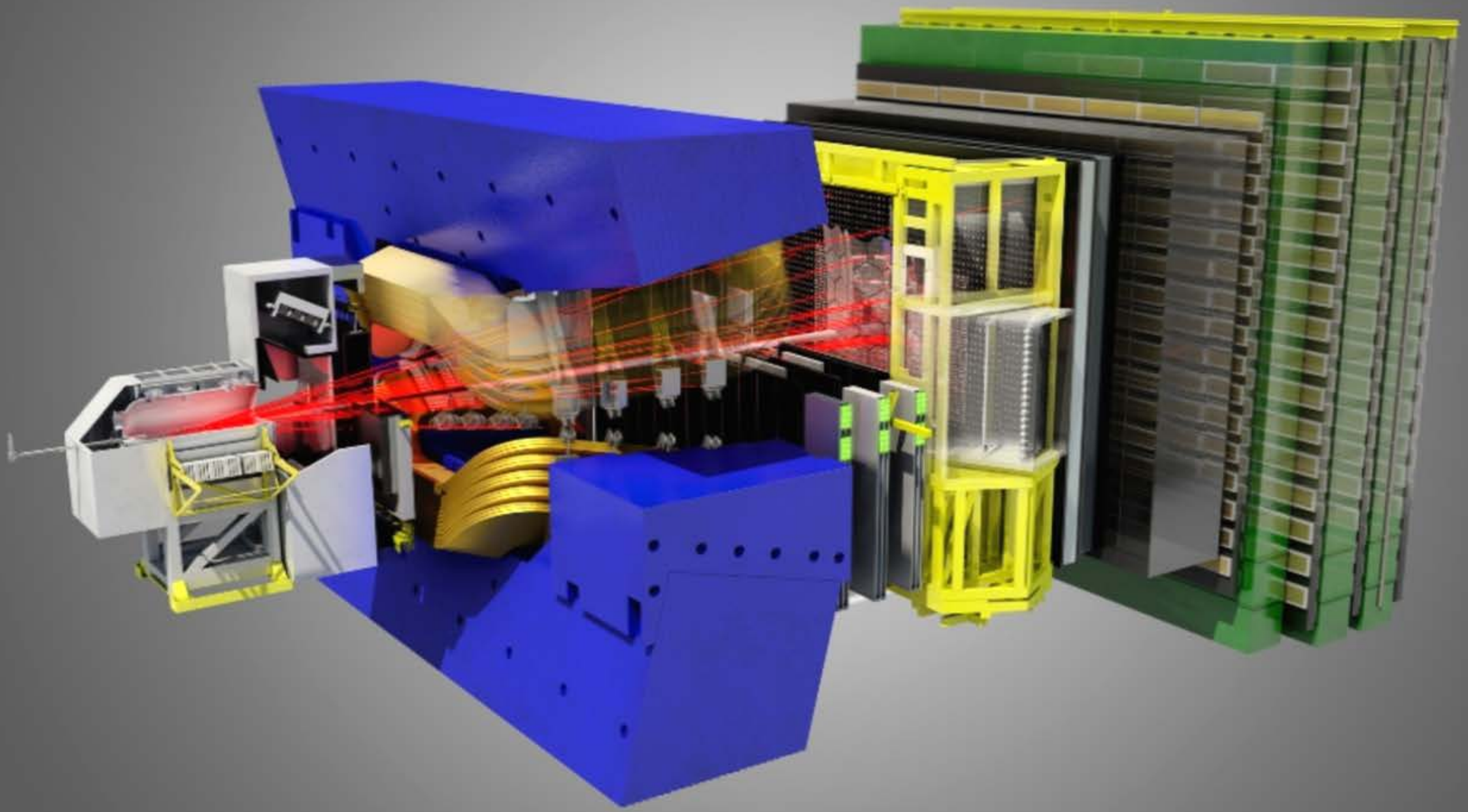
B decay anomalies @ LHCb

RED LHC, IFT, May 2017

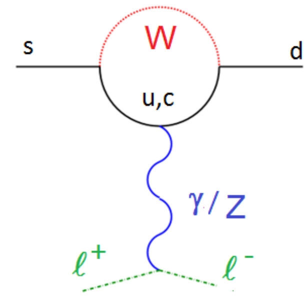
Arantza Oyanguren



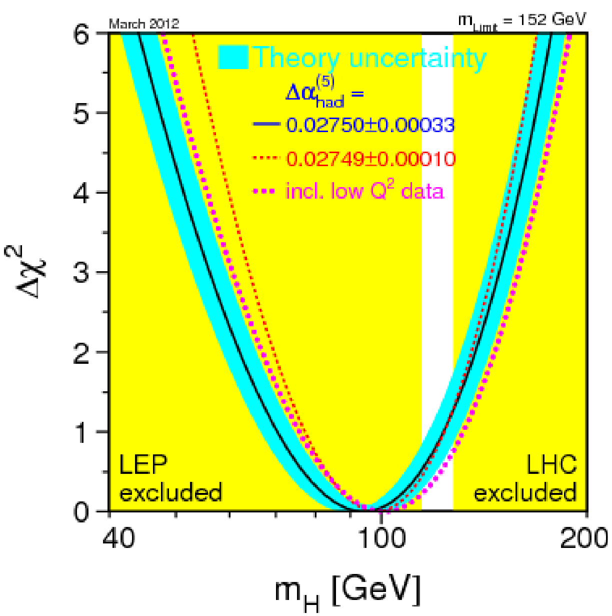
Indirect searches of New Physics

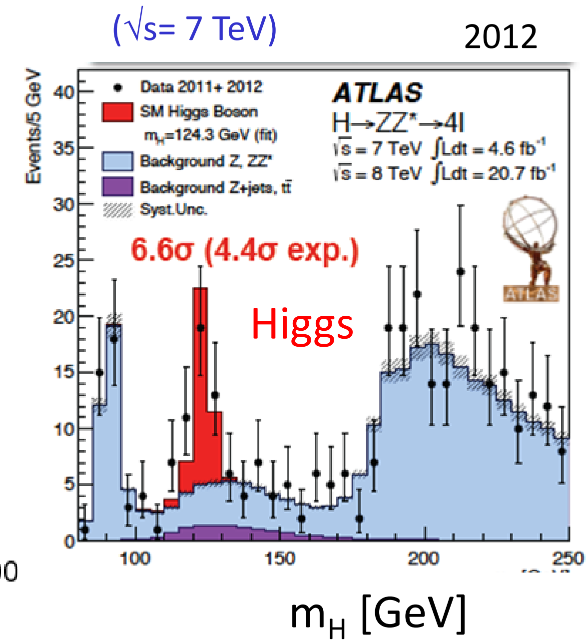
Off-Shell particles: Evidence in quantum effects (loops)

$\rightarrow$ Precision Physics *(BR's, asymmetries, angular distributions…)*



Indirect observations of **New Physics** is the portal to infer properties of heavy particles before experiments have sufficient energy to produce them.



