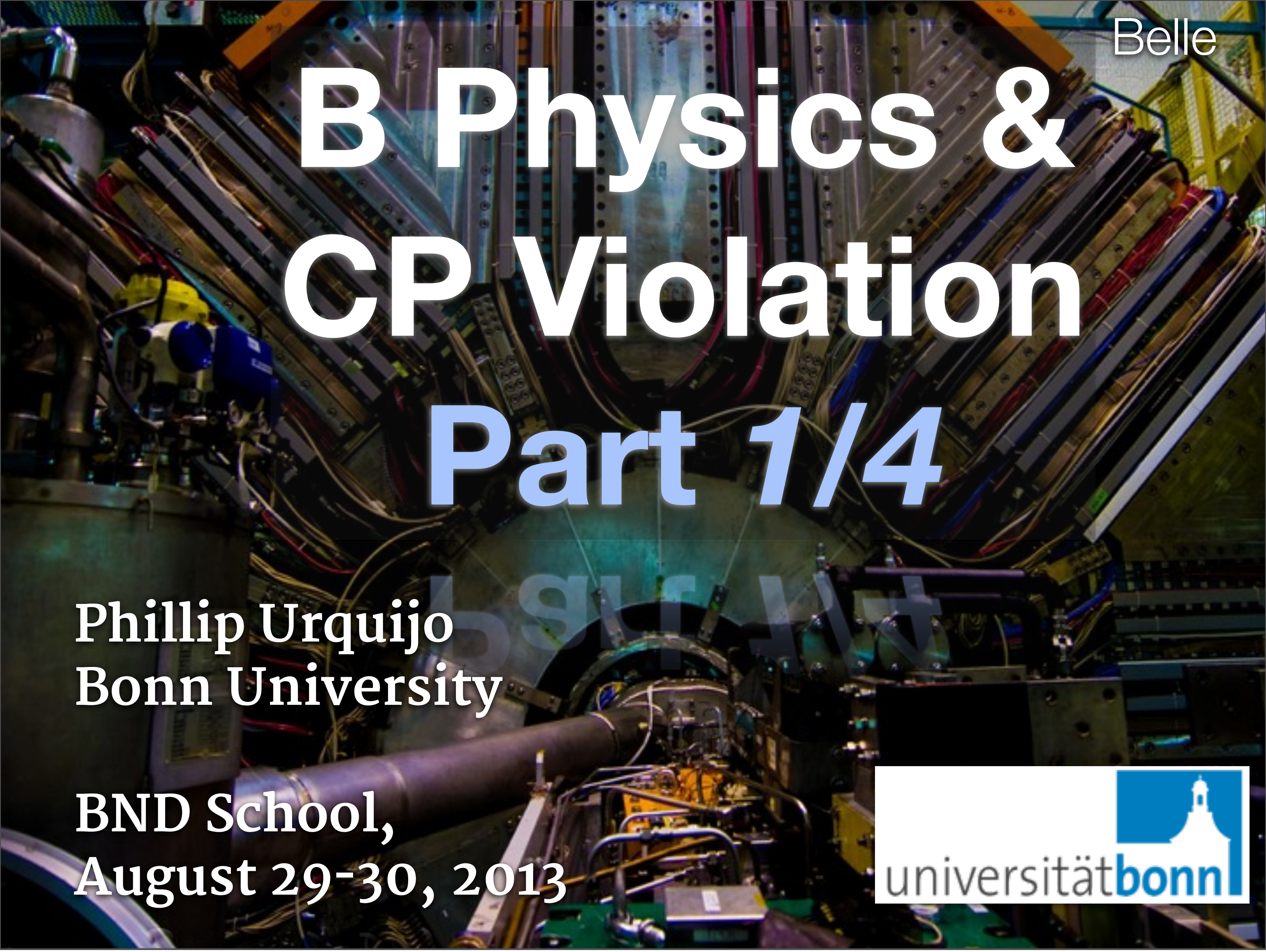


B Physics & CP Violation

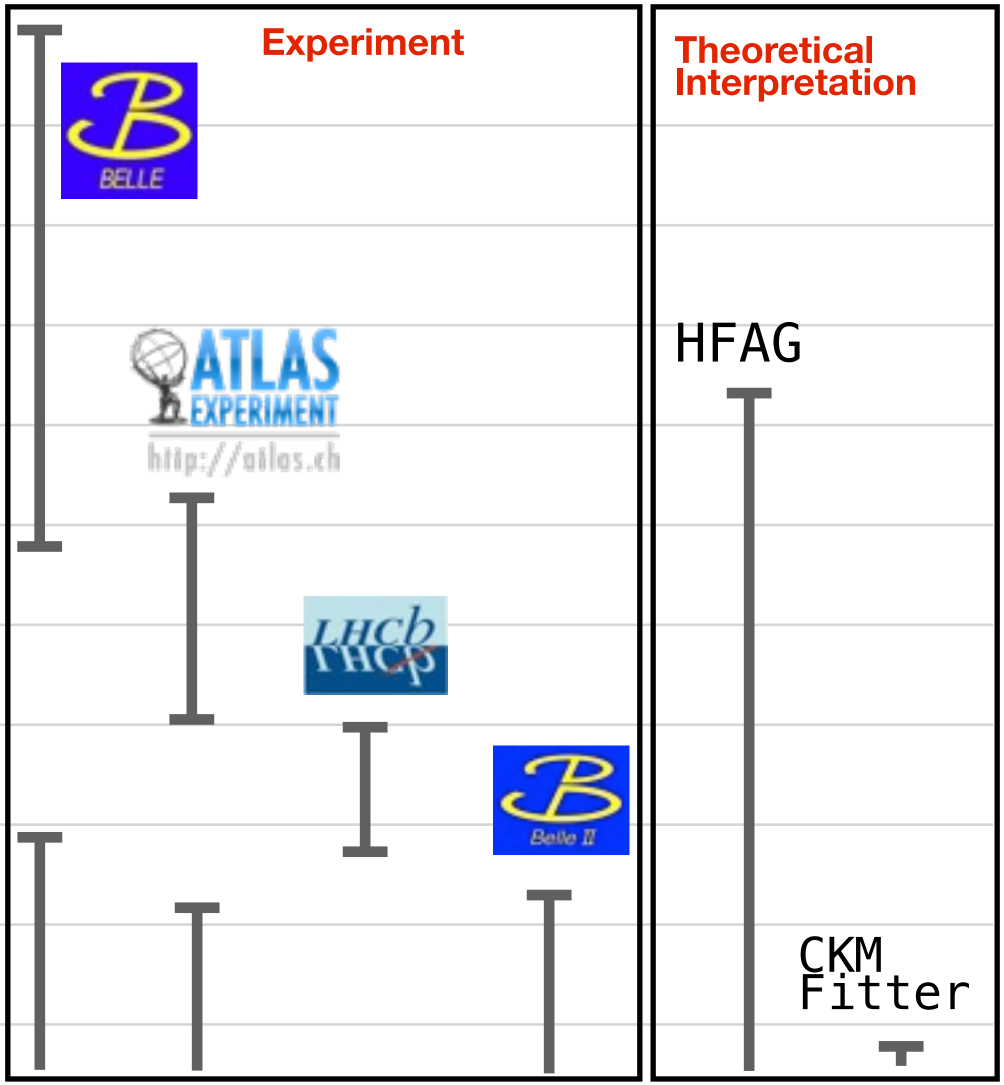
Part 1/4

Phillip Urquijo
Bonn University

BND School,
August 29-30, 2013

Who am I?

2003	**BSc (Honours)**	U. Melbourne
2004		
2005	**PhD**	U. Melbourne
2006		
2007		
2008	**Maitre-Assistant**	U. Geneva
2009		
2010	**Research Assoc.**	U. Syracuse
2011	**Junior Professor**	U. Bonn
2012	*Belle II Physics Coordinator,*	
2013	*Belle CKM Convenor*	



Outline

Part 1: Introduction to Flavour Physics

- Flavour problems in the SM
- Brief history of discovery in flavour physics
- CKM mechanism and Unitarity Triangle (UT)
- B-physics Experiments

Part 2: CP violation & CKM measurements (Triumphs of the SM)

- Meson-antimeson oscillations
- Introduction to CP violation
- Measurement of UT angles
- Measurement of UT sides

Part 3: Searches for New Physics

- Radiative Decays
- Tauonic Decays
- Purely Leptonic Decays

Part 4: The future

- Future B experiments

Simplified Standard Model

	leptons	quarks
1st generation	e^-	u
	ν_e	d
2nd generation	μ^-	c
	ν_μ	s
3rd generation	τ^-	t
	ν_τ	b

strong	E&M	weak
g	γ	$W^\pm$
		Z^0

It turns out there are two "extra" copies of particles

- Why 3 sets (= generations) of particles?
  - How do they differ?
  - How do they interact with each other?
  - Are there only 3?

Simplified Standard Model

	leptons	quarks
1st generation	e^-	u
	ν_e	d
2nd ge		
3rd ge		

strong	E&M	weak
g	γ	$W^\pm$
		Z^0

"The term flavor was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks."

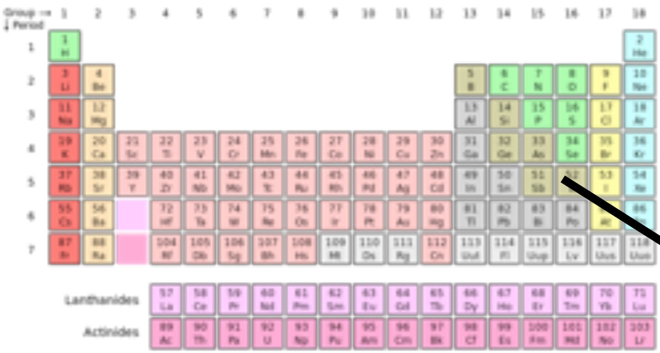
RMP 81 (2009) 1887

- Why 3 sets (= generations) of particles?
  - How do they differ?
  - How do they interact with each other?
  - Are there only 3?

The Generation Problem

Periodic Table:

End of 19th century



Explained by atomic structure (nucleus +electrons, QM and electromagnetic forces)

Hadron Table:

Mid 20th century

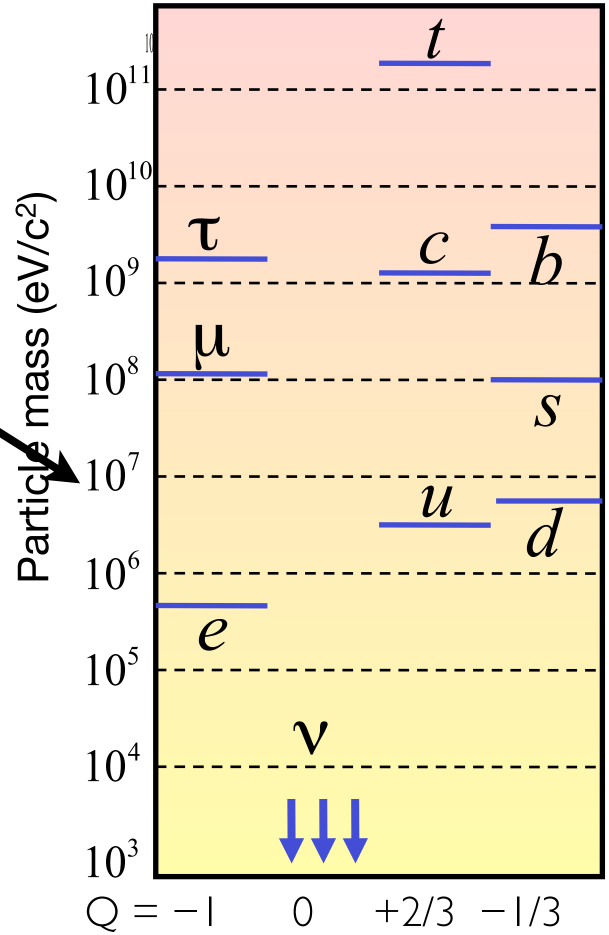
	$Q=-1$	$Q=0$	$Q=+1$
$S=0$		n	p
$S=-1$	Σ^-	Σ^0,Λ	Σ^+
$S=-2$	Ξ^+	Ξ^0	

	$Q=-1$	$Q=0$	$Q=+1$	$Q=+2$
$S=0$	Δ^-	Δ^0	Δ^+	Δ^{++}
$S=-1$	Σ^{*-}	Σ^{*0}	Σ^{*+}	
$S=-2$	Ξ^{*-}	Ξ^{*0}		
$S=-3$	Ω^-			

	$Q=-1$	$Q=0$	$Q=+1$
$S=+1$		K^0	K^+
$S=0$	π^+	π^0,η	π^+
$S=-1$	K^+	K^0	

Explained by existence of quarks and nature of strong interactions

The SM of Particle Physics

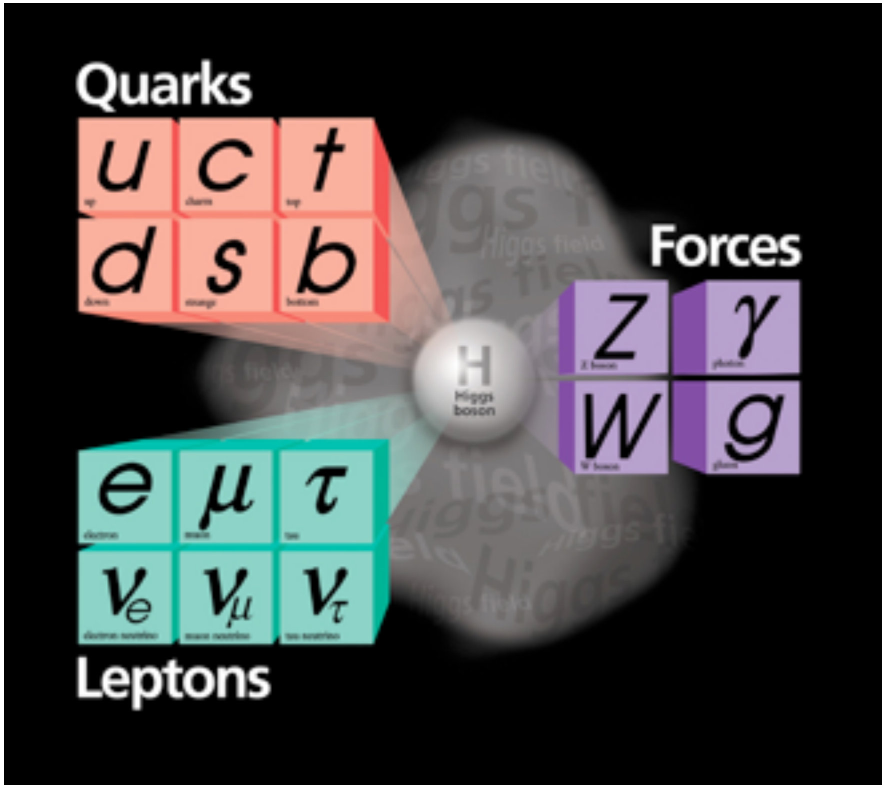


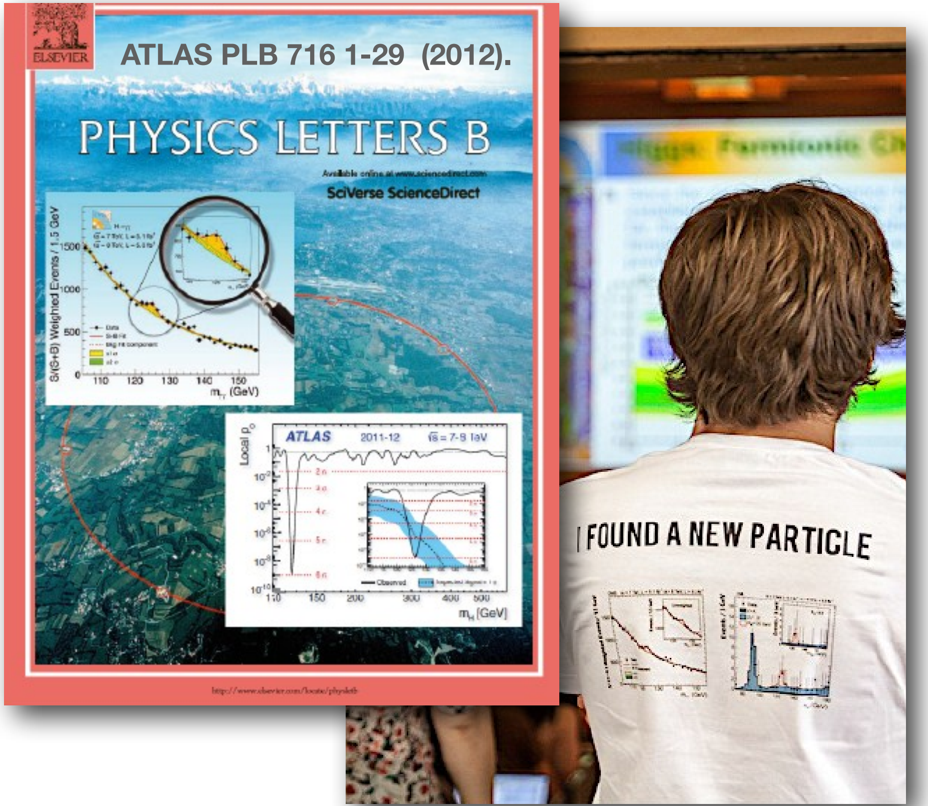
- The SM account of the 3 generations is merely a Periodic Table.

Higgs discovery

Fermion masses arise from the *Yukawa* couplings of quarks and charged leptons to the Higgs field.

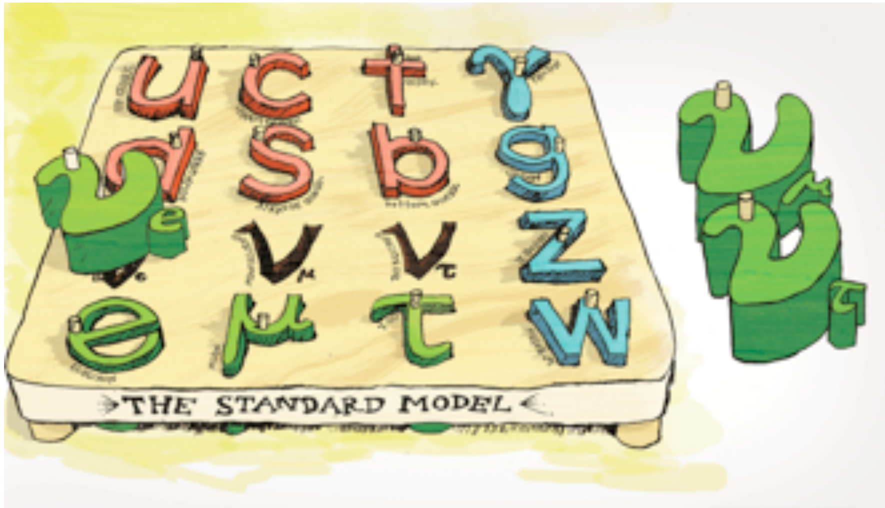
2012: LHC found ***a*** Higgs, key to explain mass, but a complete theory of mass must also explain flavour.

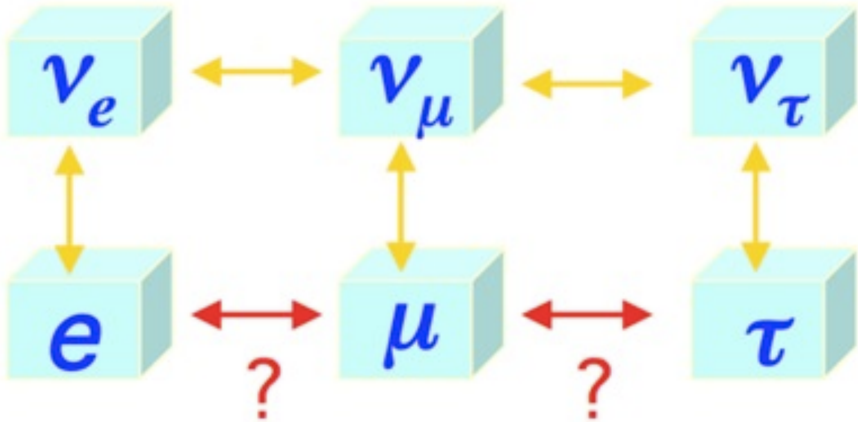


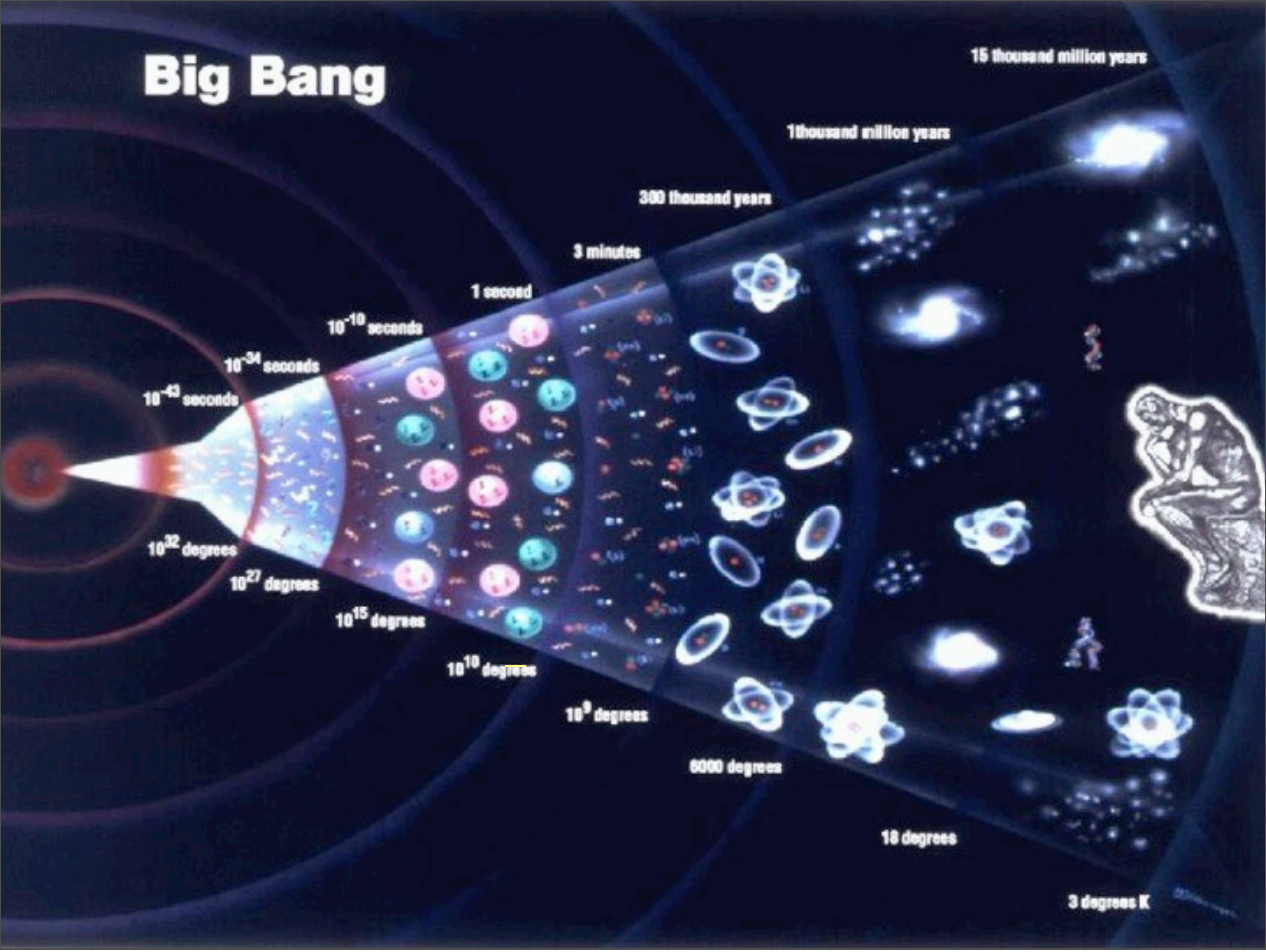


Beyond SM in the Lepton Sector

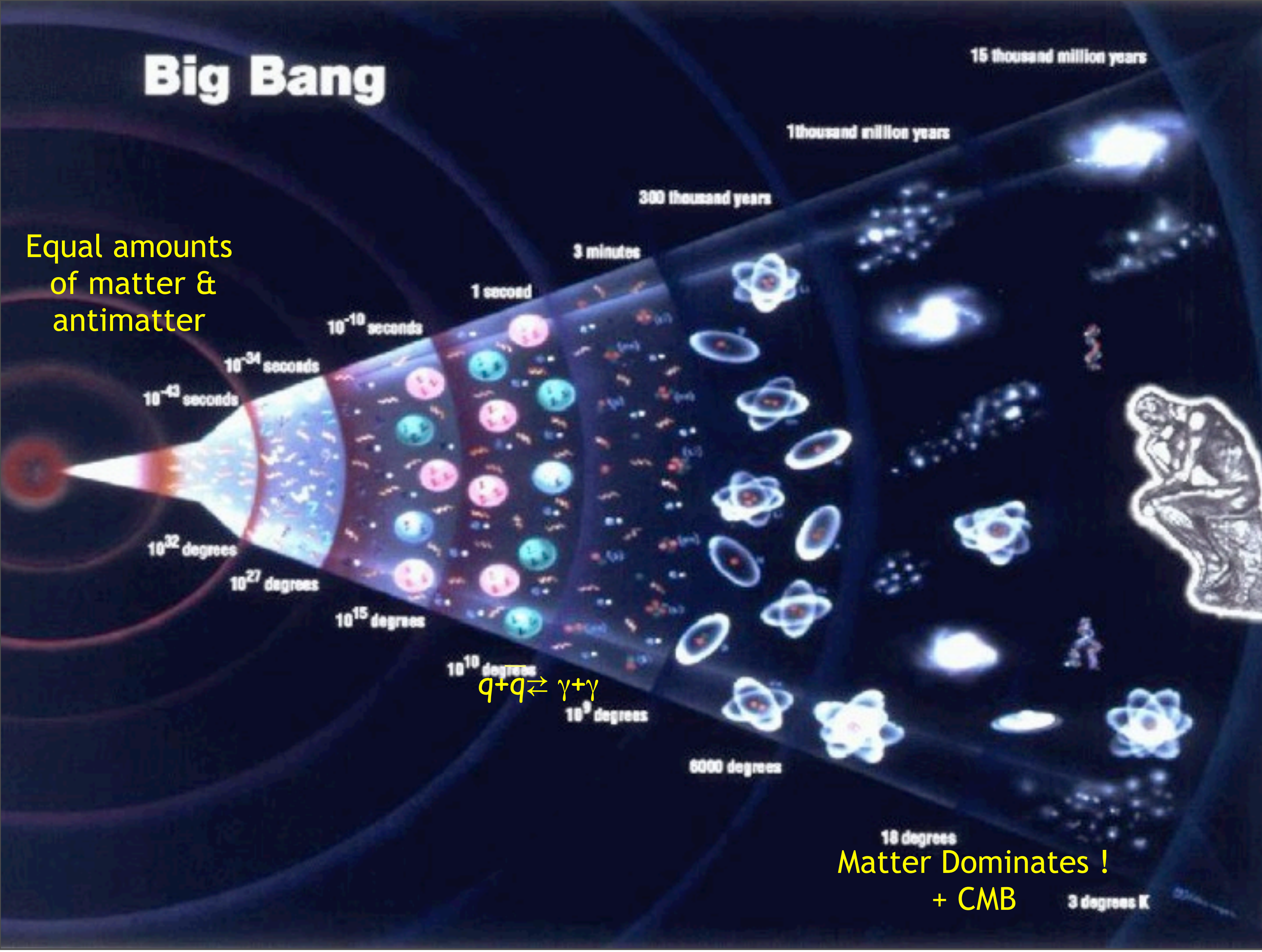
- No right-handed neutrinos in the SM, implies they are massless.
- Neutrino oscillations show they have small but finite masses.
  - Where are the R-handed Neutrinos?
- A mechanism beyond the SM is needed.







