

Introduction to Flavour Physics

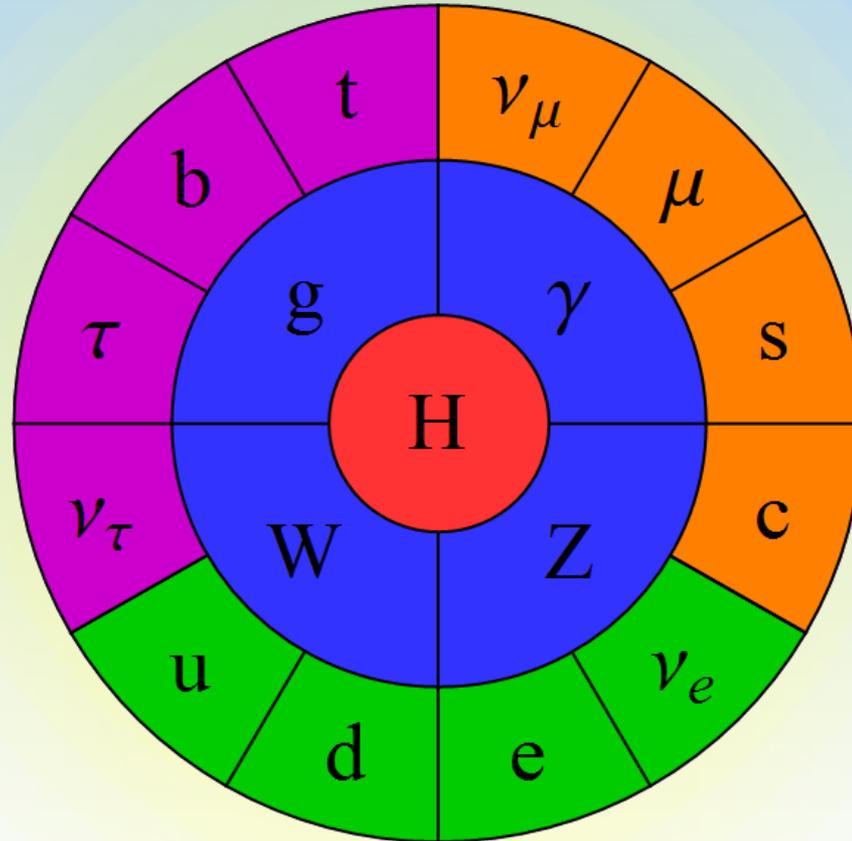
João Coelho

LAL - CNRS

01 December 2017

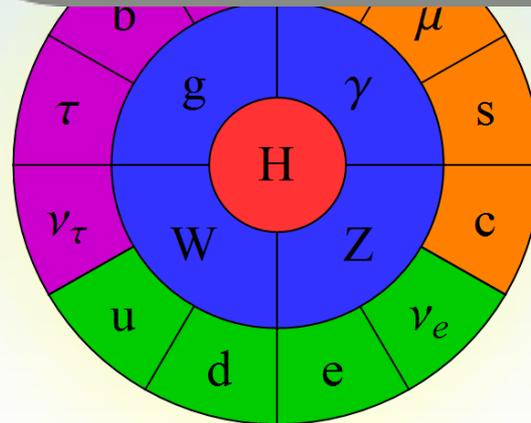
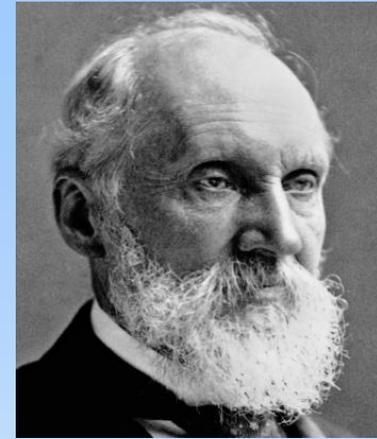


The Standard Model



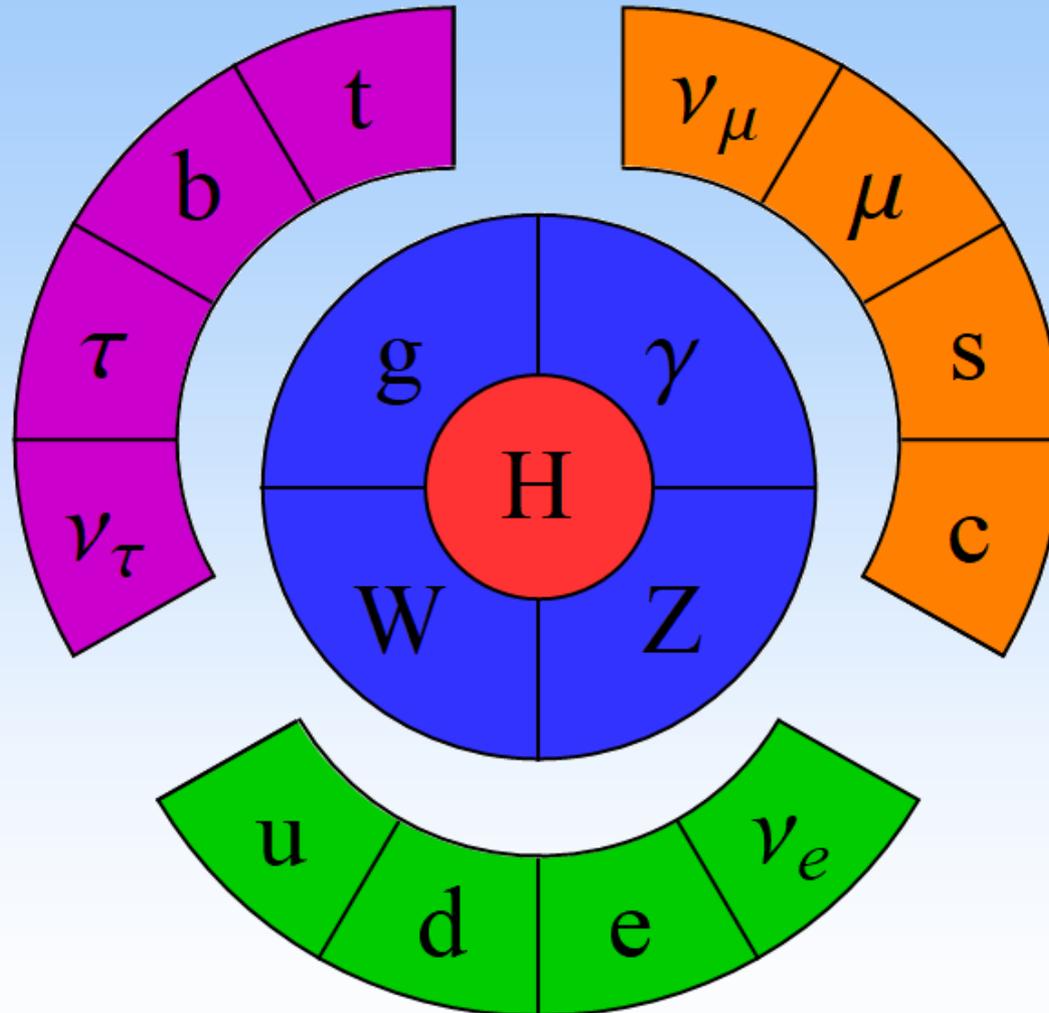
Problems with the SM

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

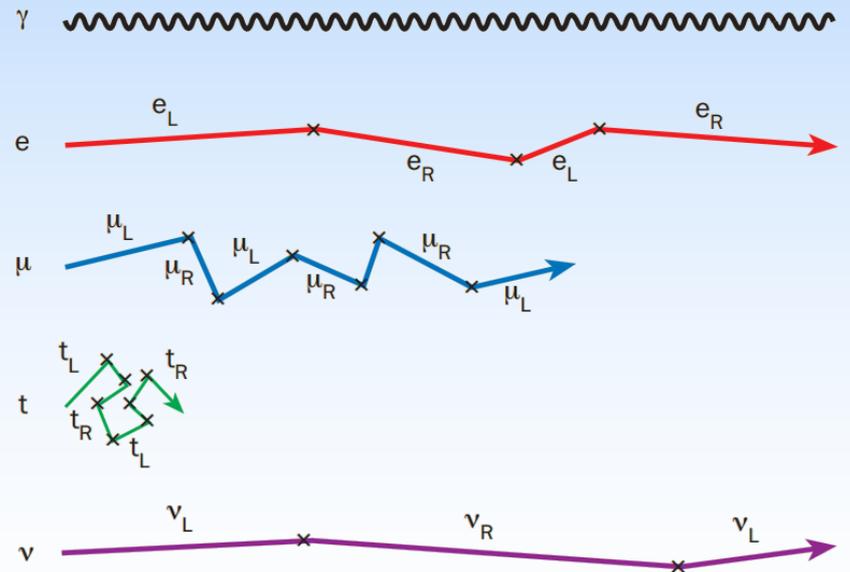
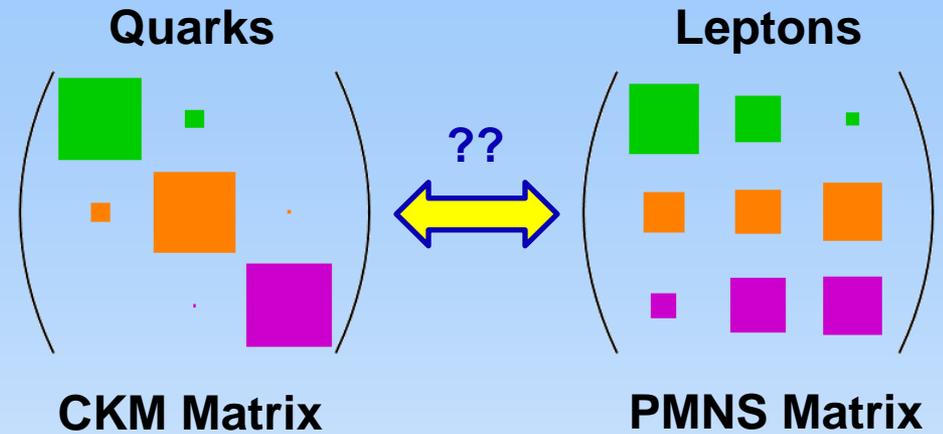
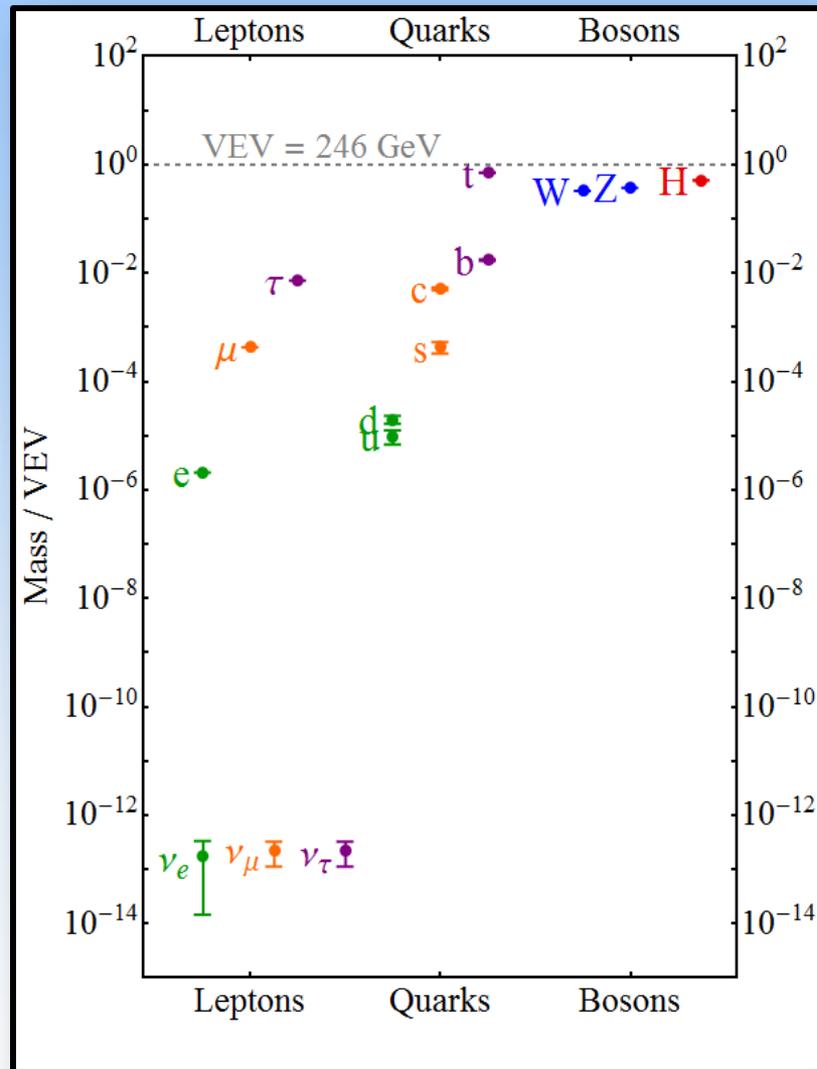


