HINTS OF POSSIBLE STANDARD MODEL DEVIATIONS AT LHCb

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TESTS OF LEPTON FLAVOR UNIVERSALITY

- In the SM, electroweak couplings of gauge bosons to leptons are independent from their flavor => Lepton Flavor Universality

- Observation of sizeable LFU violation would be a clear sign of New Physics

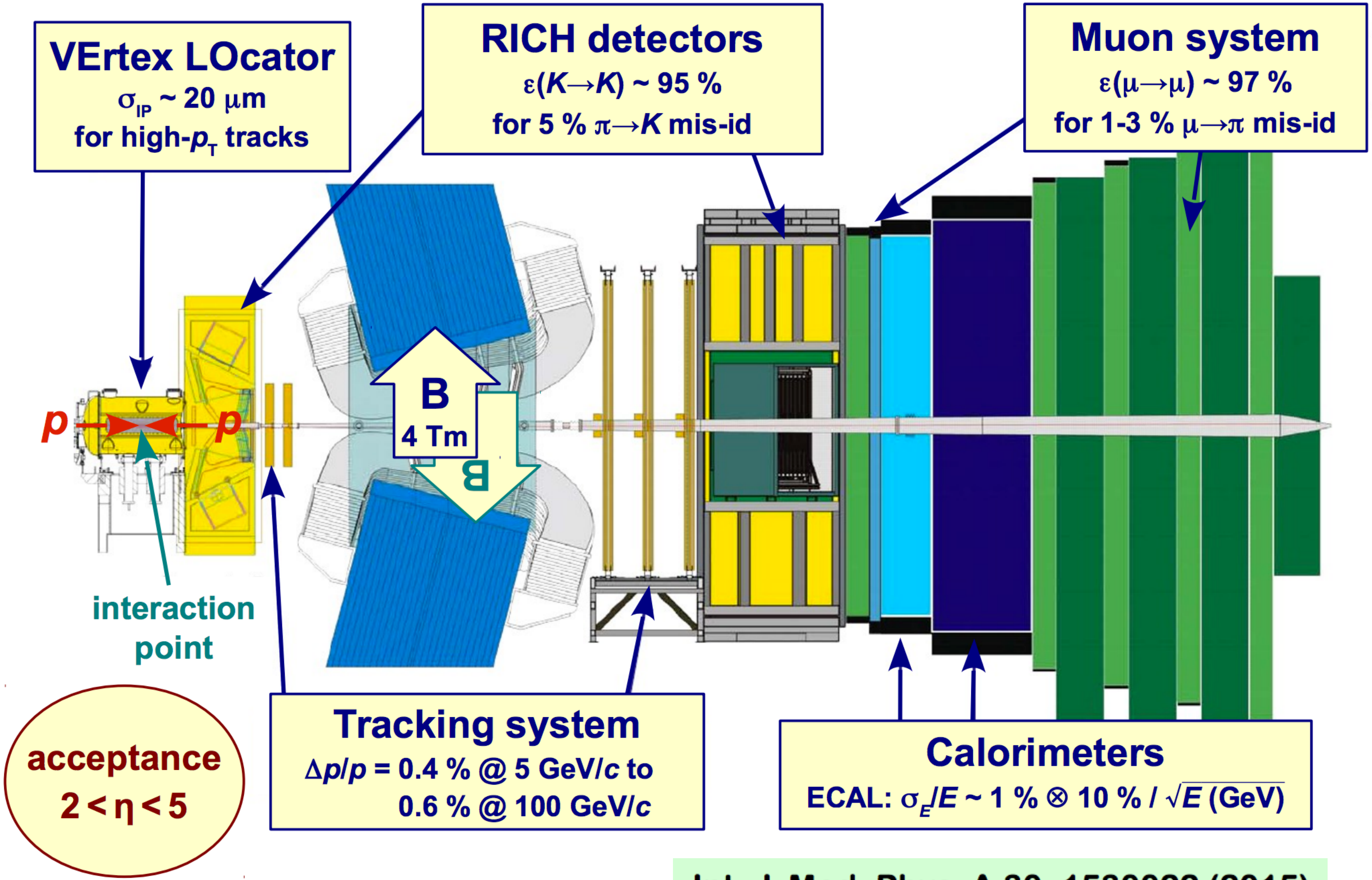
- Many tests performed in the past, comparing decays to different lepton families, with strongest limits in the EW sector.

Now LHC is allowing a new bunch of LFU tests to be performed!
(Main topic of this talk)

OUTLINE

- Lepton universality tests in b->sll
- Lepton universality tests in b->clv
- Lepton universality test in W->lv
- Conclusion

