Anomalous results in semi-leptonic B decays

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on behalf of the LHCb collaboration

Higgs tasting workshop, Benasque

19/05/16

Universität Zürich[UZH]

LHCb

B physics <—> Higgs physics

Two main ways to find new physics with b-hadrons

Study the CKM matrix

Arises from Higgs Yukawa interactions

Unitary in the SM, with one CP violating phase.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Test unitarity with many measurements.

Find new sources of CPV

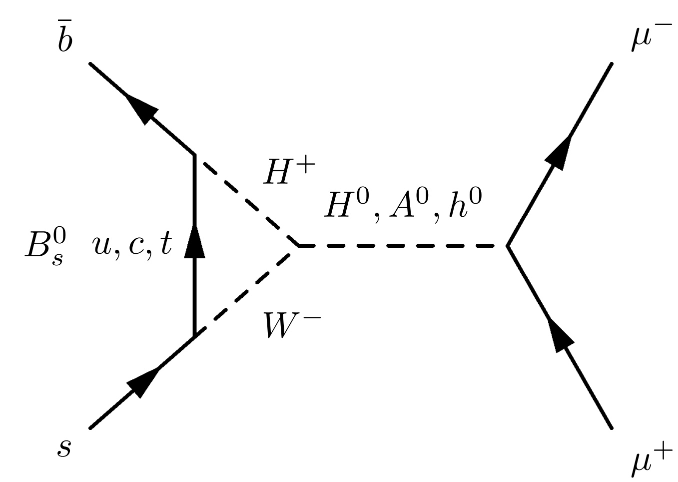
wru anti-matter!?

Measure decays of ground state b-hadrons

Properties influenced by virtual particles in NP models

Compare results to SM predictions

(need QCD input).



Particularly sensitive to NP models preferring third generation.

Both approaches sensitive to extended Higgs sector

B physics <—> Higgs physics

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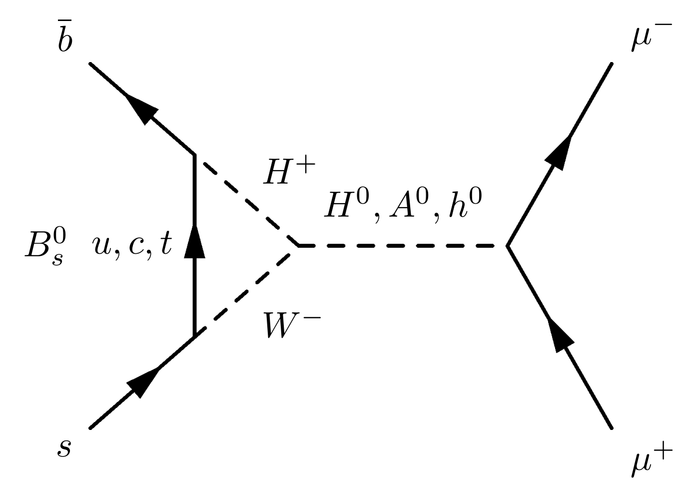
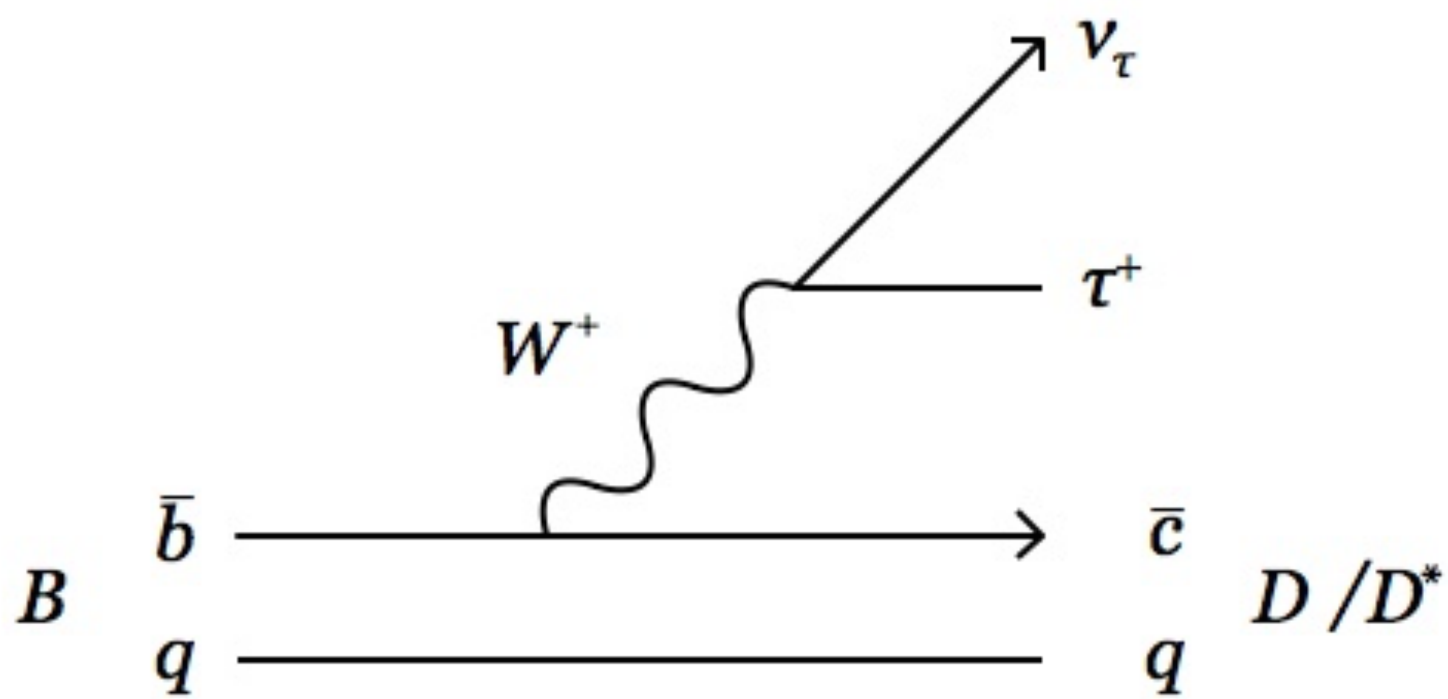


Particularly sensitive to NP models preferring third generation.

Concentrate on right-hand column today

Why semi-leptonic decays?

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



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

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

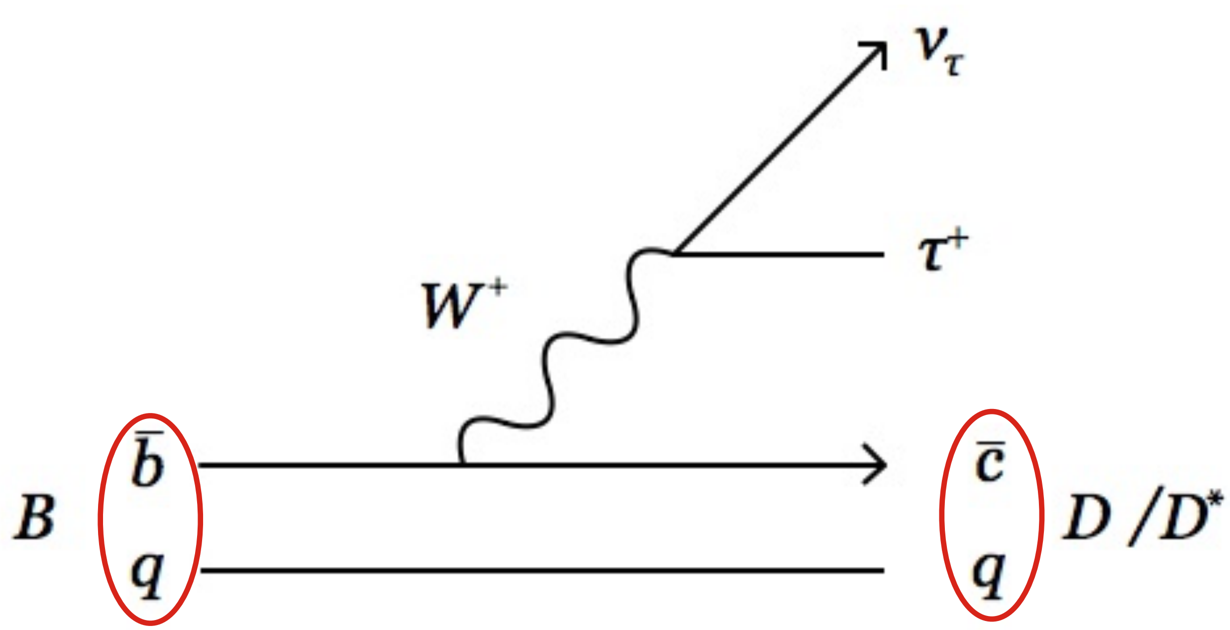
EW QCD

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

Types of semi-leptonic decay

Two types of semi-leptonic b-decay

Charged current

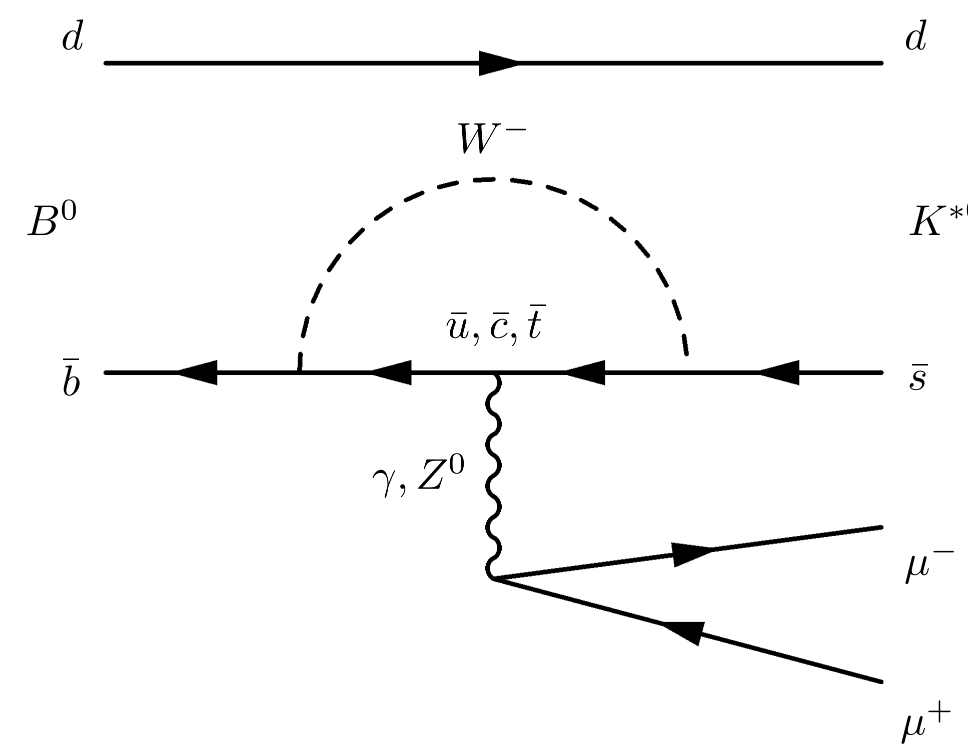


Can proceed via tree level -large O(%) branching fractions.

Factorised up to (small) QED corrections.

When you factorise, QCD part broken down into form-factors.

Neutral current



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

Factorised up to corrections from $B \to h(\to \mu^+\mu^-)h$ decays.

