Introduction to Flavour Physics

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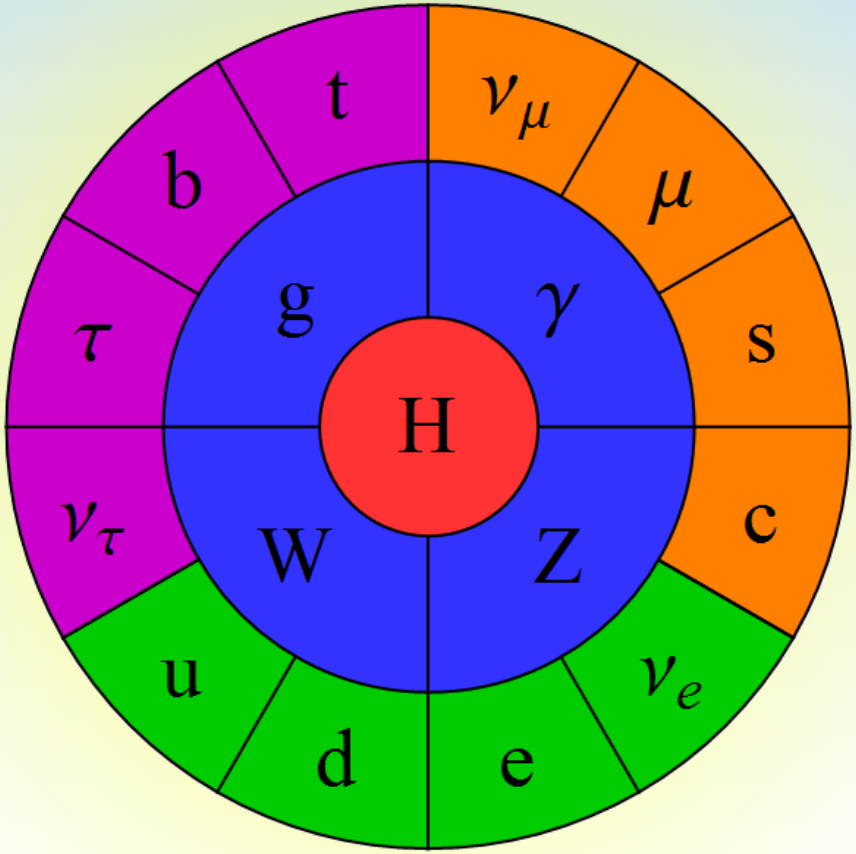
LAL - CNRS

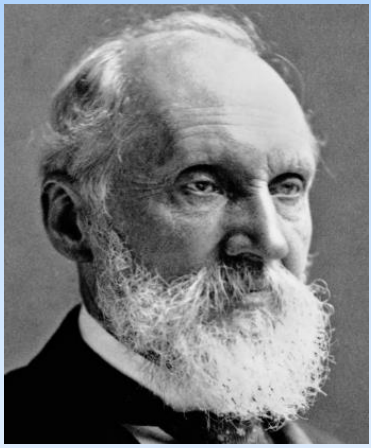
15 October 2018

The Standard Model



Problems with the SM

"The beauty and clearness of the dynamical theory […] is at present obscured by two clouds."
– Lord Kelvin, 1901

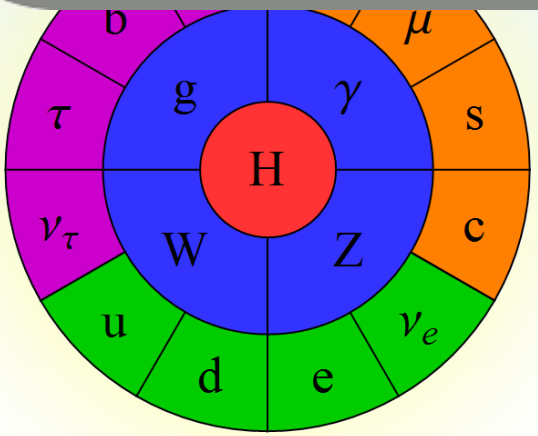


Quant[illegible] Gravity

Dark Sector

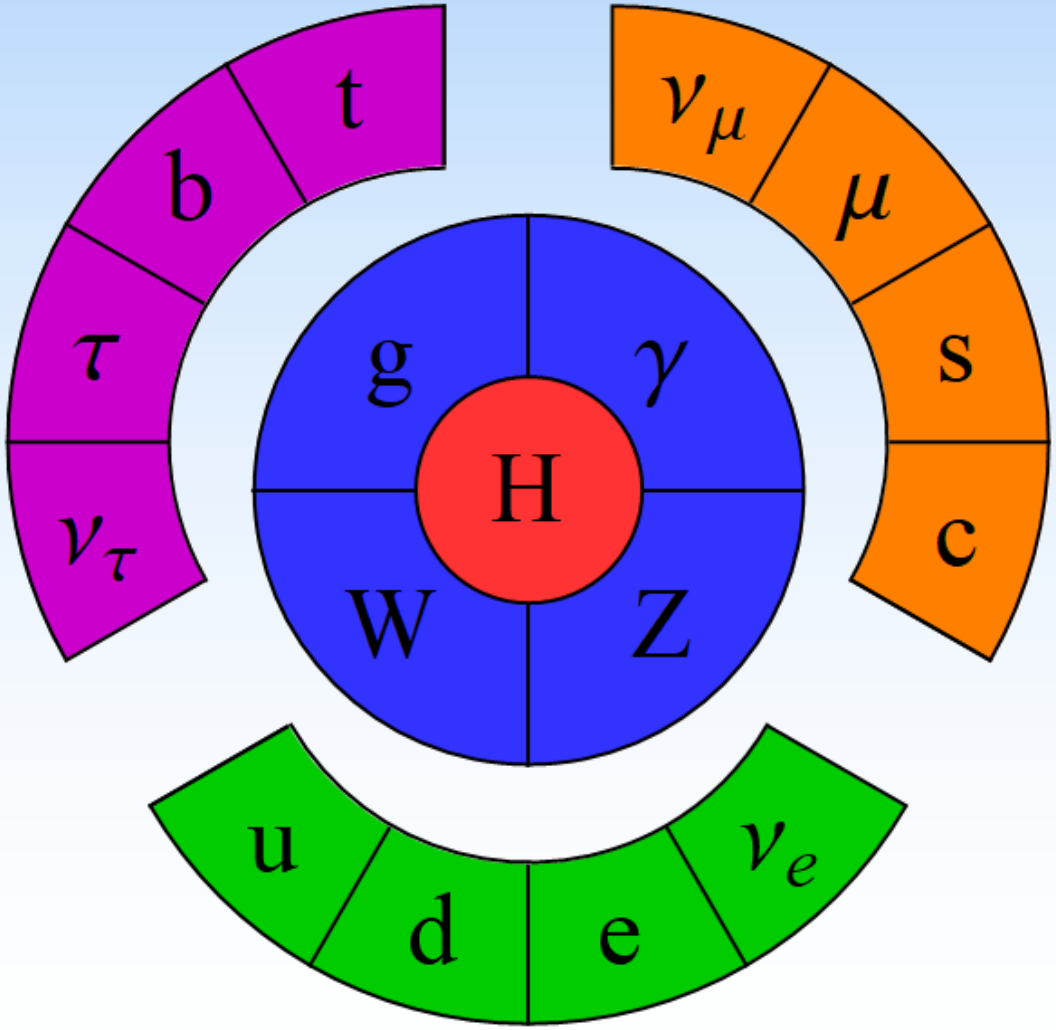
Flavour Problem

Matter-Antimatter Asymmetry

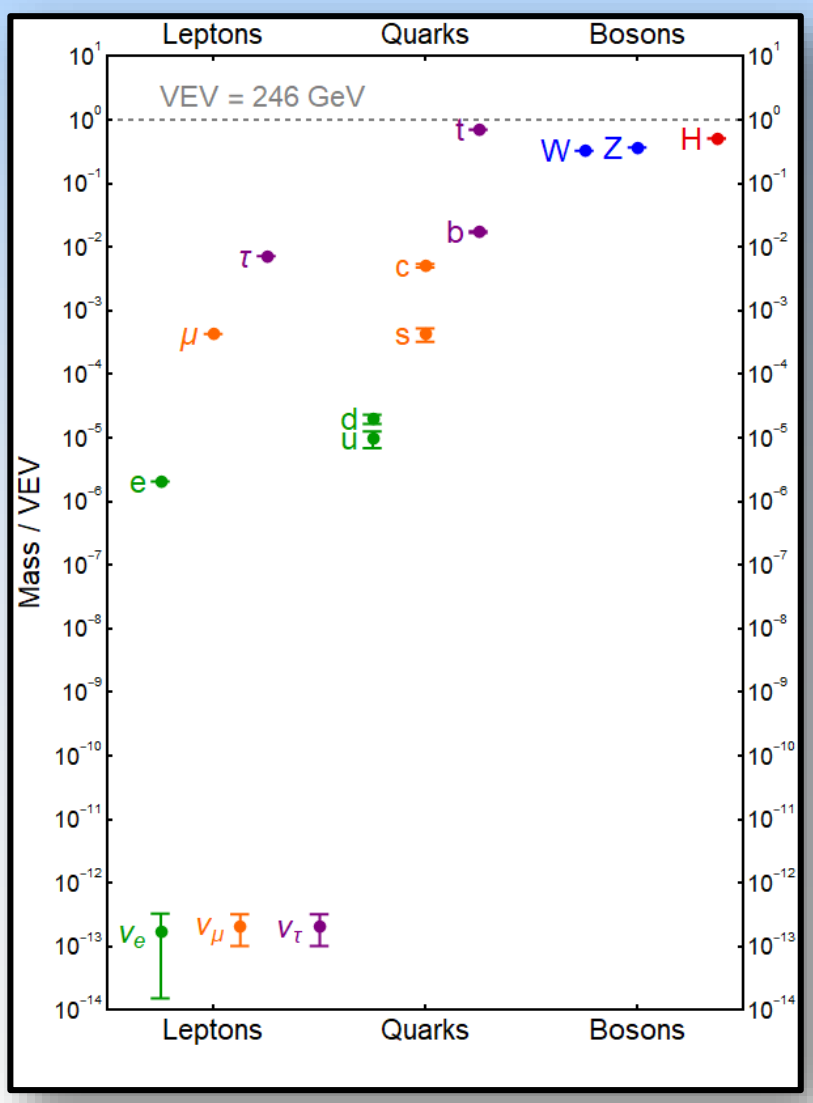


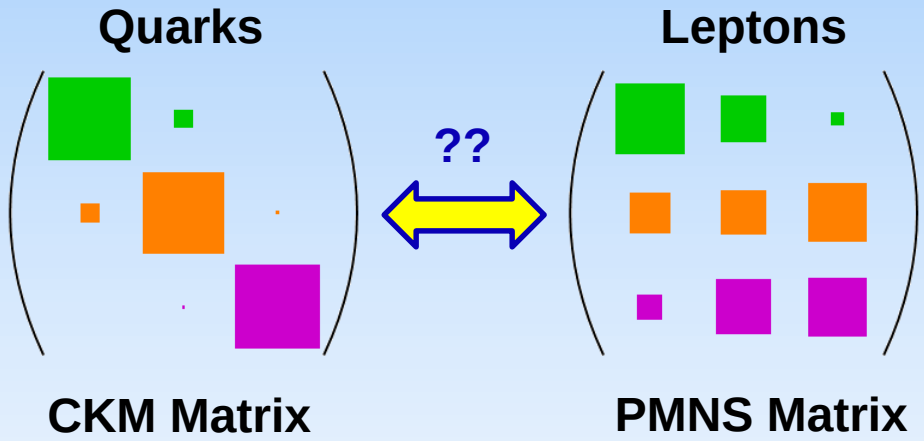
Flavour Puzzle

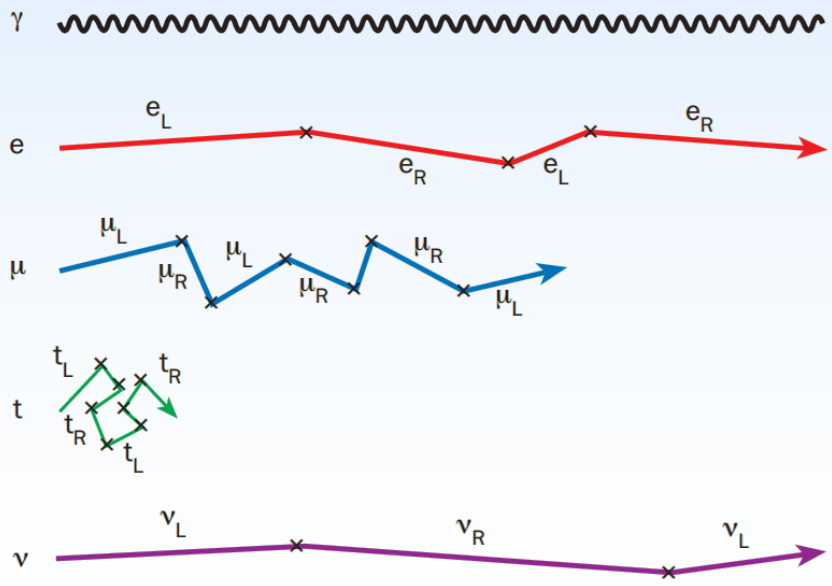
- *"Who order that?!" – I.I. Rabi, 1936*



