Belle II

(Heavy) Flavour Physics **1/2**

Rare Decays

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Melbourne
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THE UNIVERSITY OF MELBOURNE

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Outline

Part 1: Flavour and Rare decays

1. What is flavour physics & why is it interesting?
2. Brief history of flavour
3. CKM mechanism
4. Experimental facilities
5. Tree level Decays
6. Flavour Changing Neutral Currents
7. Lepton decays

Part 2: CP violation

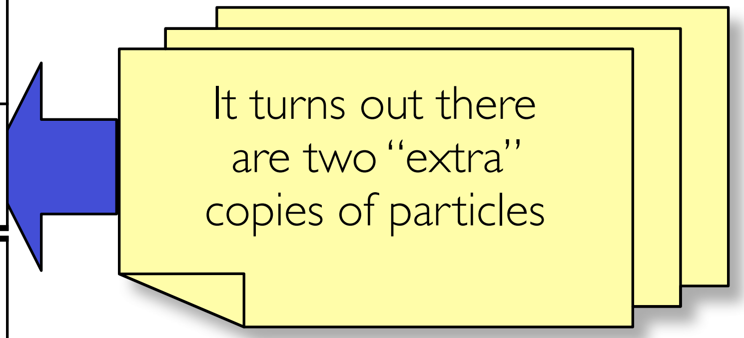
8. The Unitarity triangle
9. Meson-antimeson oscillations
10. Measurements of CP violation
11. Global analyses of flavour data & future facilities

1. Introduction

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



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

Simplified Standard Model

1st generation

2nd ge

3rd ge

leptons	quarks
e^-	u
ν_e	d

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."

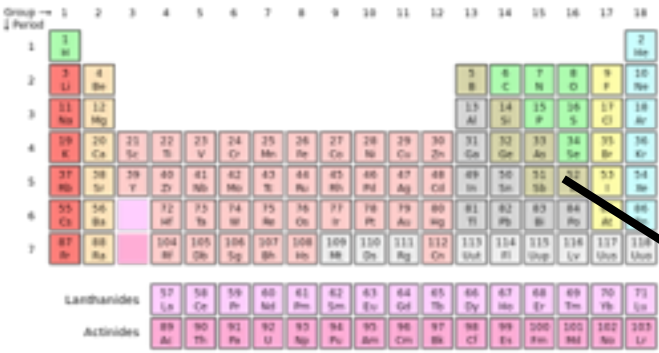
RMP 81 (2009) 1887

- 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

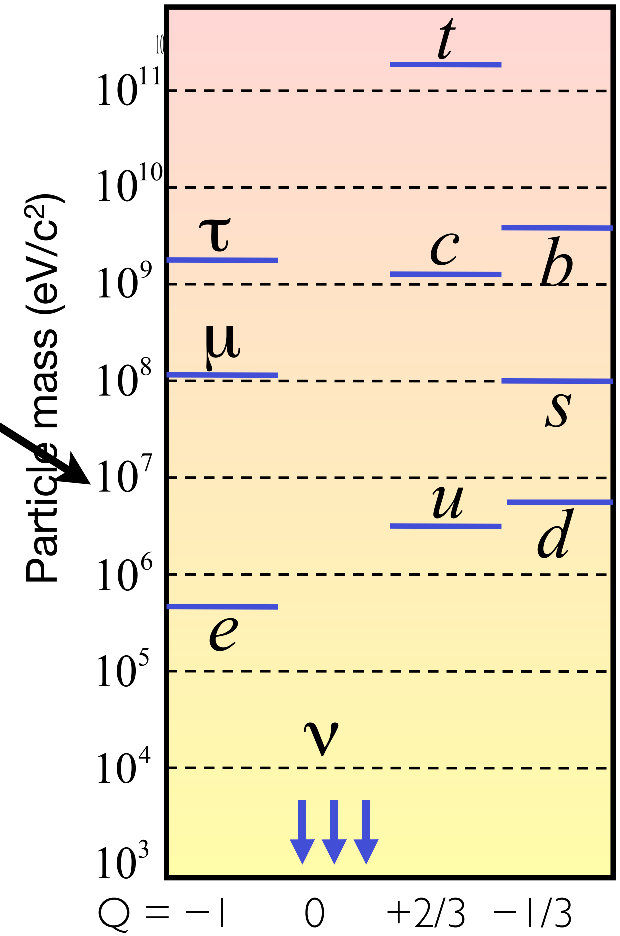
	Q= -1	Q= 0	Q=+1
S= 0		n	p
S= -1	Σ^-	Σ^0, Λ	Σ^+
S= -2	Ξ^+	Ξ^0	

	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

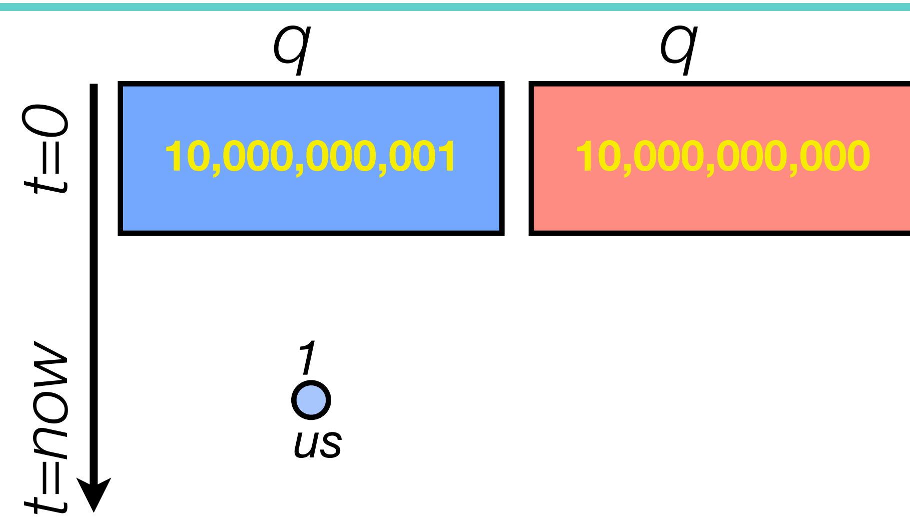
The SM of Particle Physics



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

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} $\Delta N_B/N_\gamma$.
- To create a larger asymmetry need
  - new sources of CP violation



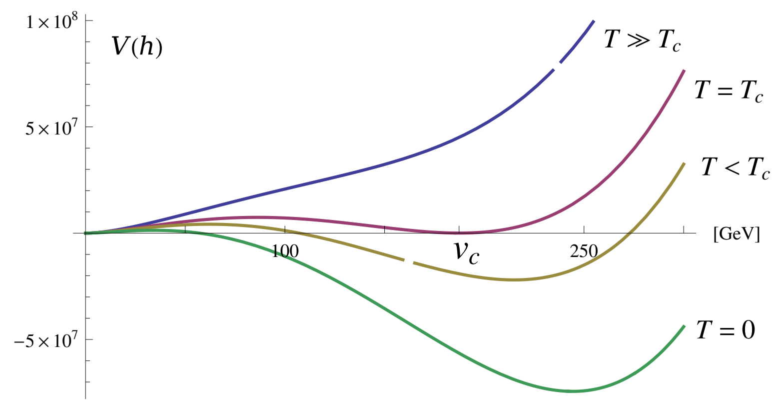
C	Charge Conjugation	particle⇔anti-particle
P	Parity	$x \to -x$, $y \to -y$, $z \to -z$
T	Time Reversal	$t \to -t$

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:

Electroweak Baryogenesis

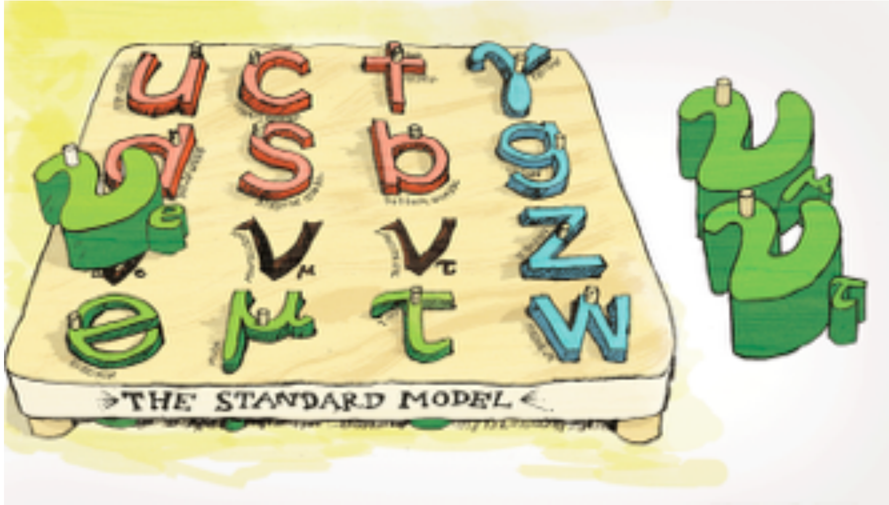
- Sakharov conditions: C, CP and B violation occurring out of equilibrium. In SM:
  - B violation unsuppressed at T≳EW scale
  - Displacement from equilibrium could be provided by a first order EW phase transition.
  - To freeze out generated BAU inside bubble, EWPT must be strongly first order, $v_c/T_c \gtrsim 1.0$
  - Not realised in SM for $m_h \gtrsim m_W$
  - CPV from CKM insufficient

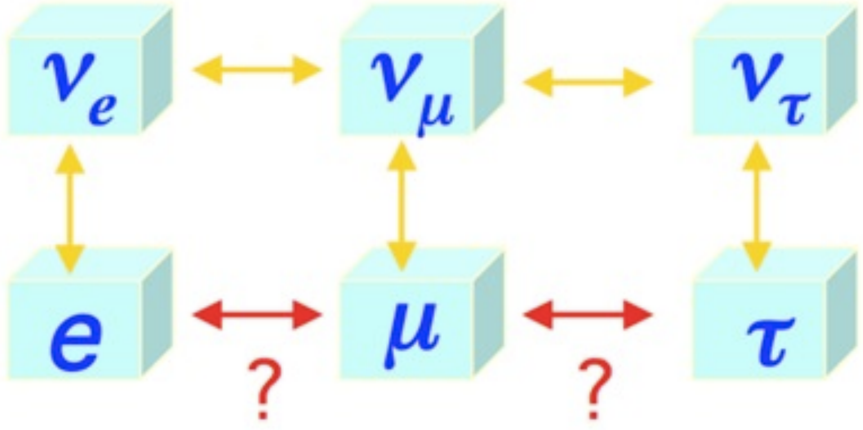


- **New CPV or extended scalar sector can both provide baryogenesis. You may not need more CPV to do it if you have a 2HDM.**

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.





The case for new physics manifesting in Flavour

Issues (addressable at a Flavour factory)

→ NP beyond the direct reach of the LHC

- Baryon asymmetry in cosmology
  → New sources of CPV in quarks and charged leptons, extra Higgs.
- Quark and Lepton flavour & mass hierarchy
  → restored L-R symmetry, extended gauge sector
- 19 free parameters
  → Extensions of SM relate some, (GUTs)

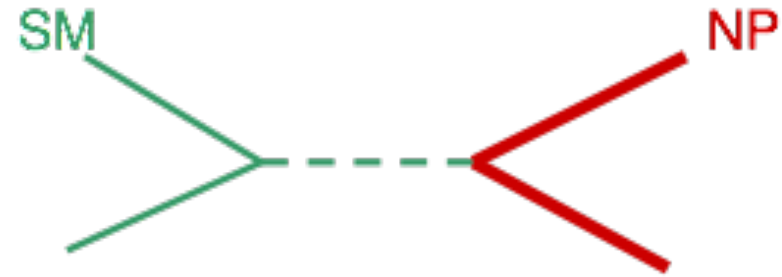
$$\mathcal{L}_{\text{Yukawa}} = g_u^{ij}\, \bar{u}_R^i\, H^T\, \epsilon\, Q_L^j - g_d^{ij}\, \bar{d}_R^i\, H^\dagger\, Q_L^j - g_e^{ij}\, \bar{e}_R^i\, H^\dagger\, L_L^j \quad + \text{h.c.}\,,$$

$$\mathcal{L}_{W^\pm\ \text{quark int.}} = \frac{g_2}{\sqrt{2}}\, W_\mu^+\, \bar{u}_L'\, \gamma^\mu\, V_{\text{CKM}}\, d_L' + \text{h.c.}\,,$$

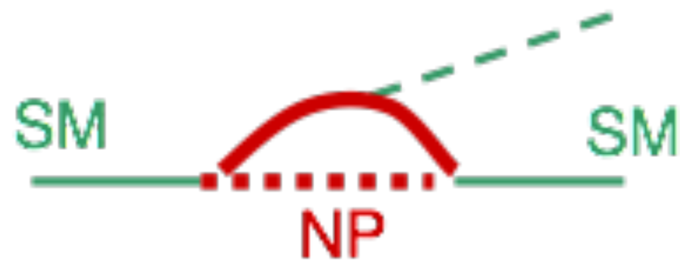
- Finite neutrino masses
  → Charged lepton flavour violation
- No (WIMP) candidates for Dark Matter
  → Hidden dark sector flavoured?

Searches for New Phenomena

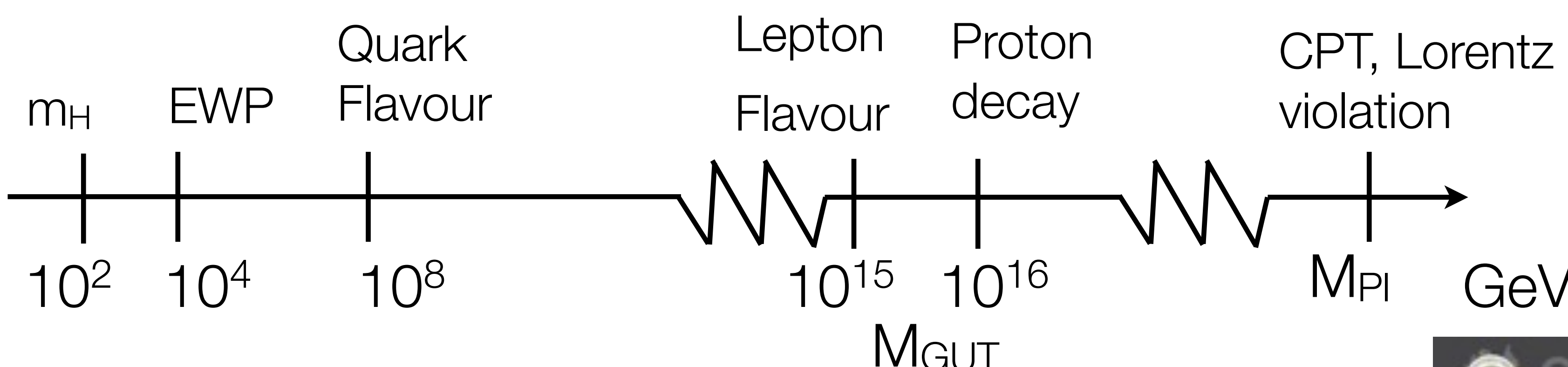
- **Energy Frontier**: Production of **new particles** from *collisions* at high-***Energy*** (**LHC**)
  - *Limited by Beam energy*



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



Maximum Energy/Mass Scale reach:



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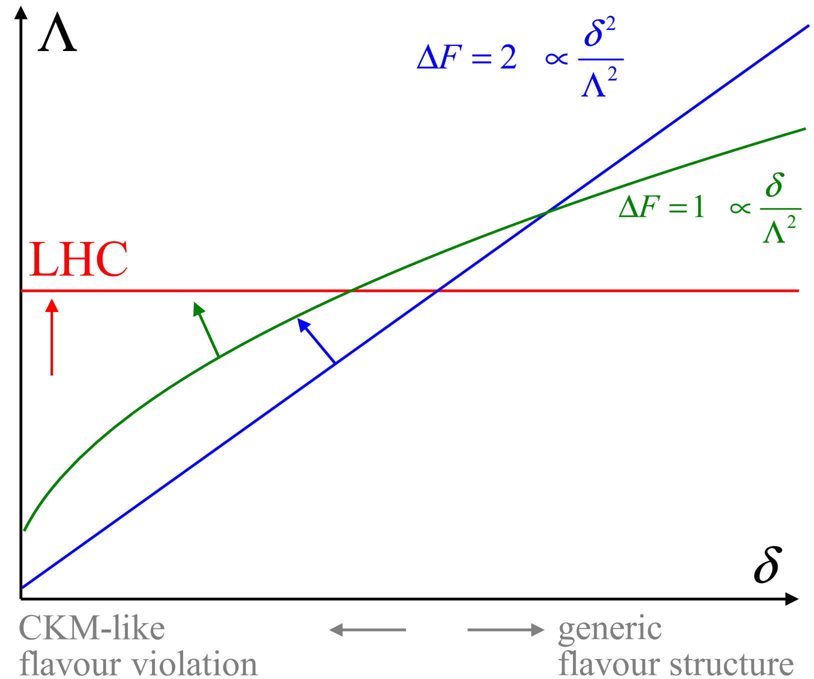

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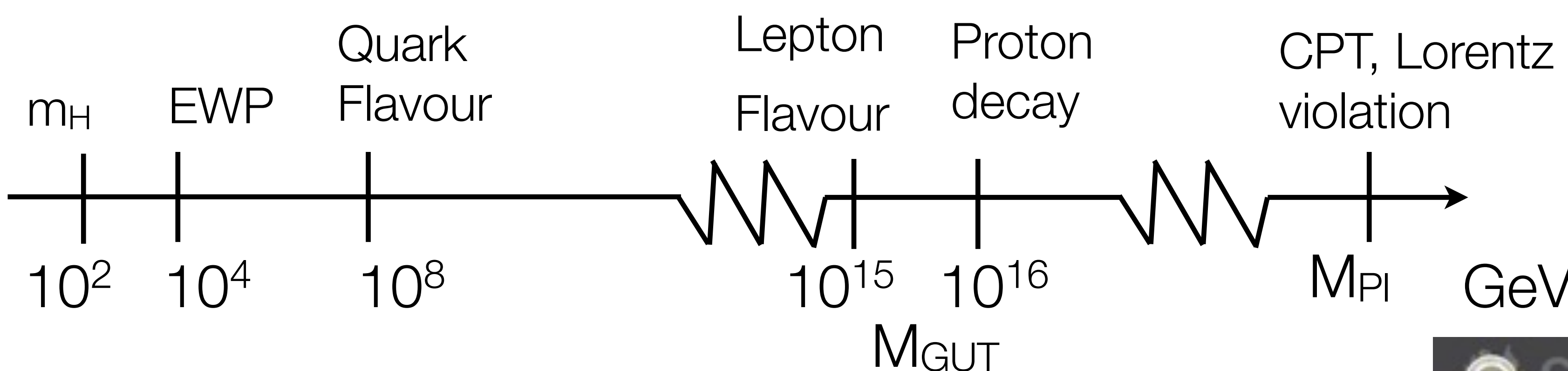


The Flavour Sector of the Standard Model

Basis of the Standard Model

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}D\psi$$ Gauge Sector

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

$$+|D_\mu h|^2 - V(h)$$ Electroweak Symmetry Breaking Sector

- Flavour Sectors contain the majority of the free parameters of the Standard Model!

  There is a lot to study!

2. Brief history of discovery

1947: Strangeness

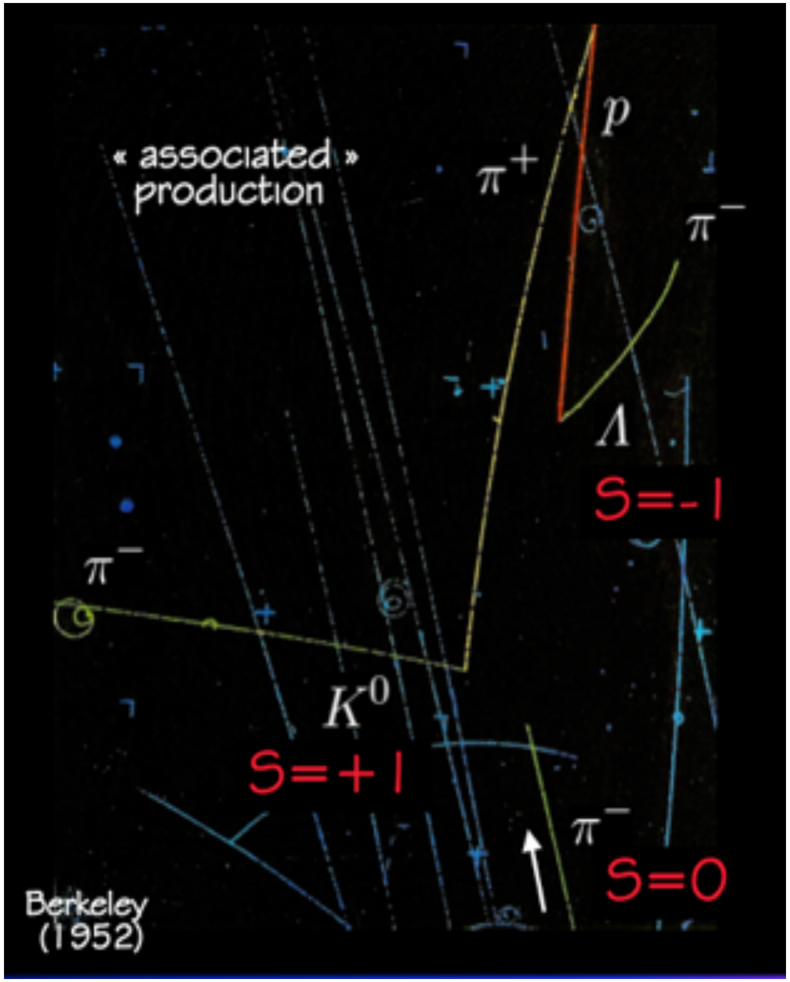
$$p + \pi^- \to \Lambda + K^0$$

New particle observed, produced in strong interaction,
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”

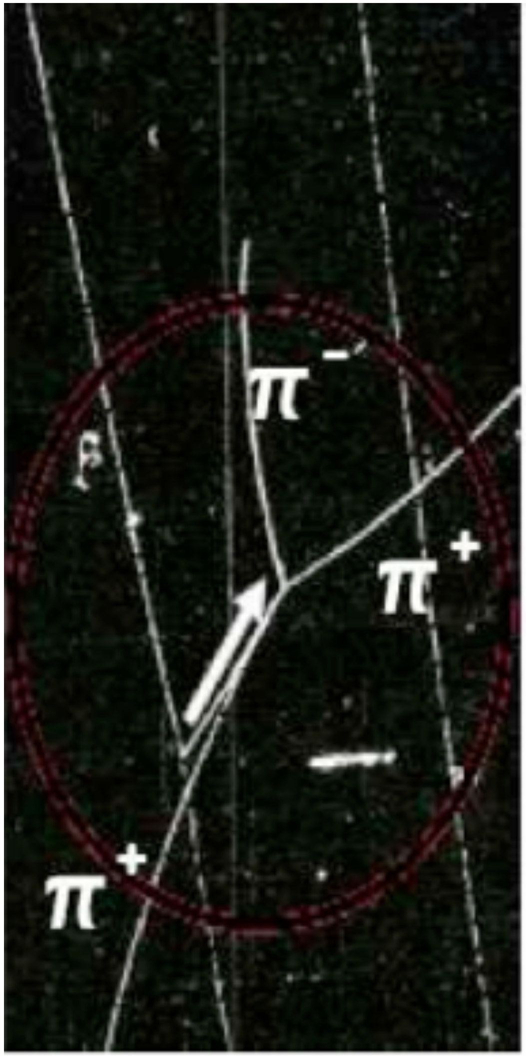
Observation of two strange mesons with

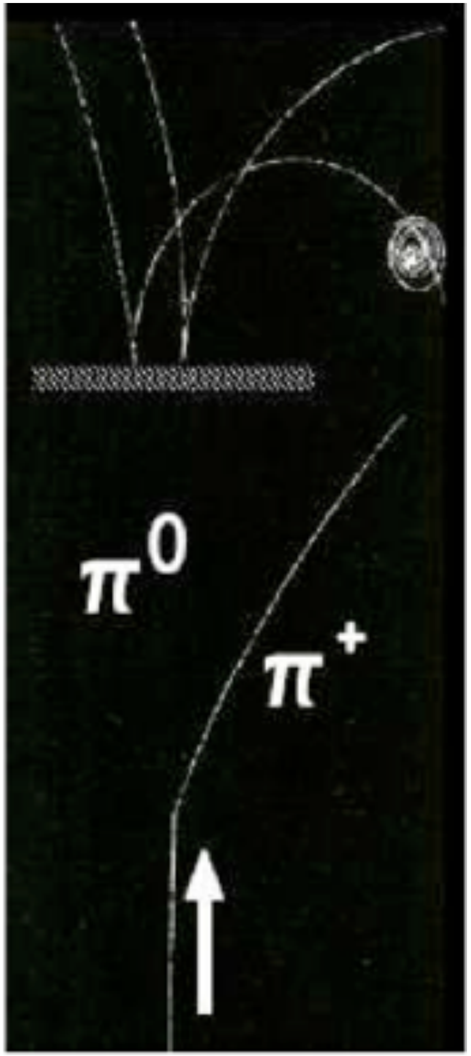
- same mass
- same production rate
- same lifetime

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

But: decay into final states with different parities

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



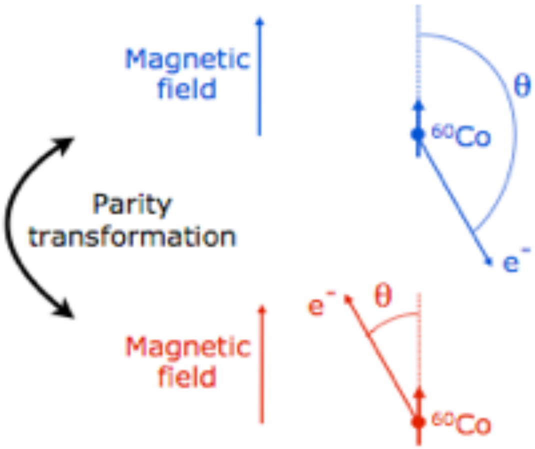


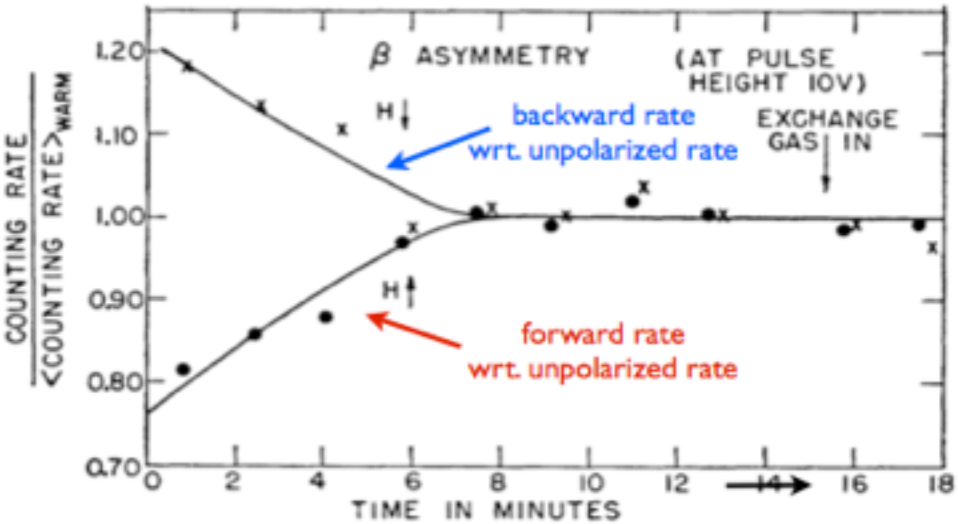
1956: Parity Violation

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 @ 0.01K

Most electrons emitted opposite to direction of field - PARITY VIOLATION





^{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.

