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Cracks in the wall?

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YETI, 14 Jan 2016

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

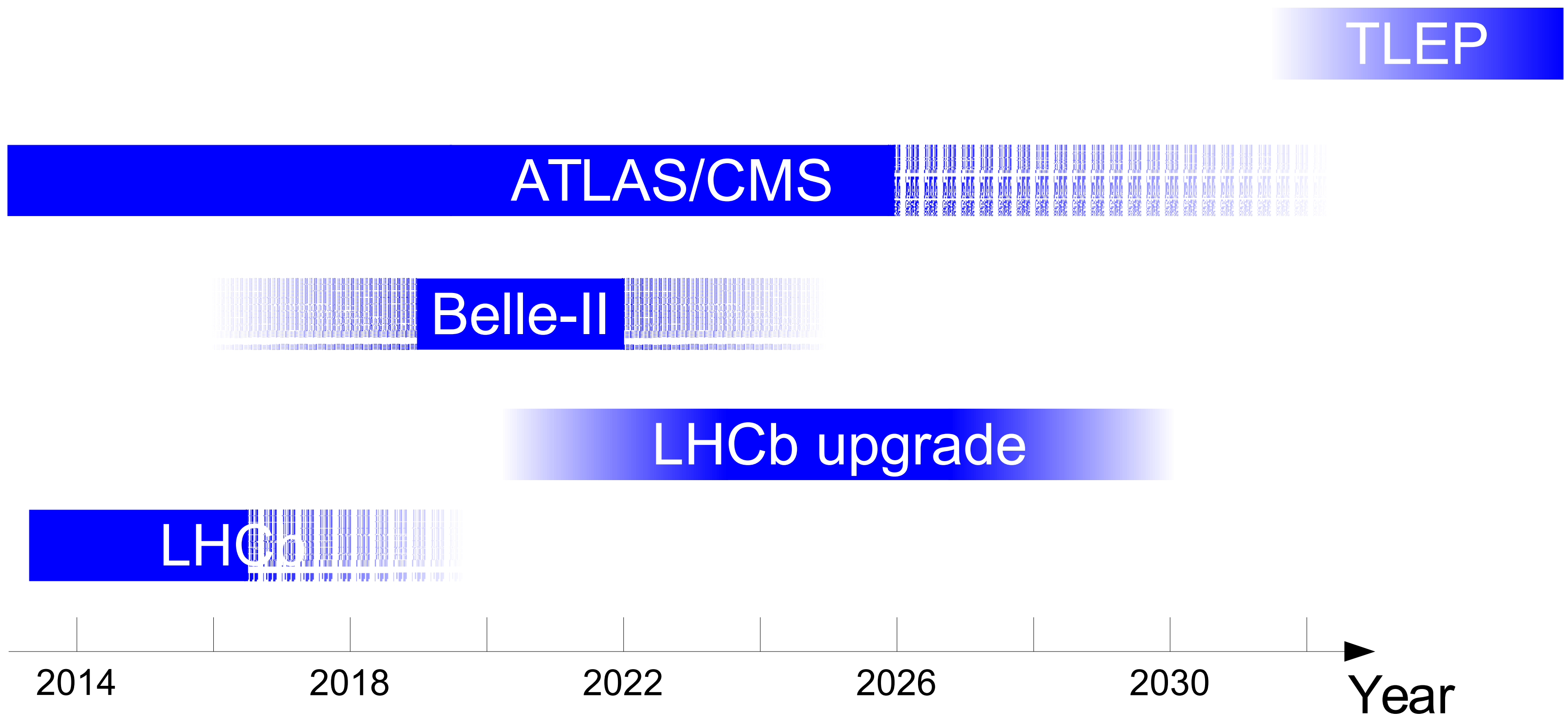
Or will the Standard Model be restored to former glory?

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

The proposed facilities available



Questions to ask

- For a given prospective measurement, we need to ask the questions
  - What level of statistical accuracy could be expected?
  - How will experimental systematics be controlled?
  - What are the theoretical uncertainties with measurement and can they be reduced?
- From answers conclude if measurement is actually interesting
- Will aim to show here that there are still plenty of interesting measurements
  - Will focus on places where anomalies are currently showing up

What ?

- Electroweak penguin decays
  - $B \to \mu^+\mu^-$
  - $B \to K^*\mu^+\mu^-$
- Lepton non-universality
  - $BF(B \to K\mu^+\mu^-)$ / $BF(B \to Ke^+e^-)$
  - $BF(B \to D^*\tau\nu)/BF(B \to D^*\mu\nu)$
- Anomalous top decays
- *CP* violation
  - 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 ?

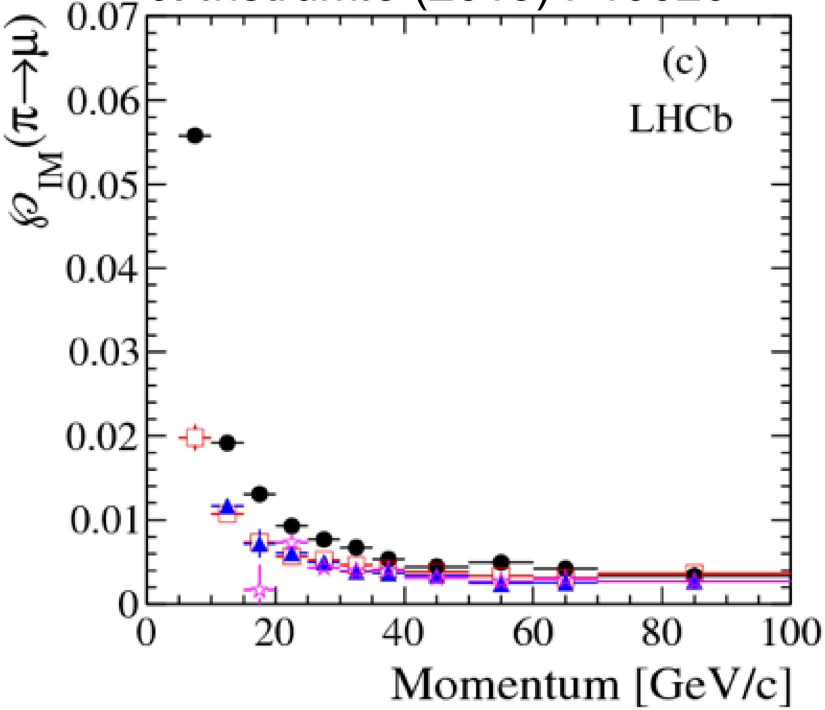
- QCD background
  - To see the effects of New Physics in heavy flavour decays we need to be able to calculate how the SM looks like
    - Uncertainties coming from QCD is the main problem here
  - Two ways out of this
    - Look for decays with leptons in
    - Look for *CP* violation
- Trigger
  - 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 for beauty and charm (and ATLAS/CMS for top)

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

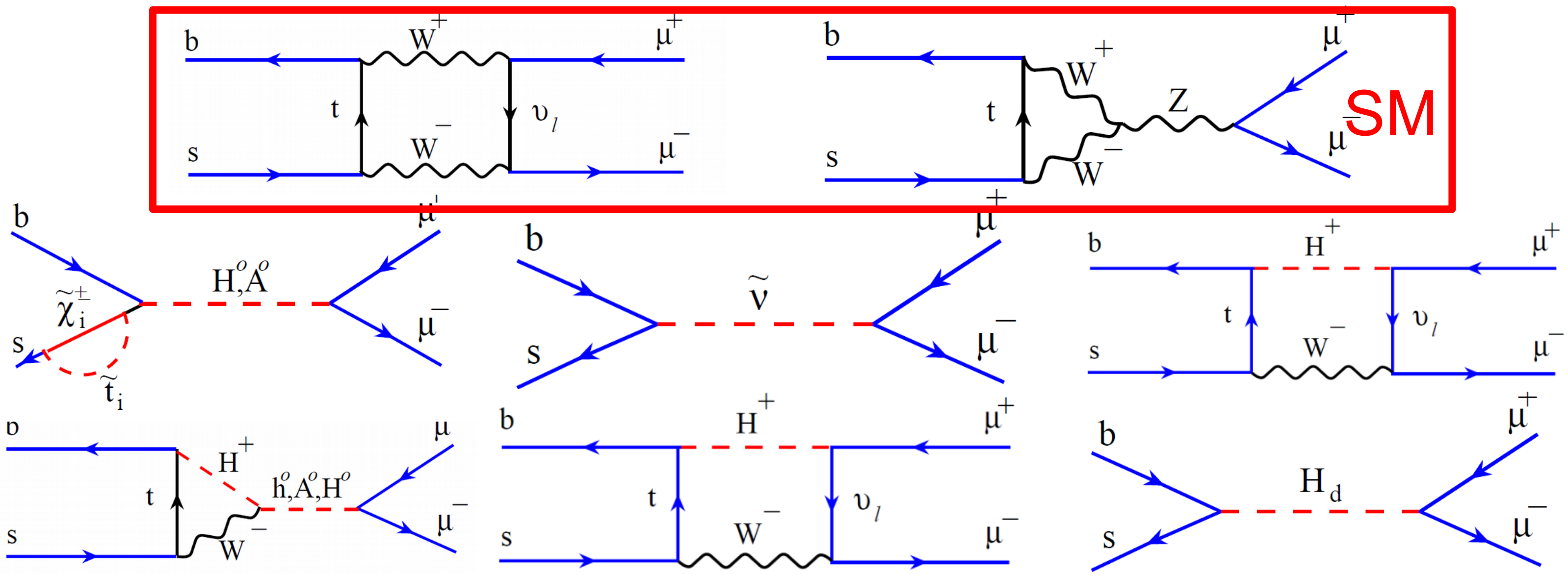
J. Instrum.8 (2013) P10020



$B \rightarrow \mu^+\mu^-$

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

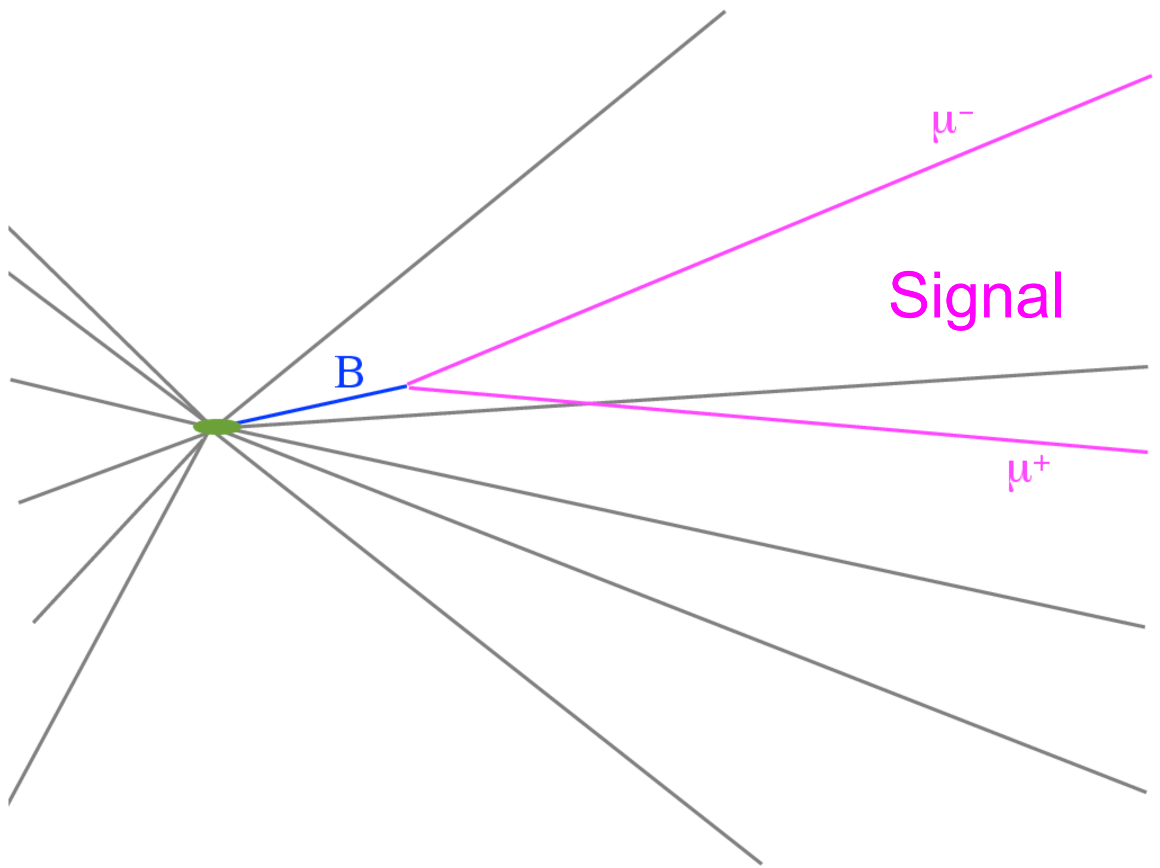
- Easy to predict SM branching fraction with great precision
  - $BF(B^0_s \rightarrow \mu^+\mu^-)_{SM} = (3.56 \pm 0.18) \times 10^{-9}$ (time averaged)
  - $BF(B^0 \rightarrow \mu^+\mu^-)_{SM} = (0.10 \pm 0.01) \times 10^{-9}$
- Sensitive to the scalar sector of flavour couplings



