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Cracks in the wall?

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on behalf of the LHCb collaboration

Madrid 9 Dec 2015

The Standard Model

The Standard Model is by now an old theory

- In particular in the area of flavour physics, a large number of anomalies have shown up in the past few years

Cracks are at a level where they can't be ignored

The Standard Model

Is this the rise of New Physics to prominence?

A new consistent theory arises from the ruins

Or will the Standard Model be restored to former glory?

Reappraisal of theoretical uncertainties makes anomalies go away

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???
- 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

What ?

Electroweak penguin decays

- $B \to \mu^+\mu^-$
- $B \to K^*\mu^+\mu^-$

Lepton non-universality

- $BF(B \to K\mu^+\mu^-)$ / $BF(B \to Ke^+e^-)$
- $BF(B \to D^*\tau\nu)/BF(B \to D^*\mu\nu)$

Inclusive vs. exclusive CKM matrix elements

- The case of $|V_{ub}|$ and $|V_{cb}|$

CP violation

- Update on lattice uncertainties for ε'/ε
- The lack of anomalies in the CKM triangle

How ?

Think of properties of quarks that we are interested in

- Lifetime
  - Both b- and c-hadrons have lifetime in ps region. With momentum in 100 GeV region this gives decay distance around 10 mm.
- Mass of bottom and top
  - Mass of decaying quark sets transverse momentum scale
    - p_T/p sets geometry of detector
    - Forward detector for c- and b-hadrons
    - 4π for t decay

How ?

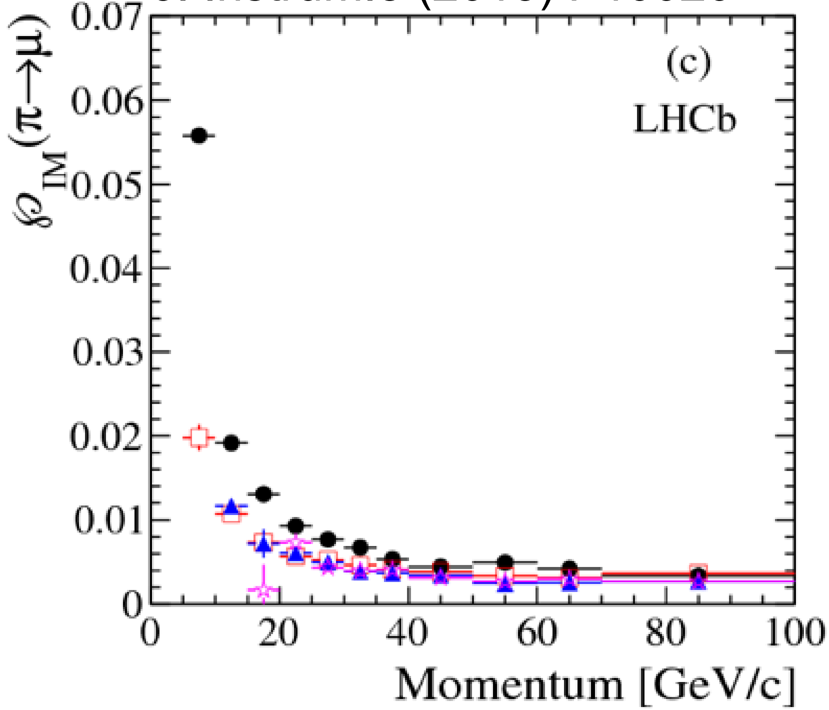
- QCD background
  - To see the effects of New Physics in heavy flavour decays we need to be able to calculate how the SM looks like
    - Uncertainties coming from QCD is the main problem here
  - Two ways out of this
    - Look for decays with leptons in
    - Look for *CP* violation
- Trigger
  - Decays of interest range from
    - Precision *CP* violation in Charm → kHz signal
    - B decays with 10^{-10} branching fraction → 10 nHz signal
- LHCb detector is optimised to fulfil those criteria

Rare decays

Look at decays which in the SM model can't happen at tree level

- Flavour changing neutral current decays the largest group
- NP can enter in at either tree or loop level
- Decays with dimuons are good candidates for rare searches
  - Rely on excellent muon identification

J. Instrum.8 (2013) P10020



Rare decays

For B mesons the rare decay search started in 1984 at CLEO

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Two-body decays of *B* mesons

Various exclusive and inclusive decays of *B* mesons have been studied using data taken with the CLEO detector at the Cornell Electron Storage Ring. The exclusive modes examined are mostly decays into two hadrons. The branching ratio for a *B* meson to decay into a charmed meson and a charged pion is found to be about 2%. Upper limits are quoted for other final states ψK^-, $\pi^+\pi^-$, $\rho^0\pi^-$, $\mu^+\mu^-$, e^+e^-, and $\mu^\pm e^\mp$. We also give an upper limit on inclusive ψ production and improved charged multiplicity measurements.

Rare decays

For B mesons the rare decay search started in 1984 at CLEO

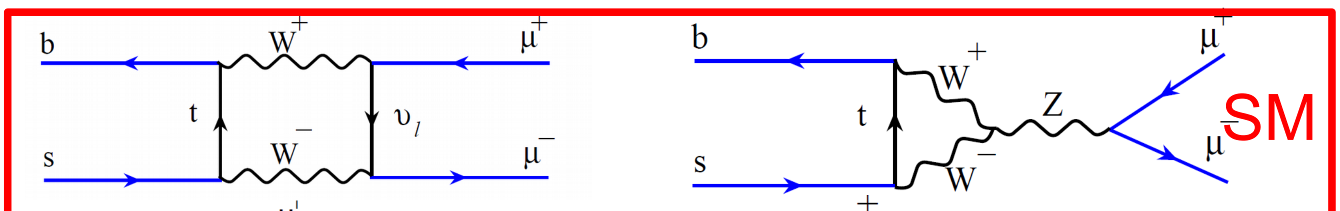
B. Search for exclusive $\overline{B}^0$ decays into two charged leptons

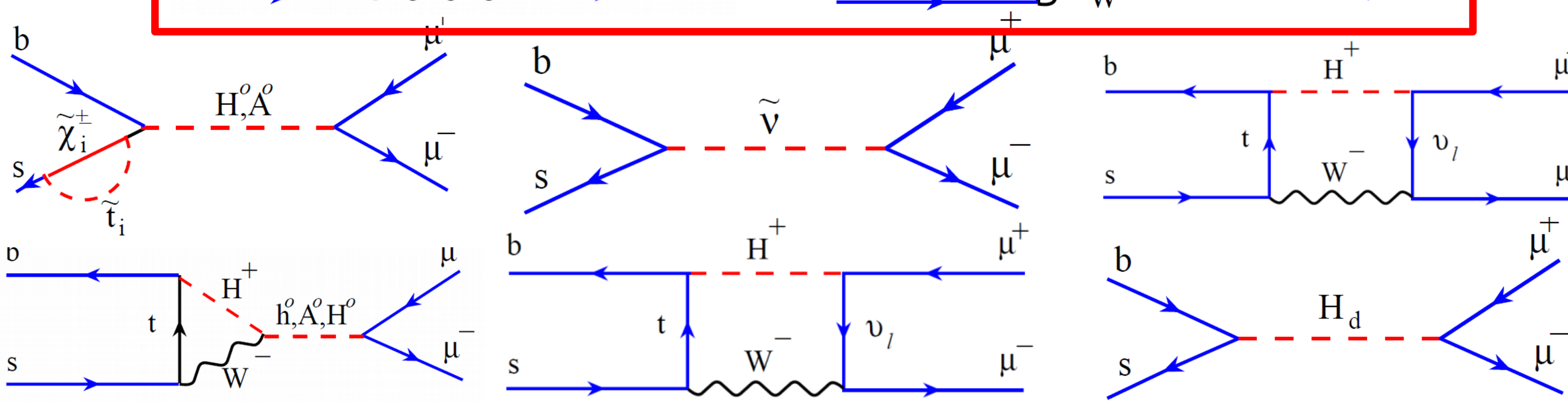
Our search for the $\pi^+\pi^-$ final state is not sensitive to the mass of the final-state particles, provided that they are light, since the mass enters only in the energy constraint. Therefore, the upper limit of 0.05% applies for any final-state particles with a pion mass or less. When the final-state particles are leptons the limits are improved by using the lepton identification capabilities of the CLEO detector.[14] For the decay $\overline{B}^0 \rightarrow \mu^+\mu^-$, we improve our limit by requiring that both muons penetrate the iron and produce signals in drift chambers. We find no such events. After correcting for detection efficiency (33%), we set an upper limit of 0.02% at 90% confidence for this decay. We im-

$B \to \mu^+\mu^-$

The two very rare decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ have attracted much interest

- Easy to predict SM branching fraction with great precision
  - $BF(B^0_s \to \mu^+\mu^-)_{SM} = (3.56 \pm 0.18) \times 10^{-9}$ (time averaged)
  - $BF(B^0 \to \mu^+\mu^-)_{SM} = (0.10 \pm 0.01) \times 10^{-9}$
- Sensitive to the scalar sector of flavour couplings

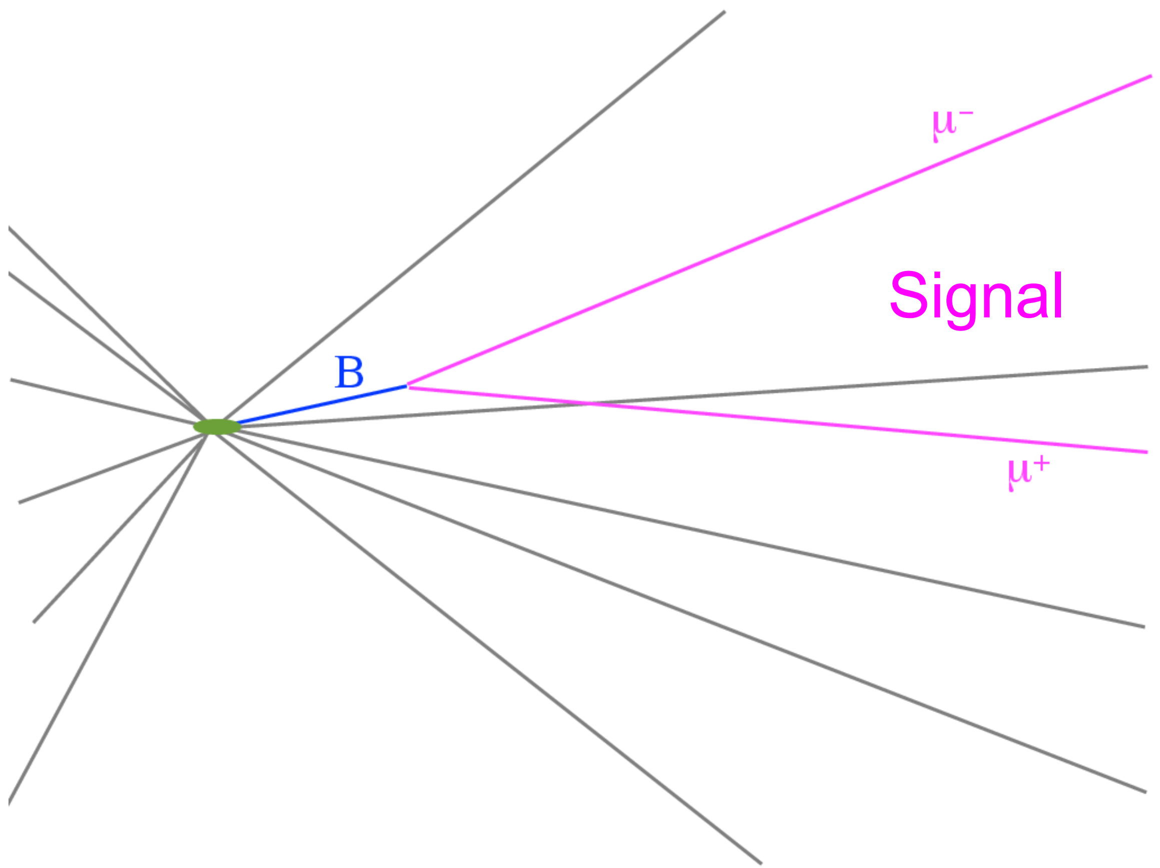




$B \to \mu^+\mu^-$

Topology of decay simple

- Challenge is to keep trigger and selection efficiency high, while rejecting combinatorial background



