S. Stone

New Physics Searches in $b\rightarrow s\ell\ell$ Decays

DPF, August, 2017

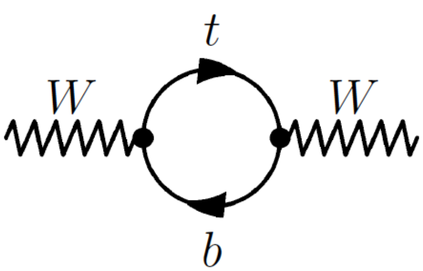
Physics rationale

- Finding New Particles, arising from New Forces is the goal of High Energy Physics
- Motivated by: dark matter, hierarchy problem, particle masses, origin of CKM elements
- ATLAS & CMS can detect these directly
- LHCb & other flavor physics experiments (Belle II, BES III, DUNE, Muon g-2, μ to e conversion) do this indirectly

Effects on M_W from quantum loops

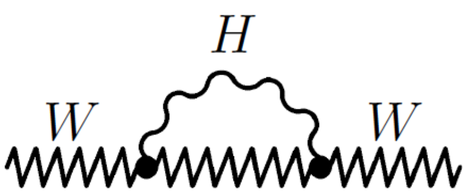
- FP probes large mass scales via virtual quantum loops. An example, of the importance of such loops are changes in the W mass
  - M_w changes due to m_t

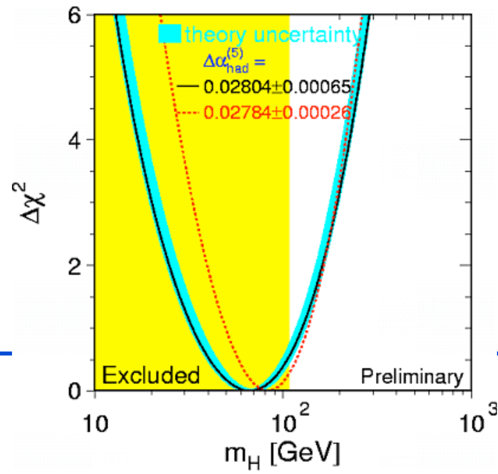
$$\frac{dM_W}{dm_t} \alpha \frac{m_t}{M_w}$$



  - M_w changes due to m_H Gave predictions of m_H prior to discovery

$$\frac{dM_W}{dm_H} \alpha - \frac{dm_H}{M_H}$$



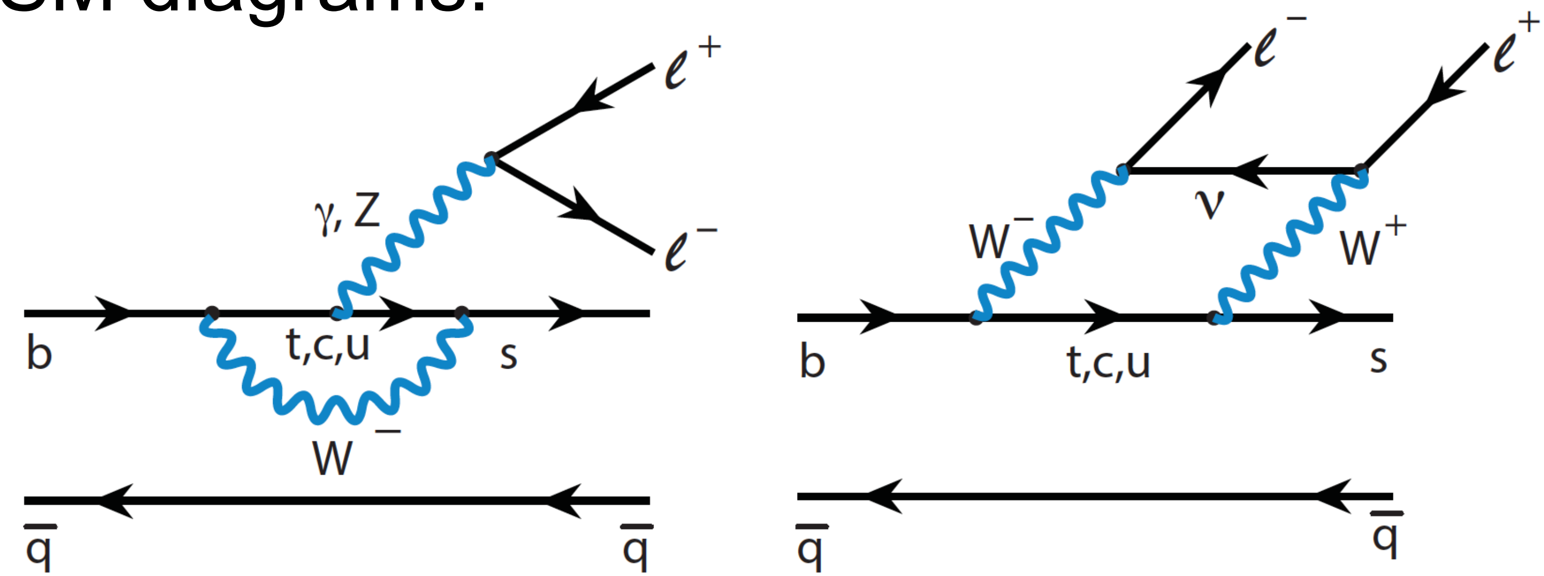


Lepton flavor universality

- In the SM differences between interactions of individual charged leptons can only be due to their masses, which leads to precise predictions
- $m_\tau/m_\mu/m_e$: 3477 / 207 / 1
- Seemed prudent to makes some tests
- Hiller & Kruger suggest order ~10% effects from some NP models (**hep-ph/0310219**)

Penguin decays

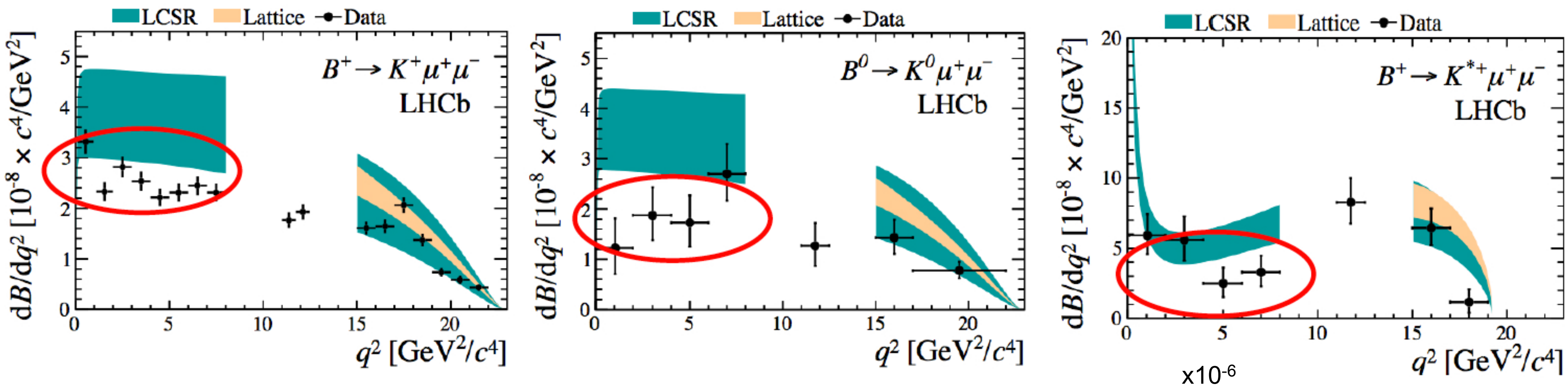
- NP may be seen easier in suppressed processes such as penguin decays
- SM diagrams:



- New particles can appear, augmenting SM ones
- Next: experimental tests

$q^2 = m^2(\mu^+\mu^-)$

$b \rightarrow h\mu^+\mu^-$ $d\mathcal{B}/dq^2$ - LHCb



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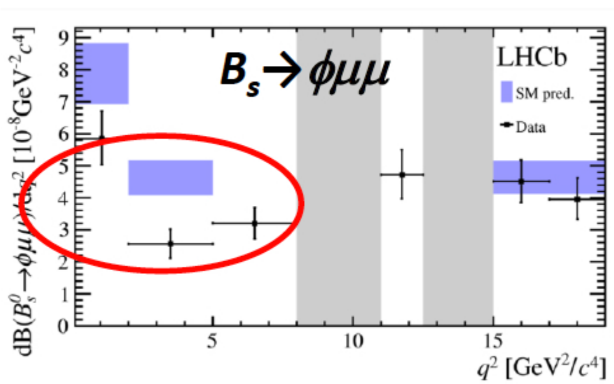