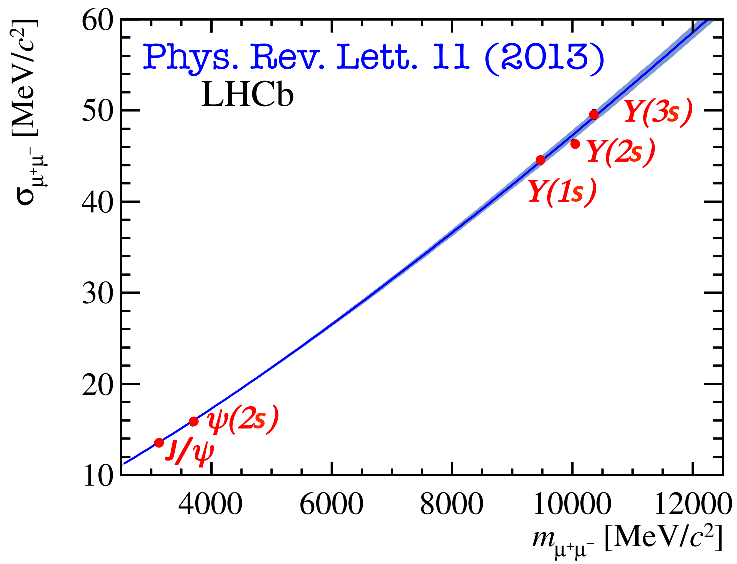
LHCb DETECTOR



Int. J. Mod. Phys. A 30, 1530022 (2015)

RECONSTRUCTION OF LEPTONS IN LHCb

Muon reconstruction extremely performant in LHCb:
- dedicated muon chambers;
- clear trigger signature;
- very efficient tracking system.

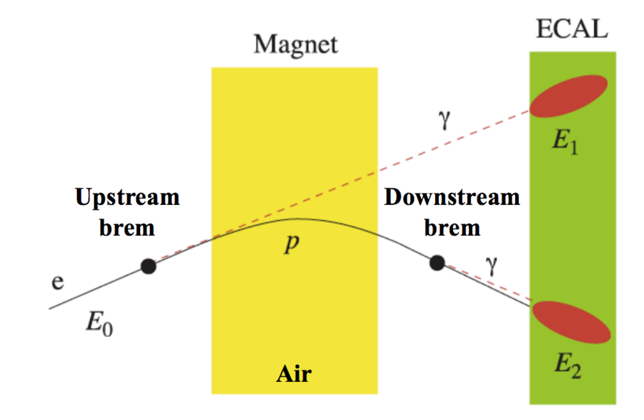


Taus reconstructed through their decay products.
- Tau decay vertex not always identified.
- Neutrinos => missing energy and degradation of the mass resolution.

Leptonic:
- BR($\tau^- \to \mu^- \nu\nu$) = 17.41 ± 0.04 %
- BR($\tau^- \to e^- \nu\nu$) = 17.83 ± 0.04 %

Hadronic:
- BR($\tau^- \to \pi^- \nu$) = 10.83 ± 0.06 %
- BR($\tau^- \to \pi^- \pi^0 \nu$) = 25.52 ± 0.09 %
- BR($\tau^- \to \pi^- \pi^0 \pi^0 \nu$) = 9.30 ± 0.11 %
- BR($\tau^- \to \pi^- \pi^+ \pi^- \nu$) = 9.31 ± 0.06 %
- BR($\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu$) = 4.62 ± 0.06 %

Electrons identified through the EM calorimeter
- high occupancy of calorimeters => hardware trigger thresholds higher than on muon
- bremsstrahlung => degradation of the *B* mass resolution



