New physics
~~SUSY~~ searches with same-sign isolated dilepton, jets and MET at CMS

Dayong Wang (UF)

Seminar at ULB 20110923

Collider Physics: the name of the game

Probing the small with the large

- The uncertainty principle relates extremely small distances to very high energies

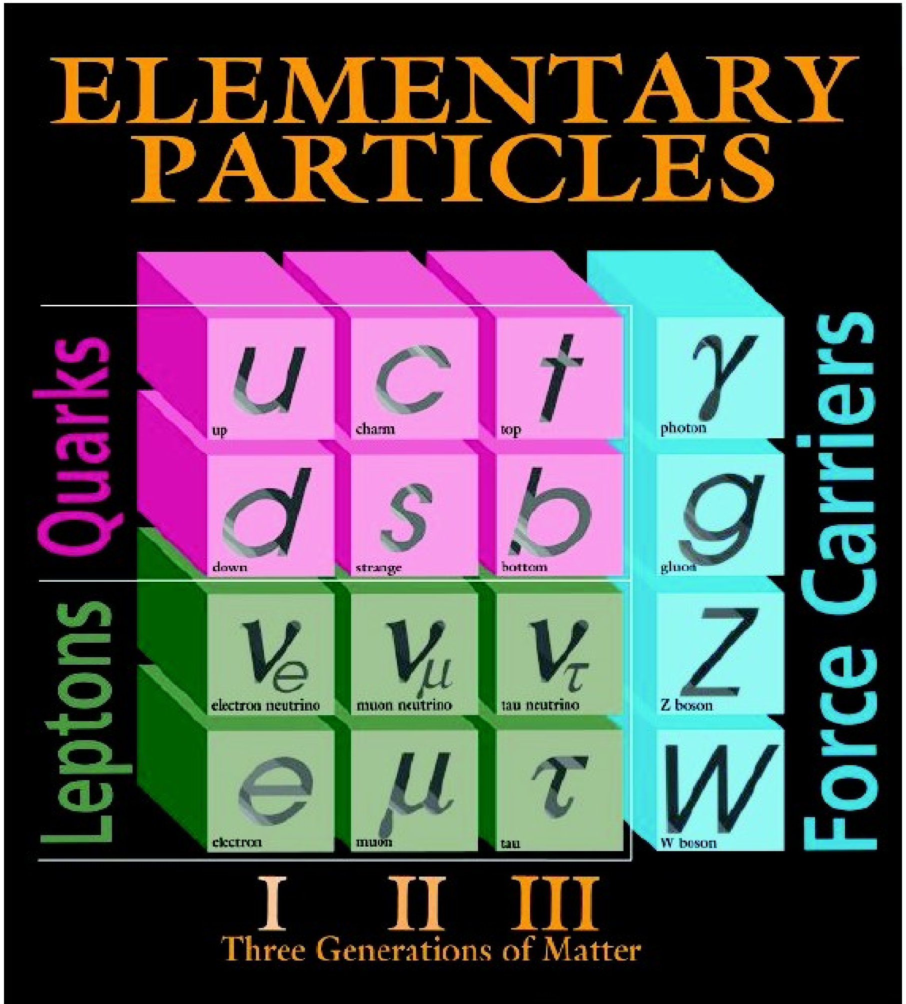
$$dp \cdot dx \sim \hbar \xrightarrow{p \sim E} 1\ \mathrm{TeV} \propto \frac{1}{2 \times 10^{-19}\ \mathrm{meters}}$$

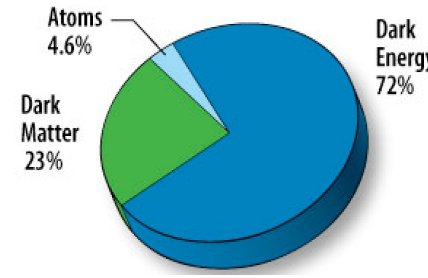
- The size of accelarator increase with energy

Probing tomorrow's physics with physics of today

- Detector, electronics, all supporting techniques
- Well known process as standard candle

Standard Model and Its Shortcomings





Its Shorcomings:
(a partial list)

- Does not include the gravitational interaction
- What about dark matter?
- Matter-Antimatter asymmetry
- The hierarchy problem

Supersymmetry and its modeling

Some of the shortcomings of the Standard Model can be overcome by introducing a new relationship between fermions and bosons known as Supersymmetry (SUSY).

The Minimal Supersymmetric Standard Model (MSSM)

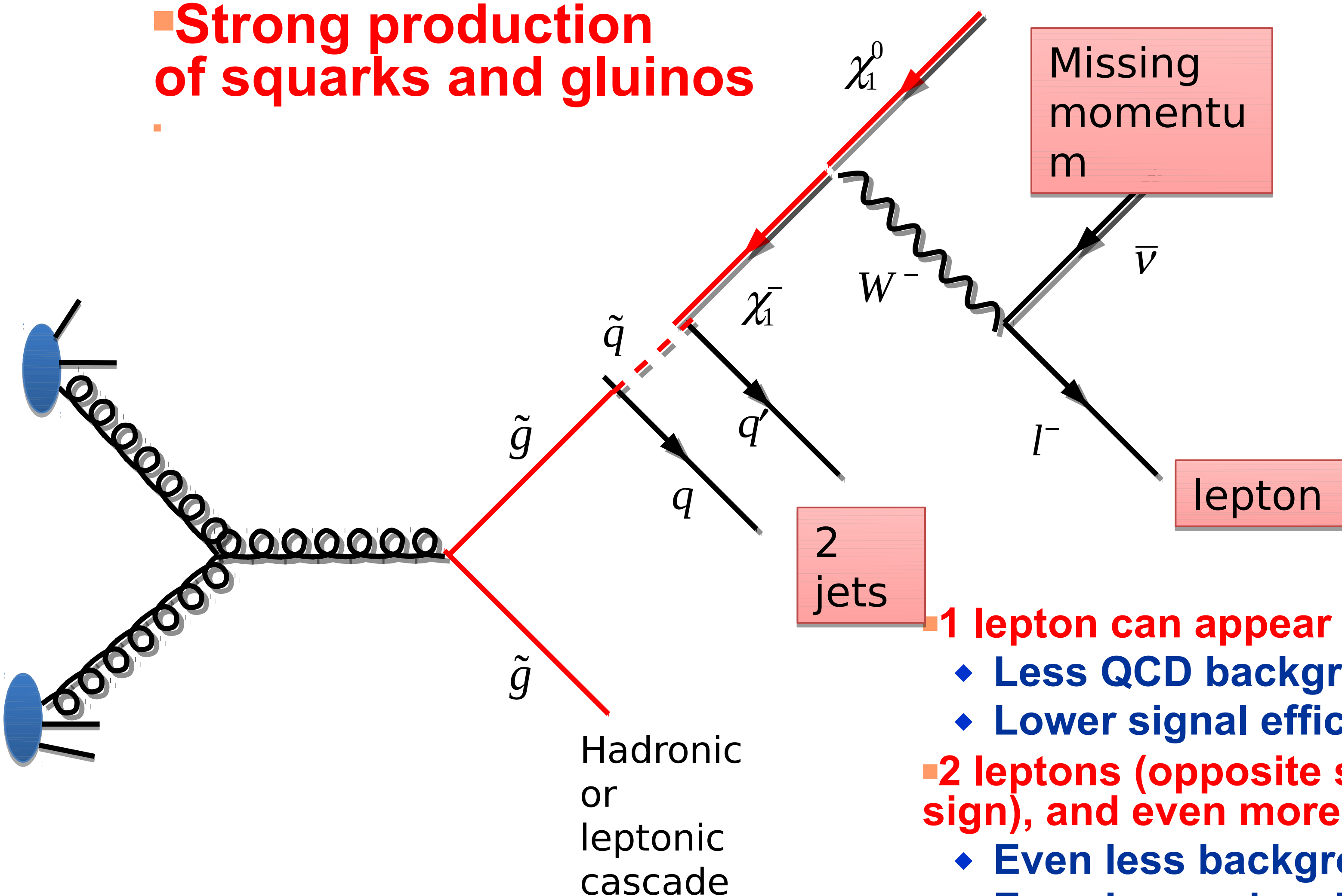
Name	spin-0	spin-1/2	spin-1
squarks, quarks (x 3 families)	$(\tilde{u}_L\ \tilde{d}_L)$	$(u_L\ d_L)$	-
	$\tilde{u}_R$	u_R	-
	$\tilde{d}_R$	d_R	-
sleptons, leptons (x 3 families)	$(\tilde{\nu}_L\ \tilde{e}_L)$	$(\nu_L\ e_L)$	-
	$\tilde{e}_R$	e_R	-
Higgs, higgsinos	$(H_u^+\ H_u^0)$	$(\tilde{H}_u^+\ \tilde{H}_u^0)$	-
	$(H_d^0\ H_d^-)$	$(\tilde{H}_d^0\ \tilde{H}_d^-)$	-
gluino, gluon	-	$\tilde{g}$	g
winos, W bosons	-	$\tilde{W}^\pm\ \tilde{W}^0$	$W^\pm\ W^0$
bino, B boson	-	$\tilde{B}^0$	B^0

5 mSUGRA Parameters

- M_0: common scalar mass at GUT scale
- $M_{1/2}$: common gaugino mass at GUT scale
- $\tan(\beta)$: ratio of vaccuum expectation values of two Higgs doublets
- A_0: a common trilinear coupling constant at GUT scale
- sign(μ): the algebraic sign of the Higgsino mass parameter

