S. Stone

R_K & R_{K^*} Status & Outlook

Exotic hadrons & flavor physics, May 2018

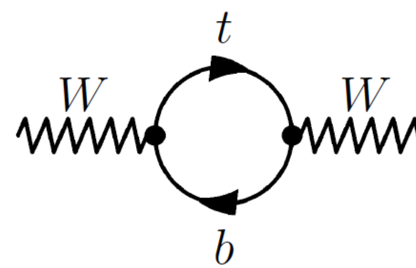
Physics rationale

- 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

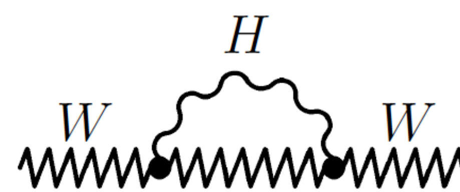
- FP probes large mass scales via virtual quantum loops. An example, of the importance of such loops are changes in the W mass
  - M_w changes due to m_t

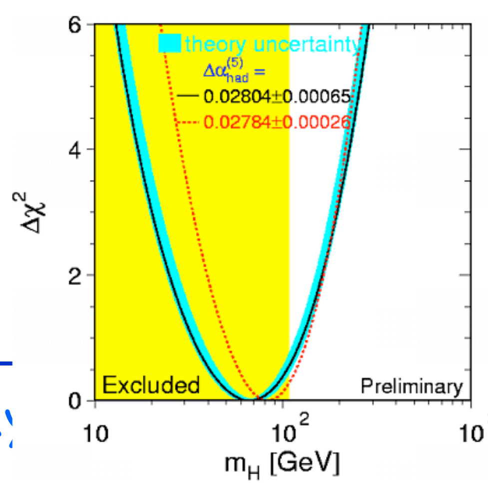
$$\frac{dM_W}{dm_t} \alpha \frac{m_t}{M_w}$$



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

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



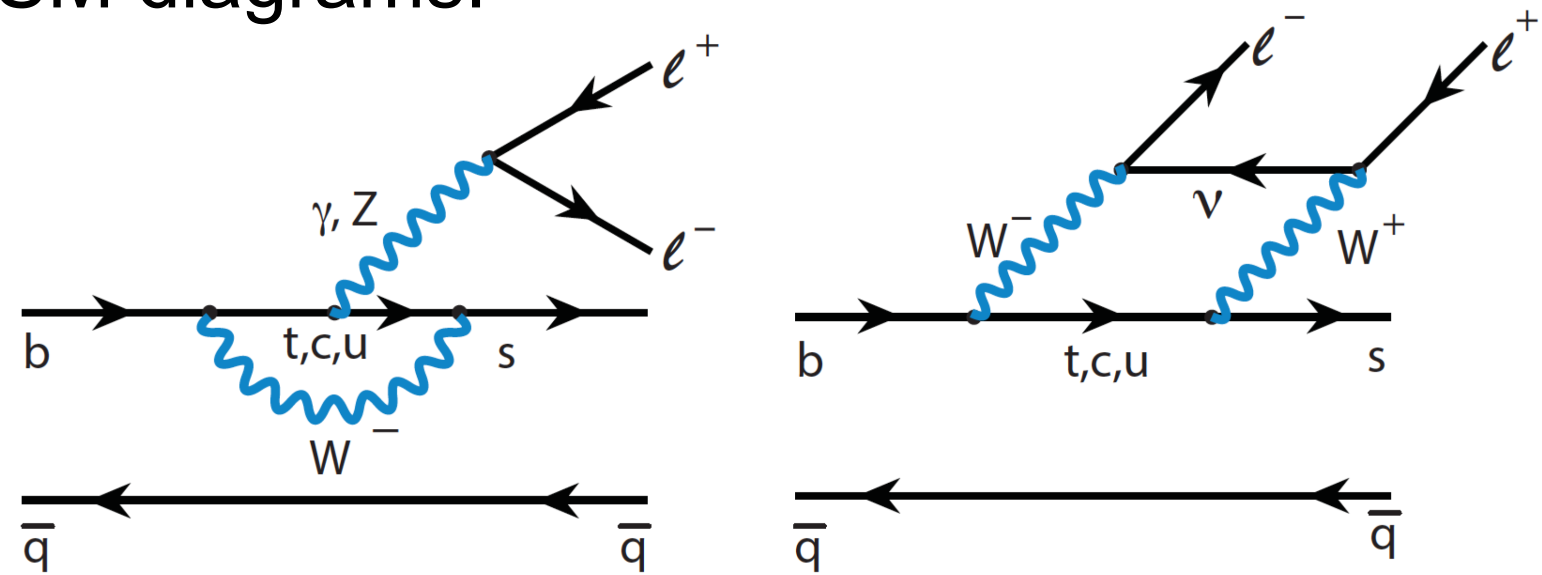


Lepton flavor universality

- 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

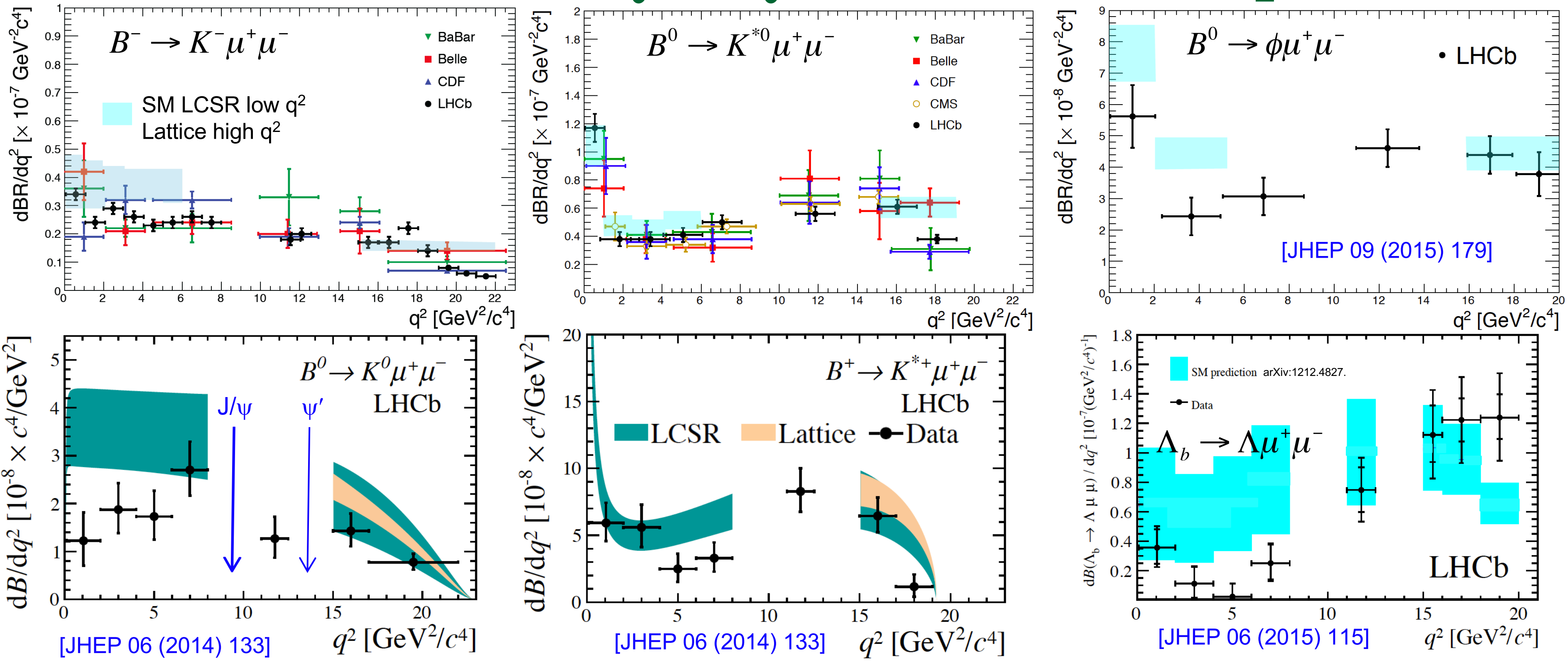
- NP may be seen easier in suppressed processes such as penguin decays
- SM diagrams:



