S. Stone

Summary of Anomalies in the B Sector

BSM using charged leptons, May 2018

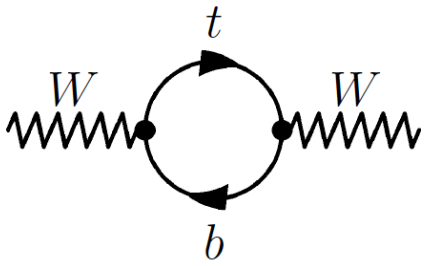
Physics rationale

- 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

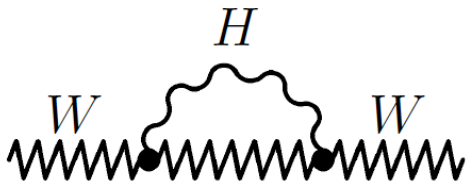
- FP probes large mass scales via virtual quantum loops. An example, of the importance of such loops are changes in the W mass
  - M_w changes due to m_t

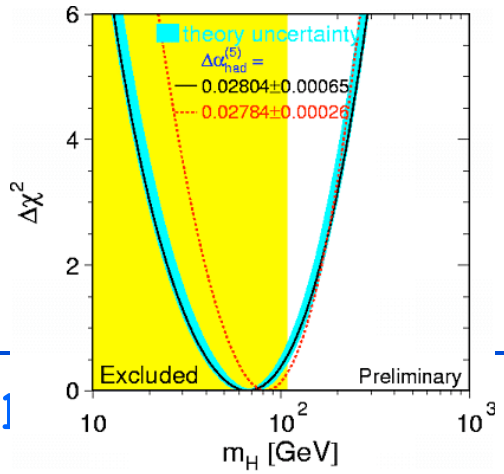
$$\frac{dM_W}{dm_t} \alpha \frac{m_t}{M_w}$$



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

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



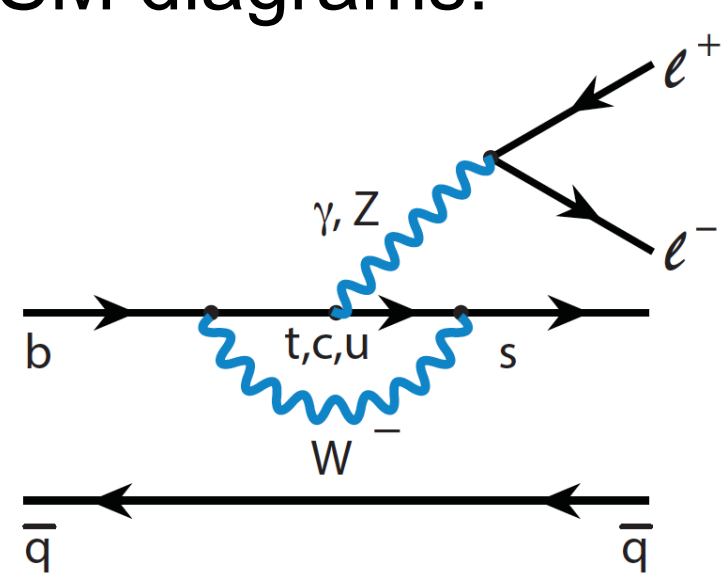


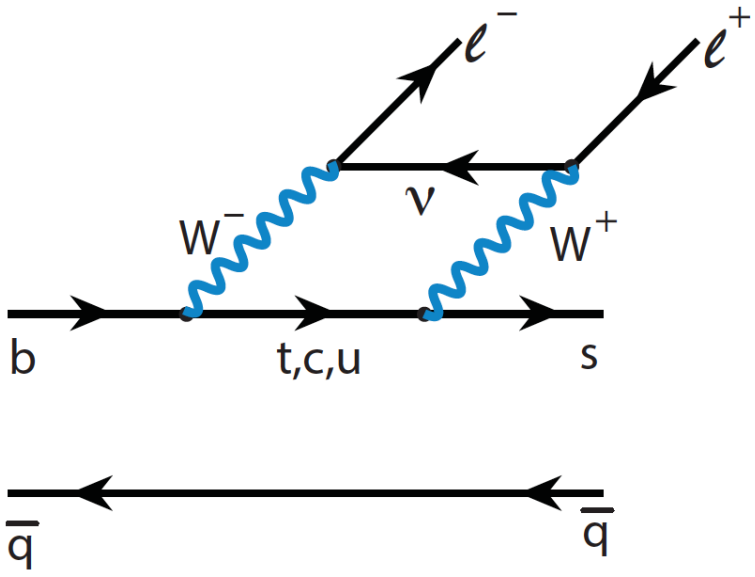
Lepton flavor universality

- 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:

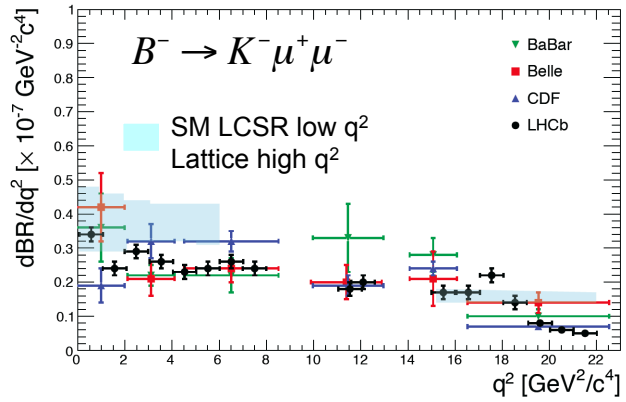


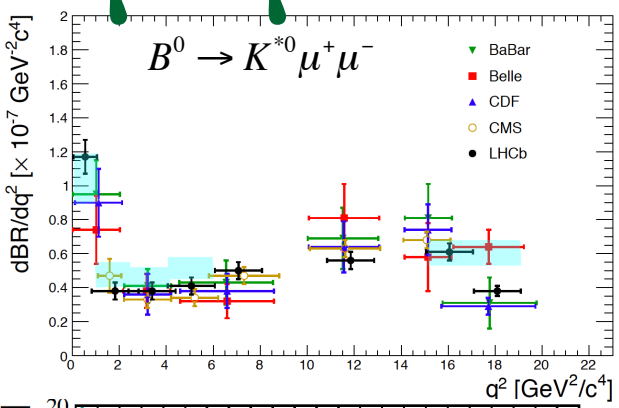


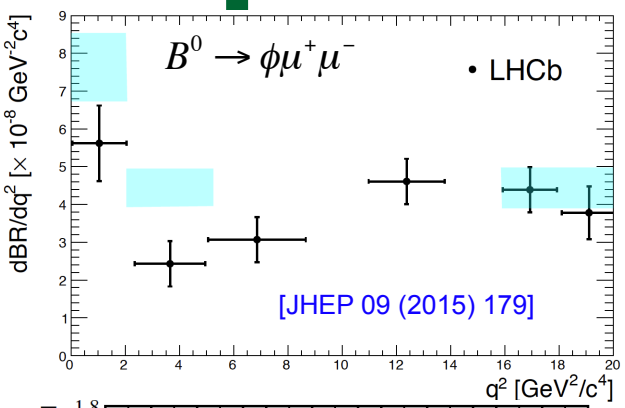
- New particles can appear, augmenting SM ones
- Next: experimental tests

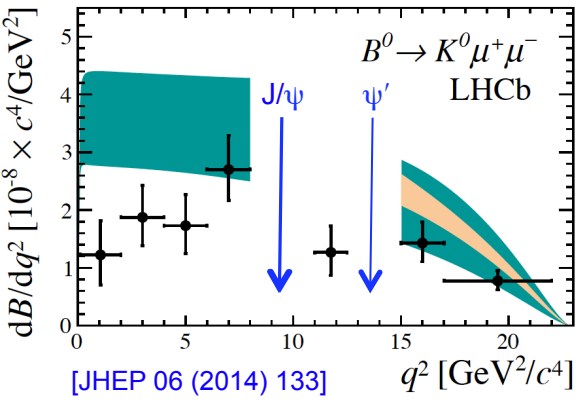
$q^2 = m^2(\mu^+\mu^-)$

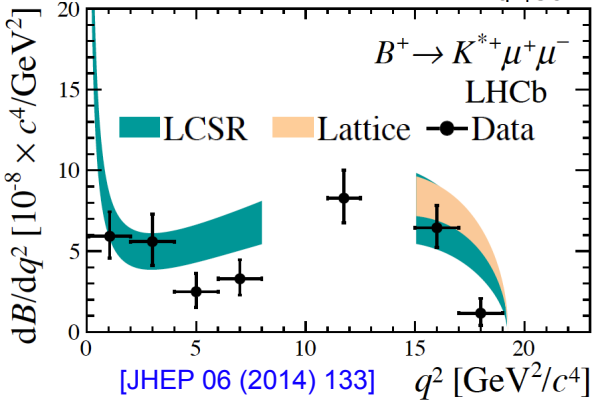
$b \to h\mu^+\mu^-$ $d\mathcal{B}/dq^2$

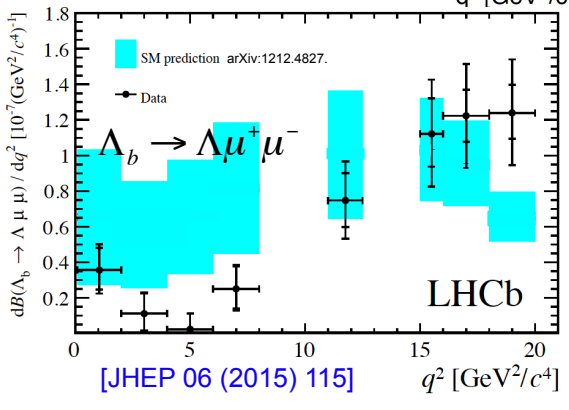








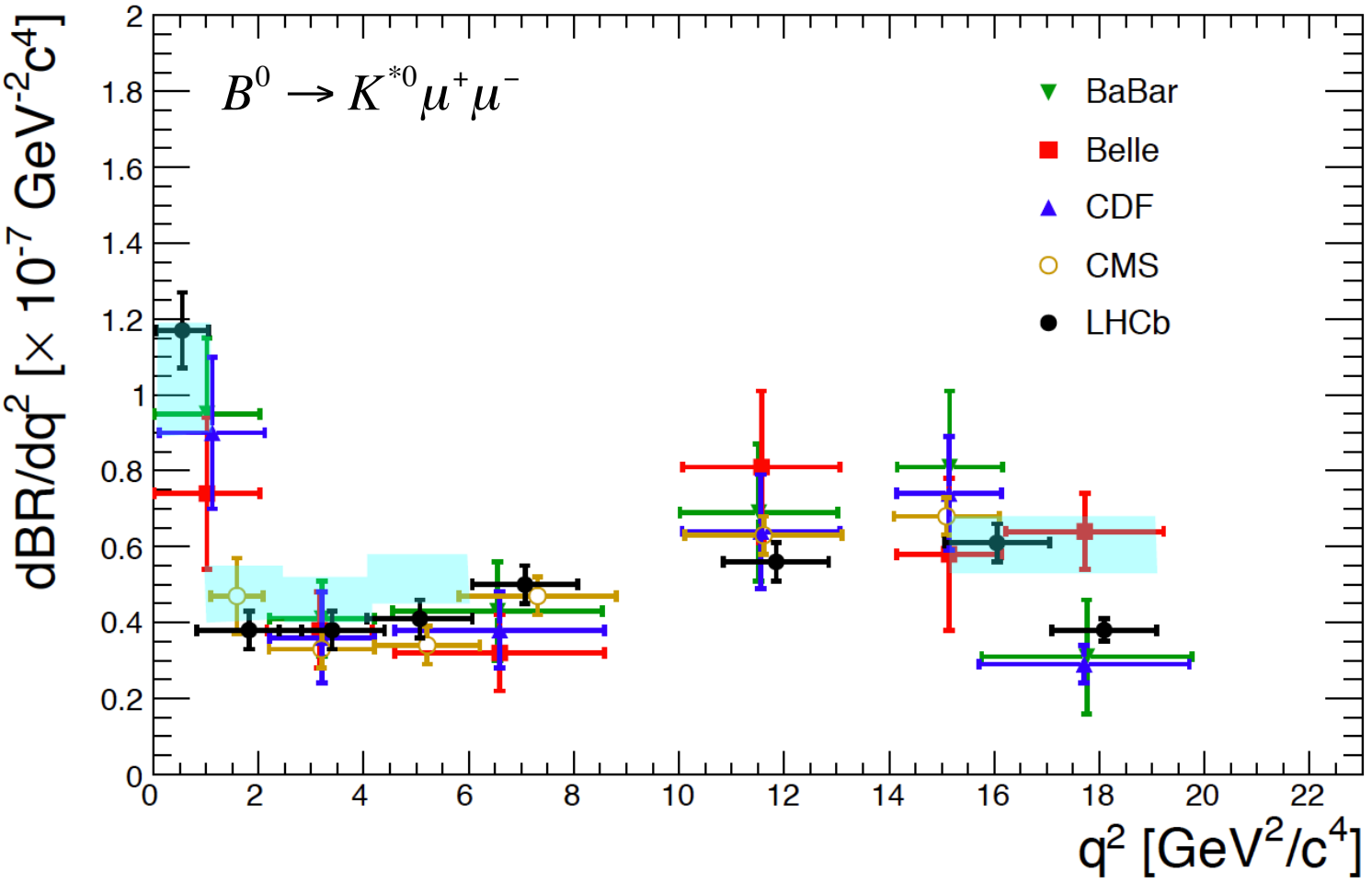




- Data generally below model predictions at low q^2
- Charmonium resonances at high q^2

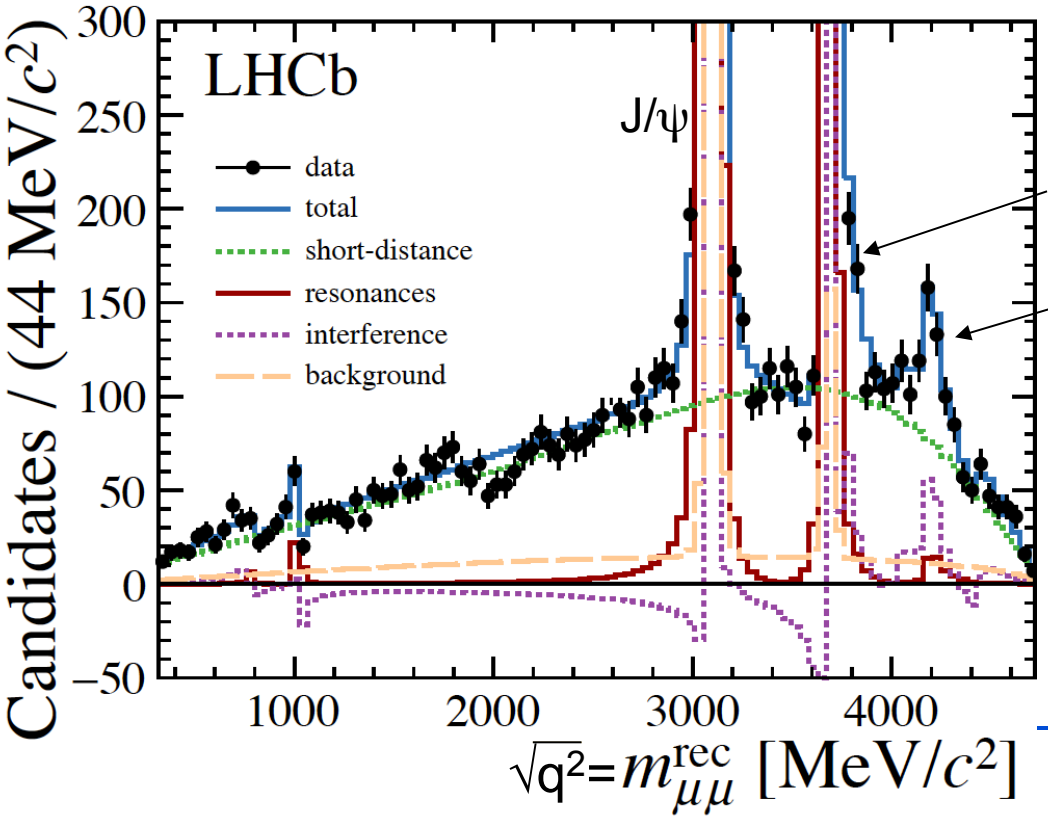
$K^*\mu^+\mu^-$ $d\mathcal{B}/dq^2$

- 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]

