Hints of lepton universality violation in semileptonic B decays

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Benasque Workshop
Flavour Physics at LHC run II

26/05/17

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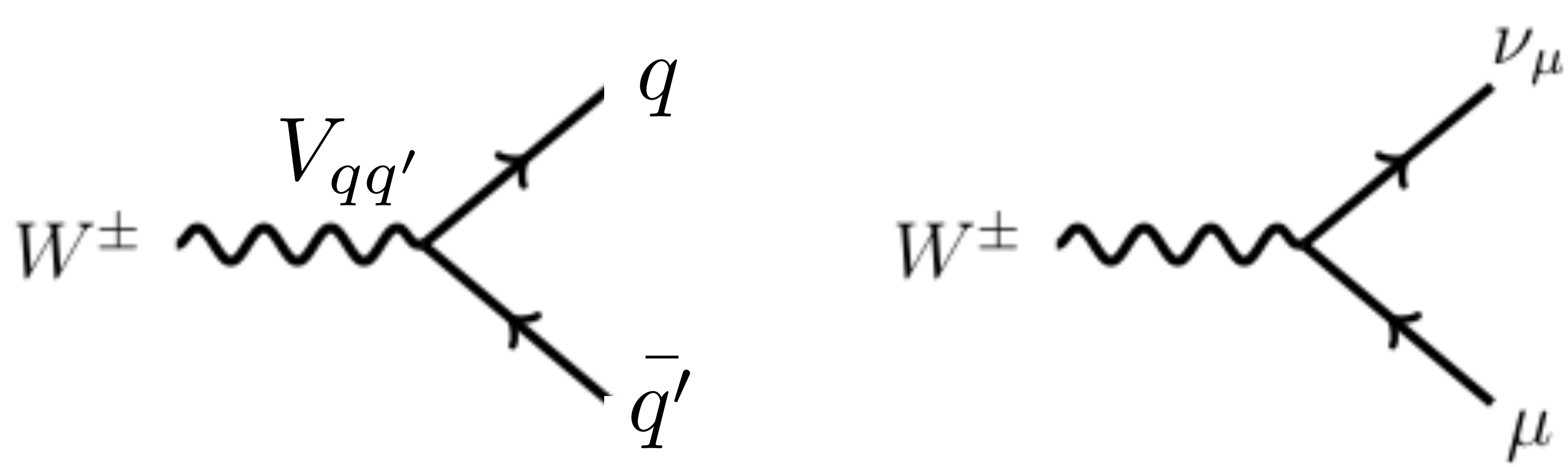
LHCb

Flavour physics and lepton universality

- Flavour physics is the study of the different generations of fermions.
- In the SM these different generations interact in a very specific way.
    - The generations of quarks interact via the CKM matrix



    - The generations of the charged leptons are identical copies of each other with regards to their electroweak couplings.

Lepton universality

- Of course, one could say that we have already seen violation of lepton universality.

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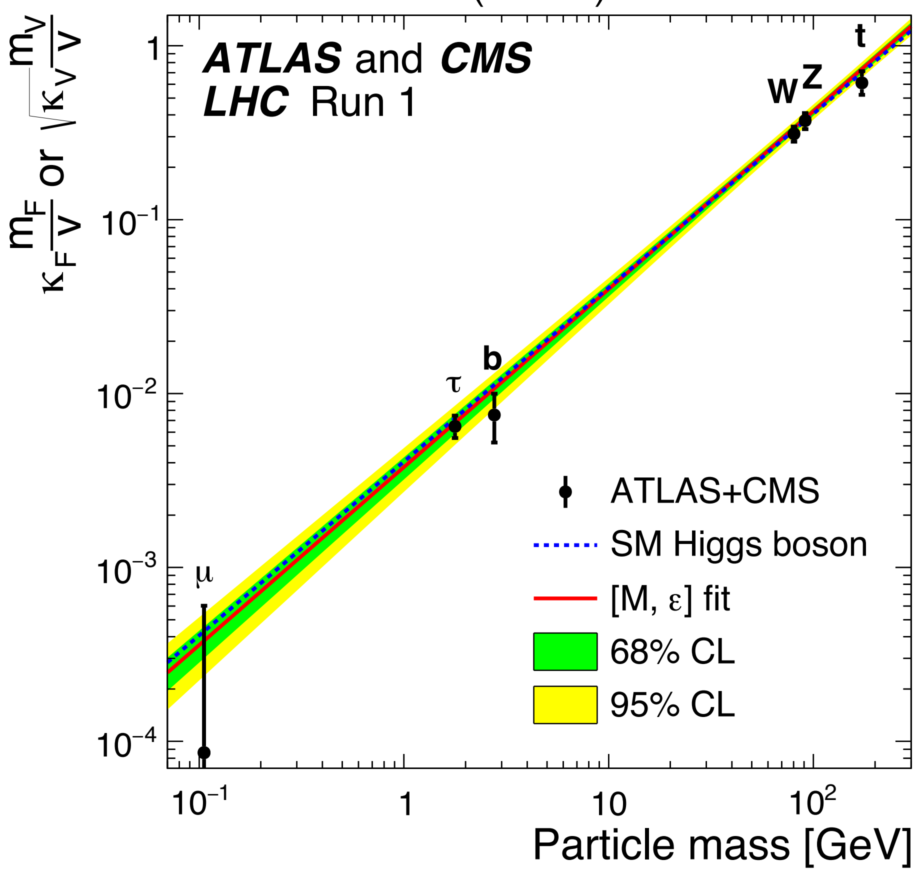


- Differences due to masses can be large.

$$\mathcal{B}(Z \to e^+e^-) = \mathcal{B}(Z \to \mu^+\mu^-) = \mathcal{B}(Z \to \tau^+\tau^-)$$

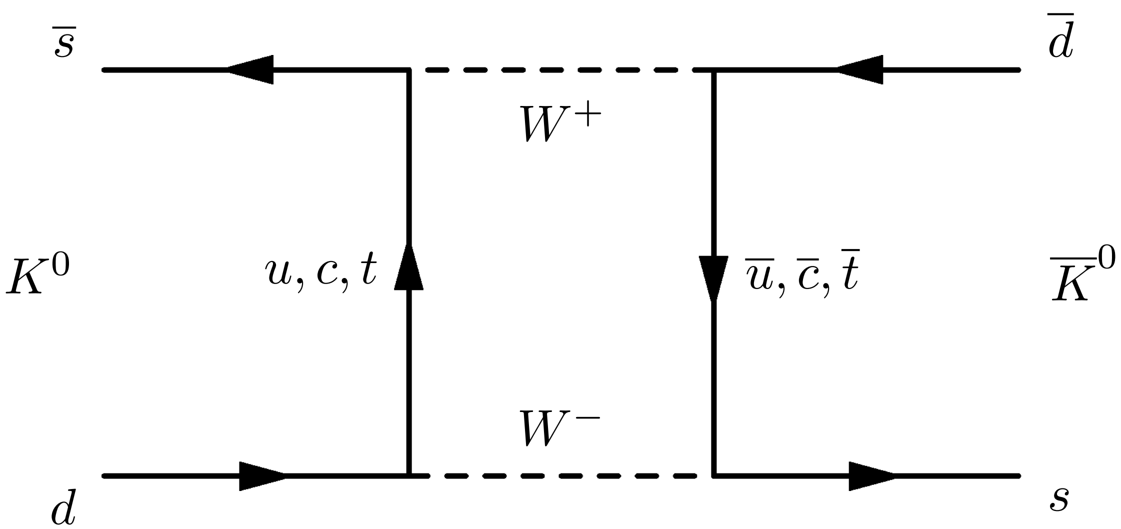
$$\mathcal{B}(\psi(2S) \to e^+e^-) = \mathcal{B}(\psi(2S) \to \mu^+\mu^-) = \mathcal{B}(\psi(2S) \to \tau^+\tau^-)/0.3885$$

We have searched for violations of lepton universality in various systems (Z, W, π decays ..), no evidence so far*.

* Apart from a small tension in W decays (e.g. https://arxiv.org/abs/1603.03779)

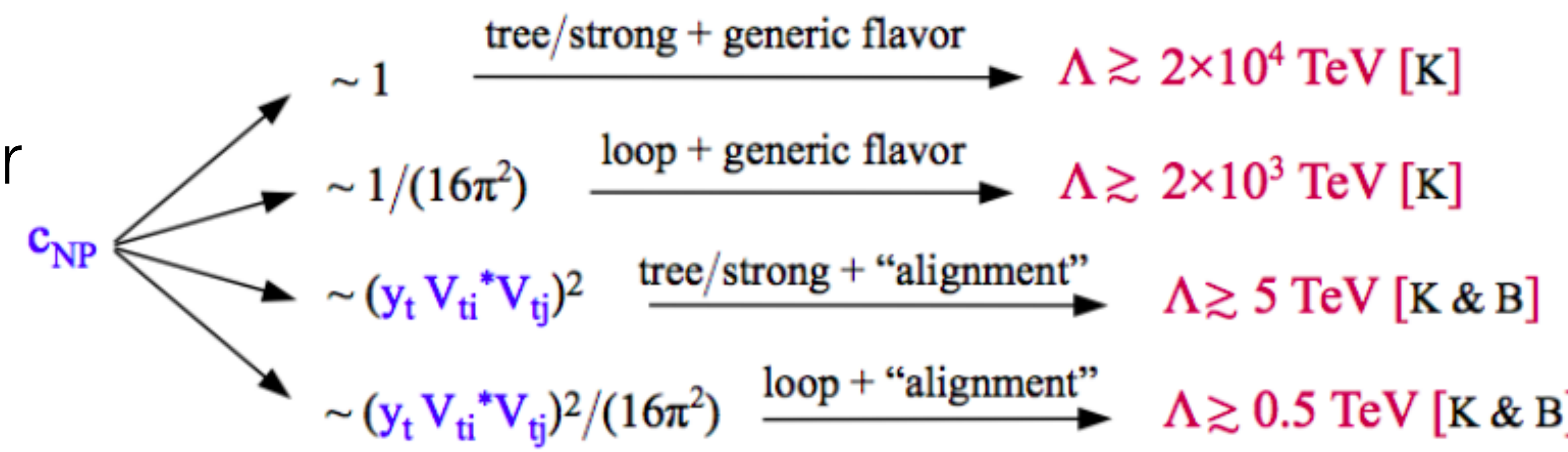
Why look in B decays

- If one assumes O(1) couplings, can get large NP contributions to mixing diagrams.



- Unfortunately, no deviations from SM predictions have been observed —> very stringent limits on the energy scale of NP.

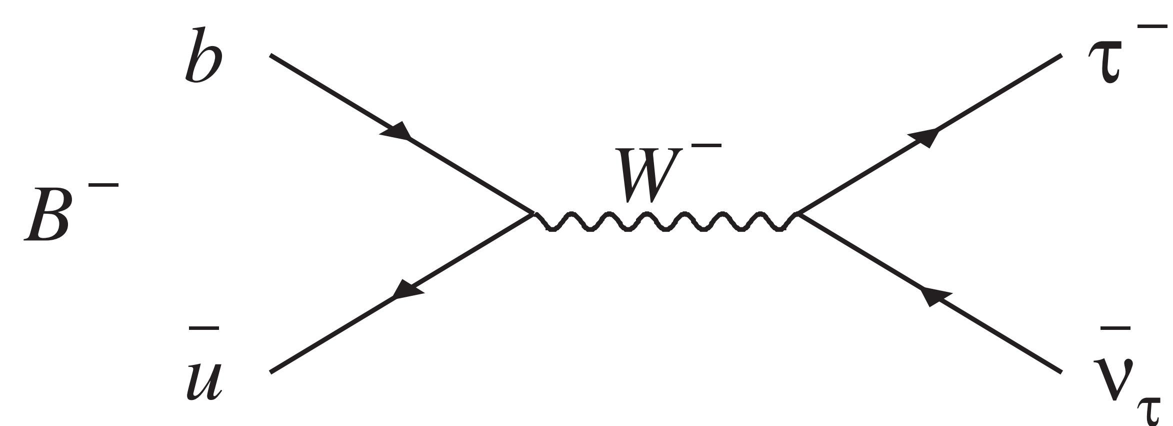
Need hierarchal flavour structure in order to satisfy naturalness problem.



B-physics becomes most powerful in this case.

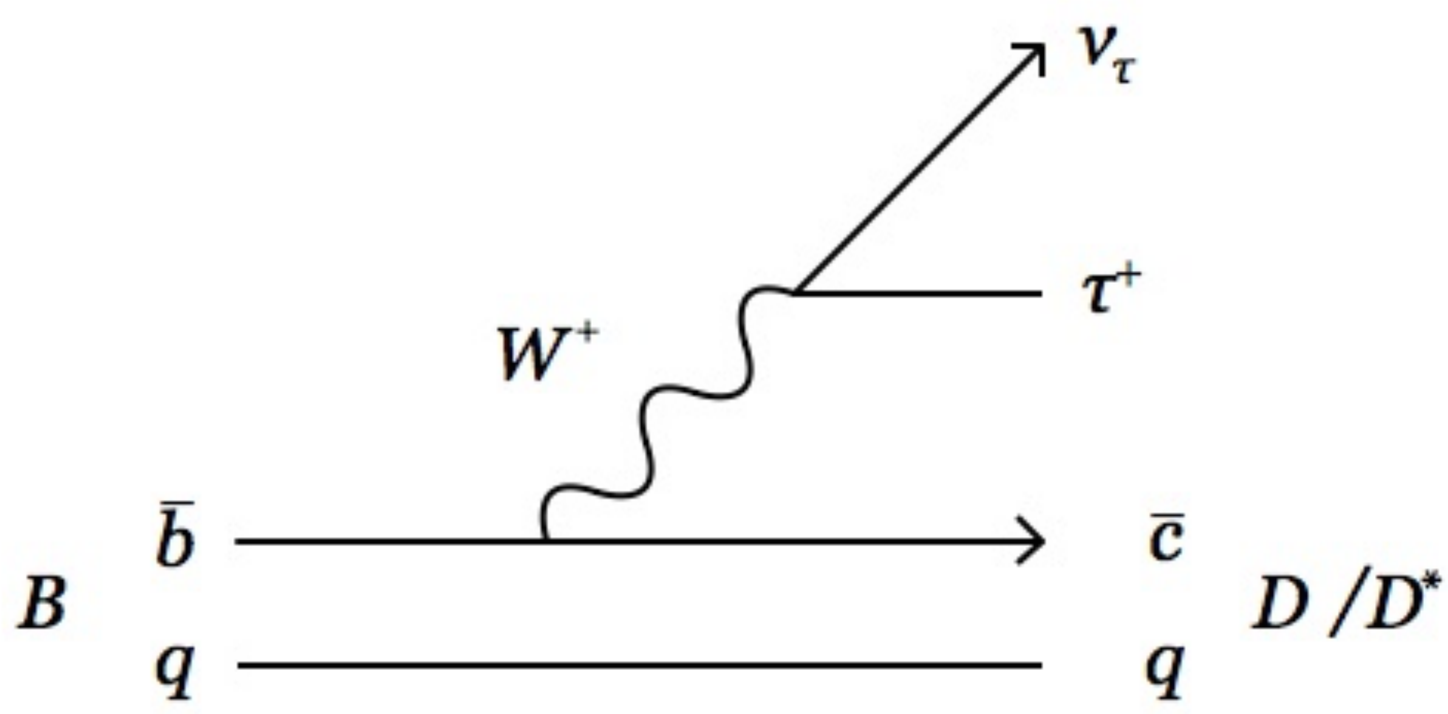
An example

- Consider the decay $B \to \tau\nu$
- Mediated by a W boson coupling to third generation fermions at both vertices.
    - Highly sensitive to a charged Higgs boson.
    - In which case, expect violation of lepton universality for decays involving a τ or muon
- Can naturally explain why we wouldn't have seen it before in e.g. kaon decays.
- Can find it even if mass > LHC energy.



Why semi-leptonic decays?