Flavour Puzzle

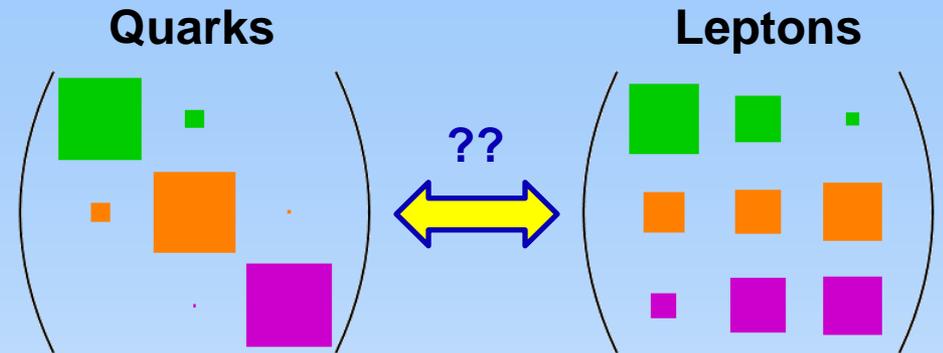
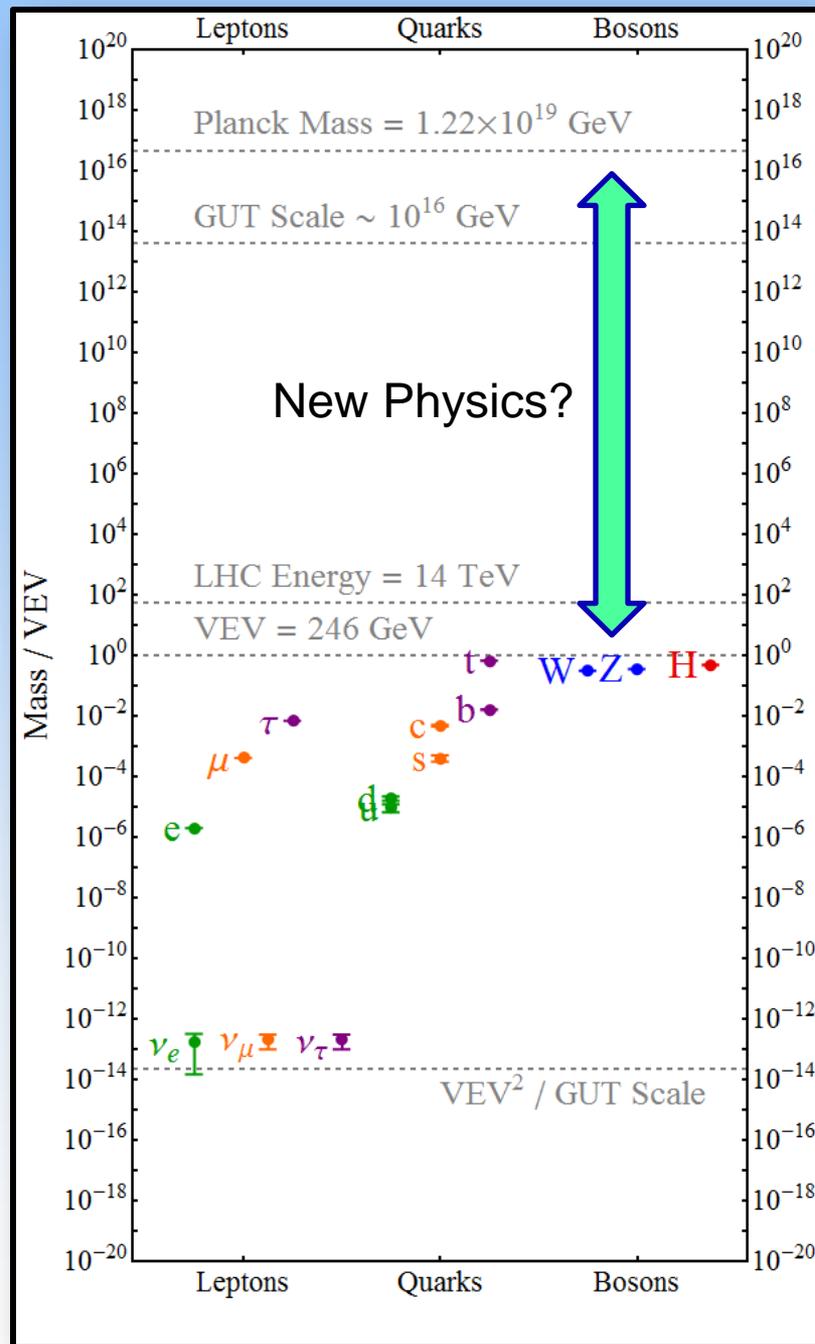
- “Who order that?!” – I.I. Rabi, 1936



Flavour Structure

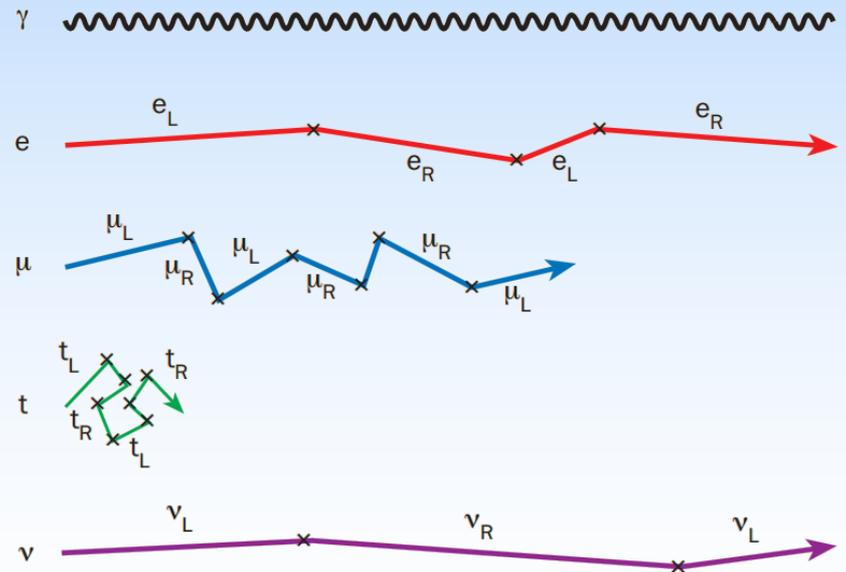


Flavour Structure

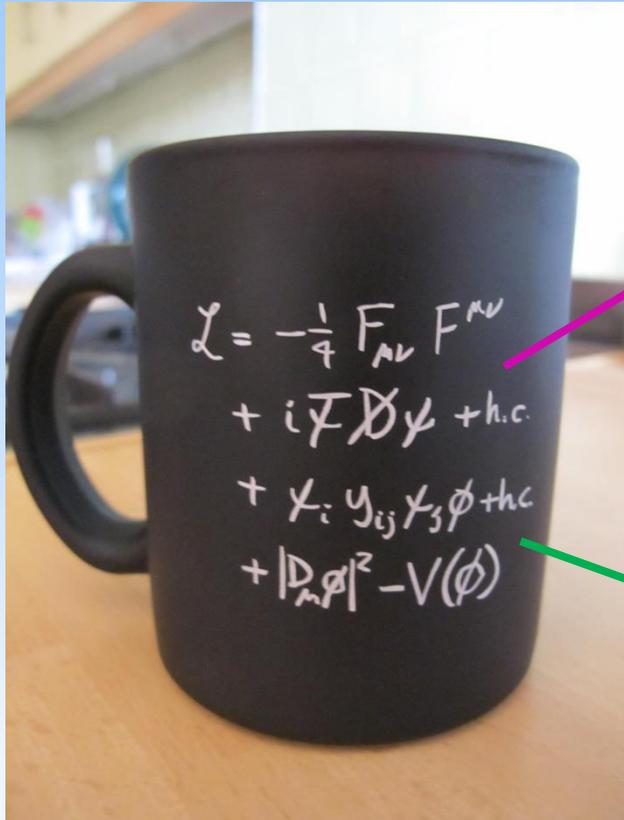


CKM Matrix

PMNS Matrix



Gauge vs Higgs



Free Parameters

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

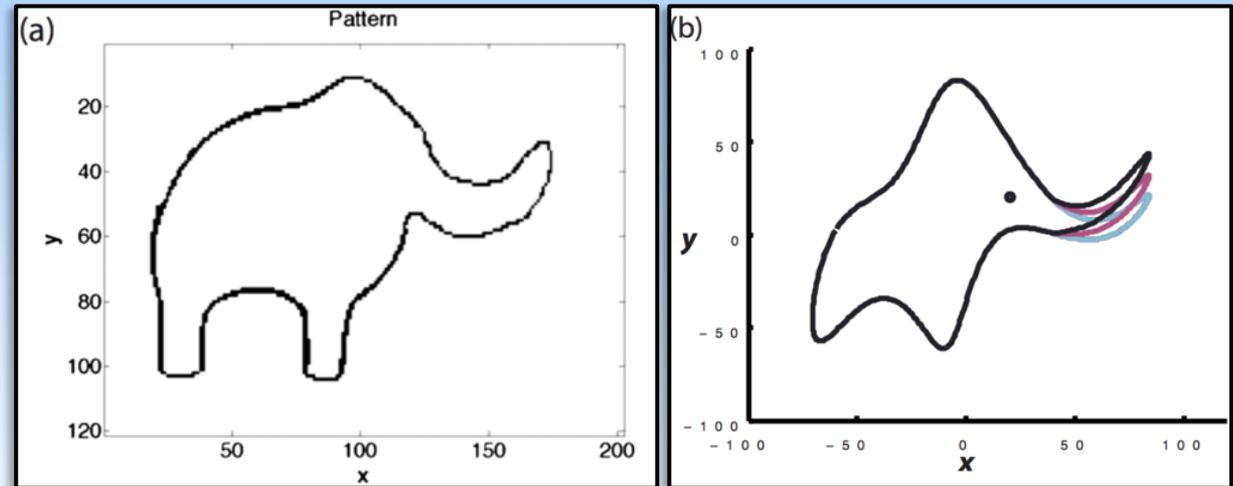
Free Parameters

- 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

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



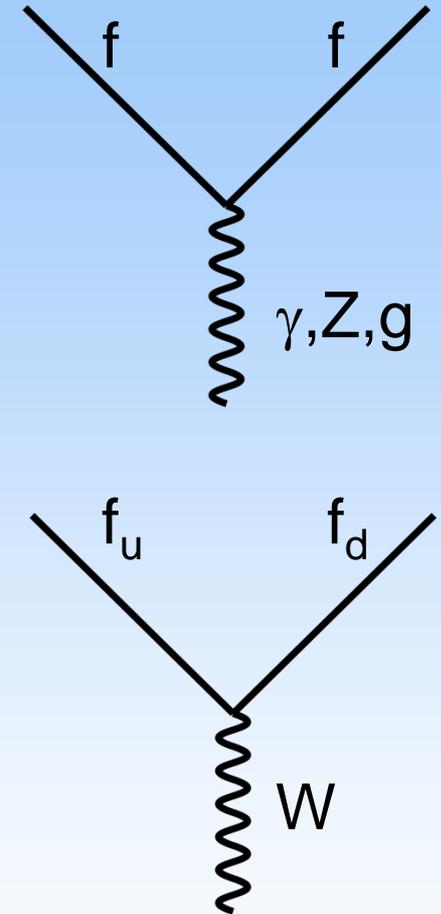
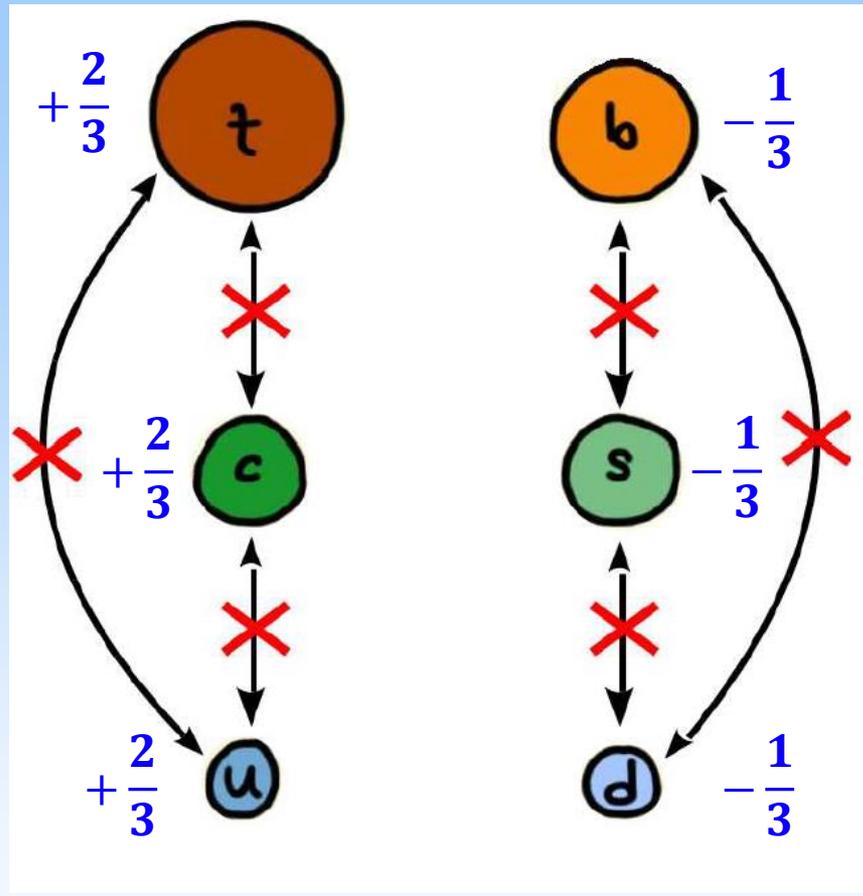
$\mathcal{L}_{\text{SM}} =$ renormalizable part of \mathcal{L}_{eff}
[= all possible operators with $d \leq 4$
compatible with the gauge symmetry]

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

- **NP** expected to be **small**
 - If FV in NP at tree level: $\Lambda > 10^3 - 10^5 \text{ TeV}$ ($c_n \sim 1$)
 - NP also respects SM flavour structure? ($c_n \ll 1$)
- Large SM \rightarrow needs very high precision
- **Suppressed SM \rightarrow NP can compete**
- Forbidden SM \rightarrow NP smoking gun