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

Topology of decay simple

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



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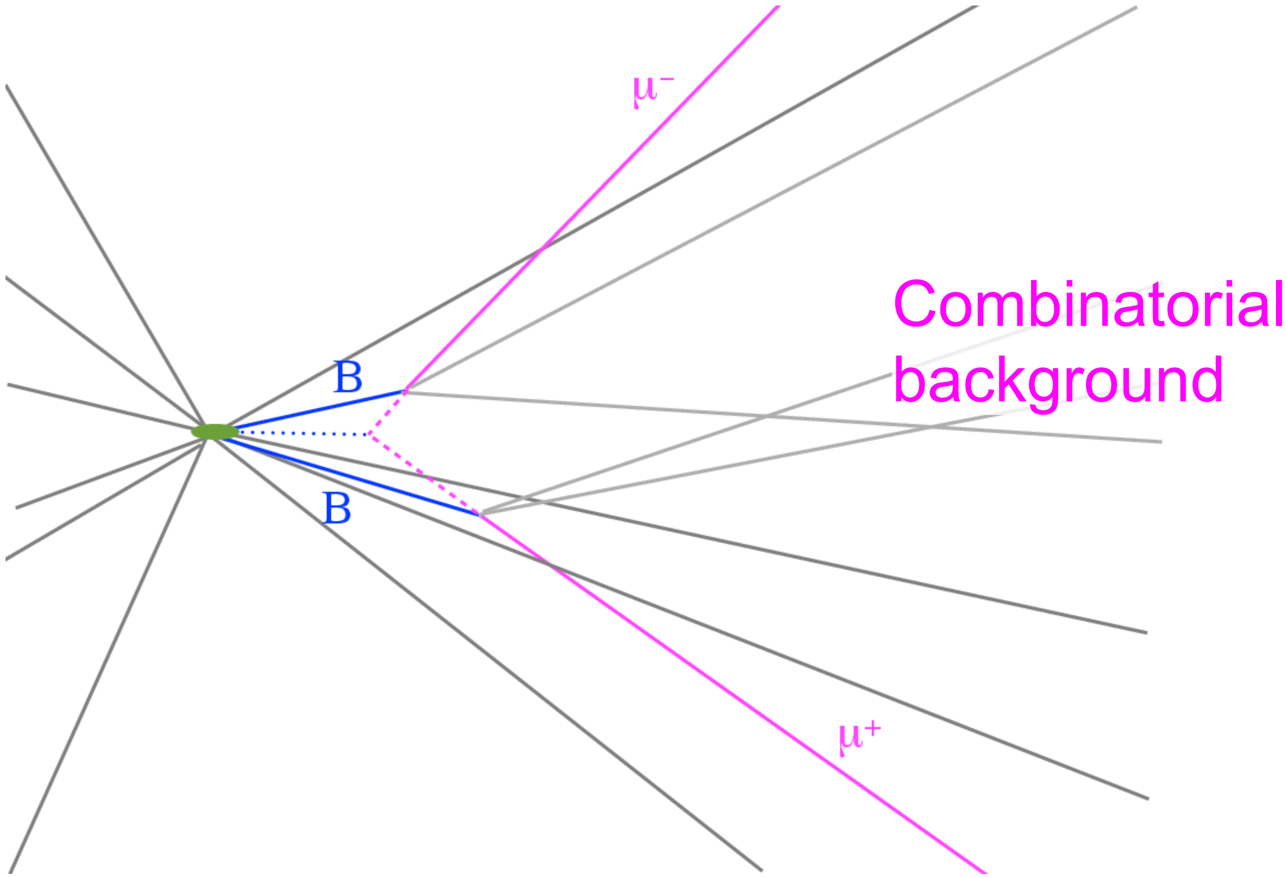


$B \to \mu^+\mu^-$

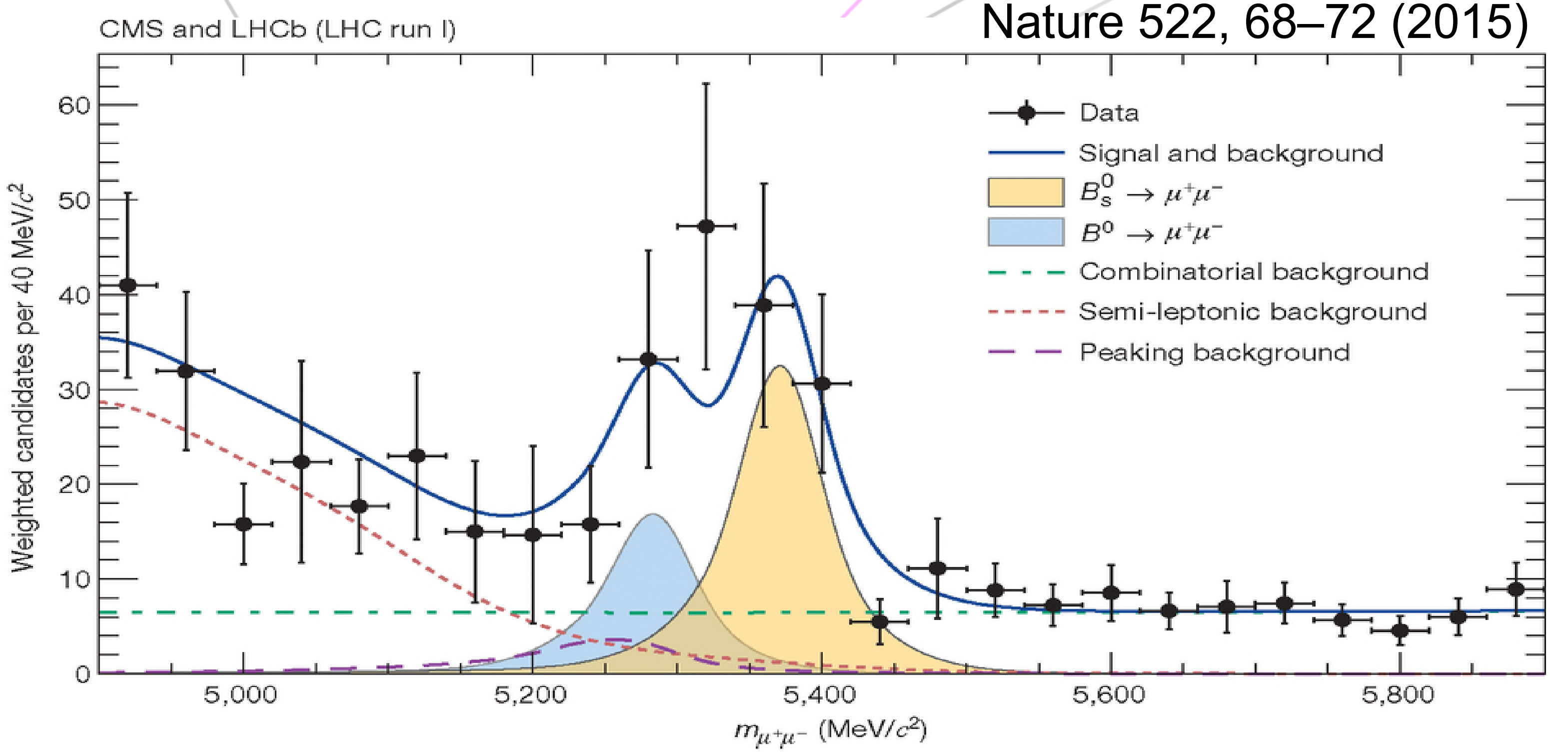
LHCb+CMS combined for observation of $B^0_s \to \mu^+\mu^-$

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

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

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

Nature 522, 68–72 (2015)