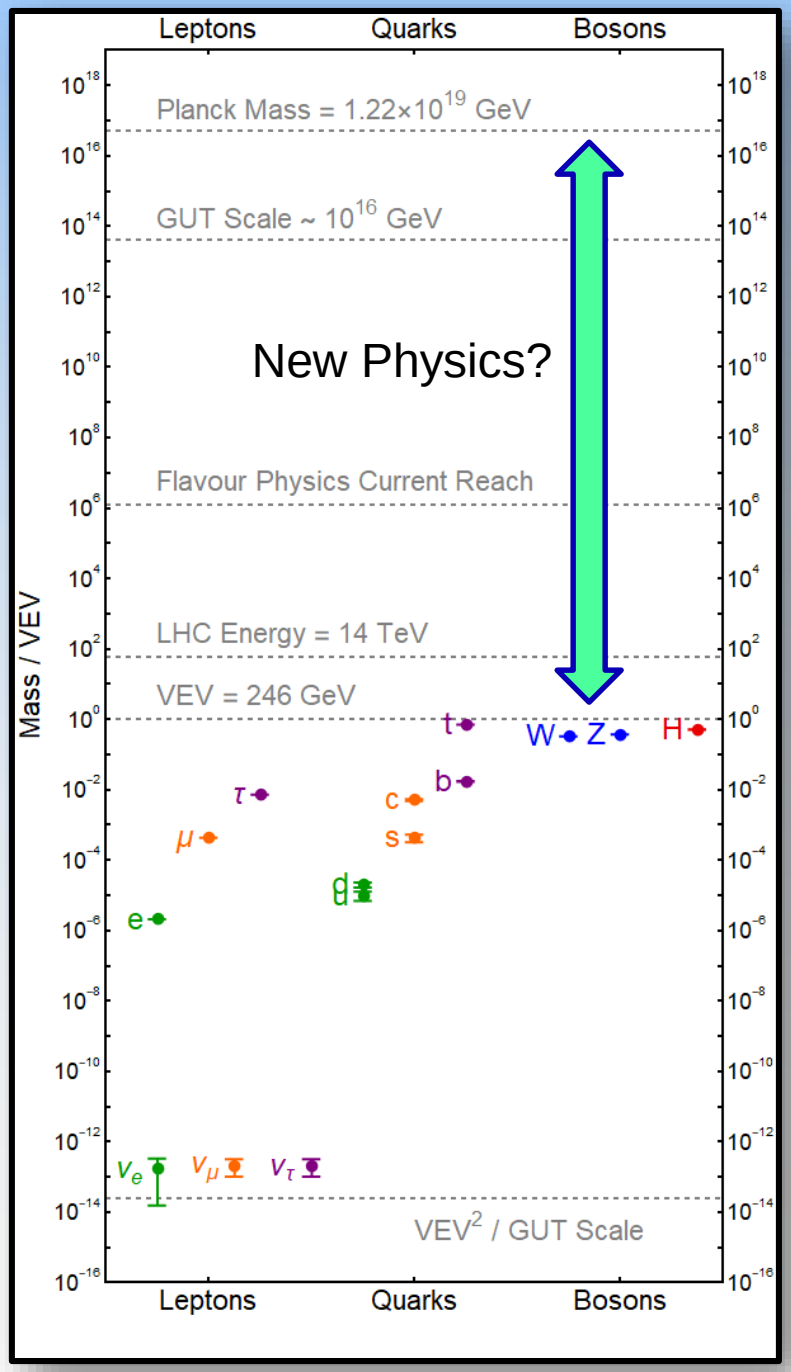
Flavour Structure

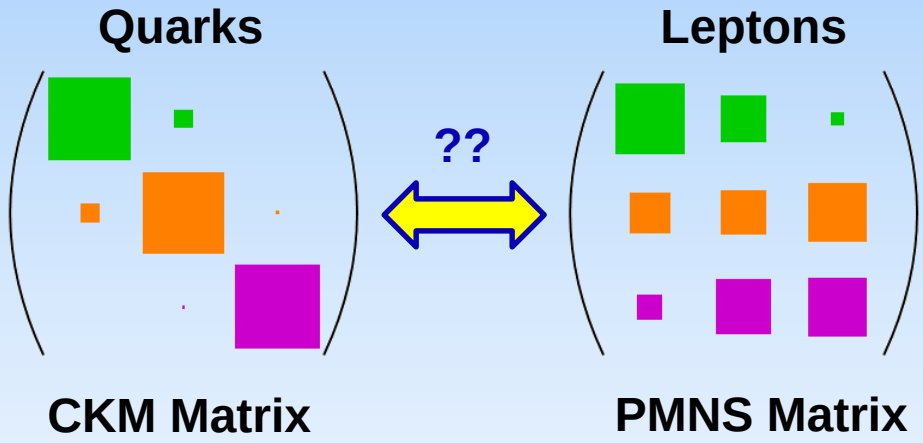


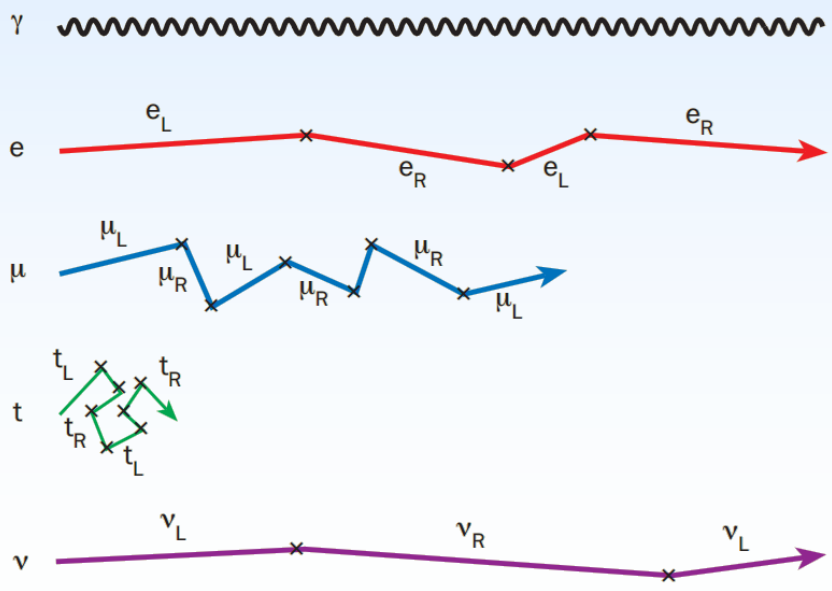




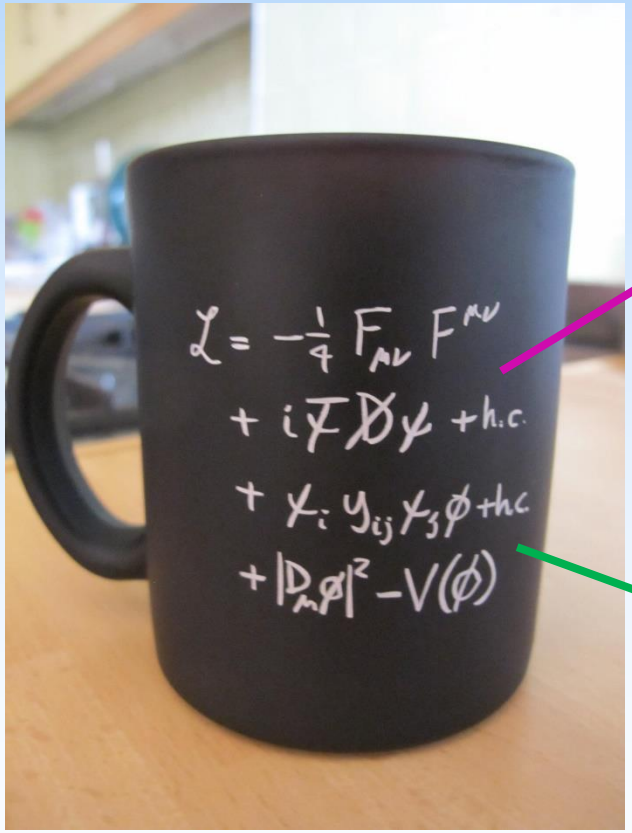
Flavour Structure







Gauge vs Higgs



Free Parameters

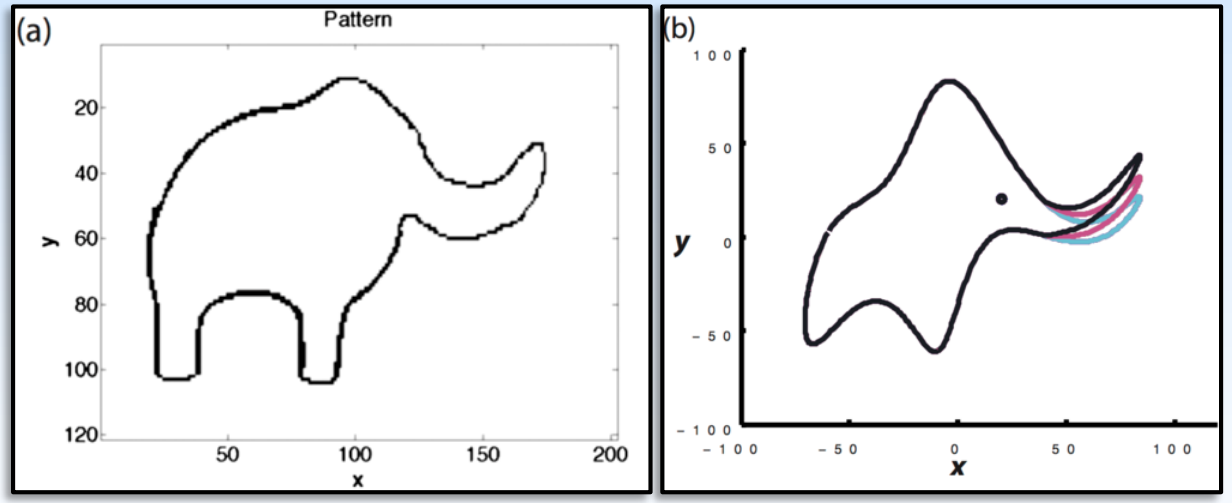
- **3 gauge couplings**
- **1 QCD CP phase (= 0 ?)**

Free Parameters

- **Vacuum Expectation Value**
- **Higgs mass**
- **6 quark masses**
- **6 lepton masses (maybe*)**
- **3 quark mixing angles**
- **3 lepton mixing angles***
- **1 quark CP phase**
- **1 lepton CP phase***

Free Parameters

"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk" – von Neumann



Am. J. Phys. 78, 648 (2010)

New Physics Operators

G. Isidori
CERN HEP
School 2012

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{gauge}}(A_a, \psi_i) + \mathscr{L}_{\text{Higgs}}(\phi, A_a, \psi_i) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

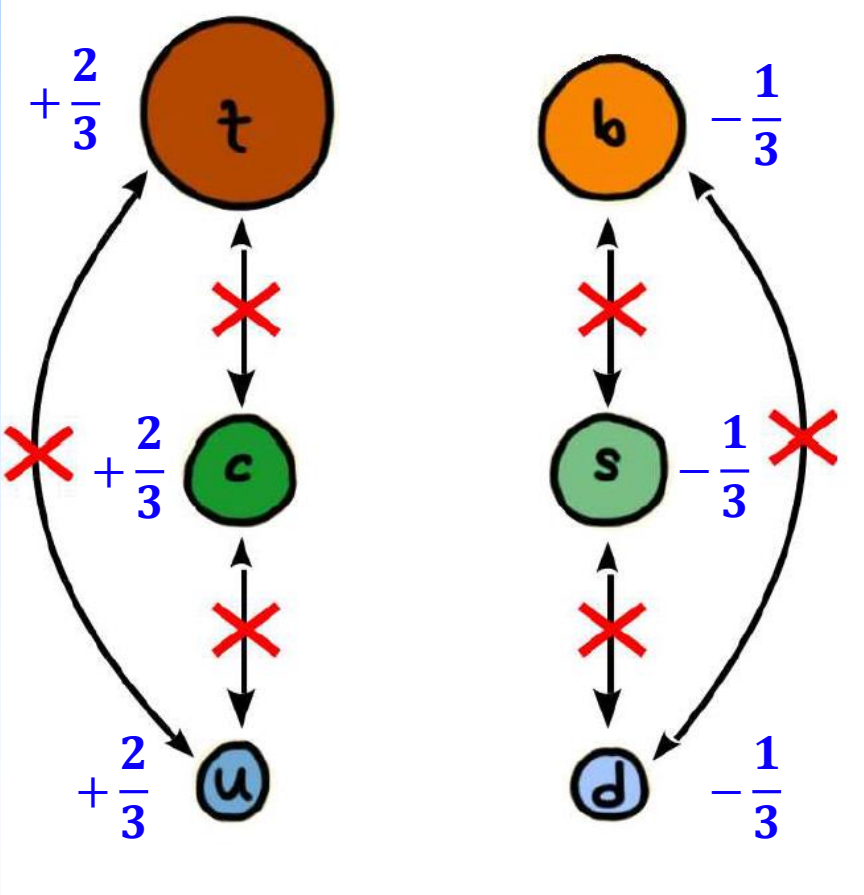
$\mathscr{L}_{\text{SM}}$ = renormalizable part of $\mathscr{L}_{\text{eff}}$
[= all possible operators with $d \leq 4$ compatible with the gauge symmetry]

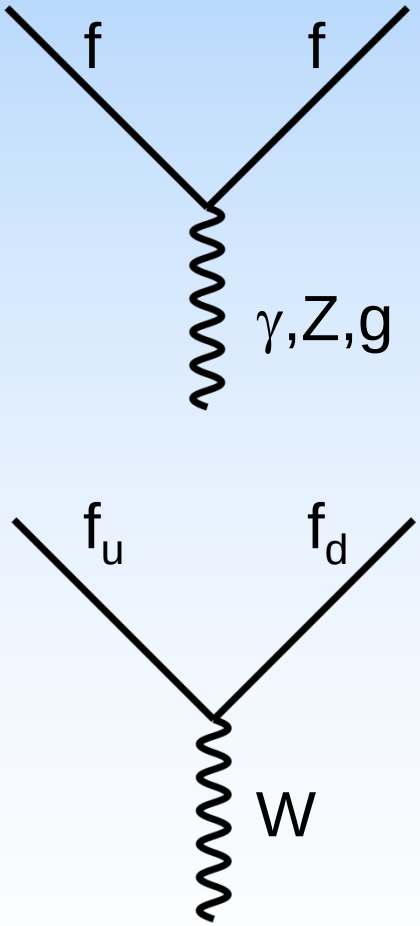
operators of $d \geq 5$ containing SM fields only and compatible with the SM gauge symmetry