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

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

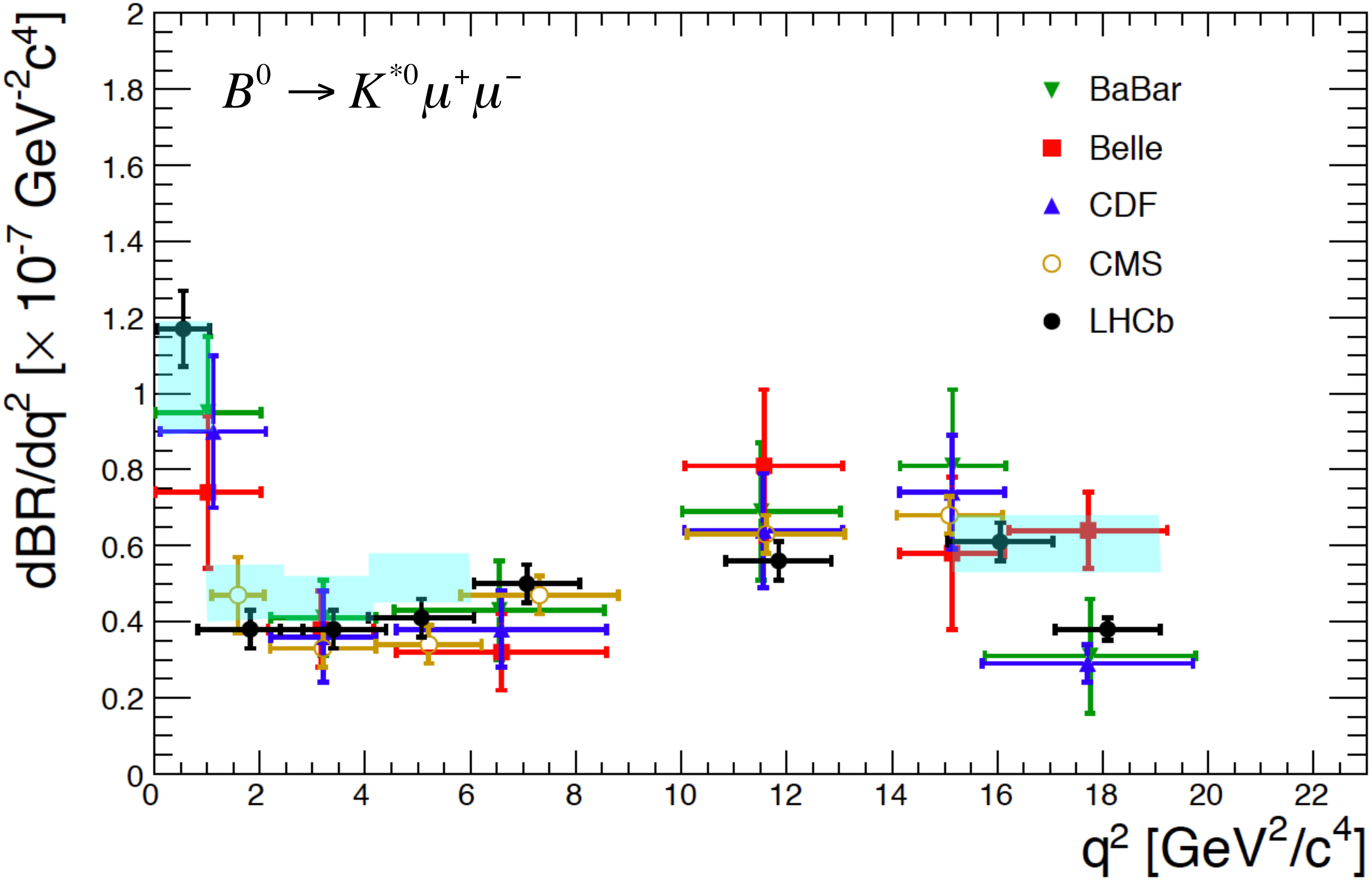
$q^2 = m^2(\mu^+\mu^-)$



- Data generally below model predictions at low q^2
- Charmonium resonances at high q^2

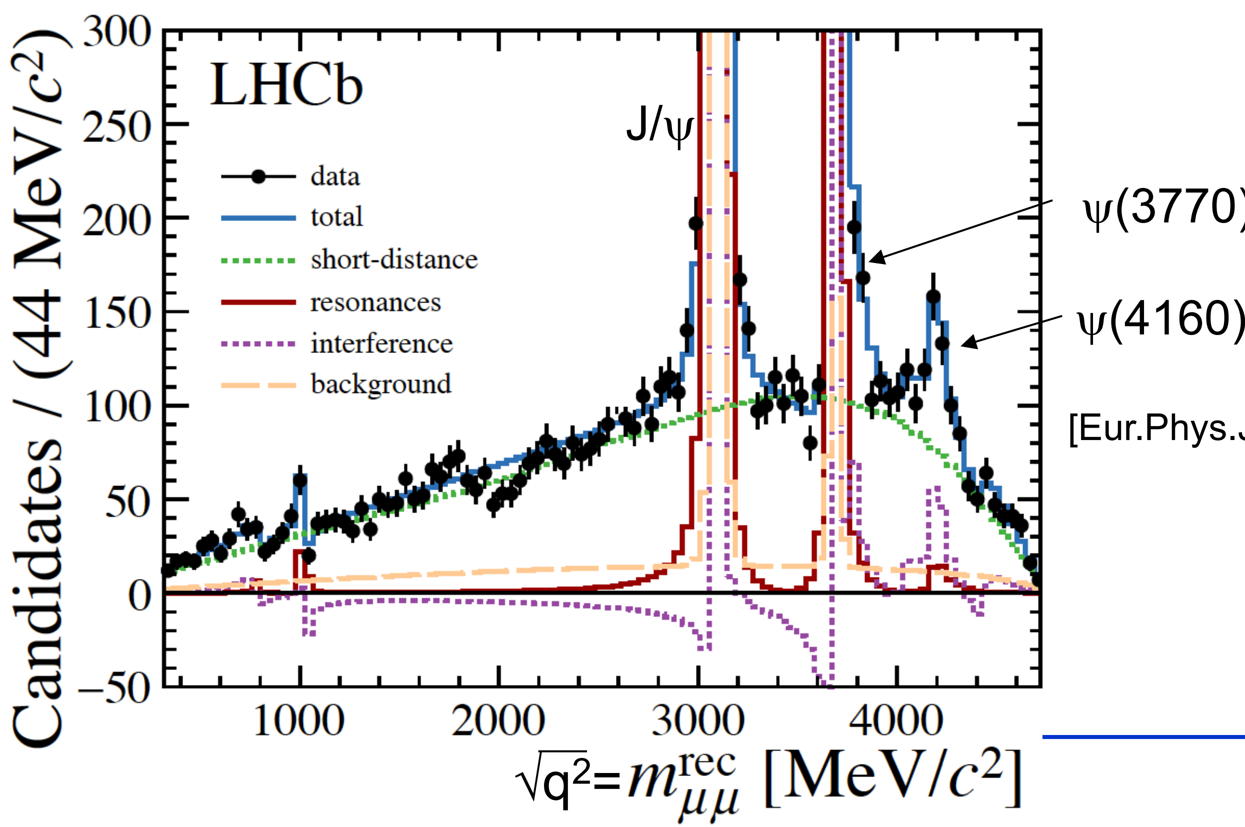
$K^{*}\mu^{+}\mu^{-}$ $d\mathcal{B}/dq^{2}$

- Enlarged



Resonances

- Presence of charmonium states at high q^2 confirmed in $B^- \to K^- \mu^+ \mu^-$.
- So look for NP in low q2 region



[Eur.Phys.J. C77 (2017), 161]

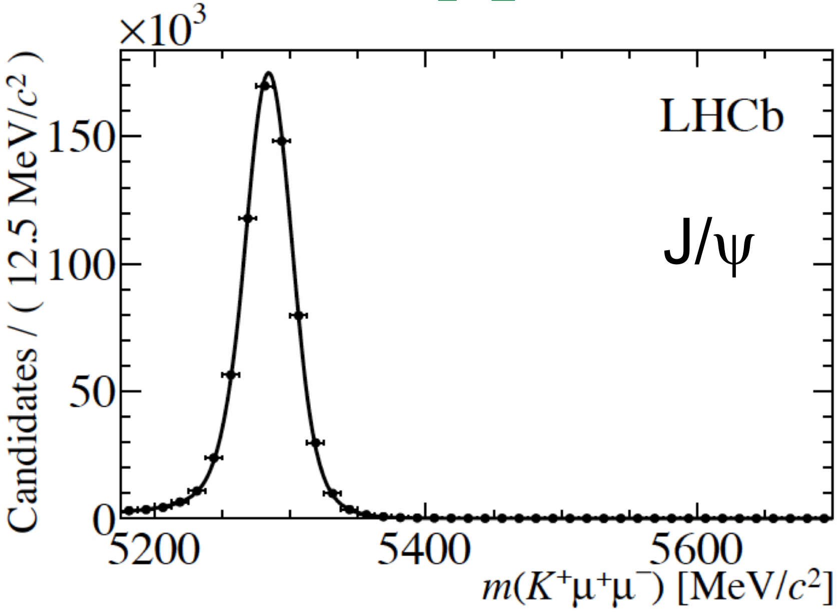
$R_K=(B^-\to K^-\mu^+\mu^-)/(B^-\to K^-e^+e^-)$

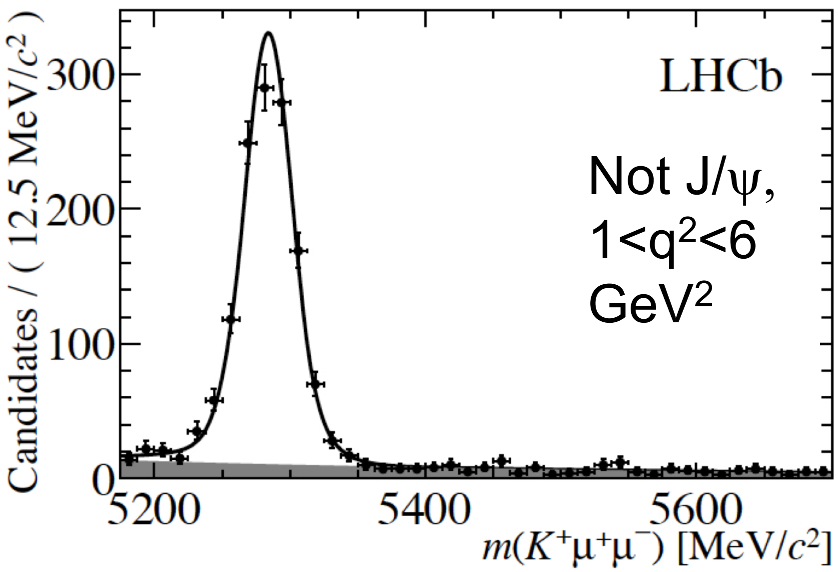
- Dedicated analysis to measure the ratio
- Actually measure the double ratio:

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

- Use the J/ψ to determine signal shapes & as a normalization for each mode
- Measurement made in the interval $1<q^2<6$ GeV^2

R_K dimuon data

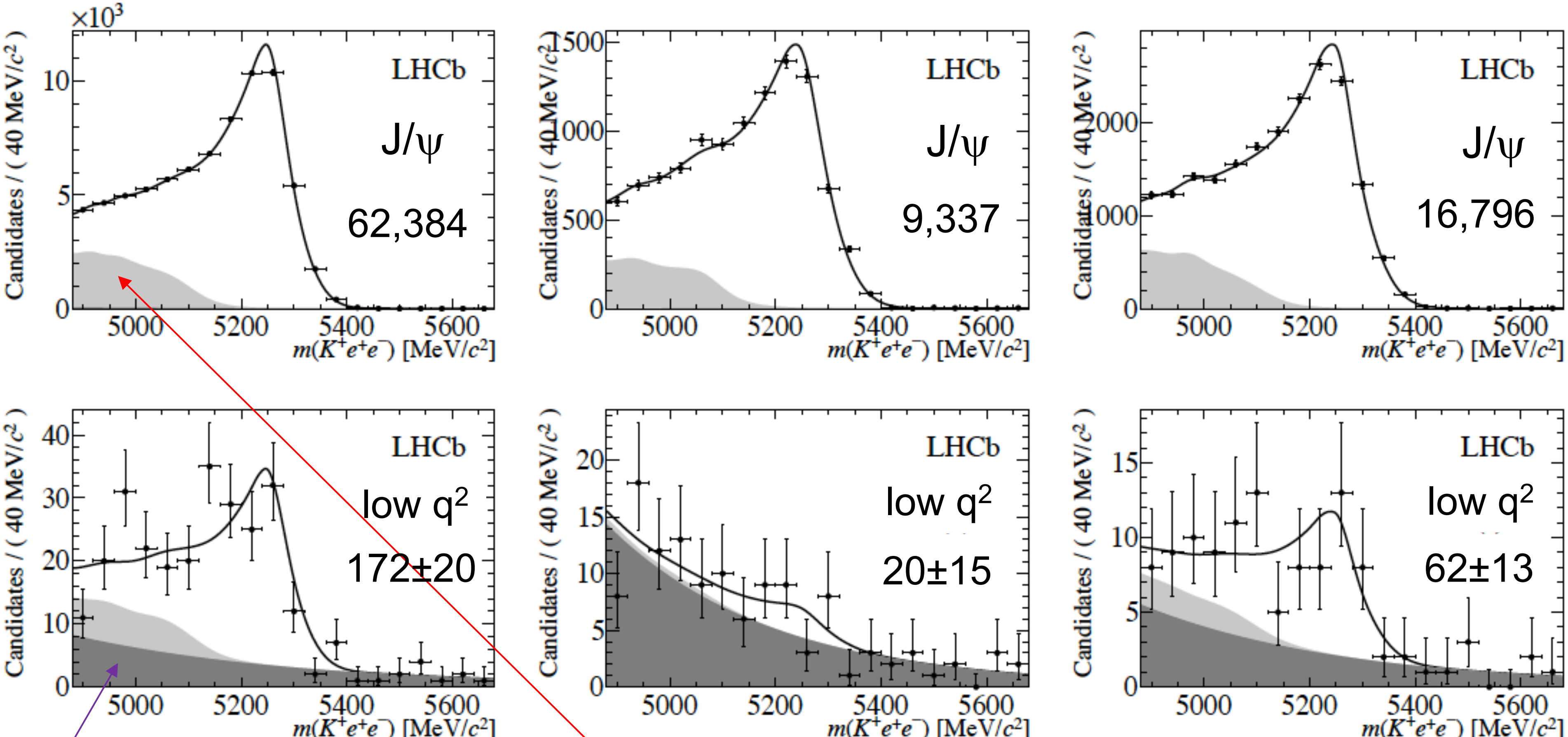




- # J/ψ events: 667,046±882
- # Low q^2 events: 1226±41

Kee mass distributions

- Trigger: $e^{\pm}$ K other



Combinatoric background

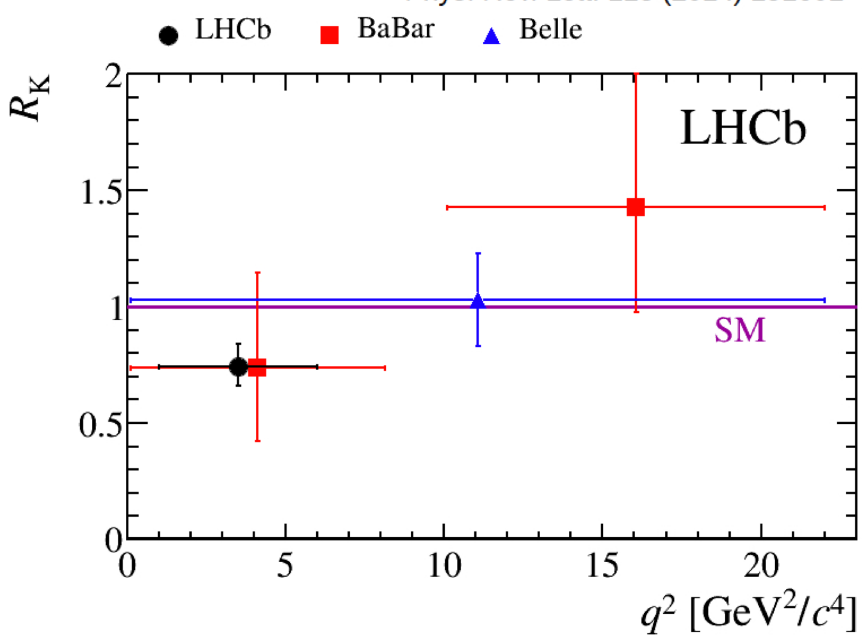
Partially reconstructed B decays

R_K results

- $$R_K \equiv \frac{\mathcal{B}\left(B^- \to K^-\mu^+\mu^-\right)}{\mathcal{B}\left(B^- \to K^-e^+e^-\right)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