SUSY searches at hadron colliders

- **Strong production of squarks and gluinos**



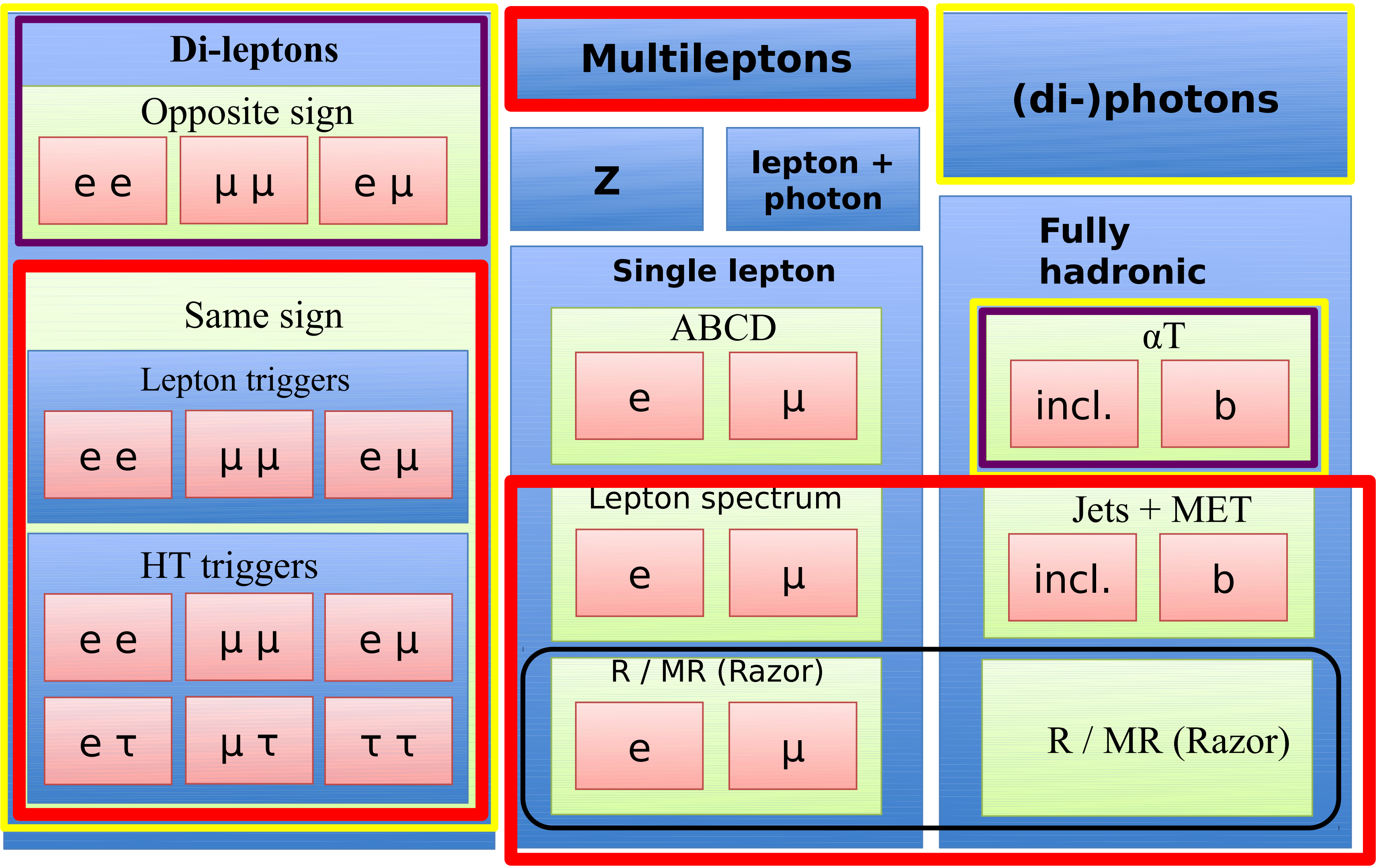
- **1 lepton can appear**
  - **Less QCD background**
  - **Lower signal efficiency**
- **2 leptons (opposite sign, same sign), and even more**
  - **Even less background**
  - **Even lower signal efficiency**

The CMS Strategy for SUSY searches

- Generic searches addressing most possible final states
- Robust physics objects
  - leptons, jets, missing momentum, τ's…
- Data-driven background prediction for all searches
- Well established statistical techniques

All Channels covered by CMS

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS



SSDL signature in new physics scenarios

- **SUSY**
  - Phys. Lett. B 315(1993) 349
  - Phys. Rev. D 52(1995) 133
  - Phys. Rev. D 53(1996) 6241
- **Universal Extra Dimensions**
  - Phys. Rev. D 66(2002) 056006
- **Pair production of fermionic top partners T5/3**
  - JHEP 06(2008) 026
- **Heavy Majorana neutrinos**
  - Phy. Lett. B 400(1997) 331
- **Same sign top-pair resonance in warped extra dimensions**
  - JHEP 04(2009) 056

- Part-II: The LHC and the CMS experiment
  - General introduction
  - Probe physics of tomorrow with physics of today
  - Examples
    - Leptonic: Level-1(hardware) endcap muon triggers
    - Hadronic: understanding Missing Transverse Energy(MET)

The Large Hadron Collider(LHC)

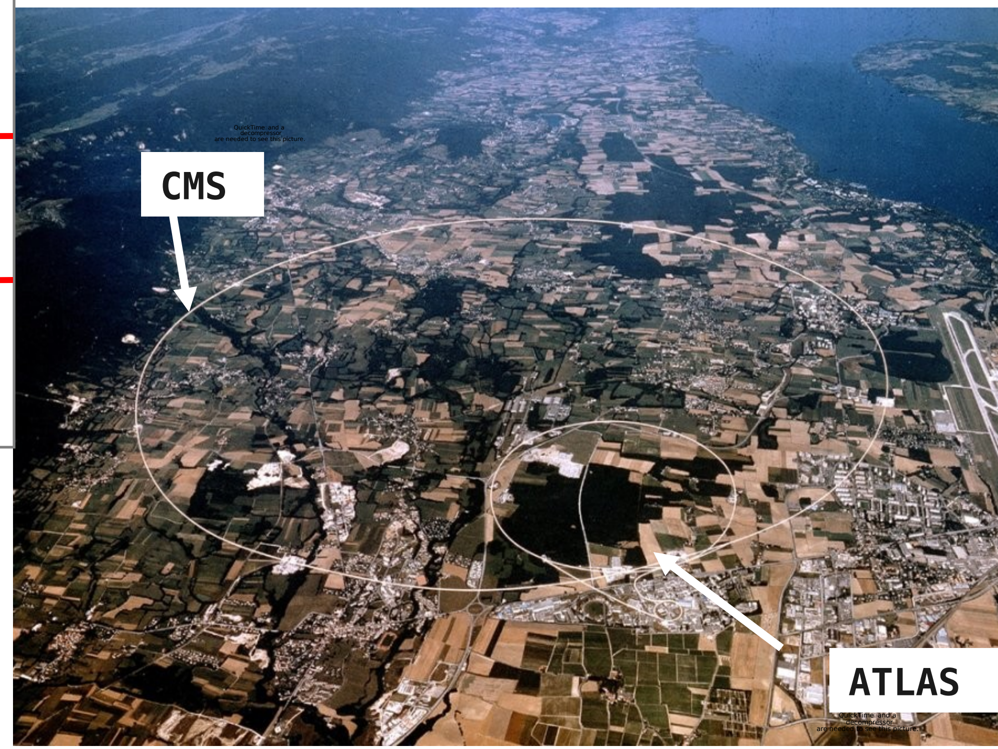
A proton-proton collider

Parameter	Design	Achieved in 2010
√s	14 TeV	7 TeV
Luminosity (L)	10^{34} cm^{-2} s^{-1}	2x10^{32} cm^{-2}s^{-1}
Bunches per beam	2808	368

- The total expected events produced for process *X* in the data:

$$N^{events} = s\left(pp \rightarrow X\right) \cdot \int L \cdot dt$$

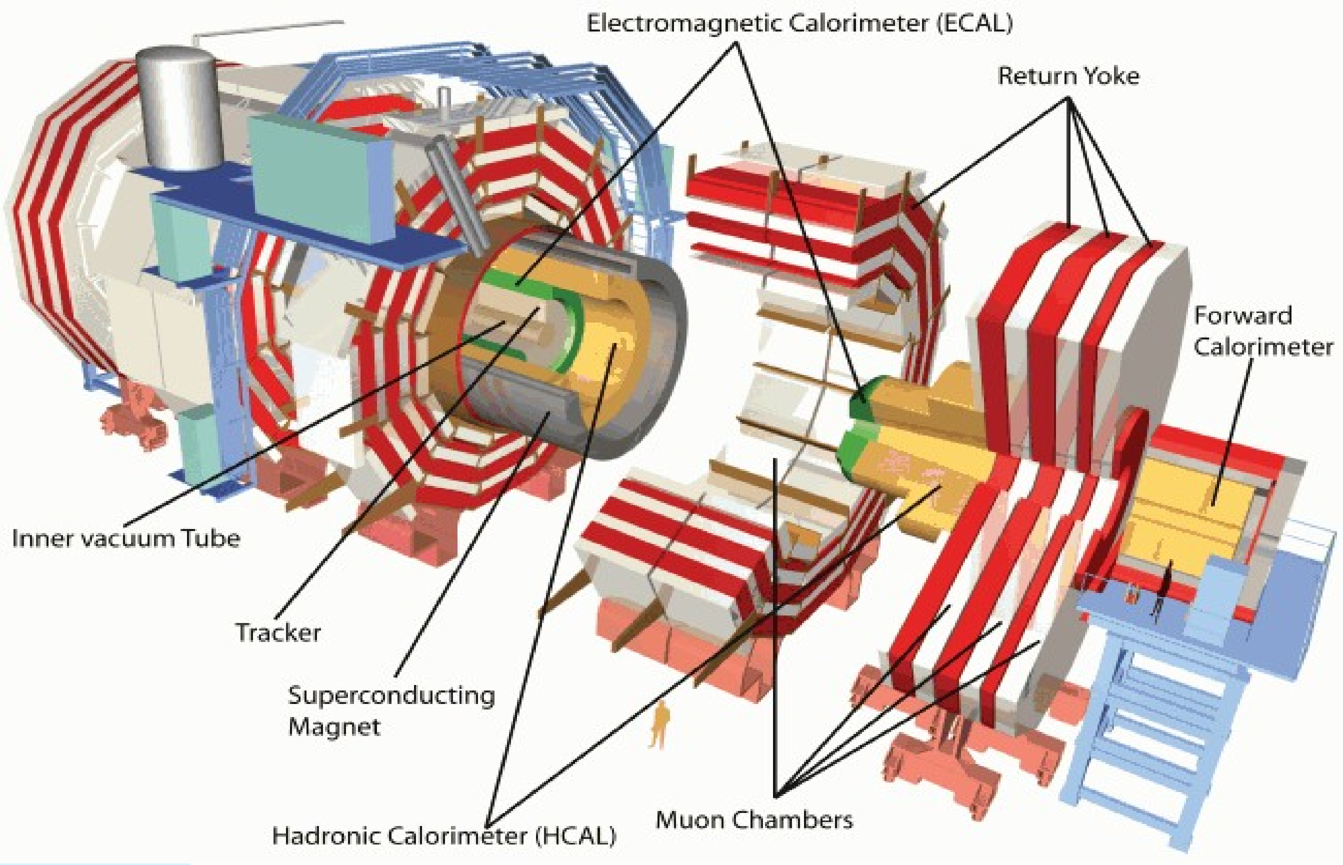
- **In 2010 the LHC produced ~35 pb^{-1} of good data**



9 km

The Compact Muon Solenoid(CMS)

A general purpose particle detector capable of directly detecting all species of stable particles known to exist, except for the weakly interacting neutrino

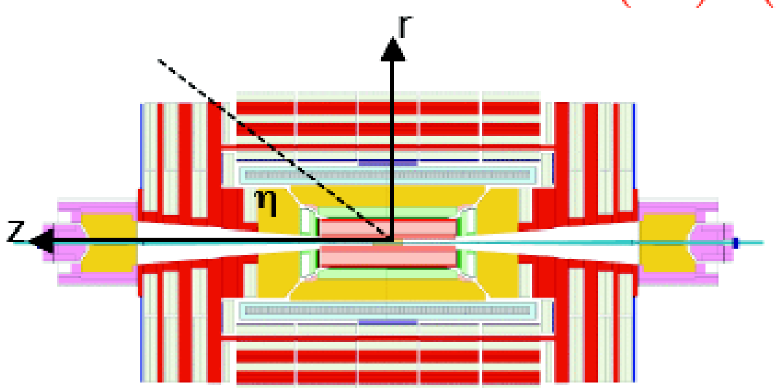


- 14,000 tons
- 15 meters in diameter
- 21 meters long
- 3.8 Tesla B-Field
- 100 meters underground
- 3,600 collaborators
- 180 institutions
- 38 countries

The CMS Cooridinate System

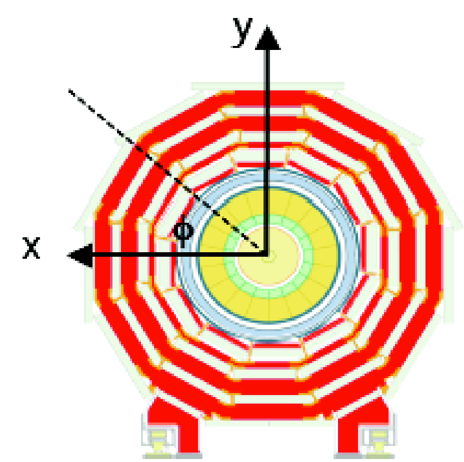
Directions of outgoing particles from proton collisions can be deduced from two observables:

- Azimuthal Angle: ϕ
  - Particles produced uniformly with respect to ϕ
- Pseudorapidity: $\eta = -\ln(\tan(\theta/2))$
  - Particles produced approximately uniform with respect to η
  - NOT uniform with respect to θ
  - Difference in η between two particles is Lorentz Invariant under longitudinal boosts - important since initial P_z is unknown
- Distance Metric: $(\Delta R)^2=(\Delta\phi)^2+(\Delta\eta)^2$



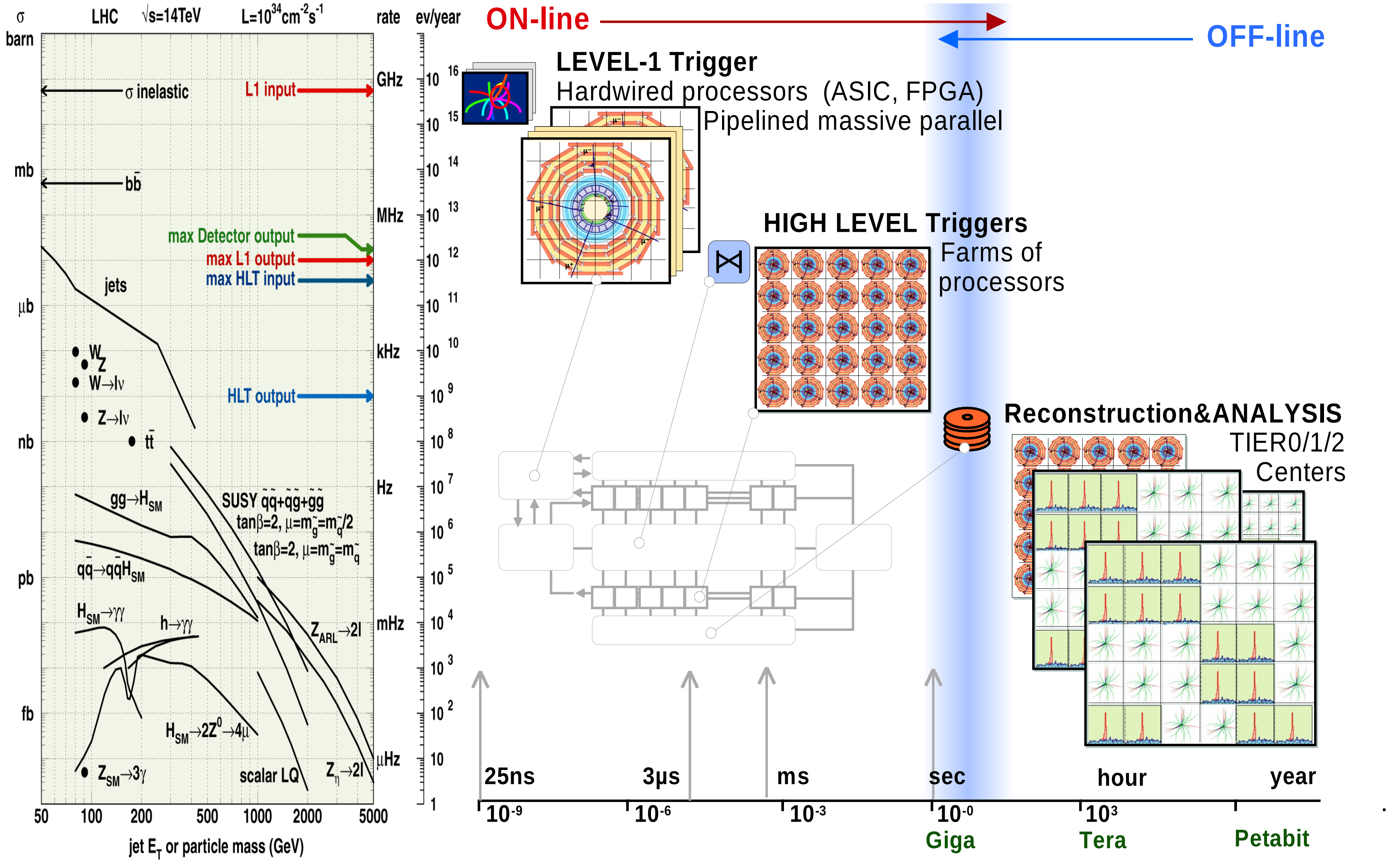
Longitudinal View of CMS

θ (degrees)	η
0	infinite
5	3.13
10	2.44
20	1.74
30	1.31
45	0.88
60	0.55
80	0.175
90	0

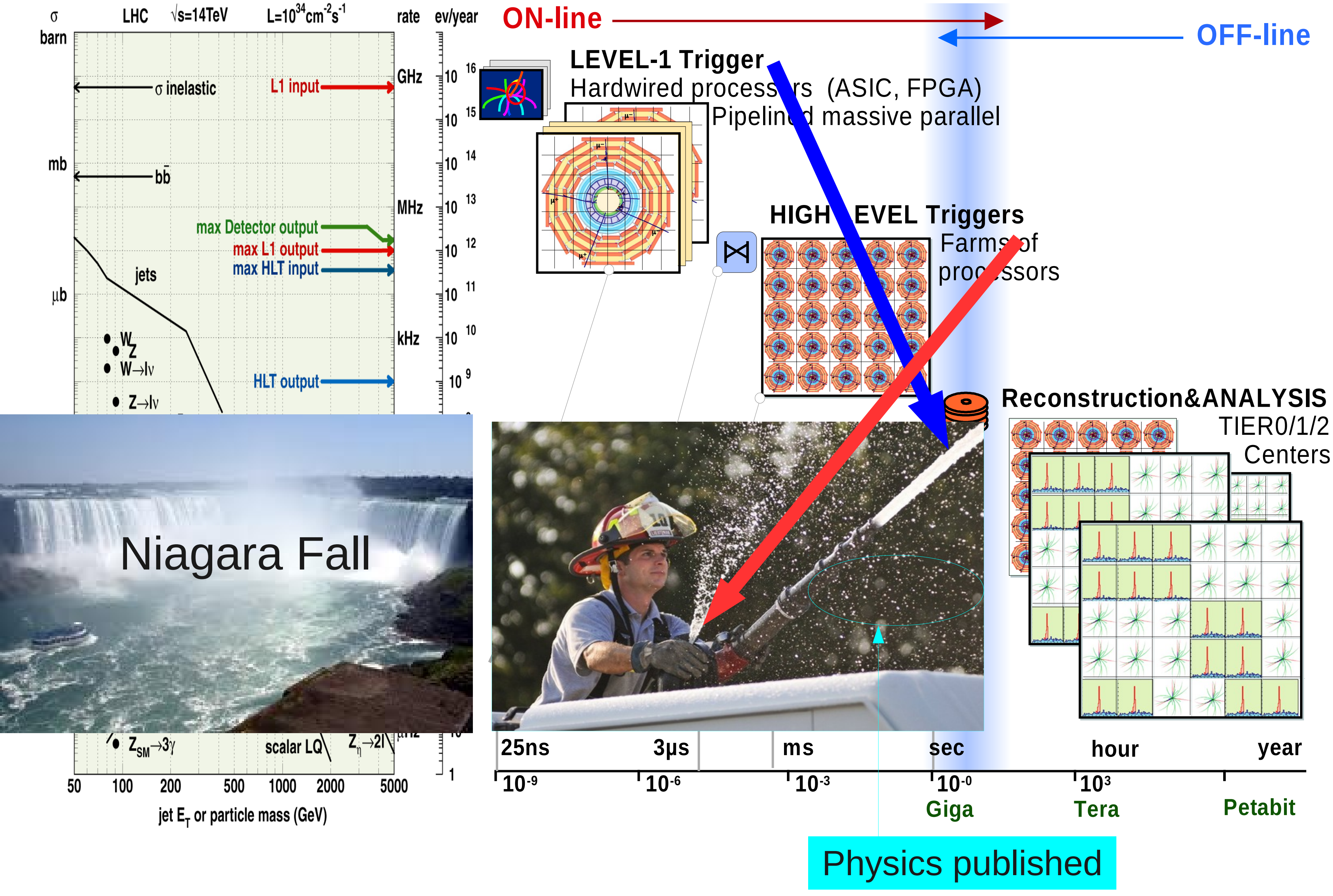


Transverse View of CMS

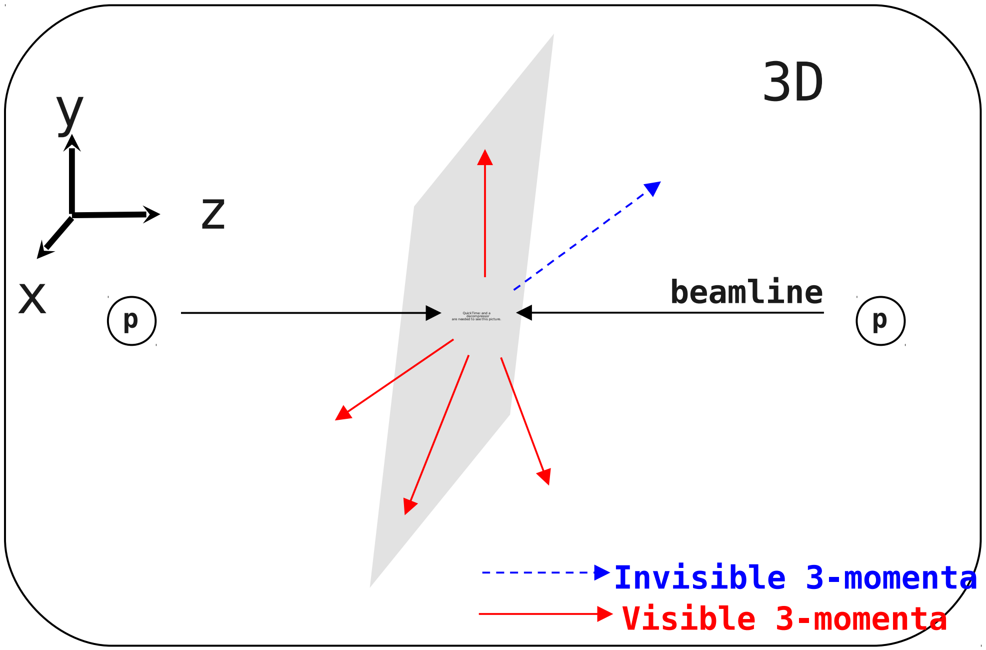
Physics selection at the LHC

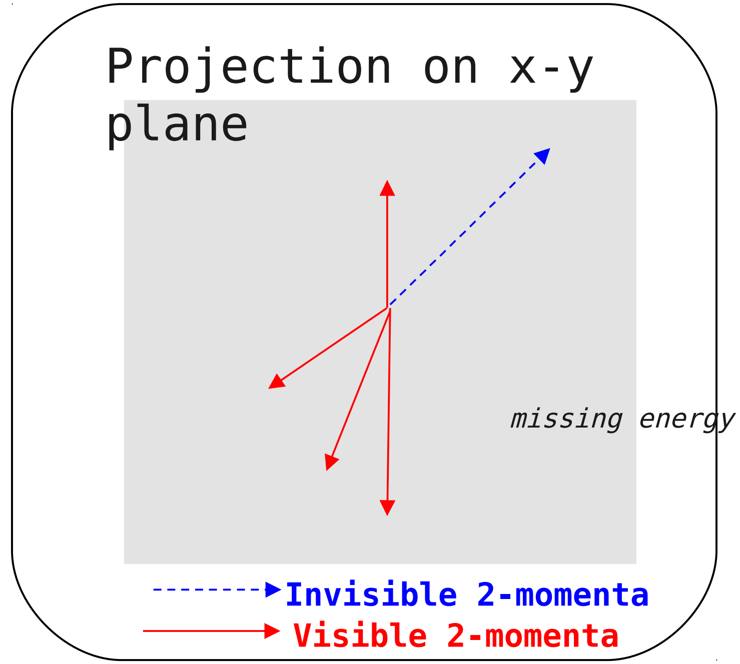


Physics selection at the LHC



Invisible Particles@LHC: MET





The E_T is calculated by summing vectorially over the transverse momenta of all of the reconstructed particle candidates in the event:

$$|\vec{E}_T| = \left| \sum_{j}^{\text{all particles}} \hat{x}\left(p_T^j \cdot \cos(j)\right) + \hat{y}\left(p_T^j \cdot \sin(j)\right) \right|$$