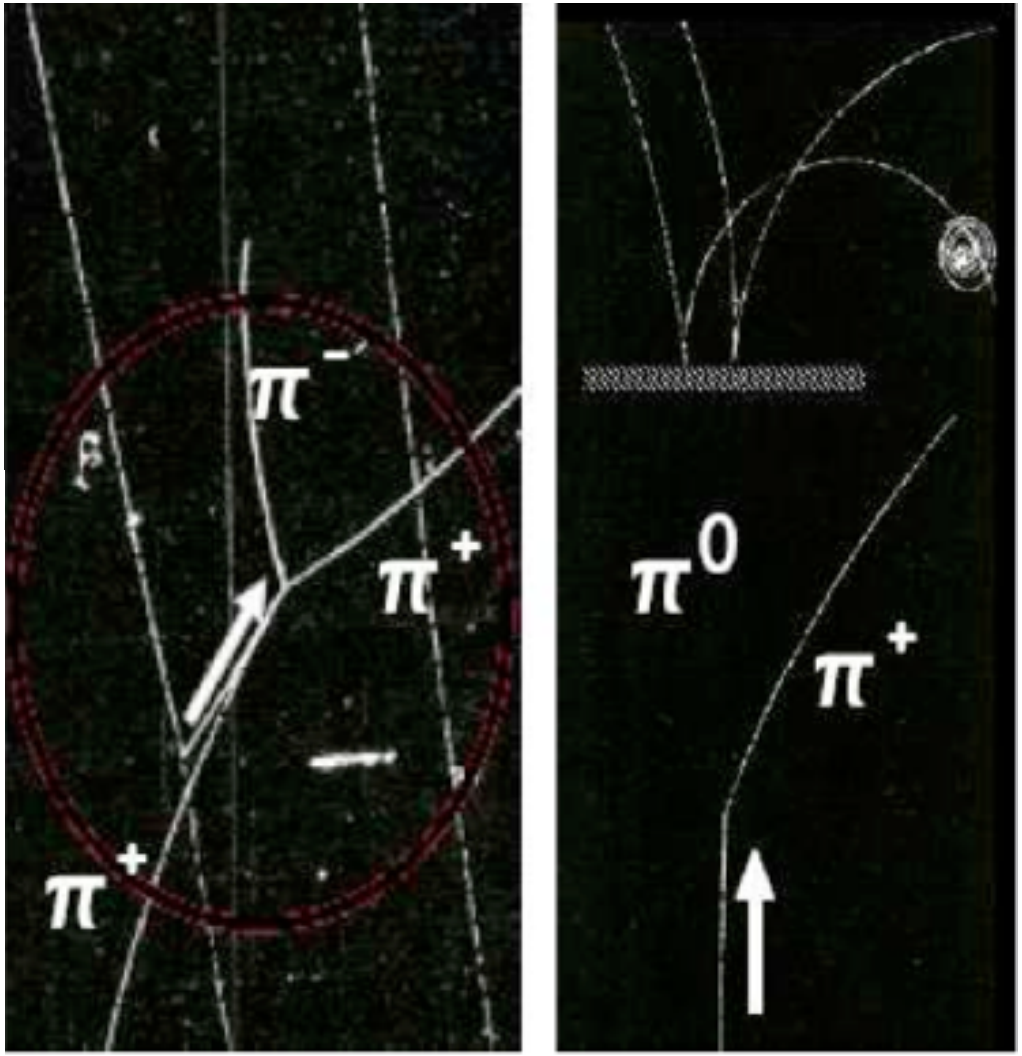
$$\theta = \tau = K^+$$

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

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

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

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

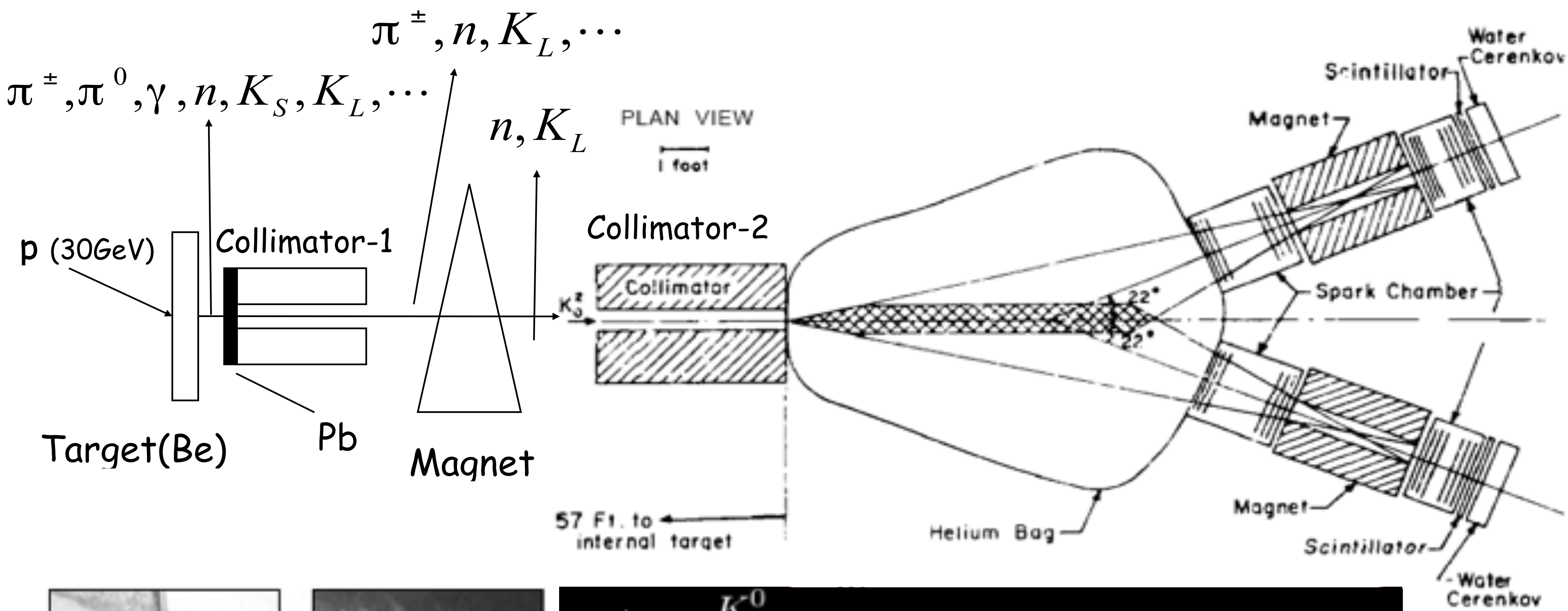
- CP operator gives:

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

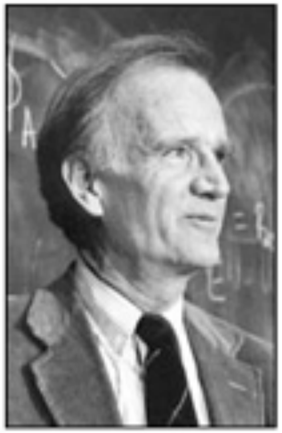
- Thus:

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

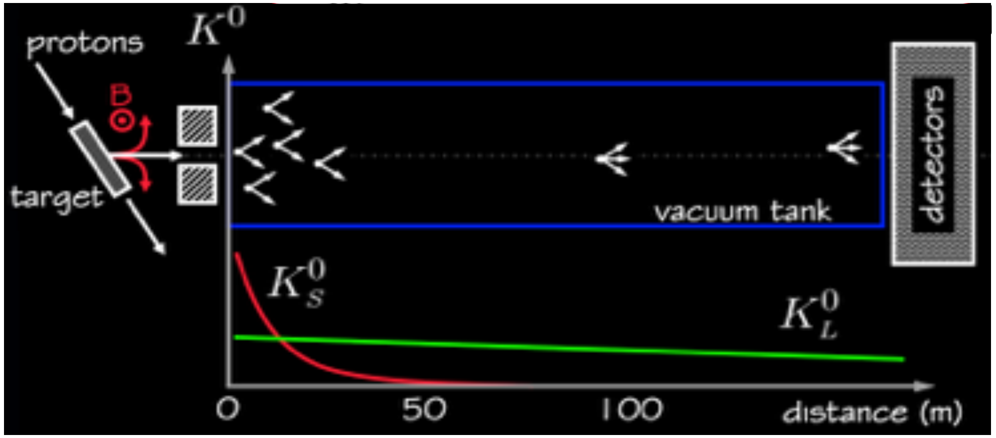
1964: CP Violation - Cronin-Fitch Experiment



James Cronin



Val Fitch



CP violation was discovered in 1964 by Cronin, Fitch et al.

But seen only as a ~0.2% effect in certain K_L decays (e.g. $K_L \rightarrow \pi\pi$)

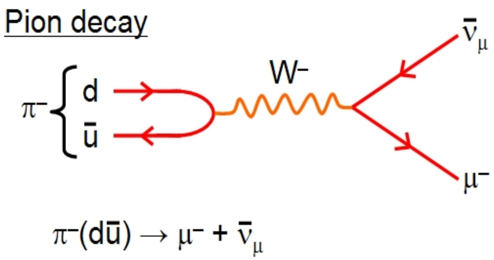
(not in π or nuclear β-decays)

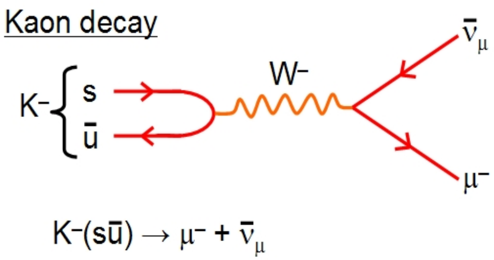
1963: Cabibbo mixing

- The weak coupling didn't look universal
- Cabibbo (1963) - weak interactions couple to a linear combination

$$d' = \cos\theta_C \cdot d + \sin\theta_C \cdot s$$

$$\frac{s \to u\, W^-}{d \to u\, W^-} = \frac{\sin^2\theta_C}{\cos^2\theta_C} \approx \frac{1}{20}$$





- But, if the neutral weak currents also couple to d' expect large FCNC. Experimentally BR $(K \to \mu\,\mu) \sim 7 \times 10^{-9}$

1970: The GIM Mechanism

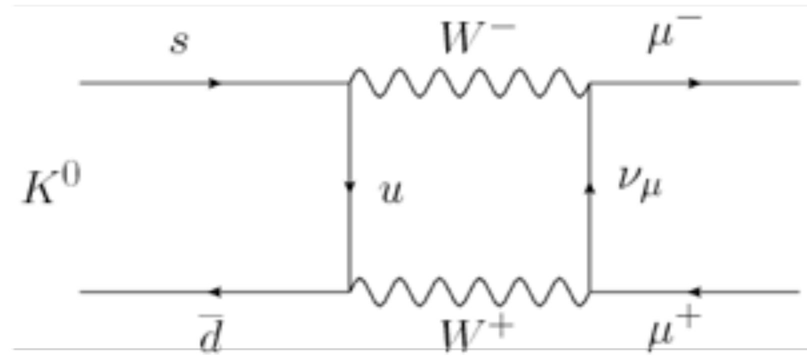
- Observed branching ratio $\boldsymbol{K^0 \rightarrow \mu^+\mu^-}$

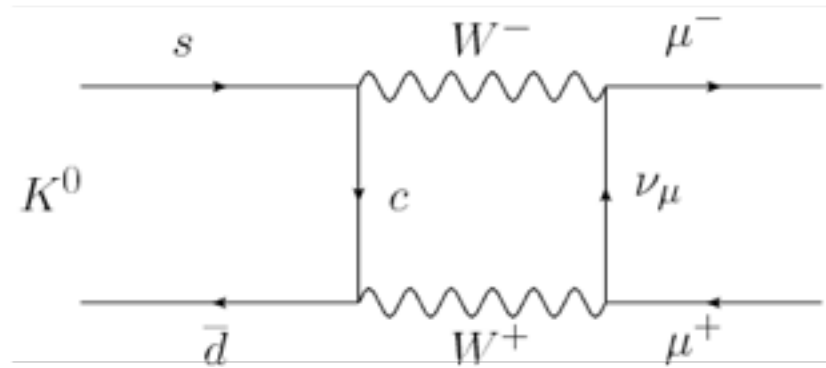
$$\frac{\mathcal{B}K_L \to \mu^+\mu^-}{\mathcal{B}K_L \to \text{all}} = (7.2 \pm 0.5) \times 10^{-9}$$

- 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"
  - Prediction of m(c)≈1.5GeV





1973: The CKM Mechanism

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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)

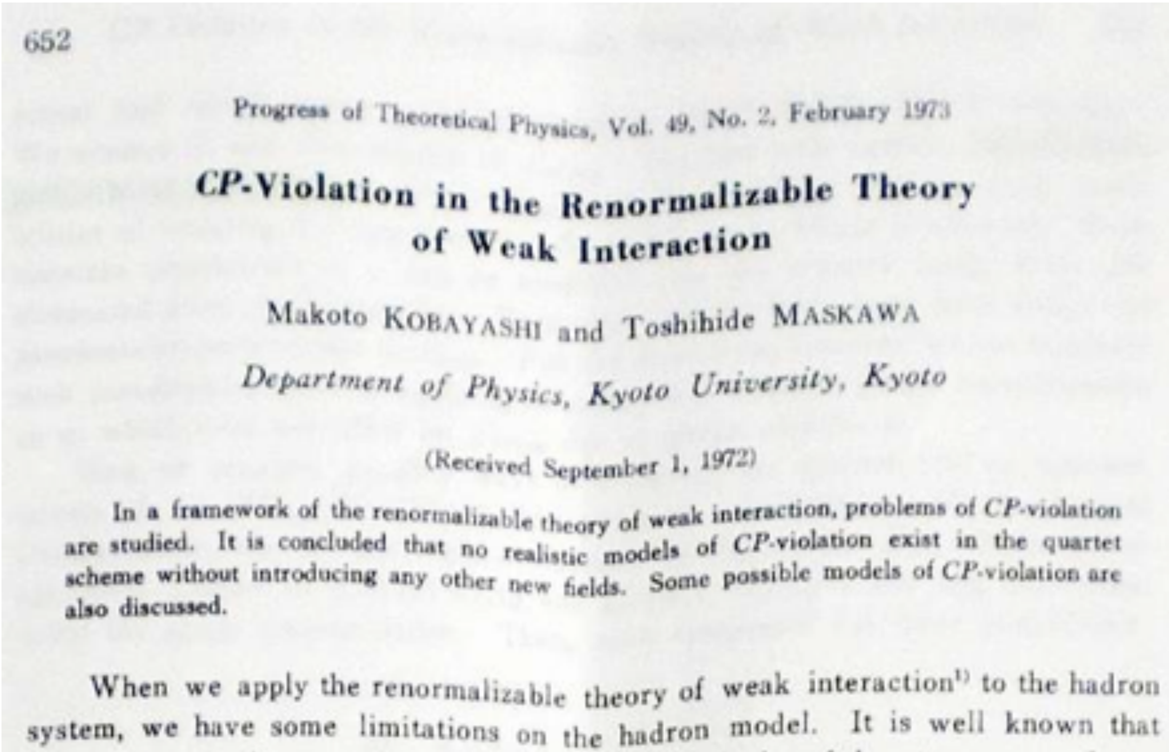
In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

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

Charm hadn't been "discovered" yet!

Need a complex coupling specific to weak strangeness-changing processes

1973: The CKM Mechanism



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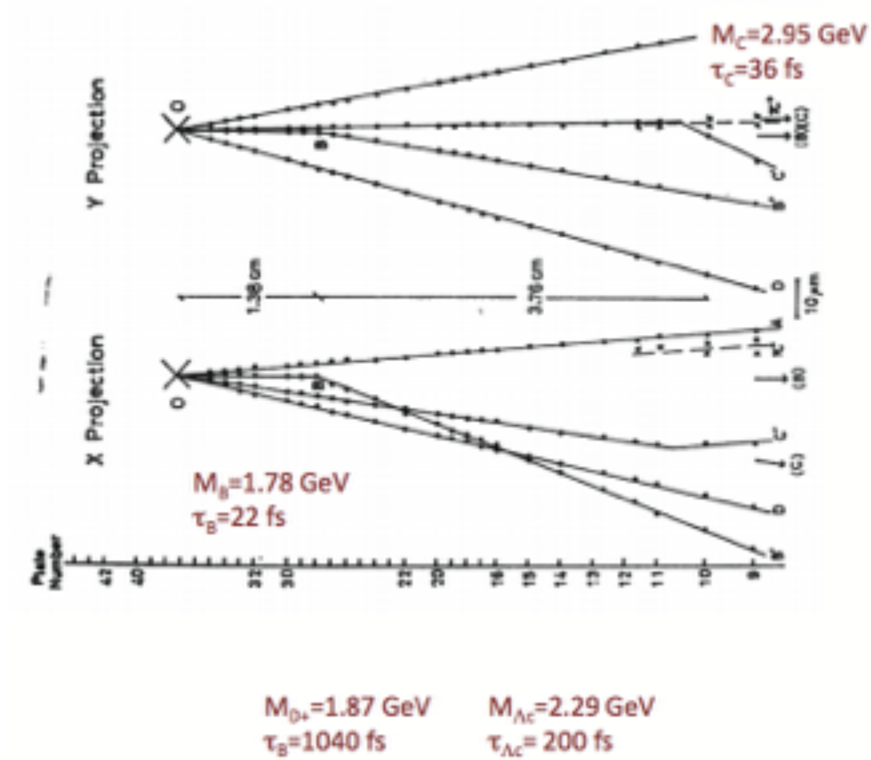
Charm hadn't been "discovered" yet!

Need a complex coupling specific to weak strangeness-changing processes

But cannot accomplish this with only two generations of quarks (u, d, s, ..). Require a third generation of quarks.

Insight… First hint of Charm was in 1971!

- **Announced at cosmic ray conference in Hobart in 1971!**



Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

Institute for Nuclear Study
University of Tokyo
**Yokohama National University*

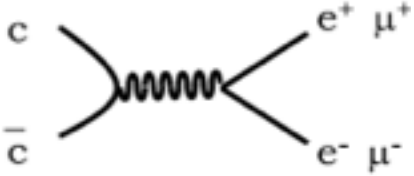
August 9, 1971

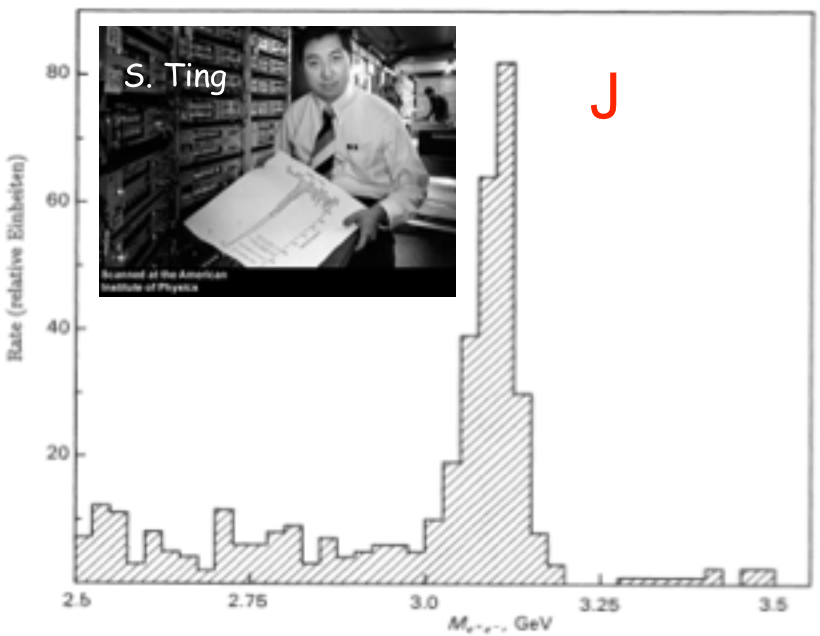
Assumed decay mode	M_x GeV	T_x sec
$X \to \pi^0 + \pi^{\pm}$	1.78	2.2×10^{-14}
$X \to \pi^0 + p$	2.95	3.6×10^{-14}

1974: Discovery of the Charm Quark

Brookhaven (S. Ting)

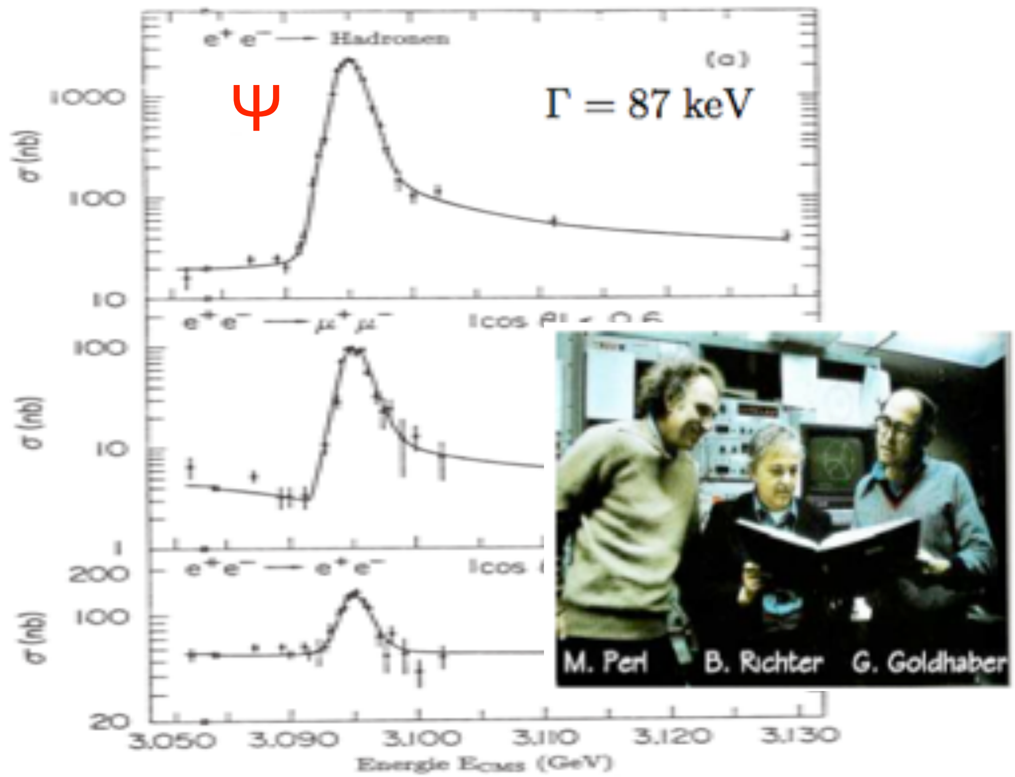
$$p + Be \rightarrow e^+e^- + X$$





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)

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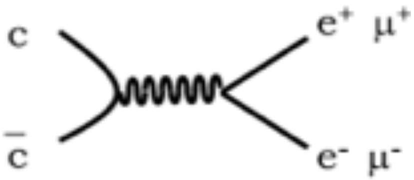

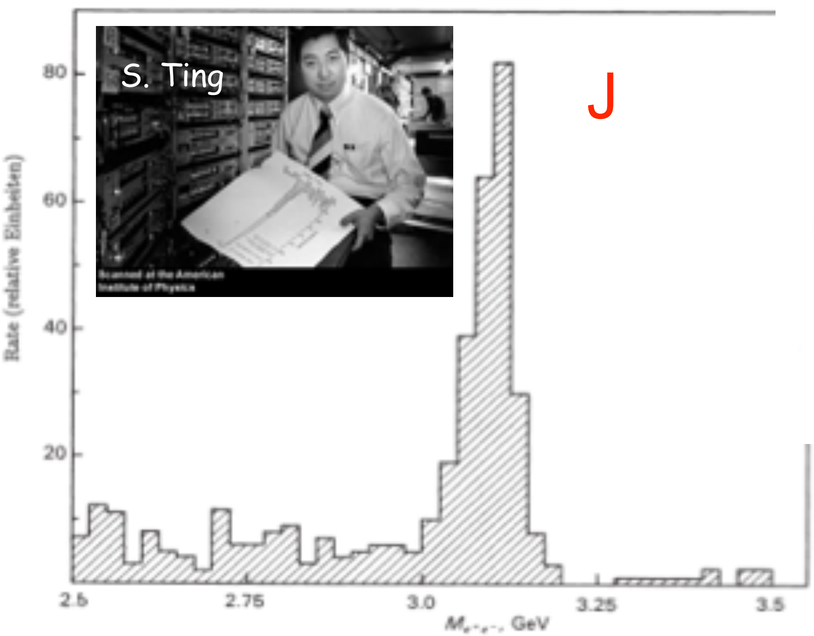

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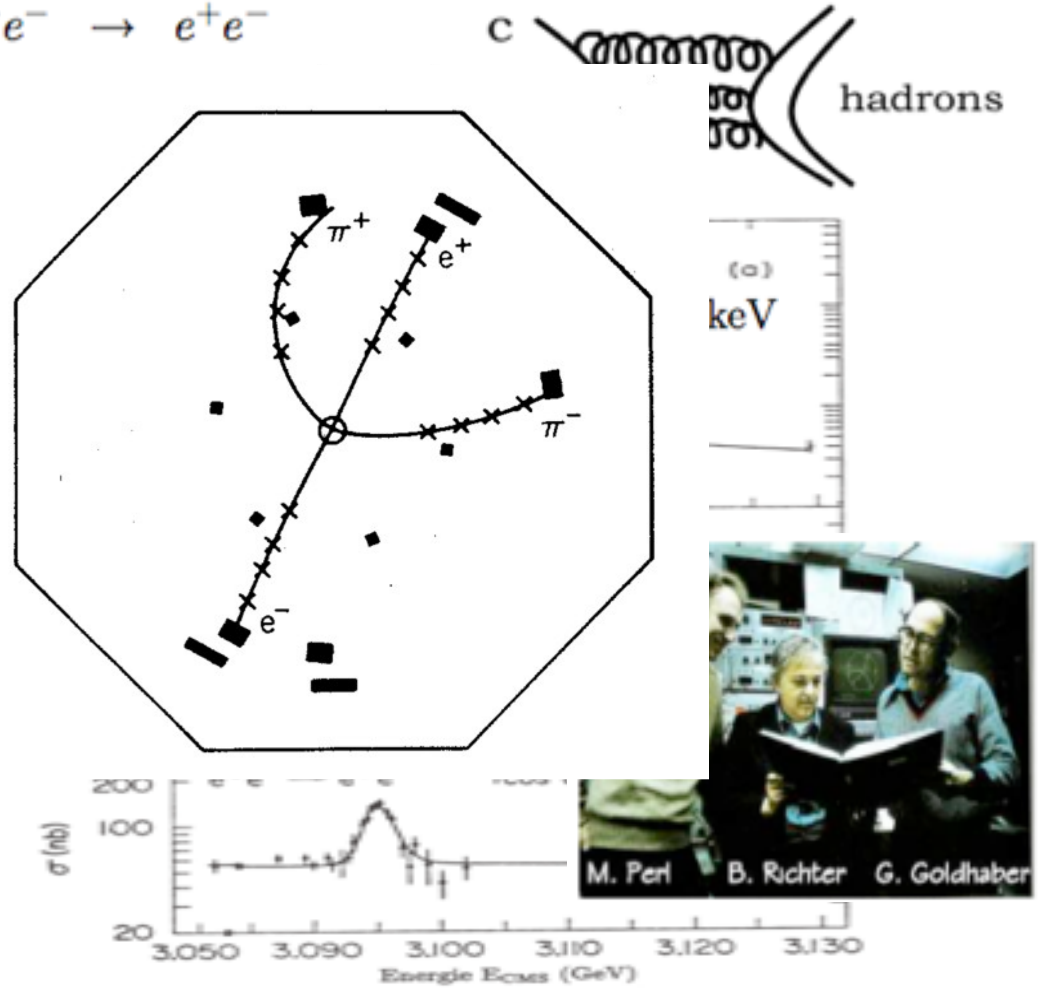
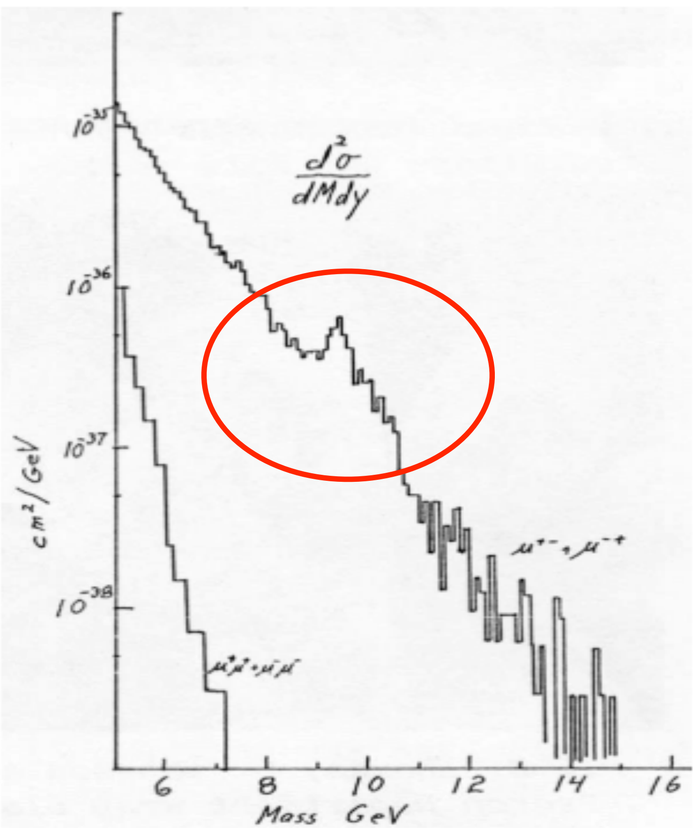


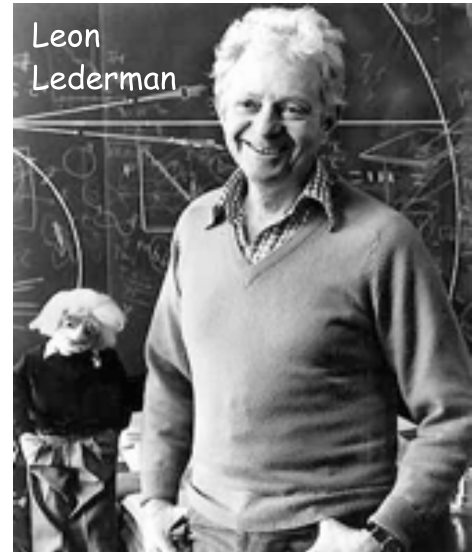
→ Discovered charmonium in 1974 : J/Ψ (Nobel Prize 1976)

1977: Discovery of the Bottom Quark

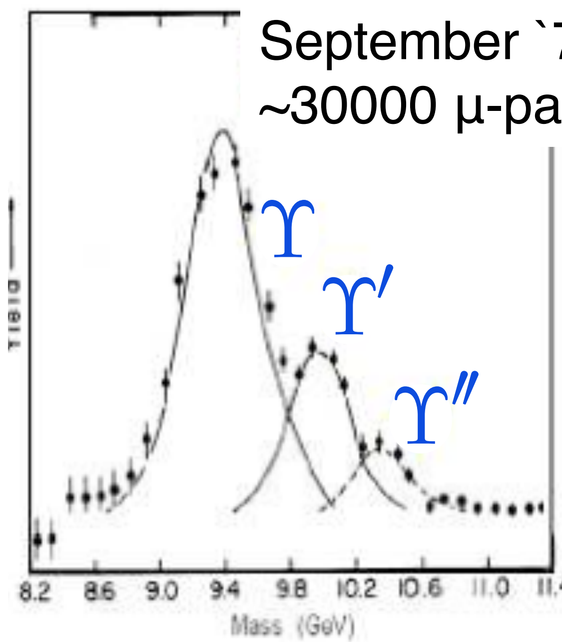
Are there really 3 generations?
Fermilab E288 Experiment observed excess of di-muon events at a mass of around 9-10 GeV (3 resonances)

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



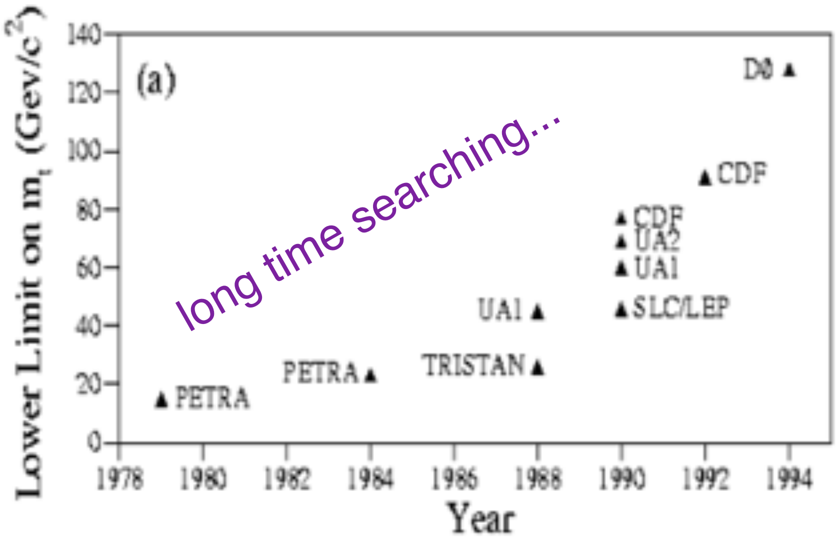


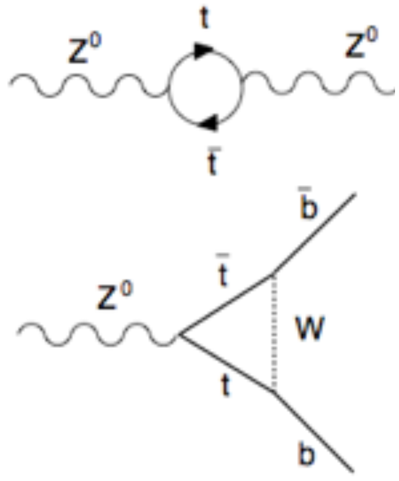
September `77:
~30000 μ-pairs



Discovery of bottomonium!