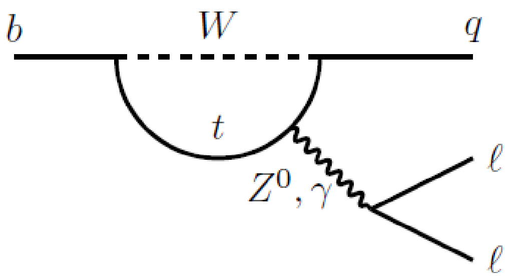


$\rightarrow$ **Complementarity of indirect and direct searches is crucial !**

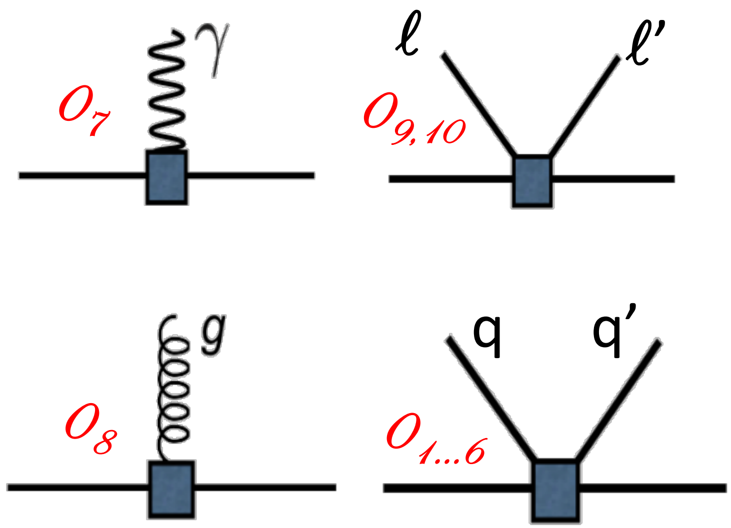
Operator Product Expansion

- Weak decay processes:

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_i V_{\text{CKM}}^{\,i} \underbrace{(C_i \mathcal{O}_i}_{\text{Left handed}} + \underbrace{C_i' \mathcal{O}_i')}_{\text{Right handed}}$$



OPE: a series of effective vertices multiplied by effective coupling constants ***C_i***.



Electroweak scale ~ $1/M_W$

New Physics scale ~ $1/\mathbf{M_{NP}}$

$C_i = C_i^{SM} + C_i^{NP}$

$C'_i = \cancel{C'_i}^{SM} + C'^{NP}_i$

Primed $C'_i \rightarrow$ right handed currents: suppressed in SM

- Wilson coefficients $\mathbf{C_i^{(\prime)}(\mu,\alpha_s)}$ encode short-distance physics: sensitive to $E > M_{EW}$ (i.e. $E > M_W, M_Z$)

Operator Product Expansion

- New Physics expected to affect the Wilson coefficients C^{SM}_i + C_i^{NP}

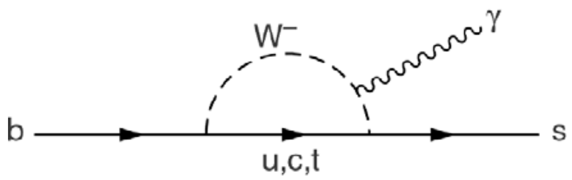
Wilson coeff. dependence in *b* → *s* decays (rare processes):

→ **Leptonic decays:** Branching fraction of $B_s \to \mu^+\mu^-$ ($C_{10}^{(\prime)}$)

→ **Radiative decays:** $B \to X_s \gamma$ ($C_7^{(\prime)}$)

→ **Semileptonic decays:** angular observables of $B \to X\ell^+\ell^-$ ($C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$)

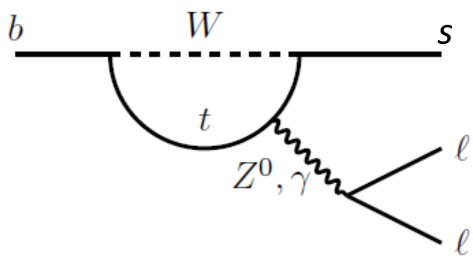
Ex: Decay width for $B \to X_s\gamma$



$$\Gamma^{(SM)}_{B\to X_s\gamma} = \frac{\alpha_{\rm em} G_F^2 m_b^5}{32\pi^4} |V_{tb}V_{ts}|^2 C_7^2(m_b)$$

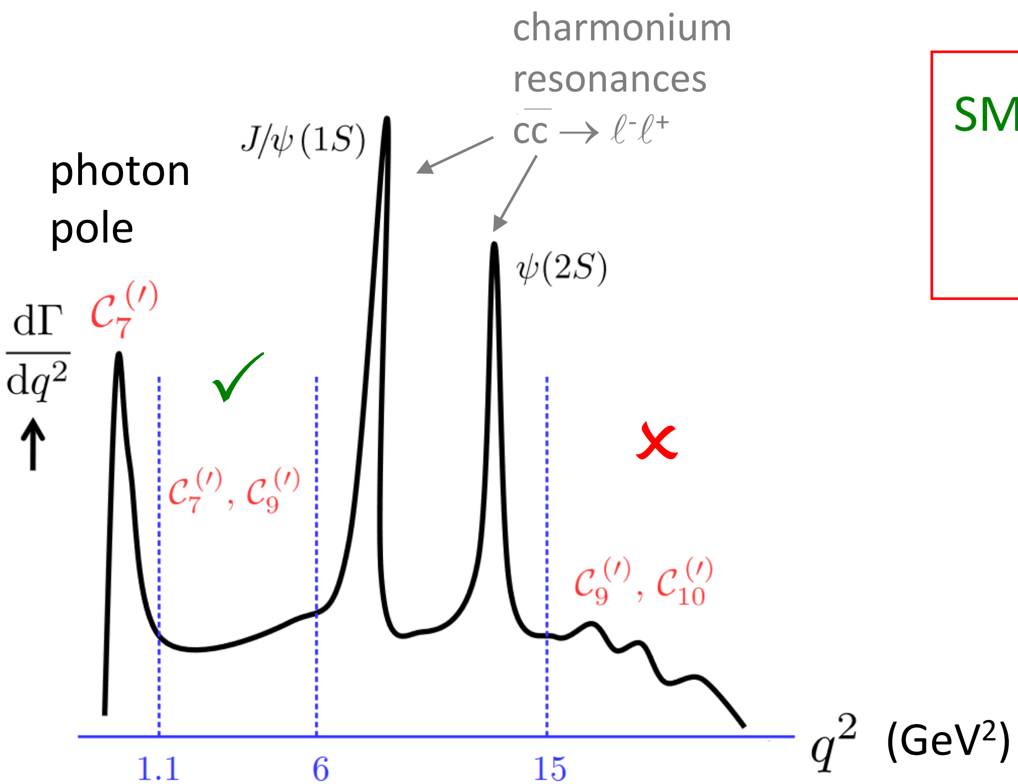
Operator Product Expansion

Ex: $B \rightarrow K^* \ell^- \ell^+$



$q^2 = (p_{\ell^+} + p_{\ell^-})^2$

Differential branching fraction: $d\Gamma/dq^2$



SM values ($\mu = m_b$):	$C_7 \sim -0.33$
	$C_9 \sim 4.27$
	$C_{10} \sim -4.17$

(Everything else small or negligible)