Anomalies

- Today I will talk about three anomalies in these decays.
  - $R(D^{(*)})$
  - R_K
  - P_5'

Anomaly #1

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

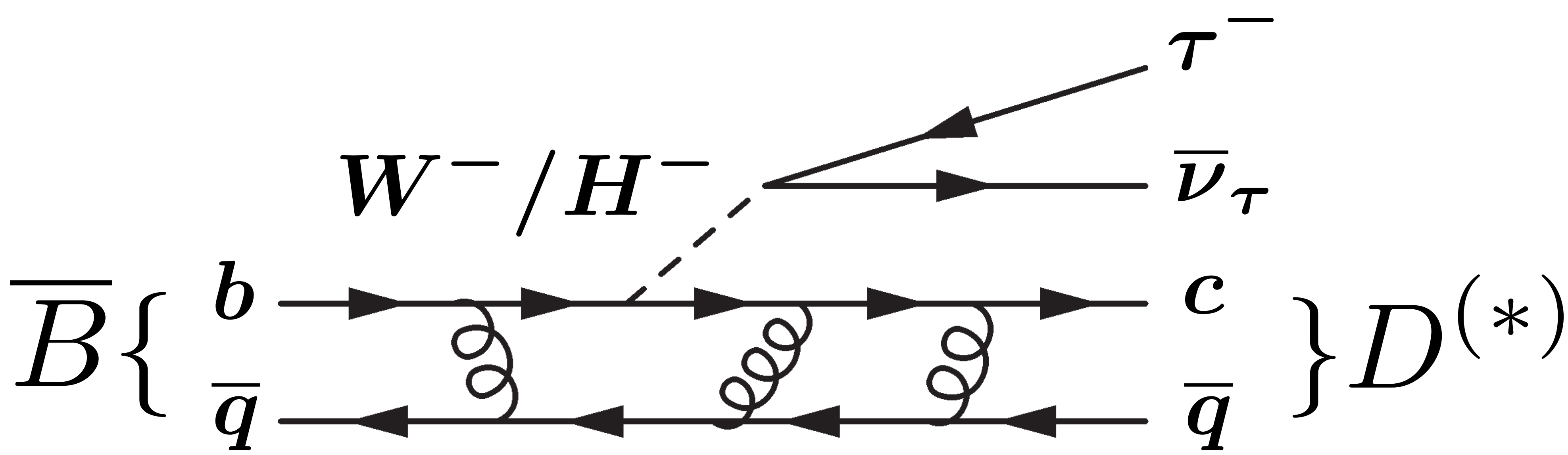
R(D*)

- 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

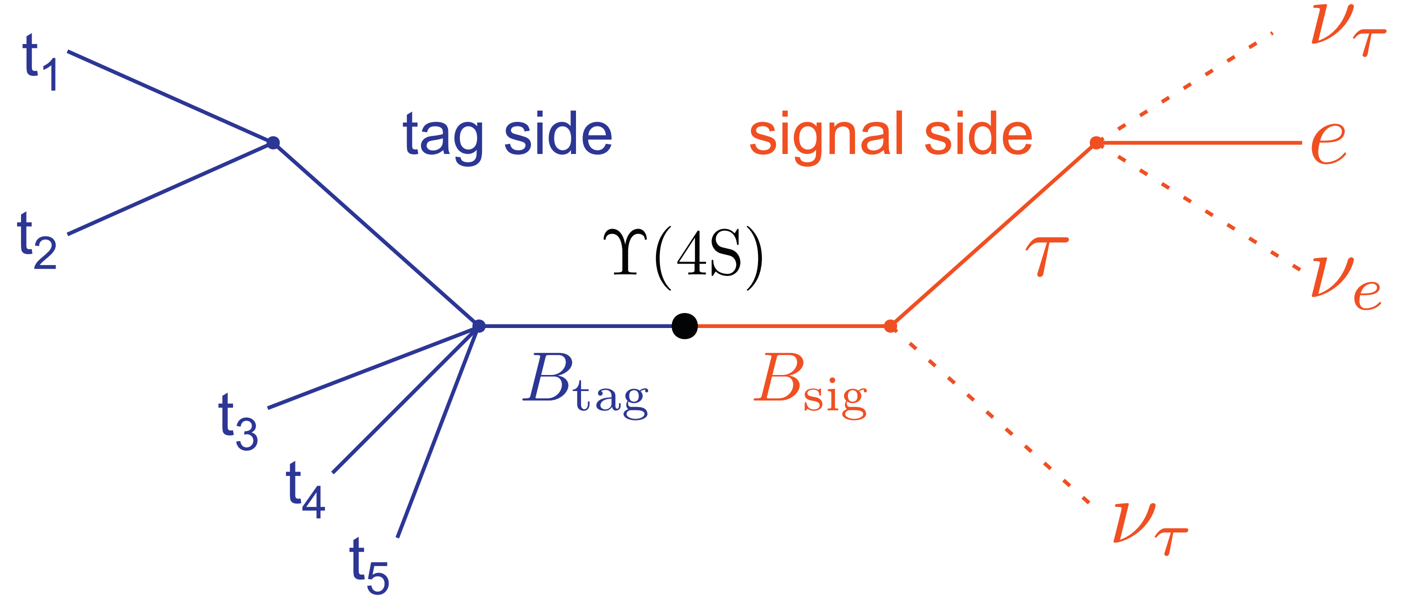
	BaBar	Belle	LHCb
#B's produced	O(400M)	O(700M)	O(800B)*
Production mechanism	$\Upsilon(4S) \to B\bar{B}$	$\Upsilon(4S) \to B\bar{B}$	$pp \to gg \to b\bar{b}$
Publications	Phys.Rev.Lett 109, 101802 (2012) Phys. Rev. D 88, 072012 (2013)	Phys.Rev.D 92, 072014 (2015) arXiv:1603.06711	Phys.Rev.Lett.115, 111803 (2015)

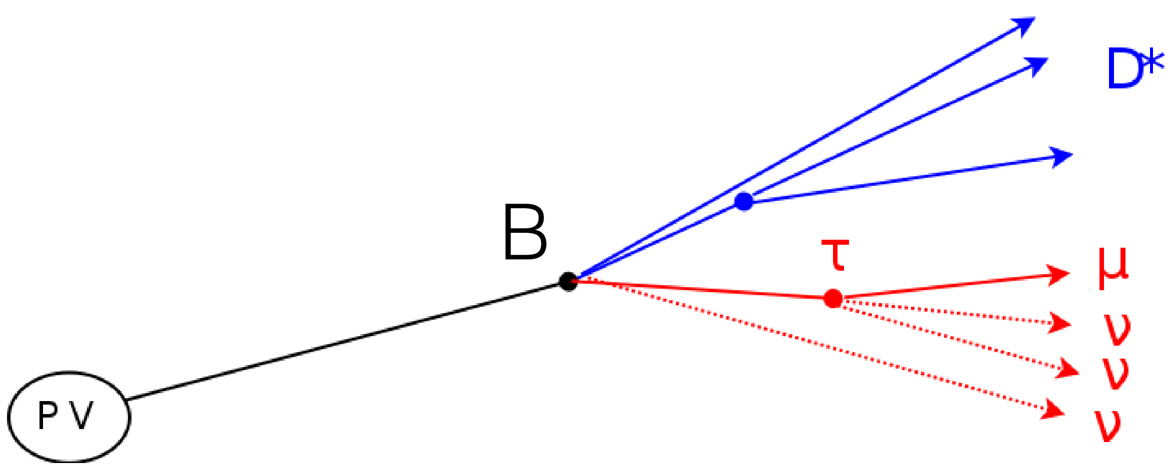
* during run 1 of the LHC

Experimental challenges

- Three neutrinos in the final state (using τ—>μνν).
  - No sharp peak to fit in any distribution.

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





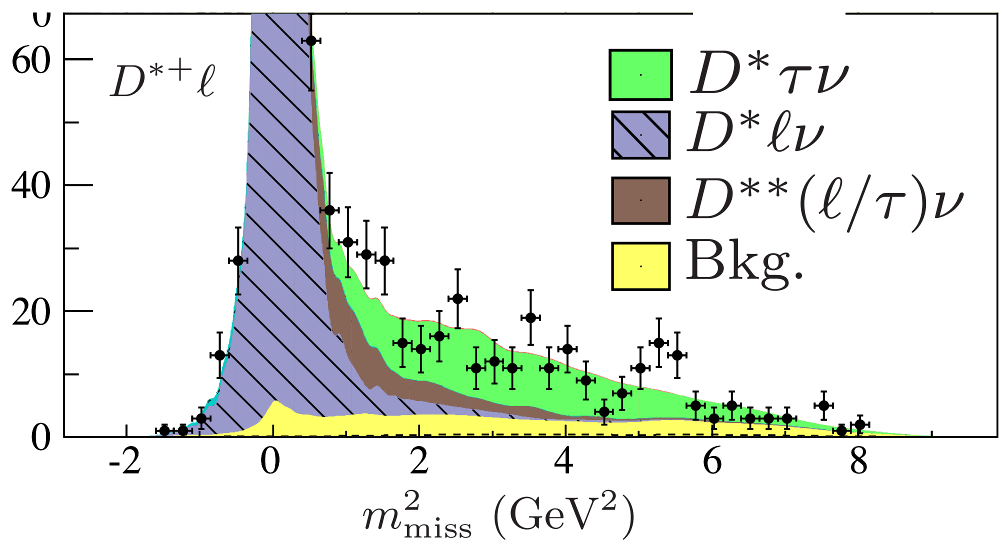
- More difficult at LHCb, compensate using large boost (flight information) and huge B production.

Signal fits

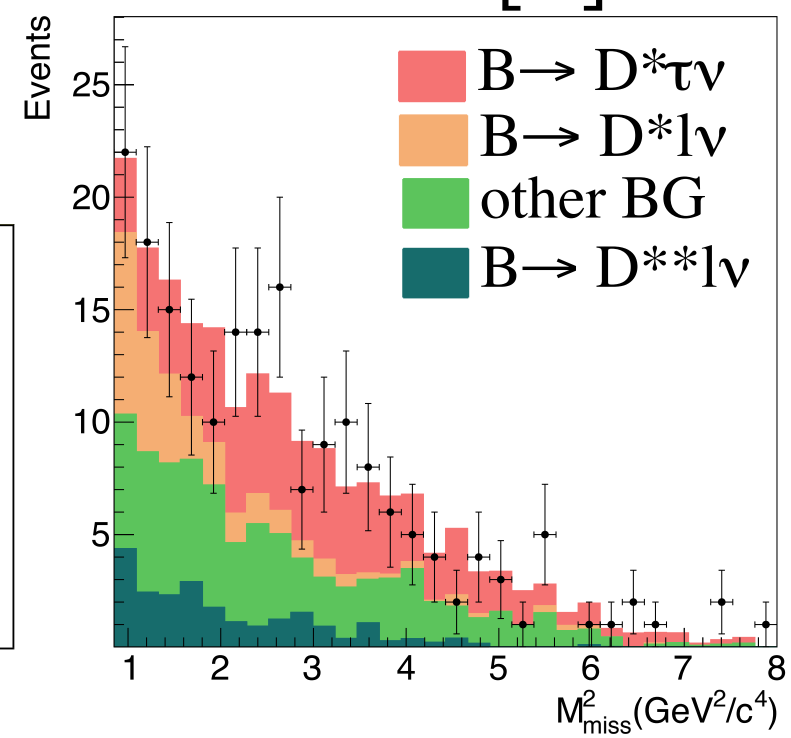
- Three main backgrounds:

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

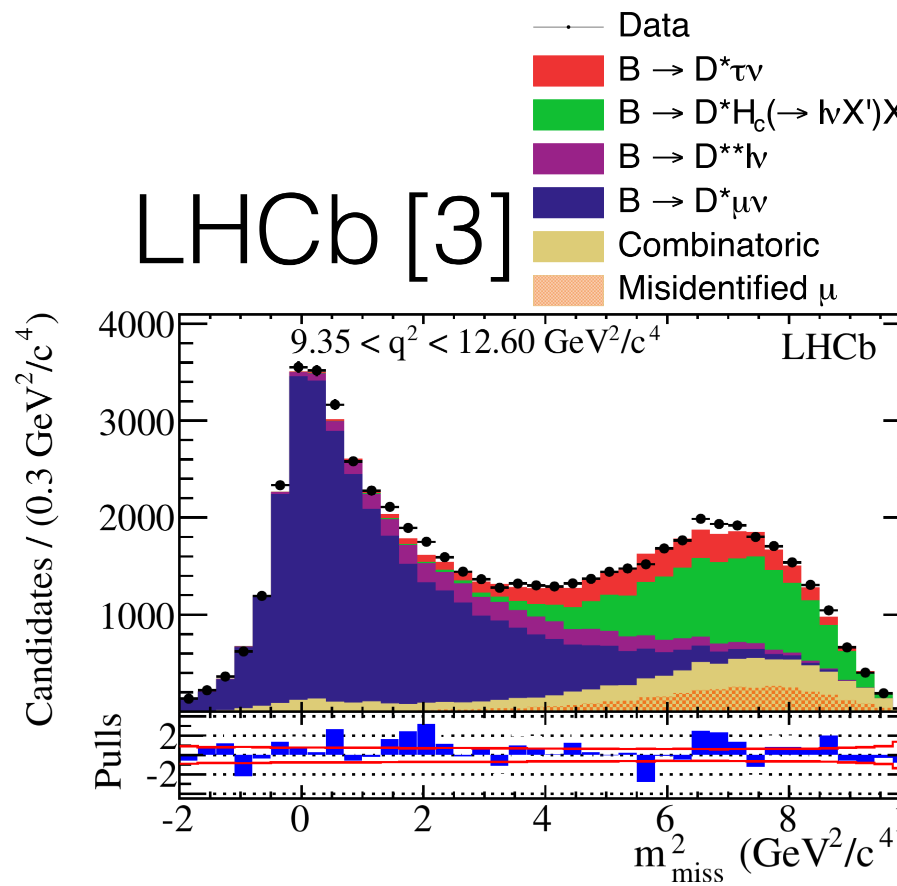
BaBar [1]



Belle [2]



LHCb [3]

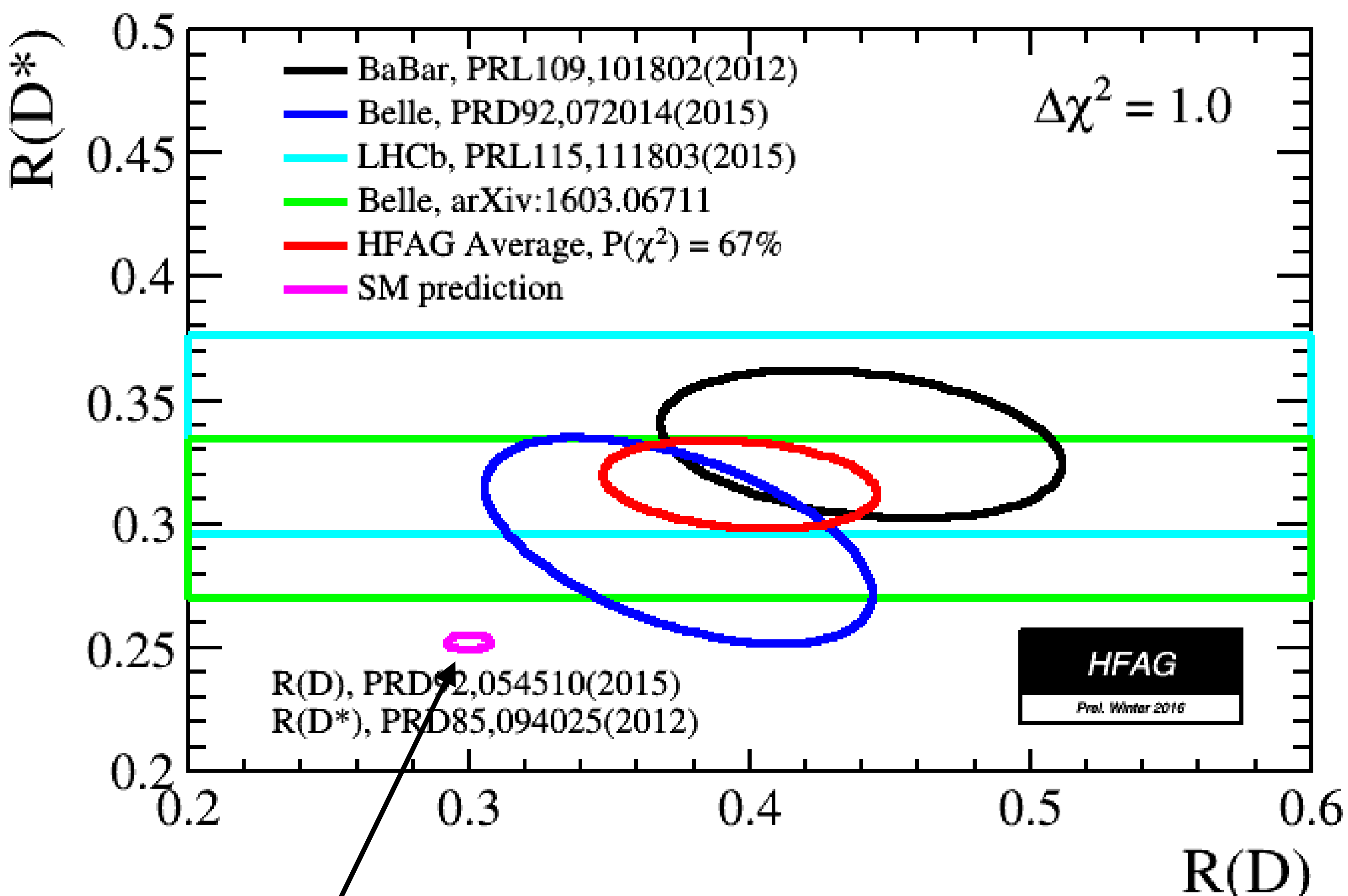


- Fit variables which discriminate between muon and tauonic mode.

[1] Phys. Rev. D 88, 072012 (2013)
[2] Phys.Rev.D 92, 072014 (2015)
[3] Phys.Rev.Lett.115, 111803 (2015)

Results

- 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)

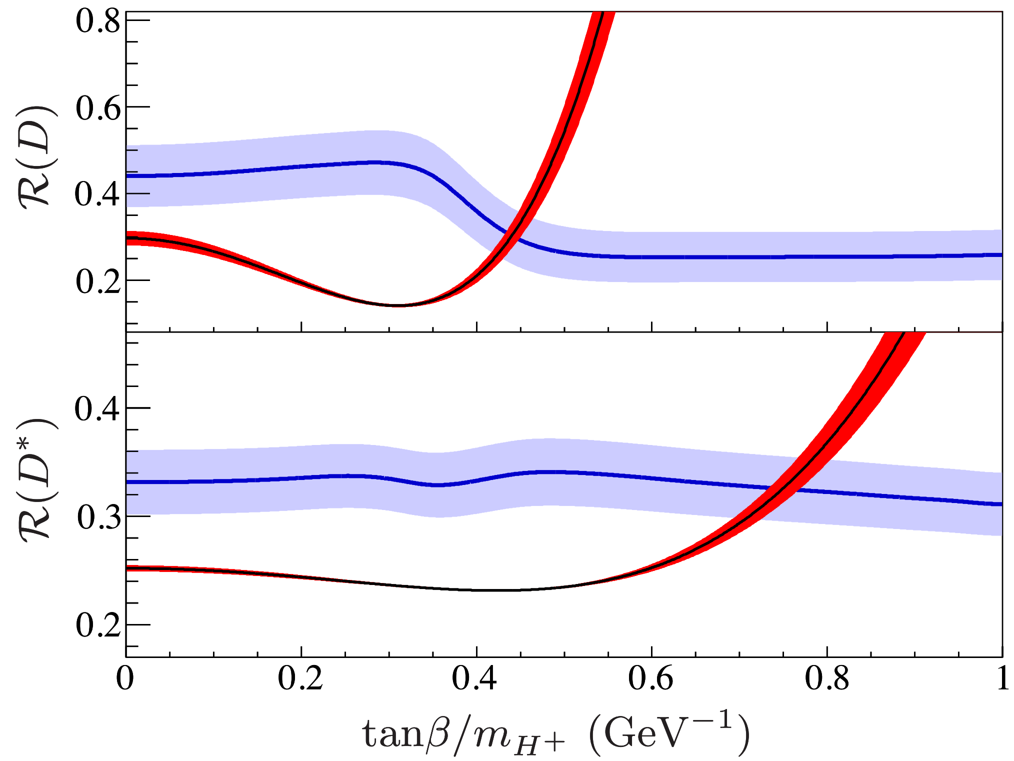
QCD uncertainties very small - unlikely to be explanation.

Latest HFAG average [1] quotes **4σ** from SM prediction

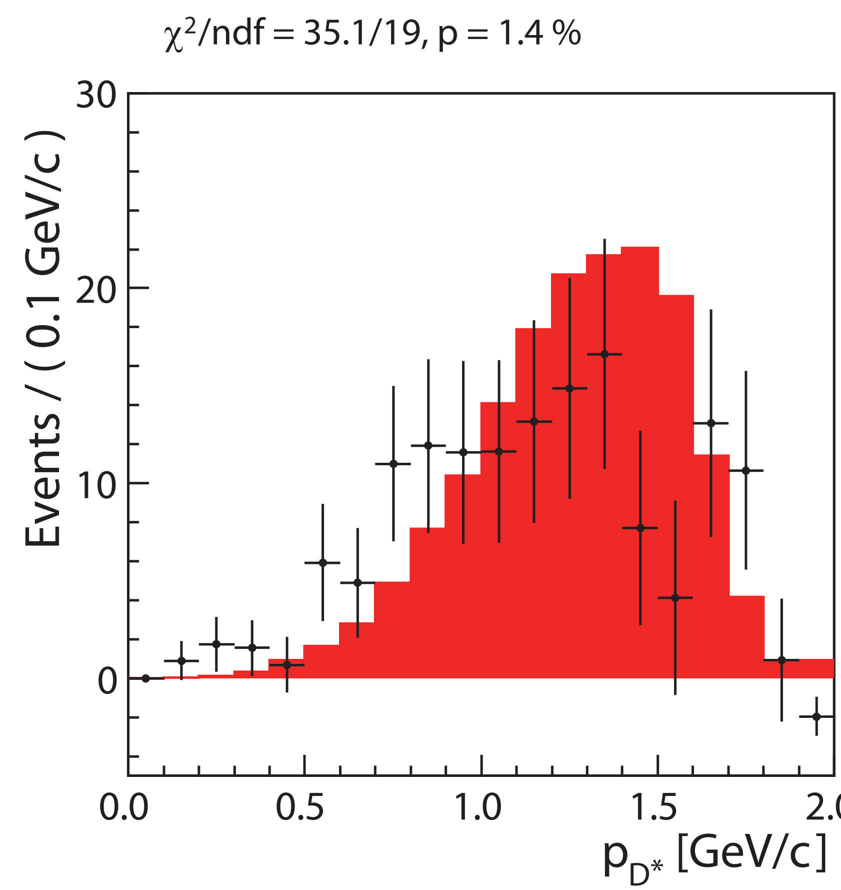
[1] http://www.slac.stanford.edu/xorg/hfag/semi/winter16/winter16_dtaunu.html

Possible NP models

Phys. Rev. D 88, 072012 (2013)



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



Phys.Rev.D 92, 072014 (2015)

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

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

Still several 2HDM models can explain it, related to H—>τμ?