GIM Mechanism

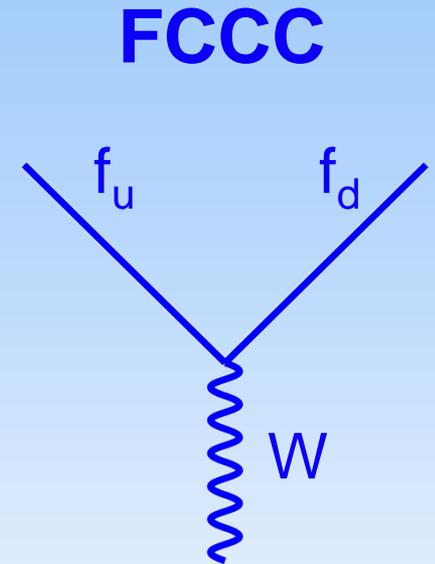
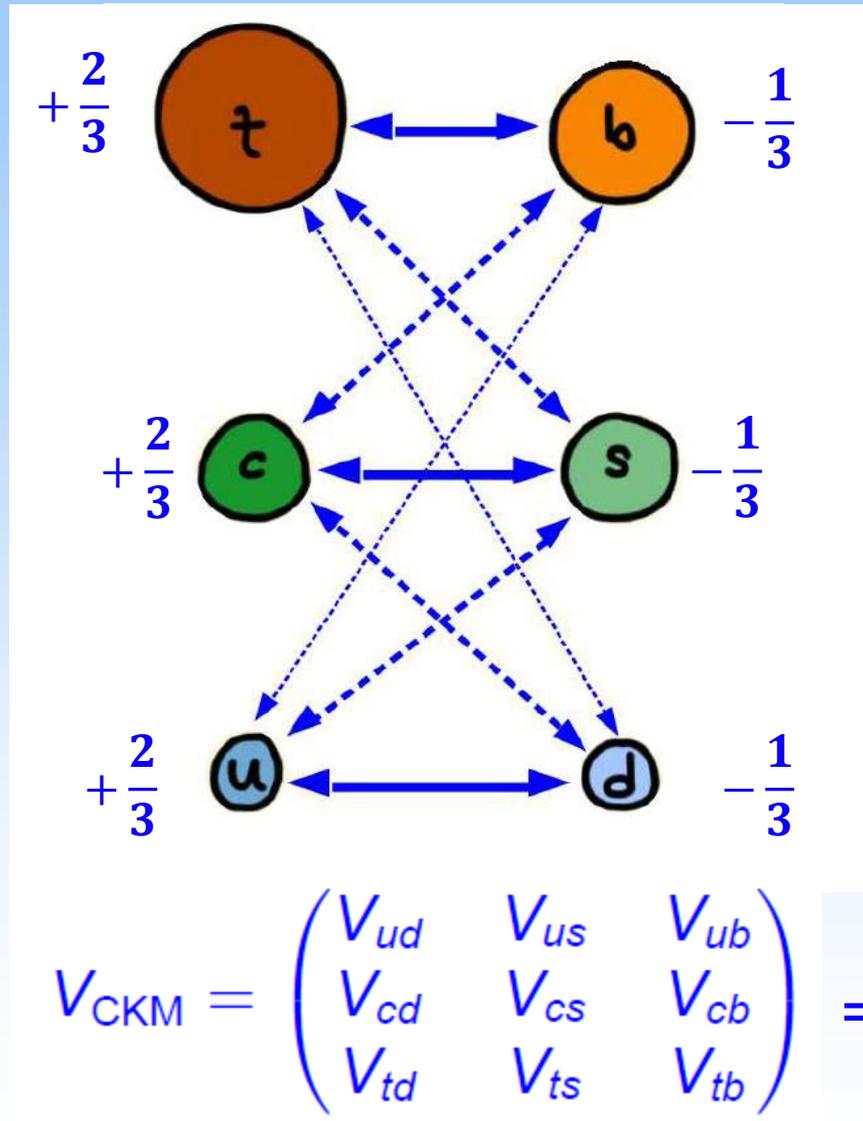
W. Altmannshofer
ACP Colloquium 2014



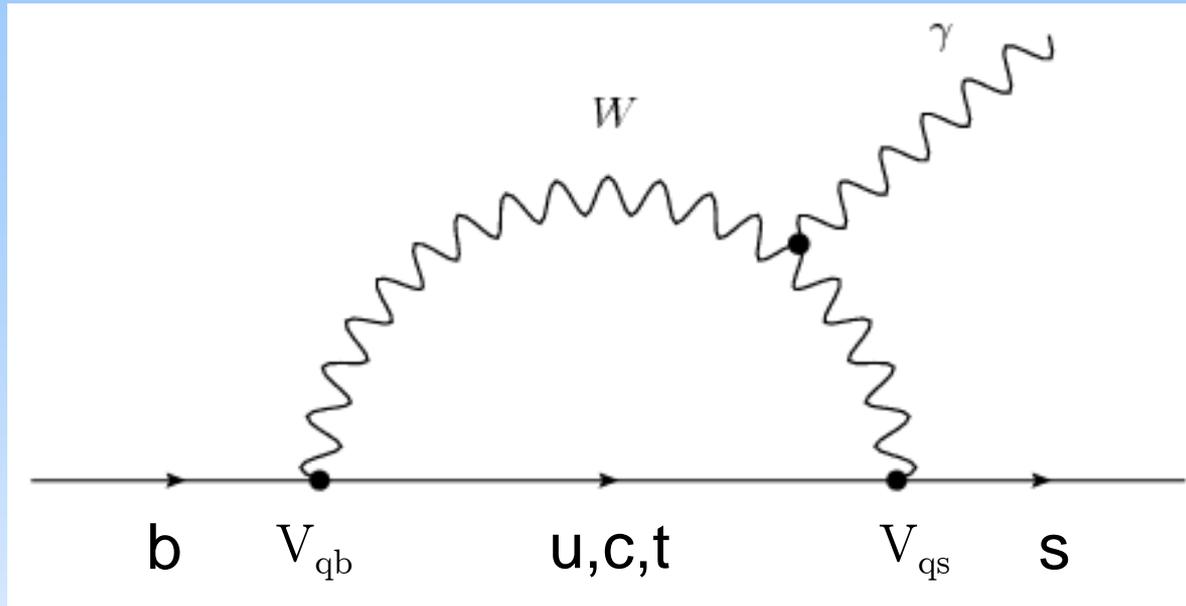
No FCNC at tree level

GIM Mechanism

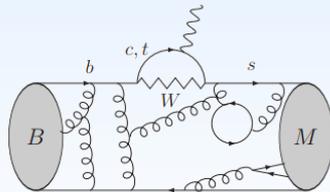
W. Altmannshofer
ACP Colloquium 2014



Example



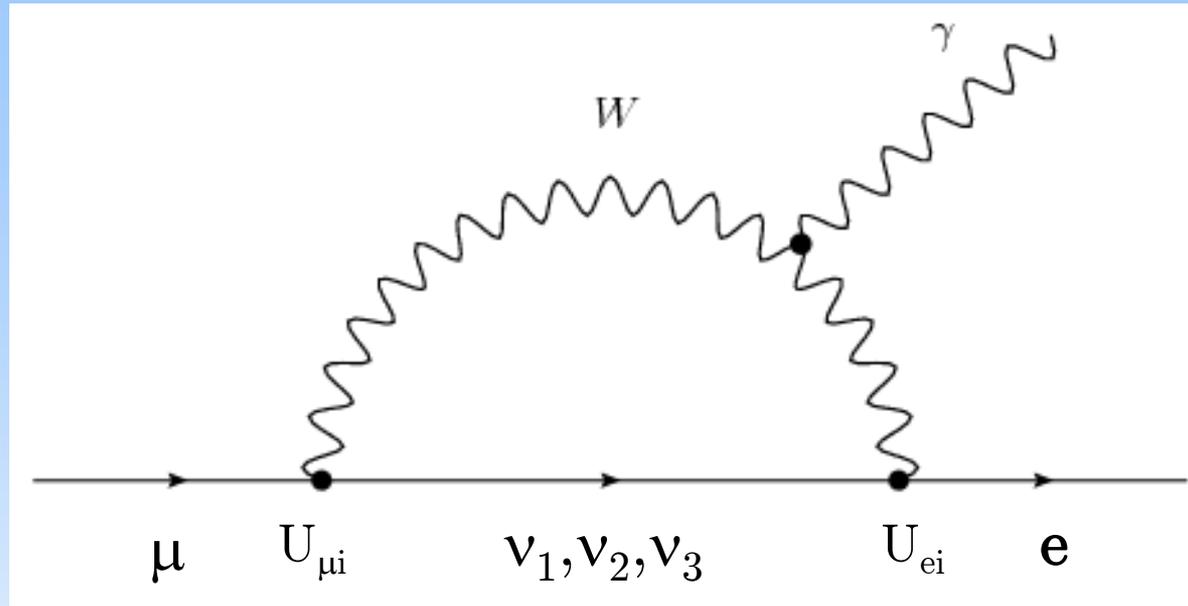
$$\mathcal{B}(b \rightarrow s\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{q=c,t} V_{qb}^* V_{qs} \frac{\Delta m_{qu}^2}{M_W^2} \right|^2 \sim 10^{-6}$$



+QCD Effects

$$\mathcal{B}(\bar{B} \rightarrow X_s \gamma) = (3.29 \pm 0.52) \times 10^{-4} \quad \text{BABAR 2012}$$

Example



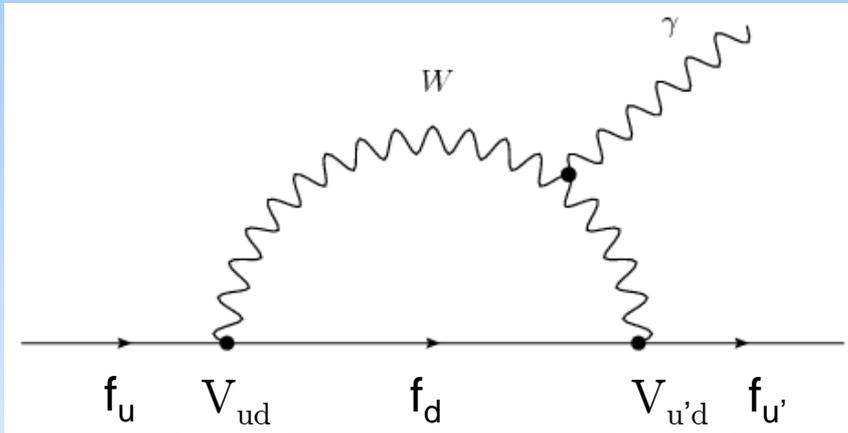
arXiv:1307.5787

$$\mathcal{B}(\mu \rightarrow e \gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{i1}^2}{M_W^2} \right|^2 \sim 10^{-54}$$

Lepton Flavour Violation extremely suppressed in SM

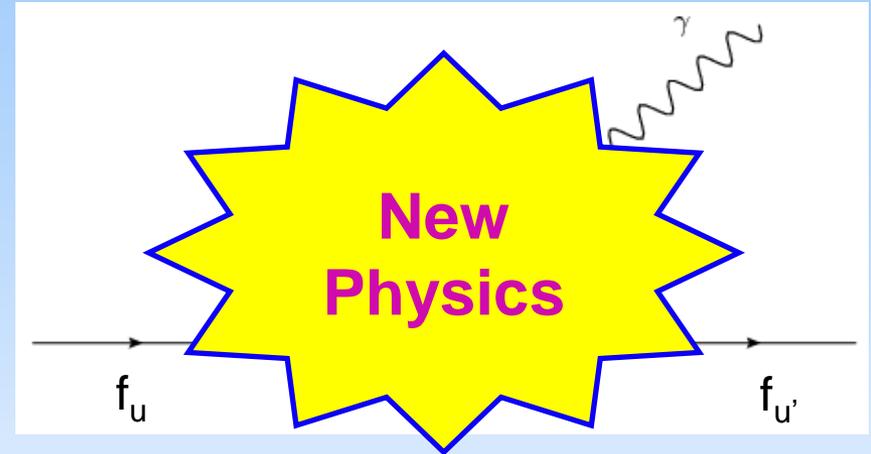
New Physics?

SM: GIM Suppressed



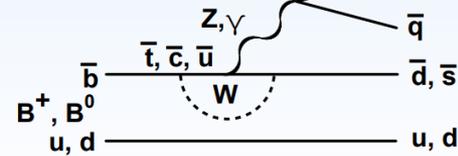
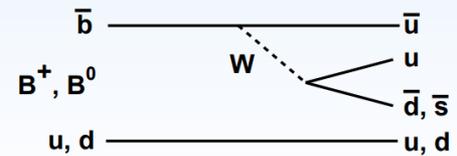
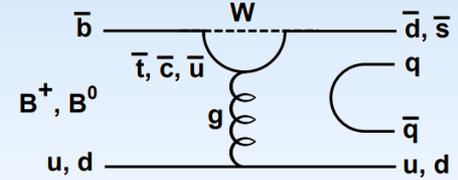
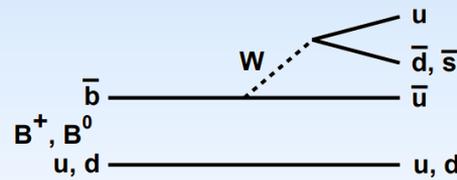
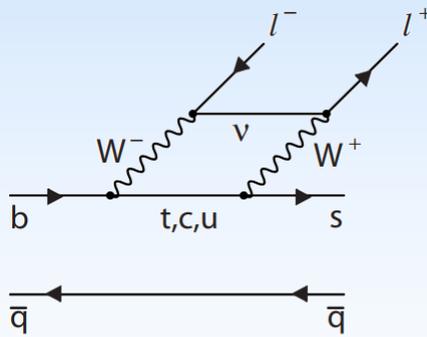
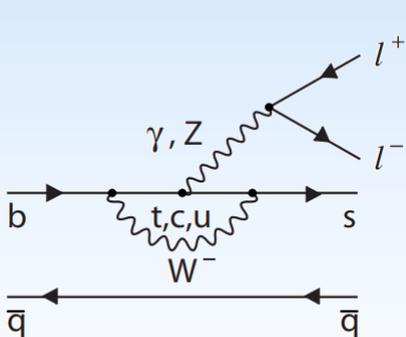
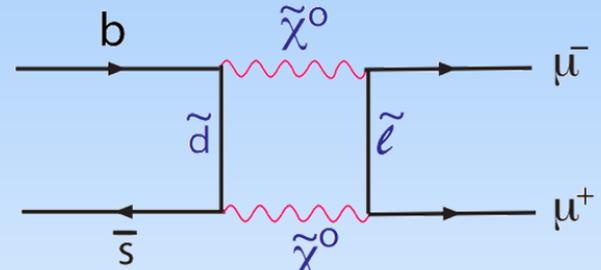
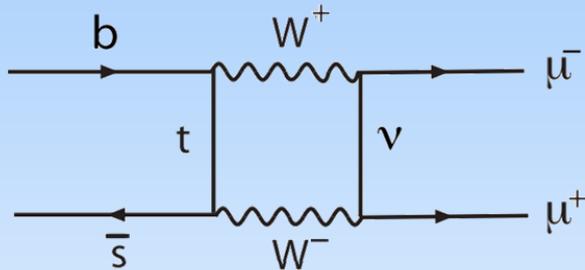
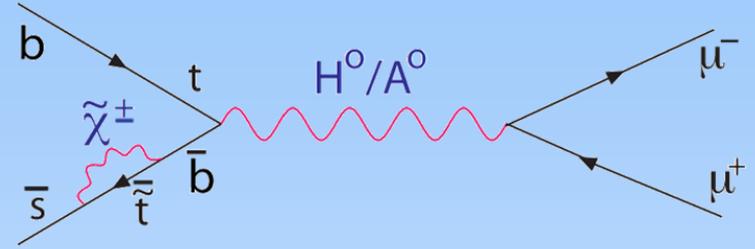
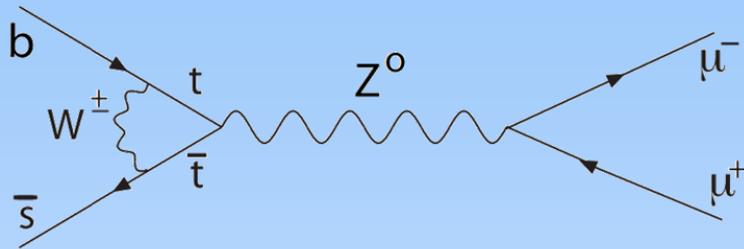
+

