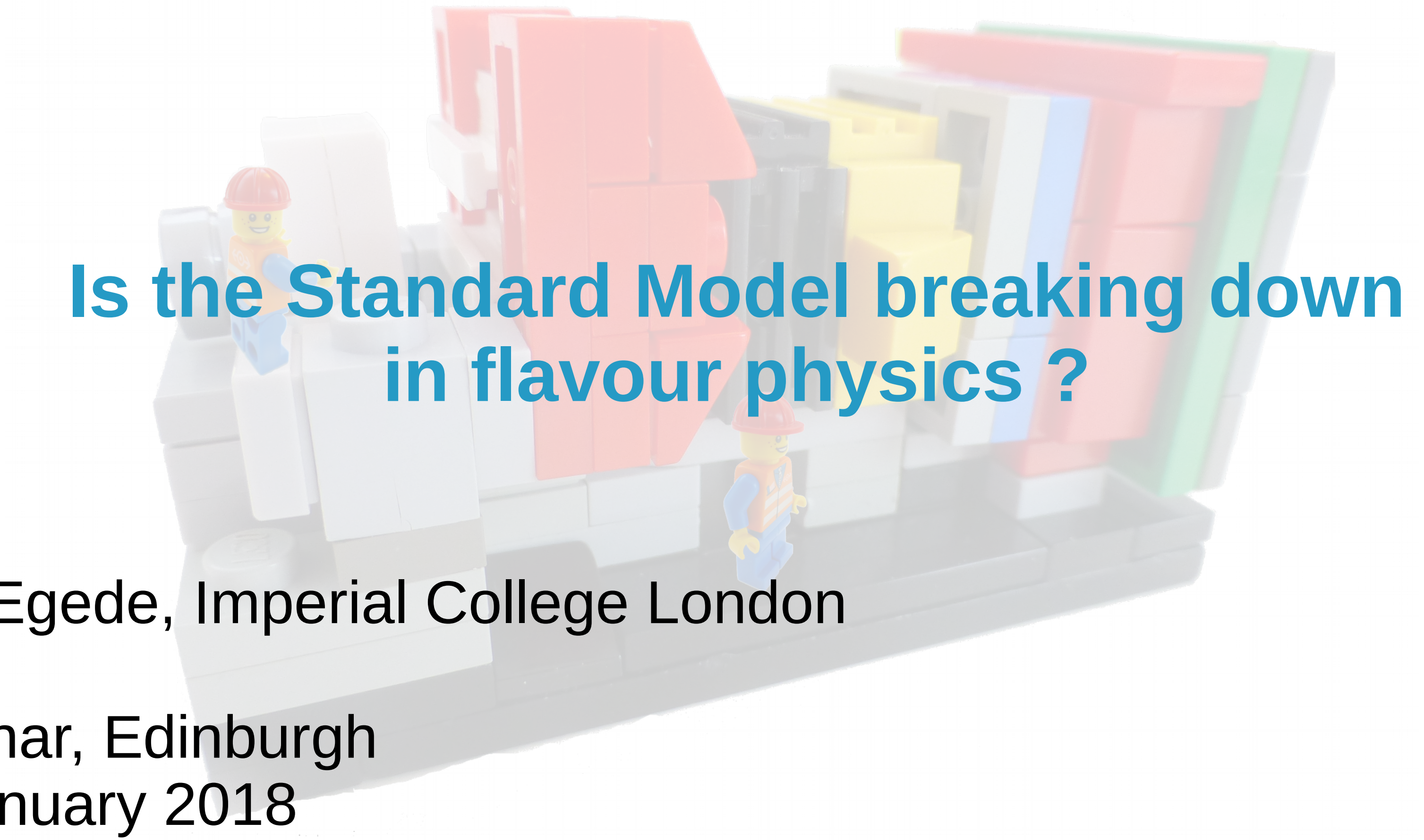


Is the Standard Model breaking down in flavour physics ?

Ulrik Egede, Imperial College London

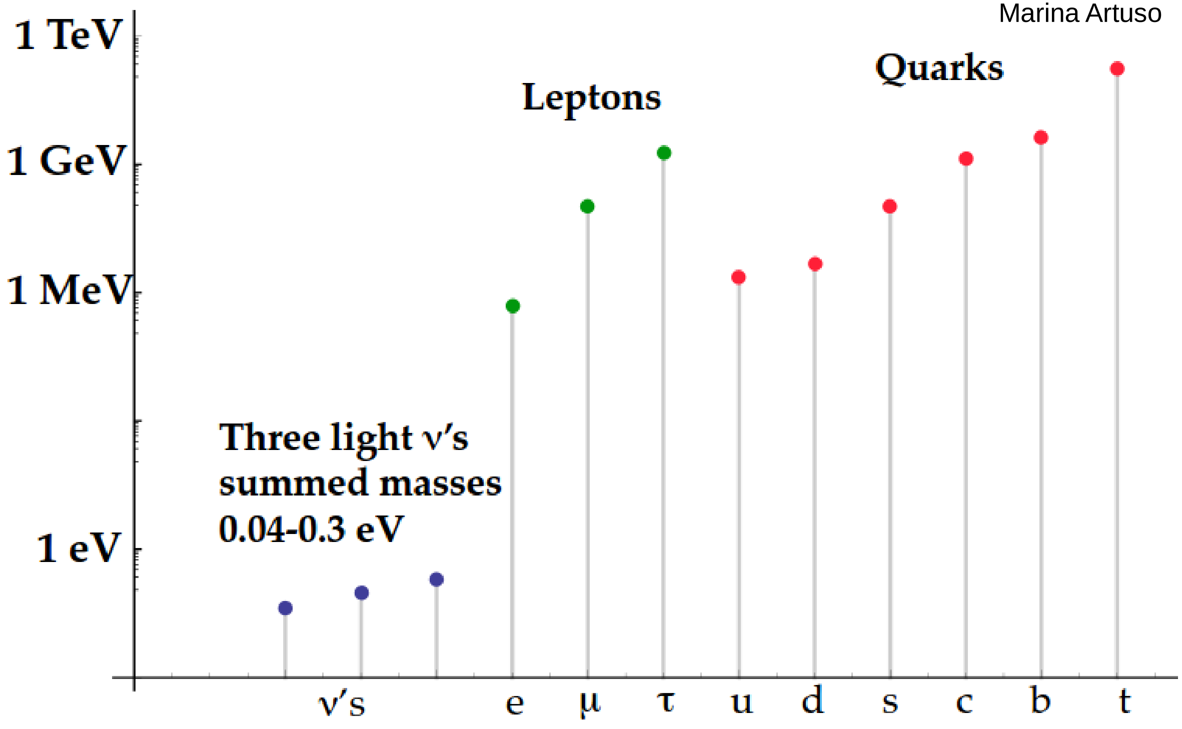
Seminar, Edinburgh
11 January 2018

Why flavour physics?

Any physics model (SM or NP) has to deal with the observed flavour structure we observe

- In SM this is through the Yukawa couplings to the Higgs field and the weak force
- Misalignment of these gives structure of CKM matrix
  - Wide range:
    - $m_u = O(10^{-5})\ m_t$
    - $|V_{ub}|=O(10^{-3})\ |V_{tb}|$
  - Why???

Marina Artuso



Why flavour physics?

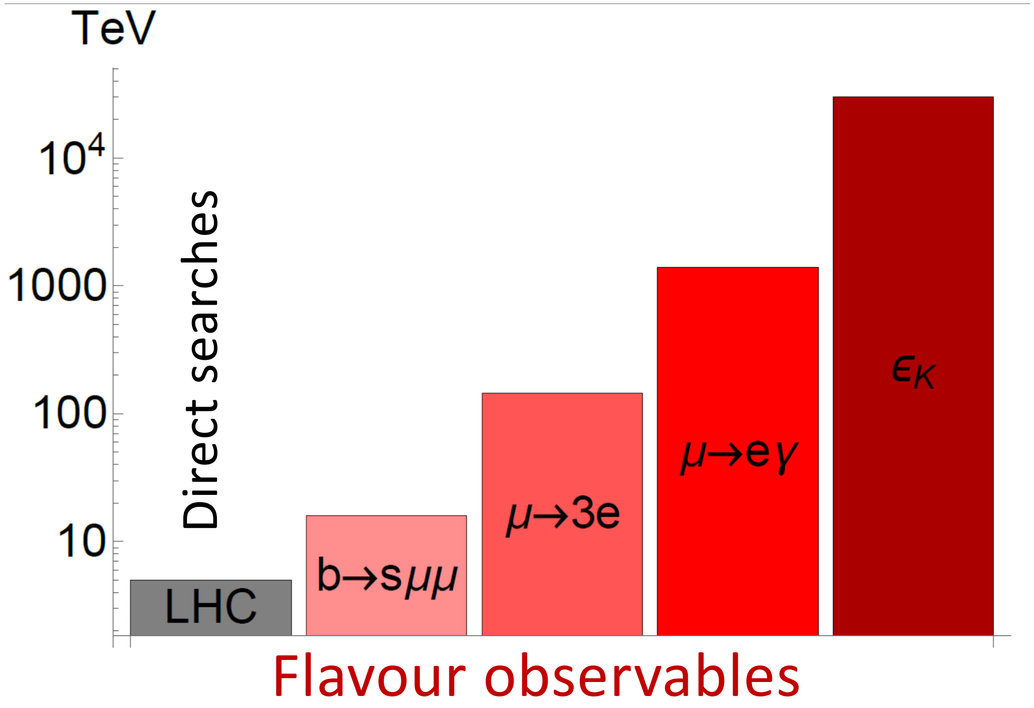
Any NP model with new flavoured particles or flavour breaking interactions must "hide" behind SM interactions

- NP mass scale very large
  - >~100 TeV or
- NP mimics Yukawa couplings
  - minimal flavour violation

