Flavor Anomalies
on the Eve of the Run-2 Verdict

Diego Guadagnoli
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Flavor anomalies

⓿ ***A first qualitative observation***

A whole range of $b \to s$ measurements involving a $\mu\mu$ pair display a consistent pattern:
Exp < SM

Flavor anomalies

LHCb 2014

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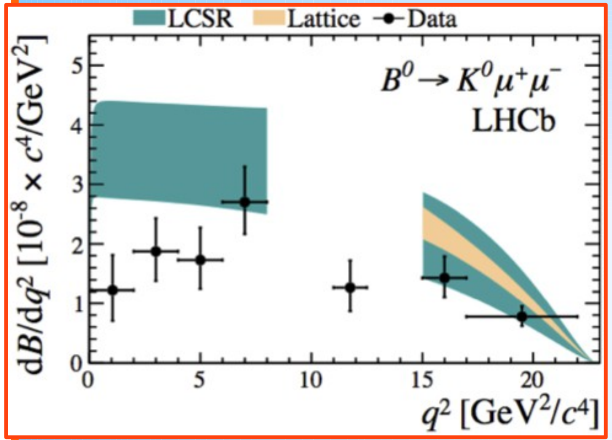

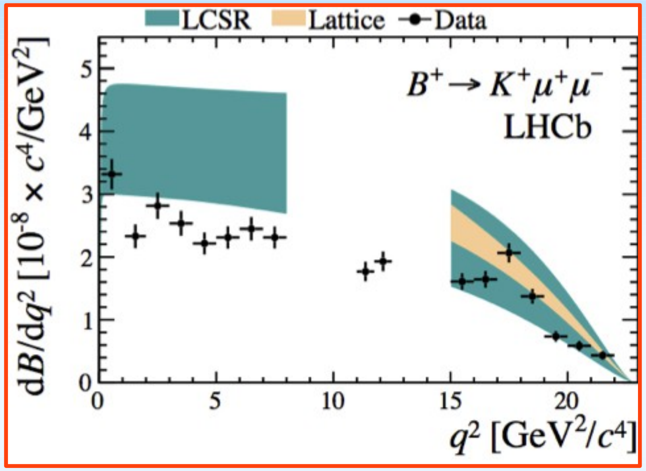

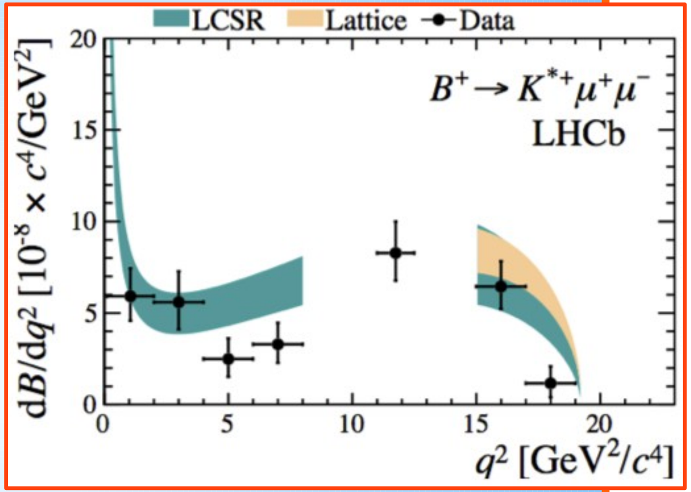

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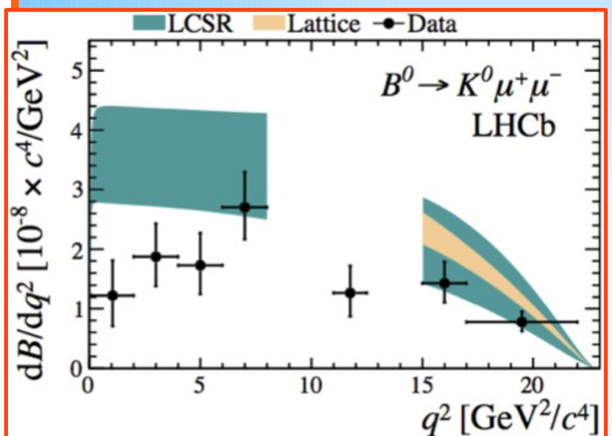
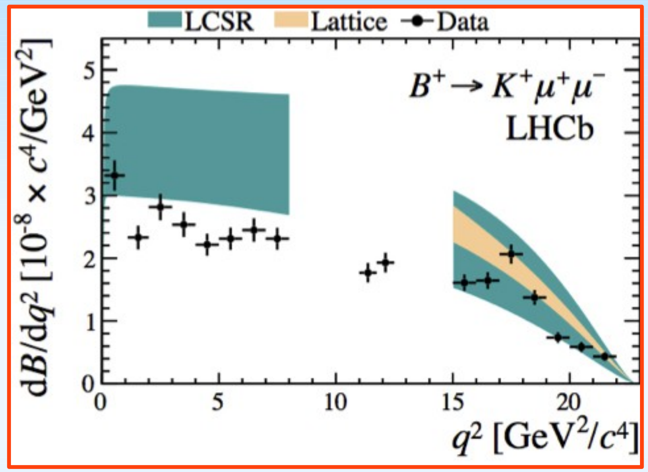
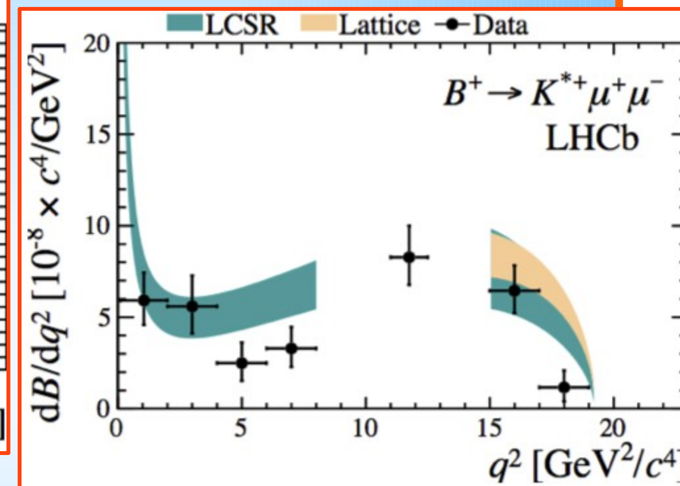
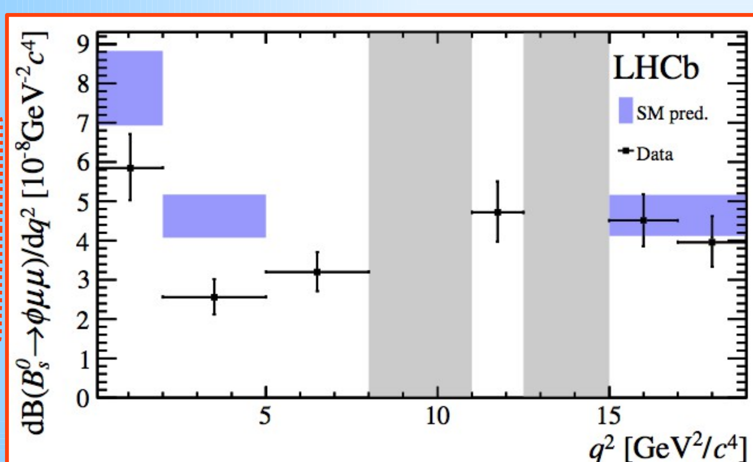
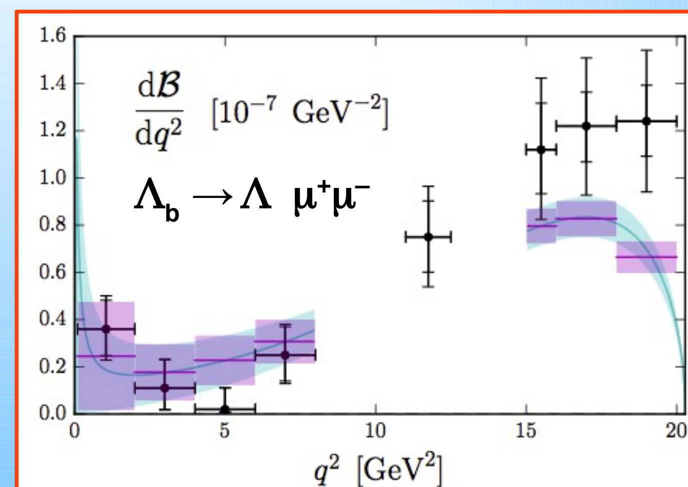