Big Bang
15 thousand million years
1thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K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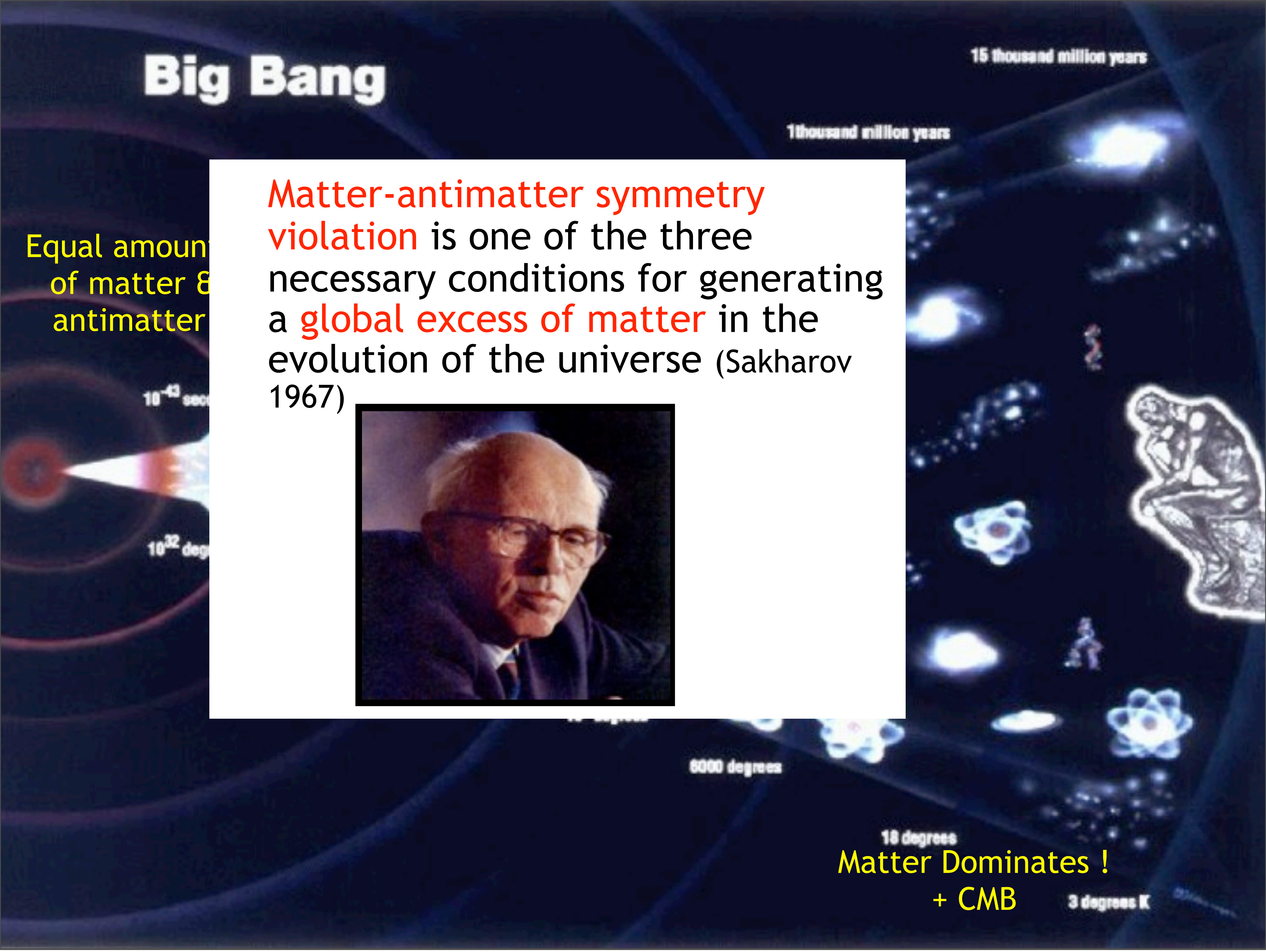
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
Equal amounts of matter & antimatter
$q+\bar{q} \rightleftarrows \gamma+\gamma$
Matter Dominates !
+ CMB



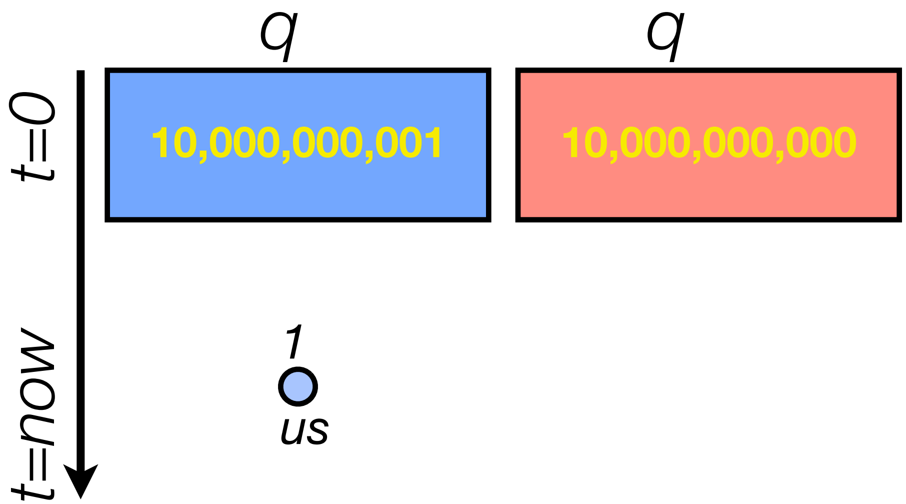
Equal amoun
of matter &
antimatter

Matter-antimatter symmetry violation is one of the three necessary conditions for generating a global excess of matter in the evolution of the universe (Sakharov 1967)

Matter Dominates !
+ CMB

Matter-AntiMatter Asymmetry

- Abundance of matter over antimatter, Why?
  $(N_{baryon}-N_{antibaryon})/N_\gamma \sim 10^{-10}$



- The *Only* CP violating phase in SM leads to 10^{-17} $\Delta N_B/N_\gamma$. (*from Jarlskog invariant*)
- To create a larger asymmetry need
  - new sources of CP violation
  - that occur at high energy scales

C	Charge Conjugation	particle⇔anti-particle
P	Parity	x→-x, y→-y,z→-z
T	Time Reversal	t→-t

where do we find it?

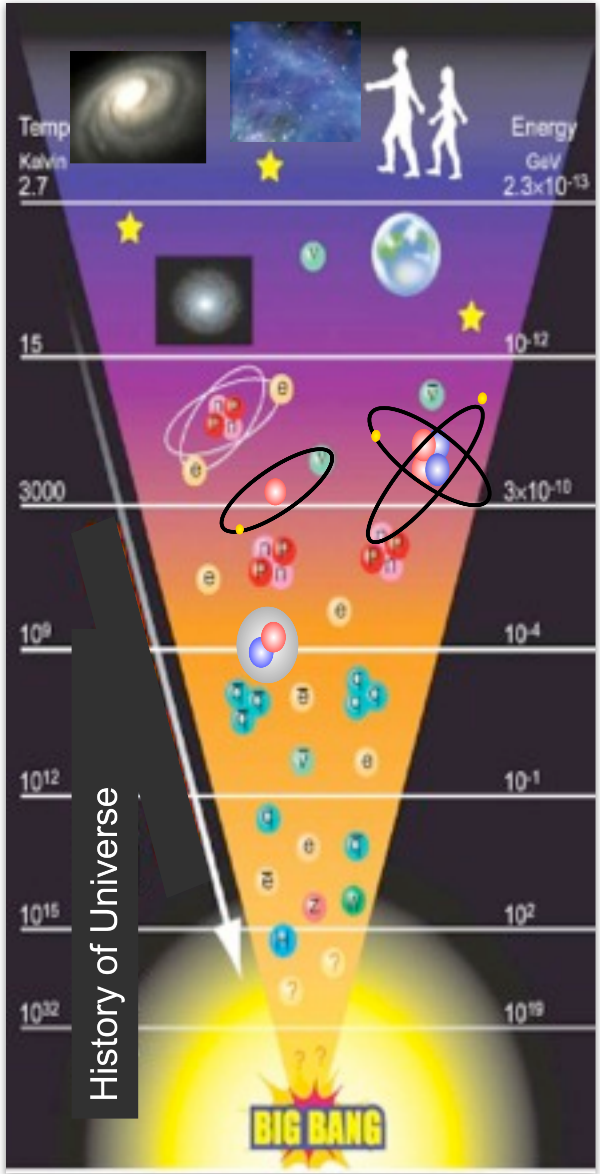
- **quark sector**: discrepancies with KM predictions
- **lepton sector**: CP violation in neutrino oscillations
- gauge sector, extra dimensions, other new physics:

Key Aims of Flavour Physics Research

1. Search for new symmetries to explain the mass **spectrum** of fundamental particles.

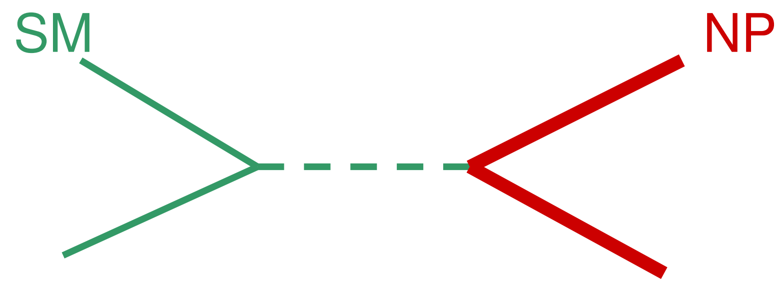
2. Search for sources of matter-antimatter (CP) asymmetry in flavour to explain cosmological observations.

3. Understand the interplay of mass and CP asymmetries in a coherent theory of flavour & mass generation.



Flavour phenomena & possible absence of new physics at LHC point to existence of new symmetries at energies beyond the LHC.

Searches for New Phenomena



- **Energy Frontier**: Production of **new particles** from *collisions* at high-***Energy*** (**LHC**)
  - *Limited by Beam Energy*

- **Flavour Frontier**: **virtual production of new particles** to probe energies beyond the energy frontier.
  - Often **first clues** about new phenomena, e.g. **weak force**, **c, b, t** quarks, Higgs boson.
  - High precision required: very tiny effects

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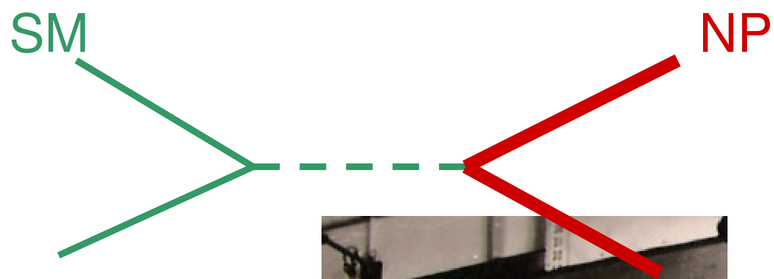

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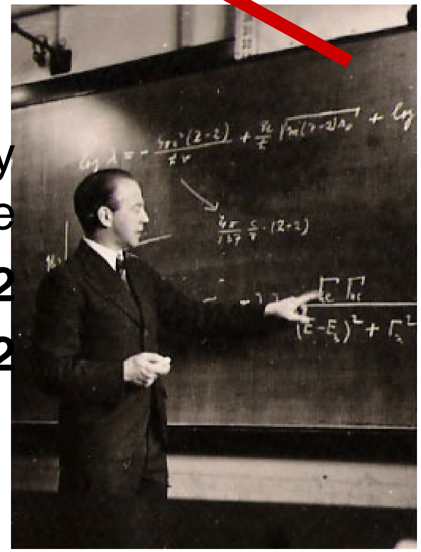
Heisenberg's Uncertainty Principle

$\Delta E \, \Delta t = \hbar/2$

i.e. **$\Delta m \, \Delta t = \hbar/2$**



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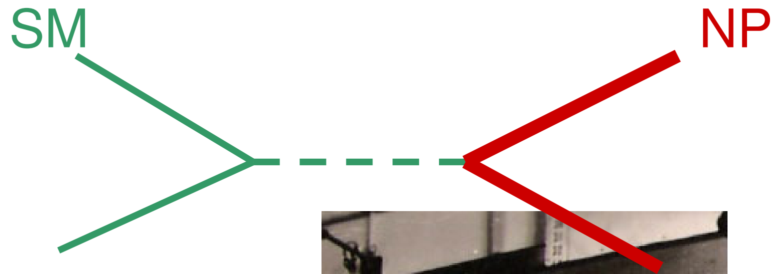

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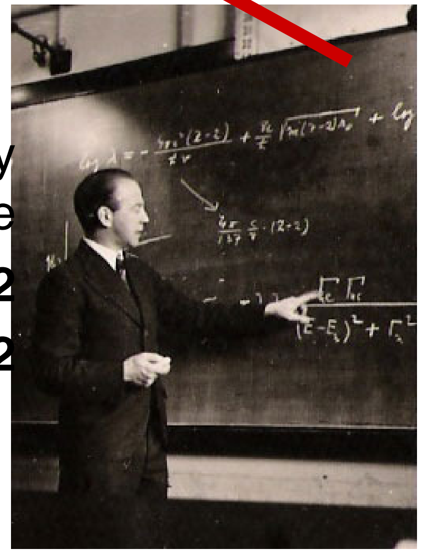

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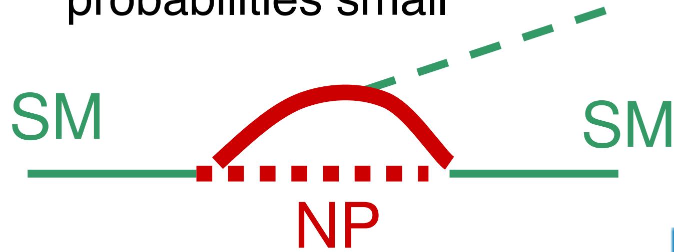
Highly virtual, thus probabilities small



Searches for New Phenomena

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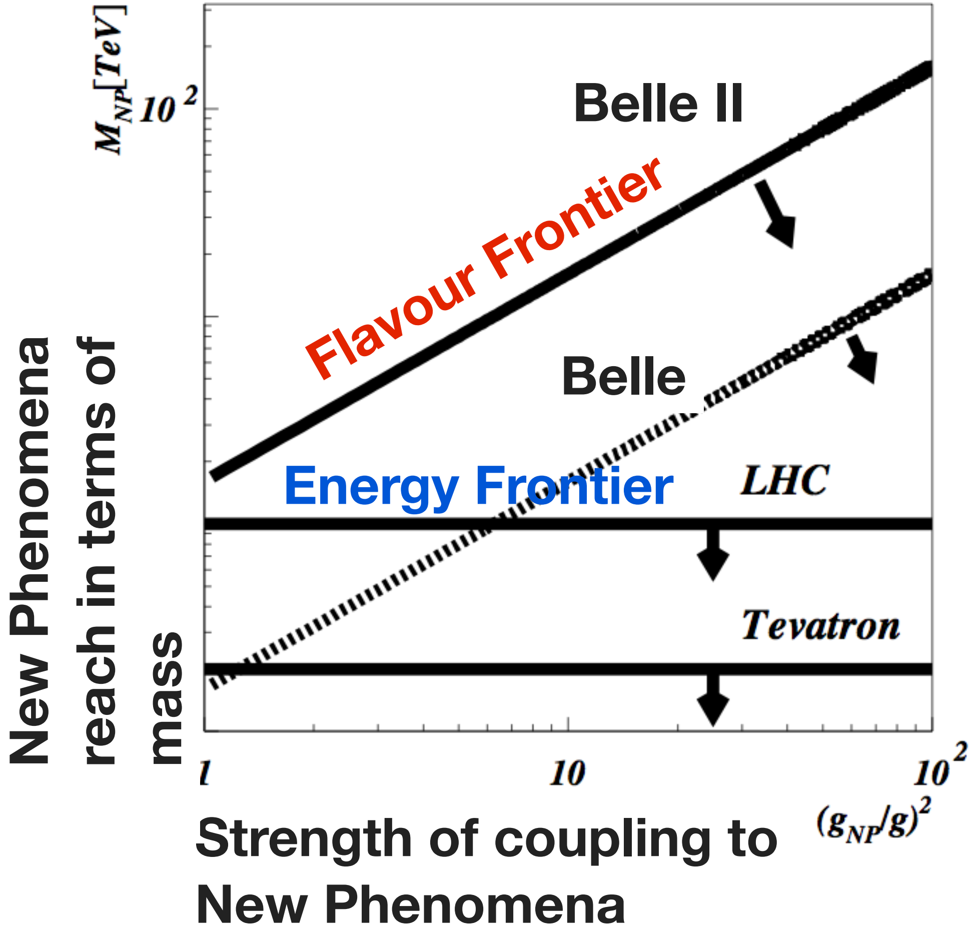
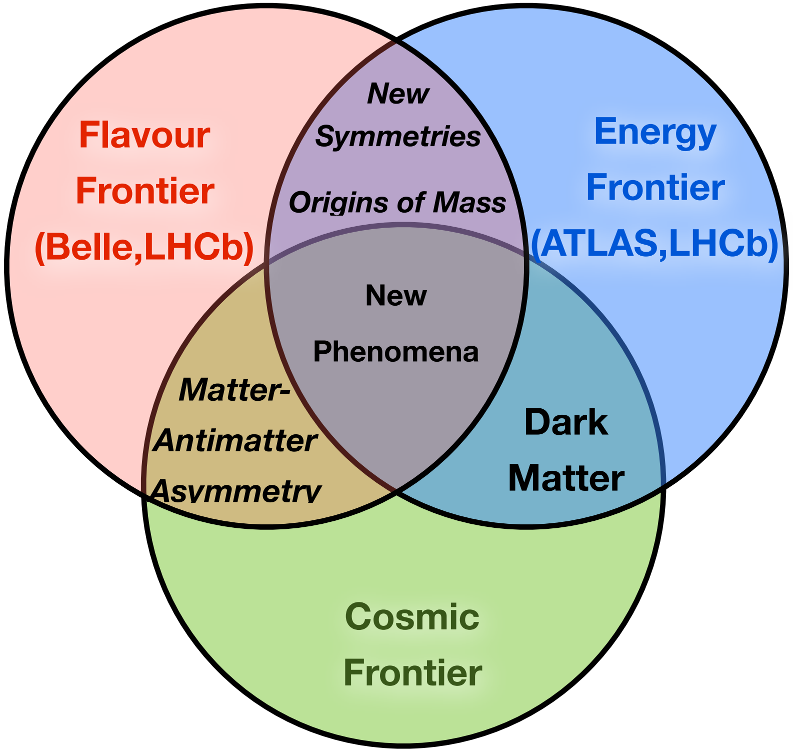
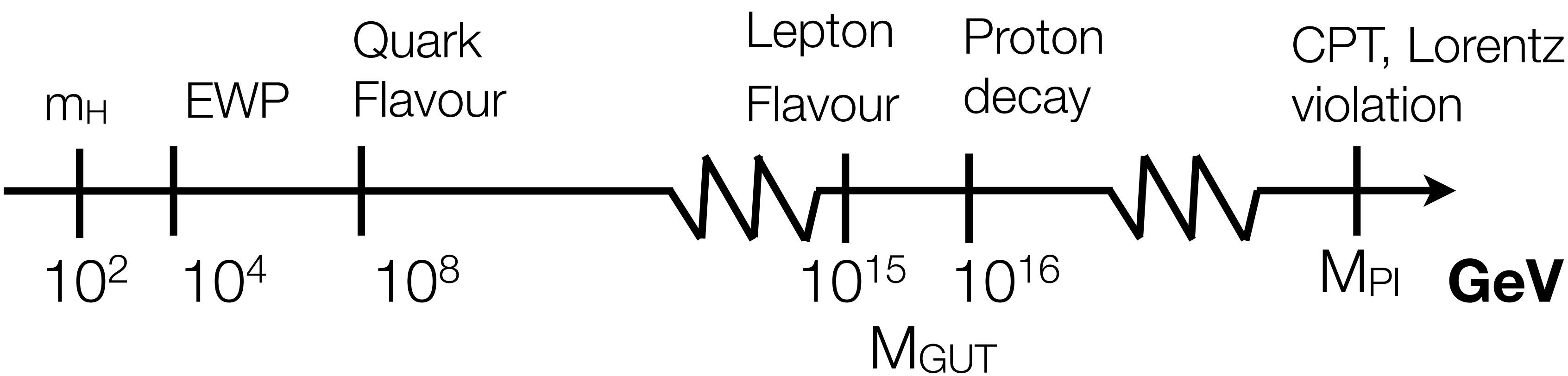


Advancing the Energy Frontier

- Need data on CP violation, Quark Flavour Transitions, Lepton Flavour Violation, proton decay...
  - Complemented by Direct searches at LHC, Studying CMB in Cosmology



- Maximum Energy/Mass Scale reach:



Flavour Physics

Brief history of discovery

Discovery of Anti-Matter (Anti-Particles)

Each particle has an anti-particle

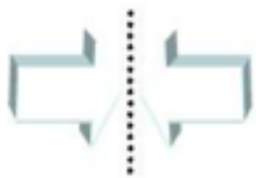
e.g. $u \leftrightarrow \bar{u}, \quad d \leftrightarrow \bar{d}, \quad e^- \leftrightarrow e^+, \quad \nu_e \leftrightarrow \bar{\nu}_e$

Anti-particle concept: P. Dirac, 1928

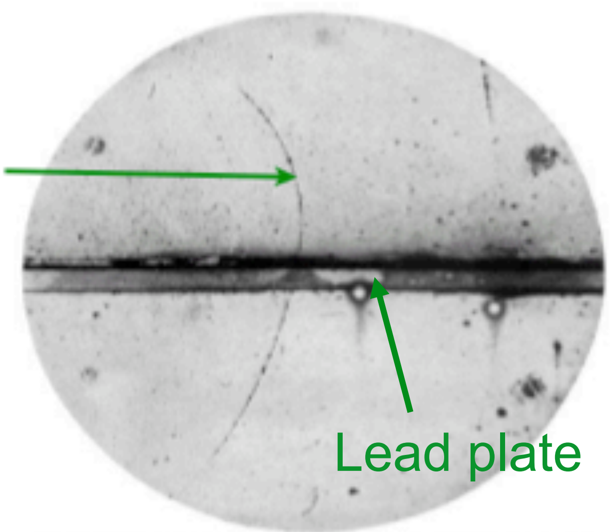
Compared to its partner, an anti-particle has

- same mass
- opposite electric charge
- opposite additive quantum numbers

C  $e^+ \to e^-$

P  $\vec{x} \to -\vec{x}$

Track left by a positron



Discovery of e^+ (positron) in cosmic rays by C. Anderson, 1933

Anti-Hydrogen = $e^+\bar{p}$ bound state discovered 1995 (CERN)