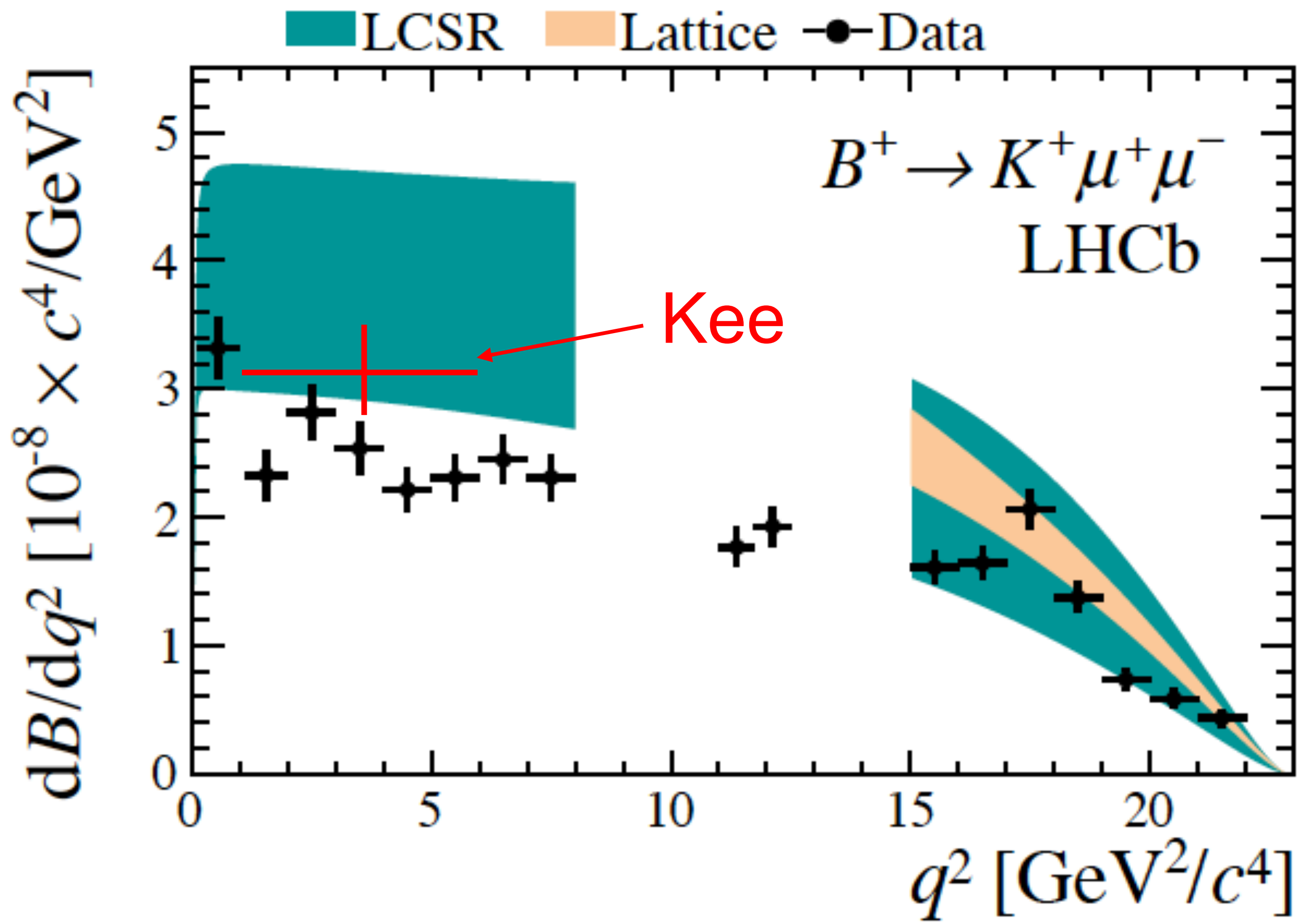
for $1<q^2<6$ GeV^2, 2.6σ from SM

Phys. Rev. Lett. 113 (2014) 151601



Branching ratio comparison

- Some evidence that Kee is consistent with SM branching ratio and Kμμ is not



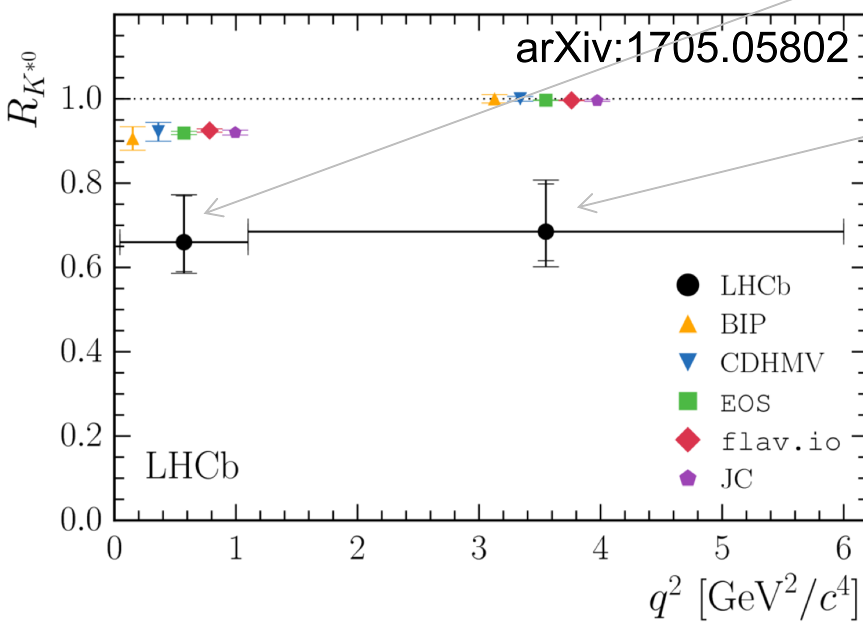
$B^0 \to K^{*0}\ell^+\ell^-$

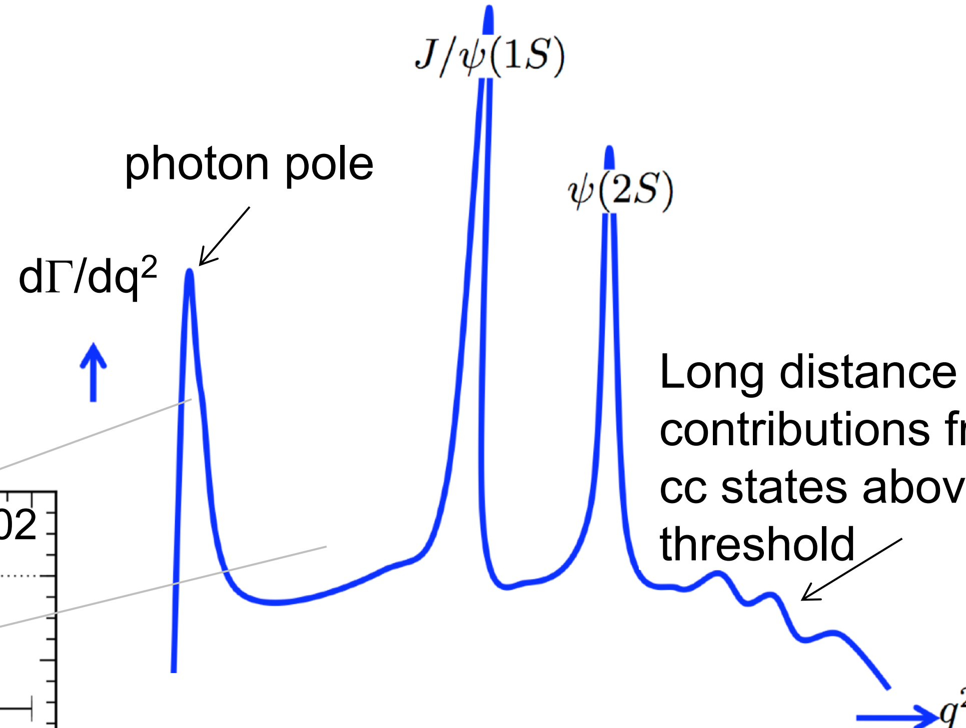
- SM expectations

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

Also measured as a double ratio

- LHCb data

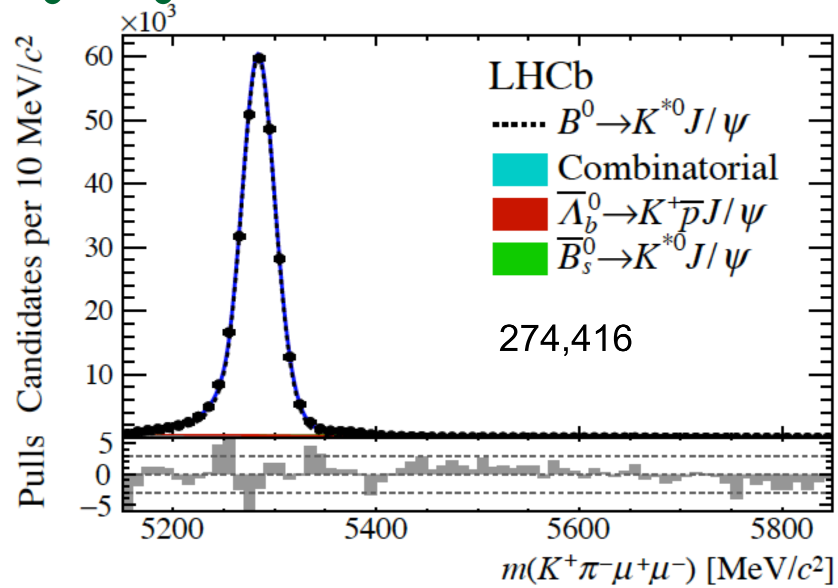


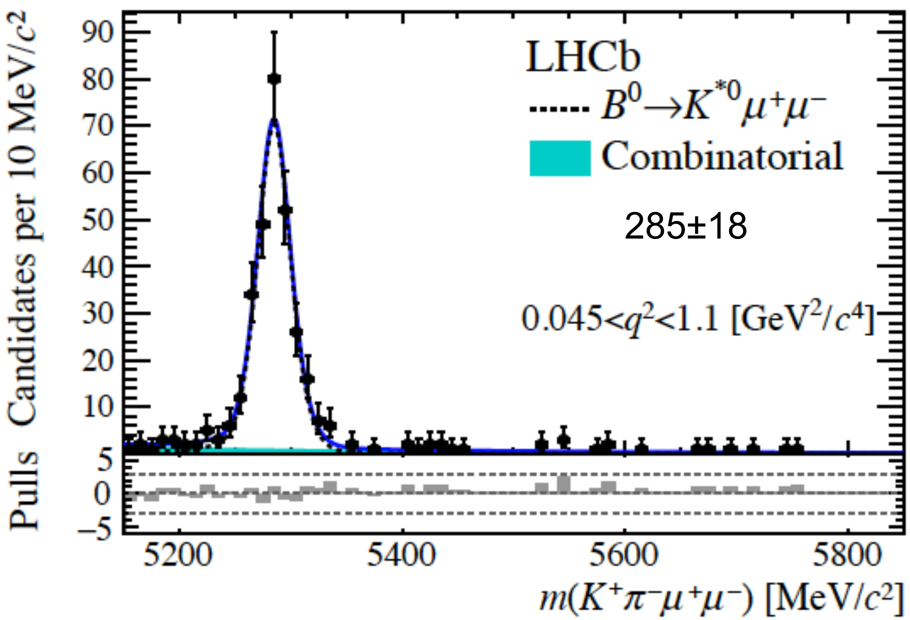


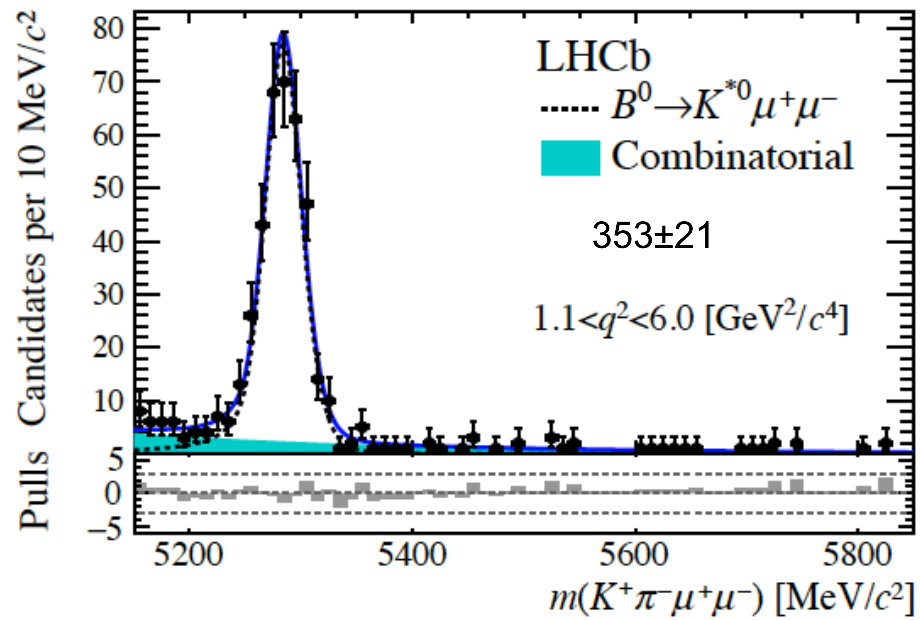
- $R_{K^*} = 0.660^{+0.110}_{-0.070} \pm 0.024,\ 0.045 < q^2 < 1.1$
- $R_{K^*} = 0.685^{+0.113}_{-0.069} \pm 0.047,\ 1.1 < q^2 < 6.0$
- Each ~2.4σ from SM

K*μμ

- Almost background free J/ψ sample, again signal shape used in low q^2 bins.