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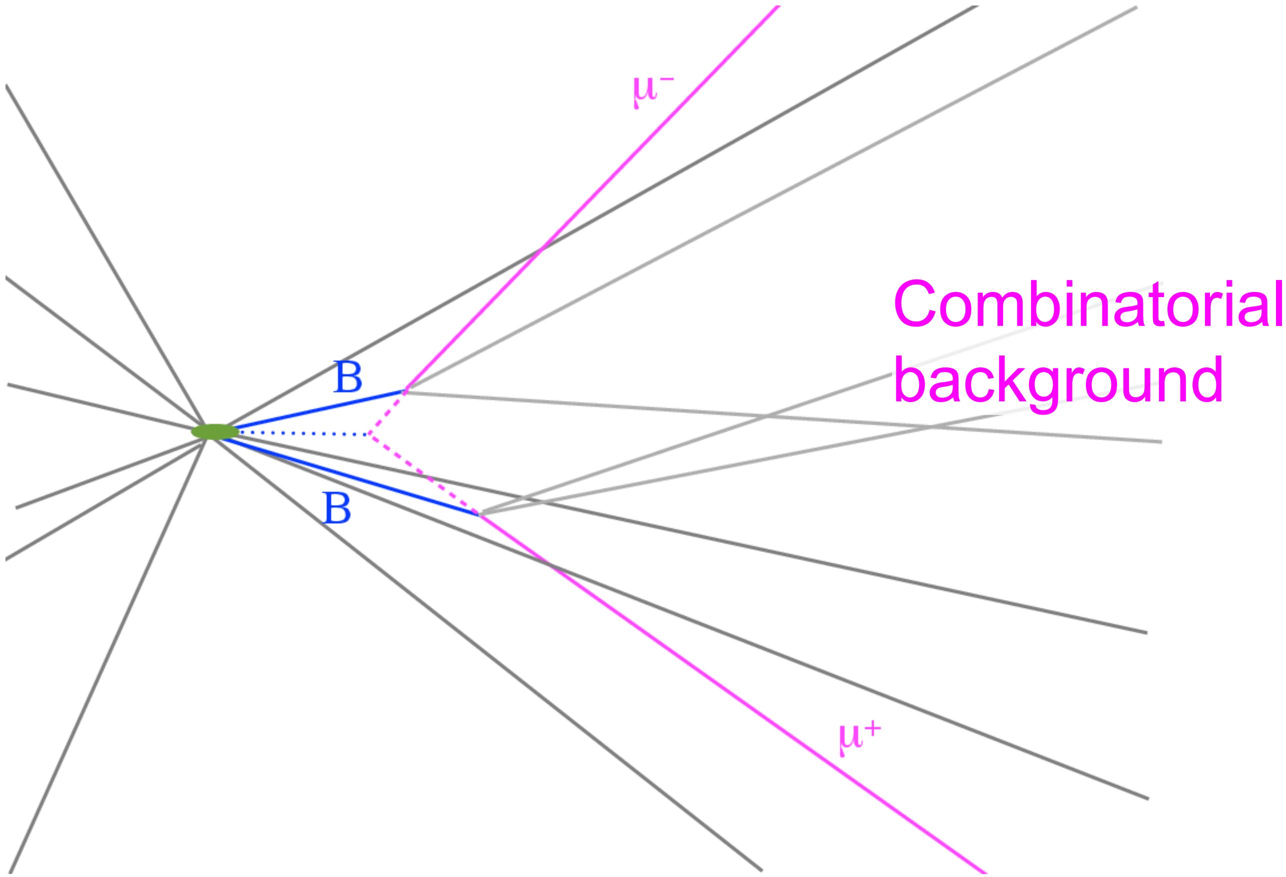


$B \to \mu^+\mu^-$

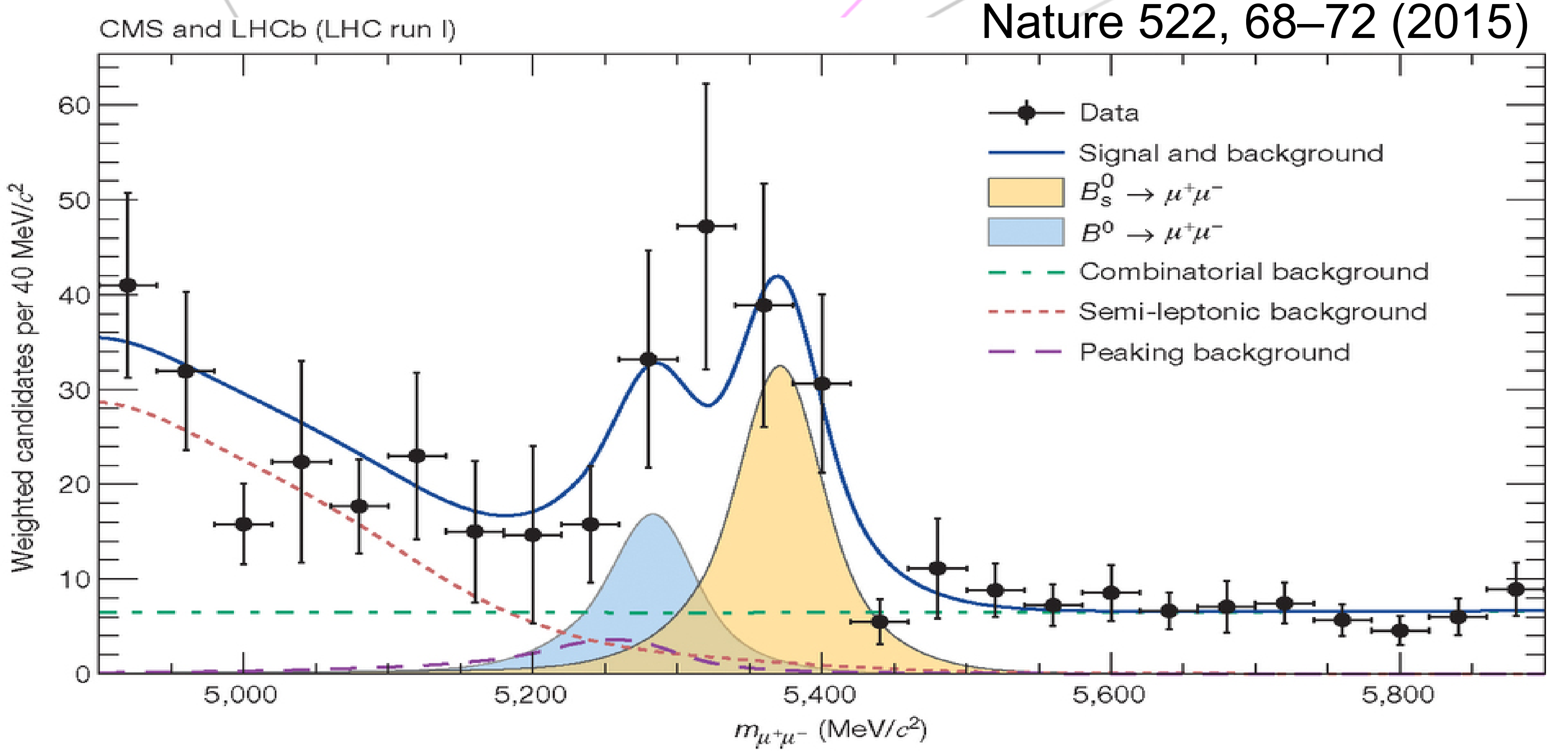
LHCb+CMS combined for observation of $B^0_s \to \mu^+\mu^-$

$$\mathrm{BF} = \left(2.8^{+0.7}_{-0.6}\right)\times 10^{-9}$$ 6.2σ significant

Evidence for $B^0 \to \mu^+\mu^-$

$$\mathrm{BF} = \left(3.9^{+1.6}_{-1.4}\right)\times 10^{-10}$$ 3.2σ significant

Nature 522, 68–72 (2015)

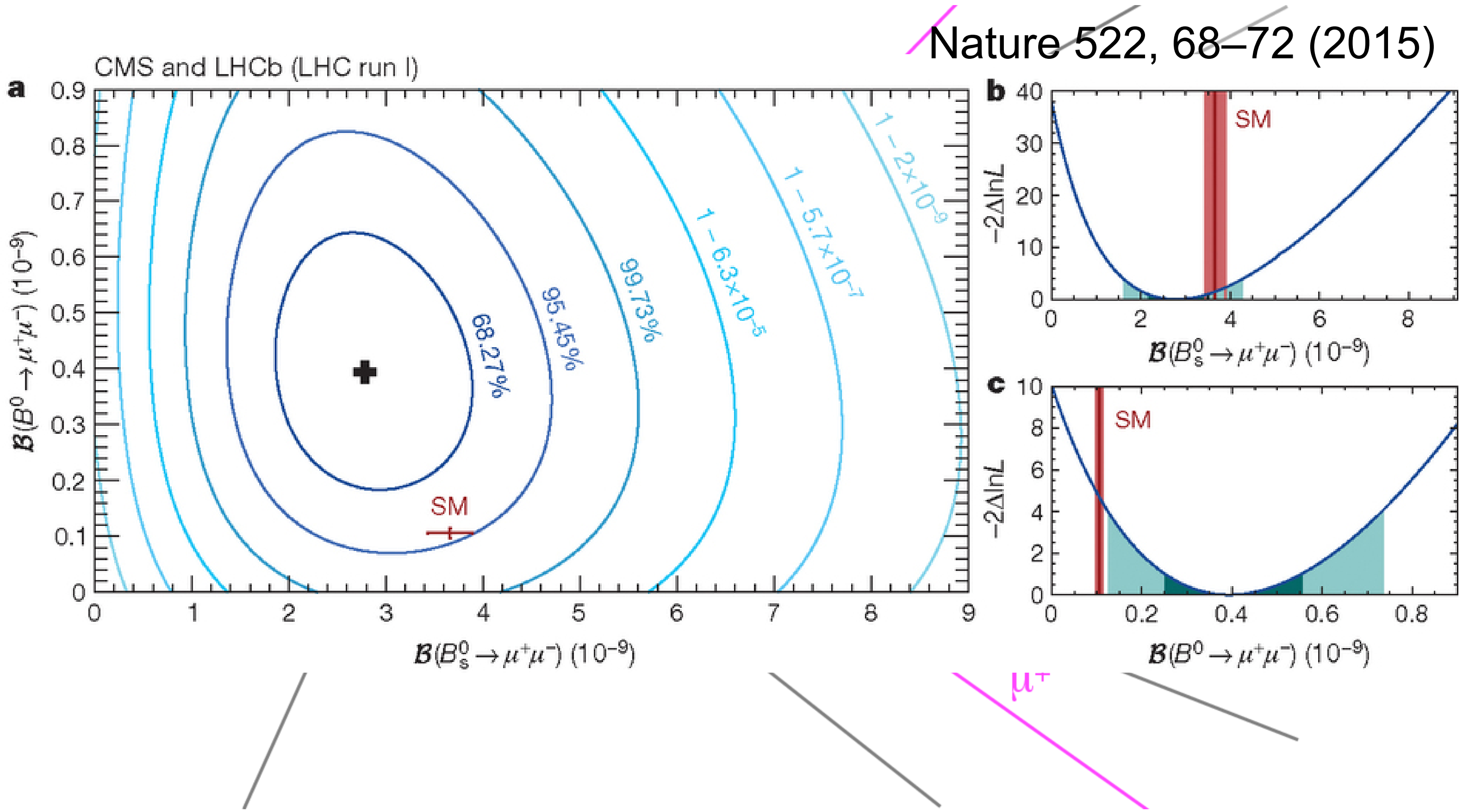


B→μ⁺μ⁻

Topology of decay simple

Challenge is to keep trigger and selection efficiency high, while rejecting combinatorial background

Nature 522, 68–72 (2015)



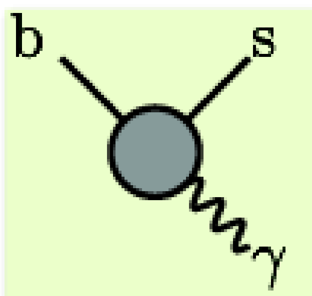
The penguin laboratory

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

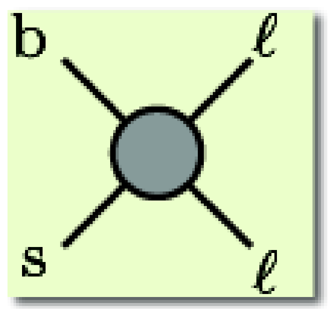
On the other hand NP can show up at either tree or loop level

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

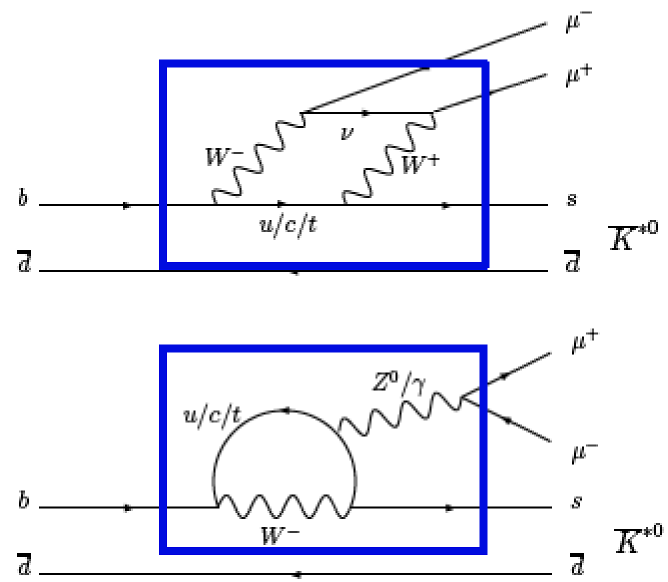
Interference between these



$O_{7\gamma}$



$O_{9,10}$



... and their right-handed counterparts

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

The Wilson coefficients describe the effective couplings from a higher energy scale

The matrix element of the decay is controlled by the K^{*0} polarisation amplitudes

- These are functions of the Wilson coefficients as well as the form factors arising from hadronic effects
  - The form factors can be calculated using light cone sum rules (mainly at low q^2) or lattice QCD (mainly large q^2)

$$A_{\perp}^{L,R} = N\sqrt{2}\lambda^{1/2}\left[\left\{(\mathcal{C}_9^{(\text{eff})} + \mathcal{C}_9^{\prime(\text{eff})}) \mp (\mathcal{C}_{10}^{(\text{eff})} + \mathcal{C}_{10}^{\prime(\text{eff})})\right\}\frac{V(q^2)}{m_B + m_{K^*}} + \right.$$
$$\left. + \frac{2m_b}{q^2}(\mathcal{C}_7^{(\text{eff})} + \mathcal{C}_7^{\prime(\text{eff})})T_1(q^2)\right],$$