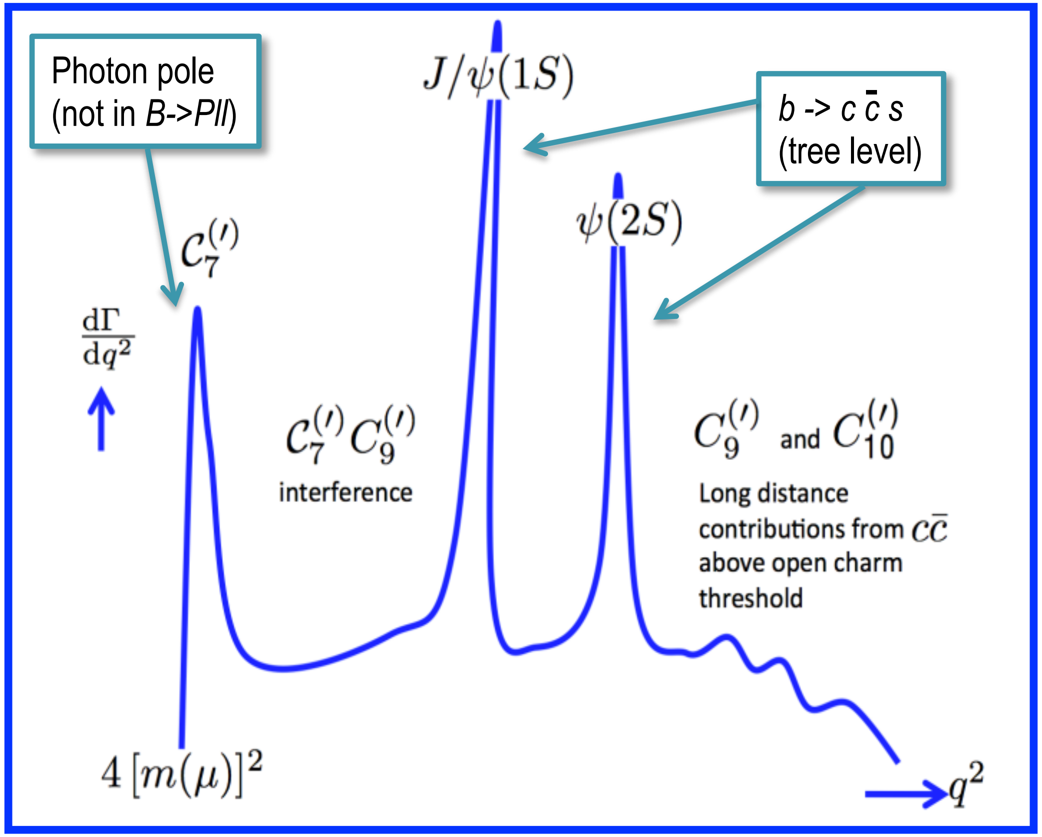
EFFECTIVE THEORY APPROACH

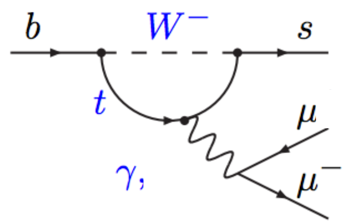
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\text{right-handed part suppressed in SM}} \Big]$$

i = 1, 2	Tree
i = 3 -6, 8	Gluon penguin
i = 7	Photon penguin
i = 9, 10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin

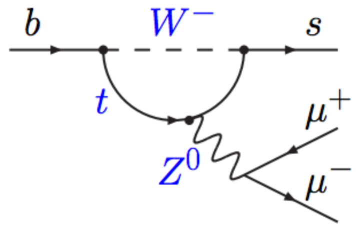
Operators O_i: long-distance effects, non-perturbative

Wilson coefficients C_i: short-distance effects, perturbative

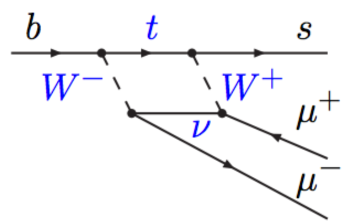




O_7



O_9



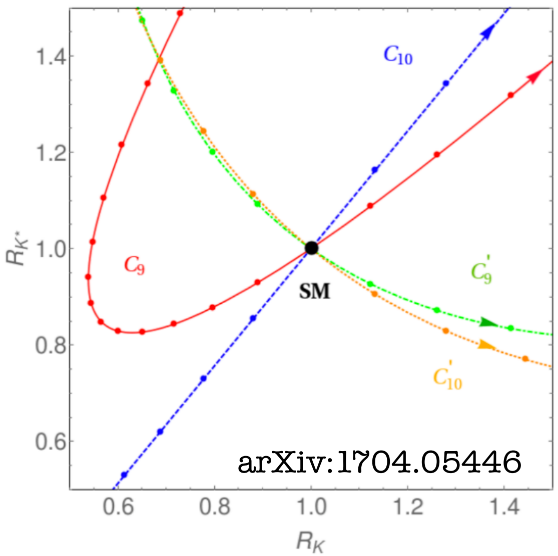
O_{10}

THE LU TEST R_H

$$R_H = \frac{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B \to H \ell^+ \ell^-)}{dq^2}}{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B \to H \ell'^+ \ell'^-)}{dq^2}}$$

(*H* = any hadronic system)

- Expected to be 1 in the Standard Model, apart from precisely predictable phase space effects and helicity-suppressed contributions.
- Theoretical uncertainty at 10^{-3}, QED effects at % level (arXiv:1605.07633)
- Not affected by QCD effects (ex: charm loops)
- Different ratios provide complementary information:



R_{K^*} DATASET AFTER PRESELECTION

- In LHCb we use the double ratio of the rare to the J/ψ channel to reduce systematic uncertainities:

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

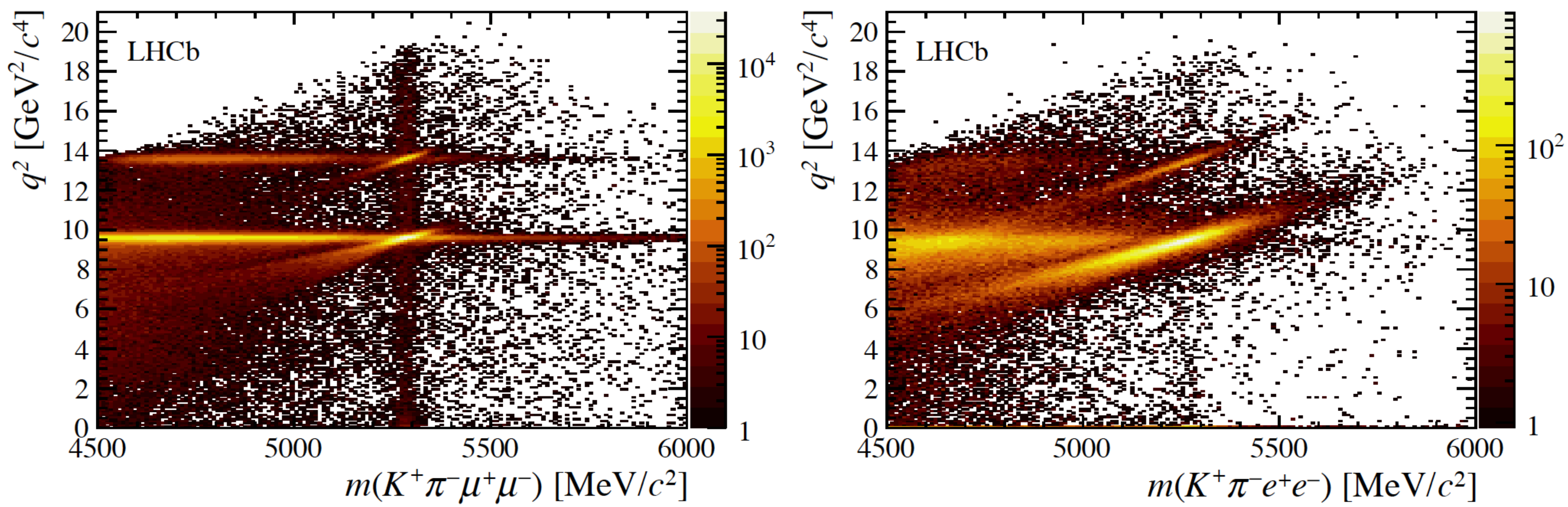
- All run1 ($3fb^{-1}$)