Both choices can be argued to be un-natural

Further measurements required

Andreas Crevellin

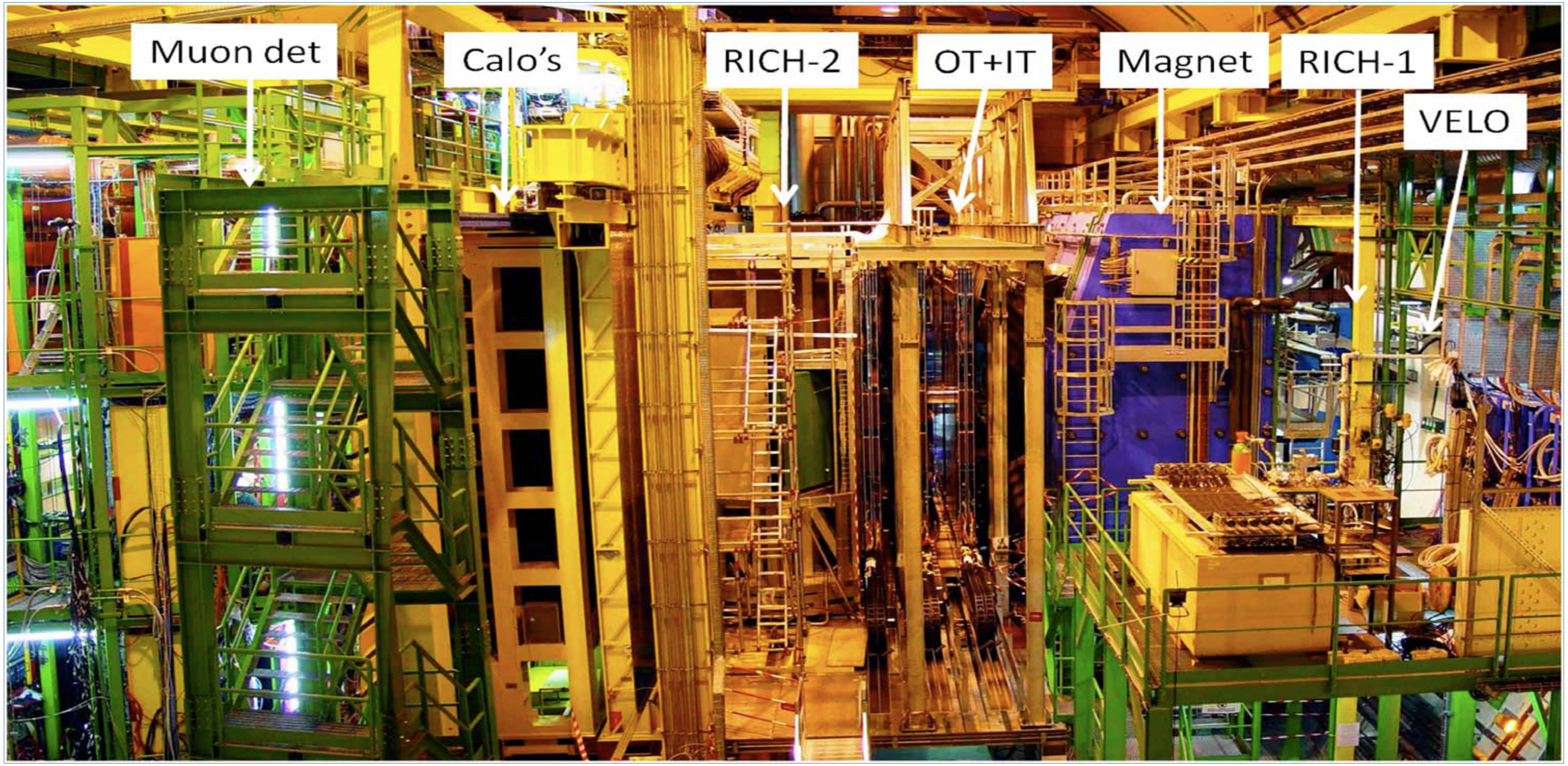


Potential for discovery of NP

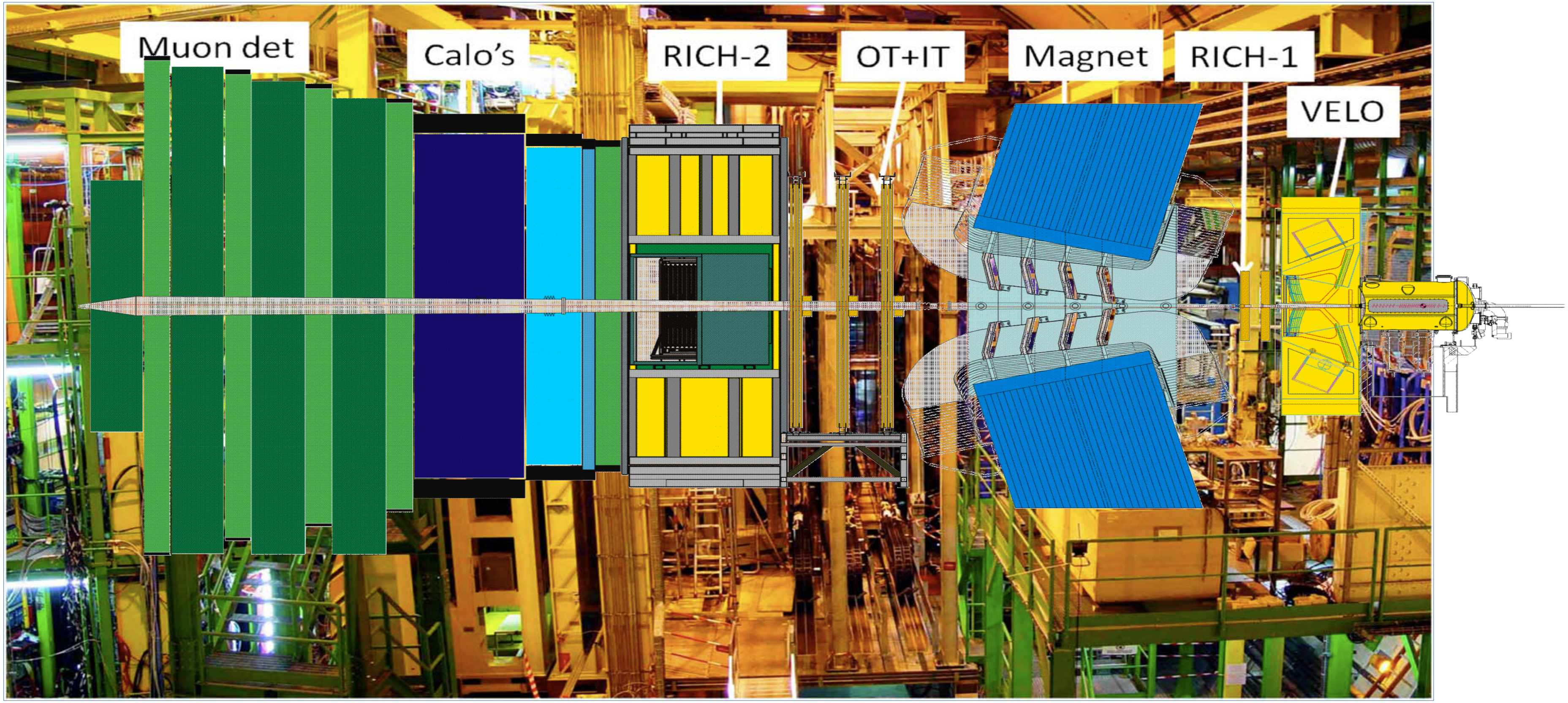
For a given prospective measurement, we need to ask the questions

- Can we learn something from the measurement?
- What are the theoretical uncertainties and can they be reduced?
- Do we know SM parameters well enough?
- What level of statistical accuracy is expected?
- How will experimental systematic uncertainties be controlled?
- How can everything be cross checked?

The LHCb experiment

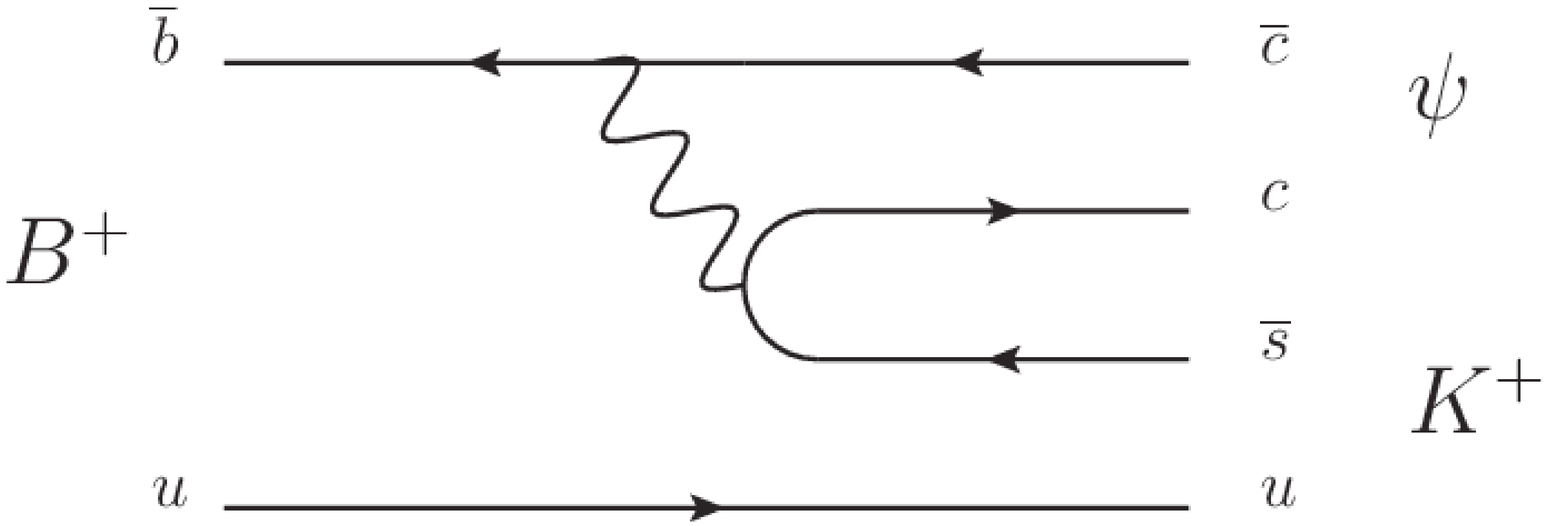


The LHCb experiment



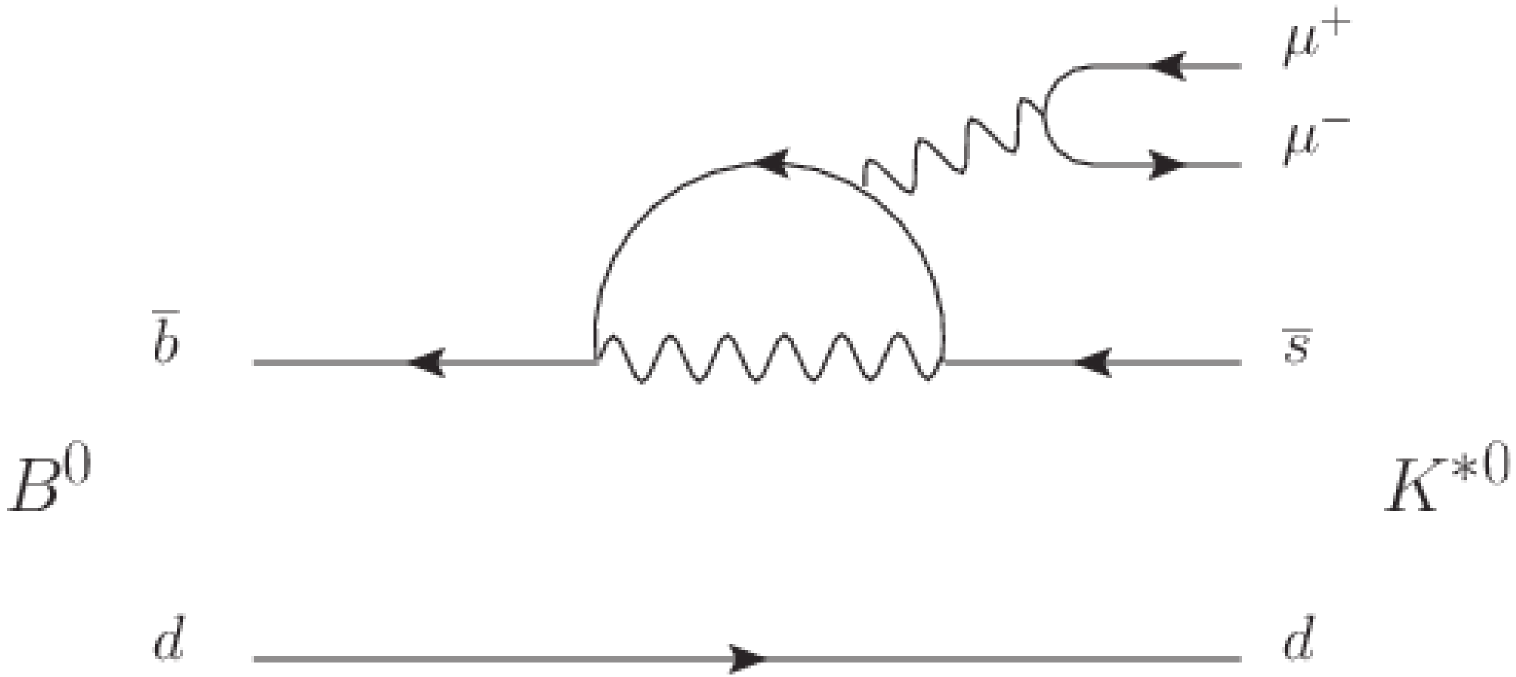
What can beauty reveal?

Typical beauty meson decay



What can beauty reveal?

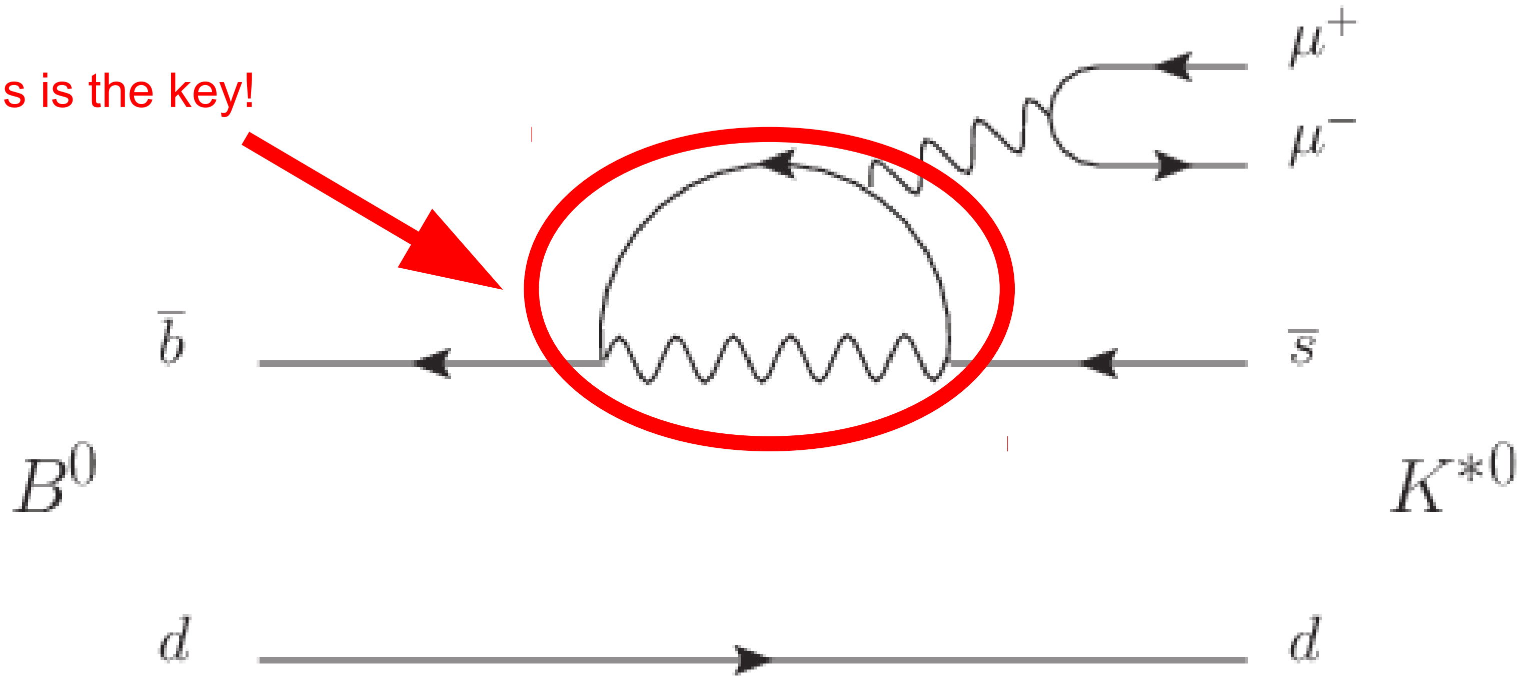
Rare beauty meson decay



What can beauty reveal?

Rare beauty meson decay

This is the key!