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

The angular distribution can be fully described through the coefficients of an expansion in spherical harmonics

$$\frac{d^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_j I_j(q^2) f_j(\vec{\Omega})$$

$$\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_j \bar{I}_j(q^2) f_j(\vec{\Omega})$$

Which can then form CP averaged quantities and CP asymmetries

$$S_j = (I_j + \bar{I}_j) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right)$$

$$A_j = (I_j - \bar{I}_j) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right)$$

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

Each of the angular coefficients can be expressed as a sum of bilinears of the K^{*0} polarisation amplitudes

$$I_5 = \mathfrak{Re}\left(\mathcal{A}_0^L \mathcal{A}_\perp^{L*} - \mathcal{A}_0^R \mathcal{A}_\perp^{R*}\right)$$

And ratios can be formed where the theoretical uncertainty can be reduced

$$P'_5 = S_5 \sqrt{F_L(1-F_L)} \qquad , F_L \equiv S_{1c}$$

Several observables also have reduced uncertainty of zero points

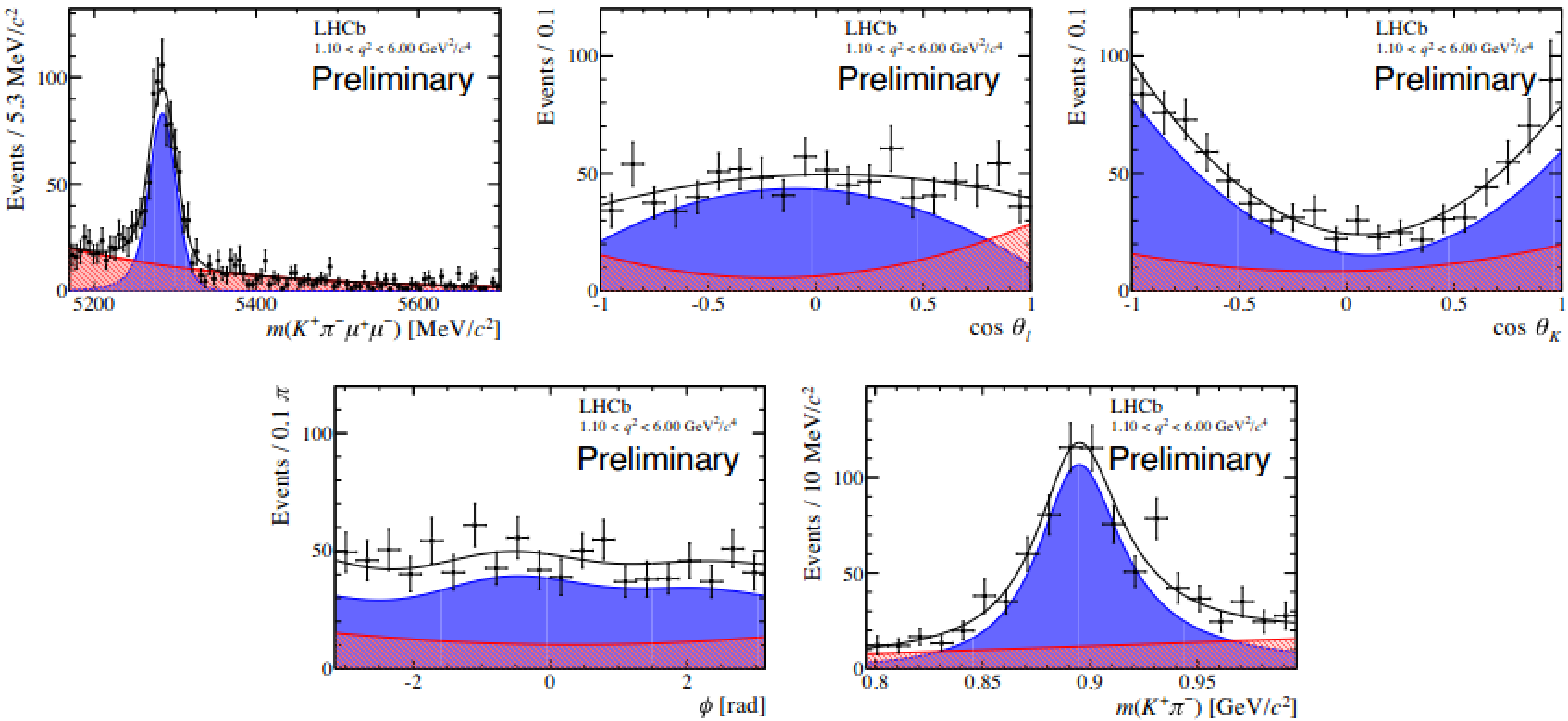
$$A_{FB} = \frac{3}{4} S_{6s}$$

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

In each bin of q^2, 5 dimensions have to be considered

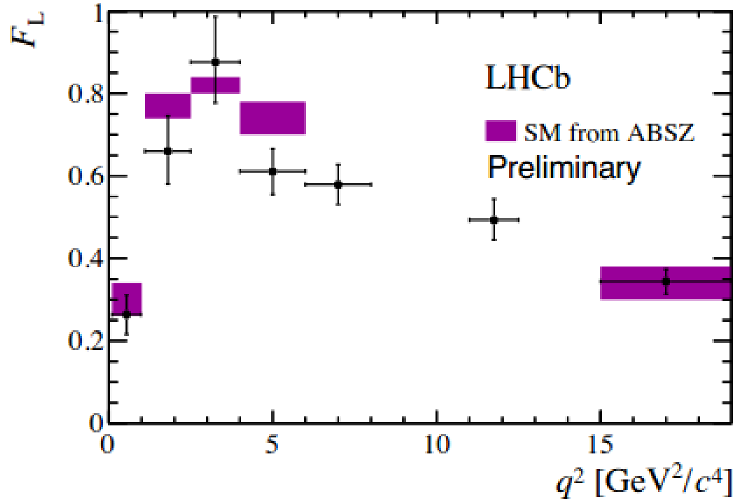
- The $m_{K\pi}$ distribution is fitted first, then the other 4 simultaneously

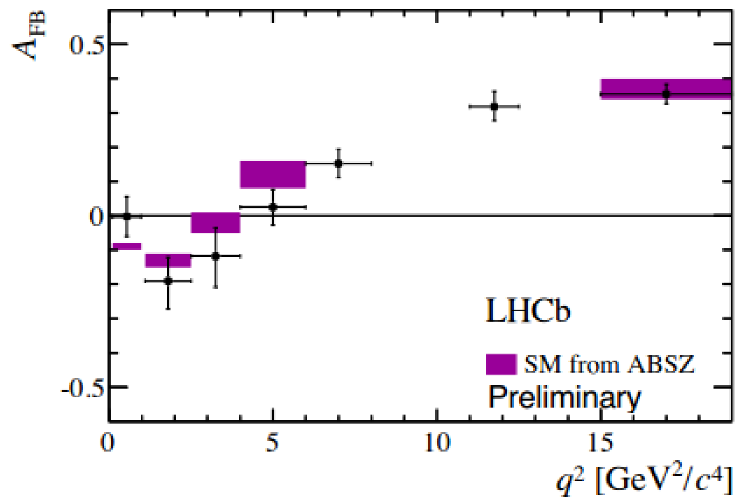
https://indico.cern.ch/event/395704/

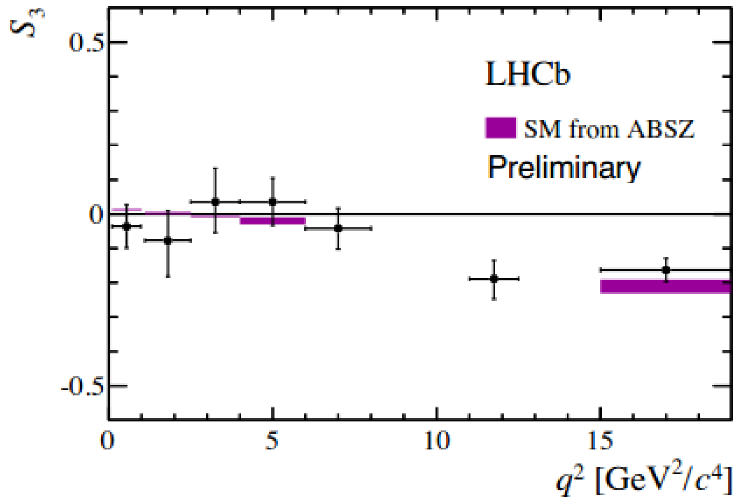


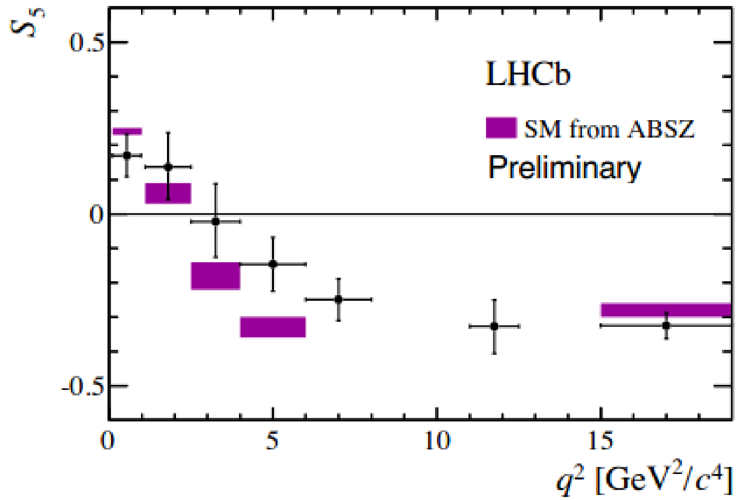
$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