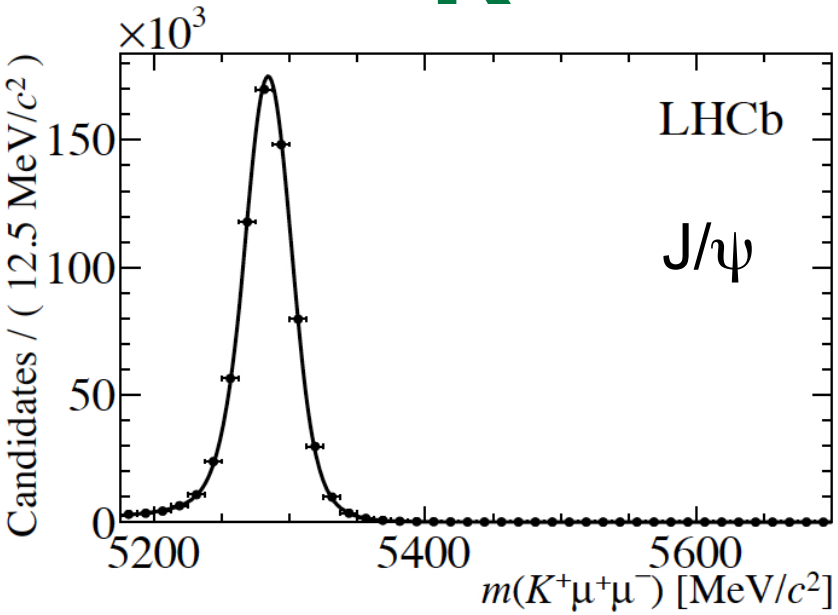
$R_K=(B^-\to K^-\mu^+\mu^-)/(B^-\to K^-e^+e^-)$

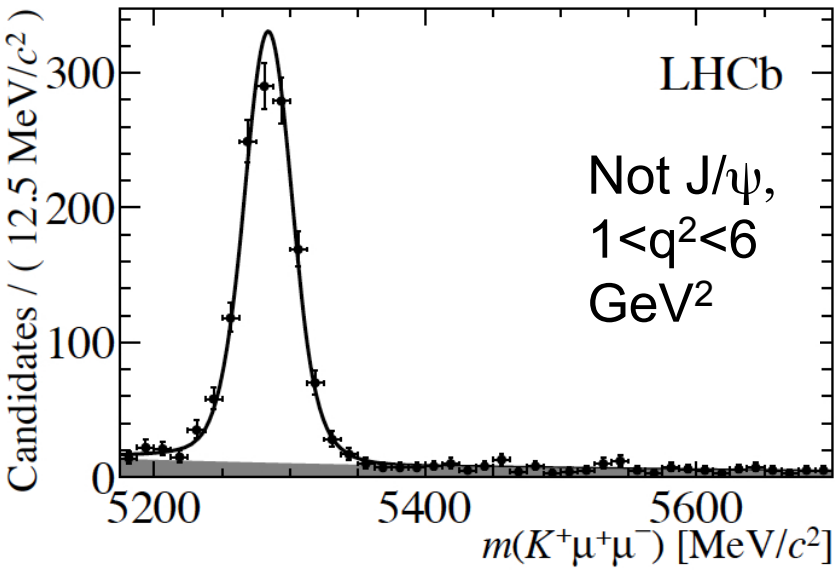
- Dedicated analysis to measure the ratio
- Actually measure the double ratio:

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

- 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





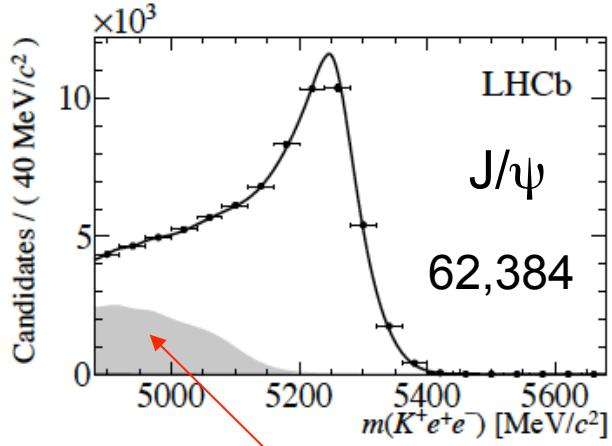
- # J/ψ events: 667,046±882
- # Low q^2 events: 1226±41

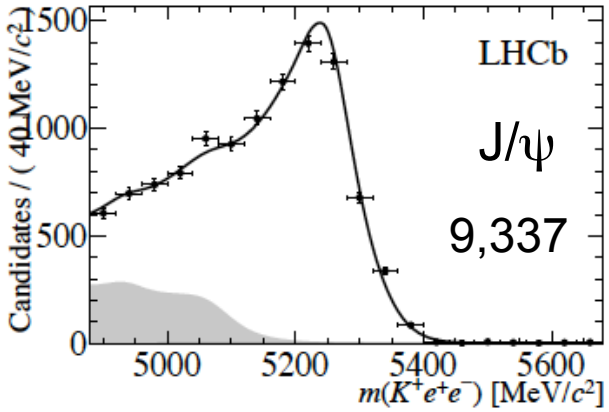
Kee mass distributions

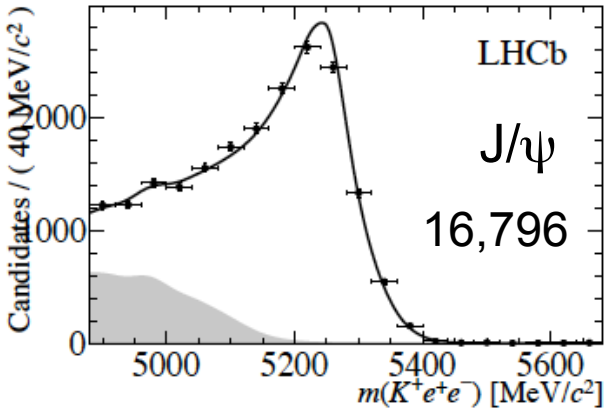
- Trigger: $e^{\pm}$

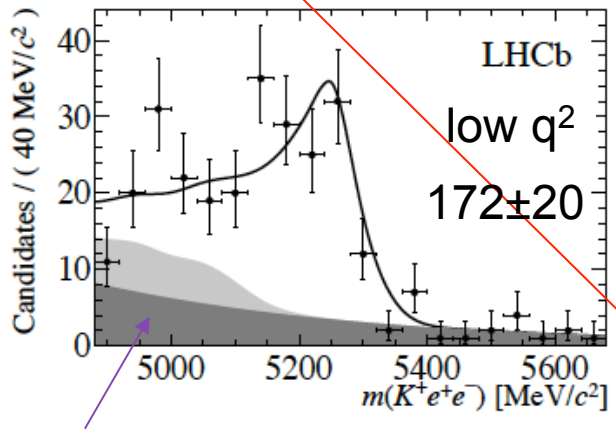
K

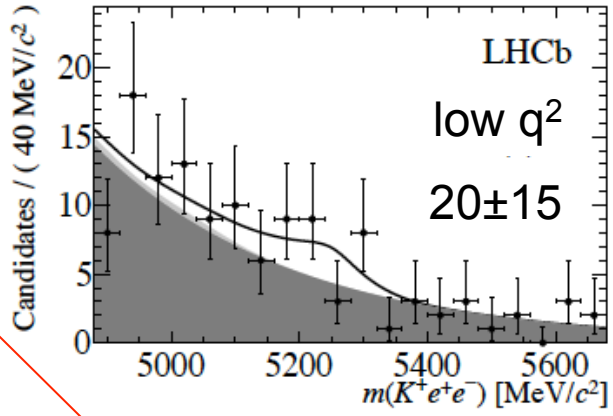
other

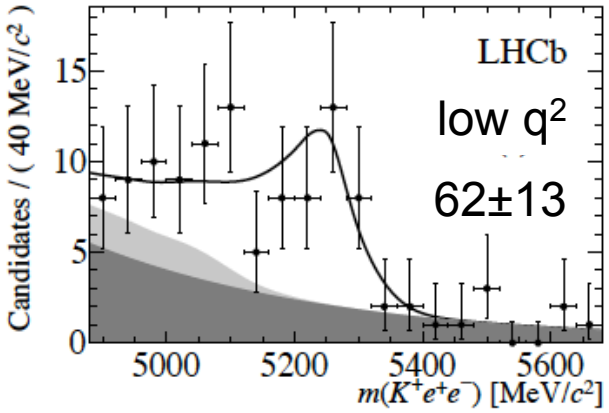












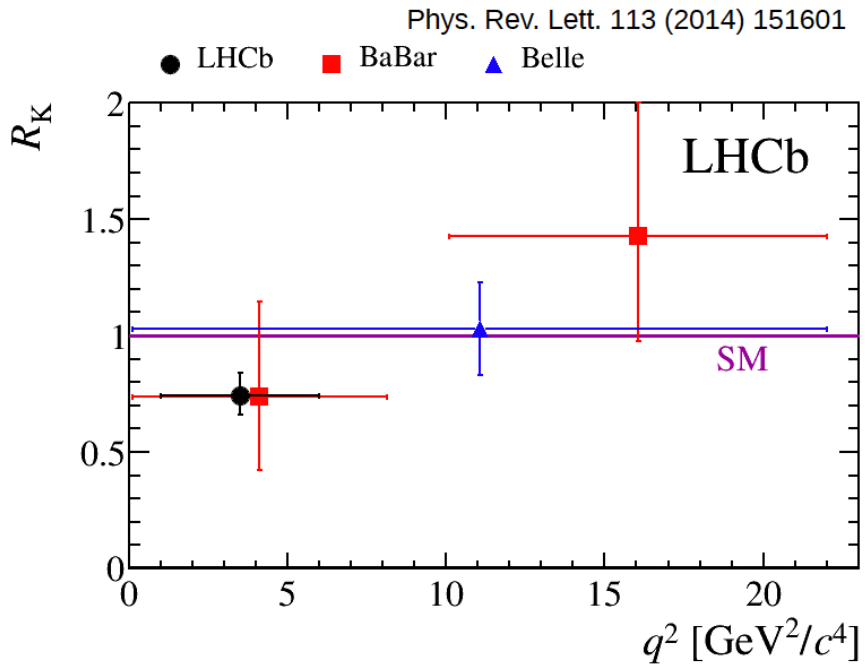
Combinatoric background

Partially reconstructed B decays

R_K results

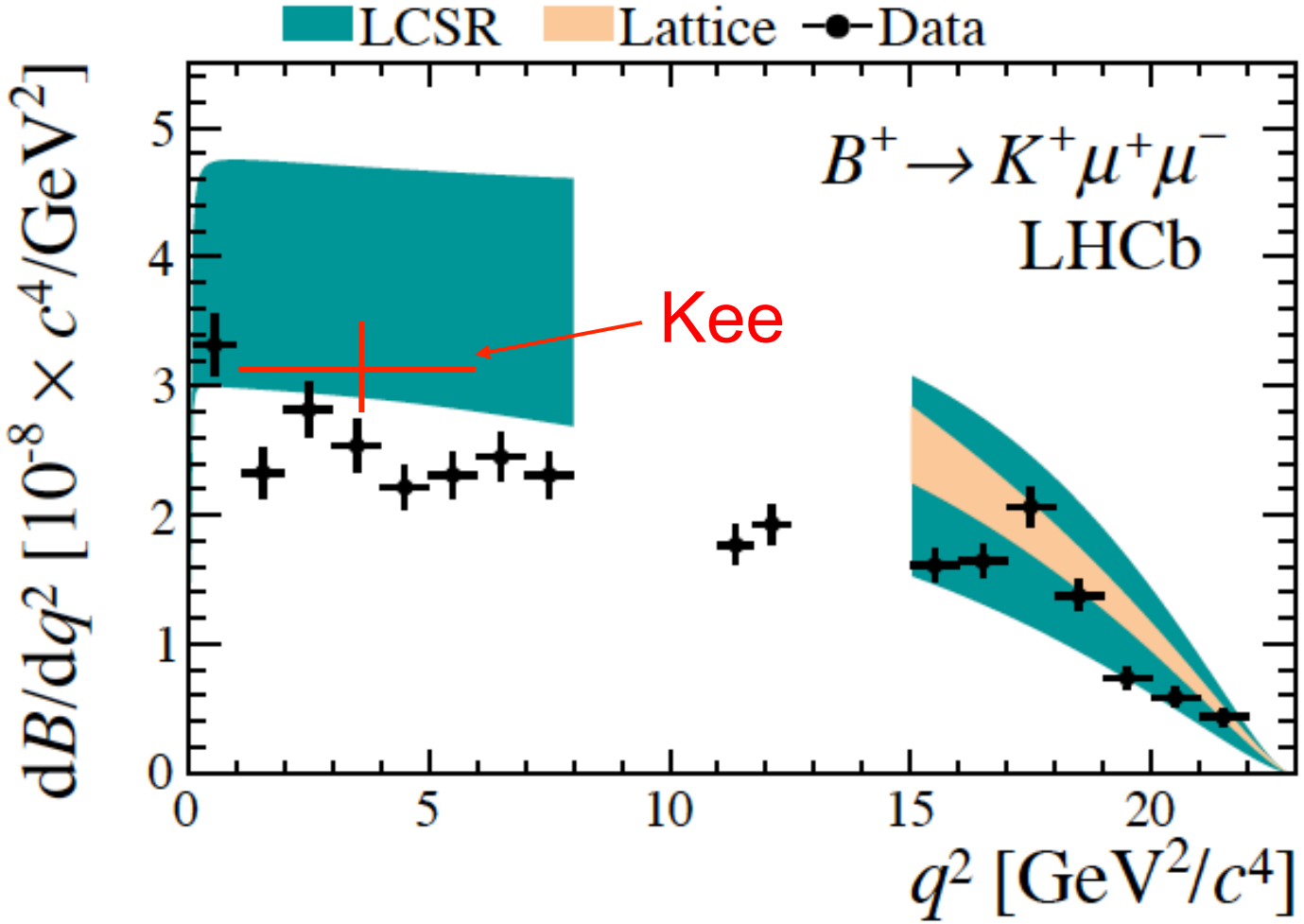
- $$R_K \equiv \frac{\mathcal{B}\left(B^- \to K^- \mu^+ \mu^-\right)}{\mathcal{B}\left(B^- \to K^- e^+ e^-\right)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