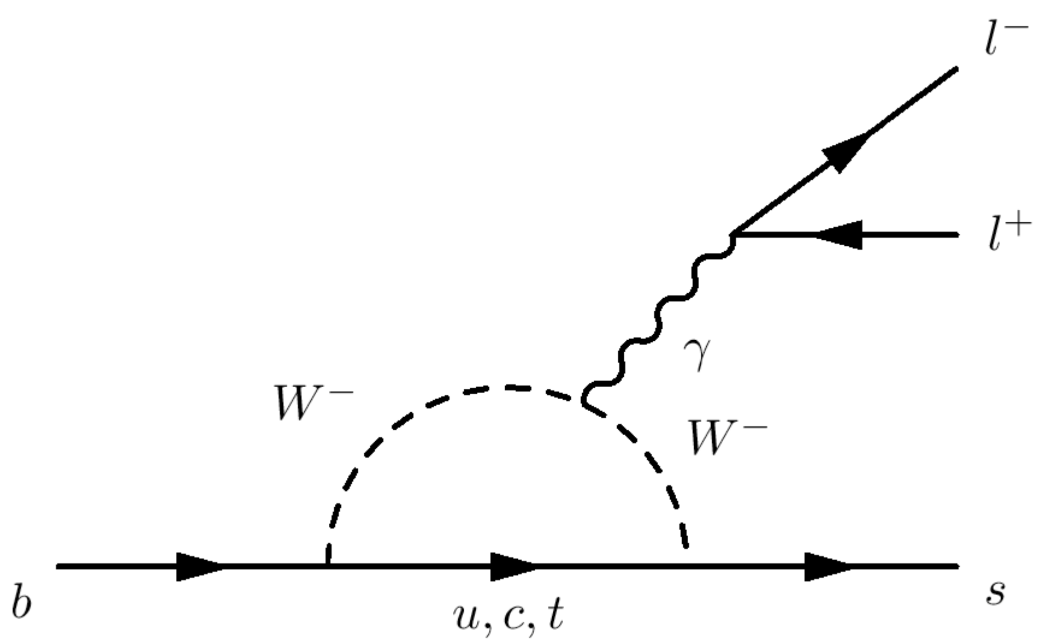
A. Crivellin, J. Heeck, P. Stoffer, Phys. Rev. Lett. 116, 081801 (2016)

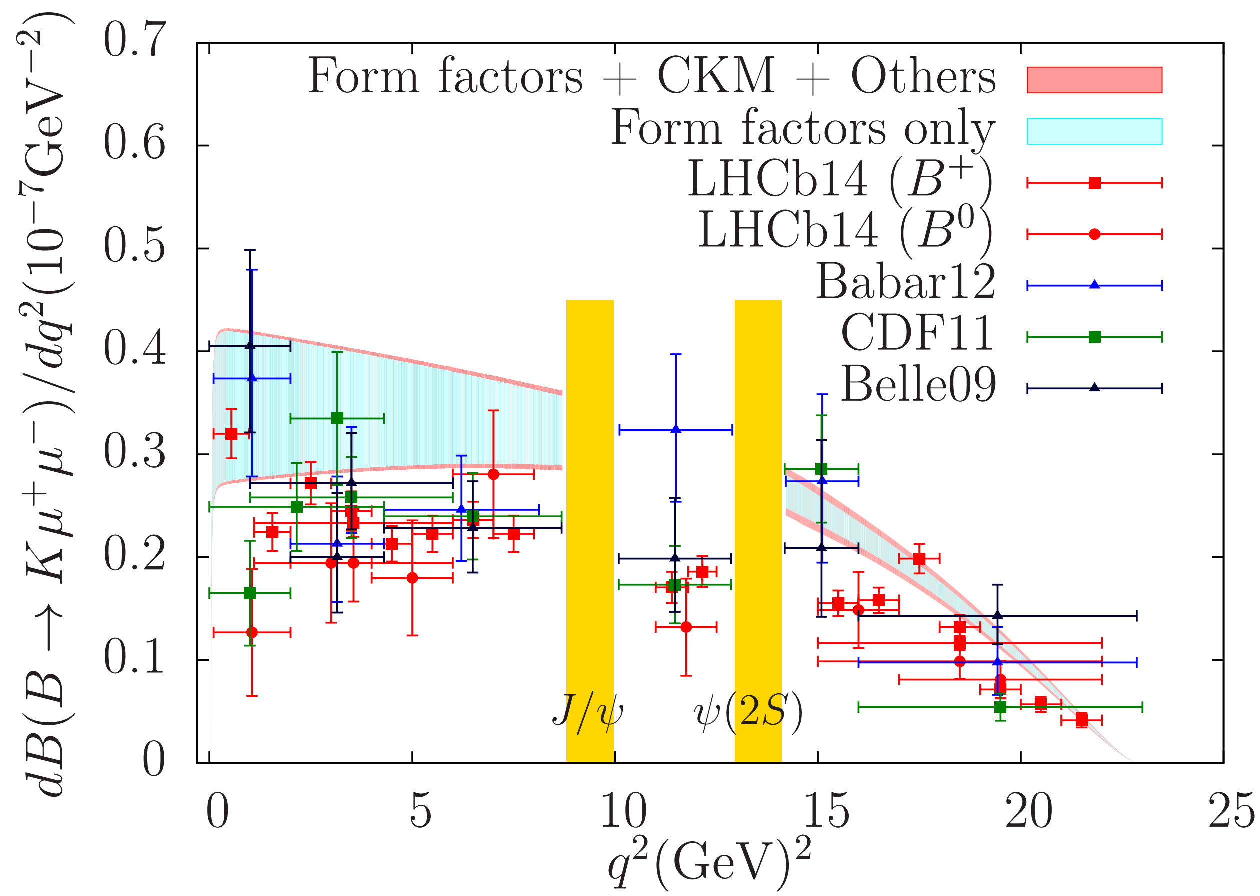
Anomaly #2

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

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

- The decay $B^+ \to K^+\ell^+\ell^-$ is a semileptonic b—>s transistion.





Fermilab Lattice and MILC, Phys. Rev. D 93, 034005 (2016)

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

- 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

- Most precise measurement from LHCb.
- Electrons difficult due to Bremsstrahlung.
- If miss one of two hadrons, known as ‘partially reconstructed’ background.

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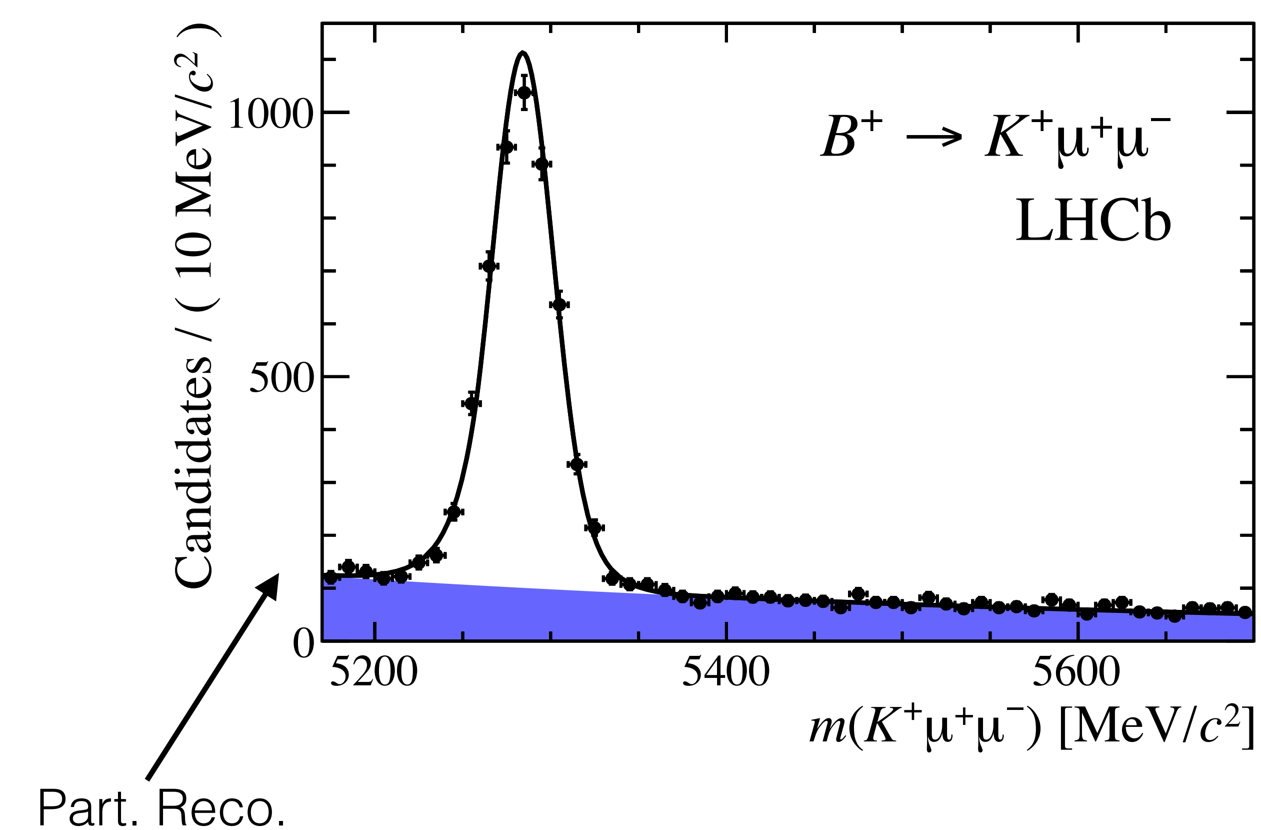
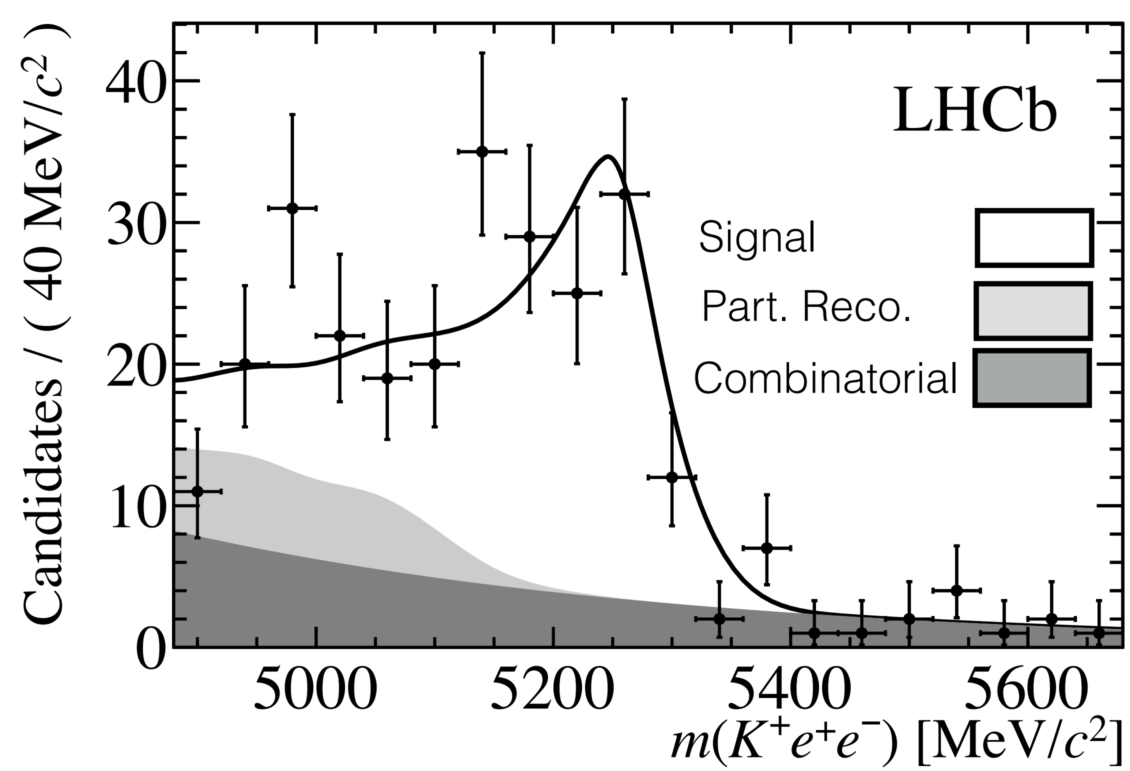