LHCb 2015





LHCb 2015 & Detmold+Meinel '16

b → s data

We know that BR measurements suffer from large f.f. uncertainties.
However, here's a clean quantity:

❶ $$R_K(q^2_{\rm min}, q^2_{\rm max}) \equiv \frac{BR(B^+ \to K^+ \mu\mu)}{BR(B^+ \to K^+ e\, e)}\Bigg|_{[q^2_{\rm min}, q^2_{\rm max}]}$$

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- *the electron channel would be an obvious culprit (brems + low stats).*
  But disagreement is rather in muons
- *muons are among the most reliable objects within LHCb*

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❹ ***$B \to K^*\ \mu\mu$ angular analysis:*** *discrepancy in one combination of the angular expansion coefficients, known as P'_5*

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B → K* μμ angular analysis:
The P'_5 anomaly

- *From LHCb's full angular analysis of the decay products in B → K* μμ, one can construct observables with limited sensitivity to form factors.*

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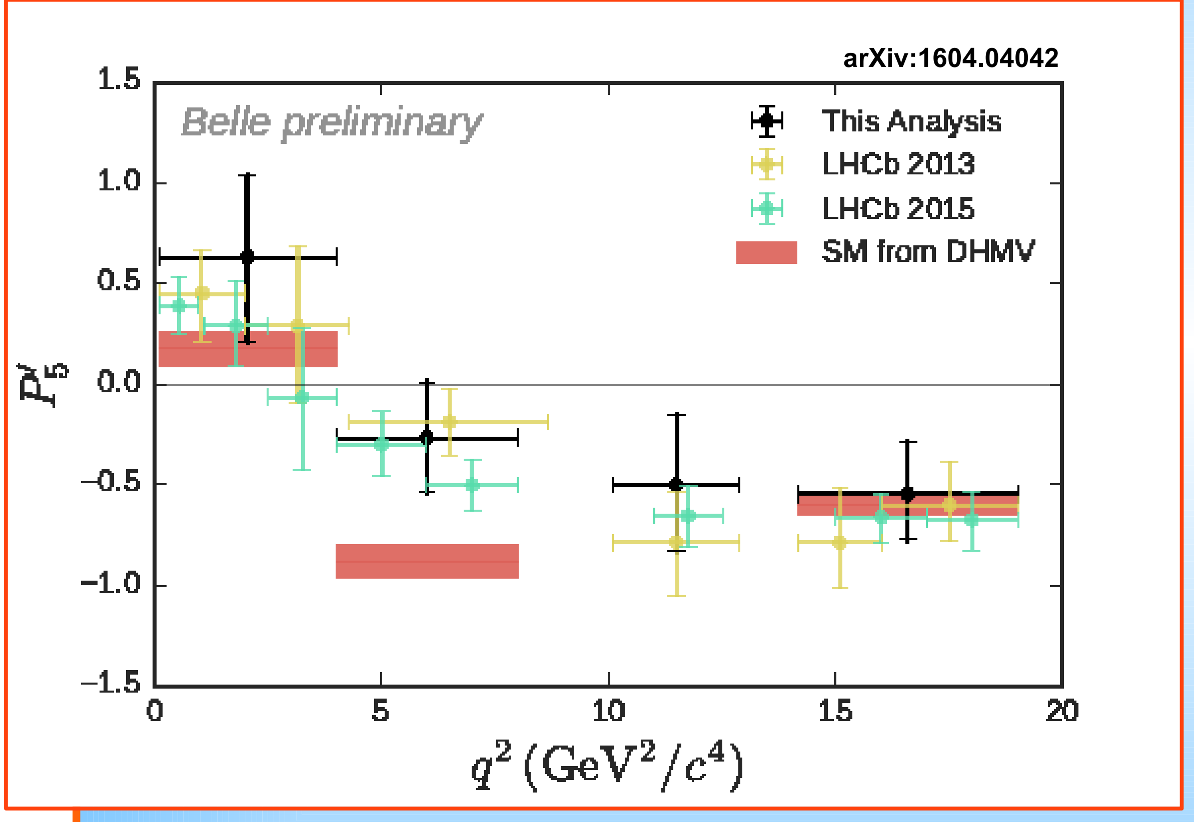