NP: Δ Suppressed



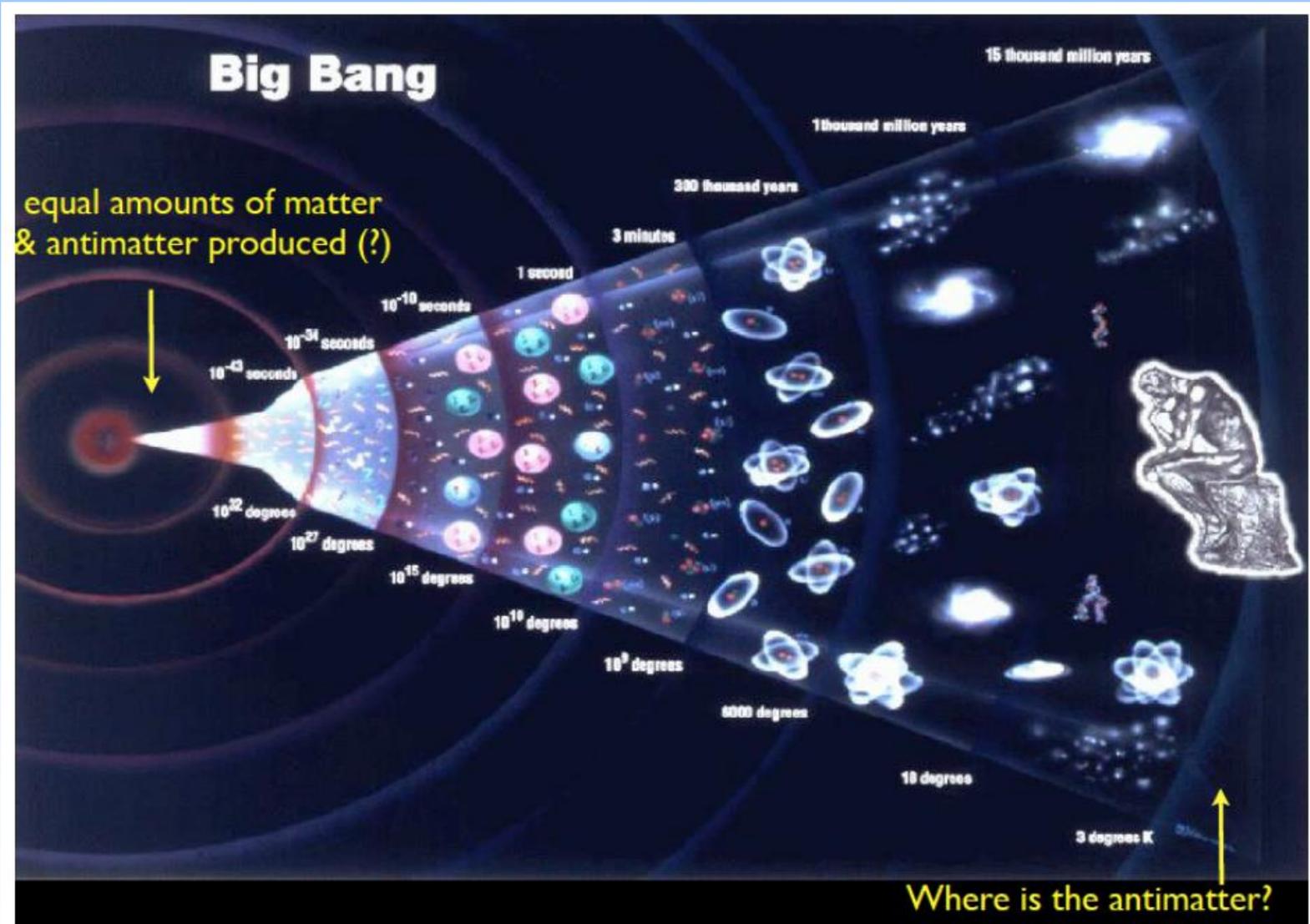
New Physics in Rare Decays?

Many Processes to Explore



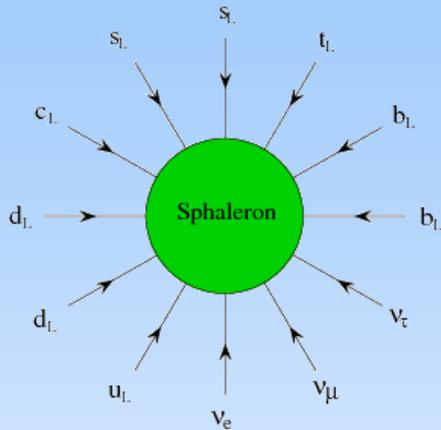
Matter-Antimatter Asymmetry

Y. Amhis
JRJC
2013

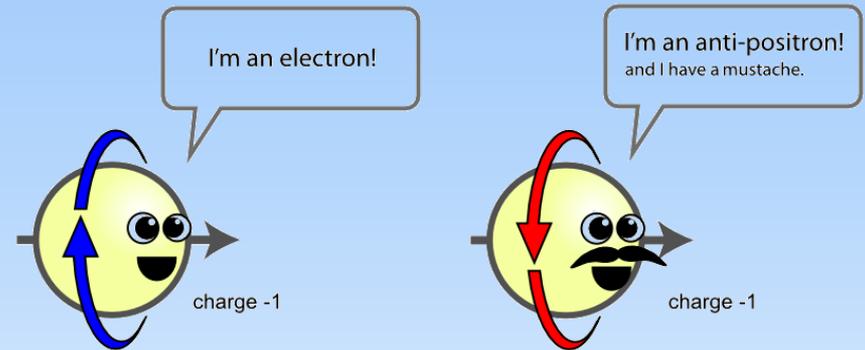


Sakharov Conditions

Baryon Number Violation

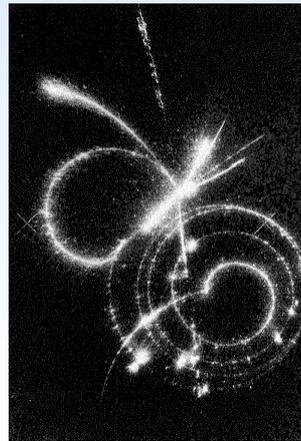
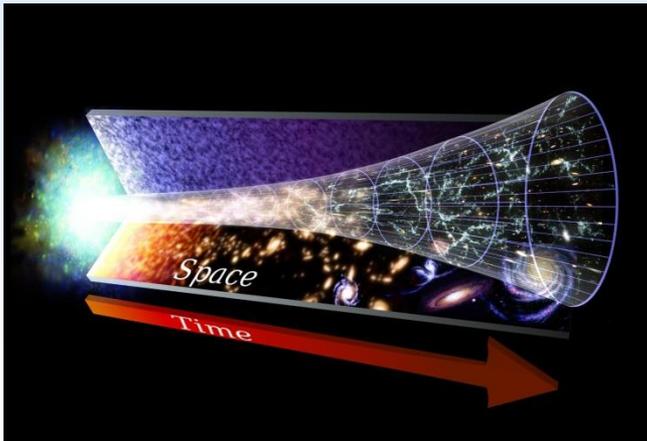


