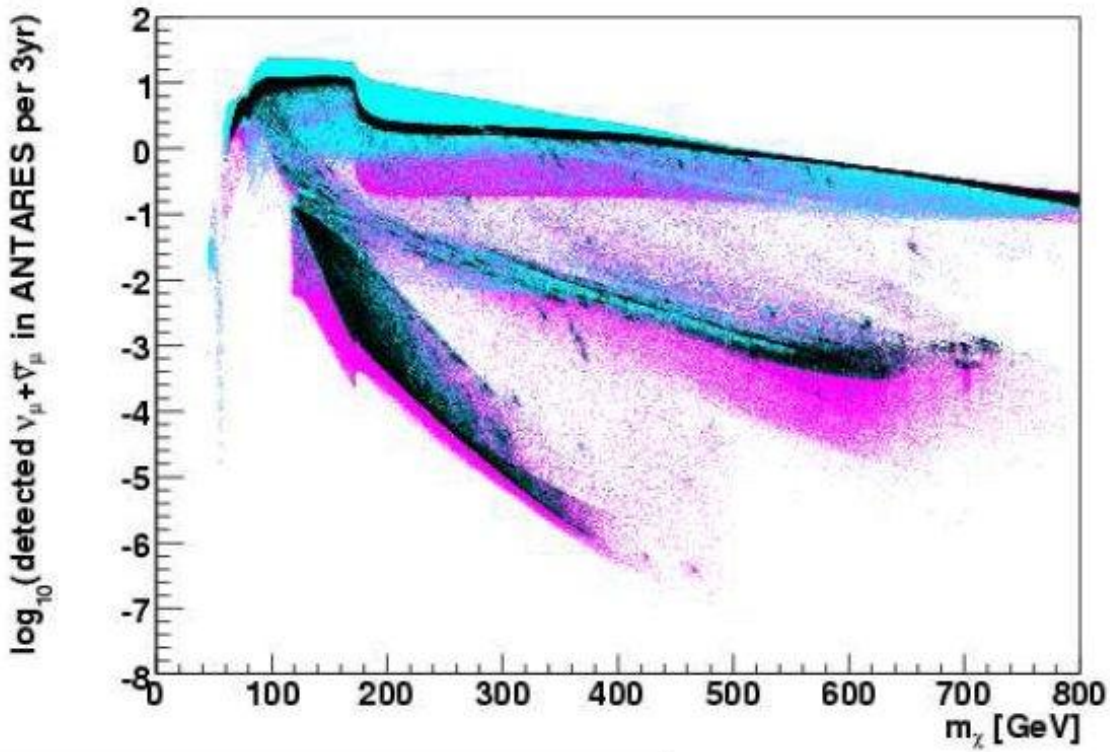
μ is small -> Higgsino fraction of χ is relatively large, therefore $\chi\chi$ -> *WW*/*ZZ* dominates

- *$0 < m_0 < 8000$ GeV*
- *$0 < m_{1/2} < 2000$ GeV*
- *$0 < \tan(\beta) < 60$*
- *$-3m_0 < A_0 < 3m_0$*
- *sign(μ) = +1*

Antares detection rates

Detected $\nu_\mu + \overline{\nu}_\mu$ events from the Sun in Antares per 3 years vs. m_χ:

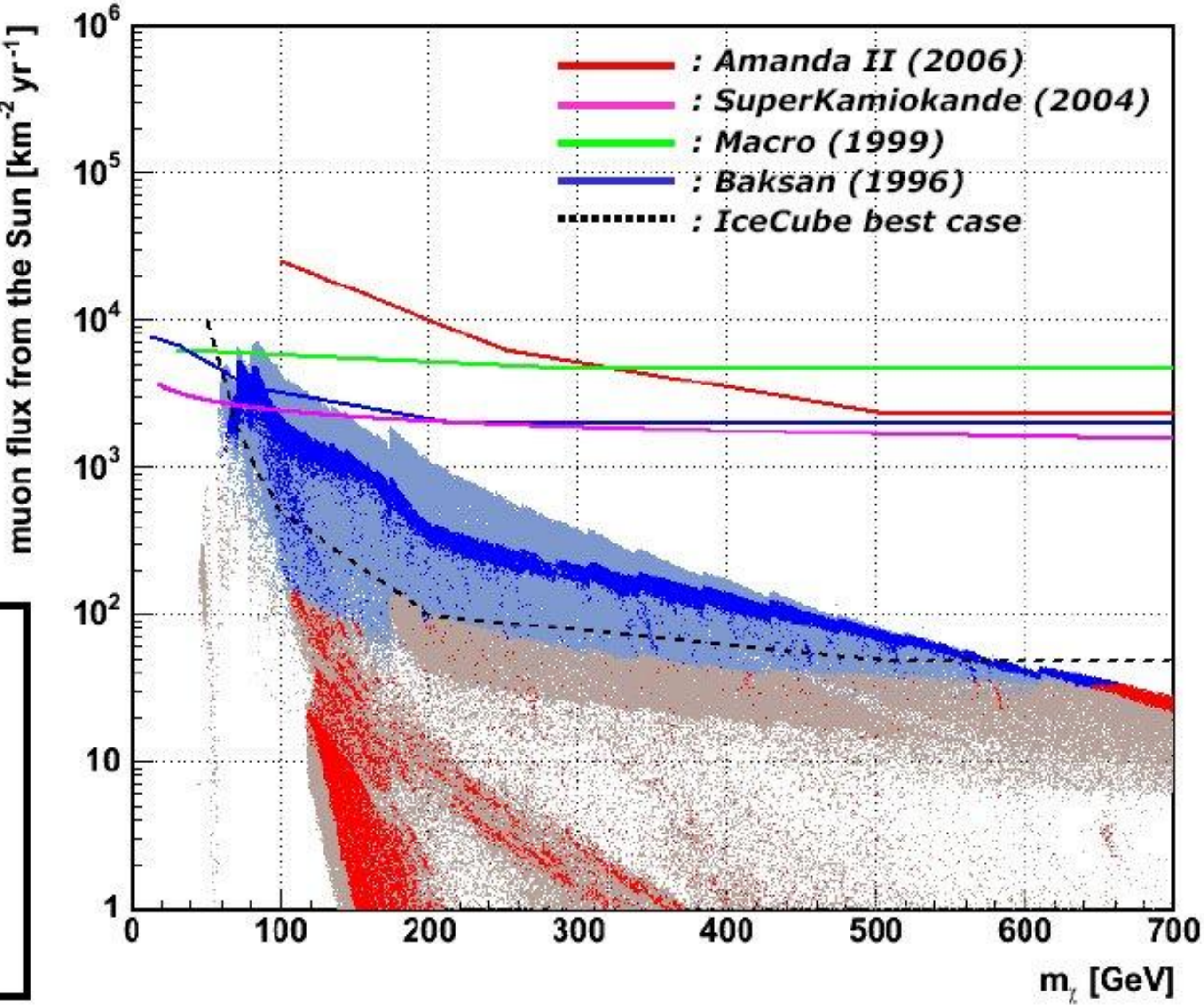
Detection rate (t) =
$\nu_\mu + \bar{\nu}_\mu$ flux (E_ν, θ_ν, t) ·
Effective Area (E_ν, θ_ν) ·
Sun's θ_ν distribution



- *: Models for which $\Omega_\chi h^2 < 1$* (magenta)
- *: Models for which $0.094 < \Omega_\chi h^2 < 0.129$* (black)
- *: Models for which $\Omega_\chi h^2 < 0.094$* (green)

Outlook: KM3NeT

μ flux from the Sun excludable by KM3NeT per km² per year vs. m_χ



Some remarkable signals seen so far:

PAMELA and ATIC excess in positrons, Fermi results;