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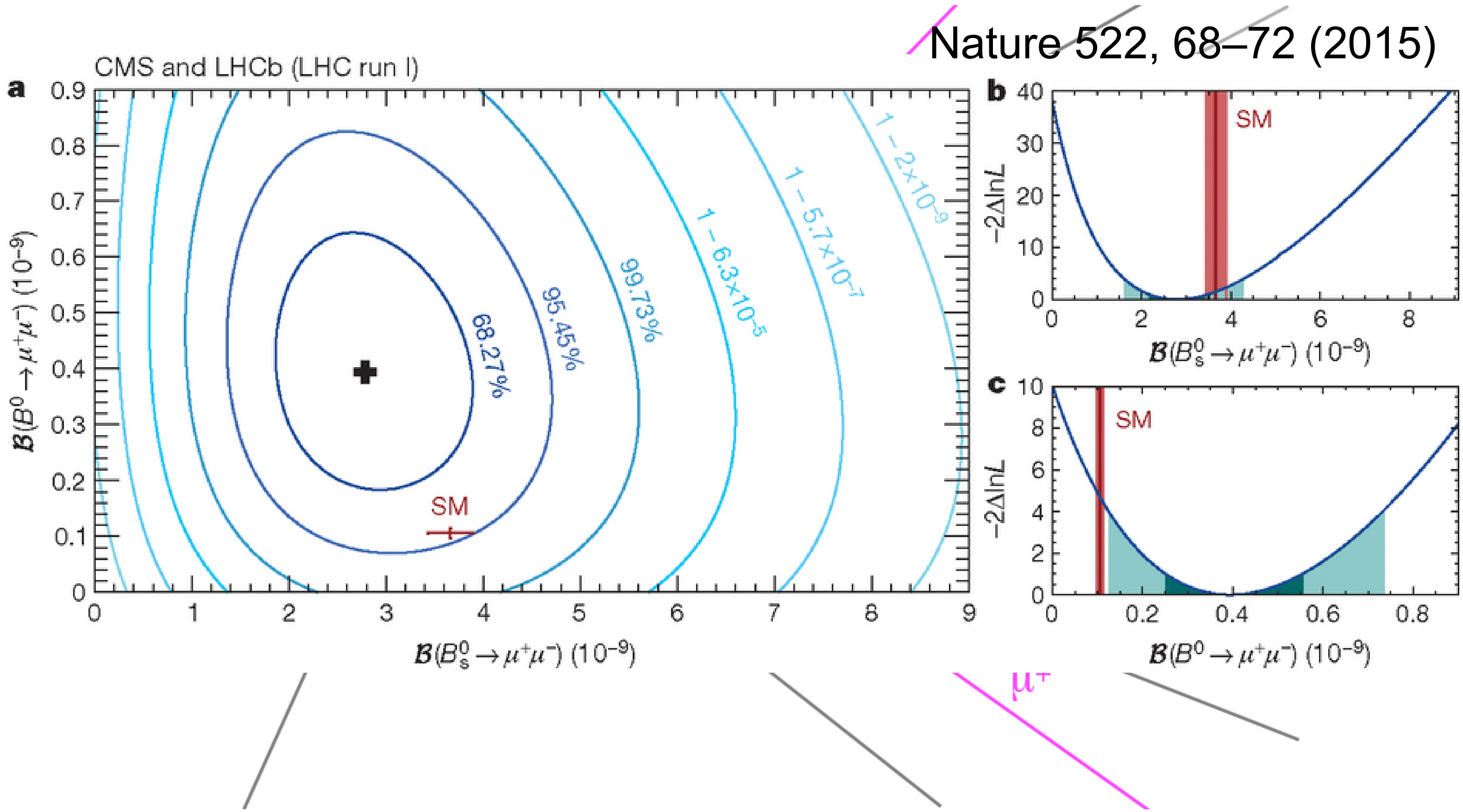
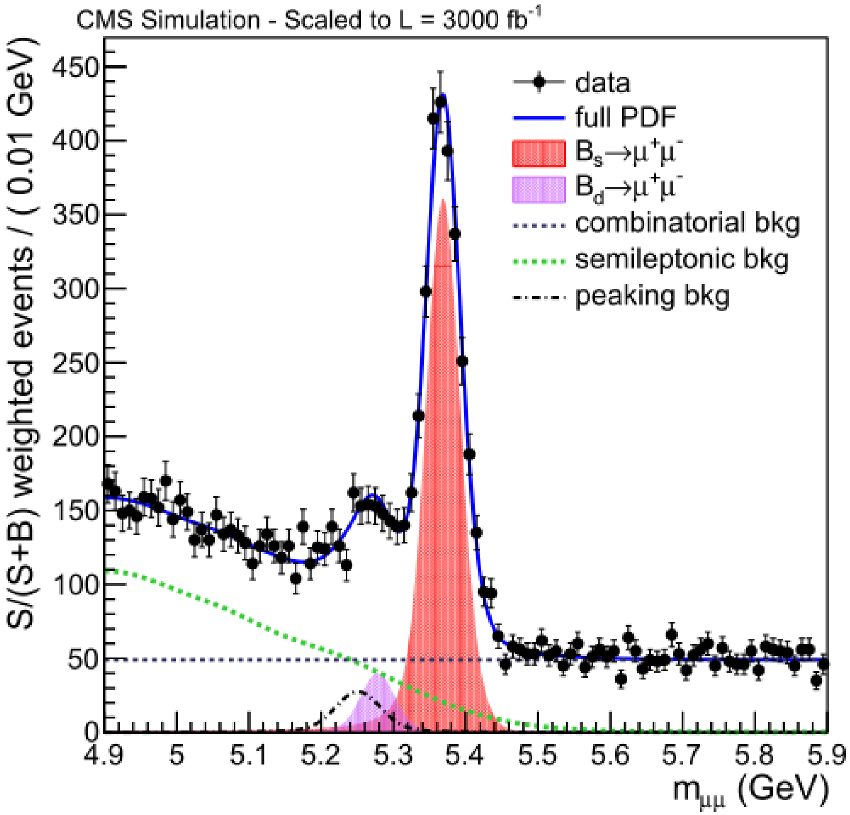


$B \to \mu^+\mu^-$

For Run II, the clear goal is to aim observation of $B^0 \to \mu^+\mu^-$

- In the SM suppressed by $|V_{ts}|^2/|V_{td}|^2 \sim 25$
- LHCb upgrade expect to measure the ratio to a 35% accuracy
- CMS upgrade at full 3 ab^{-1} expected to reduce this to 21%
  - Depends critically on ability to keep peaking backgrounds under control

CMS PAS FTR-13-016



$B^0_s \to \tau^+\tau^-$ an interesting opportunity for TLEP

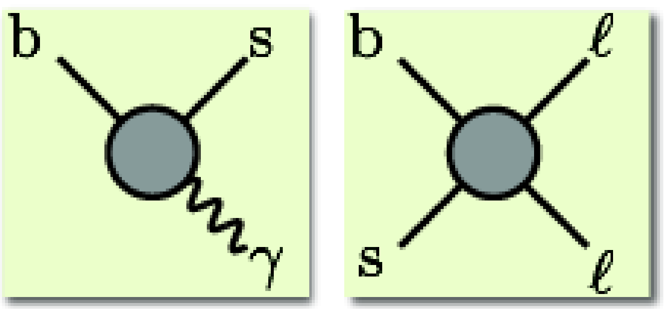
The penguin laboratory

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

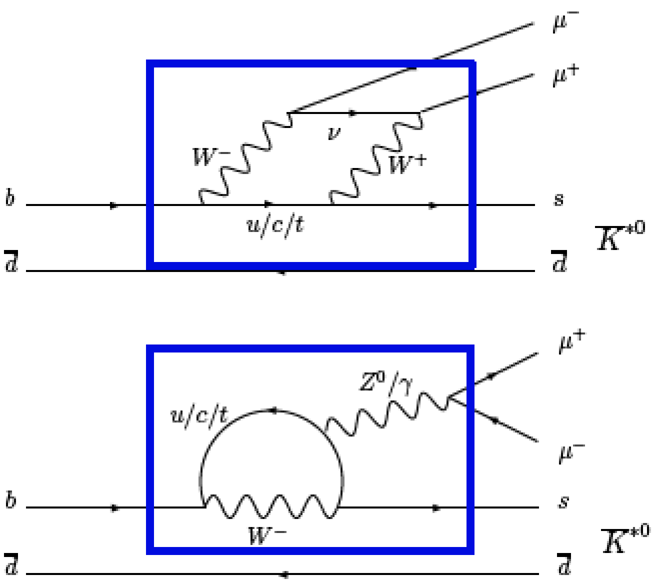
On the other hand NP can show up at either tree or loop level

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

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

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

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

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

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

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

Which can then form CP averaged quantities and CP asymmetries

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

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

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

$$P'_5 = S_5\sqrt{F_L(1-F_L)} \ , \quad 2F_L \equiv S_{1c}$$

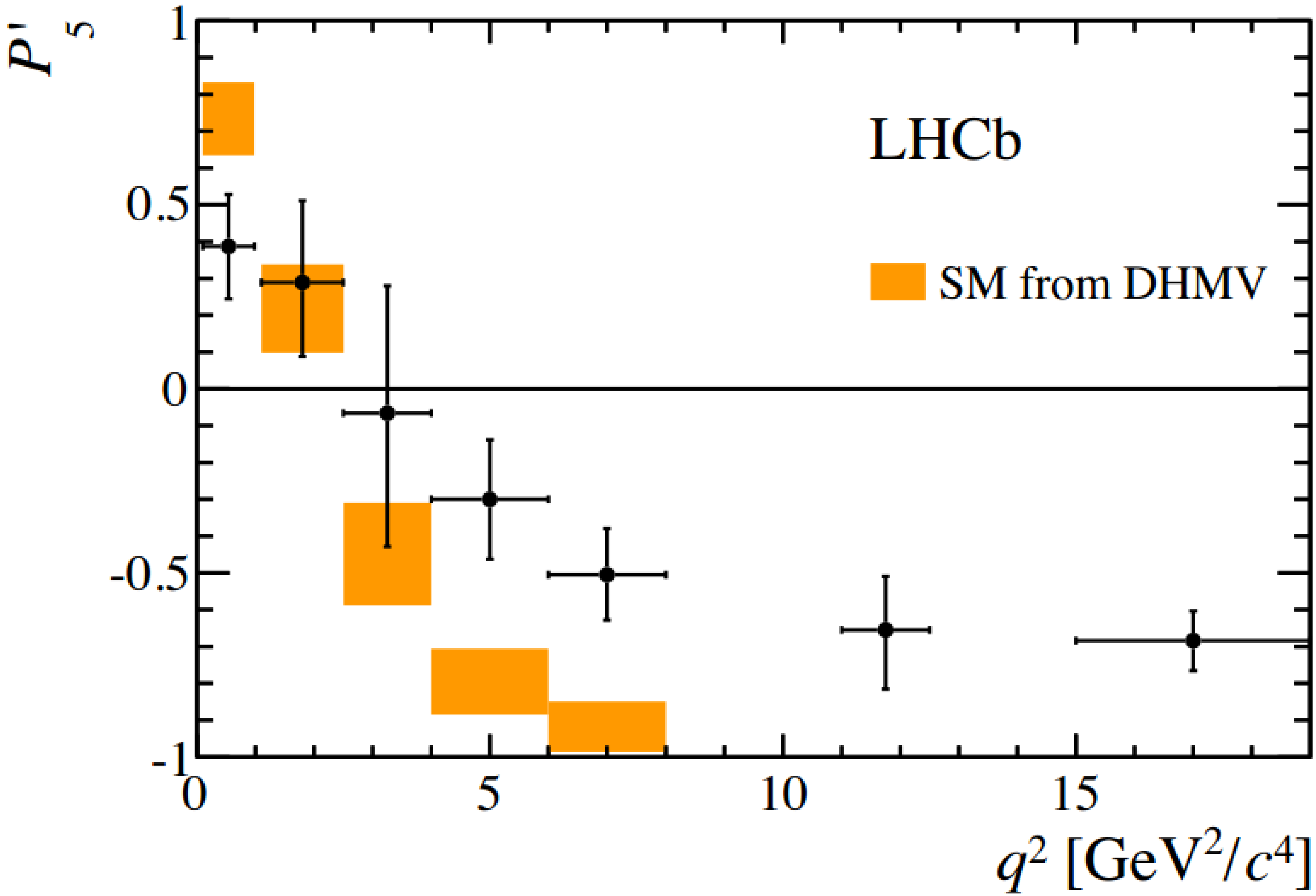
Several observables also have reduced uncertainty of zero points