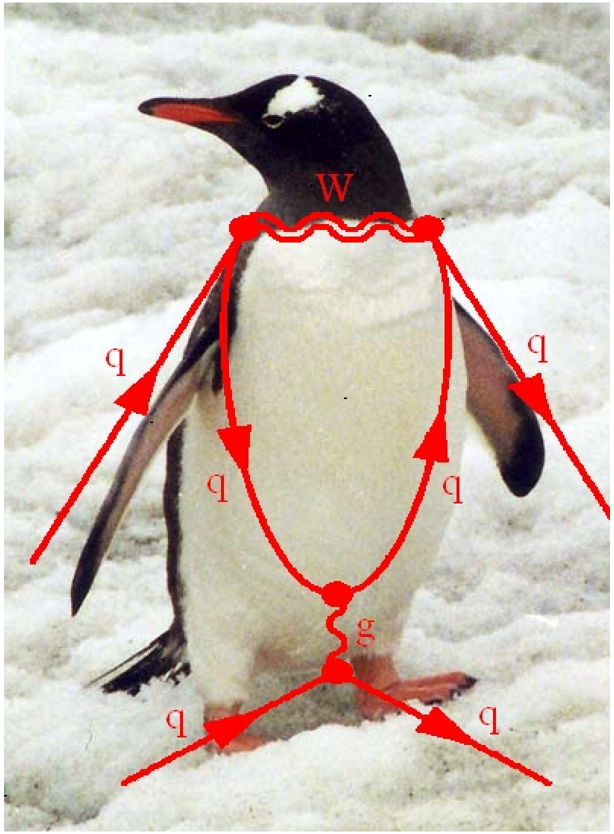
The uncertainty principle

Quantum mechanics allows to create a massive object for a very short time period

$$\left.\begin{aligned} \text{Energy} * \text{time} &\sim \hbar/2 \\ E &= mc^2 \end{aligned}\right\} \quad \Rightarrow \quad t \leqslant \frac{\hbar}{2mc^2}$$

A particle with mass 10 times above what can be produced directly at LHC, can exist for 10^{-29} seconds

These decays are called penguins

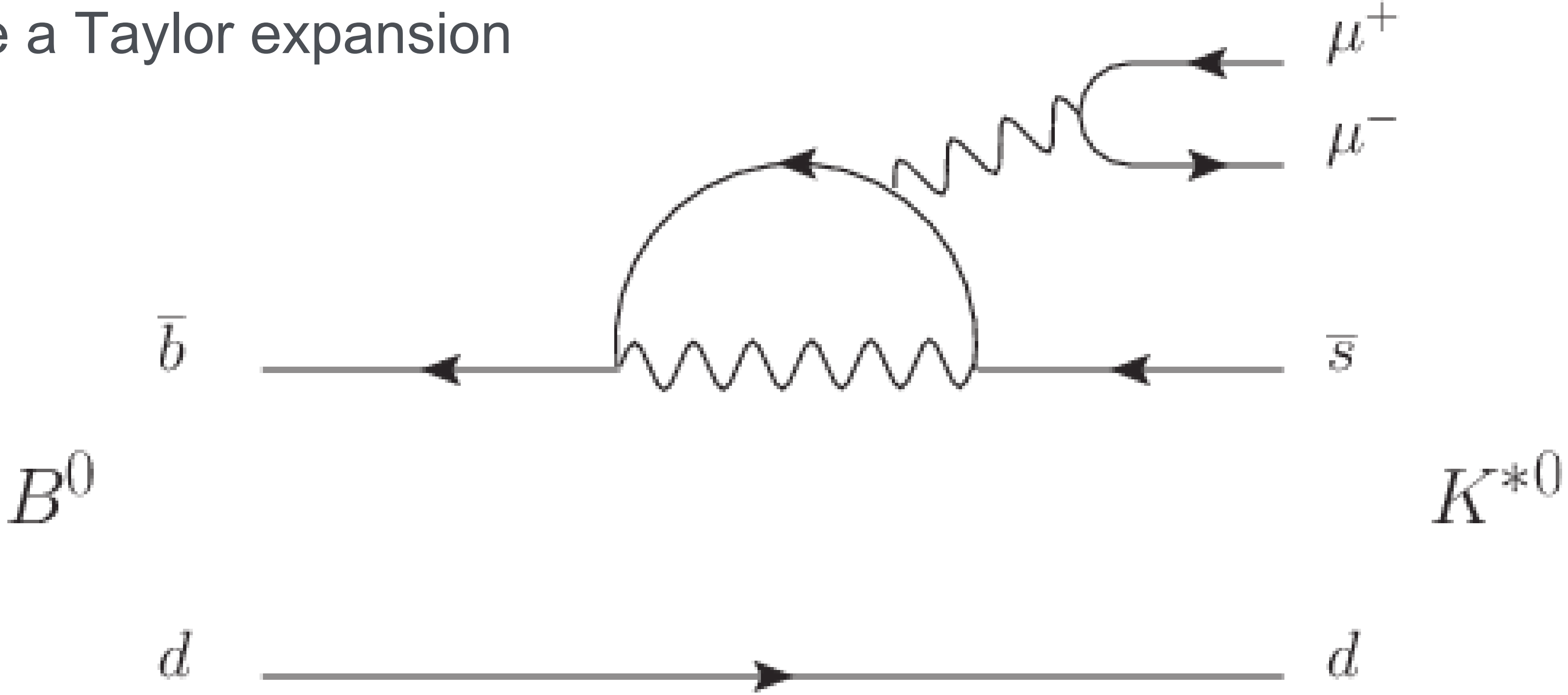


Strong force in the way

Most calculations of expected decay rates are done using Feynman diagrams

Works just like a Taylor expansion

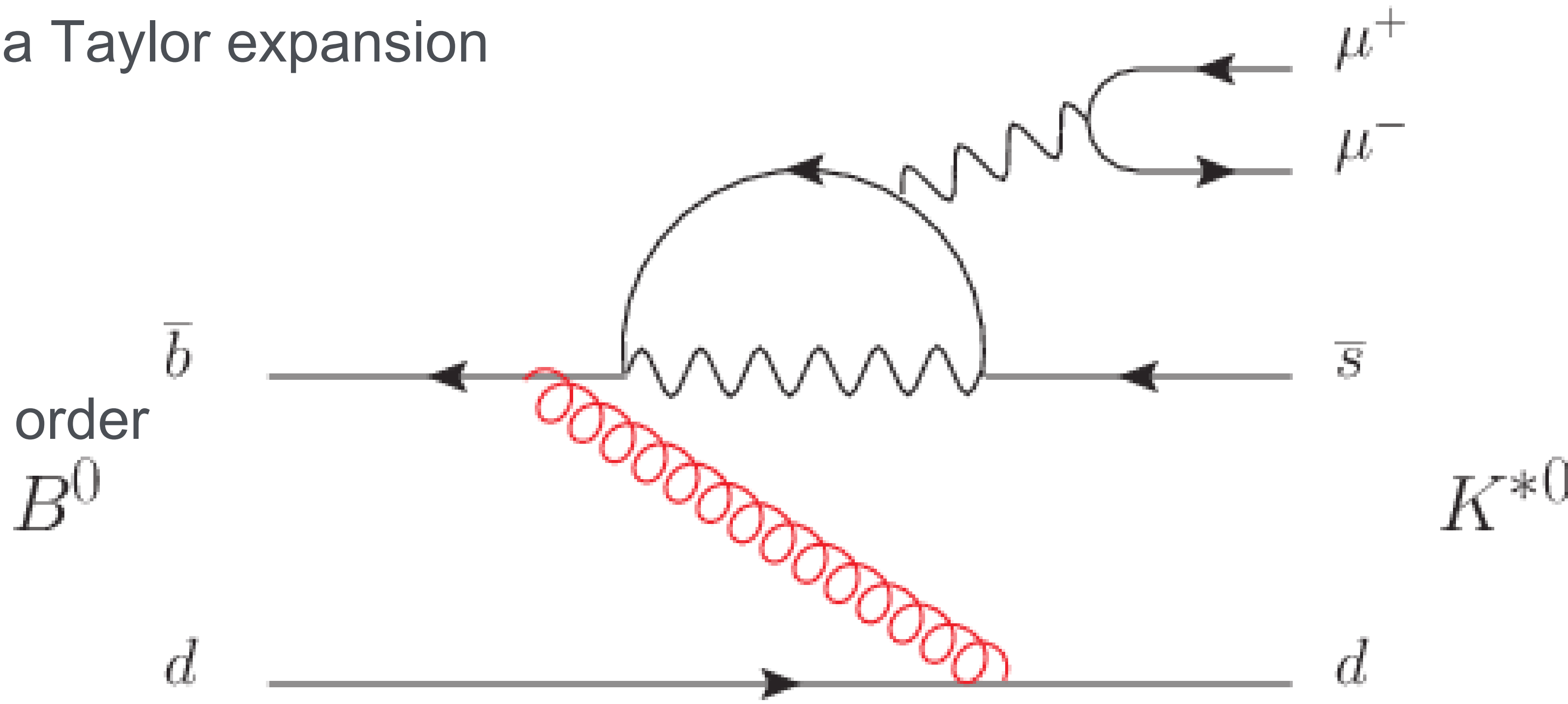
Leading order



Strong force in the way

Most calculations of expected decay rates are done using Feynman diagrams

- Works just like a Taylor expansion
- Next to leading order

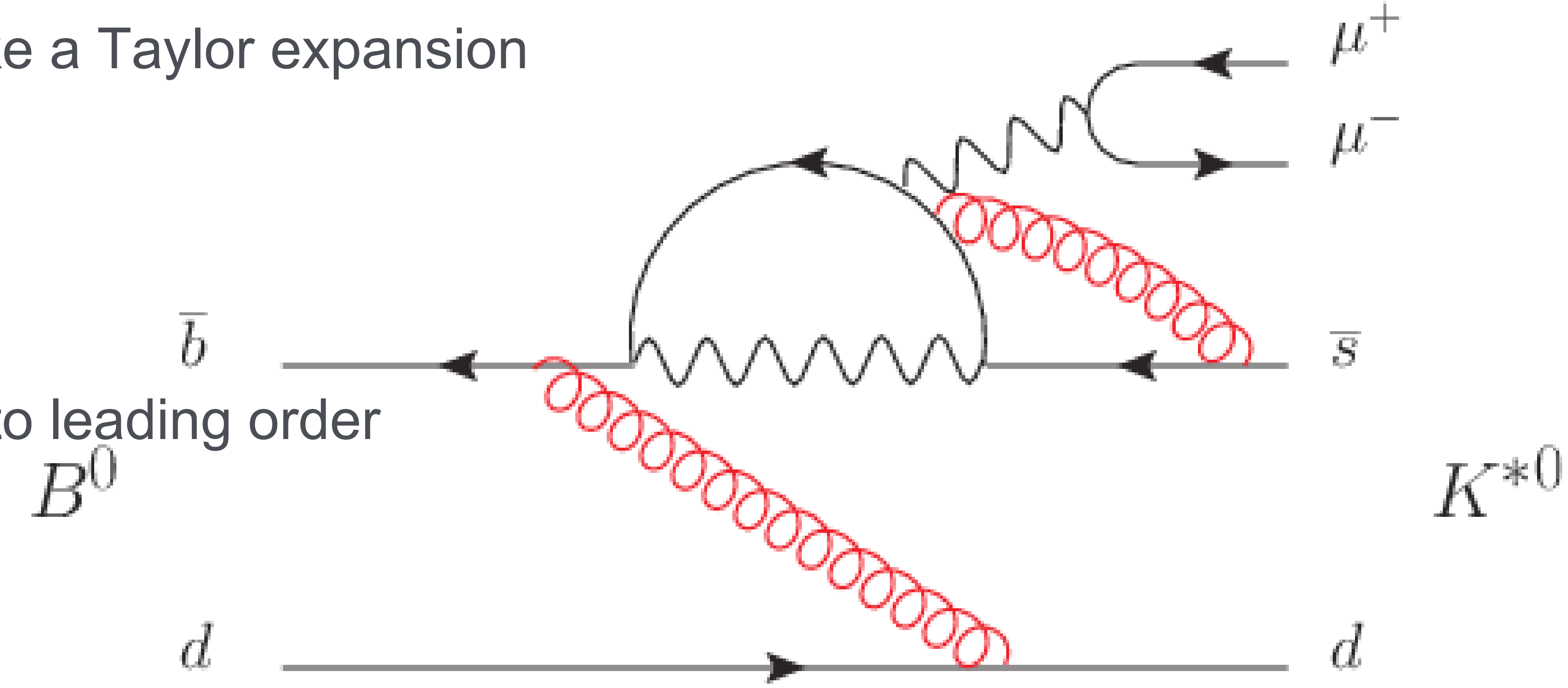


Strong force in the way

Most calculations of expected decay rates are done using Feynman diagrams

Works just like a Taylor expansion

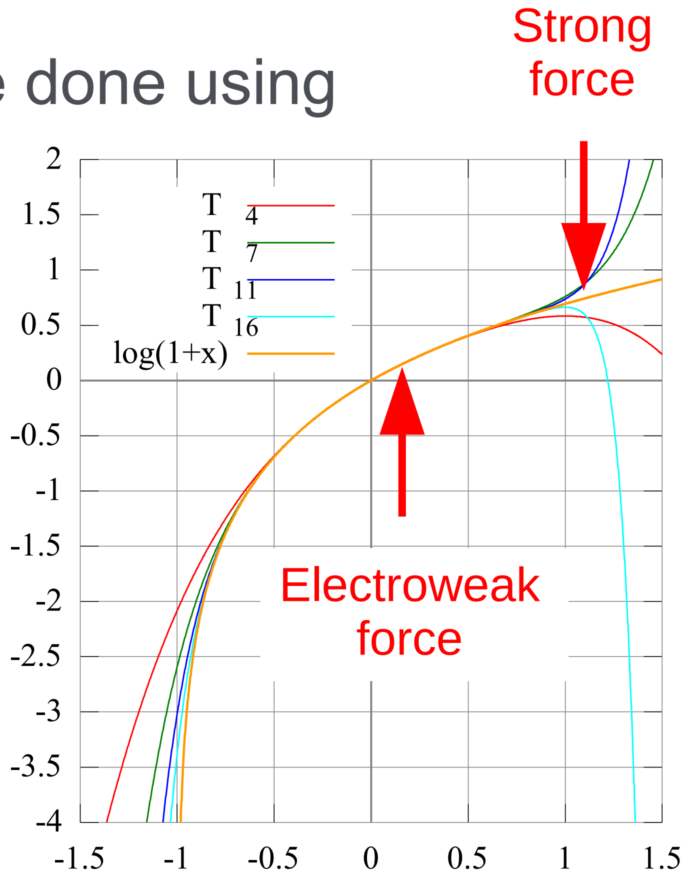
Next to next to leading order



Strong force in the way

Most calculations of expected decay rates are done using Feynman diagrams

- Works just like a Taylor expansion
- But can in just the same way turn problematic
- Strong coupling constant too large so series may not converge