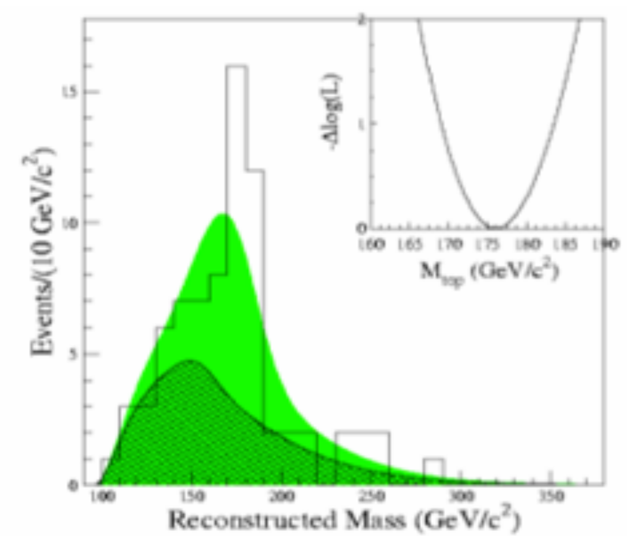
1995: Discovery of the Top Quark (20 year anniversary)





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

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



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

Historical discovery highlights in heavy quarks

James Watson Cronin — Val Logsdon Fitch

1964 Fitch and Cronin discover **CP violation** (indirect CP in K)

1970 $\Gamma(K^0 \to \mu\mu) \ll \Gamma(K^+ \to \mu\nu)$
Glashow-Iliopoulos–Maiani: No tree level FCNC ⇒ **Charm** inferred

1973 CPV in K due to **3rd generation**: Kobayashi & Maskawa (not a new force)

1987 Argus (DESY) *B* mixing
$\Delta m_B \Rightarrow \boldsymbol{m_t} \gg \boldsymbol{m_W}$

Photo: Kyodo/Reuters — **Makoto Kobayashi**; Photo: Kyoto University — **Toshihide Maskawa**

2002 BABAR/Belle establish indirect CP violation in B_d mesons, **confirming KM theory**

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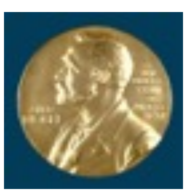


Photo: Kyodo/Reuters

Makoto Kobayashi

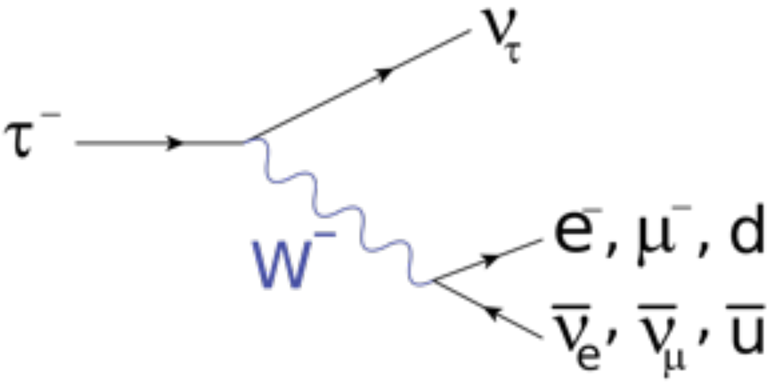
Photo: Kyoto University

Toshihide Maskawa

2002 BABAR/Belle establish indirect CP violation in B_d mesons, **confirming KM theory**

Charged leptons

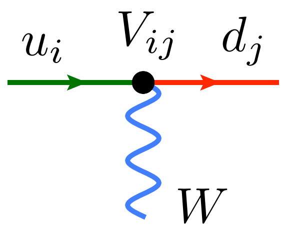
- Anderson, Neddermeyer discovered the μ with cosmic rays at Caltech in 1936. But because its mass was so close to the Yukawa pion, it was not recognized as a heavy electron until 1947 → I.Rabi:"Who ordered that?".
- In 1962 Lederman, Schwartz and Steinberger discovered that there were at least two kind of neutrinos with different properties.Using $\pi \rightarrow \mu\nu$ decays,
- The τ lepton was observed in a series of experiments between 1974-77 by Perl et al. at SLAC. They found a number of unexplained events of the type e+e—→ eμ+ ≥ 2 undetected. The interpretation was e+e —> τ+τ—> eμ+4ν with m_τ~1.6-2 GeV.



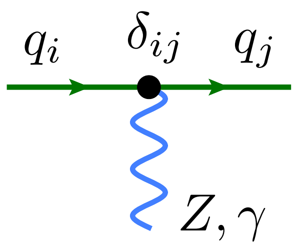
3. The CKM mechanism

Weak Interaction

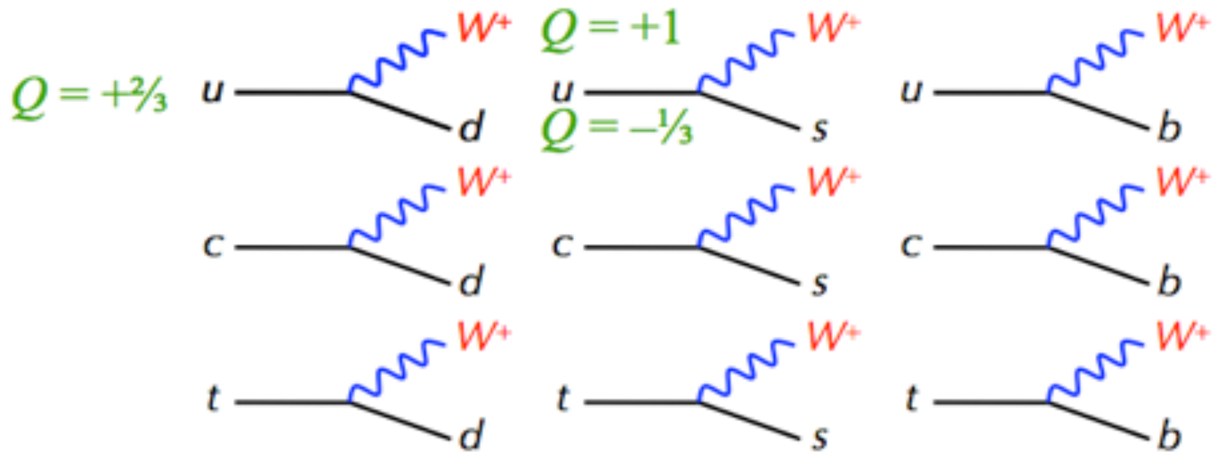
The SM describes the mixing of quarks of different generations through the weak force.



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 unitary ! | Mass eigenstate

→ 4 independent parameters (3 Euler angles, 1 phase)
Single source of CPV in the SM.

The (Flavour) Parameters of the SM

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

2 Electroweak symmetry breaking: v, m_H

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}...)

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

(3 lepton mixing angles + 1 phase)

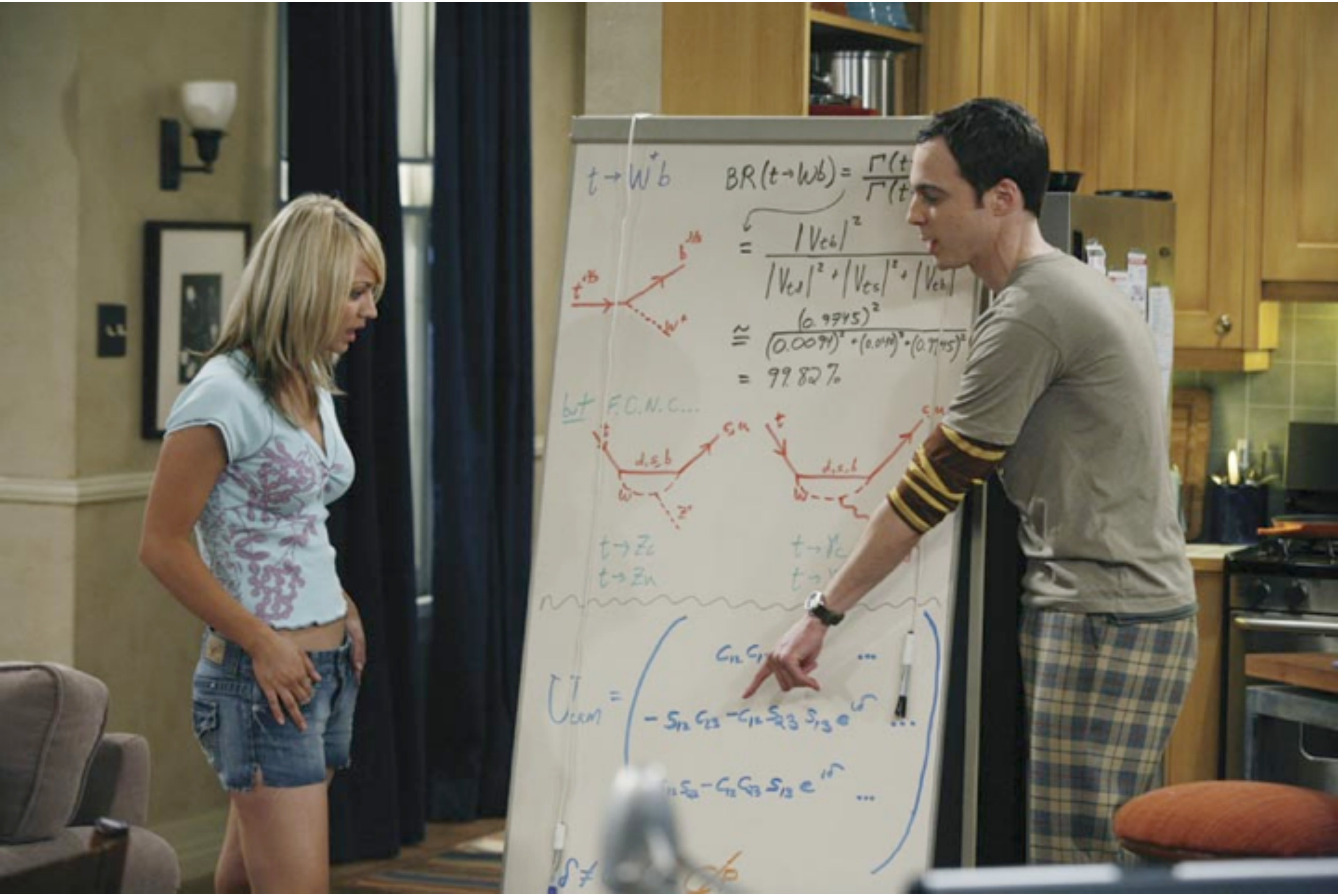
()=with neutrino masses

CKM matrix

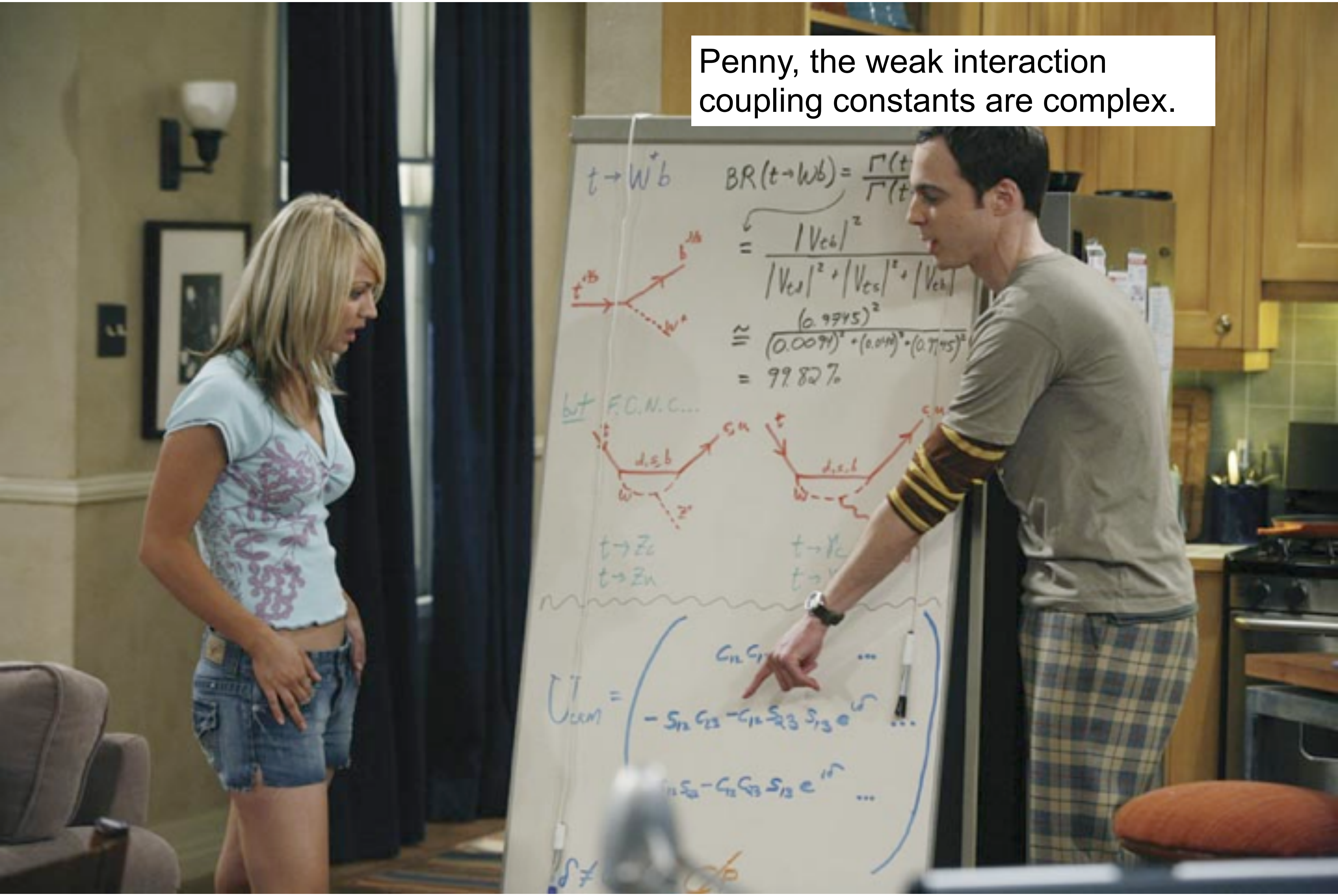
PMNS matrix

Flavour Parameters

“The Big Bang Theory”

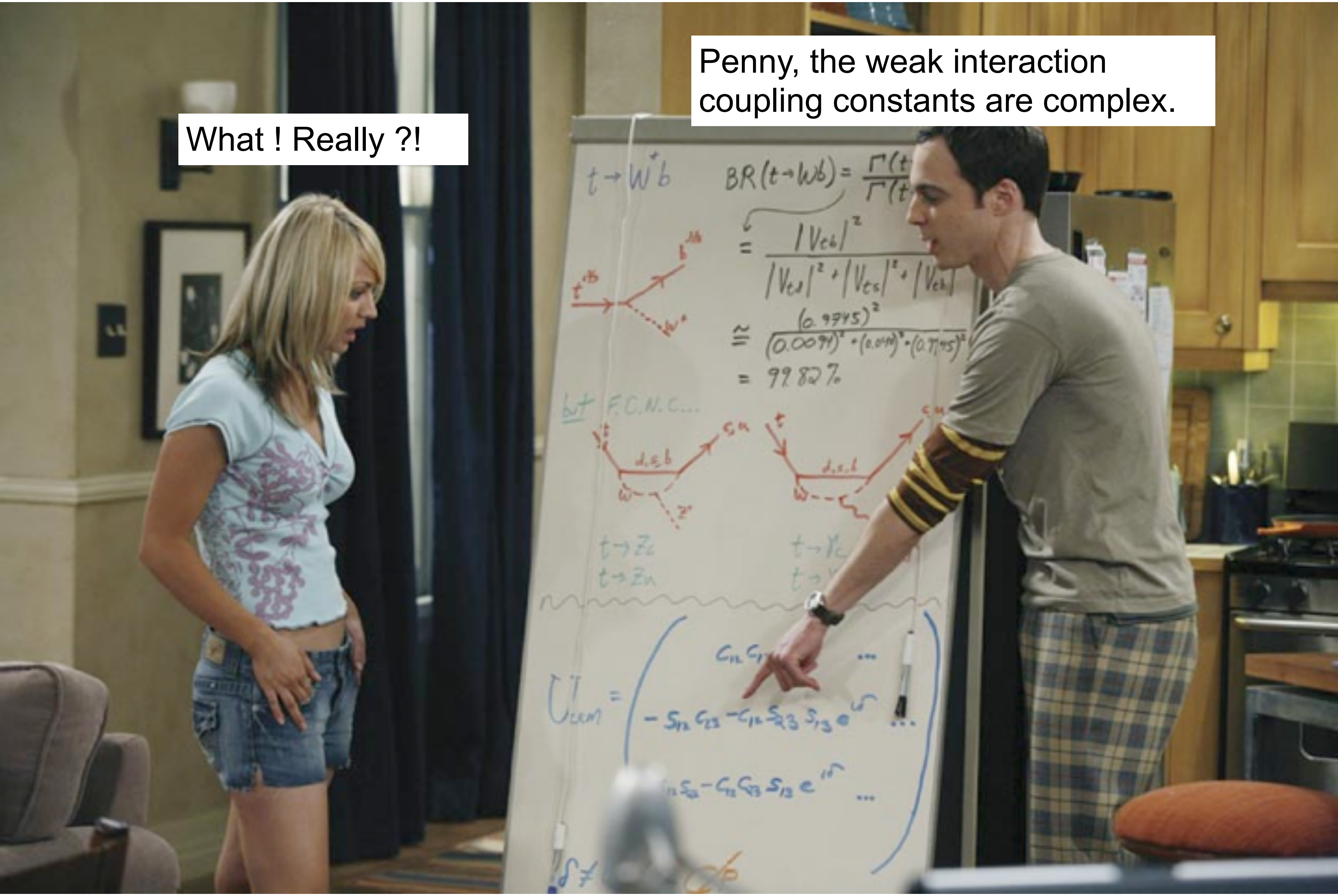


“The Big Bang Theory”



Penny, the weak interaction coupling constants are complex.

“The Big Bang Theory”



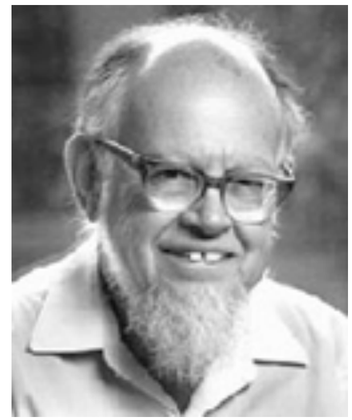
Hierarchy of the CKM Matrix

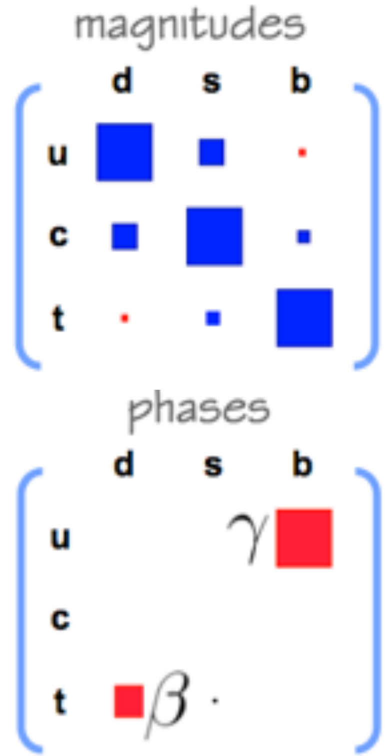
- Wolfenstein Parametrization: Expansion in $\lambda = \sin\theta_C \approx 0.22$

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

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

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



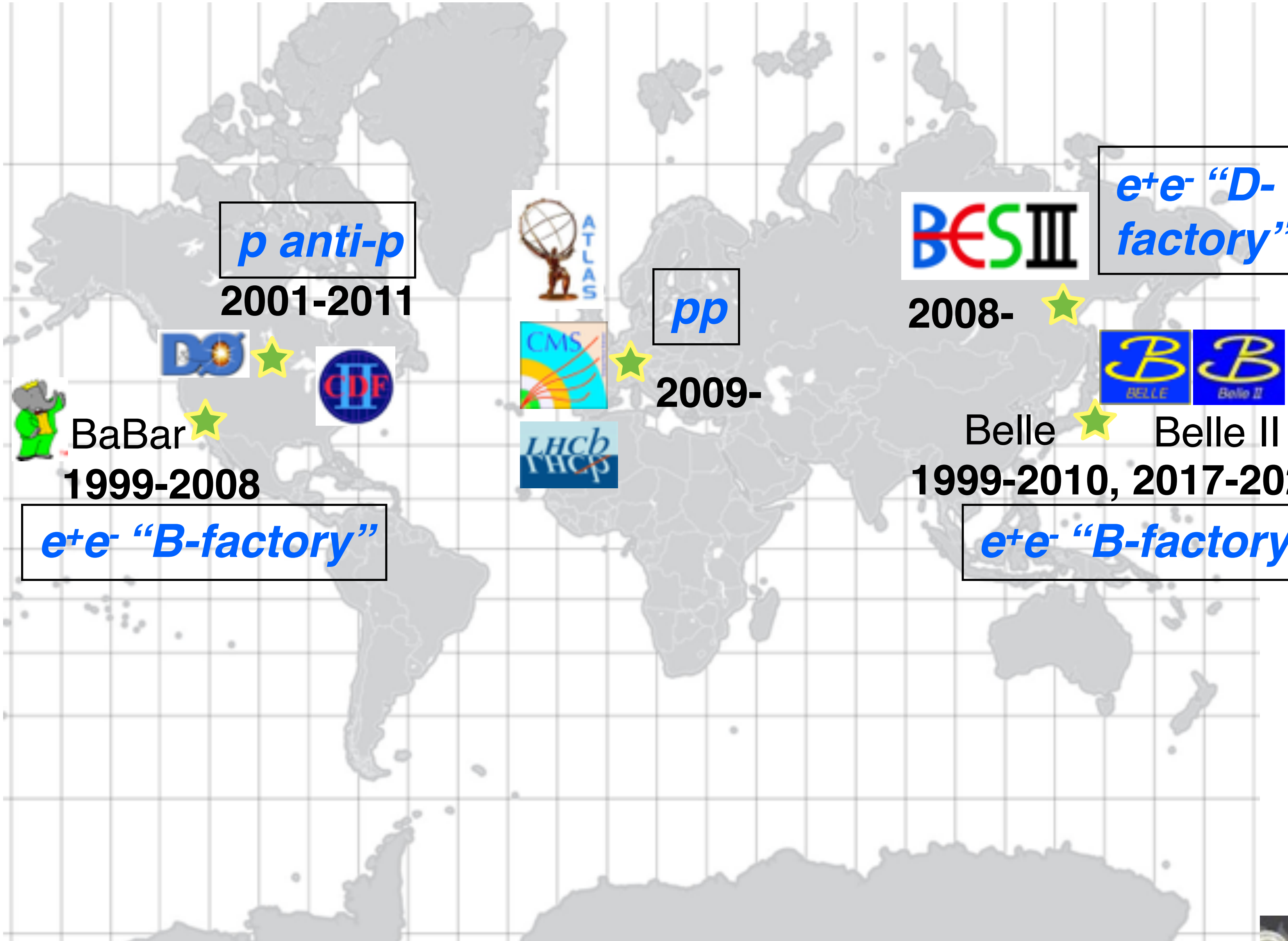


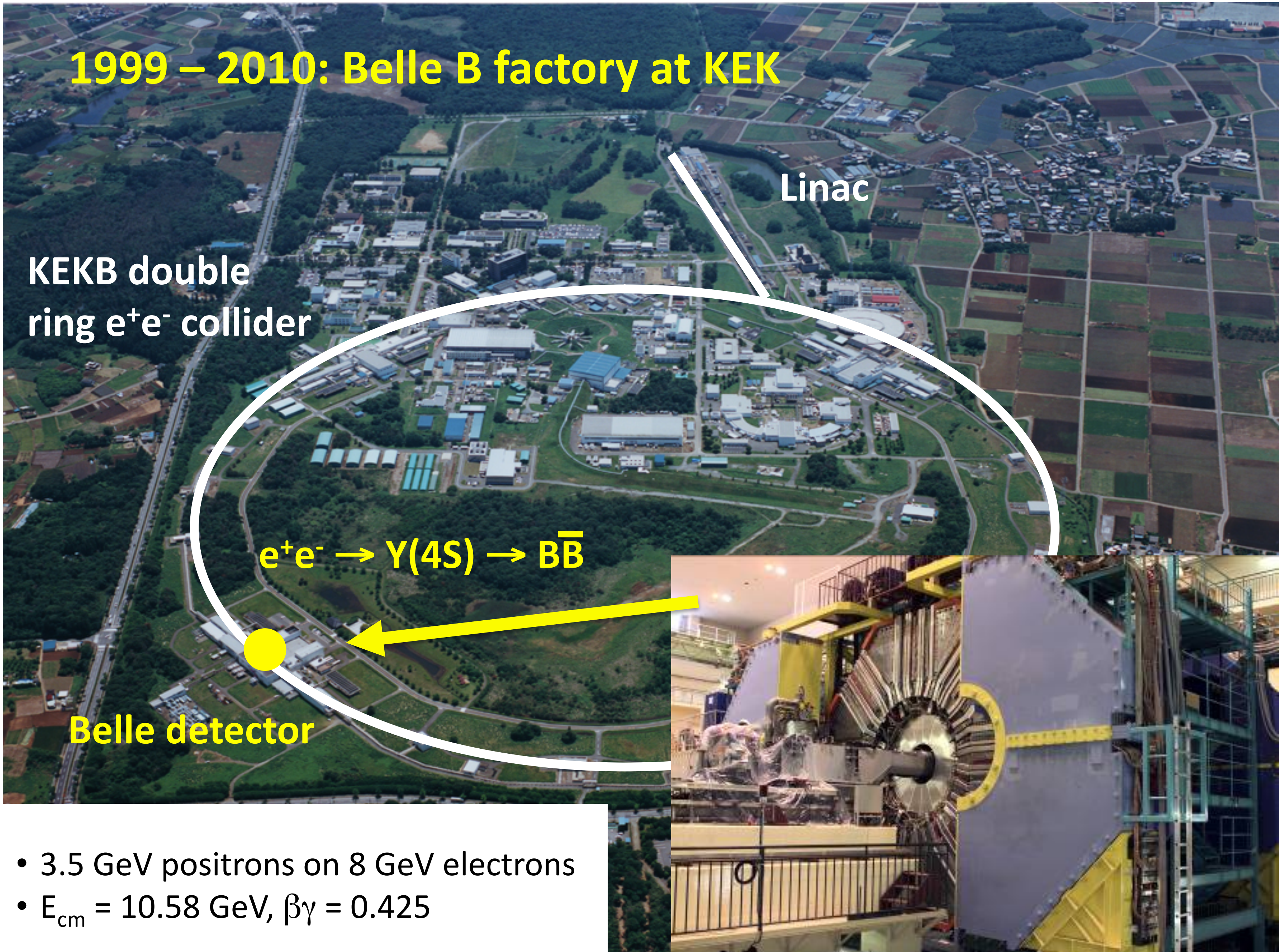
$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda^2 \equiv \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2\lambda^4 \equiv \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad \bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

4. Experimental B, D, τ facilities

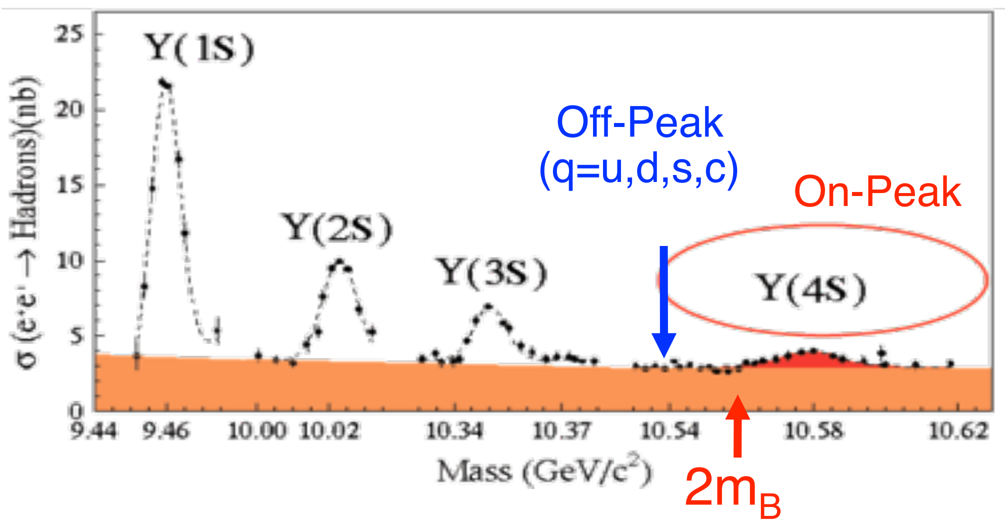
Where are B, D, τ Mesons Produced?