C Violation

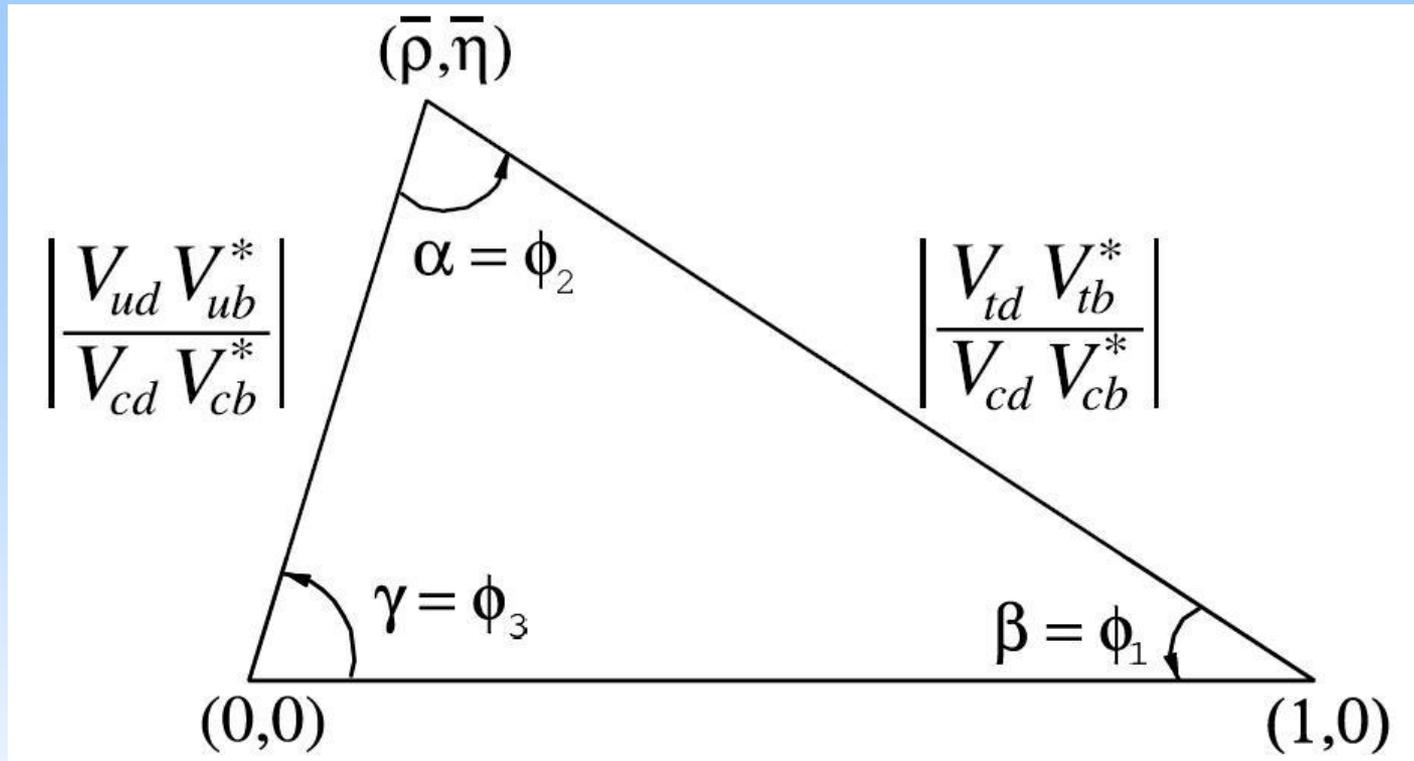


Depart from thermal equilibrium

CP Violation

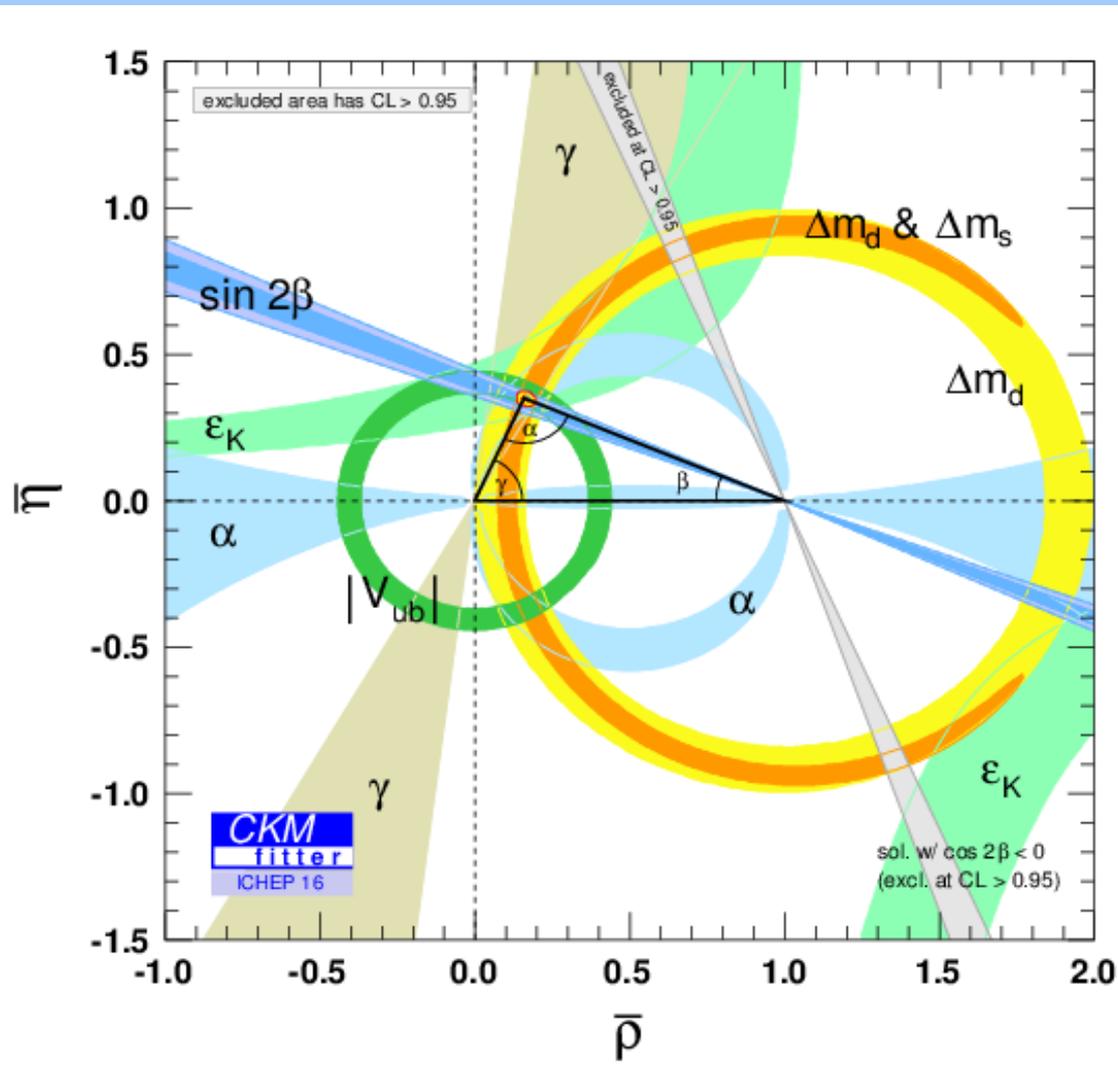


CKM Triangle

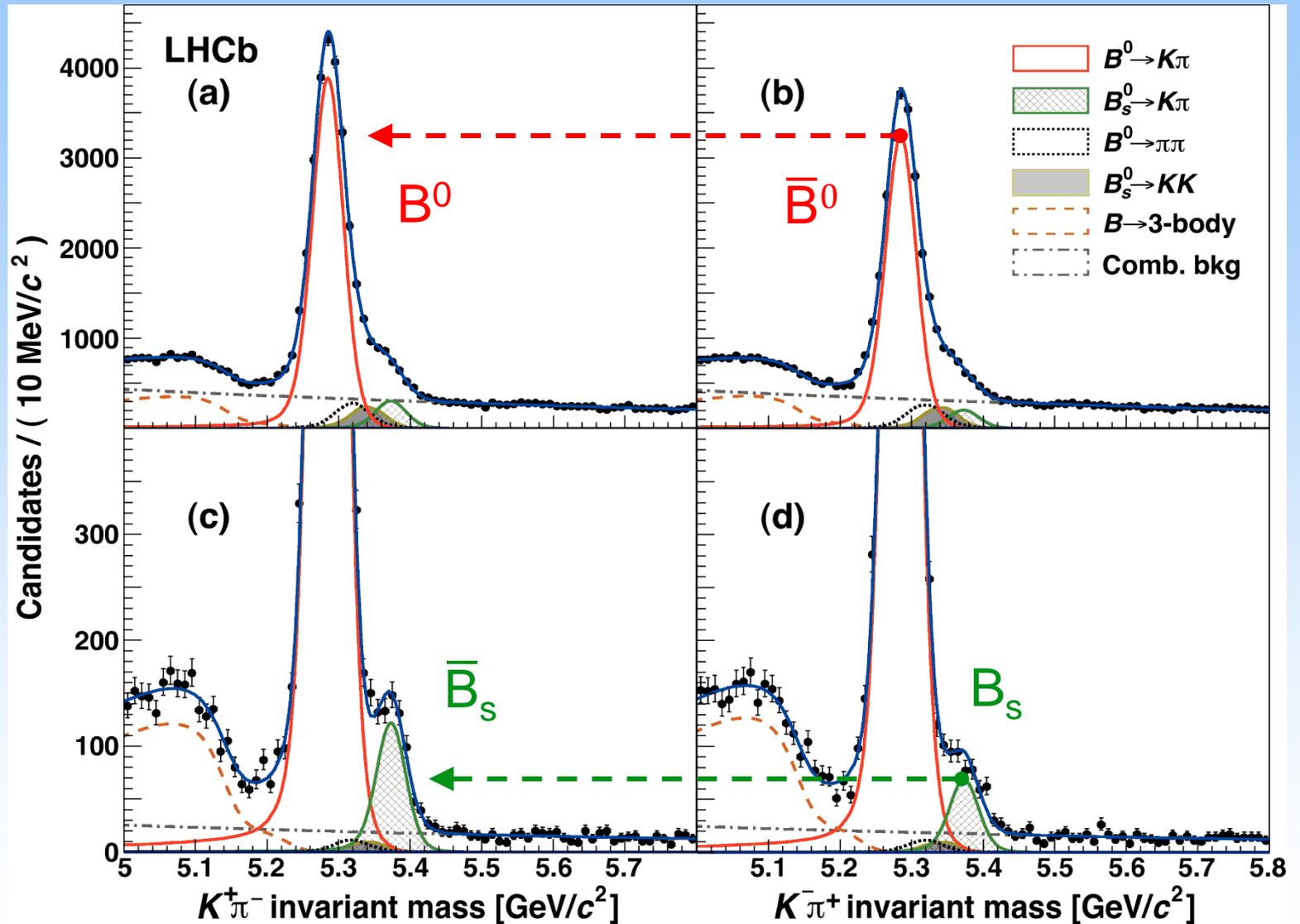


- CKM elements may be complex
- This gives rise to CP violation
- Can construct triangle in complex plane

CKM Triangle

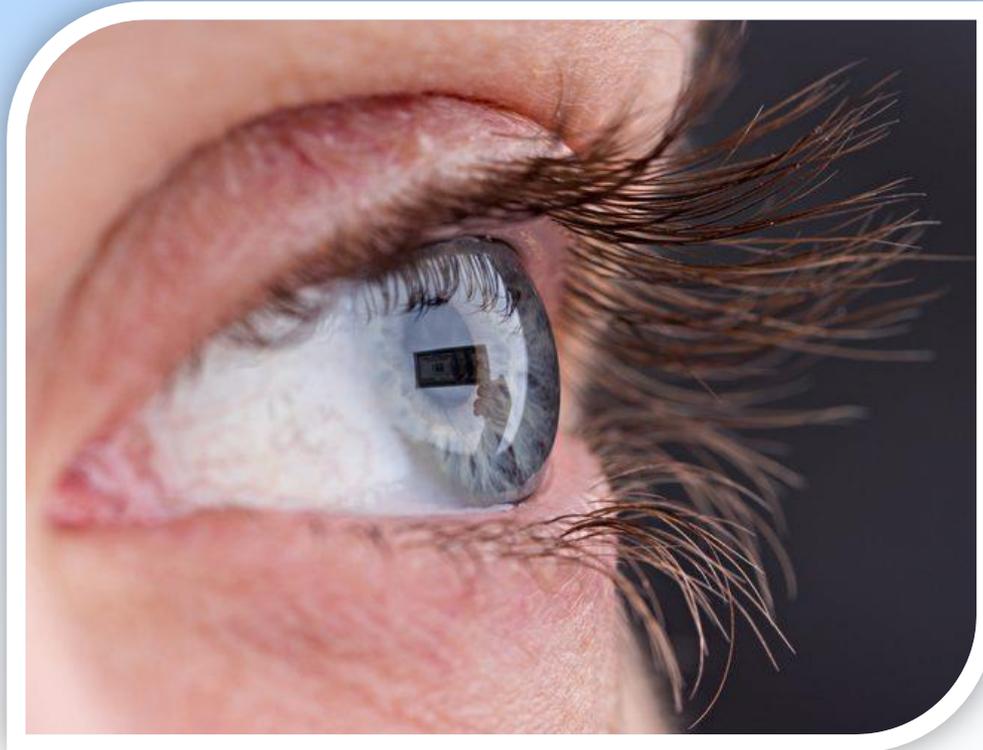


Example CP violation



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** ($\sim 70 \mu\text{g}$)*

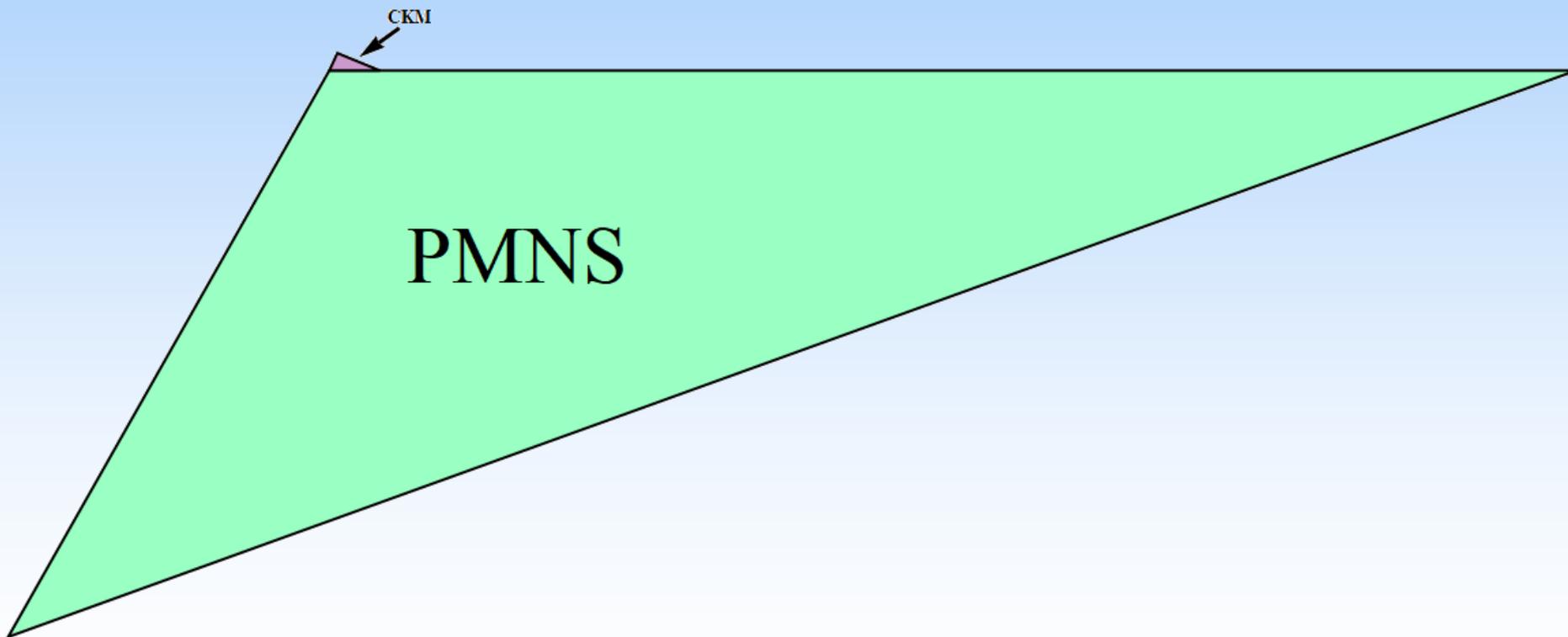


*Or up to your middle ear bones ($\sim 70 \text{ mg}$)



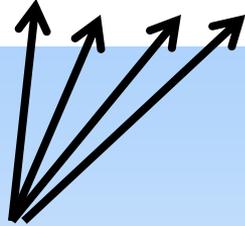
Size Matters

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



Mass Differences

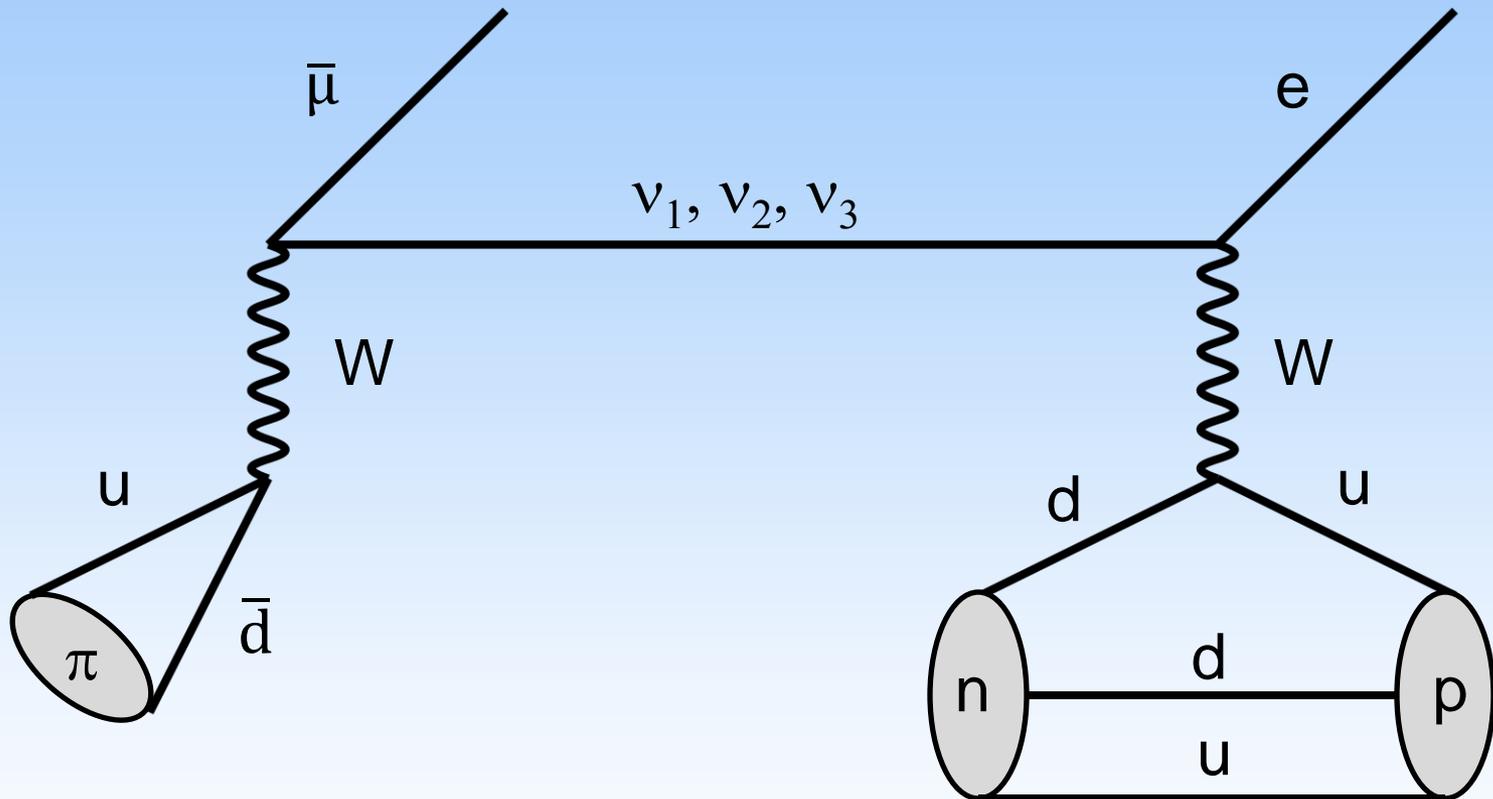
$$\delta_{CP} \sim \alpha_{wk}^2 \lambda_t^4 \lambda_b^2 \lambda_s \lambda_d \sin^2 \theta_1 \sin \theta_2 \sin \theta_3 \sin \delta \sim 10^{-16} .$$