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

LHCb : ArXiv: 1512.04442

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

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

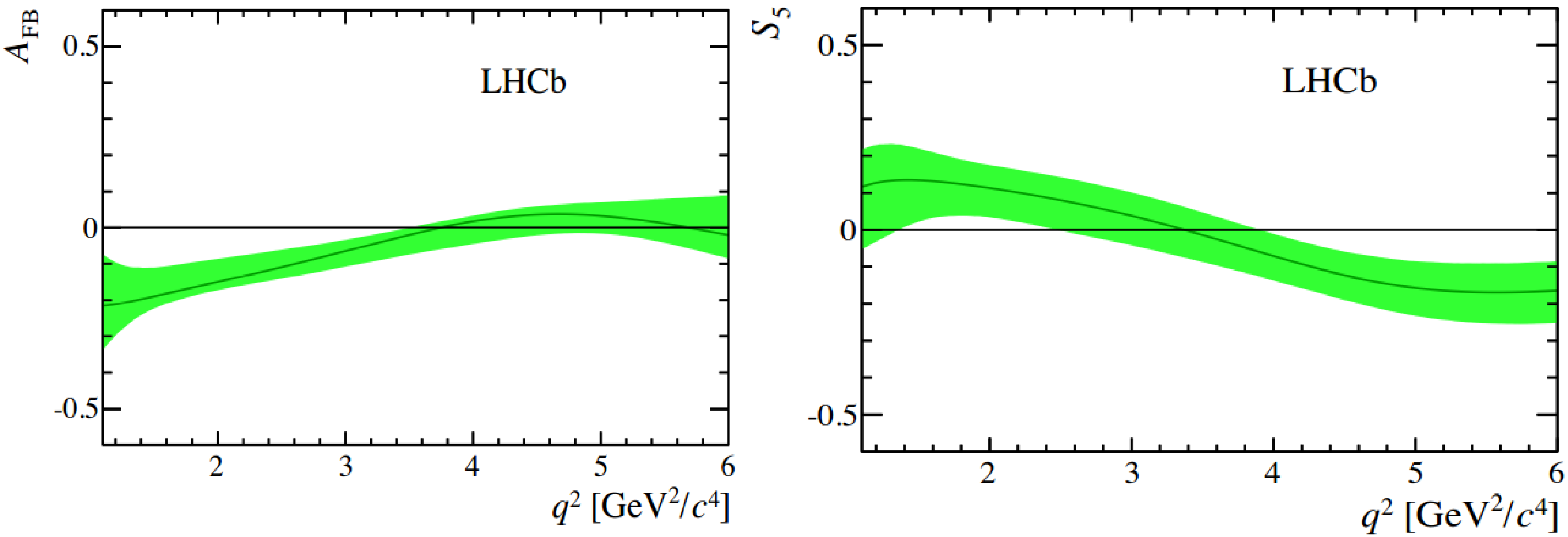


LHCb : ArXiv: 1512.04442

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

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

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



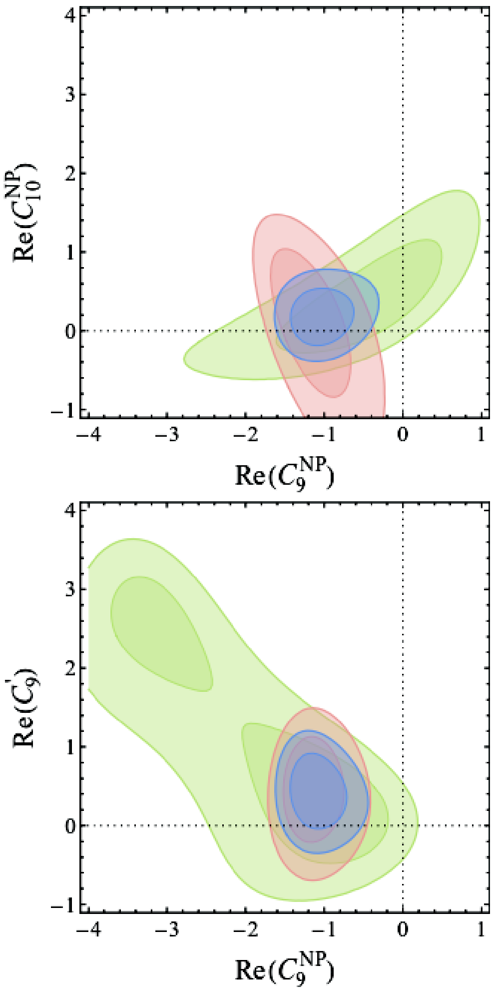
$$q_0^2(S_5) \in [2.49, 3.95]\,\mathrm{GeV}^2/c^4 \quad @\ 68\%\ \mathrm{CL}$$

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

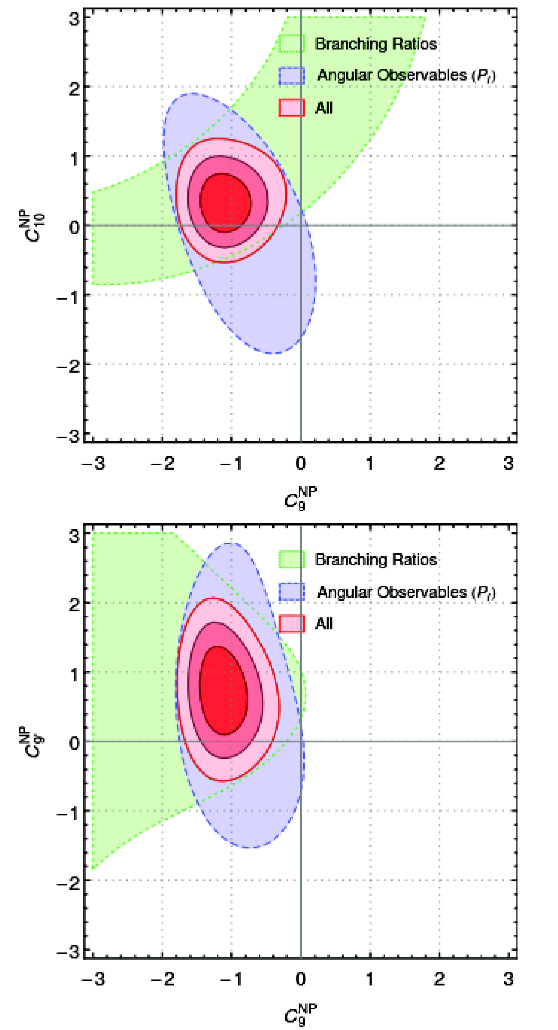
Performing global fits

From C. Bobeth, LHCb implications workshop

[Altmannshofer/Straub 1411.3161 & 1503.06199]



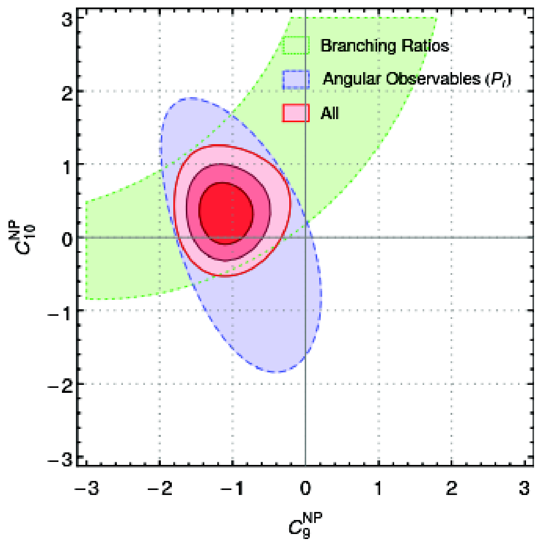
[Descotes-Genon/Hofer/Matias/Virto 1510.04239]

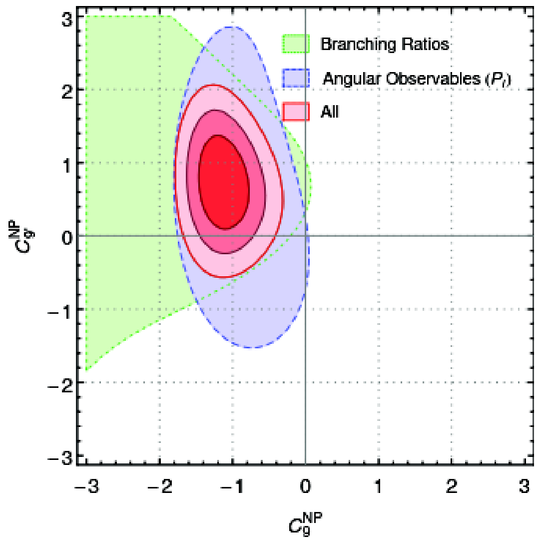


angular obs's (S_i) branching ratios

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 0.1% level

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

For μ-τ universality the 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}

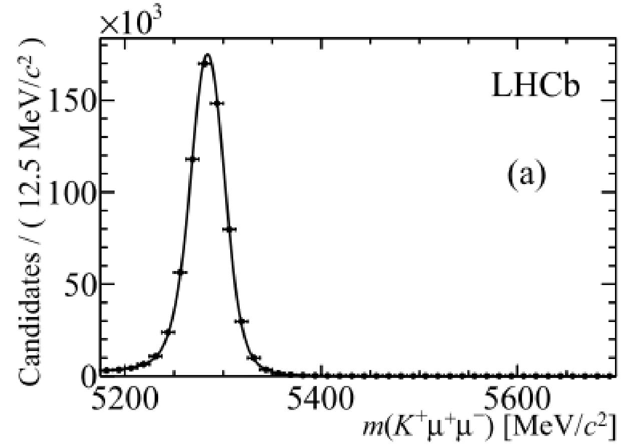
The ratio

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

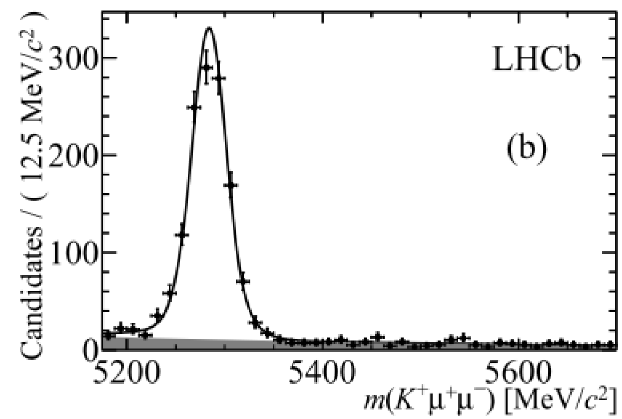
Sensitive to lepton flavour violating NP

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



$B^+ \to K^+ J/\psi$

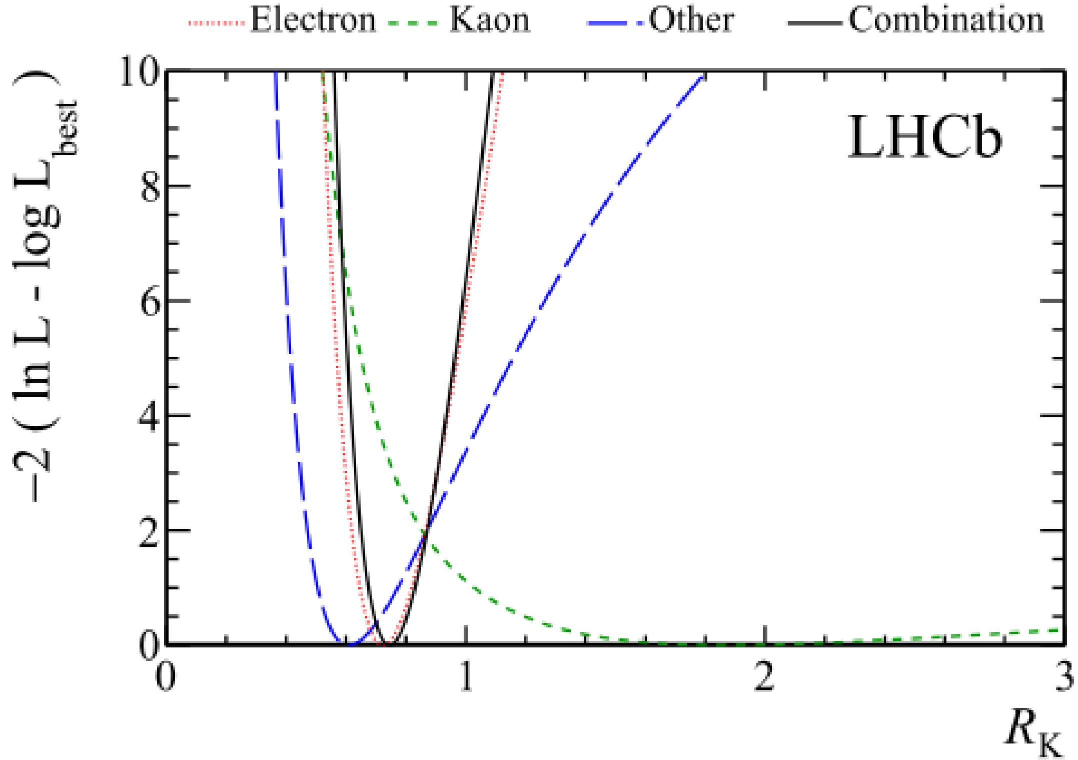


$B^+ \to K^+\mu^+\mu^-$

LHCb : PRL113, 151601 (2014)