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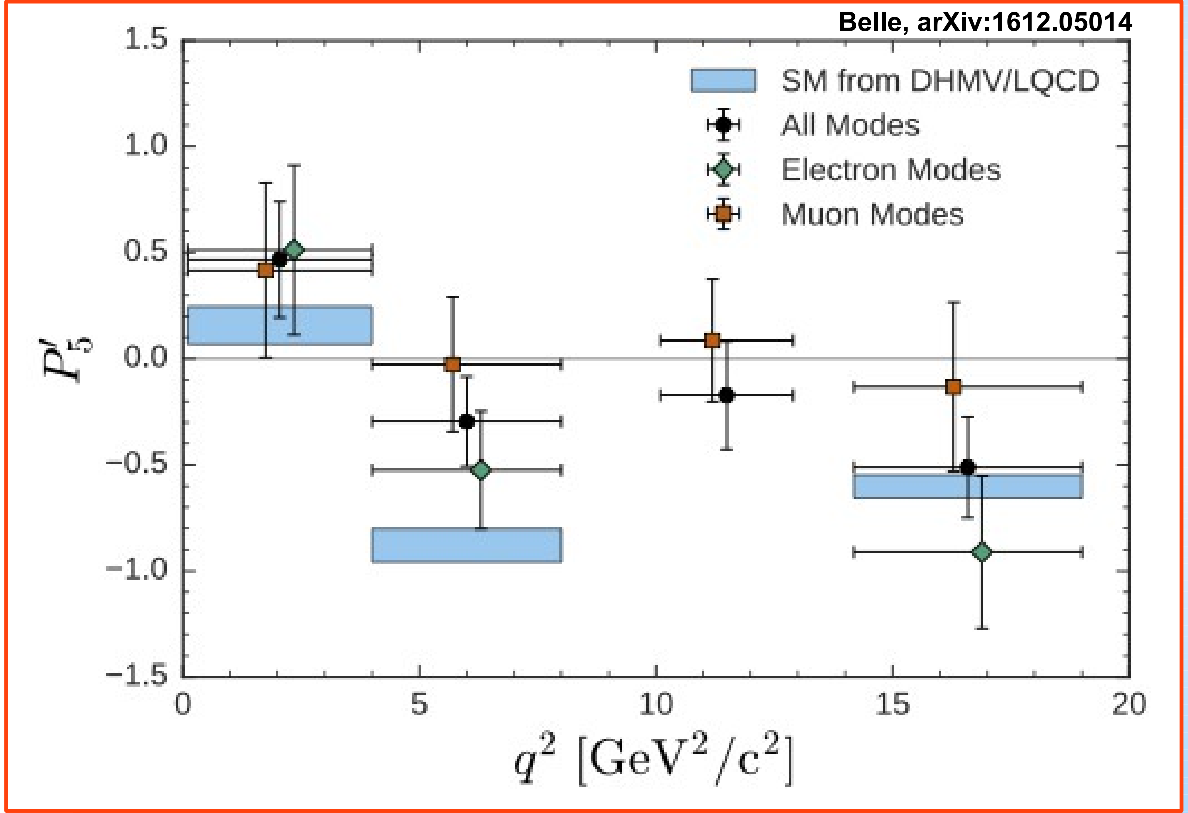

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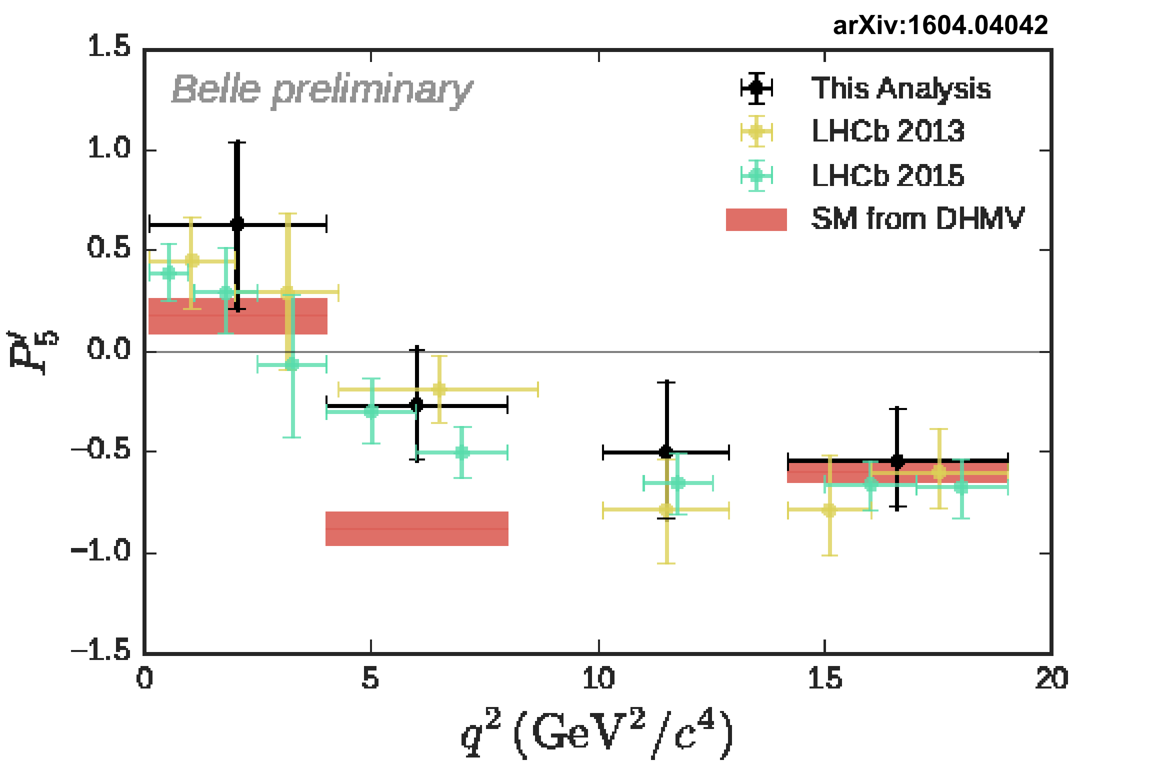