- A decay is semi-leptonic if its products are part leptons and part hadrons.



$$\frac{d\Gamma}{dq^2}(B \to D\ell\nu) \propto$$

$$G_F^2 |V_{cb}|^2 f(q^2)^2$$

EW QCD

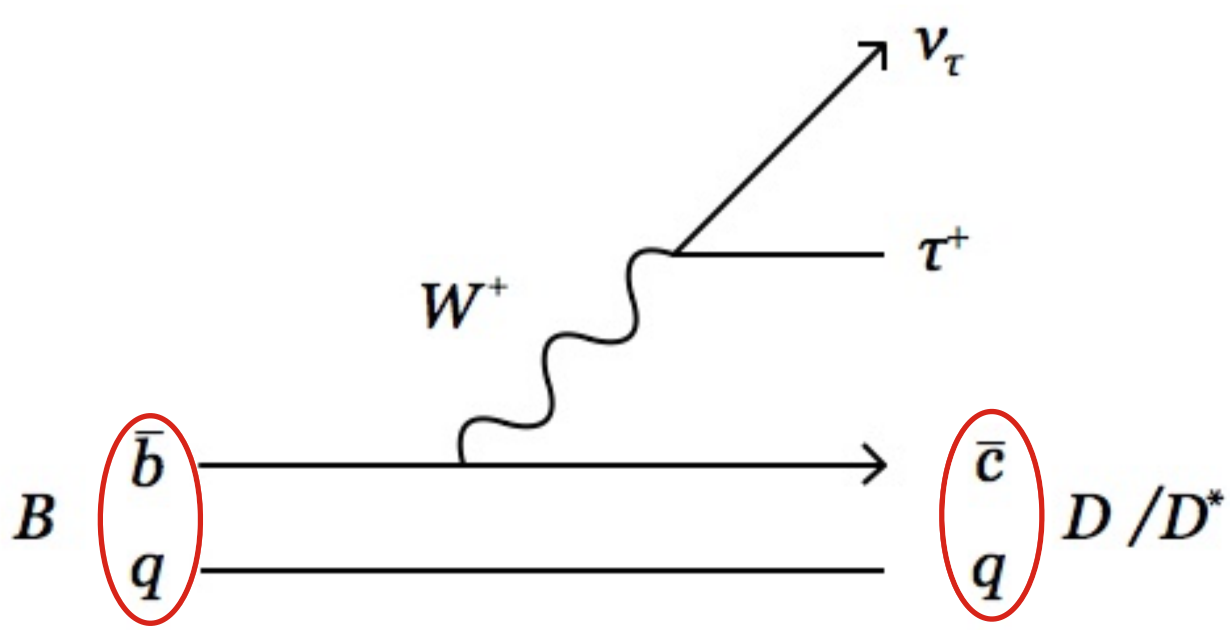
- These decays can be **factorised** into the weak and strong parts, greatly simplifying theoretical calculations.

- Lepton universality ratios further cancel theoretical uncertainties.

Types of semi-leptonic decay

Two types of semi-leptonic B decay

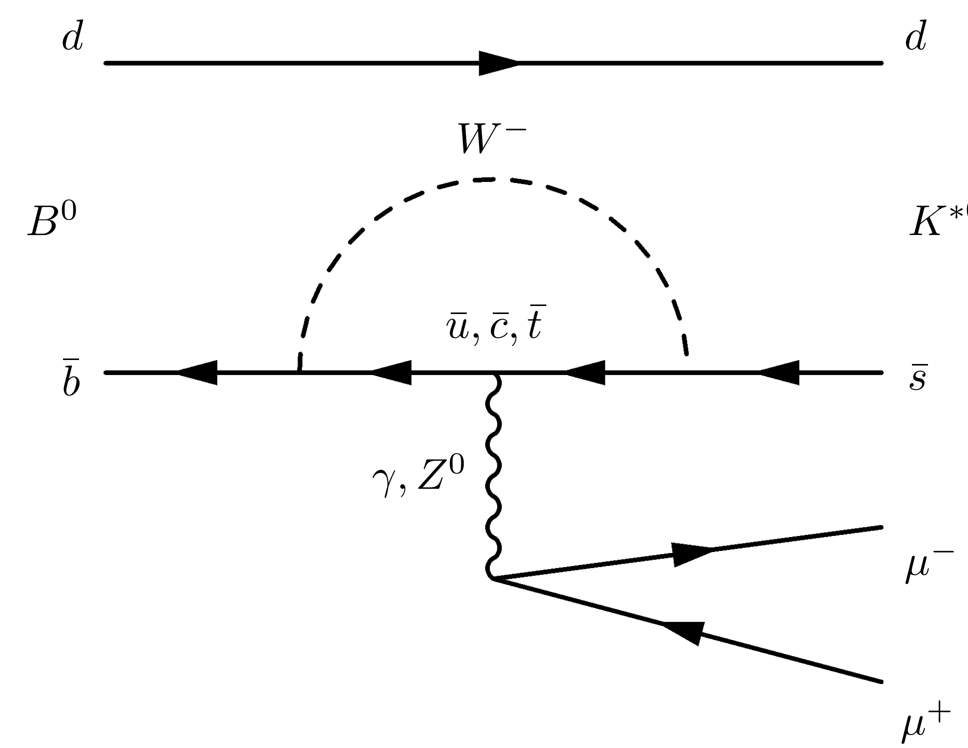
Charged current



Can proceed via tree level -large O(%) branching fractions.

NP sensitivity up to about 1 TeV

Neutral current



Forbidden at tree level - low O(10^{-6}) branching fractions.

NP sensitivity up to about 100 TeV

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

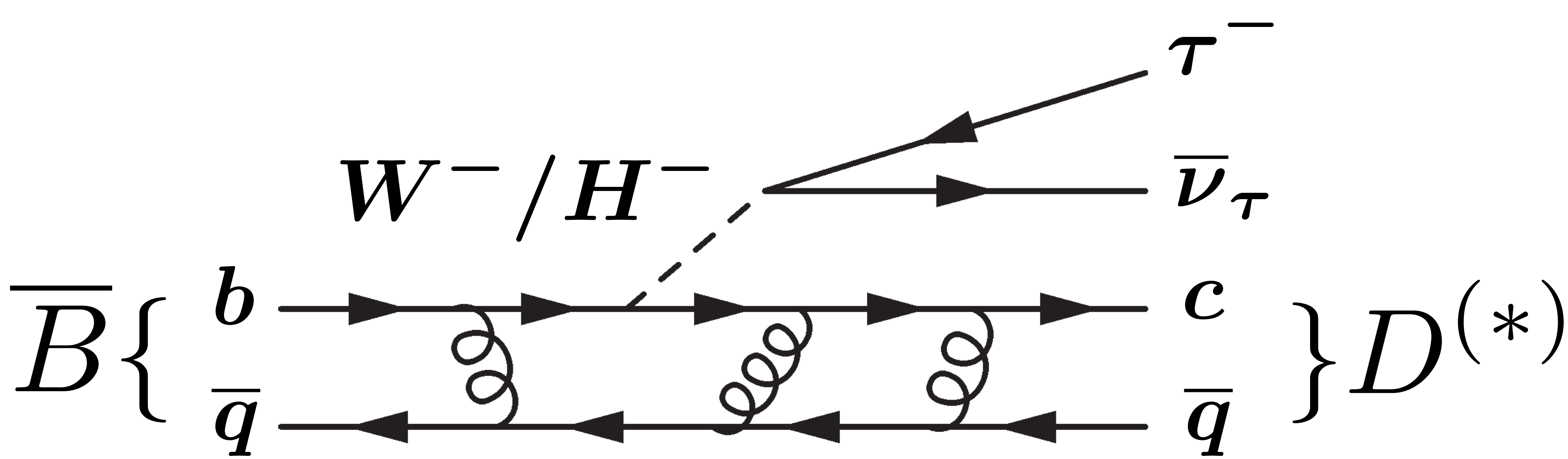
R(D*)

- Large rate of charged current decays allow for measurement in semi-tauonic decays.

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

- Form ratio of decays with different lepton generations.
- Cancel QCD/expt uncertainties.

- R(D*) sensitive to any physics model favouring 3rd generation leptons (e.g. charged Higgs).



Who has made measurements

- Three experiments have made measurements

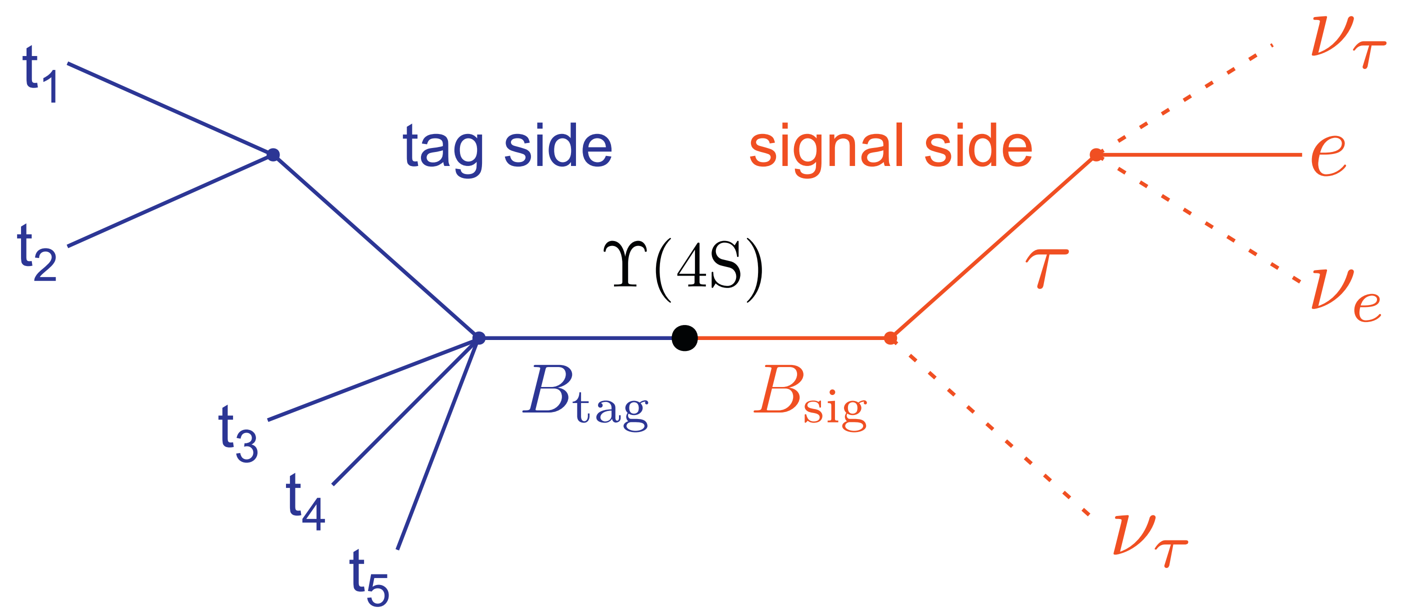
	BaBar	Belle	LHCb
#B's produced	O(400M)	O(700M)	O(800B)*
Production mechanism	$\Upsilon(4S) \to B\bar{B}$	$\Upsilon(4S) \to B\bar{B}$	$pp \to gg \to b\bar{b}$
Publications	Phys.Rev.Lett 109, 101802 (2012) Phys. Rev. D 88, 072012 (2013)	Phys.Rev.D 92, 072014 (2015) Phys. Rev. D 94, 072007 (2016) arXiv:1612.00529	Phys.Rev.Lett.115, 111803 (2015)

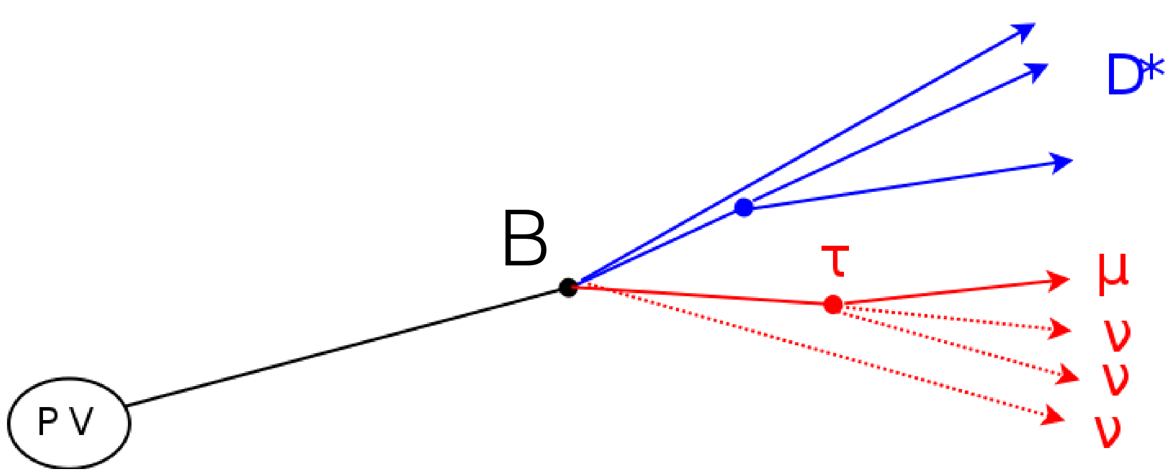
* during run 1 of the LHC

Experimental challenges

- Three neutrinos in the final state (using $\tau \to \mu\nu\nu$).
  - No sharp peak to fit in any distribution.

- At B-factories, can control this using ‘tagging’ technique.





- More difficult at LHCb, compensate using large boost (flight information) and huge B production.

Signal fits

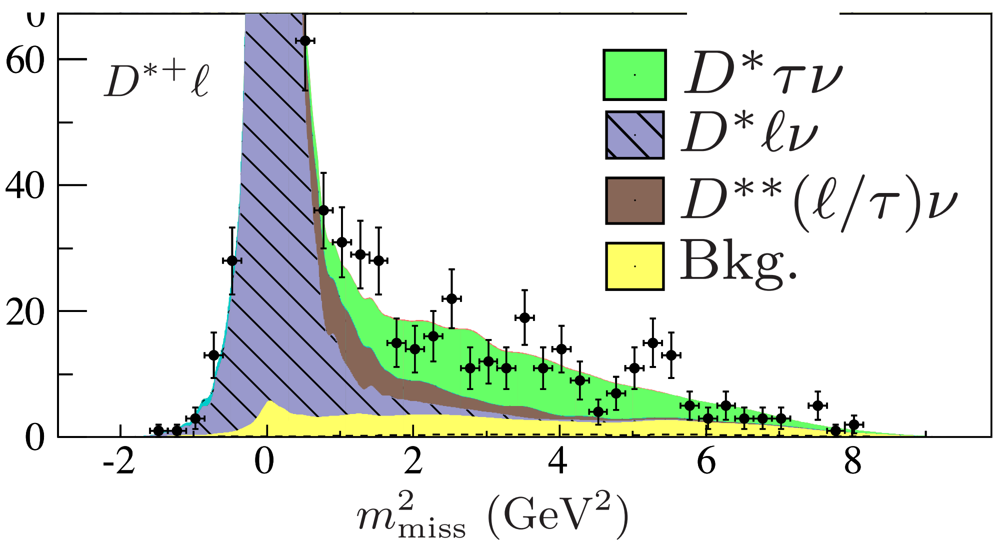
- Three main backgrounds:

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

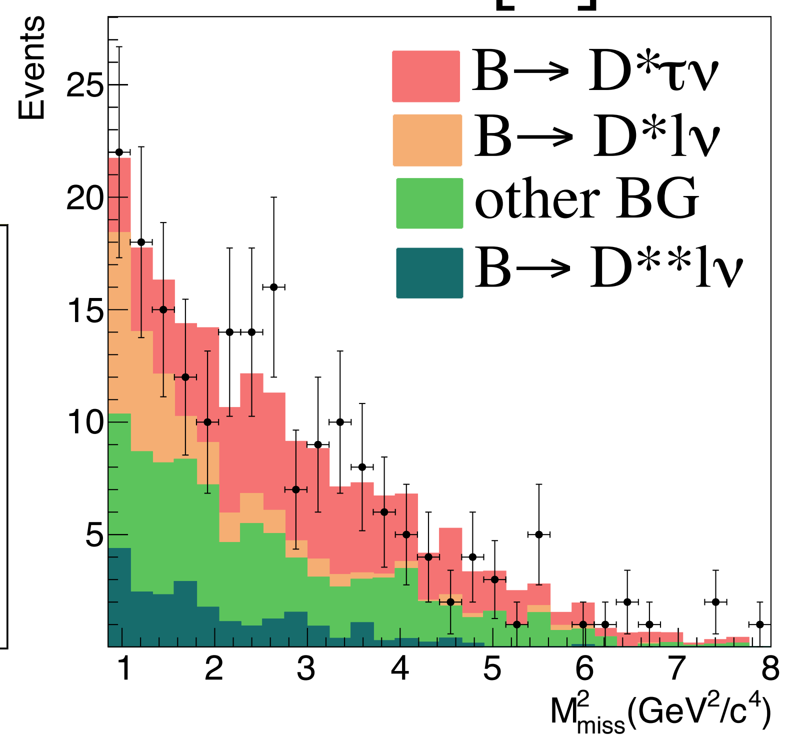
  $B \to D^{**} \ell \nu$

  $B \to D^* D X$

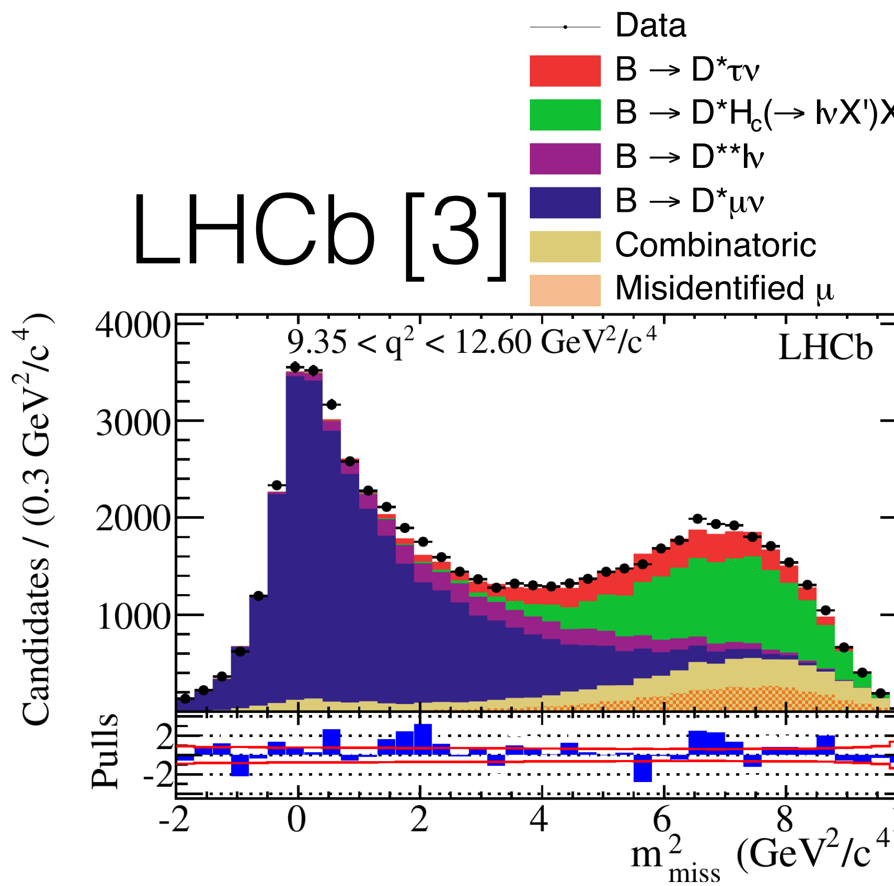
BaBar [1]



Belle [2]



LHCb [3]



- Fit variables which discriminate between muon and tauonic mode.