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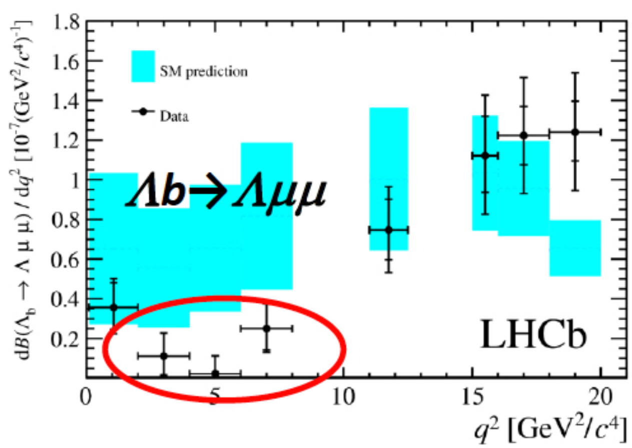

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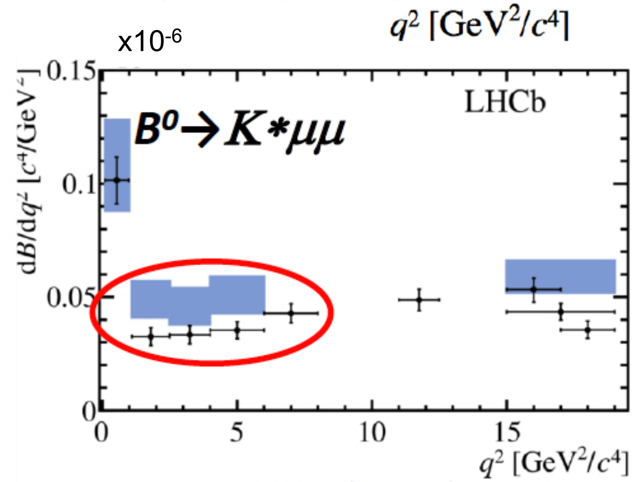

JHEP 11(2016)047
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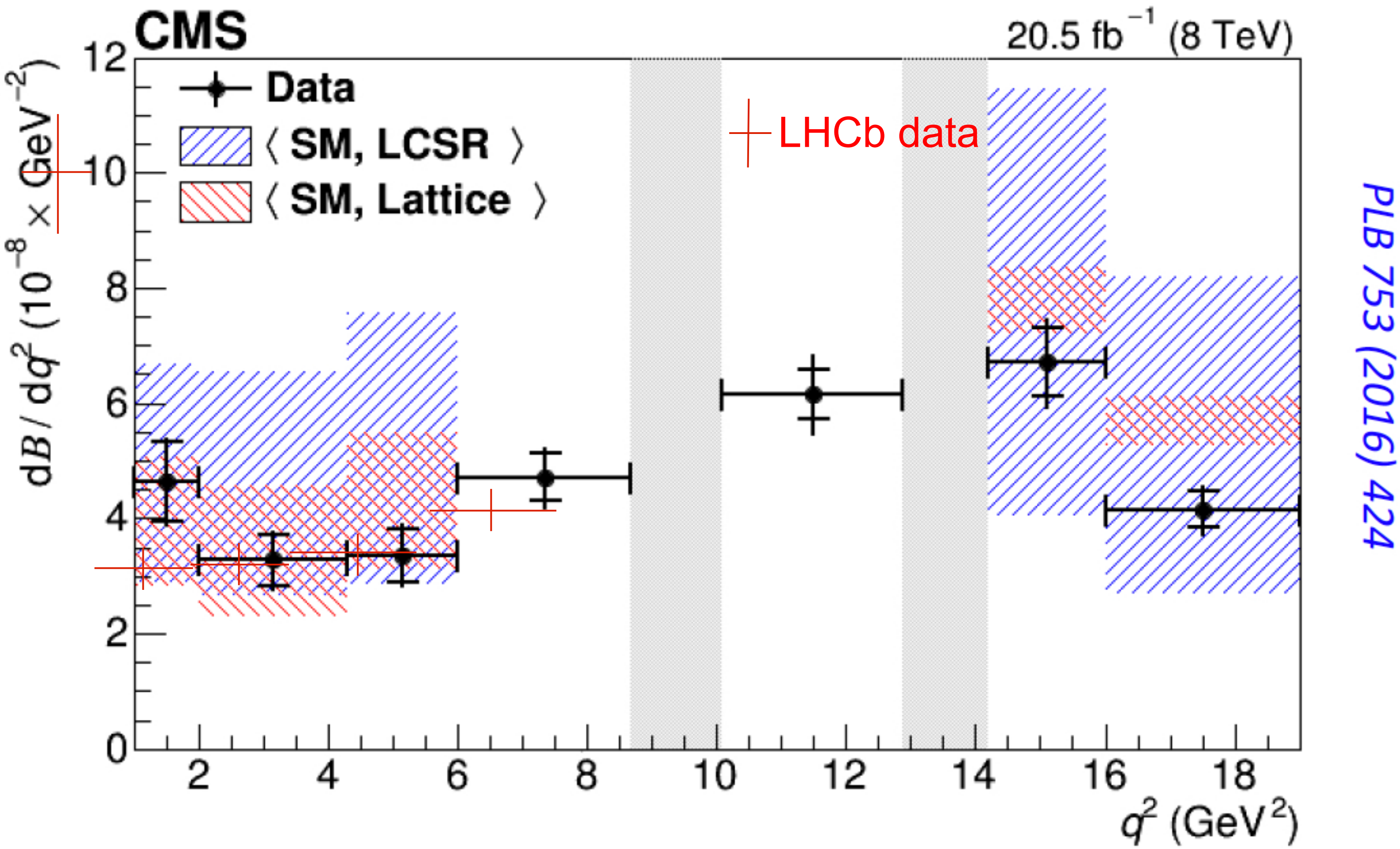
- Data generally below model predictions at low q^2

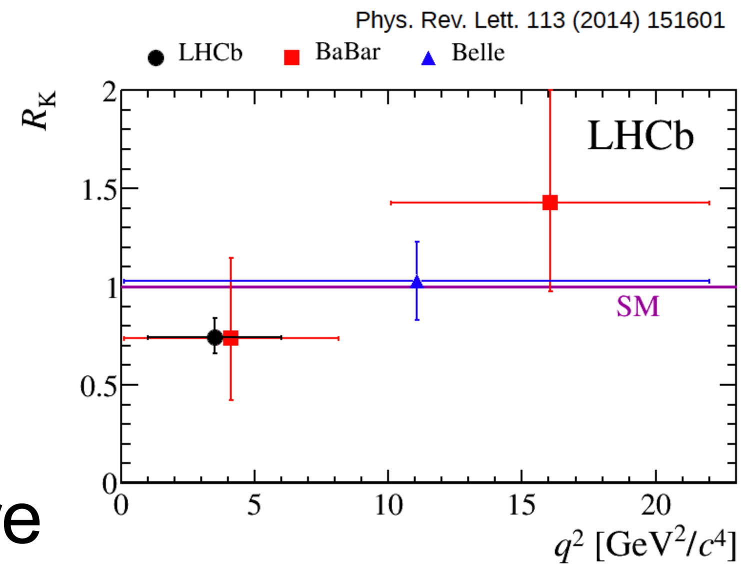
CMS $K^*\mu^+\mu^-$ $d\mathcal{B}/dq^2$

- Same for CMS, good agreement with LHCb, note different models

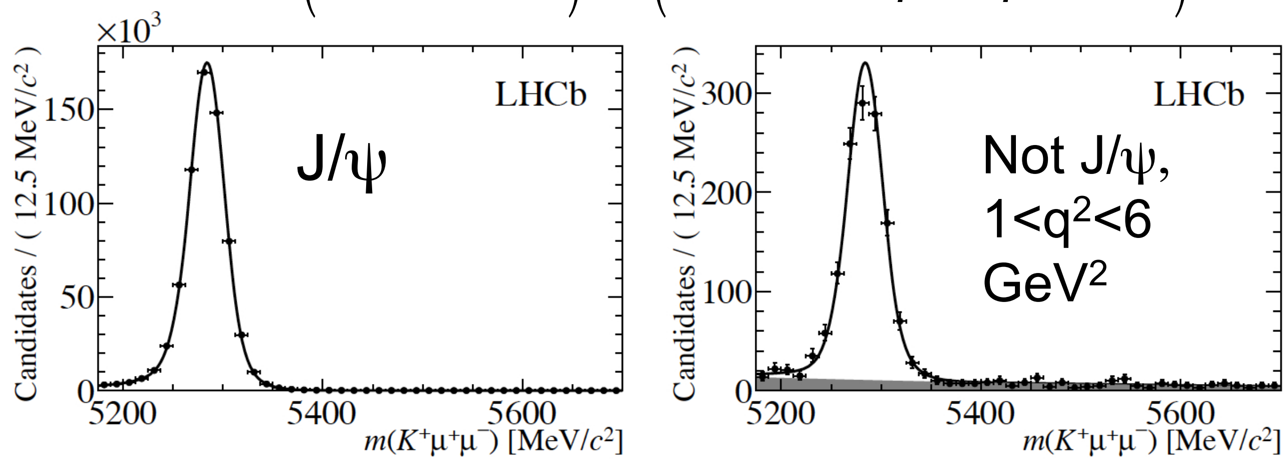


$B^- \to K^- \ell^+ \ell^-$

- $$R_K \equiv \frac{\mathcal{B}\left(B^- \to K^- \mu^+ \mu^-\right)}{\mathcal{B}\left(B^- \to K^- e^+ e^-\right)}$$