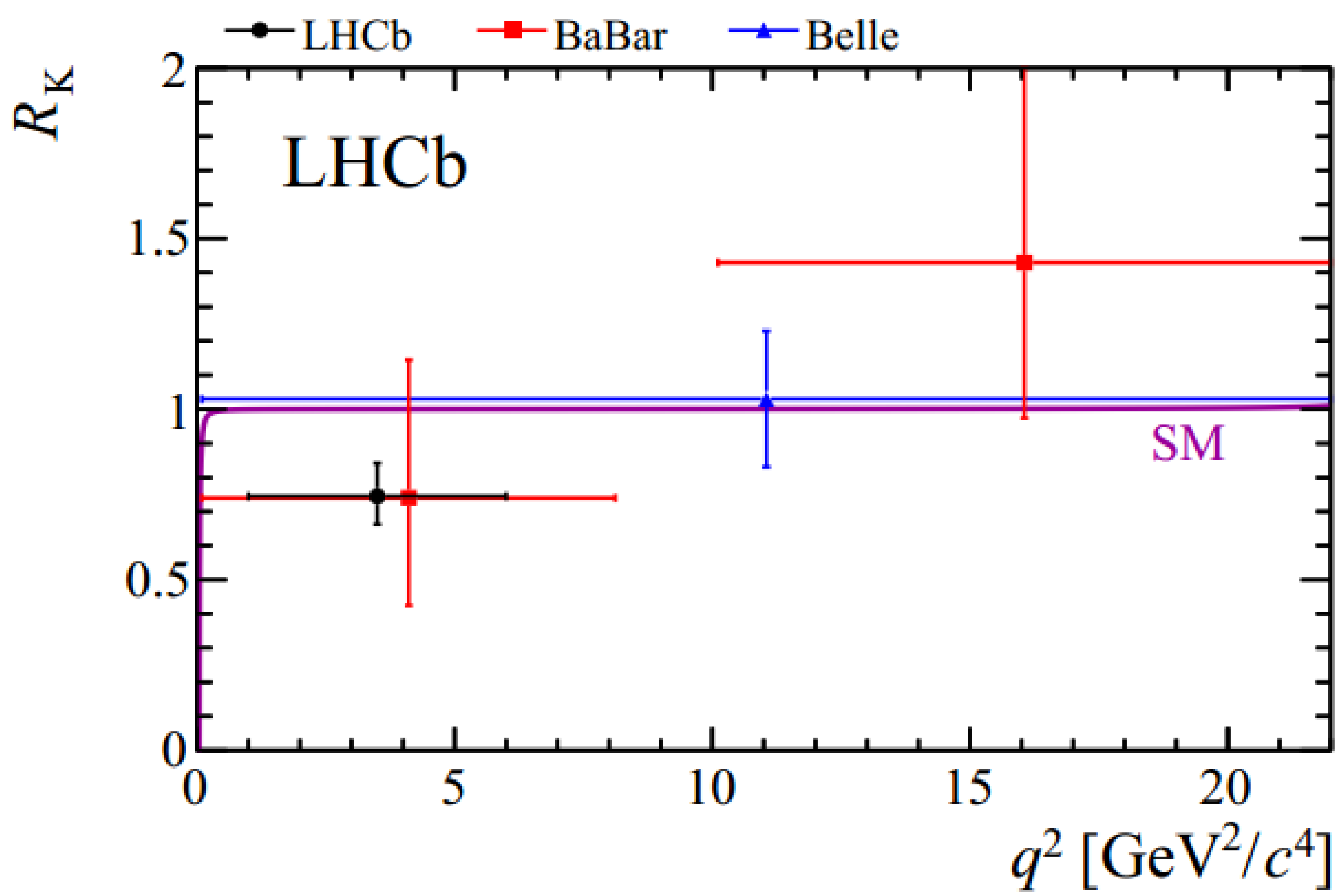
Phys. Rev. Lett. 113, 151601 (2014)



Result

- Take ratio of signal yields and correct for efficiency to get R_K[1].

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



LHCb: Phys. Rev. Lett. 113, 151601 (2014)
BaBar: Phys. Rev. D 86,032012 (2012)
Belle: Phys. Rev. Lett. 103,171801 (2009)

- LHCb result is 2.6σ from the SM prediction of unity.

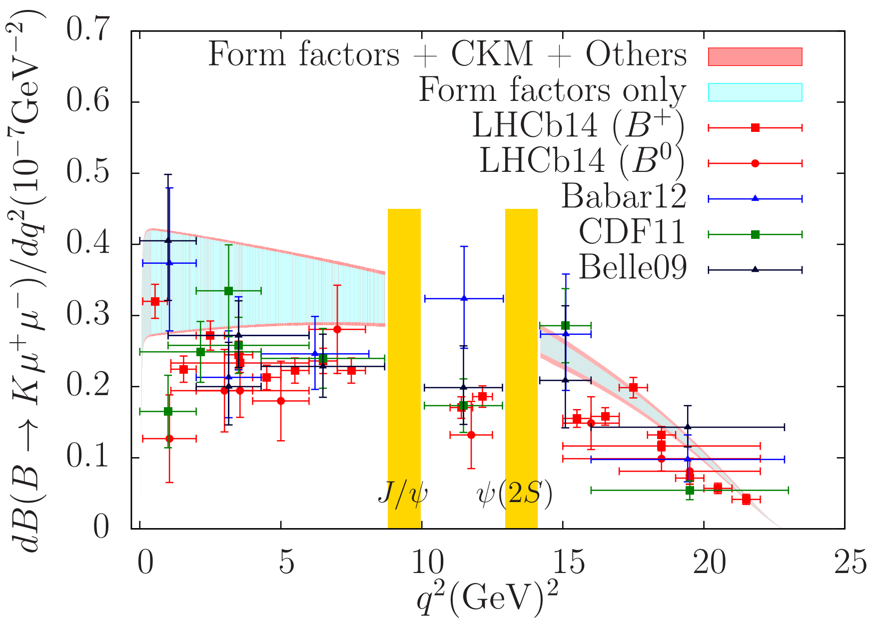
[1]We take double ratio with J/ψ control channels to further cancel systematic uncertainties.

Remarks

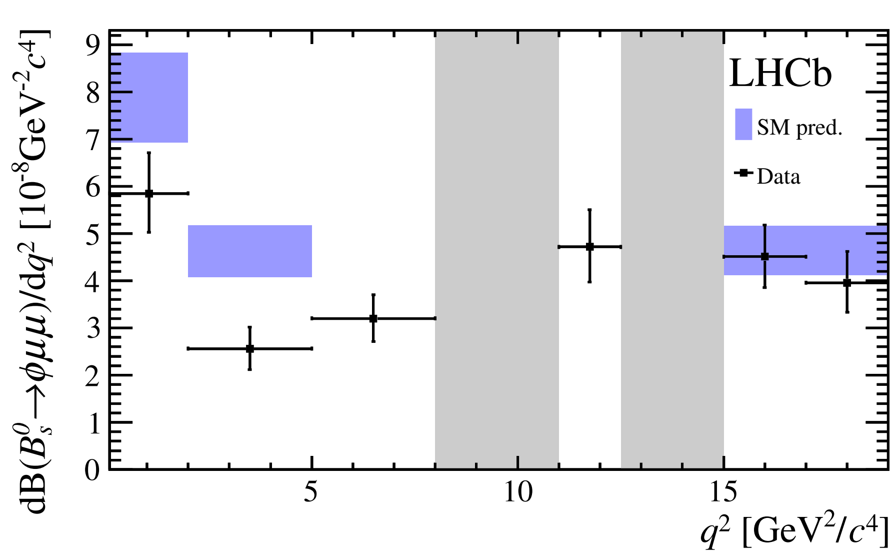
- All of the muonic b—>sll branching fractions tend to be below the SM prediction.

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

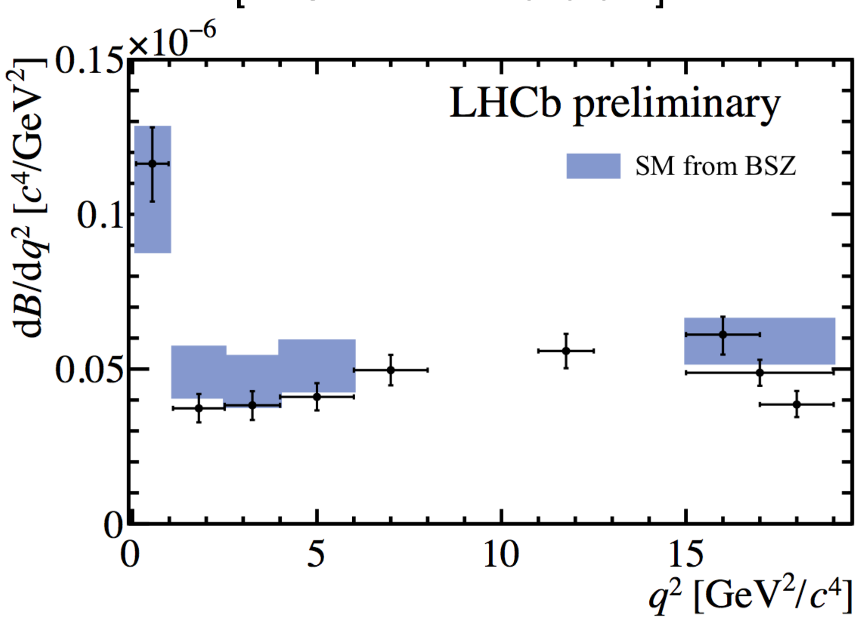
FNAL/MILC, Phys. Rev. D 93, 034005 (2016)



JHEP 09 179 (2015)



[LHCb-PAPER-2016-012]



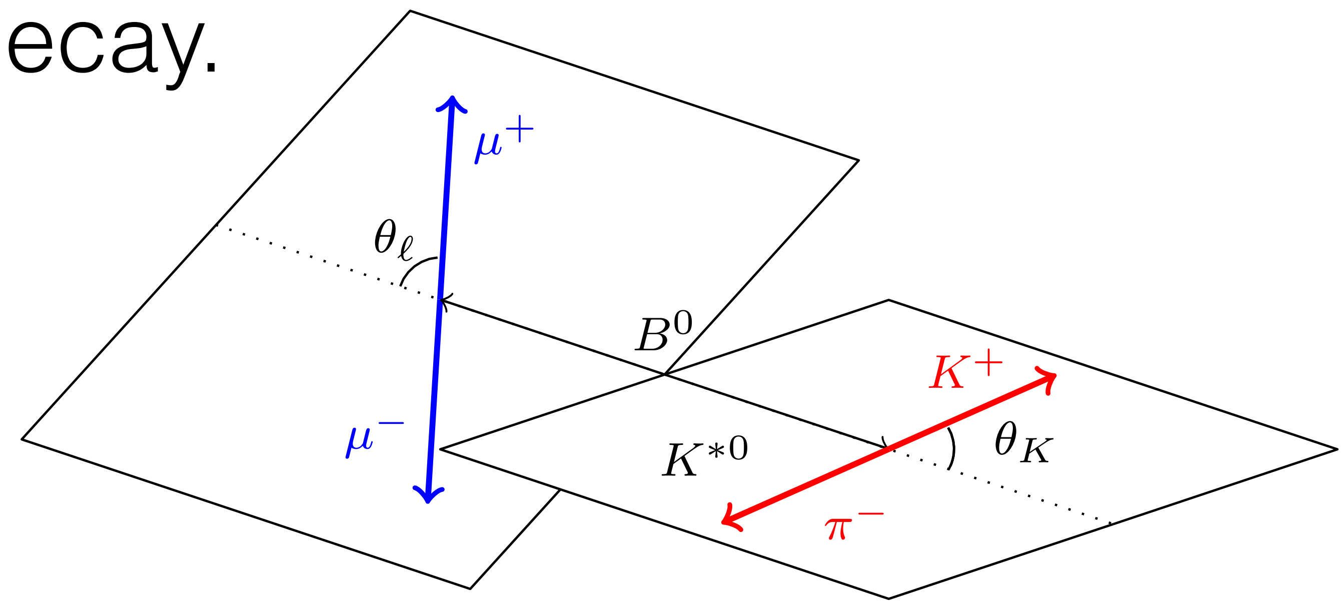
- Its not particularly significant, but at least things are consistent, and that's before anomaly #3 …

Anomaly #3

$$P_5' = \sqrt{2}\,\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_\parallel|^2)}}$$

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.

$$P_5' = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_{||}|^2)}}$$

Results

- Measure 15 observables, most consistent with SM.
- One particular one, P_5' shows a significant discrepancy.