for $1<q^2<6$ GeV^2, 2.6σ from SM



Branching ratio comparison

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



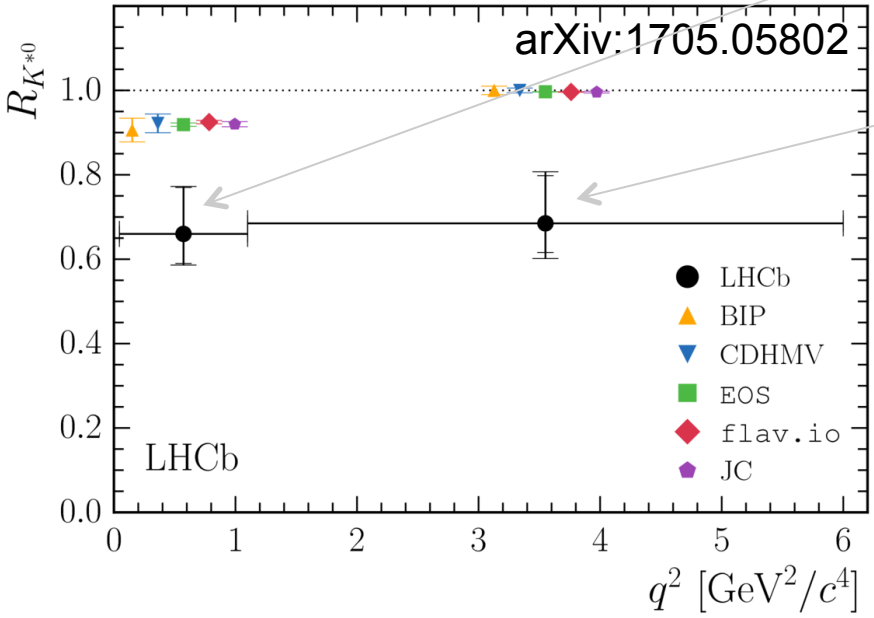
$B^0 \to K^{*0} \ell^+ \ell^-$

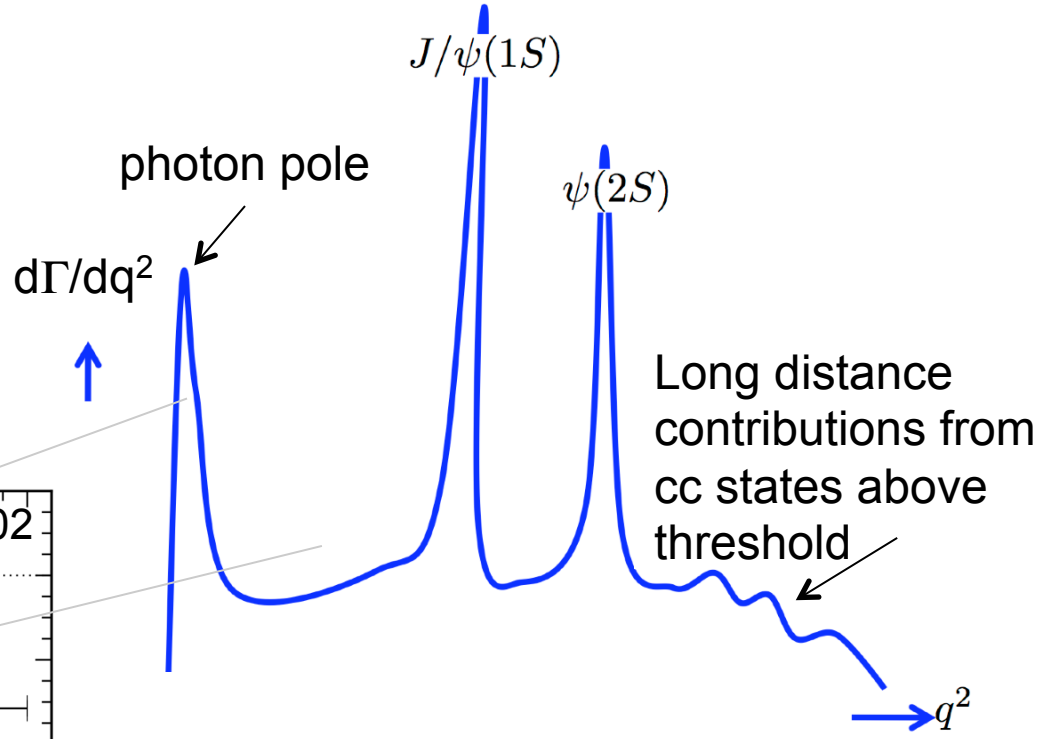
- SM expectations

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

Also measured as a double ratio

- LHCb data

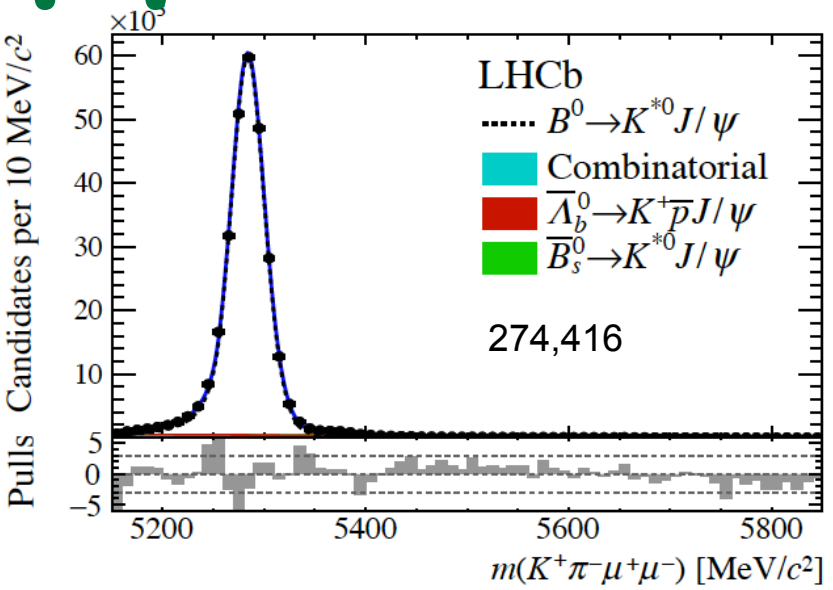


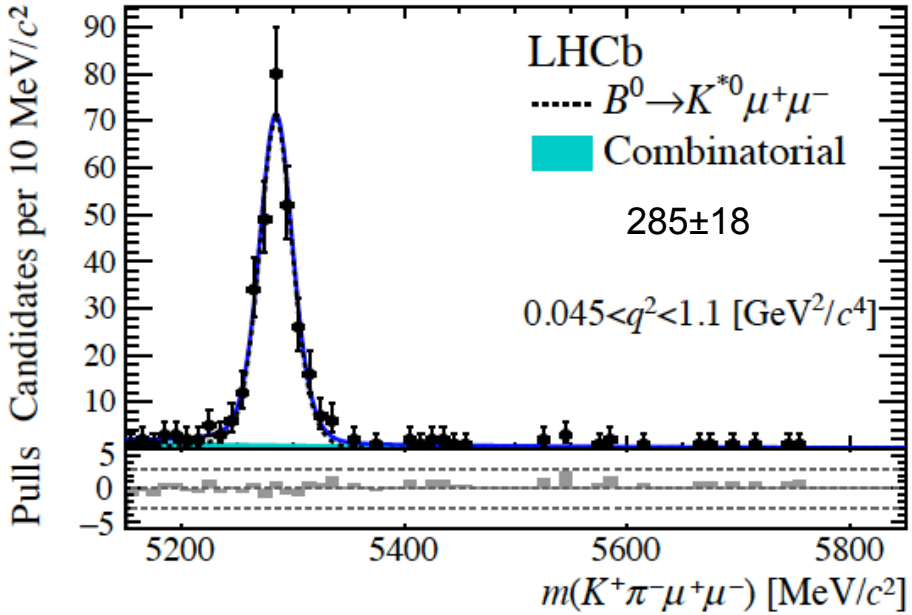


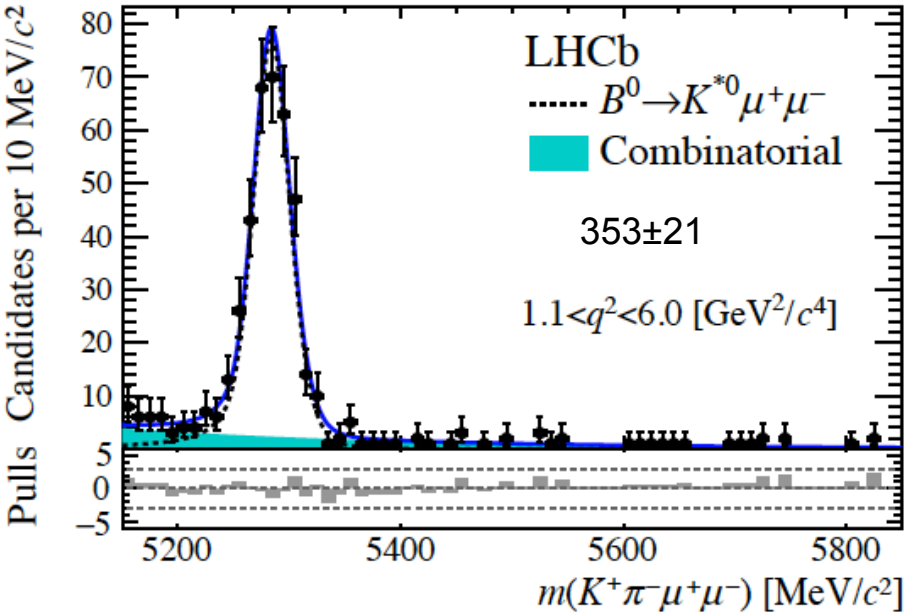
- $R_{K^*} = 0.660^{+0.110}_{-0.070} \pm 0.024,\ 0.045 < q^2 < 1.1$
- $R_{K^*} = 0.685^{+0.113}_{-0.069} \pm 0.047,\ 1.1 < q^2 < 6.0$
- Each ~2.4σ from SM

K*μμ

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

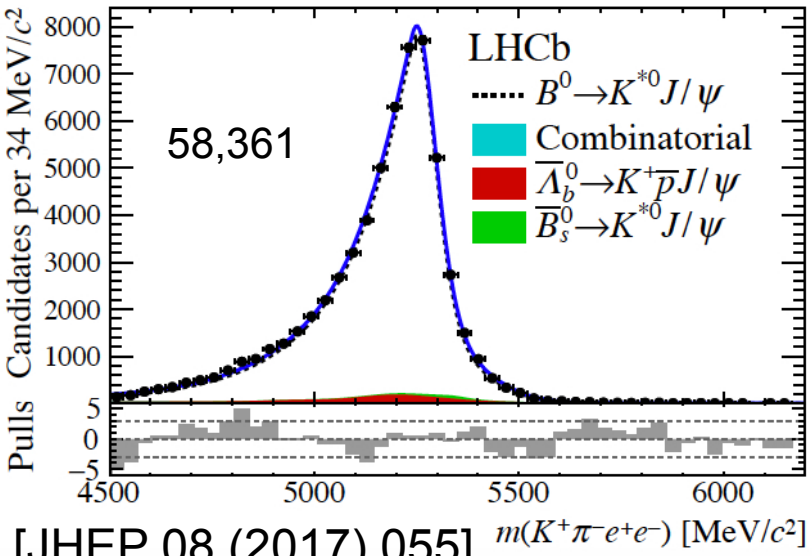




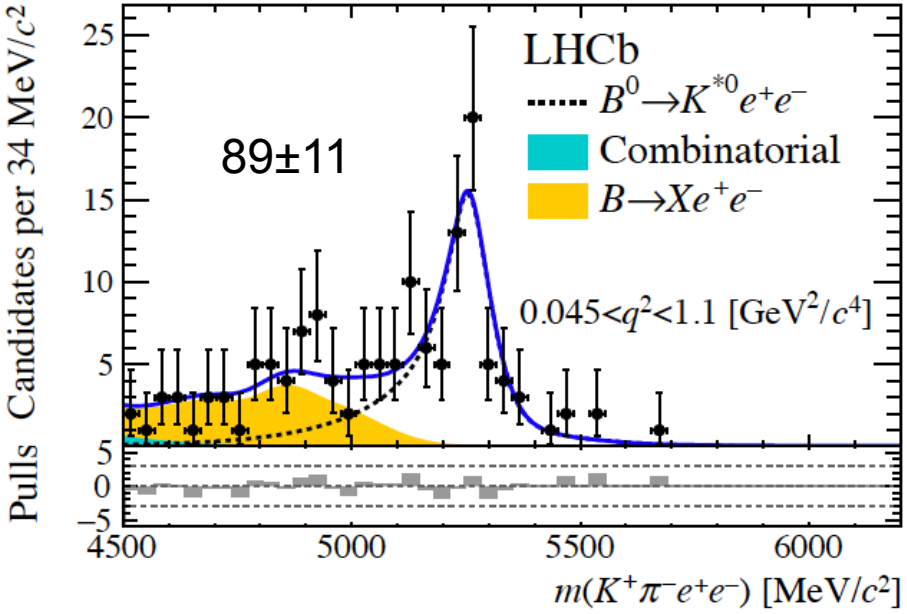


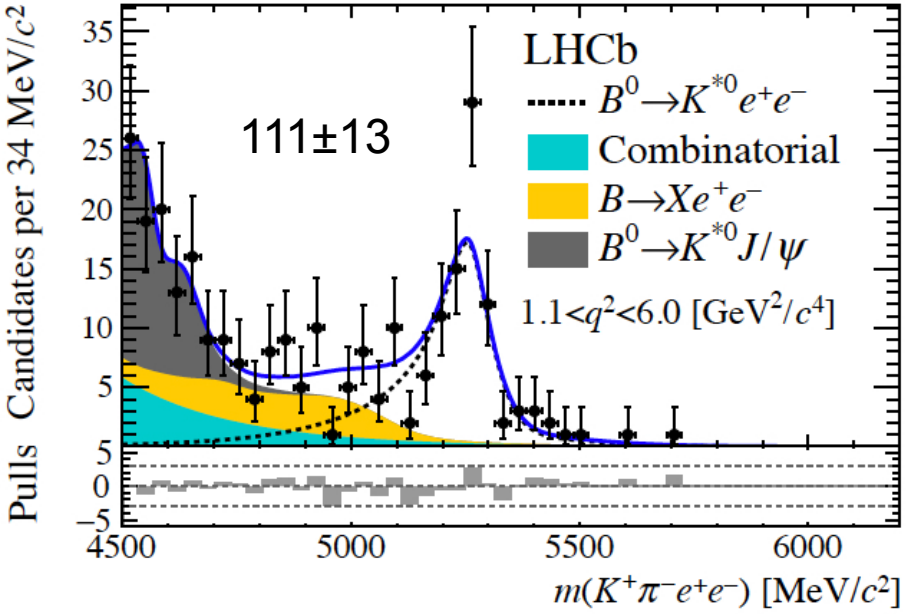
$B^0 \rightarrow K^{*0} e^+ e^-$

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



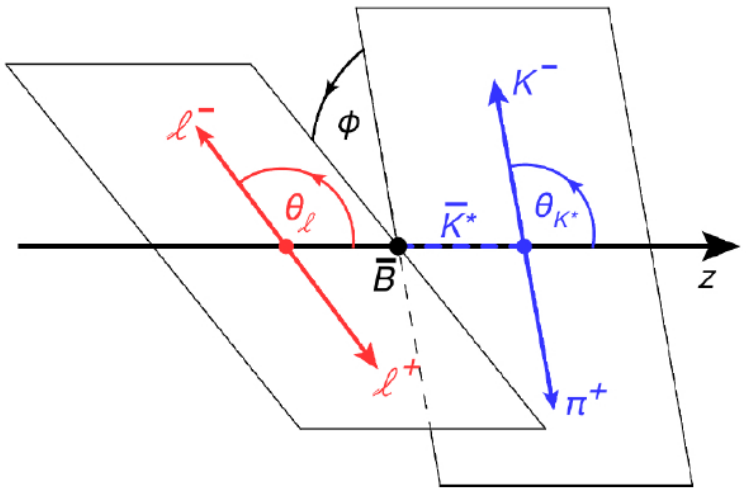
[JHEP 08 (2017) 055]