B decay anomalies at LHCb

Measurements performed at LHCb:

- **Differential branching fractions**
  ($B^0 \to K^{(*)0}\mu^+\mu^-$, $B^+ \to K^{(*)+}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, $B^+ \to \pi^+\mu^+\mu^-$ and $\Lambda_b \to \Lambda\mu^+\mu^-$)
  $\rightarrow$ Affected by hadronic uncertainties in the theory predictions

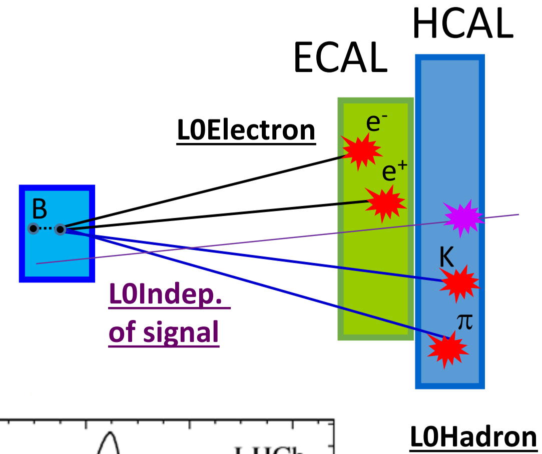
- **Angular analyses**
  ($B^0 \to K^{(*)0}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$ $B^0 \to K^{*0}e^+e^-$ and $\Lambda_b \to \Lambda\mu^+\mu^-$)
  $\rightarrow$ Observables with smaller theory uncertainties

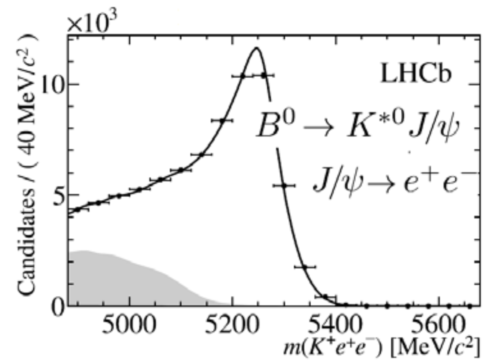
- **Test of Lepton Flavour Universality**
  ($B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$)
  $\rightarrow$ Hadronic uncertainties in theory predictions cancel in ratios

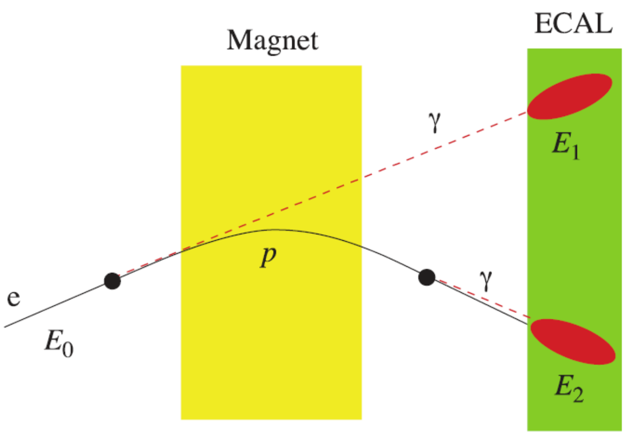
Claim on experimental issues

Decays involving leptons:

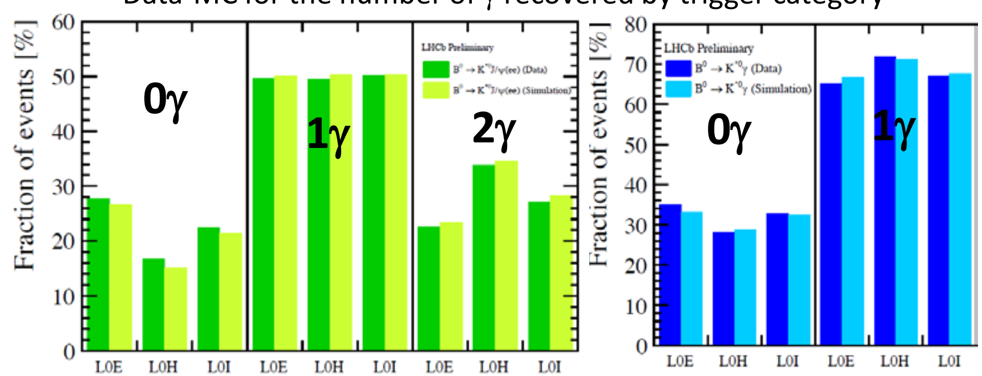
- LHCb is far better with muons than electrons
- *Trigger*, reconstruction, selection and particle identification are harder with electrons
- Mass resolution affected by *e bremsstrahlung* $\rightarrow$ need energy recovery
- Mass shape modelled according to the number of *bremsstrahlung* recovered







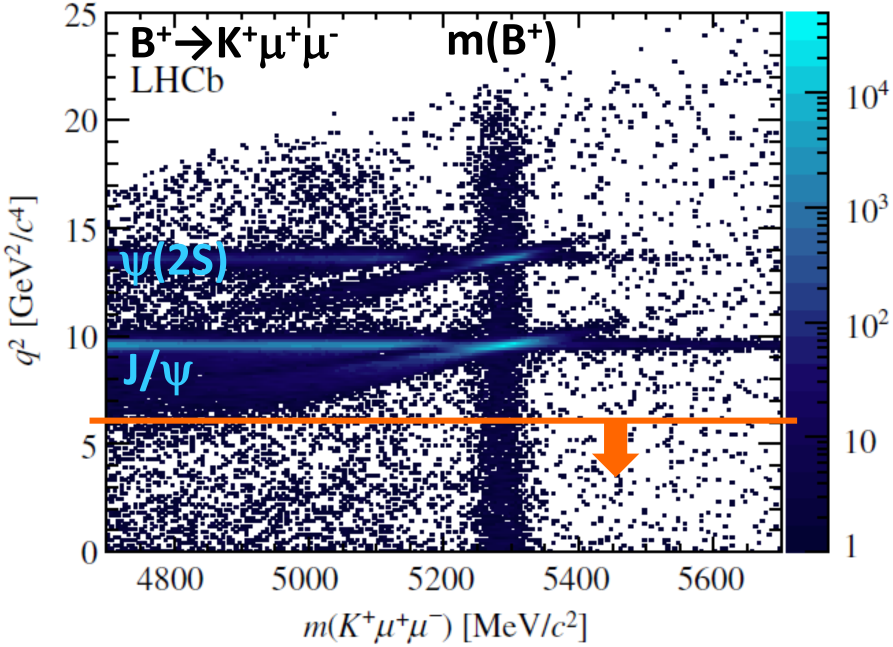
Data-MC for the number of γ recovered by trigger category