The total hadronic activity in the event is characterized by H_T:

$$H_T = \sum_{j}^{\text{all jets}} |p_T^j|$$

Part-III: the analysis

Full details see: JHEP 1106, 077 (2011)

Search signatures

m_B drives the production cross-section

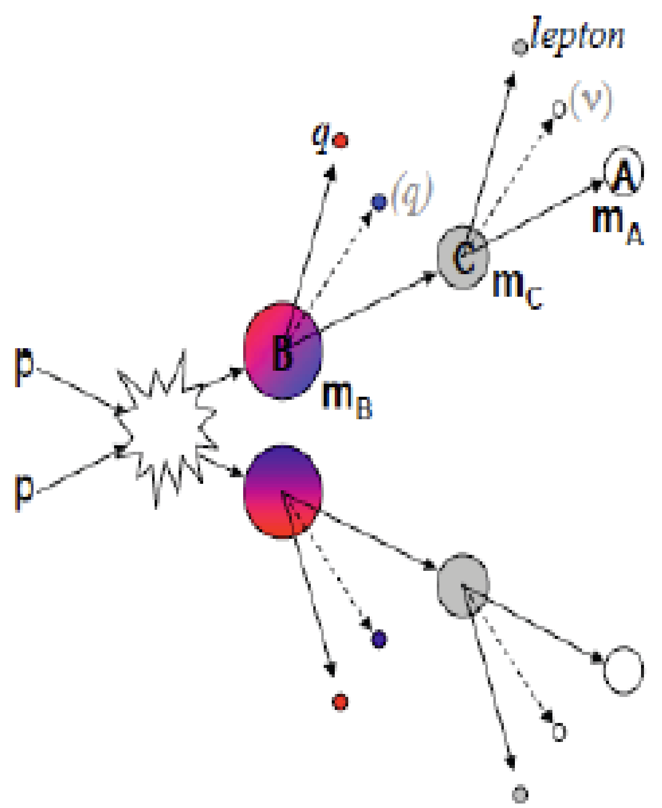
Δm_{BC} influences the total hadronic activity

Δm_{CA} influences the p_T of the leptons

Missing transverse energy (E_T^{miss}) is large so long as Δm_{BA} is large

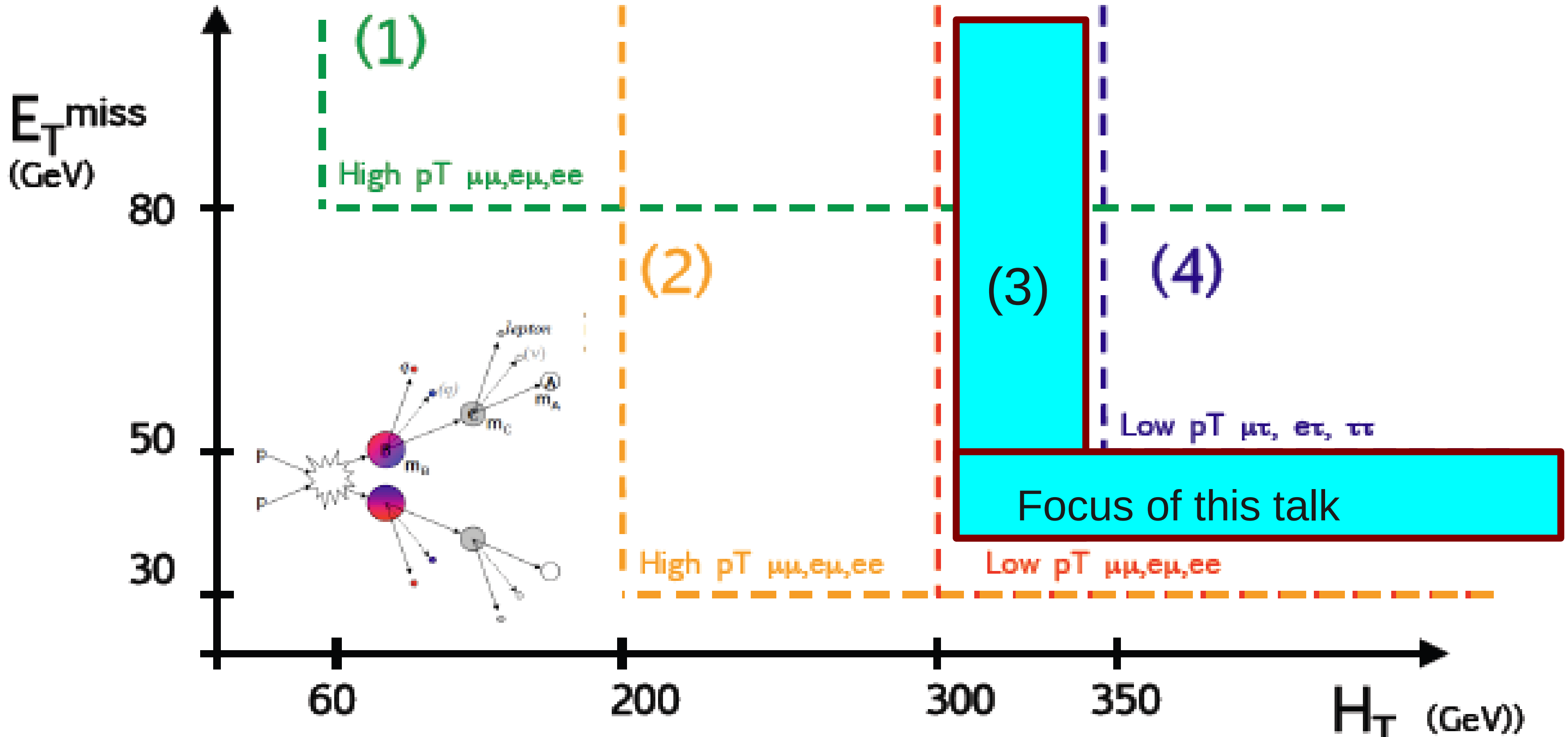
Tau enhancement can be a natural outcome in various SUSY models

A: LSP [dark-matter motivated; expect E_T^{miss}]
B: gluino/squark [large σ; expect jets]
C: chargino [gives exclusive same-sign leptons]



Four search regions

We try to cover many possibilities for Δm_{BC}, Δm_{CA}, Δm_{BA}



	Signal Region 1	Signal Region 2	Signal Region 3	Signal Region 4
Δm_{BC}	small	large	large	large
Δm_{CA}	large	large	small	small
Δm_{BA}	large	small	small	moderate

Background Classification

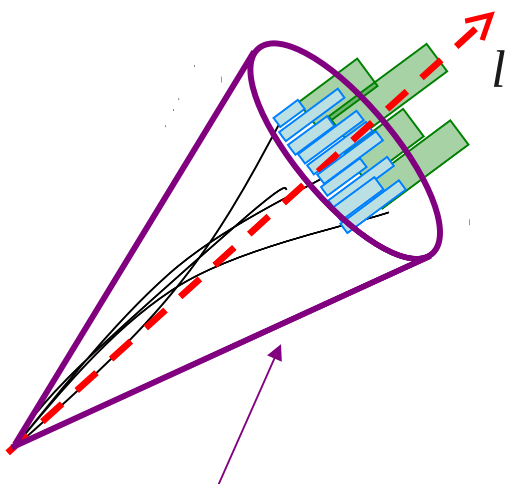
Type		Sources
2 same-sign prompt leptons: – small, but irreducible, contribution – reasonably well understood→**taken from MC**	N^{SS}_{p-p}	$qq \to qqW^{\pm}W^{\pm}$, WZ, ZZ, WWW, $t\bar{t}$W, double parton scattering 2´$(qq \to W^{\pm})$
2 opposite-sign prompt leptons + charge misidentification (appears as same-sign) – small contribution – relying on MC is not safe→**derive from data**	N^{OS}_{p-p}	$t\bar{t}$, tW, Drell-Yan, $W^{\pm}W^{m}$, WZ, ZZ
1 prompt lepton + 1 fake lepton – dominant contribution – relying on MC is not safe → **derive from data**	N^{SS}_{p-f}	$(t\bar{t},\ tW,\ tb) \to l\nu + \text{jets}$ $W+$jets, Drell-Yan$+$jets VV$\to l+$jets
2 fake leptons – sub-dominant contribution – relying on MC is impossible→**derive from data**	N^{SS}_{f-f}	QCD $t\bar{t}$(all-hadronic)

$$N^{\text{tot}}_{\text{bgd}} = N^{SS}_{p-p} + N^{OS}_{p-p} + N^{SS}_{p-f} + N^{SS}_{f-f}$$

Lepton Selection

Muons (μ) and electrons (e) up to $|\eta| < 2.4$ are reconstructed using standard techniques on CMS. This analysis focuses on the parameter space that features "soft leptons" (low transverse momenta)

- $p_T(\mu) > 5$ GeV & $p_T(e) > 10$ GeV



Isolation cone: $\Delta R = \sqrt{(\Delta\eta)^2+(\Delta\phi)^2} < 0.3$

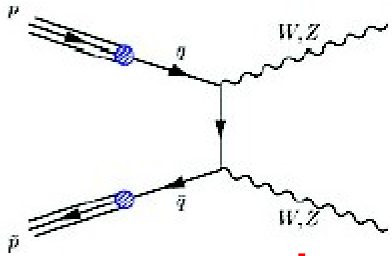
The relative isolations (RelIso) observable is used to distinguish prompt from non-prompt leptons:

$$\frac{\sum_{DR<0.3} P_T^{\text{Track}} + E_T^{\text{ECAL}} + E_T^{\text{HCAL}}}{P_T^l} < 0.15$$

Leptons are ***"prompt" (signal-like)*** if they come from W/Z/χ decays and ***"non-prompt" (fake)*** if the come from hadron decays.

A requirement is placed on the transverse impact parameter at $d_0 < 0.02$ cm in order to suppress leptons from heavy-flavor quark decays.