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









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

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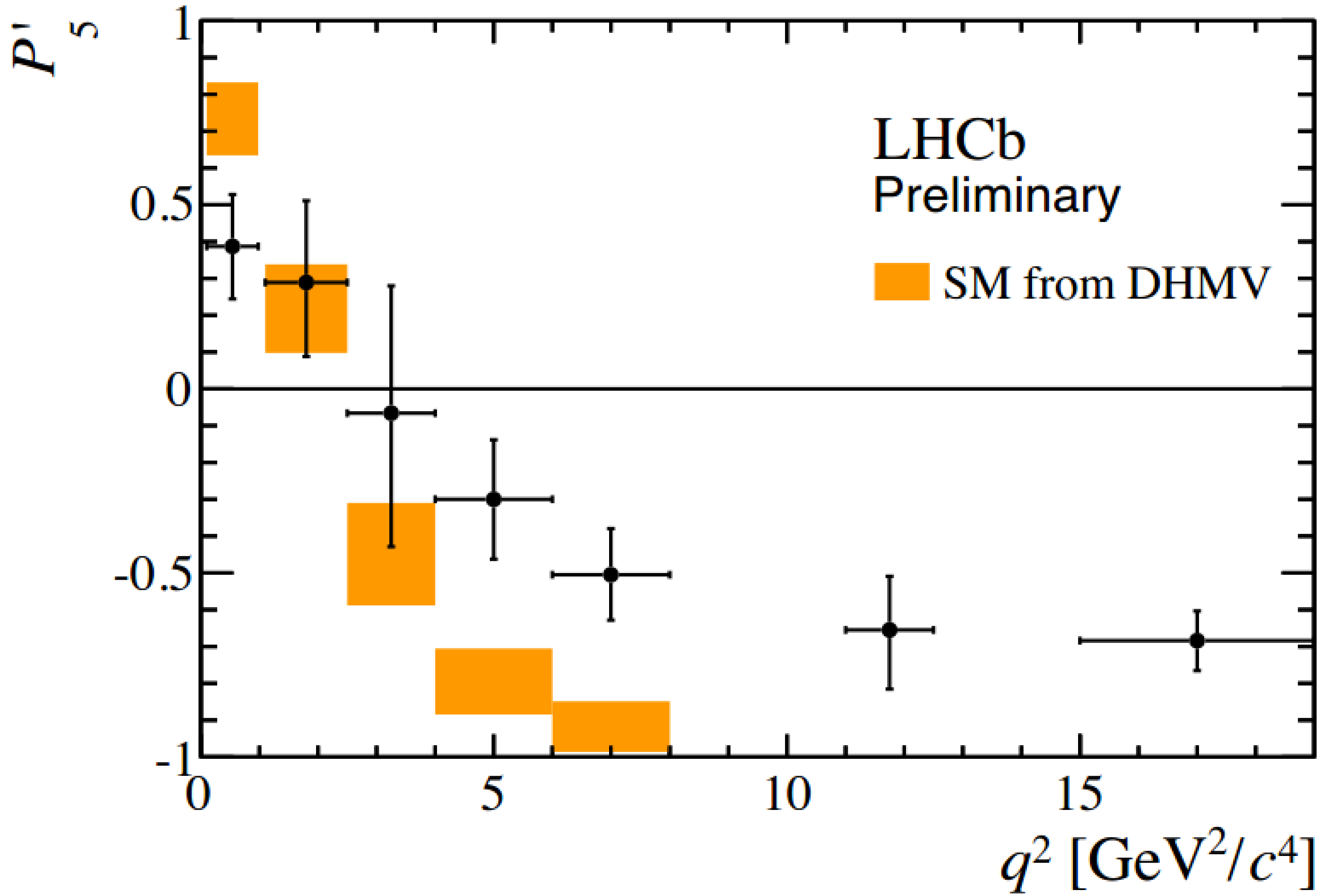
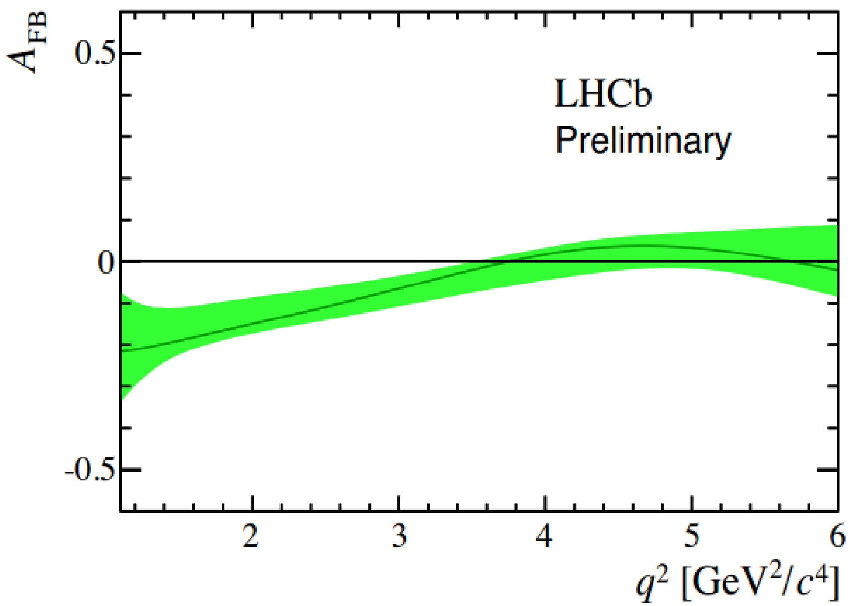
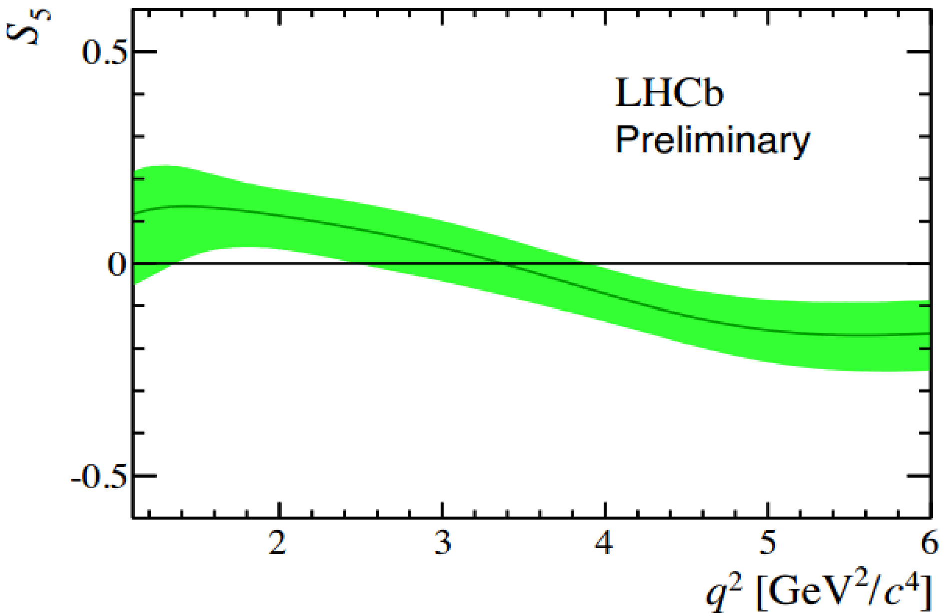


$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

Unbinned fit result in region $1<q^2< 6$ GeV^2

See UE, Petridis, Patel (JHEP 06 (2015) 084) for method





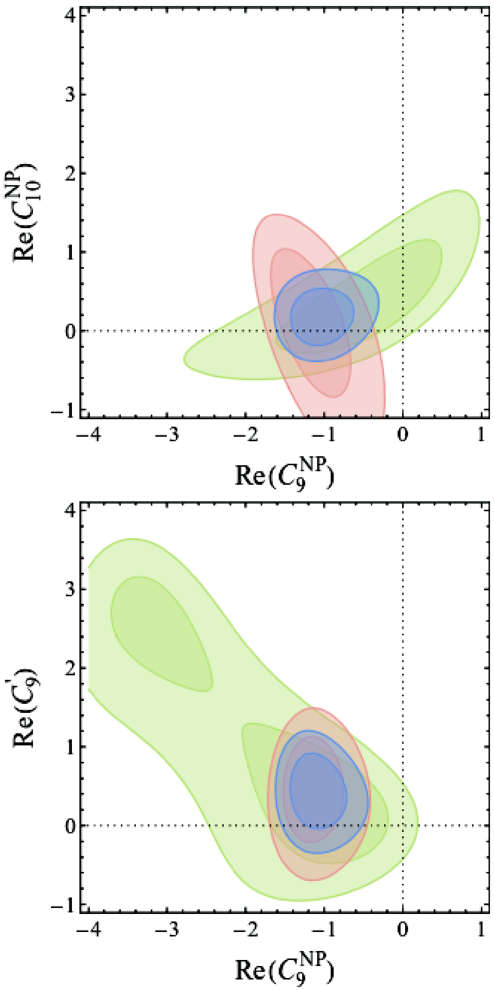
$$q_0^2(S_5) \in [2.49, 3.95]\,\mathrm{GeV}^2/c^4 \quad @\ 68\%\ \mathrm{CL}$$

$$q_0^2(A_{\mathrm{FB}}) \in [3.40, 4.87]\,\mathrm{GeV}^2/c^4 \quad @\ 68\%\ \mathrm{CL}$$

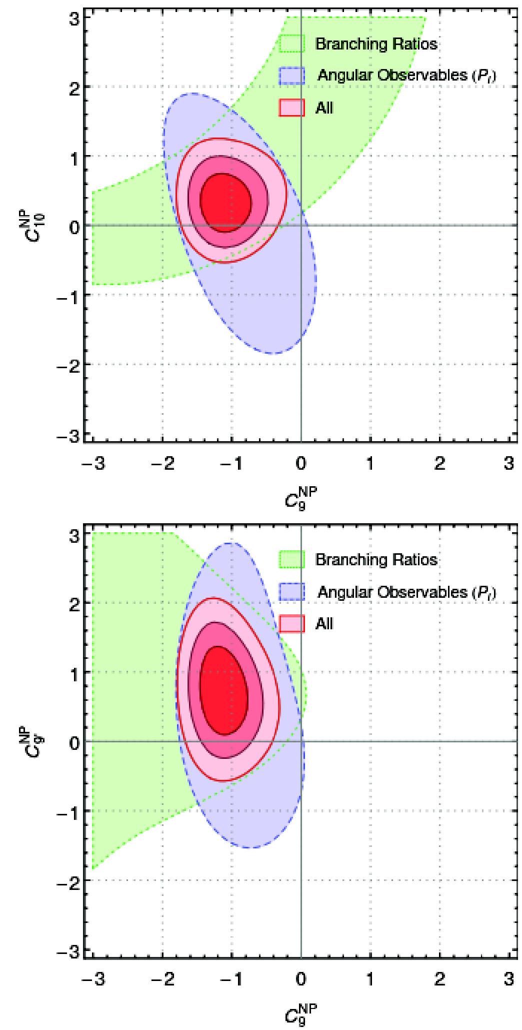
Performing global fits

From C. Bobeth, LHCb implications workshop

[Altmannshofer/Straub 1411.3161 & 1503.06199]



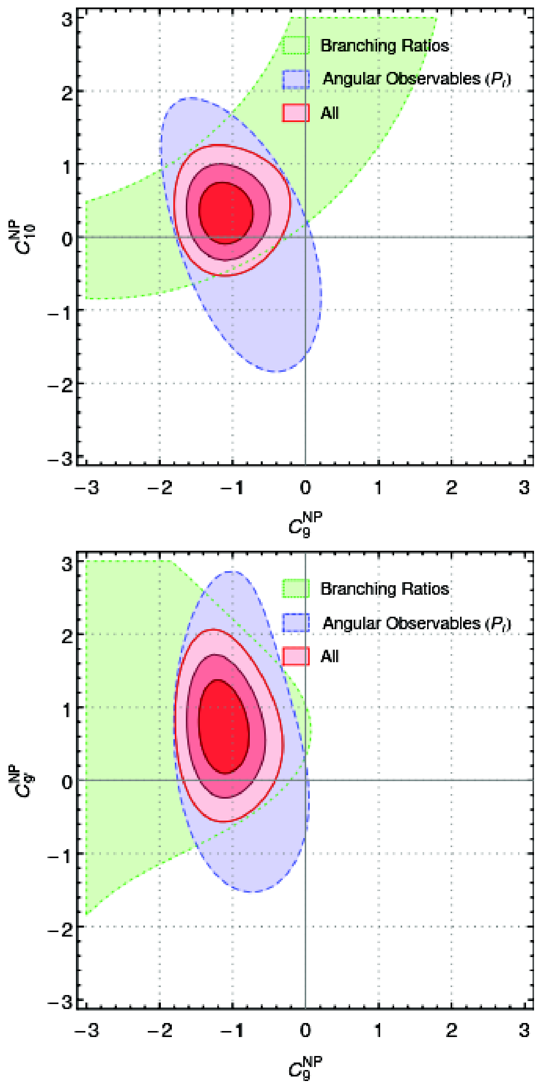
[Descotes-Genon/Hofer/Matias/Virto 1510.04239]



angular obs's (S_i) branching ratios

Performing global fits

[Descotes-Genon/Hofer/Matias/Virto 1510.04239]



The SM is disfavoured at ~4σ in all the different fits

Several options for NP fit that are hard to distinguish

- $C_9^{NP} = -1$, $C_{10}^{NP} = 0$
  - Leads towards Z' type models
- $C_9^{NP} = -C_{10}^{NP} = -1$
  - Leptoquark models
- $C_9^{NP} = -C_9'^{NP} = -1$
  - Leads to L-R symmetric models

Lepton non-universality

Lepton universality is one of the corner stones of the Standard Model

Only theoretical uncertainty in ratios of semileptonic decays is from different masses of quarks

Z decays tested lepton universality at the per-mille level

Heavy flavour decays test e-μ universality in $B \to Kl\nu$ at the 5% level

For μ-τ universality to constraints are poorer

- In charm, a single constraint by $BF(D_s^+ \to \tau^+\nu)/BF(D_s^+ \to \mu^+\nu)$ at 10% level

LHCb : PRL113, 151601 (2014)

Lepton universality test in $B^+ \to K^+ l^+ l^-$

Due to lepton universality, the $B \to K\mu\mu$ and $B \to Kee$ decays should have same BF to within a factor 10^{-3}

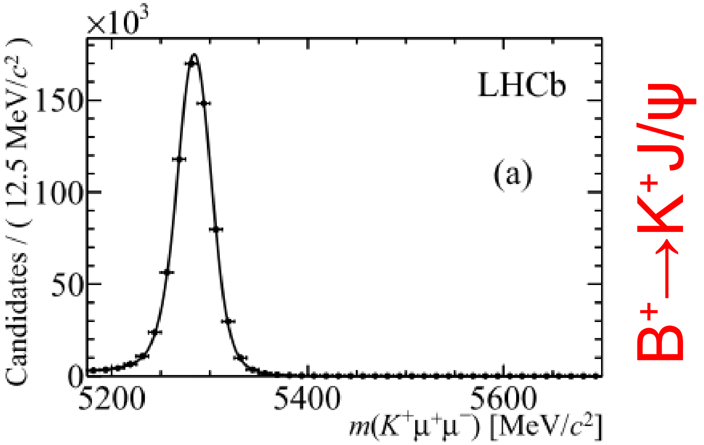
The ratio

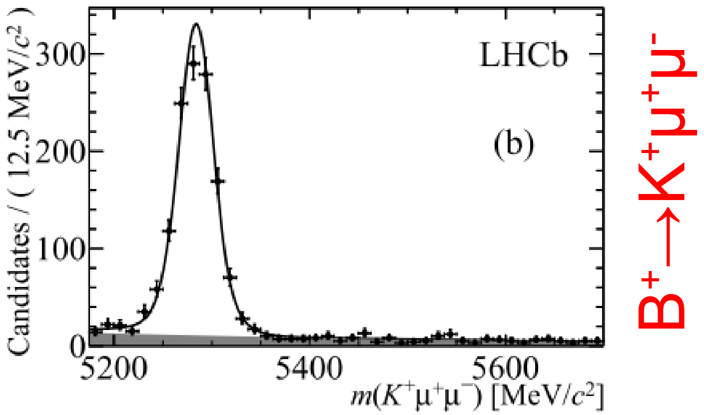
$$R_K = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma[B^+ \to K^+ e^+ e^-]}{dq^2} dq^2}$$

Sensitive to lepton flavour violating NP

Look in $q^2 < 6\ \mathrm{GeV}^2$ region

Muon mode and its control mode $B^+ \to K^+ J/\psi$, $J/\psi \to \mu\mu$ are easy