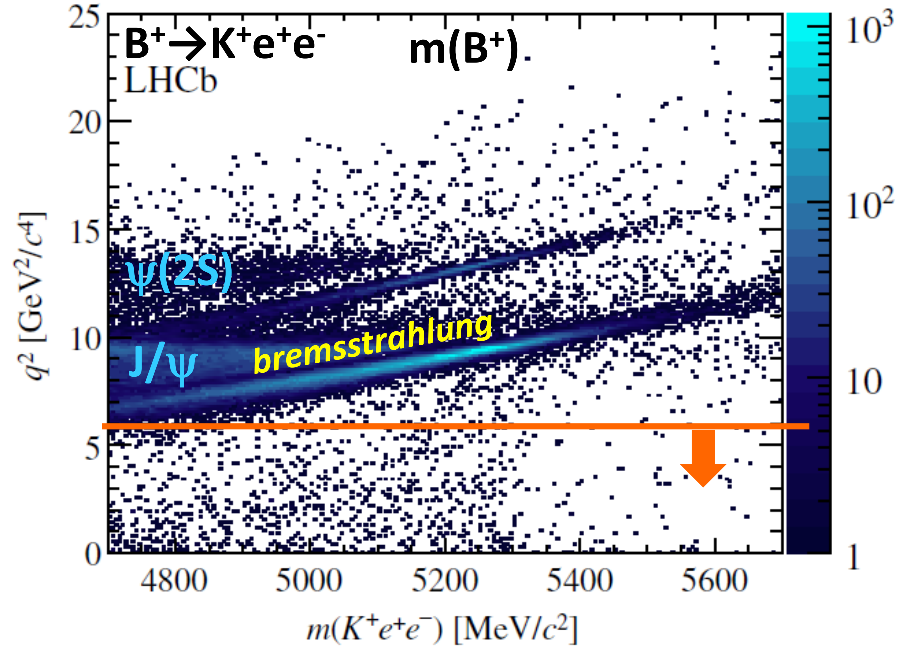


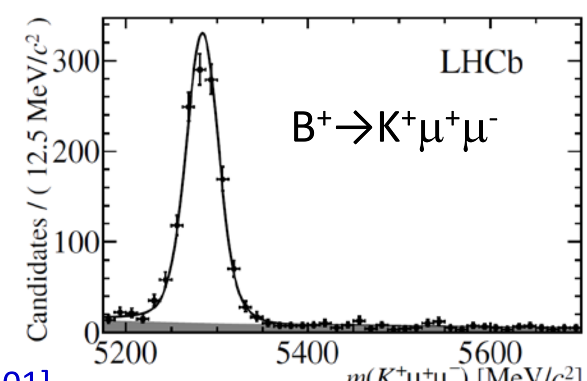
B → K* J/Ψ (→ e⁺e⁻)   B → K* γ (→ e⁺e⁻)

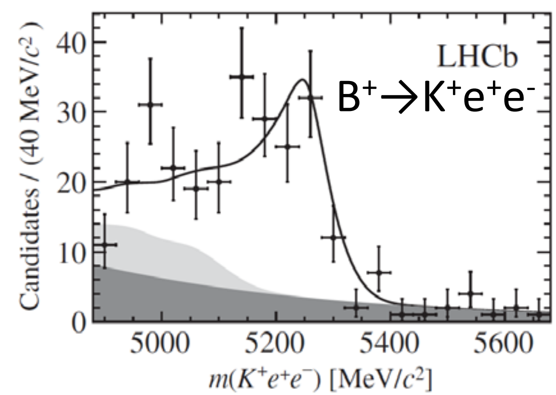
Claim on experimental issues

B mass vesus q^2 for $B^+ \to K^+ \ell^+ \ell^-$







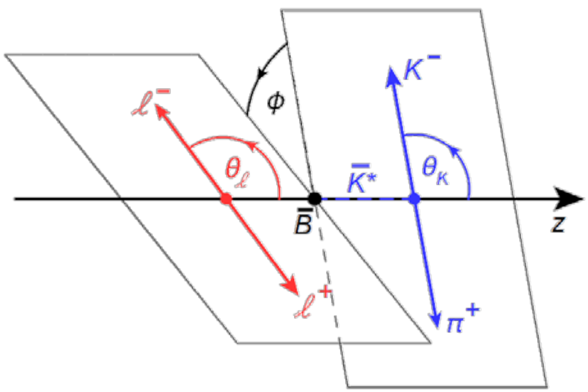


[PRL 113 (2014) 151601]

B decay anomalies at LHCb: P’$_5$

Angular distribution in B$\to$ K*$\ell^-\ell^+$: q^2 and three angles

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2}=\frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K+F_L\cos^2\theta_K+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos2\theta_\ell$$
$$-F_L\cos^2\theta_K\cos2\theta_\ell+S_3\sin^2\theta_K\sin^2\theta_\ell\cos2\phi+S_4\sin2\theta_K\sin2\theta_\ell\cos\phi$$
$$+S_5\sin2\theta_K\sin\theta_\ell\cos\phi+S_6\sin^2\theta_K\cos\theta_\ell+S_7\sin2\theta_K\sin\theta_\ell\sin\phi$$
$$+S_8\sin2\theta_K\sin2\theta_\ell\sin\phi+S_9\sin^2\theta_K\sin^2\theta_\ell\sin2\phi\Big]$$

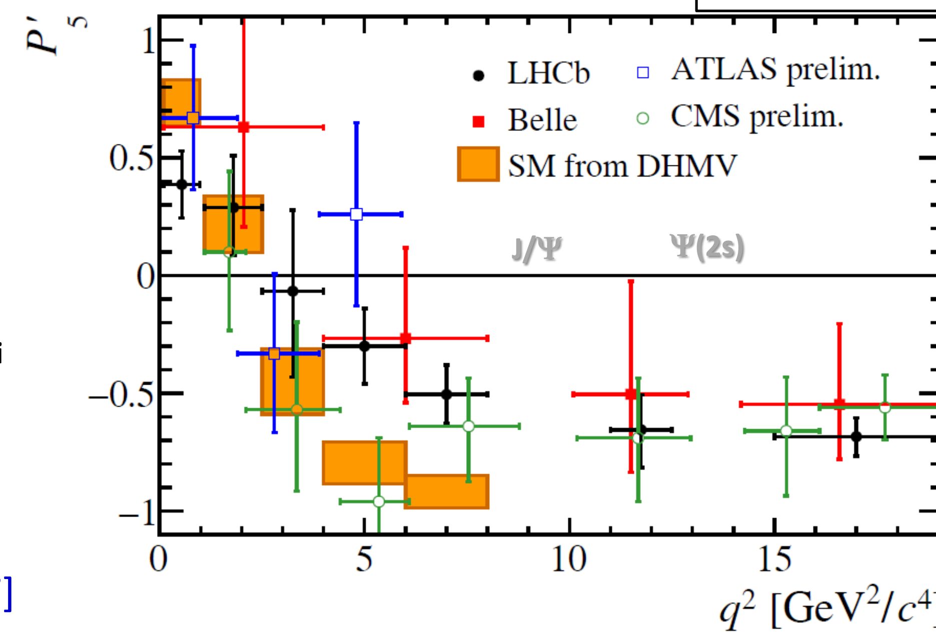


- JHEP 02 (2016) 104
- PRL 118 (2017) 111801
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

$$\boxed{P'_{i=4,5,6,8}=\frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}}$$