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

For the electron channel, analysis divided up in categories



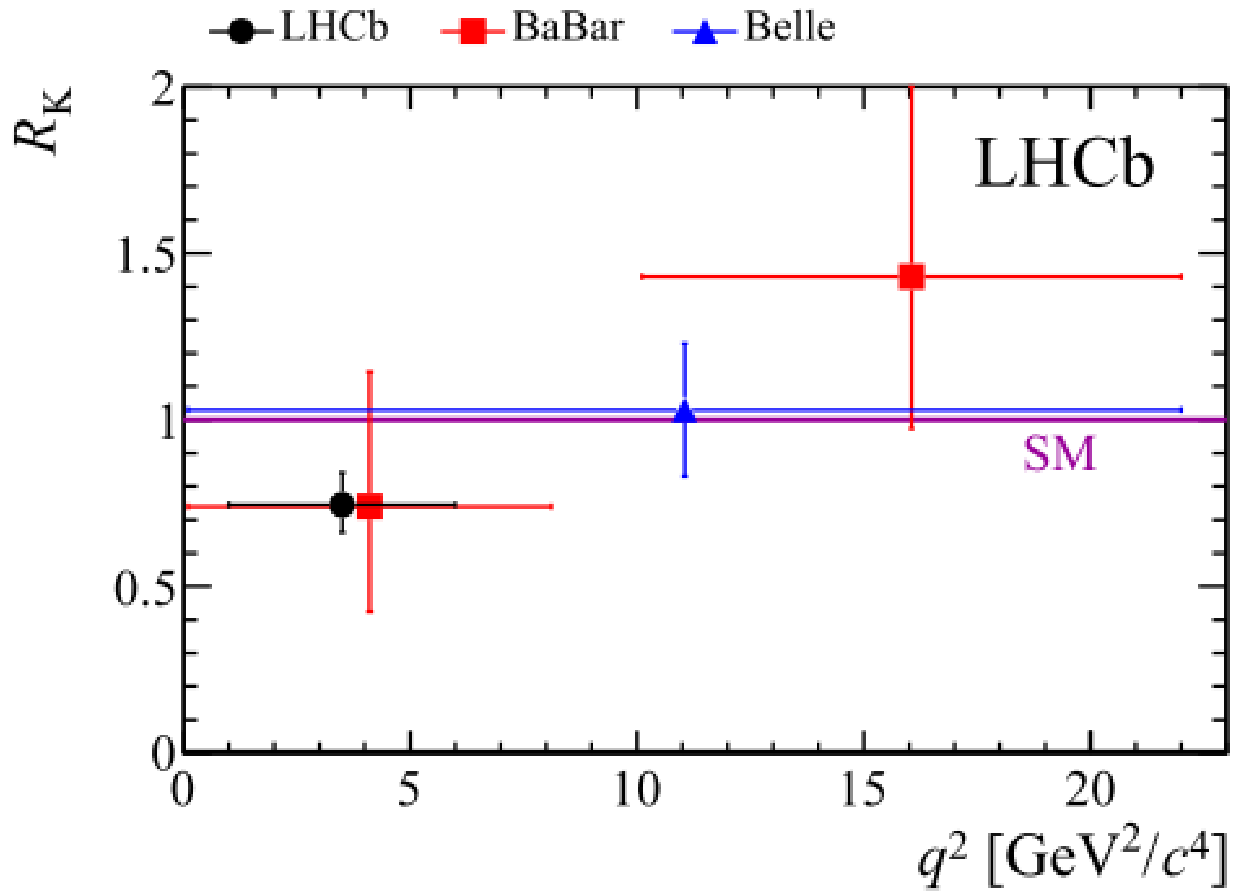
Electron mode control overall uncertainty

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

LHCb : PRL113, 151601 (2014)

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

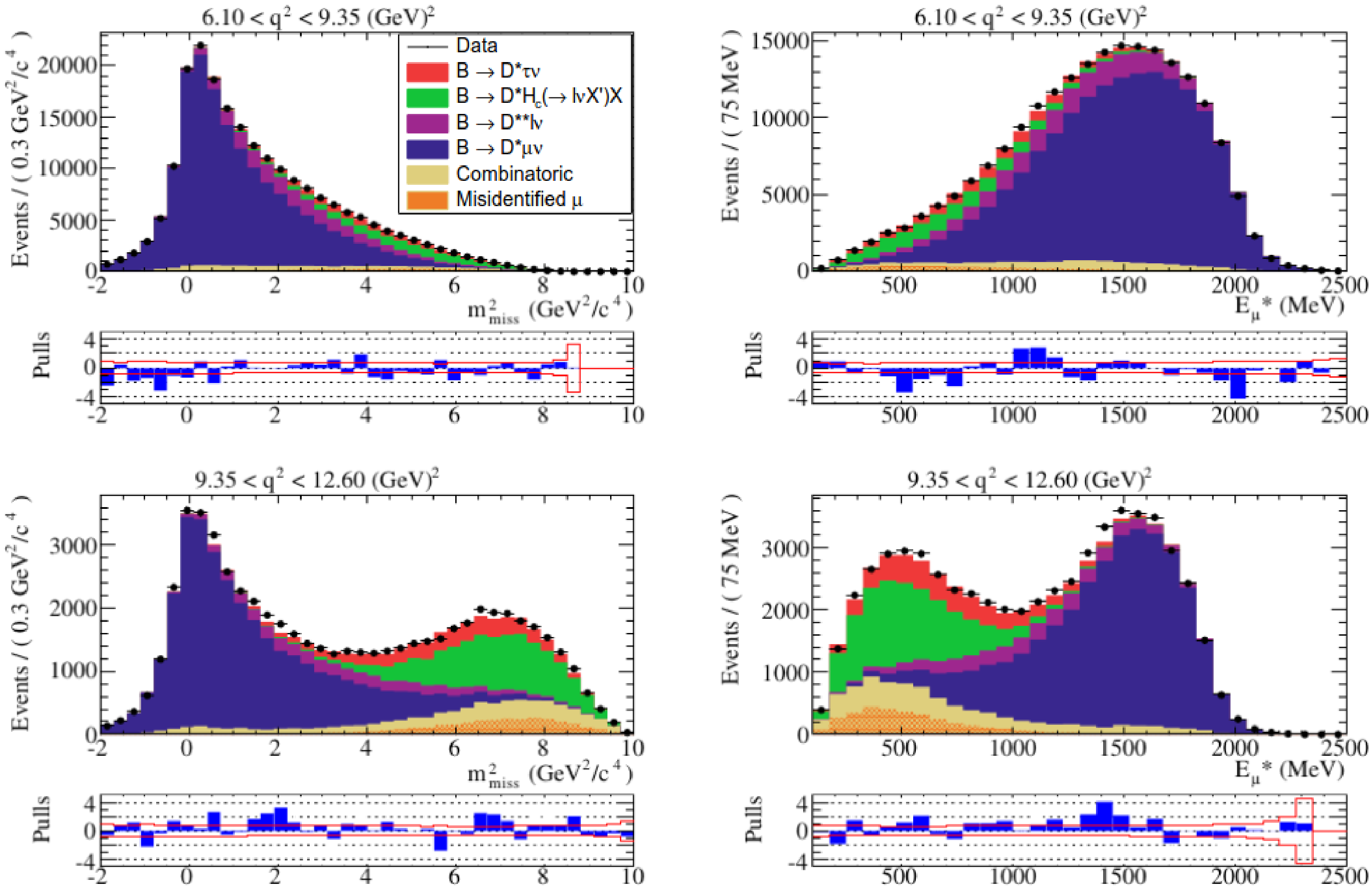
Measurement is compatible with earlier, but less precise measurements



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

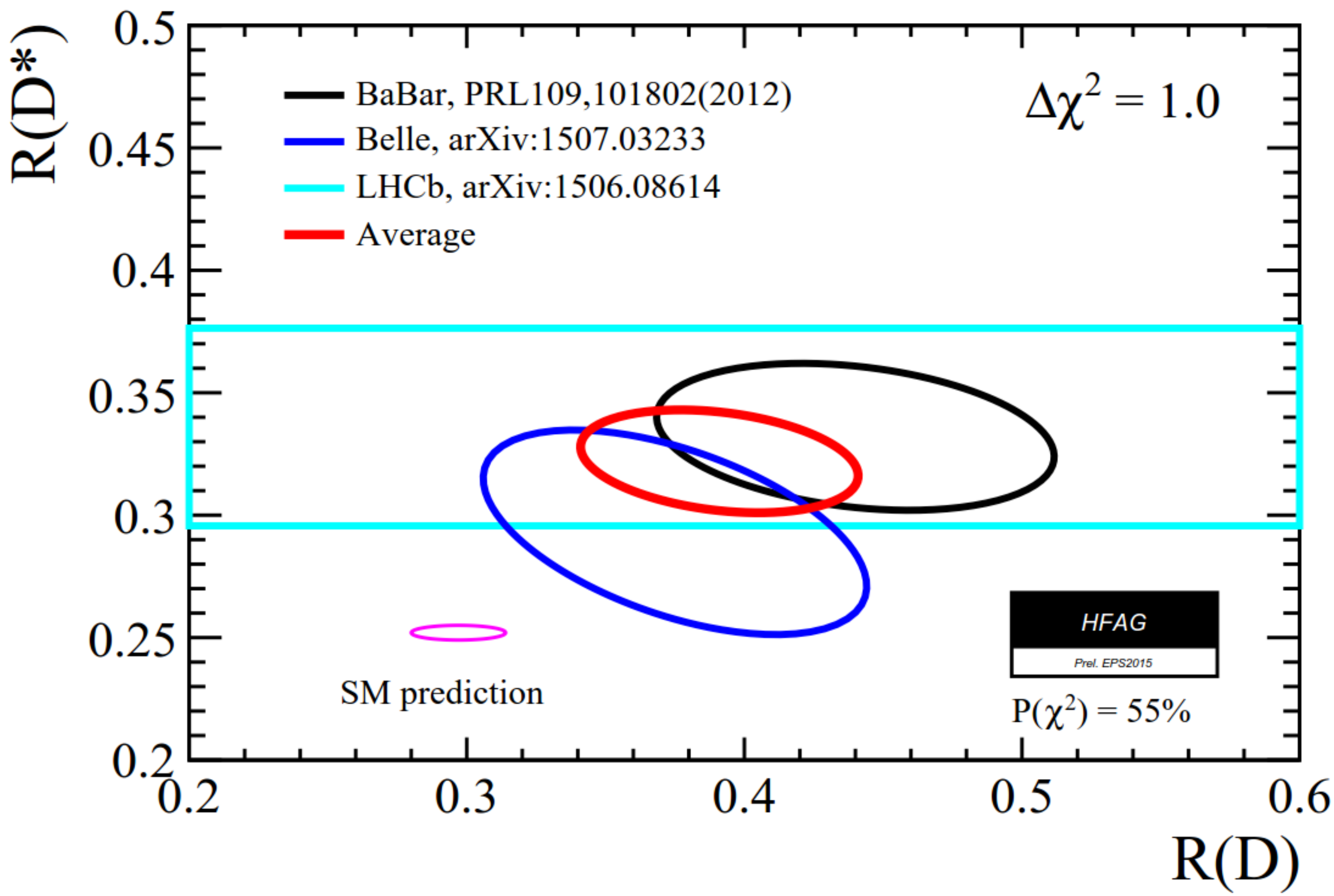
LHCb recent result

Phys. Rev. Lett. 115 (2015) 112001



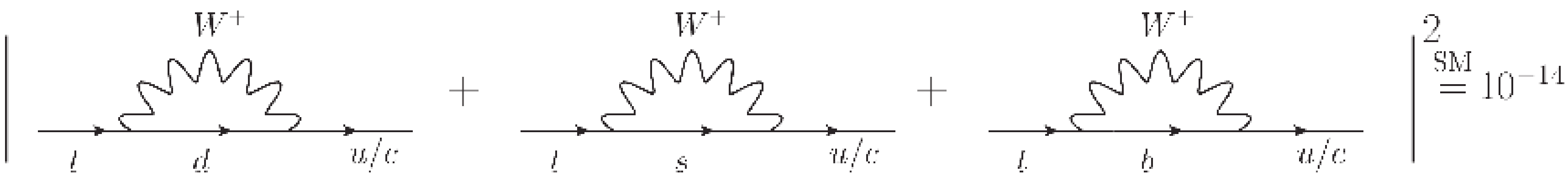
$B^+ \rightarrow D^{(*)+} \tau \nu$ global fit