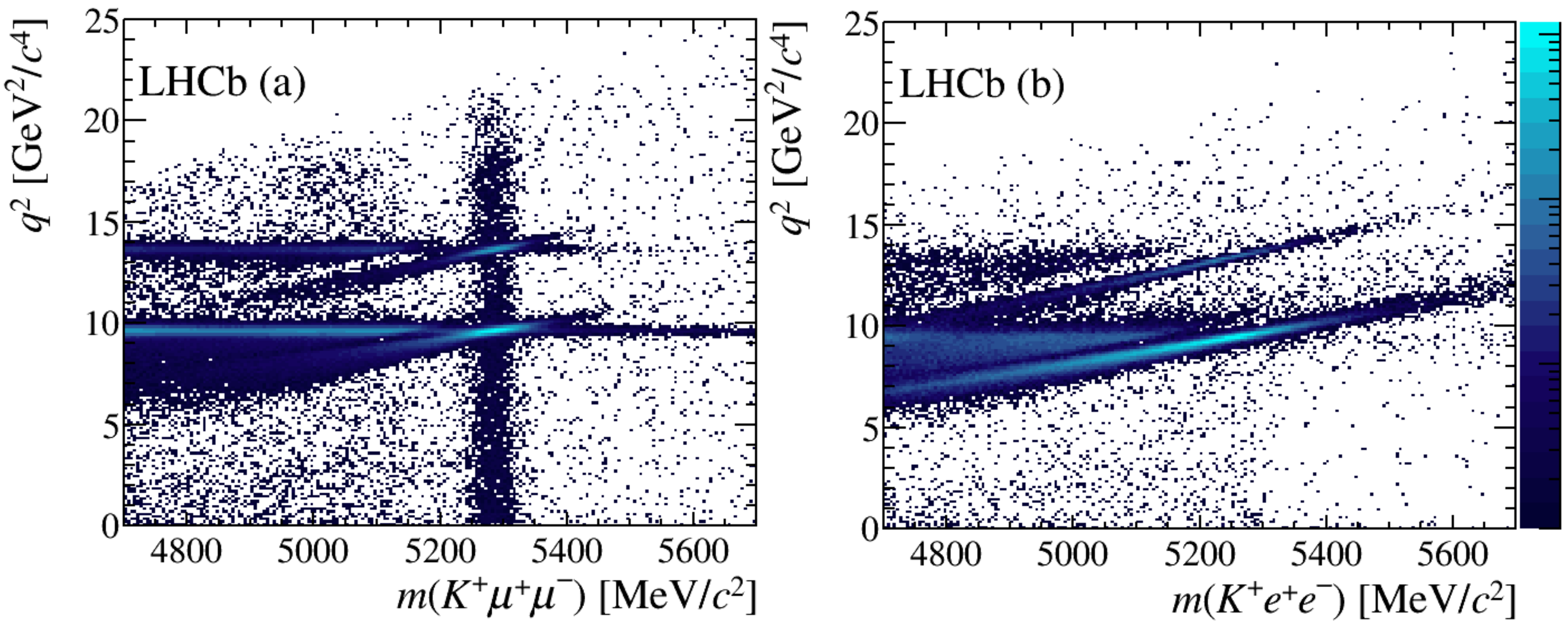


LHCb : PRL113, 151601 (2014)

Lepton universality test in $B^+ \to K^+ l^+ l^-$

The electron mode and its corresponding J/ψ control mode are very different to the muon mode due to bremsstrahlung from electrons.

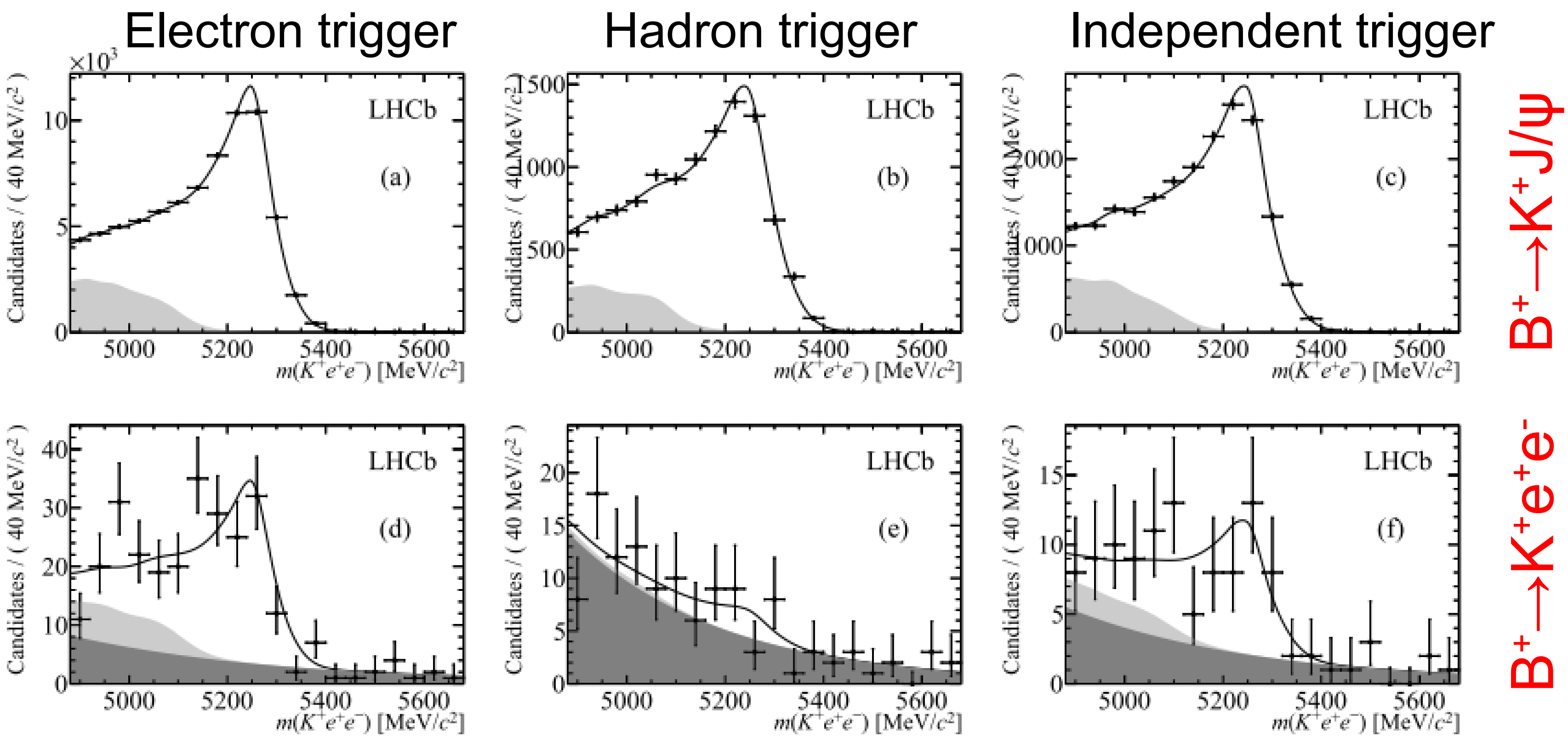
Many corrections are required for electron mode using combination of control mode and simulation



LHCb : PRL113, 151601 (2014)

Lepton universality test in $B^+ \to K^+ l^+ l^-$

For the electron channel, analysis divided up in categories



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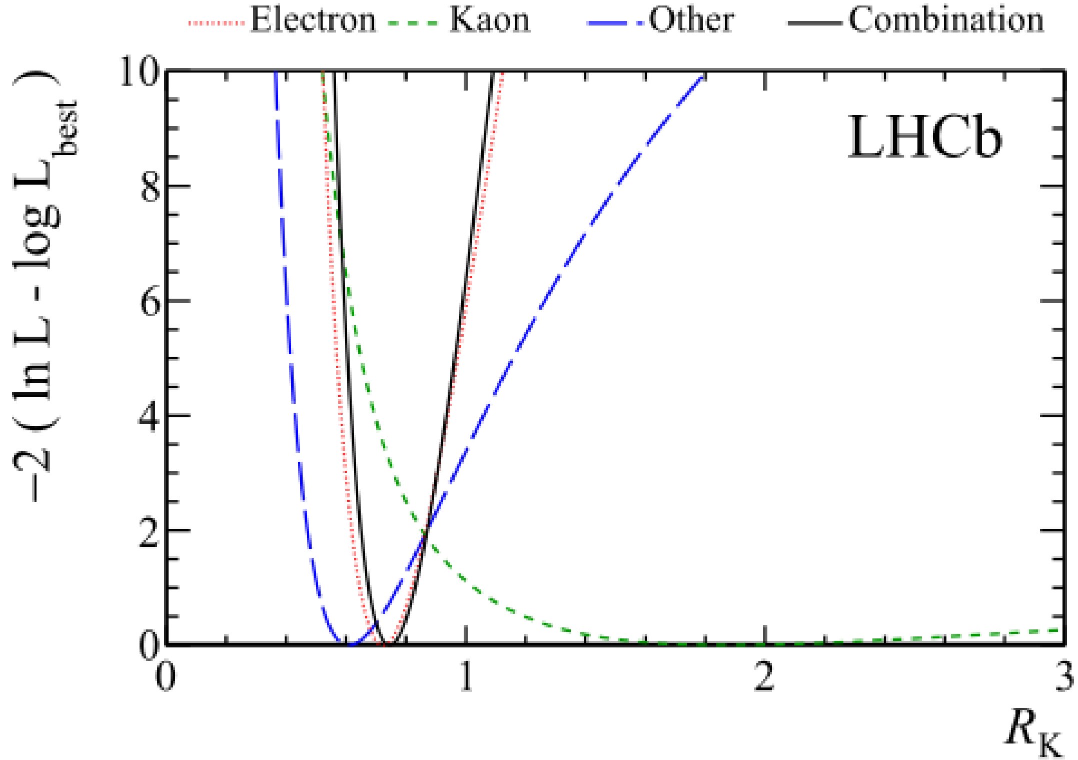


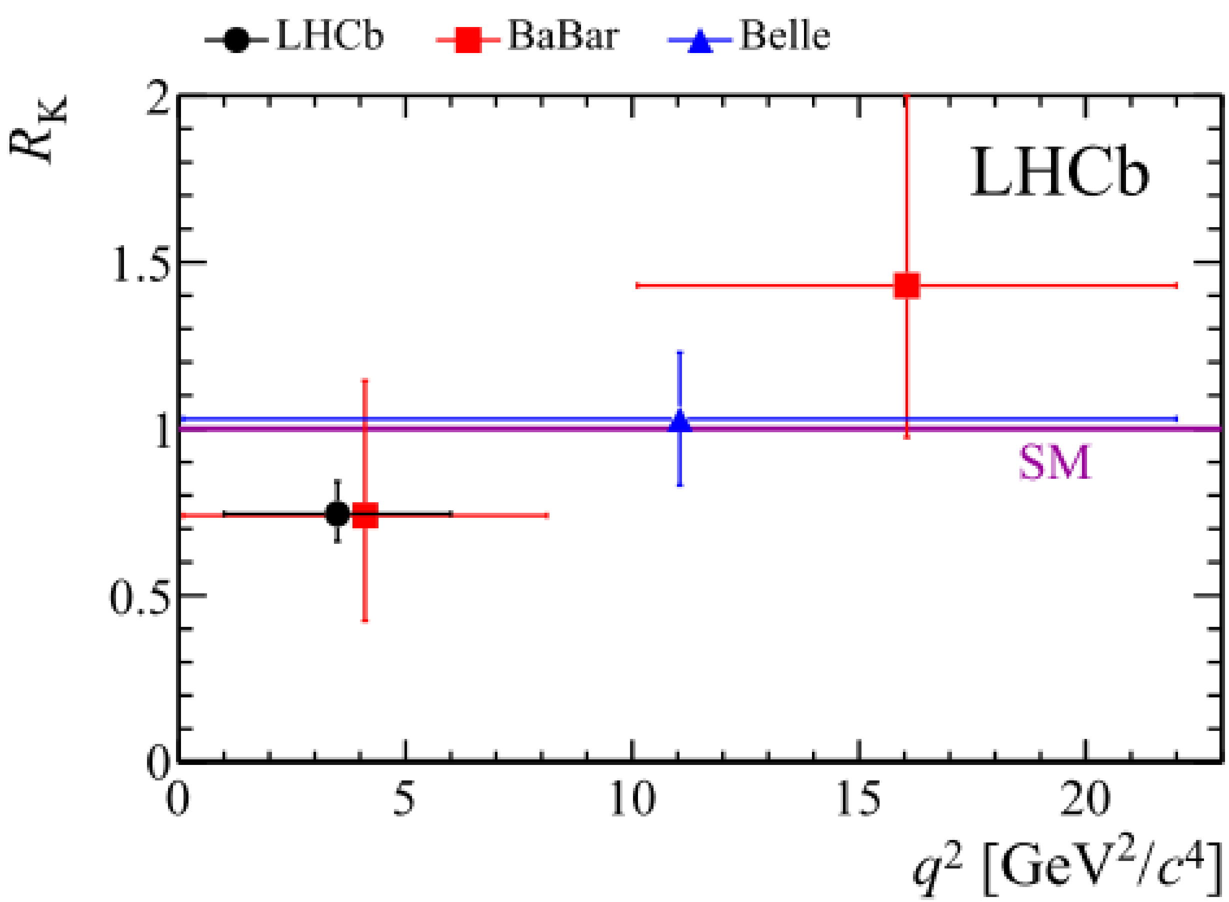
Electron mode control overall uncertainty