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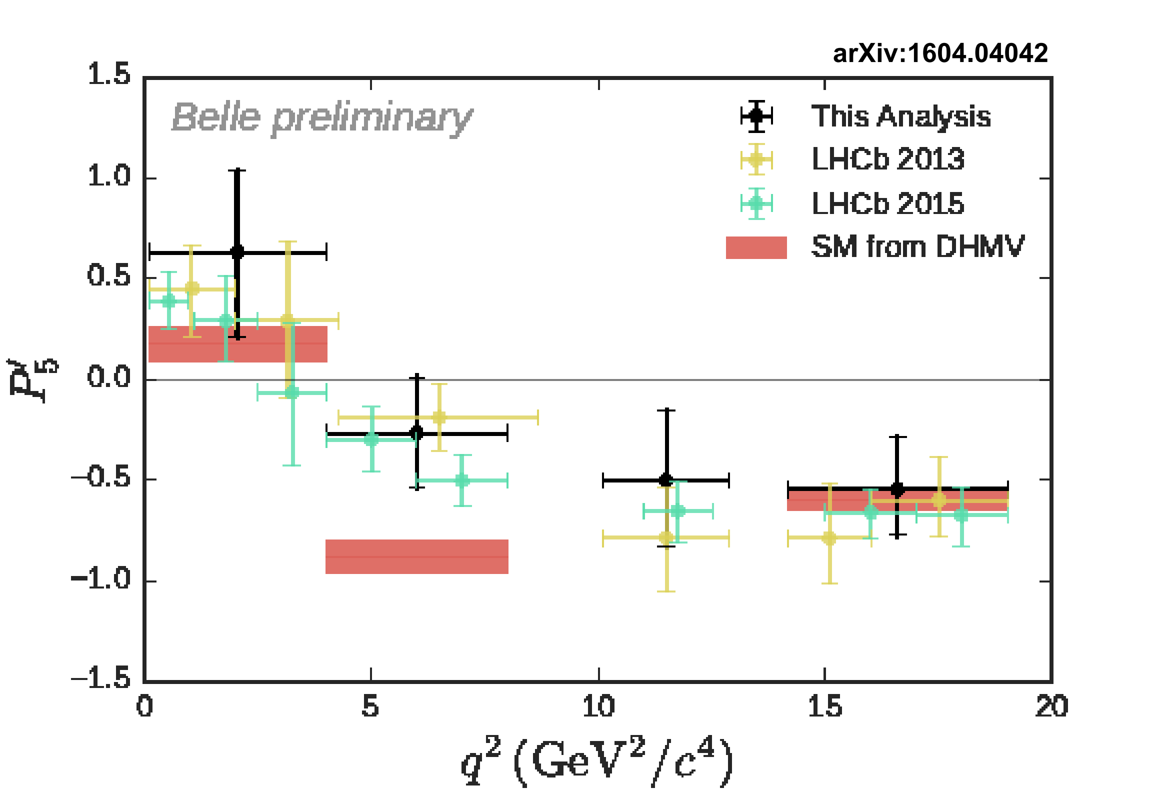

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- Crucial issue:

  How important departures from the infinite-m_b limit are, for q^2 approaching $4\,m_c^2$.

  In fact, $c\bar{c}$ contributions are suppressed by $q^2 - 4\,m_c^2$.

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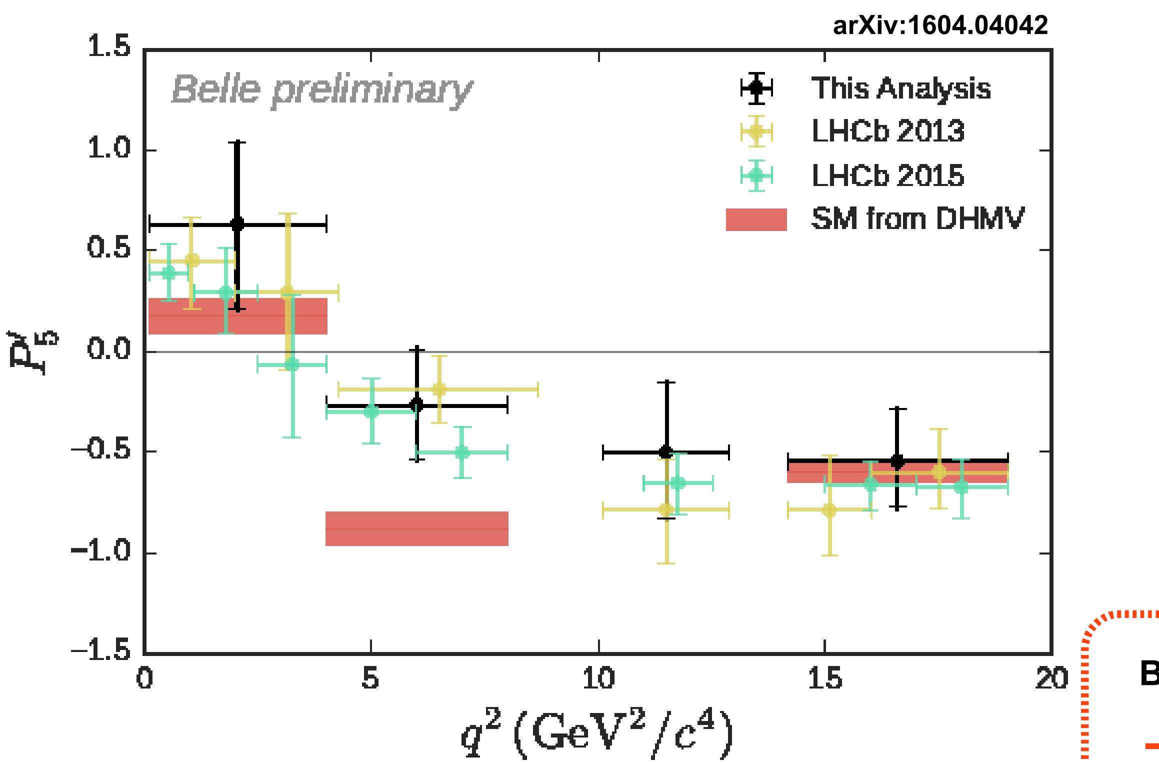