1947: Strangeness

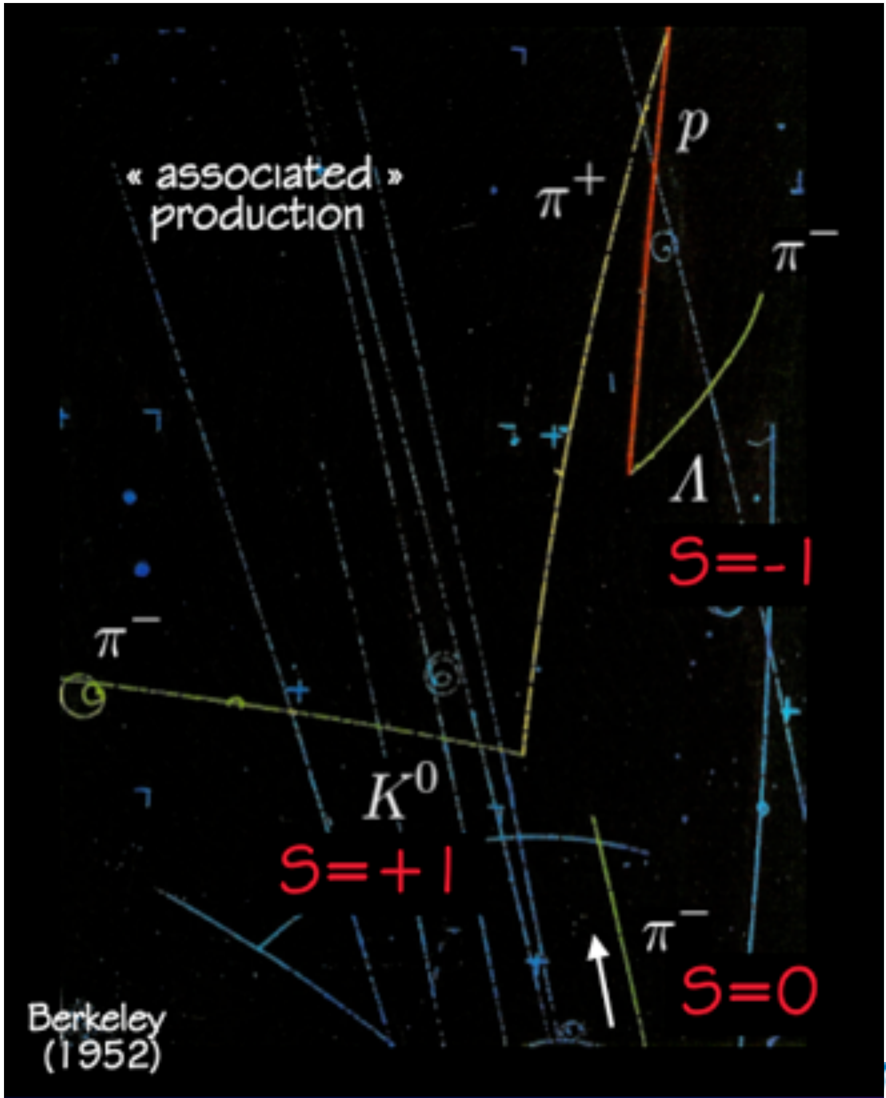
$$p + \pi^- \rightarrow \Lambda + K^0$$

New particle observed, produced in strong interaction,
with long lifetime (decays only weakly)

→Observation of the “Kaon” in 1947

→ M. Gell-Mann, K. Nishijima (1953)
Introduce new quantum number
Strangeness S

- S conserved in strong interactions
- S not conserved in weak interactions



1950-56: The “Θ - τ Puzzle”

Observation of two strange mesons with

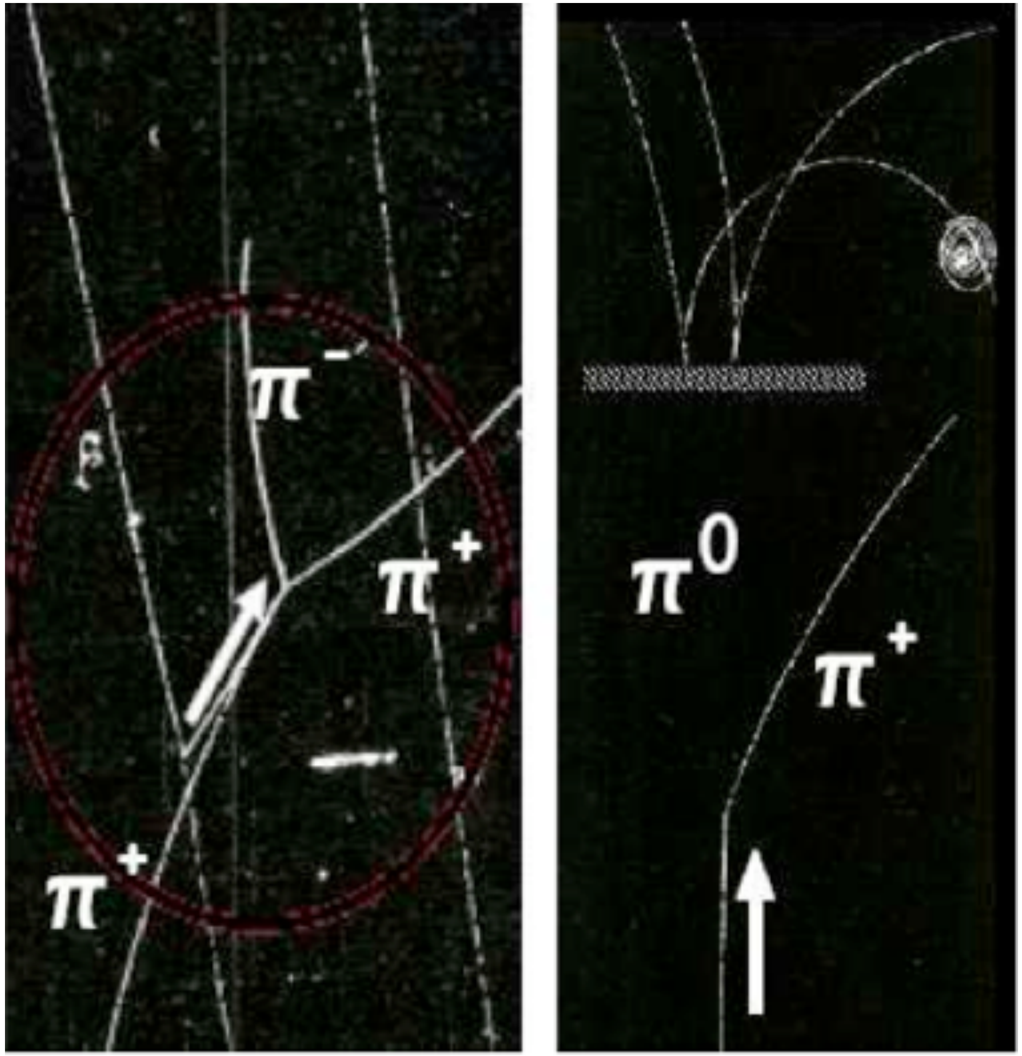
- same mass
- same production rate
- same lifetime

$$\theta \to \pi^+\pi^0; \qquad P(\pi^+\pi^0) = +1$$

$$\tau \to \pi^+\pi^+\pi^-; P(\pi^+\pi^+\pi^-) = -1$$

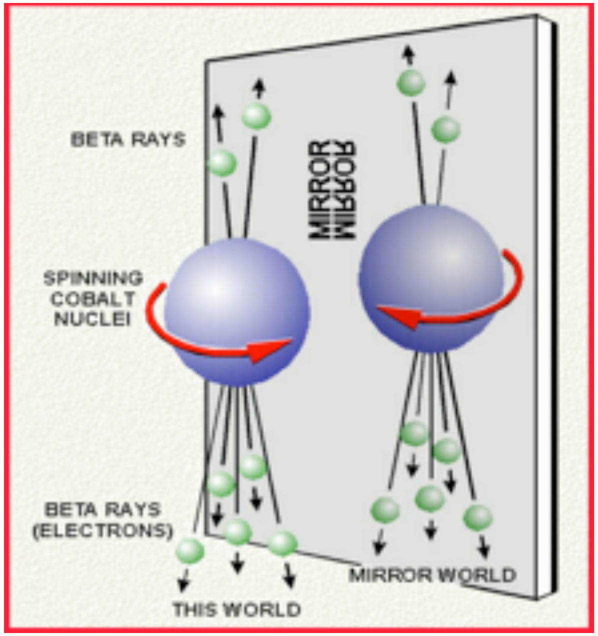
But: decay into final states with different parities

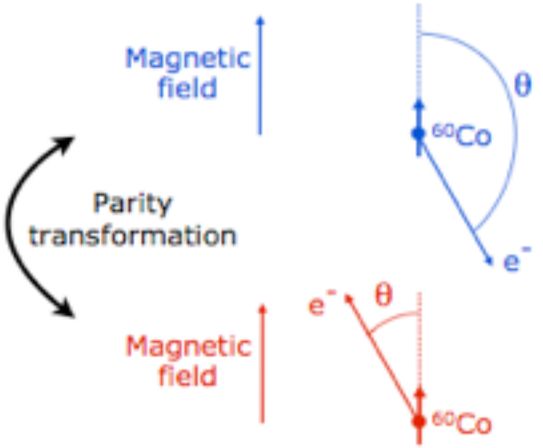
1956: Lee and Yang
“Is parity violated in the weak interaction?”

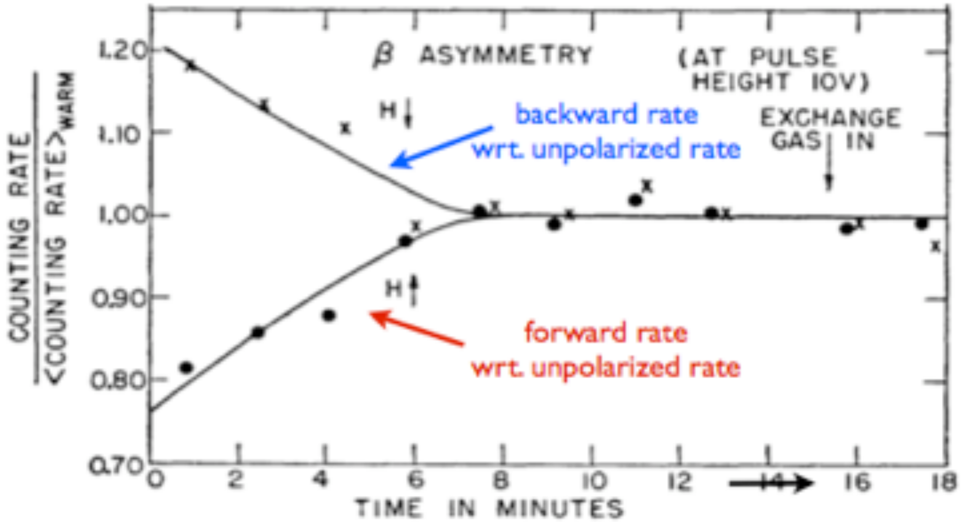


1956: Parity Violation

Beta rays(e^-) from the Co^{60} atoms emitted asymmetrically under parity inversion (by magnetic field). Co^{60} atoms had to be kept cold to avoid thermal vibrations.







^{60}Co polarization decreases as a function of time as the temperature increases

Θ - τ Puzzle: The Solution

$$\theta \to \pi^+\pi^0; \qquad P(\pi^+\pi^0) = +1$$

$$\tau \to \pi^+\pi^+\pi^-; P(\pi^+\pi^+\pi^-) = -1$$

Parity is maximally violated in weak interactions.
Its the *same* particle.

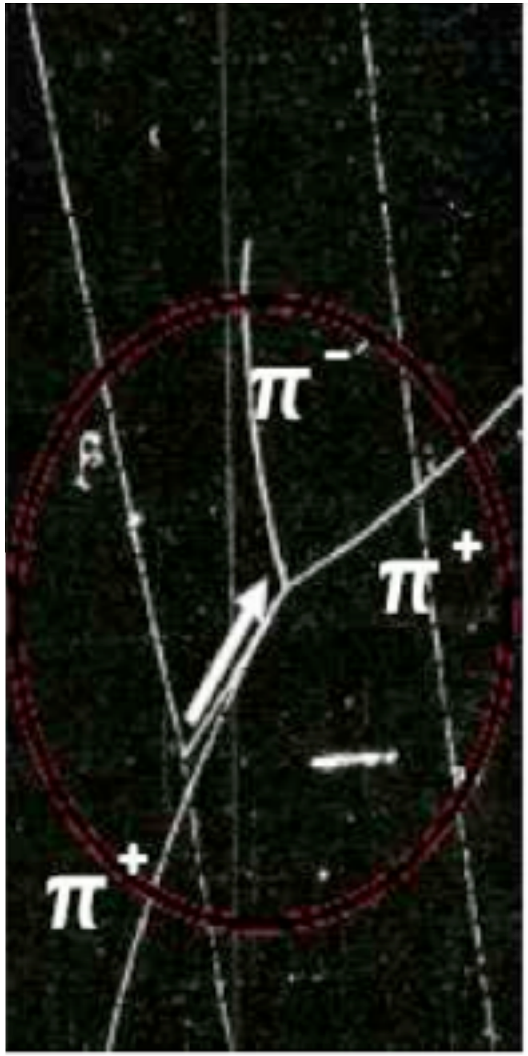
$$\theta = \tau = K^+$$

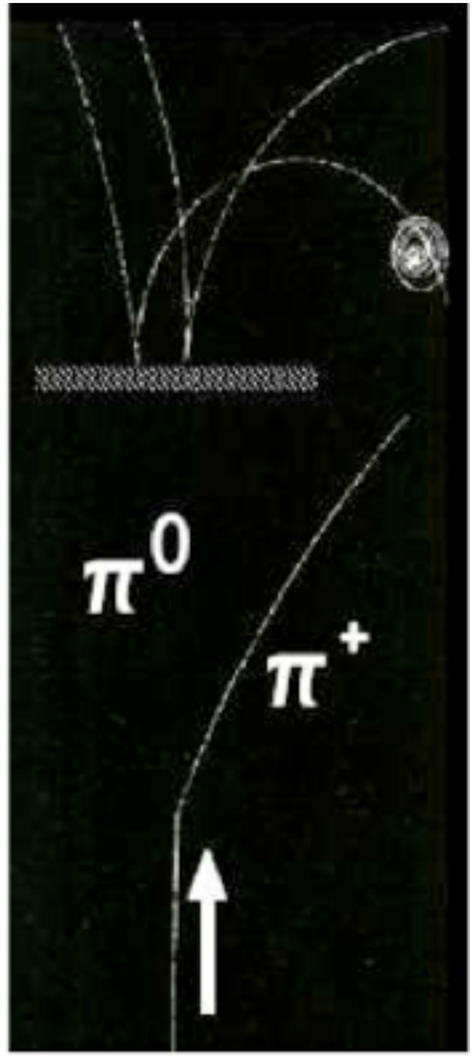
$\boxed{K^\pm}$ $\qquad I(J^P) = \frac{1}{2}(0^-)$

K^+ DECAY MODES

K^- modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Hadronic modes		
Γ_9	$\pi^+\pi^0$	(21.13 ±0.14) %	S=1.1
Γ_{10}	$\pi^+\pi^0\pi^0$	(1.73 ±0.04) %	S=1.2
Γ_{11}	$\pi^+\pi^+\pi^-$	(5.576±0.031) %	S=1.1





Citation: S. Eidelman et al. (Particle Data Group), Phys. Lett. B 592, 1 (2004) (URL: http://pdg.lbl.gov)

1964: CP Violation - Cronin-Fitch Experiment

- Both $K^0 \rightarrow \pi\pi$ and anti-$K^0 \rightarrow \pi\pi$ occur
  - K^0 may turn into its antiparticle, so are not mass eigenstates.
- The eigenstates are:

$$|K_S^0\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$$

$$|K_L^0\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$$

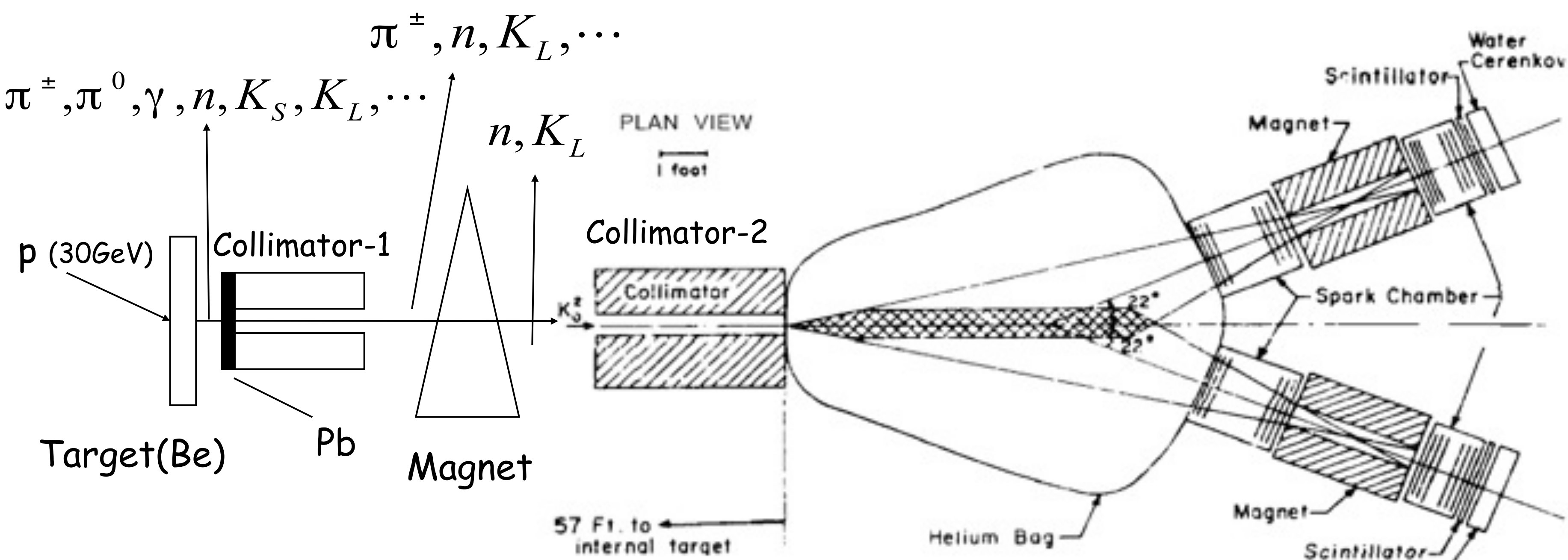
- CP operator gives:

$$\mathbf{CP}|K^0\rangle = |\bar{K}^0\rangle, \mathbf{CP}|K_S\rangle = +|\bar{K}_S\rangle, \mathbf{CP}|K_L\rangle = -|\bar{K}_L\rangle$$

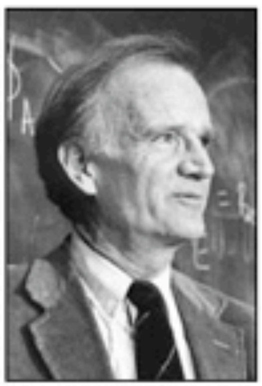
- Thus:

$$\text{only } K_S \rightarrow \pi\pi, \text{ but } K_L \rightarrow 3\pi$$

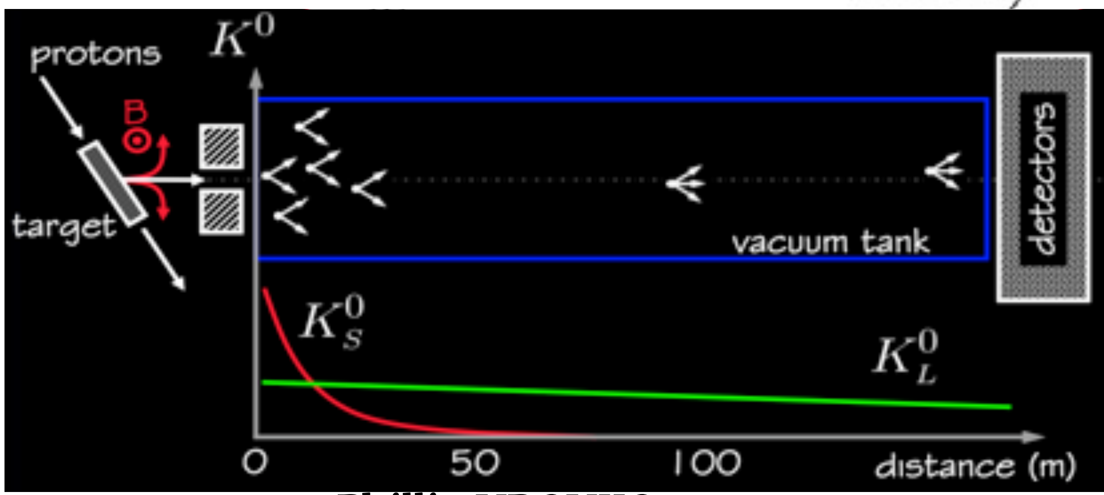
1964: CP Violation - Cronin-Fitch Experiment



James Cronin



Val Fitch



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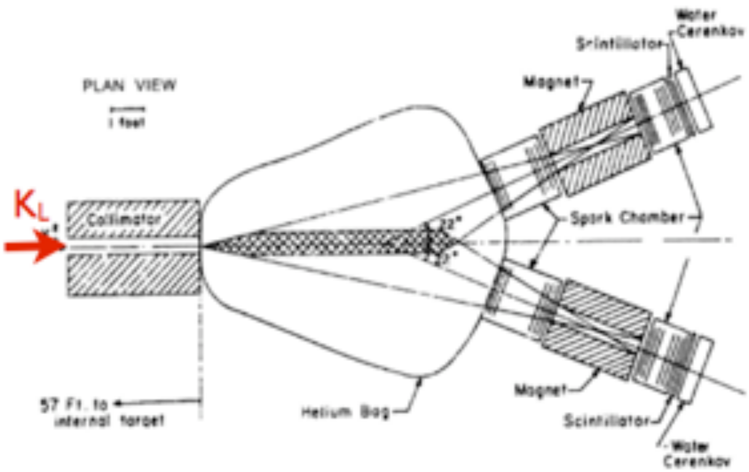
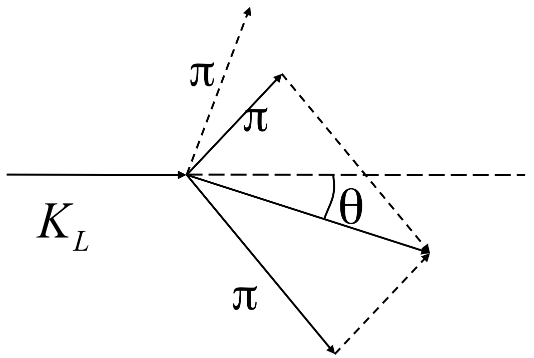
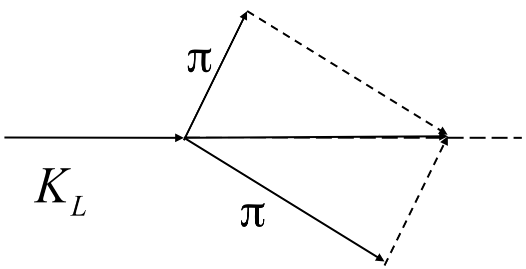
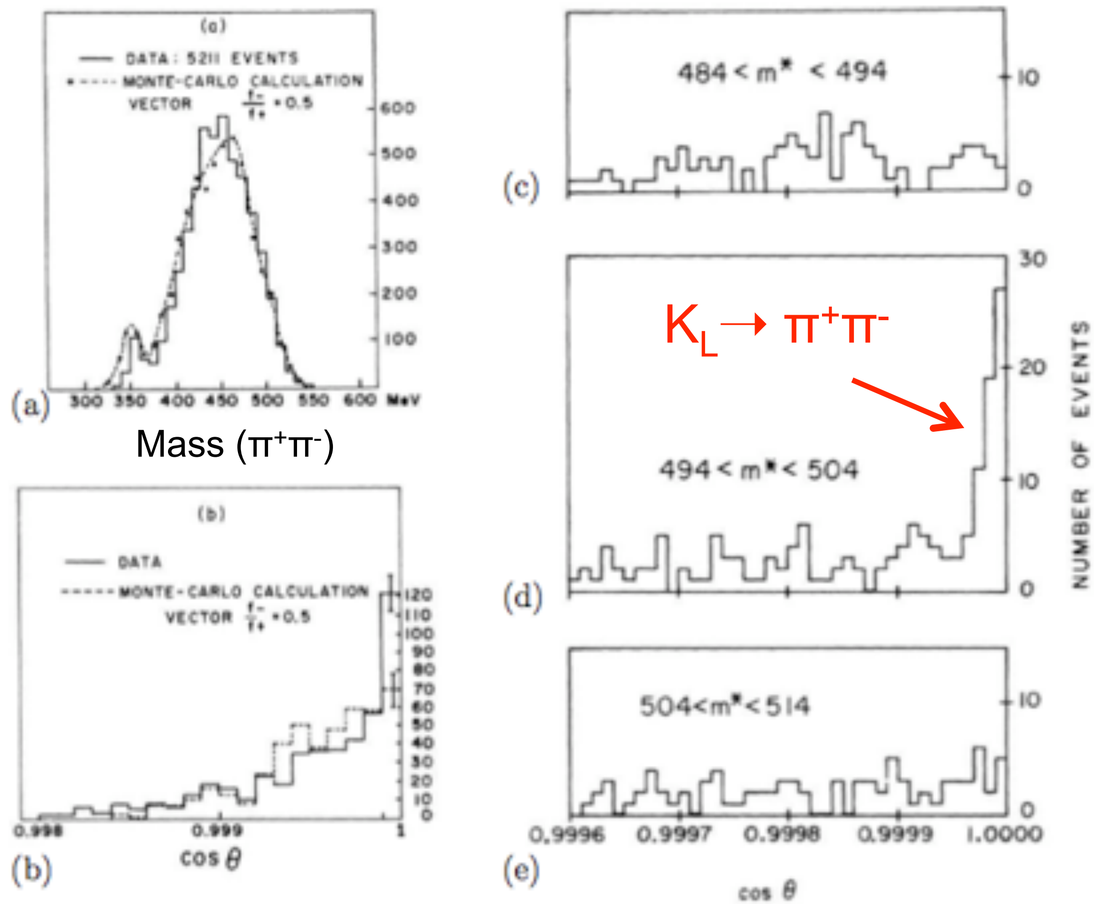


2 Variables: $\pi^+\pi^-$ inv. mass and cos(θ)







1970: The GIM Mechanism

- Observed branching ratio $K^0 \to \mu^+\mu^-$

$$\frac{\mathcal{B}K_L \to \mu^+\mu^-}{\mathcal{B}K_L \to \text{all}} = (7.2 \pm 0.5) \times 10^{-9}$$

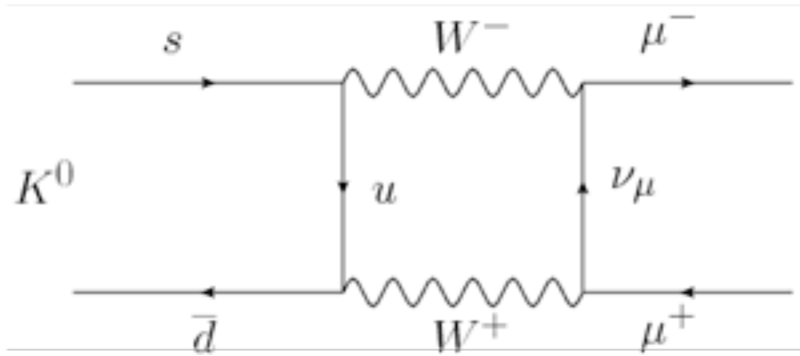
- In contradiction with theoretical expectation in the 3 quark model

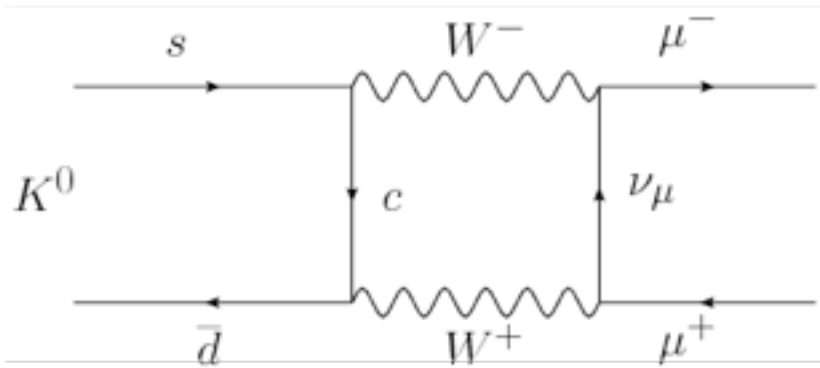
⇒**G**lashow, **I**liopoulos, **M**aiani

- Prediction of a 2nd up type quark, additional Feynman graph cancels the "*u*-box graph"

$$\Delta m_k + \mathcal{B}(K_L \to \mu^+\mu^-)$$

  – Prediction of m(c)≈1.5GeV





1973: The CKM Mechanism

Adding CPV to the picture led to the prediction of a third quark family before the charm was even discovered!