- Analysis in two q^2 bins:
  - low-q^2 $[0.045, 1.1]$ GeV^2/c^4
  - central-q^2 $[1.1, 6]$ GeV^2/c^4

arXiv:
1705.05802

Dataset after preselection

arXiv:1705.05802



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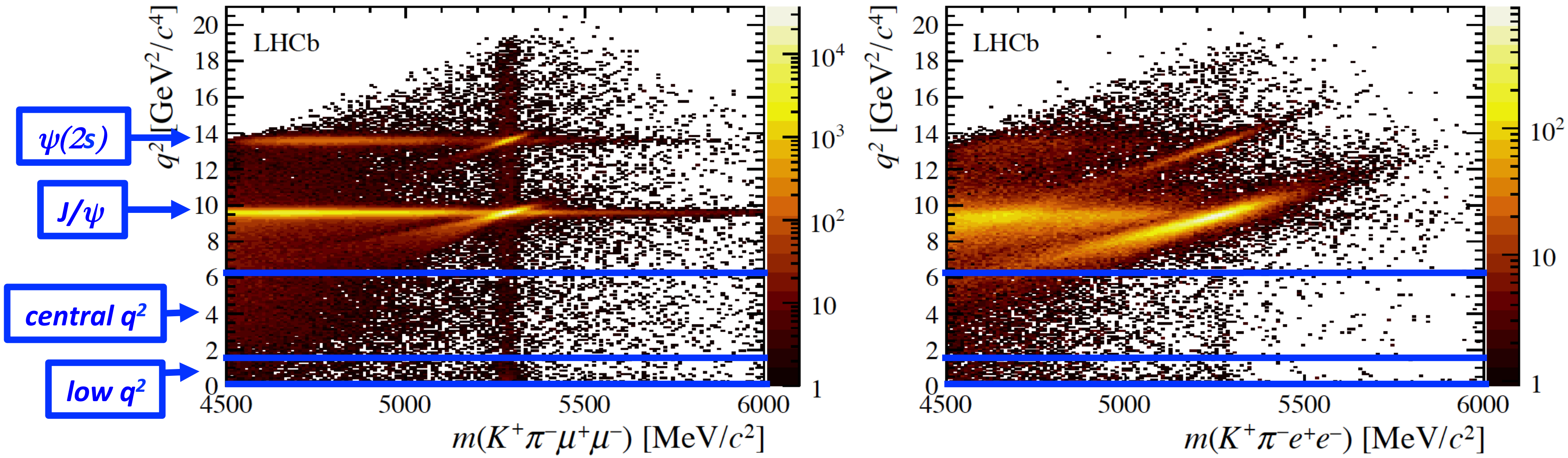