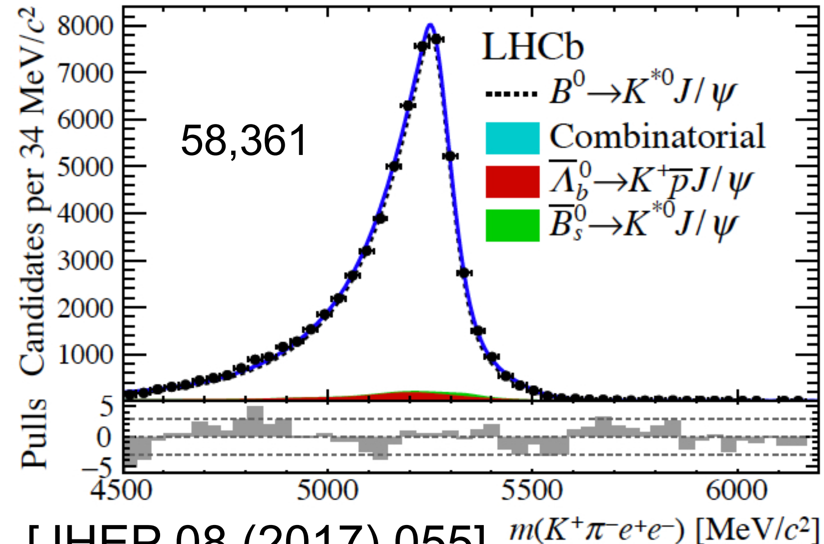




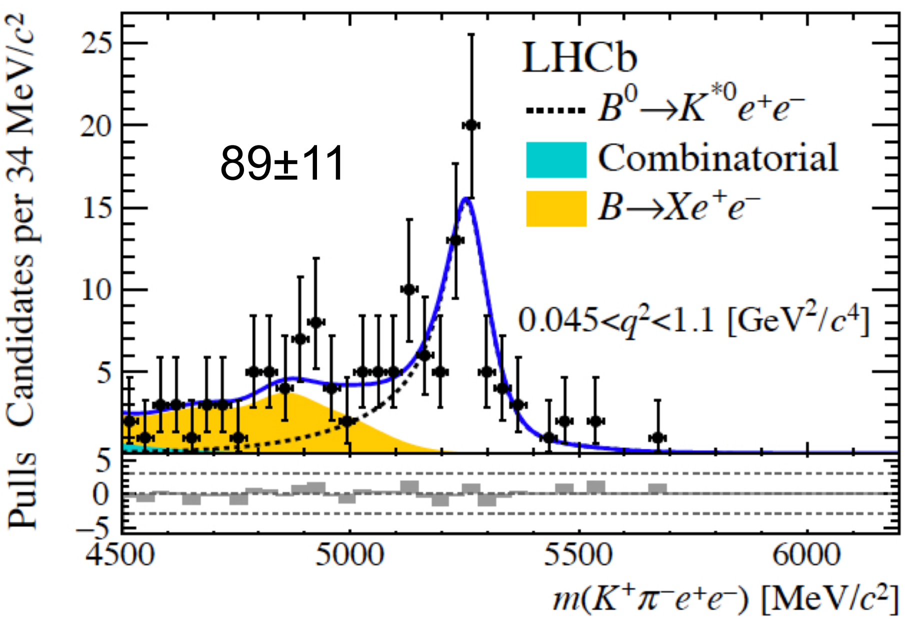


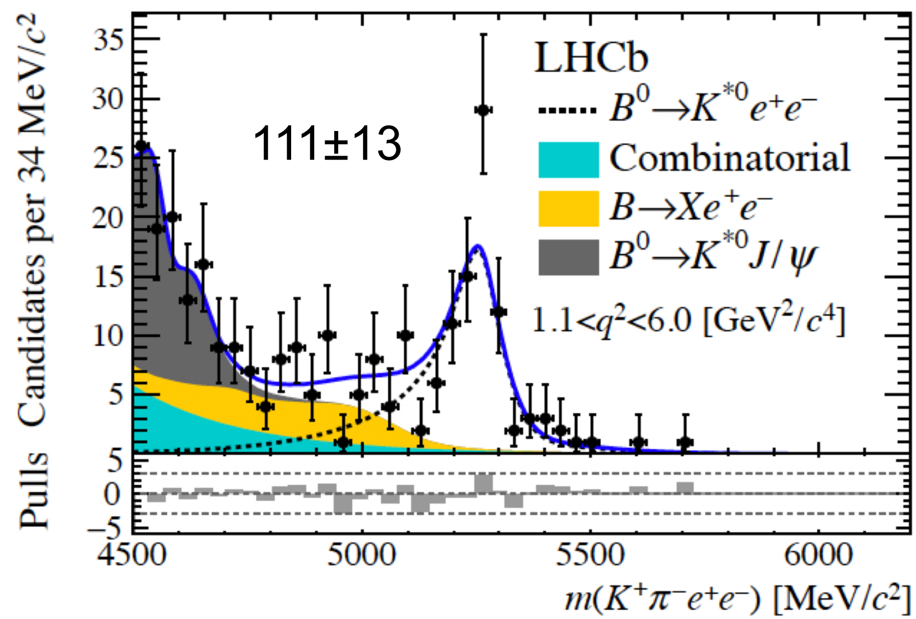
$B^0 \to K^{*0} e^+ e^-$

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



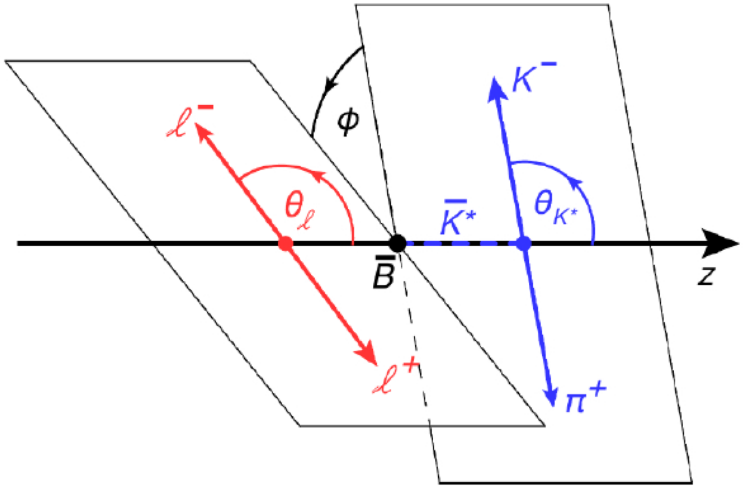
[JHEP 08 (2017) 055]





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

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



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

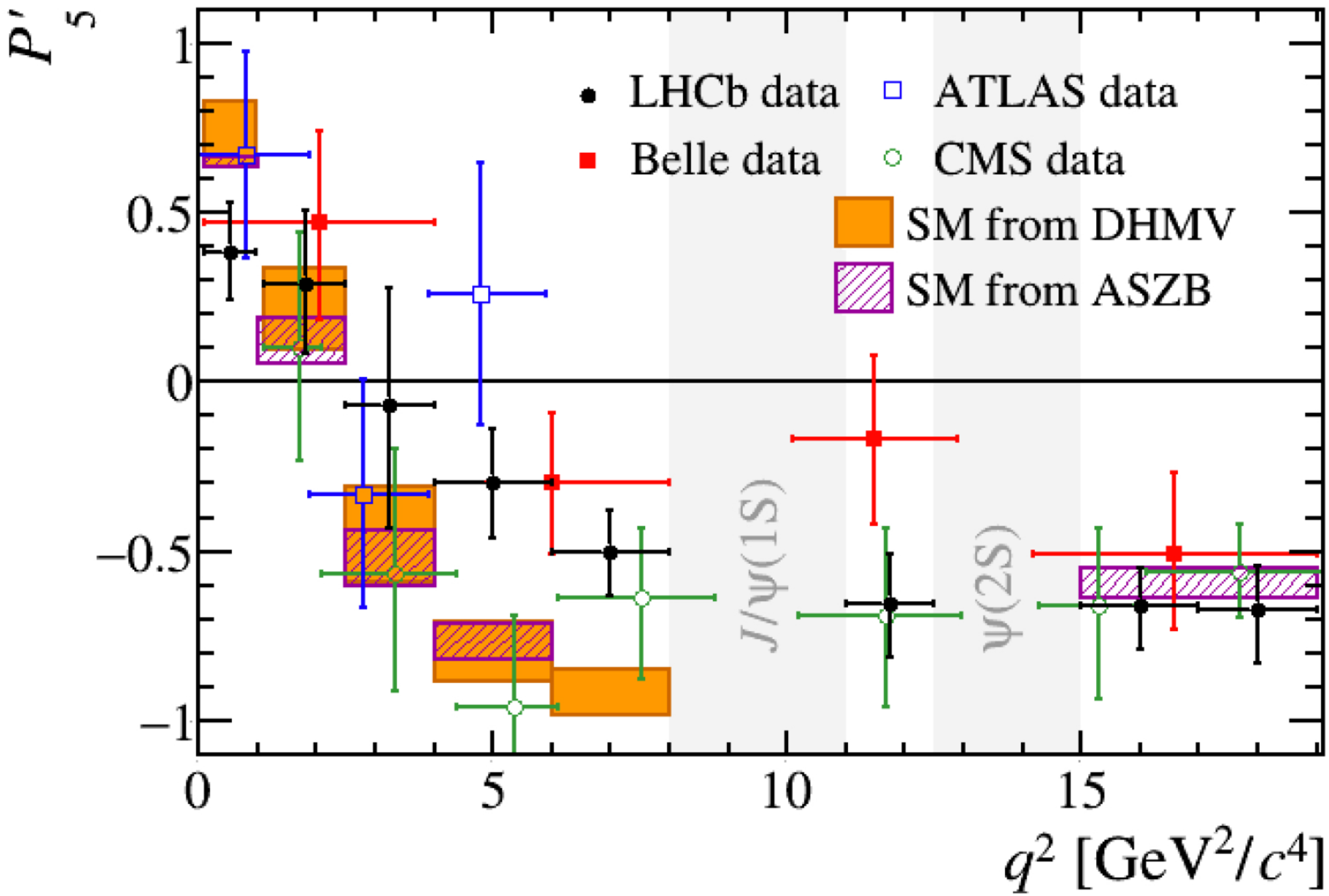
A cleaner set of observables, where hadronic form factor uncertainties cancel at the leading order, can be defined