Prompt-Prompt Same-Sign Di-Leptons: N^{SS}_{p-p}



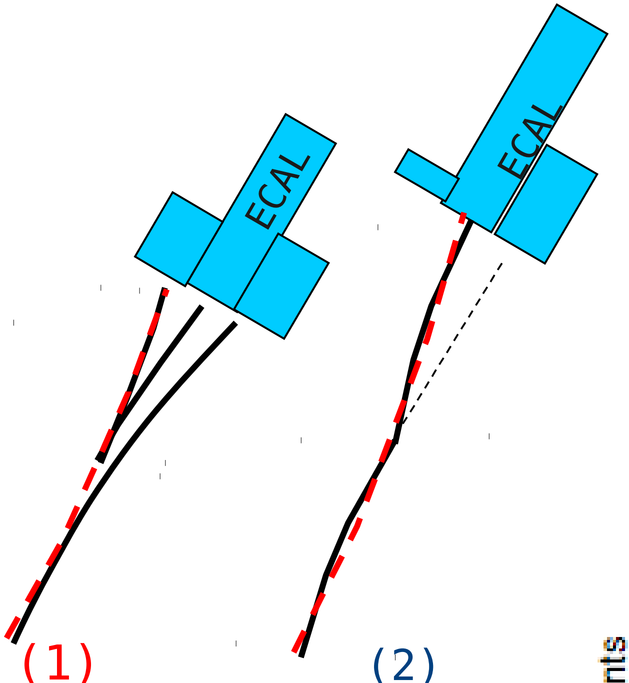
- These backgrounds include:
  - Di-boson production: $q\bar{q} \rightarrow WZ, ZZ$
  - Double "W-sstrahlung": $qq \rightarrow q'q'W^{\pm}W^{\pm}$
  - Double-parton scattering: $2´(qq \rightarrow W^{\pm})$
- Small predicted cross-sections, so these are not expected to be abundant in only 35pb^{-1} of data
- Monte-Carlo based estimates are therefore used with:
  - 50% error assumed for cross-sections (conservative)
  - 18% error from experimental acceptance

Di-lepton channel	$\mu\mu$	ee	$e\mu$	total
Number of expected events for VV	0.006	0.000	0.019	0.025
Theoretical systematic error	$\pm$0.003	$\pm$0.007	$\pm$0.010	$\pm$0.013
Number of expected events for $qq \rightarrow q'q'W^{\pm}W^{\pm}$	0.021	0.012	0.025	0.058
Theoretical systematic error	$\pm$0.011	$\pm$0.006	$\pm$0.013	$\pm$0.029
Total Prompt-Prompt backgrounds	0.026	0.012	0.044	0.083
Experimental errors	$\pm$0.005	$\pm$0.002	$\pm$0.008	$\pm$0.015
Total errors	$\pm$0.014	$\pm$0.007	$\pm$0.023	$\pm$0.044

$$N^{SS}_{p-p} = 0.083 \pm 0.044$$

Prompt-Prompt Opposite-Sign Di-Leptons: N^{OS}_{p-p}

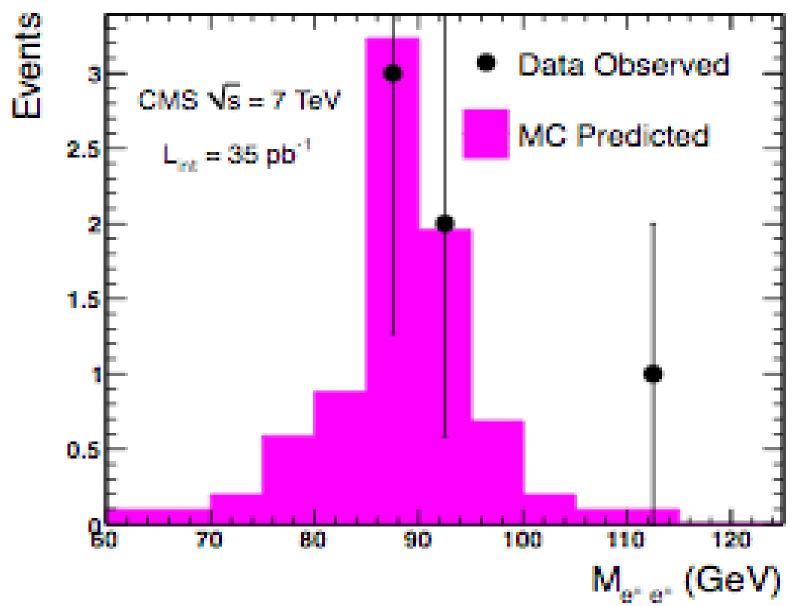
(charge mis-reconstruction)



- **Probability for this mistake (charge mis-ID) to occur can be measured in data by looking at rate of Z-boson decays, which feature same-sign electrons**

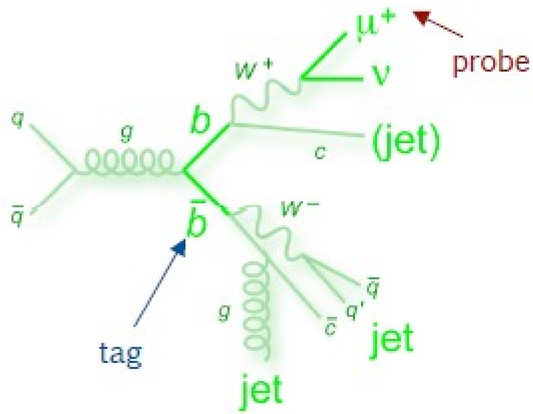
- **Multiply this charge flip rate by # of opposite-sign dilepton events in the signal region (mostly tt)**

$$e_{\text{flip}} = \frac{1}{2}\frac{N(Z \rightarrow e^{\pm} e^{\pm})}{N(Z \rightarrow e^{\pm} e^{\mp})} = \frac{1}{2}\frac{5}{3642} = 0.007 \pm 0.0003$$



$$N^{OS}_{p-p} = 0.012 \pm 0.006$$

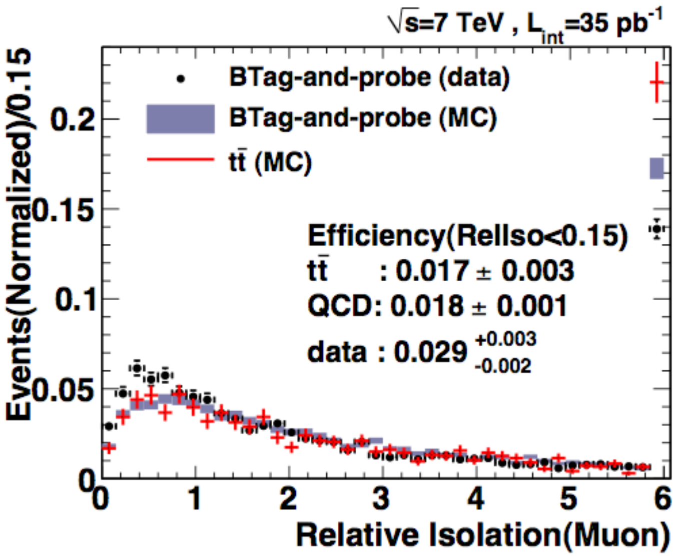
- **Recipe for the Btag-And-Probe Method**
  - Select a bb control sample using a high-purity b-jet tagging algorithm
    - Tag = b-tagged jet
    - Probe = lepton in opposite hemisphere: ΔR(lepton,jet) > 1.0
  - Build a RelIso template for the probe-leptons in bins of lepton-p_T and jet multiplicity (N_{jets})
  - Use tt MC to re-weight the templates
    - MC should model p_T and N_{jets} well
  - Obtain the RelIso selection efficiency for fake leptons in top events from re-weighted templates
  - Multiply efficiency by # of events in the *sideband region*

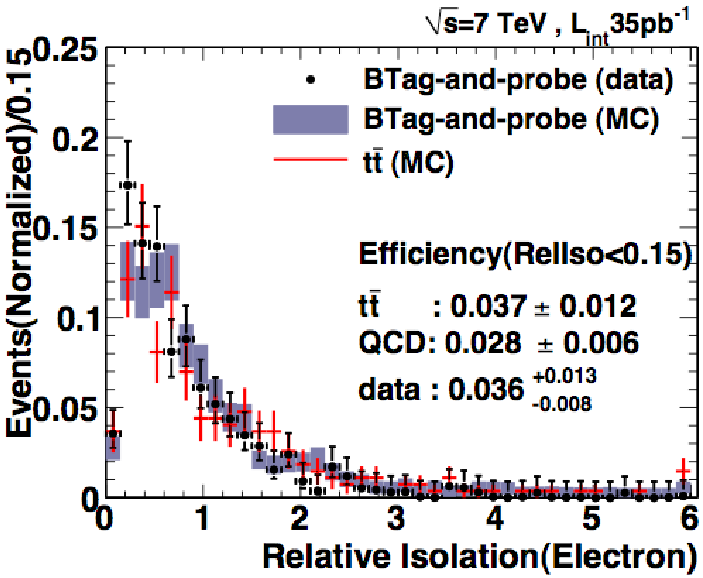


sideband region : all final selection requirements imposed except for RelIso on the least isolated lepton

Fake-Prompt Same-Sign Di-Leptons: N^{SS}_{p-f}

Re-weighted RelIso templates for muons and electrons





$$\langle e \rangle_m^{(b)} = 0.029^{+0.003}_{-0.002}$$

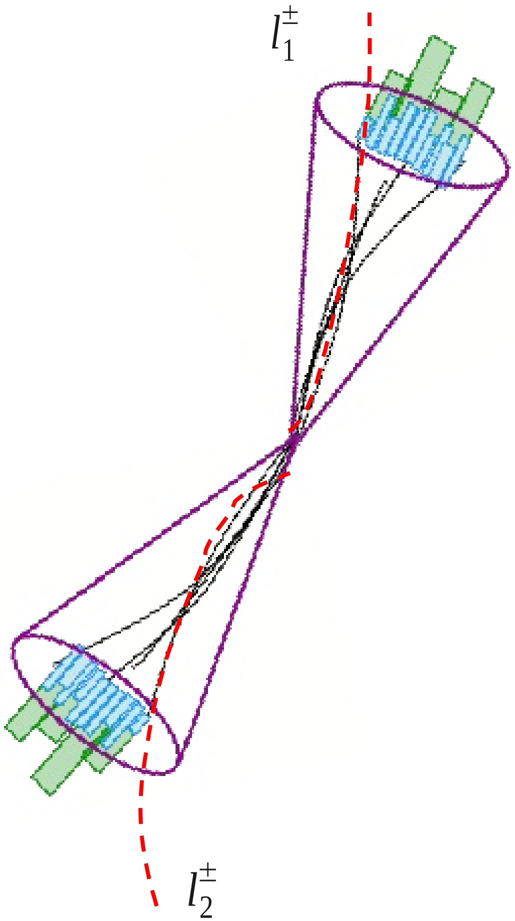
$$\langle e \rangle_e^{(b)} = 0.036^{+0.013}_{-0.008}$$

Gray curve shows the re-weighting procedure performed on QCD MC, and it agrees nicely with tt MC (red). The **black markers** show the re-weighting procedure with data.

$$N^{SS}_{p-f} = 0.522 \pm 0.354$$

Fake-Fake Same-Sign Di-Leptons: N_{f-f}^{SS}

(aka QCD)



- The background from QCD events can be estimated by exploiting the fact that the 3 variables used in the final selection are <u>uncorrelated</u>

$$(i)\ \text{RelIso}(l_1^{\pm}) < 0.15$$
$$(ii)\ \text{RelIso}(l_2^{\pm}) < 0.15$$
$$(iii)\ \not{E}_T > 30\ \text{GeV}$$

- Qualitatively, for QCD events we expect
  - The two fake leptons to come from different jets
    - RelIso calculations should involve different tracks and calorimeter deposits
  - The missing energy (if any) should come from jet mismeasurement and not from neutrino activity
- The 3 selection efficiencies should factorize:

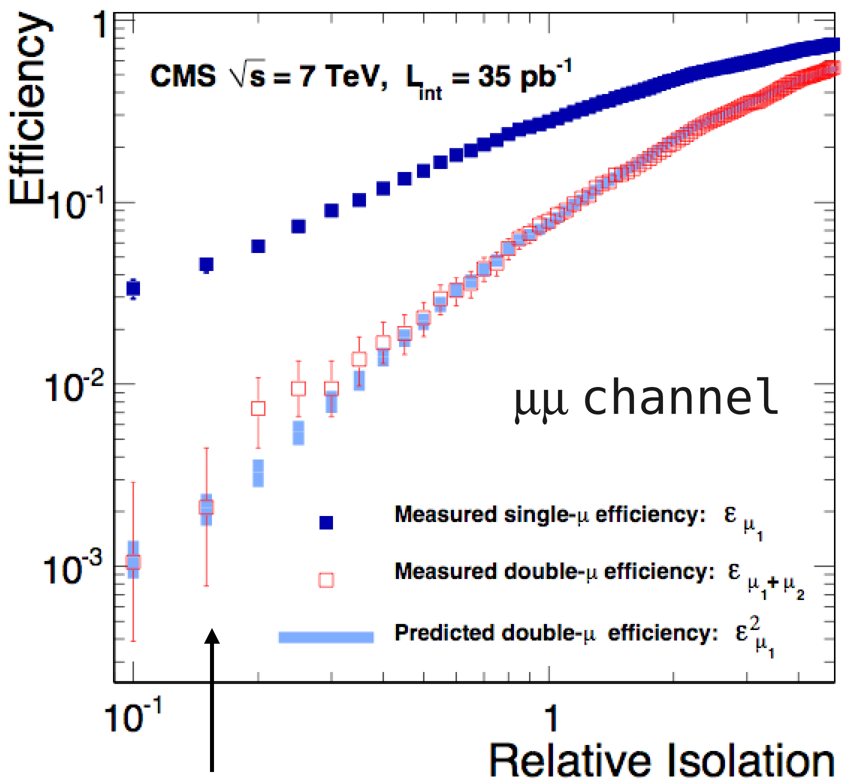
$$e_{l_1 l_2 \not{E}_T} = e_{l_1} e_{l_2} e_{\not{E}_T}$$

- This background estimation method is aptly named: *"The Factorization Method"*

Fake-Fake Same-Sign Di-Leptons: N_{f-f}^{SS}

Proof that RelIso(μ_1) factorizes from RelIso(μ_2) in QCD:

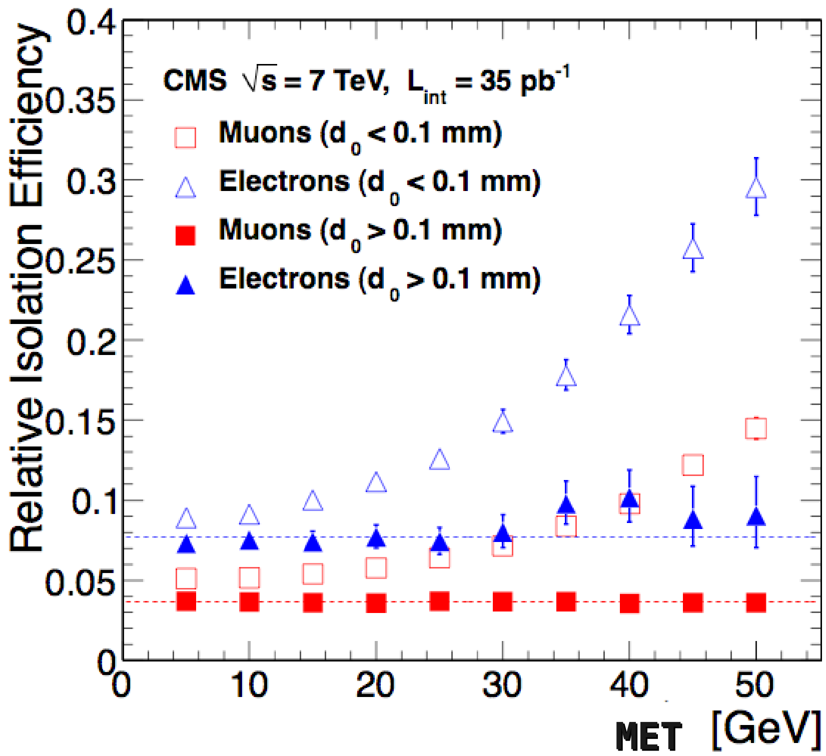
$$e_{m_1 m_2} = e_{m_1} e_{m_2} = (e_m)^2$$



RelIso(μ_1) < 0.15

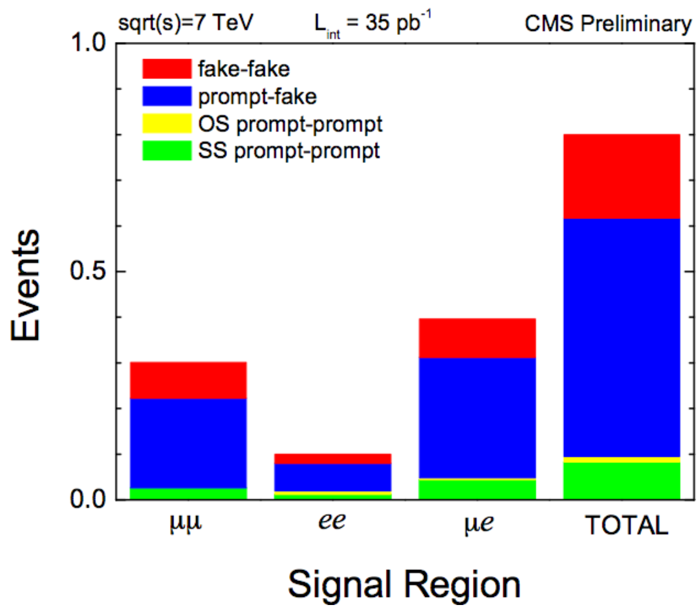
Proof that RelIso factorizes from MET in QCD:

$$e_{m,E_T} = e_m e_{E_T} \quad \text{and} \quad e_{e,E_T} = e_e e_{E_T}$$



$$N_{f-f}^{SS} = 0.183 \pm 0.169$$

Summary of Background Rates



$$N_{\mathrm{bgd}}^{\mathrm{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{p-f}^{SS} + N_{f-f}^{SS} = 0.80 \pm 0.33$$

And when we count the total number of events observed in the data which pass all event selection requirements, we get…

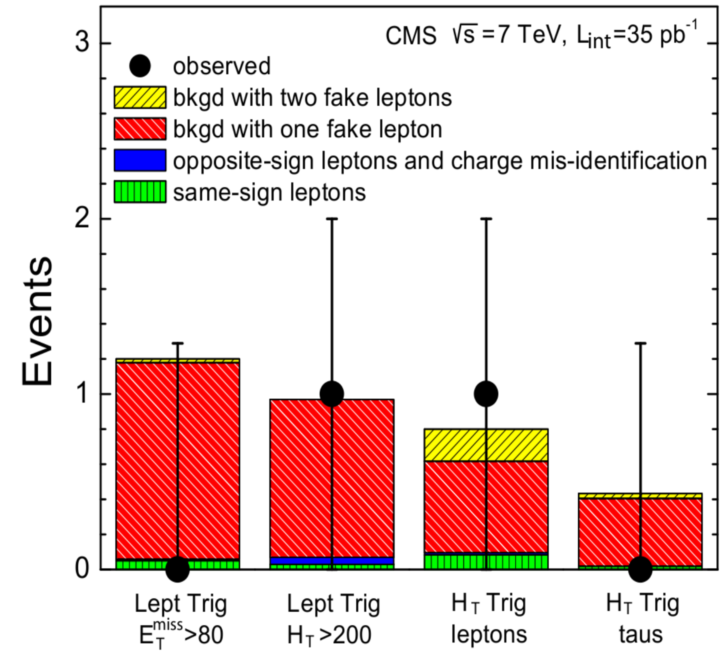
Observed Event Yields in Signal Region for 35 pb^{-1}

$$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{p-f}^{SS} + N_{f-f}^{SS} = 0.80 \pm 0.33$$

1 event is observed from the e^+e^+ channel, which is consistent with the background only hypothesis.