- **NP** expected to be **small** arXiv:1302.0661
  - Given CKM data, for d=6: $\frac{\Lambda}{\sqrt{c_n}}$ **> 10^2 – 10^5 TeV**
  - Large SM -> needs very high precision
  - **Suppressed SM -> NP can compete**
  - Forbidden SM -> NP smoking gun

GIM Mechanism

W. Altmannshofer
ACP Colloquium 2014

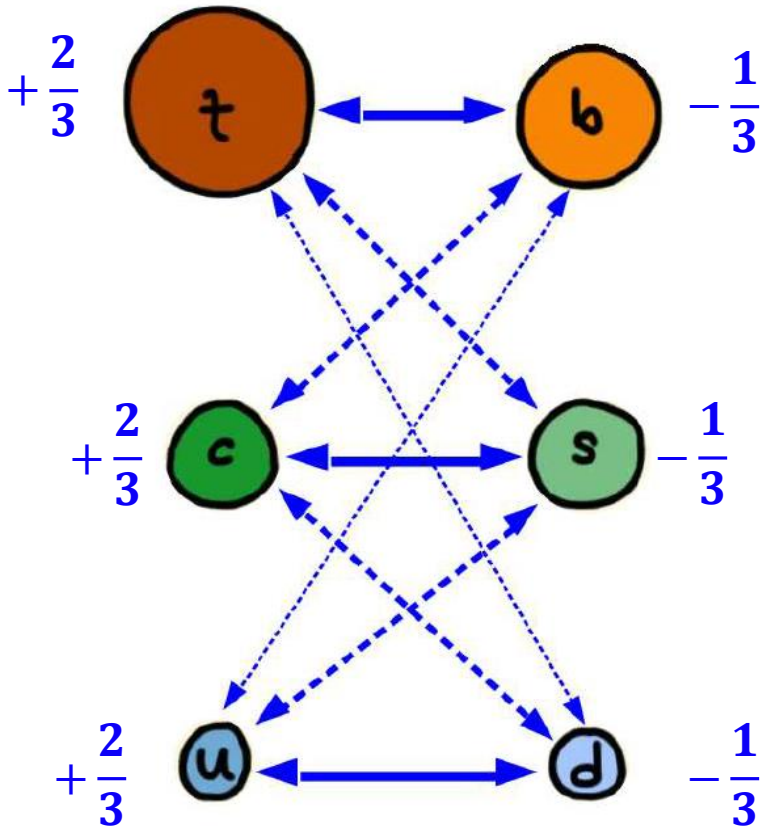




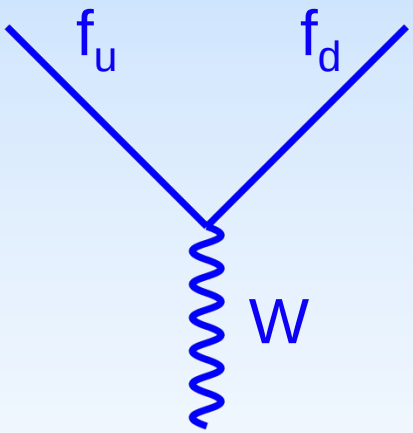
No FCNC at tree level

GIM Mechanism

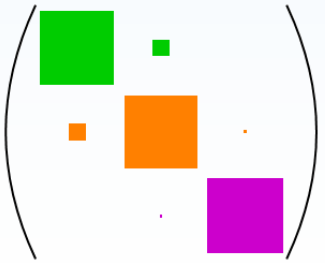
W. Altmannshofer
ACP Colloquium 2014



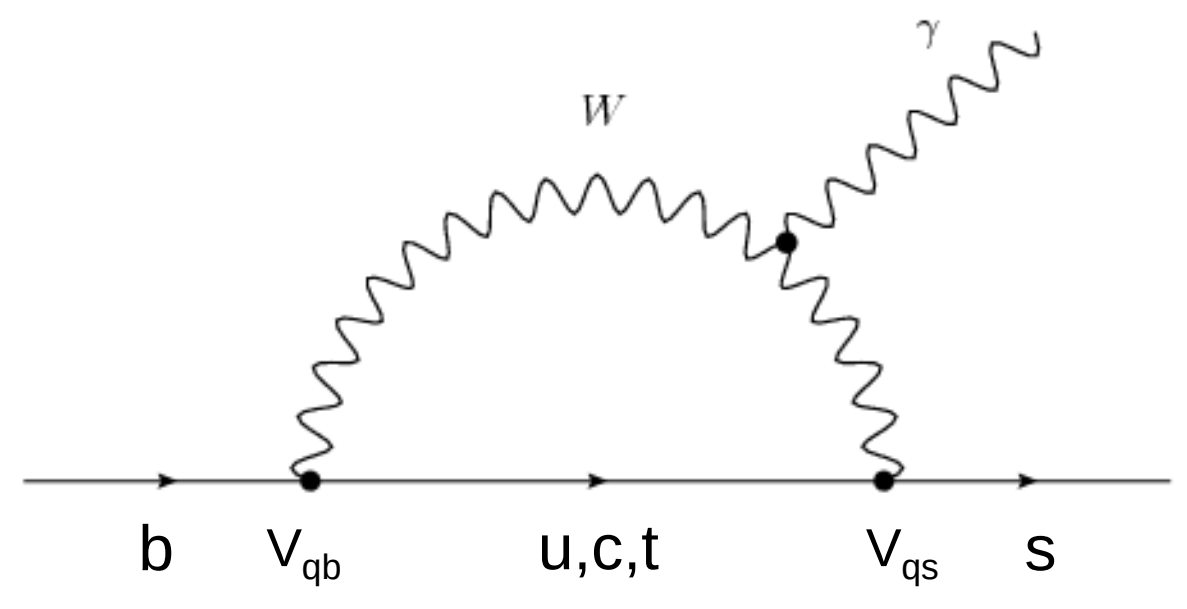
FCCC



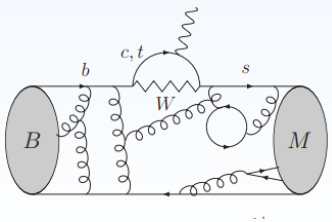
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$



Example



$$\mathcal{B}(b \to s\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{q=c,t} V_{qb}^* V_{qs} \frac{\Delta m_{qu}^2}{M_W^2} \right|^2 \sim 10^{-6}$$



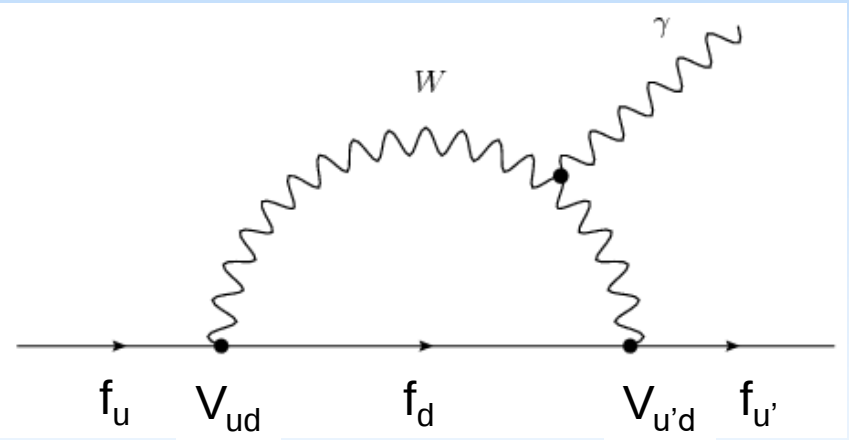
+QCD Effects

$$\mathcal{B}(\bar{B} \to X_s\gamma) = (3.29 \pm 0.52) \times 10^{-4}$$

BABAR 2012

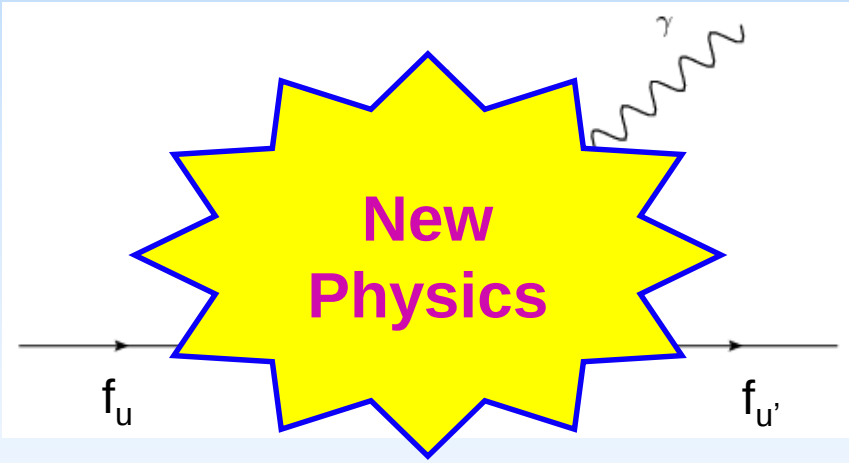
New Physics?

SM: GIM Suppressed



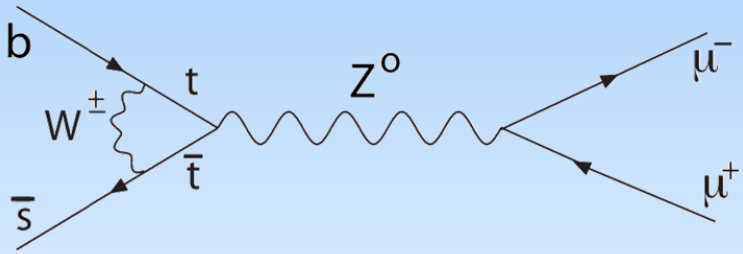
+

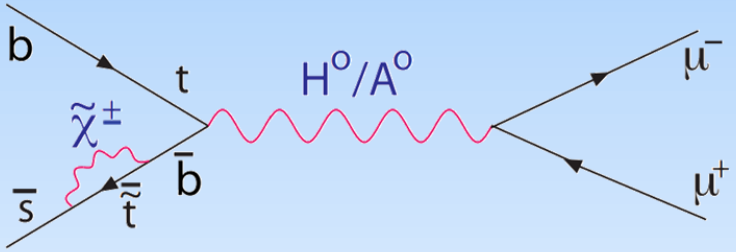
NP: Λ Suppressed

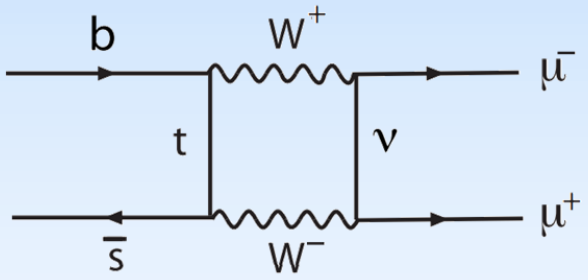


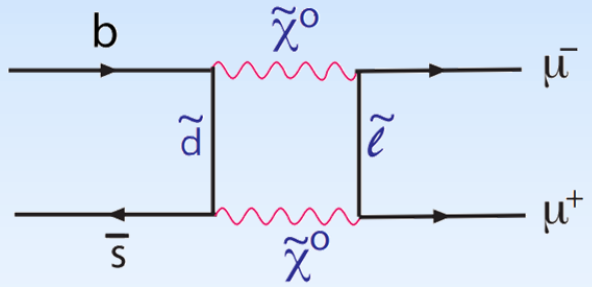
New Physics in Rare Decays?