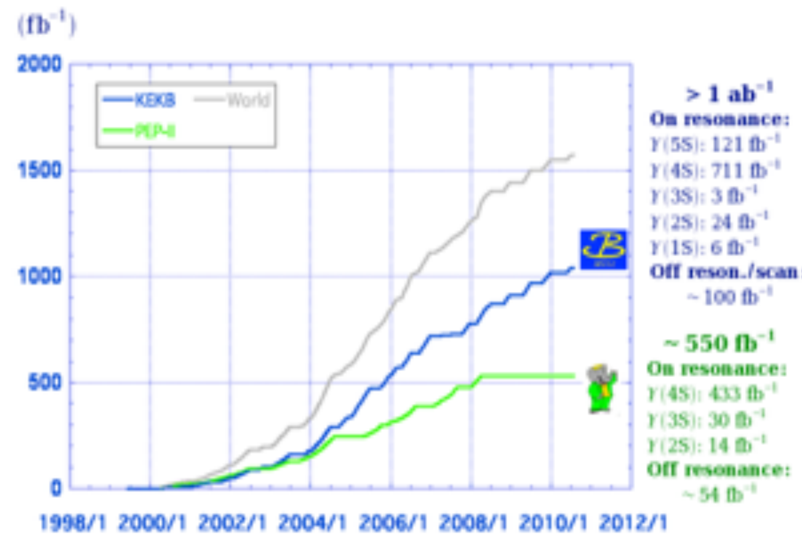




- 3.5 GeV positrons on 8 GeV electrons
- E_{cm} = 10.58 GeV, $\beta\gamma$ = 0.425

Production of B Mesons @ e+e- colliders

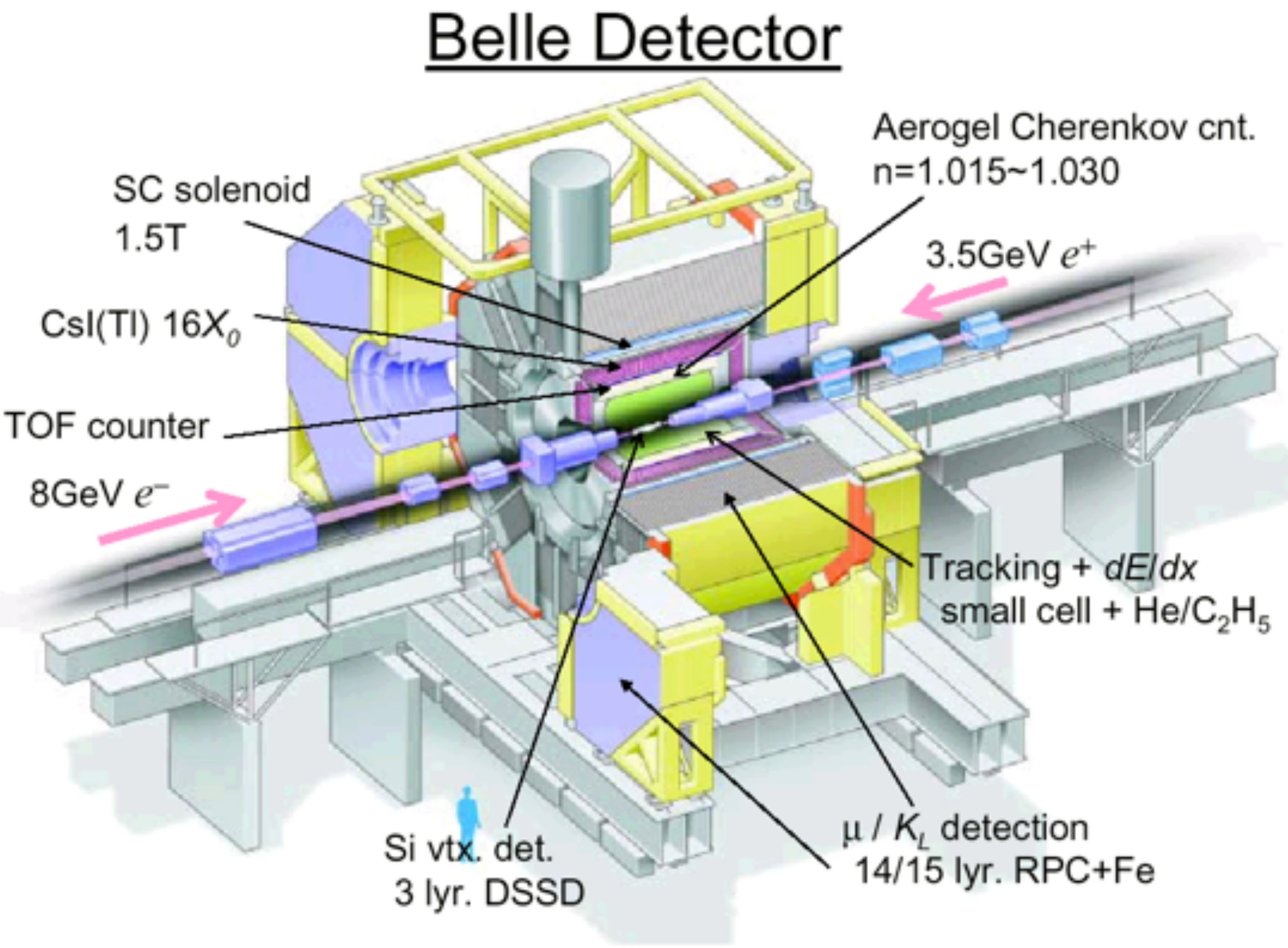




- Centre-of-mass energy = mass of Υ(4S)

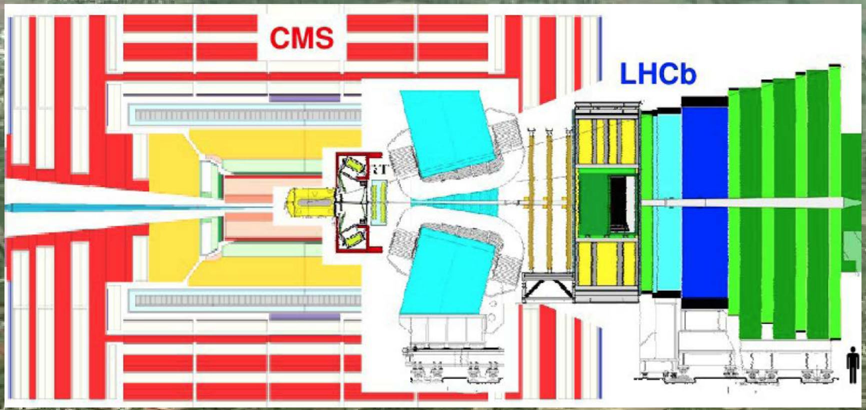
- Υ(4S) is bound $b\bar{b}$-state that decays to ~100% to B^+B^- or $B^0\bar{B}^0$ pairs
- $1\ fb^{-1} \sim 1.1$ Million B pairs

The B-Factory Experiments

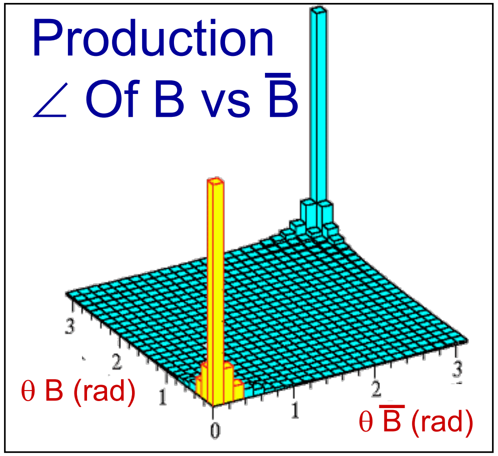


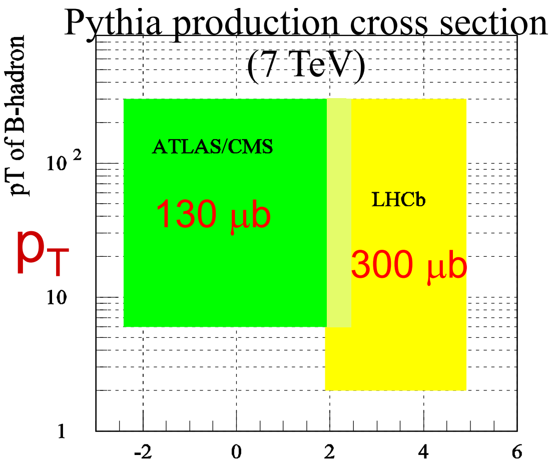
LHC 2009-

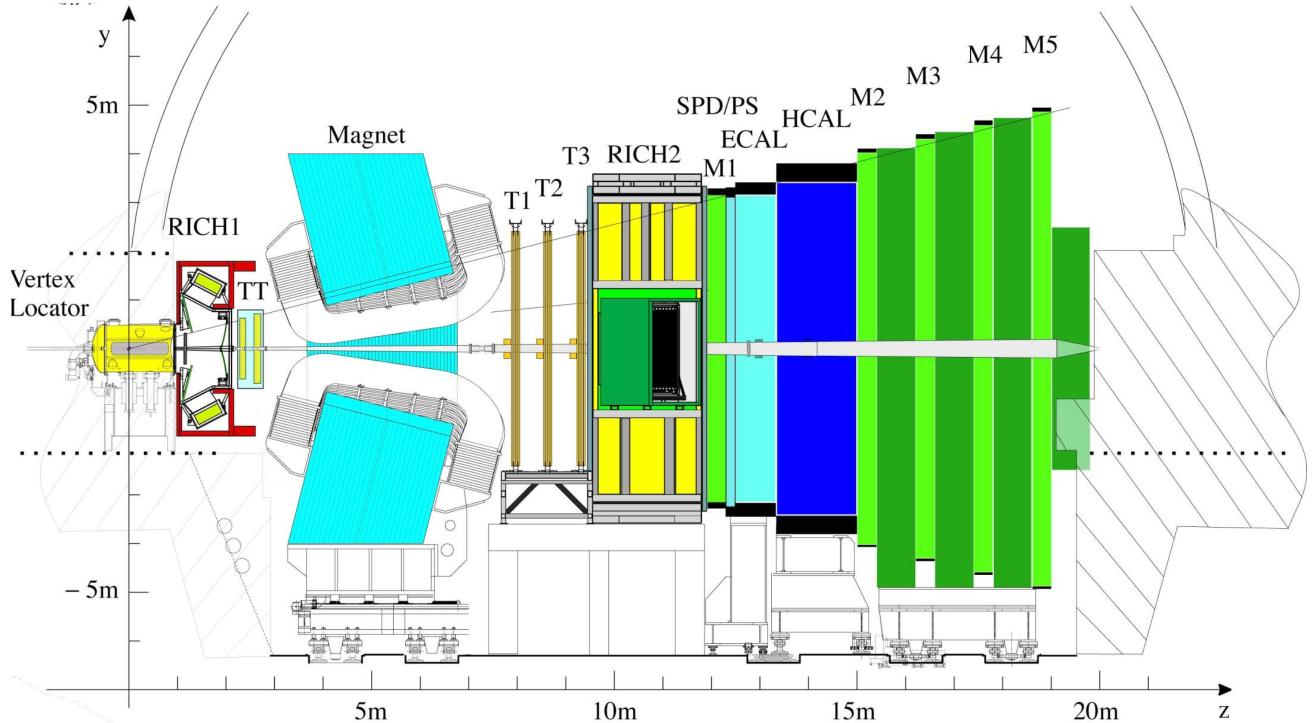
- More than 10^{12} b-anti-b pairs (10^9 at B-factories)produced already and growing.
  - LHCb dedicated B-physics detector
  - B-physics programs at CMS and ATLAS.



The LHCb Detector







b Production at Hadron Colliders

	e+e- (PEPII, KEKB)	pp→b anti-bX ($\sqrt{s}$=7TeV) LHC
Prod. σbb	1 nb	~300μb
typ. bb rate	10 Hz	~300kHz
purity	~1/4	~0.6%
pile-up	0	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

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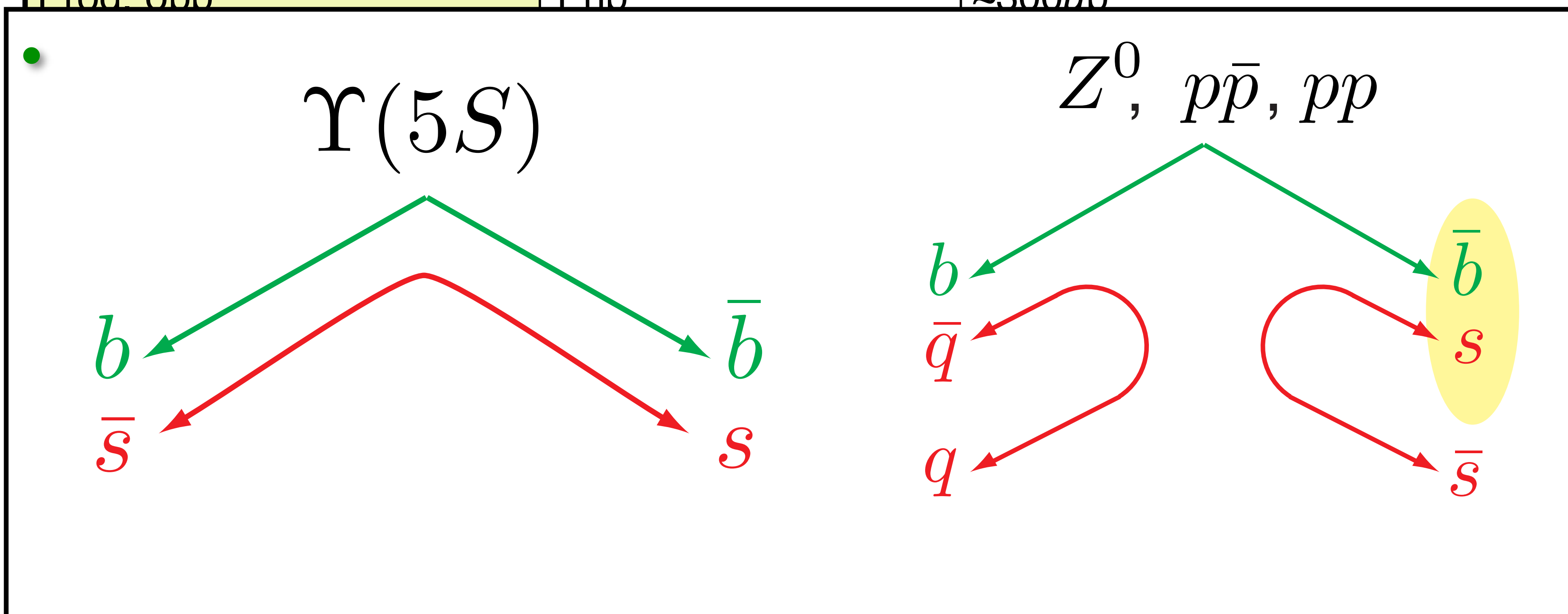
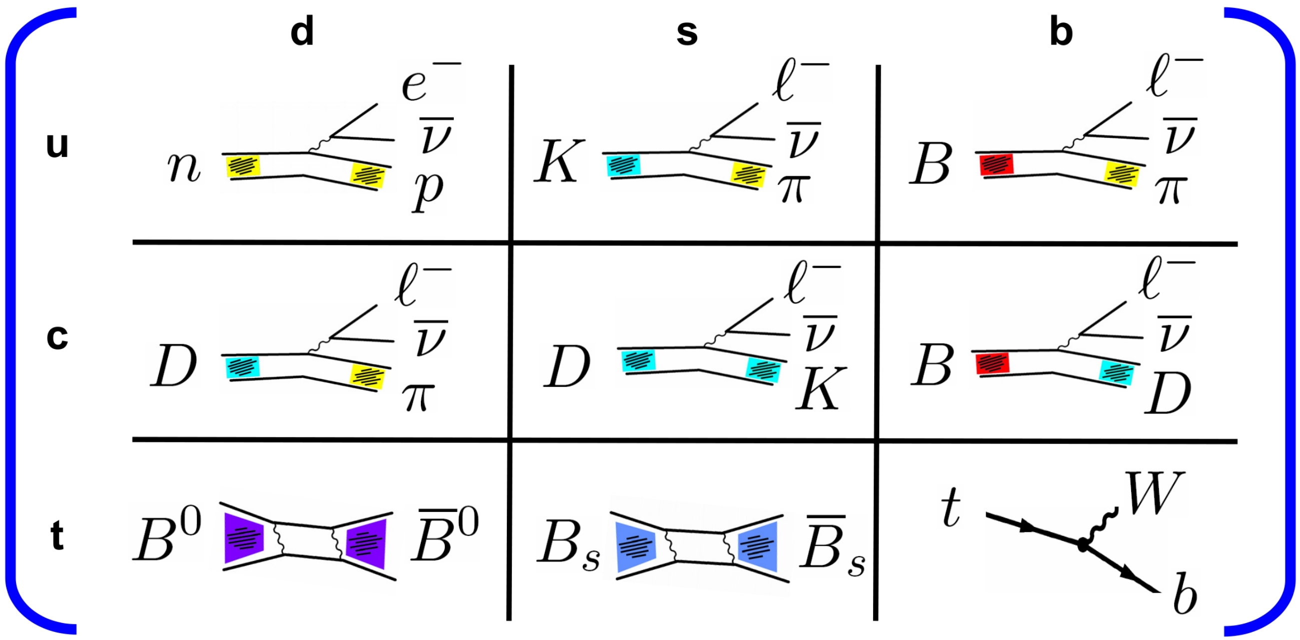


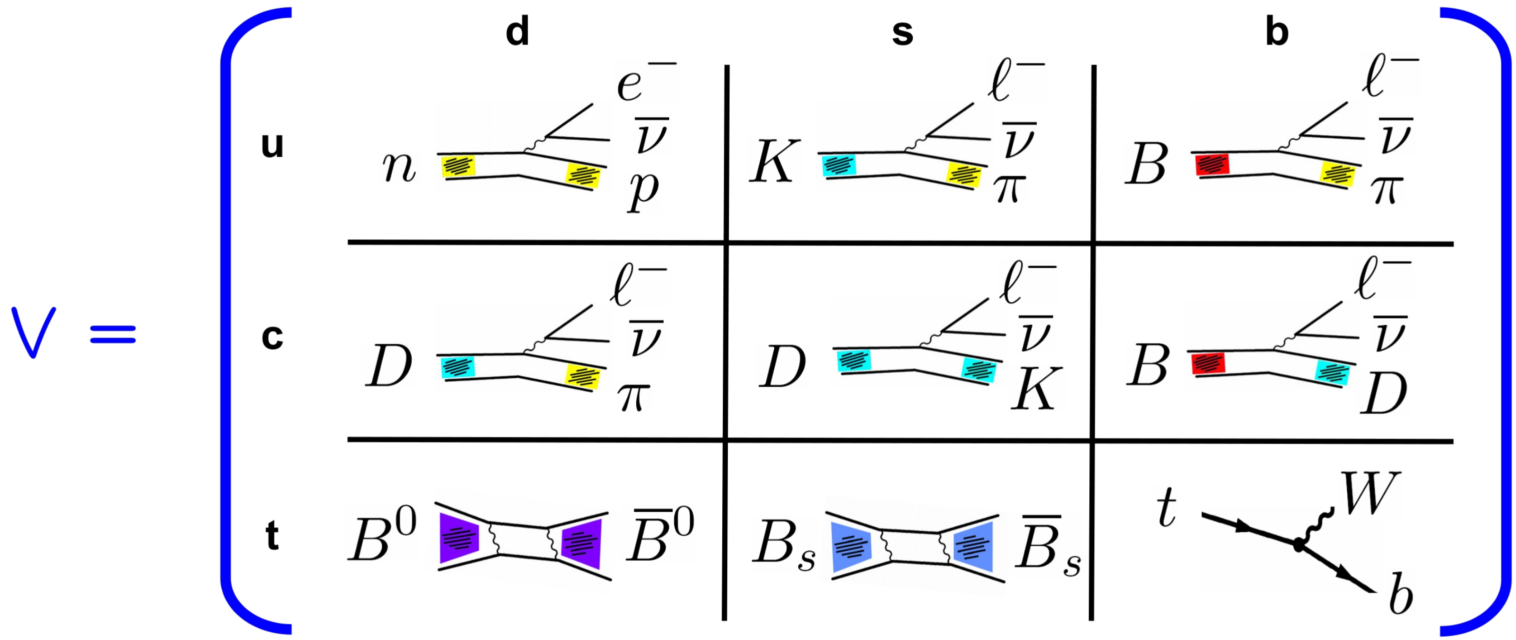
5. Tree level measurements

CKM Metrology

V =

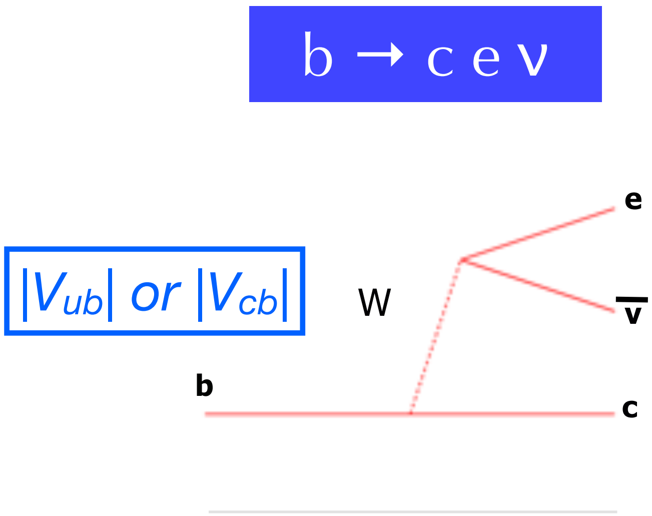


CKM Metrology



UT CKM Parameter	Measurement	δV/V
V_{ub}**	$(4.4\pm0.5)10^{-3}$	10%
V_{cb}	$(4.1\pm0.1)10^{-2}$	2%
V_{td}/V_{ts}		3%
V_{cd}	0.228 ± 0.006	3%
V_{tb}	$\sim1.03\pm0.04$	4%

Semileptonic Decays



Decay properties depend directly on $|V_{cb}|$ & $|V_{ub}|$ and m_b: perturbative (α_s^n).

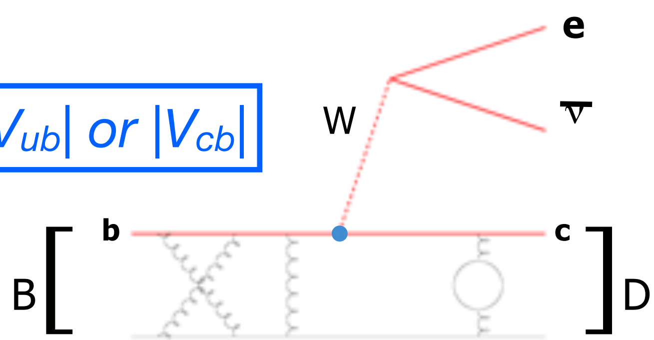
- $|V_{ub}| \approx 0.004$ the smallest element – not easy!

CoEPP

Semileptonic Decays

$B \rightarrow D e \nu$

$|V_{ub}|$ *or* $|V_{cb}|$



Decay properties depend directly on $|V_{cb}|$ & $|V_{ub}|$ and m_b: perturbative (α_s^n).

Quarks are bound in hadrons. Interactions of *b*-quark & light-quark in the *B are very important.*

- $|V_{ub}| \approx 0.004$ the smallest element – not easy!

2 paths to |Vub|

- Exclusive measurements "easier" experimentally, but QCD form factors are challenging to calculate

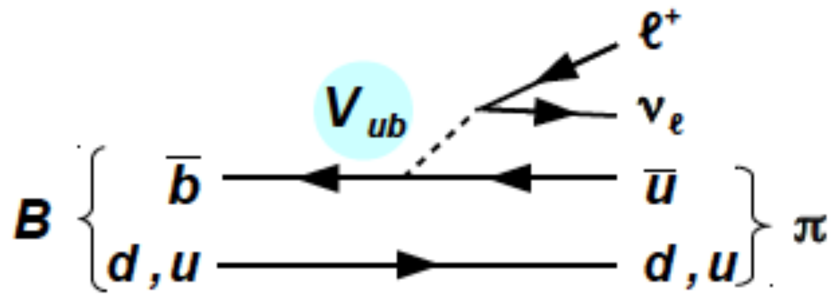
$$|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$$
$$|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3}$$

- Inclusive more robust theoretically, but need to control experimental background

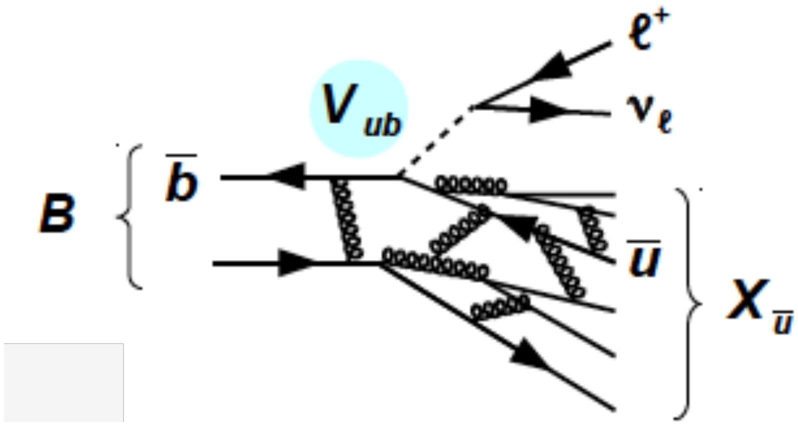
$$|V_{ub}| = (4.41 \pm 0.15) \times 10^{-3}$$
$$|V_{cb}| = (42.4 \pm 0.9) \times 10^{-3}$$

Inclusive ~3 σ higher!

specific hadronic final state

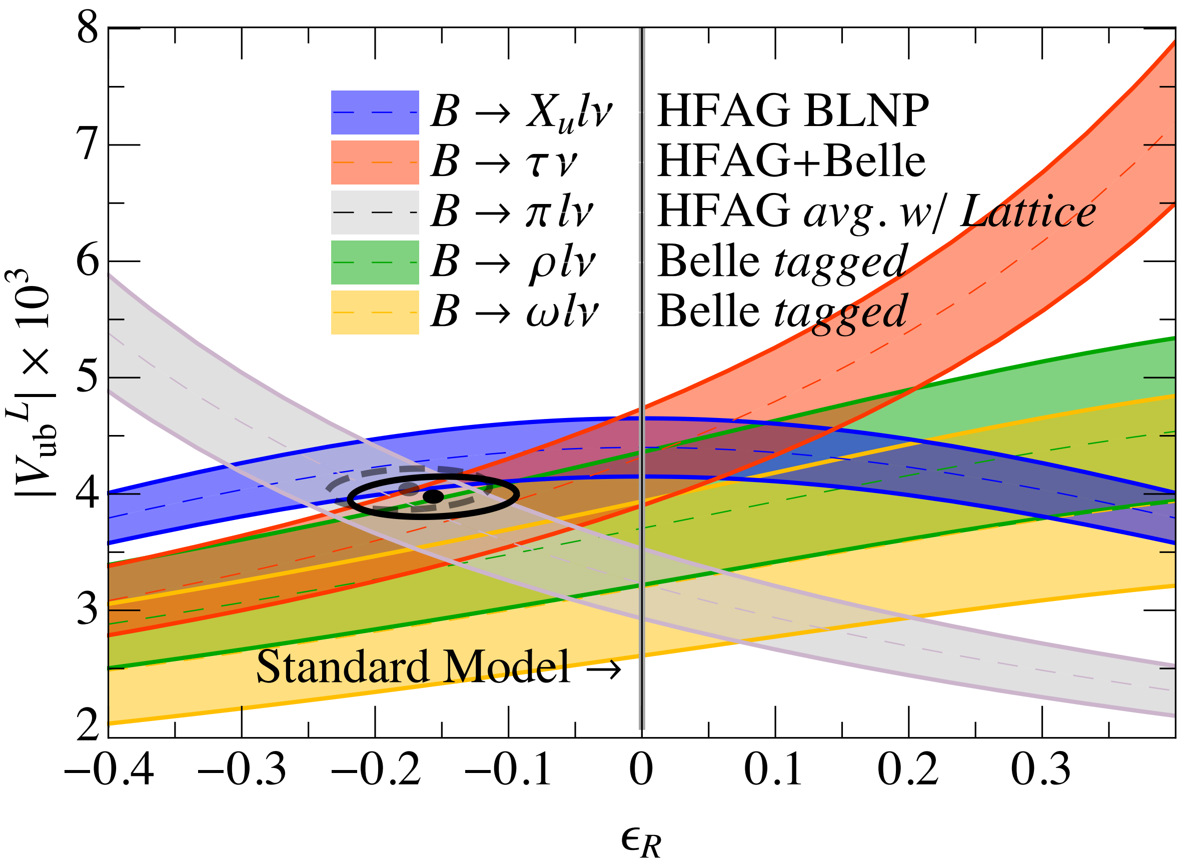


all hadronic final states



Restored Left-Right Symmetry?

- Add new physics: ***right handed currents*** with coupling V_{ub}^R
  - $B \to \pi l \nu$ rate goes as $|V_{ub}^L + V_{ub}^R|^2$
  - $B \to \tau \nu$ rate goes as $|V_{ub}^L - V_{ub}^R|^2$
  - $B \to X_u l \nu$ rate goes as $|V_{ub}^L| + |V_{ub}^R|^2$



1. $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
   - → New heavy gauge bosons (W′, Z′, H).
   - → $V_L = V_{CKM}$ and V_R — 5 more CP phases.

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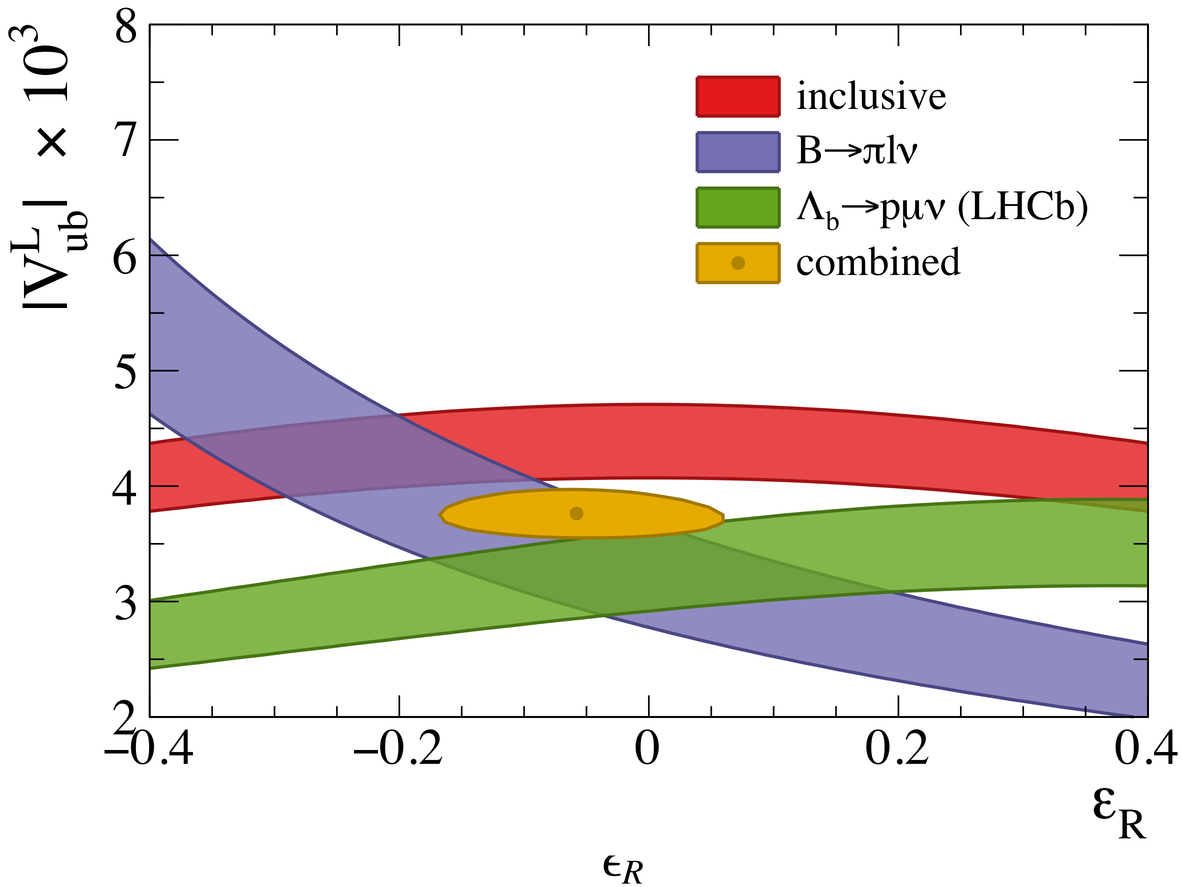

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   - → New heavy gauge bosons (W′, Z′, H).
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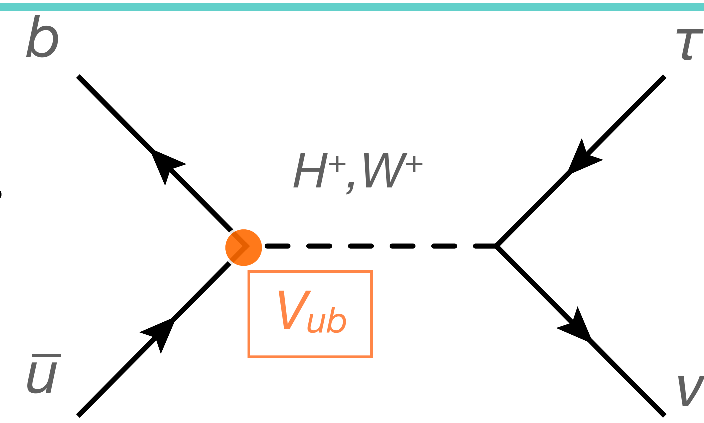
Belle II Flagship: H^+ Search in $B^+ \to \tau\nu, \mu\nu$



Helicity suppressed - very small in SM.