DAMA

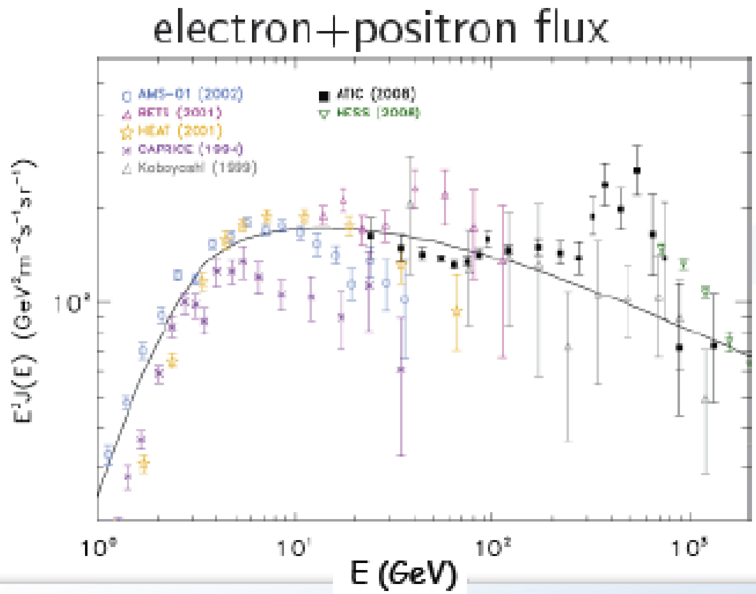
WMAP Haze
(diffuse microwave emission, also seen by Fermi. $M_X \sim 30$ GeV.
But: astrophysical backgrounds? Where are anti-protons?)

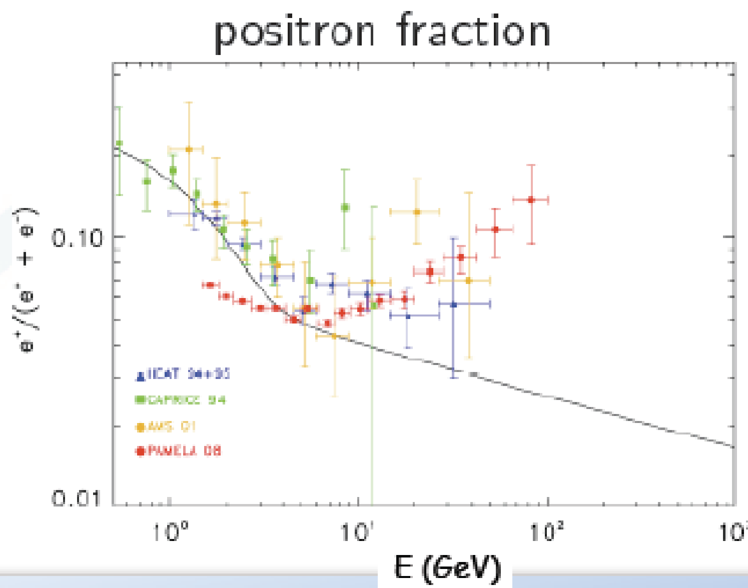
Integral 511 keV line
($e^+ e^-$ annihilation, e^+ from DM? e^+ little energy → (too) low M_X ?)

EGRET diffuse galactic spectrum
(Excess in gamma rays > 1 GeV in EGRET spectrum,
consistent with $M_X \sim 60$ GeV, but where are anti-protons?
Now killed by Fermi)

EGRET diffuse extragalactic spectrum
(Astrophysical sources? Spectrum does not fit in models)