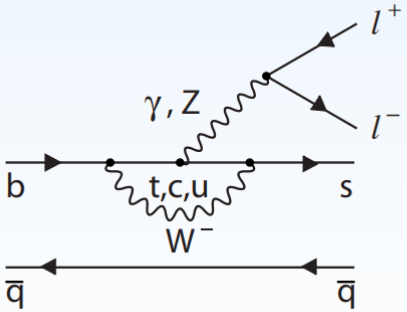
Many Processes to Explore

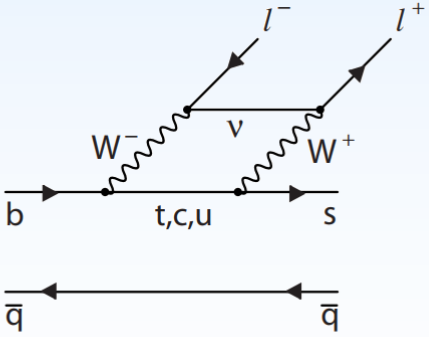


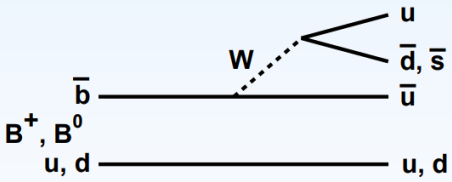


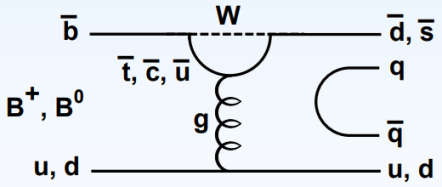


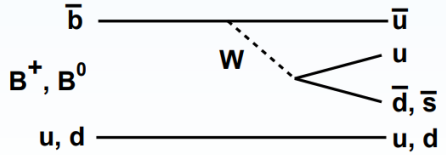


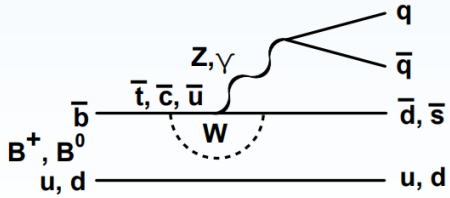






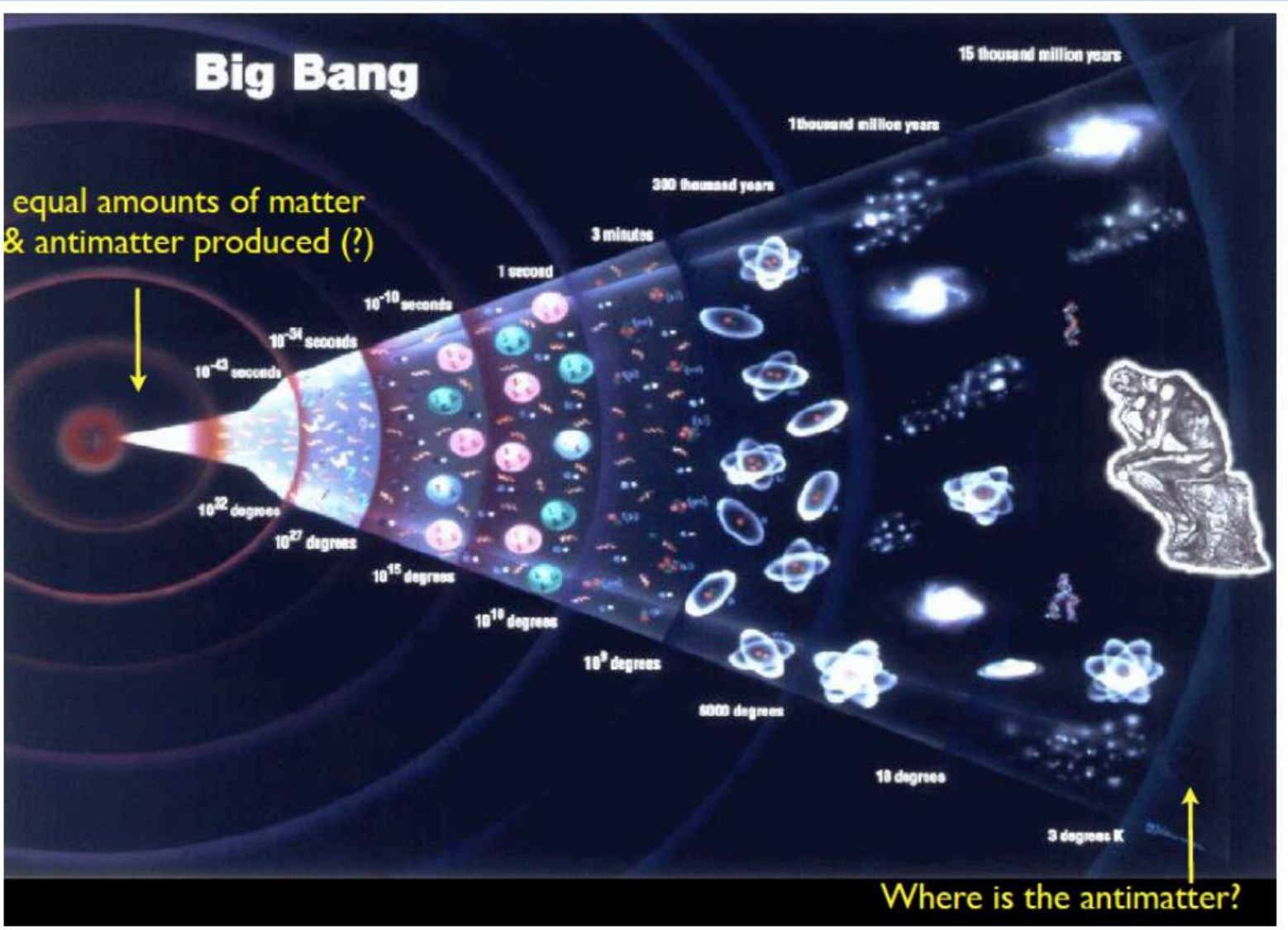






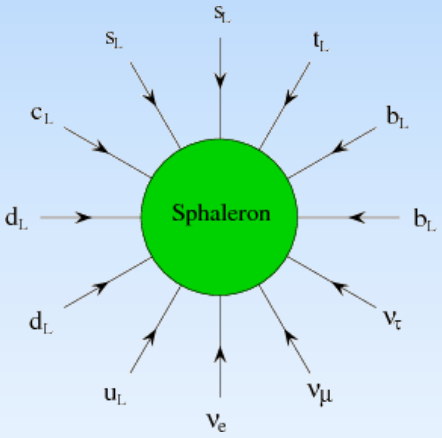
Matter-Antimatter Asymmetry

Y. Amhis
JRJC
2013

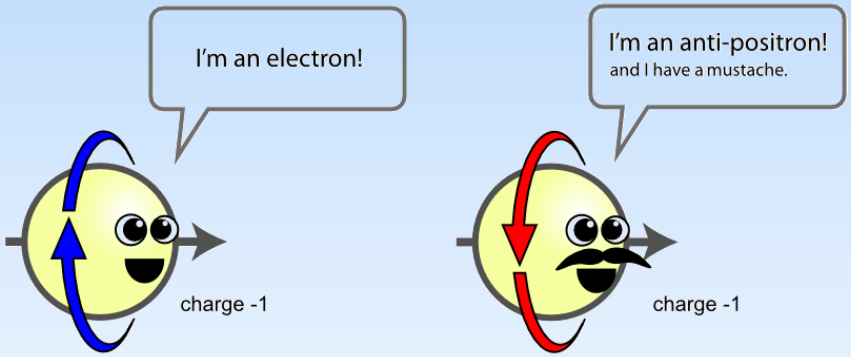


Sakharov Conditions

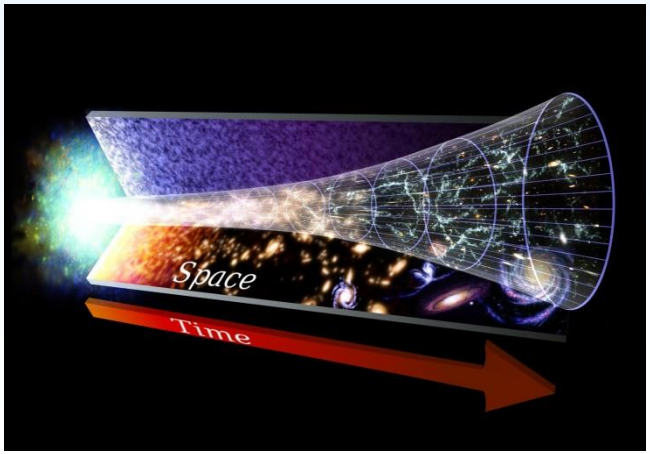
Baryon Number Violation

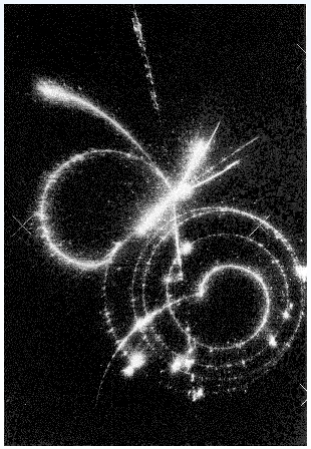


C Violation



Depart from thermal equilibrium

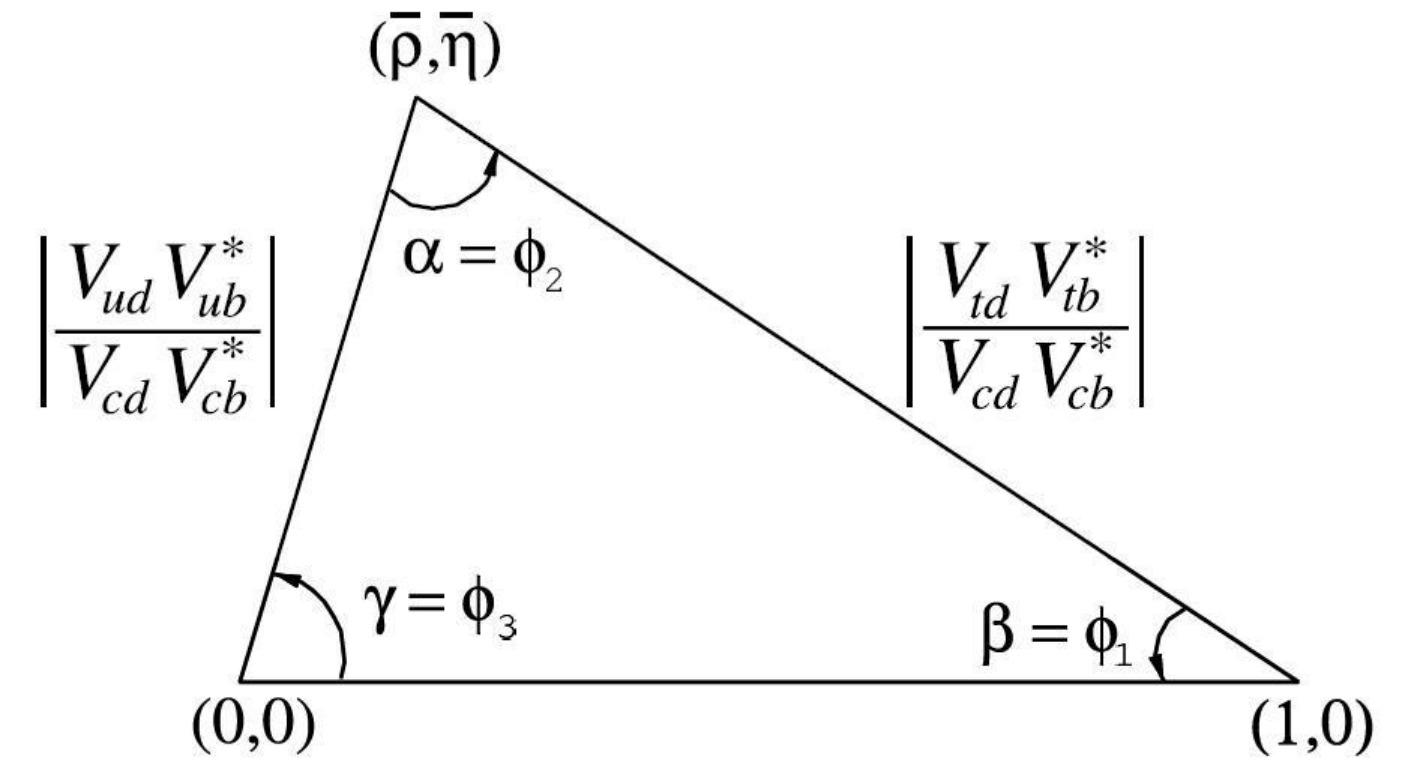




CP Violation

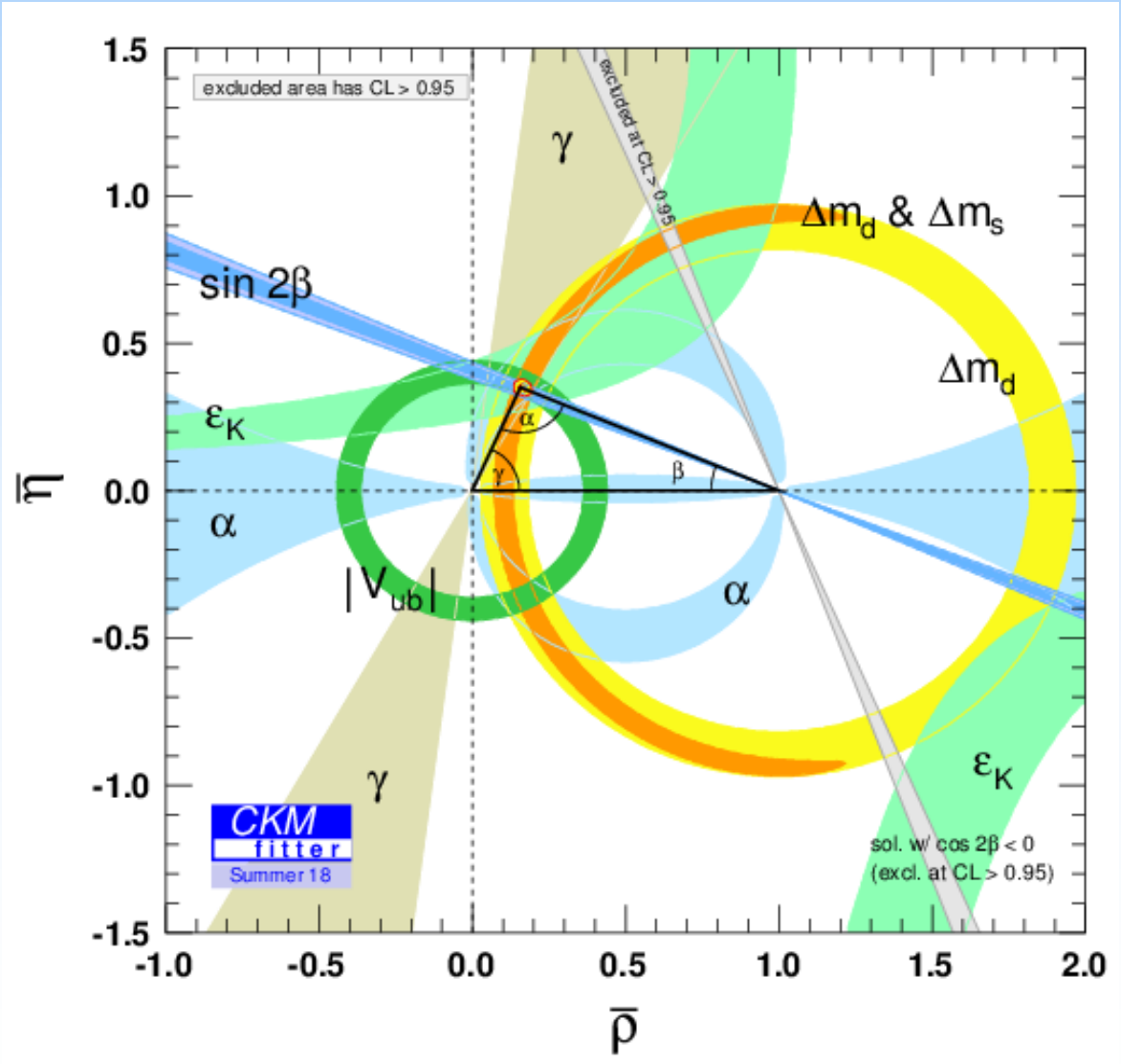
?