[1] Phys. Rev. D 88, 072012 (2013)

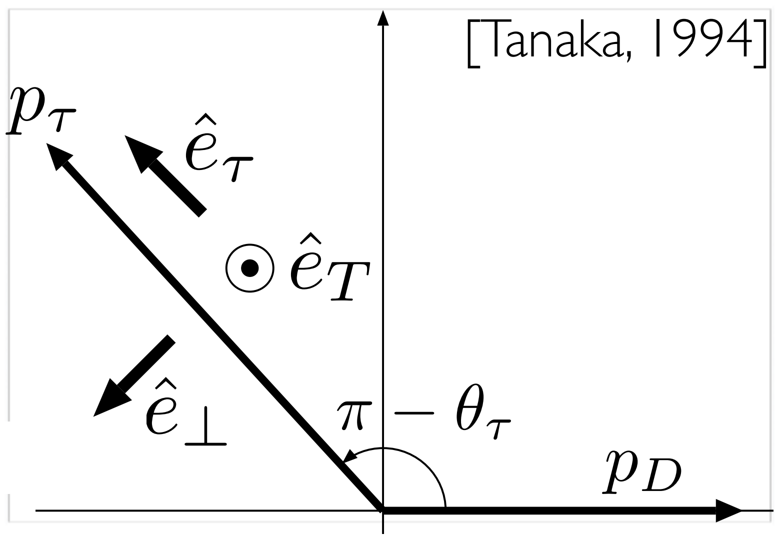
[2] Phys.Rev.D 92, 072014 (2015)

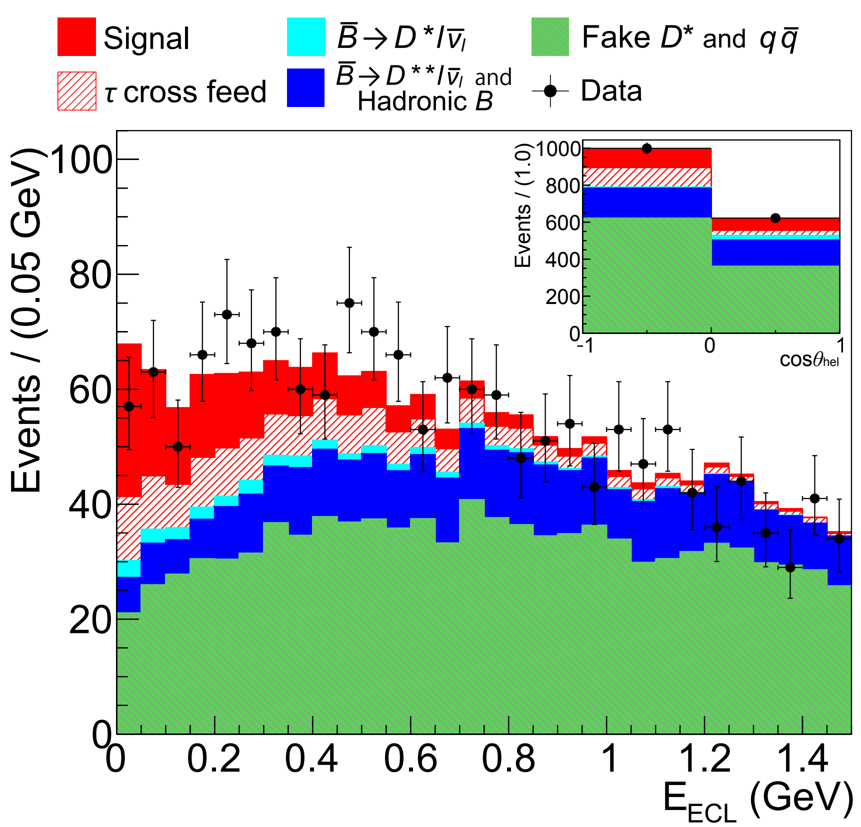
[3] Phys.Rev.Lett.115, 111803 (2015)

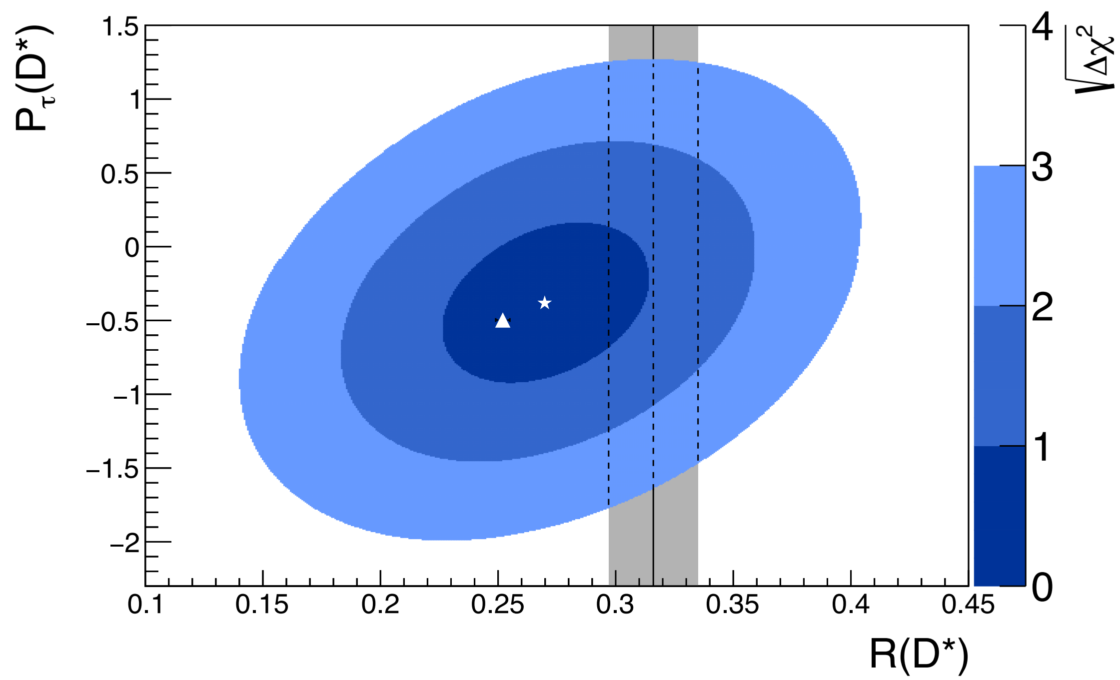
Latest result from Belle

arXiv:1612.00529, submitted to PRL

- First result to use hadronic $\tau \to \pi\nu$ decays.



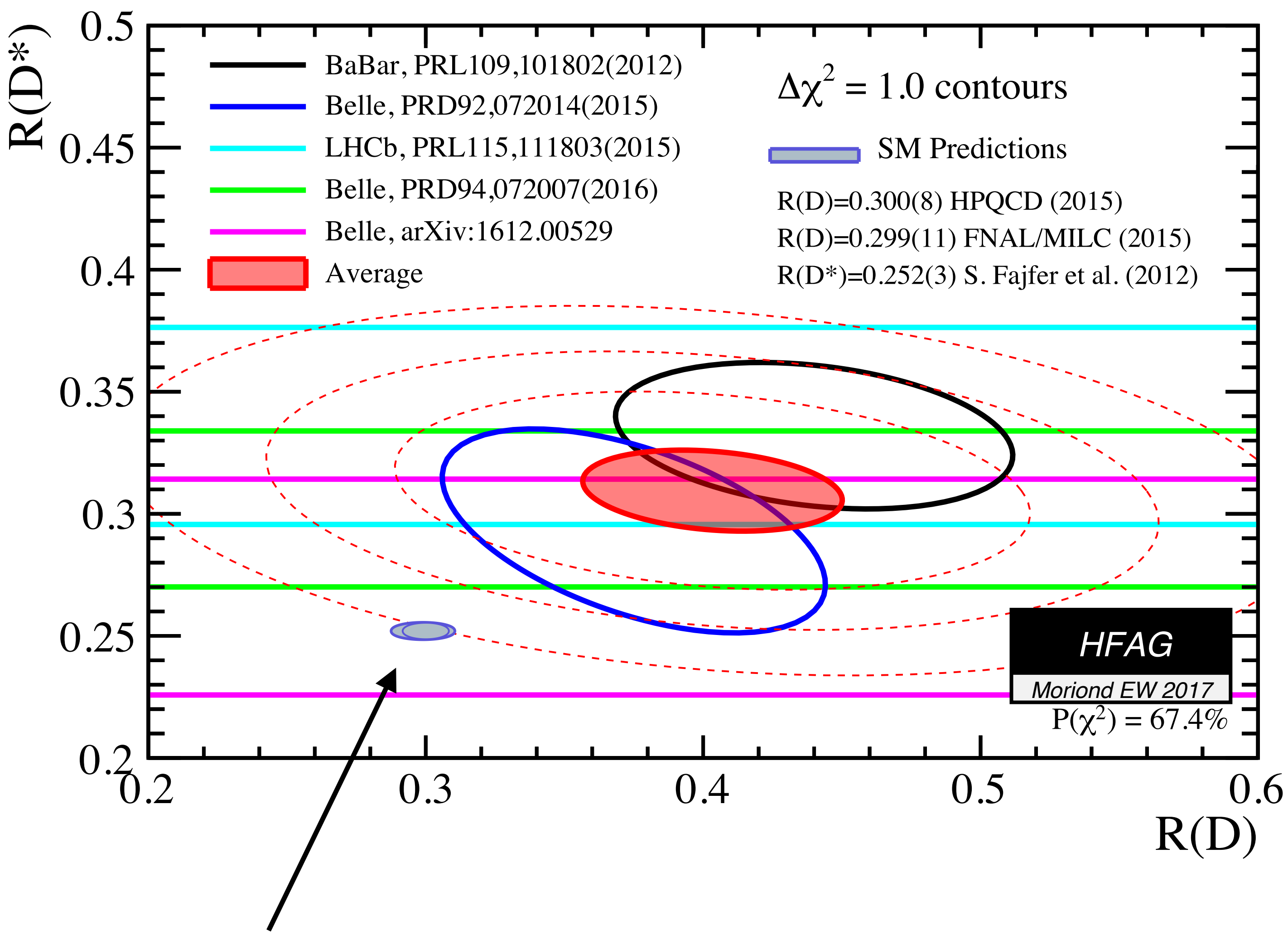




- Also first measurement to measure τ polarisation.

Combination

- All experiments see an excess of signal w.r.t. SM prediction.



Horizontal bands refer to R(D*), ellipses refer to both R(D*,D)

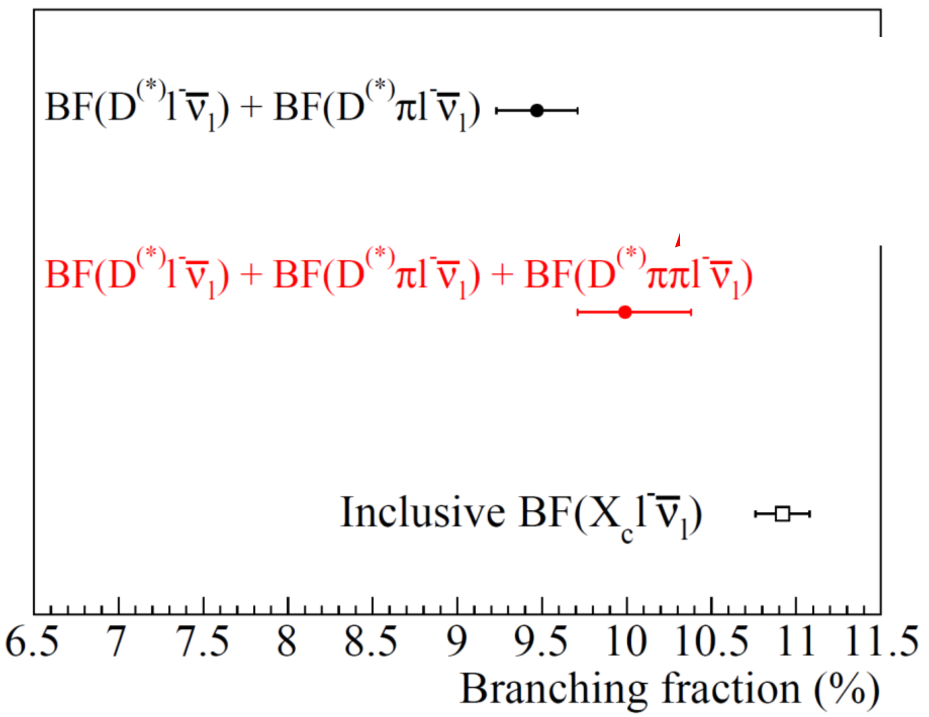
QCD uncertainties very small - unlikely to be explanation.

Latest HFAG average [1] quotes **3.9σ** from SM prediction

[1] http://www.slac.stanford.edu/xorg/hfag/semi/winter16/winter16_dtaunu.html

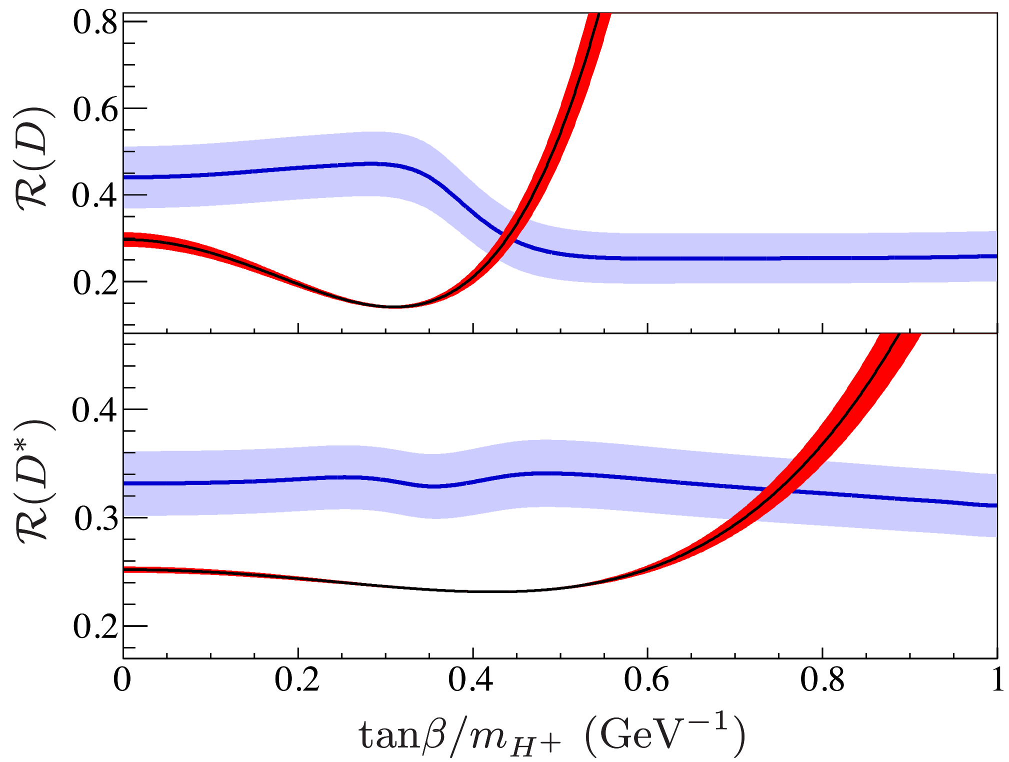
Remarks

- Because this measurement is so difficult, it has received a fairly healthy level of scepticism by the theory community.
- People are worried about backgrounds from $B \to D^{**}\ell\nu$ decays where the charm spectrum is not so well measured.
- This is unlikely to be the issue:
  - Rely on data for control of background.
  - B-factories/LHCb have very different background levels