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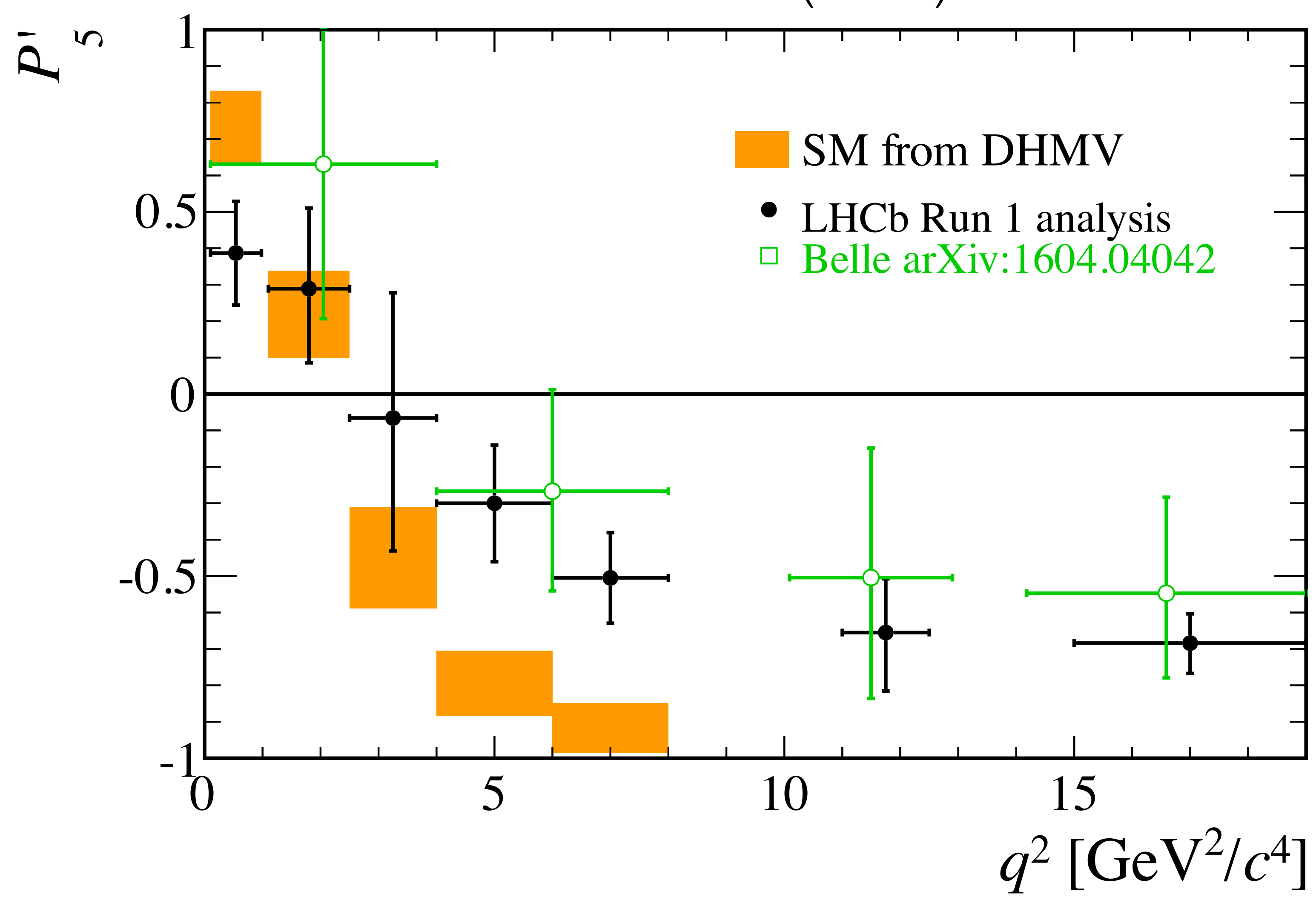
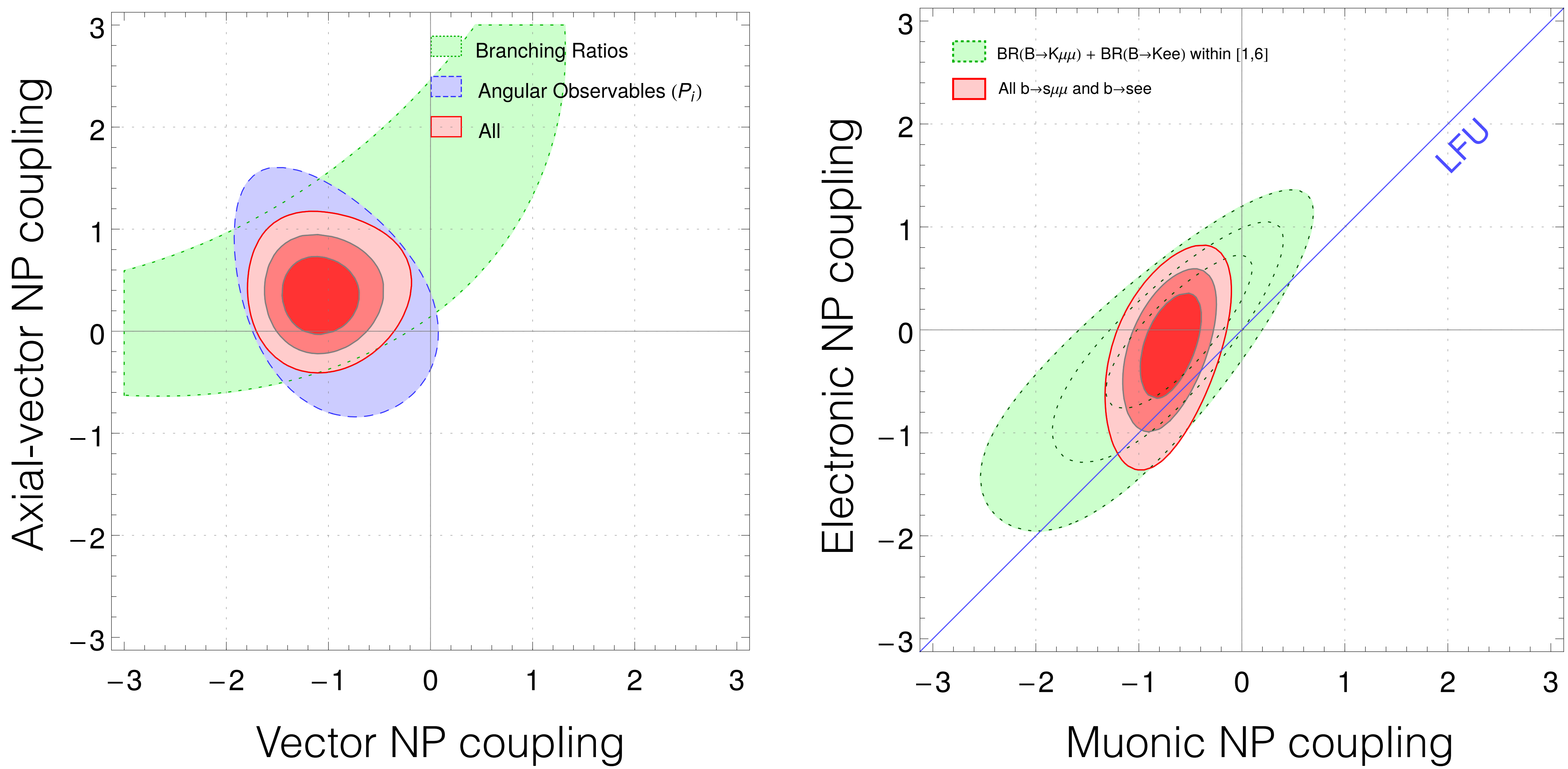


- Residual uncertainties under debate (see discussion session).

Interpretation

- Global fits say purely vector contribution is destructively interfering with penguin diagram can cause such a discrepancy.

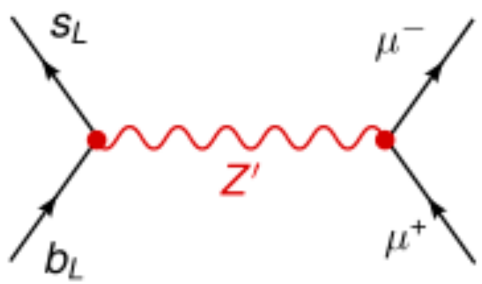
  - This matches with low BFs and R_K.



Descotes-Genon, Hofer, Matias, Virto, arXiv:1510.04239
(consistent results found by Altmannshofer, Straub, arXiv:1411.3161)

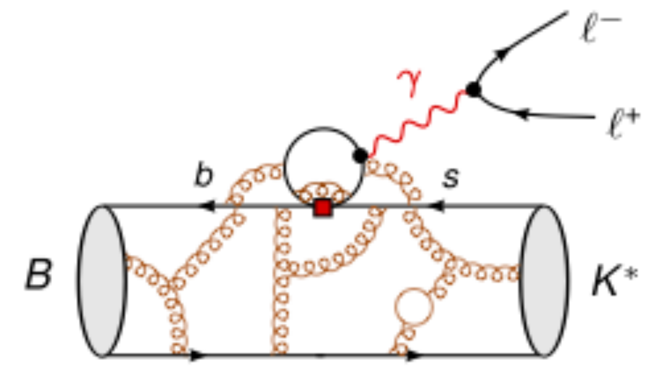
But is it QCD or NP?

Optimist's view point



Vector-like contribution could come from new tree level contribution from a Z' with a mass of a few TeV (the Z' will also contribute to mixing, a challenge for model builders)

Pessimist's view point

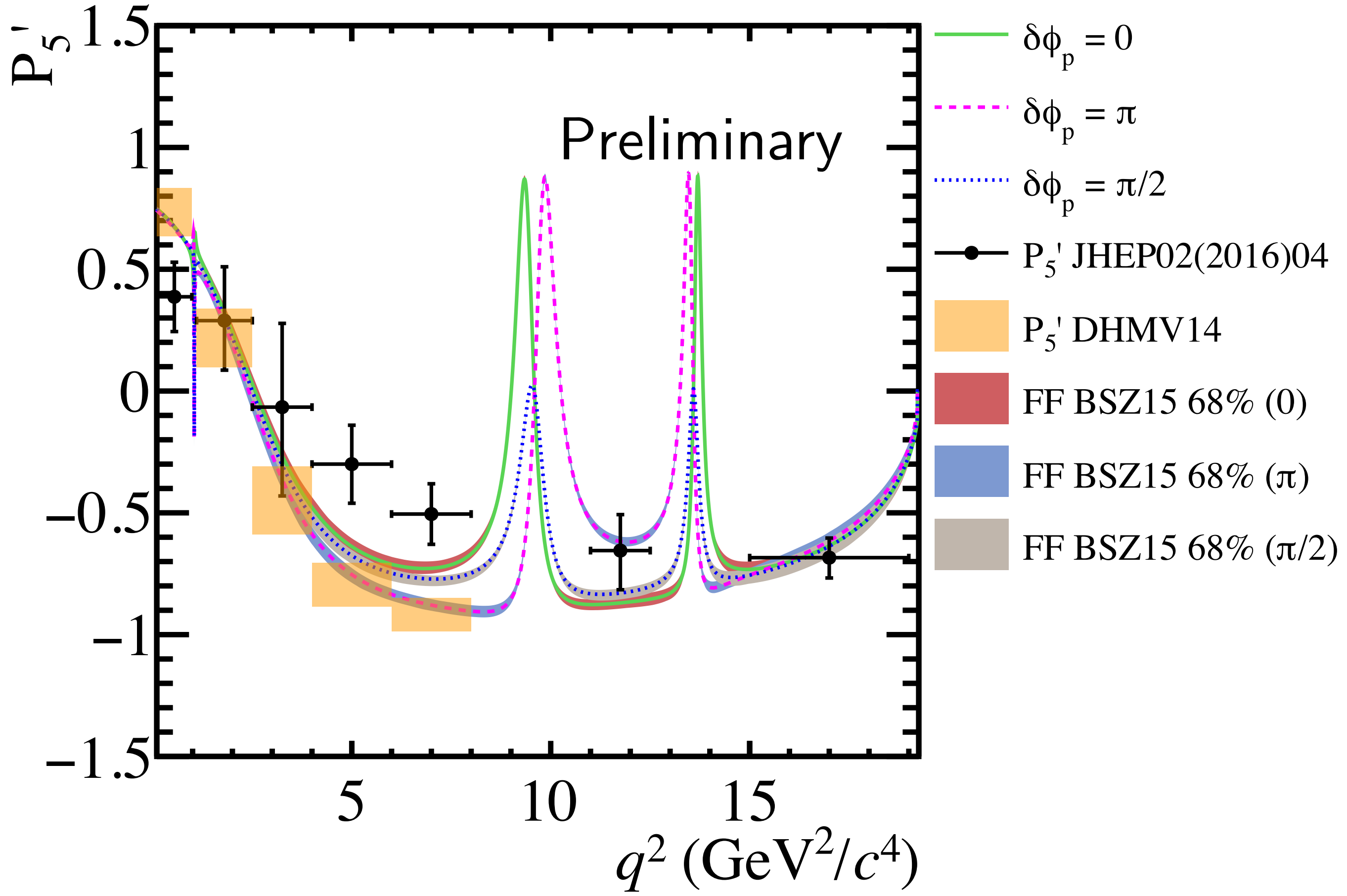


Vector-like contribution could point to a problem with our understanding of QCD, e.g. are we correctly estimating the contribution for charm loops that produce dimuon pairs via a virtual photon.