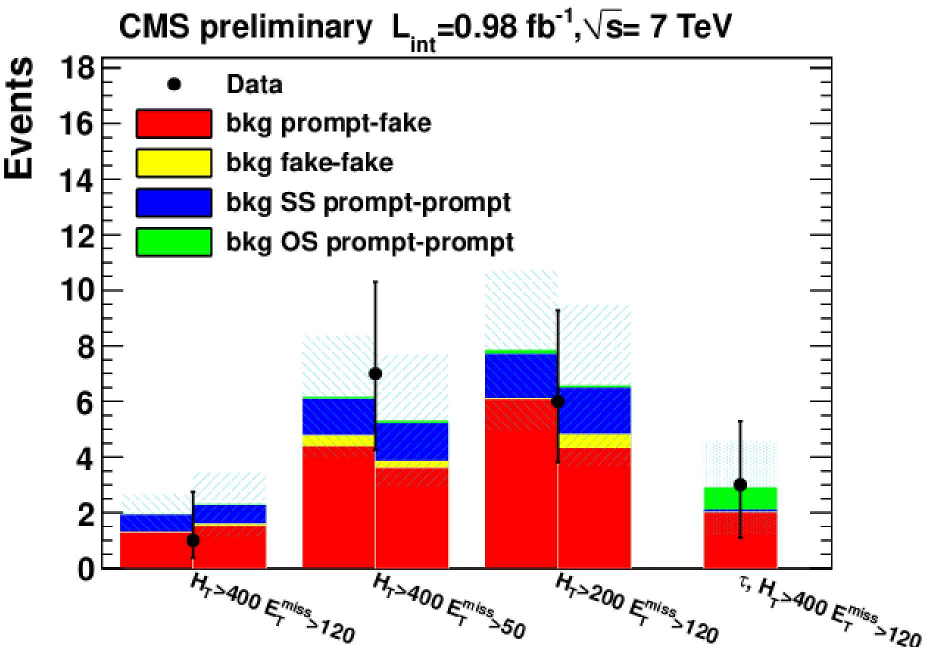
Grand summary of results

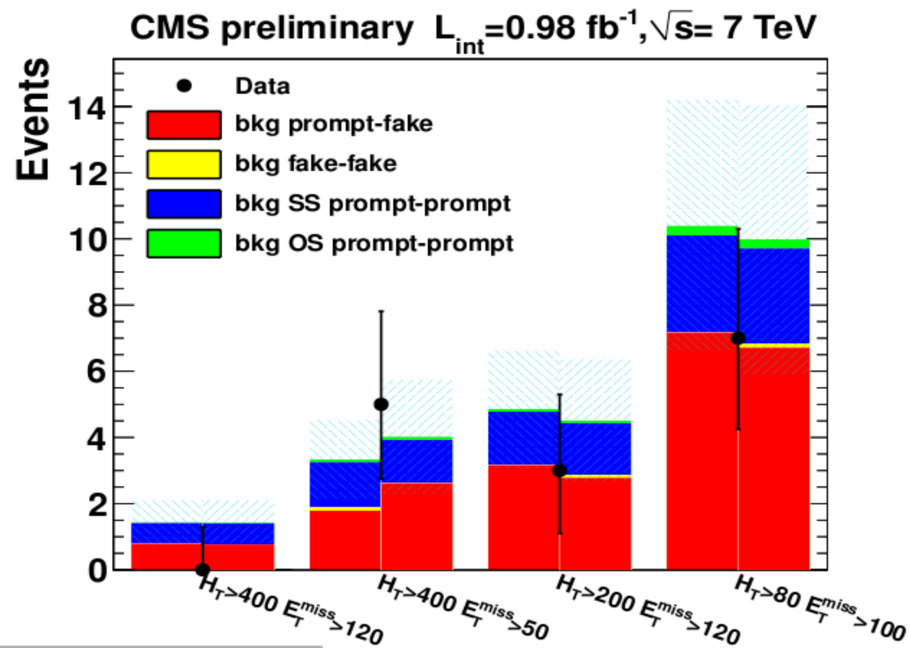
Search Region	ee	$\mu\mu$	$e\mu$	total	95% CL UL Yield
Lepton Trigger					
$E_T^{miss} > 80$ GeV					
MC	0.05	0.07	0.23	0.35	
predicted BG	$\mathbf{0.23^{+0.35}_{-0.23}}$	$\mathbf{0.23^{+0.26}_{-0.23}}$	$\mathbf{0.74 \pm 0.55}$	$\mathbf{1.2 \pm 0.8}$	
observed	**0**	**0**	**0**	**0**	**3.1**
$H_T > 200$ GeV					
MC	0.04	0.10	0.17	0.32	
predicted BG	$\mathbf{0.71 \pm 0.58}$	$\mathbf{0.01^{+0.24}_{-0.01}}$	$\mathbf{0.25^{+0.27}_{-0.25}}$	$\mathbf{0.97 \pm 0.74}$	
observed	**0**	**0**	**1**	**1**	**4.3**
H_T Trigger					
Low-p_T					
MC	0.05	0.16	0.21	0.41	
predicted BG	$\mathbf{0.10 \pm 0.07}$	$\mathbf{0.30 \pm 0.13}$	$\mathbf{0.40 \pm 0.18}$	$\mathbf{0.80 \pm 0.31}$	
observed	**1**	**0**	**0**	**1**	**4.4**
	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$	total	95% CL UL Yield
τ_h enriched					
MC	0.36	0.47	0.08	0.91	
predicted BG	$\mathbf{0.10 \pm 0.10}$	$\mathbf{0.17 \pm 0.14}$	$\mathbf{0.02 \pm 0.01}$	$\mathbf{0.29 \pm 0.17}$	
observed	**0**	**0**	**0**	**0**	**3.4**



- **No excess observed in any signal region**
- **Upper limits range from 3.1 to 4.4 events at 95% C.L.**
  - **Bayesian w/ flat prior on signal strength**
  - **Lognormal pdf for systematic errors**
  - **Errors on bkg and signal assumed to be uncorrelated**
- **Exclusion region in cMSSM exceeds LEP and Tevatron exps**

0.98 fb^{-1} updates (July 2011)





Method	Bayesian	LEP CL_s	LHC CL_s
Inclusive dileptons			
Search region 1	4.0	3.8	3.7
Search region 2	9.2	9.1	8.9
Search region 3	7.5	7.5	7.3
High-p_T dileptons			
Search region 1	3.1	3.1	3.0
Search region 2	8.1	7.9	7.5
Search region 3	5.3	5.2	5.2
Search region 4	7.4	7.6	6.0
τ dileptons			
Search region 1	6.2	6.1	5.8

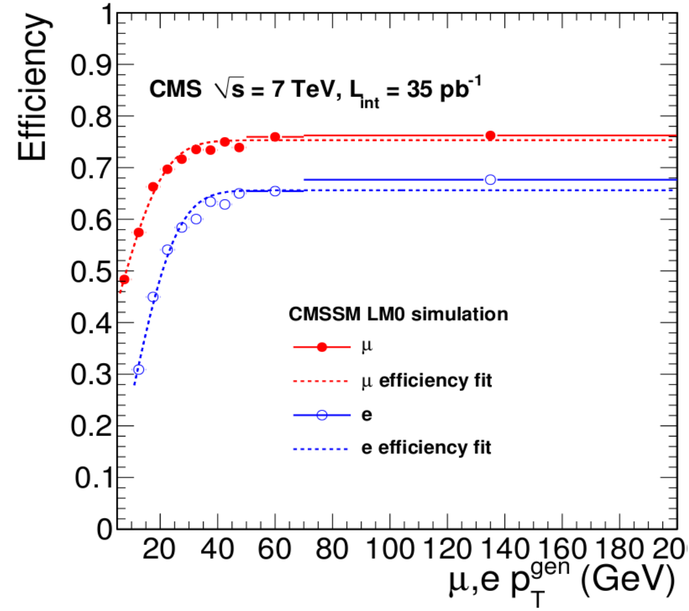
Part-IV: Interpretation of the results

- **Efforts for model independent interpretations**
  - Signal Acceptance Model
- **Examples**
  - Exclusion limit for the benchmark mSUGRA parameters
  - SUSY models with Sneutrino as LSP
  - Same sign tops from the FCNC based Z' models

Signal Acceptance Model

Lepton efficiencies:

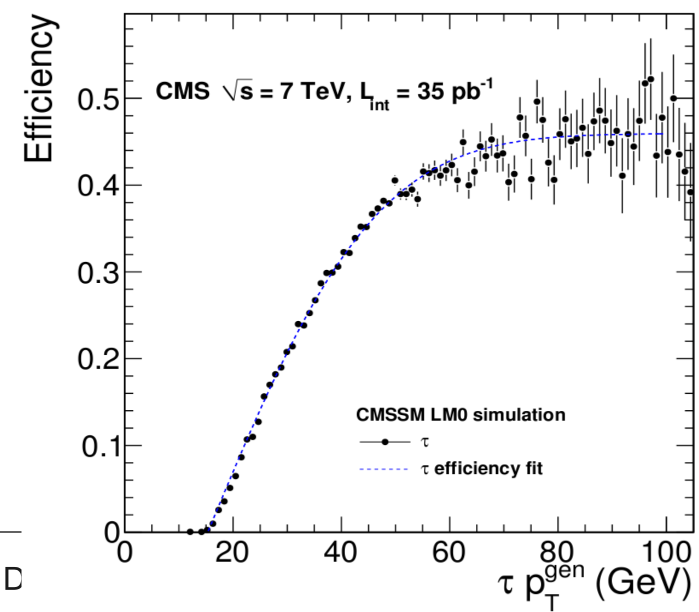
$$\epsilon(x) = \text{par}(1) + \text{par}(2) \cdot \left(\text{erf}\left(\frac{x - x_0}{\text{par}(3)}\right) - 1\right)$$



Lepton isolation corrections:

$$\Delta\varepsilon = -0.10 \frac{<n> -25}{15},$$

where $<n>$ is the average number of stable charged particles with $p_T > 3$ and $|\eta| < 2.4$

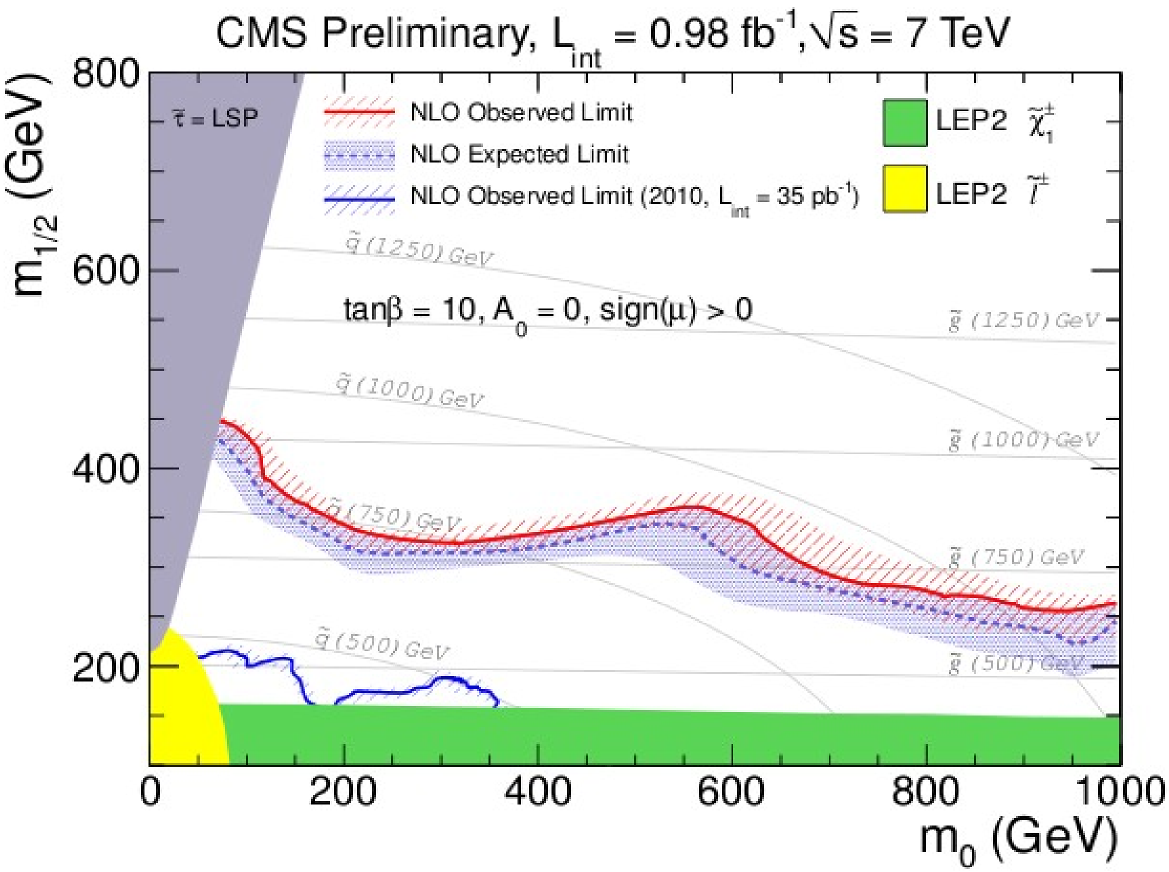


H_T: smear by 20-30% depending on the generated H_T (quarks and gluons from hard-scatter)