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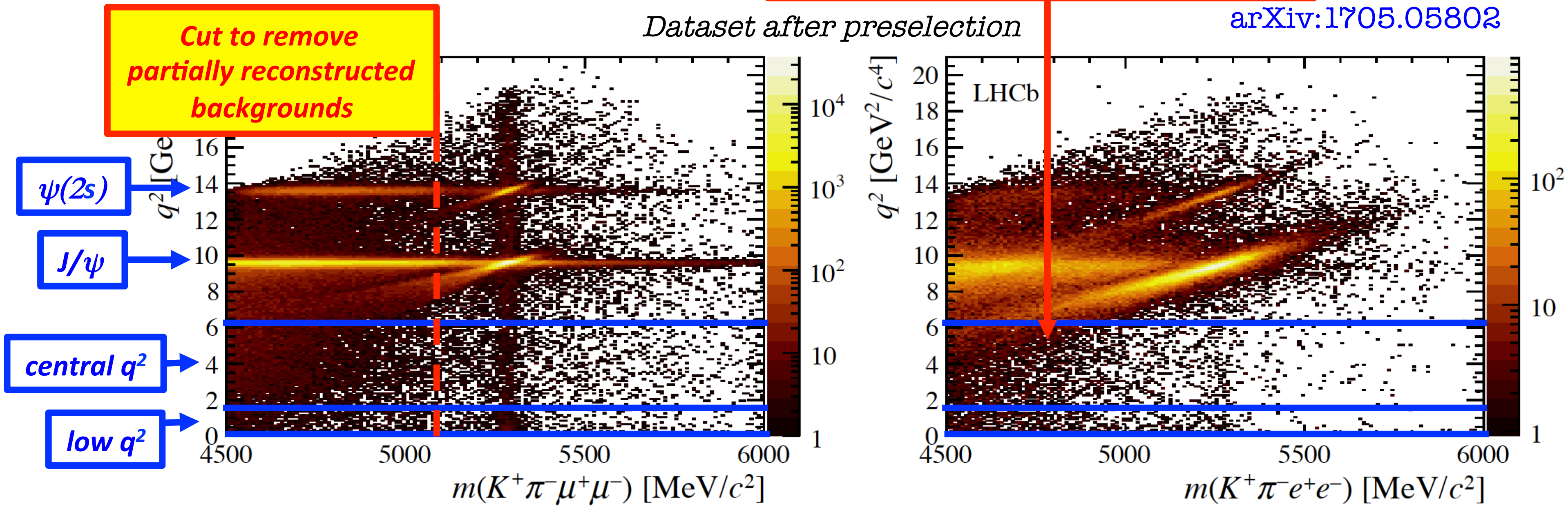
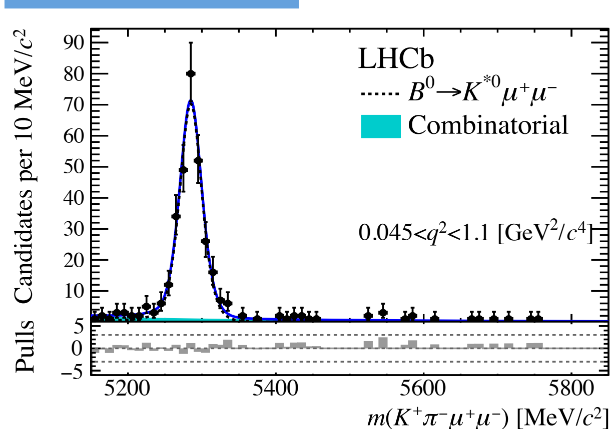