CKM Triangle

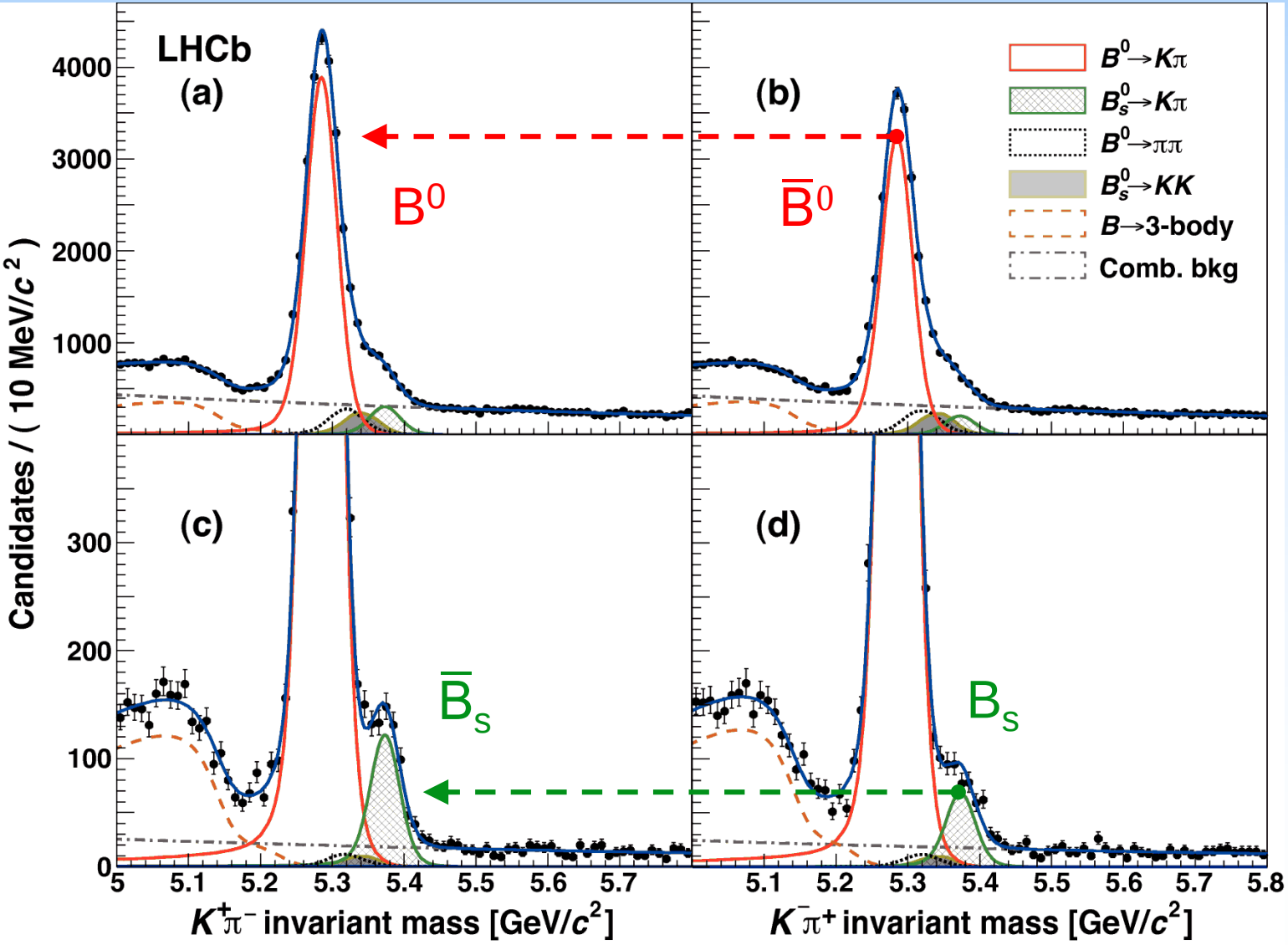


- CKM elements may be complex
- This gives rise to CP violation
- Can construct triangle in complex plane

CKM Triangle



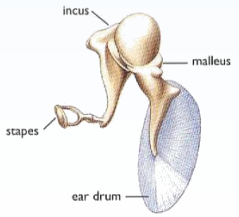
Example CP violation



Is that enough?

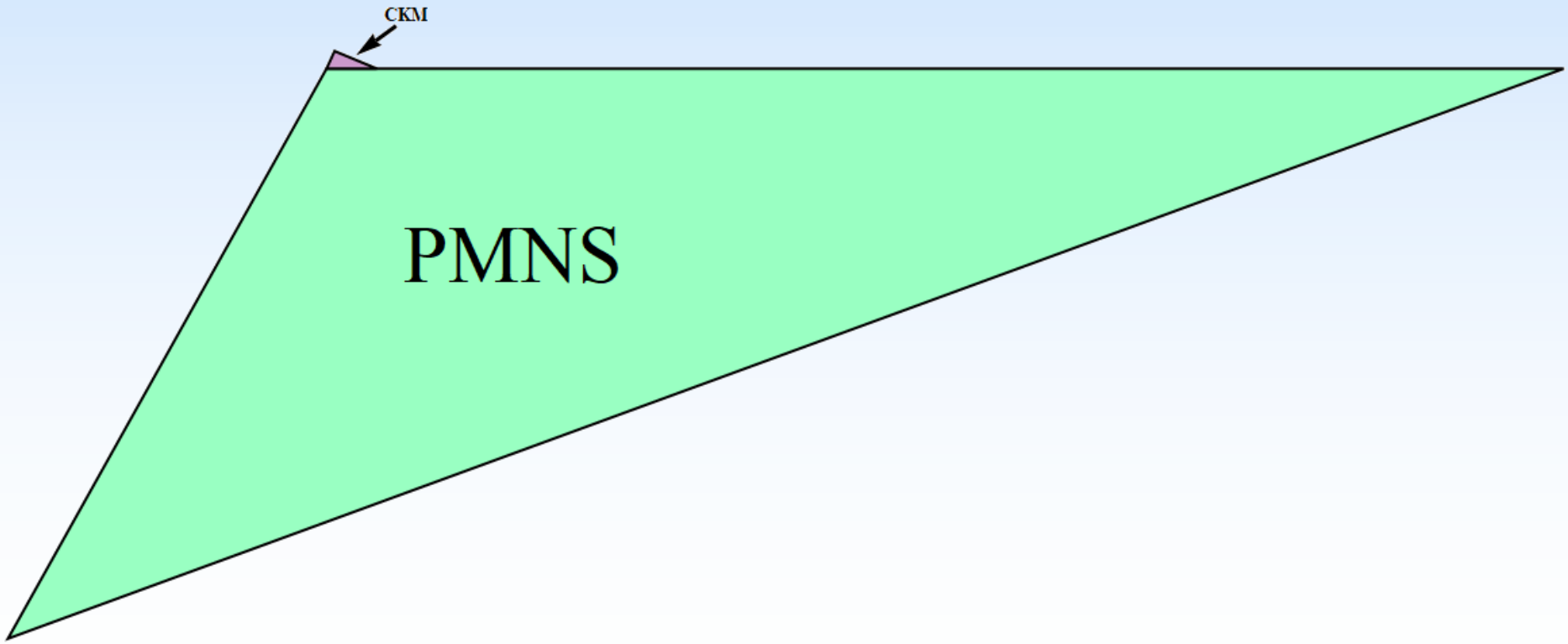
- Observed baryon/photon ratio is $\eta \sim 10^{-10}$
- CPV from quarks in SM contributes only $10^{-19} - 10^{-16}$
- i.e.: CKM responsible for **one eyelash/person** (~70 μg)*

*Or up to your middle ear bones (~70 mg)



Size Matters

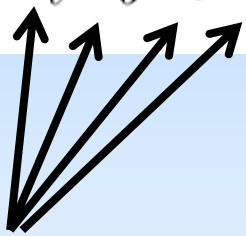
- **CKM** triangle is **~800x smaller** than PMNS triangle
- All CPV observables prop. to area of triangle (J/2)



A. Cohen
Proceedings
SSI 2001

Mass Differences

$$\delta_{CP} \sim \alpha_{wk}^2 \lambda_t^4 \lambda_b^2 \lambda_s \lambda_d \sin^2\theta_1 \sin\theta_2 \sin\theta_3 \sin\delta \sim 10^{-16} \ .$$

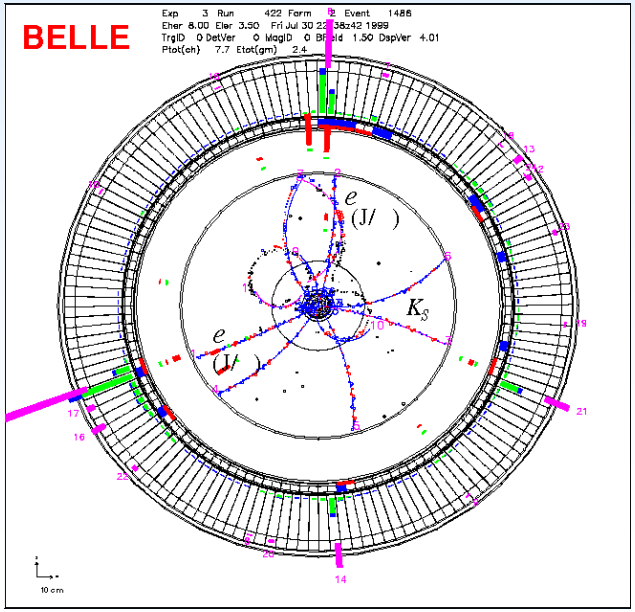


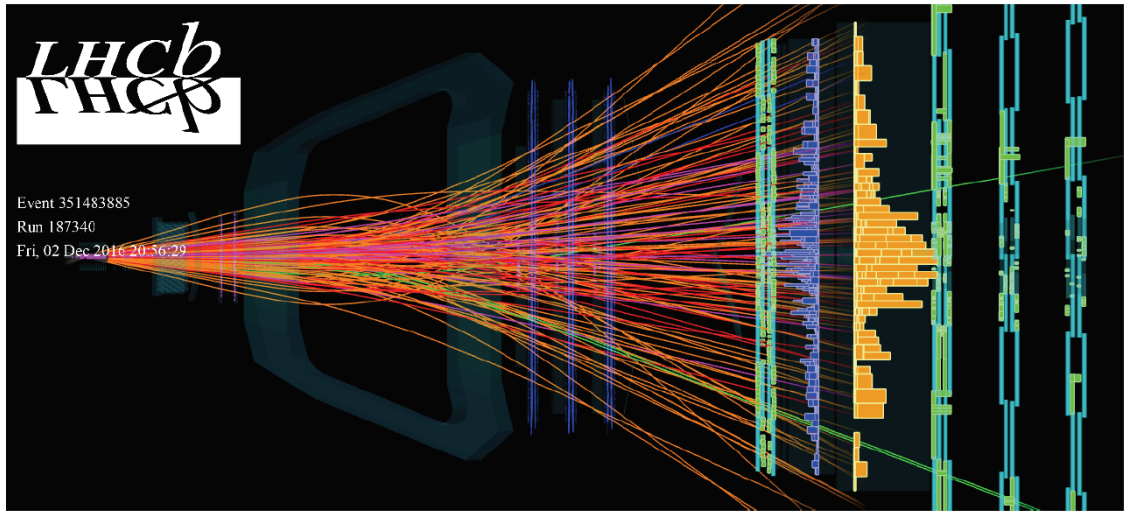
- Quark mass differences generate further suppression
- Neutrino sector even more suppressed unless heavy Majorana neutrinos exist
- **Need to find new sources of CP violation**

B Factories vs LHCb

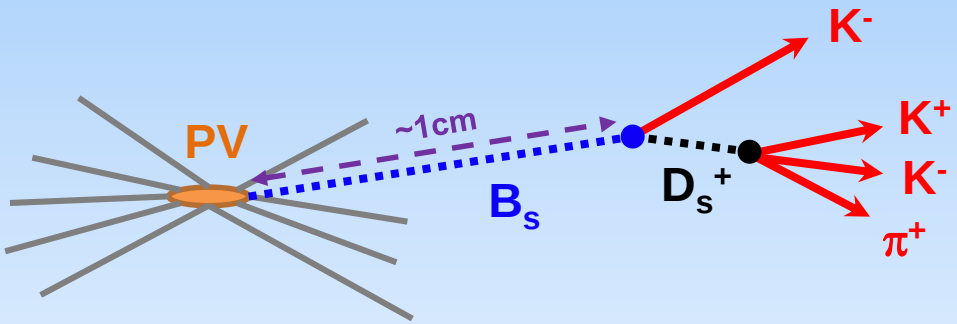
- CM: 10.6 GeV
- Clean environment
- ~4π coverage
- High Luminosity:
  - Belle/BaBar: ~10^2 fb^{-1}/yr
  - Belle II: ~10^4 fb^{-1}/yr
- Lower x-section (1 nb)
- 10^8 - 10^{10} $b\bar{b}$ / yr

- CM: 7-14 TeV
- High multiplicity environment
- 4% solid-angle coverage
- Luminosity limited:
  - Current: ~2 fb^{-1}/yr
  - Future: 5 - 50 fb^{-1}/yr
- Very high x-section (~600 μb)
- 10^{12} - 10^{13} $b\bar{b}$ / yr