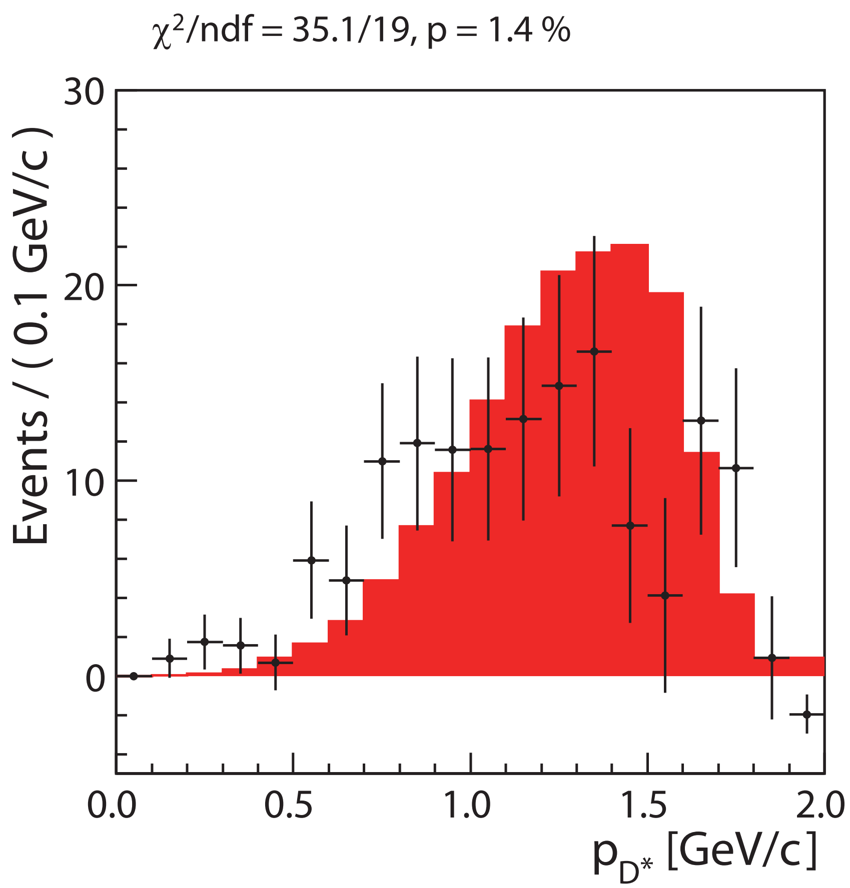


Constraining models

Phys. Rev. D 88, 072012 (2013)



- The central values of R(D*) and R(D) cannot be explained by 2HDM type II.



(c)R_2 type leptoquark model with $C_T = +0.36$.

Phys.Rev.D 92, 072014 (2015)

- Can also compare kinematic distributions to narrow down model possibilities.

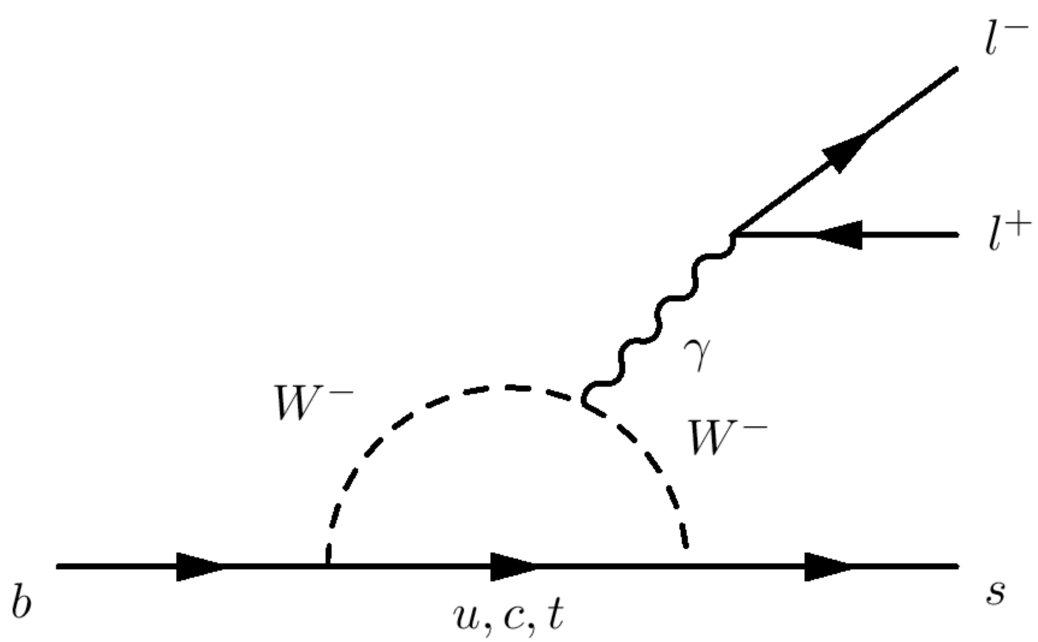
Difficult in general to explain with a scalar particle, constraints from B_c disfavour this (arXiv:1611.06676).

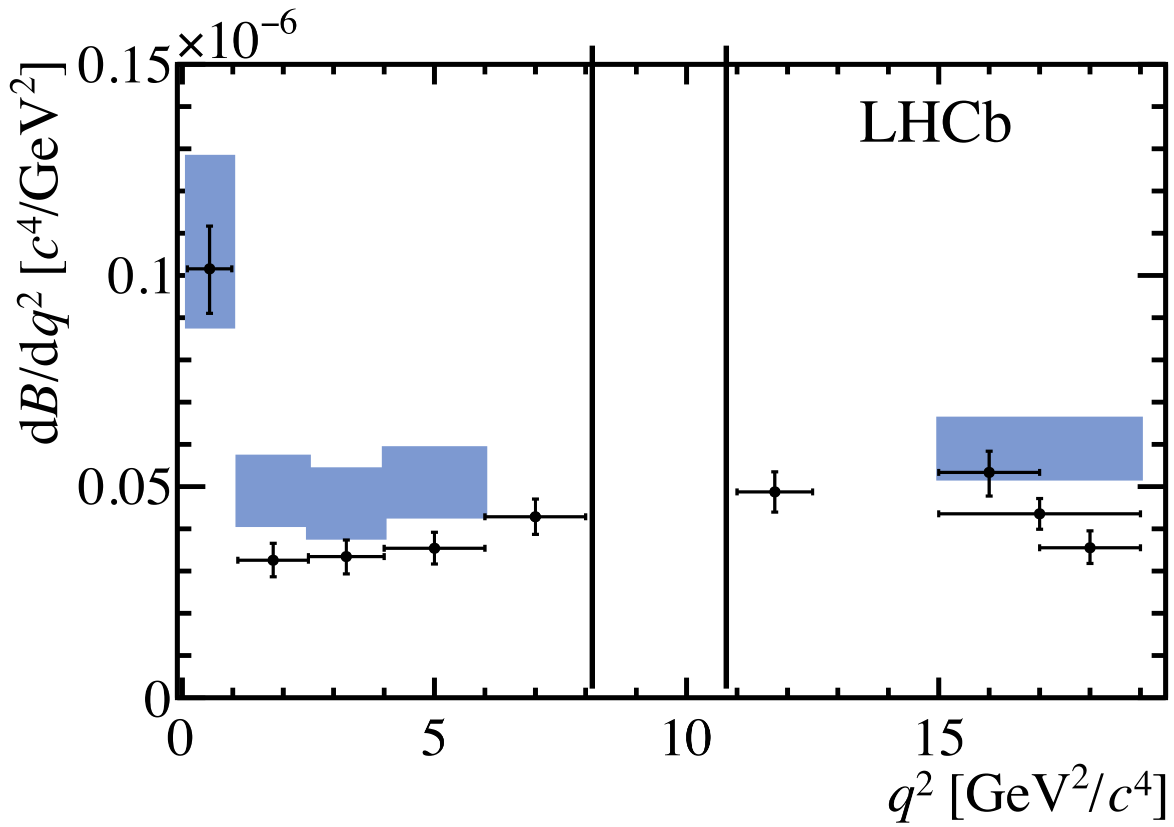
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

Plots liberally borrowed from Simone Bifani's recent CERN seminar: https://indico.cern.ch/event/580620/

$B \to K^{(*)}\ell\ell$

- The decay $B \to K^{(*)}\ell\ell$ is a semileptonic b—>s transition.





- q^2 is the four-momentum transferred to the di-leptons.

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- The branching fraction of the muonic mode has been well measured and is slightly below the SM prediction.

$R_{K^{(*)}}$

- Here take ratio of light leptons,

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

- Muon and electron masses small compared to b-quark.
    - R_K is essentially unity in SM, with no uncertainty.
- QED effects can be large but this is accounted for in the measurements.

Measurement at LHCb

LHCb-PAPER-2017-013, arXiv:1705.05802

- Most precise measurements of $R_{K^{(*)}}$ from LHCb.
- Results use run 1 data - 3fb^{-1} of luminosity.
- Measure the double ratio with the resonant mode $B \to K^{(*)}(J/\psi \to \ell^+\ell^-)$

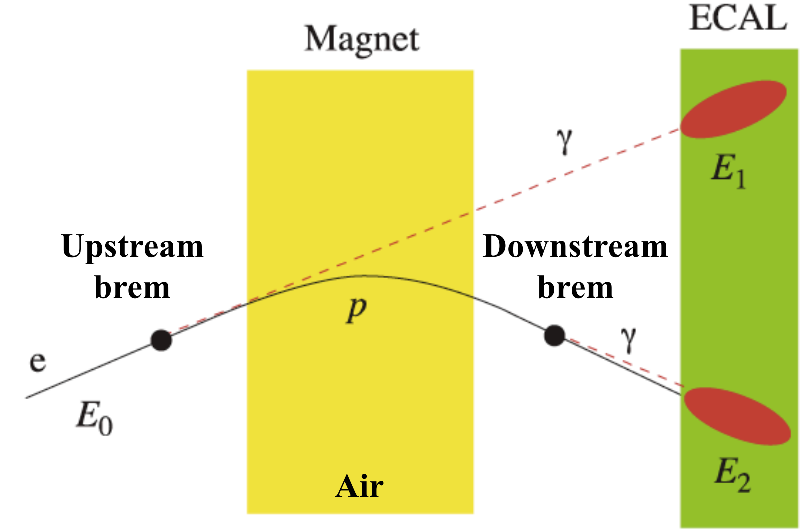
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

- Use normalisation channel to correct simulation and signal mass shapes.
- Fit B mass in low and central q^2 regions:

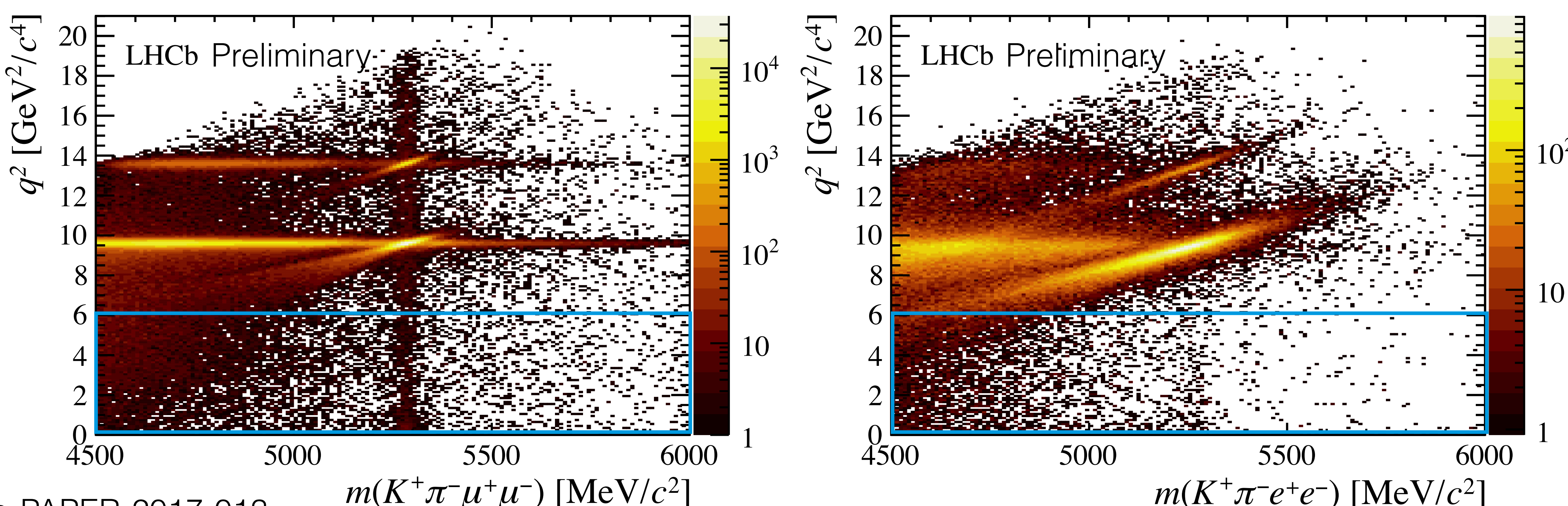
‘low’ region	‘central’ region
$0.045 < q^2 < 1.1\mathrm{GeV}^2/\mathrm{c}^4$	$1.1 < q^2 < 6.0\mathrm{GeV}^2/\mathrm{c}^4$

Bremsstrahlung issues

- Electrons more difficult than muons due to bremsstrahlung.
- Get background from the J/ψ and ψ(2S) leaking into signal region.