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

LHCb : PRL113, 151601 (2014)

Lepton universality test in $B^+ \to K^+ l^+ l^-$

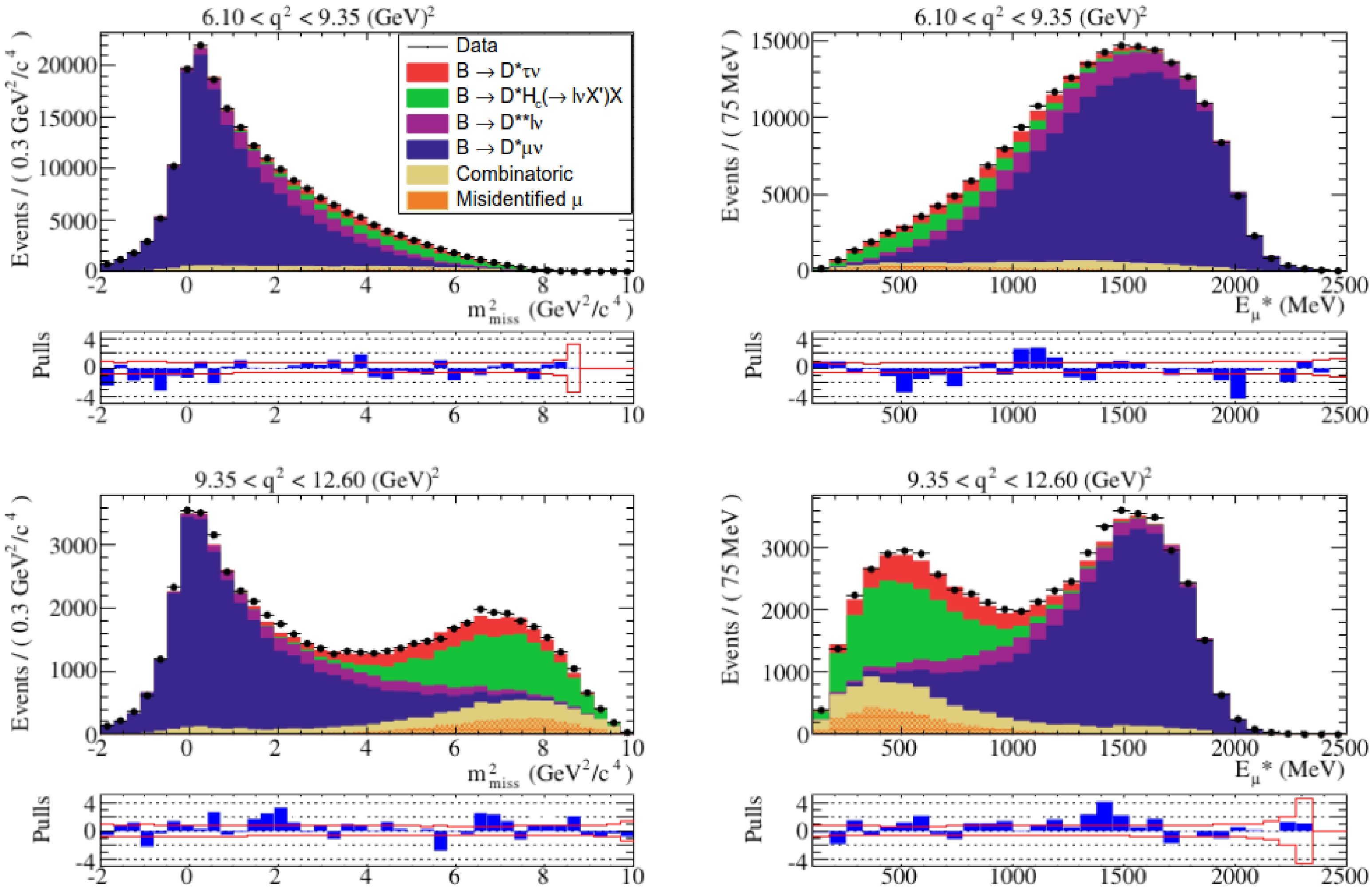
Measurement is compatible with earlier, but less precise measurements



$B^+ \rightarrow D^{*+} \tau \nu$

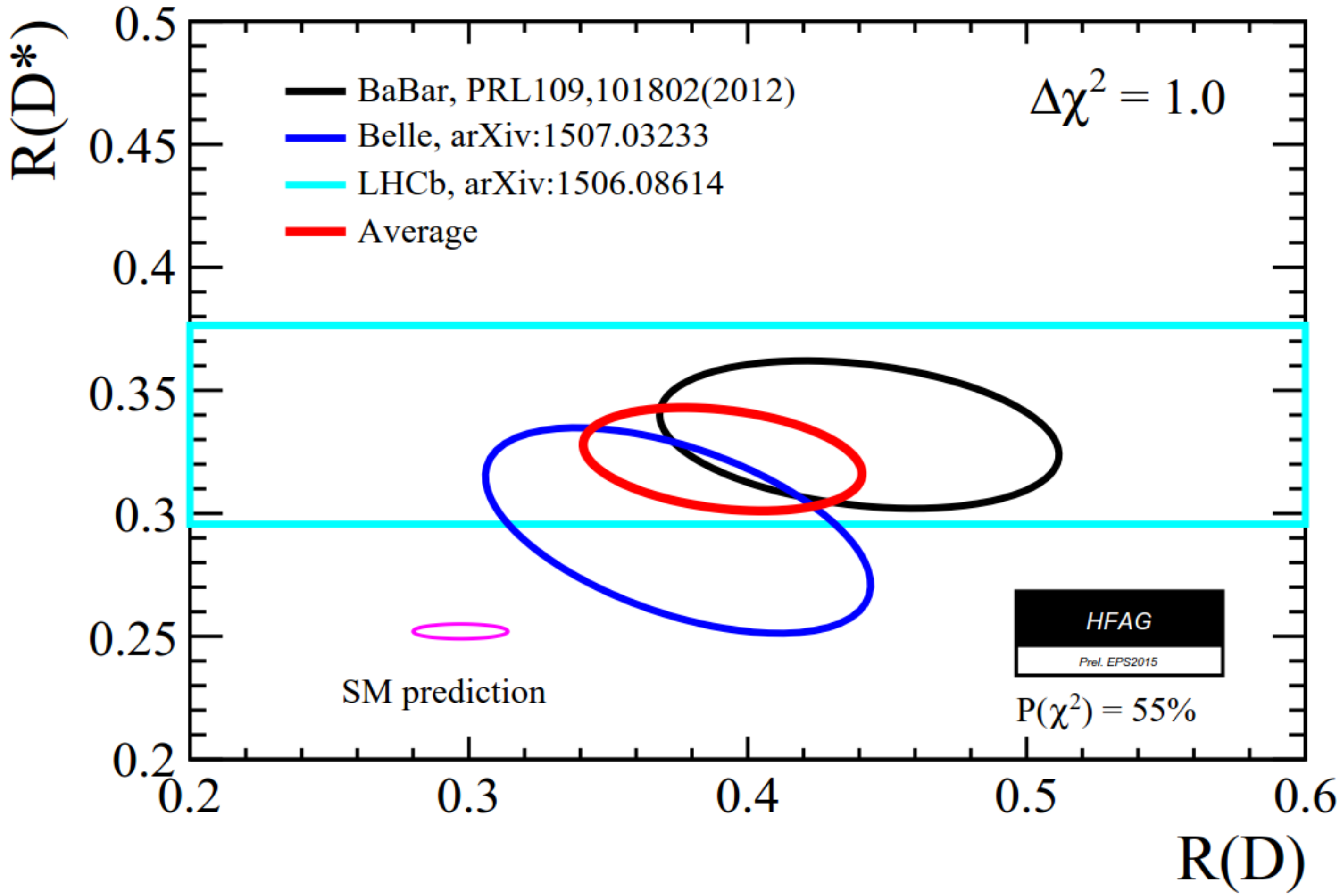
LHCb recent result

Phys. Rev. Lett. 115 (2015) 112001



$B^+ \rightarrow D^{(*)+} \tau \nu$ global fit

The measurements are internally consistent and have a 4σ tension with SM prediction



Measurement of $|V_{ub}|/|V_{cb}|$

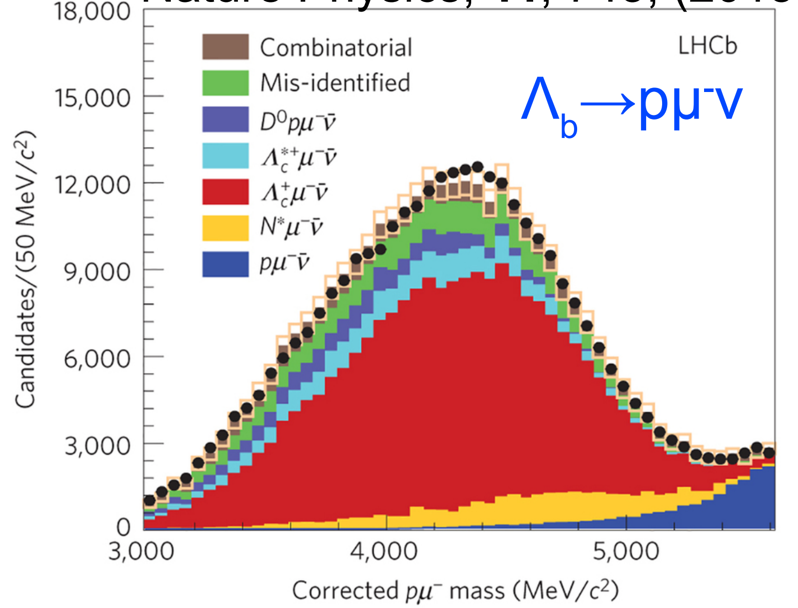
The ratio of CKM elements can be measured from

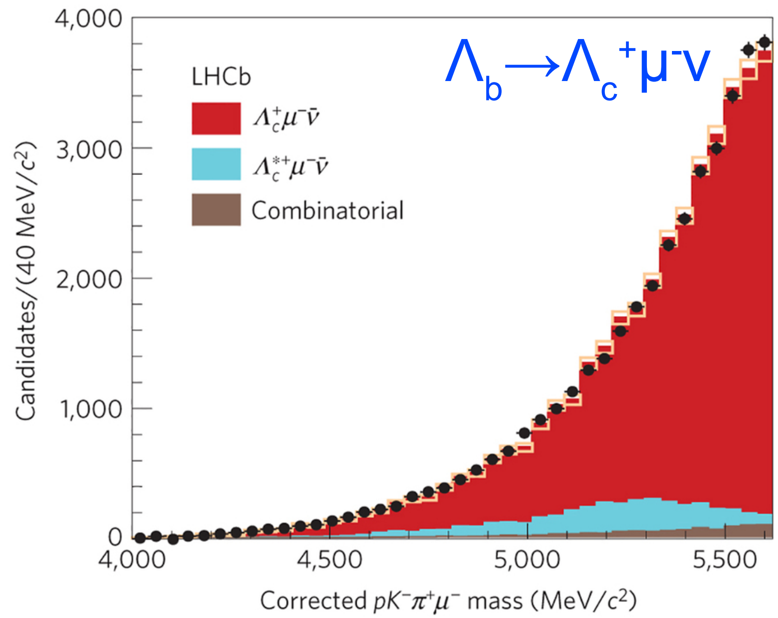
- The BF ratio of $\Lambda_b \rightarrow p\mu^- \nu$ and $\Lambda_b \rightarrow \Lambda_c^+ \mu^- \nu$ combined with Lattice QCD prediction of form factors
- Only events in the high q^2 region is considered to lower lattice uncertainty

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004$$

Uncertainty dominated by $BF(\Lambda_c^+ \rightarrow pK\pi)$ and lattice form factors

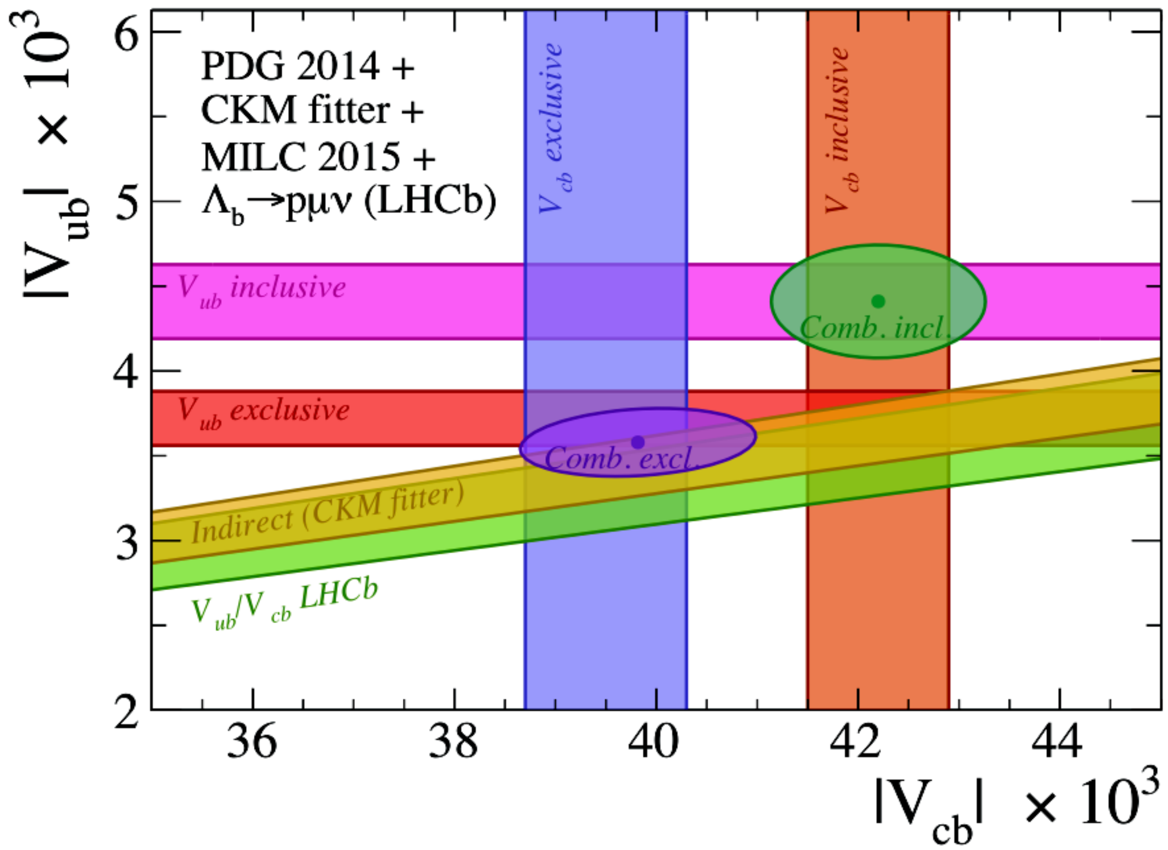
Nature Physics, **11**, 743, (2015)