Interesting Features of Cosmic Ray Electrons



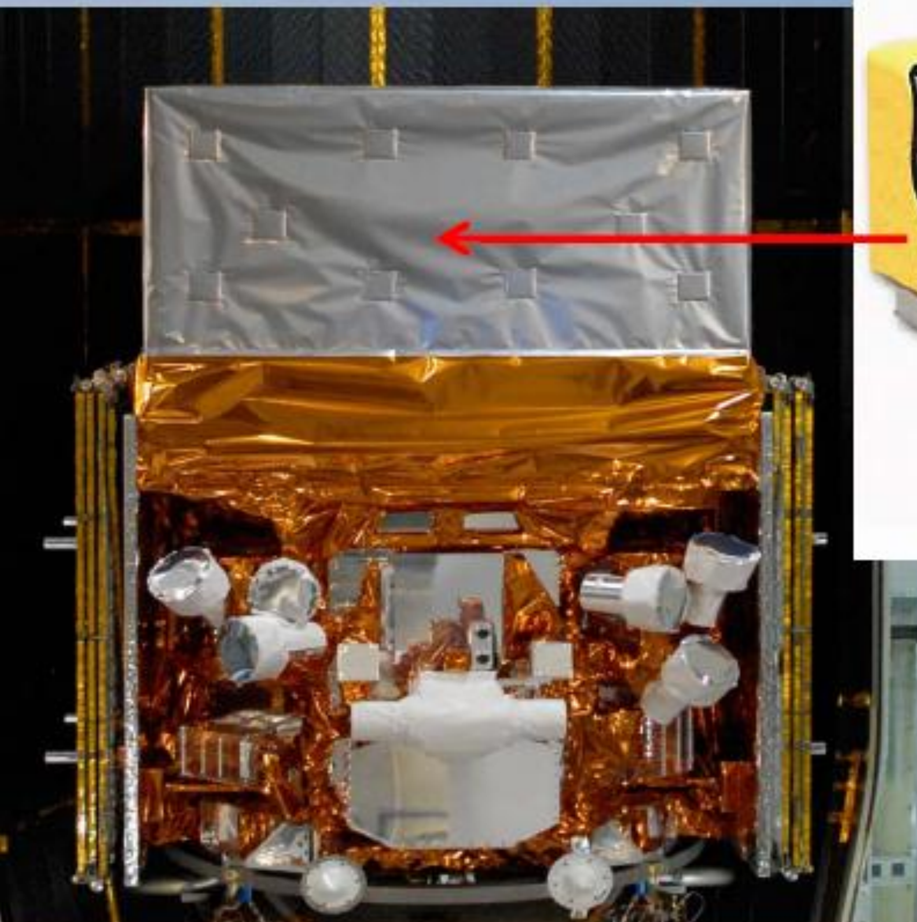


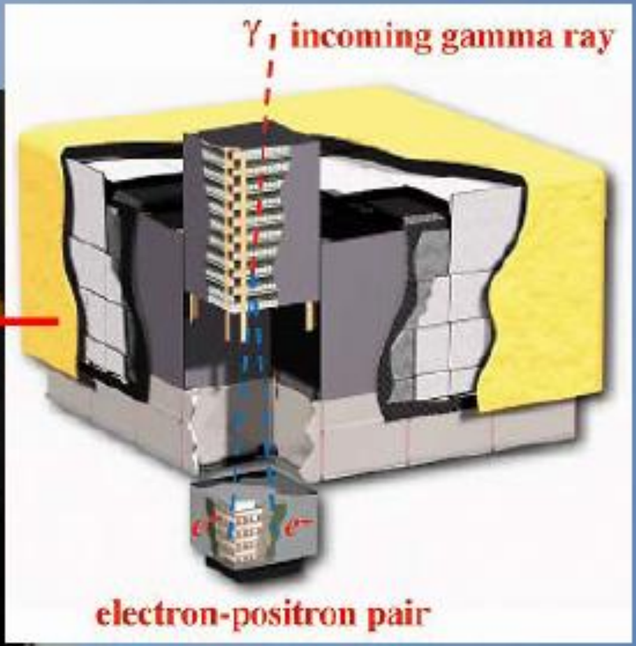
- **Spectral Features:**
  - ★ ATIC excess around 600 GeV
  - ★ H.E.S.S possible cutoff around 1 TeV
- Pamela shows excess in positron fraction
- Lots of new papers on the subject!
- Fermi LAT is an excellent electron/positron detector.