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

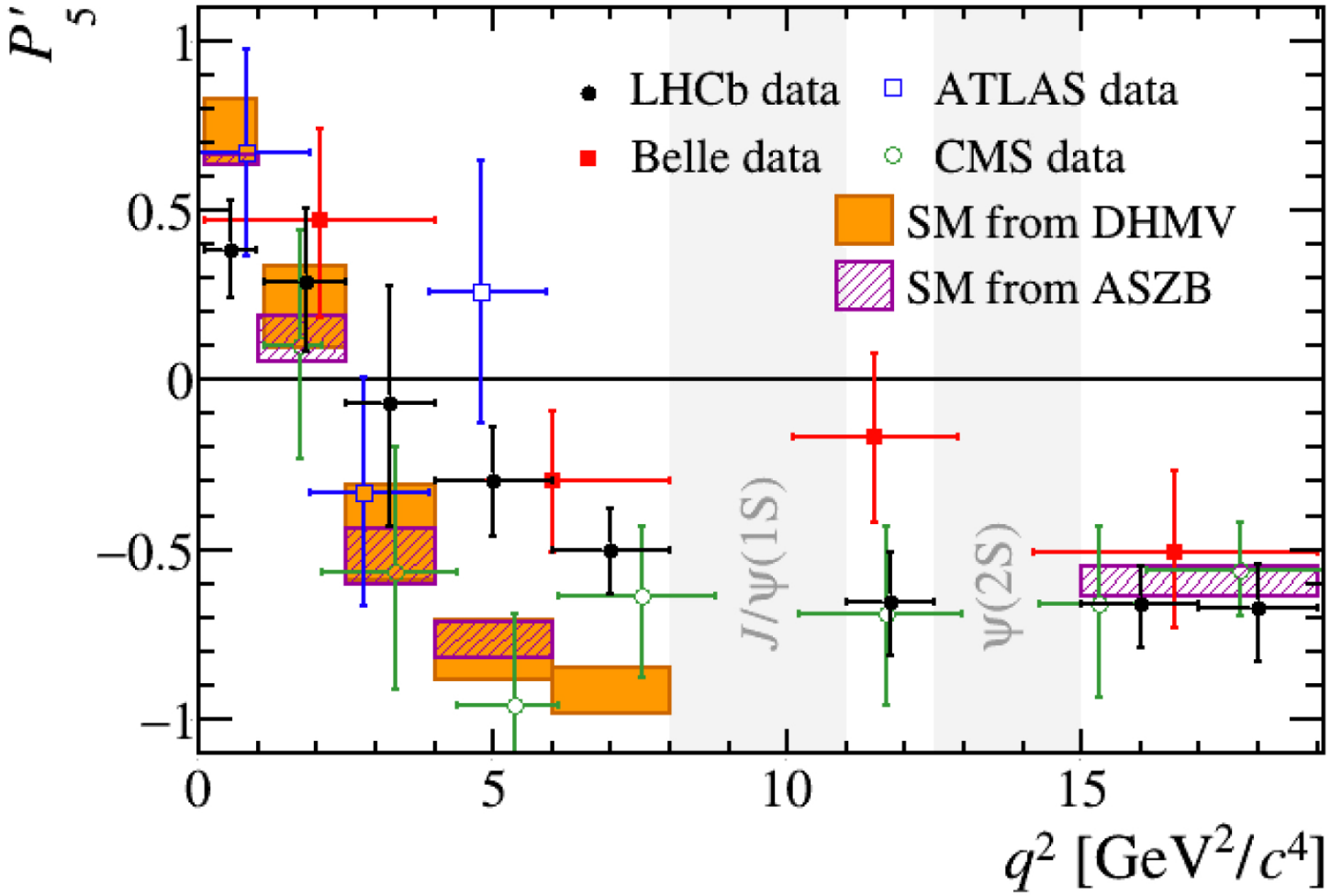
A cleaner set of observables, where hadronic form factor uncertainties cancel at the leading order, can be defined

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

From Justine Serrano

The curious case of P_5'

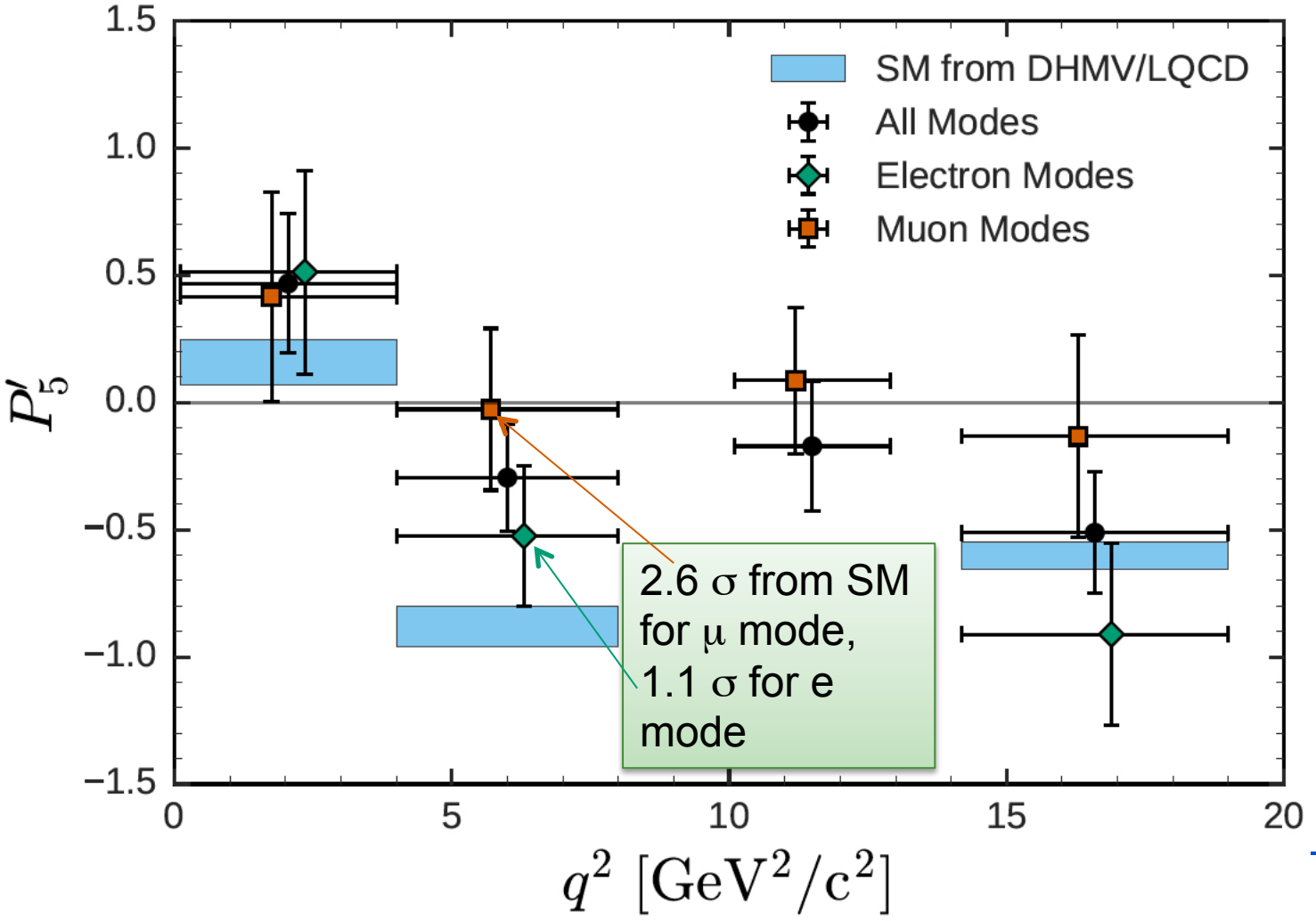
- Most angular observables agree with SM
- Deviation in P_5' near q^2=~6 GeV^2



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 obervables	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 II	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 $\mathcal{O}_i$
- 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

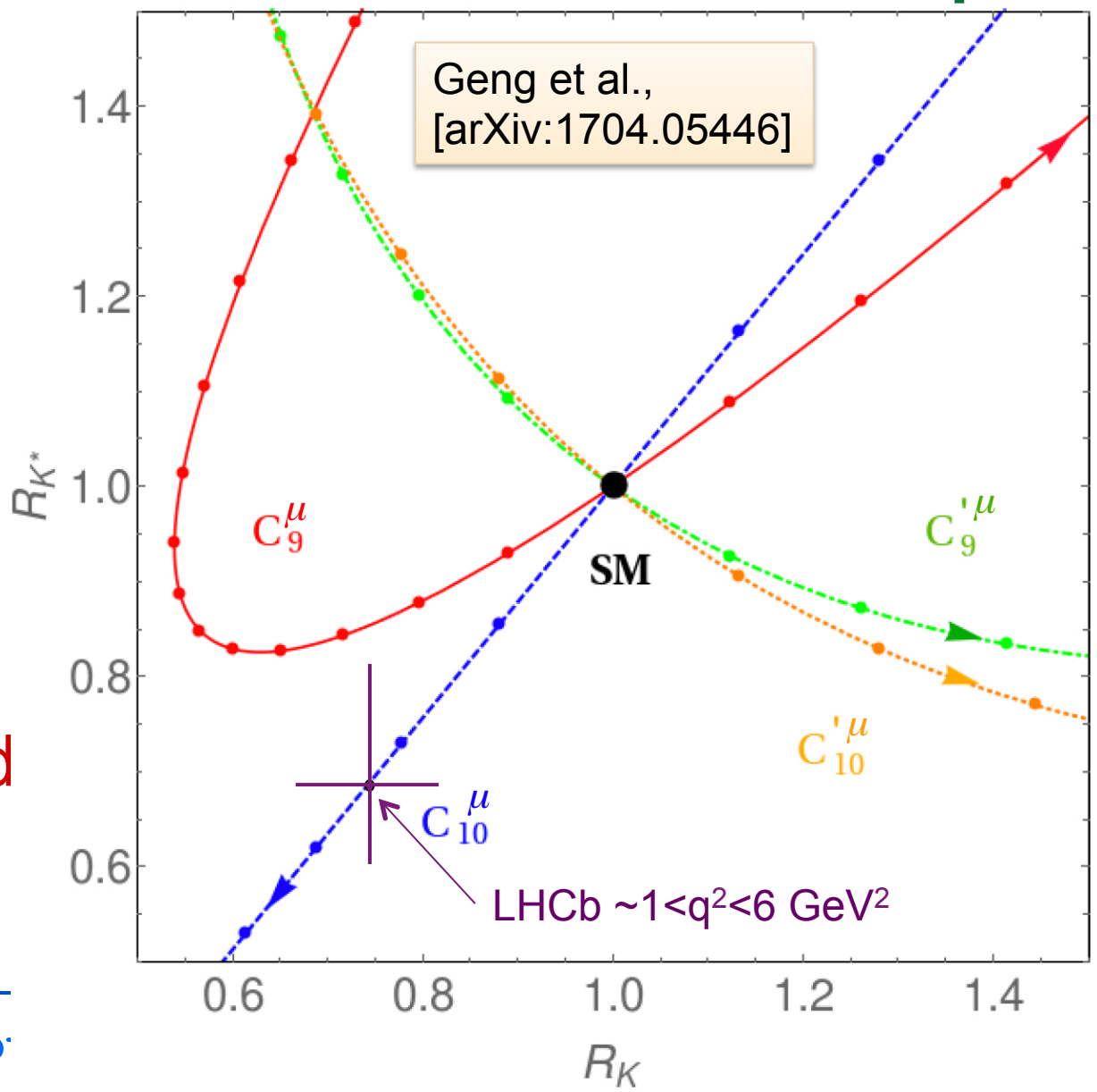
Operators contributing to LFU

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

  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 $C_{10}'^\mu$



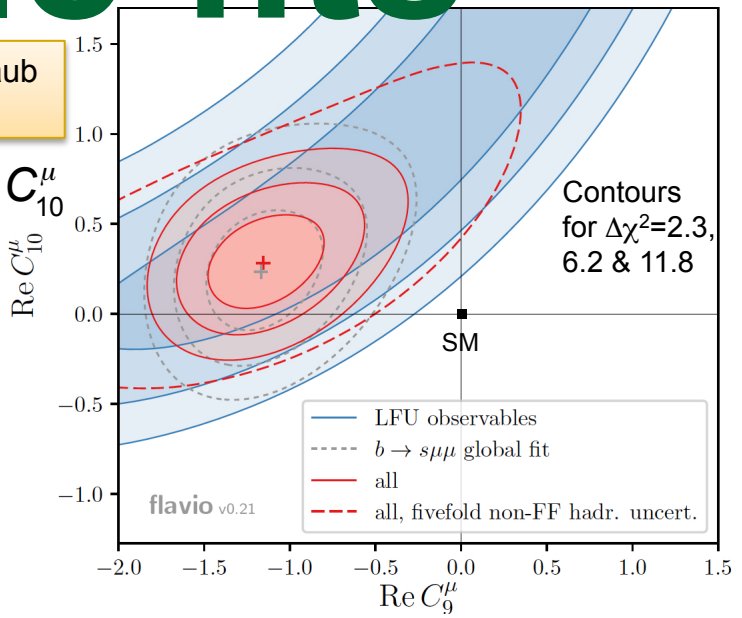
BSM using charged lep

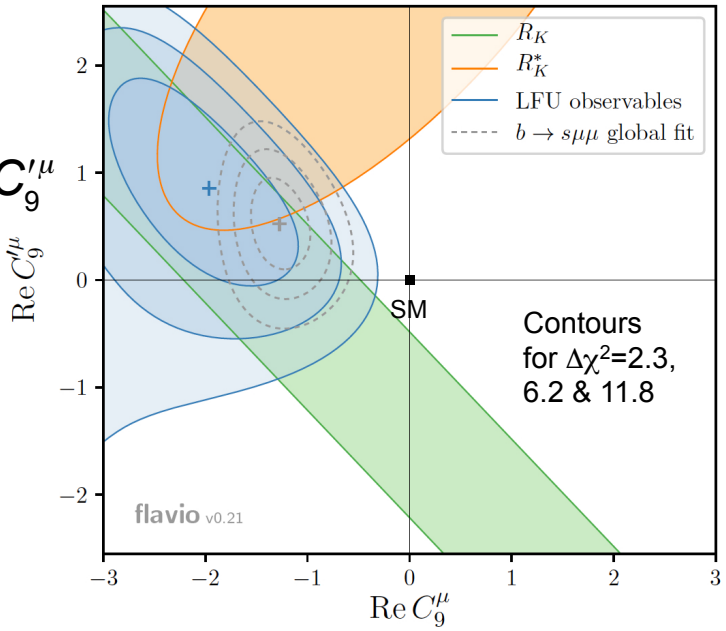
Example fits

- 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

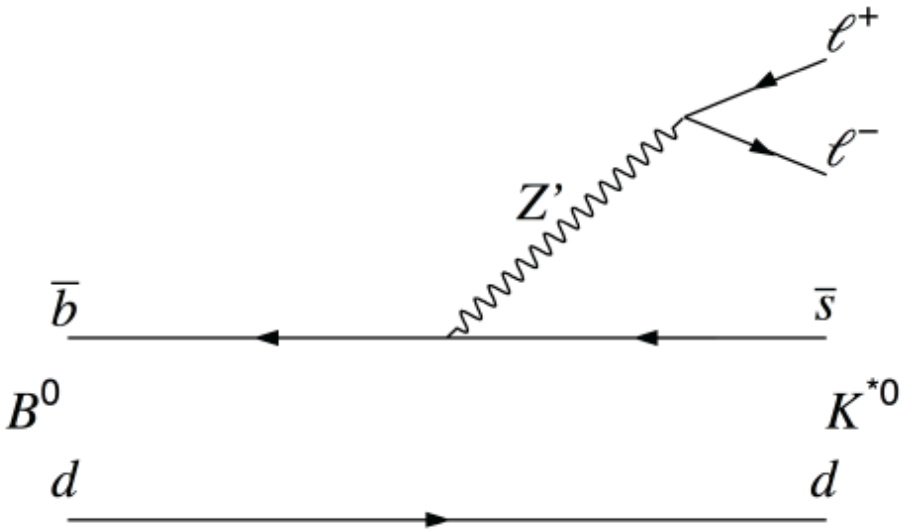


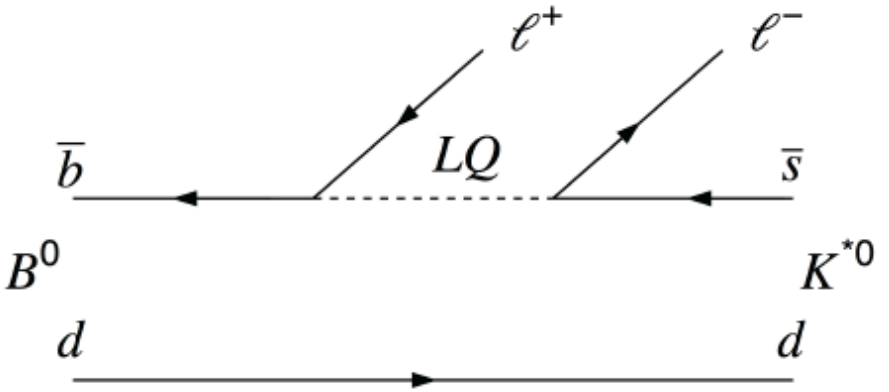


- Here $ReC_{9(10)}^{\mu}$ is diff wrt SM. Prefers ReC_9^{μ}~-1, (SM is 0)

NP diagrams

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





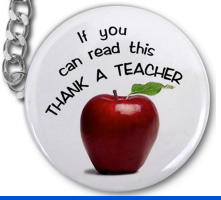
Should we believe LFU violation?