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

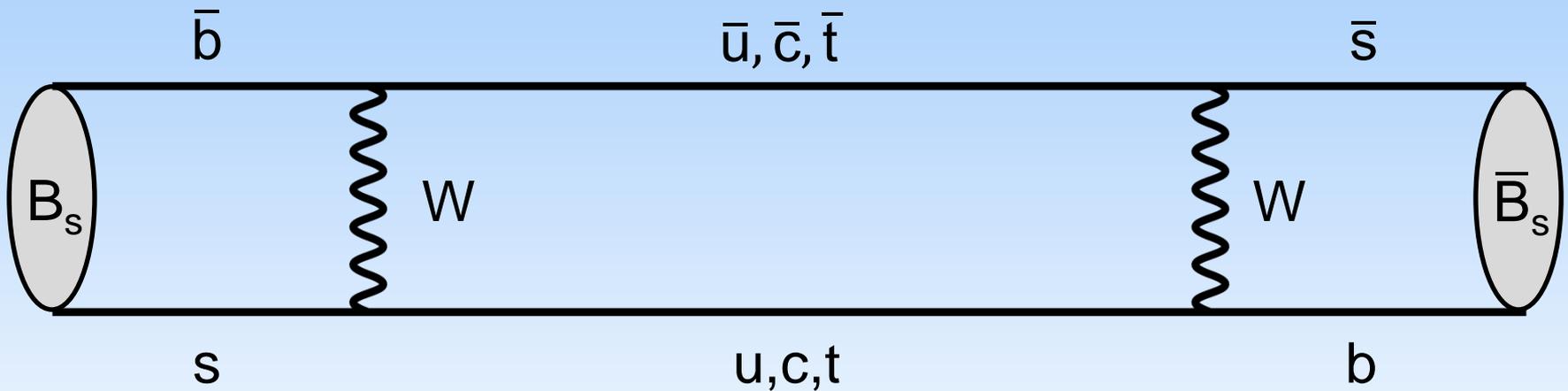
Oscillations

Neutrino Oscillation

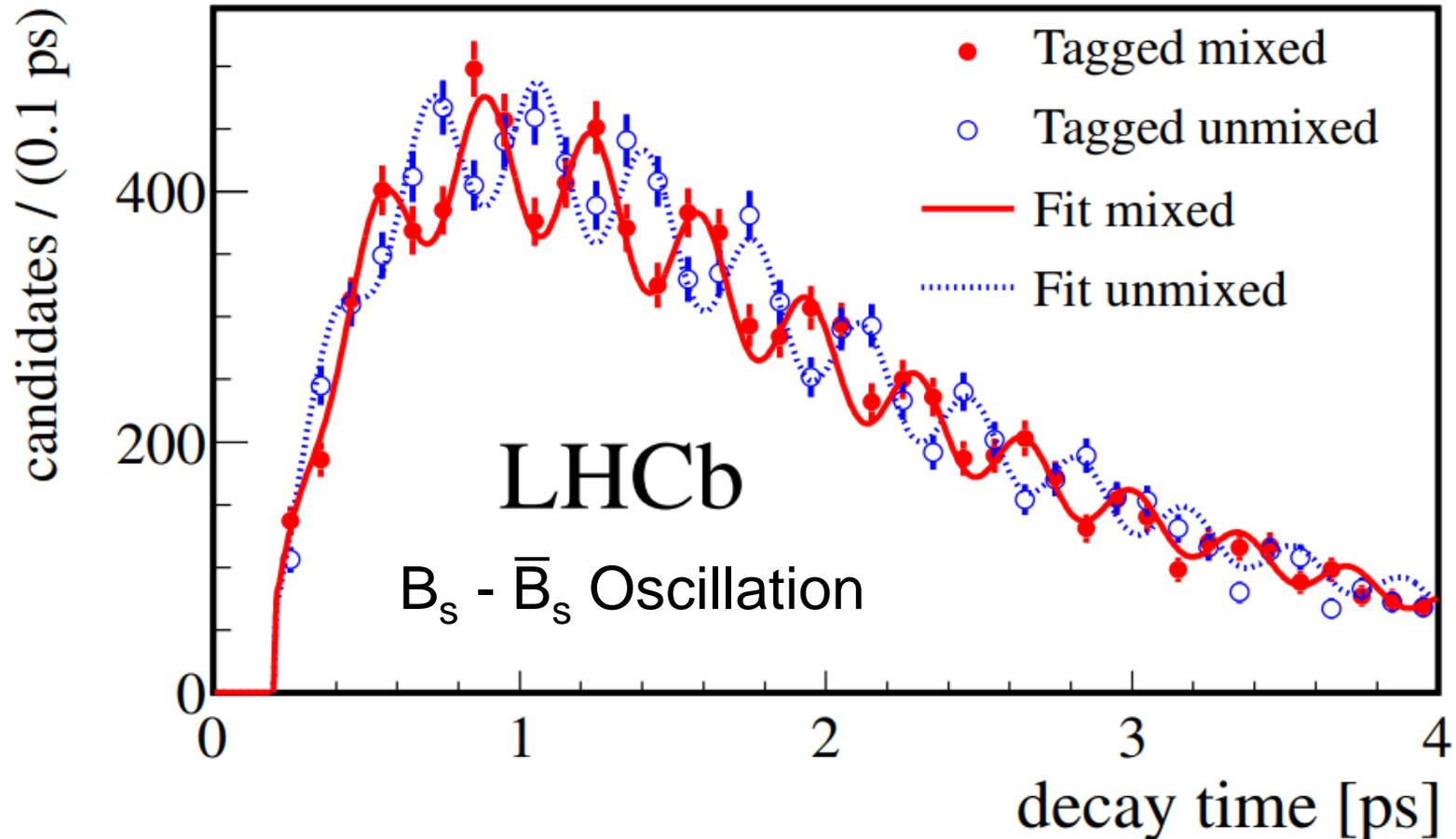


Hadrons too can oscillate!

B_s Oscillation



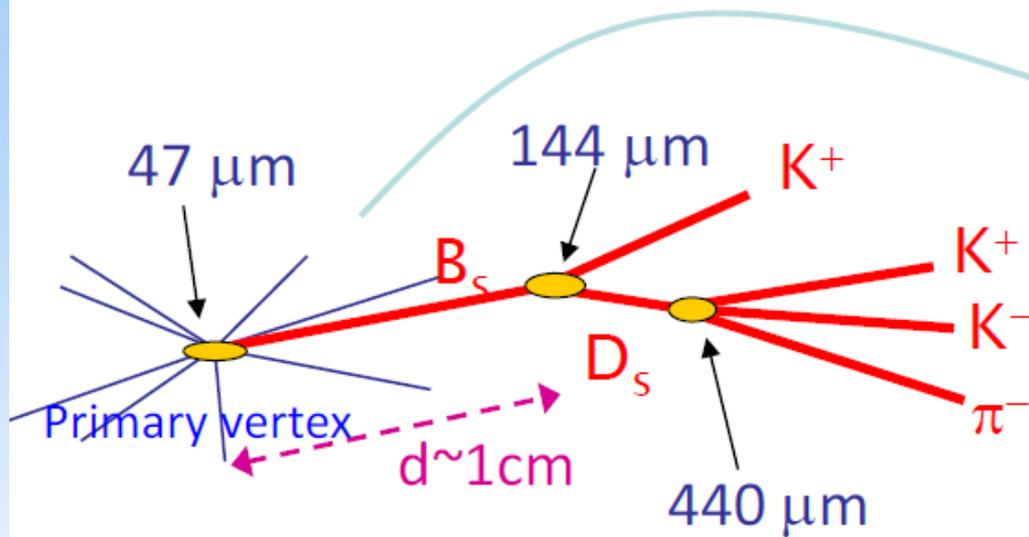
Example Oscillations



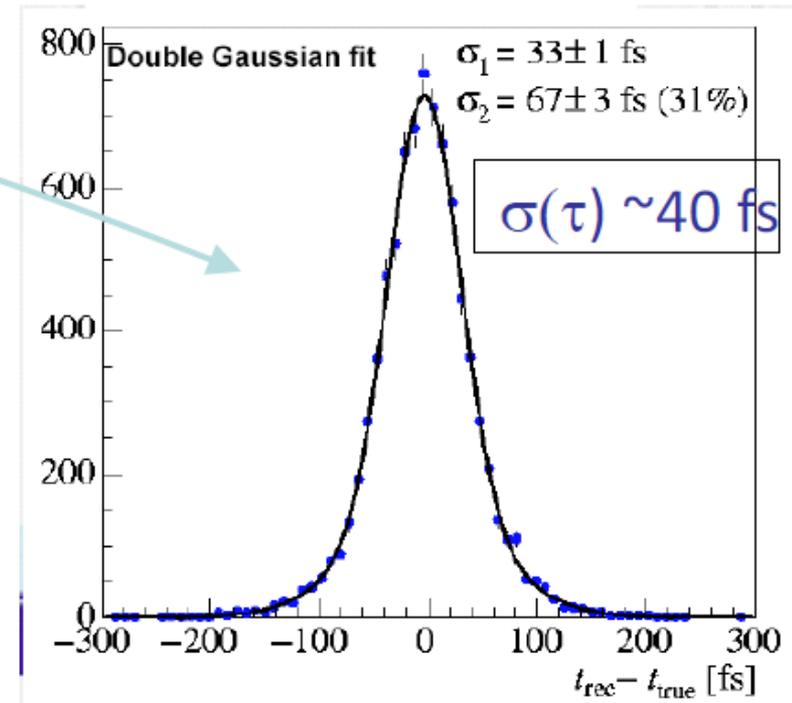
$$\Delta m_s = 17.768 \pm 0.024 \text{ ps}^{-1} = 11.695 \pm 0.016 \text{ meV}$$