The Fermi Gamma-Ray Space Telescope

June 11, 2008 12:05 PM EDT; Cape Canaveral

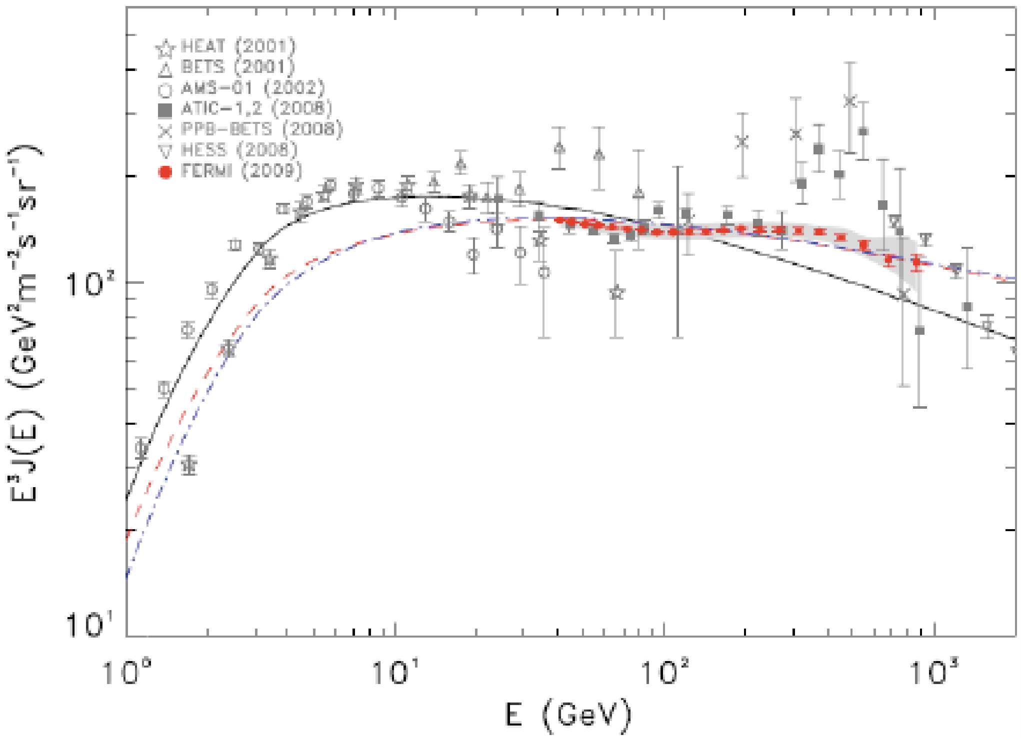
Large Area Telescope (LAT)





LAT images the sky one photon at a time: γ-ray converts in LAT to an electron and a positron; direction and energy of these particles tell us the direction and energy of the photon

Resulting Fermi Electron Spectrum



- Excellent Statistics: ~4.5M evts
  - >400 elec 0.772 – 1 TeV
- No Evidence of prominent spectral feature seen by ATIC.
  - ATIC excess 300–800 GeV: 70 e
  - Fermi would expect ~7000 e
- Fermi Data not compatible with prelaunch expectation from diffuse galactic emission.
  - Diffuse model can be modified.
  - **Doesn't account for positrons**

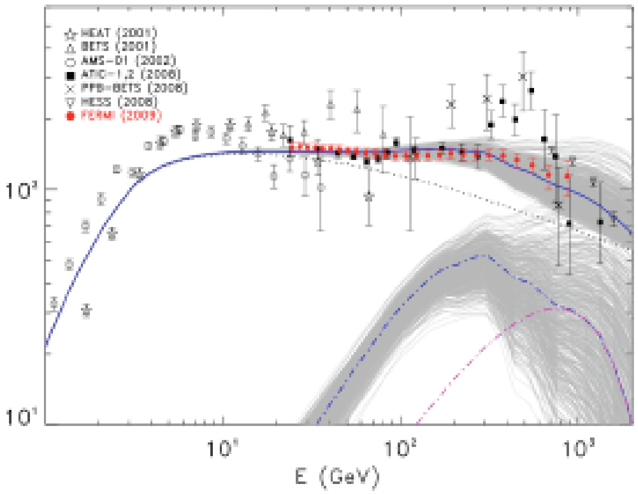
Measured spectrum well described by **power-law** within current values of **systematic** errors