$$P_5' \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

From Justine Serrano

The curious case of P_5'

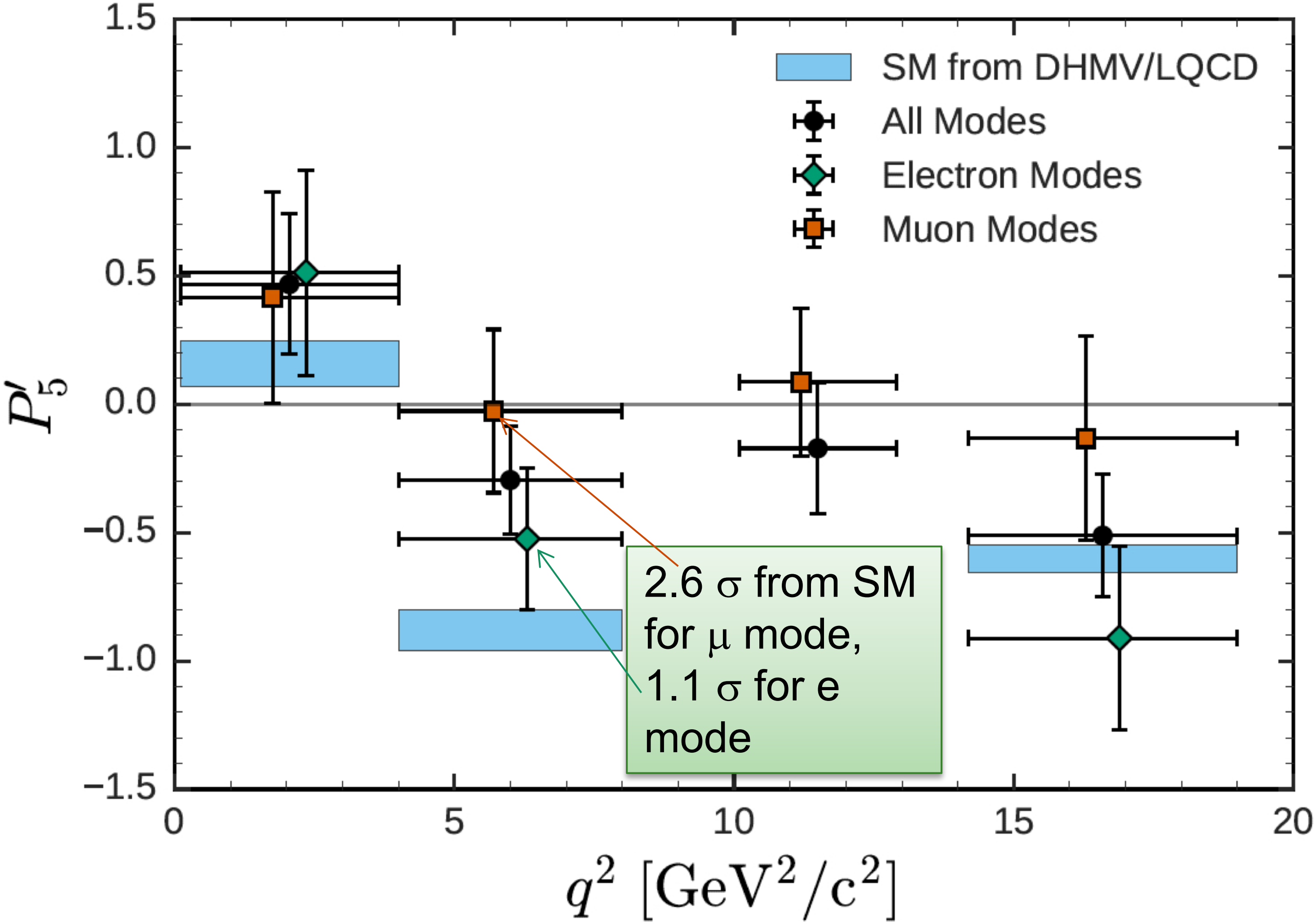
- Most angular observables agree with SM
- Deviation in P_5' near q^2=~6 GeV^2



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

Lepton universality test in P_5'

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



Exp. references

	dataset	Angles and modes used	Measured observables	Reference
ATLAS EXPERIMENT	8TeV data ($20.3\ fb^{-1}$)	(θ_l, θ_K, ϕ) with folding technique, ℓ=μ	F_L , S_j, P'_i	*ATLAS-CONF-2017-023*
LHCb	Run1 data ($3fb^{-1}$)	Full angular analysis (θ_l, θ_K, ϕ), ℓ=μ*	A_{FB}, F_L , S_j, P'_i Branching ratios	*JHEP 02 (2016) 104* *JHEP 06 (2014)133*
CMS	8TeV data ($20.5\ fb^{-1}$)	(θ_l, θ_K, ϕ) 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	(θ_l, θ_K, ϕ) with folding technique, also B^+ modes, ℓ=e,μ	A_{FB}, F_L , S_j, P'_i, and also Qi	*PRL 118 (2017) 111801*
CDF	$6.8fb^{-1}$	ℓ = μ	Branching ratios	*PRL 107 (2011)201802*