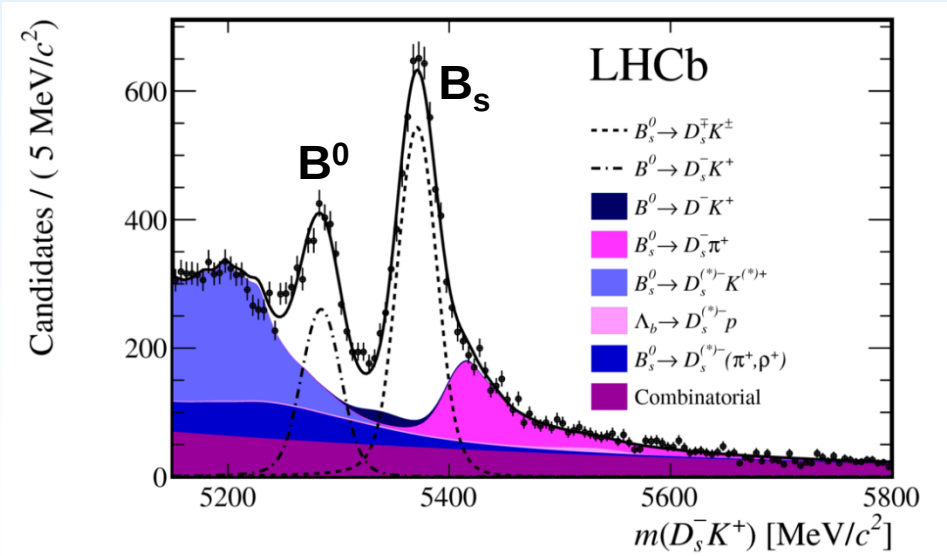




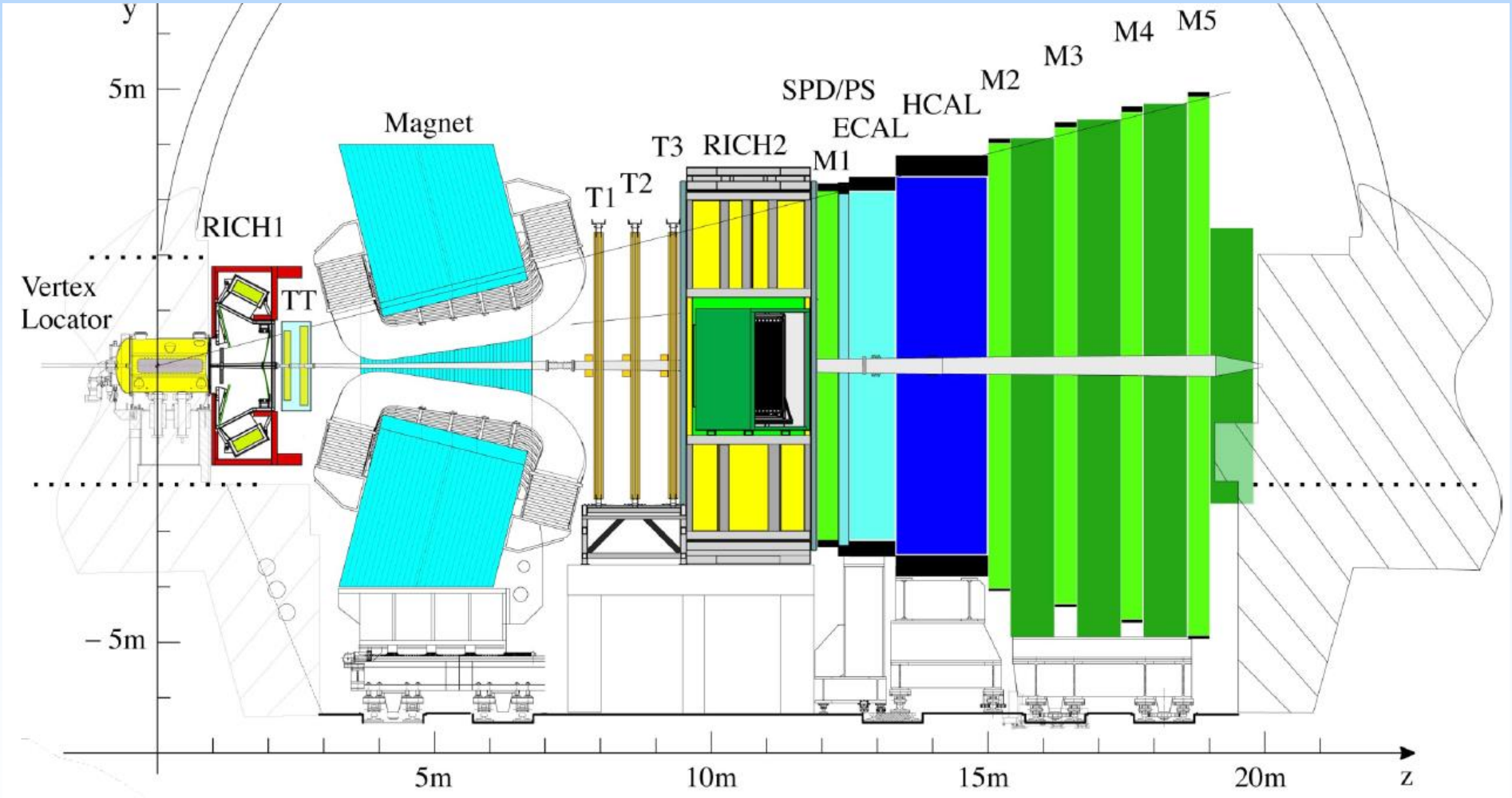
Experimental Challenges



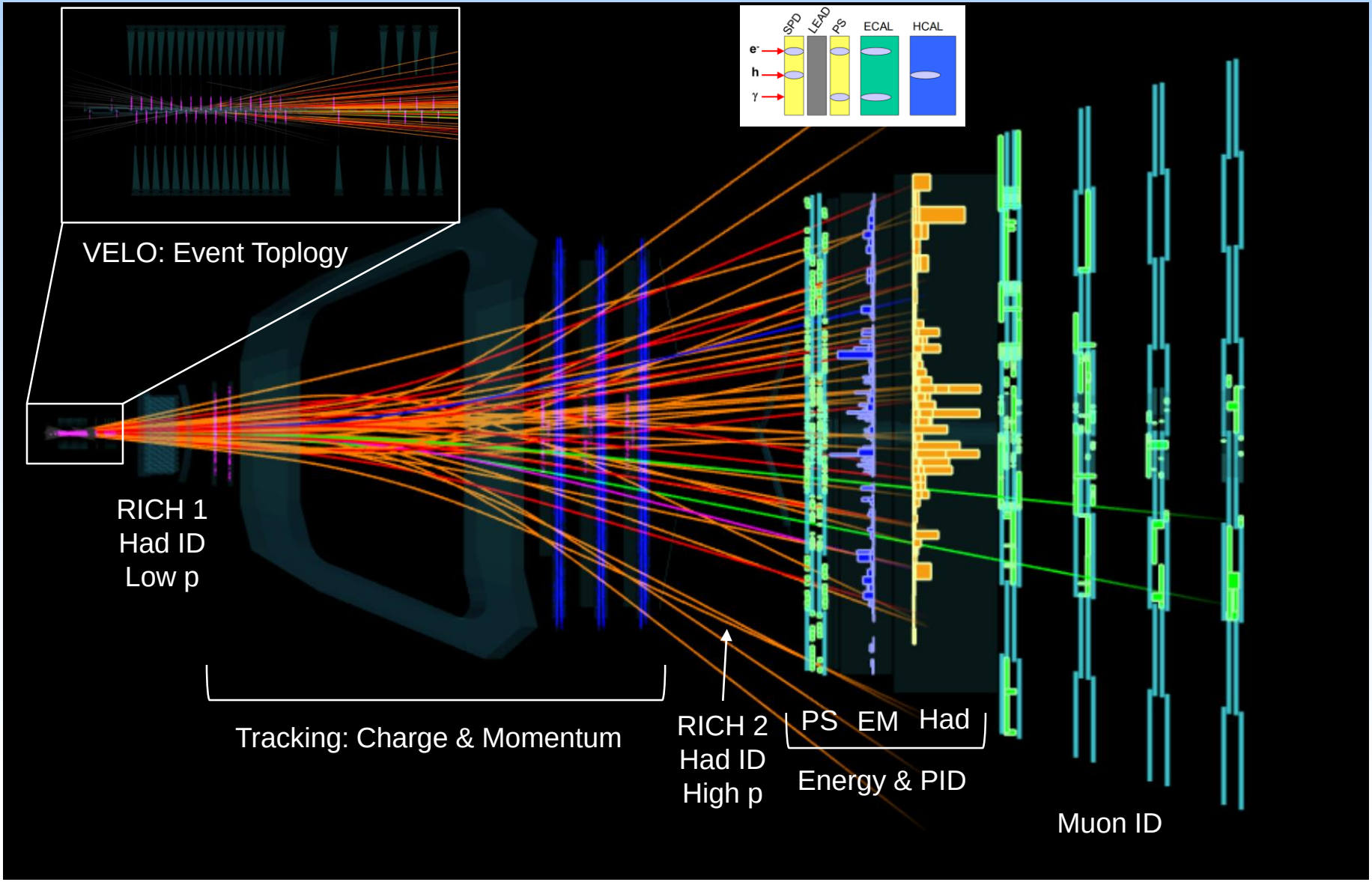
- Identify particles
- Select event topology
- Measure charge & momenta
- Build observable / discriminant variable