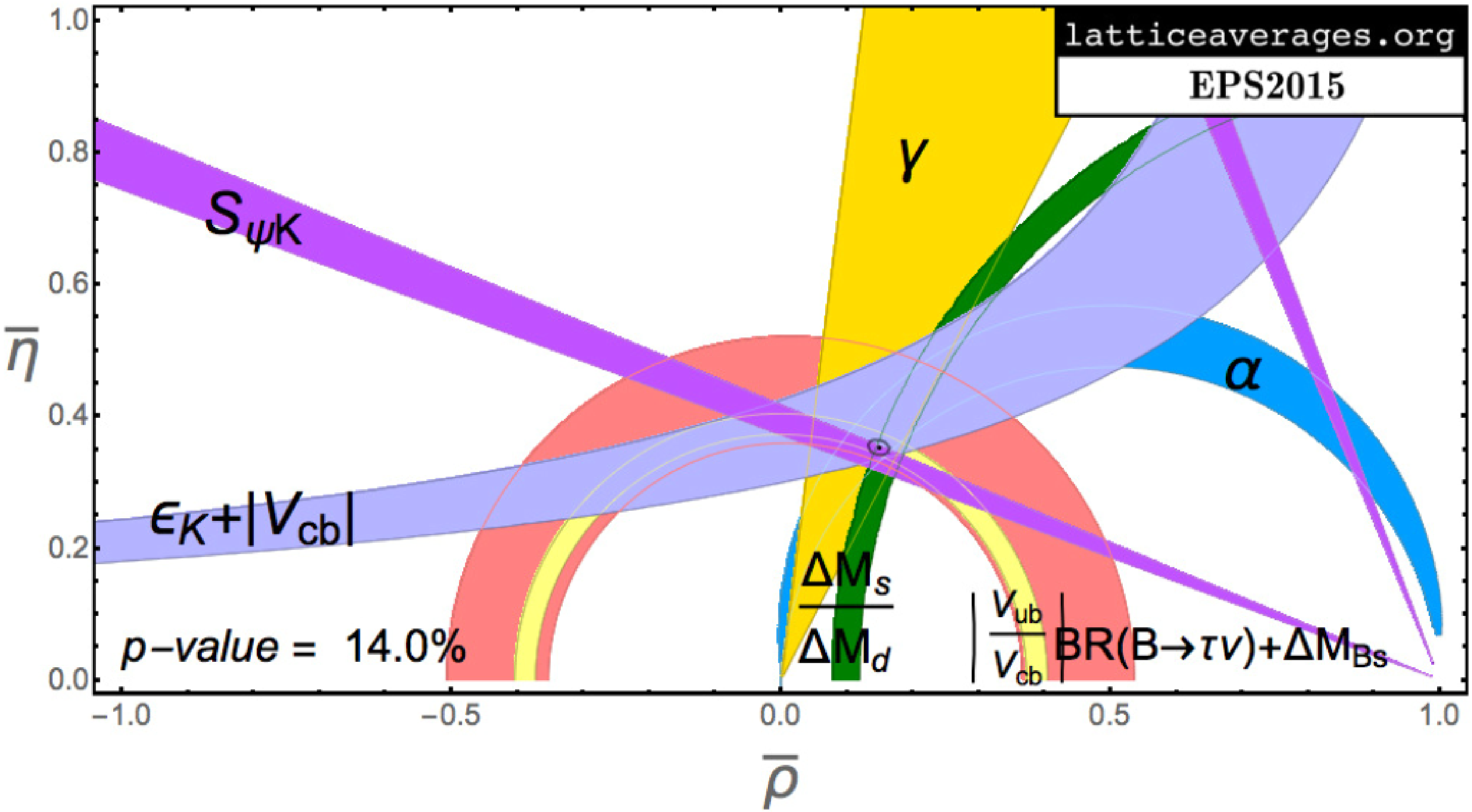
CKM matrix elements (incl. vs excl.)

Combining the new LHCb measurement with existing measurements of $|V_{cb}|$ and $|V_{ub}|$ enhance discrepancy between inclusive and exclusive measurements



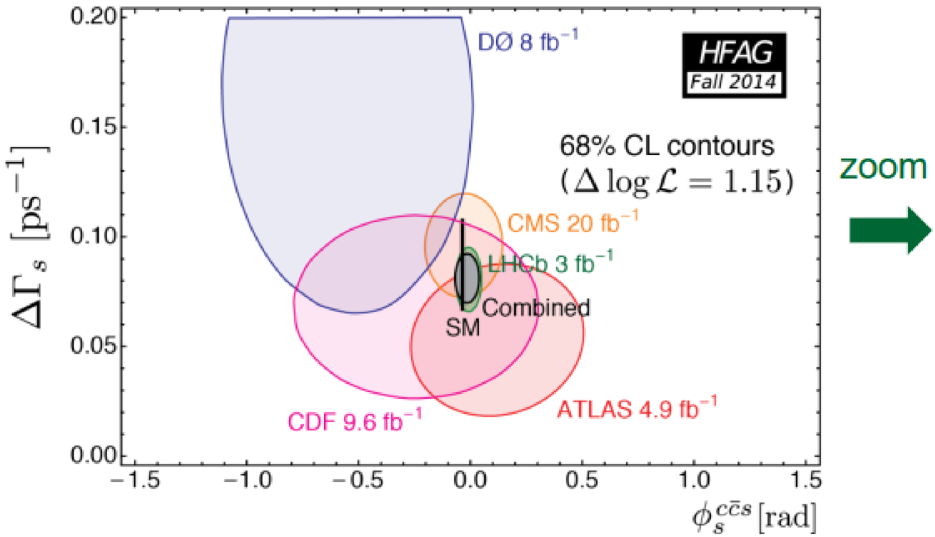
No heavy flavour *CP* violation anomalies?

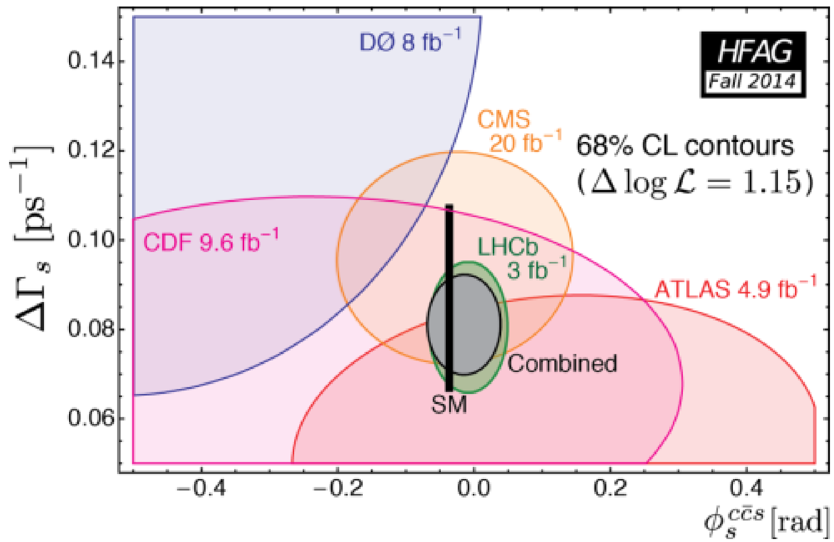
The global CKM fits do not show any anomalies



No heavy flavour *CP* violation anomalies?

But there is still plenty of scope for NP to show up in B^0_s oscillations





The theoretical uncertainty is still very small compared to experimental uncertainty

CP violation

The updates in Lattice QCD has led to an big development for kaon physics as well

	RBC-UKQCD	Ishizuka *et al.*	experiment
$\mathrm{Re}(A_0) \times 10^8$ (GeV)	$46.6(10.0)_{\mathrm{stat}}(12.1)_{\mathrm{sys}}$	24.26(38)	33.201(18)
$\mathrm{Re}(A_2) \times 10^8$ (GeV)	$1.50(4)_{\mathrm{stat}}(14)_{\mathrm{sys}}$	60(36)	1.474(4)
$\mathrm{Re}(\varepsilon'/\varepsilon) \times 10^4$	$1.38(5.15)_{\mathrm{stat}}(4.43)_{\mathrm{sys}}$	0.8(3.5)	16.6(2.3)

RBC-UKQCD: PRL 115, 212001 (2015)

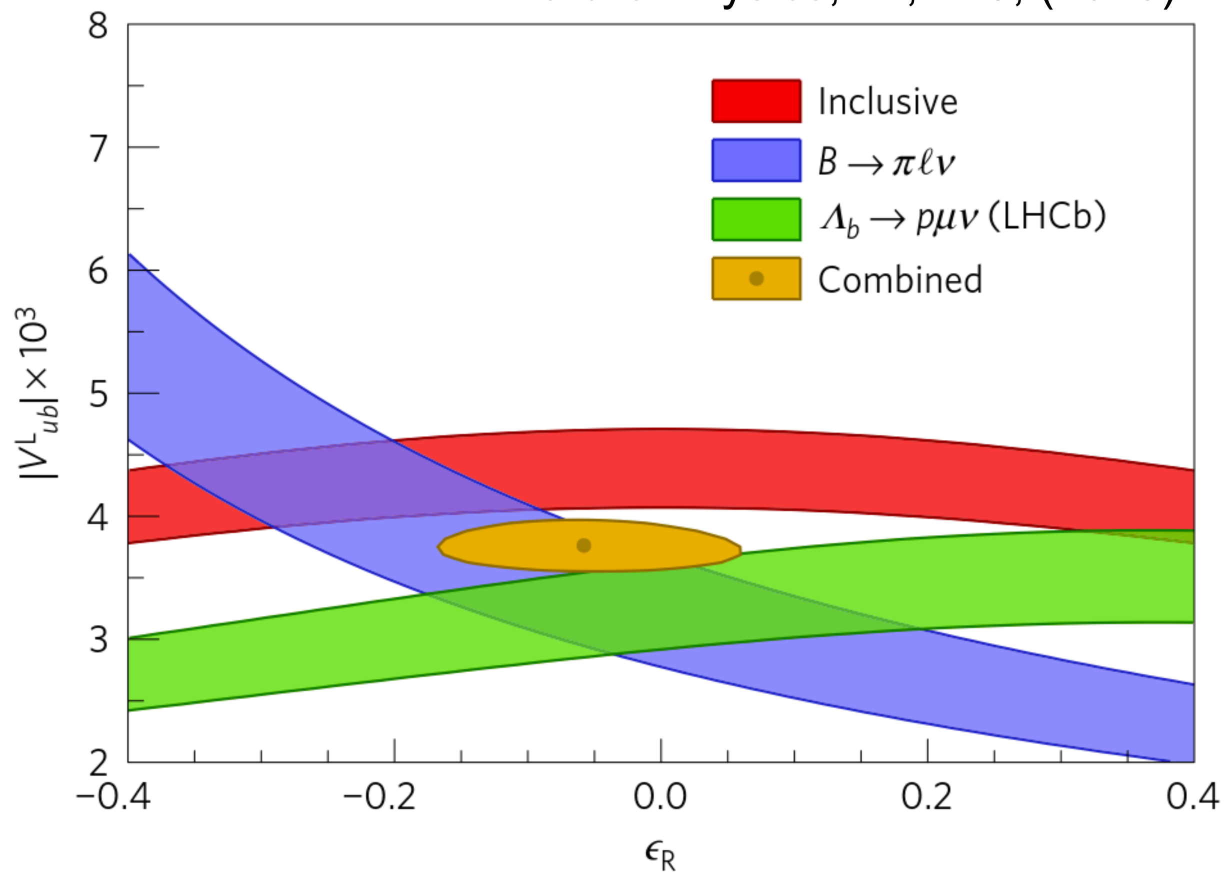
Ishizuka et al.: PRD 92, 074503 (2015)

There is now a significant disagreement with respect to the experimental measurement of έ/ε

Right-handed currents?