Measurements

Look at measurements with leptons to improve theory predictions

Electroweak penguins

$B \to K^{(*)} \mu^+ \mu^-$

Lepton universality

$B \to K^{(*)} \mu^+ \mu^-$ vs $B \to K^{(*)} e^+ e^-$

$B \to D^{(*)} \mu^- \nu$ vs $B \to D^{(*)} \tau^- \nu$

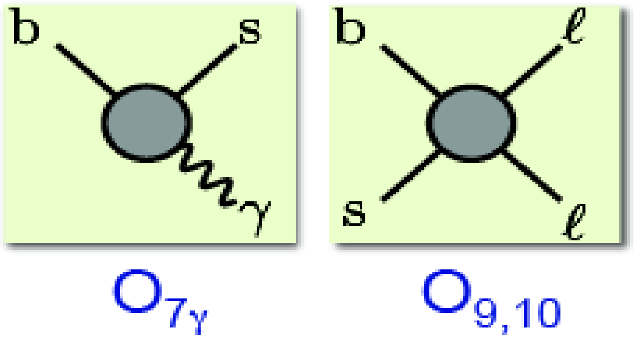
The penguin laboratory

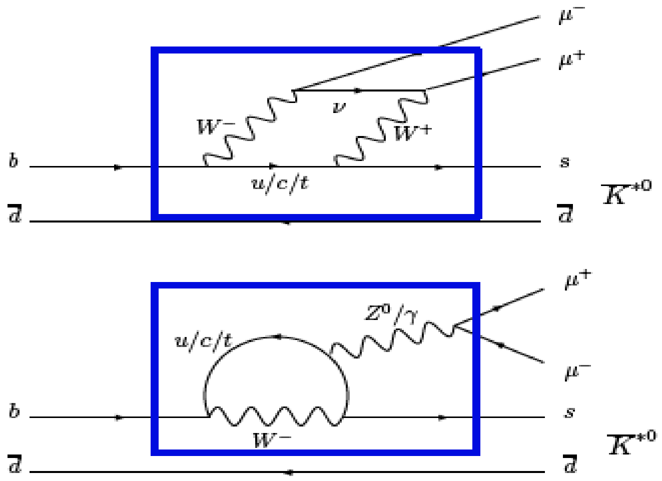
The decay $B^0 \to K^{*0}\mu^+\mu^-$, $K^{*0} \to K^-\pi^+$ is in the SM only possible at loop level

- On the other hand NP can show up at either tree or loop level

Angular analysis of 4-body $K^-\pi^+\mu^+\mu^-$ final state brings large number of observables

Interference between these





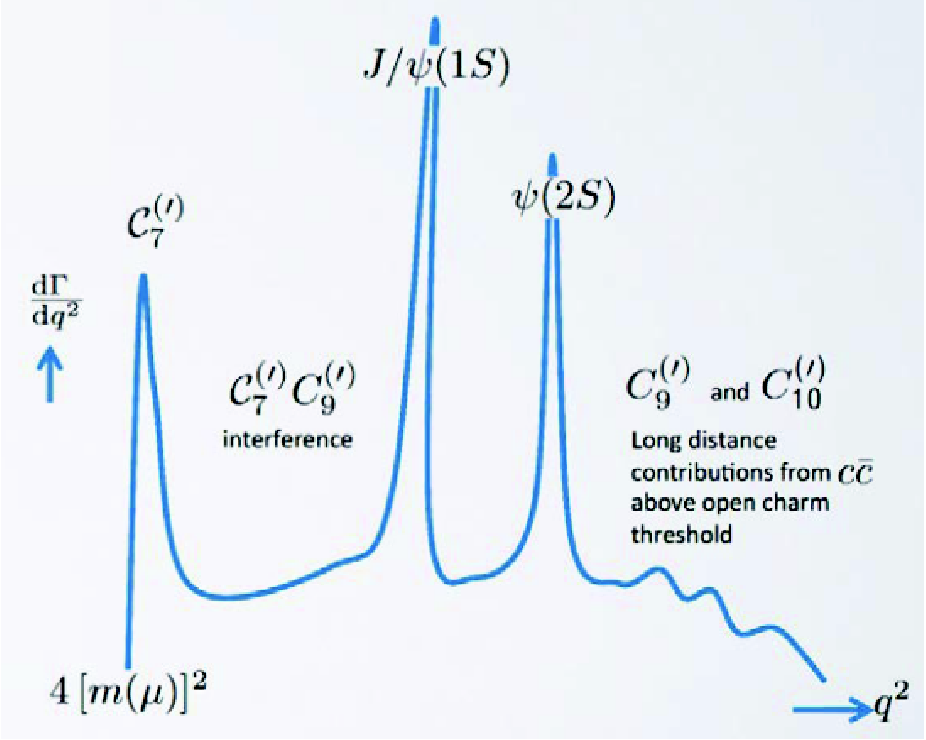
Topology of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

The loop (SM) loop level diagram interferes with tree level $B \rightarrow (c\bar{c})J/K^0$ followed by $(c\bar{c}) \rightarrow \mu^+\mu^-$

Gives multiple regions in $q^2 = m^2_{\mu\mu}$

In addition three angles in 4-body decay

Special combination (“observables”) reduce uncertainty from form factors



$B^+ \to K^+\mu^+\mu^-$ branching fraction

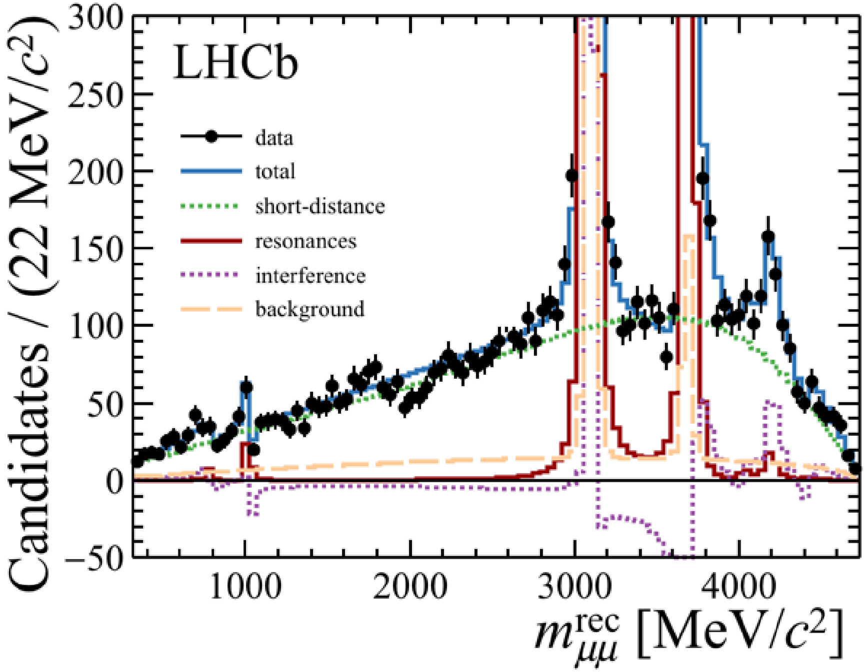
With knowledge of the form factors, the branching fraction can tell about the Wilson coefficients

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{128\pi^5}|\boldsymbol{k}|\beta\left\{\frac{2}{3}|\boldsymbol{k}|^2\beta^2\left|\mathcal{C}_{10}f_+(q^2)\right|^2 + \frac{4m_\mu^2(m_B^2-m_K^2)^2}{q^2m_B^2}\left|\mathcal{C}_{10}f_0(q^2)\right|^2 + |\boldsymbol{k}|^2\left[1-\frac{1}{3}\beta^2\right]\left|\mathcal{C}_9f_+(q^2)+2\mathcal{C}_7\frac{m_b+m_s}{m_B+m_K}f_T(q^2)\right|^2\right\}$$

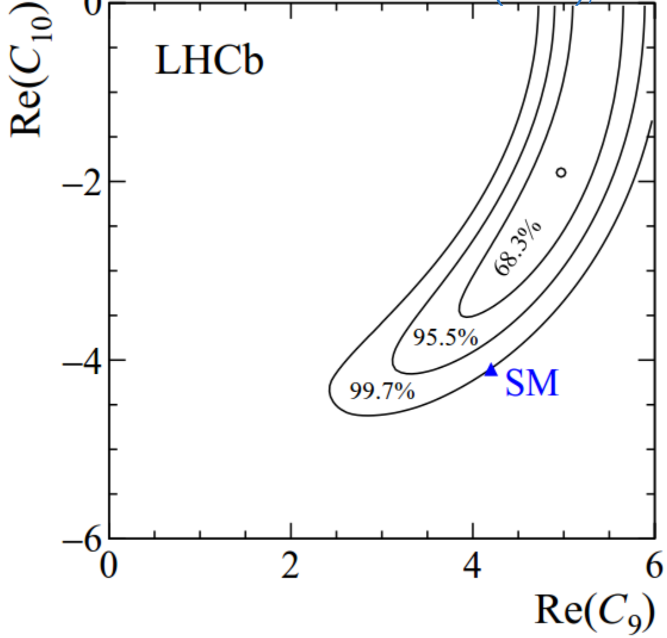
The C_9 we measure has interference from vector resonances

$$\mathcal{C}_9^{\text{eff}} = \mathcal{C}_9 + \sum_j \eta_j e^{i\delta_j} A_j^{\text{res}}(q^2)$$

$B^+ \to K^+\mu^+\mu^-$ branching fraction



EPJ C77 (2017), 161



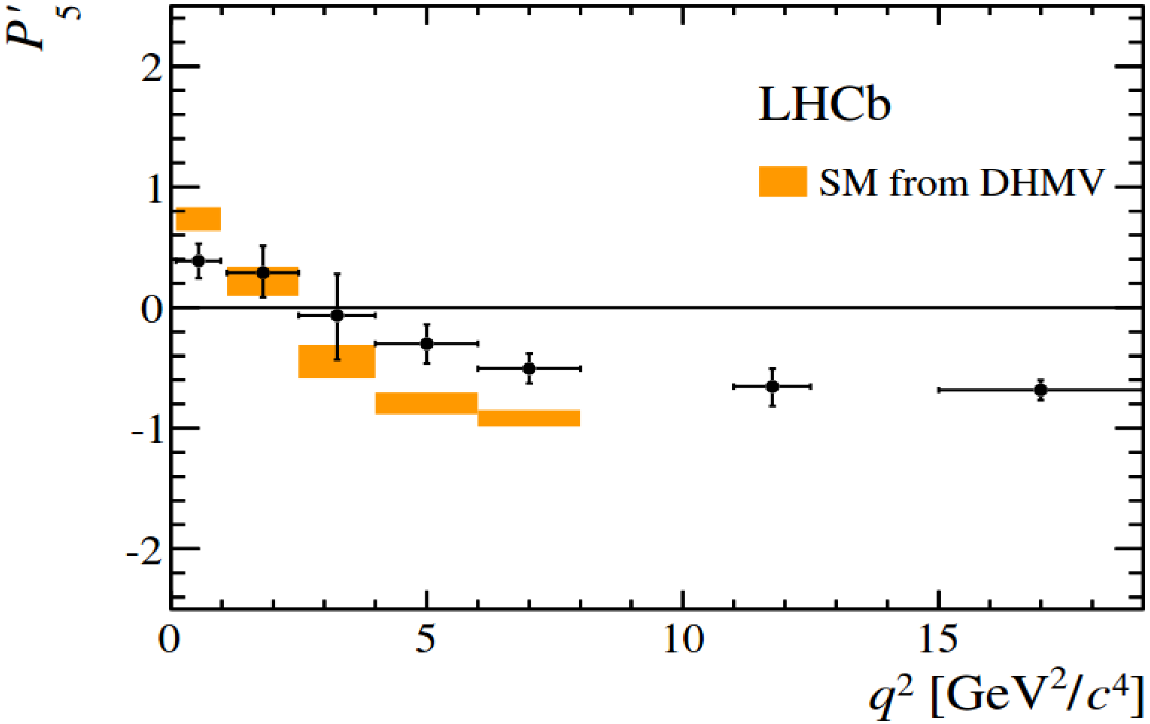
Branching fraction is below SM expectation