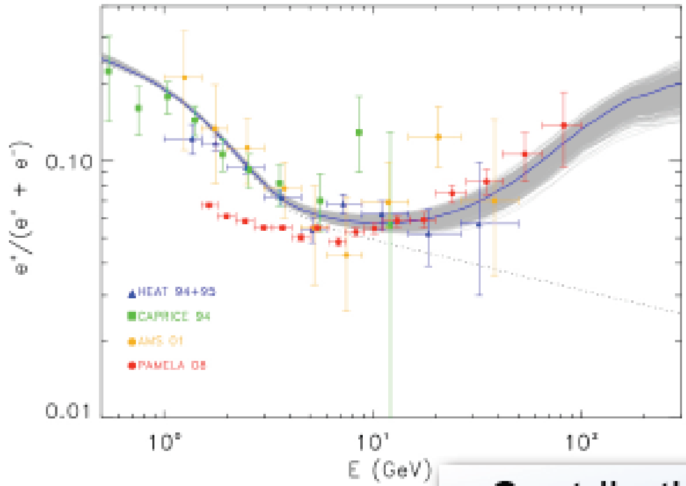
$$J_{e^\pm} = (175.40 \pm 6.09) \left(\frac{E}{1\ \mathrm{GeV}}\right)^{-(3.045 \pm 0.008)} \mathrm{GeV}^{-1}\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

with χ^2 per degree of freedom of 9.7 / 23

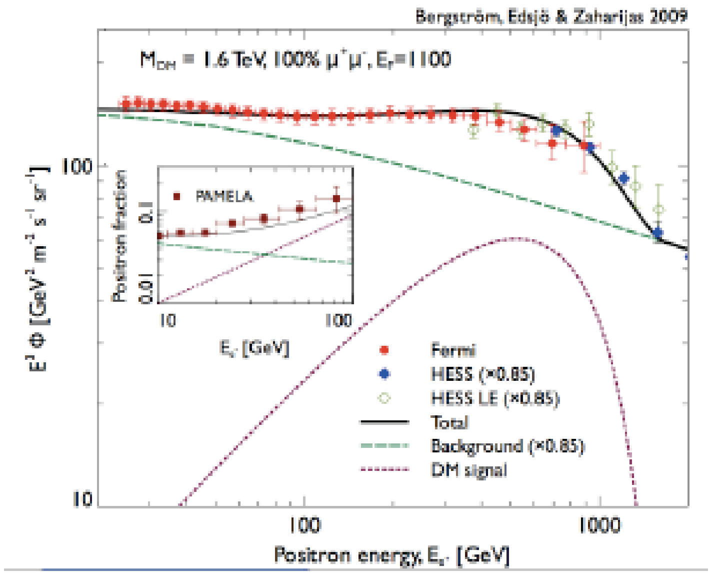
Possible Explanations

arXiv:0905.0636 [asto-ph.HE]





Grey Lines: Possible contribution with varied parameters (injection index, cutoff energy, etc.)
Blue dot-dash: Representative choice of parameters.
Blue Solid: Diffuse Model + Pulsars