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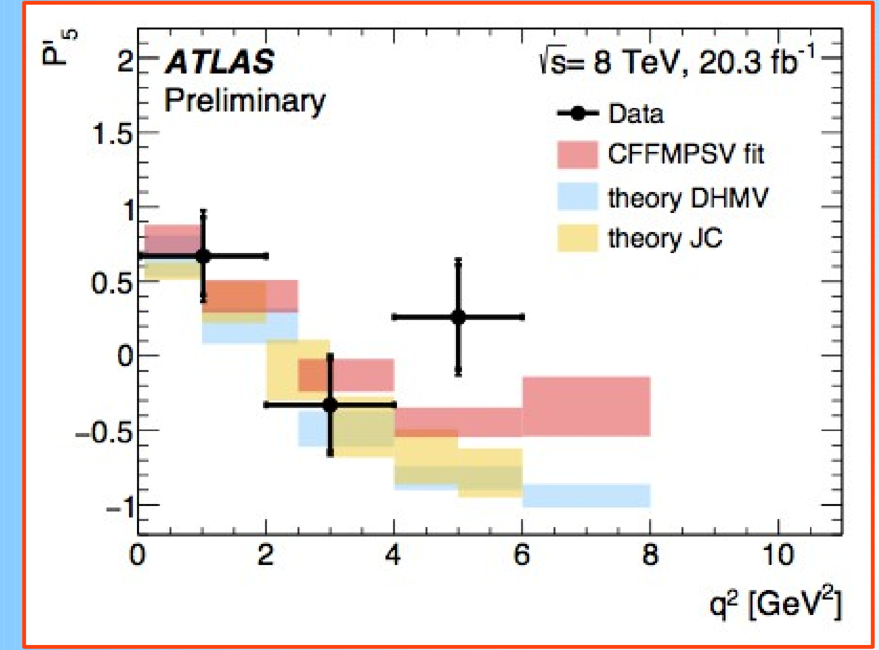
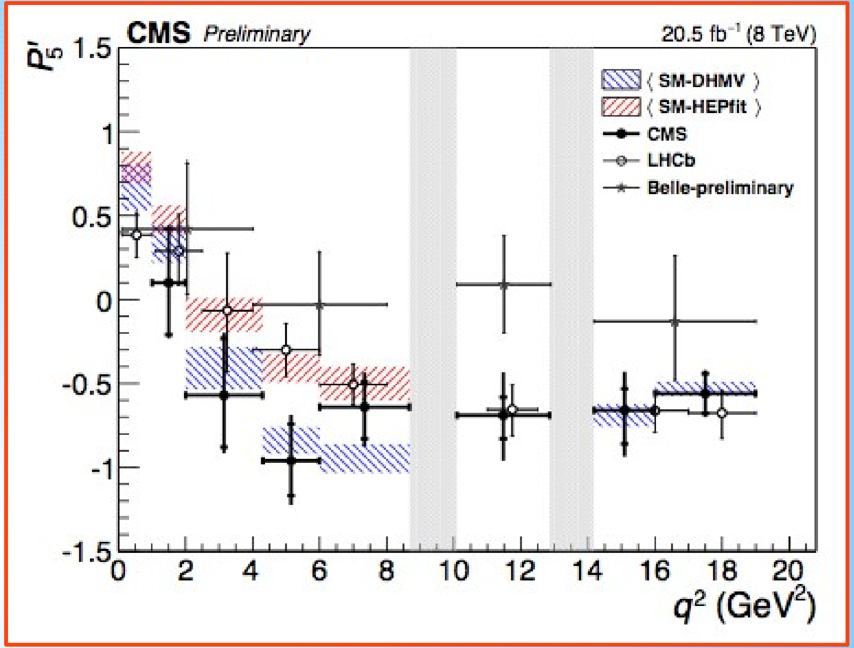
But interesting nonetheless, because:

- *Effect is again in the same region:* $m^2_{\mu\mu} \in [1, 6]\ \mathrm{GeV}^2$
- *Compatibility between 1/fb and 3/fb LHCb analyses and a recent Belle analysis*

$B \to K^* \mu\mu$ angular analysis:
post-Moriond update





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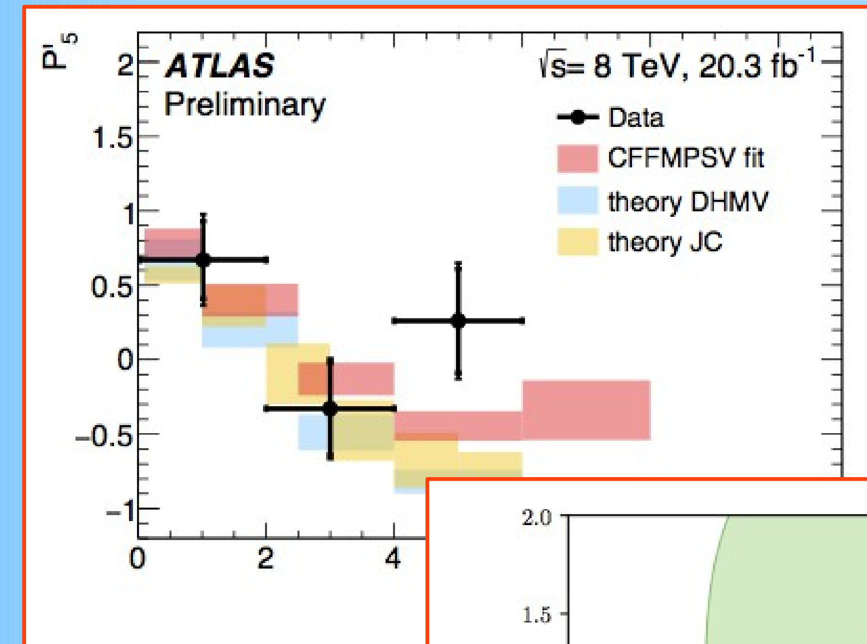