Functions of q^2 and Wilson coef. **C$_i$**
Optimized observables:
cancelation of form factor
dependencies: P’$_i$

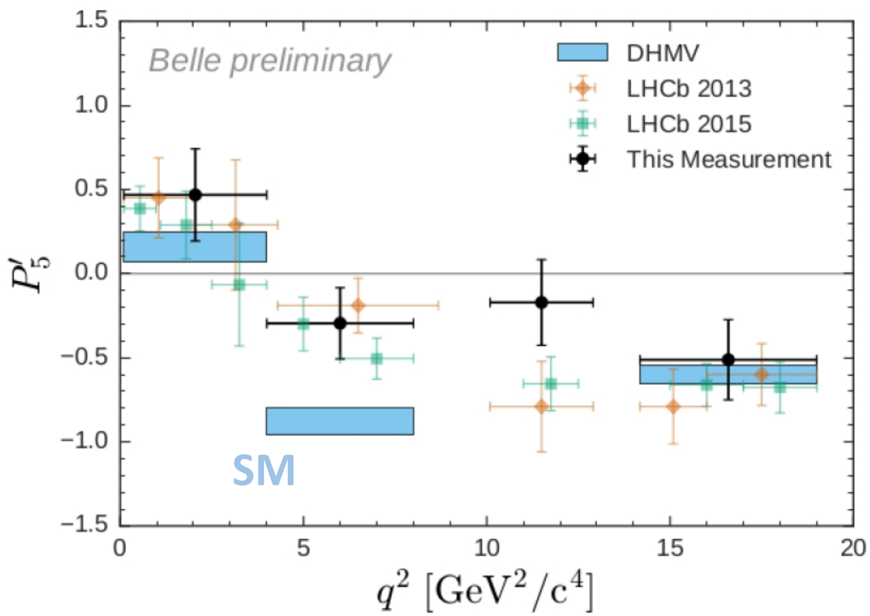
[Descotes-Genon et al, JHEP 05 (2013) 137]

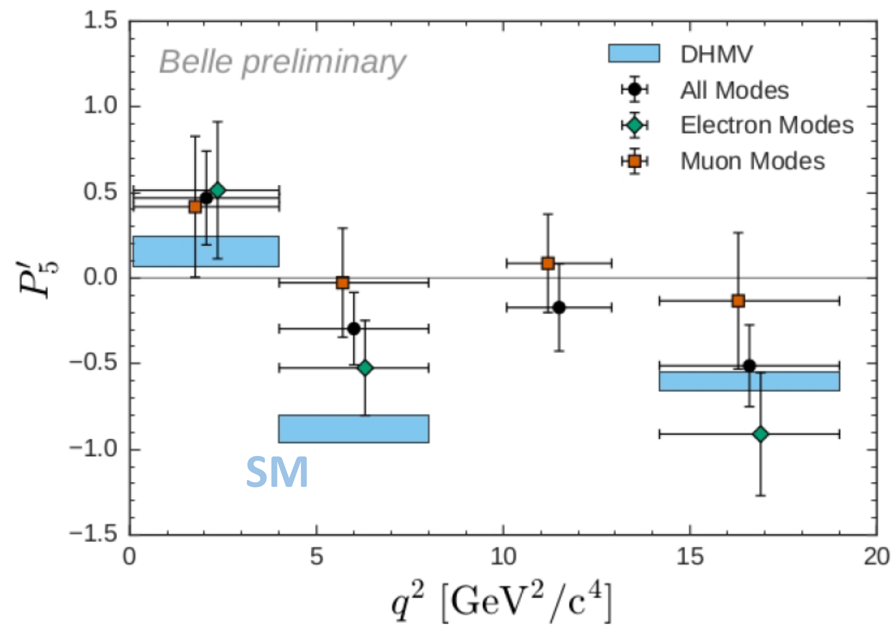


B decay anomalies at LHCb: P'$_5$

Angular distribution in $B \to K^* \ell^- \ell^+$:   Muons vs Electrons at Belle:

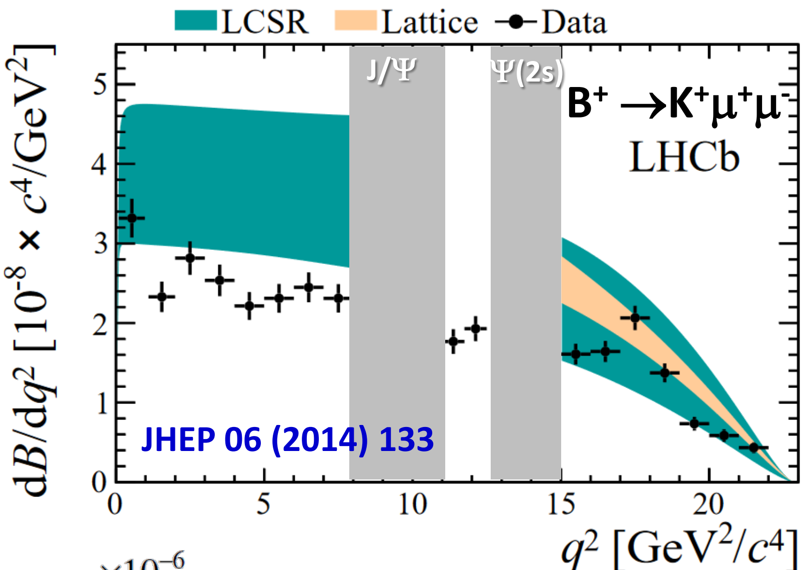
[Belle arXiv:1612.05014]