Yes

- R measurements are double ratio's to J/ψ, LHCb's check with $K^*J/\psi \to e^+e^-/\mu^+\mu^- = 1.043 \pm 0.006 \pm 0.045$
- $\mathcal{B}(B^- \to K^- e^+ e^-)$ 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

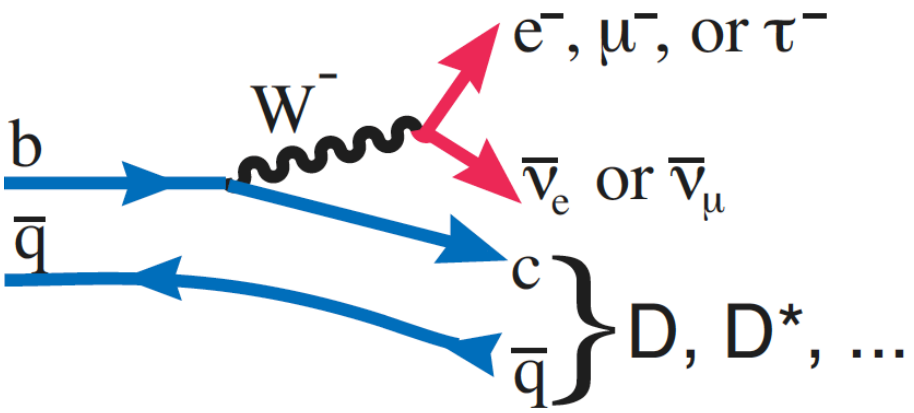


$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

where ℓ indicates e or μ or their average

Theory basics

- Compare the most prolific B decays, the semileptonic decays where the virtual W^- can materialize as either an $e^-\nu$, $\mu^-\nu$, or $\tau^-\nu$.



- To calculate decay width need form-factors. Can use HQET and/or lattice QCD.
- Standard Model predictions are robust R_D=0.300±0.008, and R_{D^*}= 0.252±0.003

Technique at B factories

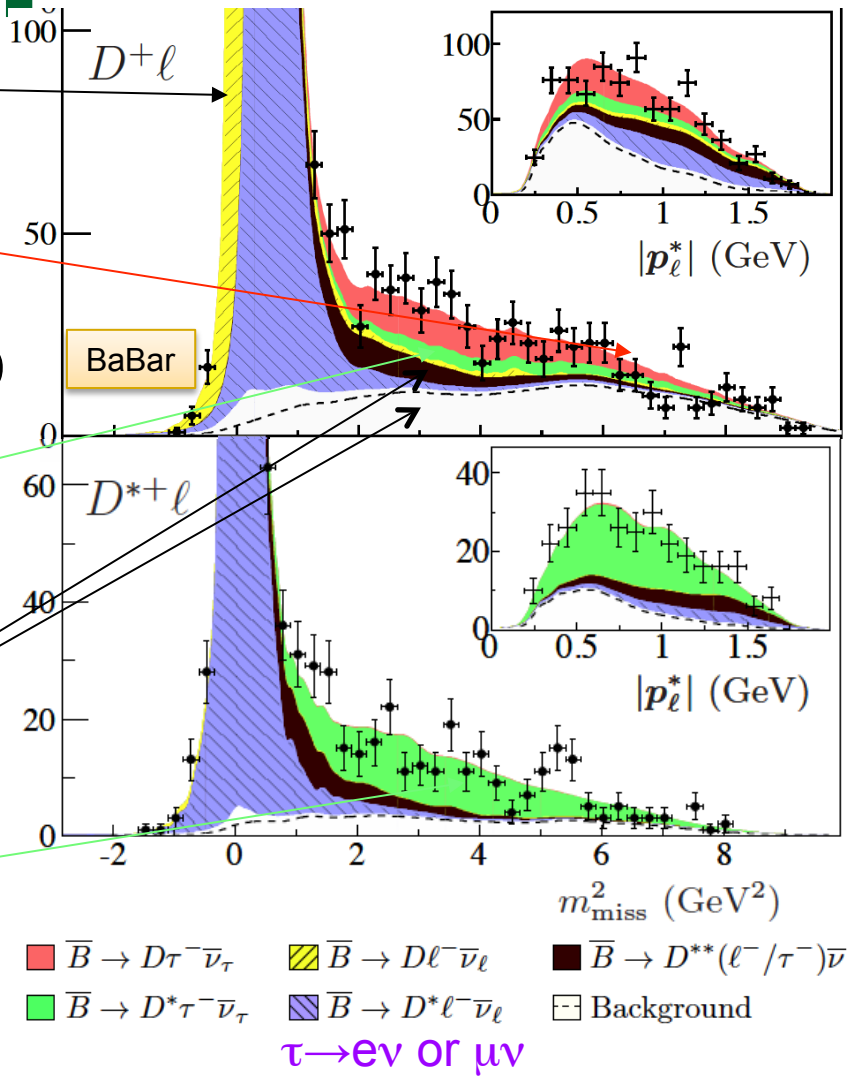
- Since $e^+e^- \rightarrow B_1B_2$ can fully reconstruct one B_i in a fully hadronic decay mode. Then look for the evidence of semileptonic decay (SL) by finding either an e^-, μ^-, or τ^-.
- For τ^- use either the $e^-\nu\nu$, $\mu^-\nu\nu$, $\pi^-\nu$, or $\rho^-\nu$ decays
- Since the time resolution is a relatively poor 900 fs for the B's, cannot separate the B vertices or the τ^- vertex [τ(B)~1500 fs, $\tau(\tau)$~290 fs]
- Compute M^2 using -p(B_i) for the SL decay where
- $M^2 = (p_{e^+e^-} - p_{B_i} - p_{D^{(*)}} - p_\ell)^2$, where the p's are 4-vecs

Technique at B factories II

- Also use the lepton 3-momentum in the center of mass frame for candidate events (p_ℓ^*) as a discriminating variable (for $M^2>1$ GeV^2)
- $D^*\tau\nu$ events will populate the $M^2>1$ GeV^2
- Consider $D^*\mu\nu$ events, expect a peak at $M^2=0$, but not from backgrounds
- For $D\mu\nu$ events also expect a peak at $M^2=0$, but not for $D^*\mu\nu$ events or backgrounds
- Backgrounds: continuum, combinatoric, fake $D^{(*)}$, fake ℓ, $D^{**}\ell\,\nu$, $B\to D^{(*)}D_s$, $D_s\to\mu^-\nu$, $\tau^-\nu$.

e^+e^- spectra

- M^2 for $D\ell\nu$ shows peak at 0, larger peak ~0.5 Gev^2 for $D^*\ell\nu$. The signal $D\tau\nu$ events form a band out to the M^2 end point. Here there is background from $D^*\tau\nu$ and other sources
- M^2 for $D^*\ell\nu$ shows peak at 0, band for $D^*\tau\nu$, +backgrounds

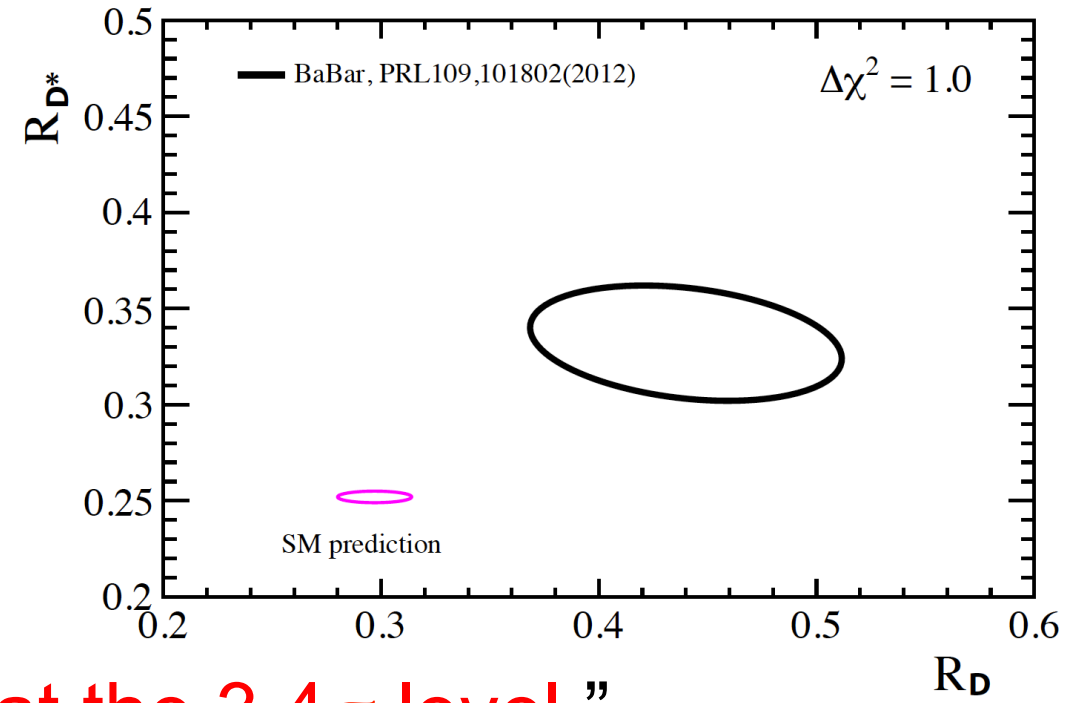


e^+e^- spectra II

- Background shapes depend on unknown D** form-factors. These are constrained by using samples of $D^{(*)}\pi^0\ell\nu$ events (BaBar only) (but note that its possible to have more than 1π).
- Requiring small Missing energy is used to try & limit non $D^{(*)}\ell\nu$ events.
- Fit to M^2 & p_ℓ^* gives yields.

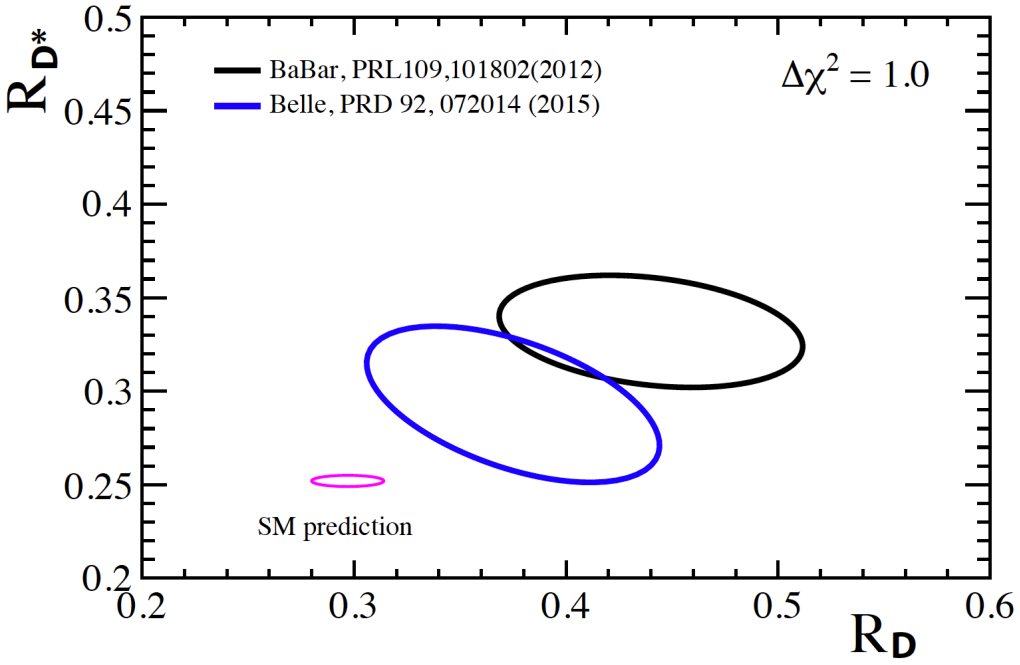
BaBar results

- First came BaBar [PRL 109, 101802 (2012)]
- R_D =0.440±0.058±0.042 (SM=0.300±0.008)
  R_{D^*}=0.332±0.024±0.018 (SM=0.252±0.003)
- "Our measurements exceed the SM predictions by 2.0σ & 2.7σ… Thus the possibility of both agreeing with the SM prediction is excluded at the 3.4σ level."



Belle results

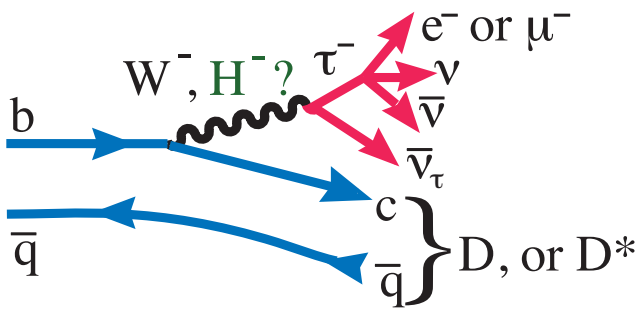
- R_D =0.375±0.064±0.026 (SM=0.300±0.008)
  R_{D^*}=0.293±0.038±0.015 (SM=0.252±0.003)
- "Our result lies between the SM expectation, the BaBar measurement, & is compatible with both."
- Using $\tau \to \pi\nu$ & $\rho\nu$



Belle also measures $R_{D^*} = 0.270 \pm 0.035^{+0.028}_{-0.025}$

Two Higgs doublet model

- Possibility of charged Higgs mediator
- Both BaBar & Belle consider:



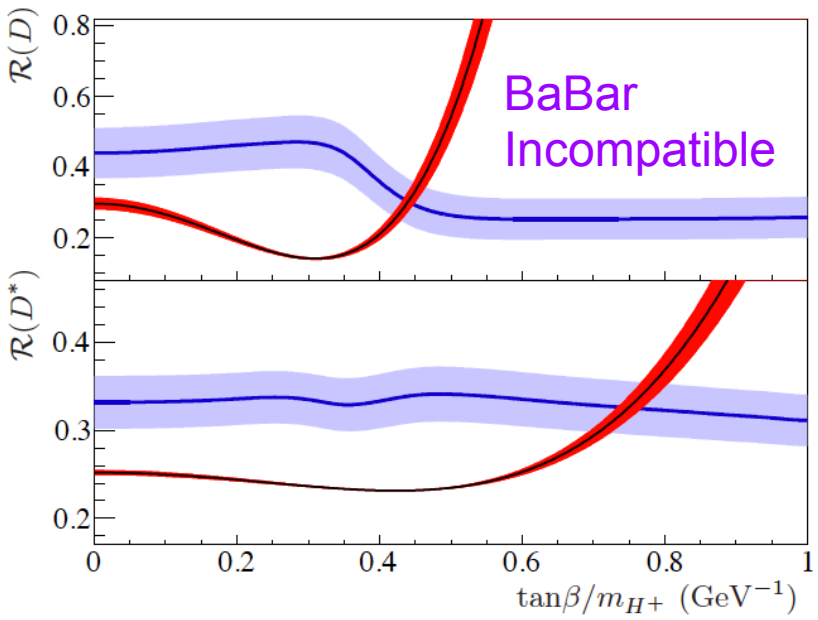


FIG. 2. (Color online) Comparison of the results of this analysis (light gray, blue) with predictions that include a charged Higgs boson of type II 2HDM (dark gray, red). The SM corresponds to $\tan\beta/m_{H+} = 0$.