NP could interfere *e.g.* **charged Higgs.**

$$\mathrm{BR}(B_u \to \tau\nu_\tau) = \left[\frac{G_F^2 f_B^2 |V_{ub}|^2}{8\pi} \tau_B m_B m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2\right] \left[1 - \left(\frac{m_B^2}{m_{H^+}^2}\right) \lambda_{bb}\lambda_{\tau\tau}\right]^2$$

BF_{SM} **r_H**

The B meson decay constant

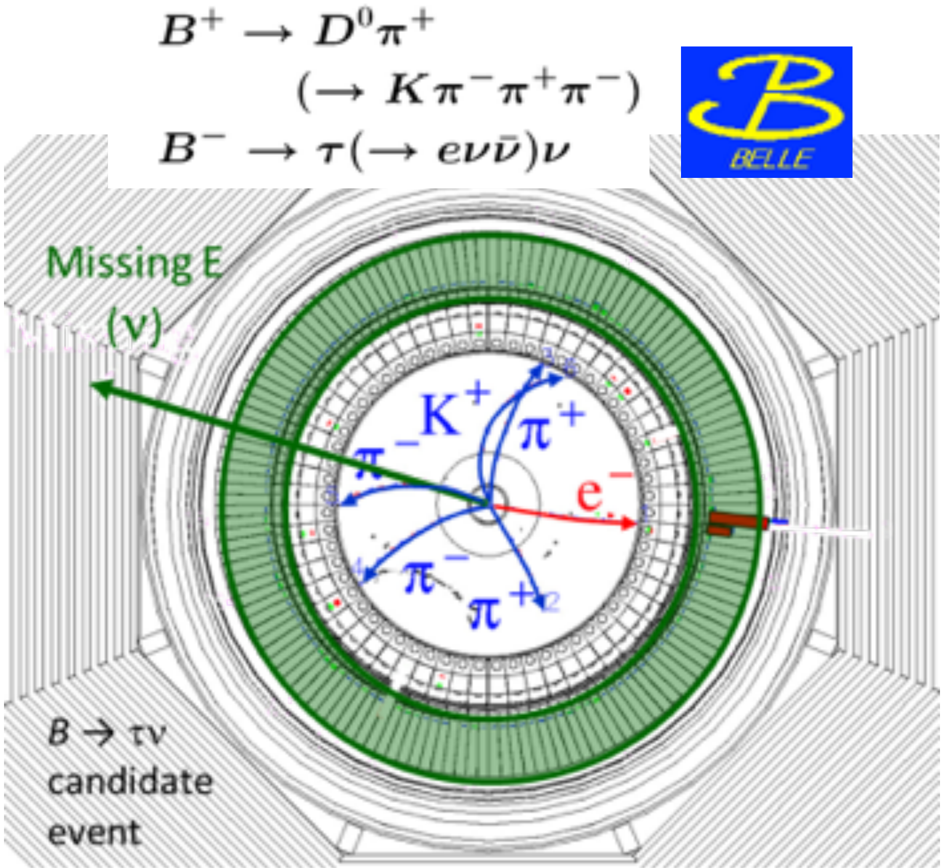
$|V_{ub}|$: from indep. measurements.

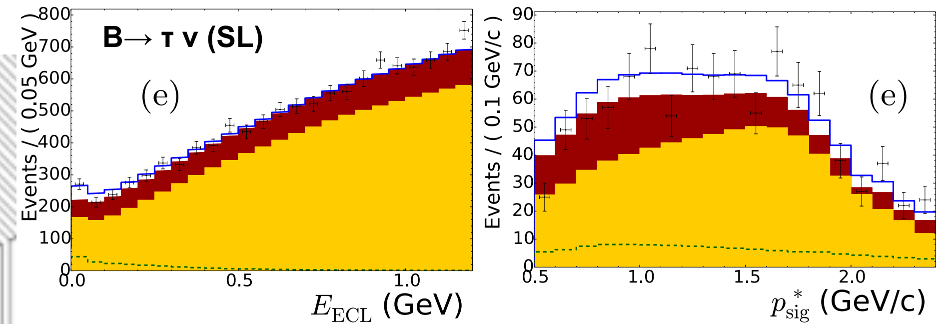
2HDM types

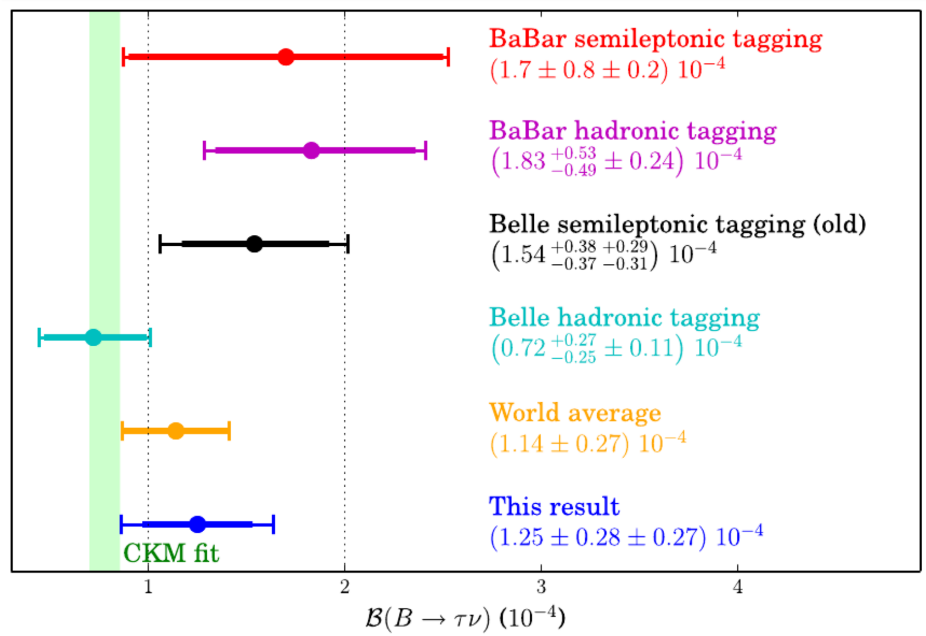
Type	λ_{DD}	λ_{LL}
I	$\cot\beta$	$\cot\beta$
II	$-\tan\beta$	$-\tan\beta$
III	$-\tan\beta$	$\cot\beta$
IV	$\cot\beta$	$-\tan\beta$

B→τν Measurements

Belle, B→ τ ν (Had) PRL110 131801 (2013)
Belle, B→ τ ν (SL) PRD 92, 5, 051102 (2015)







The clean e+e- environment makes this possible

Consumer's guide to charged Higgs

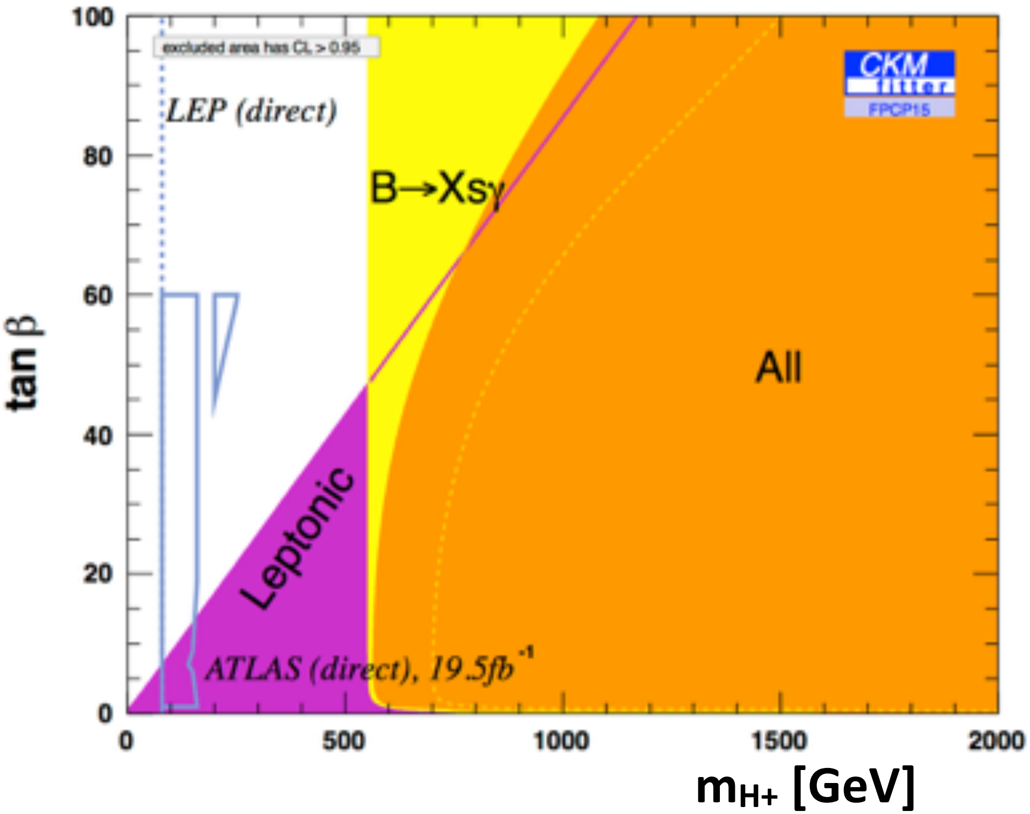
- *Higgs doublet of type I* (ϕ_1 couples to upper (u-type) and lower (d-type) generations. No fermions couple to ϕ_2)

- *Higgs doublet of type II* (ϕ_u couples to u type quarks, ϕ_d couples to d-type quarks, u and d couplings are different; $\tan(\beta) = v_u/v_d$) [favored NP scenario e.g. MSSM, generic SUSY]

- *Higgs doublet of type III* (not type I or type II; anything goes. "FCNC hell"→many FCNC signatures)

NP Fits with CKMFitter

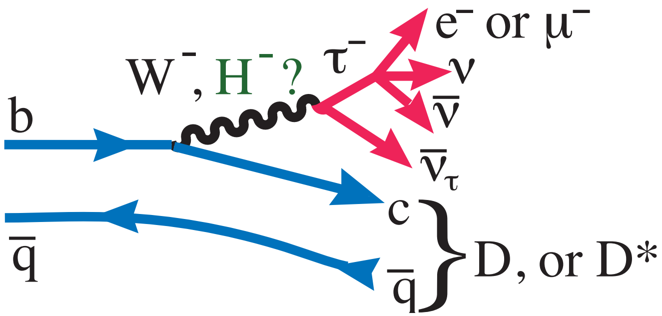
L. Pesantez, PU, CKMFitter, 2015



The current flavour results place stronger constraints than direct searches from LHC exps.

	Belle Ave.	Belle II	
		5 ab^{-1}	50 ab^{-1}
$B \to \tau\nu$	96(1±22%)	10%	3%
$B \to \mu\nu$	<1.7	20%	7%

Most curious hint of NP in heavy flavour



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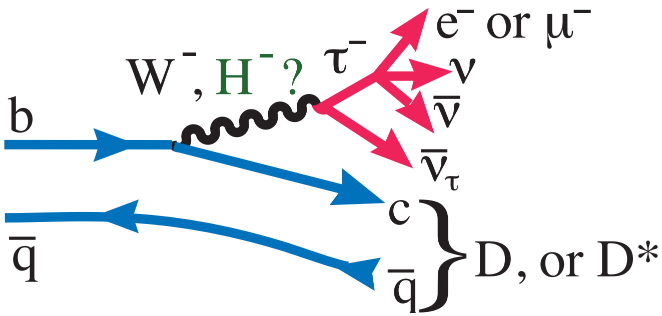

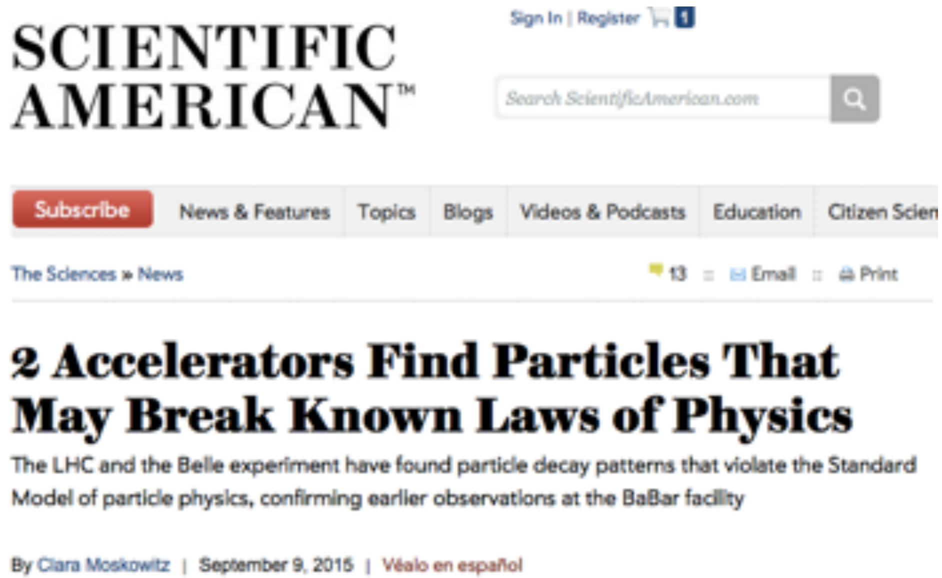

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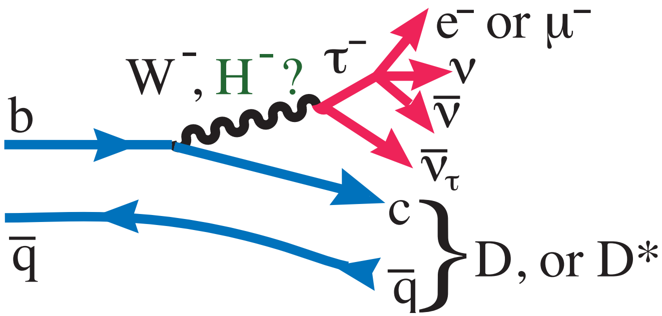

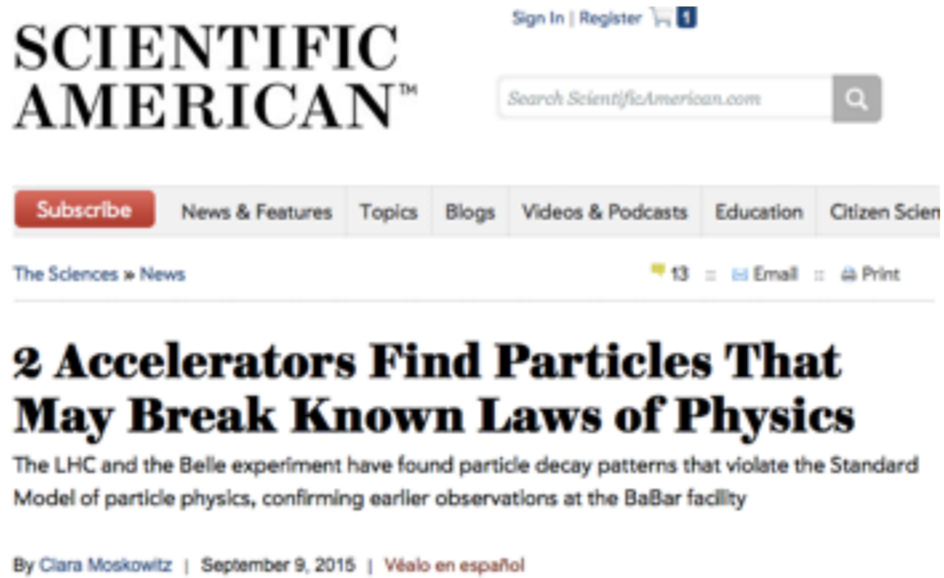
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The Sciences » News

2 Accelerators Find Particles That May Break Known Laws of Physics

The LHC and the Belle experiment have found particle decay patterns that violate the Standard Model of particle physics, confirming earlier observations at the BaBar facility

By Clara Moskowitz | September 9, 2015 | Véalo en español


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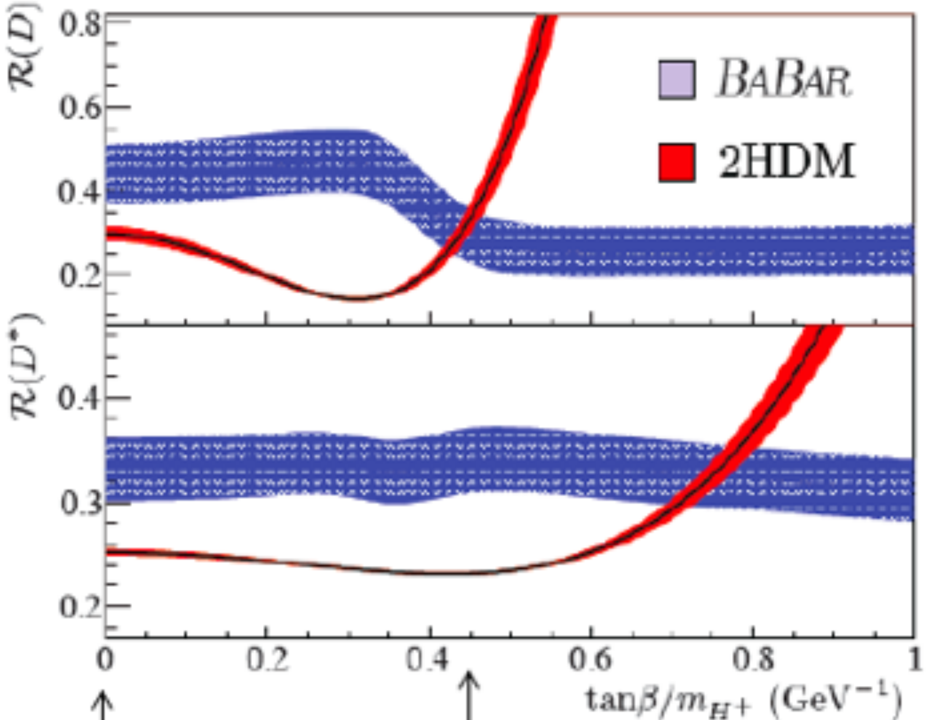
Democracy suffers a blow—in particle physics

Three independent B-meson experiments suggest that the charged leptons may not be so equal after all.

Steven K. Blau 17 September 2015

Limits on Type II 2HDM From Babar

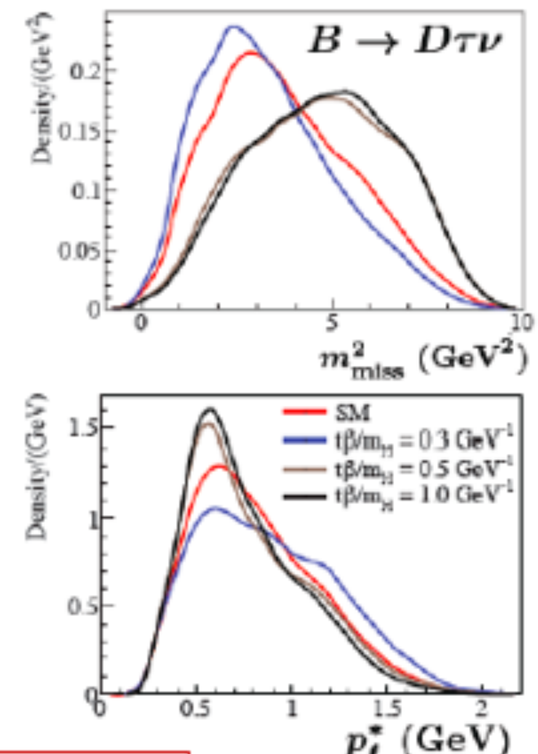


$\tan\beta/m_{H+} =$
0.44 ± 0.02 GeV^{-1}

$\tan\beta/m_{H+} =$
0.75 ± 0.04 GeV^{-1}

SM

2HDM modifies fit-variable distribution and hence the efficiency



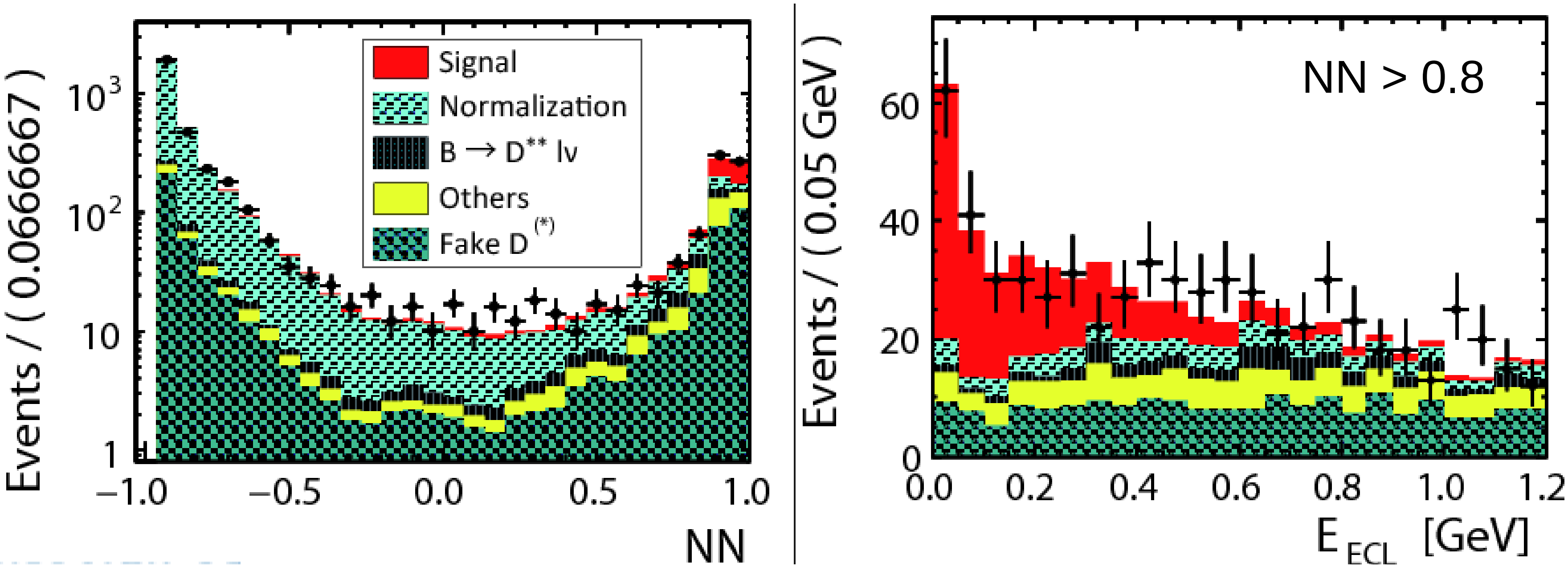
Best point is $\tan\beta/m_{H+} = 0.45$ GeV^{-1}, excluded at 99.8% CL (3.1 σ).
All other values (with $m_{H+} > 15$ GeV) are worse.

$R(D^{(*)}) = BR(B \to D^{(*)} \tau \nu)/BR(B \to D^{(*)} l \nu)$

Babar, Phys.Rev.D 88, 072012 (2013)
Belle, Phys.Rev.D 92, 072014 (2015)
Belle, [arXiv:1603.06711]
LHCb, PRL.115,111803 (2015)

- Reconstruct one B in $\Upsilon(4S) \to BB$ event
  - Either hadronic or semileptonic decay mode
  - First application of semileptonic tagging for $B \to D(^*)\tau\nu$
- Look for signal in the recoil, $B \to D^*\tau\nu$, $D^* \to D\pi$, $D \to$ many, $\tau \to l\nu\nu$,

$$R(D^*) = 0.302 \pm 0.030 \pm 0.011$$

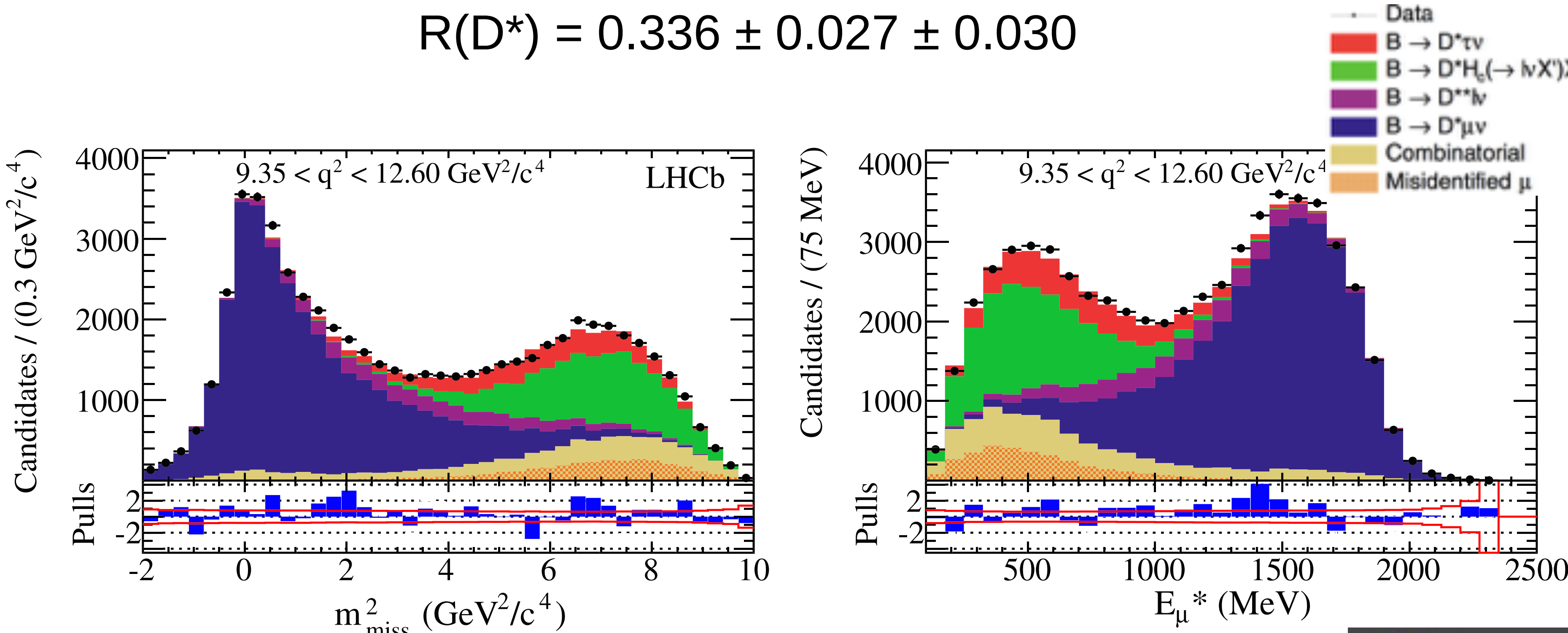


R(D^(*)) @ LHCb

Babar, Phys.Rev.D 88, 072012 (2013)
Belle, Phys.Rev.D 92, 072014 (2015)
Belle, [arXiv:1603.06711]
LHCb, PRL.115,111803 (2015)

- Identify $B \rightarrow D^* \tau\nu$, $D^* \rightarrow D\pi$, $D \rightarrow K\pi$, $\tau \rightarrow \mu\nu\nu$
- Require significant B, D, τ flight distances, fit in M_{miss}^2, q^2 and E_μ

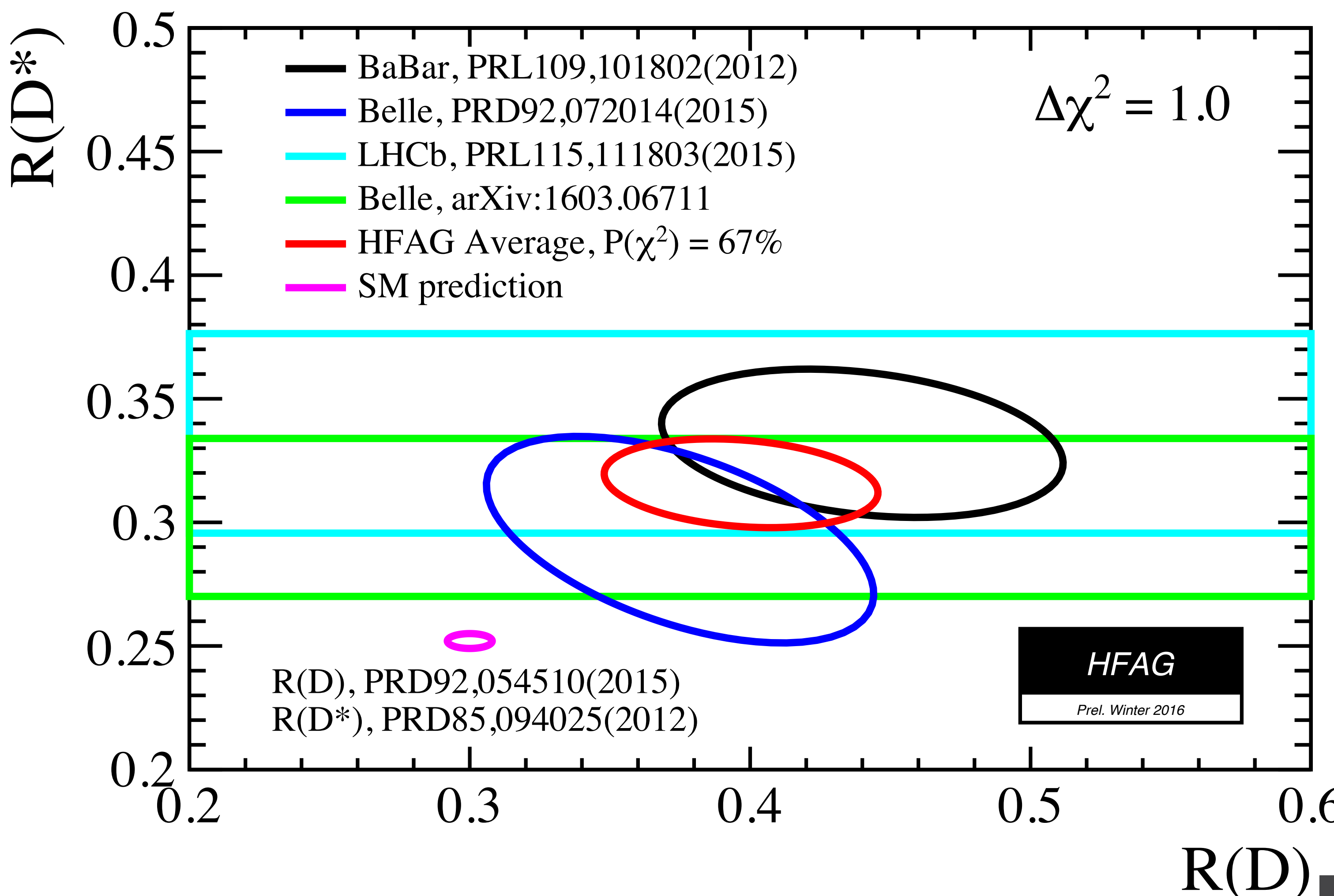
$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$