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 $\mathcal{O}_i$

$\mathcal{O}_{1,2}$: *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*

- 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

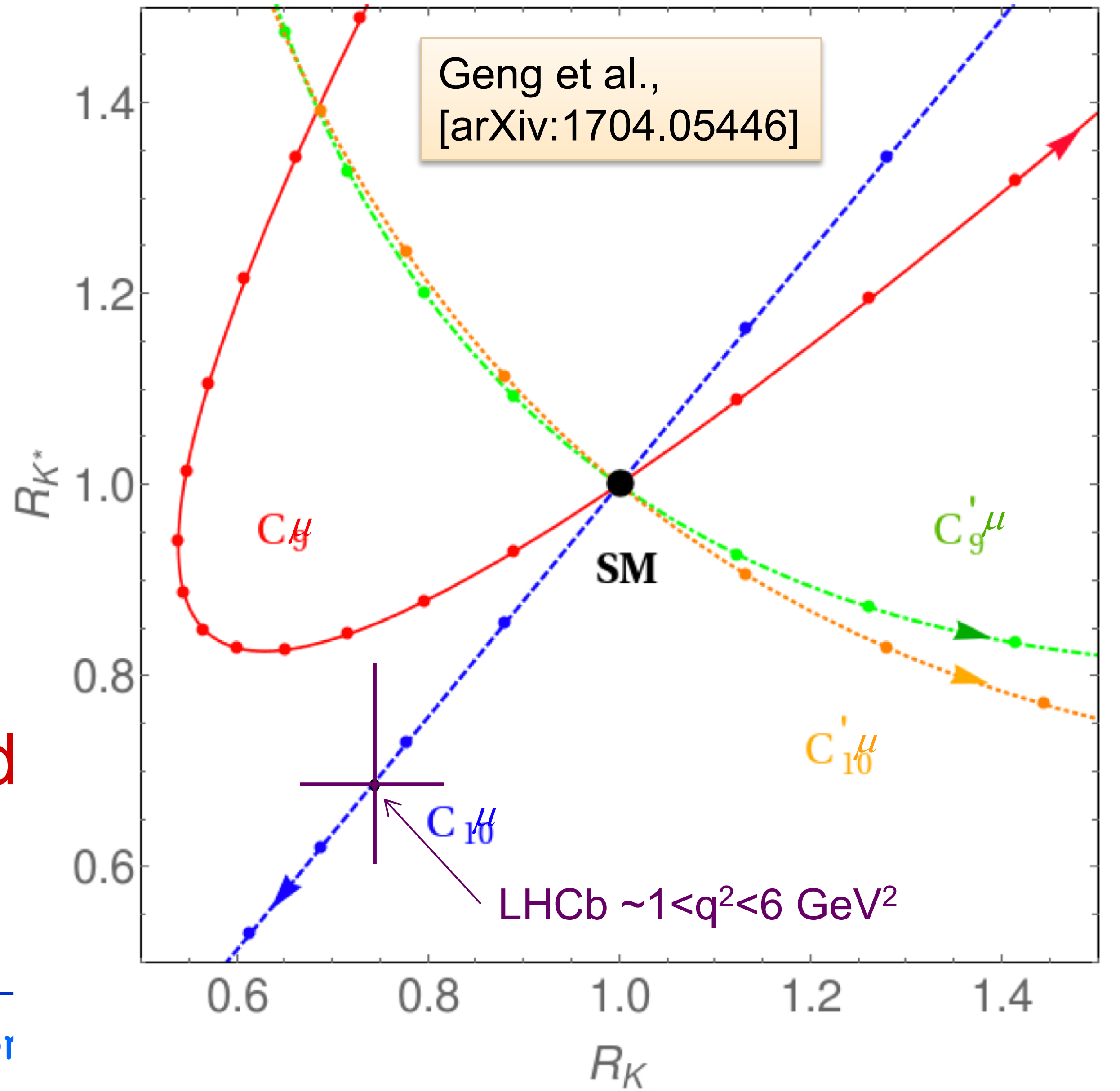
Operators contributing to LFU

- $O_9^{(\prime)} = \frac{\alpha_{EM}}{4\pi}\left(\bar{s}\gamma^{\mu}P_{L(R)}b\right)\left(\bar{\ell}\gamma_{\mu}\ell\right), \quad O_{10}^{(\prime)} = \frac{\alpha_{EM}}{4\pi}\left(\bar{s}\gamma^{\mu}P_{L(R)}b\right)\left(\bar{\ell}\gamma_{\mu}\gamma_5\ell\right)$,

  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 $C_{10}'^\mu$



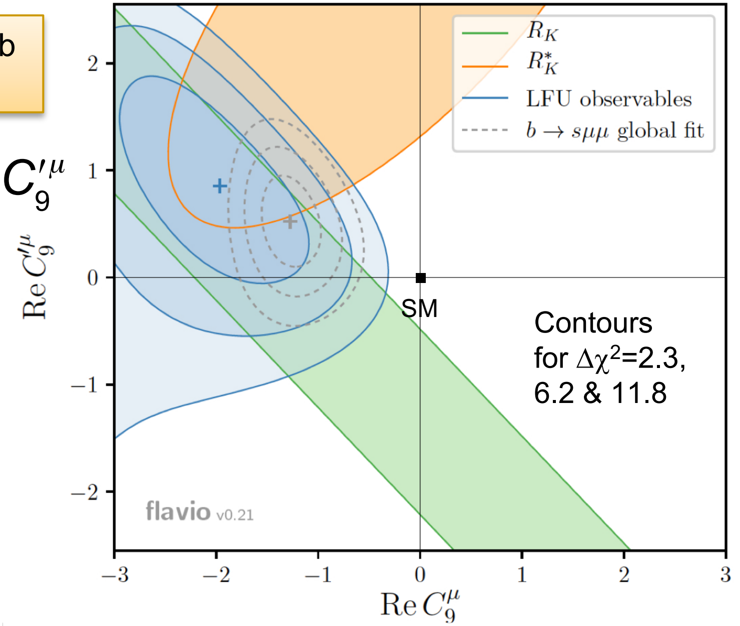
Example fits

- Two separate fits

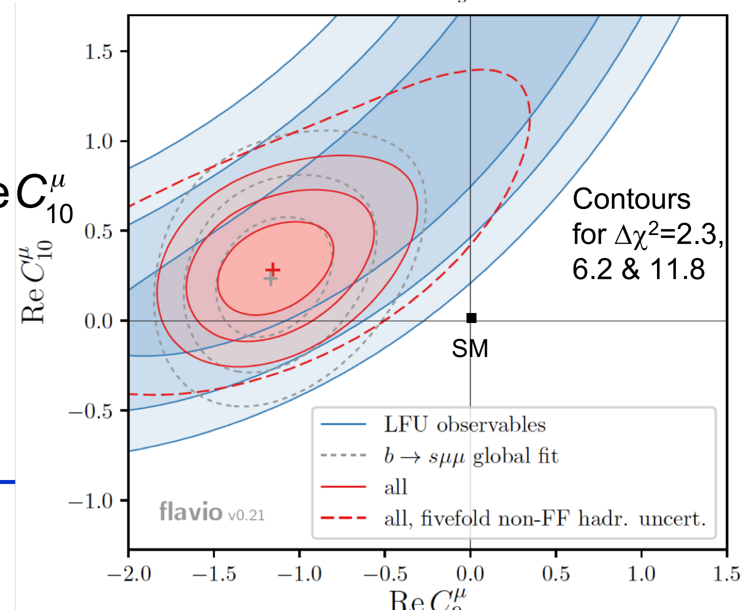
Altmannshofer, Stangl & Straub [arXiv:1704.05435]

  - 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, $\mathcal{B}(b\to X_s\mu\mu)$ from BaBar; red dashed line with hadronic uncertainties x5
- Here $ReC_{9(10)}^{\mu}$ is diff wrt SM. Prefers ReC_9^{μ}~-1, (SM is 0)

$\mathrm{Re}\,C_9^{\prime\mu}$

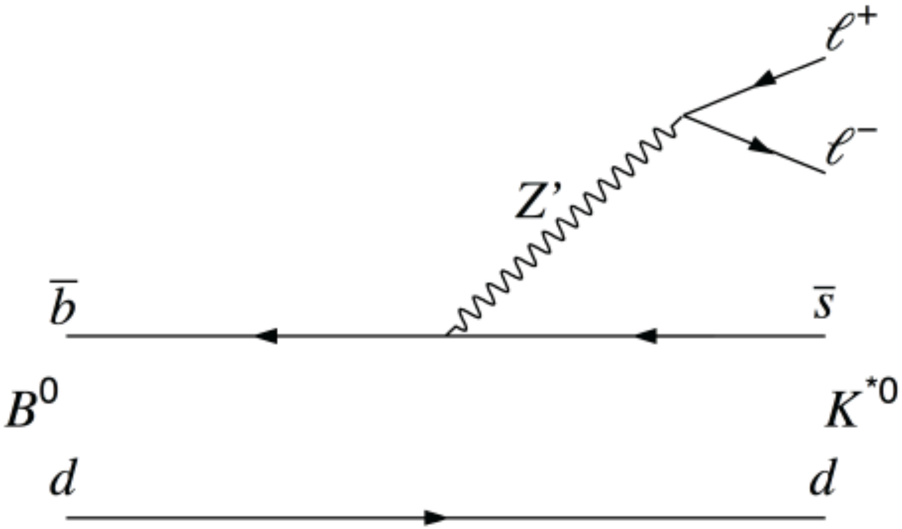


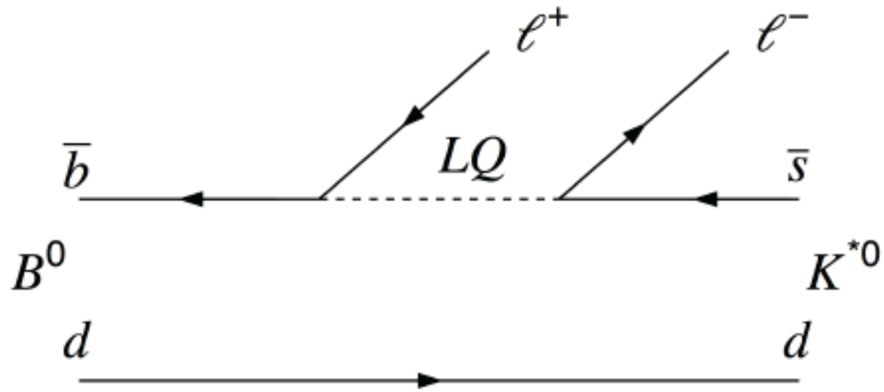
$\mathrm{Re}\,C_{10}^{\mu}$



NP diagrams

- Either of these processes could interfere with the SM diagrams & can explain the data





Should we believe LFU violation?

Yes

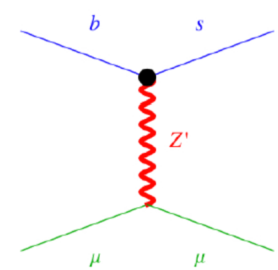
- R measurements are double ratio's to J/ψ, LHCb's check with $K^*J/\psi\rightarrow e^+e^-/\mu^+\mu^-$ =1.043±0.006±0.045
- $\mathcal{B}(B^-\rightarrow K^-e^+e^-)$ agrees with SM prediction puts onus on muon mode which is well measured and low
- Both R_K & R_{K^*} are different than ~1
- Supporting evidence of effects in angular distributions

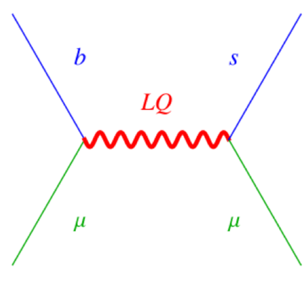
No, not yet

- 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

Conclusions

- We may be seeing the first hints of physics beyond the SM in a failure of lepton flavor universality in $B \to K^{(*)}\ell^+\ell^-$ a suppressed decay
- 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?