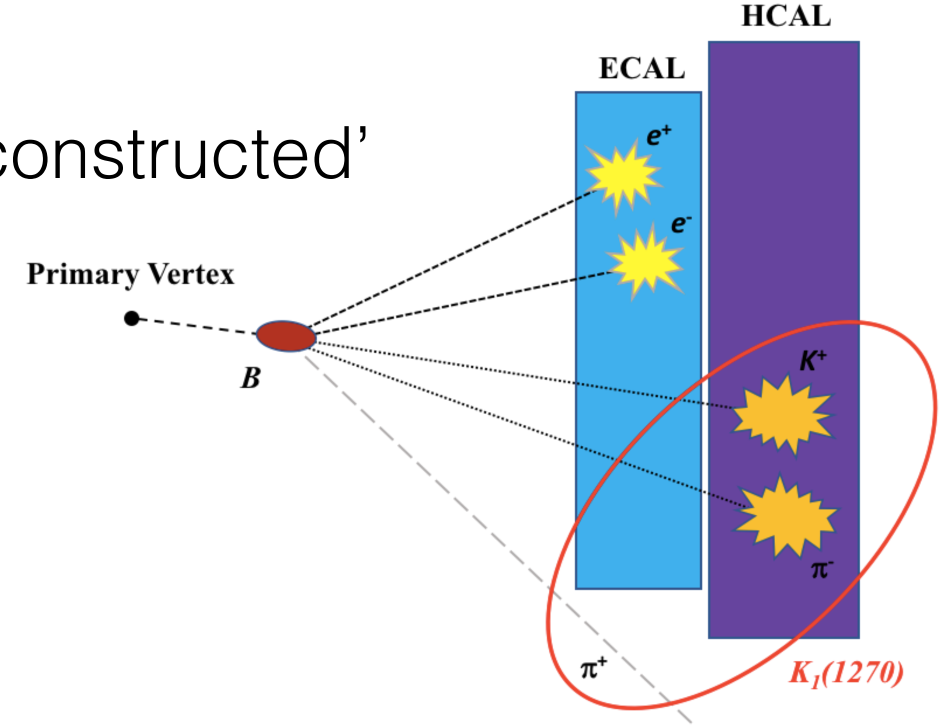
LHCb-PAPER-2017-013



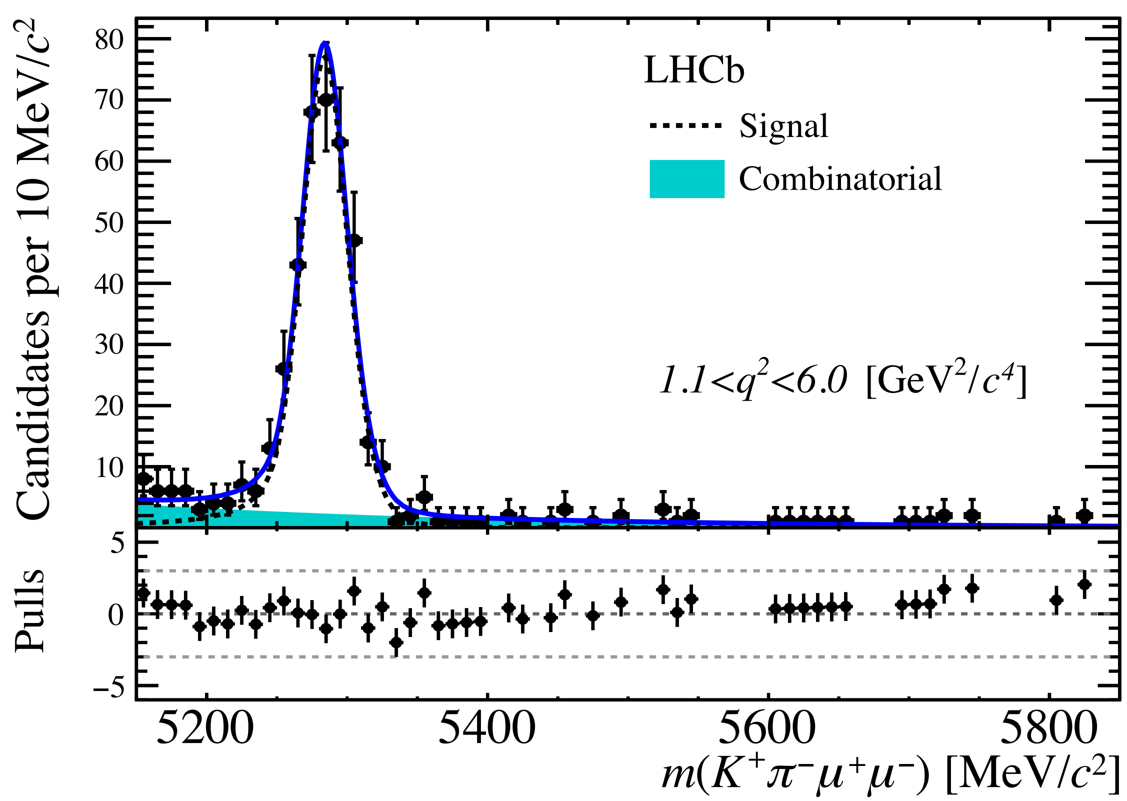
LHCb-PAPER-2017-013
arXiv:1705.05802

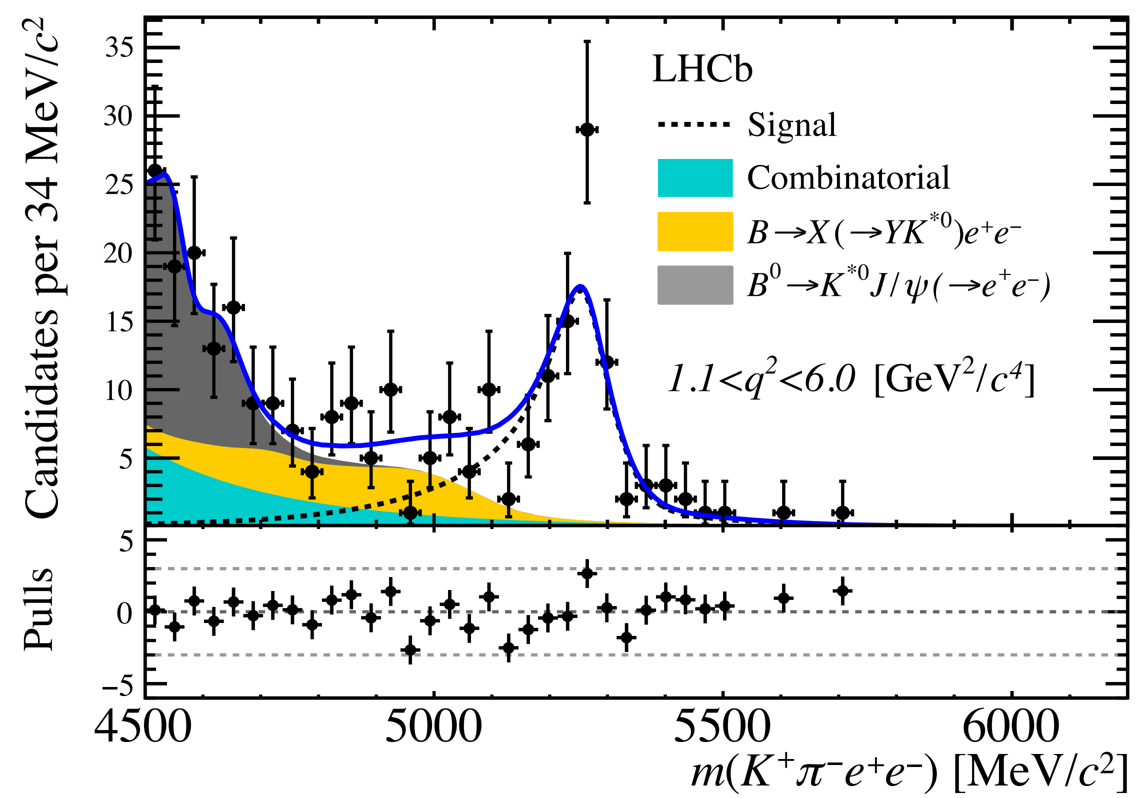
Bremsstrahlung issues

- Easier to confuse signal with ‘partially reconstructed’ background.



LHCb-PAPER-2017-013, arXiv:1705.05802



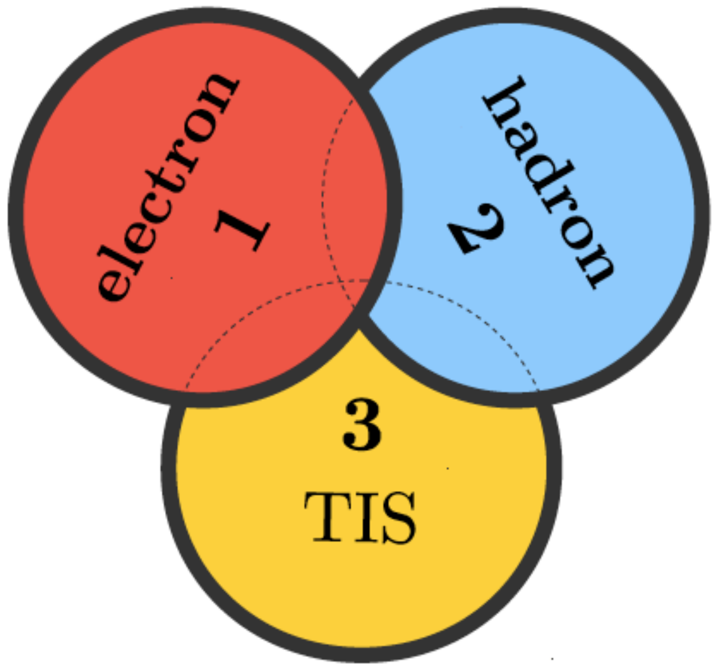


Correcting for efficiency

- The double ratio means that only efficiency differences due to kinematics can affect the result.

- Simulation is also corrected for using control samples.
  - If these corrections are not used, the result only changes by 5%.

- Split data depending on how event was triggered.
  - Important for cross-checks.



Cross-checks

LHCb-PAPER-2017-013

- Most powerful cross-check for efficiency, measure single ratio for the J/ψ modes.

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi\,(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi\,(\to e^+e^-))} = 1.043 \pm 0.006\,(\mathrm{stat}) \pm 0.045\,(\mathrm{syst})$$

Other cross-checks include other double ratios who's precision is known.

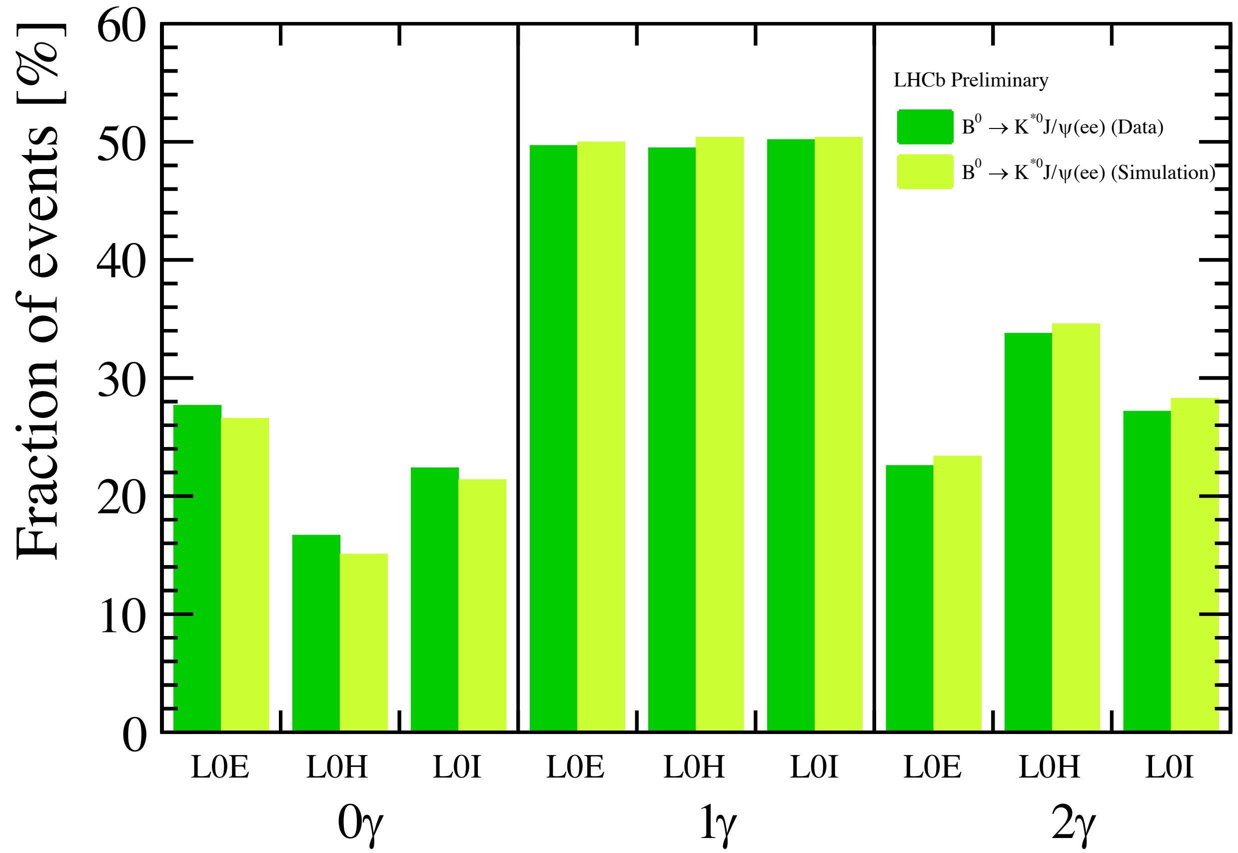
$$\mathcal{R}_{\psi(2S)} = \frac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi\,(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi\,(\to e^+e^-))}$$

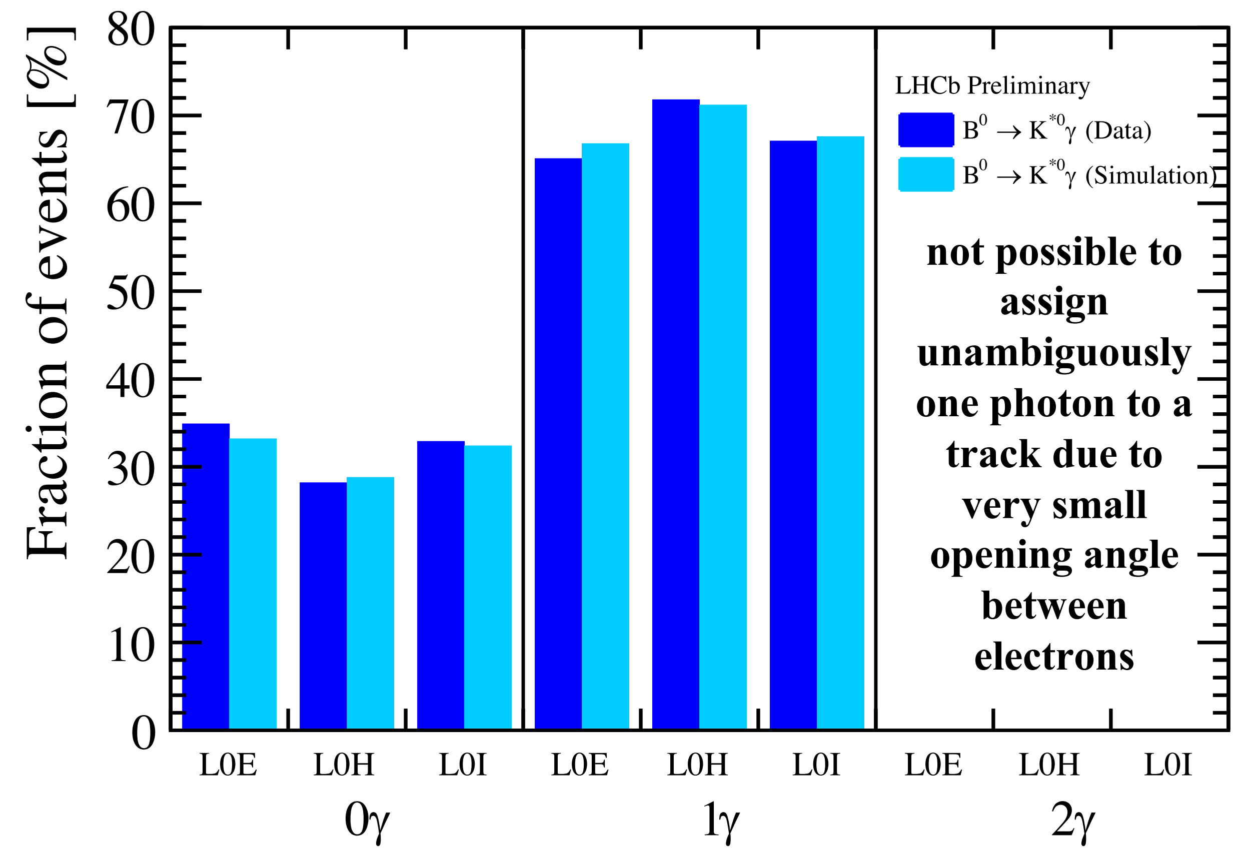
$$r_{\gamma} = \frac{\mathcal{B}(B^0 \to K^{*0} \gamma(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi\,(\to e^+e^-))}$$

Both of which are found to be compatible with expectations.

Cross-checks (II)

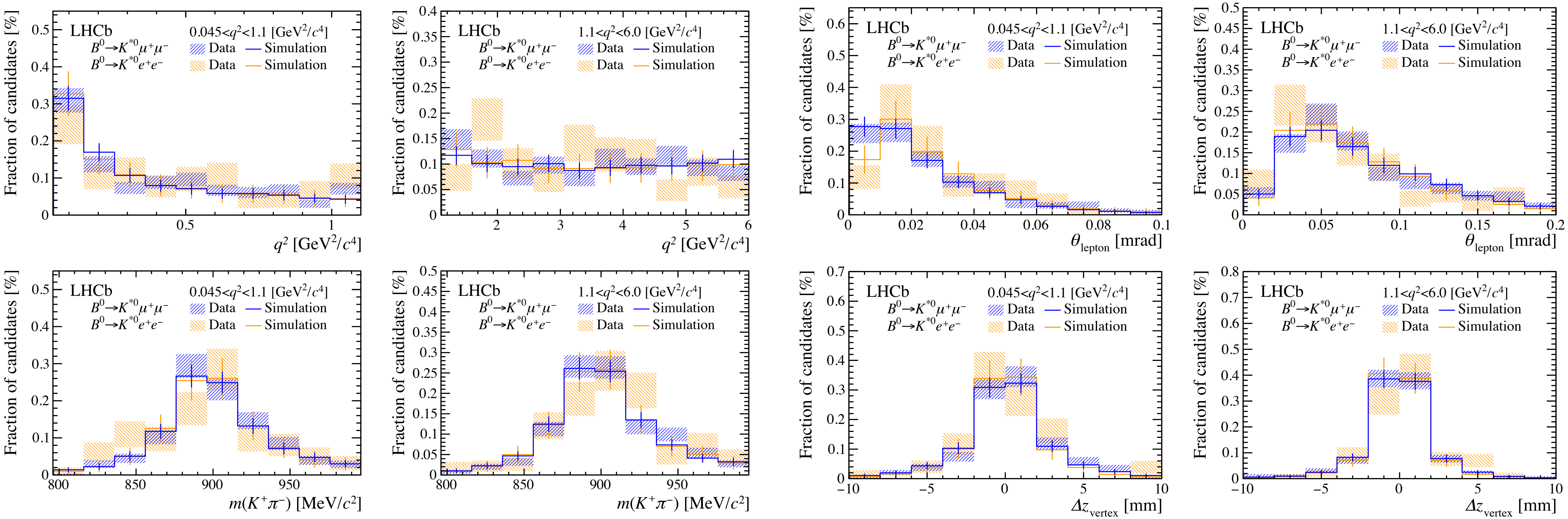
- Compare bremsstrahlung/trigger categories between data and simulation.