- Related to how factorisable b—>sll diagrams are, more on this in the discussion session …

Propsect for controlling charm

- Charm contribution dominated by J/ψ resonance.
- Size known but phase w.r.t. penguin not.



- Can have significant effect on predictions

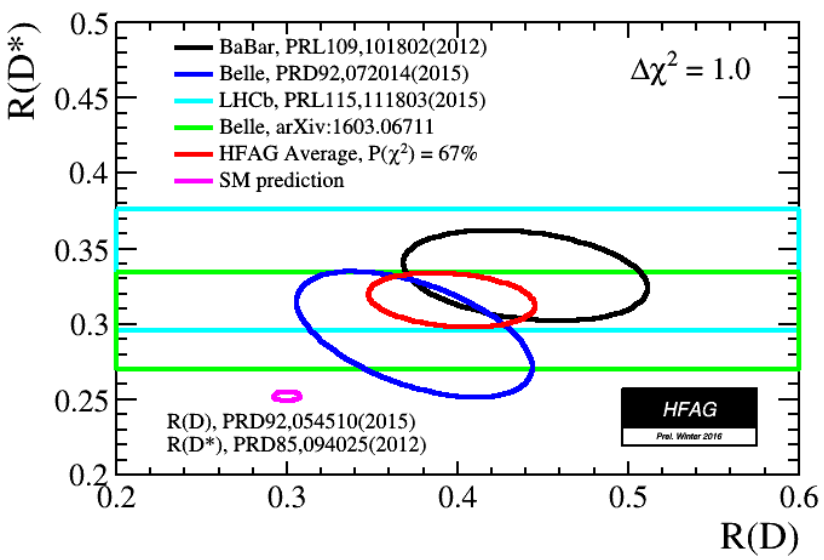
- We plan to fit for this phase using our data (see K. Petridis talk [here]).

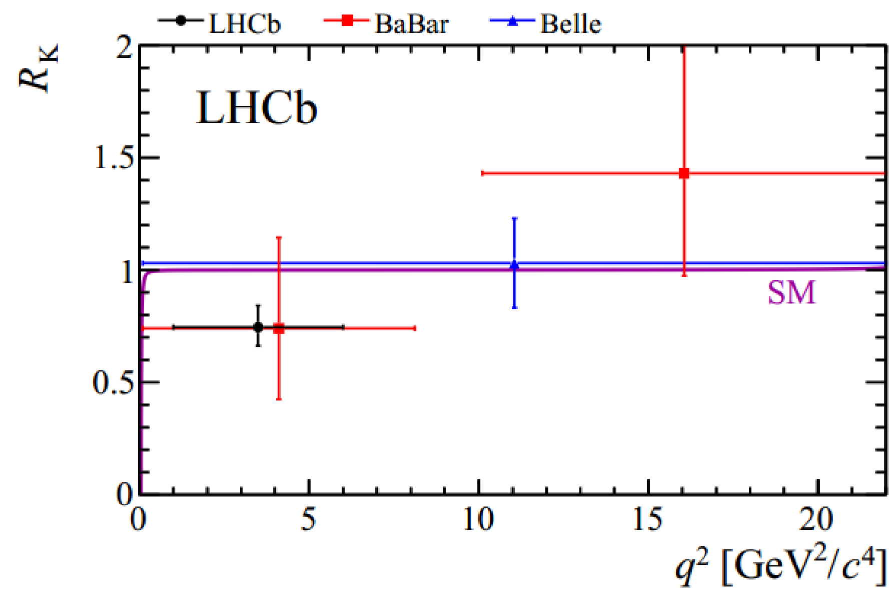
Summary and outlook

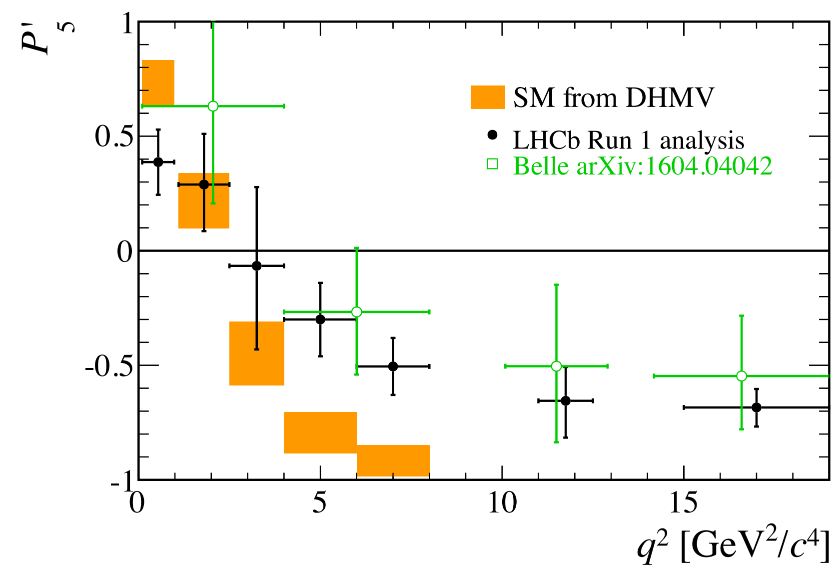
- The Higgs sector and b-physics are inexorably intertwined.
  - Not only is SM flavour violation due to the Higgs, but b-physics in particular is sensitive to Higgs extensions.
- Always fight QCD when searching for NP in these decays.
- Control this by
  - Looking at semi-leptonic decays (factorisation)
  - Measuring ratios of observables (LFU, angular analysis).

Summary and outlook

- I discussed three anomalies in these decays.







- Can have models which link all of these: **L. Calibbi, A.Crivellin. and T. Ota, PRL, arXiv:1506.02661**

- Updates from LHCb are coming soon so there's no point in getting too excited yet.

    - Expect improved precision on R(D*,D0), R(K).

    - Expect new LFU tests like R(K*) soon and improvements to R(K).

    - Plan to use data to control hadronic uncertainties in P_5'.

Back-ups

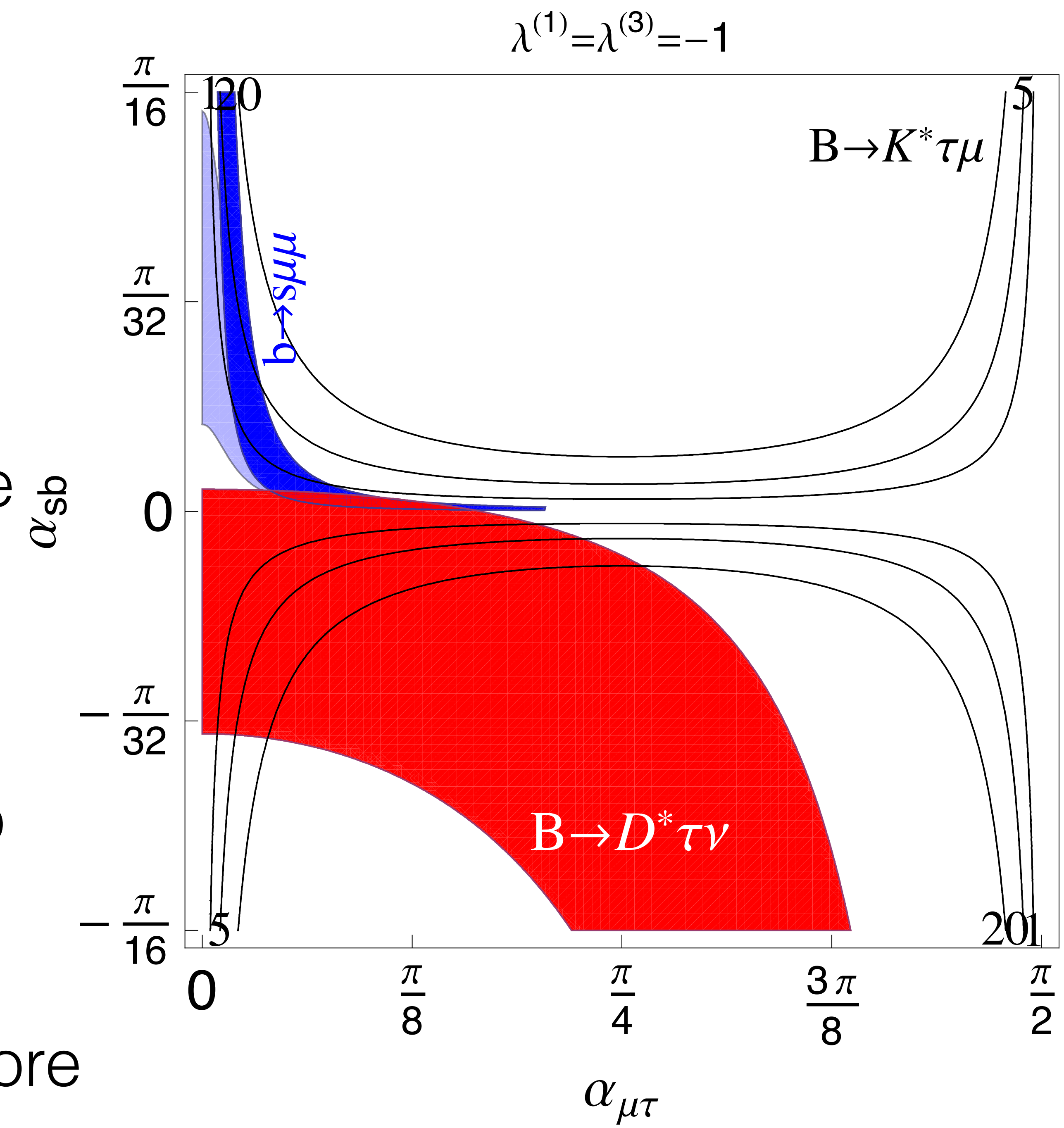
Linking with R(D*)

- There are models which can link these anomalies together.

e.g. Tree level lepto-quark with large couplings to third generation.

α_{ab} parameters proportional ratio of NP coupling between fields a and b

Will these anomalies hold up with more data?