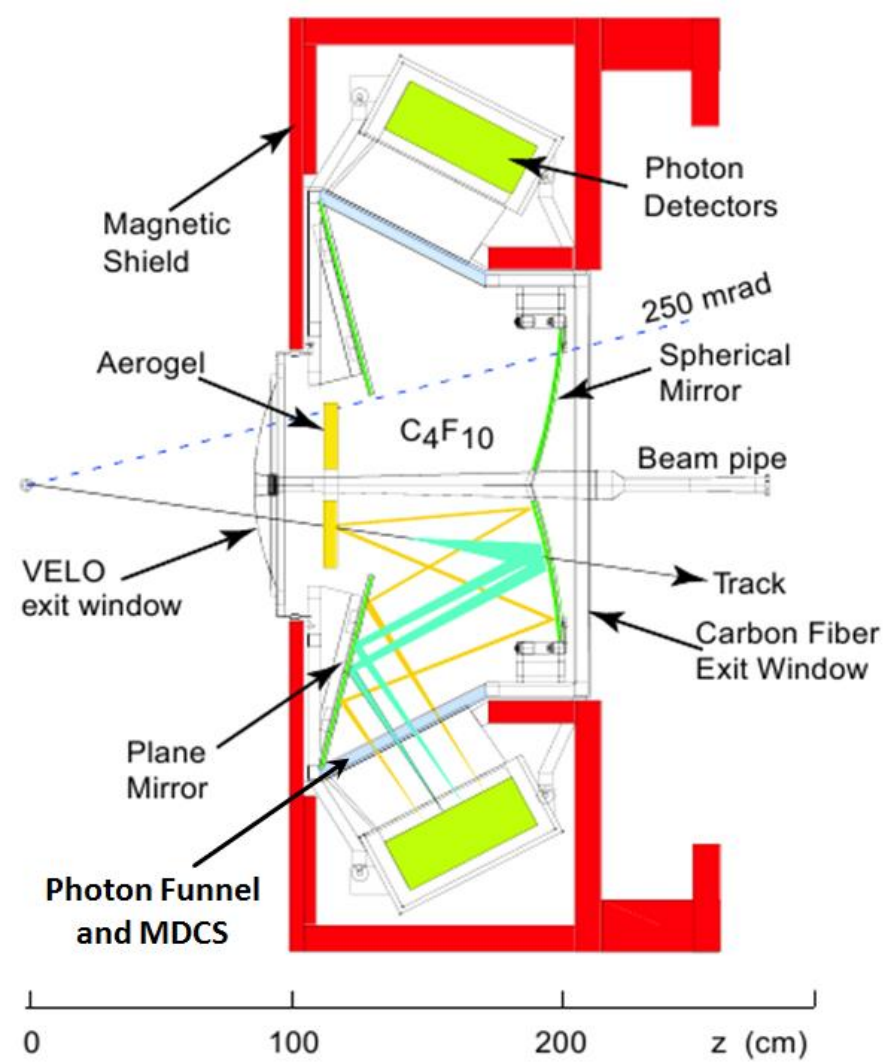
Detector Scheme

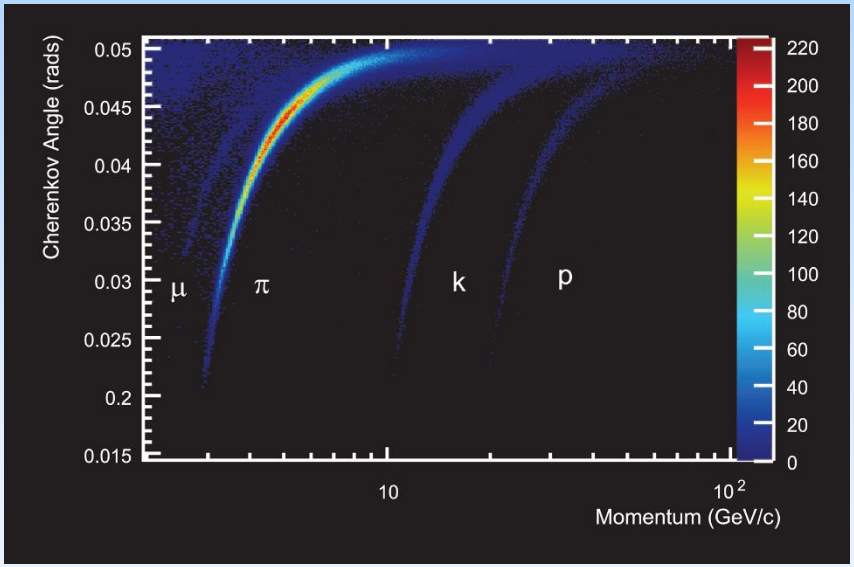


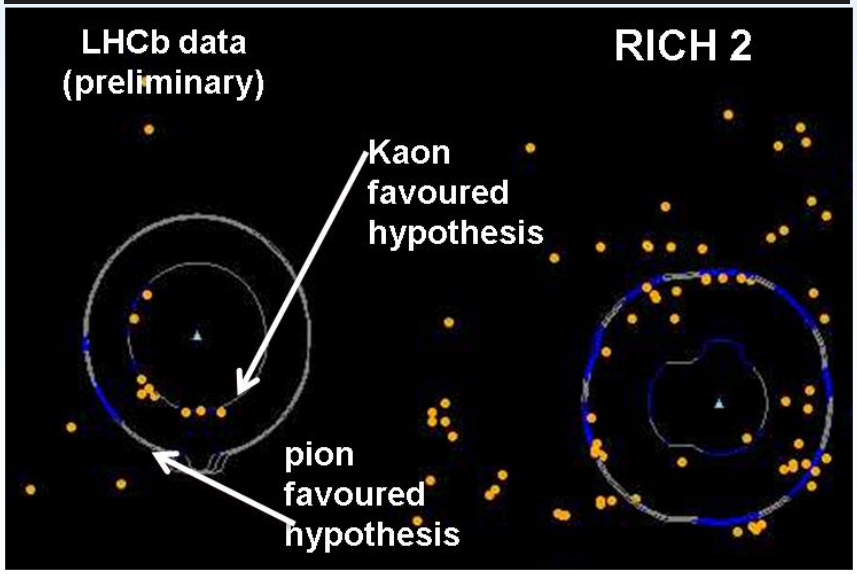
Event Example



RICH Detector

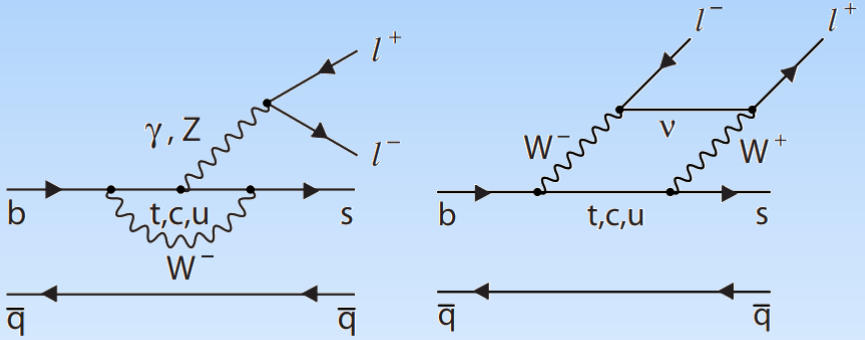




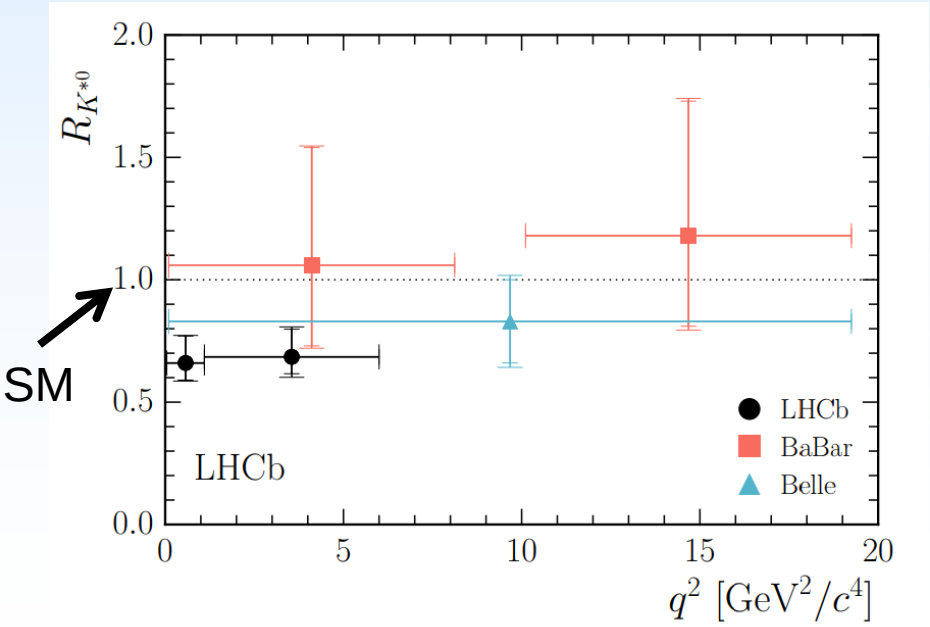


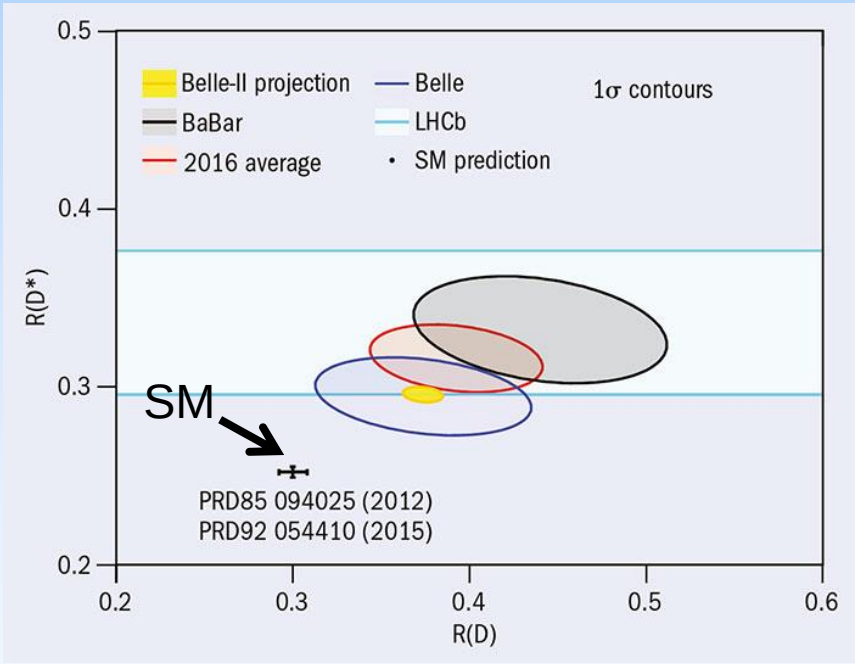
Are we there yet?

Anomalies (LFUV)

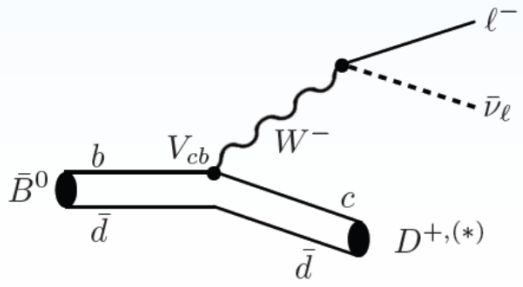


$$R(K^*) = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$$



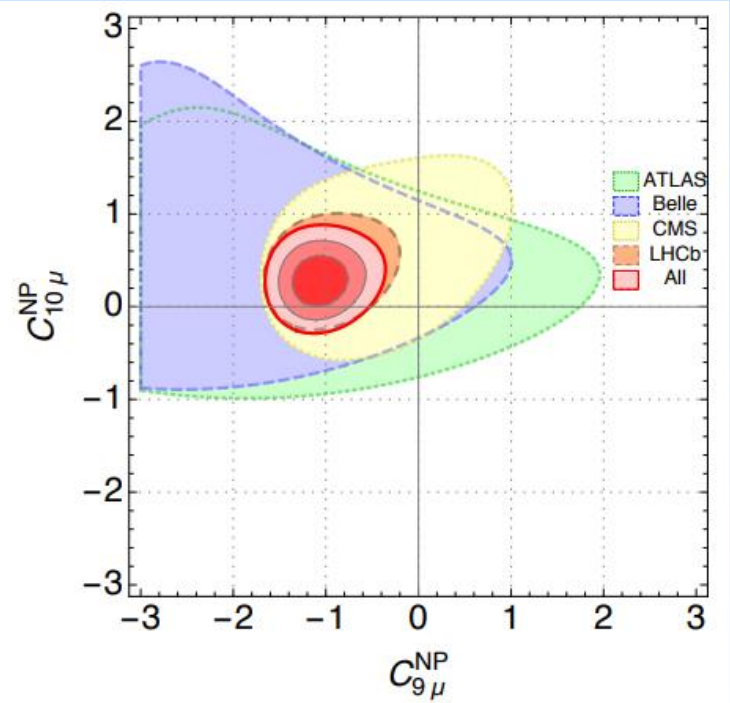


$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$



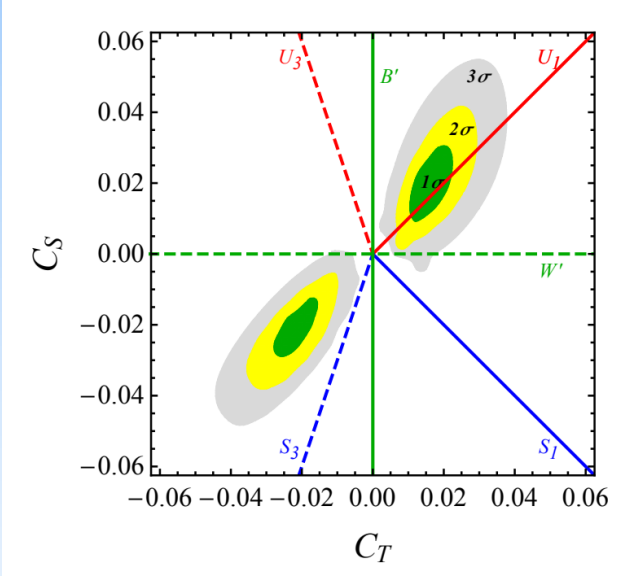
Implications

Effective Field Theory



arXiv:1704.05340

Model Discrimination



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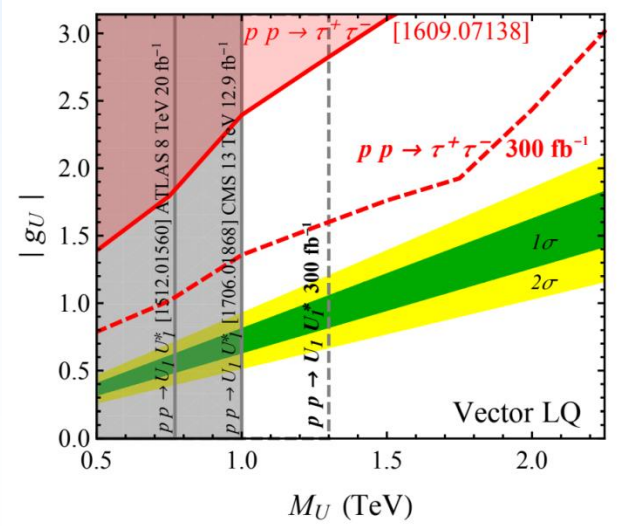
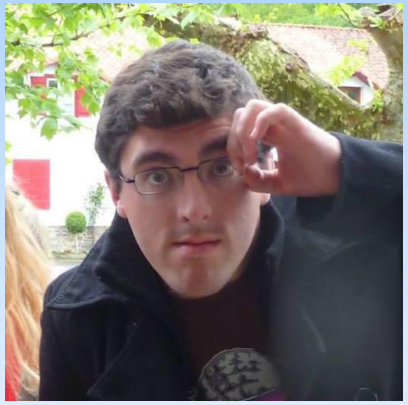
Direct Bounds