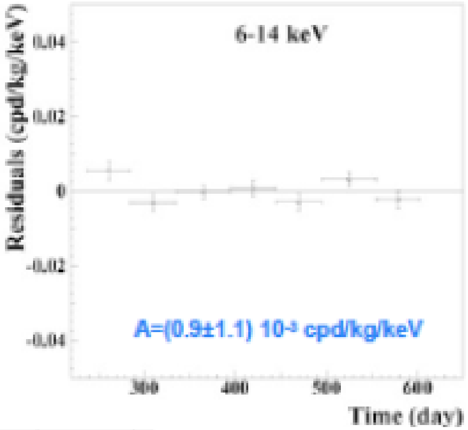


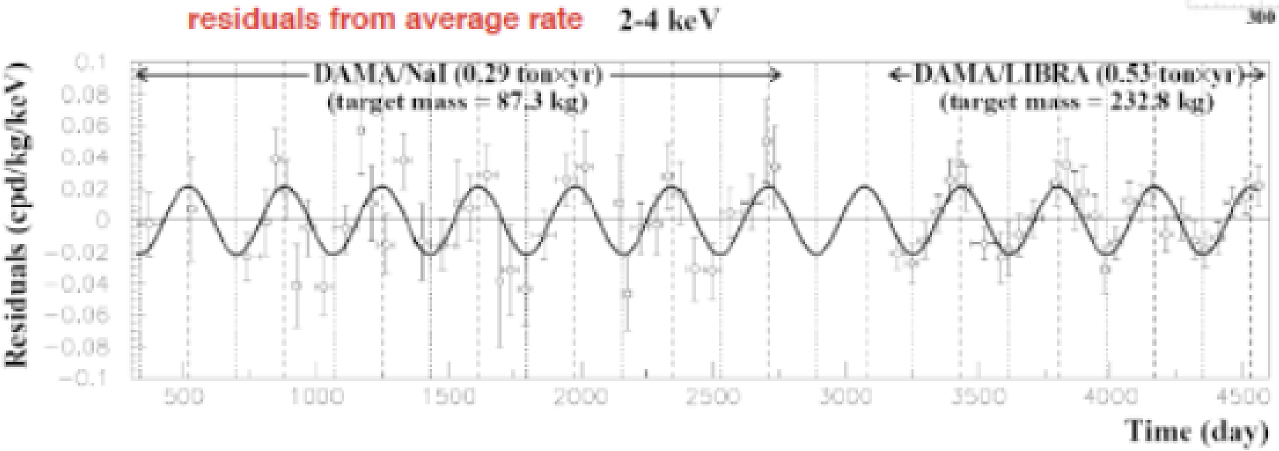
- Contributions from nearby, age appropriate, pulsars.
  - ★ From ATNF Catalog
- Provides a reasonable modification to the electron spectrum.
- Also, modifies the position fraction in a reasonable fashion.

- DM also can provide an explanation
- DM answer typically requires substantial boost factors and preferential final states.

DAMA/LIBRA Results 2008

- 250 kg NaI detectors, each viewed by 2 PMTs.
- 4 years of data: Total exposure of 0.82 ton x year
- Event rate modulation confirmed in 2008 with a 8.3 σ CL
- No modulation above 6 keV
- WIMP hypothesis difficult to reconcile with other experiments





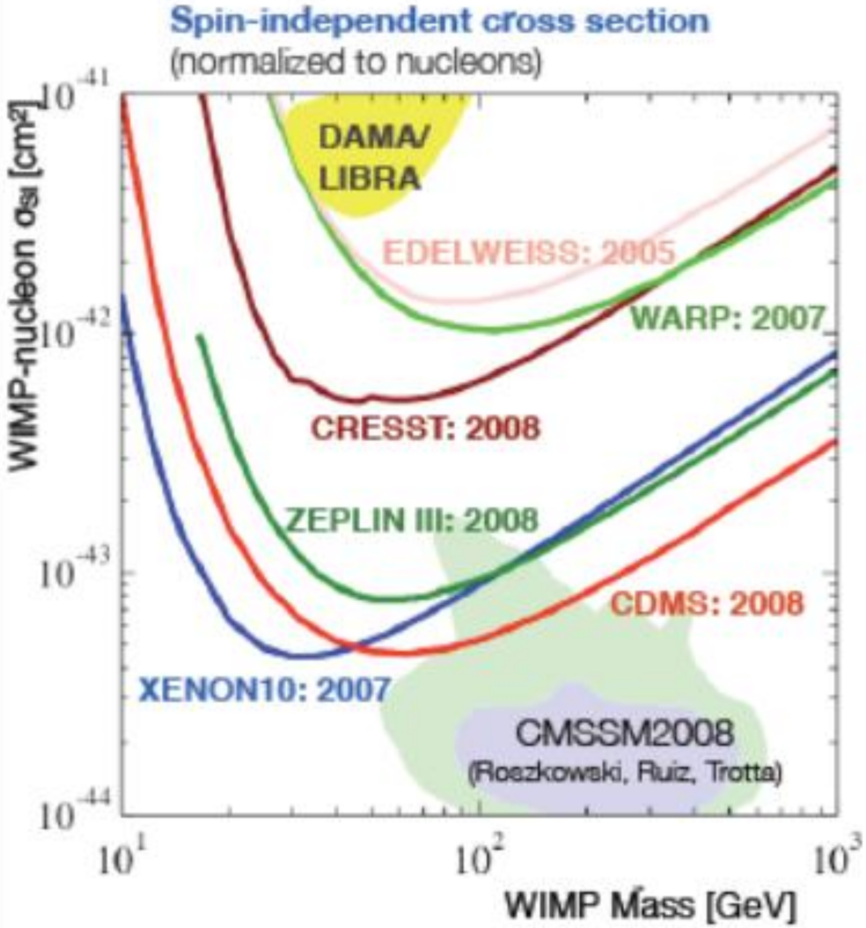
$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E)\cos\omega(t - t_0)$$