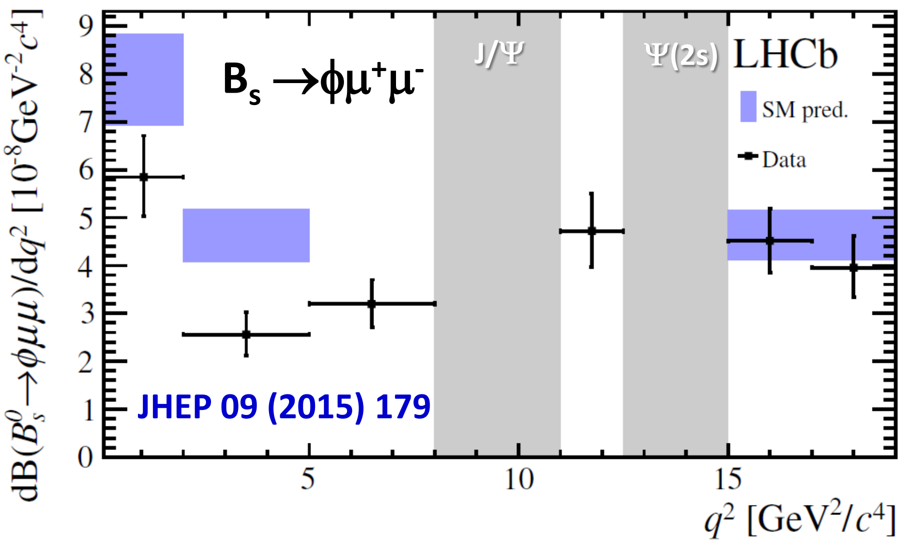


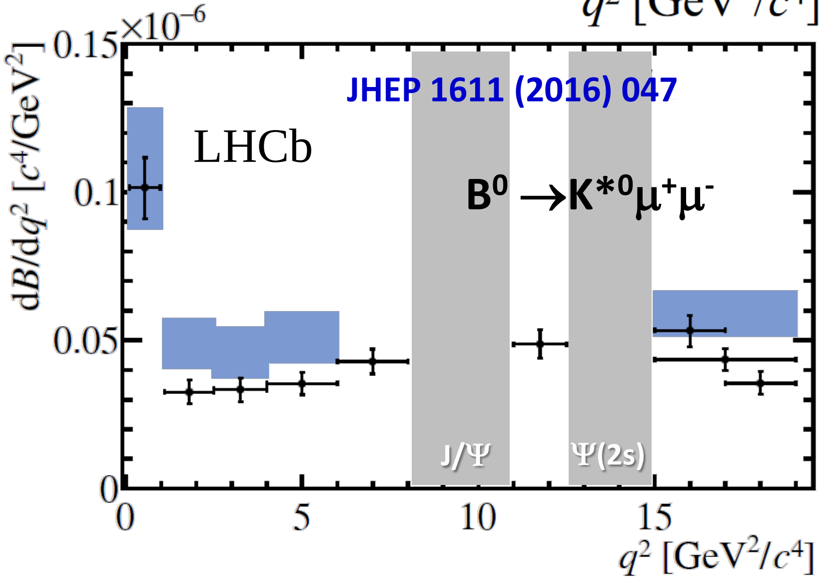


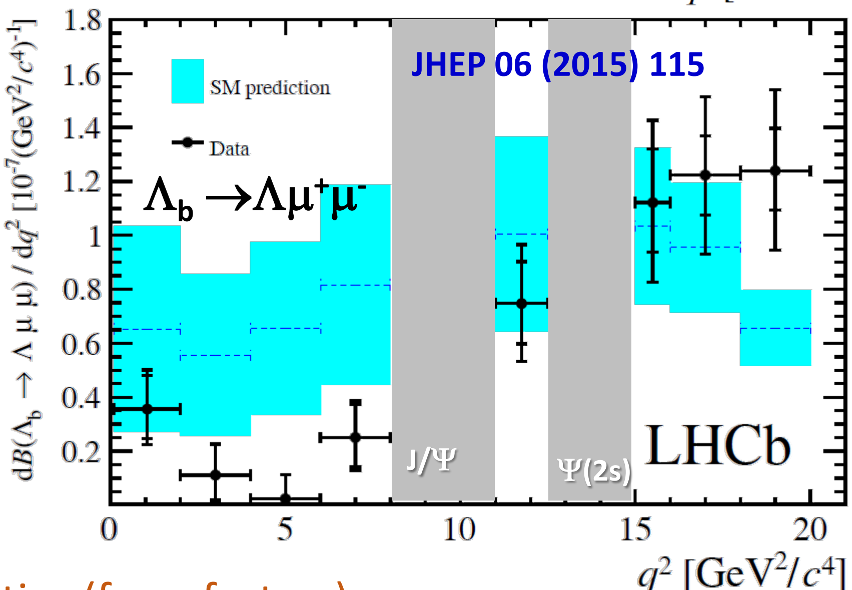
Everything consistent, P'5 anomaly confirmed, still large statistical uncertainties, but… mode with electrons is more SM compatible … (?)

B decay anomalies at LHCb: d[BR's]/dq²









Theory affected by hadronic uncertainties (form factors)

B decay anomalies at LHCb: R_K

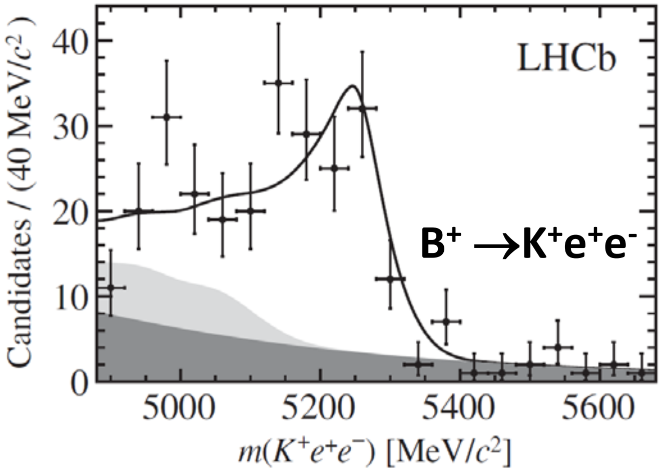
Theory clean observable

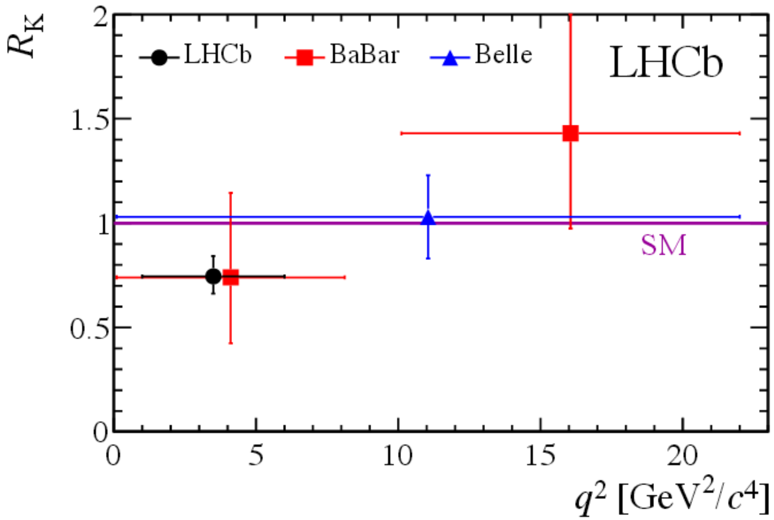
In the SM all leptons are expected to behave in the same way:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 1.000 + O(m_\mu^2/m_b^2) \text{ (SM)}$$

- Experimentally, use the $B \to K J/\psi(\to ee)$ and $B \to K J/\psi(\to \mu\mu)$ to perform a double ratio

- Precise theory prediction due to cancellation of hadronic form factor uncertainties