More on CKM later...

652

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

When we apply the renormalizable theory of weak interaction[1] to the hadron system, we have some limitations on the hadron model. It is well known that

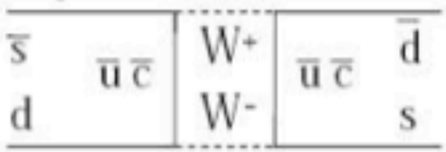
Alternatives explanations...

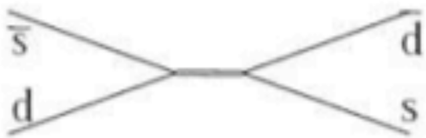
VIOLATION OF CP INVARIANCE AND THE POSSIBILITY OF VERY WEAK INTERACTIONS*

L. Wolfenstein
Carnegie Institute of Technology, Pittsburgh, Pennsylvania

(Received 31 August 1964)

"Superweak model", CPV only in $\Delta F = 2$ transitions



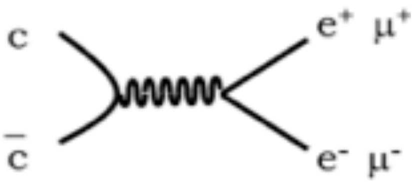


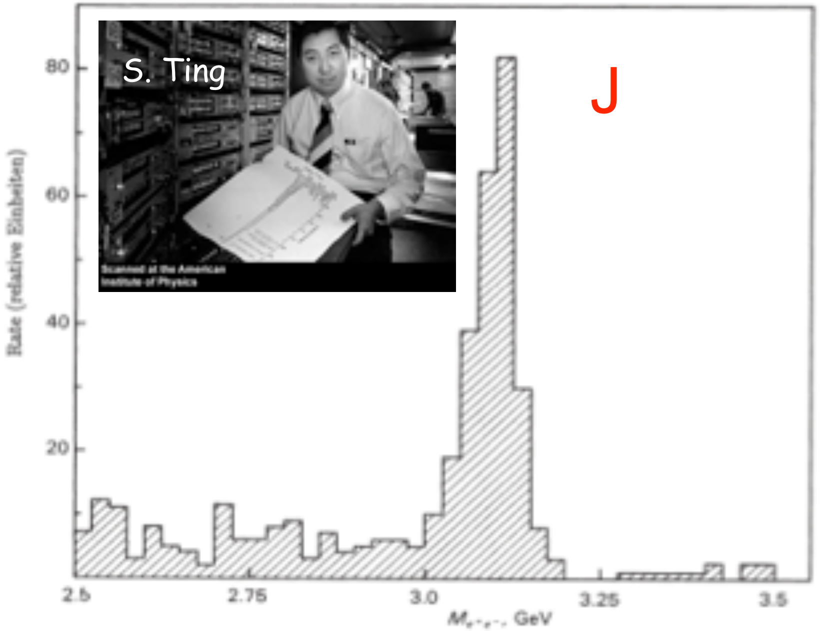
Didn't work because they didn't predict CP violation in decay amplitudes.

1974: Discovery of the Charm Quark

Brookhaven (S. Ting)

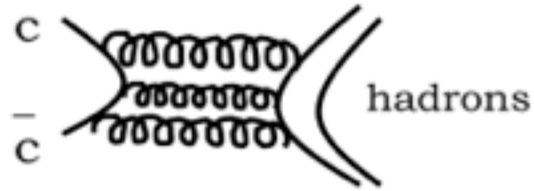
$$p + Be \rightarrow e^+e^- + X$$

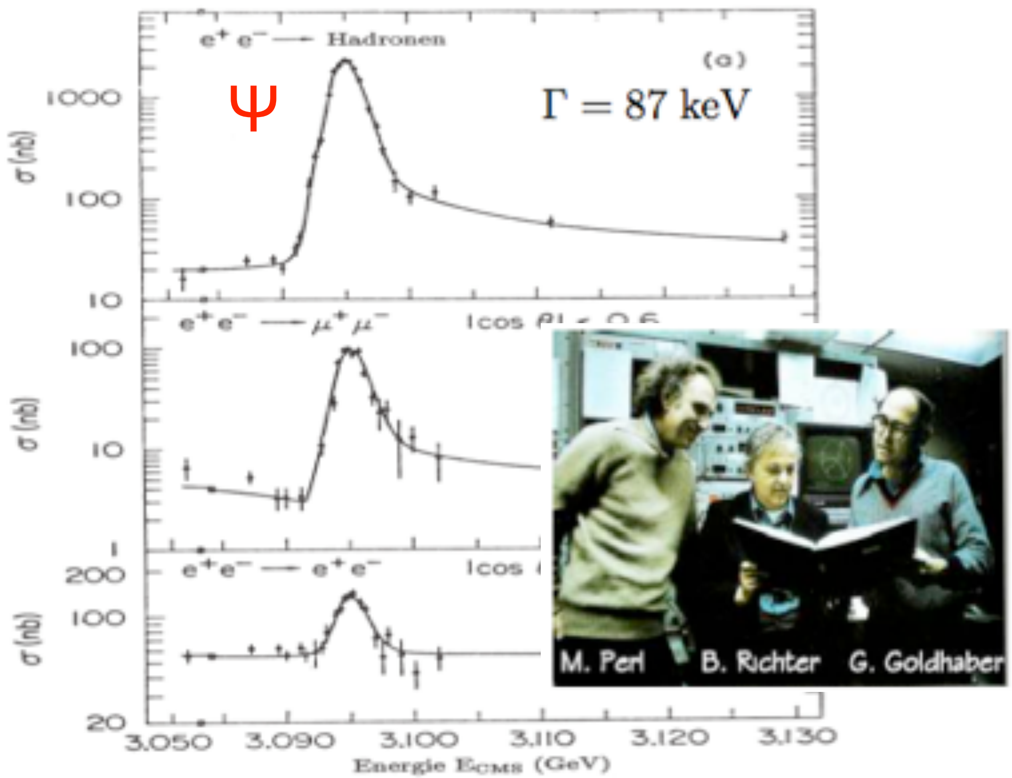




SLAC (B. Richter)

$$e^+e^- \rightarrow e^+e^-$$
$$e^+e^- \rightarrow \mu^+\mu^-$$
$$e^+e^- \rightarrow Hadronen$$





→ Discovered charmonium in 1974 : J/Ψ (Nobel Prize 1976)

→ Discovery of open charm in 1976: $D^0 \rightarrow K^+\pi^-$

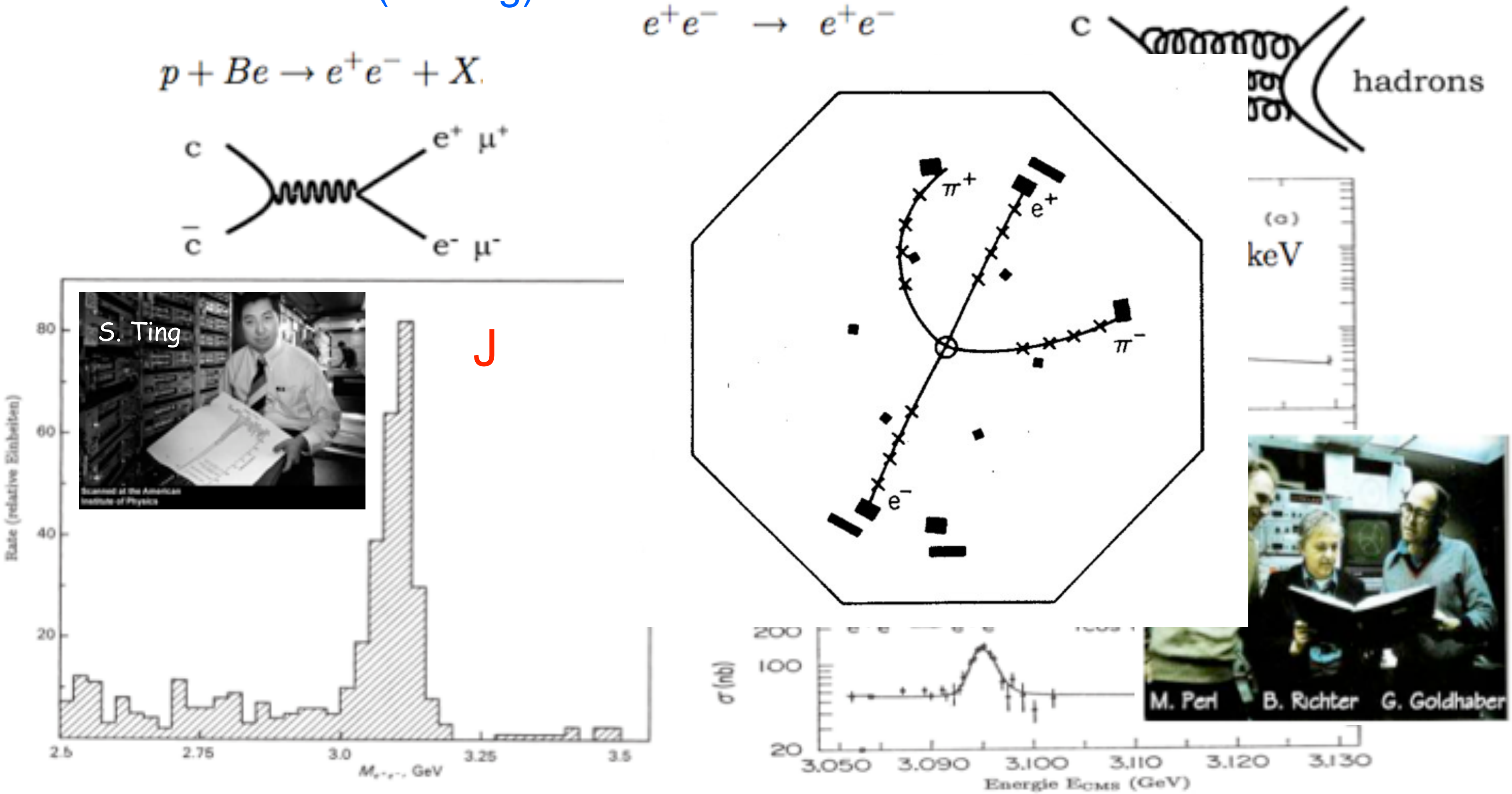
1974: Discovery of the Charm Quark

Brookhaven (S. Ting)

SLAC (B. Richter)

$p + Be \rightarrow e^+e^- + X$

$e^+e^- \rightarrow e^+e^-$



→ Discovered charmonium in 1974 : J/Ψ (Nobel Prize 1976)

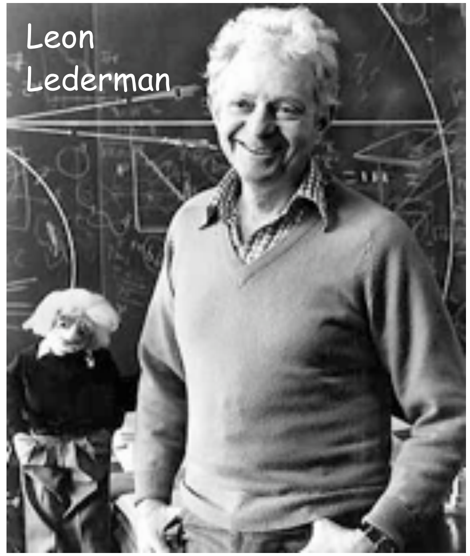
→ Discovery of open charm in 1976: $D^0 \rightarrow K^+\pi^-$

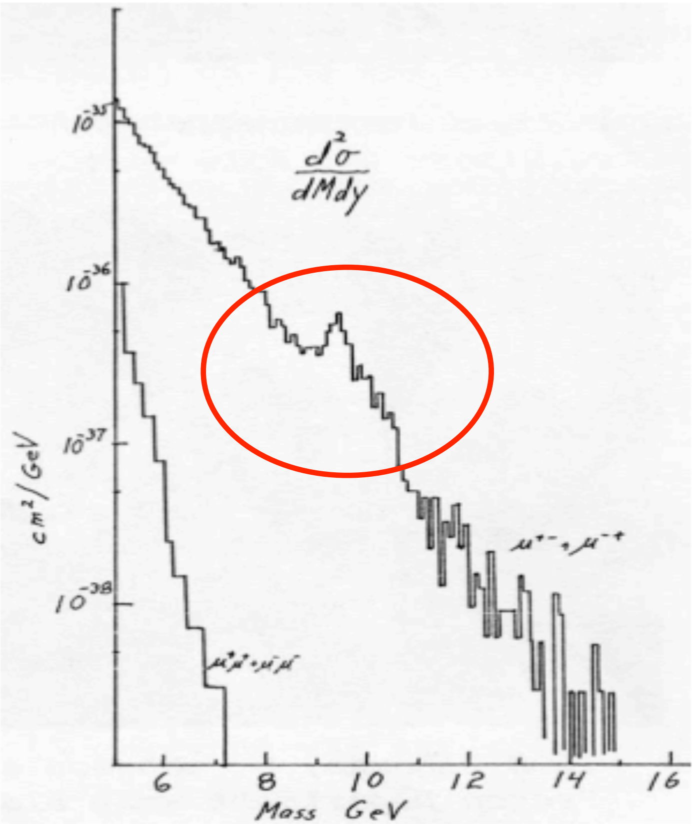
1977: Discovery of the Bottom Quark

Are there really 3 generations?

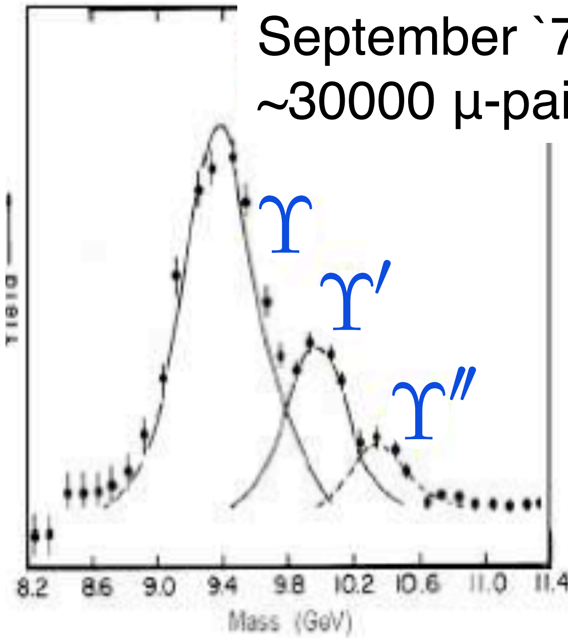
Fermilab E288 Experiment observed excess of di-muon events at a mass of around 9-10 GeV (3 resonances)

$$p + \mathrm{Cu} \rightarrow \mu^+\mu^- + X$$





September `77:
~30000 μ-pairs



Discovery of bottomonium!

The Standard Model & CP Violation

CKM mechanism

The Flavour Sector of the Standard Model

Basis of the Standard Model

$$\mathcal{L} = \boxed{-\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}\not{D}\psi} \quad \text{Gauge Sector}$$

$$\boxed{+\,\psi_i\lambda_{ij}\psi_j h + \text{h.c.}} \quad \text{Flavour Sector}$$

$$\boxed{+\,|D_\mu h|^2 - V(h)} \quad \text{Electroweak Symmetry Breaking Sector}$$

- Quark Sector contains the majority of the free parameters of the Standard Model!

  There is a lot to study!

The (Flavour) Parameters of the SM

3 Gauge couplings: α_{EM}, α_{weak}, α_{strong}

2 Electroweak symmetry breaking: v, m_H

Flavour Parameters

6 quark masses: m_u, m_d, m_s, m_c, m_b, m_t

4 quark mixing: A, λ, ρ, η (from V_{ud}, V_{us}...)

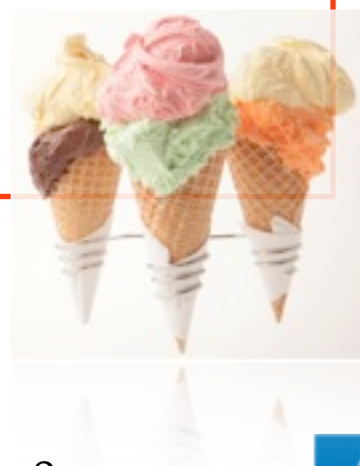
CKM matrix

3(+3 neutrino) lepton masses: m_e, m_μ,m_τ

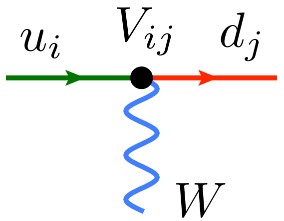
(3 lepton mixing angles + 1 phase)

PMNS matrix

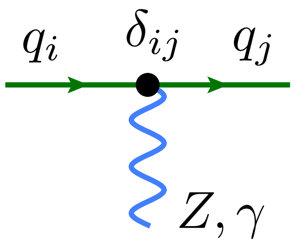
()=with neutrino masses



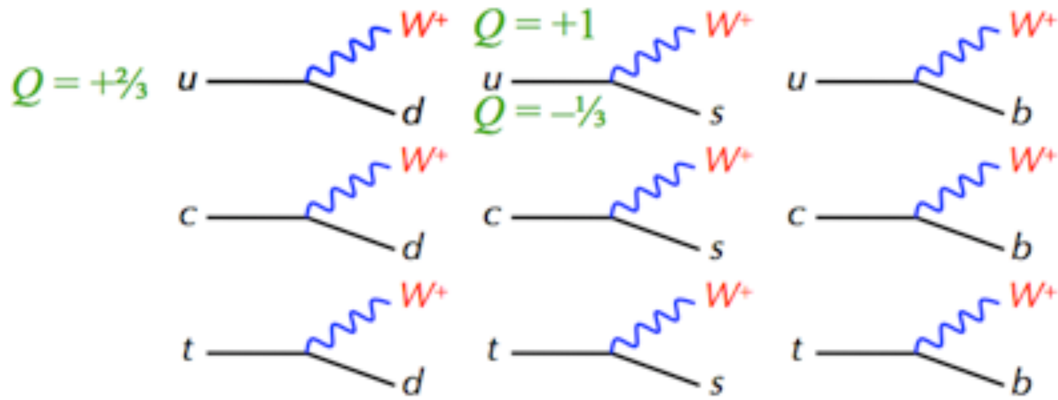
Weak Interaction



V: CKM matrix



δ: unit matrix



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Flavour eigenstates | Quark-mixing matrix | Mass eigenstate

unitary !

4 independent parameters
(3 Euler angles, 1 phase):

18 (complex 3x3 matrix) – 5 (relative quark phases) - 9 (unitarity conditions)

$$\langle q_i | V_{ij} | q_j \rangle \rightarrow \langle q_i | e^{-i\phi_i} V_{ij} e^{i\phi_j} | q_j \rangle$$

$$V_{ij} \rightarrow e^{i(\phi_j - \phi_i)} V_{ij}$$

Hierarchy of the CKM Matrix

- Wolfenstein Parametrization: Expansion in $\lambda = \sin\theta_C \approx 0.22$

(4 parameters: $\lambda \approx 0.22$, $A \approx 1$, ρ, η)

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & \lambda & 0 \\ -\lambda & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \mathcal{O}(\lambda^2)$$

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

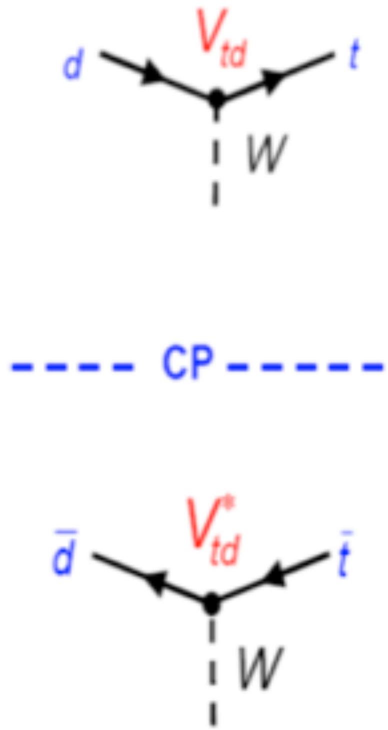
$$= \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda+(1-2(\rho+i\eta))A^2\lambda^5/2 & 1-\lambda^2/2-(1+4A^2)\lambda^4/8 & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2+(1-2(\rho-i\eta))A\lambda^4/2 & 1-A^2\lambda^4/2 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

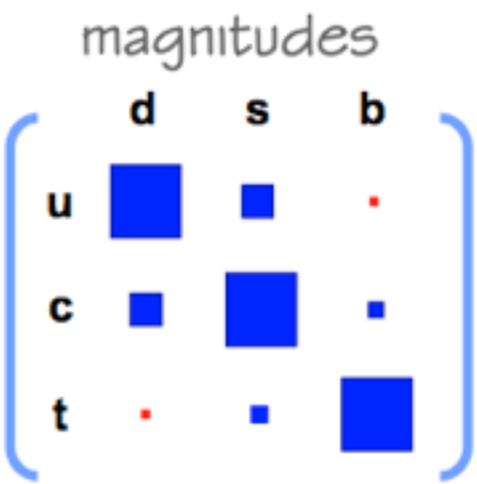
Parameterisation good to λ^3 in real part & λ^5 in imaginary part

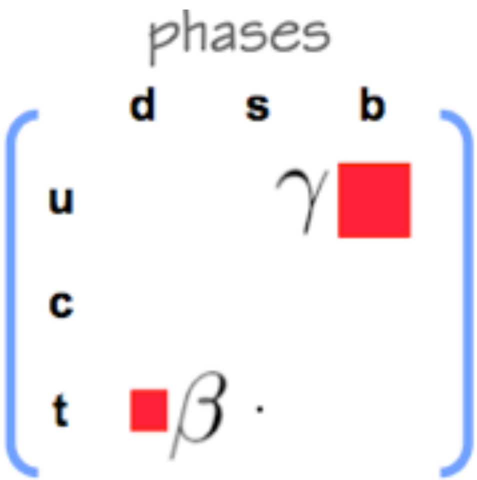
Hierarchy of the CKM Matrix

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

Complex number
Source of CP violation
in the Standard Model







CKM Matrix – Magnitude

PDG 2010

semileptonic / leptonic kaon decays
hadronic tau decays

superallowed $0^+ \to 0^+$ β decays

semileptonic / leptonic B decays

$$\begin{pmatrix} 0.97425 \pm 0.00022 & 0.2252 \pm 0.0009 & (3.89 \pm 0.44) \times 10^{-3} \\ 0.230 \pm 0.011 & 1.023 \pm 0.036 & (40.6 \pm 1.3) \times 10^{-3} \\ (8.4 \pm 0.6) \times 10^{-3} & (38.7 \pm 2.1) \times 10^{-3} & 0.88 \pm 0.07 \end{pmatrix}$$

semileptonic charm decays
charm production in neutrino beams

semileptonic B decays

semileptonic / leptonic charm decays

B_d oscillations

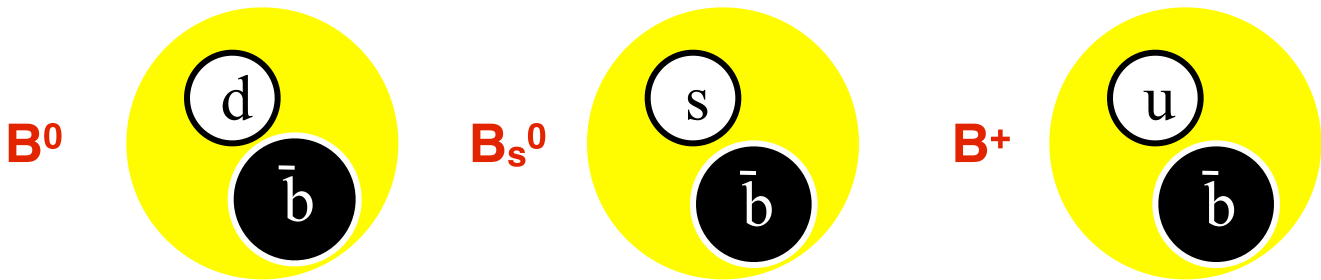
single top production

B_s oscillations

theory inputs (eg., lattice calculations) required

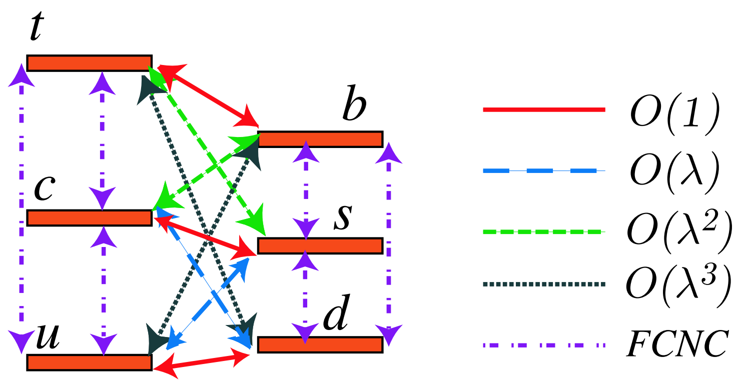
Why is b-quark physics interesting?