- LHCb $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$ for $1<q^2<6$ GeV^2, 2.6σ from SM. Actually measure the double ratio: $$R_K \equiv \frac{\mathcal{B}\left(B^- \to K^- \mu^+ \mu^-\right) / \mathcal{B}\left(B^- \to K^- J/\psi, J/\psi \to \mu^+ \mu^-\right)}{\mathcal{B}\left(B^- \to K^- e^+ e^-\right) / \mathcal{B}\left(B^- \to K^- J/\psi, J/\psi \to e^+ e^-\right)}$$
- Measured $\mathcal{B}$ for Kee agrees with SM prediction



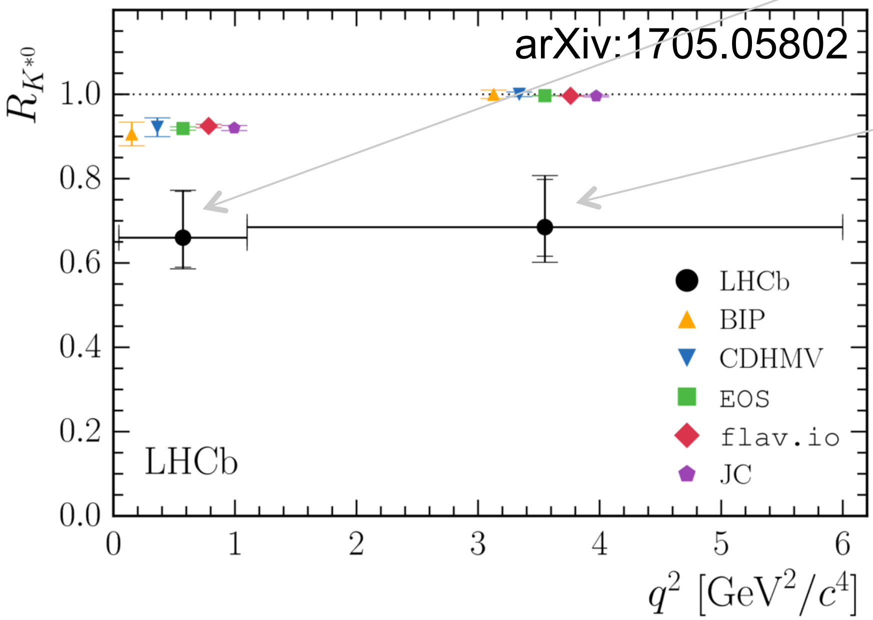
$B^0 \to K^{*0} \ell^+ \ell^-$

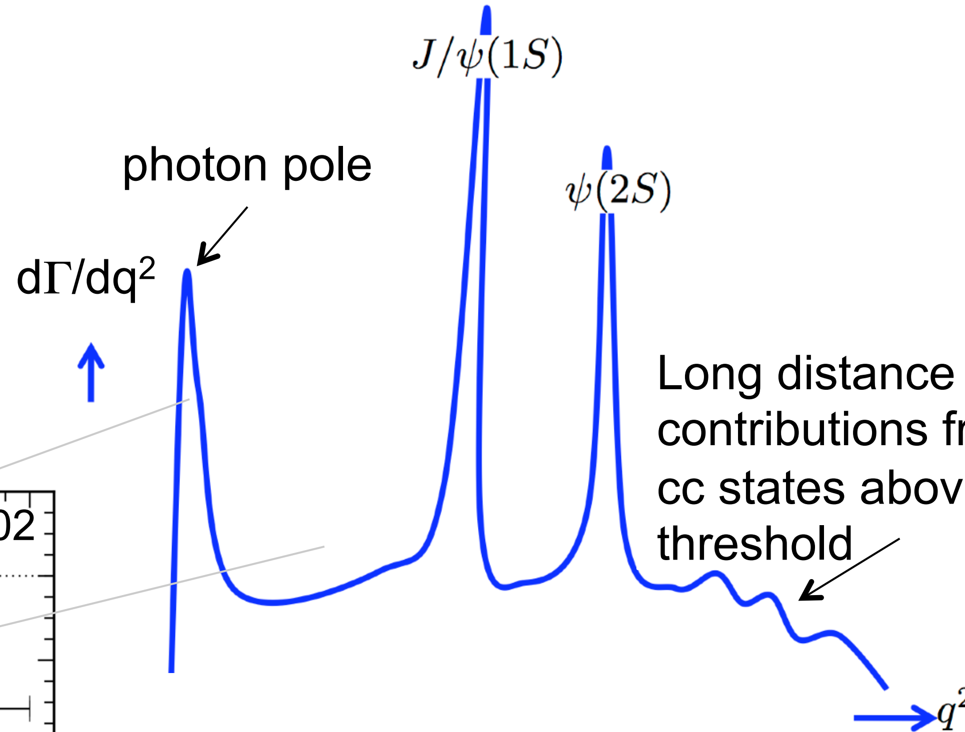
- SM expectations

$$R_{K^*} \equiv \frac{\mathcal{B}\left(B^0 \to K^{*0}\mu^+\mu^-\right)}{\mathcal{B}\left(B^0 \to K^{*0}e^+e^-\right)}$$

Also measured as a double ratio

- LHCb data

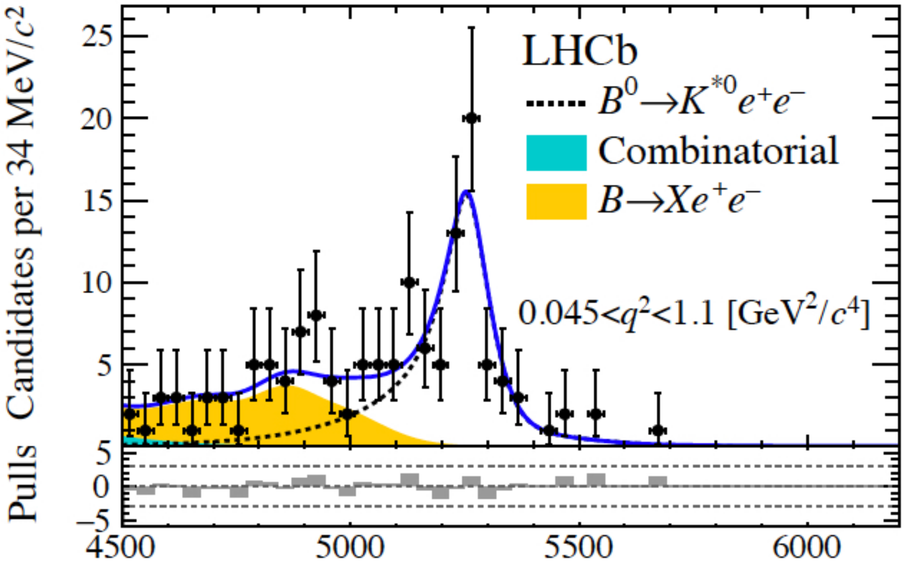


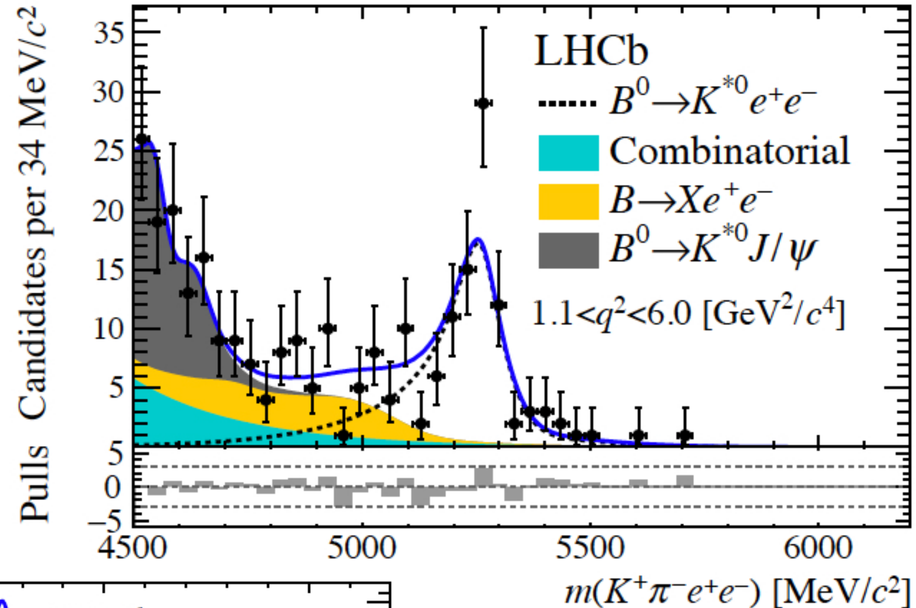


- $R_{K^*} = 0.660^{+0.110}_{-0.070} \pm 0.024,\ 0.045 < q^2 < 1.1$
- $R_{K^*} = 0.685^{+0.113}_{-0.069} \pm 0.047,\ 1.1 < q^2 < 6.0$
- Each ~2.4σ from SM