Experimental Challenges

Example: $B_s \rightarrow D_s K$



Decay time resolution = 40 fs

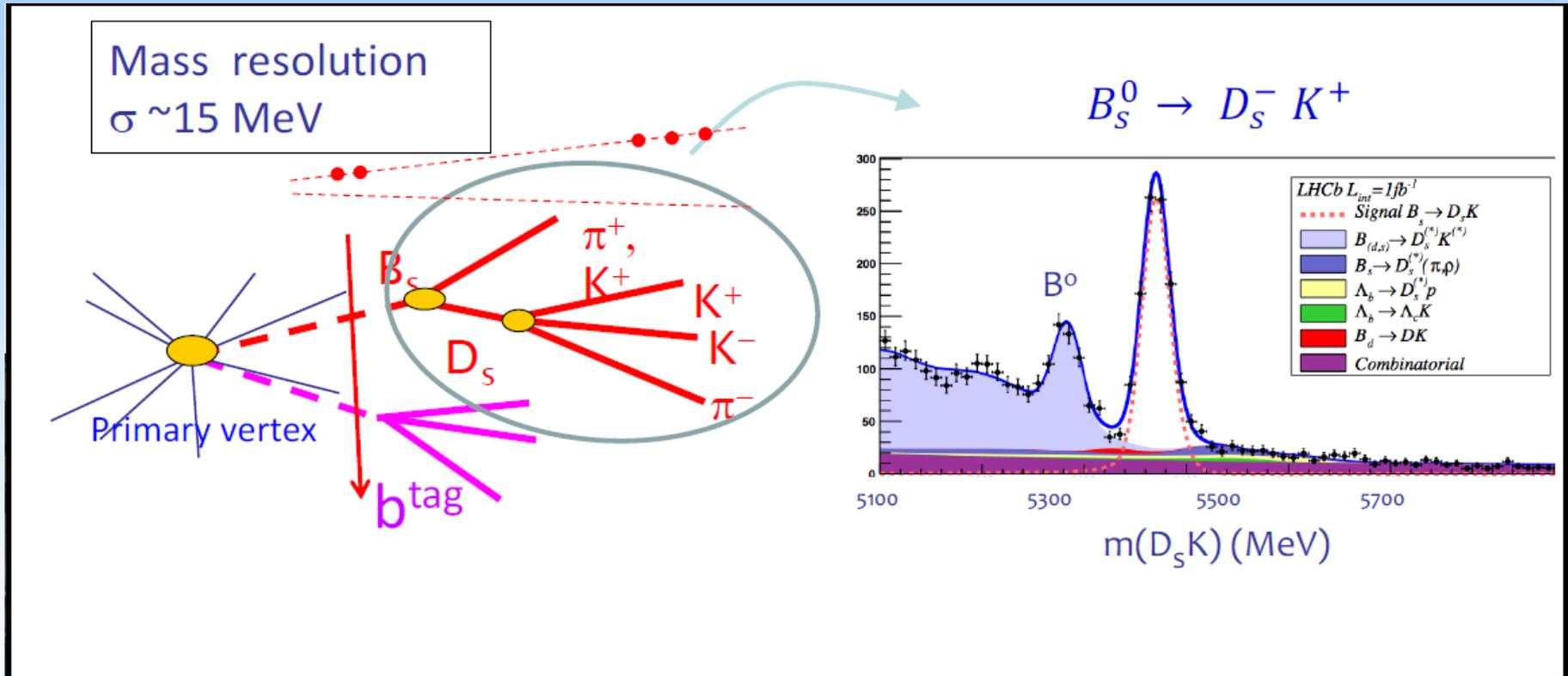


Tracking

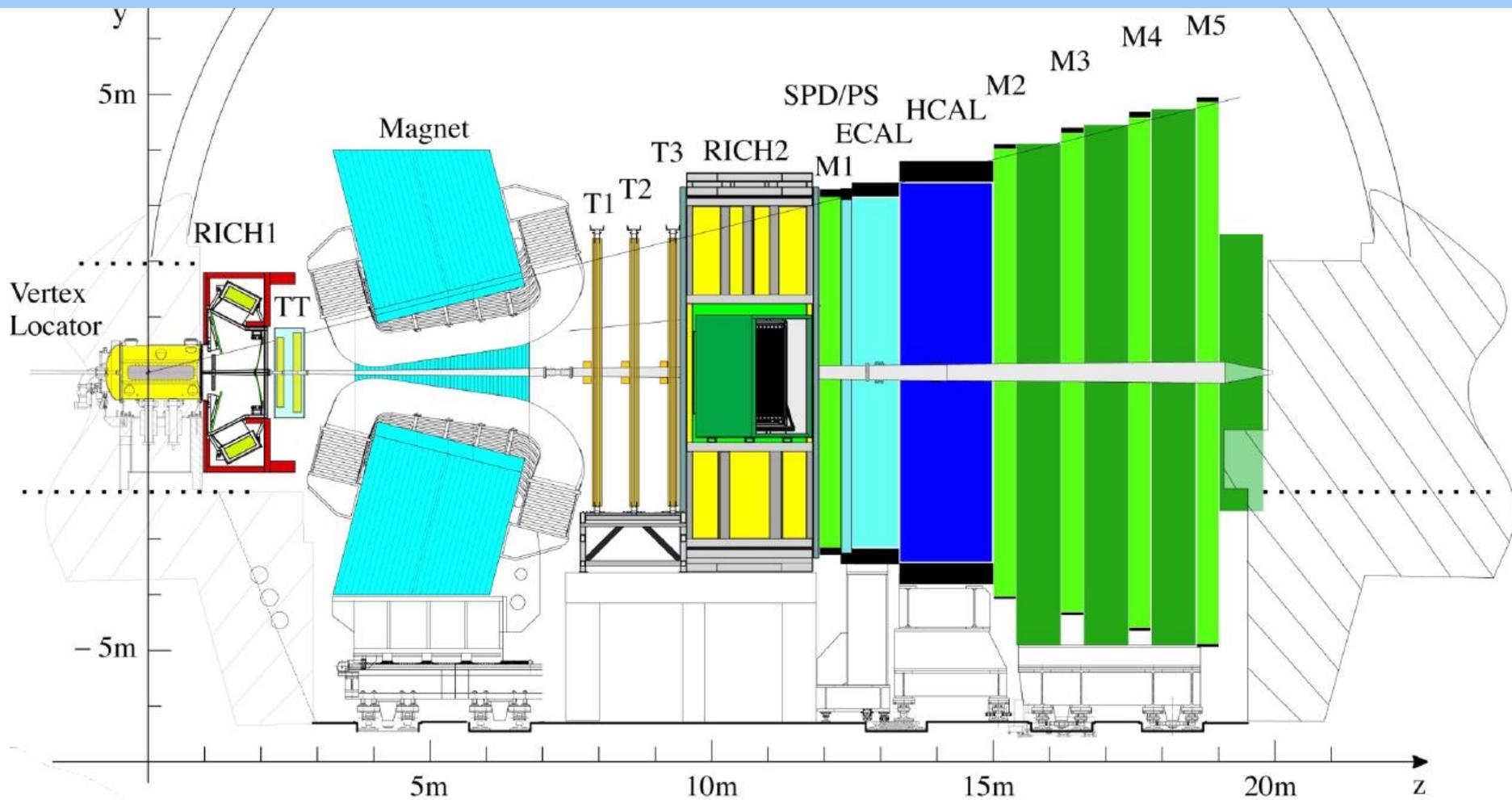


Mass Resolution

- Reconstruct invariant masses with very high precision



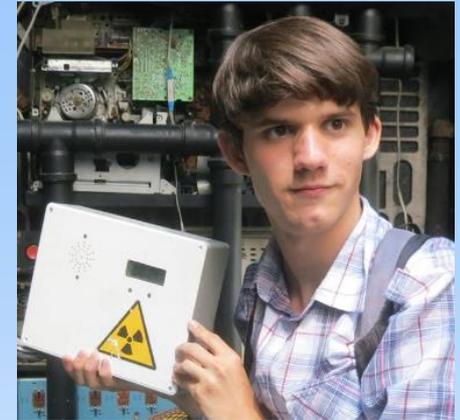
Detector Scheme



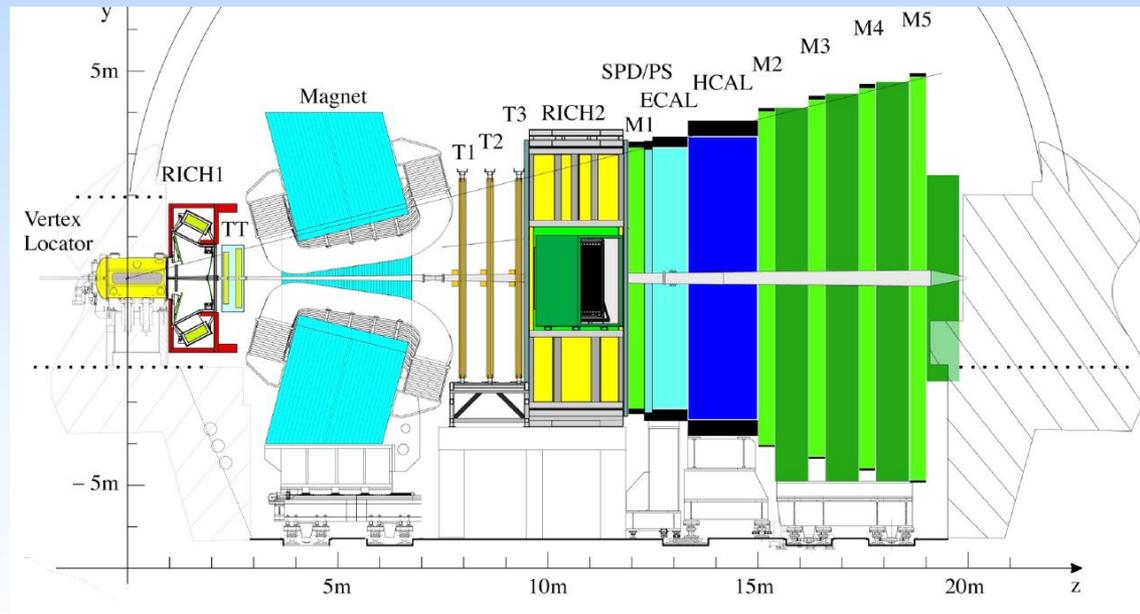
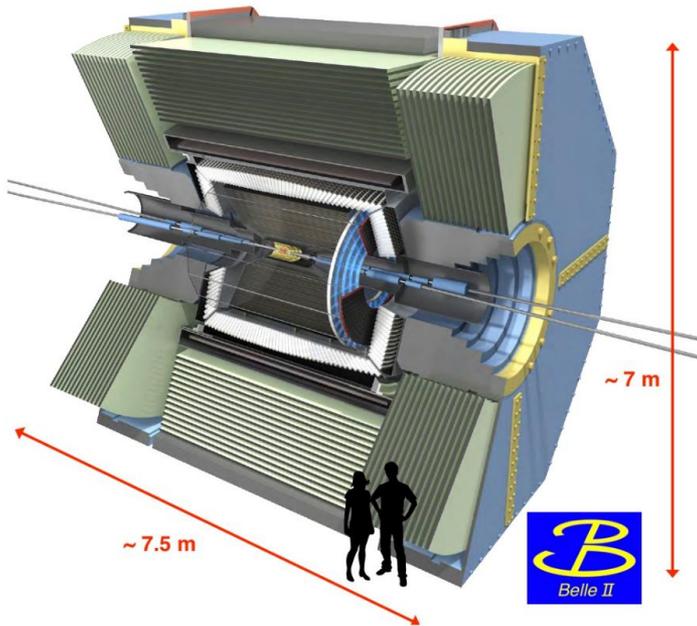
Belle II vs LHCb



Daniel
Cuesta
IPHC



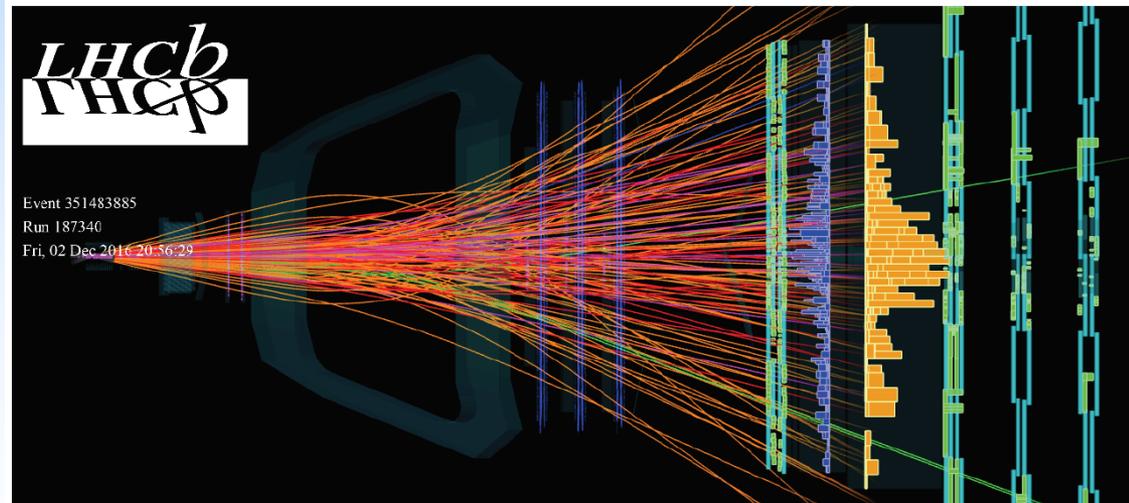
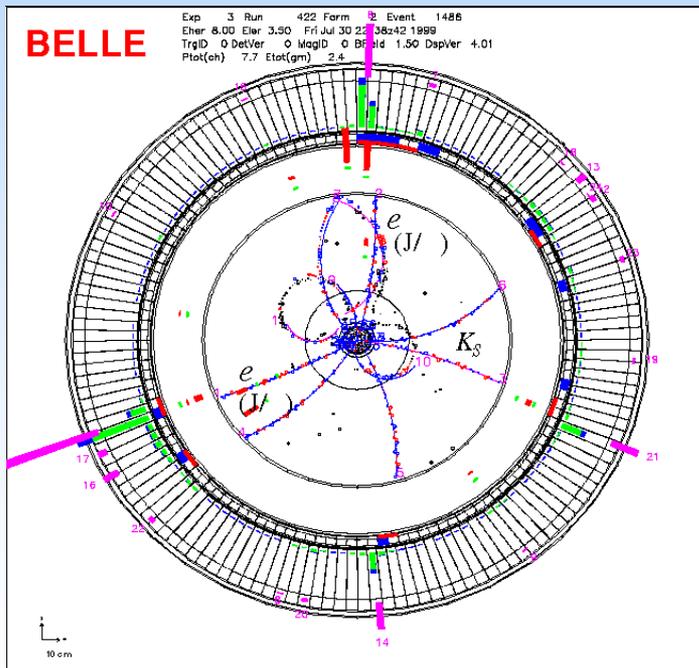
Vitalii
Lisovskyi
LAL



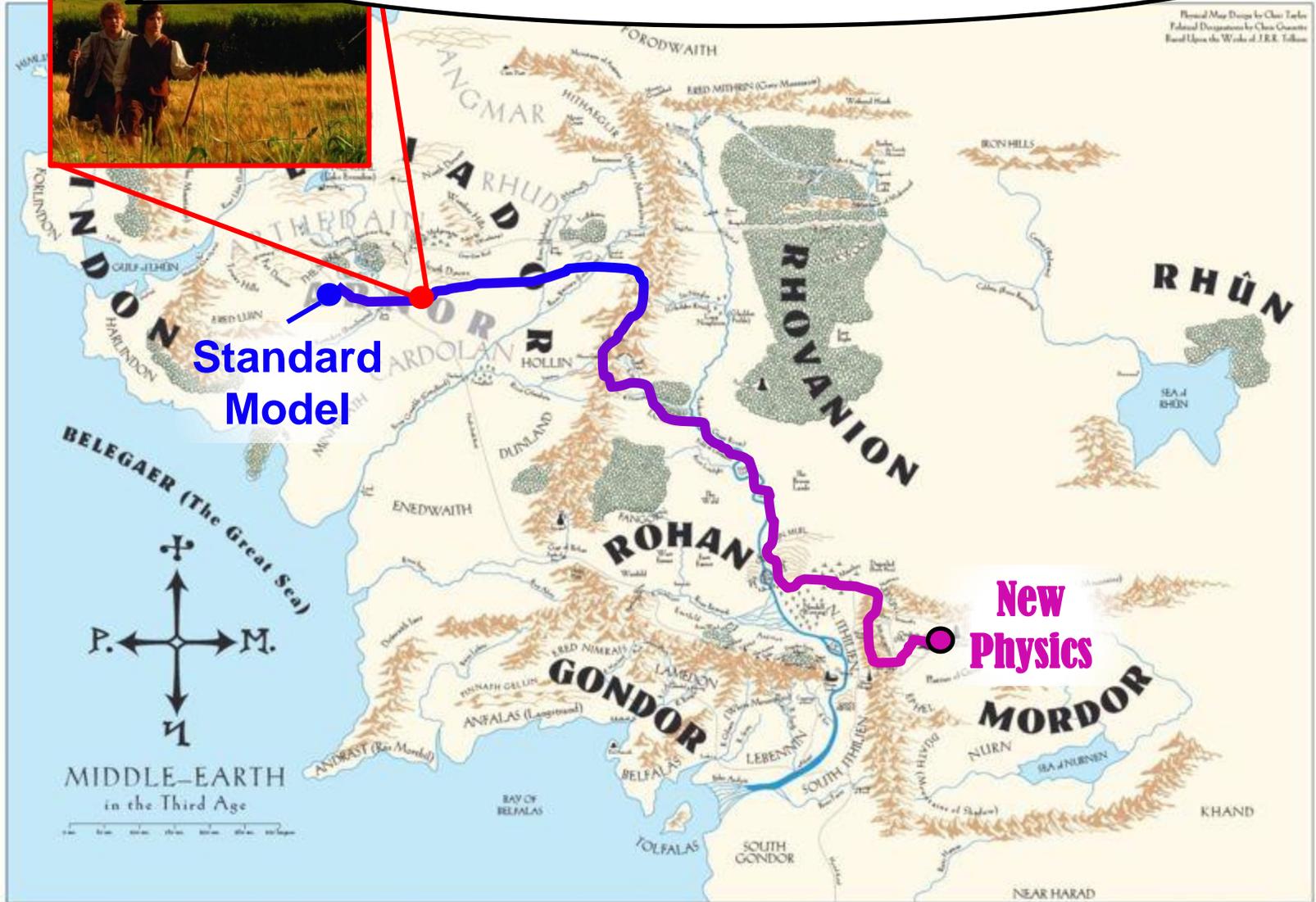
Belle II vs LHCb

- CM: 10.6 GeV
- Clean environment
- $\sim 4\pi$ coverage
- High Luminosity ($\sim 10^4$ fb/yr)
- Lower x-section (1 nb)