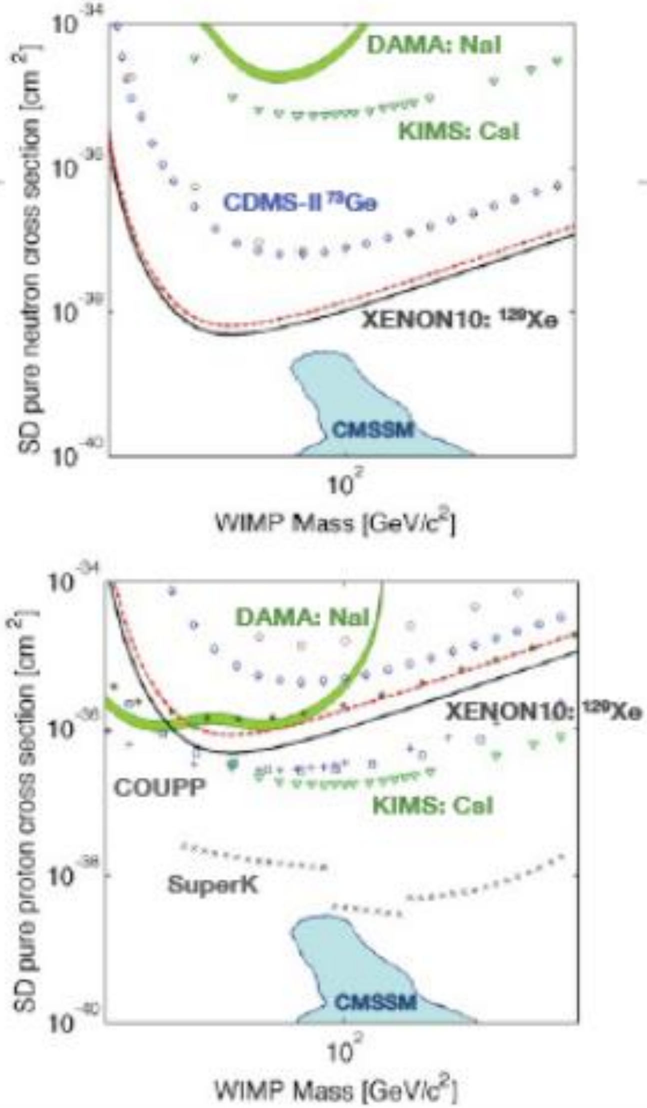
S_m = (0.0215 ± 0.0026) counts/(day kg keV)

t_0 = 144 ± 8 days

T = 0.998±0.003 year

Experimental Results: July 2009





Spin-dependent

Conclusion: active area of research,
very interesting prospects for next ~5 years,
complementarity between experiments