This is seen in all other electroweak penguin decays with muons

$B^0 \rightarrow K^{*0}\mu^+\mu^-$ angular analysis

Results based on 3 fb^{-1} from LHCb

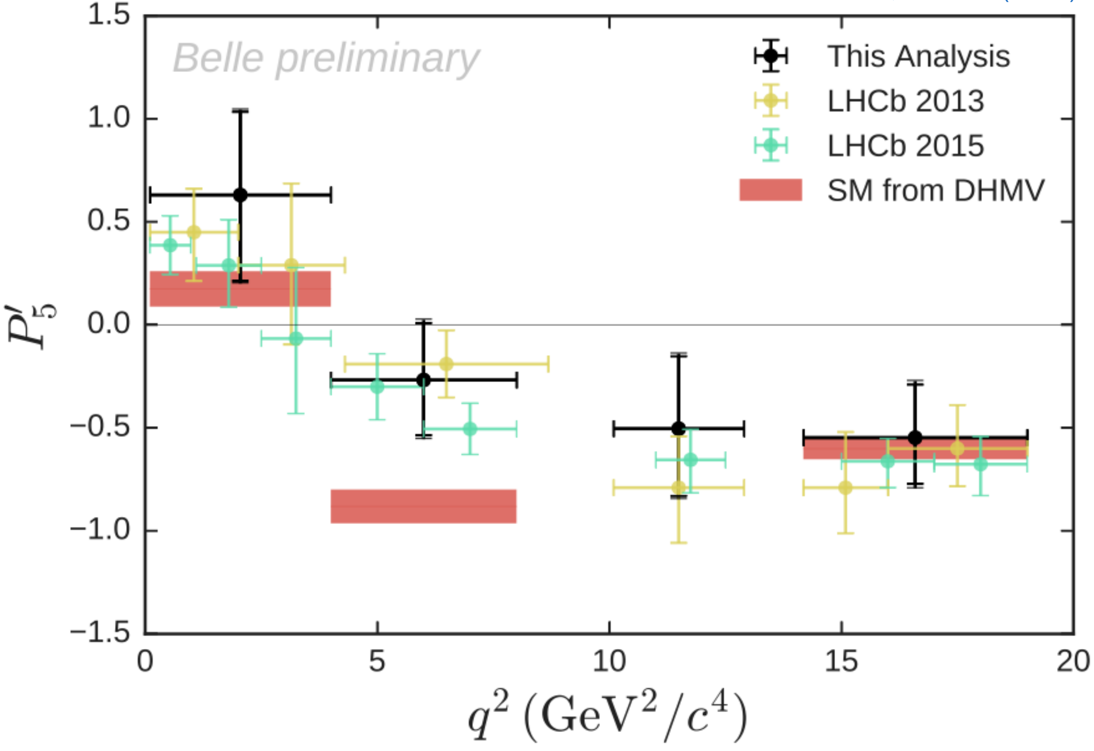
JHEP 02 (2016) 104



$B^0 \to K^{*0} l^+ l^-$ angular analysis

Result from BELLE supports the deviation from SM expectation

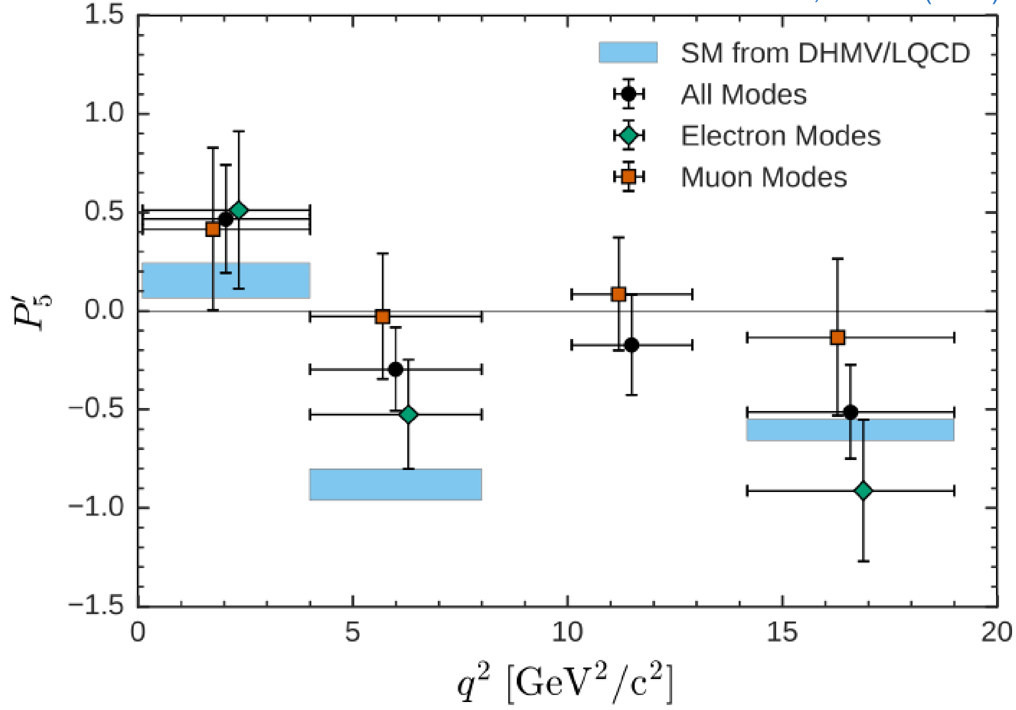
PRL 118, 111801 (2017)



$B^0 \to K^{*0} l^+ l^-$ angular analysis

The BELLE result can also be split into electrons and muons

PRL 118, 111801 (2017)



Check list for $B^0 \to K^{*0} l^+ l^-$ angular analysis

The strengths and weaknesses are different

- Can we learn something from the measurement? ☑ ☑
  - Angles provide all the observables at the same time
- What are the theoretical uncertainties and can they be reduced? ☐
  - The effect of charm loops will need much work in the future
- Do we know SM parameters well enough? ☑
- What level of statistical accuracy is expected? ☑
- How will experimental systematic uncertainties be controlled? ☑
- How can everything be cross checked? ☑

Lepton non-universality

Lepton universality is one of the key features of the Standard Model

The only difference for decays with electrons, muons and taus is from their mass

- Effect of this is easy to correct for in predictions
- Discovery of lepton flavour non-universality is a key signature of New Physics

Unfortunately the identification of leptons is anything but universal!

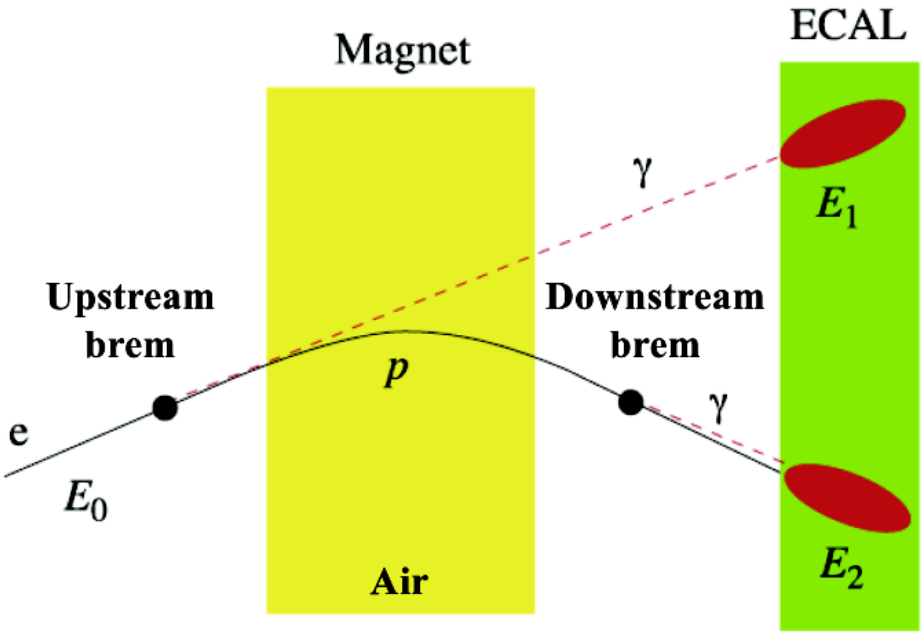
Muon identification

Muons are the perfect particles for identification

- No radiation (as they are heavy)
- They are stable within a particle physics detector
- No strong interaction so they are the only charged particles passing through absorber

Electron identification

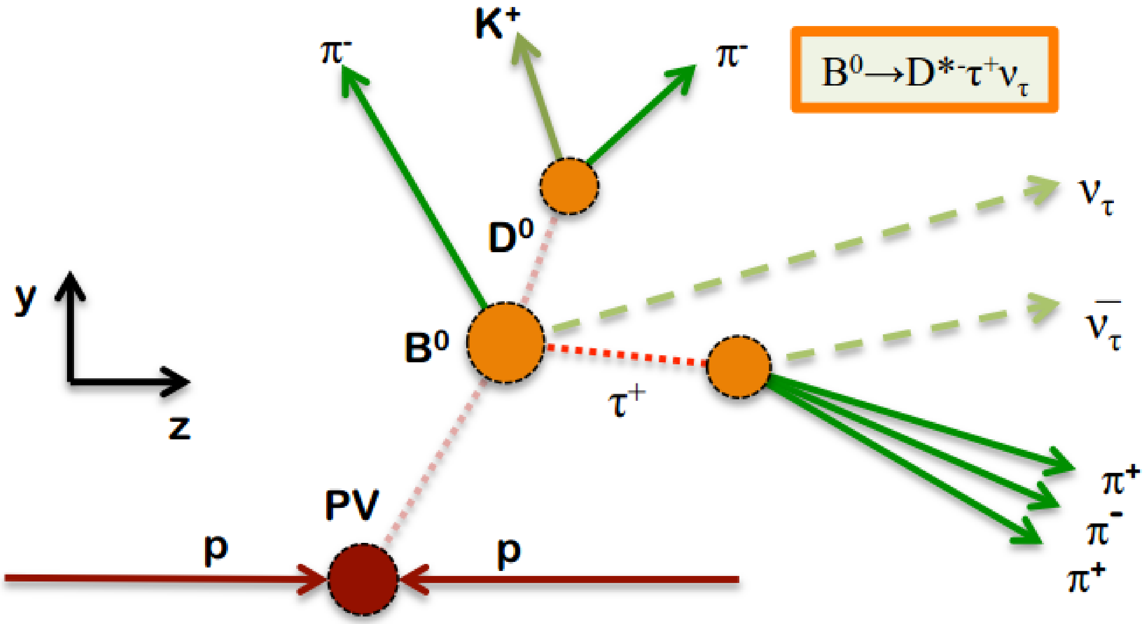
- Electrons are very light
  - When they pass through material they emit bremsstrahlung
    - Curvature in magnetic field will measure too low momentum
  - Photons can convert and fake electrons
  - Background from $\pi^0 \rightarrow \gamma\gamma$ decay that can fake electrons
- Bremsstrahlung recovery can (partially) fix this



Tau identification

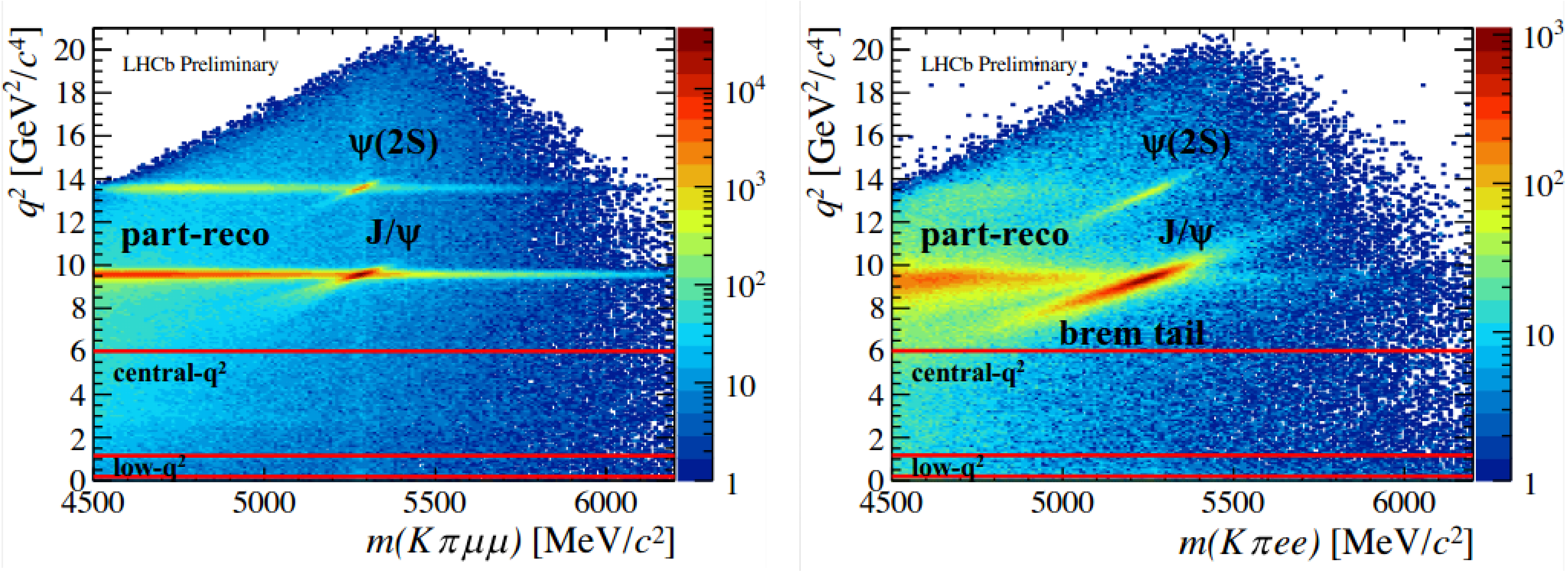
The identification of a tau lepton is really hard

- A short lifetime of 10^{-12} s means we only see decay products
- Hadronic decays with pions and a neutrino
- Semileptonic decay, $\tau \to \mu \bar{\nu} \nu$ has just one track and two neutrinos
- Mass and lifetime very similar to D_s which has very similar decays