The $\Lambda_b \rightarrow p\mu\nu$ result does not support earlier ideas about a right handed current affecting the $|V_{ub}|$ measurements

Nature Physics, **11**, 743, (2015)



Interpretations

To understand the different anomalies, different approaches have gained some traction

- There is a problem with the uncertainties
  - Experimental side most like for lepton non-universality measurements
  - Theory side more likely for electroweak penguin angular analysis
- Introduce a leptoquark sector
  - Provides straight forward explanation of lepton non-universality
- Introduce a Z' that allows for flavour changing neutral currents at tree level
  - Aims mainly at $B \to K^* \mu^+ \mu^-$ but can also explain R_K

Problem with the uncertainties

- That the "NP" shows up in C9 is somewhat problematic
  - Most of the Standard Model uncertainties are there as well
  - Traditional fix is $C_9 \rightarrow C_9 + Y(q^2)$ to take charm loops into account
- From S. Jäger

SJ, Martin Camalich 1412.3183

Example

manifestly form-factor-scheme-independent

$$P_5' = P_5'|_\infty \left(1 + \frac{a_{V_-} - a_{T_-}}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} C_7^{\rm eff} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\perp}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})} + \frac{a_{V_0} - a_{T_0}}{\xi_\parallel} 2\, C_7^{\rm eff} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\parallel}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})} + 8\pi^2 \frac{\tilde{h}_-}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{C_{9,\perp} + C_{9,\parallel}} + \text{further terms} \right) + \mathcal{O}(\Lambda^2/m_B^2)$$

heavy-quark-limit result

("charm loop" power correction)

(**truncated** after 3 out of 11 independent power-correction terms!)

Leptoquarks

Latest attempt on leptoquarks attempts to explain nearly all anomalies

- Assumes hierarchical coupling matrices

MITP/15-100
November 9, 2015

arXiv:1511.01900

One Leptoquark to Rule Them All:
A Minimal Explanation for $R_{D^{(*)}}$, R_K and $(g-2)_\mu$

Martin Bauer[a] and Matthias Neubert[b,c]

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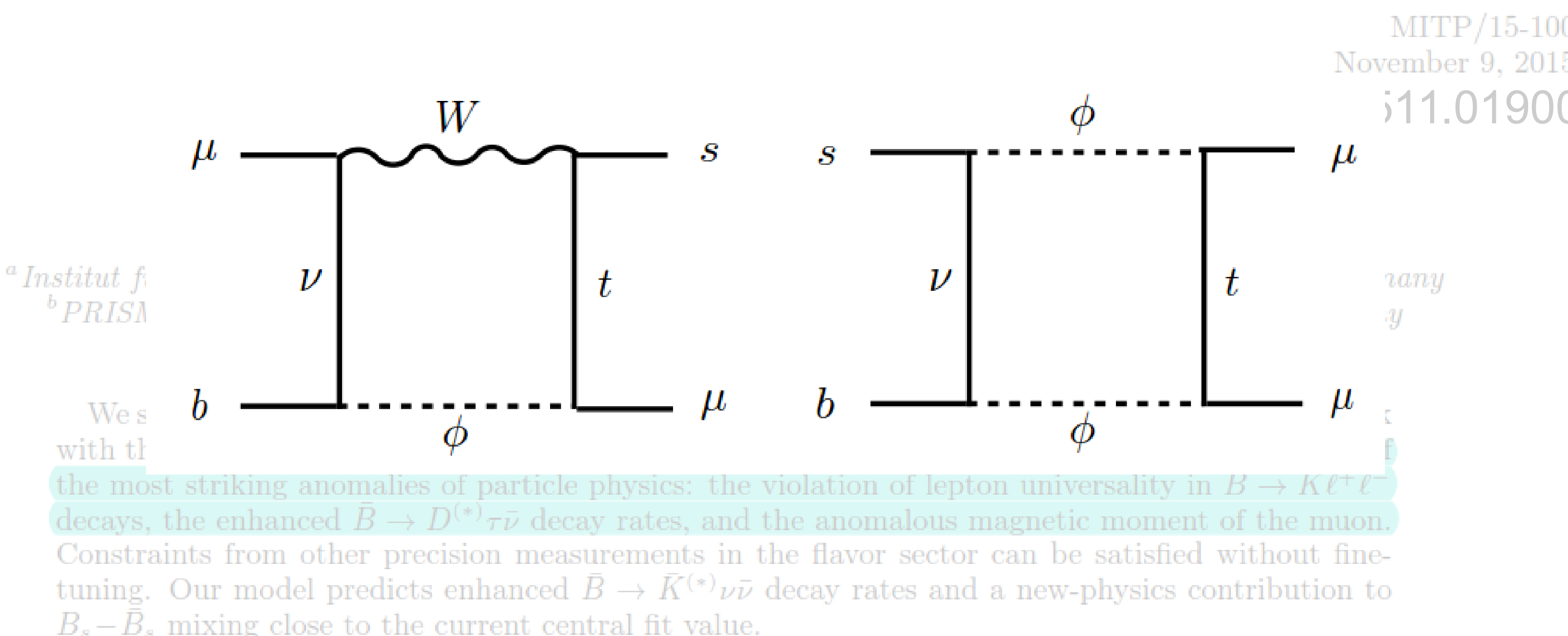
[b] *PRISMA Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany*
[c] *Department of Physics & LEPP, Cornell University, Ithaca, NY 14853, U.S.A.*

We show that by adding a single new scalar particle to the Standard Model, a TeV-scale leptoquark with the quantum numbers of a right-handed down quark, one can explain in a natural way three of the most striking anomalies of particle physics: the violation of lepton universality in $\bar{B} \to \bar{K}\ell^+\ell^-$ decays, the enhanced $\bar{B} \to D^{(*)}\tau\bar{\nu}$ decay rates, and the anomalous magnetic moment of the muon. Constraints from other precision measurements in the flavor sector can be satisfied without fine-tuning. Our model predicts enhanced $\bar{B} \to \bar{K}^{(*)}\nu\bar{\nu}$ decay rates and a new-physics contribution to $B_s - \bar{B}_s$ mixing close to the current central fit value.

Leptoquarks

Latest attempt on leptoquarks attempts to explain nearly all anomalies

- Assumes hierarchical coupling matrices
- Loop diagrams explain R_K



Z' models

Many variations of Z' models have been proposed

- The example below tries to include the CMS H→μτ result as well

PRL **114**, 151801 (2015) PHYSICAL REVIEW LETTERS week ending 17 APRIL 2015

Explaining $h \to \mu^{\pm}\tau^{\mp}$, $B \to K^{*}\mu^{+}\mu^{-}$, and $B \to K\mu^{+}\mu^{-}/B \to Ke^{+}e^{-}$ in a Two-Higgs-Doublet Model with Gauged L_{μ}-L_{τ}

Andreas Crivellin,[1] Giancarlo D'Ambrosio,[1,2] and Julian Heeck[3]
[1]*CERN Theory Division, CH–1211 Geneva 23, Switzerland*
[2]*INFN-Sezione di Napoli, Via Cintia, 80126 Napoli, Italy*
[3]*Service de Physique Théorique, Université Libre de Bruxelles, Boulevard du Triomphe, CP225, 1050 Brussels, Belgium*
(Received 13 January 2015; published 14 April 2015)

The LHC has observed, so far, 3 deviations from the Standard Model (SM) predictions in flavor observables: LHCb reported anomalies in $B \to K^{*}\mu^{+}\mu^{-}$ and $R(K) = B \to K\mu^{+}\mu^{-}/B \to Ke^{+}e^{-}$, while CMS found an excess in $h \to \mu\tau$. We show, for the first time, how these deviations from the SM can be explained within a single well-motivated model: a two-Higgs-doublet model with gauged L_{μ}-L_{τ} symmetry. We find that, despite the constraints from $\tau \to \mu\mu\mu$ and B_s-$\bar{B}_s$ mixing, one can explain $h \to \mu\tau$, $B \to K^{*}\mu^{+}\mu^{-}$ and $R(K)$ simultaneously, obtaining interesting correlations among the observables.

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Z' models

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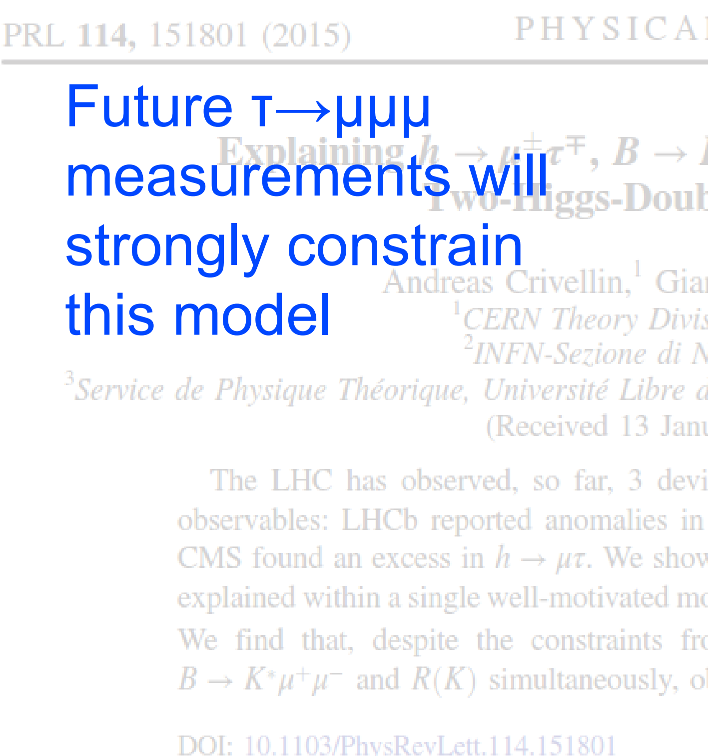
PRL **114**, 151801 (2015) PHYSICAL

Explaining $h \to \mu^\pm\tau^\mp$, $B \to$ ...
Two-Higgs-Doub...

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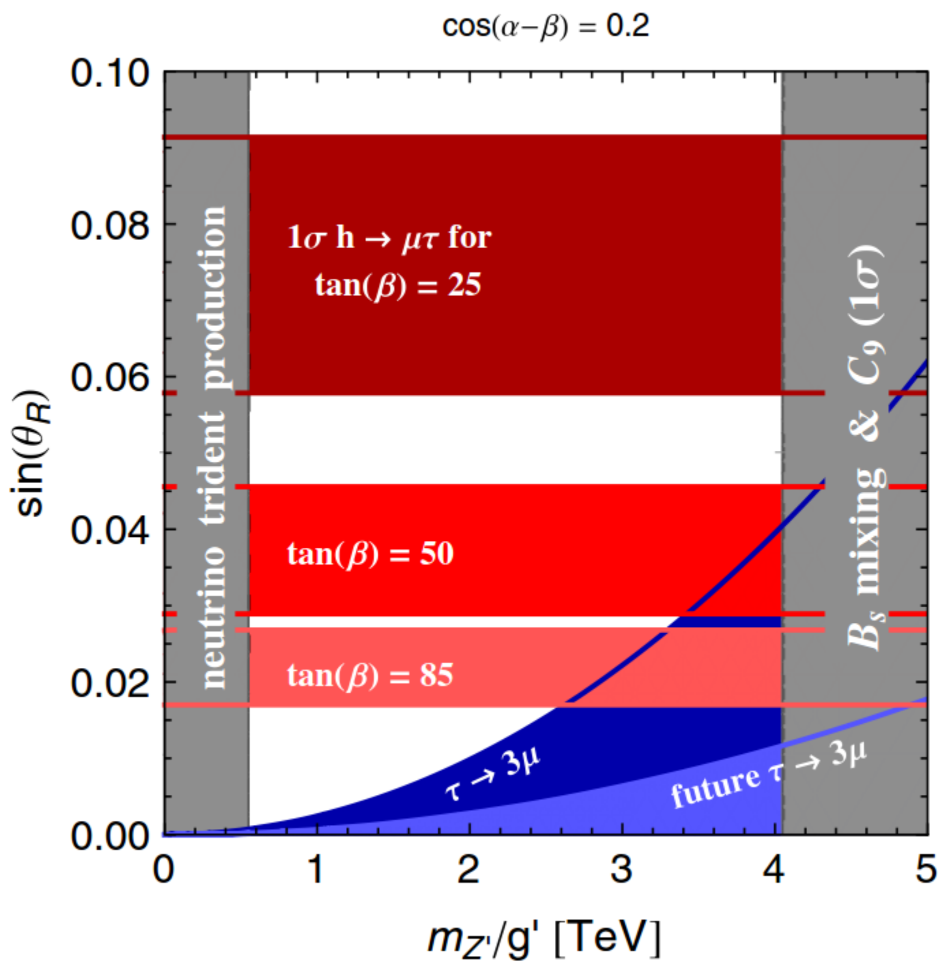
DOI: 10.1103/PhysRevLett.114.151801

- Future τ→μμμ measurements will strongly constrain this model



Conclusion

- Flavour physics has sensitivity to mass scales that are well above the direct production scale accessible
  - Many areas where measurements are far away from systematics limits imposed by experiments or theory
  - Challenge is in many cases to obtain even larger event samples
- A range of measurements are coming out which are in significant tension with the SM
  - $B \to K^* \mu^+ \mu^-$, $B \to K l^+ l^-$, $B \to D l \nu$, ε'/ε
- Phenomenologists and experimentalists need to talk even more in order further understanding
  - How to cross check experimental and theoretical uncertainties
  - Develop new measurements