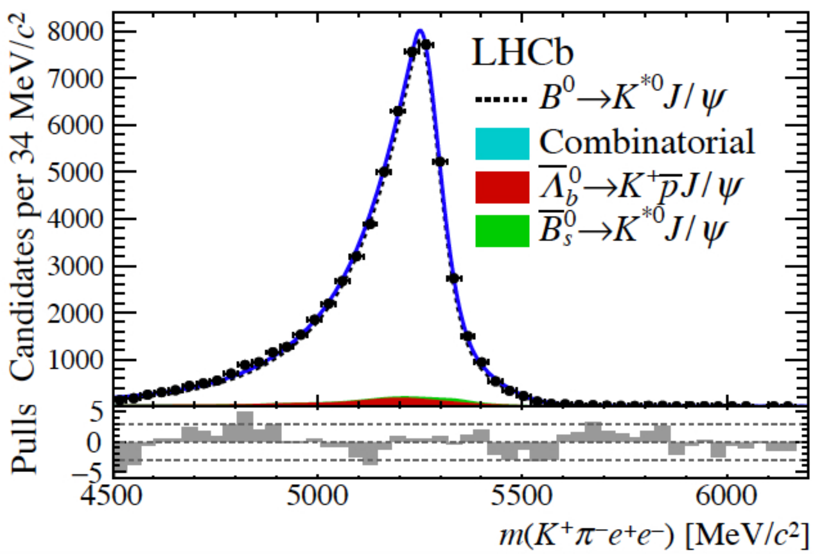
$B^0 \rightarrow K^{*0} e^+ e^-$

- Invariant mass spectra, J/ψ shape is used to model signal



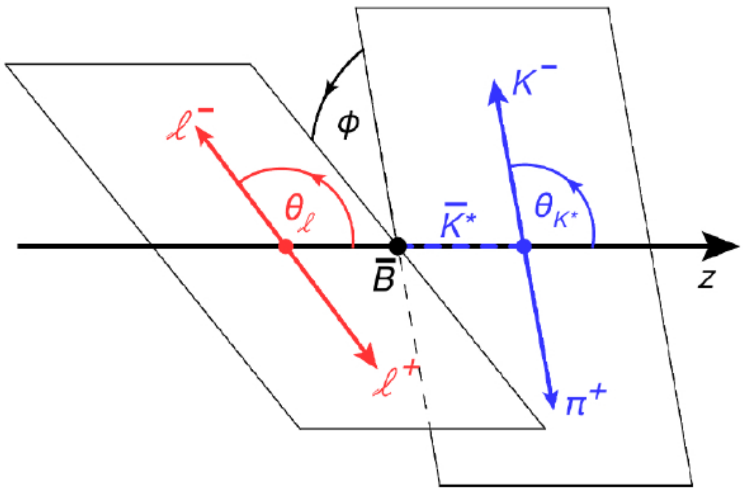


arXiv:1705.05802



Angular observables in $K^*\mu^+\mu^-$

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2\,d\vec{\Omega}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_l - F_L\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi + \frac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big].$$



(A_{FB}, F_L and S_j) are the observables

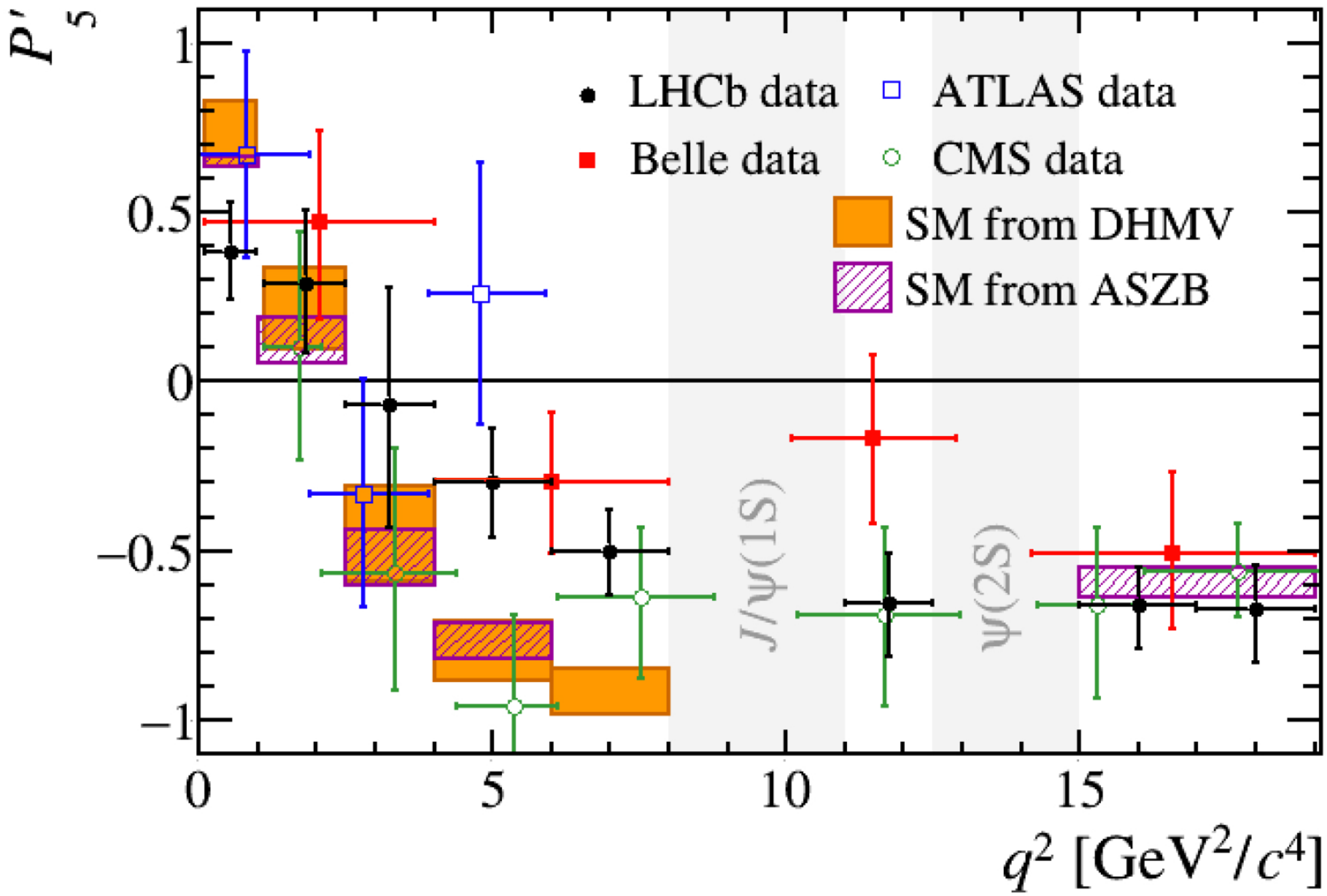
A cleaner set of observables, where hadronic form factor uncertainties cancel at the leading order, can be defined

$$P'_5 \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

From Justine Serrano

The curious case of P_5'