$B \to K^{(*)}\mu^+\mu^-$ vs $B \to K^{(*)}e^+e^-$

The effect of the $c\bar{c}$ resonances very different in two decays



$B \rightarrow K^{(*)}\mu^+\mu^-$ vs $B \rightarrow K^{(*)}e^+e^-$

The dependence on the efficiency of reconstructing electrons can be reduced through double ratio

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

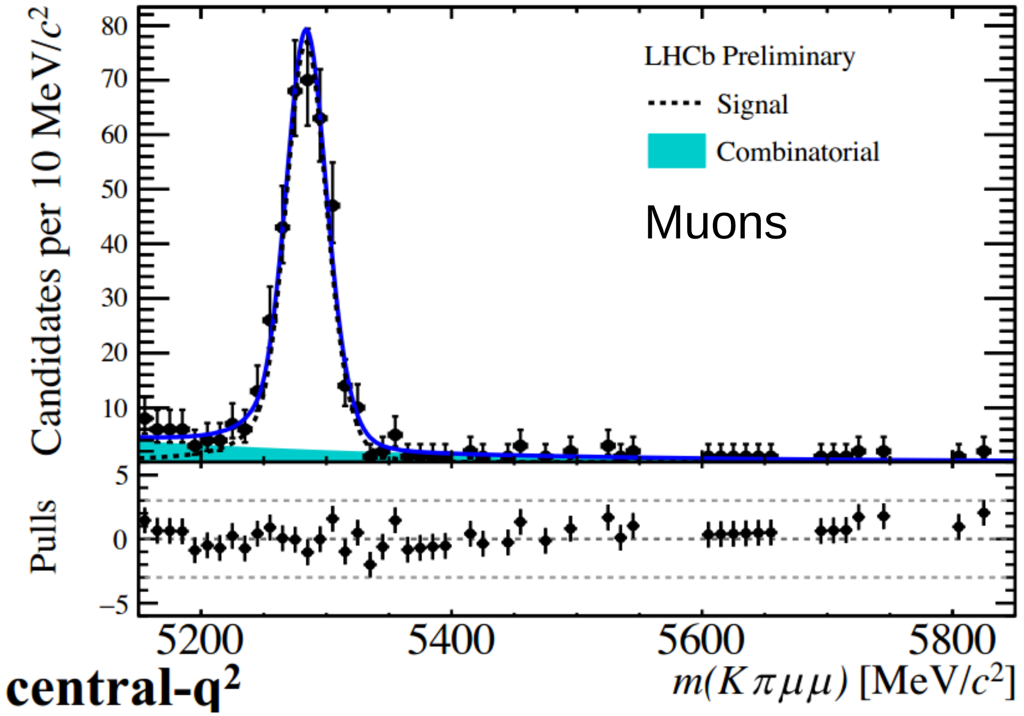
↓

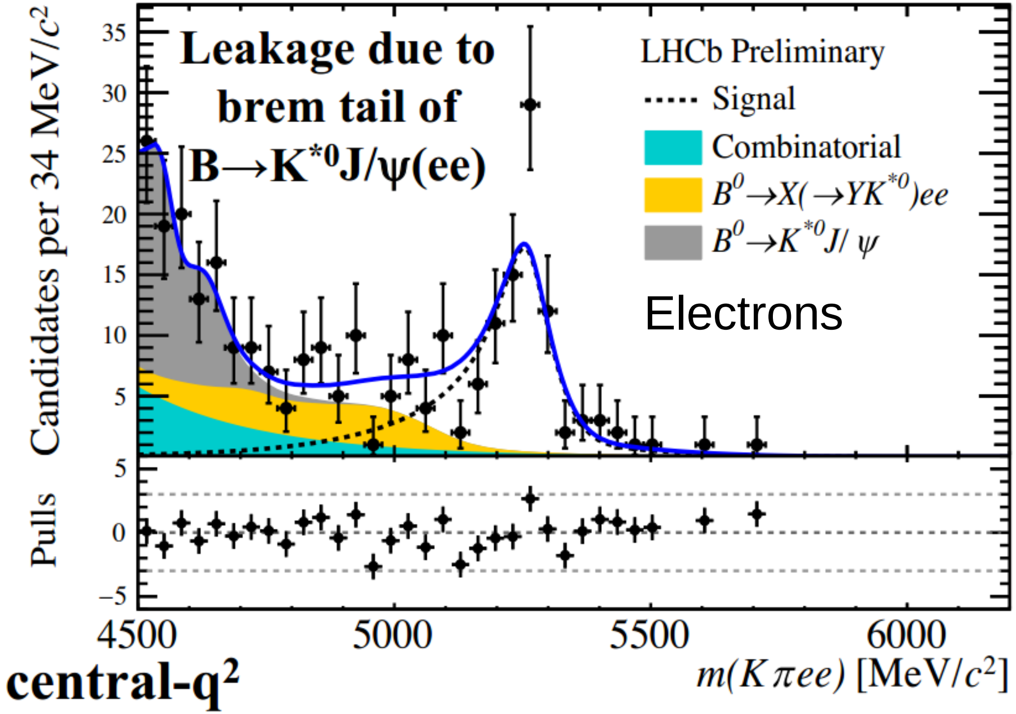
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0}J/\psi(\rightarrow \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \rightarrow K^{*0}e^+e^-)}{\mathcal{B}(B^0 \rightarrow K^{*0}J/\psi(\rightarrow e^+e^-))}$$

The $J/\psi \rightarrow l^+l^-$ proceed through virtual photon and is measured to be lepton-universal

$B \to K^{(*)}\mu^+\mu^-$ vs $B \to K^{(*)}e^+e^-$

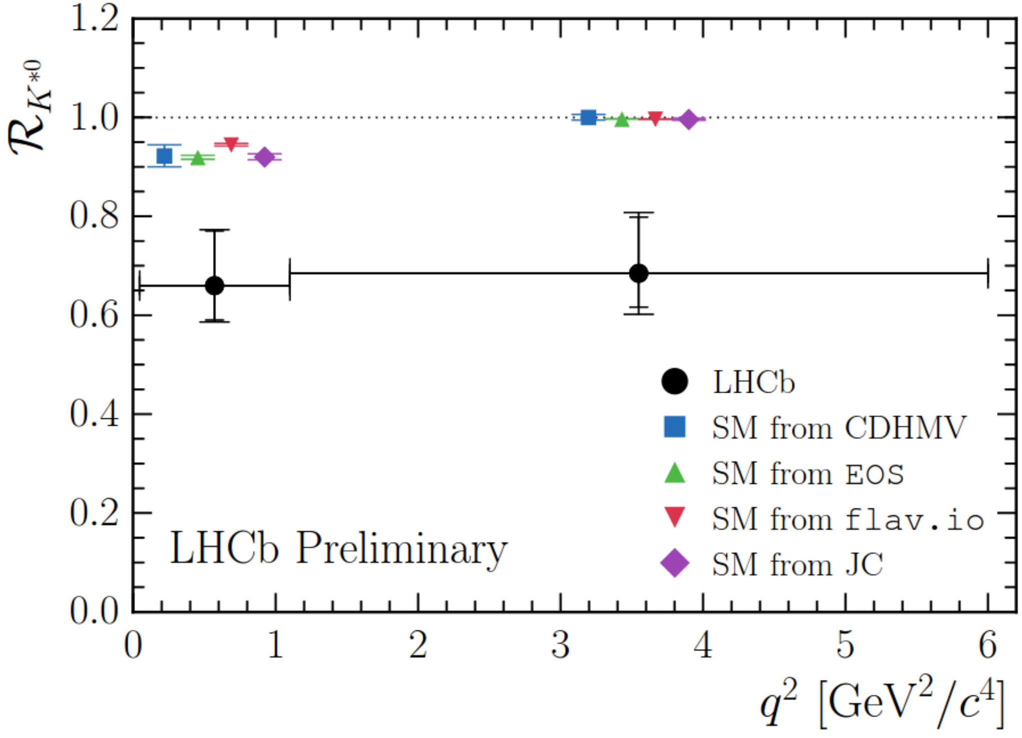
Reconstructed peaks in the muon and electron modes

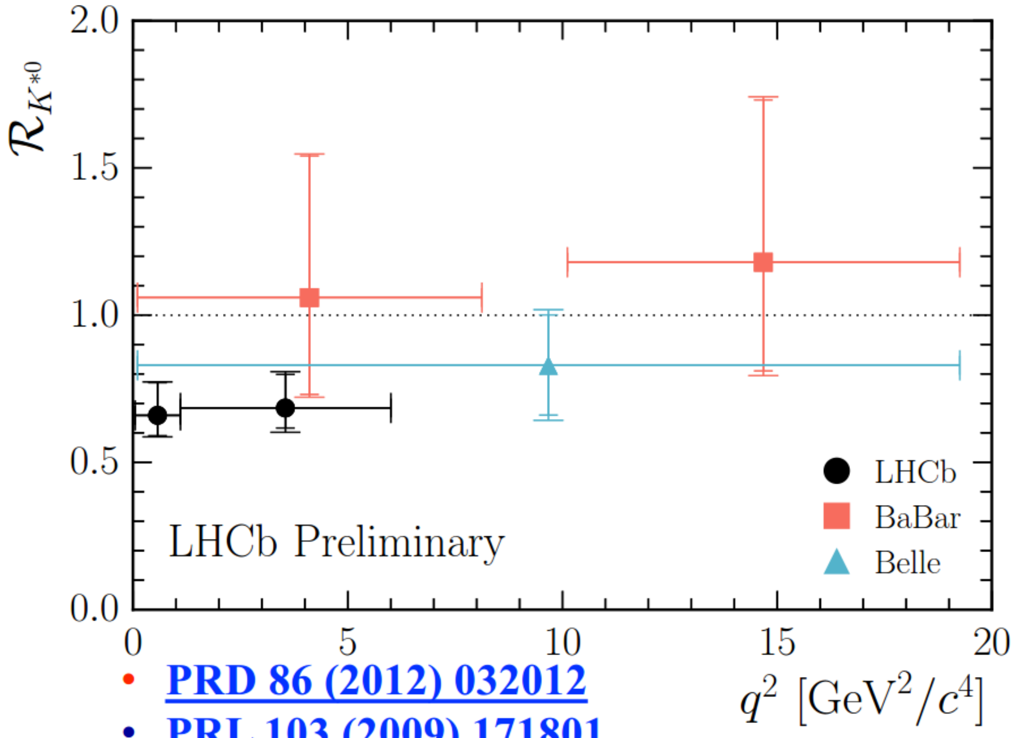




$B \to K^{(*)}\mu^+\mu^-$ vs $B \to K^{(*)}e^+e^-$

The measured ratio is 2-2.5σ below SM expectation in each bin





- [PRD 86 (2012) 032012](#)
- [PRL 103 (2009) 171801](#)

Check list for lepton universality

Here the challenge is moving to the experimental side

- Can we learn something from the measurement? ☑
- What are the theoretical uncertainties and can they be reduced? ☑
- Do we know SM parameters well enough? ☑
- What level of statistical accuracy is expected? ☐
- … but more data is on the way and BELLE-II will be equal competitor
- How will experimental systematic uncertainties be controlled? ☐
  - Comparisons between electrons and muons will always be a challenge
- How can everything be cross checked? ☑

Semileptonic decays

The test for lepton universality can also be extended to taus

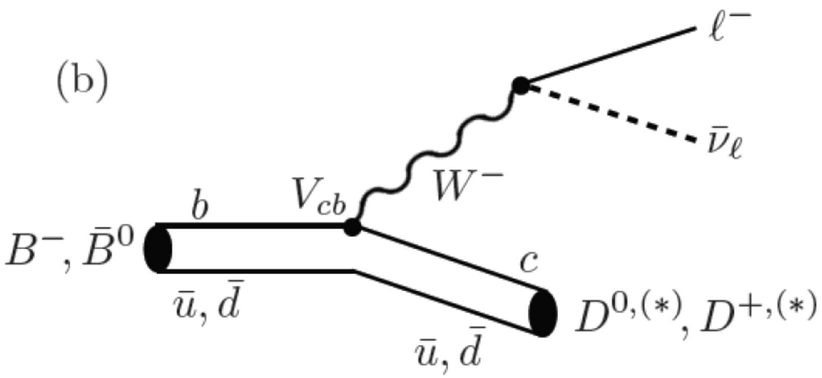
- Electroweak penguin decays with taus extremely challenging and so far never observed

Instead look at the SM tree level semileptonic decays

$$\frac{d\Gamma^{SM}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}{dq^2} = \underbrace{\frac{G_F^2\,|V_{cb}|^2\,|p^*_{D^{(*)}}|\,q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2}_{\text{universal and phase space factors}} \tag{3}$$

$$\times \underbrace{\left[(|H_+|^2+|H_-|^2+|H_0|^2)\left(1+\frac{m_\ell^2}{2q^2}\right)+\frac{3m_\ell^2}{2q^2}|H_s|^2\right]}_{\text{hadronic effects}} .$$

(b)



Semileptonic decays

Latest measurement from LHCb look at $\tau \to \pi^+ \pi^- \pi^+ \nu$ final states

$$R(D^*) = \frac{BF(B \to D^* \tau \nu)}{BF(B \to D^* \mu \nu)} \stackrel{\text{SM}}{=} 0.252 \pm 0.003$$

Normalisation done though a very similar known final state

$$K_{had}(D^*) = \frac{BR(B^0 \to D^{*-} \tau^+ \nu_\tau)}{BR(B^0 \to D^{*-} \pi^+ \pi^- \pi^+)} = \frac{N(B^0 \to D^{*-} \tau^+ \nu_\tau)}{N(B^0 \to D^{*+} \pi^- \pi^+ \pi^-)} \times \frac{1}{BR(\tau^+ \to \pi^+ \pi^- \pi^+ (\pi^0) \bar{\nu}_\tau)} \times \frac{\varepsilon(B^0 \to D^{*+} \pi^- \pi^+ \pi^-)}{\varepsilon(B^0 \to D^{*-} \tau^+ \nu_\tau)}$$