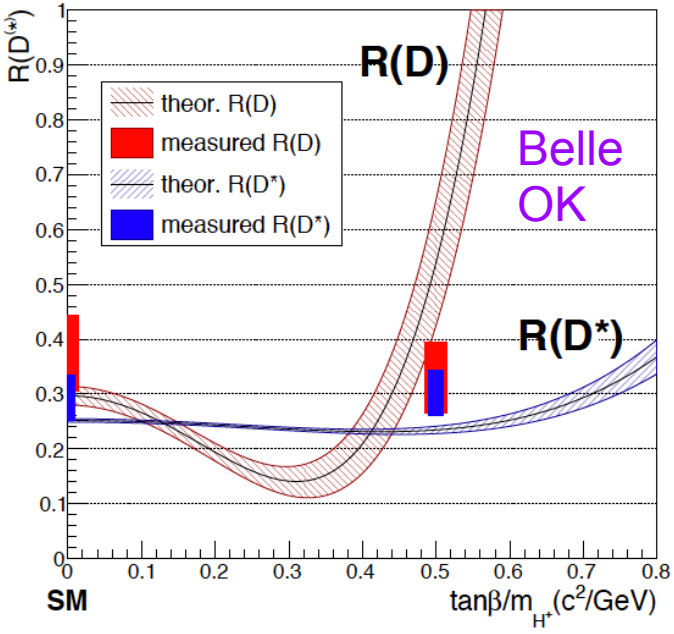


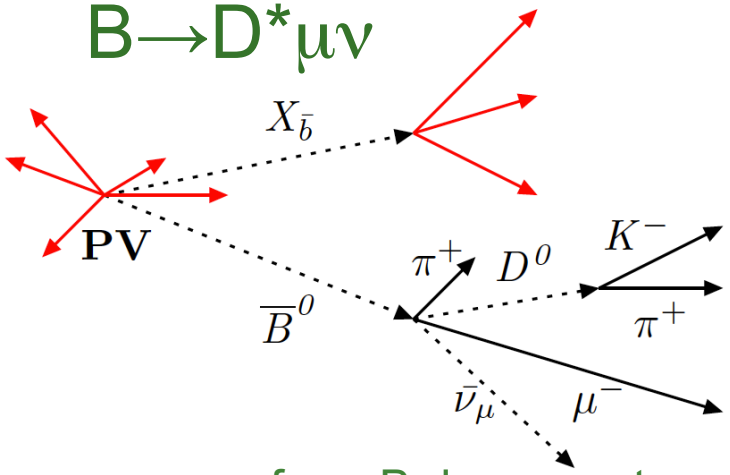
FIG. 7. Theoretical predictions with $1\,\sigma$ error ranges for $R(D)$ (red) and $R(D^*)$ (blue) for different values of $\tan\beta/m_{H+}$ in the 2HDM of type II. The fit results for $\tan\beta/m_{H+} = 0.5\,c^2/\text{GeV}$ and SM are shown with their $1\,\sigma$ ranges as red and blue bars with arbitrary width for better visibility.

Technique at LHCb

- For τ^- use either $\mu^-\nu\nu$, $\pi^-\pi^-\pi^+\nu$, decays
- Make use of the excellent time resolution for B's of ~40 fs. First $\tau^-\to\mu^-\nu\nu$ event topology.

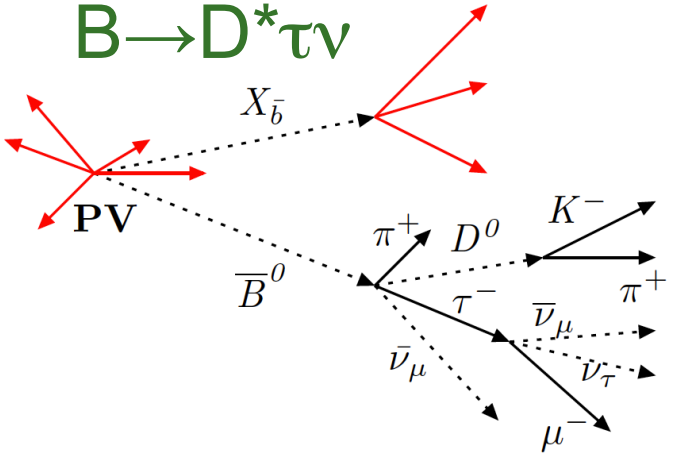
  Only $D^{*+}\ell\nu$ done, $D^{*+}\to\pi^+D^0$, $D^0\to K^-\pi^+$
- B direction is measured

$B\to D^*\mu\nu$



μ comes from B decay vertex

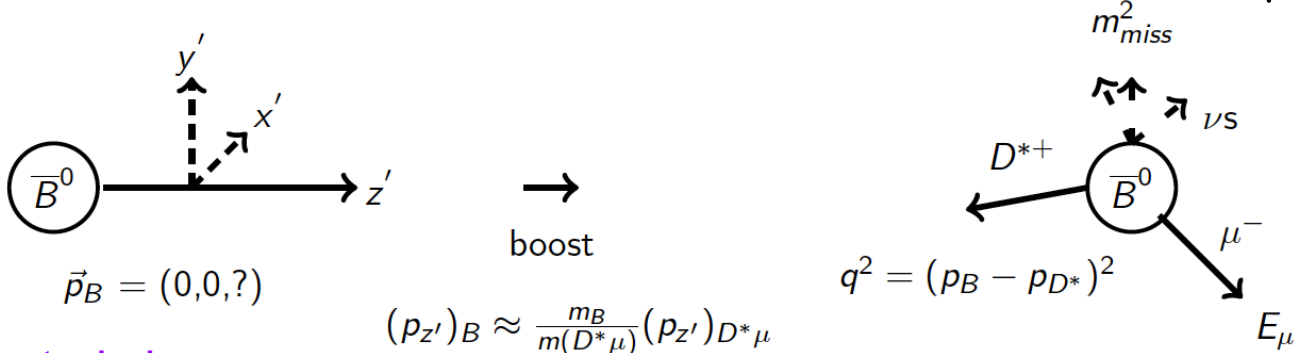
$B\to D^*\tau\nu$



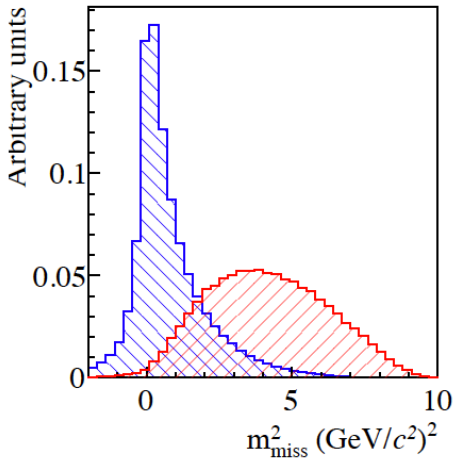
μ misses B decay vertex & PV

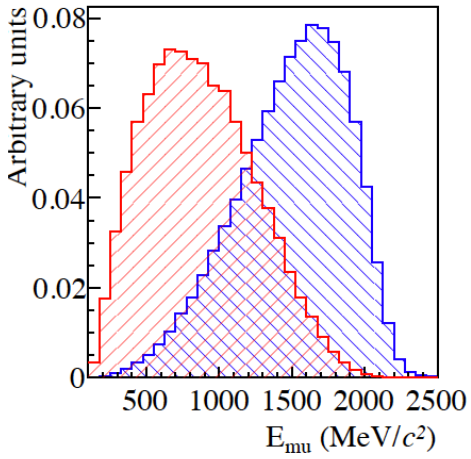
Determing M^2

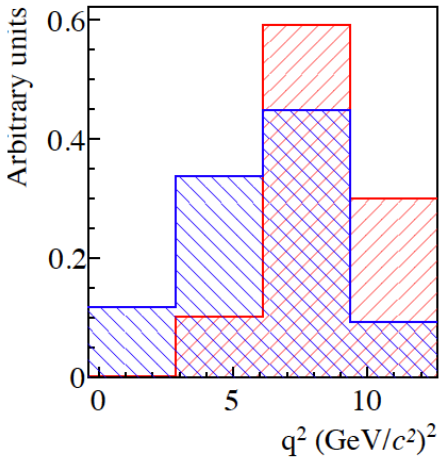
- Use same discrimination variables as in B factories, here called here m^2_{miss} & E_μ



Expected shapes







$B^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ $B^0 \to D^{*+}\mu^-\overline{\nu}_\mu$

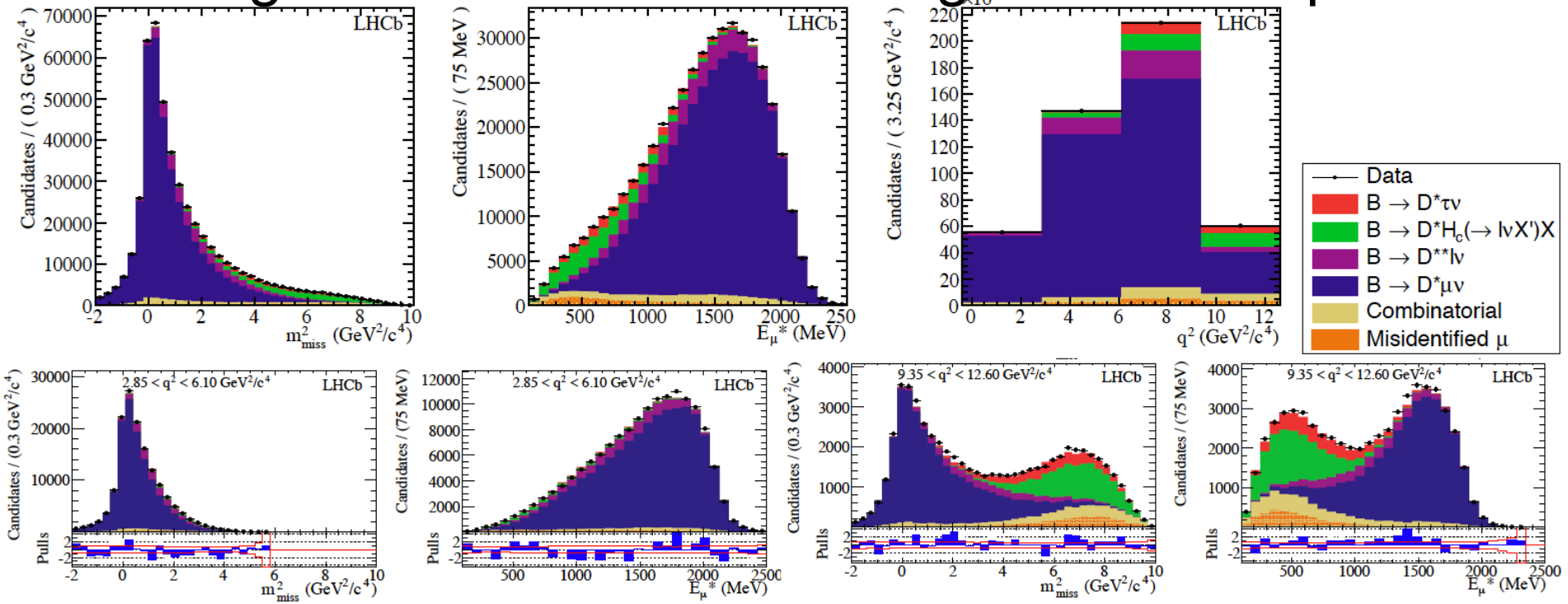
Systematic uncertainties

- Backgrounds similar to that of B factories

Model uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

Fit to data

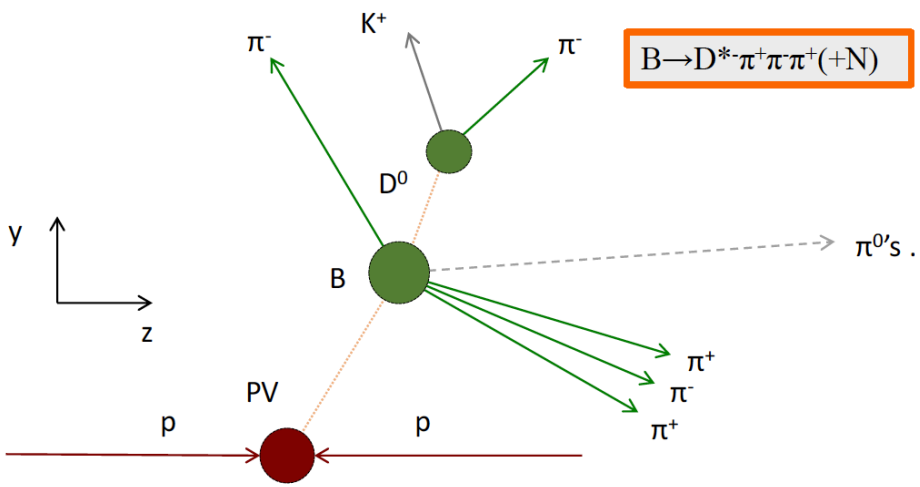
- 3D fit to M^2, q^2 & E_μ $R_{D^*} = 0.336 \pm 0.027 \pm 0.030$
- $B \to D^* \tau \nu$ contribution most prominent at large q^2
- Backgrounds constrained using control samples

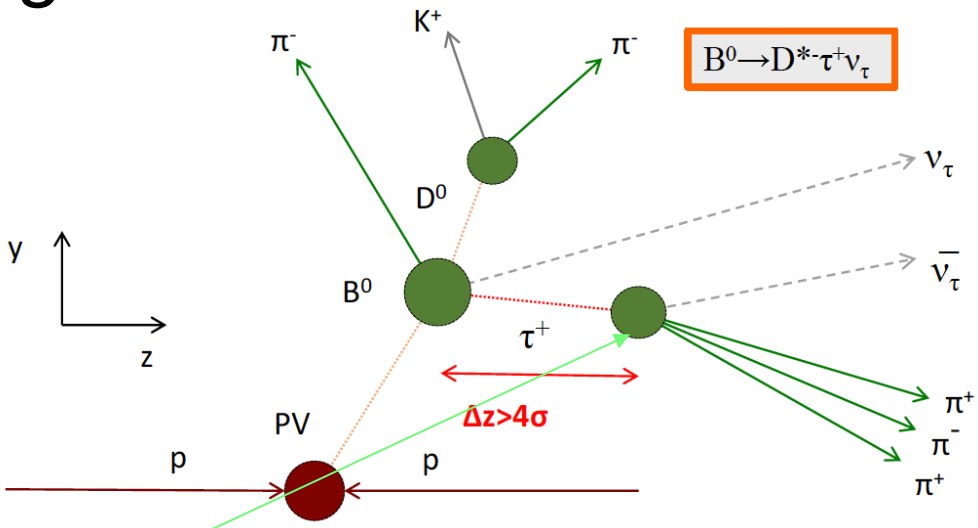


- R_{D^*}=0.336±0.027±0.030 *[PRL 115, 111803 (2015)]*

$\tau^- \rightarrow \pi^-\pi^-\pi^+\nu$

- Here the 3π form a separate vertex
- Normalization from $B^0 \rightarrow D^{*+}\pi^-\pi^-\pi^+$
- Also a source of background