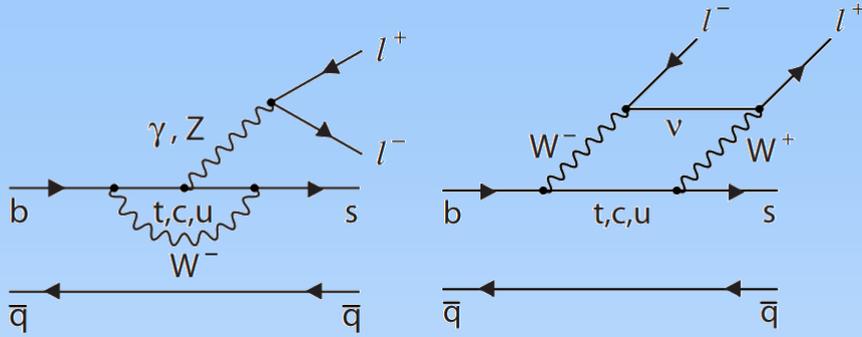
- CM: 13 TeV
- High multiplicity environment
- 4% solid-angle coverage
- Luminosity limited (~ 2 fb/yr)
- Very high x-section ($600 \mu\text{b}$)



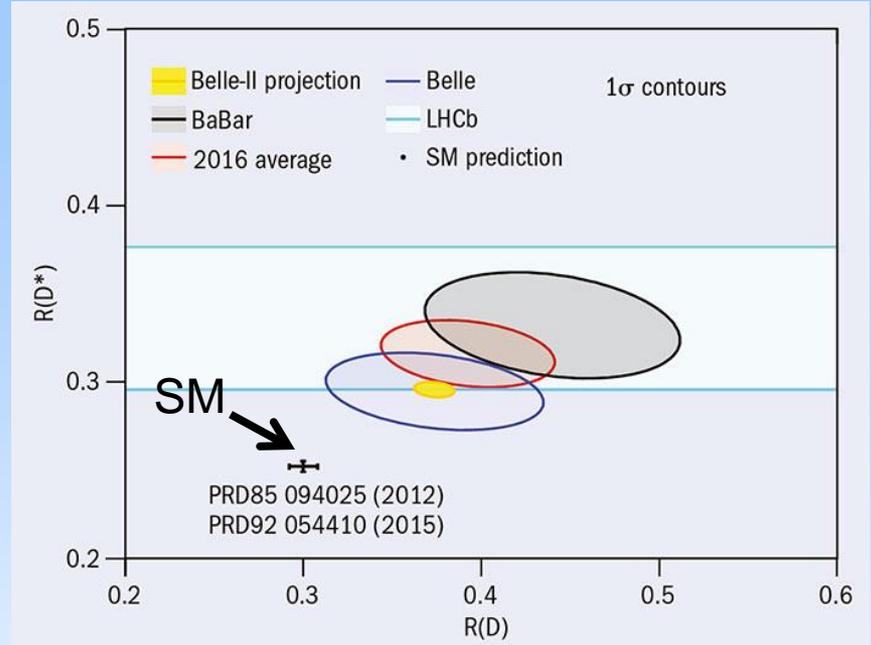
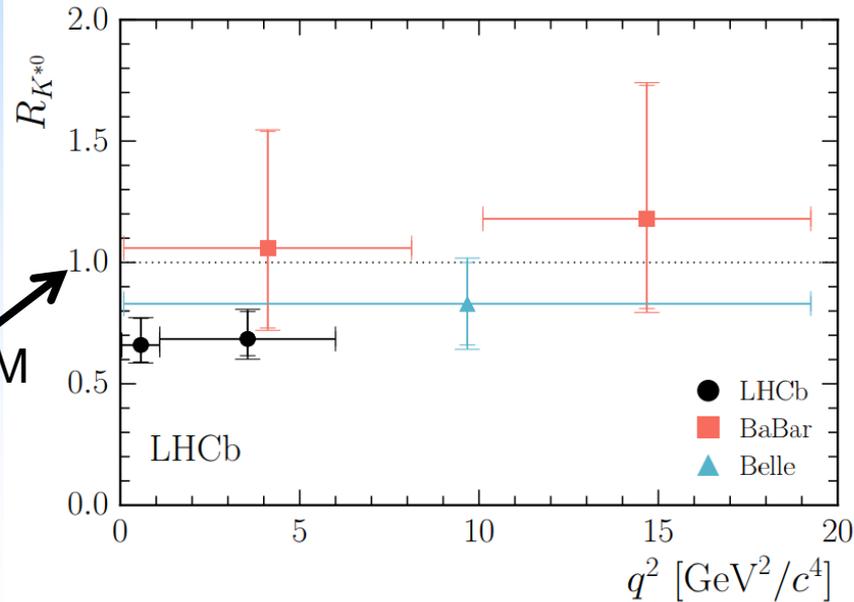
Are we there yet?



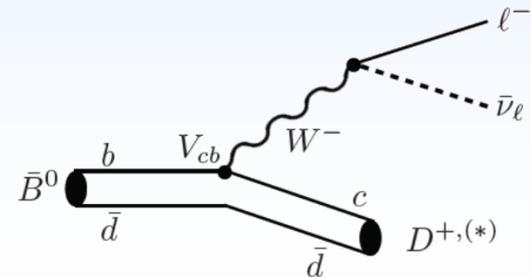
Anomalies (LFUV)



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

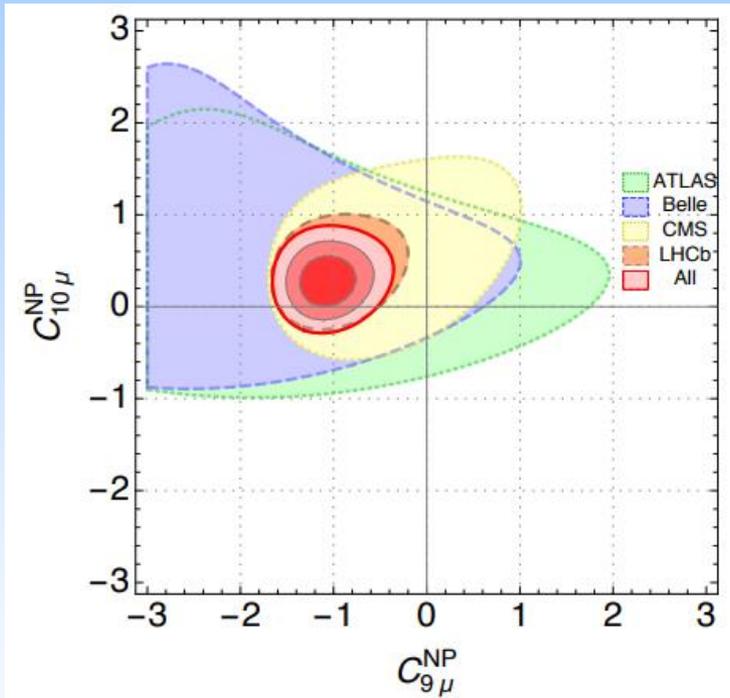


$$R(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)}$$



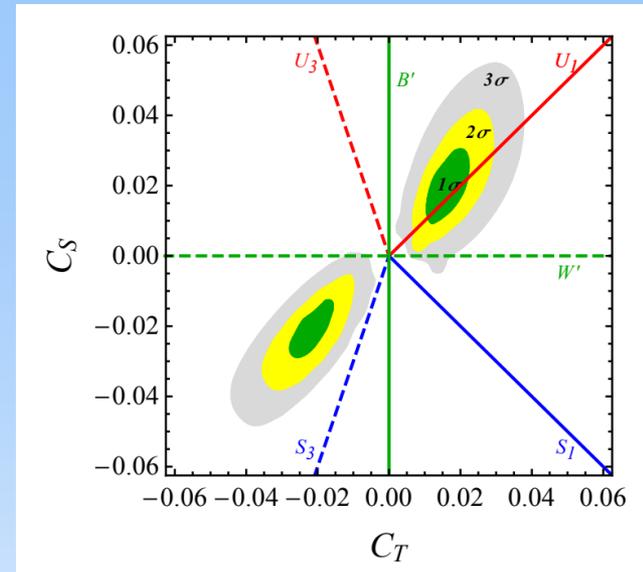
Implications

Effective Field Theory

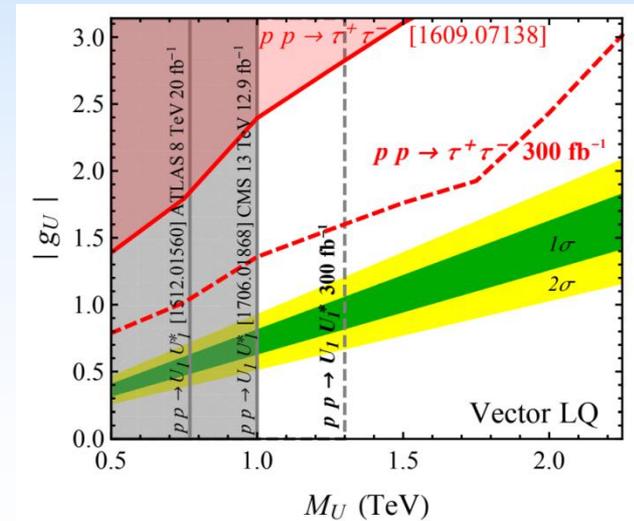


arXiv:1704.05340

Model Discrimination



Direct Bounds



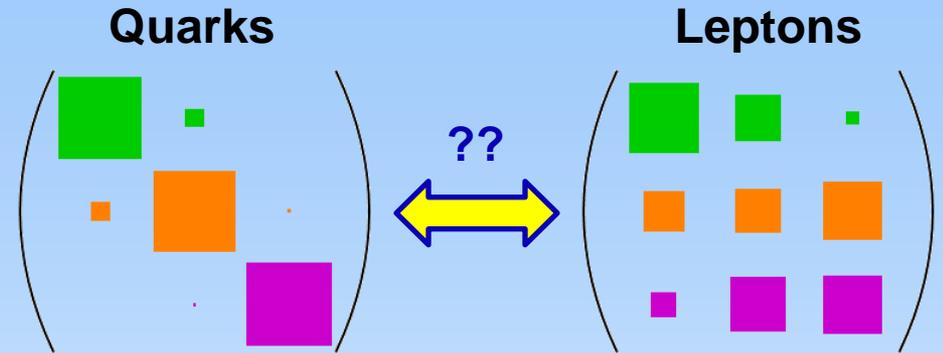
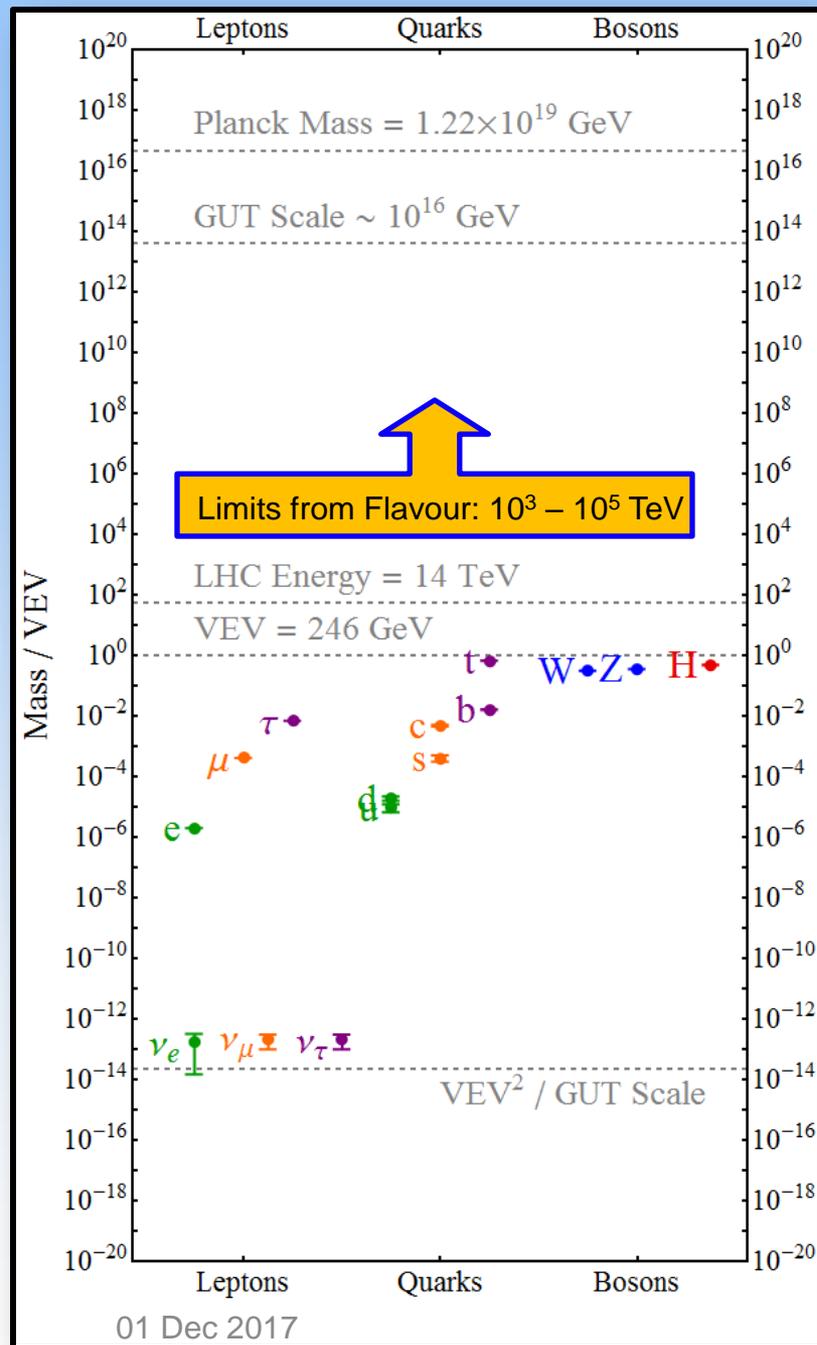
JHEP 1711 (2017) 044

Conclusions

- Exploring **flavour symmetries** of the Standard Model
- **Precision measurements** of loop processes probe new physics at very high energy scales
- Interesting anomalies pointing towards **LFUV**
- Much more data to come. **Stay tuned!**

Thank you!

Flavour Structure



CKM Matrix

PMNS Matrix