And value then determined from

$$R(D^*) = K_{had}(D^*) \times \frac{BR(B^0 \to D^{*-} \pi^+ \pi^- \pi^+)}{BR(B^0 \to D^{*-} \mu^+ \nu_\mu)}$$

[~4% precision]

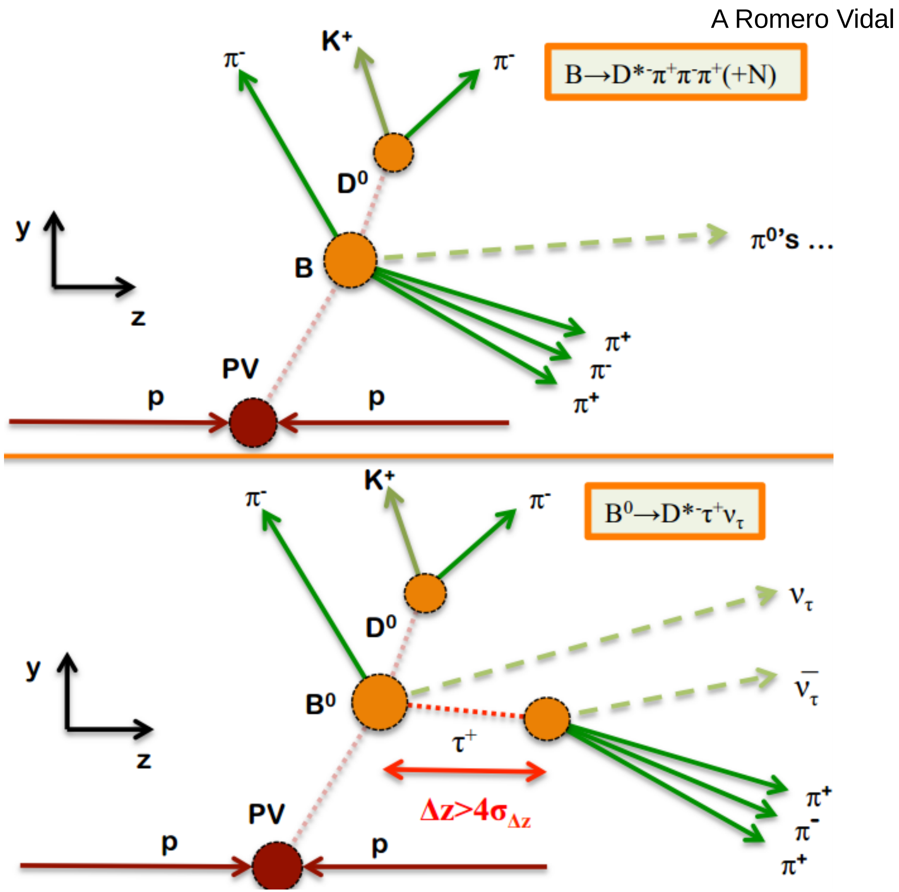
[~2% precision]

[PDG 2016]

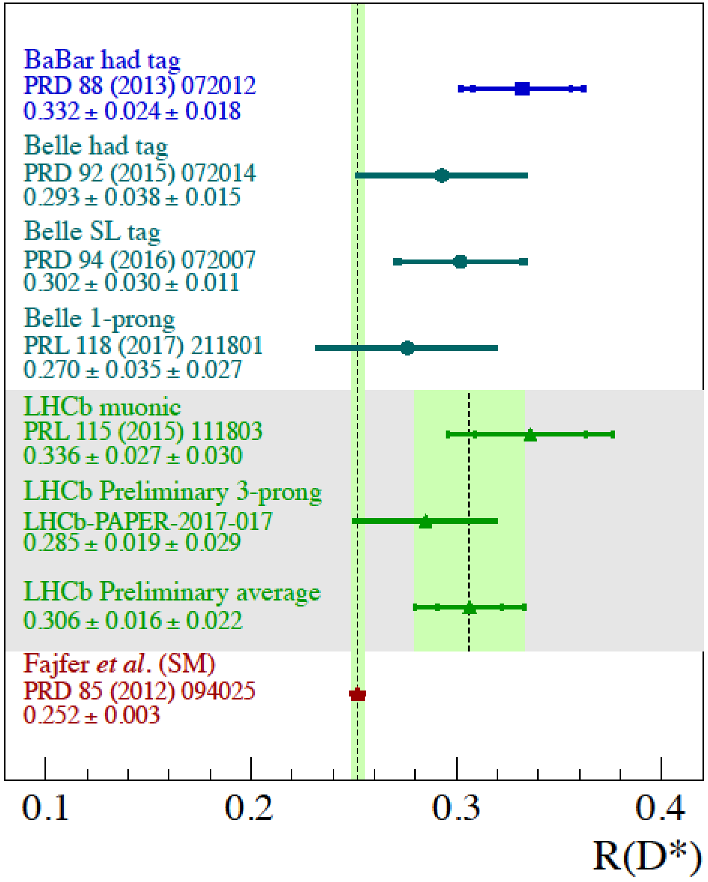
Semileptonic decays

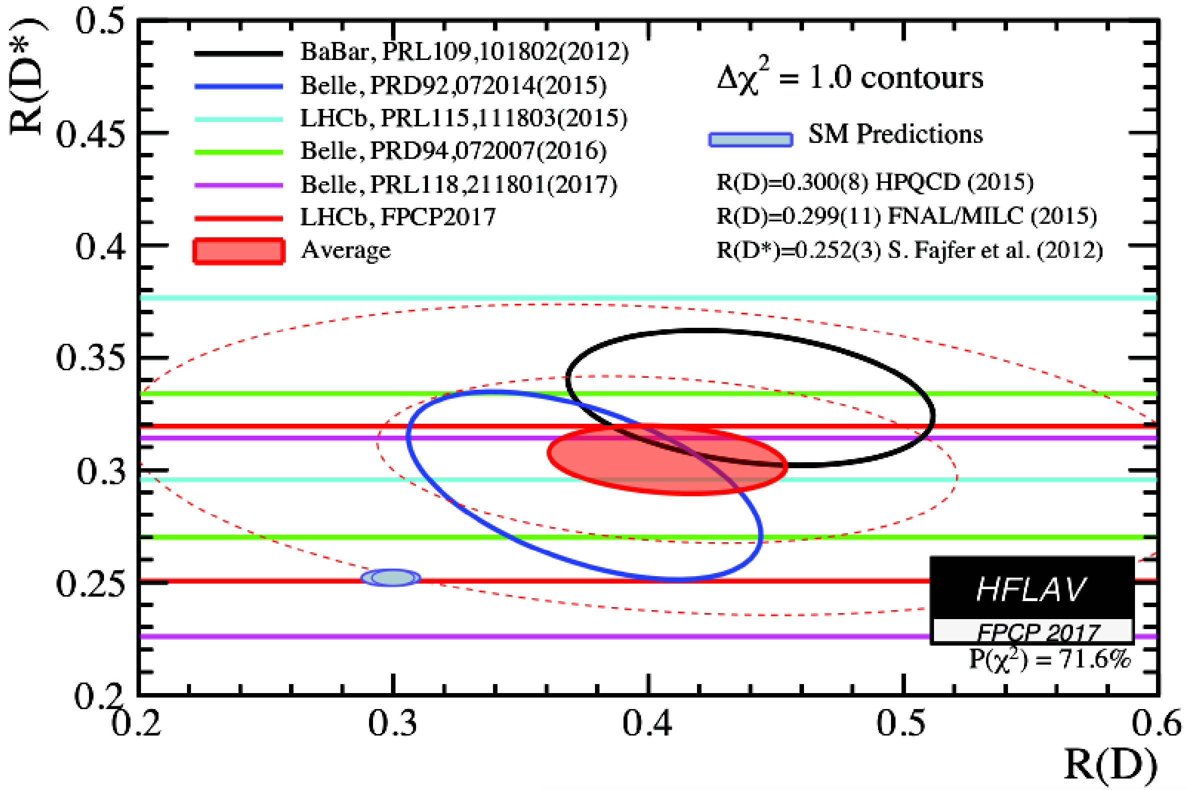
The similar topology of signal and normalisation reduce systematic uncertainty

R(D*)=0.285±0.019(stat)±0.025(syst)



Semileptonic decays





Possible New Physics interpretations

quantumdiaries.org

Possible New Physics interpretations

First of all the effect is large!

- 20% effect against SM for muons in electroweak penguins
- 30% effect against SM for taus in tree level decays

Many constraints to consider

- No signs of NP at CMS and ATLAS, push mass scale to above few TeV
- Effect is small or absent in $B\text{-}\overline{B}$ oscillations
- Proton decay constraints
- $\mu \rightarrow e$ conversion constraints

Explanation will tell us something fundamental about what **flavour** is

Possible New Physics interpretations

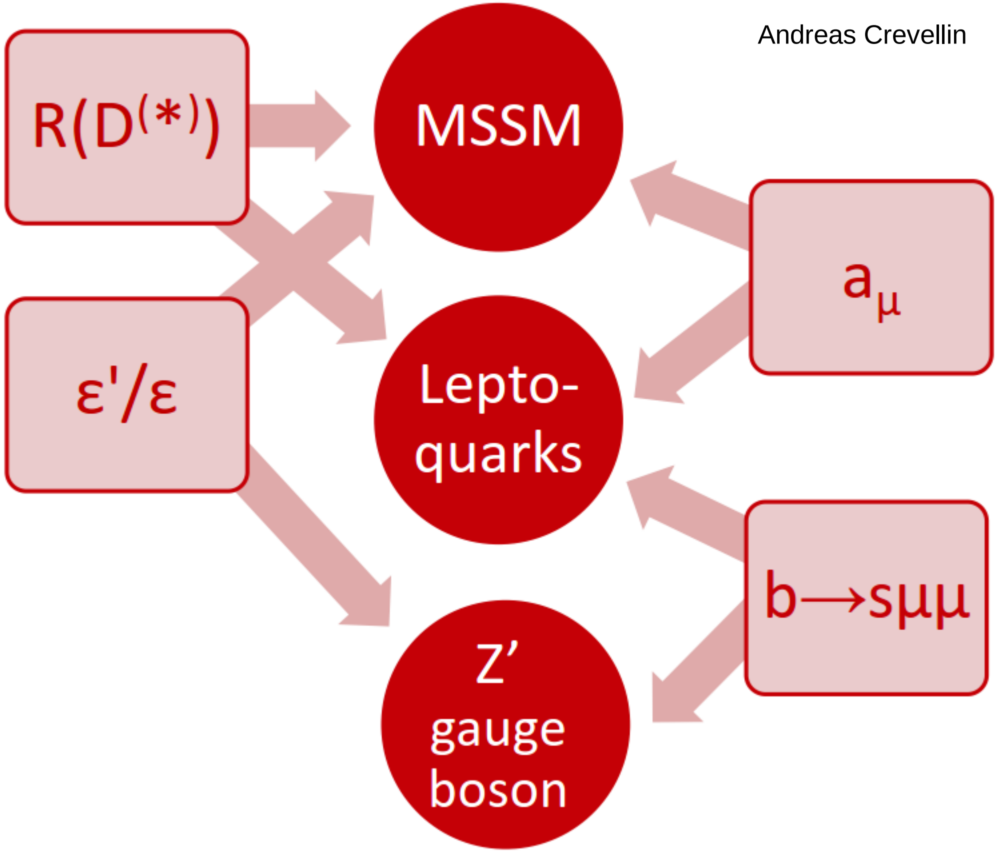
Huge number of models proposed

- Z’

  U. Haisch et al. 1308.1959, Buras et al. 1311.6729
  W. Altmannshofer et al. 1403.1269, AC. et al. 1501.00993, .

- Leptoquarks

  Gudrun Hiller, Martin Schmaltz
  arXiv:1411.4773
  B. Gripaios, M. Nardecchia, S.A. Renner.
  arXiv:1412.1791
  D. Bečirević, N. Košnik, O. Sumensari,
  R. Zukanovich Funchal, arXiv:1608.07583
  L. Calibbi, AC. T. Ota, PRL 2015
  ...

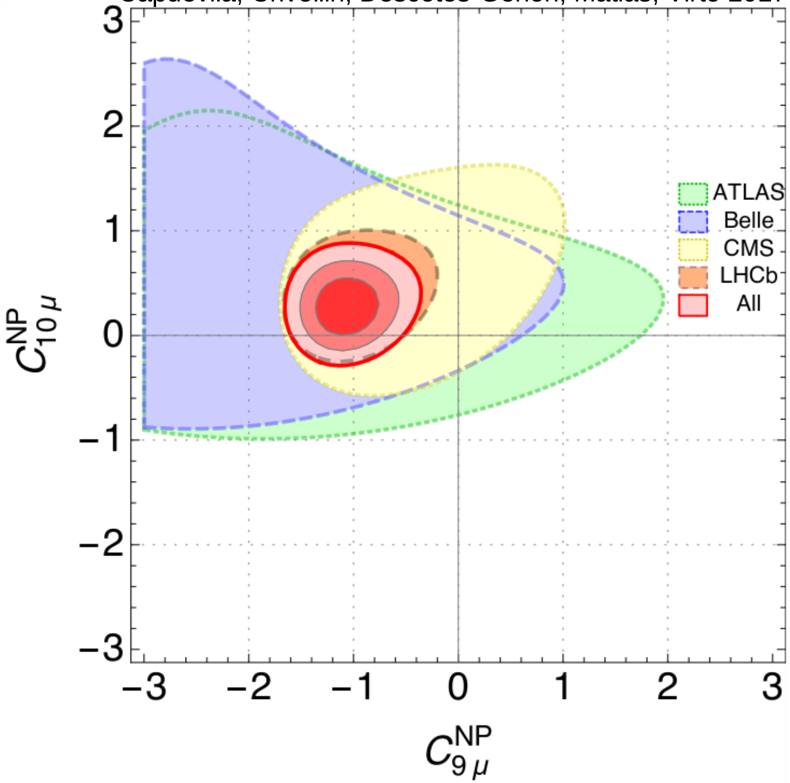


Possible New Physics interpretations

Look at a global fit to all of the electroweak penguin decays

- The fits are favouring NP in the Wilson coefficients C_9 and C_{10}
- If only C_9 points to Z' models
- If both points to LQ models

Capdevila, Crivellin, Descotes-Genon, Matias, Virto 2017



Fit shown here has in total 175 experimental measurements

- tension with SM at 5σ level!