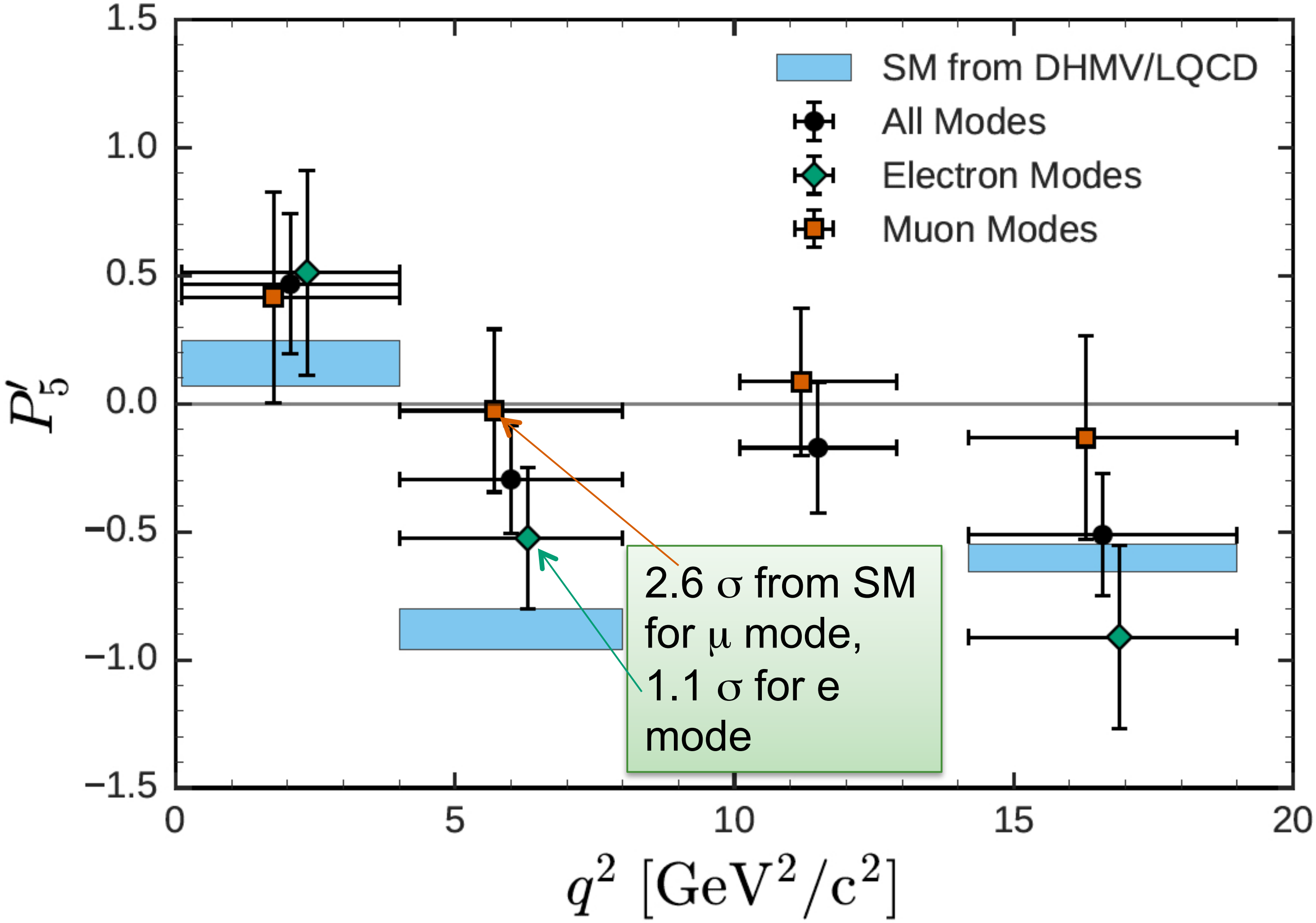
- Most angular observables agree with SM
- Deviation in P_5' near q^2=~6 GeV^2



FF from LQSR (JHEP 08 (2016) 98) and LQCD (arXiv:1501.00367)

Lepton universality test in P_5'

- Belle does both e's & μ's (PRL 118, 111801, 2017)



Exp. references

	dataset	Angles and modes used	Measured obervables	Reference
ATLAS EXPERIMENT	8TeV data (20.3 fb^{-1})	$(\theta_l, \theta_K, \phi)$ with folding technique, ℓ=μ	F_L , S_j, P'_i	*ATLAS-CONF-2017-023*
LHCb	Run1 data ($3fb^{-1}$)	Full angular analysis $(\theta_l, \theta_K, \phi)$, ℓ=μ*	A_{FB}, F_L , S_j, P'_i	*JHEP 02 (2016) 104*
CMS	8TeV data (20.5 fb^{-1})	$(\theta_l, \theta_K, \phi)$ with folding technique ℓ=μ	P'_5, P_1 A_{FB}, F_L measured in a previous paper	*CMS-PAS-BPH-15-008* *PLB 753 (2016) 424*
	All	(θ_l, θ_K), also B^+ modes ℓ=e,μ	A_{FB}, F_L	*PRD 93 (2016) 052015*
BELLE	All	$(\theta_l, \theta_K, \phi)$ with folding technique, also B^+ modes, ℓ=e,μ	A_{FB}, F_L , S_j, P'_i, and also Qi	*PRL 118 (2017) 111801*

Justine Serrano

*Angular analysis for e modes also performed at low q2 in *JHEP04(2015)064*

Effective Hamiltonian

- Integrate out heavy degrees of freedom, then

$$\mathcal{H}_{eff}^{SM} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_{\ell=e,\mu} \left(C_1 \mathcal{O}_1^{\ell} + C_2 \mathcal{O}_2^{\ell} + \sum_{i=3}^{10} C_i^{\ell} \mathcal{O}_i^{\ell} \right)$$

, where C_i's are Wilson coeff. & $\mathcal{O}_i$ are operators. Can use independent C_i^{μ} & C_i^{e}.

- Different processes are described by different $\mathcal{O}_i$
- NP can appear in C_i's
- Also include inherently NP chirality flipped operators $\mathcal{O}_9'$ & $\mathcal{O}_{10}'$ as additional possibilities.
- Allows for a model independent analysis

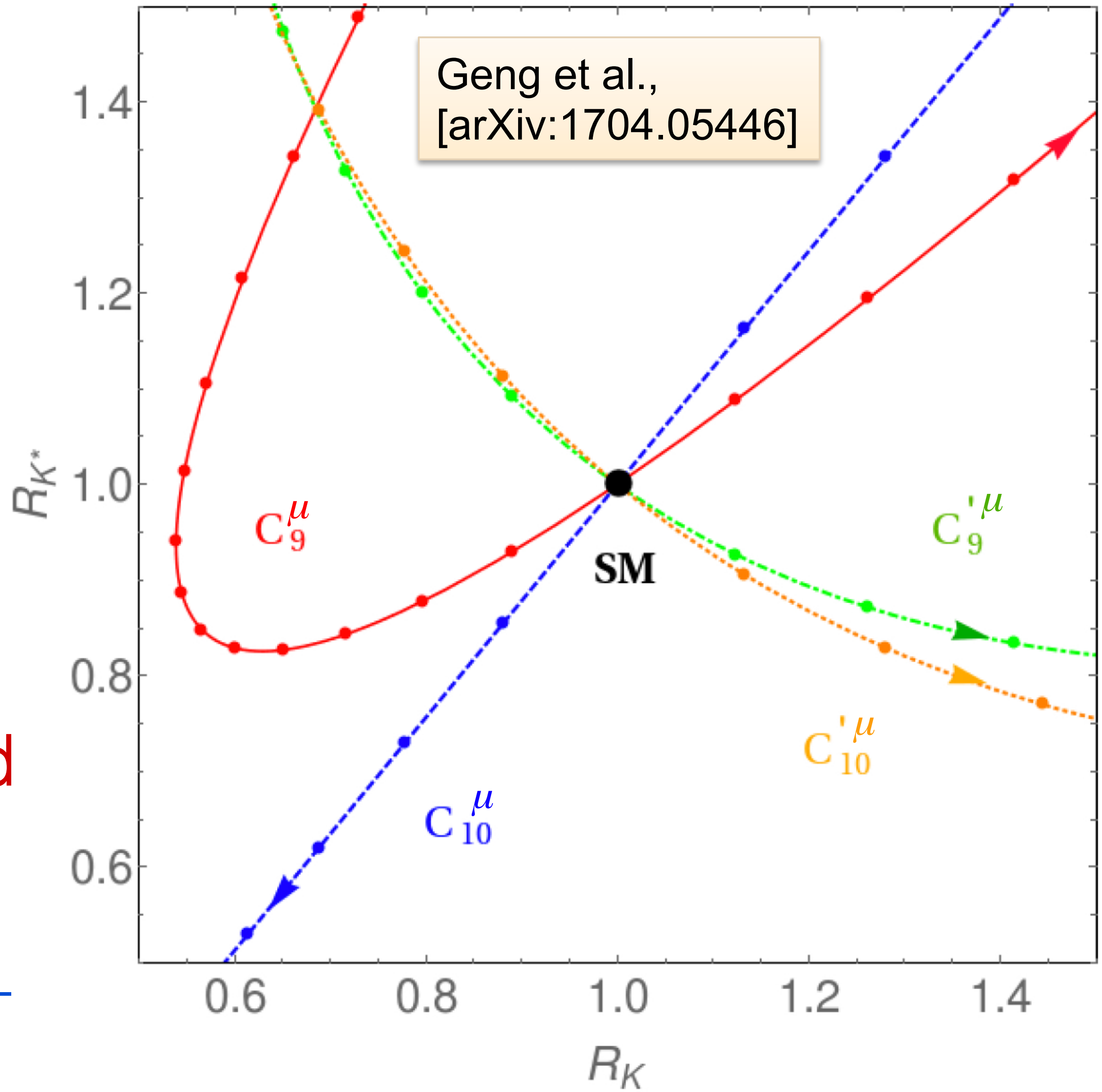
$\mathcal{O}_{1,2}$: Current-current
$\mathcal{O}_{3,4,5,6}$: QCD penguins
$\mathcal{O}_7$: Electromagnetic penguin
$\mathcal{O}_8$: Chromo-magnetic penguin
$\mathcal{O}_{9,10}$: Electroweak penguin