Outlook: Data

- Belle II will have ~40x more data, allowing significant results even with part of the $\int\mathcal{L}$
- CMS now is triggering on a single μ. Plans to park 10 B B's this year, especially when $\mathcal{L}$ is low. Uses up to 4kHz bandwidth. ATLAS will test $K^{(*)}e^+e^-$ triggers.
- LHCb Run I data set is 3/fb, Run II thus far is 3.8/fb, plus 2018 data~1.8/fb for a total of 5.6/fb
- Effective b yields are Run II/Run I ~2.5
- So after Run II is over will have 5.7 times more b events than the results presented here for Run I + Run II. Thus 2.6σ effects should go to 6σ if the central values stay the same

Outlook II

- LHCb prospects are even better
  - Can improve ε's with clever algorithms
  - Can use more decay modes, e.g. $B^- \to K^-\pi^+\pi^-\ell^+\ell^-$, which has about the same branching fraction as $K^-\ell^+\ell^-$,& $\Lambda_b \to pK^-\ell^+\ell^-$
- Run III and beyond: After Upgrade I, expect a lot more luminosity ~50/fb, but calorimeter will be somewhat compromised by ~6 interactions per crossing

Upgrade II

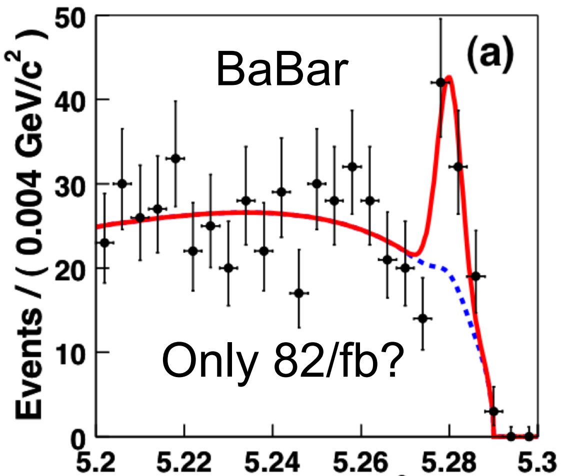
- Run at higher luminosity, maybe up to x10
- Chambers on magnet faces to capture more tracks, especially from higher multiplicity decays
- Improved central tracking, Silicon close to beam near the fiber tracker
- Vastly improved EM calorimeter. Smaller cells, timing to pick out primary vertex.

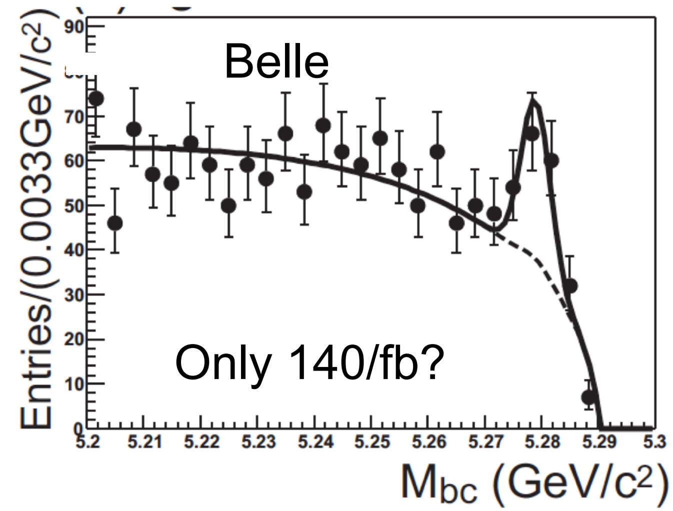
The End

Backup slides

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

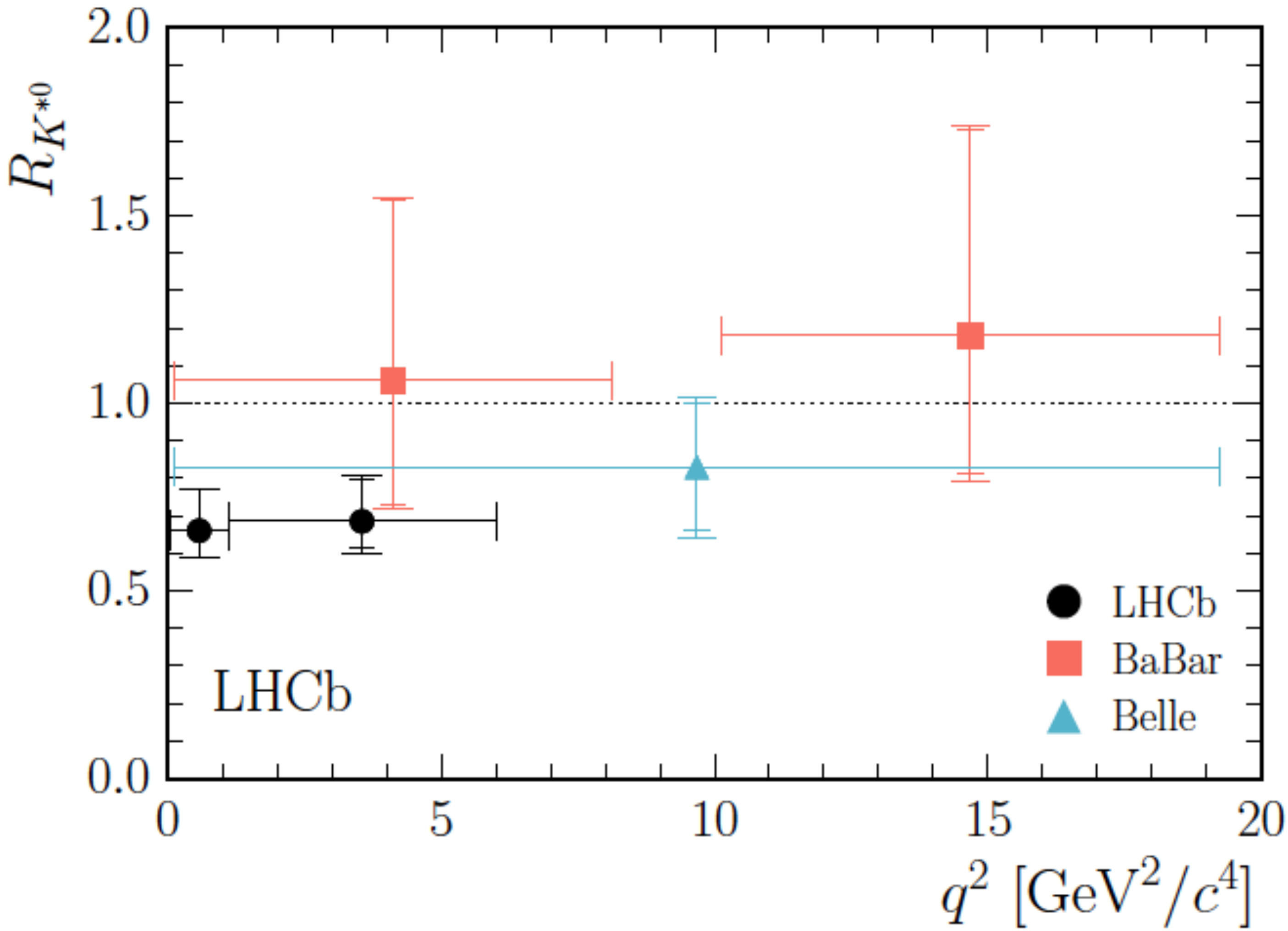
- Define two q^2 regions: low 1-6, high >14.4 GeV^2
- Low again probes C_7, while high C_9 & C_{10}
- Data





- 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

R_{K^*}



Another fit

- arXiv:1704.05446

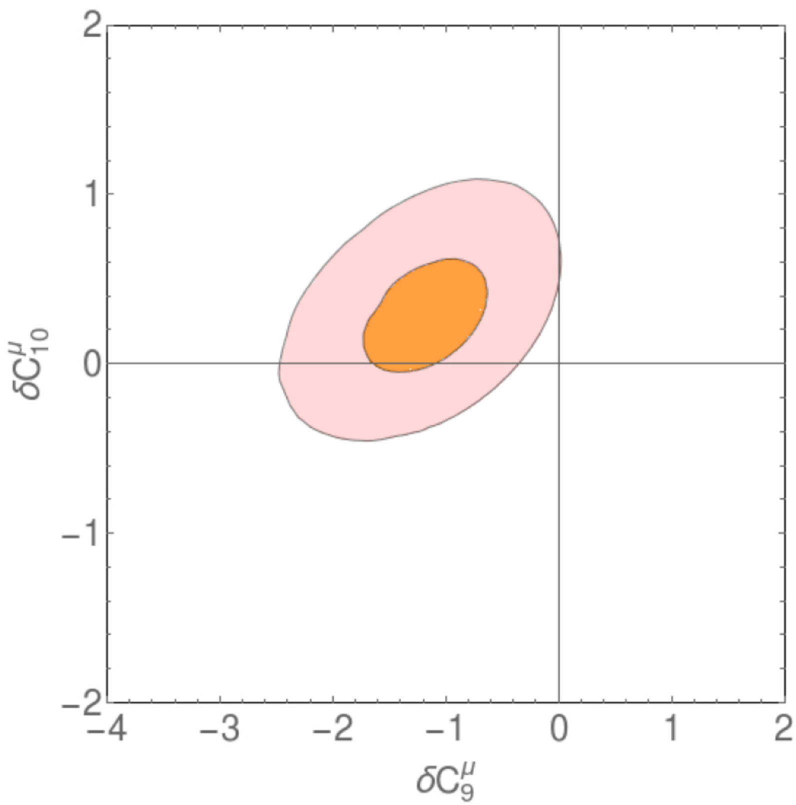


FIG. 5: Fit results for LUV data, $\overline{BR}(B_s \to \mu\mu)$, and $b \to s\mu\mu$ angular observables, as described in the text.

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