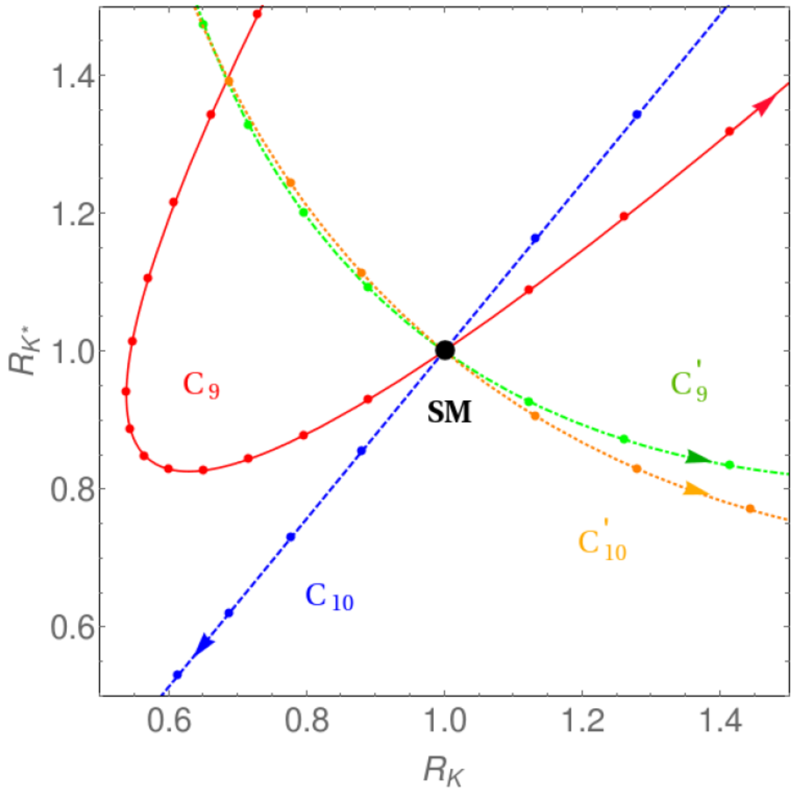
Possible New Physics interpretations

The lepton universality observables give us a unique way to separate the impact of C_9 and C_{10}

A measurement is required in both $B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^-$

More data required, but route is very clear from theory

Geng, Grinstein, Jäger, Martin Camalich, Ren, Shi
arXiv: 1704.05446



From null test to classification

If NP is there, we need to understand its properties

- $B^+ \rightarrow \pi^+\mu^+\mu^-$ BF compared to $B^+ \rightarrow K^+\mu^+\mu^-$
  - Can help us understand if NP observes minimal flavour violation
- Search for $B^+ \rightarrow K^+e^+\mu^-$, $B^+ \rightarrow K^+\tau^+\mu^-$
  - Is NP flavour diagonal in lepton sector
- Measure R_K and R_{K^*} in $b \rightarrow d$ transitions, $B \rightarrow \pi/\rho/p\bar{p}\, l^+l^-$
  - Does NP depend on quark sector
- Measure $B^+ \rightarrow p\bar{p}\tau^+\nu$ relative to $B^+ \rightarrow p\bar{p}\mu^+\nu$
  - Does new physics care about $b \rightarrow c$ vs. $b \rightarrow u$ transitions?

What about direct searches?

If there is new physics at the TeV scale, we might be able to see a resonance at the LHC.

For a tree-level mediated NP effect, we are sensitive to λ^2/M^2 in B decays

$$\frac{\lambda^2}{M^2} = 20\%\,\mathrm{SM} \sim 20\% \frac{g^4}{m_W^2} \frac{1}{16\pi^2} V_{tb} V_{ts}^* \sim \frac{1}{(30\,\mathrm{TeV})^2}$$

Or in a minimal flavour violating model (where NP follows CKM structure)

$$\frac{\lambda^2}{M^2} = 20\%\,\mathrm{SM} \sim 20\% \frac{g^4}{m_W^2} \frac{1}{16\pi^2} \sim \frac{1}{(6\,\mathrm{TeV})^2}$$

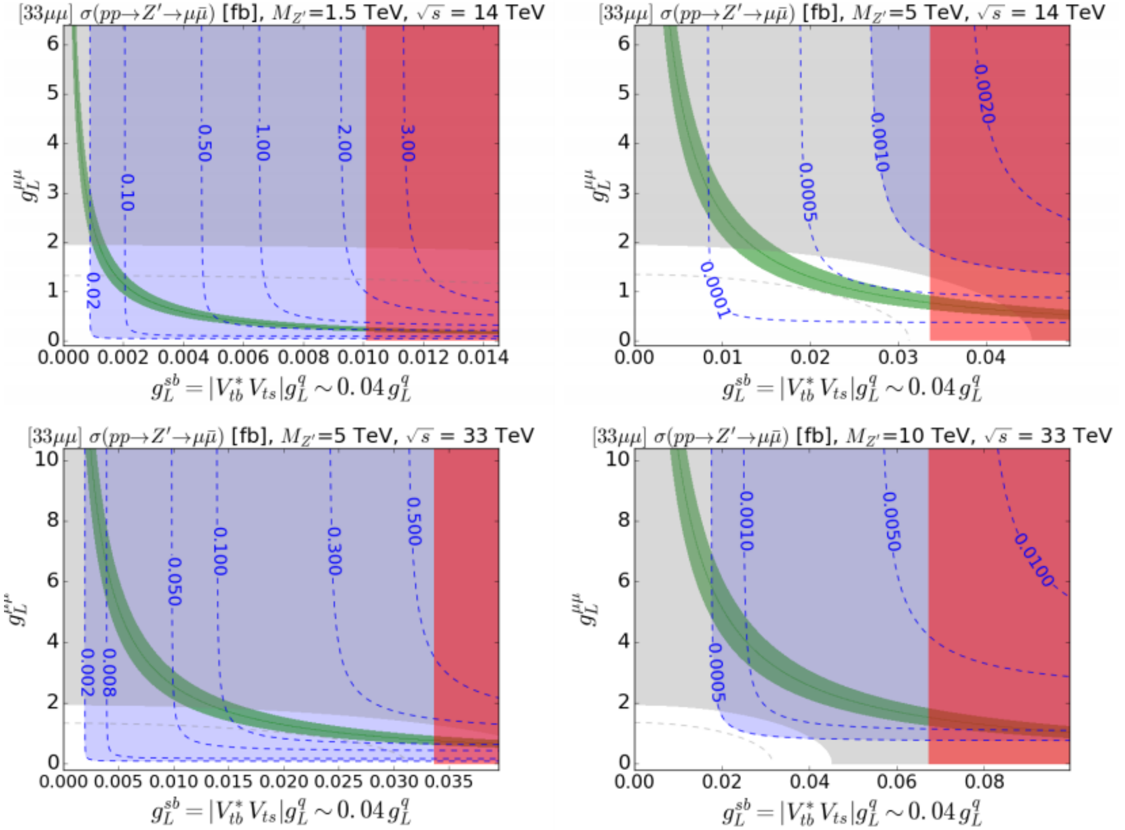
A no-lose theorem for an LHC energy upgrade?

An obvious signal is looking for Z’→μ+μ-

LHC @ 13 TeV covers up to a few TeV

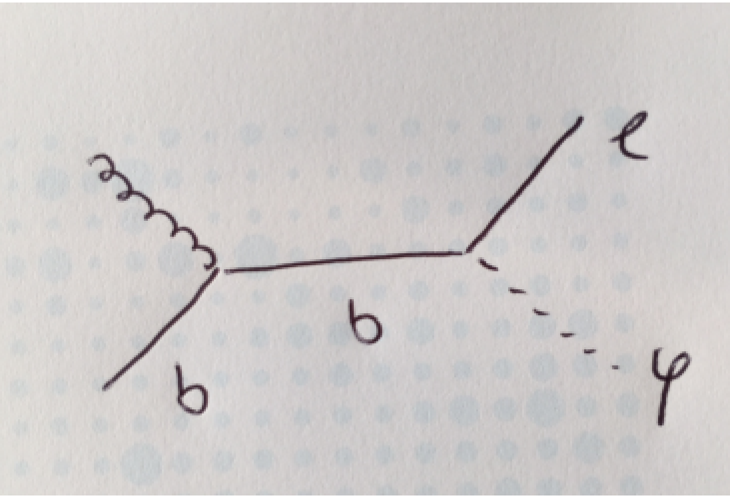
HE-LHC @ 33 TeV gives complete coverage given other constraints

B C Allanach,B Gripaios, T You, arXiv:1710.06363

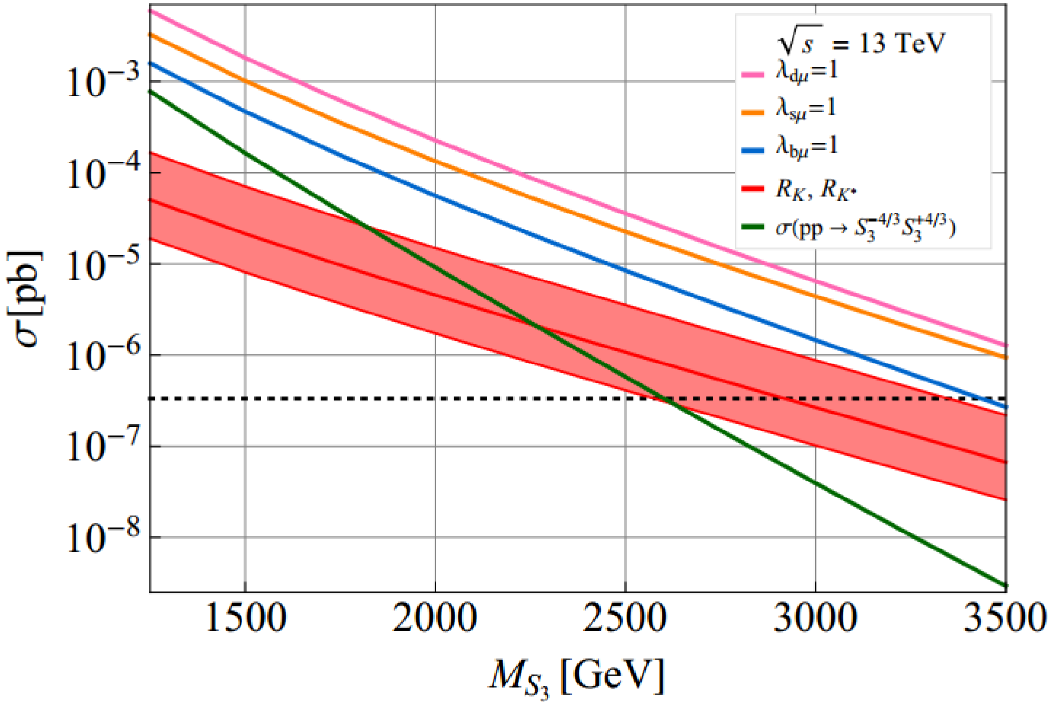


LQ production @ LHC 13 TeV

When the LQ mass goes above ~ 2 TeV, single production is favoured discovery mode

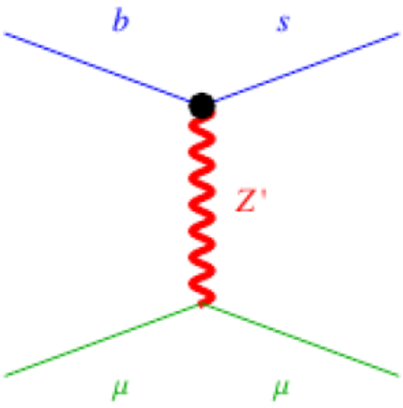


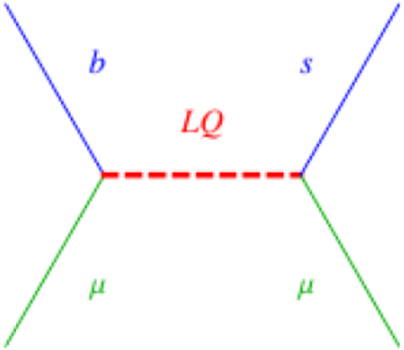
G. Hiller, D Loose, I Nisandzic (in preparation)

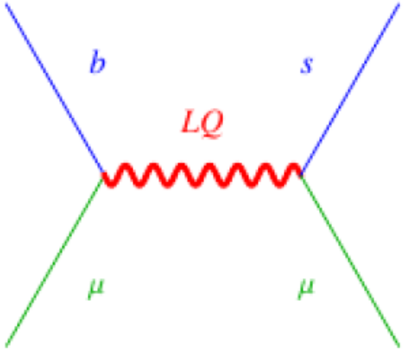


Conclusion

If NP is there for discovery in Flavour Physics, we have a rich programme ahead of us to understand it!







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