Operators contributing to LFU

- $O_9^{(\prime)} = \frac{\alpha_{EM}}{4\pi}\left(\bar{s}\gamma^{\mu}P_{L(R)}b\right)\left(\bar{\ell}\gamma_{\mu}\ell\right), \quad O_{10}^{(\prime)} = \frac{\alpha_{EM}}{4\pi}\left(\bar{s}\gamma^{\mu}P_{L(R)}b\right)\left(\bar{\ell}\gamma_{\mu}\gamma_5\ell\right)$,
  where P_L & P_R are left & right handed projection operators
- $\mathcal{B}(B_s\to\mu^+\mu^-)$ provides a constraint on $C_{10}^{\mu}+C_{10}^{\mu\prime}$; other constraints from B_s mixing
- K* longitudinal part of the rate is similar to $K\ell\ell$ but with chirally flipped operators that interfere with reversed sign with the SM
- As a consequence, different C_i variations have different effects on R_K & R_{K^*}

Correlated variations in C_i's

- Parametric dependence of R_K vs R_{K^*} allowing a single C_i^μ to vary (not C_i^e)
- Decreases in both R_K & R_{K^*} can be explained by C_9^μ or C_{10}^μ, not $C_9'^\mu$ or $C_{10}'^\mu$



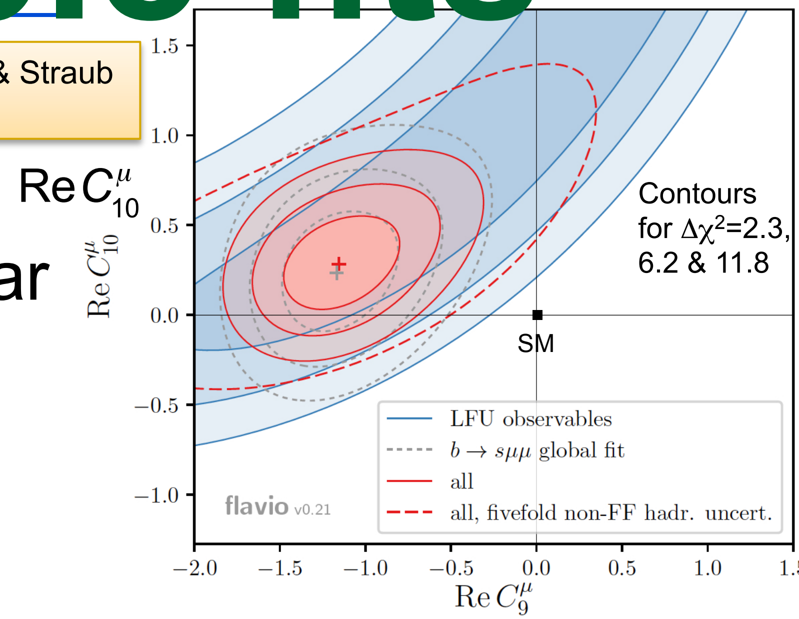
Example fits

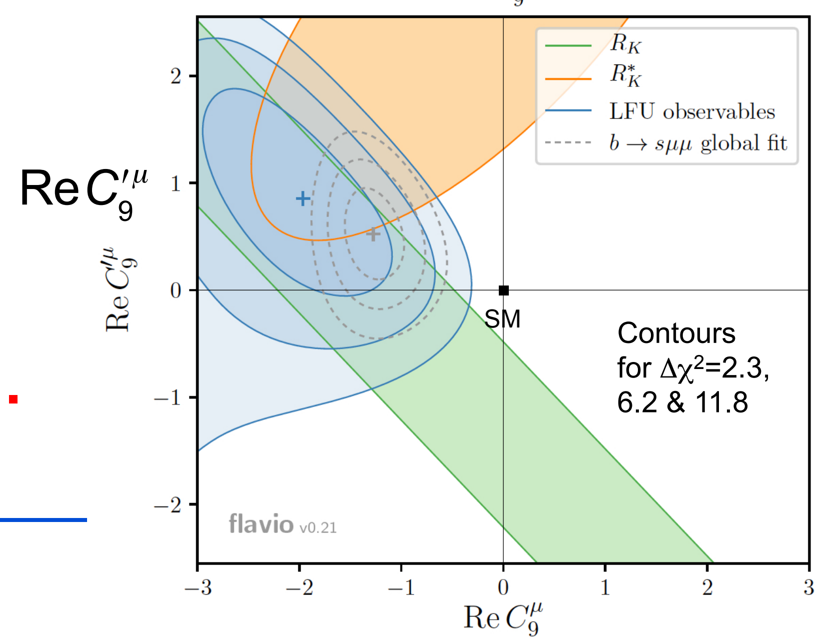
- Two separate fits

Altmannshofer, Stangl & Straub [arXiv:1704.05435]

  - 1) LFU observables: R_K, R_{K^*}, Belle e-μ differences in angular observables
  - 2) b→sμμ global fit observables: K*μμ $\mathcal{B}$ & angular, Kμμ $\mathcal{B}$, ϕμμ $\mathcal{B}$ & angular, $\mathcal{B}(b\rightarrow X_s\mu\mu)$ from BaBar; dashed lines with hadronic uncertainties x5

- Here $\mathrm{Re}C_{9(10)}^{\mu}$ is diff wrt SM. Prefers $\mathrm{Re}C_9^{\mu}$~-1, (SM is 0)





Should we believe LFU violation?

Yes

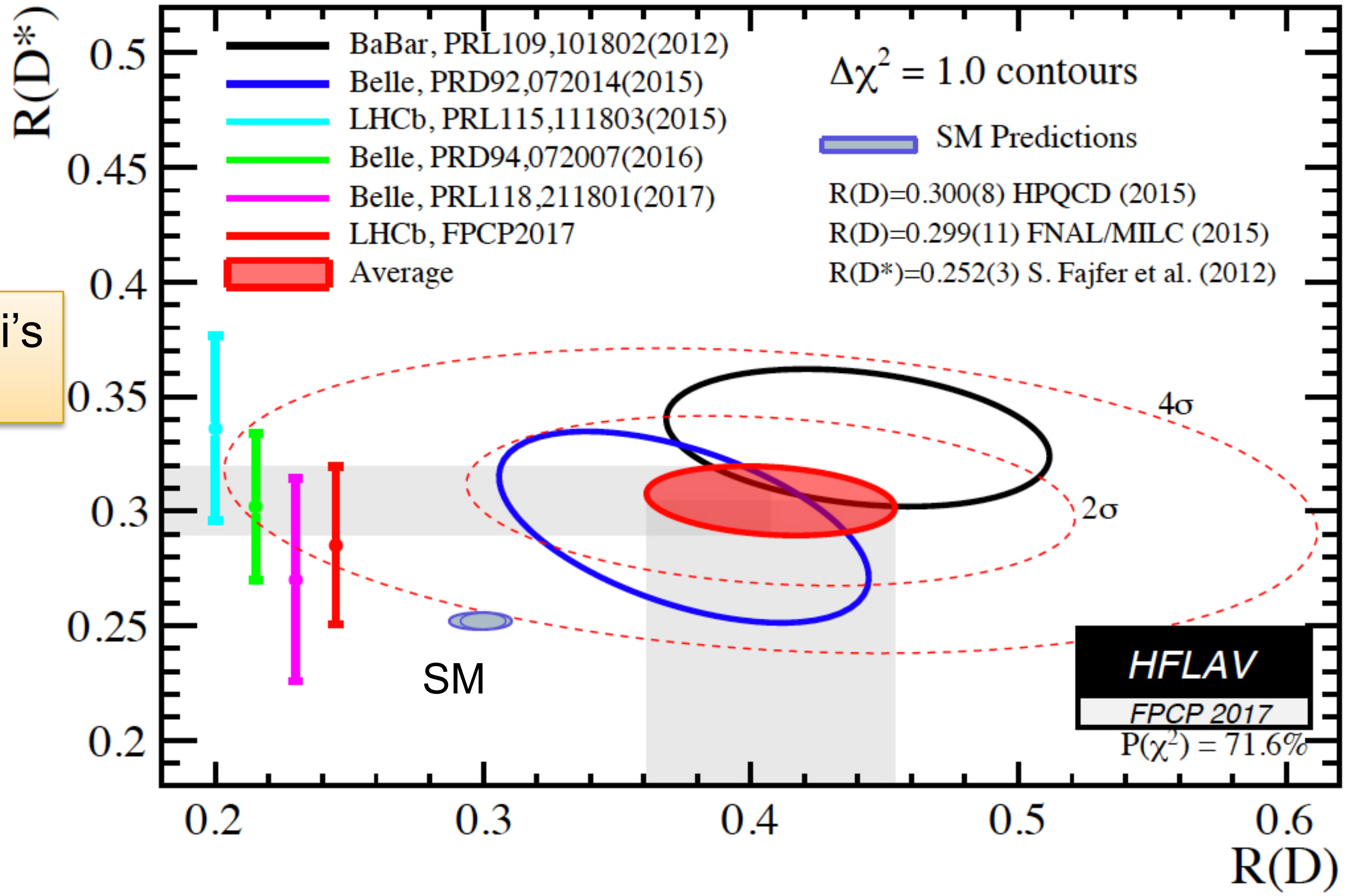
- R measurements are double ratio's to J/ψ, check with $K^*J/\psi \to e^+e^-/\mu^+\mu^-$ $=1.043\pm0.006\pm0.045$
- $\mathcal{B}(B^- \to K^- e^+ e^-)$ agrees with SM prediction puts onus on muon mode which is well measured and low
- Both R_K & R_{K^*} are different than ~1
- Supporting evidence of effects in angular distributions