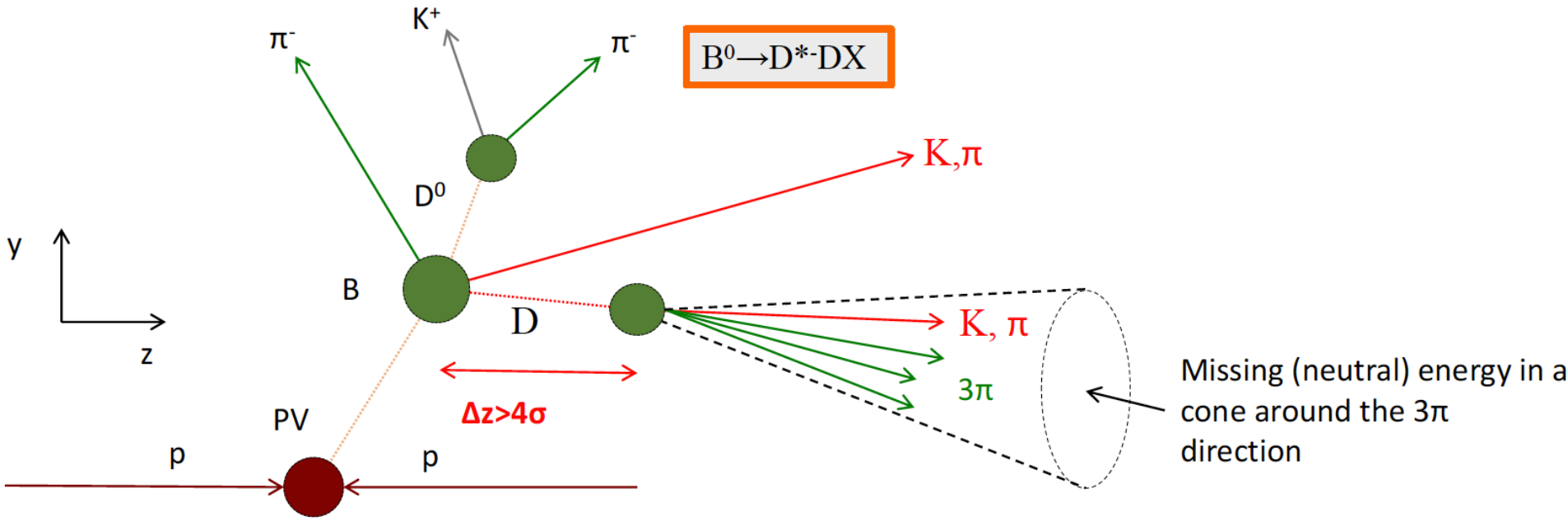




- 3π gives τ decay vertex, use lifetime to drastically reduce background

Further background reduction

- Ensure no additional charged tracks at B or τ vertices (isolation)
- Eliminate events with large neutral energy in a cone defined by the 3 pions

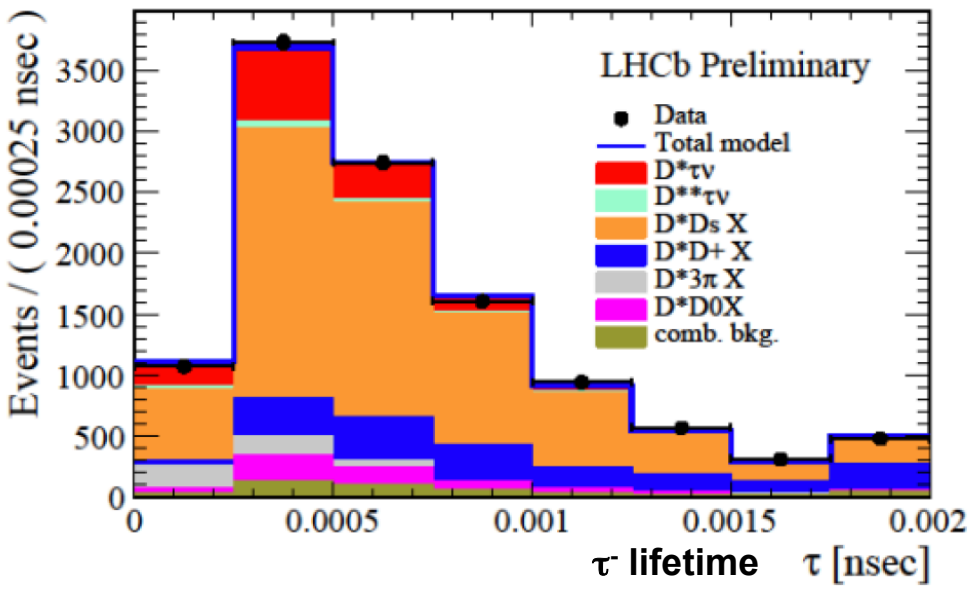


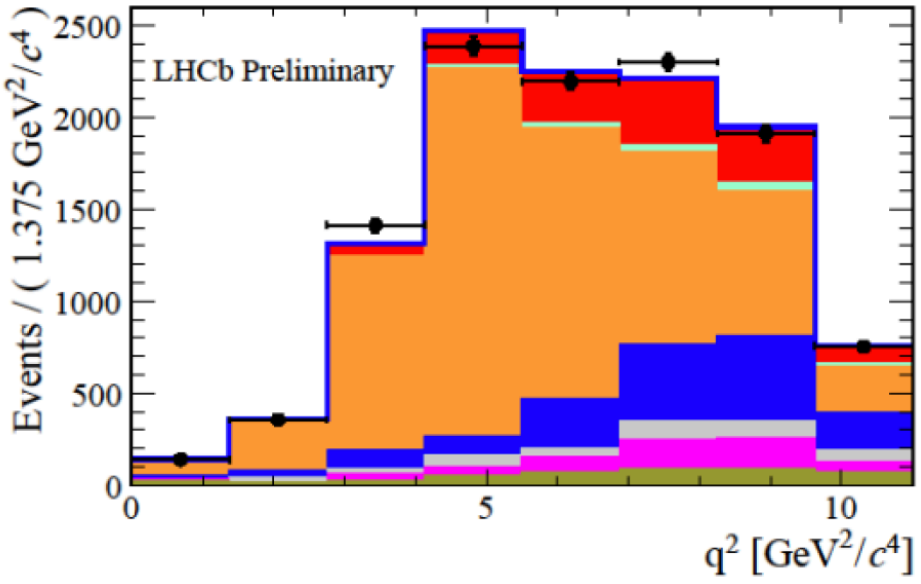
Fit model

- Extended maximum likelihood fit to data
- Fit components described by templates obtained from simulation (and corrected from control samples)

Model components	
$\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$	Ratio constrained using known BR and efficiencies.
$\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$	
$X_b \to D^{**}\tau\nu$	Ratio to signal fixed to 0.11 ± 0.04 from theory.
$B^0 \to D^{*-}D_s^+$	Relative yields constrained from $X_b \to D^* D_s^+ X$ control sample.
$B^0 \to D^{*-}D_s^{*+}$	
$B^0 \to D^{*-}D_{s0}^{*+}$	
$B^0 \to D^{*-}D_{s1}'$	
$B_s^0 \to D^{*-}D_s^+X$	
$B \to D^{**}D_s^+X$	
$X_b \to D^{*-}D^+X$	
$X_b \to D^{*-}D^0X$	Yields constrained from control samples.
$X_b \to D^{*-}\pi^+\pi^-\pi^+X$	
Comb. Bkg.	

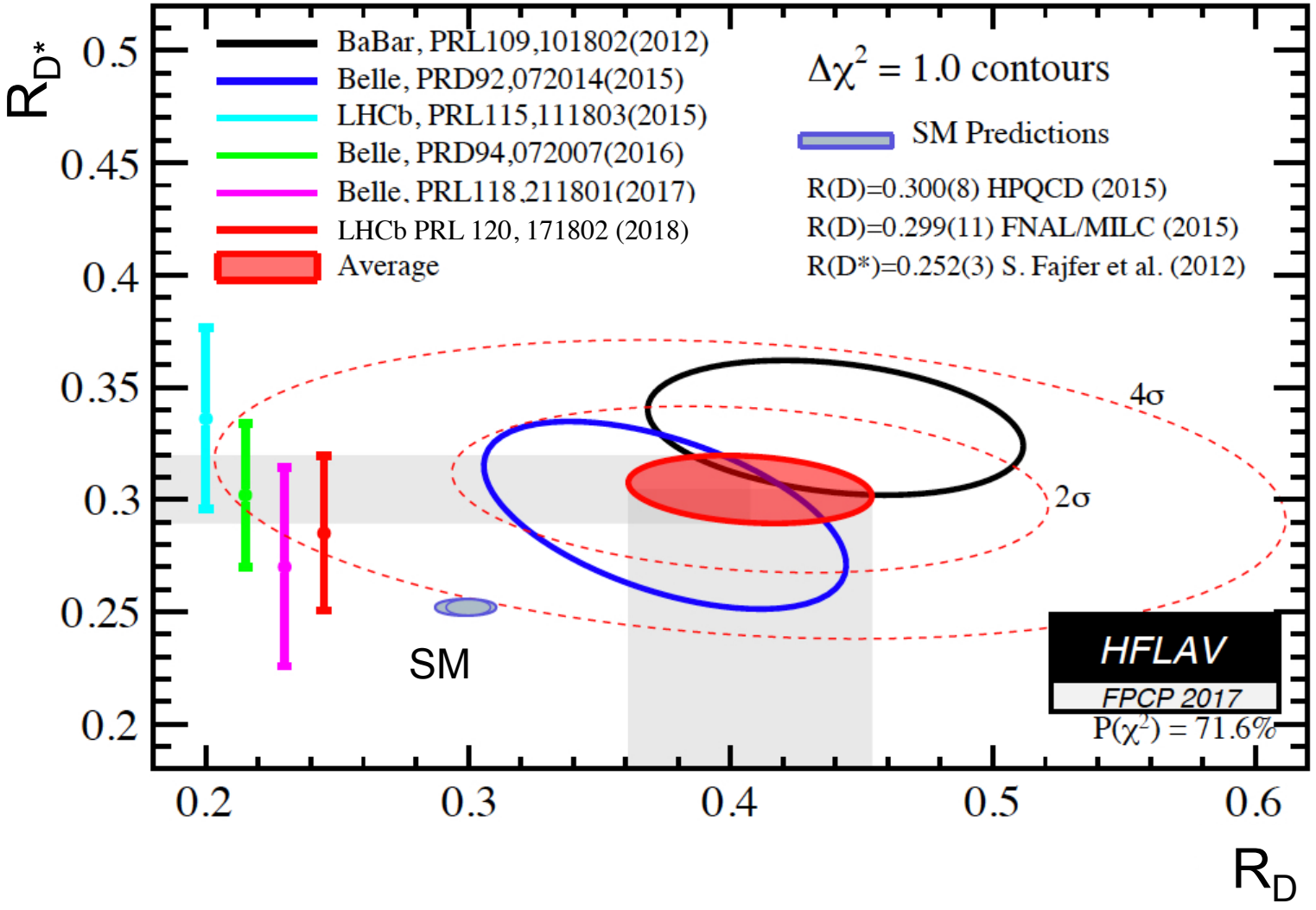
$\tau^- \to \pi^-\pi^-\pi^+\nu$ results

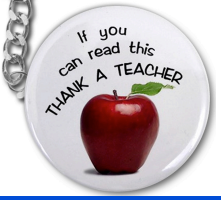




- $R_{D^*}=0.285\pm0.019\pm0.025\pm0.014$
- LHCb average $R_{D^*}=0.306\pm0.027$ 2.1σ above SM

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

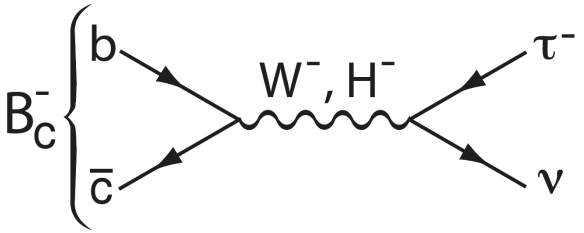




Impact of B_c decays

Constraint from B_c lifetime

- B_c^- is produced at about 1/100 the rate of B^0
- $\mathcal{B}(B_c \to \tau\nu)$ is the largest $\tau\nu$ rate in

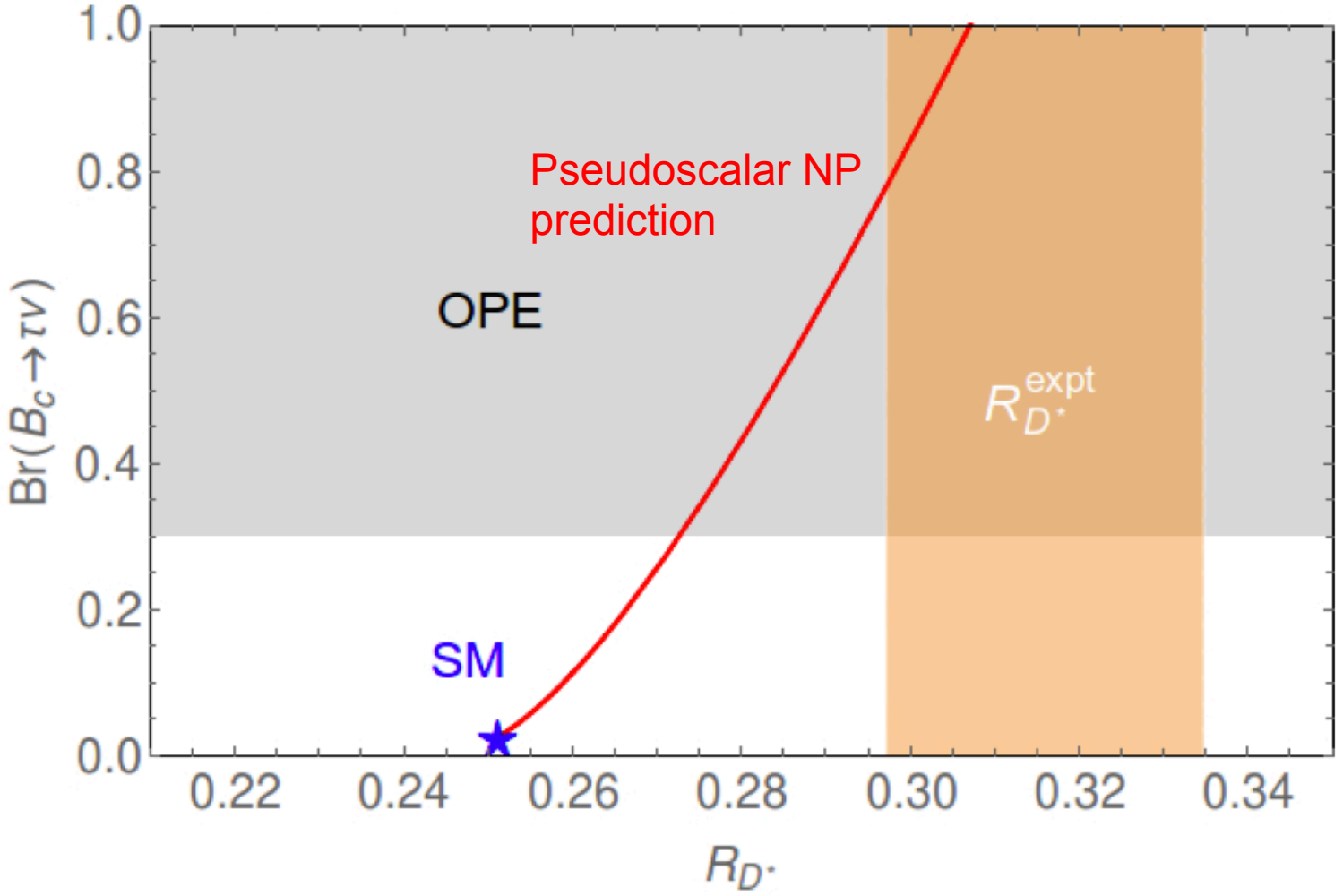


in B decays since it depends on V_{cb} contrasted with V_{ub} for the B^-. A pseudoscalar NP interaction enhance the rate by breaking the helicity suppression. Using the measured B_c lifetime 0.507±0.009 ps & the calculated $\tau_{B_c}^{OPE} = 0.52^{+0.18}_{-0.12}\ ps$ places a constraint of $\mathcal{B}(B_c \to \tau\nu)$<30%.