We need more data! (more to come from Belle)

HFAG Winter 2016

4.0 σ above SM! Several more measurements to come from LHCb & Belle
Inconsistent with a Type II 2-Higgs Doublet Model…



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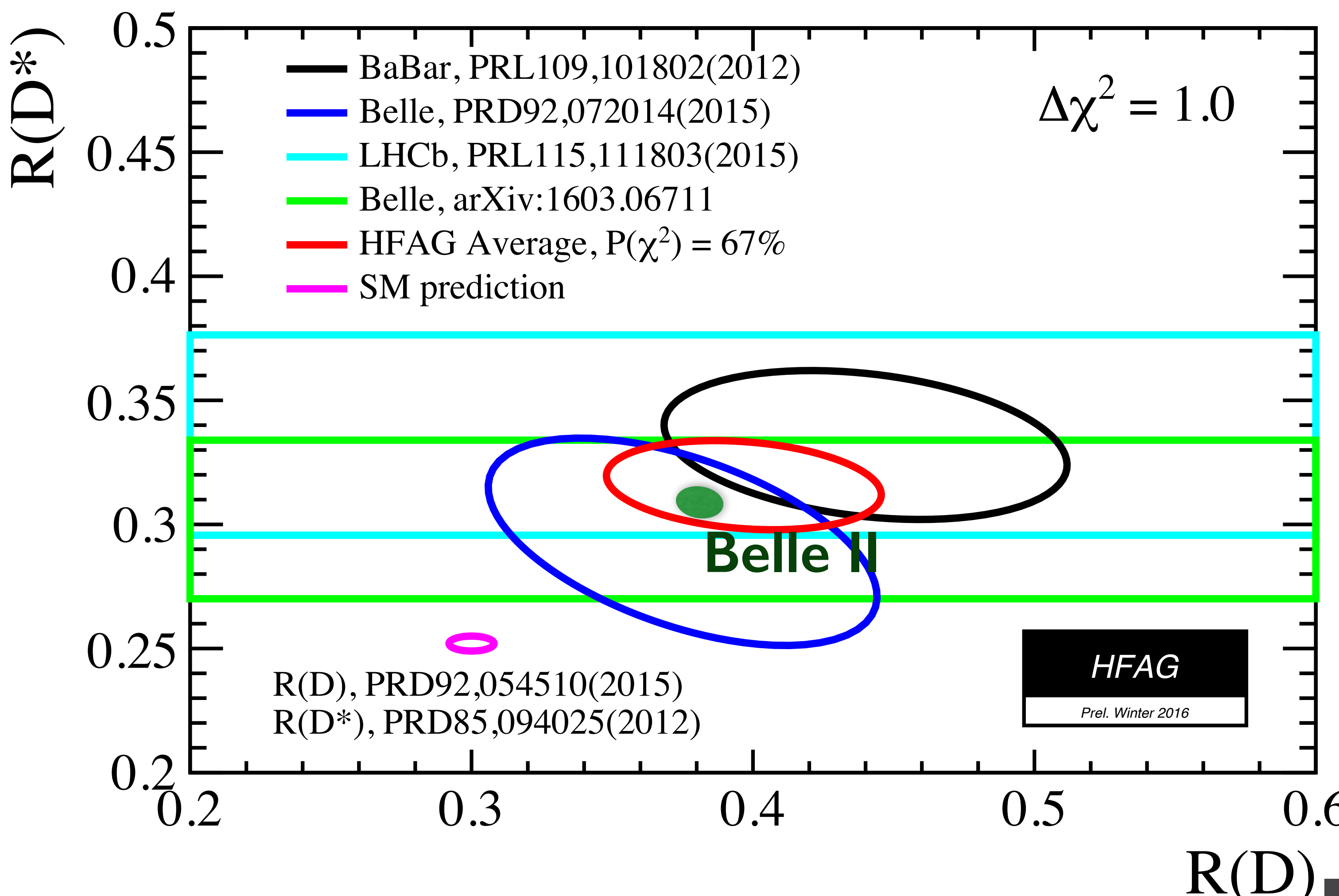

6. Flavour changing neutral currents

EW Penguins today
(More in CP violation lecture tomorrow)

FCNC decays

1. Radiative and Electroweak Penguin Decays with Flavour Changing Neutral Currents (**FCNC**) that occur in the SM **only at the loop level**

FCNC decays

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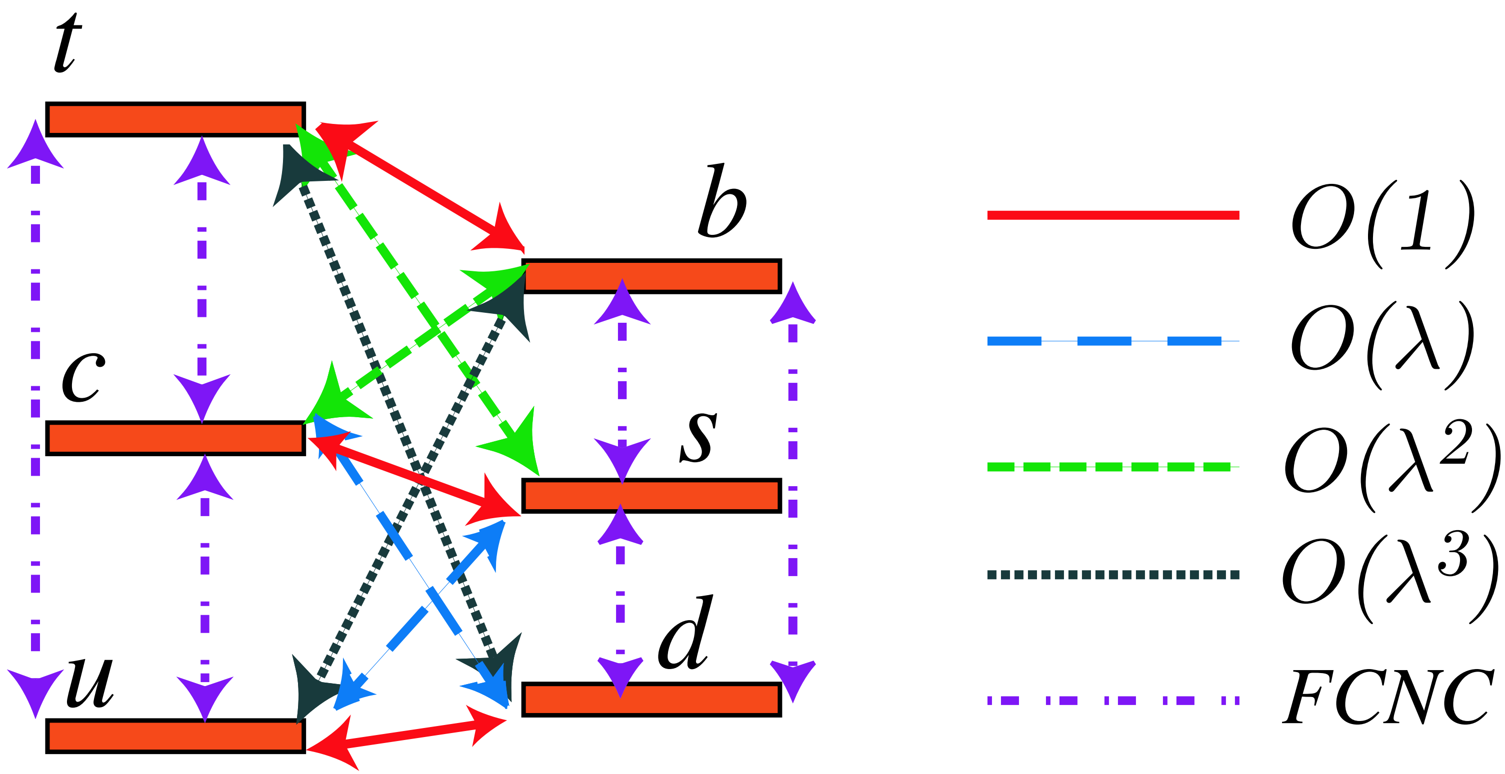


Aside: The origin of “penguins”

Symmetry Magazine Jan/Feb 2007

The origin of penguins

Told by John Ellis:

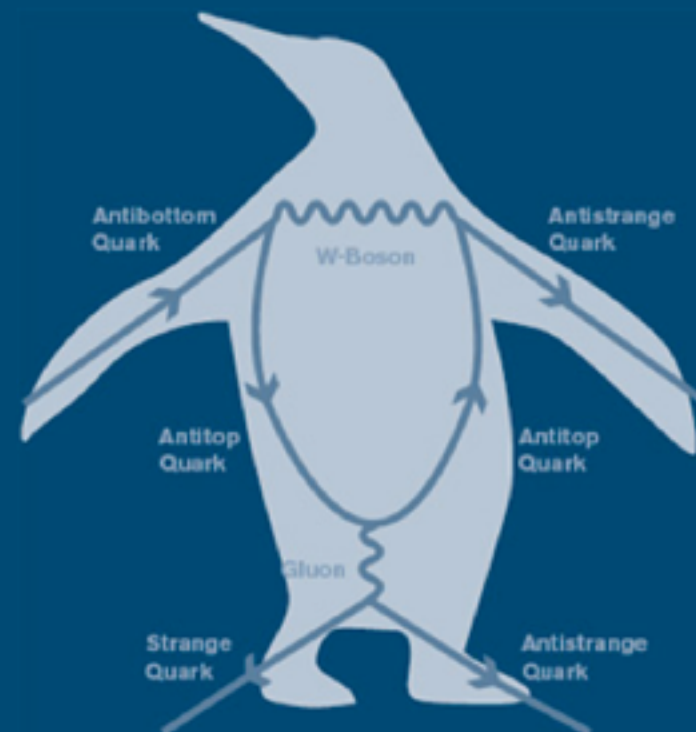
"Mary K. [Gaillard], Dimitri [Nanopoulos], and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976… The penguin name came in 1977, as follows.

In the spring of 1977, Mike Chanowitz, Mary K. and I wrote a paper on GUTs [Grand Unified Theories] predicting the *b* quark mass before it was found. When it was found a few weeks later, Mary K., Dimitri, Serge Rudaz and I immediately started working on its phenomenology.

That summer, there was a student at CERN, Melissa Franklin, who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.

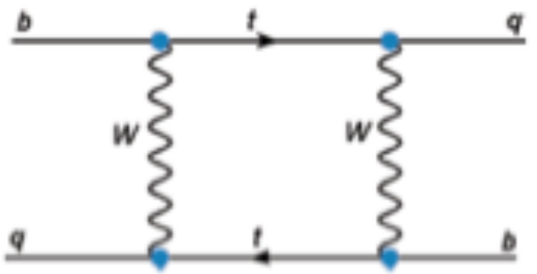
For some time, it was not clear to me how to get the word into this *b* quark paper that we were writing at the time…. Later…I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history."

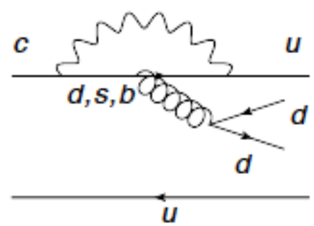
John Ellis in Mikhail Shifman's "ITEP Lectures in Particle Physics and Field Theory", *hep-ph/9510397*

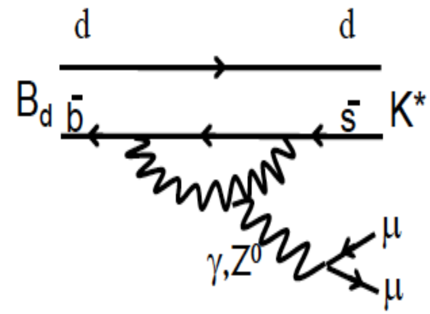


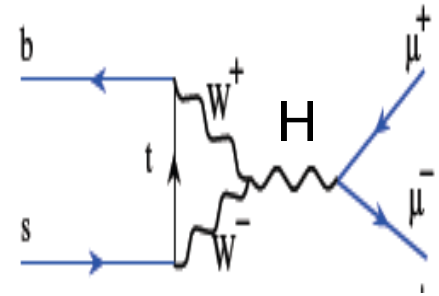
John Ellis will give a public lecture next week

FCNC loops in the SM







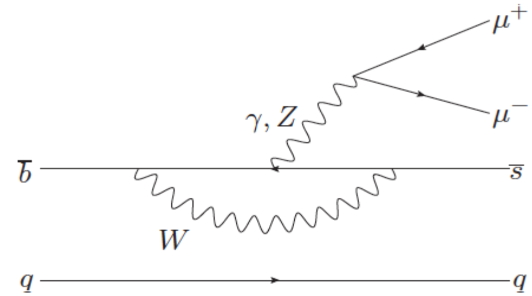


- Map of flavour transitions and types of loop processes

	b→s ($\lvert V_{tb}V_{ts}\rvert\ \alpha\ \lambda^2$)	b→d ($\lvert V_{tb}V_{td}\rvert\ \alpha\ \lambda^3$)	s→d ($\lvert V_{ts}V_{td}\rvert\ \alpha\ \lambda^5$)	c→u ($\lvert V_{cb}V_{ub}\rvert\ \alpha\ \lambda^5$)
ΔF=2 box	ΔM_{Bs}, $A_{CP}(B_s \to J/\Psi\ \Phi)$	ΔM_B, $A_{CP}(B \to J/\Psi K)$	ΔM_K, ε_K	x,y, q/p, Φ
QCD Penguin	$A_{CP}(B \to hhh)$, $B \to X_s \gamma$	$A_{CP}(B \to hhh)$, $B \to X \gamma$	$K \to \pi^0 ll$, ε'/ε	$\Delta a_{CP}(D \to hh)$
EW Penguin	$B \to K^{(*)} ll$, $B \to X_s \gamma$	$B \to \pi ll$, $B \to X \gamma$	$K \to \pi^0 ll$, $K^\pm \to \pi^\pm \nu\ \nu$	$D \to X_u ll$
Higgs Penguin	$B_s \to \mu\ \mu$	$B \to \mu\ \mu$	$K \to \mu\ \mu$	$D \to \mu\ \mu$

EW Penguin Theoretical Framework

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}$$

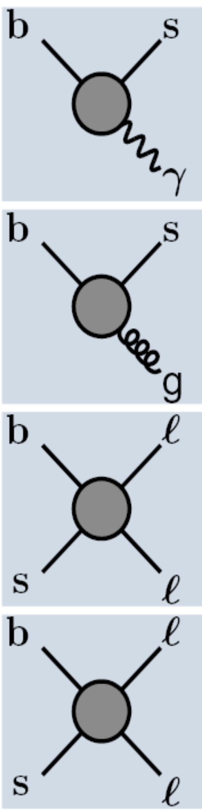


$\mathcal{O}_{7\gamma}$

$\mathcal{O}_{8g}$

$\mathcal{O}_{9\ell,10\ell}$

$\mathcal{O}_{S,P}$



- Describe b→s transitions by an effective Hamiltonian.
- **Long distance** effects absorbed in the definition of the **operators Oi**, while interesting **short distance** can be computed perturbatively in the **Wilson coefficients Ci.**

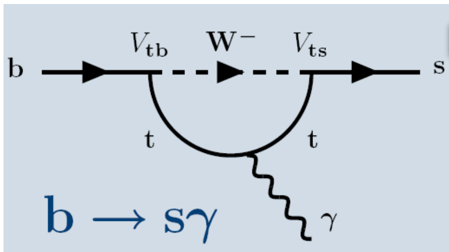
$$O_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \qquad O_8 = \frac{g m_b}{e^2}(\bar{s}\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu\, a},$$

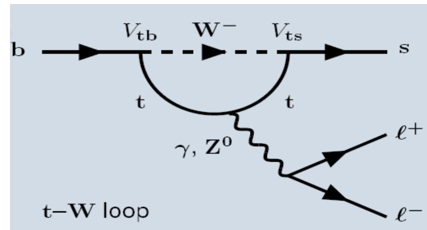
$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \qquad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$

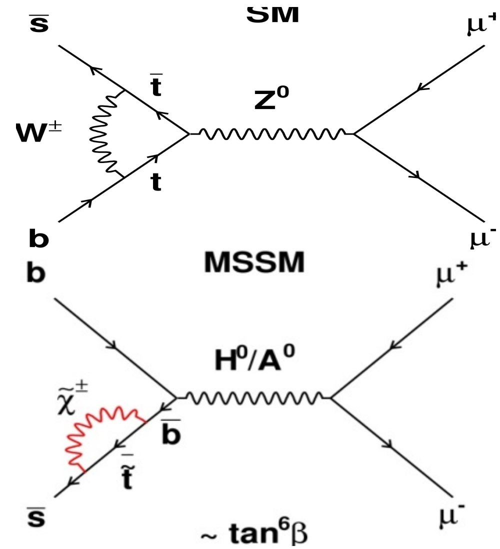
$$O_S = m_b(\bar{s}P_R b)(\bar{\ell}\ell), \qquad O_P = m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell),$$

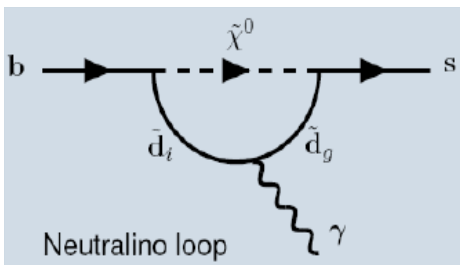
Three impersonations

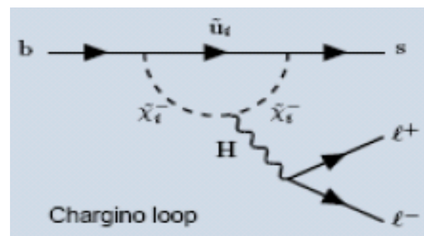
	α QED suppression	Helicity suppression
SM		
MSSM		







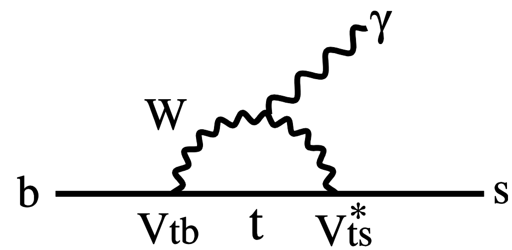


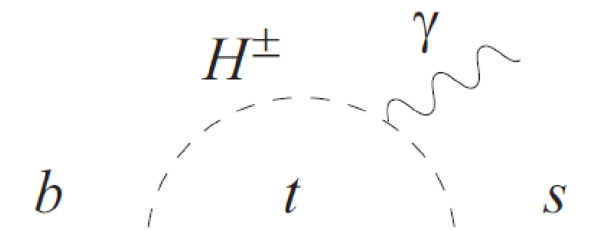


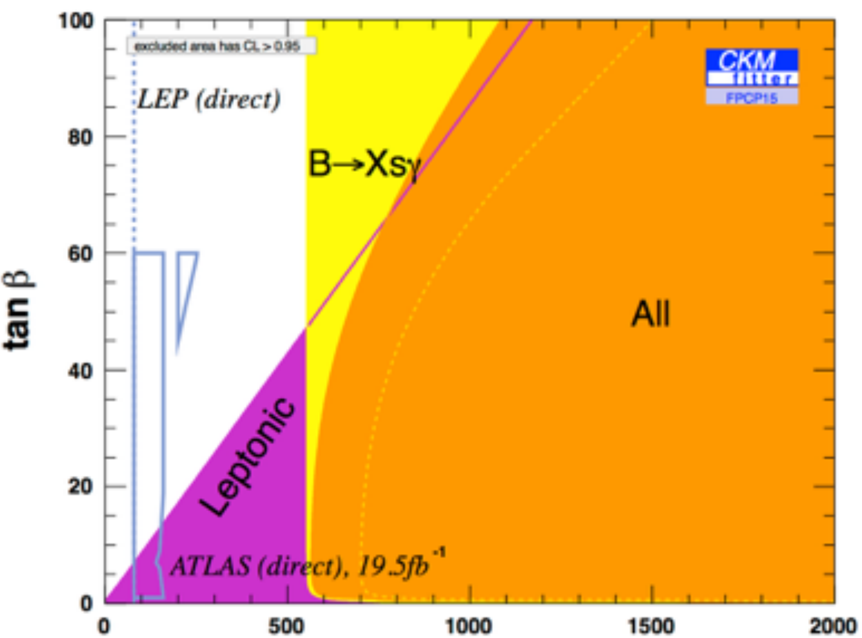
$B_s \rightarrow \phi\gamma$	$\mathcal{O}_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$	Large theory uncertainties O(20%)	$(3.5 \pm 0.4) \cdot 10^{-5}$ LHCb: arXiv:1209.0313	γ polarization
$B^0 \rightarrow K^* \mu^+ \mu^-$	$\mathcal{O}_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$ $\mathcal{O}_{9\ell(10\ell)} \sim \bar{s}_L \gamma_\mu b_L \bar{\ell} \gamma^\mu (\gamma_5) \ell$		$(1.16 \pm 0.19) \cdot 10^{-6}$ LHCb: arXiv:1205.3422	angular distributions
$B_s \rightarrow \mu^+ \mu^-$	$\mathcal{O}_{S(P)} \sim \bar{s}_L b_R \bar{\ell} (\gamma_5) \ell$	$(3.6 \pm 0.2) \cdot 10^{-9}$ helicity suppressed	$(2.8^{+0.7}_{-0.6}) \cdot 10^{-9}$ LHCb&CMS: PRL 111 (2013) 101804-05	BR

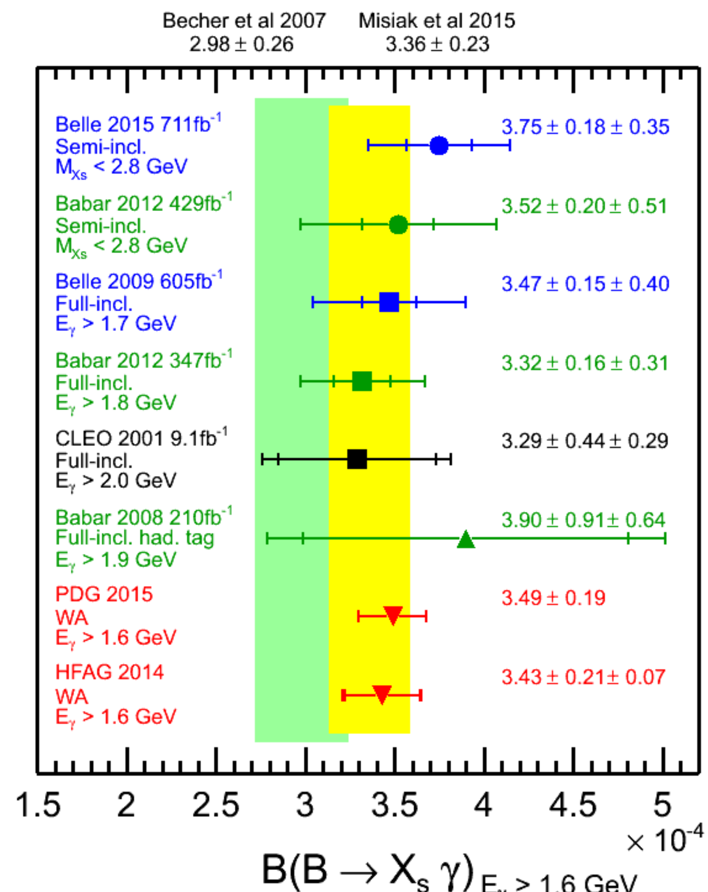
b→ s γ branching ratio

- Limits **many** NP models
- e.g. 2HDM, m(H⁺)>540 GeV





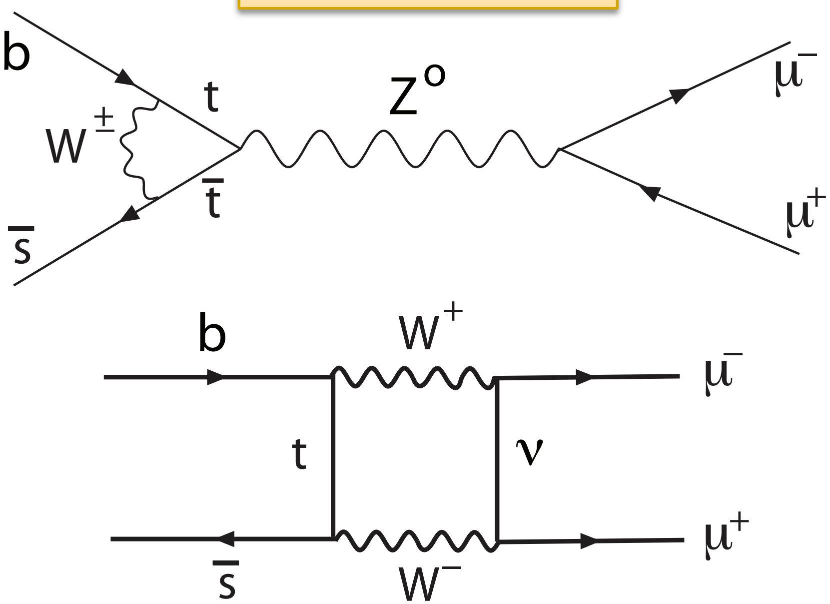




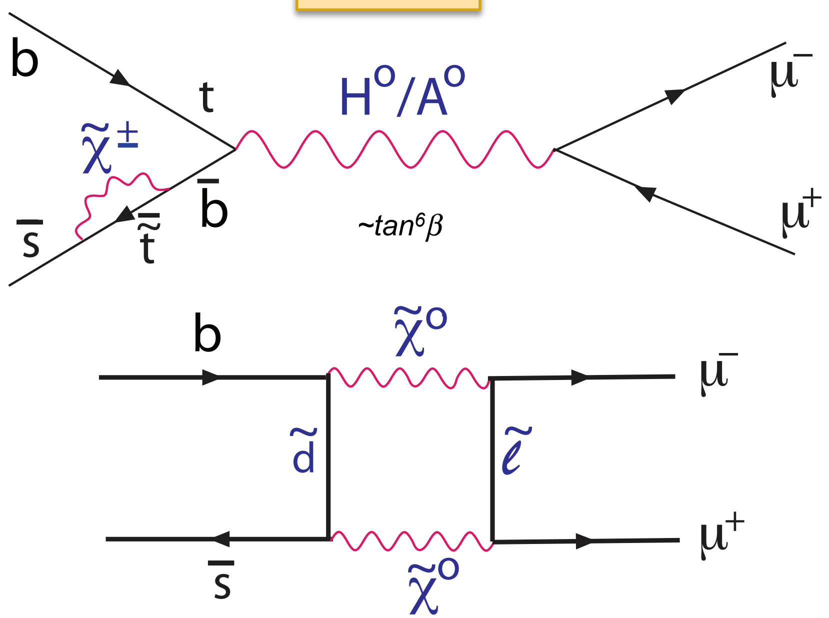
$B_s \to \mu^+\mu^-$

SM branching ratio is $(3.5\pm0.2)\times10^{-9}$ [Buras arXiv: 1012.1447], NP can make large contributions.