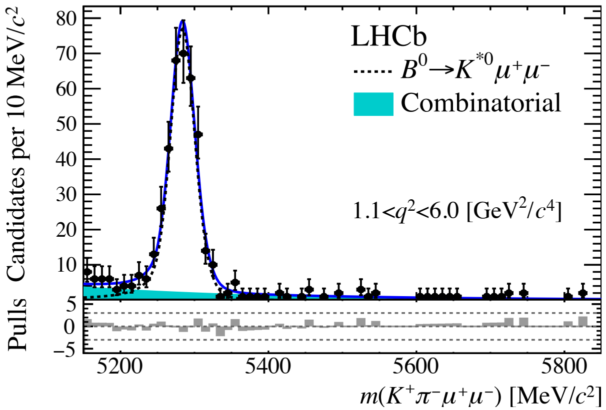
R_{K^*} YIELDS AFTER FULL SELECTION

$B^0 \to K^{*0}\mu\mu$

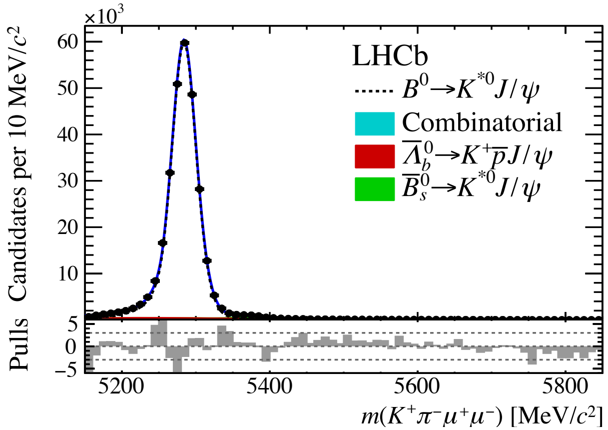
arXiv:1705.05802



Low q^2 : 285 ± 18

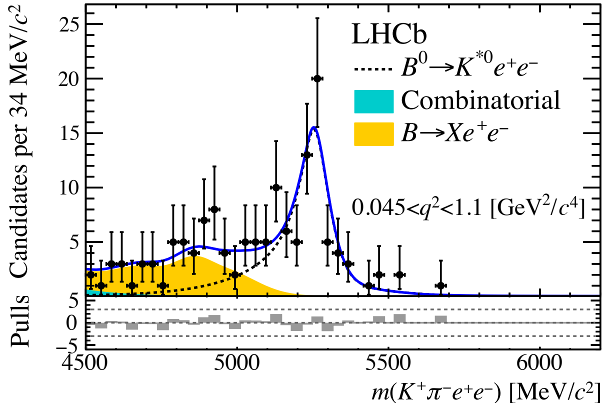


Central q^2 : 353 ± 21

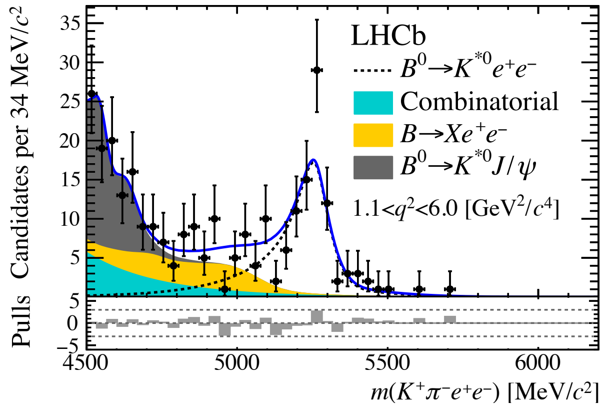


J/ψ region : 274K

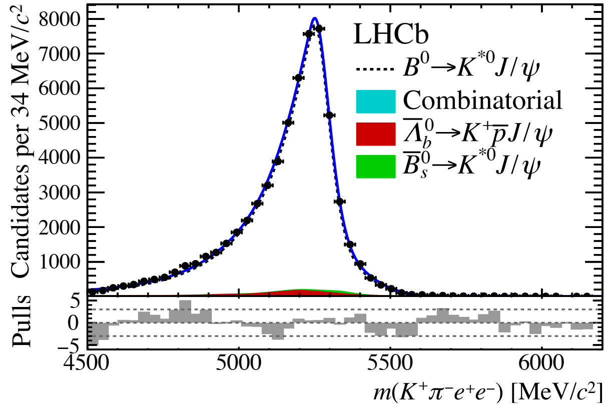
$B^0 \to K^{*0}ee$



Low q^2 : 89 ± 11



Central q^2 : 111 ± 14



J/ψ region : 58K

R_{K^*} CROSSCHECKS

arXiv:1705.05802

- **$r_{J/\psi}$ ratio** : compatible with 1 and flat as function of kinematics and event multiplicity => very stringent test! (not a double ratio)

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

- **$R_{\psi(2s)}$ and r_γ ratios** : consistent with expectations

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

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

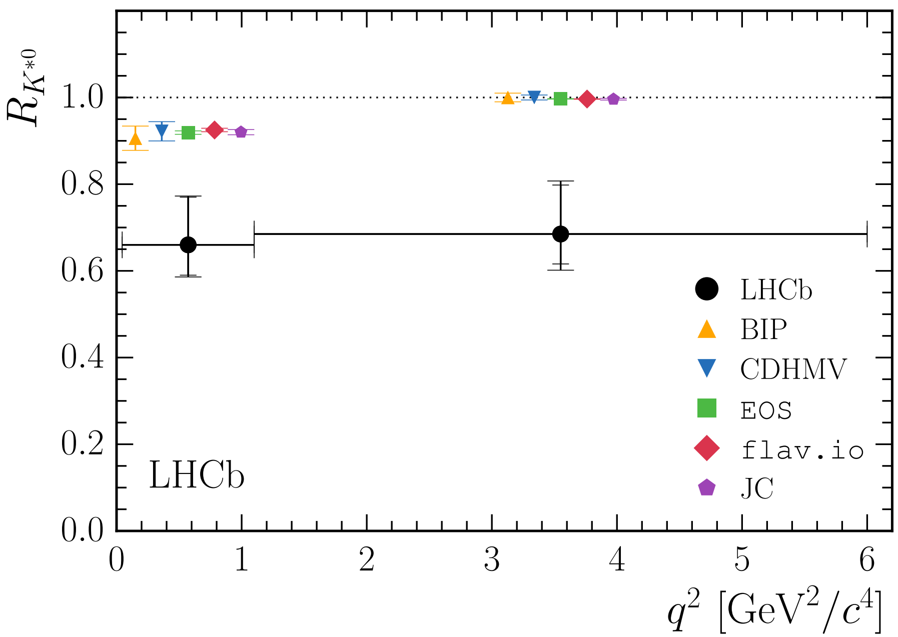
- ***BR(B->K*μμ)*** : in agreement with published LHCb result [arXiv:1606.04731].
- **No corrections to MC** : less than 5% variation on R_{K^*}.
- **Population of bremsstrahlung categories** : consistent between data and MC.
- **Kinematic distributions** : consistent among MC/background subtracted data.