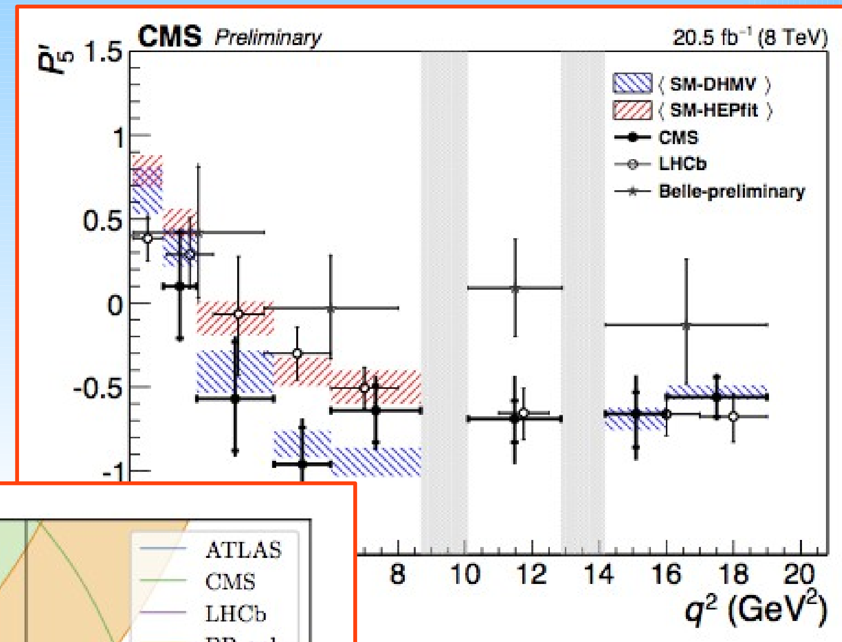

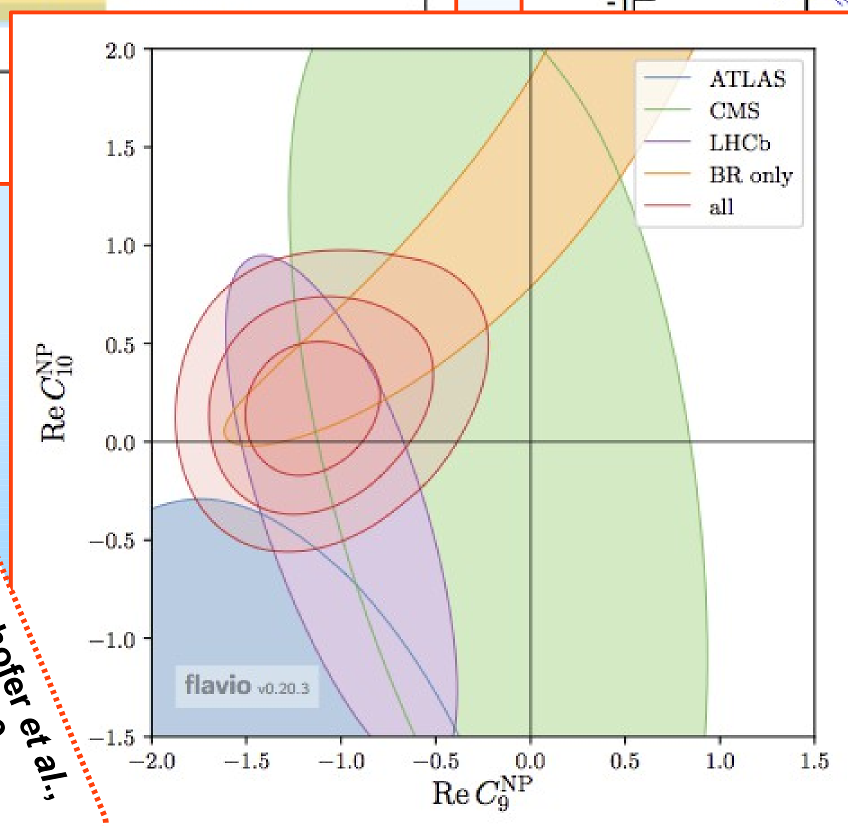

Altmannshofer et al., 1703.09189

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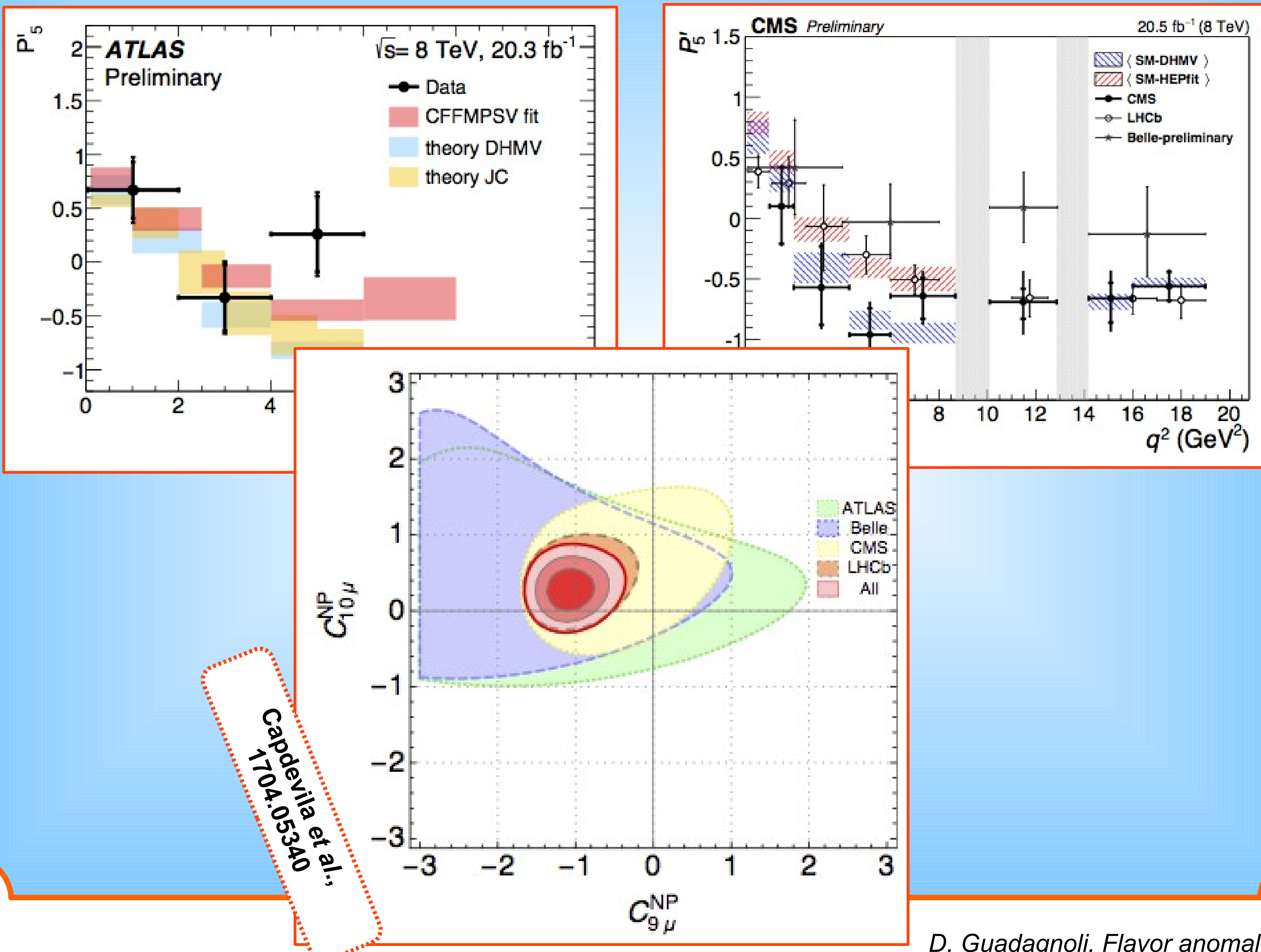