Standard Model

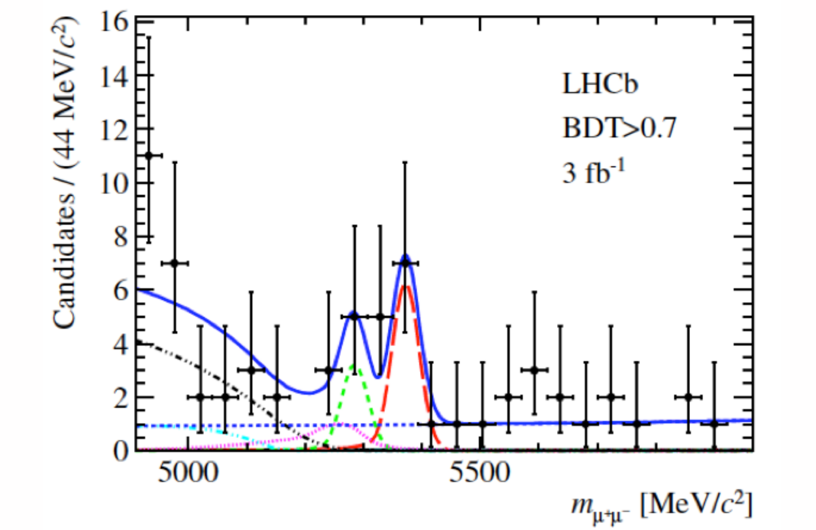


MSSM



$B_s \to \mu^+\mu^-$ Evidence

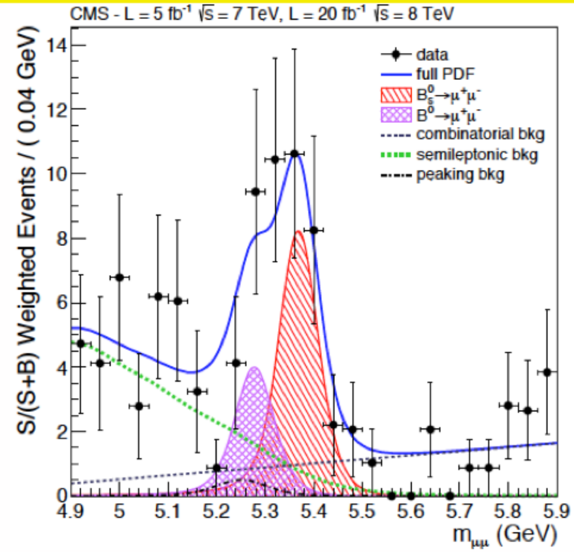
LHCb: arXiv:1307.5024, PRL.111.101805 (2013)



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9\,^{+1.1}_{-1.0}) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7\,^{+2.4}_{-2.1}) \times 10^{-10}$$

--> 4.0σ

CMS: arXiv:1307.5025, PRL. 111.101804 (2013)



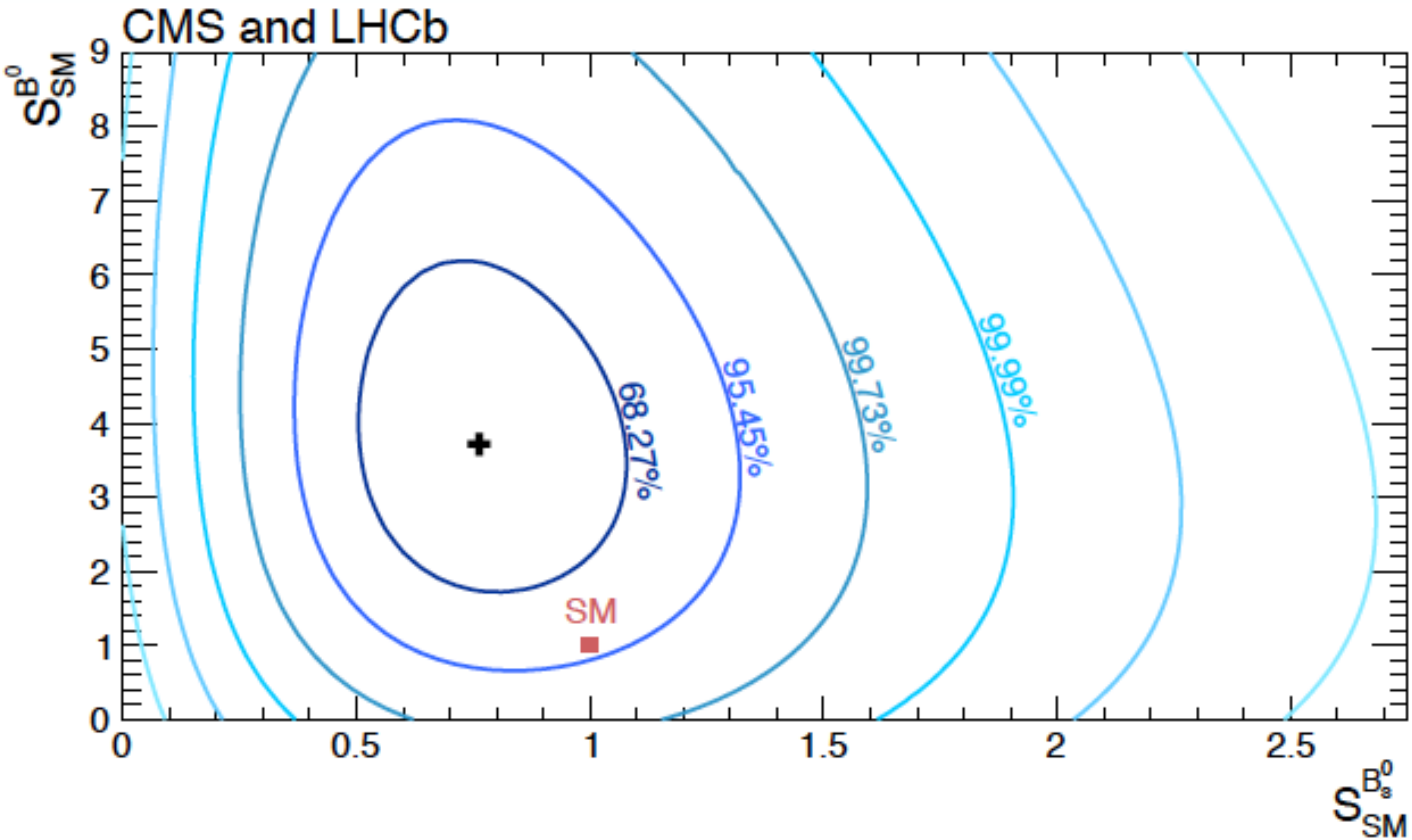
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0\,^{+1.0}_{-0.9}) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.5\,^{+2.1}_{-1.8}) \times 10^{-10}$$

--> 4.3σ

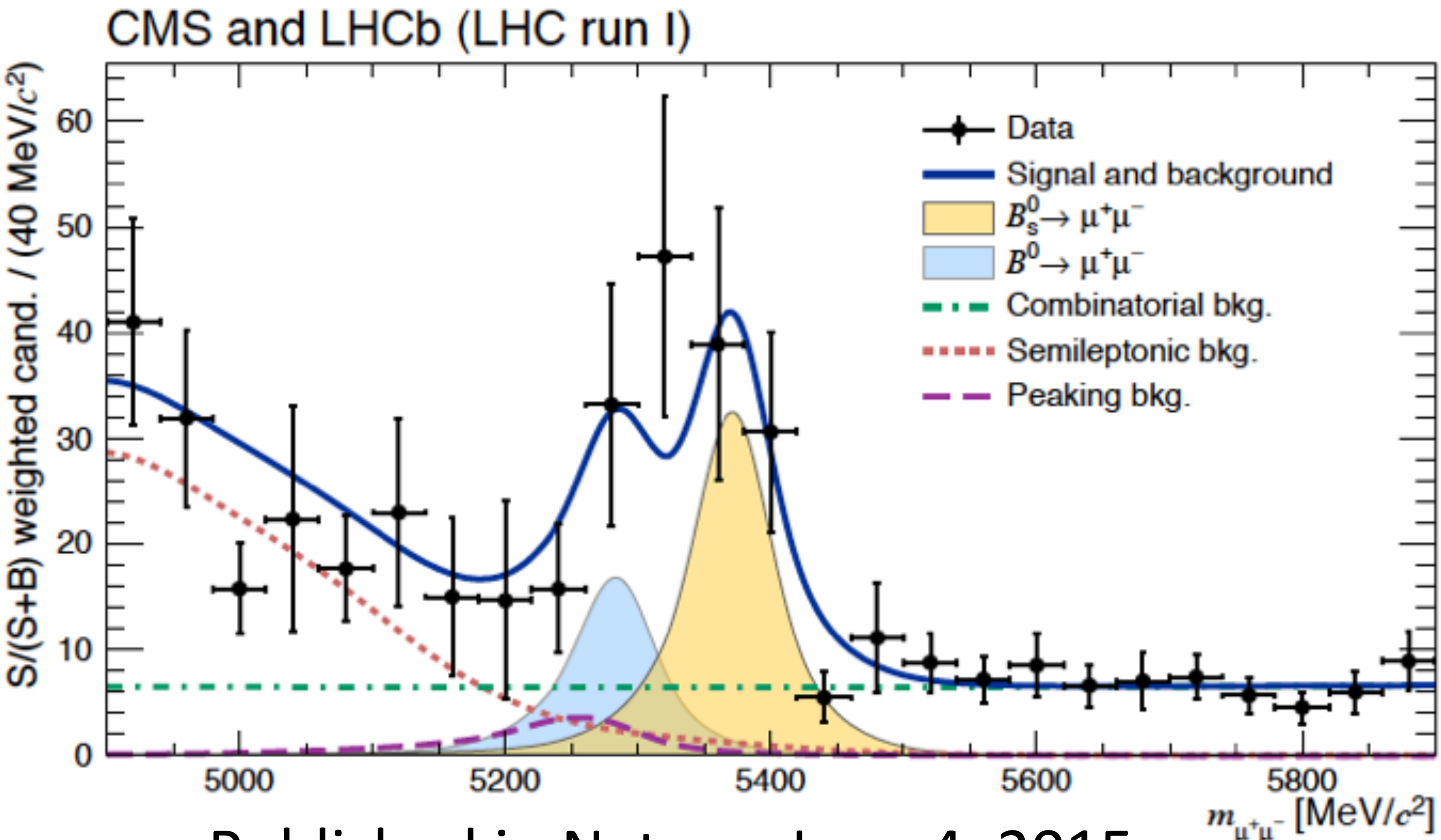
Avg: $\mathcal{B}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$

Avg: $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.6\,^{+1.6}_{-1.4}) \times 10^{-10}$ (not significant)

CMS + LHCb Comparison

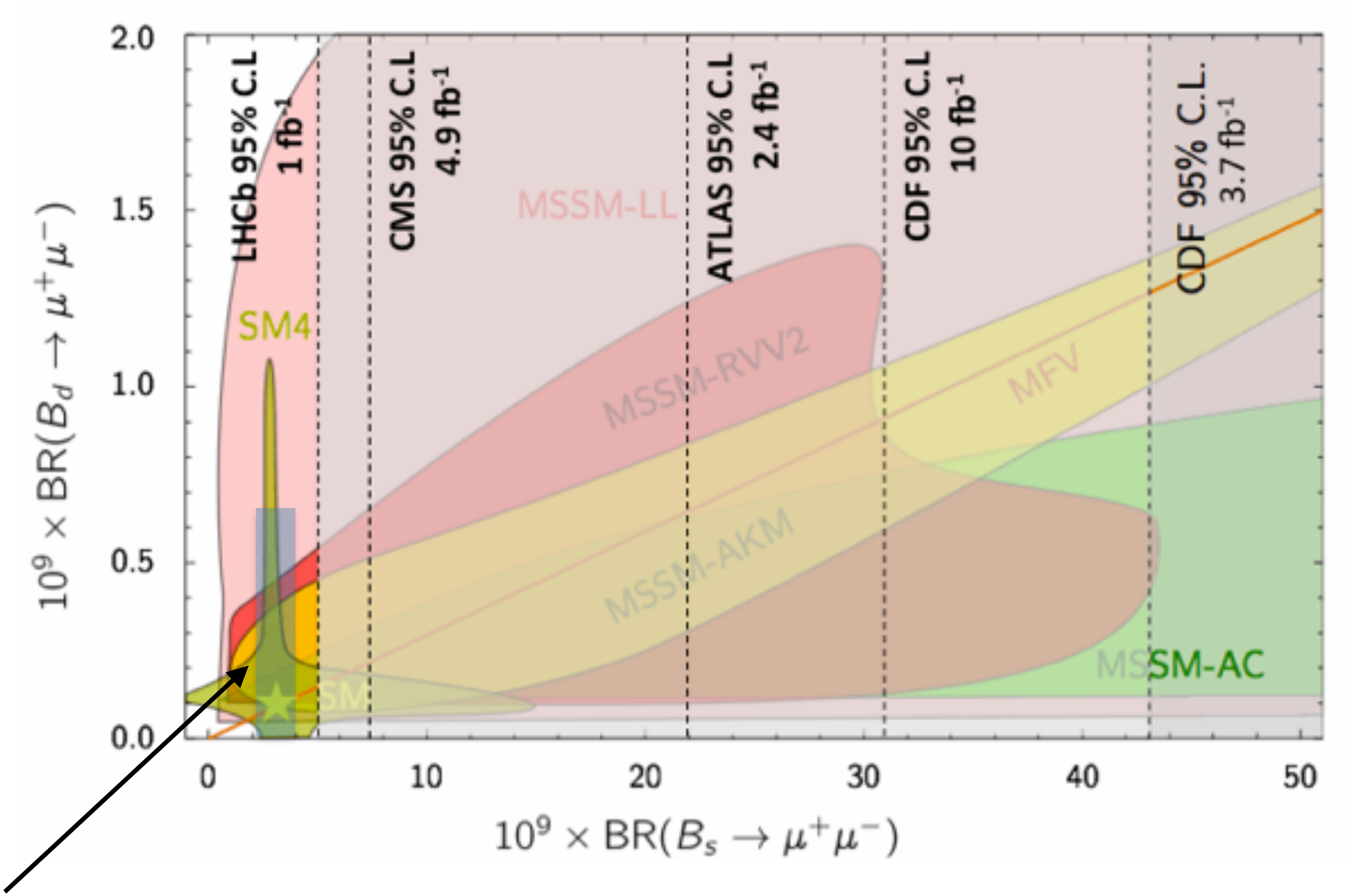


CMS + LHCb Comparison



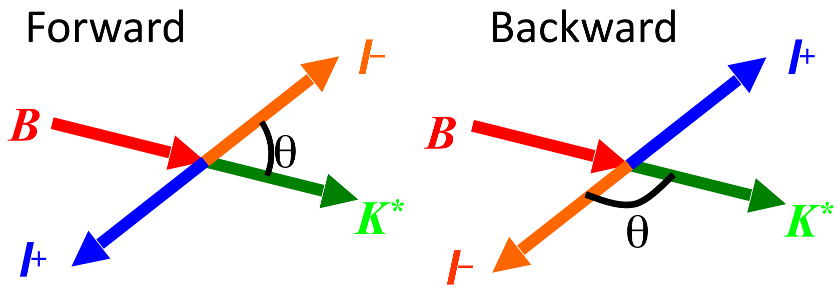
Published in Nature: June 4, 2015

Implications



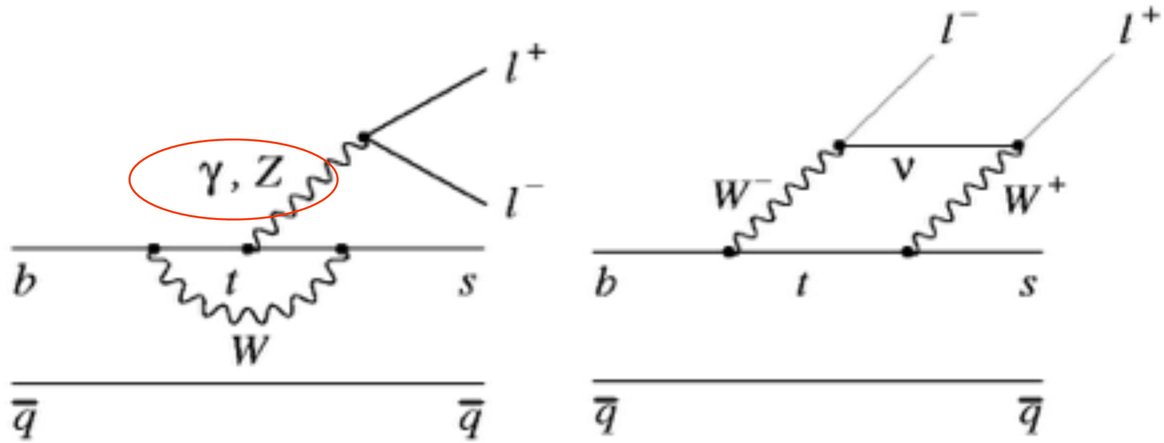
$A_{FB}(B\to K^* l^+ l^-)(q^2)$

The SM forward-backward asymmetry in $b\to s\, l^+ l^-$ arises from the ***interference*** *between γ and Z^0 contributions.*



$$A_{FB}(B\to K^*\ell^+\ell^-) = -C_{10}\xi(q^2)\left[Re(C_9)F_1 + \frac{1}{q^2}C_7F_2\right]$$

Ali, Mannel, Morozumi, PLB273, 505 (1991)

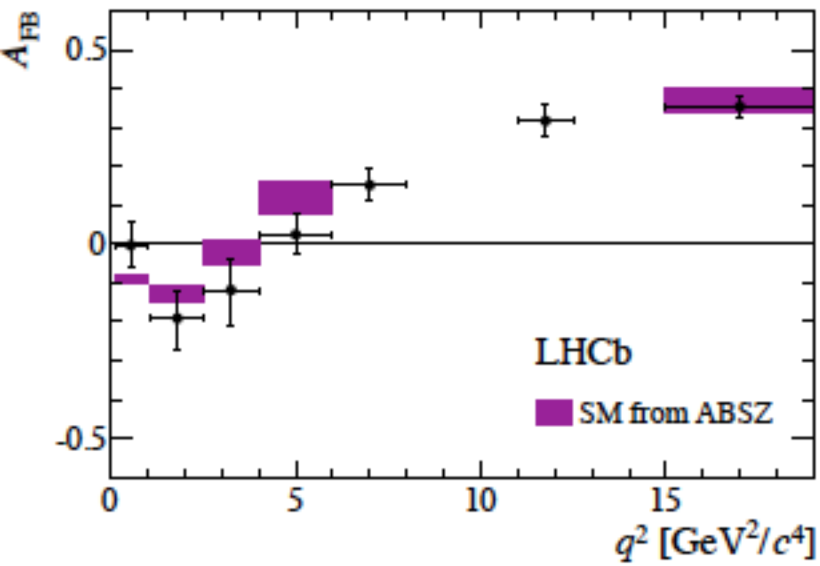


Multiple heavy particles of the SM (W, Z, top) enter in this decay.

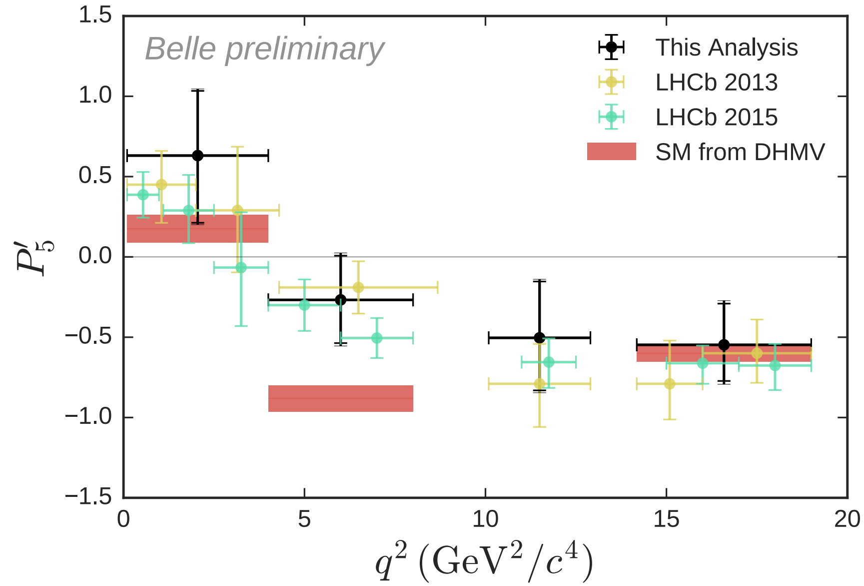
LHCb 3fb^{-1} results on $B \to K^* \mu^+\mu^-$ (q^2)

R. Aaij et al., JHEP 1602, 104 (2016)

$$A_{FB}(B \to K^*\ell^+\ell^-) = -C_{10}\xi(q^2)\left[Re(C_9)F_1 + \frac{1}{q^2}C_7F_2\right]$$



$$P_5' = \sqrt{2}\frac{\mathrm{Re}\left(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}\right)}{\sqrt{\left(|A_0^L|^2 + |A_0^R|^2\right)\left(|A_\parallel^L|^2 + |A_\parallel^R|^2 + |A_\perp^L|^2 + |A_\perp^R|^2\right)}}$$



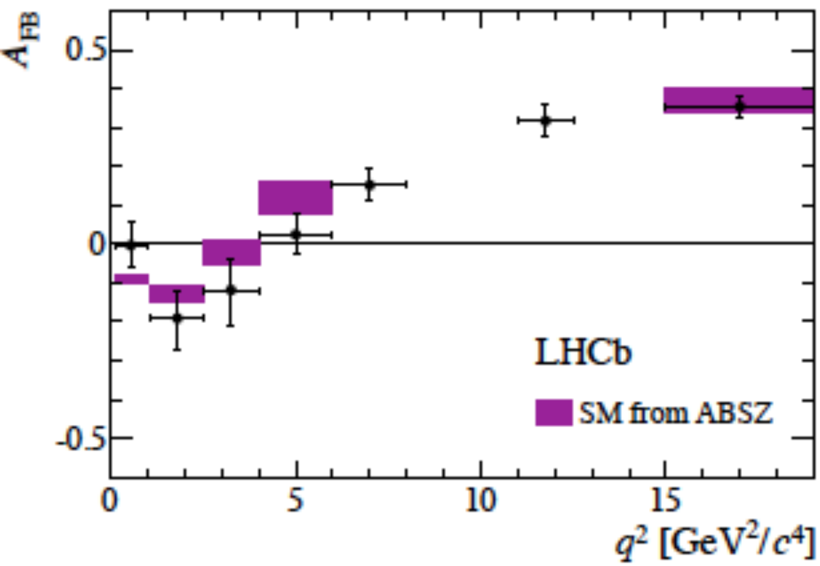
Blank regions are the J/ψ and ψ′ vetos

Theory arXiv: 1510.04329

LHCb 3fb^{-1} results on B→ K* $\mu^+\mu^-$ (q^2)

R. Aaij et al., JHEP 1602, 104 (2016)

$$A_{FB}(B \to K^*\ell^+\ell^-) = -C_{10}\xi(q^2)\left[Re(C_9)F_1 + \frac{1}{q^2}C_7F_2\right]$$



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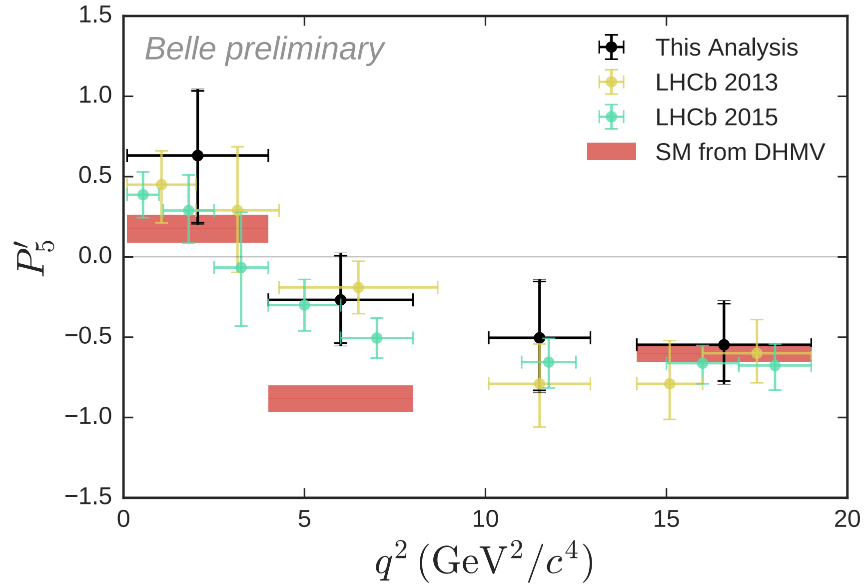

"The P_5' measurements are only compatible with the SM prediction at a level of 3.7σ.....A mild tension can also be seen in the A_{FB} distribution, where the measurements are systematically <=1σ below the SM prediction in the region $1.1<q^2< 6.0$ GeV^2"

Blank regions are the J/ψ and ψ′ vetos

Theory arXiv: 1510.04329

Recent LHCb results on $B \rightarrow K^* \mu^+\mu^- (q^2)$

Why does NP appear first in this mode (and not others) ?

Recent LHCb results on $B \to K^* \mu^+\mu^- (q^2)$

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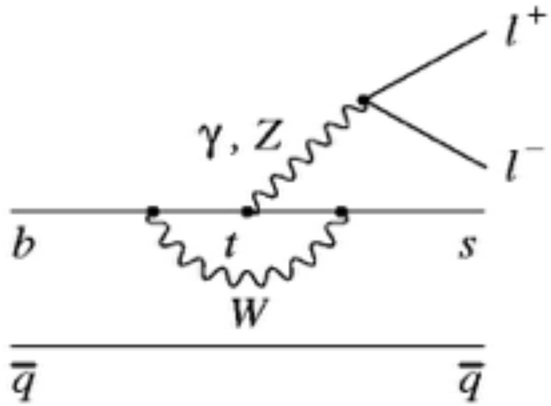
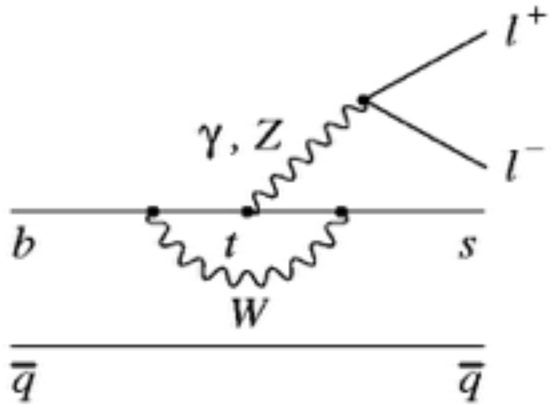


Recent LHCb results on $B \to K^{*} \mu^{+}\mu^{-} (q^2)$

Why does NP appear first in this mode (and not others) ?



Possible answer: All heavy particles of SM (t, W, Z) and maybe NP (except Higgs) appear. Sensitive to NP via interference.

Recall: Wilson coefficients

NP could mean "new particles" (bump in some mass spectrum at the LHC) or "new couplings" (flavour physics)

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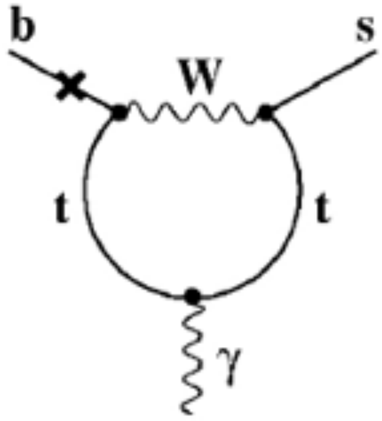
$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\Delta F=1} \propto \sum_{i=1}^{10} V^*_{ts} V_{tb} C_i Q_i + \dots$$

$$Q_7 = \frac{e}{g^2} m_b \, \bar{s}\sigma^{\mu\nu}(1+\gamma_5) F_{\mu\nu} \, b \quad \text{[real or soft photon]}$$

$$Q_9 = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5) b \, \bar{\ell}\gamma_\mu \ell \quad [b \to s\mu\mu \text{ via } Z/\text{hard } \gamma]$$

$$Q_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5) b \, \bar{\ell}\gamma_\mu\gamma_5 \ell \quad [b \to s\mu\mu \text{ via } Z]$$



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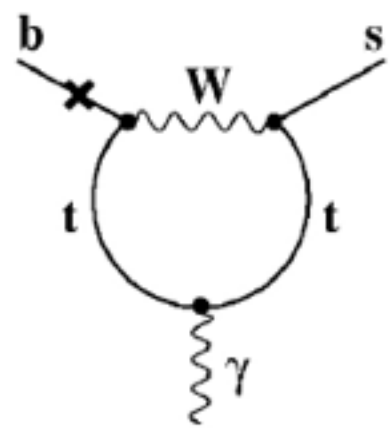
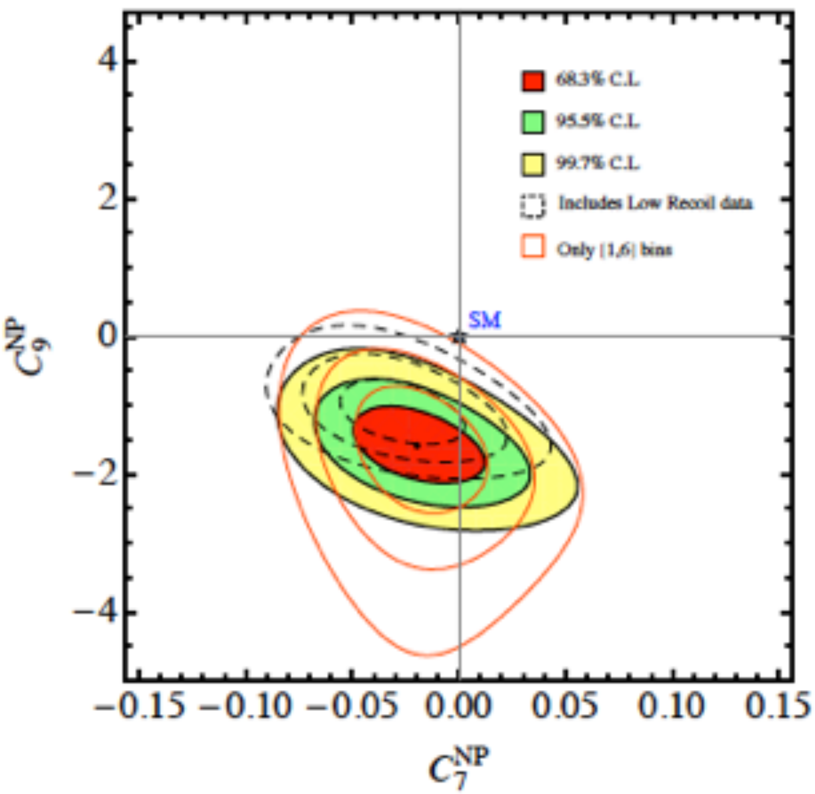


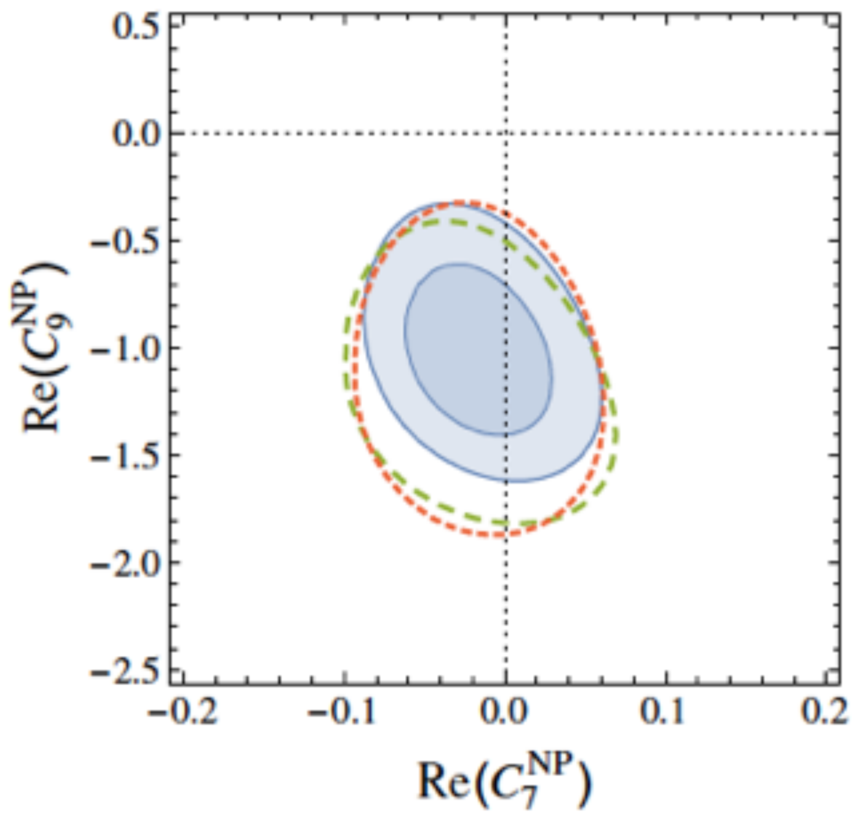
Right-handed currents: $1-\gamma_5 \rightarrow 1+\gamma_5$

Some examples of NP Fits to B→K*l l data

Descotes-Genon, Matias, Virto, arXiv 1307.5683



Altmannshofer, Straub 1503.06199

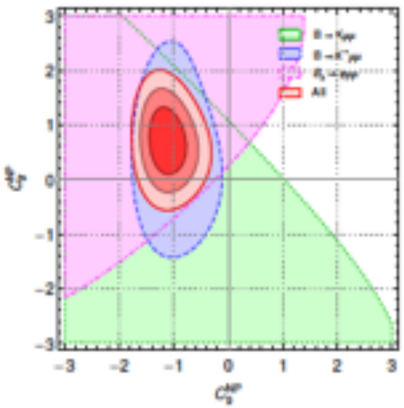


Recent example of NP Fits to B→s l l data

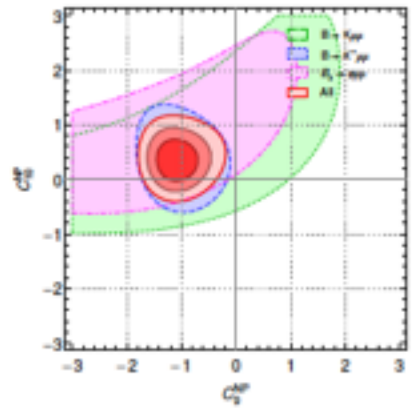
		C_7^{NP}	C_9^{NP}	C_{10}^{NP}	$C_{7'}^{NP}$	$C_{9'}^{NP}$	$C_{10'}^{NP}$
C_9^{NP}	4.47	0.07	•	1.54	0.92	2.00	1.89