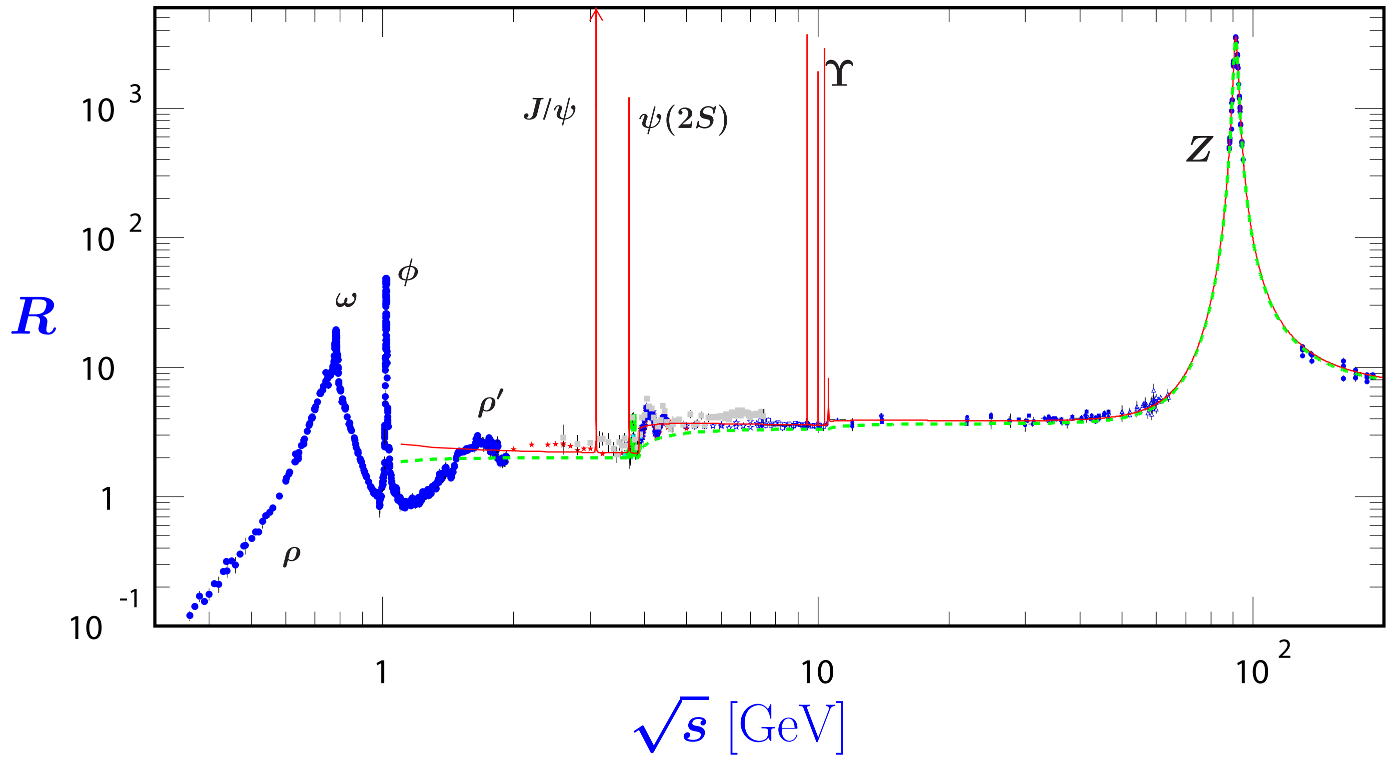
L. Calibbi, A.Crivellin. and T. Ota, PRL, arXiv:1506.02661

Quark hadron duality

- Theoretical calculations live in the partonic world.

- To translate this to reality, rely on quark-hadron duality.

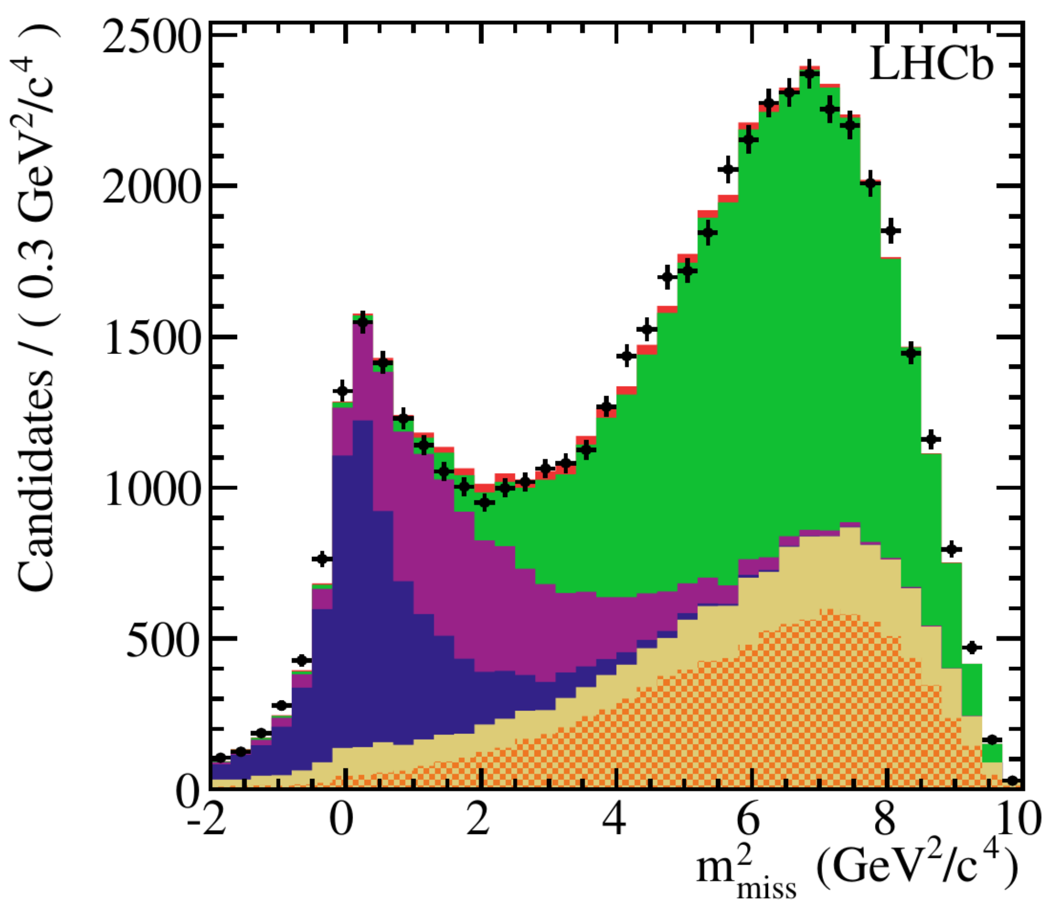
$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

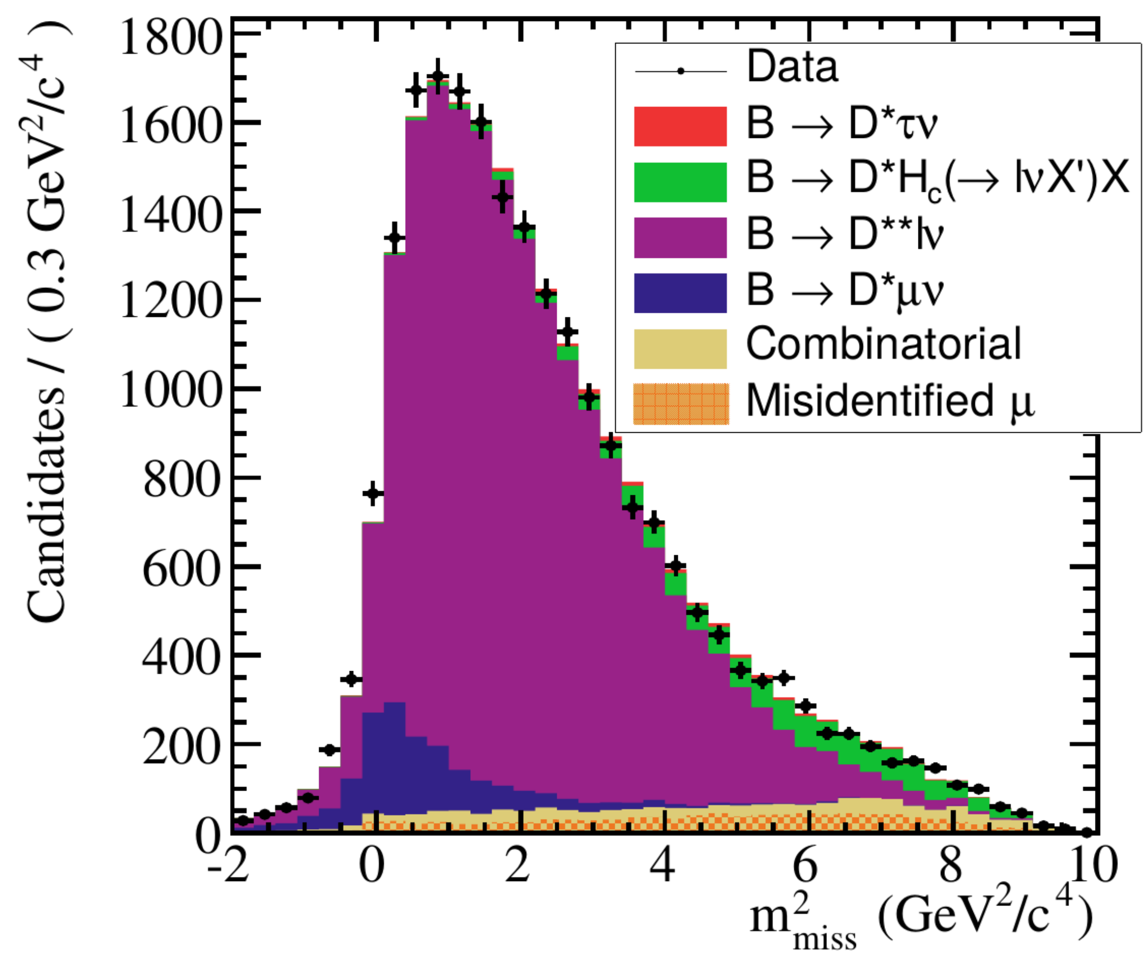


- Important not to mix the two!

R(D*) control samples

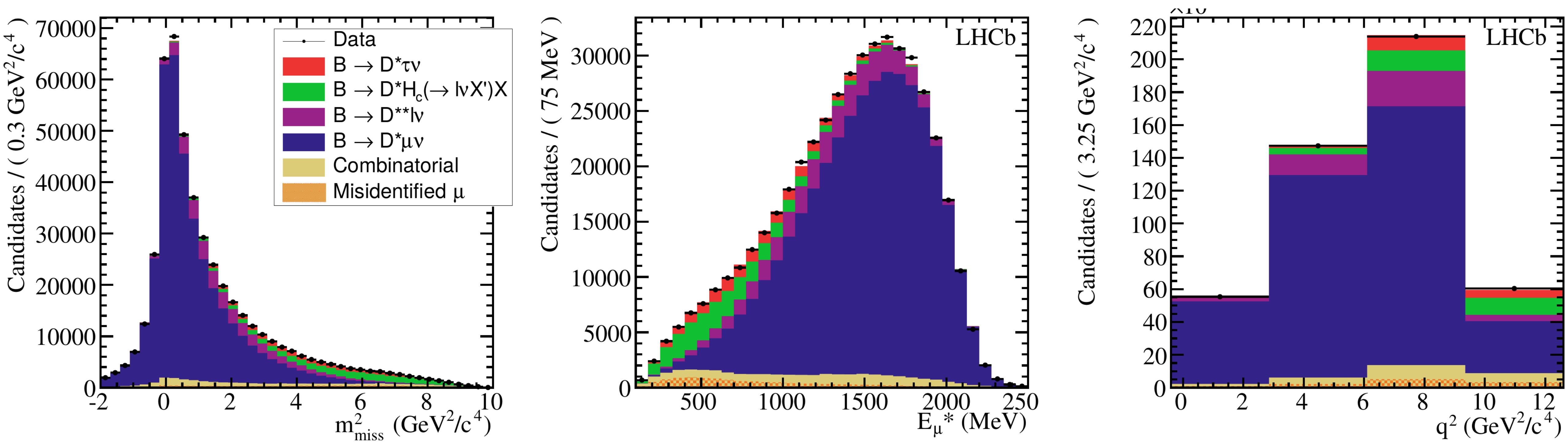
Anti-isolate signal to enrich particular backgrounds.





R(D*) 3D fit

3D fit used to discriminate signal from backgrounds



Good agreement seen everywhere

K*mm decay distribution

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

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