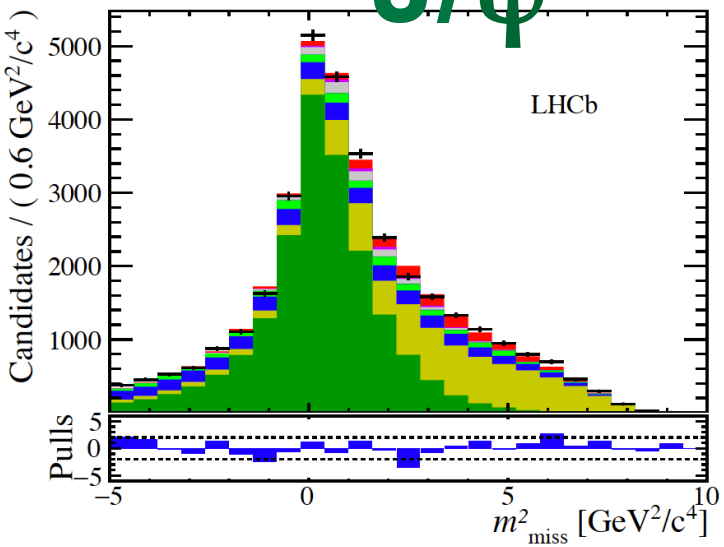
- This gives a powerfull constraint on pseudoscalar NP interactions

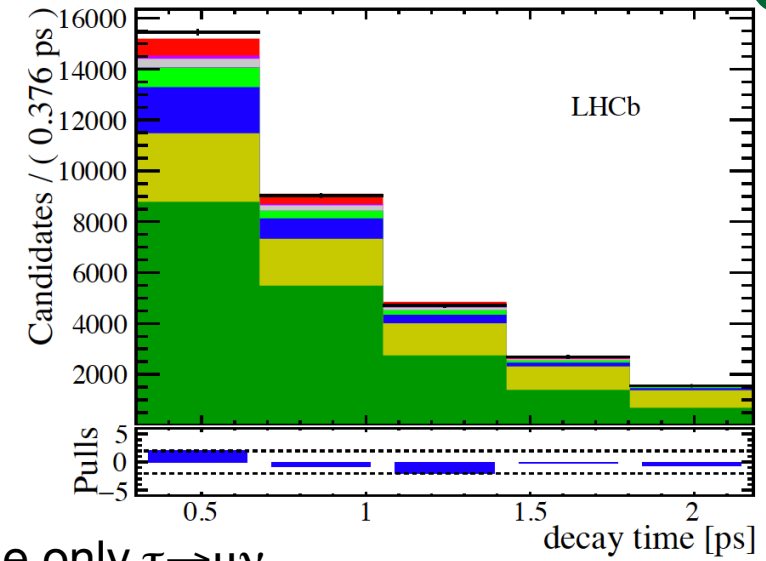
(Alzono, Grinstein & Camalich arXiv:1611.06676)

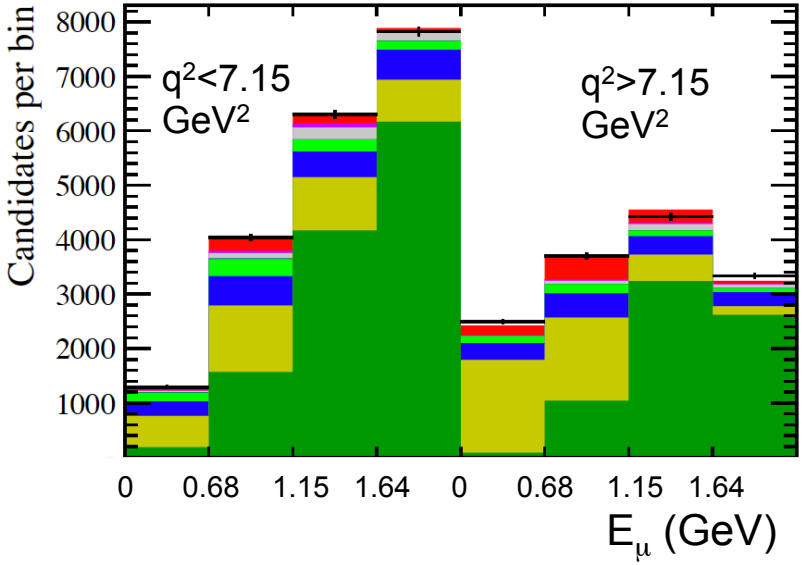
Constraint from B_c lifetime II



$R_{J/\psi}$:same strategy







Use only $\tau \to \mu\nu$

Data
Mis-ID bkg.
J/ψ comb. bkg.
$B_c^+ \to \chi_c(1P) l^+ \nu_l$
$B_c^+ \to J/\psi \tau^+ \nu_\tau$
$B_c^+ \to J/\psi \mu^+ \nu_\mu$
$J/\psi + \mu$ comb. bkg.
$B_c^+ \to J/\psi H_c^+$
$B_c^+ \to \psi(2S) l^+ \nu_l$

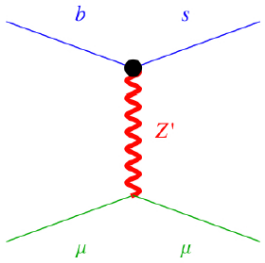
$$\mathcal{R}_{J/\psi} = \frac{\mathcal{B}(B_c \to J/\psi \tau \nu_\tau)}{\mathcal{B}(B_c \to J/\psi \ell \nu_\ell)} = 0.71 \pm 0.25,$$

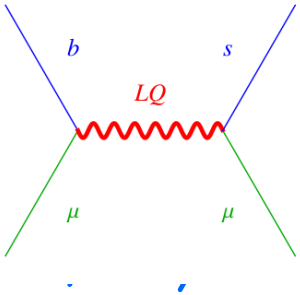
SM prediction=0.25-0.28

[Phys. Rev. Lett. 120, 121801 (2018)]

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′→bs
  - Leptoquarks





Can these be seen in direct production at the LHC?

Conclusions II

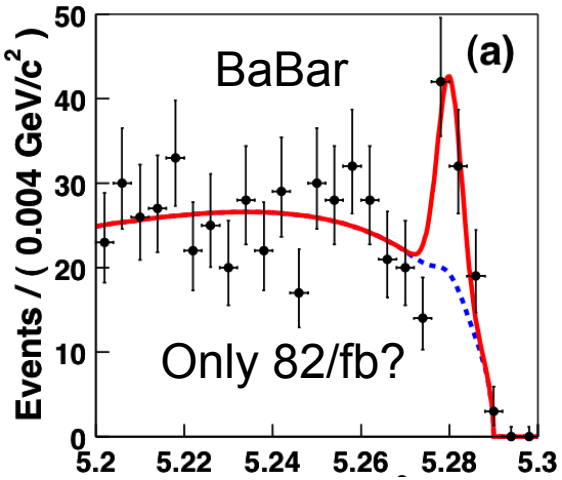
- There is some evidence for violation of lepton flavor non-universality in the tree level semileptonic decays between $B \to D^{(*)} \tau \nu$ and $B \to D^{(*)} \ell \nu$ where ℓ indicates an e or μ.
- This is a far more difficult experimental measurement than the one for $B \to K^{(*)} \mu^+ \mu^-$ versus $B \to K^{(*)} e^+ e^-$

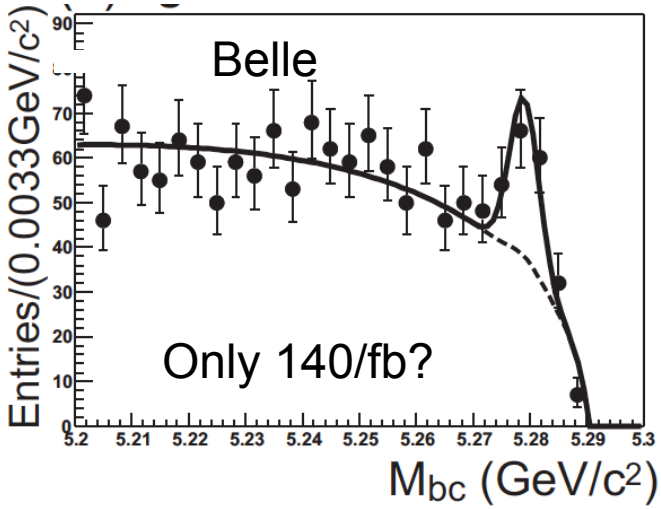
The End

Backup slides

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

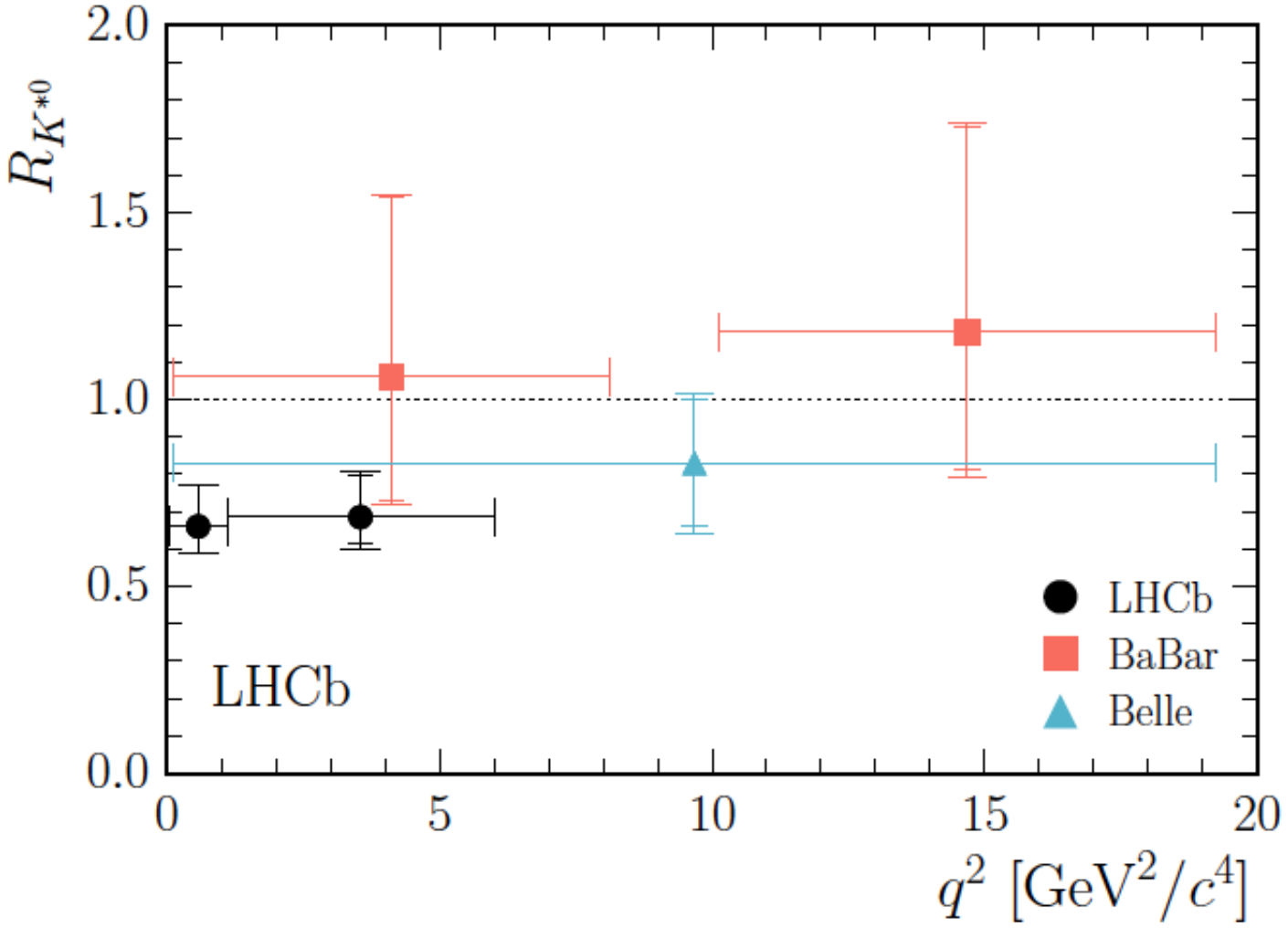
- Define two q^2 regions: low 1-6, high >14.4 GeV^2
- Low again probes C_7, while high C_9 & C_{10}
- Data





- 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

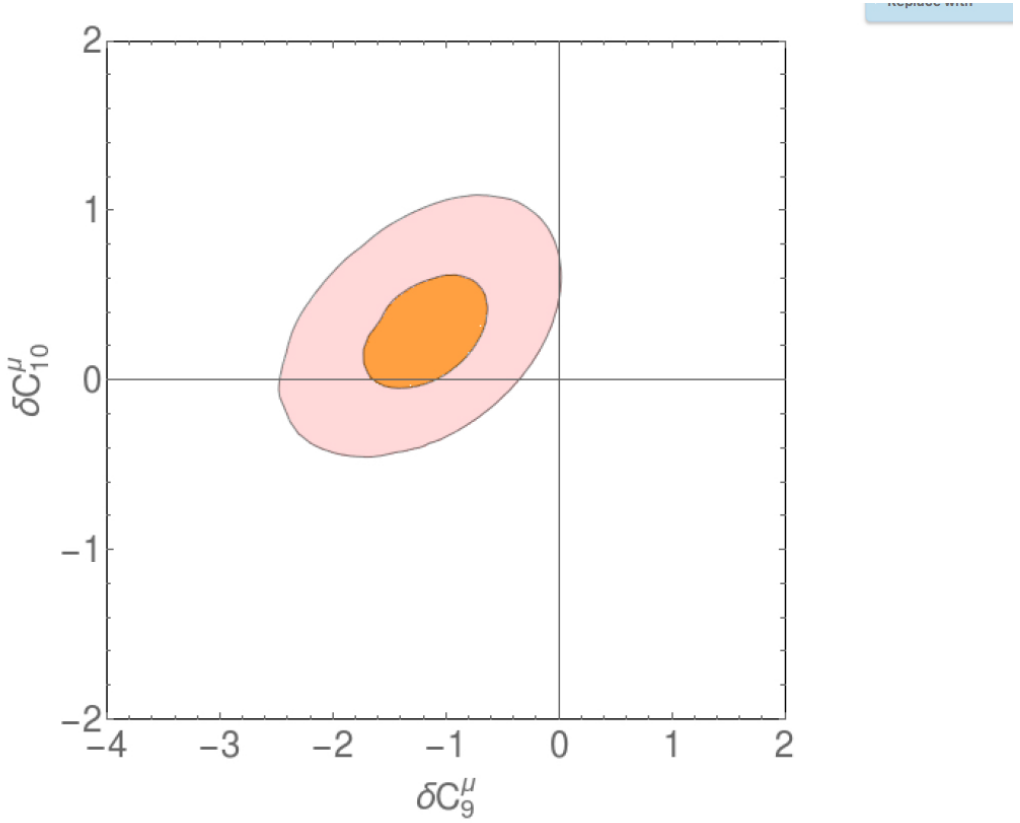
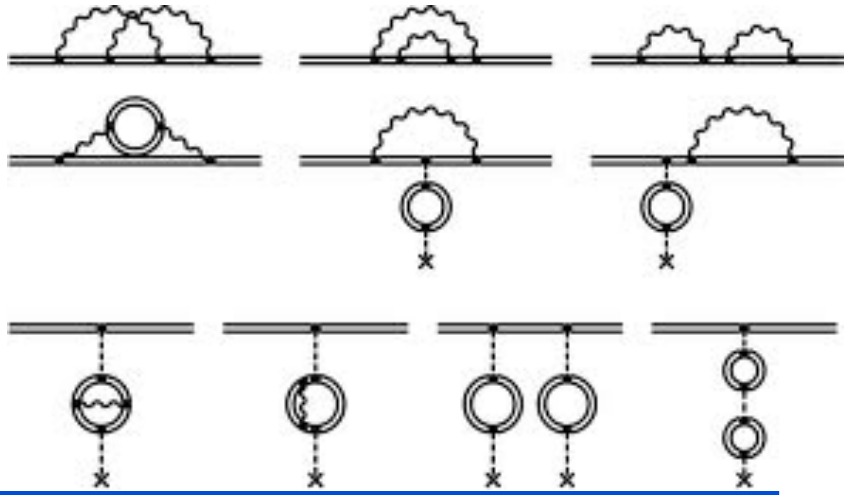


FIG. 5: Fit results for LUV data, $\overline{BR}(B_s \to \mu\mu)$, and $b \to s\mu\mu$ angular observables, as described in the text.

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