No, not yet

- Statistics are marginal in each measurement
- Need confirming evidence in other experiments for R_K & R_{K^*}
- Disturbing that R_{K^*} is not ~1 in lowest q^2 bin, which it should be, because of the photon pole
- Angular distribution evidence can be effected by hadronic uncertainties

$R_{D^{(*)}}=\mathcal{B}(B\to D^{(*)}\tau\nu)/\mathcal{B}(B\to D^{(*)}\mu\nu)$

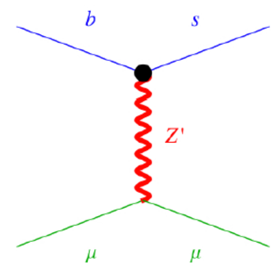
See Siddi's talk

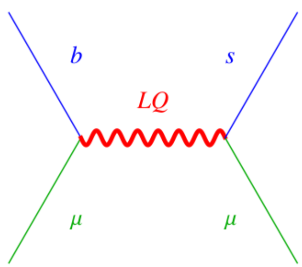


τ mode is difficult to measure as there are at least 2 missing neutrinos

Conclusions

- We may be seeing the first hints of physics beyond the SM in a failure of lepton flavor universality
- This implies lepton flavor violation, e.g. may be able to see $B^-\to K^-\tau^\pm\mu^\mp$ (Glashow, Guadagnoli & Lane **arXiv:1411.0565**)
- Viable models include:
  - Z′: not just a heavy Z, different couplings, e.g. $Z'\to bs$
  - Leptoquarks





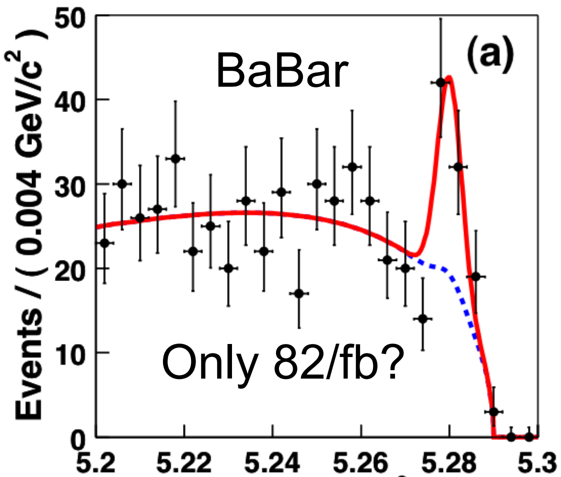
Can these be seen in direct production at the LHC?

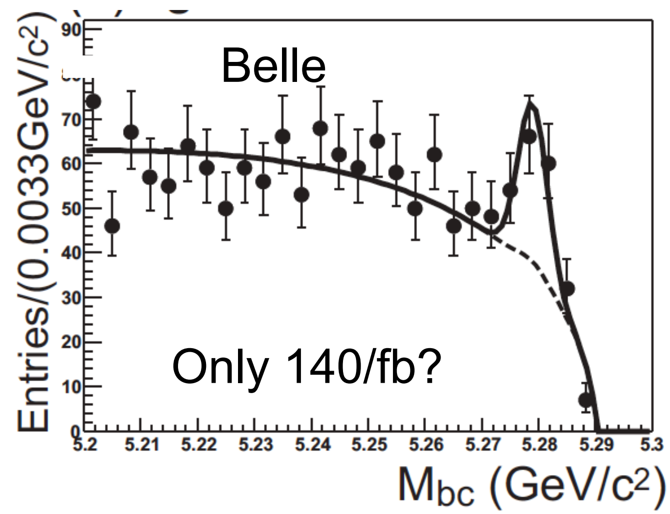
The End

Backup slides

$B \to X_s \ell^+ \ell^-$

- Define two q^2 regions: low 1-6, high >14.4 GeV^2
- Low again probes C_7, while high C_9 & C_{10}
- Data





- High q^2:
  $\mathcal{B}(B \to X_s \ell^+ \ell^-) = (4.3 \pm 1.2) \times 10^{-7}$, SM 2.3×10^{-7}
- Low q^2: $\mathcal{B}(B \to X_s \ell^+ \ell^-) = (1.63 \pm 0.50) \times 10^{-6}$, SM 1.59×10^{-7}
- $B^o \to K^{*o} \ell^+ \ell^-$, is also sensitive to C_7 at low q^2, C_9 & C_{10} at high q^2