1 GeV < q^2 < 6 GeV [PRL 113 (2014) 151601]

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

→ Consistent, but lower, than the SM at **2.6σ**

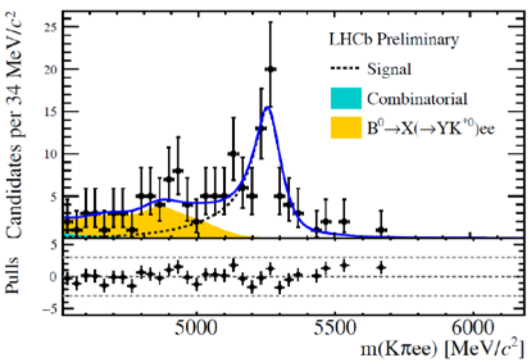
B decay anomalies at LHCb: R_{K*}

Theory clean observable

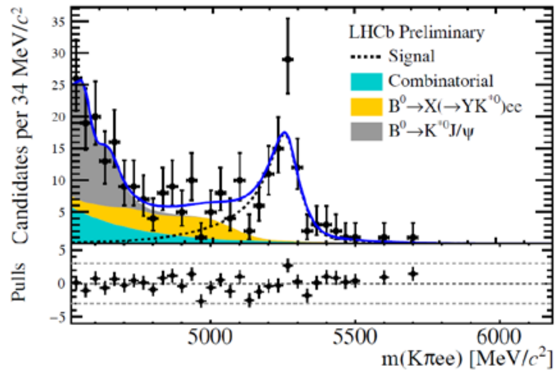
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$$

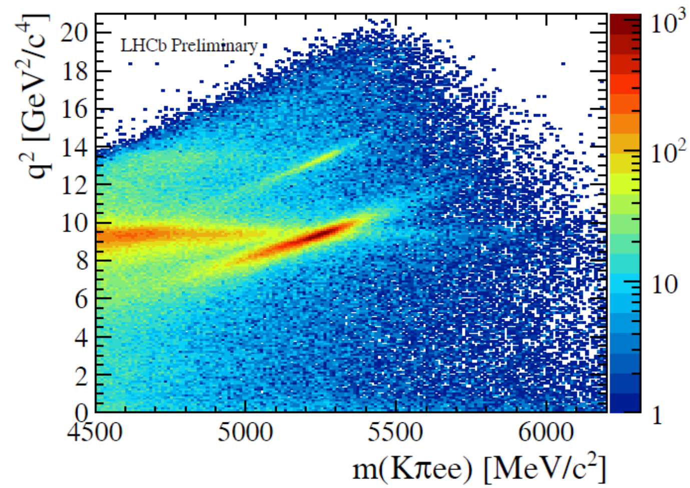
[CERN Seminar, 18th April 2017]

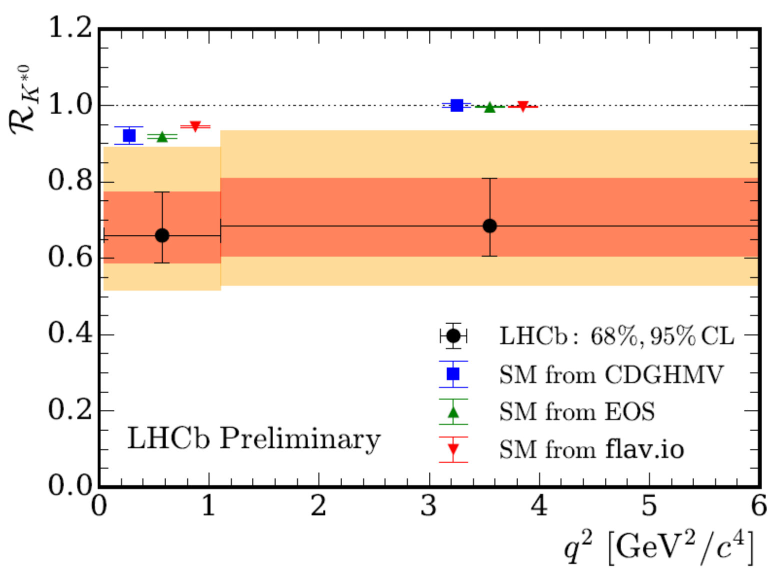
0.045 GeV < q^2 < 1.1 GeV



1.1 GeV < q^2 < 6 GeV







	low-q^2	central-q^2
SM	0.922(22)	1.000(6)
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\ 0.110}_{-\ 0.070} \pm 0.024$	$0.685\ ^{+\ 0.113}_{-\ 0.069} \pm 0.047$
95% CL	0.517–0.891	0.530–0.935

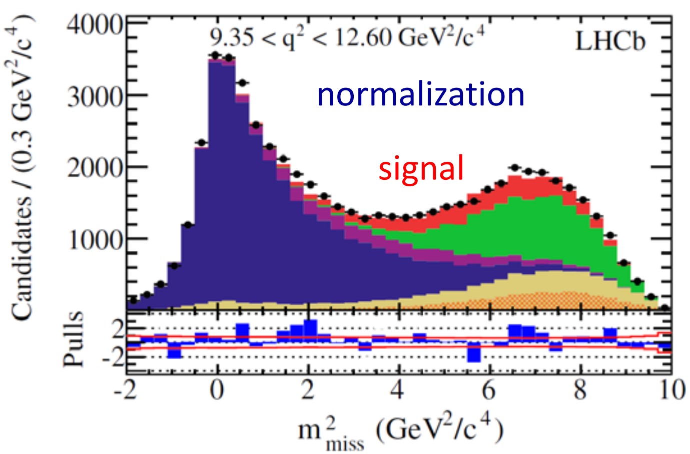
→ Consistent, but lower than the SM at **2.2-2.4σ** (low q^2) and **2.5-2.6σ** (central q^2)

Other B decay anomalies: $R_{D(*)}$

$b \rightarrow c$ anomalies:

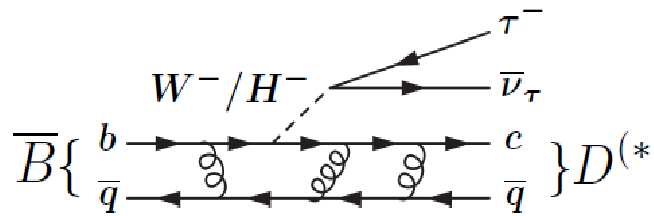
$$\mathcal{R}(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$

- Information from the missing mass squared $m_{miss}^2=(P_B-P_{D*}-P_\mu)^2$ and muon energy in several q^2 bins



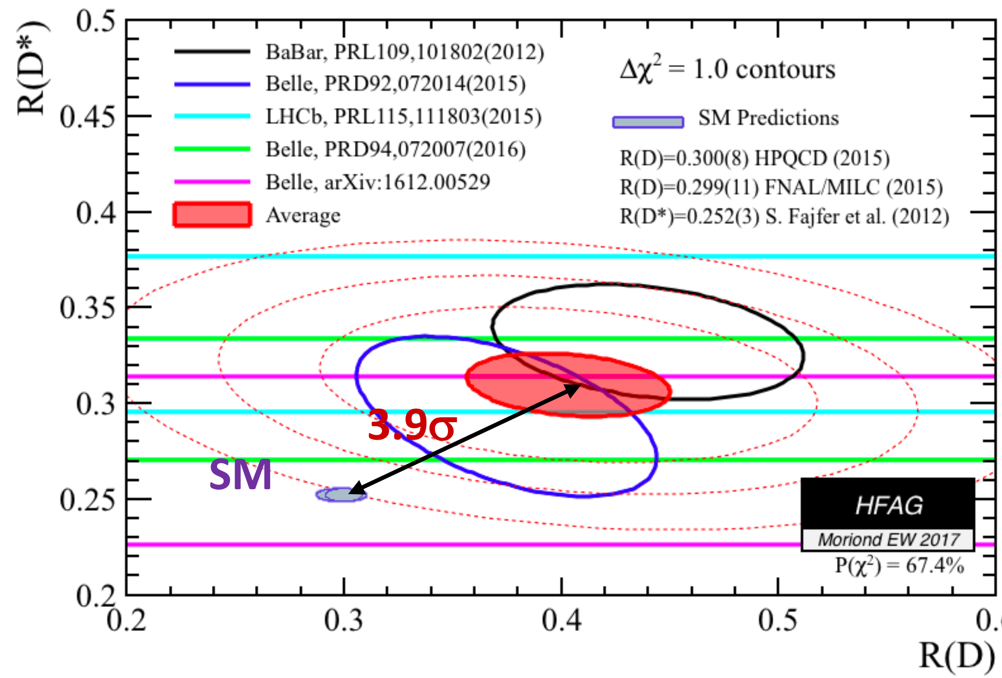
$$\boxed{\mathcal{R}(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})}$$