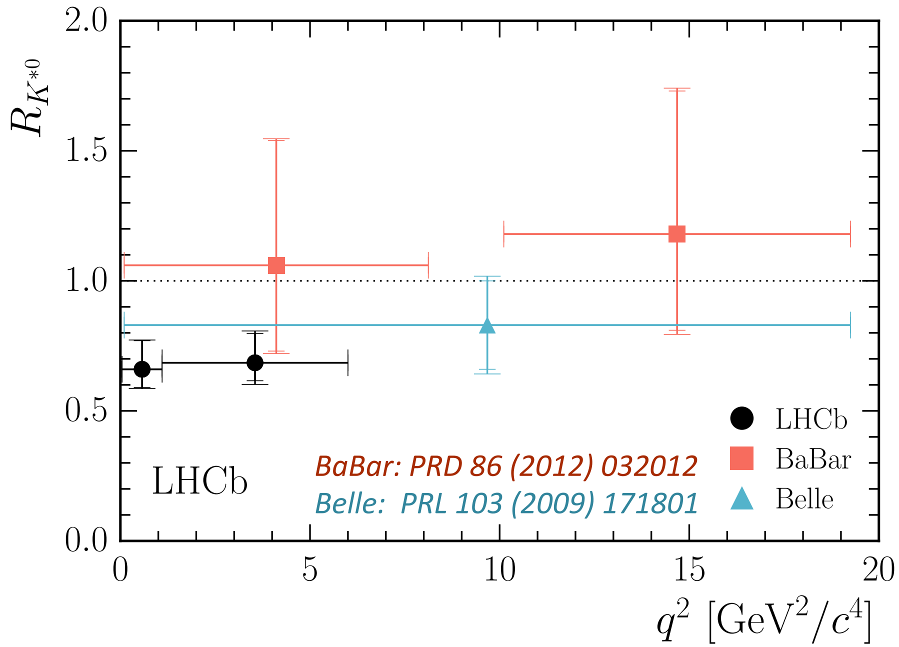
R_{K^*} RESULTS

arXiv:1705.05802

- Measurement statistically dominated.
- Compatibility with the SM:
  - 2.1-2.3 standard deviations (low-q²)
  - 2.4-2.5 standard deviations (central-q²)

	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66\ ^{+\ 0.11}_{-\ 0.07} \pm 0.03$	$0.69\ ^{+\ 0.11}_{-\ 0.07} \pm 0.05$
95.4% CL	[0.52, 0.89]	[0.53, 0.94]
99.7% CL	[0.45, 1.04]	[0.46, 1.10]





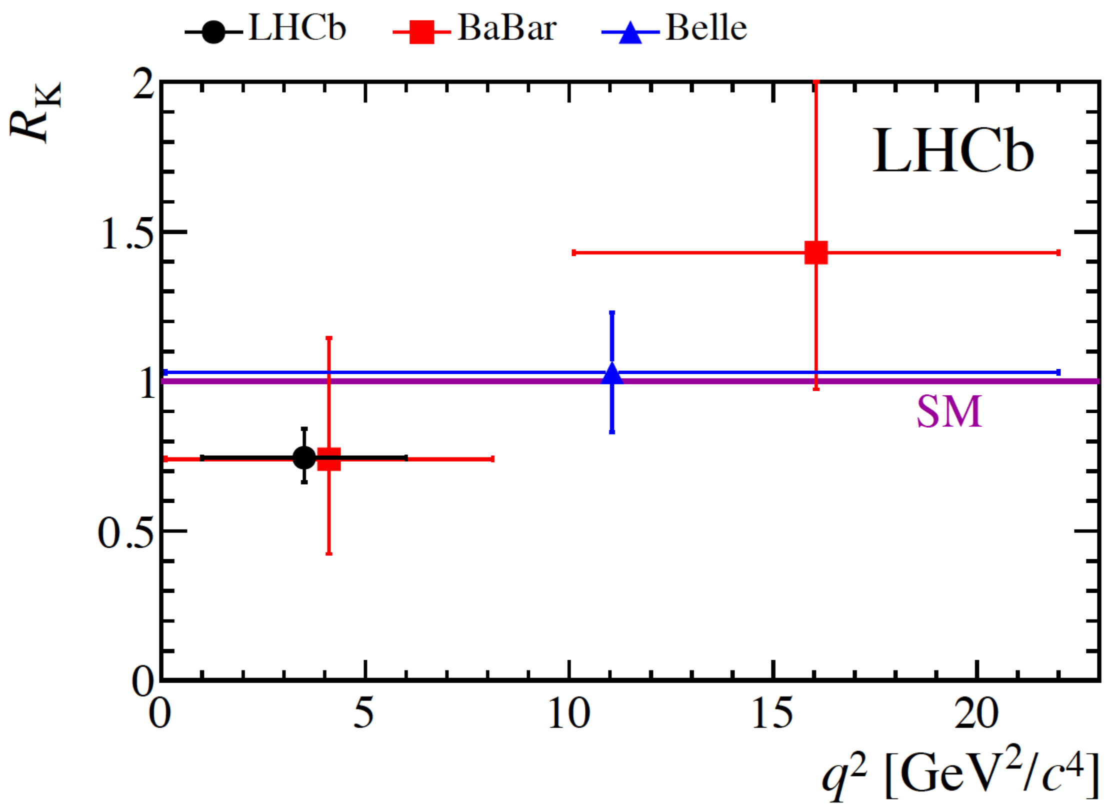
BIP	arXiv:1605.07633
CDHMV	arXiv:1510.04239, 1605.03156, 1701.08672
EOS	arXiv:1610.08761, https://eos.github.io
flav.io	arXiv:1503.05534, 1703.09189, flav-io/flavio
JC	arXiv:1412.3183

OTHER b->sll RESULTS: R_K

- Analysis on the run1 dataset: 3 fb^{-1}

PRL 113, 151601 (2014)