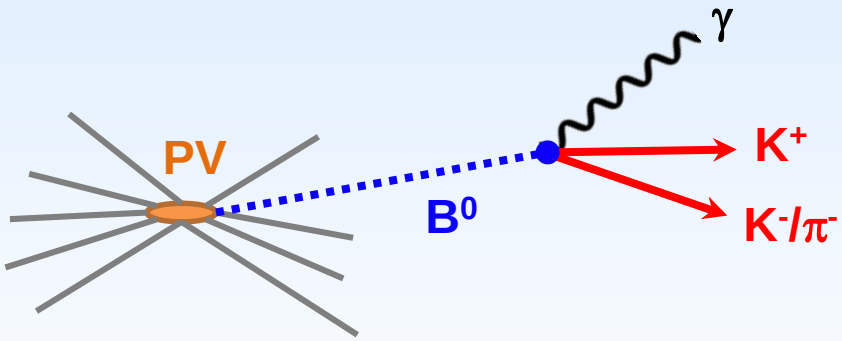


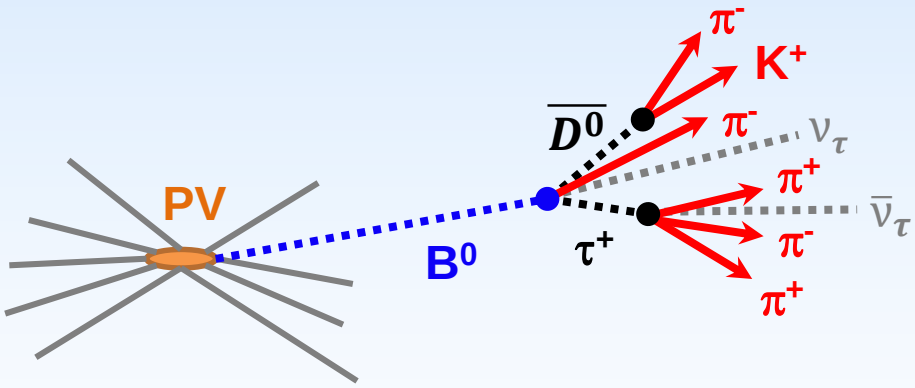
Session Talks

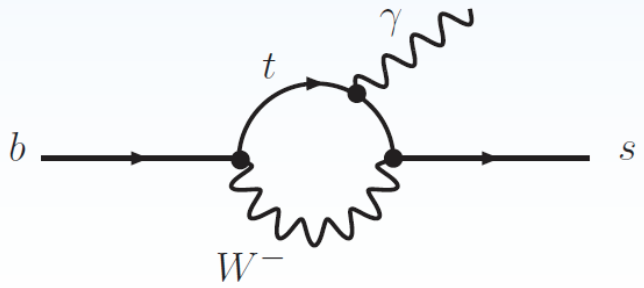


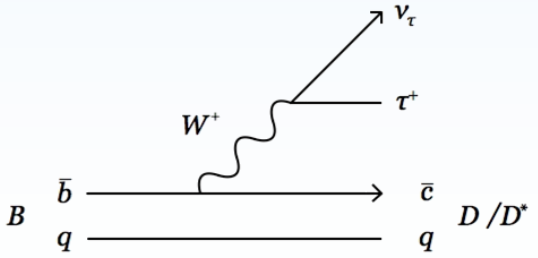
Boris Quintana LPC

Dawid Gerstel CPPM







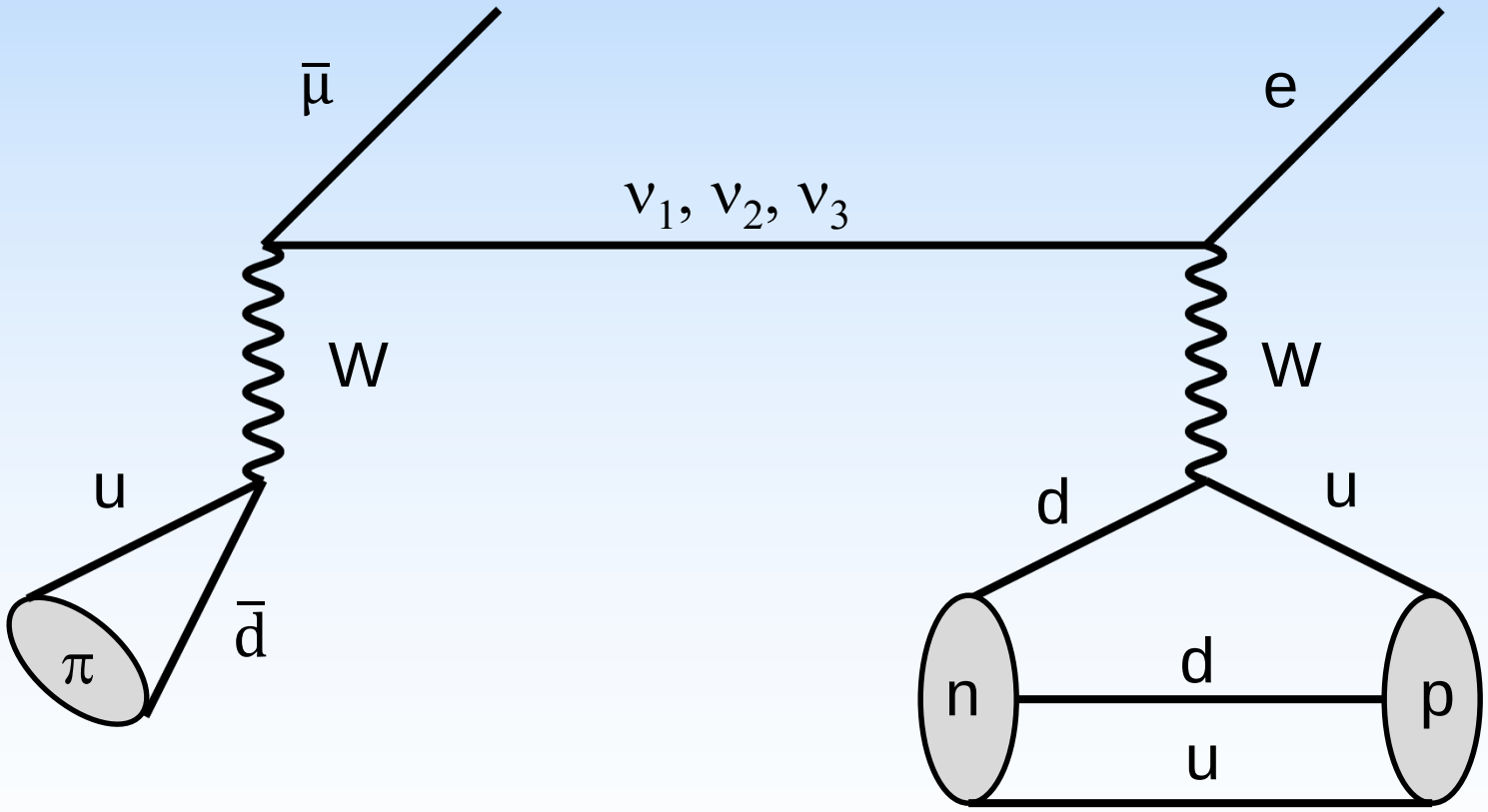


Conclusions

- Flavour physics aims to understand the **flavour structure** of the Standard Model
- **Precision measurements** of loop processes probe new physics at very high energy scales
- Anomalies hinting at possibly **New Physics**
- Now lets look at a couple of analyses on these topics

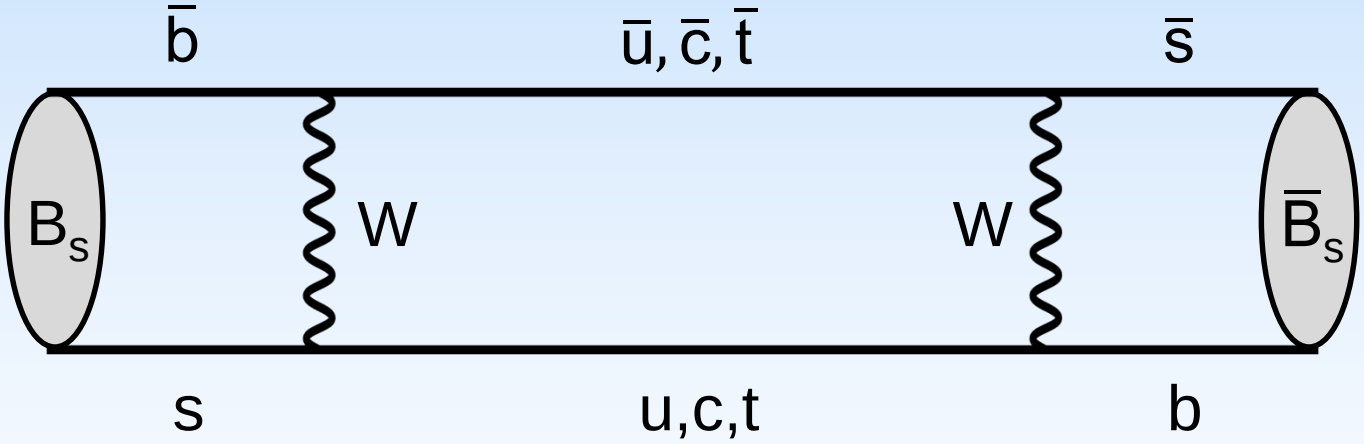
Thank you!

Neutrino Oscillations

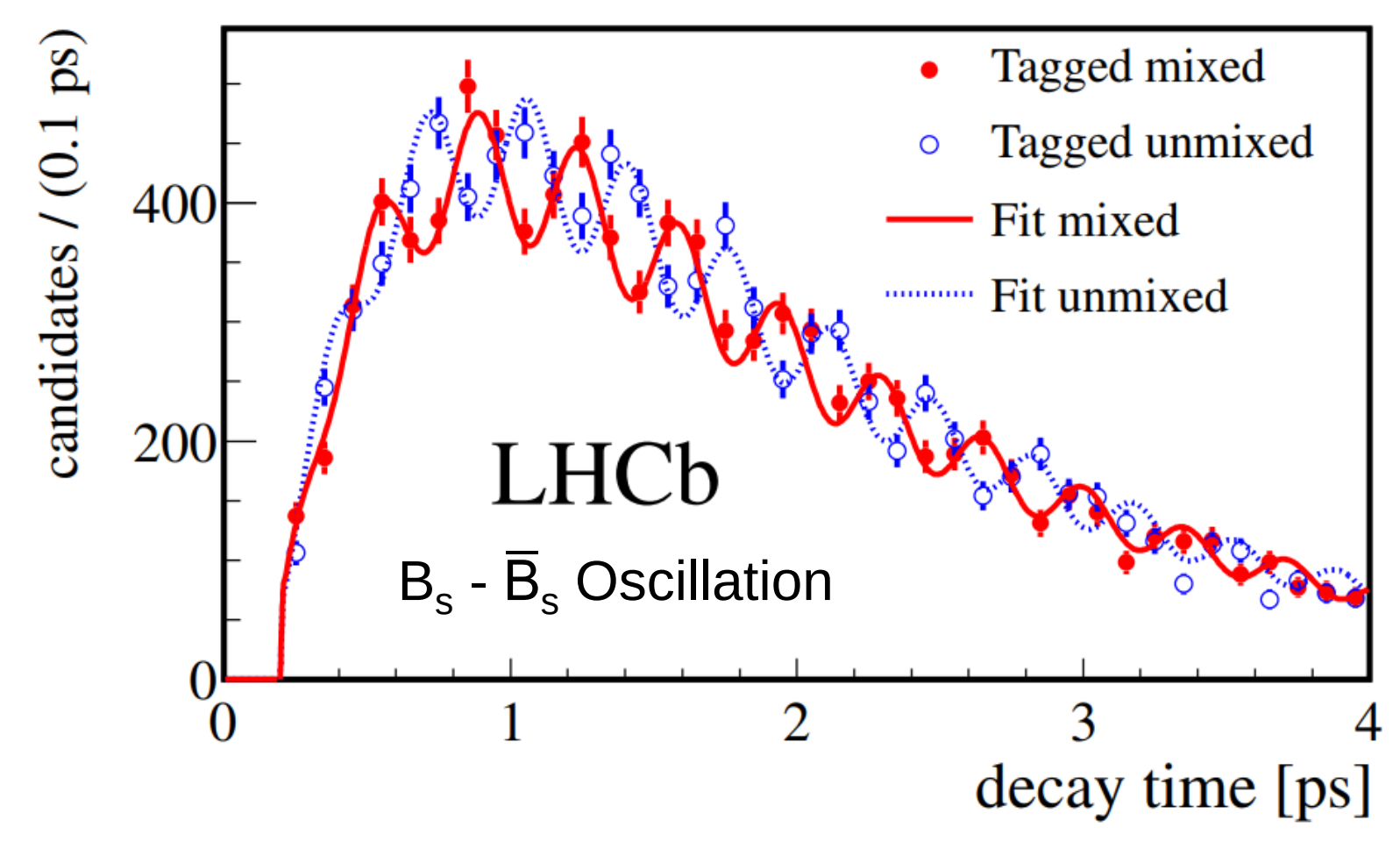


Neutral mesons oscillate!

B_s Oscillation

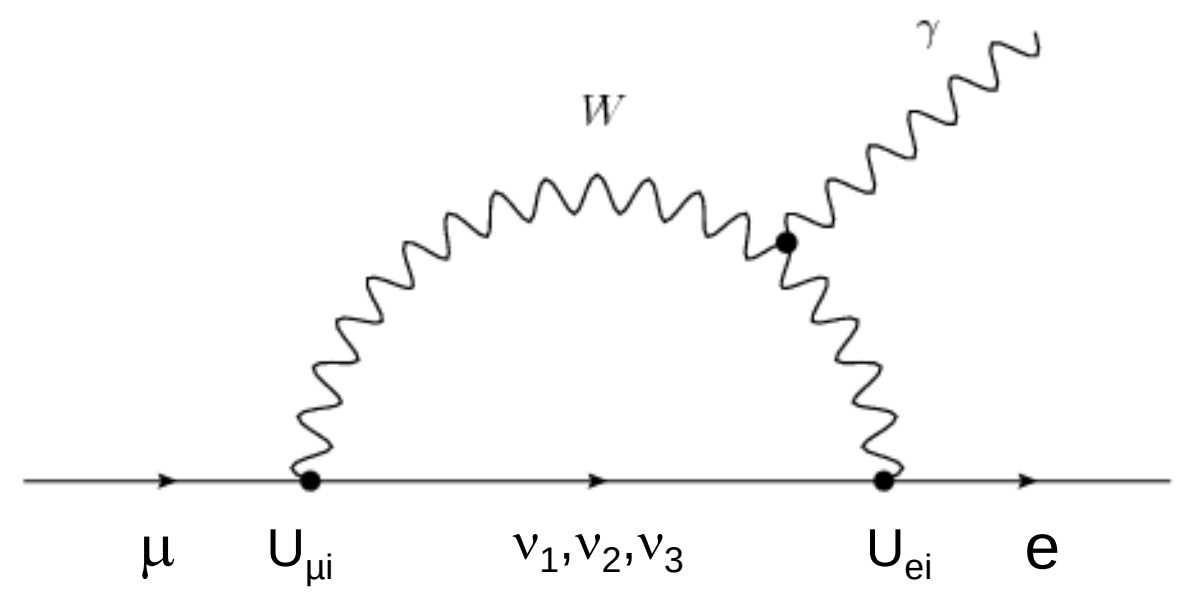


Example Oscillations



$$\Delta m_s = 17.768 \pm 0.024\ \text{ps}^{-1} = 11.695 \pm 0.016\ \text{meV}$$

Example



arXiv:1307.5787

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 \sim 10^{-54}$$

Lepton Flavour Violation extremely suppressed in SM