- Heaviest quark that forms hadronic bound states (m_b~4.7 GeV)



- Must decay to 2nd or 1st Generation
  - All decays are CKM suppressed, Long lifetime (~1.6 ps)
- High mass: **many accessible final states** (all Br's are small)

- Dominant: "**tree**" b→c
- Very suppressed "**tree**" b→u
- FCNC: "**penguin**" b→s,d
- Flavour oscillations (b→t "**box**" diagram)
- Expect large **CP asymmetries** in some B decays



Decays of the B Meson

BOTTOM MESONS
$(B = \pm 1)$

$B^+ = u\bar{b}$, $B^0 = d\bar{b}$, $\overline{B}^0 = \bar{d}\,b$, $B^- = \bar{u}\,b$, similarly for B^*'s

B^0 DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\ell^+ \nu_\ell$ anything	[nnn]	(10.33 ± 0.28) %		–
$e^+ \nu_e X_c$		(10.1 ± 0.4) %		–
$D \ell^+ \nu_\ell$ anything		(9.3 ± 0.9) %		–
$D^- \ell^+ \nu_\ell$	[nnn]	(2.17 ± 0.12) %		2309
$D^- \tau^+ \nu_\tau$		(1.1 ± 0.4) %		1909
$D^*(2010)^- \ell^+ \nu_\ell$	[nnn]	(5.01 ± 0.12) %		2257
$D^*(2010)^- \tau^+ \nu_\tau$		(1.5 ± 0.5) %	S=1.3	1837
$\overline{D}^0 \pi^- \ell^+ \nu_\ell$		$(4.3 \pm 0.6) \times 10^{-3}$		2308
$D_0^*(2400)^- \ell^+ \nu_\ell \times$ B$(D_0^{*-} \to \overline{D}^0 \pi^-)$		$(3.0 \pm 1.2) \times 10^{-3}$	S=1.8	–
$D_2^*(2460)^- \ell^+ \nu_\ell \times$ B$(D_2^{*-} \to \overline{D}^0 \pi^-)$		$(2.2 \pm 0.6) \times 10^{-3}$		2067
$\overline{D}^{(*)} n\pi \ell^+ \nu_\ell (n \geq 1)$		(2.3 ± 0.5) %		–
$D^{*0} \pi^- \ell^+ \nu_\ell$		$(4.9 \pm 0.8) \times 10^{-3}$		2256
$D_1(2420)^- \ell^+ \nu_\ell \times$ B$(D_1^- \to \overline{D}^{*0} \pi^-)$		$(2.80 \pm 0.28) \times 10^{-3}$		–
$D_1'(2430)^- \ell^+ \nu_\ell \times$ B$(D_1'^- \to \overline{D}^{*0} \pi^-)$		$(3.1 \pm 0.9) \times 10^{-3}$		–
$D_2^*(2460)^- \ell^+ \nu_\ell \times$ B$(D_2^{*-} \to \overline{D}^{*0} \pi^-)$		$(1.2 \pm 0.5) \times 10^{-3}$	S=2.7	2067
$\rho^- \ell^+ \nu_\ell$	[nnn]	$(2.47 \pm 0.33) \times 10^{-4}$		2583
$\pi^- \ell^+ \nu_\ell$	[nnn]	$(1.34 \pm 0.08) \times 10^{-4}$		2638

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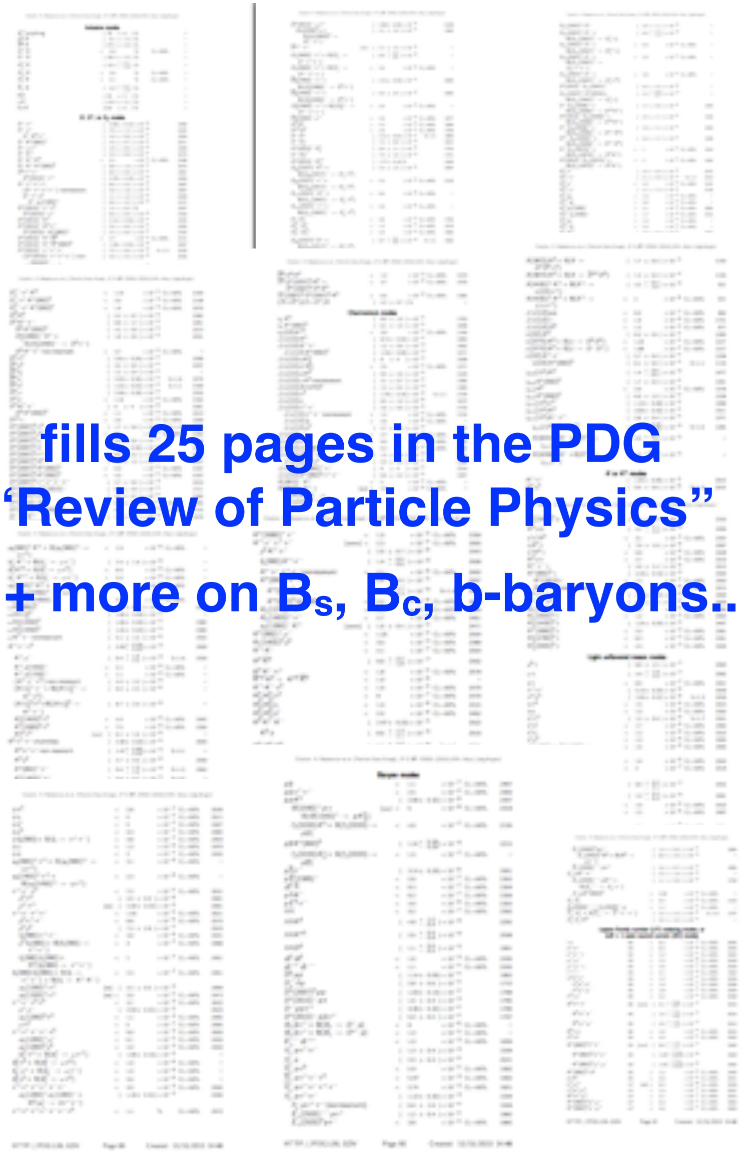


fills 25 pages in the PDG "Review of Particle Physics"

+ more on B_s, B_c, b-baryons....

The Six Unitarity Triangles

$$V^\dagger V = \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$(a)\, V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$$

$$(b)\, V_{cd}V_{ud}^* + V_{cs}V_{us}^* + V_{cb}V_{ub}^* = 0$$

$$\propto\lambda \qquad \propto\lambda \qquad \propto\lambda^5$$

$$(c)\, V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

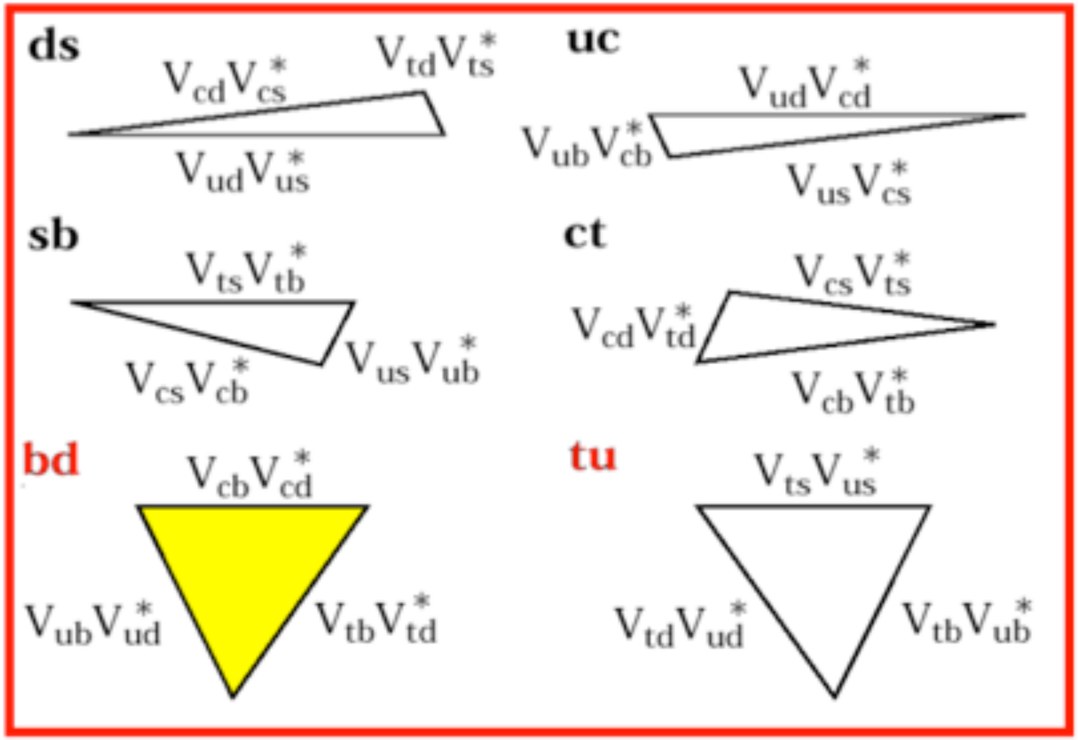
$$(d)\, V_{td}V_{cd}^* + V_{ts}V_{cs}^* + V_{tb}V_{cb}^* = 0$$

$$\propto\lambda^2 \qquad \propto\lambda^2 \qquad \propto\lambda^4$$

$$\boxed{(e)\, V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0}$$

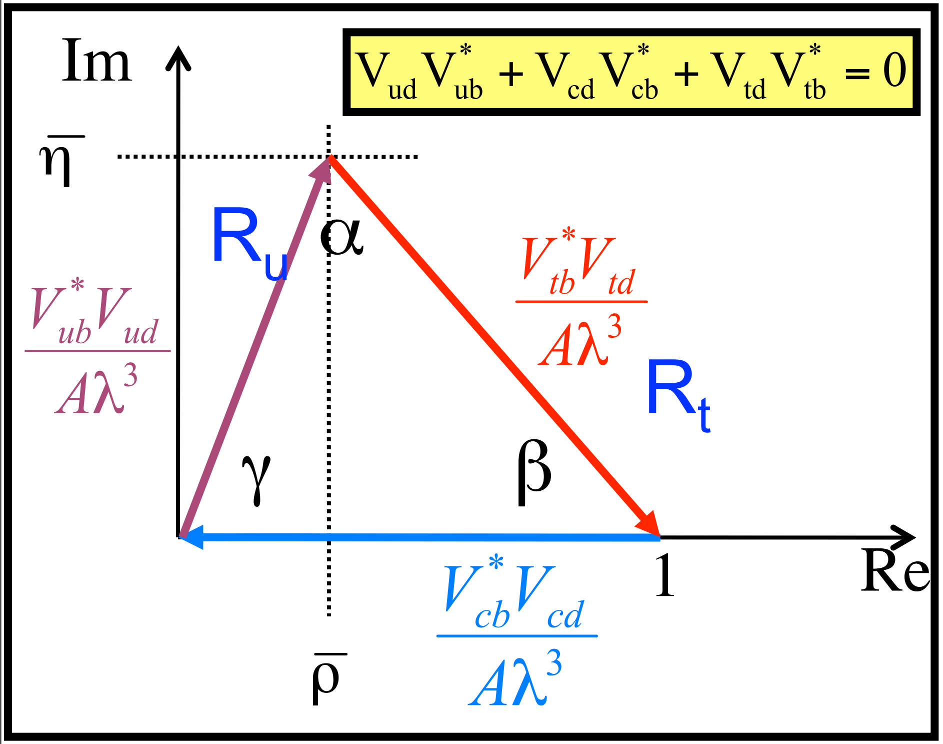
$$(f)\, V_{td}V_{ud}^* + V_{ts}V_{us}^* + V_{tb}V_{ub}^* = 0$$

$$\propto\lambda^3 \qquad \propto\lambda^3 \qquad \propto\lambda^3$$



Unitarity Triangles for B_d

The Unitarity Triangle
("B_d Triangle")



$V_{td} = |V_{td}|\, e^{-i\beta}$

$V_{ub} = |V_{ub}|\, e^{-i\gamma}$

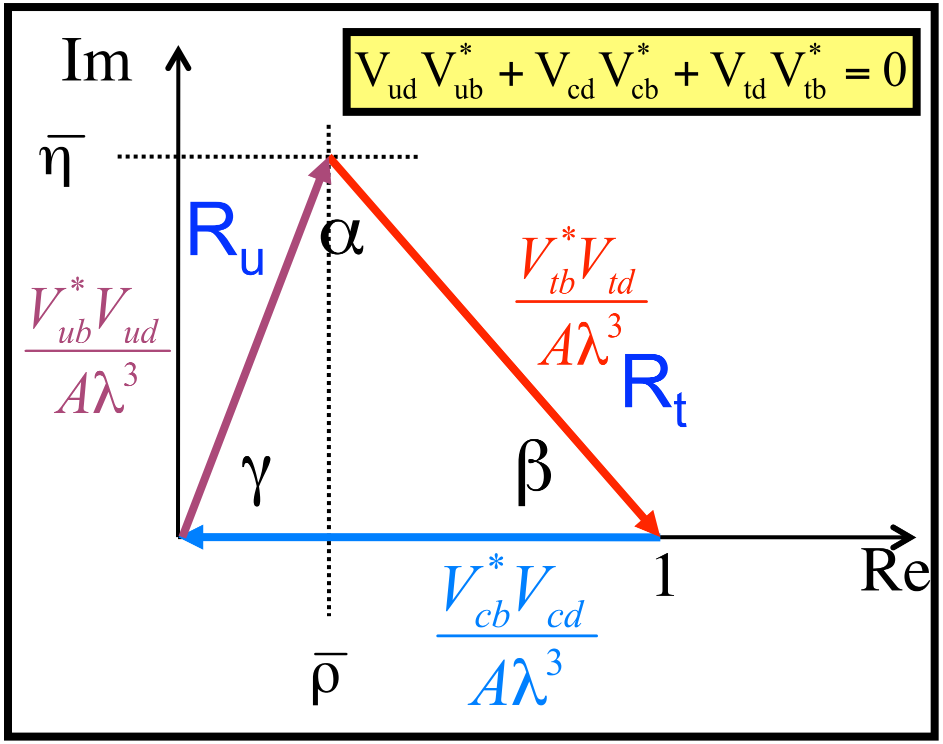
$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$

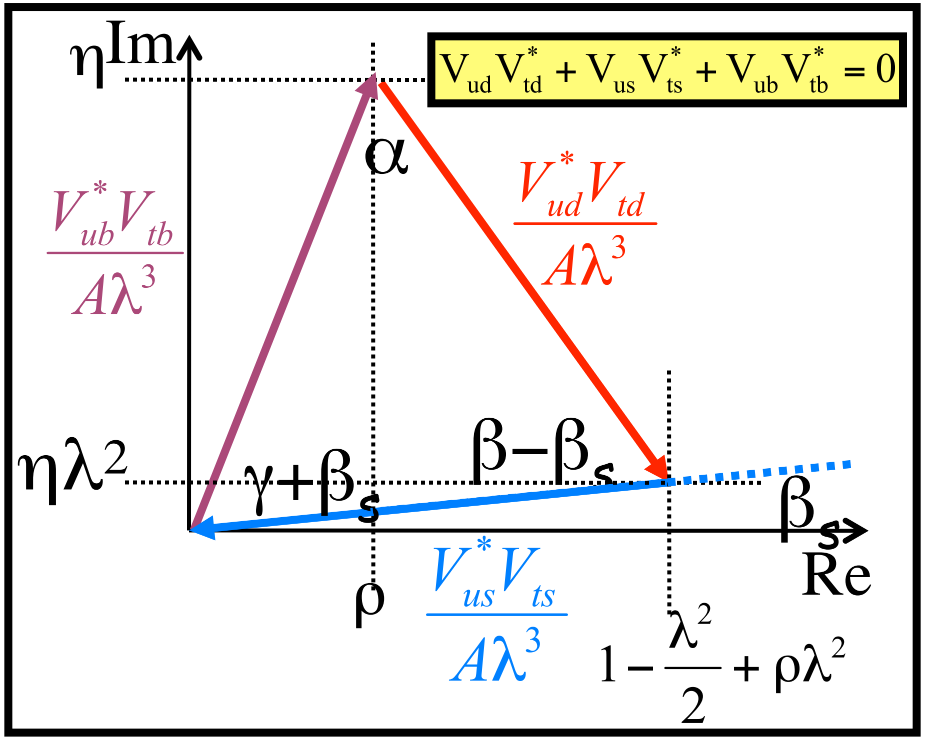
$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

Unitarity Triangles for B_d and B_s

The Unitarity Triangle
("B_d Triangle")



The "Other" Unitarity Triangle
("B_s Triangle")



B_s triangle contains very small angle, any deviation from this would be a sign of NP!

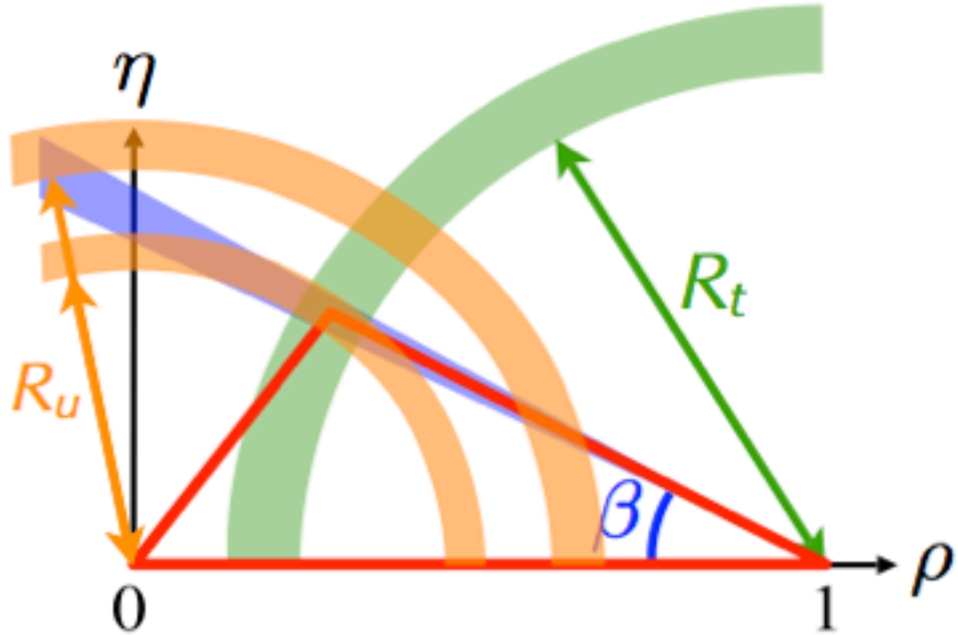
$$\beta_s \equiv \arg\left[-\frac{V_{cb}^* V_{cs}}{V_{tb}^* V_{ts}}\right] \sim \eta\lambda^2 \sim 1^{\circ}$$

Over-constraining the Unitarity Triangle

Five observables $(\alpha,\beta,\gamma,R_u,R_t)$ for 2 degrees of freedom (ρ,η)

The Unitarity Triangle can be fully determined by 2 precise measurements.

Measure more and the UT can be over-constrained, e.g. $\mathbf{R_u}$



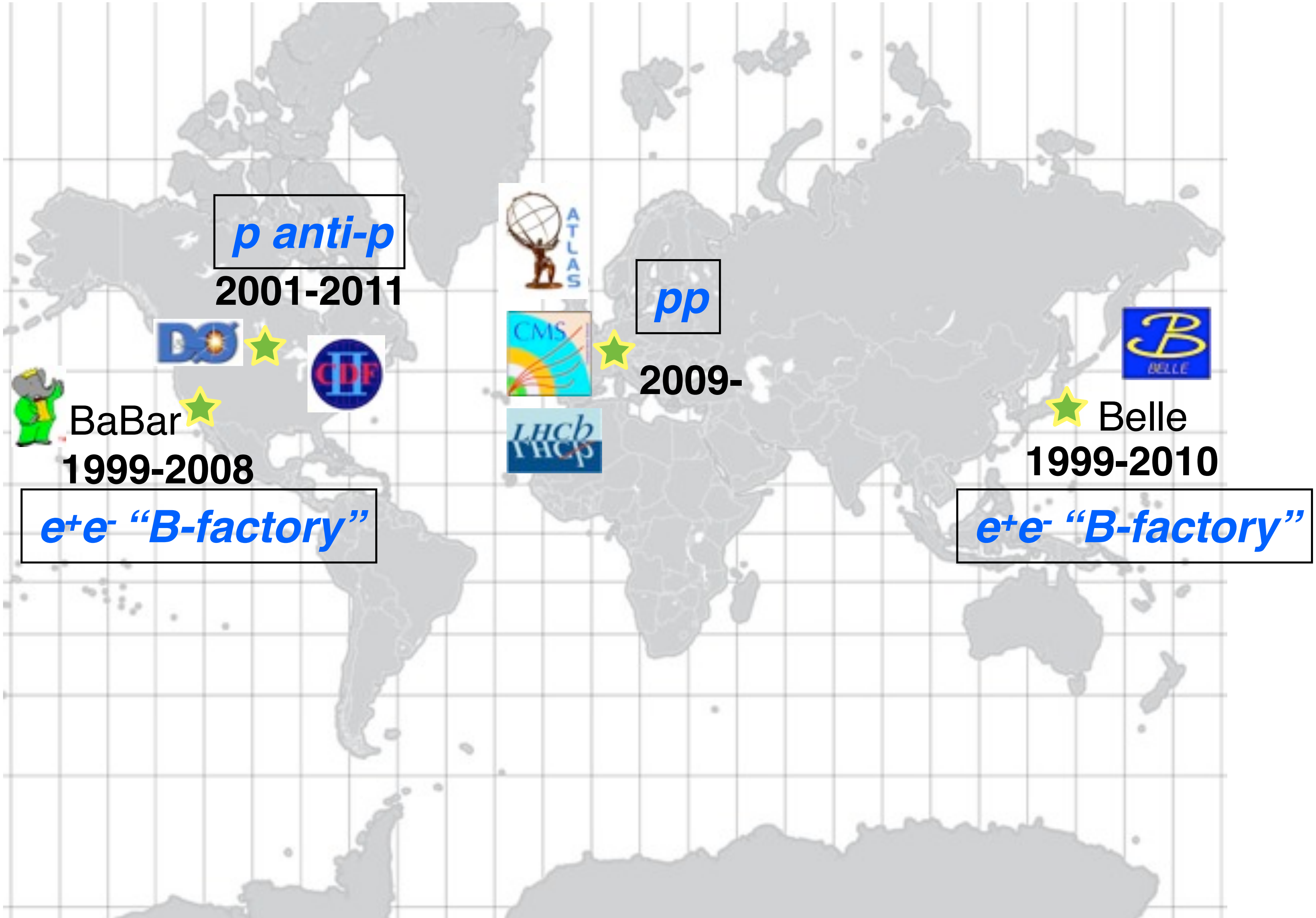
We observe **SM+new physics** (must exist), so making the constraints disagree with each other would mean discovery.

Need **at least 3** precise measurements

The B Experiments

Colliders & Detectors

Where are B Mesons Produced?