E_T^{miss}: smear by 7-25% depending on the generated H_T

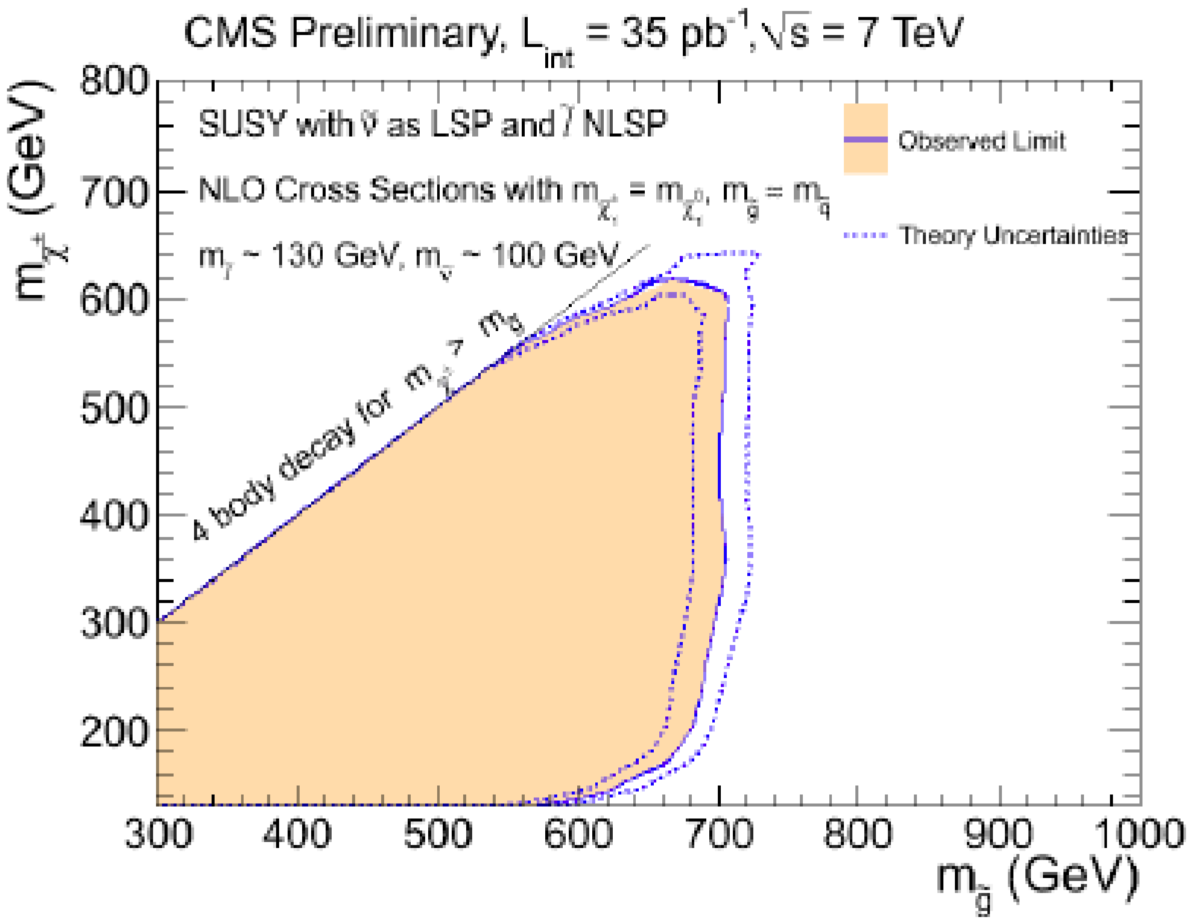
mSUGRA Exclusion Limits

It has become convention to show the limits on the m_0 vs $m_{1/2}$ plane for a particular (but arbitrary) choice of tan(β), A_0, and sign(μ)



This is approach is common because it allows us to compare results and signal sensitivities to other searches across different experiments

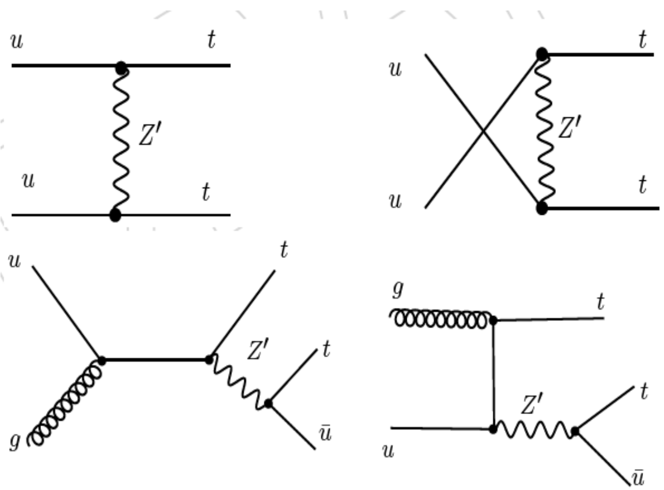
Limits on the models with sneutrino as LSP

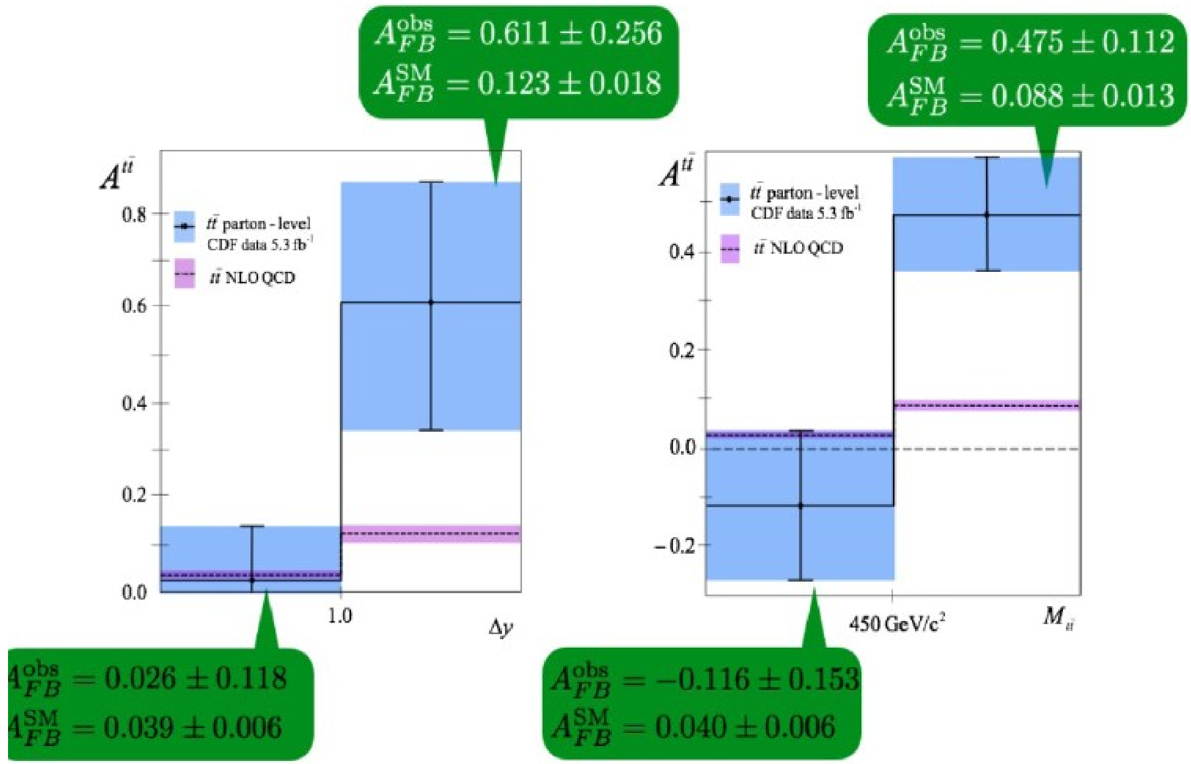


Z' model for Tevatron top pair AFB: Implications for LHC

Signatures of same sign tops are predicted from the FCNC based Z' models

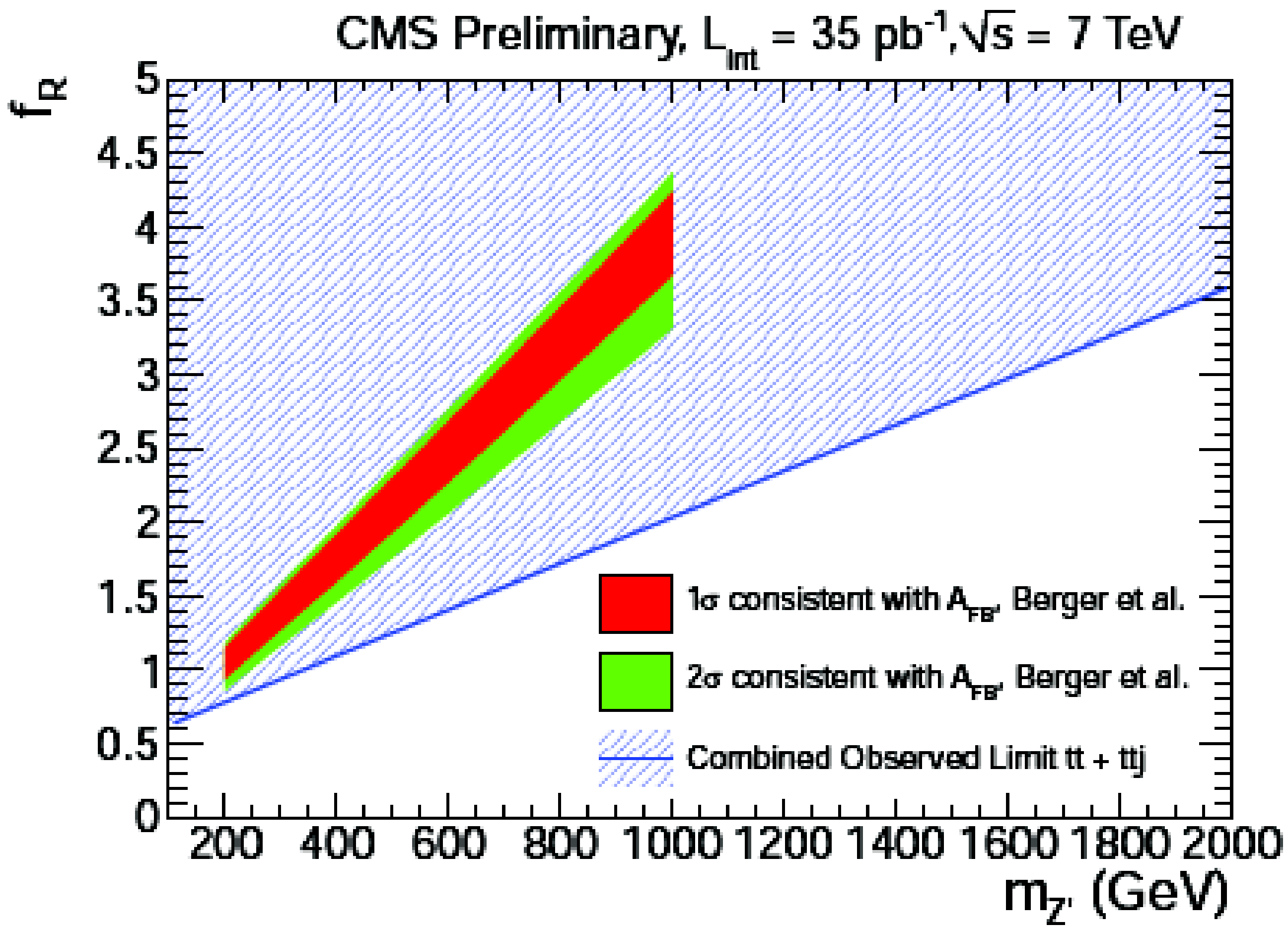
$$\mathcal{L} = g_W \bar{u}\gamma^\mu (f_L P_L + f_R P_R) t Z'_\mu +$$





CDF/D0: arxiv:1101.0034

Exclusion limits on FCNS based Z' model



ruled out

Reinterpretation of results with leptonic trigger

Summary and Outlook

- **Searched for new physics with two same-sign leptons + Jets + MET in pp-collisions at 7 TeV using the data set of L=35 pb-1 and 0.998 fb-1**
  - **Established and validated data-driven techniques for evaluating backgrounds in the context of the experimental signatures**
  - **Observed no signs of new physics; set limits on new physics;event yields in 4 signal regions**
  - **Provided parameterization of a signal acceptance to allow for interpreting the observed experimental limits in a context of a broad range of models**
  - **The results have exceeded LEP&Tevatron exps**
- **We will learn more soon**
  - **5fb^-1 is now participated by end of 2011 pp run**