L. Hofer et al., Moriond March 2016

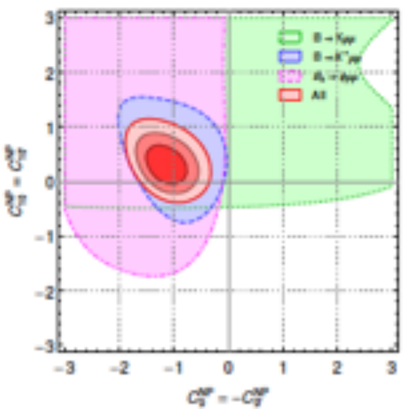
$(C_9^{NP}, C_{9'}^{NP})$
$(-1.12, 0.77)$
4.5



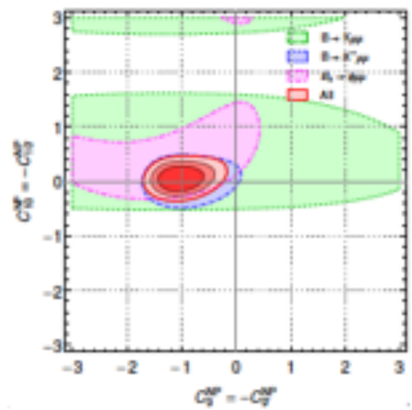
(C_9^{NP}, C_{10}^{NP})
$(-1.08, 0.33)$
4.3



$(C_9^{NP} = -C_{9'}^{NP}, C_{10}^{NP} = C_{10'}^{NP})$
$(-1.15, 0.34)$
4.7



$(C_9^{NP} = -C_{9'}^{NP}, C_{10}^{NP} = -C_{10'}^{NP})$
$(-1.06, 0.06)$
4.4



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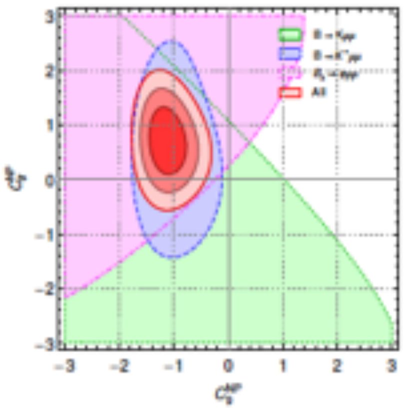

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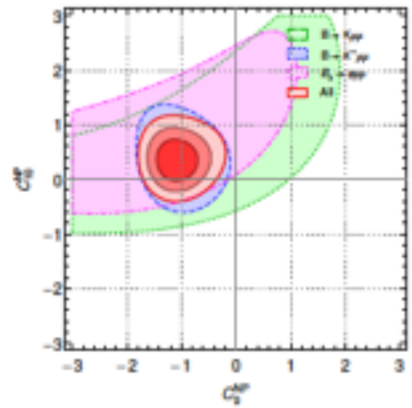

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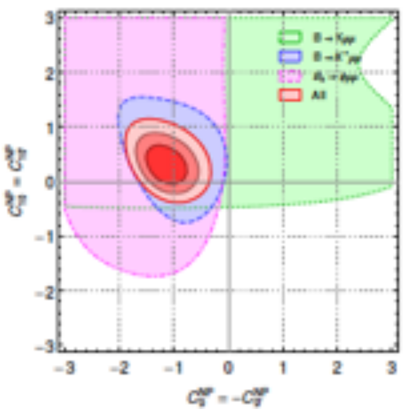

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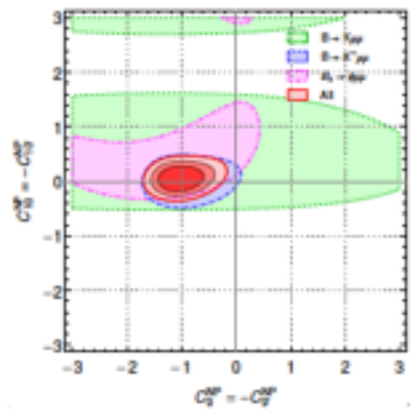
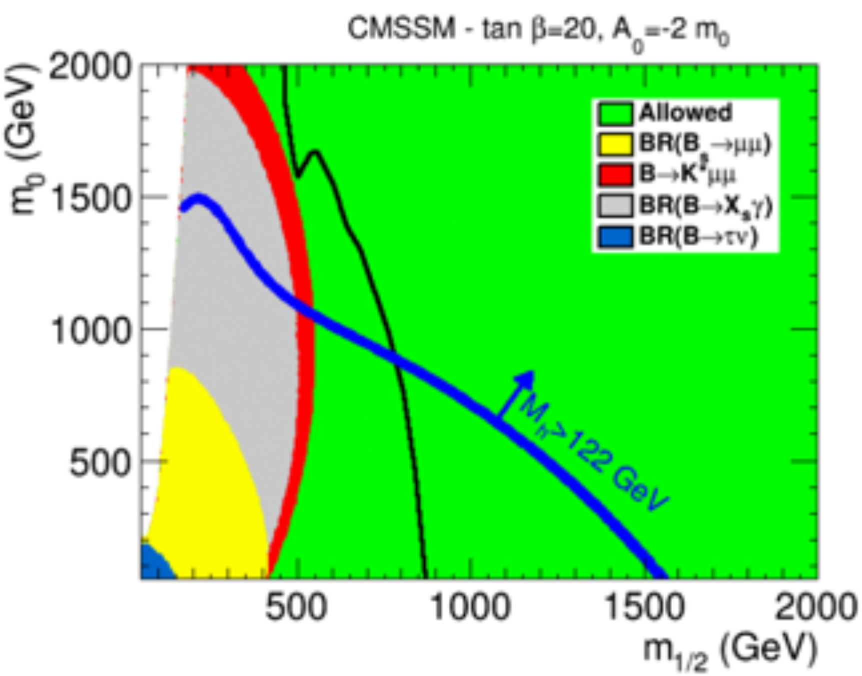
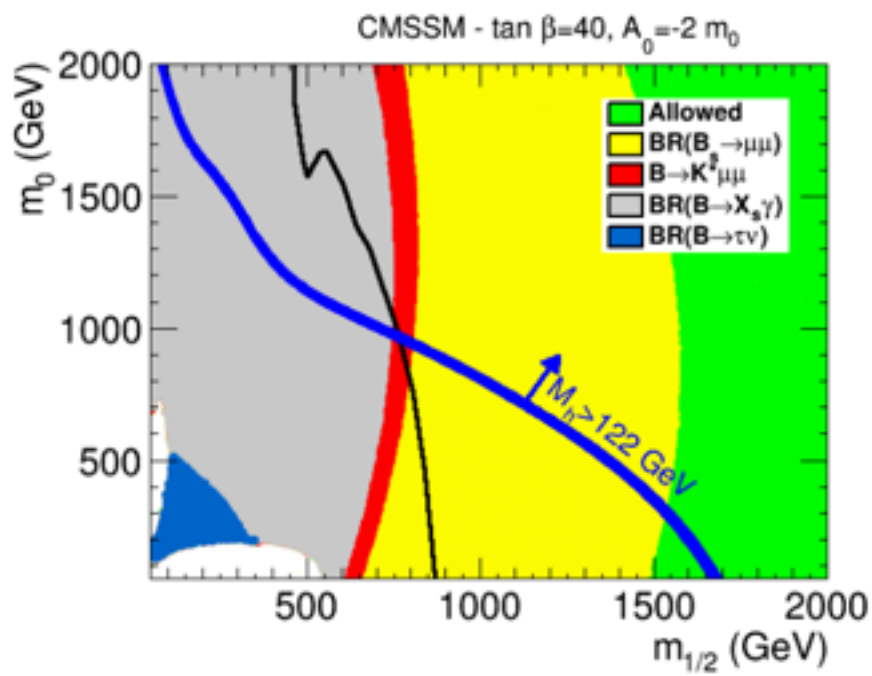


NP coupling(s) in the weak interaction?

EW Penguin implications in CMSSM

- **N. Mahmoudi, arXiv:1401.2145**
- **Black line, 8 TeV LHC direct limit**





How can we establish NP in $B \rightarrow K^* l^- l^+$?

R. Aaij et al. (LHCb collab); PRL 113, 151601 (2014)

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Observe and measure the rate for $B \to X_s \nu \nu$ and thus isolate the Z' penguin (C_9) at *Belle II*

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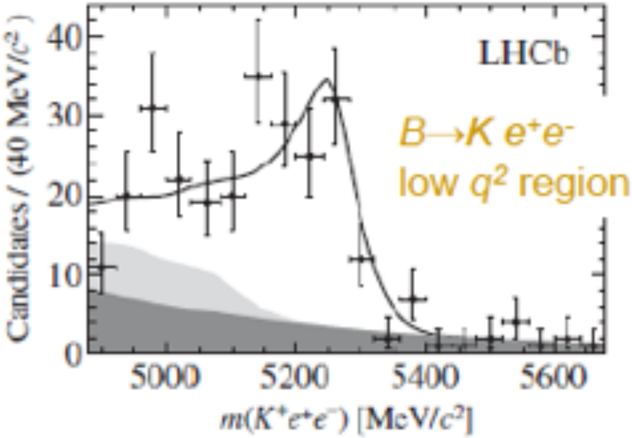

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$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

which is 2.6σ from unity, 3σ if BaBar included.

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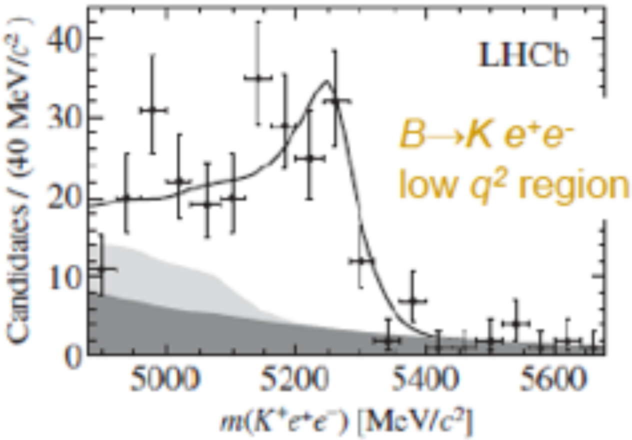

How can we establish NP in $B \rightarrow K^* l^- l^+$?

Observe and measure the rate for $B \rightarrow X_s \nu \nu$ and thus isolate the Z′ penguin (C_9) at *Belle II*

Verify hint of lepton universality breakdown at Belle II (good electron eff)

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

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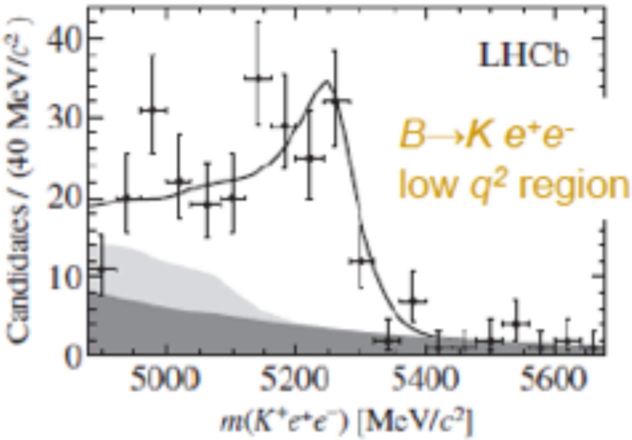
R. Aaij et al. (LHCb collab); PRL 113, 151601 (2014)



How can we establish NP in $B \to K^* l^- l^+$?

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FEATURE 27 April 2016

That's odd: Unruly penguins hint where all the antimatter went

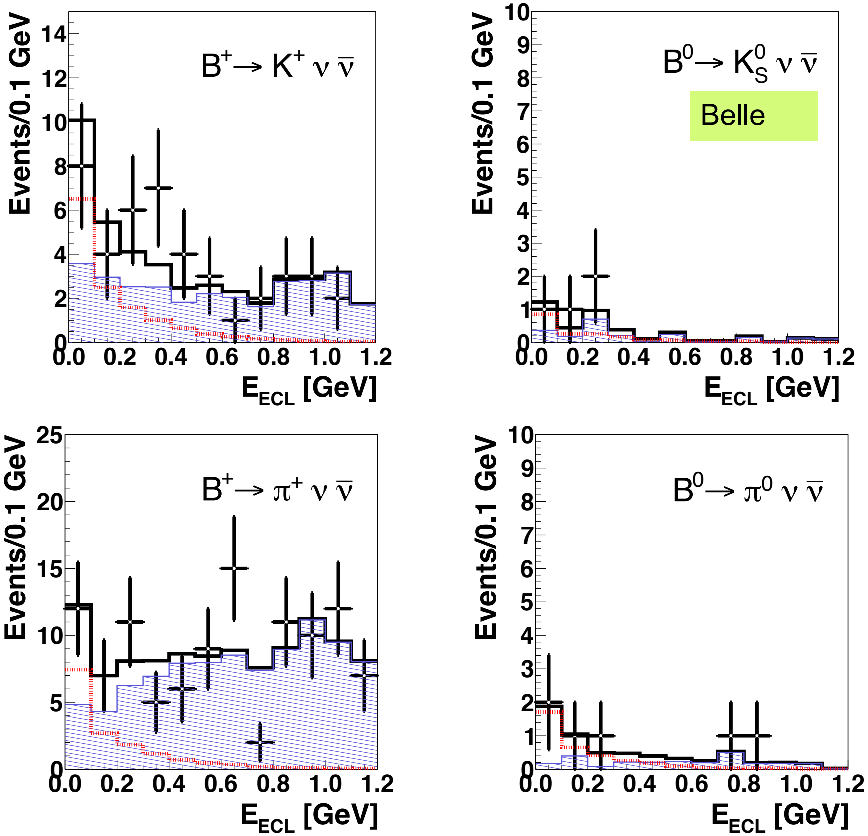
Rare "penguin" particle decays should all happen at the same rate. They don't – perhaps providing a clue to why we live in a universe made of matter

CoEPP

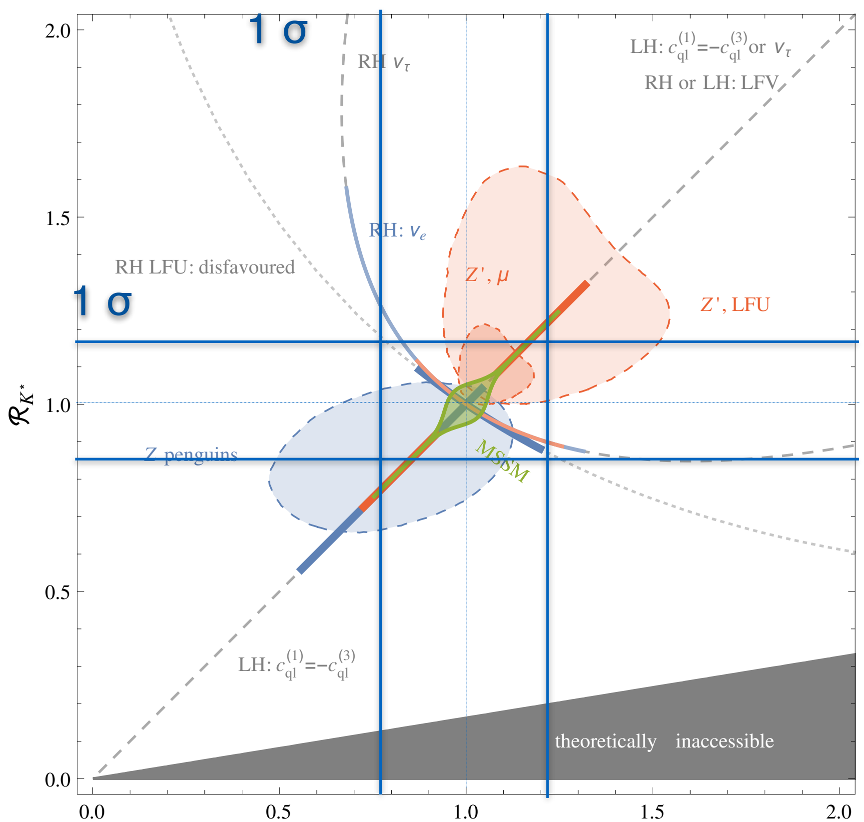
Neutrino EWP decays: DM or RH ν?

Babar, B → K(*) ν ν , PRD 87, 112005 (2013)
Belle, B → K(*)/π/ρ ν ν, PRD 87, 111103(R) (2013)

- We expect 15% precision on $B \to K^{(*)} \nu \nu$ at Belle II



Belle II expected



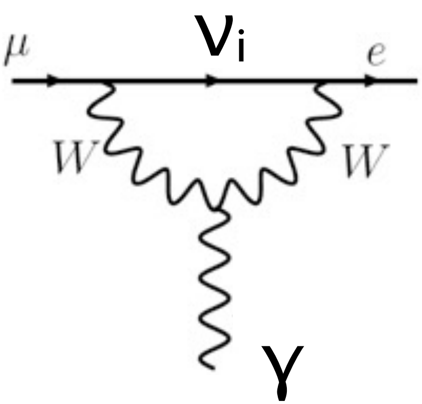
sensitive to L-R symmetry

$$\mathcal{B}(B \to K^{*+}\nu\bar{\nu})_{SM} = (9.2 \pm 1.0) \times 10^{-6}$$
$$\mathcal{B}(B \to K^{+}\nu\bar{\nu})_{SM} = (4.0 \pm 0.5) \times 10^{-6}$$

7. Leptonic Flavour Violation

CLFV: $\mu \to e\gamma$

- ν oscillations → L e, μ, τ not conserved
- In SM + massive ν, effective CLFV vertices are tiny (GIM)



$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 < 10^{-54}$$

Petcov '77, Marciano-Sanda '77 ....

- CLFV processes are an extremely clean probe of B νSM physics

$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\nu-\mathrm{mass}}$$

← dim-4 Dirac or dim5 Majorana

What generates neutrino mass?

Seesaw mechanisms are candidates

$L^{eff} = (c_{ij}/M)\, \nu^i_L \nu^j_L\, \phi\, \phi$ $\quad$ $\langle\phi\rangle = v = 246\text{GeV}$

Seesaw (tree level)

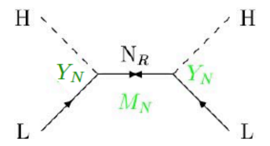
$m^{\nu}_{ij} = y_i y_j\, v^2/M$ $\quad$ $M = 10^{14}$ GeV (for $y_i = O(1)$)

Quantum Effects (Radiative Seesaw) $\quad$ N-th order of perturbation

$m^{\nu}_{ij} = [1/(16\pi^2)]^N\, C_{ij}\, v^2/M$ $\quad$ M=1 TeV

Type I:
Fermion singlet

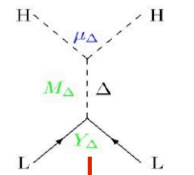
N_{R_i}



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Type II:
Scalar triplet

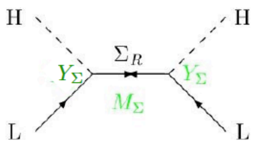
$\Delta \equiv (\Delta^{++}, \Delta^{+}, \Delta^{0})$



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Type III:
Fermion triplet

$\Sigma_i \equiv (\Sigma_i^+, \Sigma_i^0, \Sigma_i^-)$

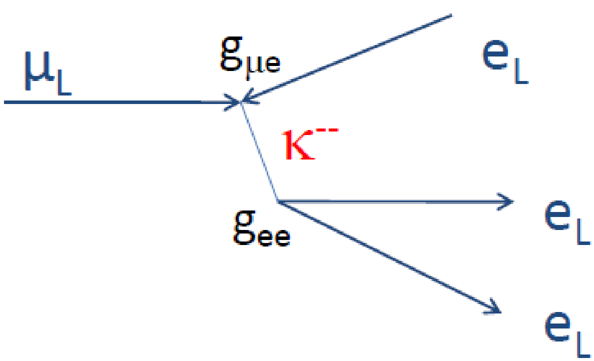


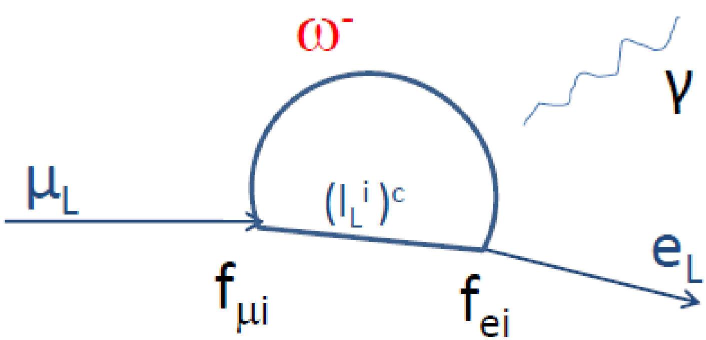
$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Extended Higgs sector

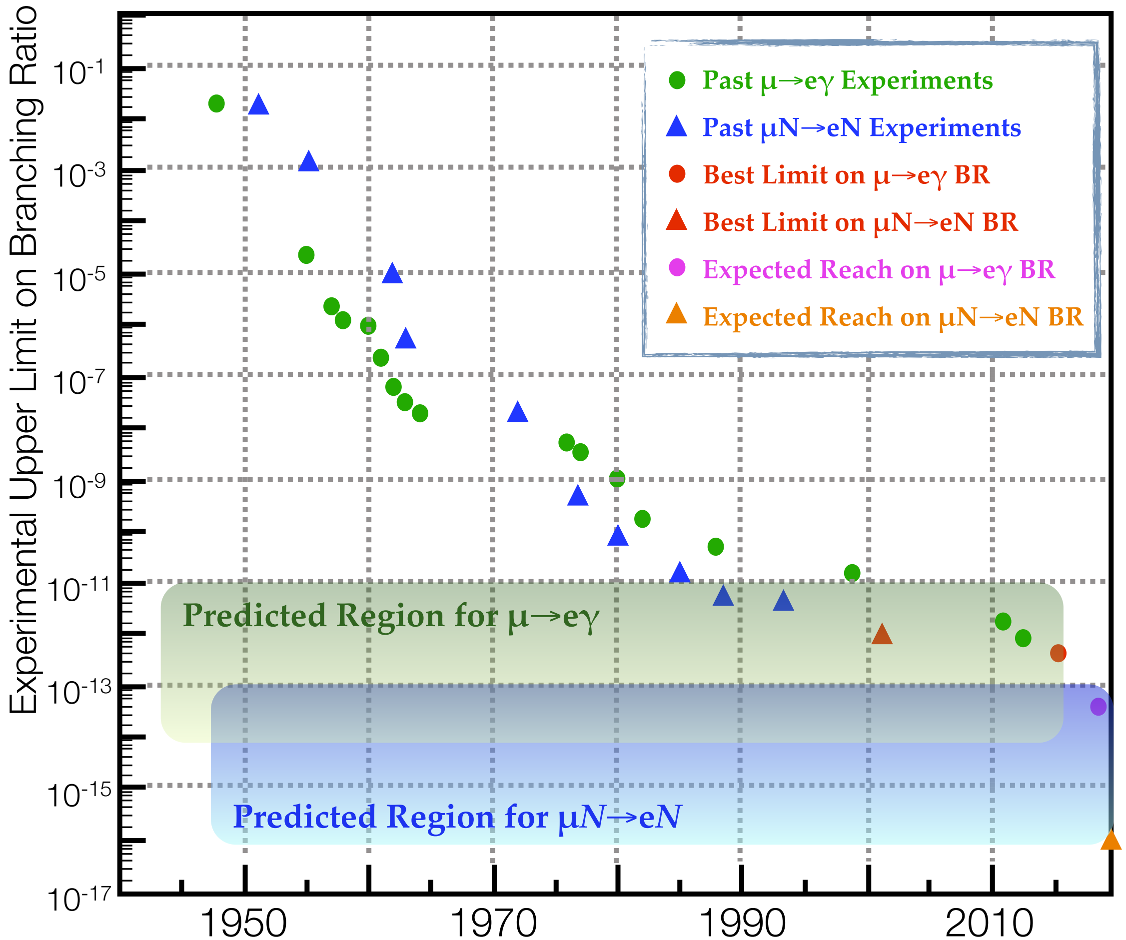
Leptoquarks

Majorana mass for RH neutrino





History of μ → e γ Vs μ N → e N



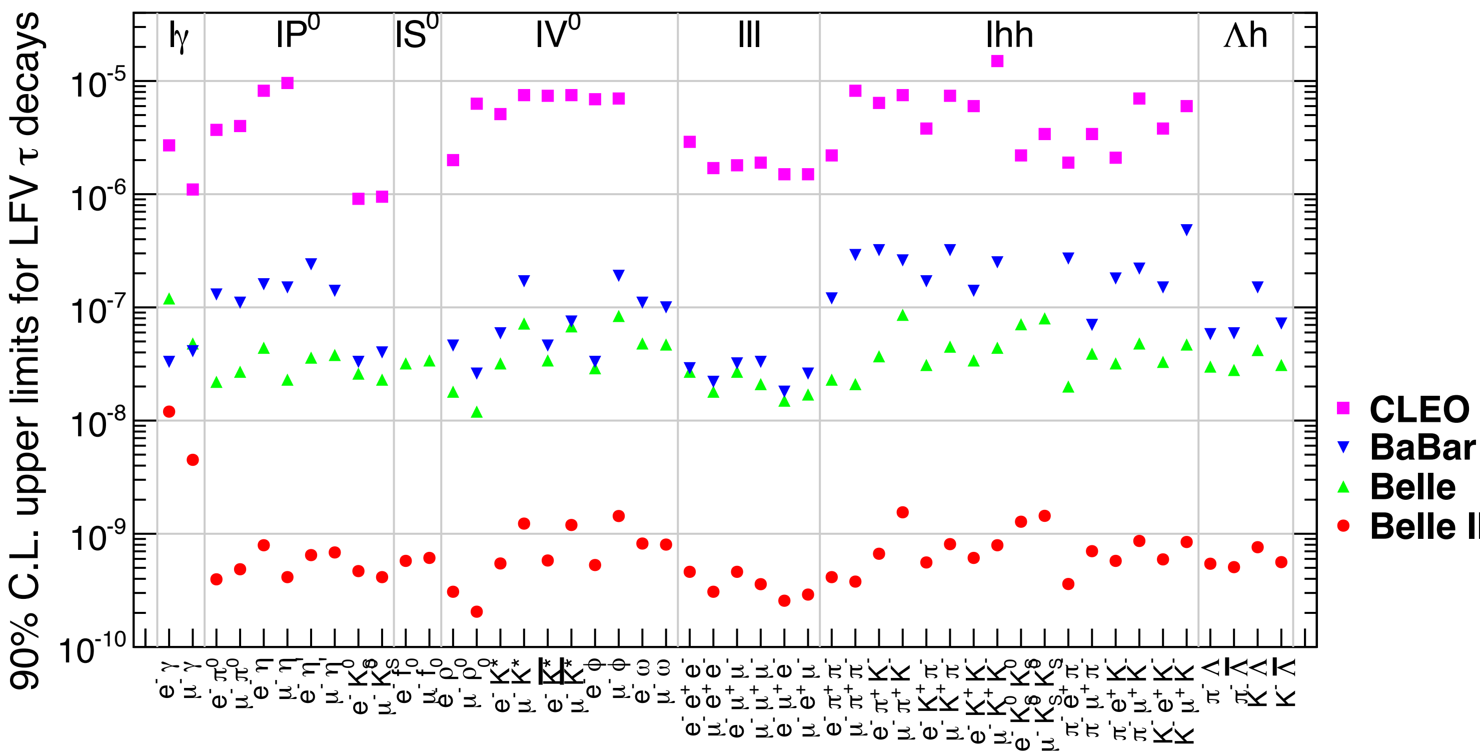
$B_{\mu\to e\gamma}$	$<$	5.7×10^{-13}	$\longrightarrow$	$10^{-/14}$ (MEG at PSI)
$B_{\mu\to 3e}$	$<$	1.0×10^{-12}	$\longrightarrow$	$10^{-15/16}$ (PSI)
$B^{Ti}_{\mu-e}$	$<$	4.3×10^{-12}	$\longrightarrow$	$10^{-16/17\to-18}$ (Mu2e, COMET)

τ Lepton Flavour Violation

Belle II Flavour Prospects (B2TiP 2014)

- Best done at e+e- B-factory colliders.
- If CLFV shows up, can determine type of particle based on modes.

	reference	$\tau \to \mu\gamma$	$\tau \to \mu\mu\mu$
SM + heavy Maj ν_R	PRD 66(2002)034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547(2002)252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68(2003)033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66(2002)115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566(2003)217	10^{-10}	10^{-7}

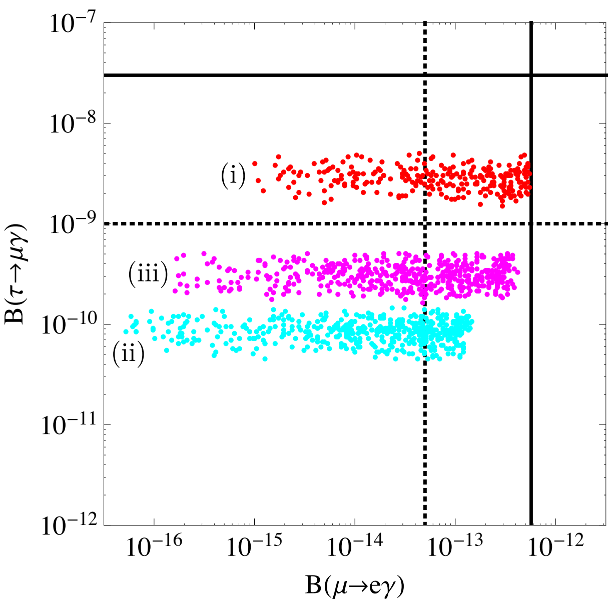


Nature of NP in τ LFV

Non-degenerate, SUSY, Type 1 Seesaw

LHC synergy with H → τ μ anomaly: Leptoquarks

T. Goto et al. Phys. Rev. D 91, 033007 (2015)



SUSY parameter:

$M_{1/2} = 1.5\,\text{TeV},\ \mu > 0,$

(i) $A_0 = -2,\ M_0 = 2\,\text{TeV},\ \tan\beta = 30$

(ii) $A_0 = 0,\ M_0 = 6\,\text{TeV},\ \tan\beta = 30$

(iii) $A_0 = 0,\ M_0 = 6\,\text{TeV},\ \tan\beta = 50$

Neutrino Yukawa:

$0 \le \theta \le \pi/2,$

$1.5 < y_{2,3} < 2.0,$

$0.01 < y_1 < 0.1$

I. Dorsner et al., JHEP 1506 (2015) 108