[PRL 115, 111803 (2015)]



Even if of different type (tree level) it can be correlated to the LFU violation in $b \rightarrow s\ell^+\ell^-$

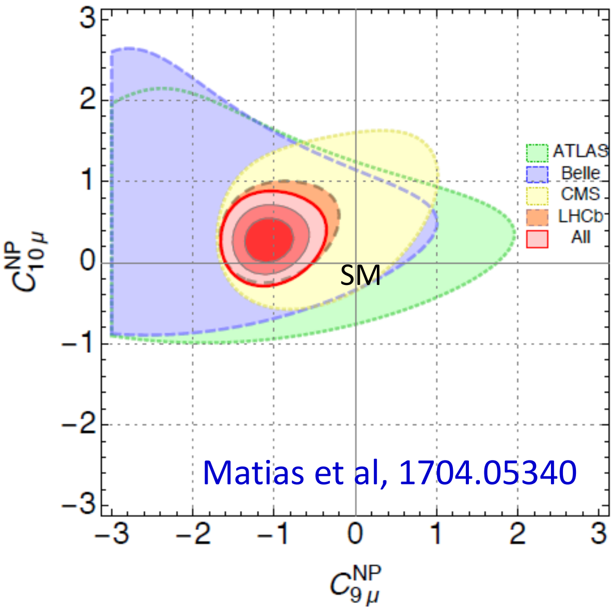
(but… form factor effects here ?)

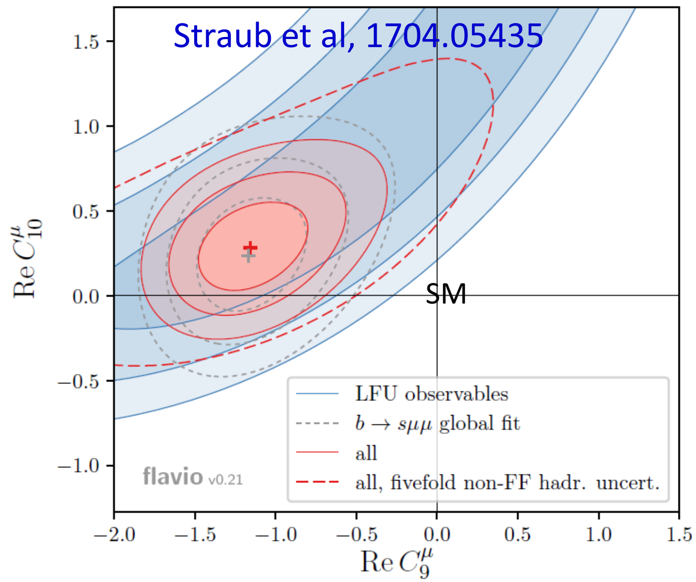


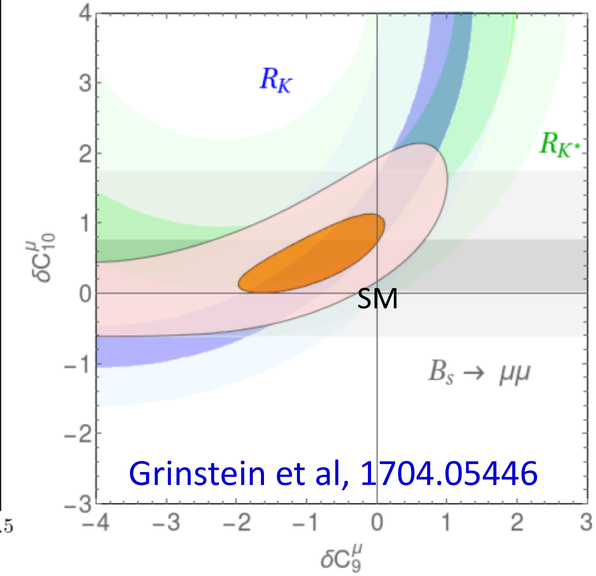
Interpretation

[More from Lars](#)

Global fits (some cases with more than 100 observables)







New Physics hypothesis preferred over SM by more than 4 - 5σ

Main effect on the $C_{9\mu}$ coefficient: **4.27^{SM}** **-1.1^{NP}**

Triggered models with Z’, leptoquarks (LQ), and composite Higgs

Prospects at LHCb

More from Fernando

- Br($B_s \to \mu^+\mu^-$) and Br($B_d \to \mu^+\mu^-$) with Run2
- R_K with improved Run1 data (new calo reco) + Run2
- R_ϕ : narrower resonance as compared to K*, but less stat. (f_s/f_d) $\mathcal{R}_\phi = \frac{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \phi e^+ e^-)}$
- $R_{\Lambda(*)}$: lepton universality in baryons, different spin structure $\mathcal{R}_{\Lambda^{(*)}} = \frac{\mathcal{B}(\Lambda_b \to \Lambda^{(*)}\mu^+\mu^-)}{\mathcal{B}(\Lambda_b \to \Lambda^{(*)} e^+ e^-)}$
- Angular analysis of $B^+ \to K^+\ell^+\ell^-$, $B^0 \to K^{*0}\ell^+\ell^-$ …
- Branching fractions, isospin asymmetries … in $B \to X\ell^+\ell^-$
- $B_s \to \phi\gamma$, $B \to K^*\gamma$, $B \to K\pi\pi\gamma$, $\Lambda_b \to \Lambda\gamma$, $\Xi_b \to \Xi\gamma$ …

channel	3fb^{-1}	Run 2	Upgrade (50fb^{-1})
$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$	2,400	9,000	80,000
$B^0 \to K^{*+}(K_S^0\pi^+)\mu^+\mu^-$	160	600	5,500
$B^0 \to K_S^0\mu^+\mu^-$	180	650	5,500
$B^+ \to K^+\mu^+\mu^-$	4700	17,500	150,000
$B^+ \to \pi^+\mu^+\mu^-$	93	350	3,000
$B_s^0 \to \mu^+\mu^-$	15	60	500
$B^0 \to K^{*0}e^+e^-$	150	550	5,000