The B Factories

PEP-II @ SLAC

Energy: 9.0 GeV e^- + 3.1 GeV e^+

Design luminosity : 3 x 10^{33} $cm^{-2}s^{-1}$

Peak luminosity : 1.207 x 10^{34} cm^{-2} s^{-1}

B mesons: rate ~ 13 Hz, 470 M $B\bar{B}$

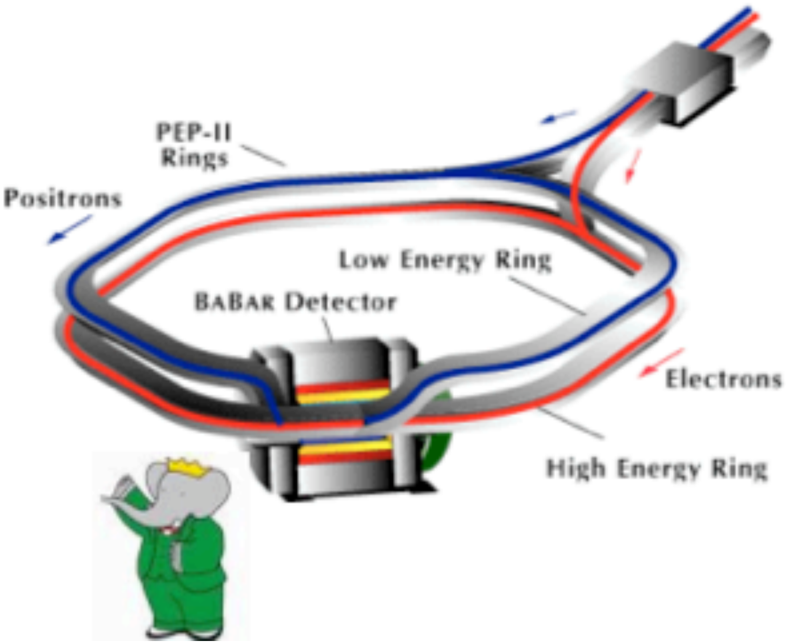
KEK-B @ KEK

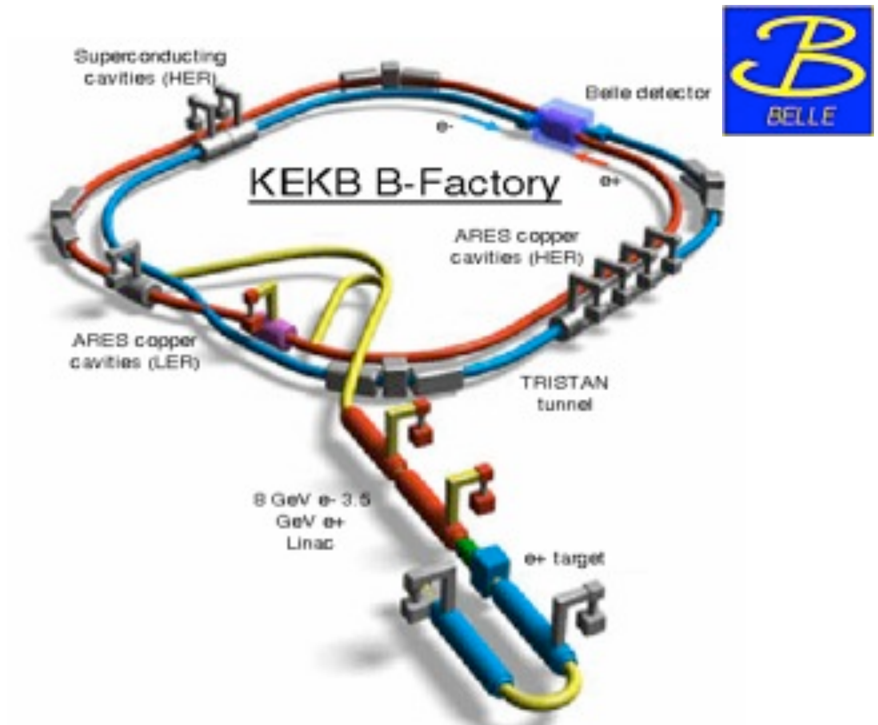
Energy: 8.0 GeV e^- +3.5 GeV e^+

Design luminosity : 1 x 10^{34} $cm^{-2}s^{-1}$

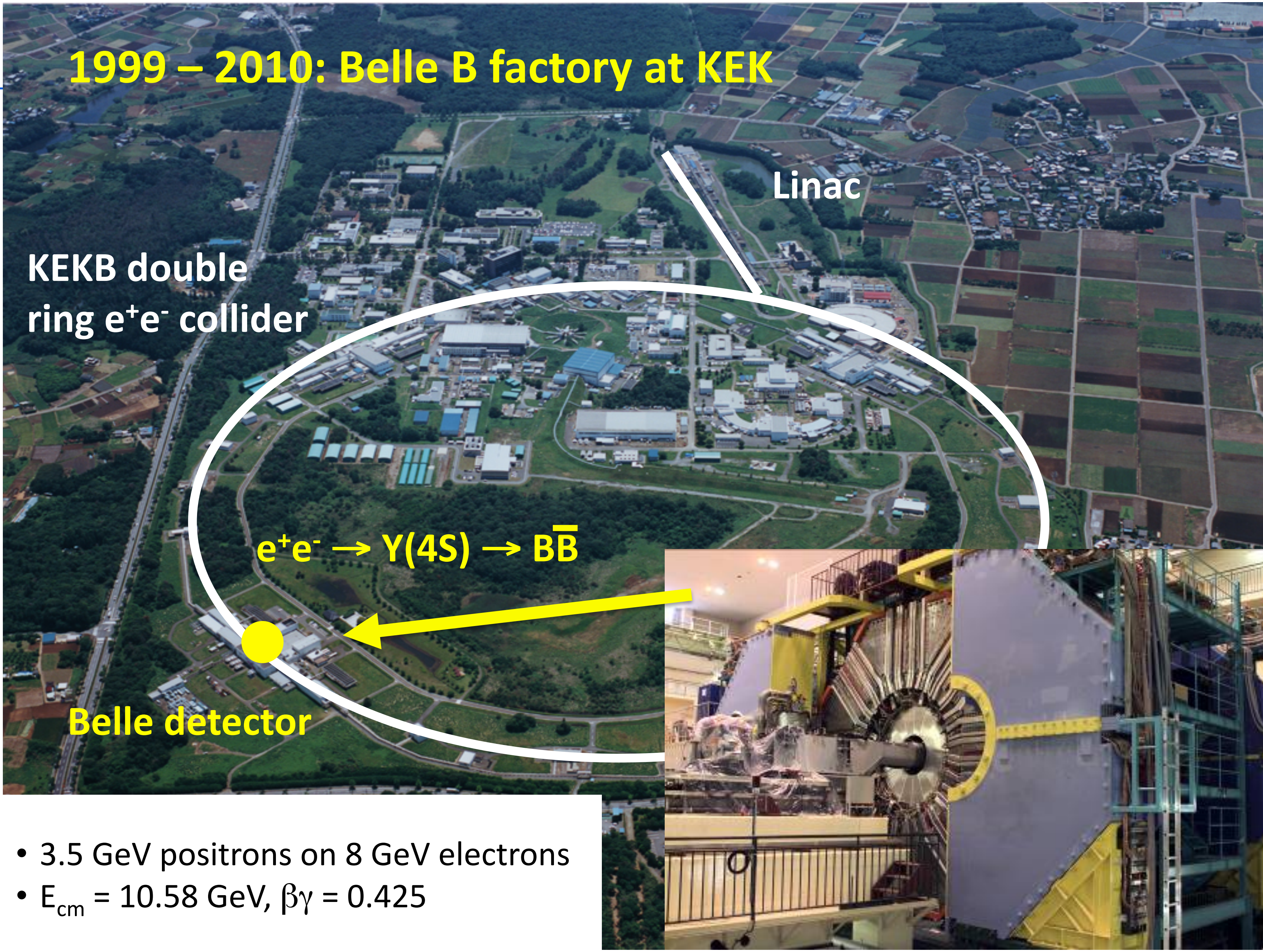
Peak luminosity : 2.11 x 10^{34} cm^{-2} s^{-1}

B mesons: rate ~ 19 Hz, 780 M $B\bar{B}$



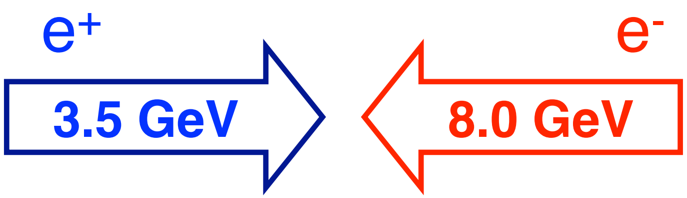


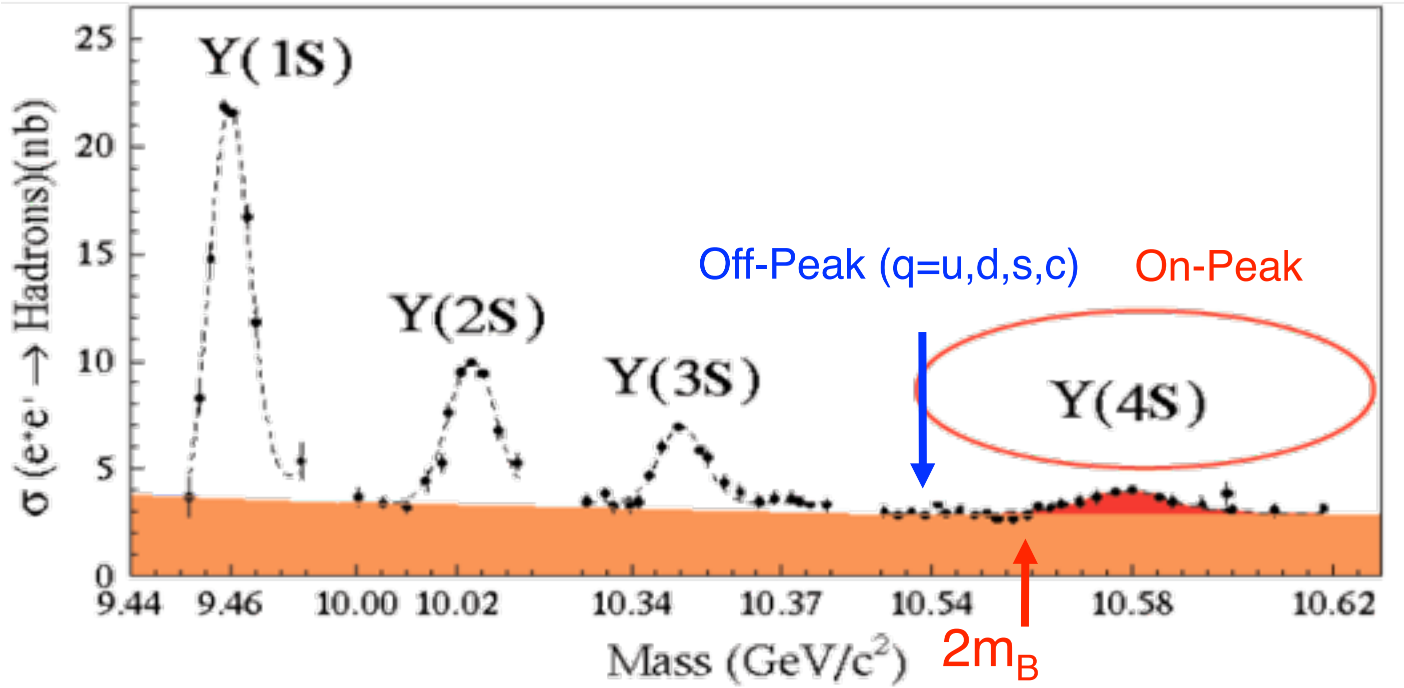
1999 – 2010: Belle B factory at KEK



- 3.5 GeV positrons on 8 GeV electrons
- E_{cm} = 10.58 GeV, $\beta\gamma$ = 0.425

Production of B Mesons



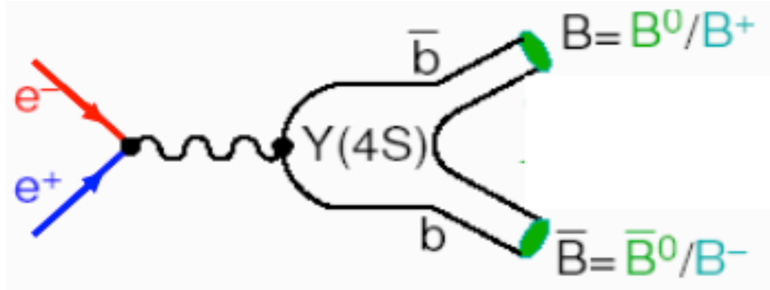


- Centre-of-mass energy = mass of Υ(4S)

- Υ(4S) is bound $b\bar{b}$-state that decays to ~100% to B^+B^- or $B^0\bar{B}^0$ pairs

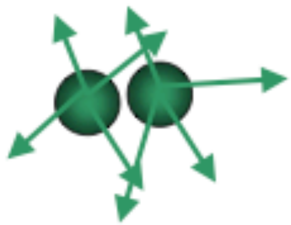
Asymmetric Beam Energies

Allows for B decay time measurement



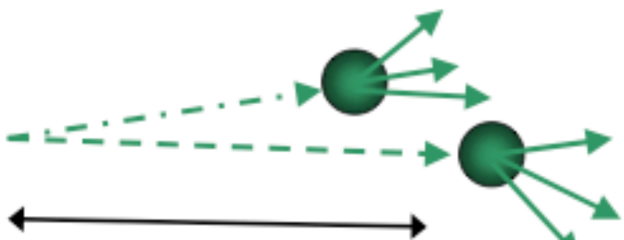
E_{CMS} =10.58 GeV

Symmetric:



B mesons at rest
⇒ decay length z ≈ 0

Asymmetric:



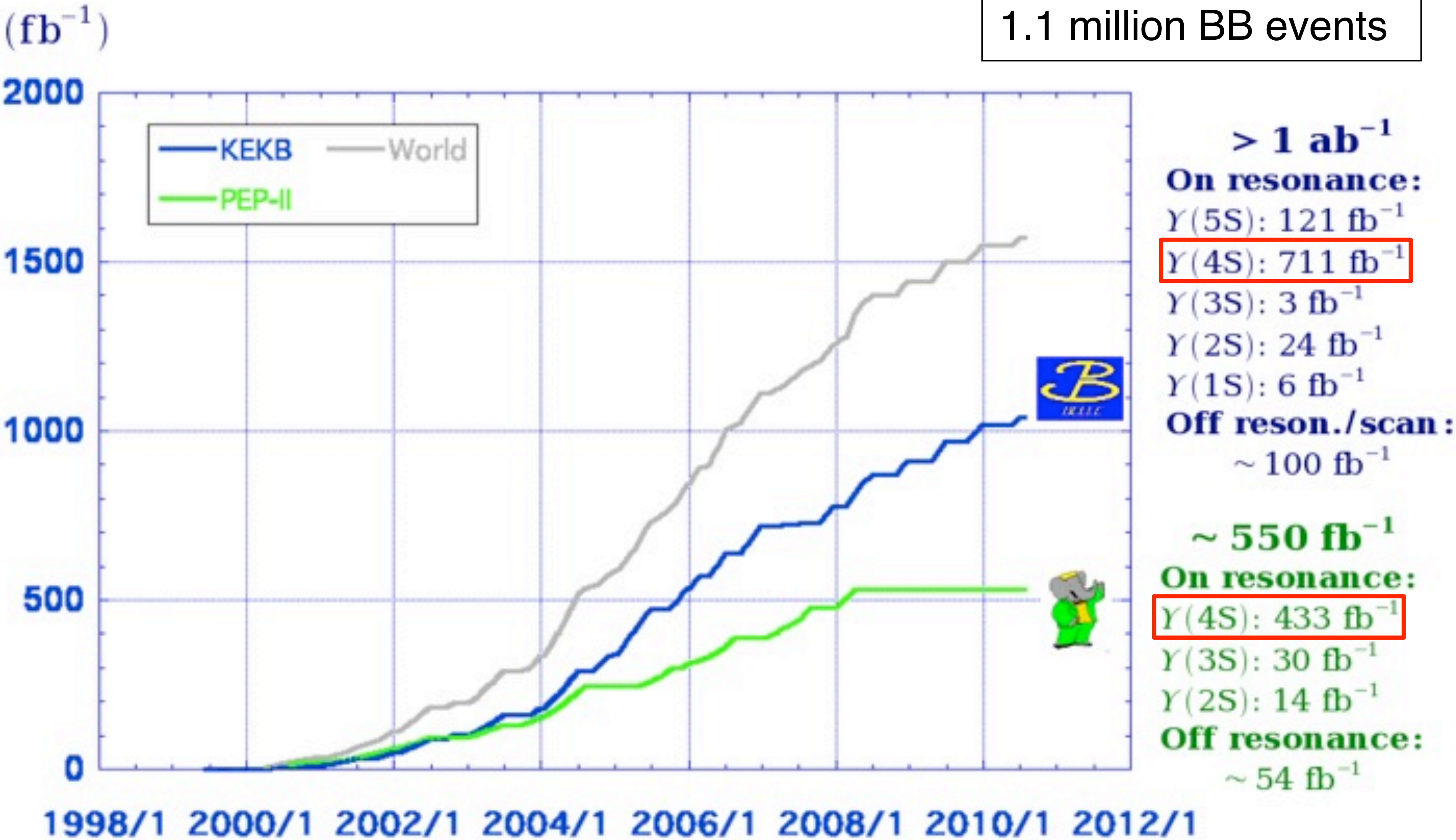
$z = c\beta\gamma\, t$

decay length
z ≈ 250μm

Boost β= 0.56 (PEPII)

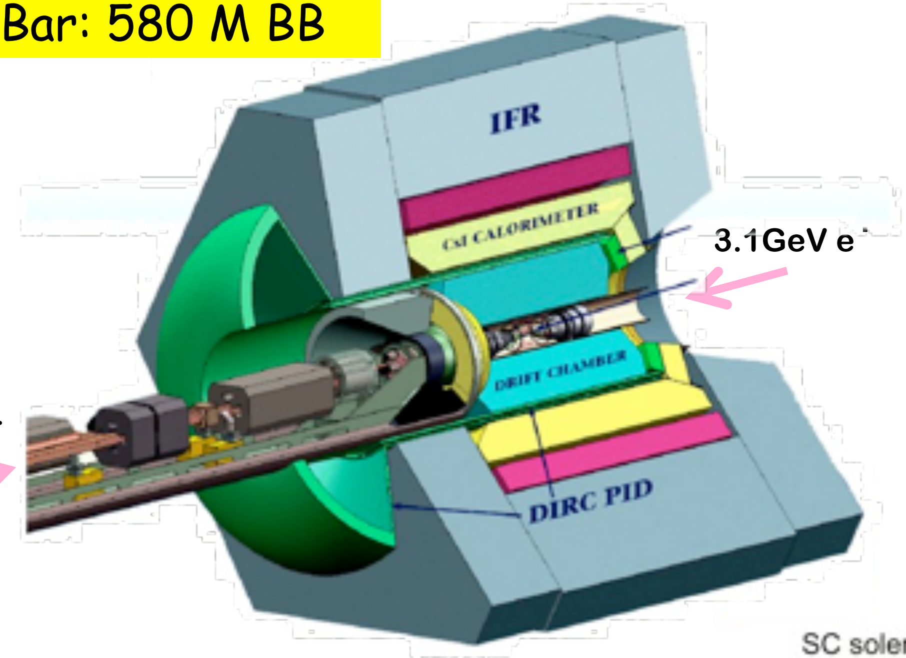
KEKB and PEP-II Luminosities

1fb^{-1} Υ(4S) data =
1.1 million BB events

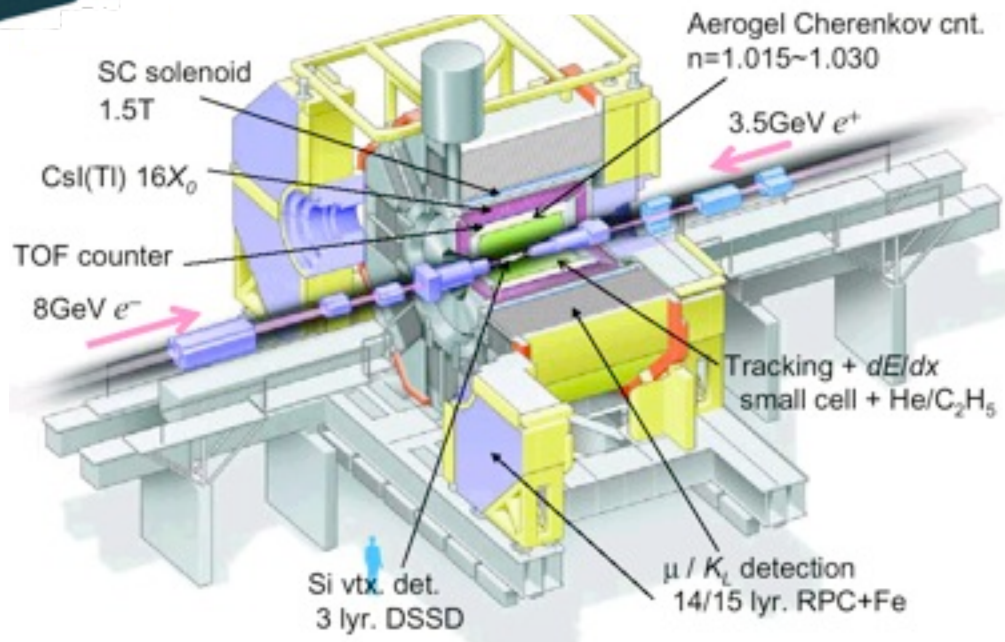


The B-Factory Experiments

BaBar: 580 M $B\bar{B}$



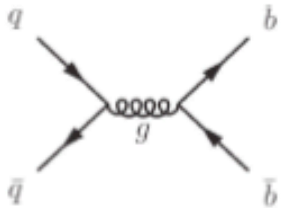
Belle: ~ 990 M $B\bar{B}$



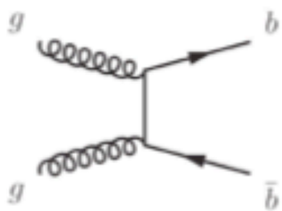
b Production at Hadron Colliders

	e+e- (PEPII, KEKB)	p anti-p→b anti-bX ($\sqrt{s}$=2TeV) Tevatron	pp→b anti-bX ($\sqrt{s}$=7TeV) LHC
Prod. σbb	1 nb	~100 μb	~300μb
typ. bb rate	10 Hz	~100 kHz	~300kHz
purity	~1/4	~0.2%	~0.6%
pile-up	0	1.7	0.5→25
B content	B^+(50%),B^0(50%)	B^+(40%),B^0(40%),B_s(10%),B_c(<1%),b-baryon(10%)	
B boost	small, βγ~0.5	large, decay vertices are displaced	
event structure	BB pair alone	many particles not associated to b	
Prod. vertex	not reconstructed	reconstructed with many tracks	
B^0 anti-B^0 mixing	coherent	incoherent→flavour tagging dilution	

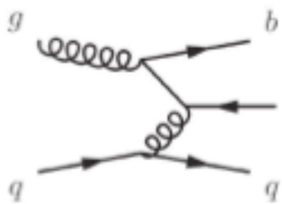
bb production at hadron colliders



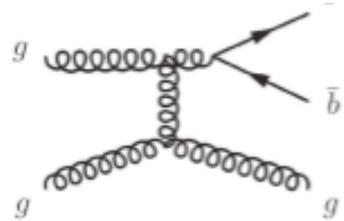
quark annihilation



gluon fusion



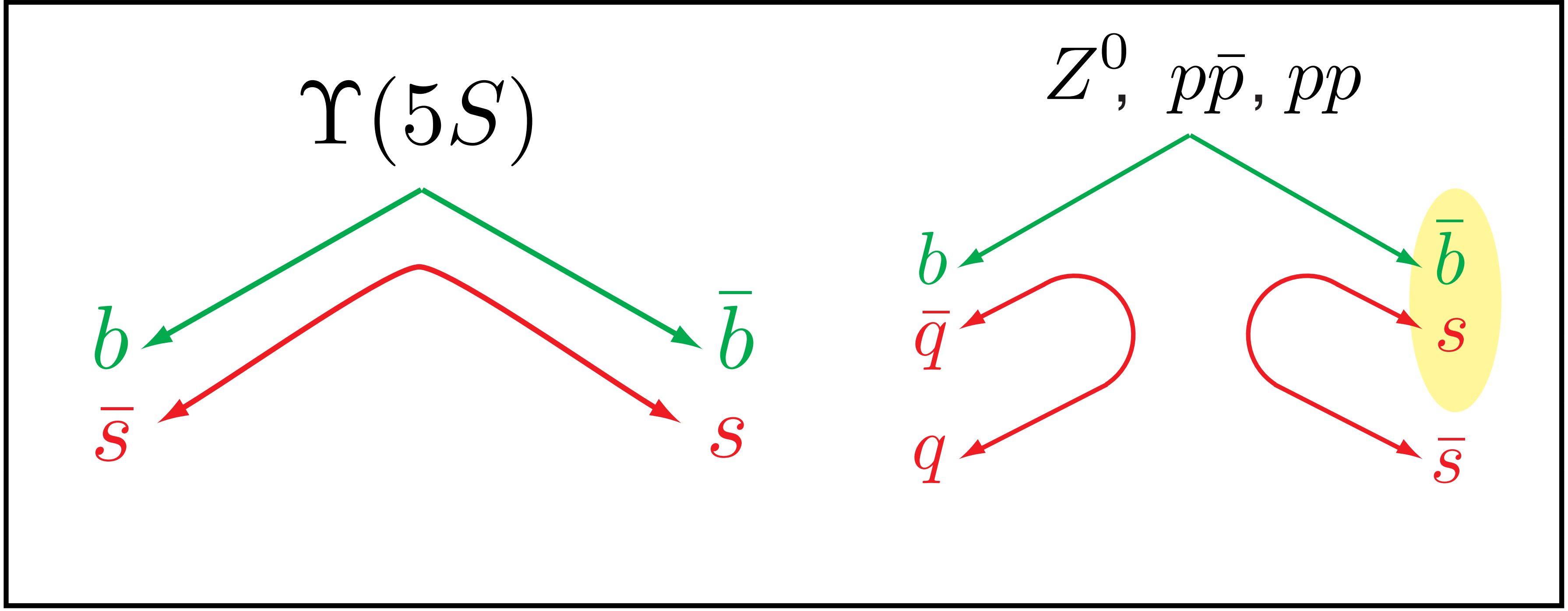
flavour excitation



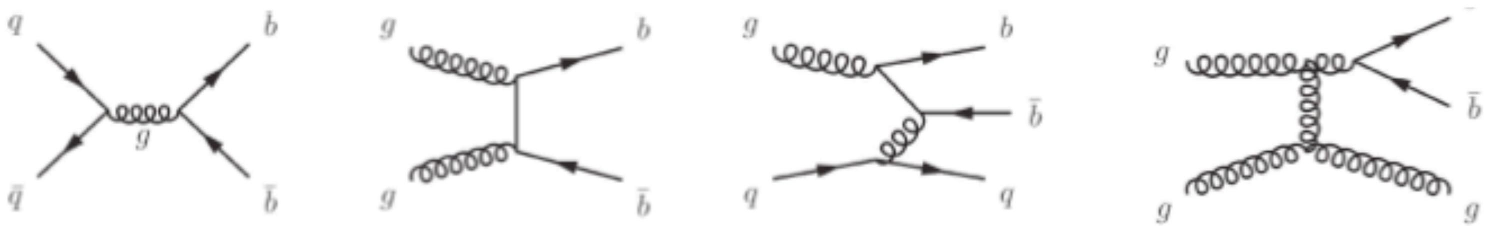
gluon splitting

b Production at Hadron Colliders

	e+e- (PEPII, KEKB)	p anti-p→b anti-bX (√s=2TeV) Tevatron	pp→b anti-bX (√s=7TeV) LHC



bb production at hadron colliders



quark annihilation

gluon fusion

flavour excitation

gluon splitting

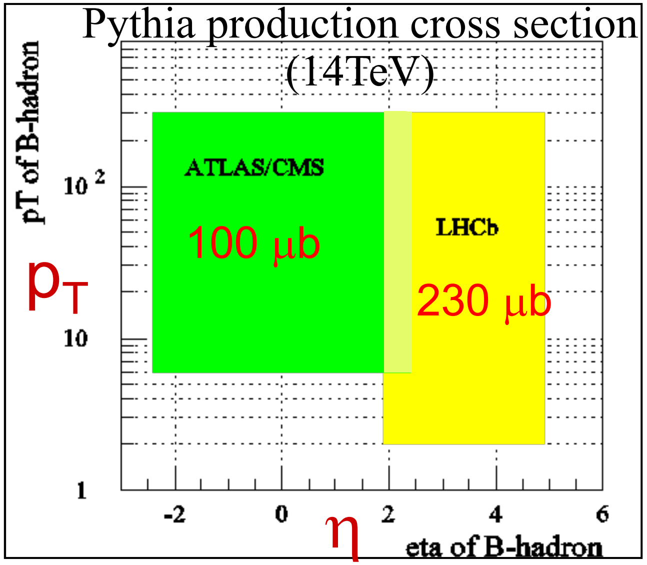
universitätbonn

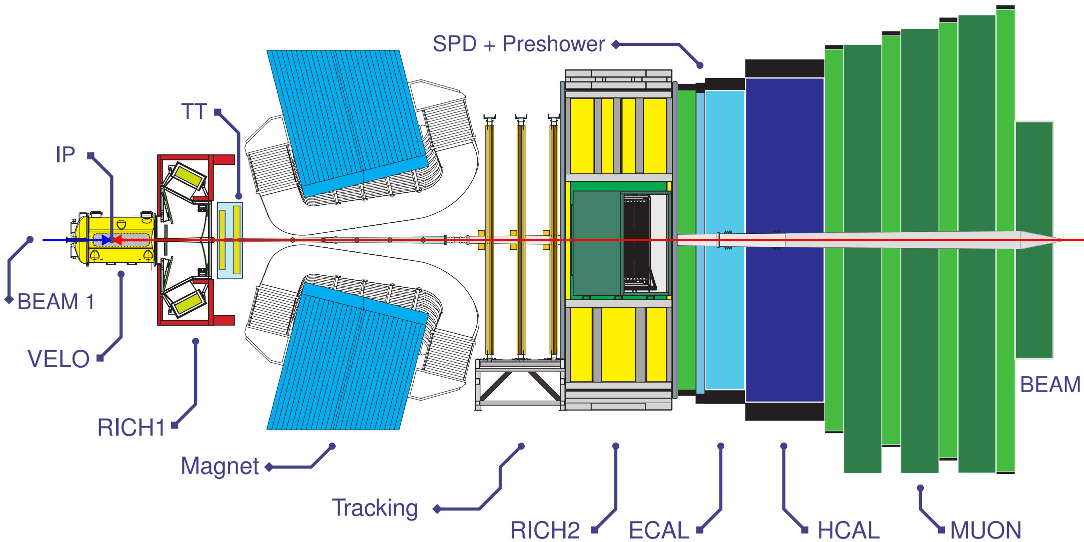
LHC 2009-

- More than 10^{12} b-anti-b pairs (10^9 at B-factories)produced already and growing.
  - LHCb dedicated B-physics detector
  - B-physics programs at CMS and ATLAS.