b → c data

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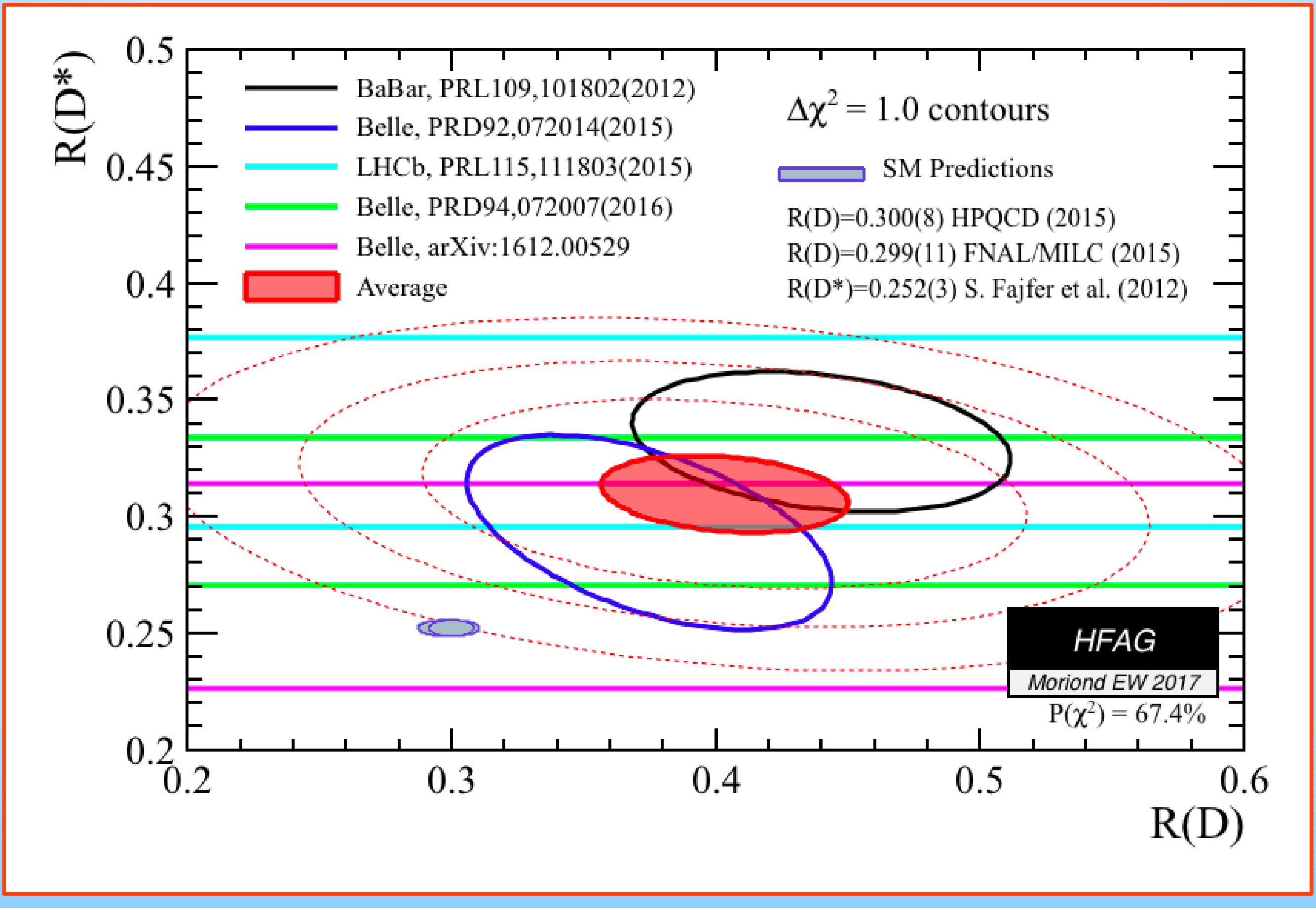

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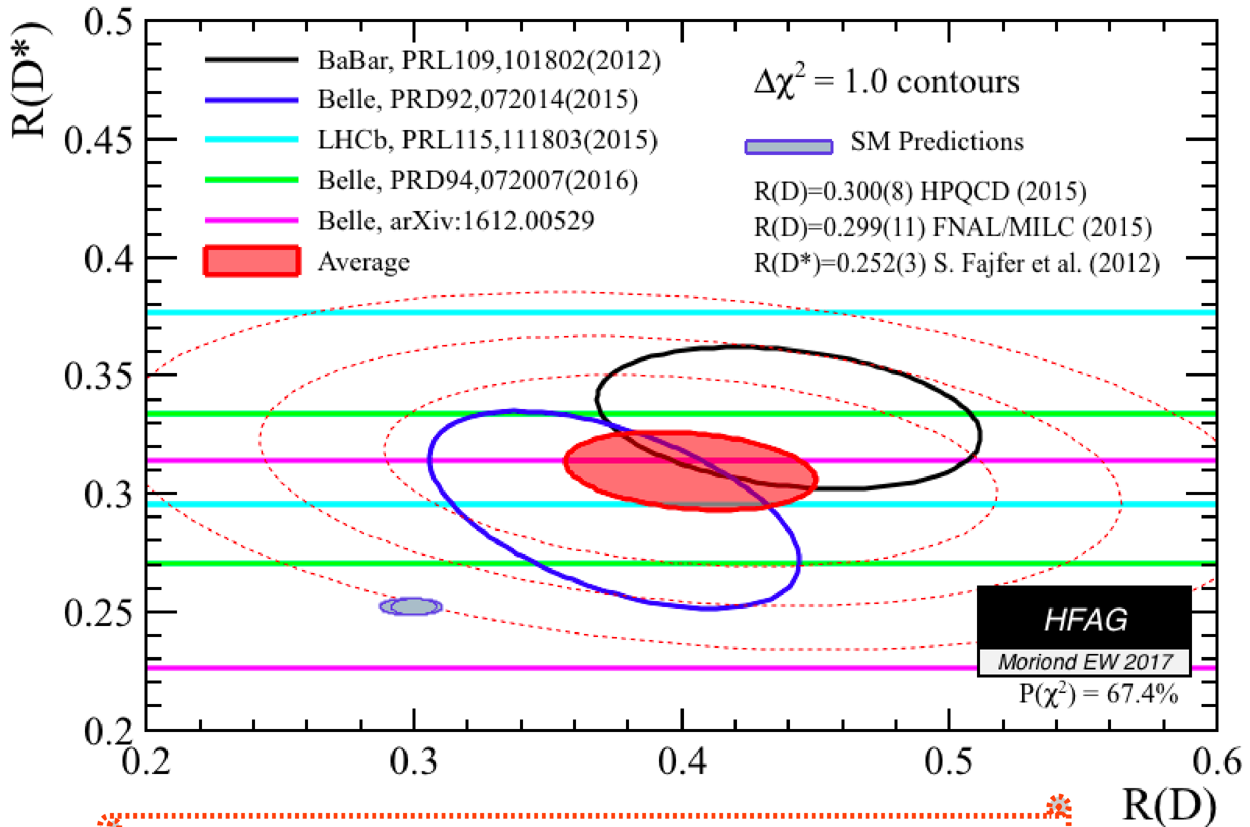