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



Flavour changing neutral currents in top

With massless quarks, flavour changing neutral current decays are forbidden in the SM (GIM mechanism)



Comparing to the top mass, all other quarks **are** nearly massless

FCNC for top ($t \rightarrow c$ X, $t \rightarrow u$ X) are suppressed by huge factor in SM

Not the case for many NP models

arXiv: 1311.2028

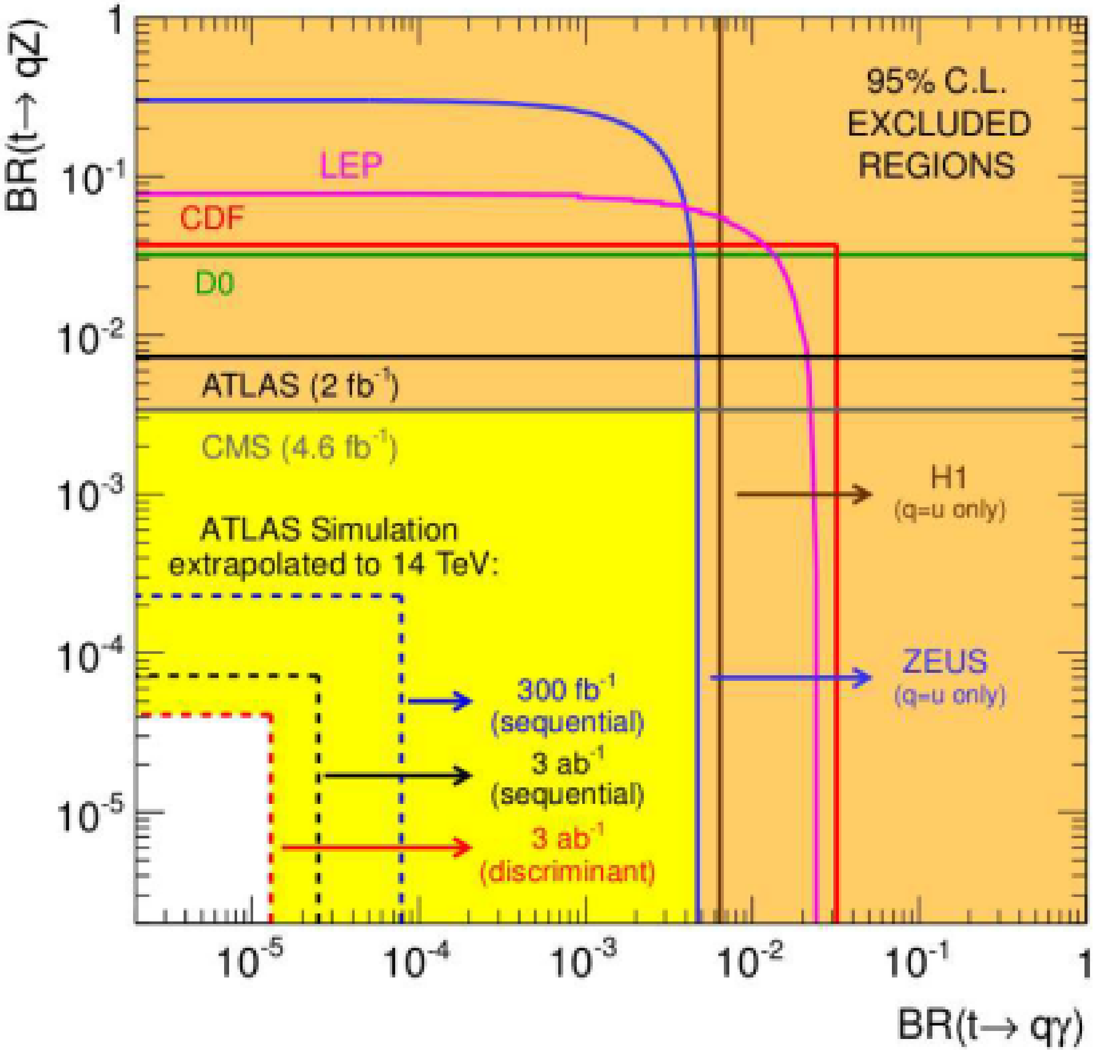
	2HDM	MSSM	RS
$t \rightarrow cZ$	$\lesssim 10^{-6}$	$\lesssim 10^{-7}$	$\lesssim 10^{-5}$
$t \rightarrow c\gamma$	$\lesssim 10^{-7}$	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$
$t \rightarrow cg$	$\lesssim 10^{-5}$	$\lesssim 10^{-7}$	$\lesssim 10^{-10}$
$t \rightarrow ch$	$\lesssim 10^{-2}$	$\lesssim 10^{-5}$	$\lesssim 10^{-4}$

Flavour changing neutral currents in top

ATLAS/CMS searches in

- single top
- t→Zq decays

ATL-PHYS-PUB-2013-007



Flavour changing neutral currents in top

ATLAS/CMS searches in

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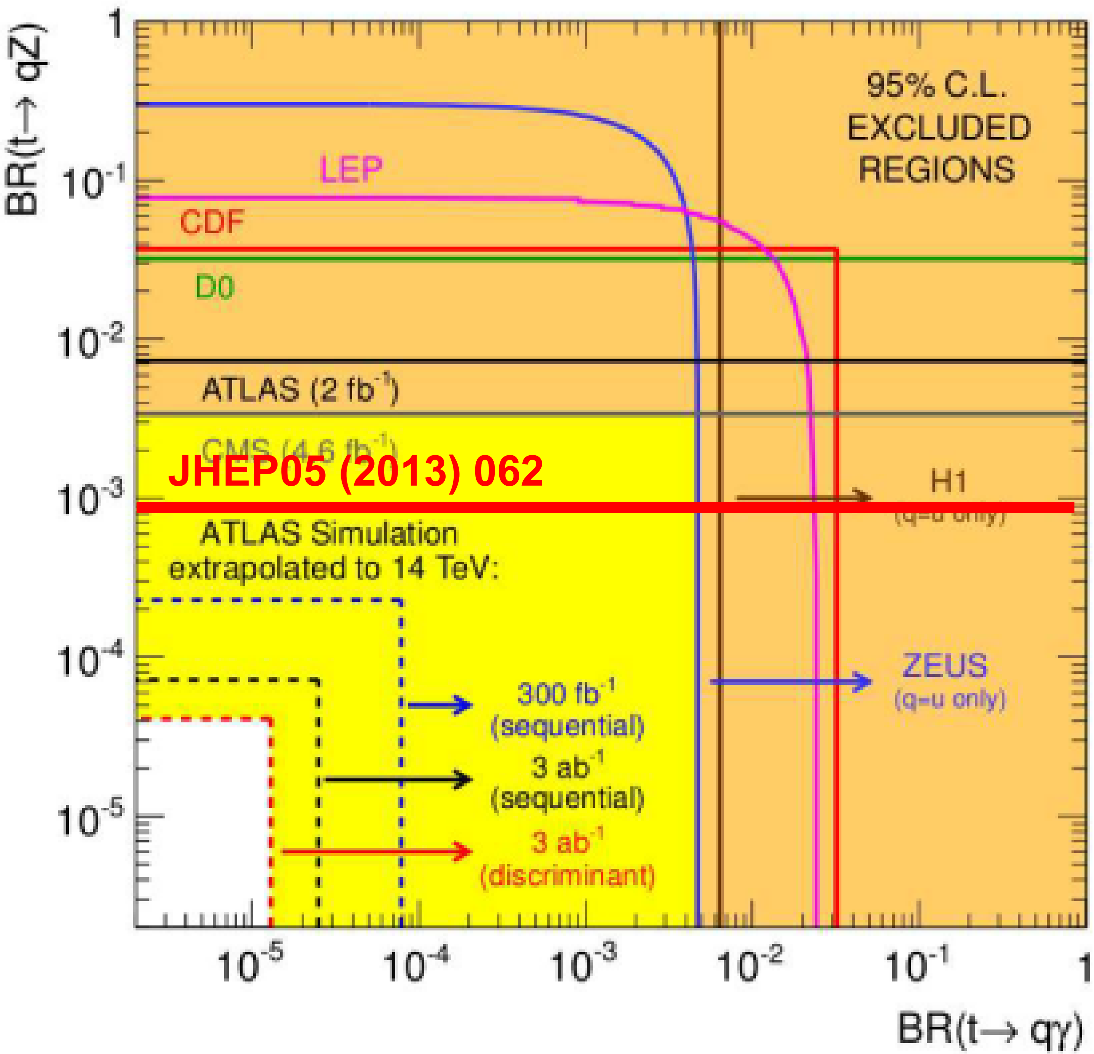
But at the moment effects on B penguin decays sets a better limit (LHCb)