LHCb

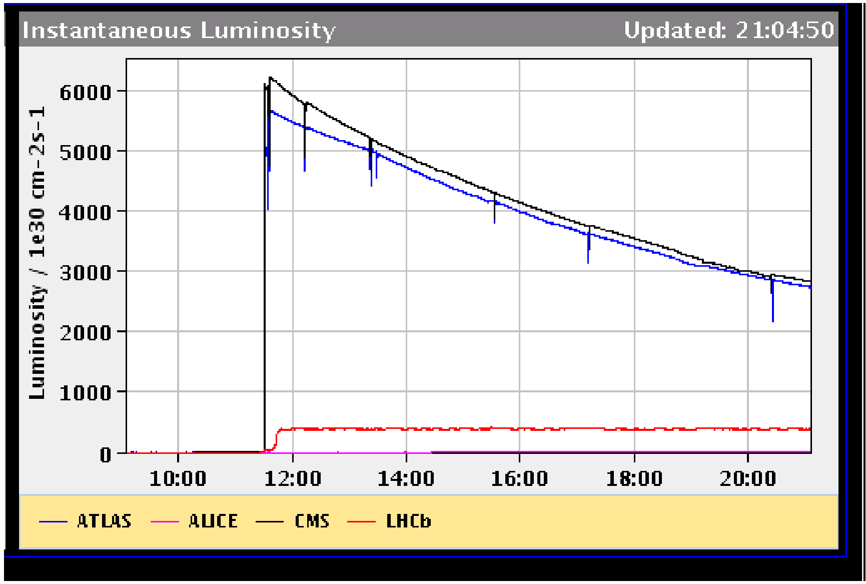
- Study **beauty**, and **charm** in forward region 4.9 > η >1.9
- Designed for time dependent analyses with fast mixing frequencies
  - Vertex reconstruction with VELO Si detector
  - Hadron identification with RICH (K/π identification using Cherenkov light emission angle)
  - ECAL for electron, photon, hadron energy measurement
- Trigger is 2 phase, hardware +software for enormous rate reduction
  - triggers on high pT tracks, leptons, displaced vertices

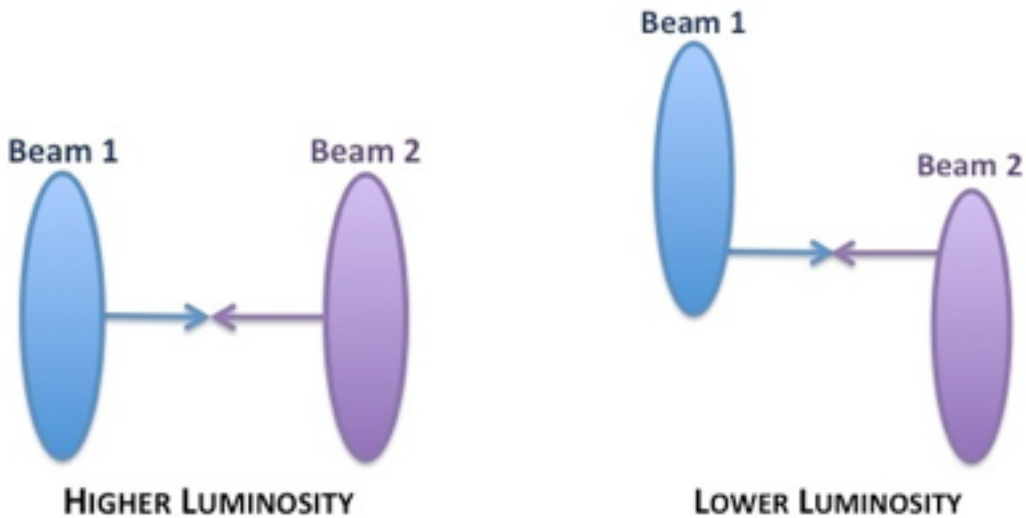




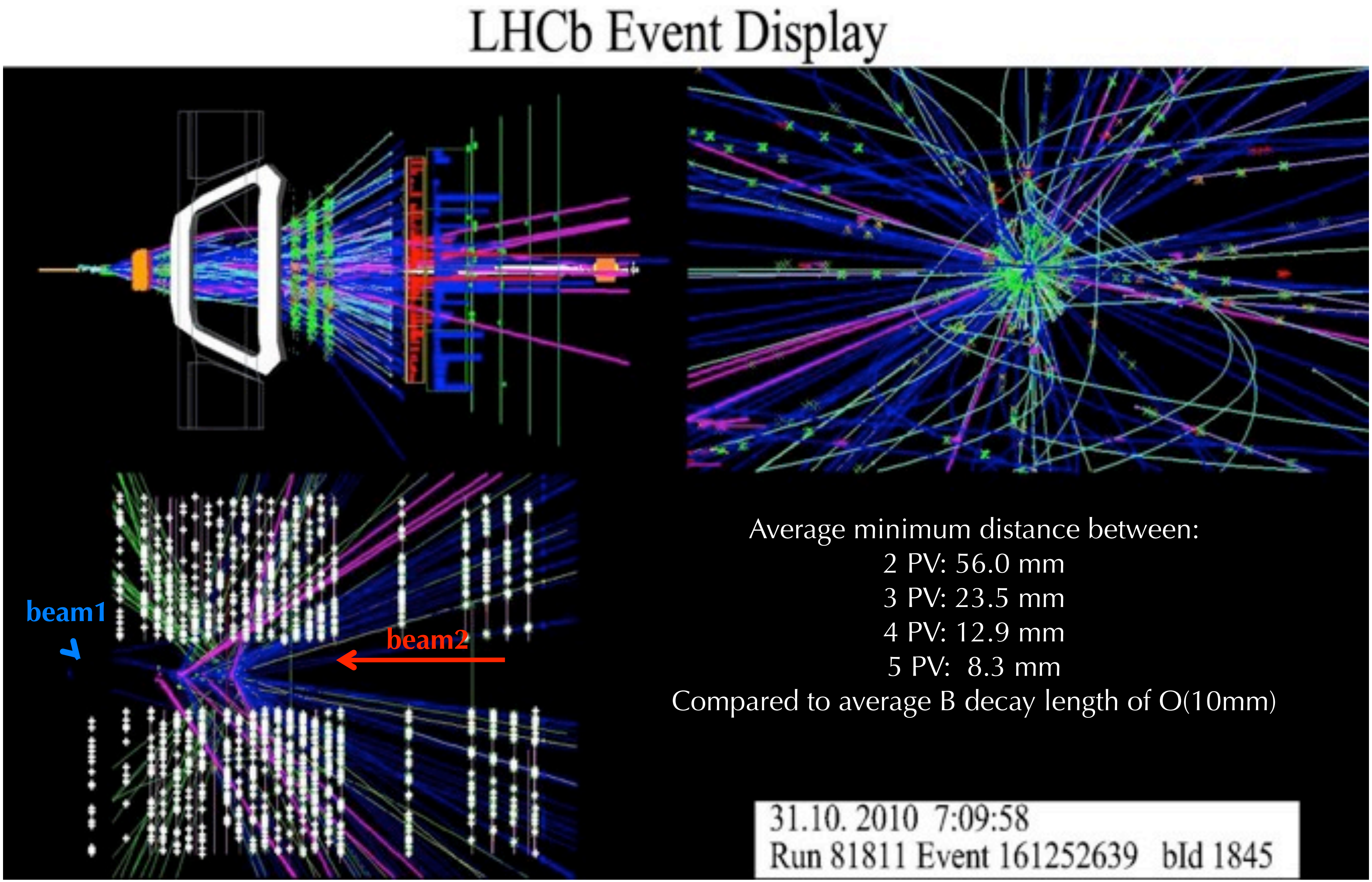
Thursday, 29 August 13

Luminosity profiles at LHC





Running in 2010 (when I was on shift)



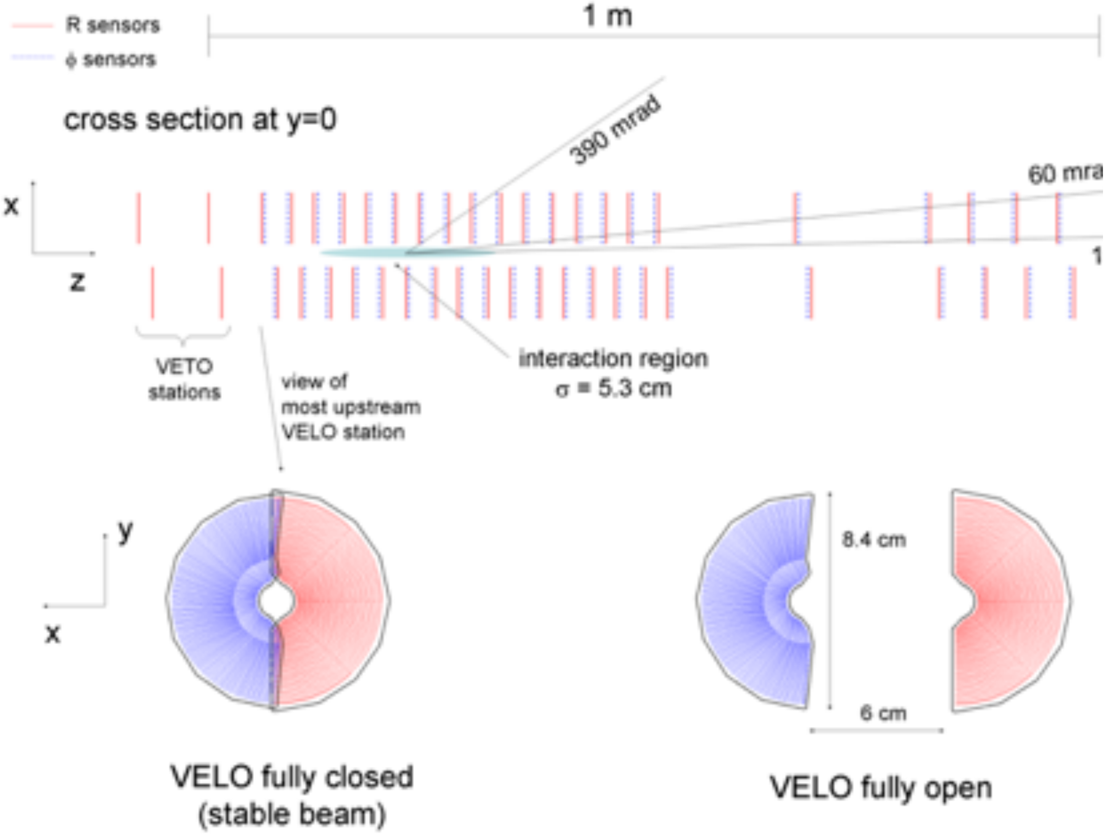
VErtex LOcator

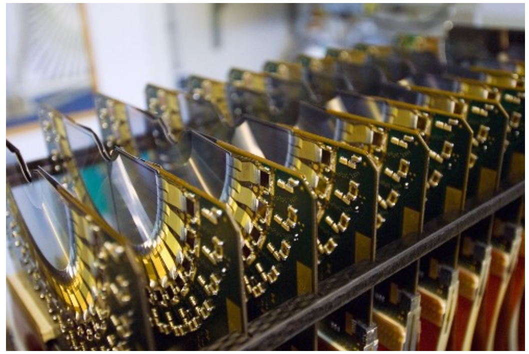
Vertex Locator (Velo)

Silicon strip detector with

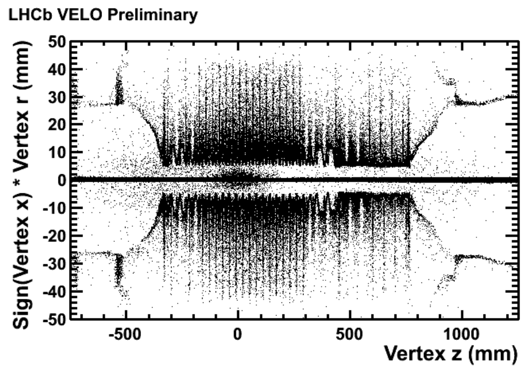
~ 5 μm hit resolution

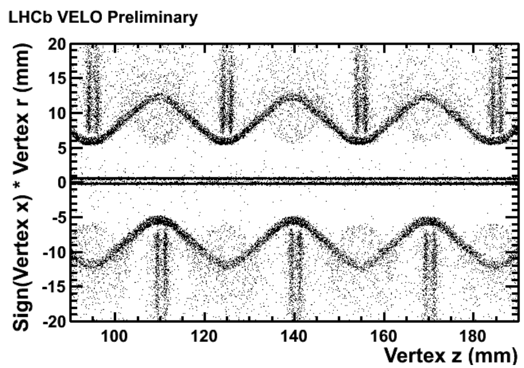
→ 30 μm IP resolution





Material imaged used beam gas collisions





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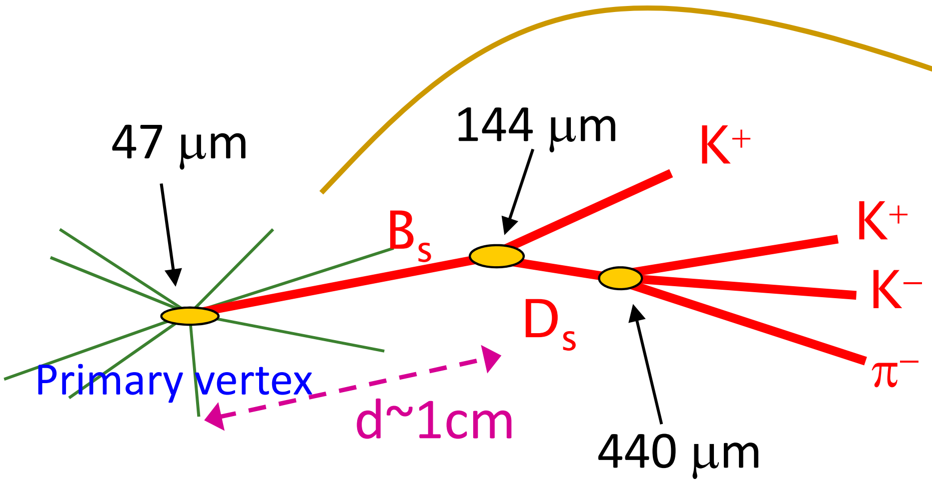
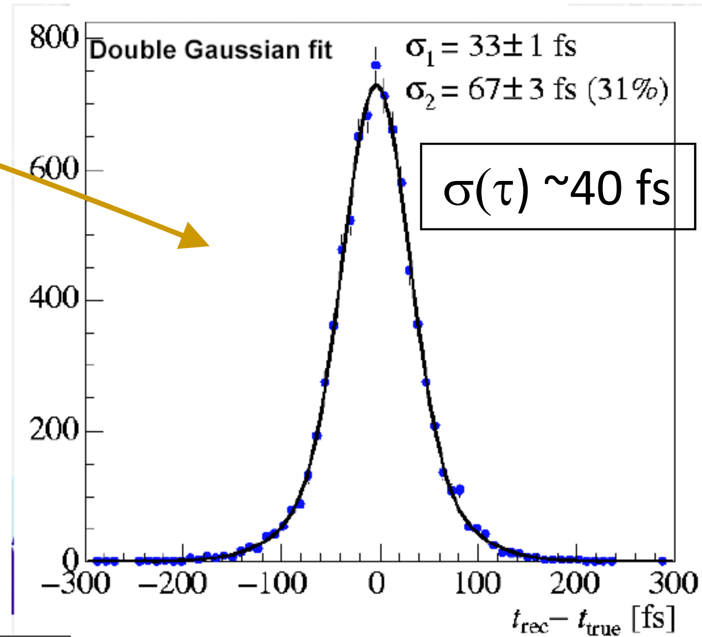
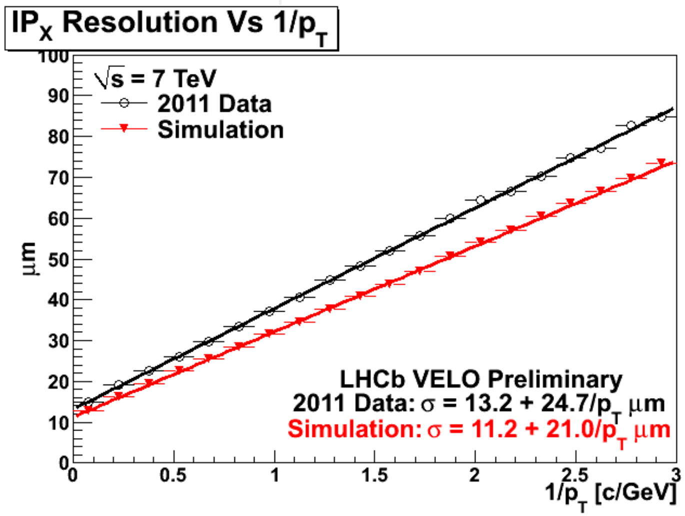
B vertex measurement

Example: $B_s \rightarrow D_s K$

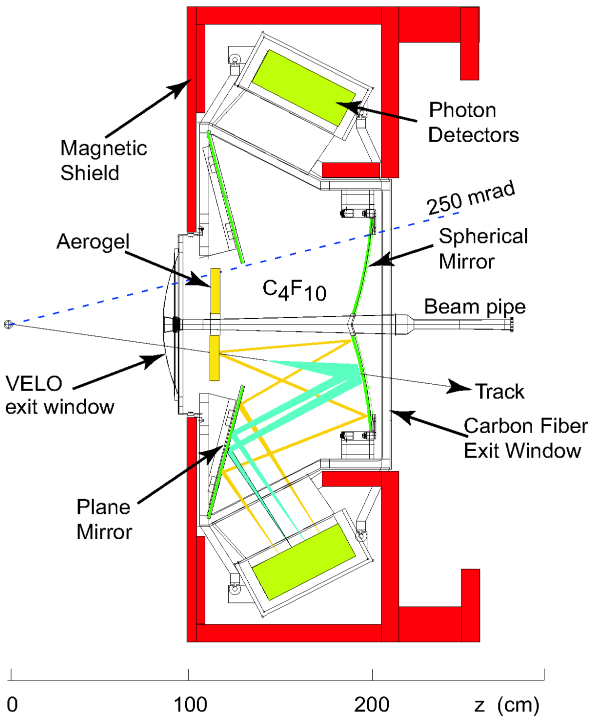


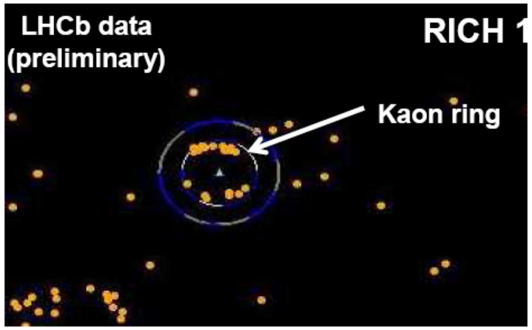


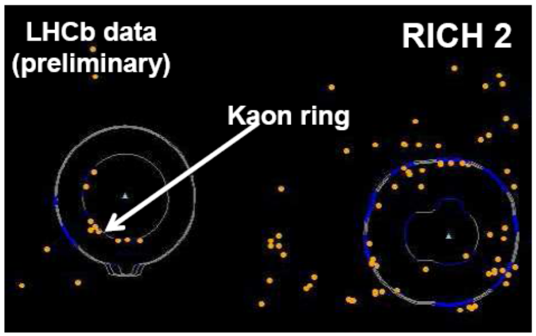
Decay time resolution = 40 fs

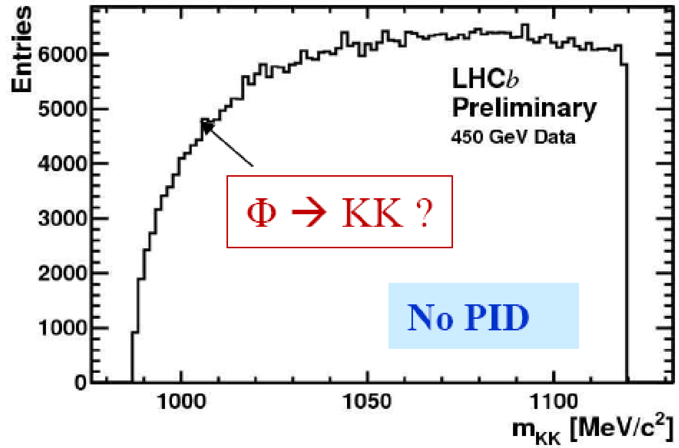


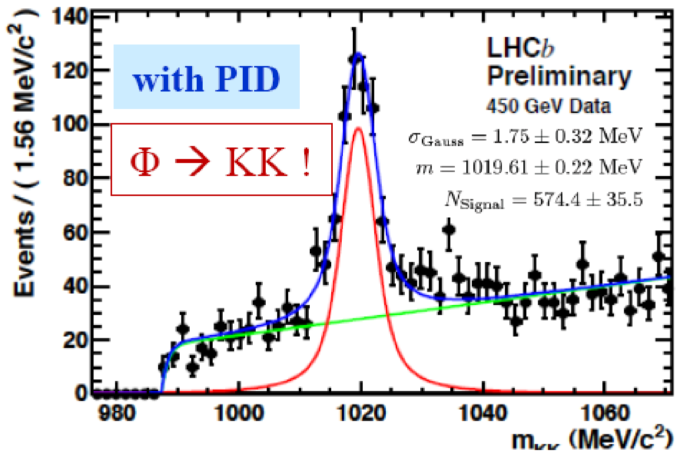
LHCb Particle Identification





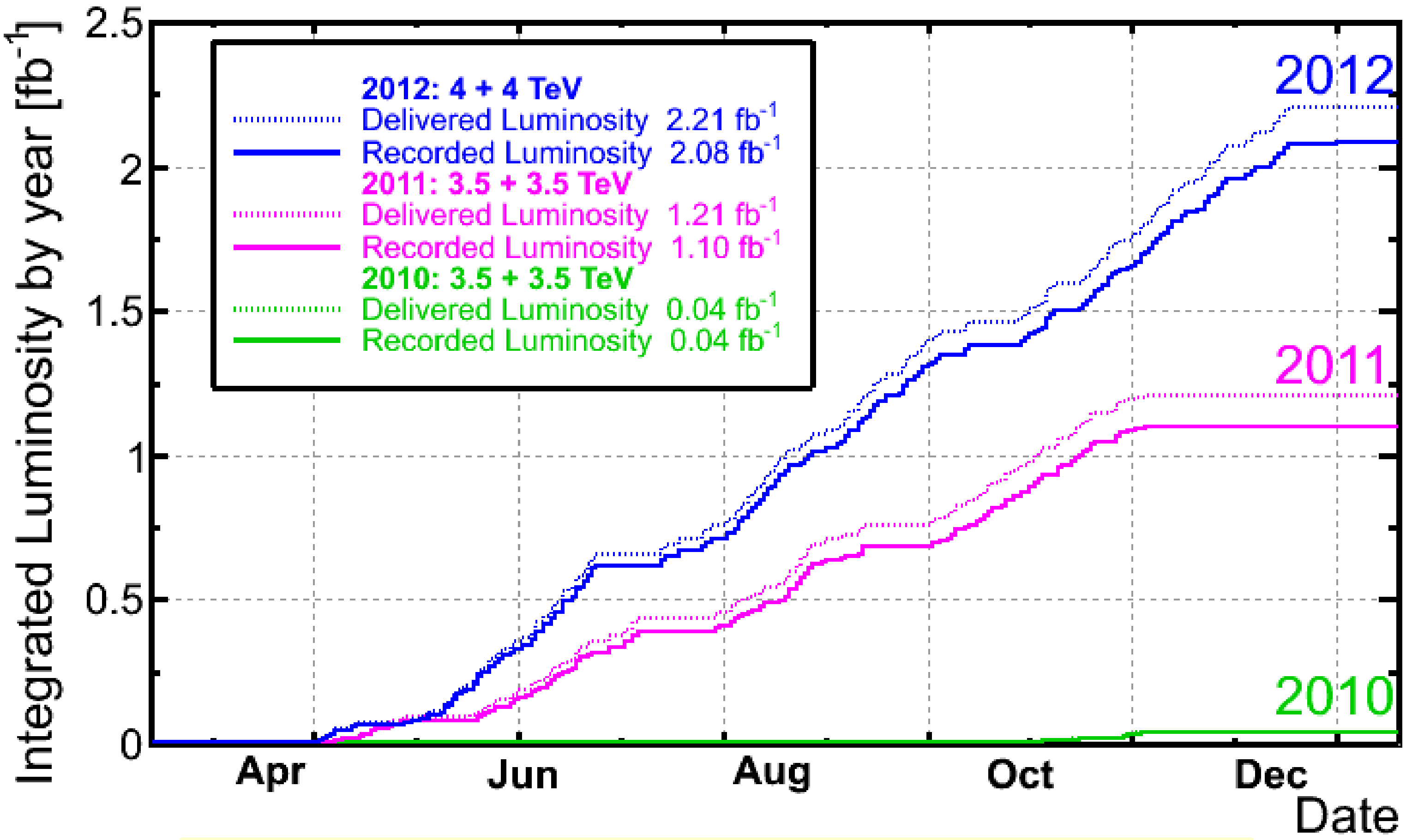






Thursday, 29 August 13

LHCb integrated luminosity



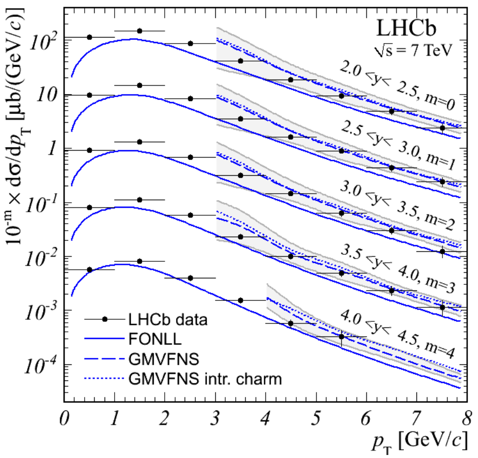
Instantaneous luminosity (2012) ~ 4 10^{32}/cm^2/s
LHCb design luminosity: 2 10^{32}/cm^2/s

What does $\int L dt$ = 1/fb mean?