Simultaneous fit to R(D) & R(D*) about 4σ away from SM

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  - **Q1:** Can we (easily) make theoretical sense of data?
  - **Q2:** What are the most immediate signatures to expect ?

Concerning Q1: can we easily make theoretical sense of these data?

- *Yes we can. Consider the following Hamiltonian*

$$H_{\mathrm{SM+NP}}(\bar{b} \to \bar{s}\mu\mu) = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{\alpha_{\mathrm{em}}}{4\pi} \left[\bar{b}_L \gamma^\lambda s_L \cdot \left(C_9^{(\mu)} \bar{\mu} \gamma_\lambda \mu \; + \; C_{10}^{(\mu)} \bar{\mu} \gamma_\lambda \gamma_5 \mu \right) \right]$$

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  - *R_K <u>and</u> R_{K^*} lower than 1*
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- *A fully quantitative test requires a global fit.*

new physics contributions to the Wilson coefficients. We find that the by far largest decrease in the χ^2 can be obtained either by a negative new physics contribution to C_9 (with $C_9^{\mathrm{NP}} \sim -30\% \times C_9^{\mathrm{SM}}$), or by new physics in the $SU(2)_L$ invariant direction $C_9^{\mathrm{NP}} = -C_{10}^{\mathrm{NP}}$, (with $C_9^{\mathrm{NP}} \sim -12\% \times C_9^{\mathrm{SM}}$). A positive NP contribution to C_{10} alone would also improve the fit, although to a lesser extent. [Altmannshofer, Straub, EPJC '15]

For analogous conclusions, see also [Ghosh, Nardecchia, Renner, JHEP '14]

Model example

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Glashow *et al.*, 2015

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  - *This rotation induces <u>LUV and LFV</u> effects*

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☑ *An analogous argument holds for purely leptonic modes*

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See:
Bhattacharya, Datta, London, Shivashankara, PLB 15

- *Being defined above the EWSB scale, our assumed operator*

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After rotation to the mass basis (unprimed), the last structure contributes to $\Gamma(b \to c\, \tau\, \bar{\nu})$

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Such effects "strongly disfavour an explanation of the R(D(*)) anomaly model-independently"

Further tests

- ***Measure more LUV ratios:*** $R_{K*}, R_{\phi}, R_{Xs}, R_{K_0(1430)}, R_{f_0}$

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  In general we have [Hiller, Schmaltz, JHEP 2015]

  $$X_{K^*} \simeq 1 - 0.41\,\mathrm{Re}\left(C'^{\mu}_{9} - C'^{\mu}_{10} - \{\mu \to e\}\right)$$

Remember

$$O'^{\ell}_{9} = (\bar{s}\gamma^{\mu}P_R b)\,(\bar{\ell}\gamma_{\mu}\ell)$$

$$O'^{\ell}_{10} = (\bar{s}\gamma^{\mu}P_R b)\,(\bar{\ell}\gamma_{\mu}\gamma_5\ell)$$

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LHCb, 1612.06764

Similar approach as Lyon, Zwicky, '14

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- *The FSR component can be systematically subtracted from data (the same way it is in $B_s \to \mu\mu$)*
- *So this measurement gives access to the ISR spectrum, to be compared with theory [Melikhov-Nikitin, '04]*

But LQCD calculation of $B \to \gamma$ f.f.'s required

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First obstacle *towards a common explanation of $b \to s\,\ell\ell$ and $b \to c\,\tau\,\nu$:*

- ***B → D(*) τ ν :*** *arises at tree level in the SM, and the effect is O(25%)*
  ⇨ *tree-level charged mediators?*

- ***B → K(*)ℓℓ :*** *again 25% effect, but this is a loop effect in the SM*

Second obstacle

- The needed NP is of the kind J_{quark} x J_{lepton}
  Hard to believe that it leaves no traces in J_{quark} x J_{quark} *and* J_{lepton} *x* J_{lepton} *as well*
  ⇨ Strong constraints from B_s-mixing & purely leptonic LFV or LUV decays

Third obstacle

Most (all?) model-building possibilities involve:

- new charged (and possibly colored) states
- with masses in the TeV region and
- with significant couplings to 3rd gen. SM fermions

⇨ *Constraints from direct searches (e.g. → ττ) potentially strong*

And yes they are!
See: [Greljo-Isidori-Marzocca]
[Faroughy-Greljo-Kamenik]

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  with any of the following transformation properties under the SM gauge group:

  - ***$SU(3)_c$: 1** or **3** (→ "leptoquark")*
  - ***$SU(2)_L$: 1** or **2** or **3***

Recap of model-building attempts

focused on models accounting for R_K & $R(D^{(*)})$

$SU(3)_c$ ↓ \ $SU(2)_L$ →	1	2	3
1			
3			

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- *Not constrained by Feruglio et al.'s argument*
- *Prediction: RK* > 1*
  (V+A) x (V–A) current invoked

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- *Not constrained by Feruglio et al.'s argument*
- *RK* prediction can be made < 1 by forbidding certain couplings*

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  - ***Data vs. theory:*** *Discrepancies go in a consistent direction.*
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- ***Theory:*** *EFT makes sense rather well of data. But hard to find convincing UV dynamics*

- *Timely to pursue further tests.*

  Examples:
  - *more measurements of R_K*
  - *more LUV quantities*
  - *other observables sensitive to C_9 & C_{10}*