ATL-PHYS-PUB-2013-007



Flavour changing neutral currents in top

ATLAS/CMS searches in

- single top
- t→Zq decays

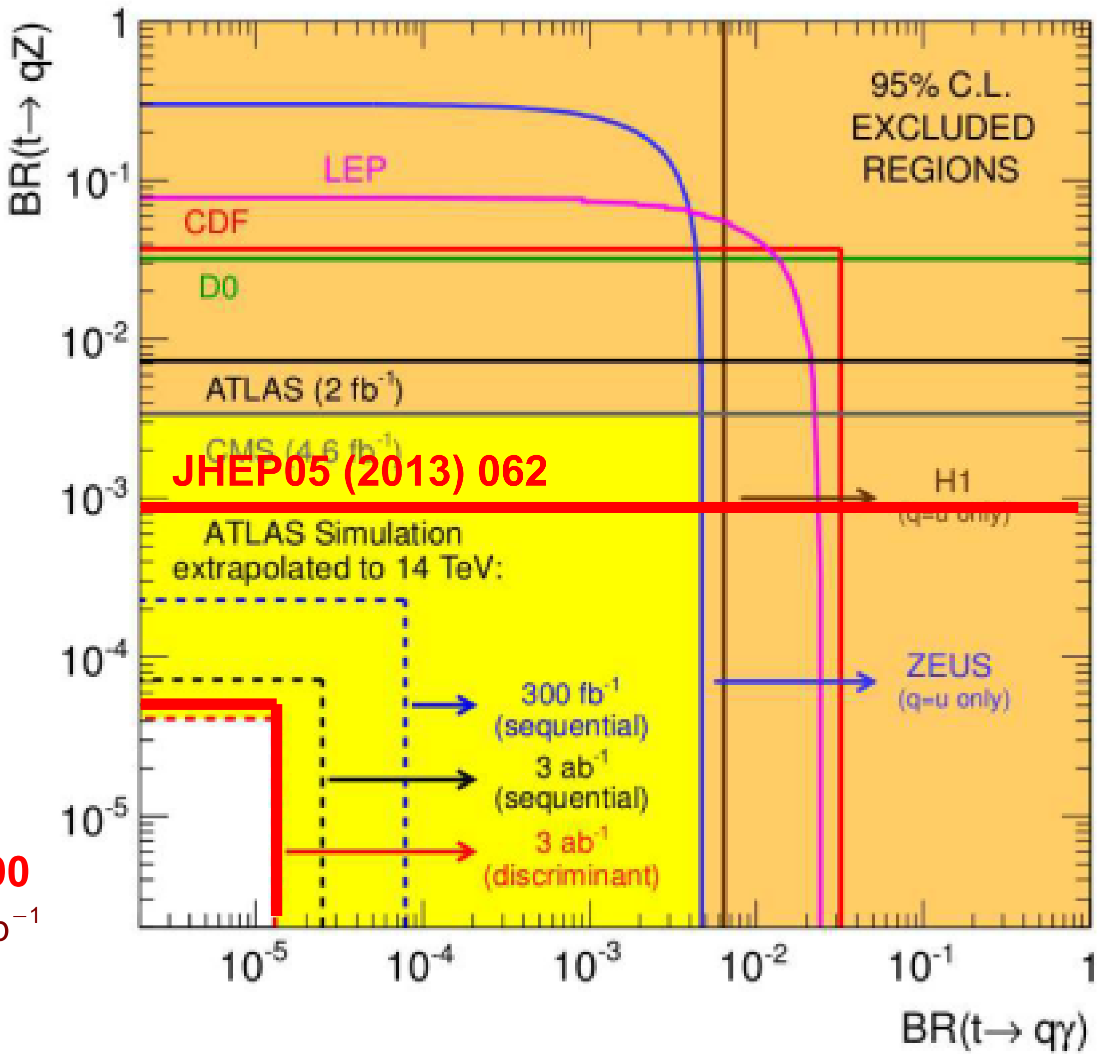
But at the moment effects on B penguin decays sets a better limit (LHCb)

But TLEP is also very competitive

arXiv:1408.2090

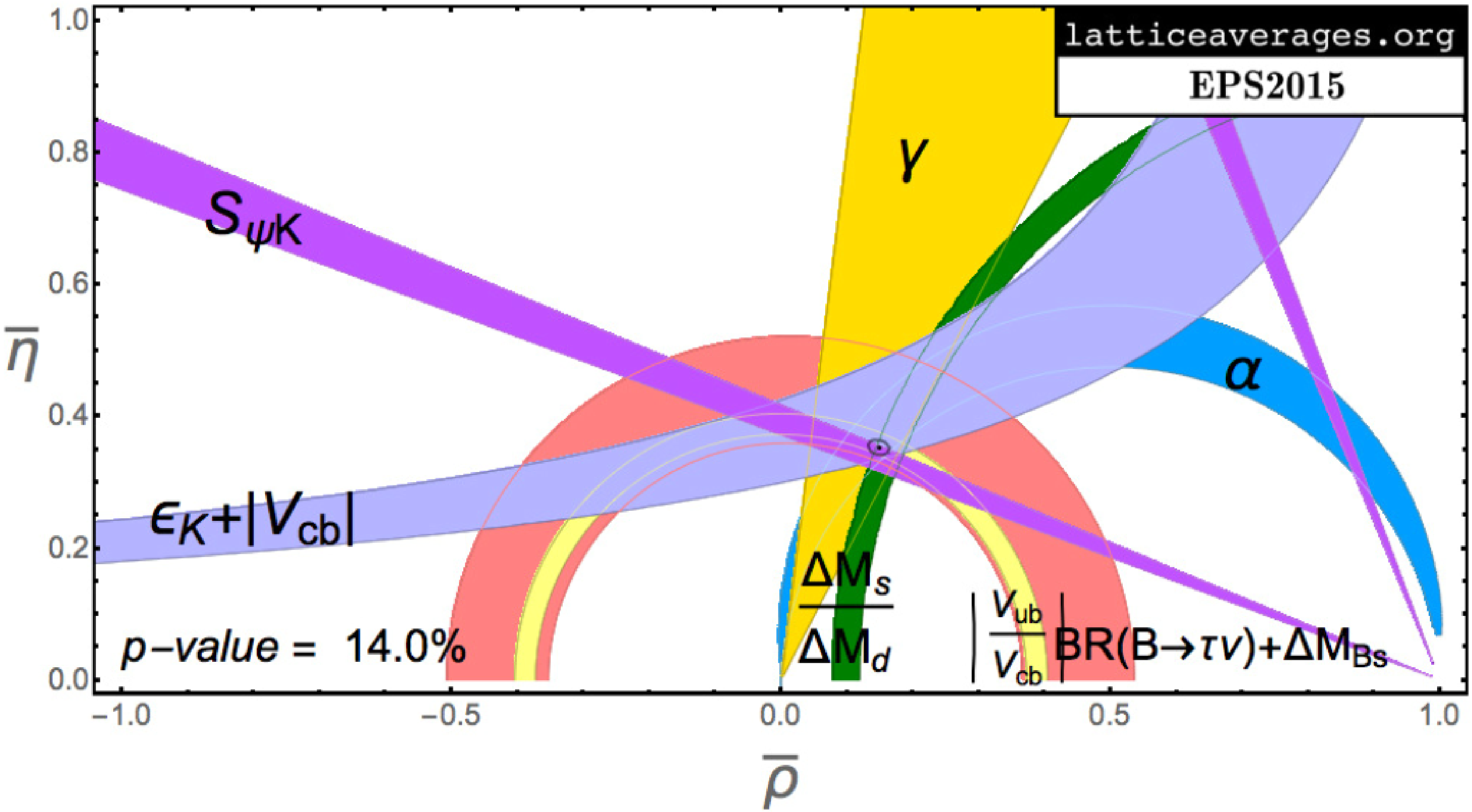
$\sqrt{s}=350\,\text{GeV},\ \int L=100\,\text{fb}^{-1}$

ATL-PHYS-PUB-2013-007



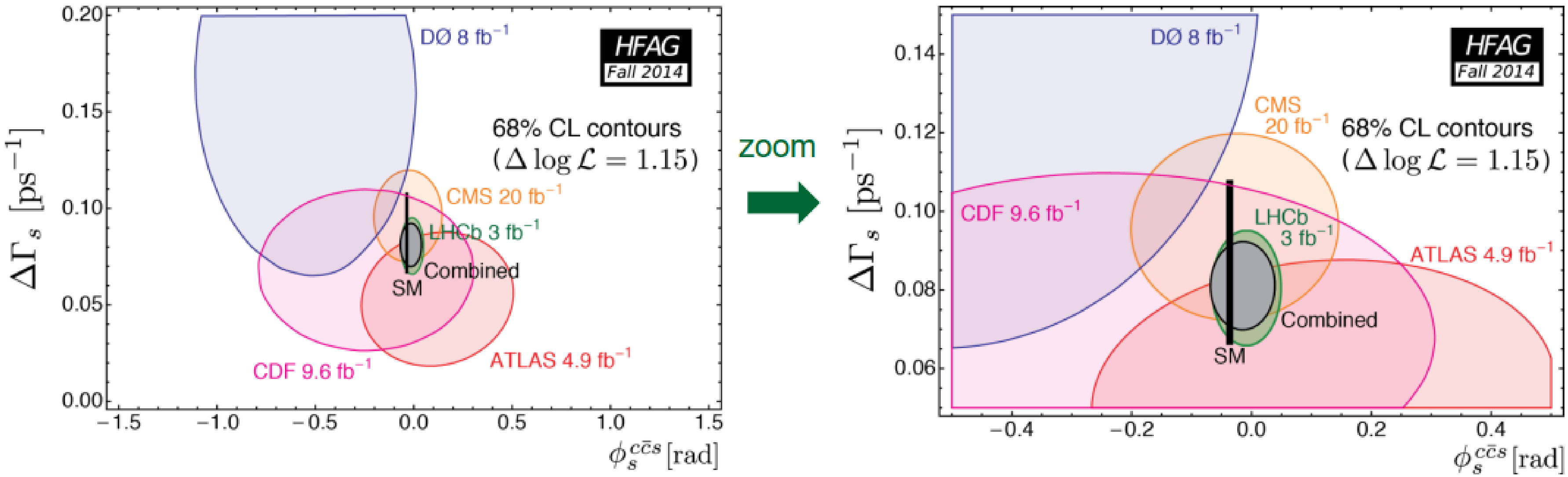
No heavy flavour *CP* violation anomalies?

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

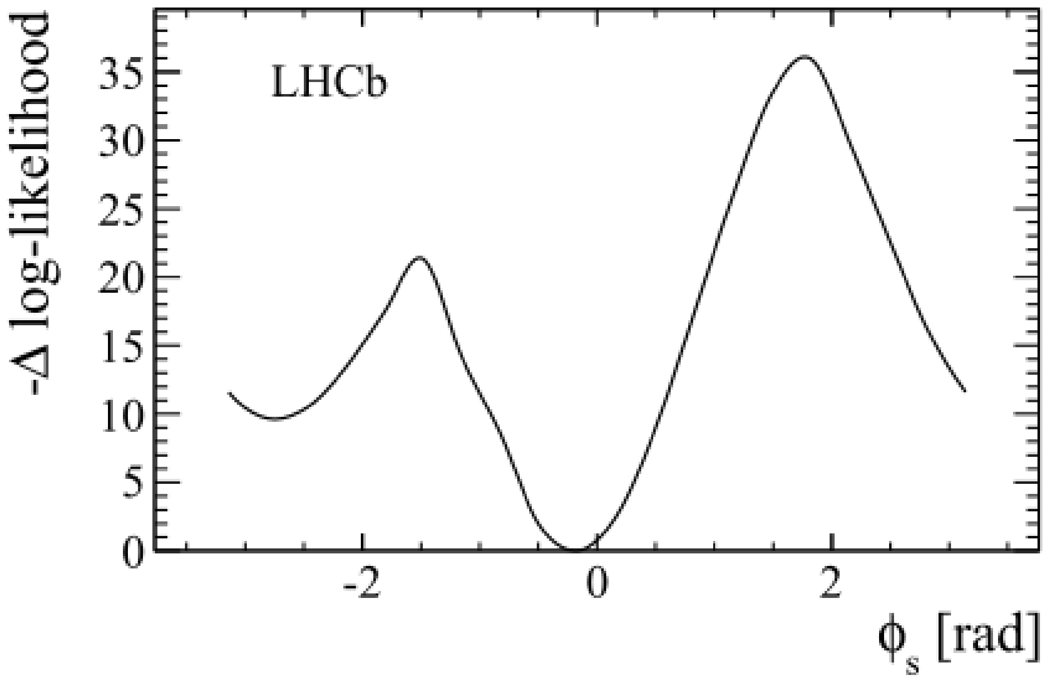


The theoretical uncertainty is still very small compared to experimental uncertainty