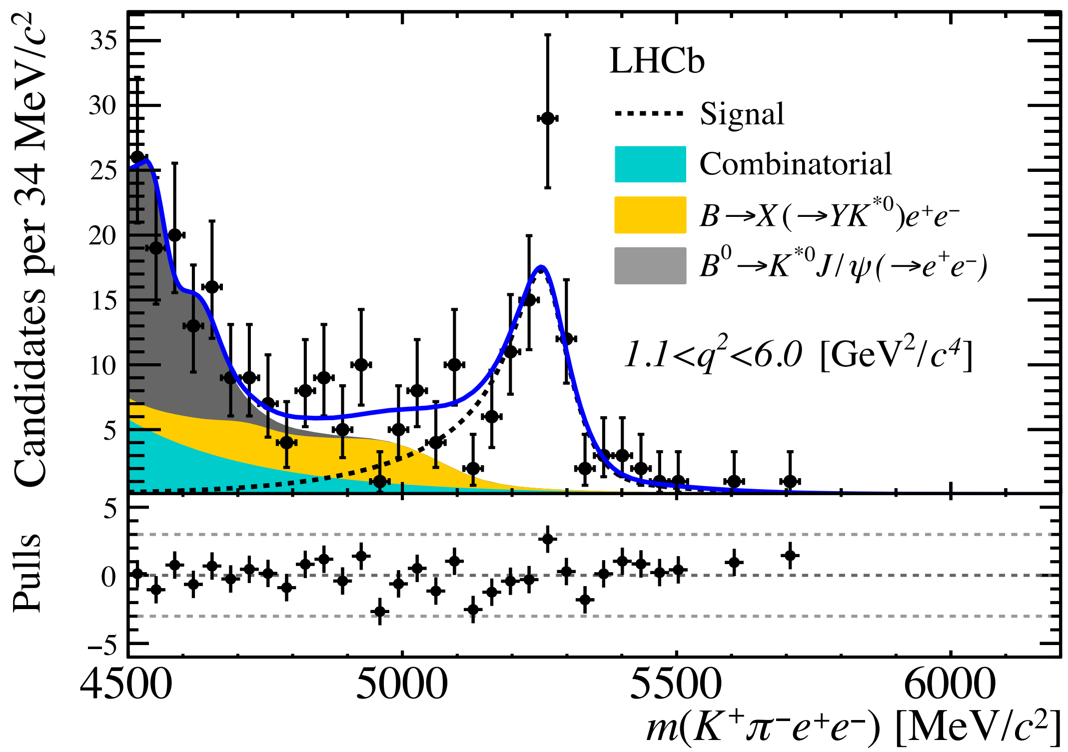
Cross-checks (III)

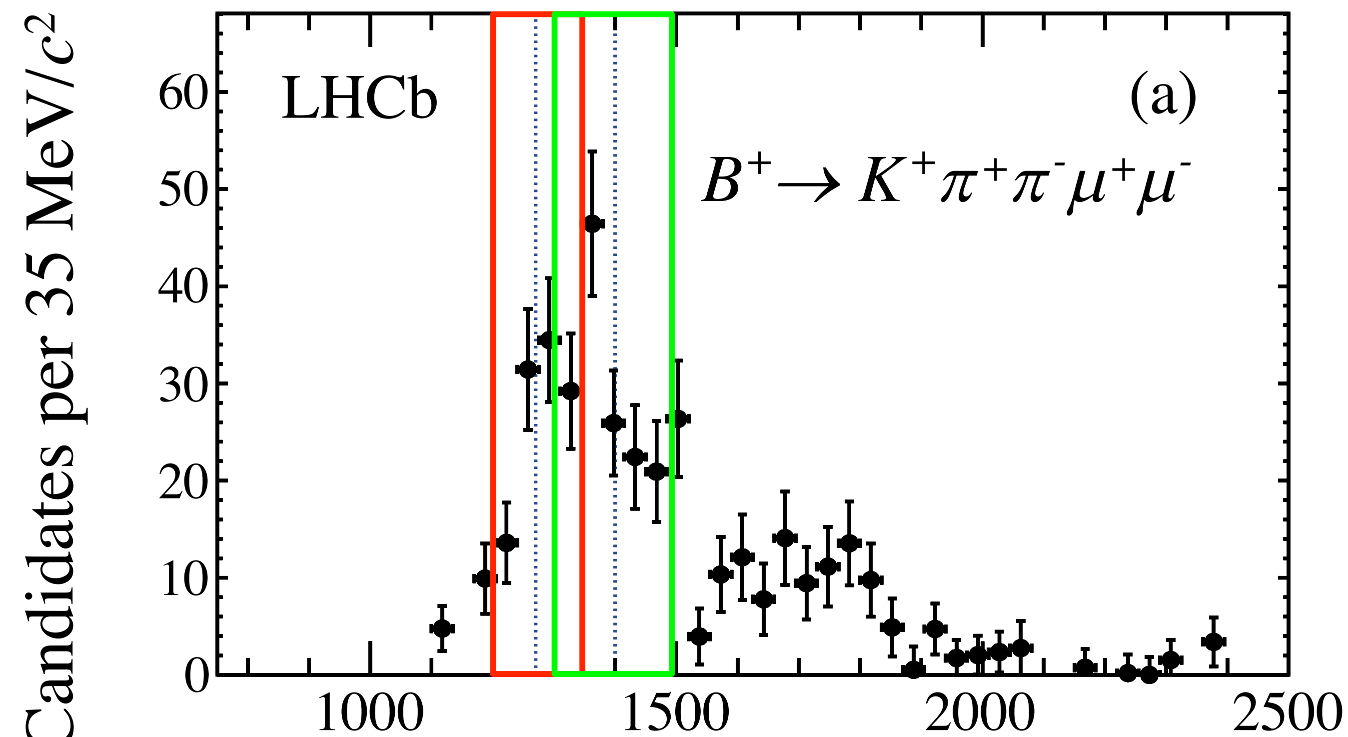
- Also compare kinematic distributions of signal peak between data/ simulation.



Cross-checks (IV)

- What about the signal yield?





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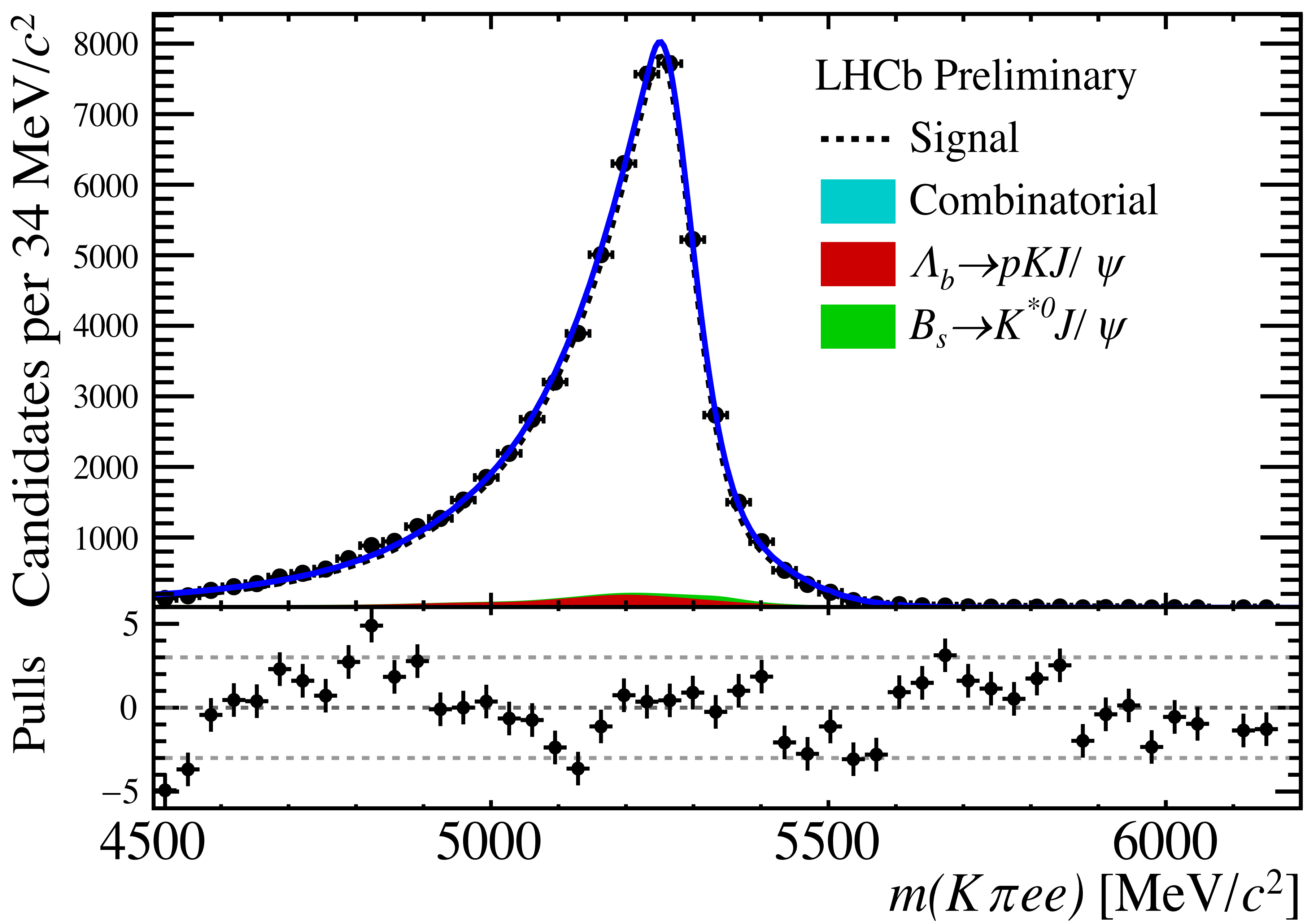
- Part. reco background controlled in two ways:
  - Using $B \to K^*(J/\psi \to e^+e^-)$
  - Using $B \to K\pi\pi\mu^+\mu^-$

Cross-checks (V)

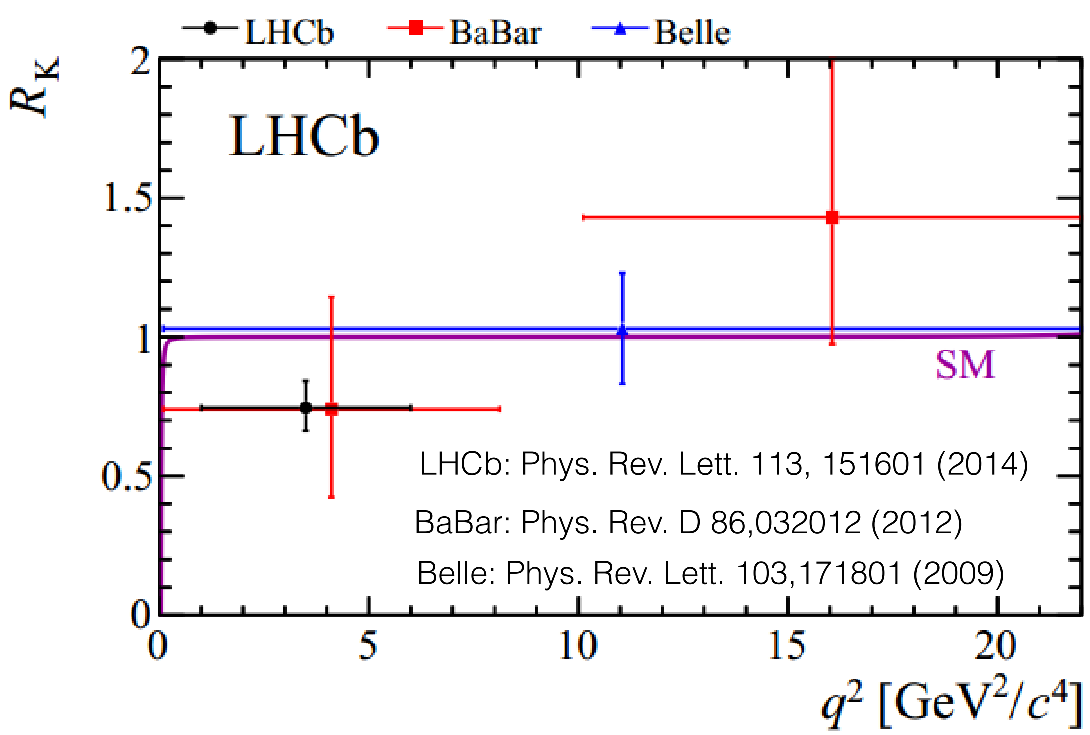
- What about modelling of signal yield?



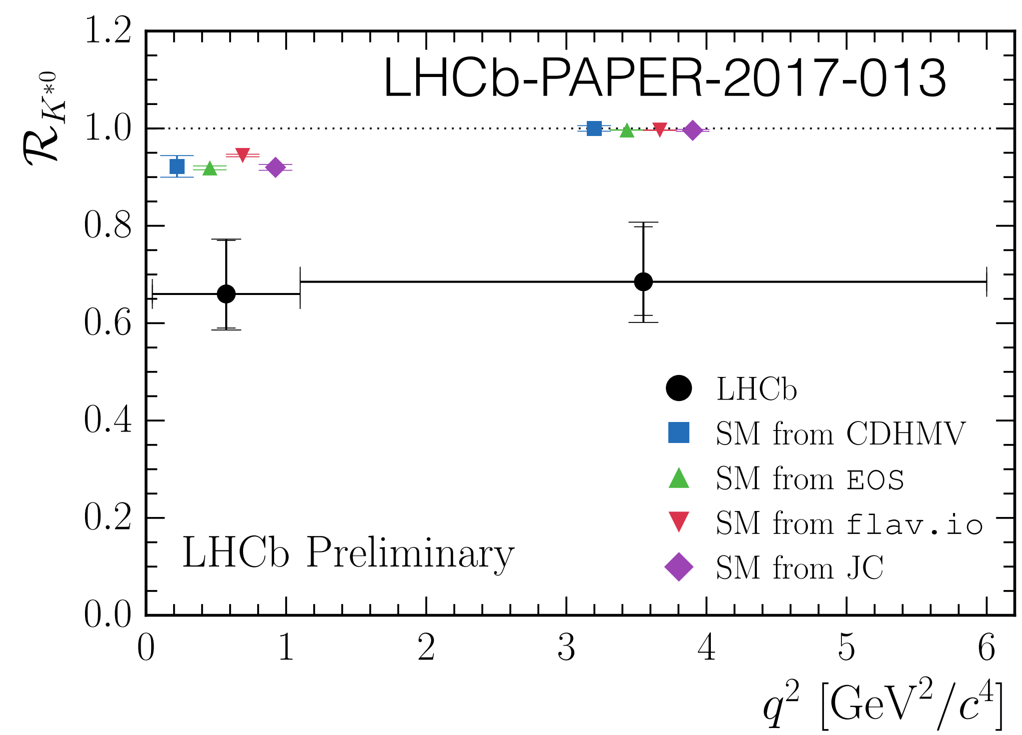
Results

- Take ratio of signal yields and correct for efficiency to get $R_{K^{(*)}}$.

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



LHCb Preliminary	**low-q^2**	**central-q^2**
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\ 0.110}_{-\ 0.070} \pm 0.024$	$0.685\ ^{+\ 0.113}_{-\ 0.069} \pm 0.047$



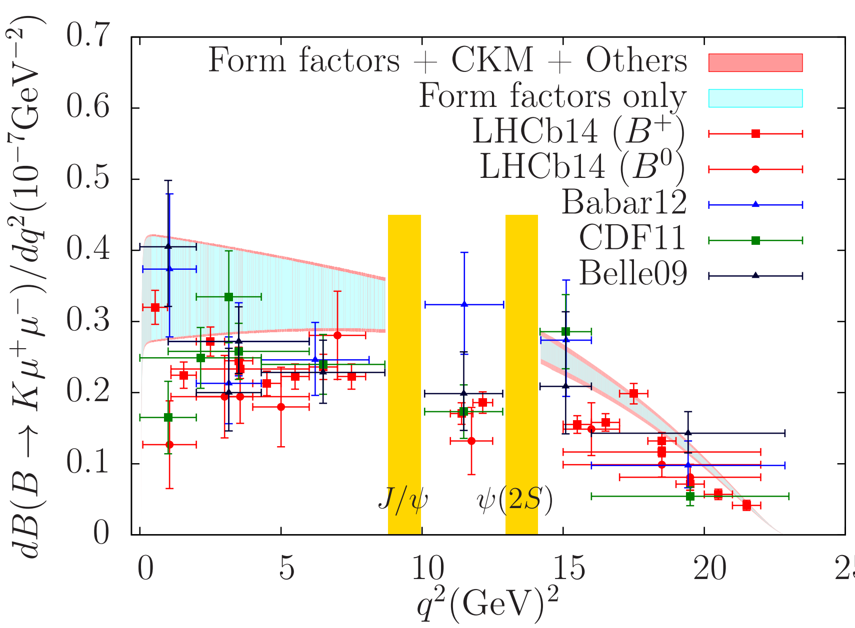
- LHCb results are 2.6 (R_K), 2.4 and 2.2σ from the SM predictions and all in the same direction.
- Error dominated by the statistical uncertainty.