Kee mass distributions

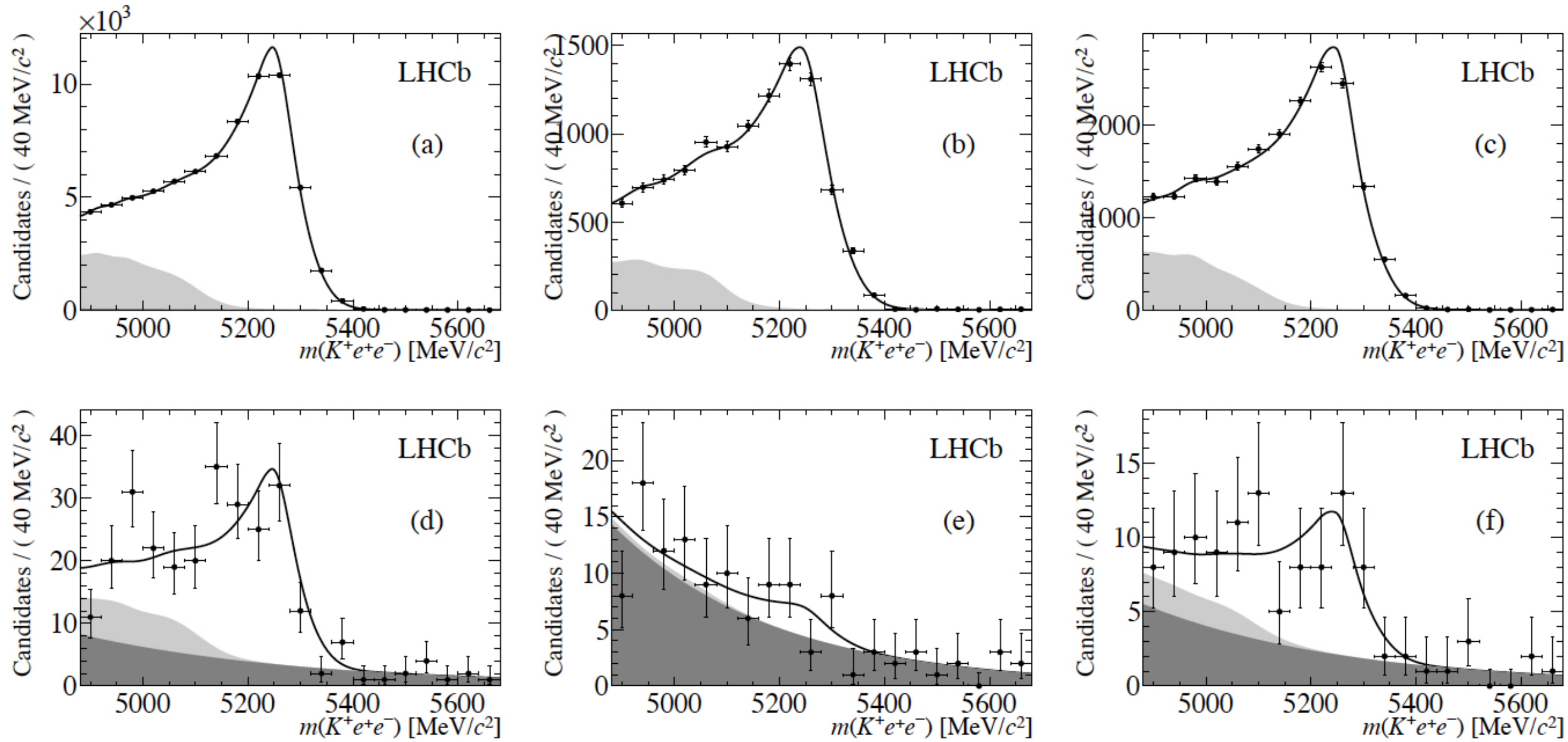
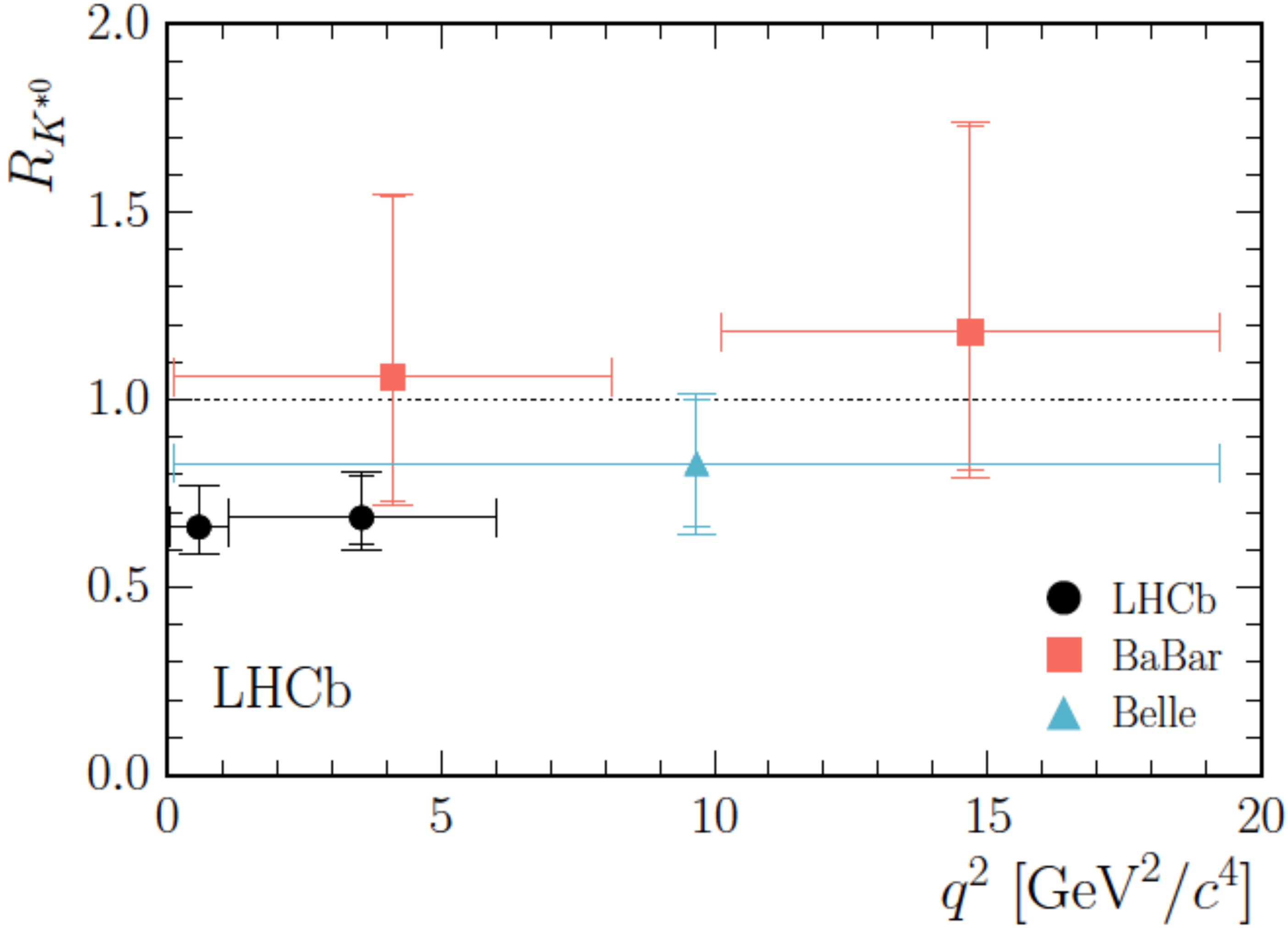


Figure 2: Mass distributions with fit projections overlaid of selected $B^+ \to J/\psi(\to e^+e^-)K^+$ candidates triggered in the hardware trigger by (a) one of the two electrons, (b) by the K^+ and (c) by other particles in the event. Mass distributions with fit projections overlaid of selected $B^+ \to K^+e^+e^-$ candidates in the same categories, triggered by (d) one of the two electrons, (e) the K^+ and (f) by other particles in the event. The total fit model is shown in black, the combinatorial background component is indicated by the dark shaded region and the background from partially reconstructed b-hadron decays by the light shaded region.

R_{K^*}



Another fit

- arXiv:1704.05446

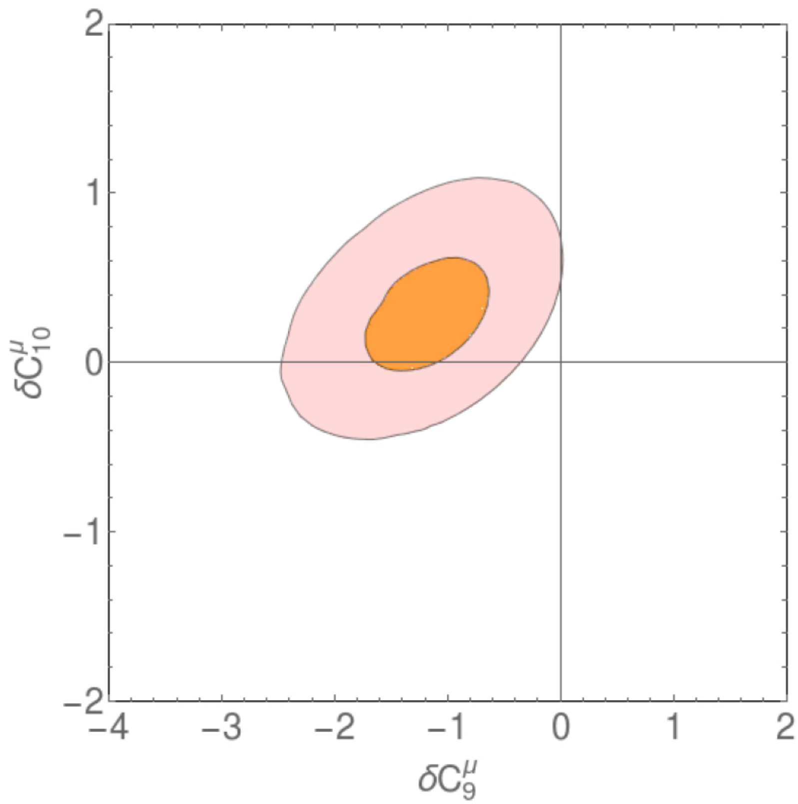


FIG. 5: Fit results for LUV data, $\overline{BR}(B_s \to \mu\mu)$, and $b \to s\mu\mu$ angular observables, as described in the text.

Seeking New Physics

- Flavor Physics as a tool for NP discovery
  - The main purpose of FP is to find and/or define the properties of physics beyond the Standard Model (SM)
  - FP probes large mass scales via virtual quantum loops. An example, of the importance of such loops is the Lamb shift in atomic hydrogen
  - A small difference in energy between $2S_{1/2}$ & $2P_{1/2}$ levels that should be of equal energy at lowest order