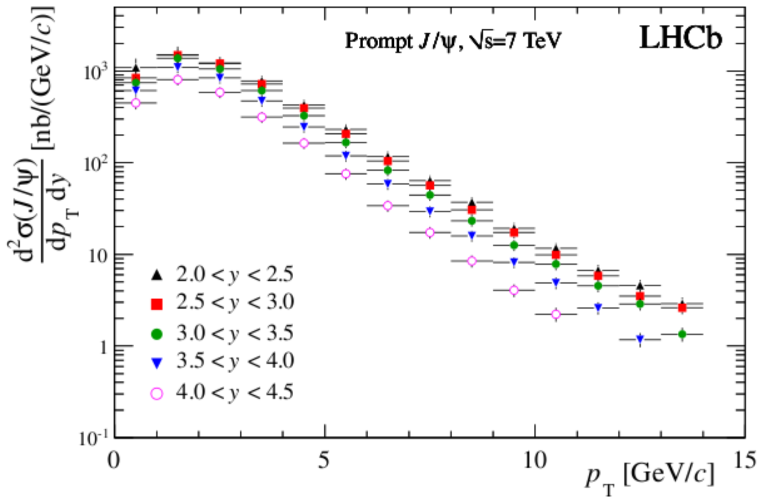
- Measured cross-section, in LHCb acceptance
  - $\sigma(pp \to bbX) = (75.3 \pm 5.4 \pm 13.0)\ \mu b$, PLB 694 (2010) 209
- So, number of bb pairs produced in 1/fb (2011 sample)
  - $\mathbf{10^{15} \times 75.3 \times 10^{-6} \sim 10^{11}}$
- Compare to combined data sample of e^+e^- "B factories"BaBar and Belle of **~10^9** BB pairs
  - for any channel where the (trigger, reconstruction, offline) efficiency not too small, LHCb has largest data sample
- *p.s.*: for charm, $\sigma(pp \to ccX) = (6.10 \pm 0.93)$ mb

Heavy flavour production @ LHC

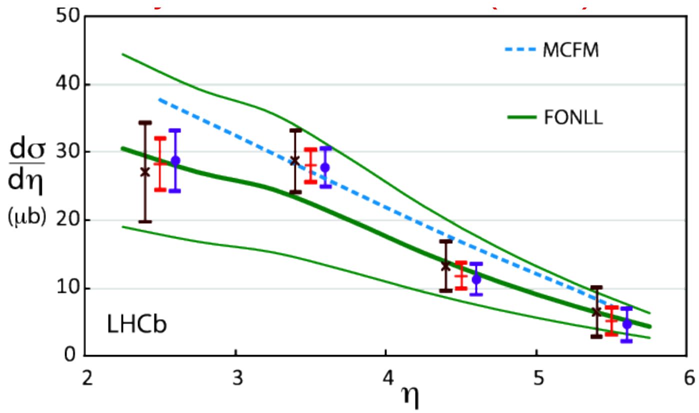
"Prompt charm production in pp collisions at √s = 7 TeV"
Nucl. Phys. B 871 (2013) 1



"Measurement of J/ψ production in pp collisions at √s = 7 TeV"
Eur. Phys. J. C 71 (2011) 1645



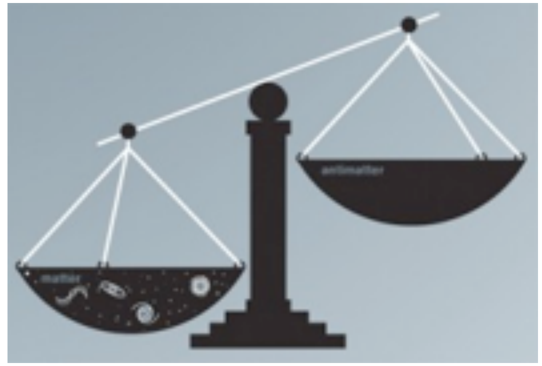
"Measurement of σ(pp→bbX) at √s = 7 TeV in the forward region"
Physics Letters B 694 (2010) 209



End of Part 1

CP Violation and the BAU

- We can estimate the magnitude of the baryon asymmetry of the Universe caused by KM CP violation
- Introduce parameterisation invariant measure of CP in quark sector, **J**.



$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx \frac{n_B}{n_\gamma} \sim \frac{J \times P_u \times P_d}{M^{12}}$$

$$F_u \, F_d \, J \neq 0$$

where:

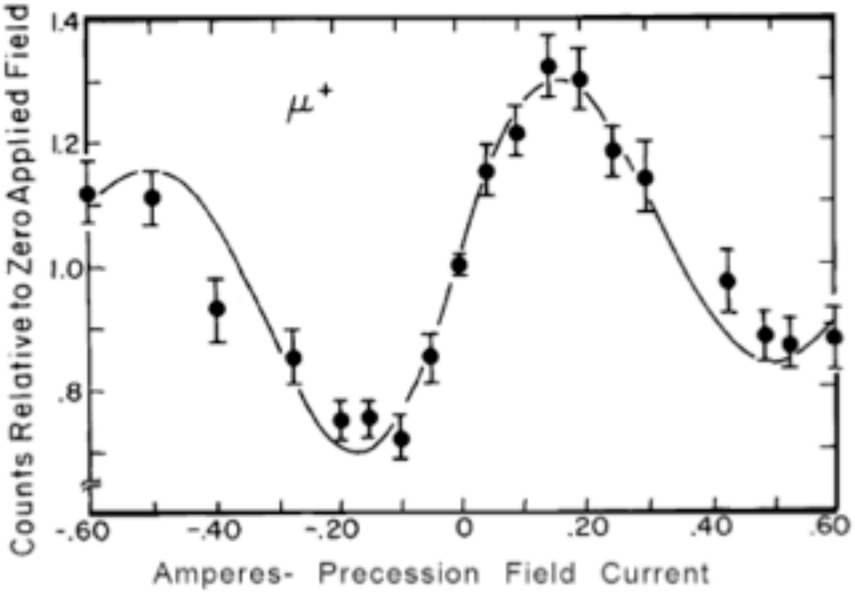
$$\begin{aligned} F_u &= (m_u^2 - m_c^2)(m_c^2 - m_t^2)(m_t^2 - m_u^2) \\ F_d &= (m_d^2 - m_s^2)(m_s^2 - m_b^2)(m_b^2 - m_d^2) \\ J &= \mathrm{Im}[V_{us} V_{cd} V_{cs}^* V_{ub}^*] \\ &= c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin\delta \\ &= A^2 \lambda^6 \eta \end{aligned}$$

Mass scale **M** can be taken to be EW scale O(100 GeV)
This gives an asymmetry **O(10^{-17})** much below observed **O(10^{-10})**

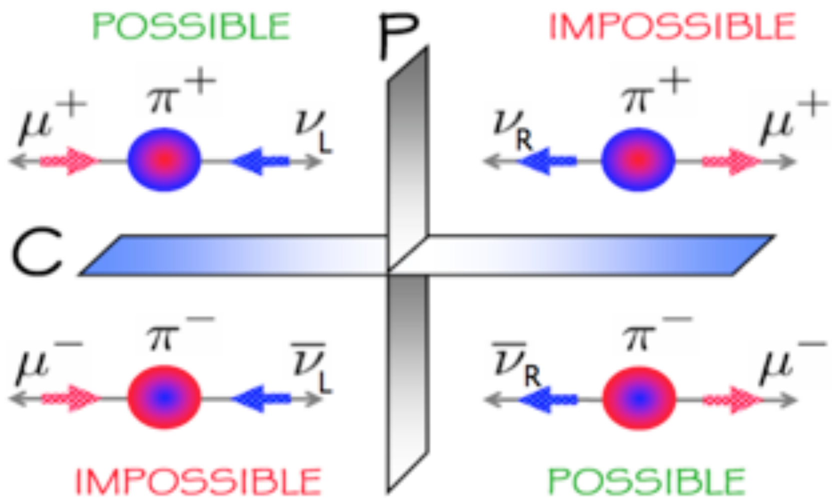
1956-57: Parity Violation

Quick verification using modified cyclotron

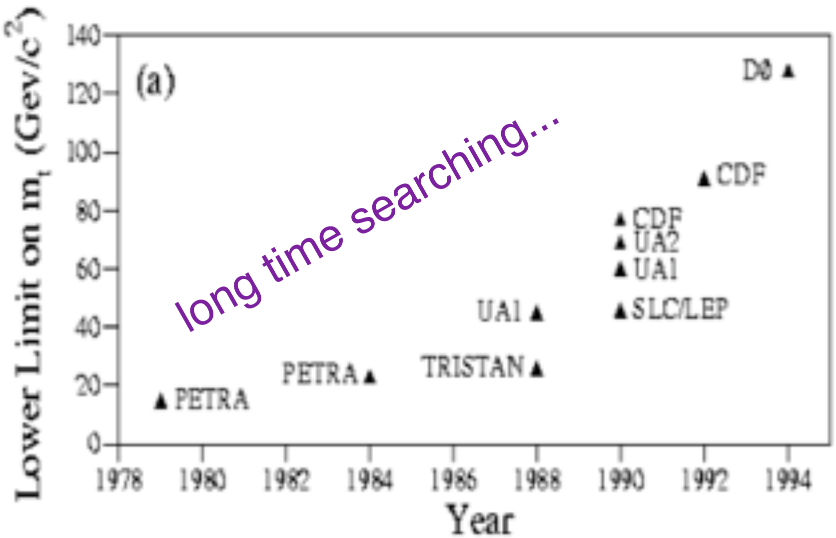
$$\pi^+ \to \mu^+ \nu$$
$$\mu^+ \to e^+ + 2\nu$$

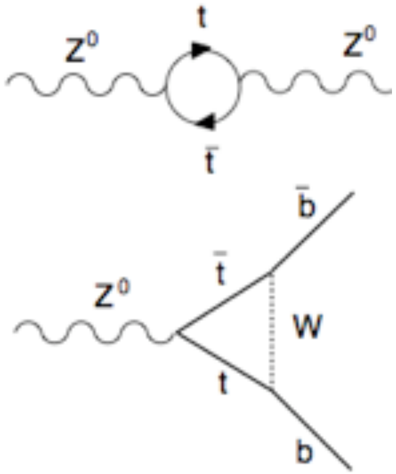


parity violation in the decay of the +ve pion leads to a polarisation of the muon along direction of travel. Similarly for the electron.



1995: Discovery of the Top Quark

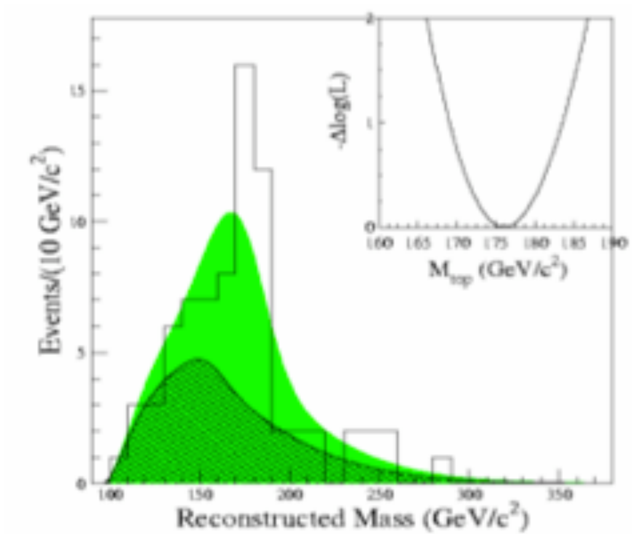




GIM+CKM+ *b*-decay prediction
m(t)~150GeV (1980)

Z0 decays@LEP (1994)
m(t)=179+12/-9GeV

1994 Direct *Observation* at the Tevatron (CDF & D0)



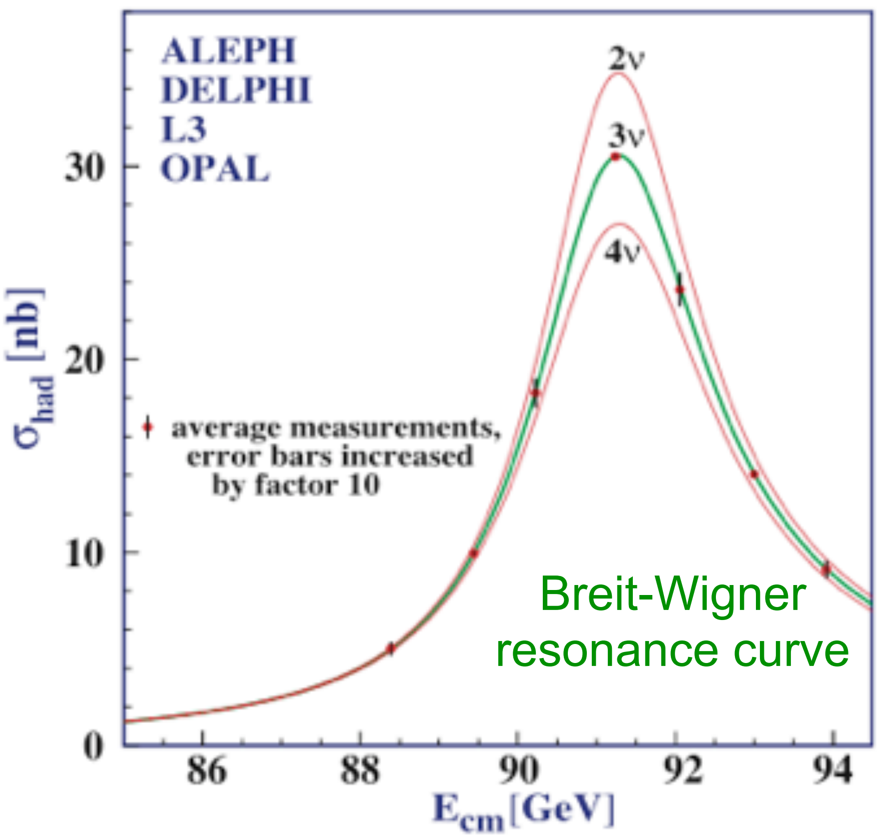
Top quark discovery@CDF (1995)
m(t)=178±8±10GeV

Are there more than three Generations?

- We do not know why there are 3 families (not predicted by Standard Model)!
- But we know that there are 3 families with light neutrinos ($m_\nu < 45\ \mathrm{GeV}/c^2$)

measurement of Z-boson width at LEP

$e^+e^- \rightarrow$ hadrons

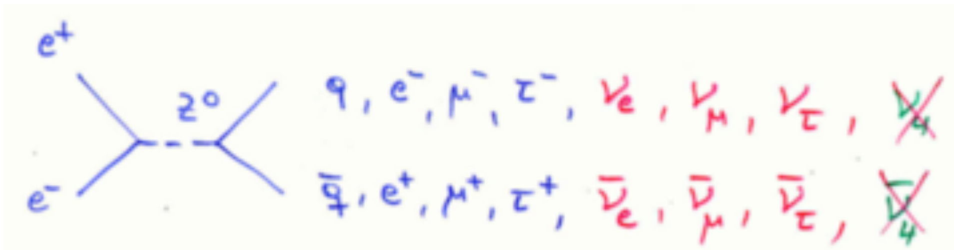


Width: $\Gamma = \hbar/\tau$ (τ: lifetime)

$$\Gamma_Z = \Gamma_e + \Gamma_\mu + \Gamma_\tau + \Gamma_{had} + n \cdot \Gamma_\nu$$

→ n = 3 neutrino families

Potential 4th family in simple SM extension would have to have heavy neutrino **($m_\nu > m_Z/2$)**

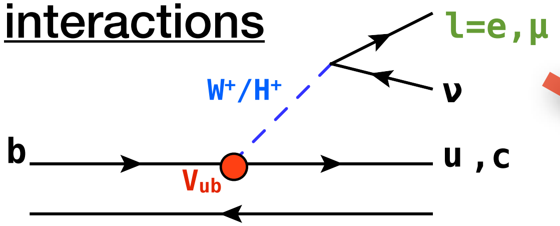


New Phenomena DNA

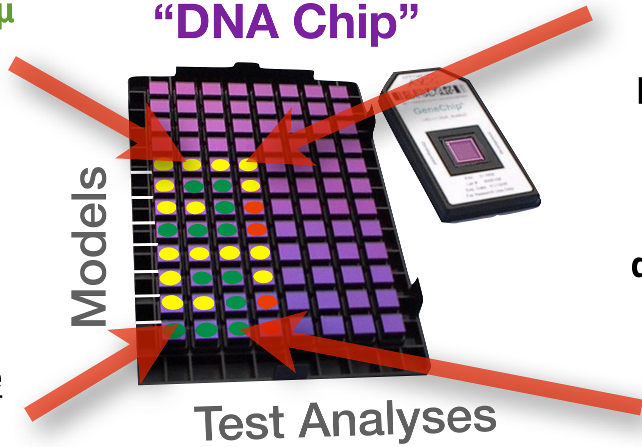
- **Different models predict different sets of quantum numbers/masses/couplings.**

  Analyse meson (bound q anti-q pair) & lepton decays in a variety of signatures. e.g.

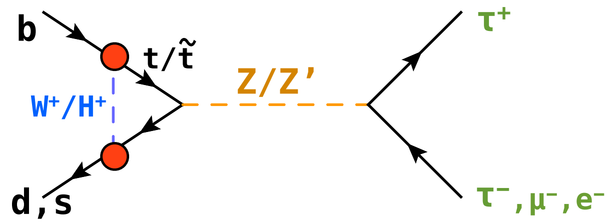
<u>Precision tests of quark interactions</u>



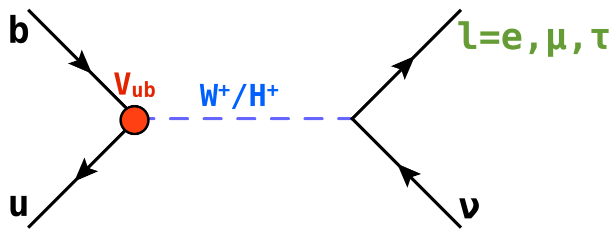
New Physics "DNA Chip"



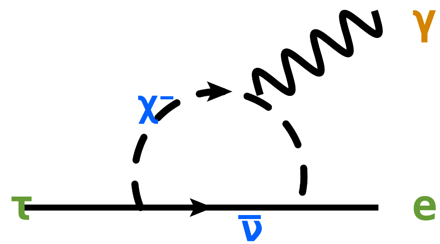
<u>Flavour Changing Neutral Current Interactions</u>



<u>New Phenomena in rare decay processes</u>

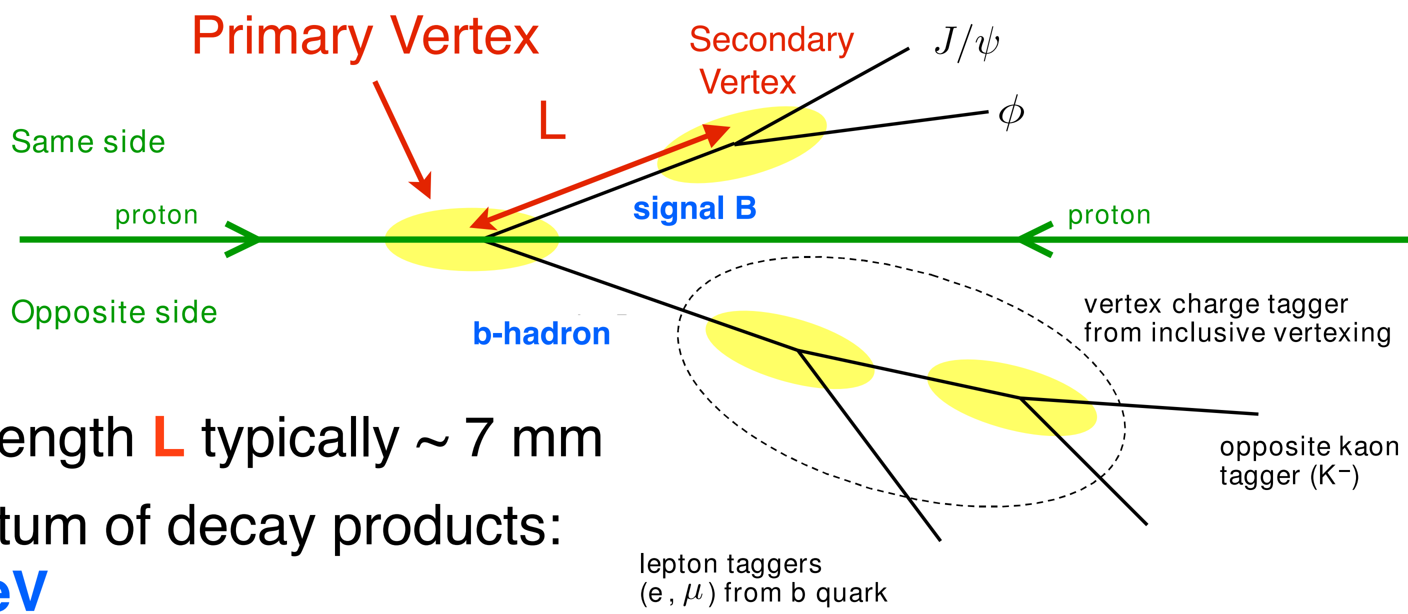


<u>Search for lepton flavour violation (neutrino mass...)</u>



b Production at Hadron Colliders

At LHC Gluon-gluon fusion is prominent production mechanism. If gluons do not have equal momenta, ***b anti-b* system** can have significant momentum and go forward in the CM.



Decay length L typically ~ 7 mm

momentum of decay products:
1-60 GeV

Requirements same as at all heavy flavour experiments:
- Good vertex resolution to identify PV & SV
- Good momentum resolution to measure proper time
- Particle ID to select decay products

Unitarity of the CKM Matrix

$$V^\dagger V = \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

rows 1×1, uu	$\lvert V_{ud}\rvert^2 + \lvert V_{us}\rvert^2 + \lvert V_{ub}\rvert^2 = 1$
rows 2×2, cc	$\lvert V_{cd}\rvert^2 + \lvert V_{cs}\rvert^2 + \lvert V_{cb}\rvert^2 = 1$
rows 3×3, tt	$\lvert V_{td}\rvert^2 + \lvert V_{ts}\rvert^2 + \lvert V_{tb}\rvert^2 = 1$
columns 1×1, dd	$\lvert V_{ud}\rvert^2 + \lvert V_{cd}\rvert^2 + \lvert V_{td}\rvert^2 = 1$
columns 2×2, ss	$\lvert V_{us}\rvert^2 + \lvert V_{cs}\rvert^2 + \lvert V_{ts}\rvert^2 = 1$
columns 3×3, bb	$\lvert V_{ub}\rvert^2 + \lvert V_{cb}\rvert^2 + \lvert V_{tb}\rvert^2 = 1$
rows 1×2, cu	$V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0$
rows 1×3, tu	$V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0$
rows 2×3, tc	$V_{cd}^* V_{td} + V_{cs}^* V_{ts} + V_{cb}^* V_{tb} = 0$
columns 1×2, sd	$V_{ud} V_{us}^* + V_{cd} V_{cs}^* + V_{td} V_{ts}^* = 0$
columns 1×3, bd	$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$
columns 2×3, bs	$V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0$