Remarks I

- All of the muonic b—>sll branching fractions tend to be below the SM prediction. See Fernando's talk for more details.

- If NP doesn't couple (strongly) to first generation, one would naively expect R_K to be less than unity.

FNAL/MILC, Phys. Rev. D 93, 034005 (2016)



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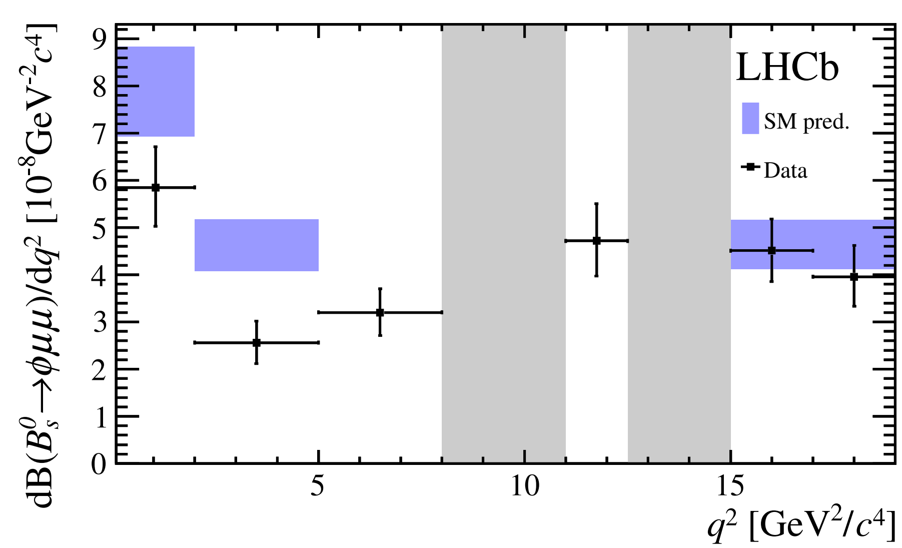

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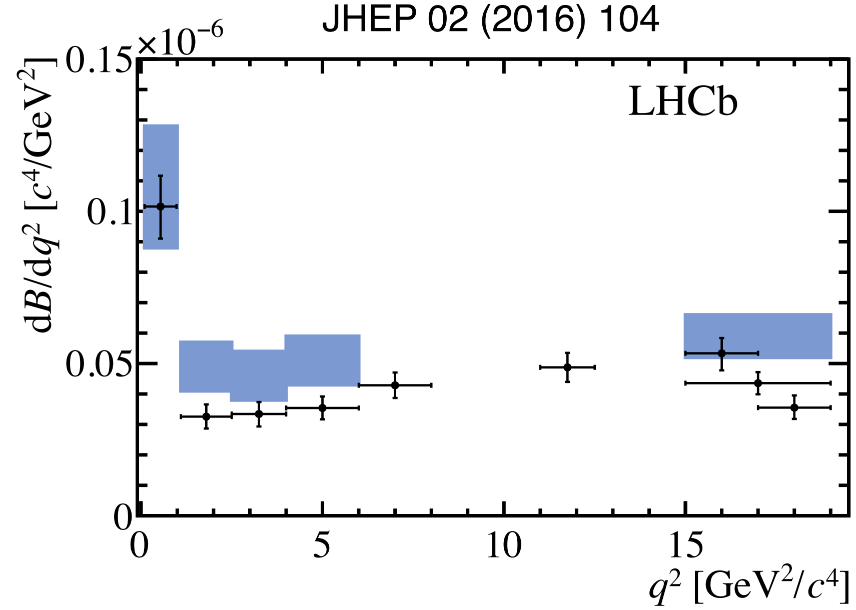

- Its not particularly significant, but at least things are consistent.

Remarks II

- We are also seeing something strange in the angular distribution of the muonic decay, $B \to K^* \mu\mu$. See Fernando's talk for more details.

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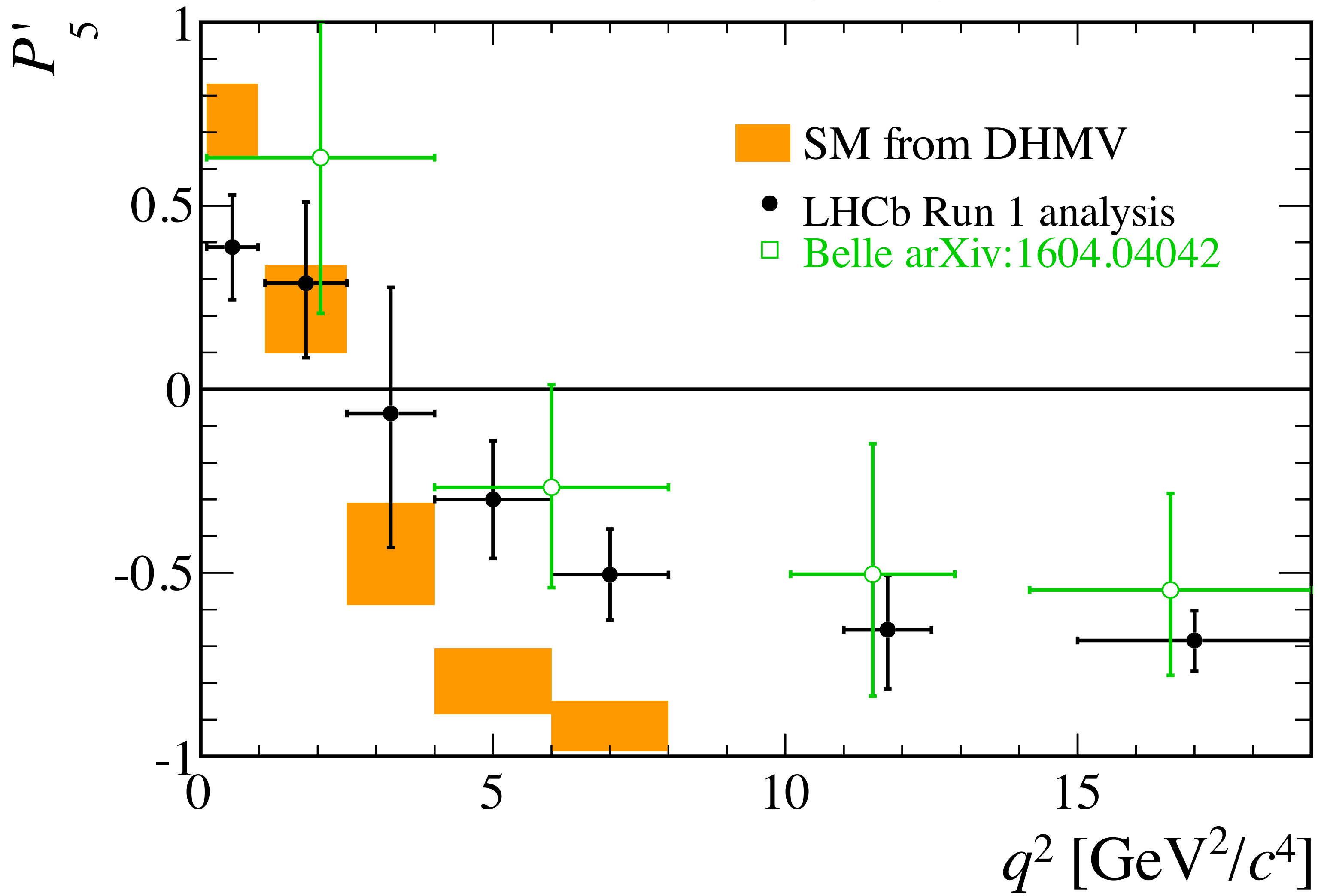
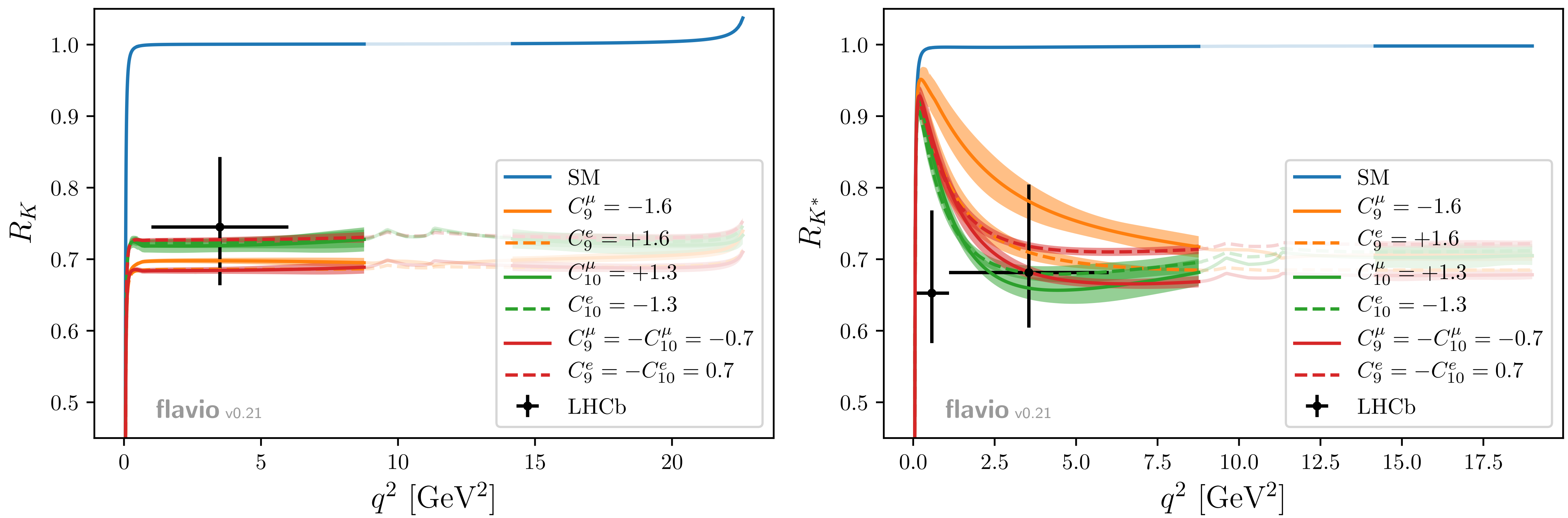


- The global significance here is about 3.5, although now the theoretical uncertainty is not negligible.

Remarks III

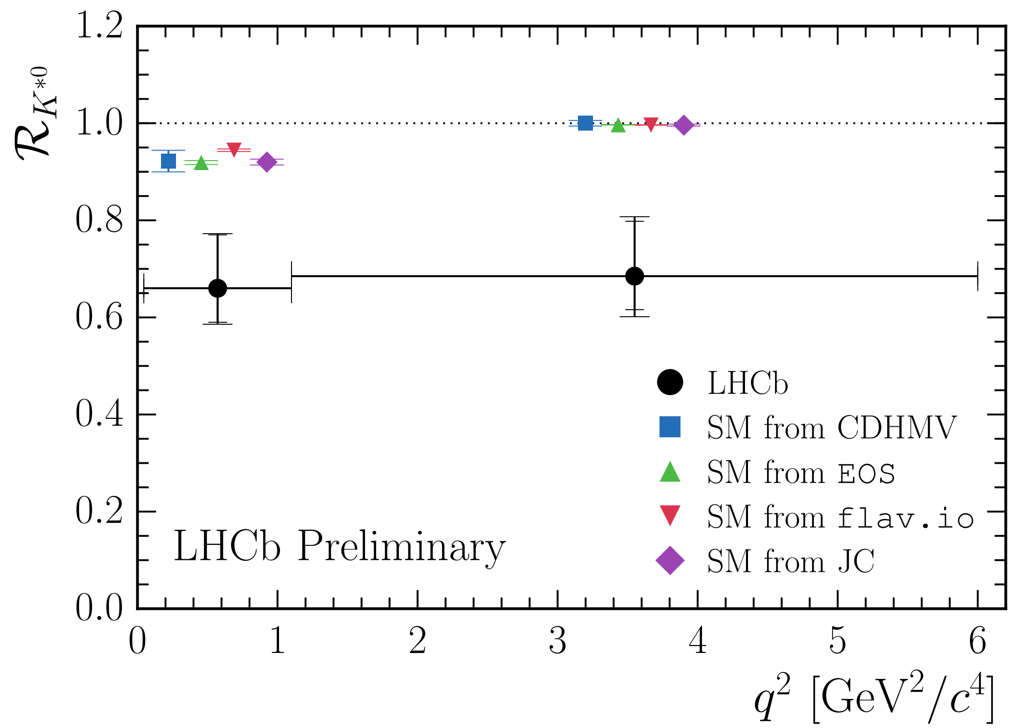
- Global fits suggest a mostly vector like contribution is destructively interfering with muonic amplitude can cause such a discrepancy.
  - This matches with low BFs and angular analysis of K*μμ.

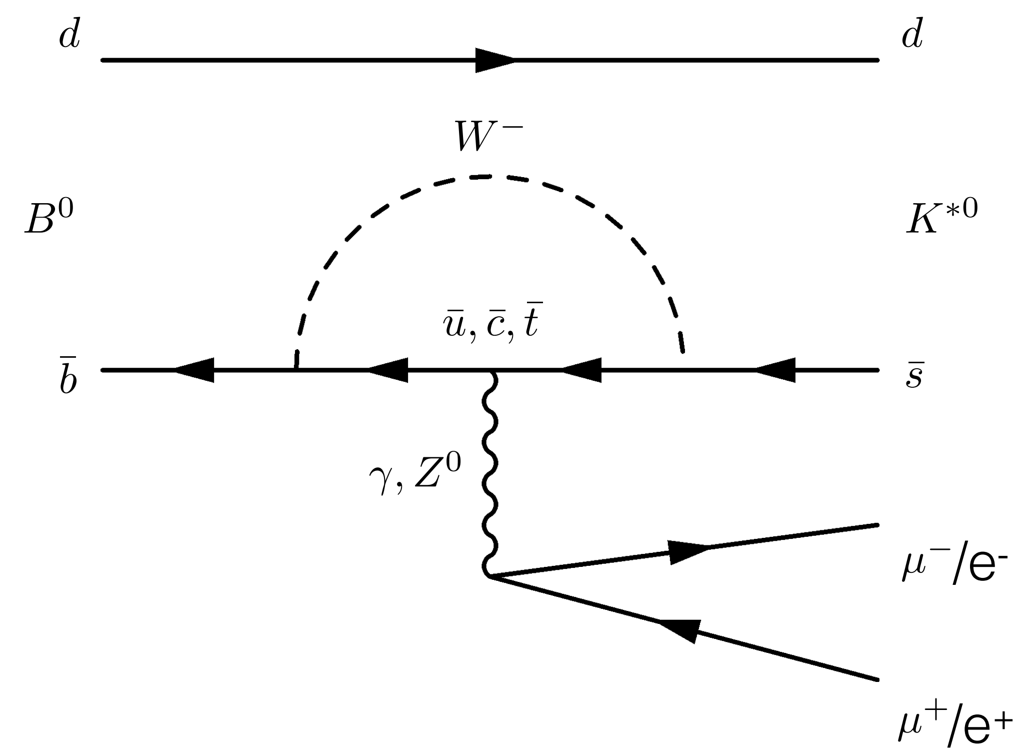
Altmannshofer et al. arXiv:1704.05435v1



Remarks IV

- If we assume NP is heavy, its hard to accommodate the shift in the first q^2 bin.