LHCb : PRD 90 (2014) 5, 052011

CP violation in $B^0_s \rightarrow \varphi\varphi$

Current status of LHCb $B^0_s \rightarrow \varphi\varphi$ measurement



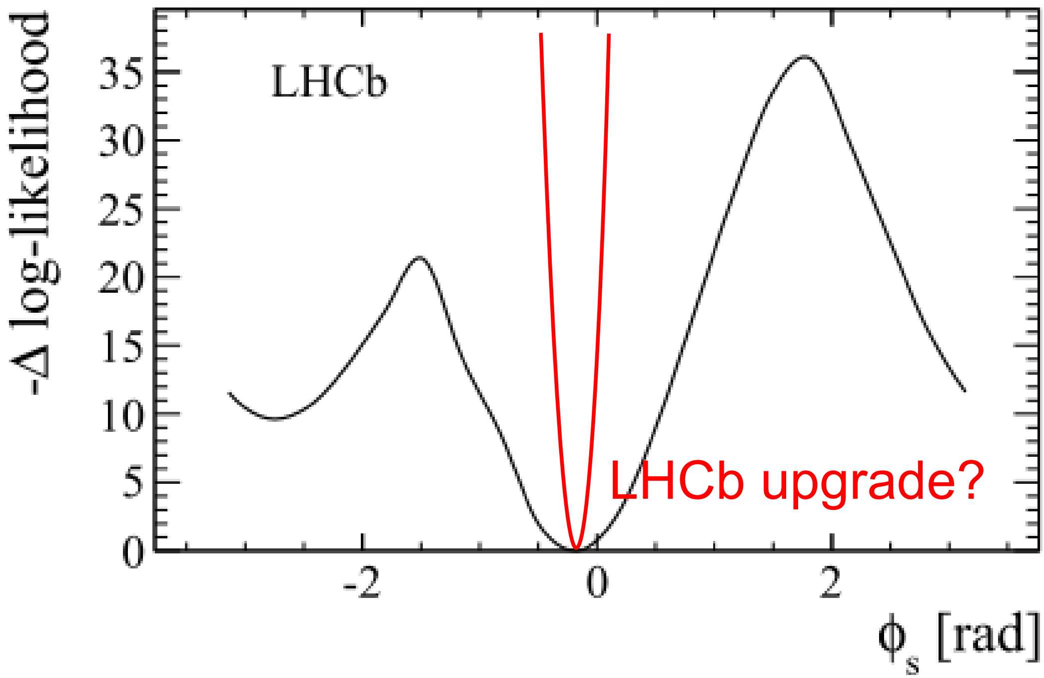
No significant CP violation observed

$$\phi_s = -0.17 \pm 0.15\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})\ \ \mathrm{rad}$$

LHCb : PRD 90 (2014) 5, 052011

CP violation in $B^0_s \rightarrow \varphi\varphi$

Current status of LHCb $B^0_s \rightarrow \varphi\varphi$ measurement



LHCb upgrade will bring precision on this down to 0.02

- Same level as the current theoretical uncertainty

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

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

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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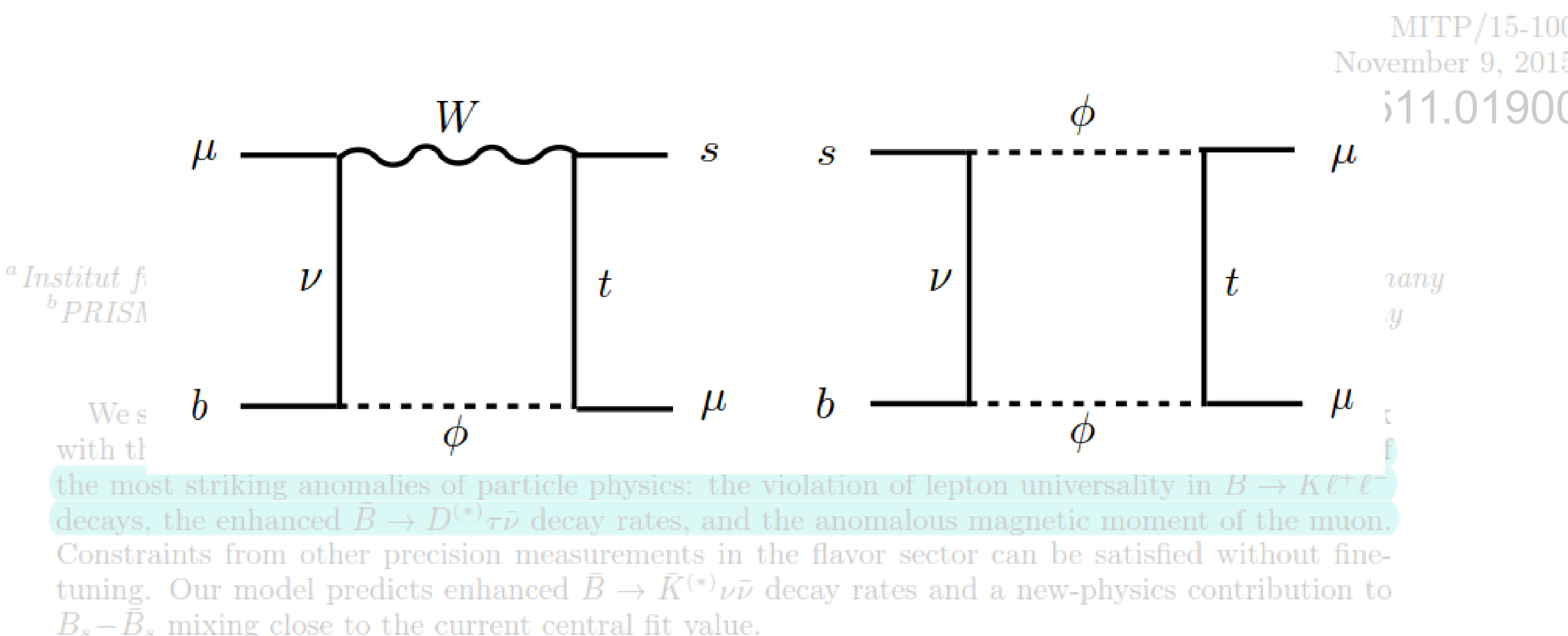
We show that by adding a single new scalar particle to the Standard Model, a TeV-scale leptoquark with the quantum numbers of a right-handed down quark, one can explain in a natural way three of the most striking anomalies of particle physics: the violation of lepton universality in $\bar{B} \to \bar{K}\ell^+\ell^-$ 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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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}

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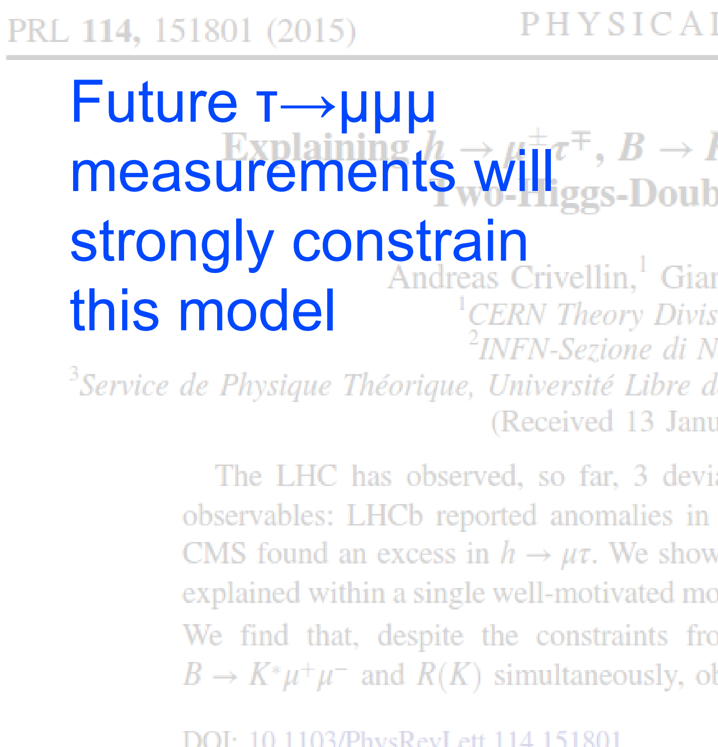
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Explaining $h \to \mu^\pm\tau^\mp$, $B \to K$ ... Two-Higgs-Doub...

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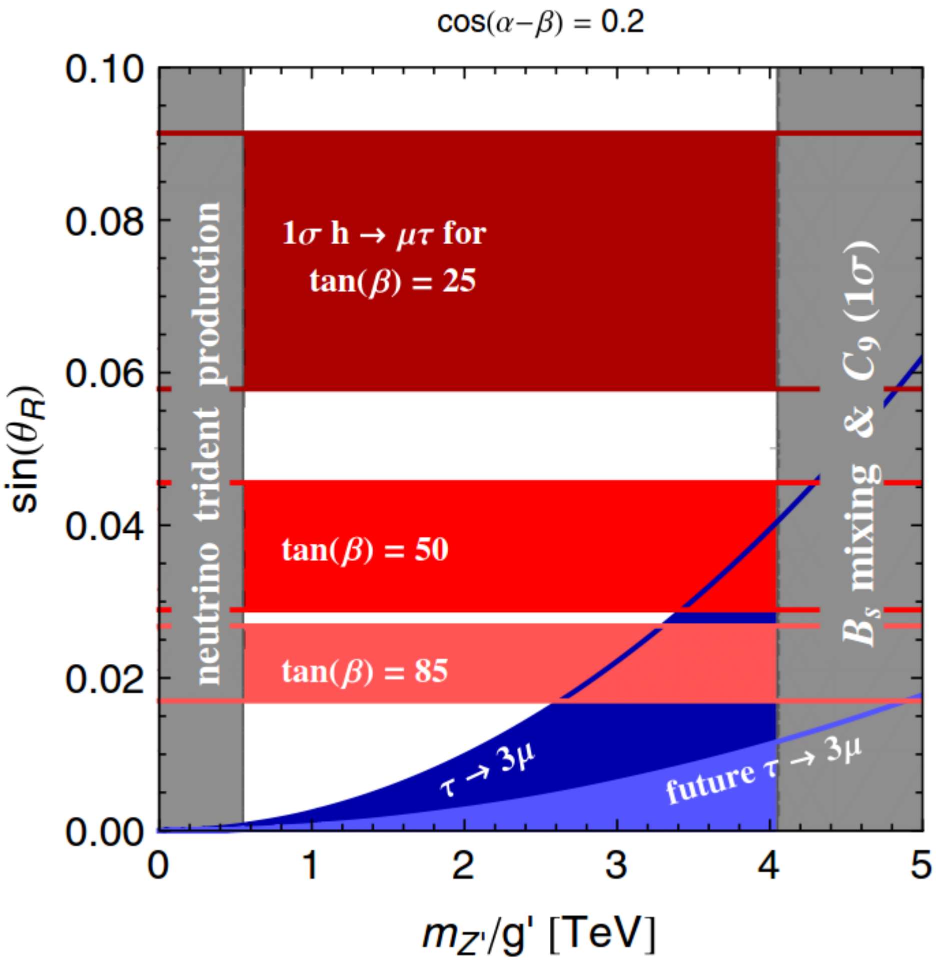
- Future τ→μμμ measurements will strongly constrain this model



Conclusion

Heavy flavour physics has a rich future ahead

- Will the current anomalies turn into discoveries?

Key is to ensure that both theoretical and systematic uncertainties are under control

All future facilities

- LHCb upgrade, Belle-II, CMS/ATLAS, TLEP

have their respective strengths

As always the combined information is what will be able to reveal New Physics