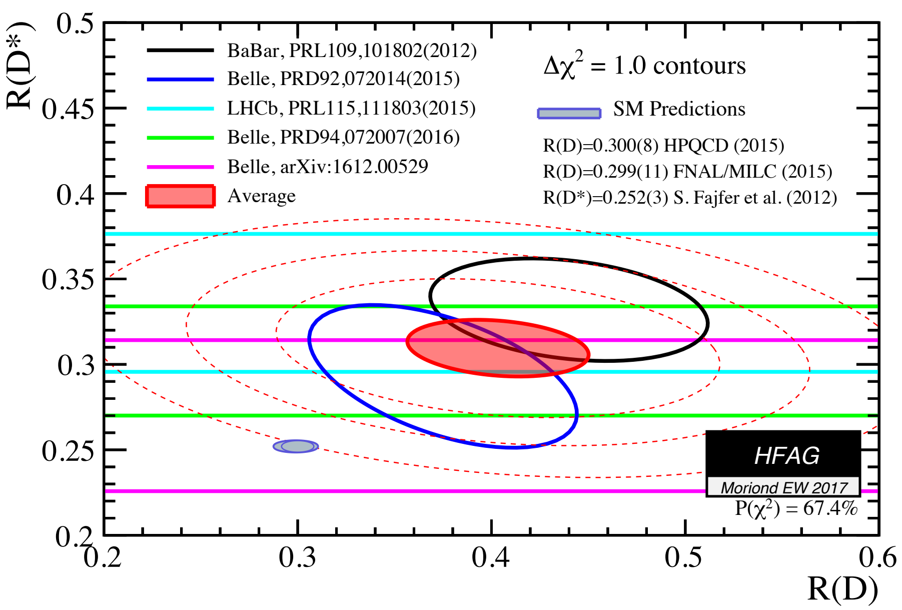


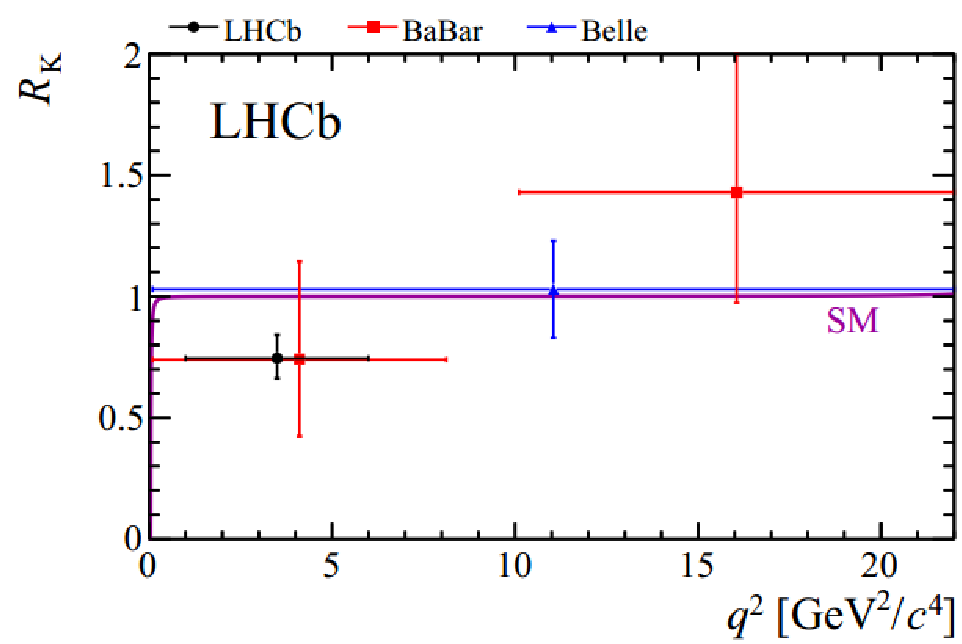
- At low q^2, the decay amplitude is dominated by the photon diagram - must be lepton universal!

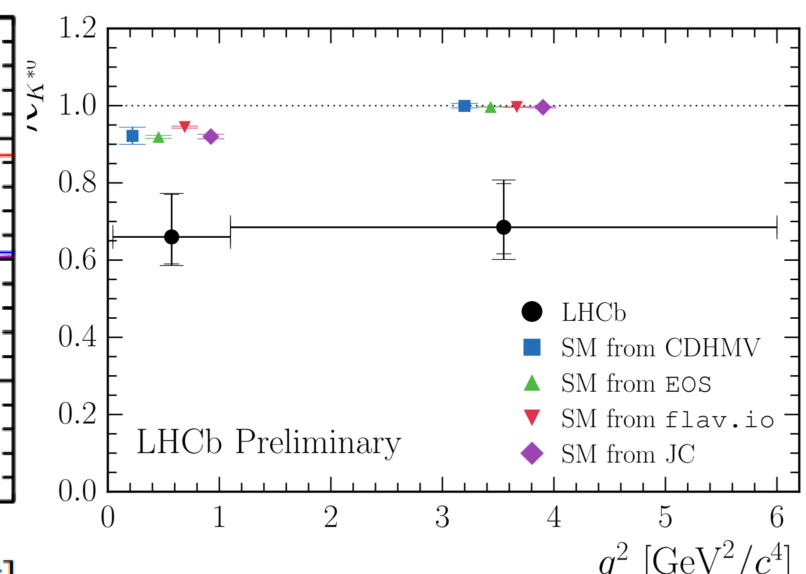
- There are models which get around this with light mediators (see e.g. Sala, Straub, arXiv:1704.06188).

Summary and outlook

- Tests of lepton universality are excellent ways of looking for new physics.
    - In B decays, one is naturally sensitive to models coupling more strongly to the 2nd or 3rd generations.
- We have two anomalies in both tree- and loop-level semileptonic B decays.







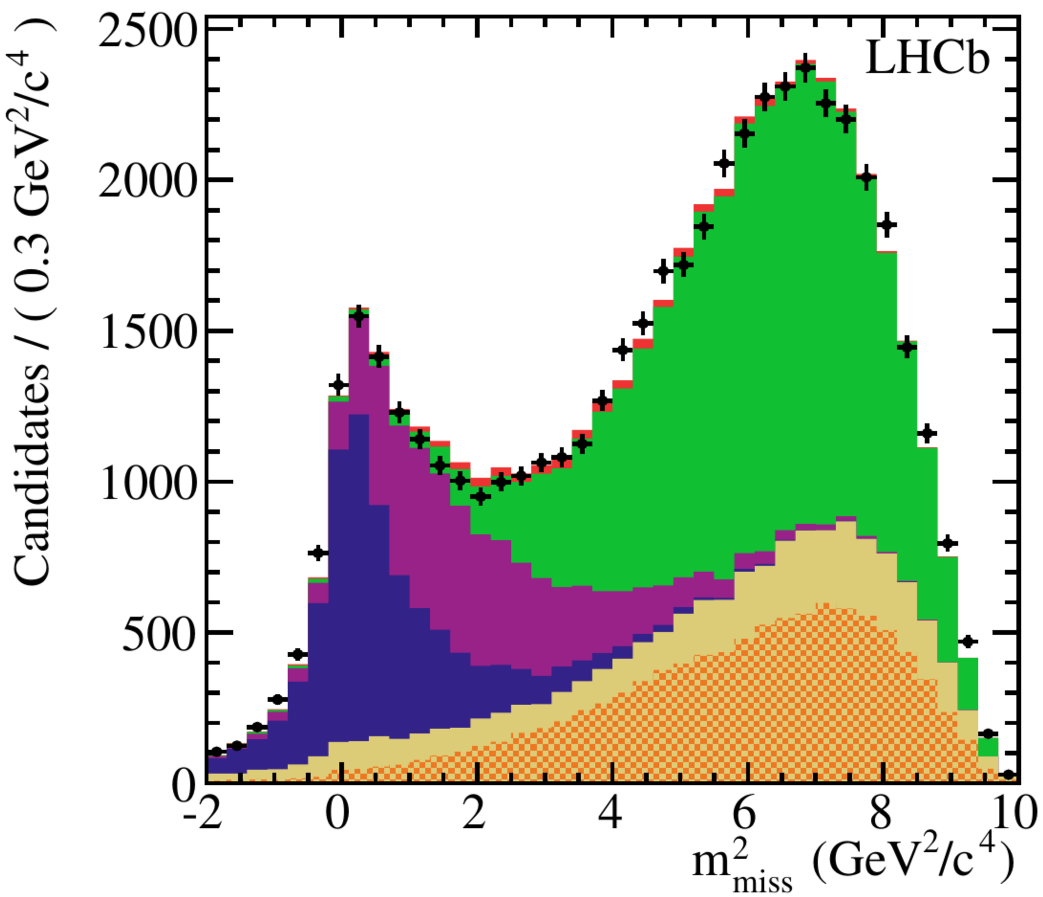
Summary and outlook

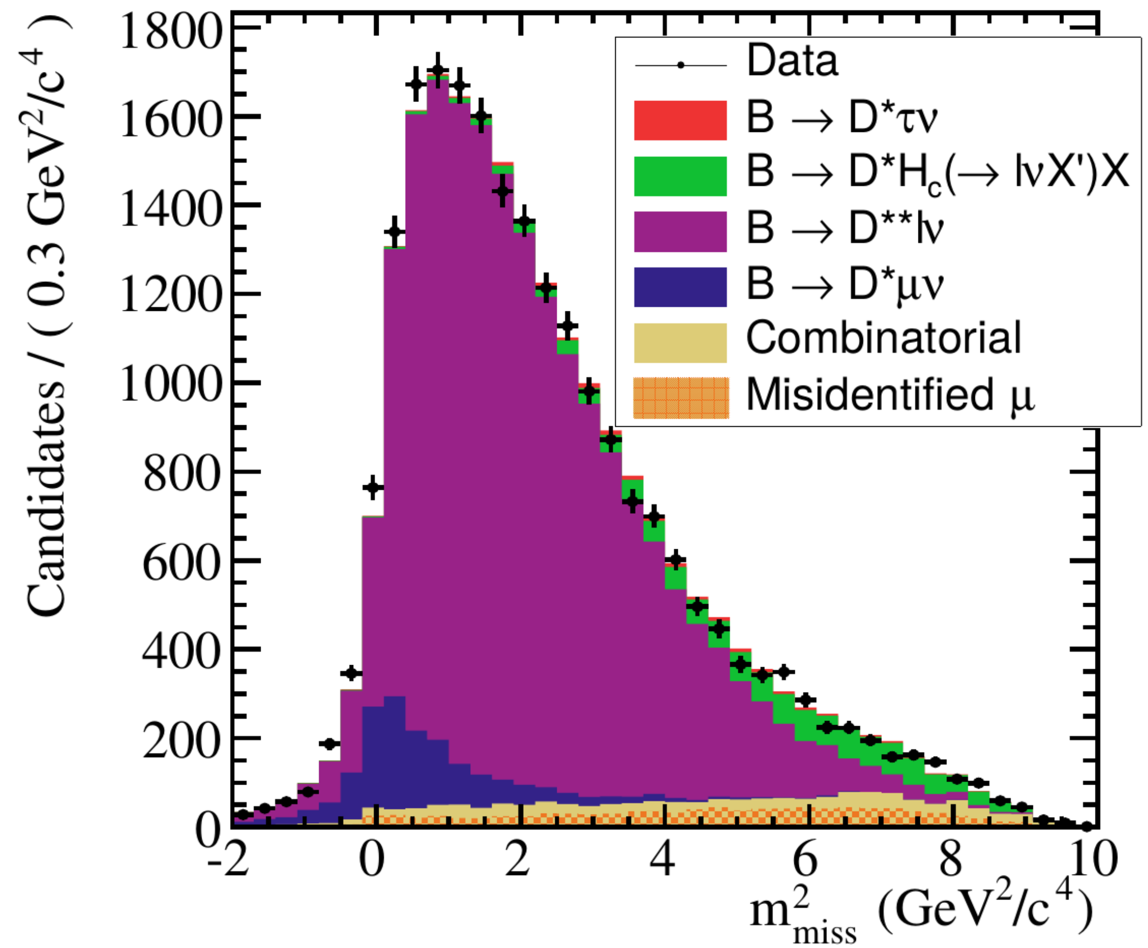
- Updates from LHCb are coming soon so there's no need to make your mind up yet.
  - All these results are based on run I data, the LHC has already produced the same number of B hadrons in our detector.
  - Expect improved precision on $R(D^*,D^0)$ and R_K.
  - Measurement of $R(D^*)$ with hadronic tau decays expected very soon.
  - Can also compare the angular distribution of these decays between the electronic and muonic versions.
- Next one should be very soon.

Back-ups

R(D*) control samples

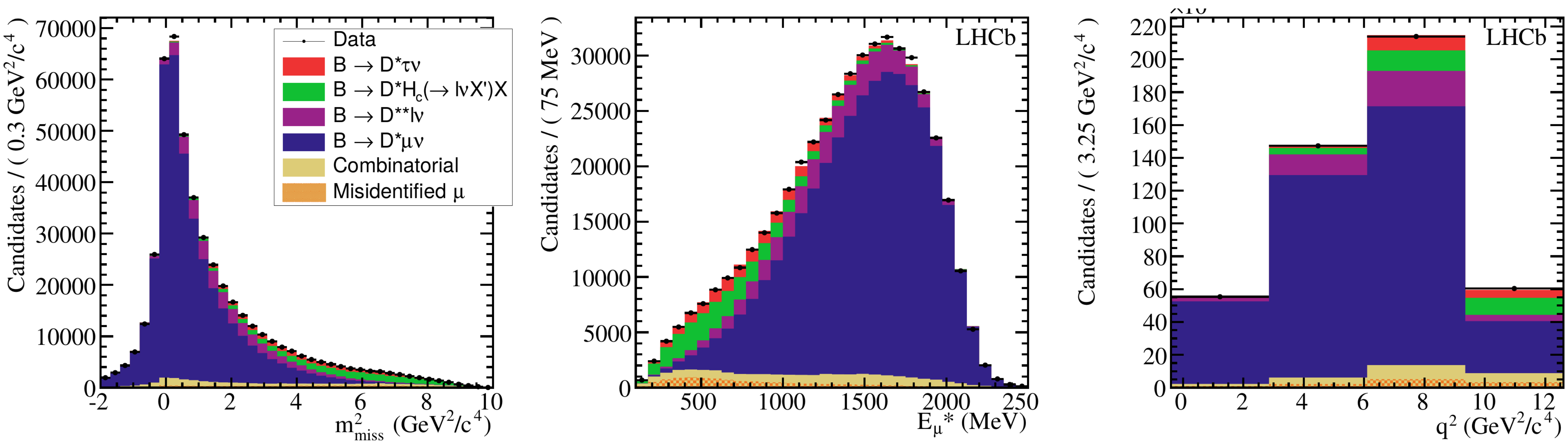
Anti-isolate signal to enrich particular backgrounds.





R(D*) 3D fit

3D fit used to discriminate signal from backgrounds



Good agreement seen everywhere

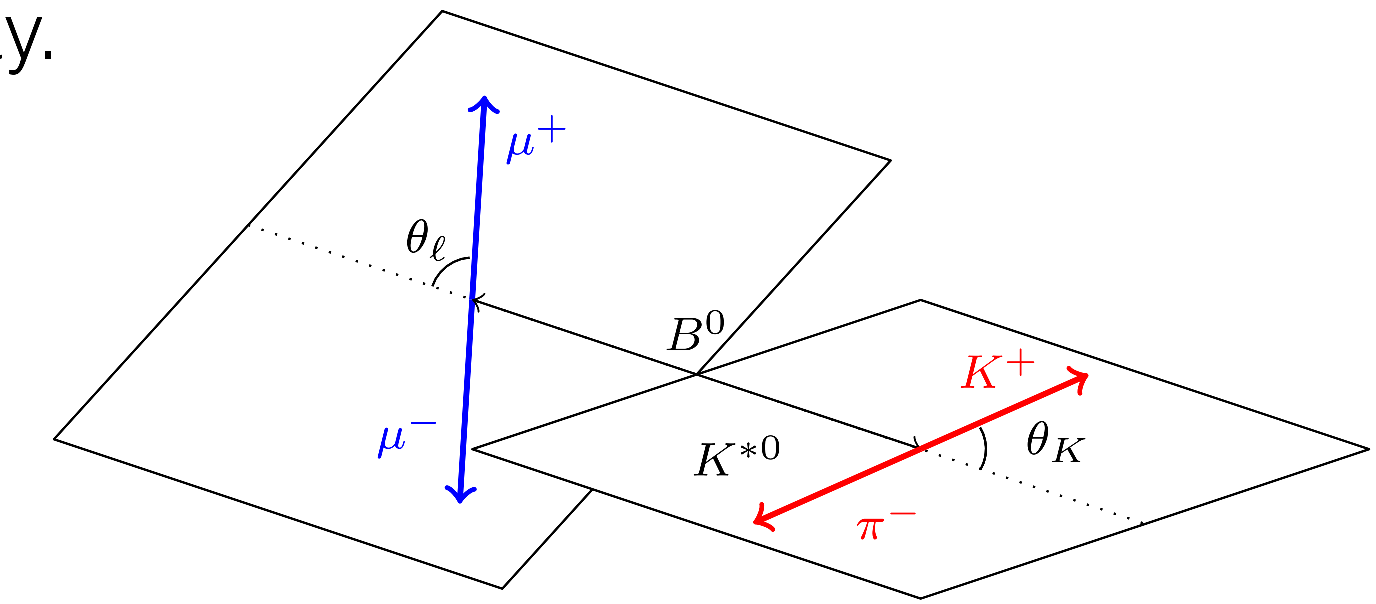
K*mm decay distribution

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

$$P_1 = \frac{2\,S_3}{(1-F_\mathrm{L})} = A_\mathrm{T}^{(2)}\,,$$
$$P_2 = \frac{2}{3}\frac{A_\mathrm{FB}}{(1-F_\mathrm{L})}\,,$$
$$P_3 = \frac{-S_9}{(1-F_\mathrm{L})}\,,$$
$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}\,,$$
$$P'_6 = \frac{S_7}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}\,.$$

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

- Now we move to a P—>VV decay.
    - Rich angular structure.



- Angular analysis desirable because:
    - Partially cancel QCD uncertainty.
    - Probe the helicity structure of NP.

$$P'_5 = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_{||}|^2)}}$$