- Performed in the q^2 range [1, 6] GeV^2/c^4

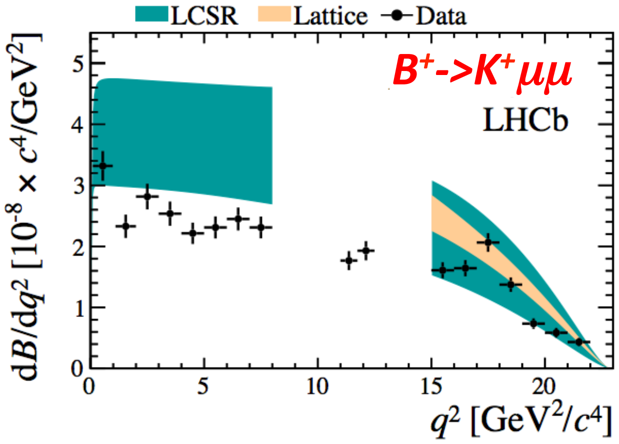


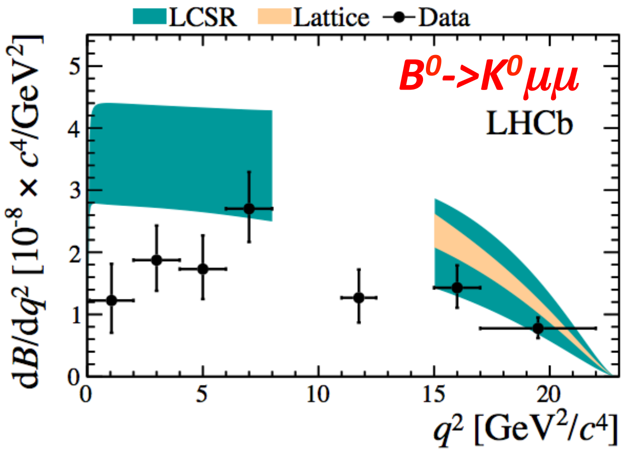
Compatible with Standard Model at 2.6σ

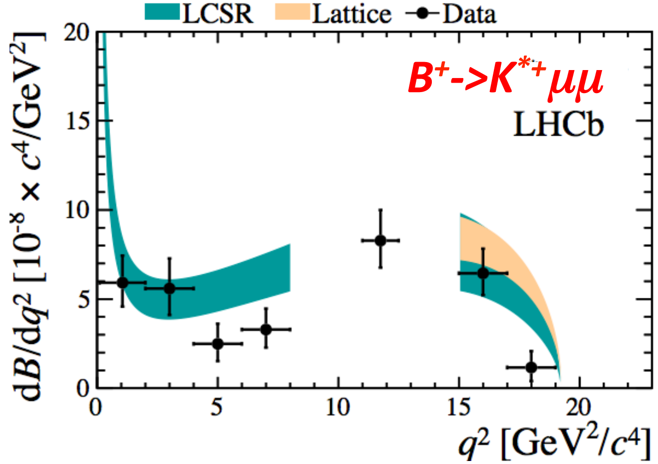
OTHER b->sll RESULTS: BRs

Measured ***BR*** **with muons are consistently lower than predicted in SM**

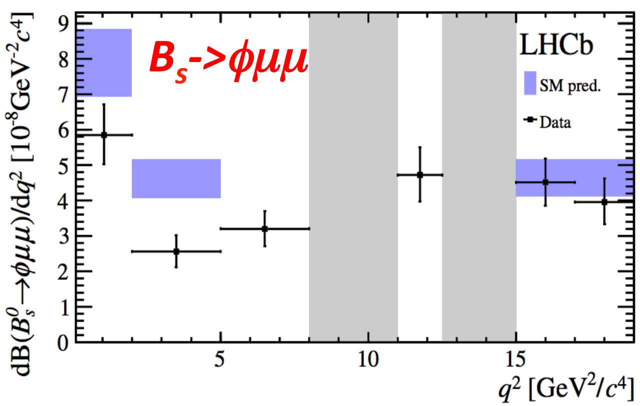
JHEP 06 (2014) 133



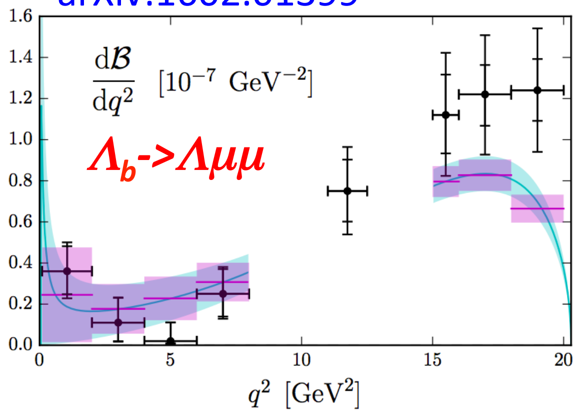




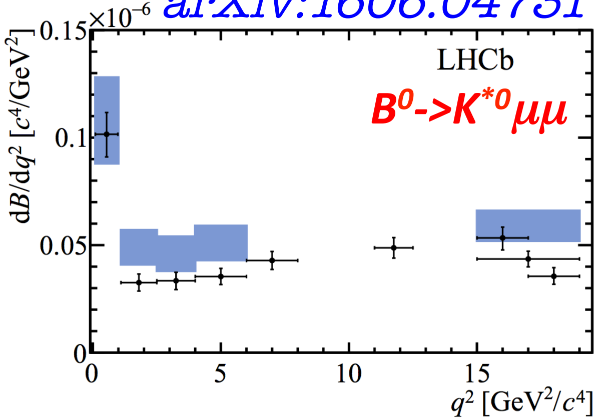
JHEP 09 (2015) 179



JHEP 06 (2015) 115 and
arXiv:1602.01399

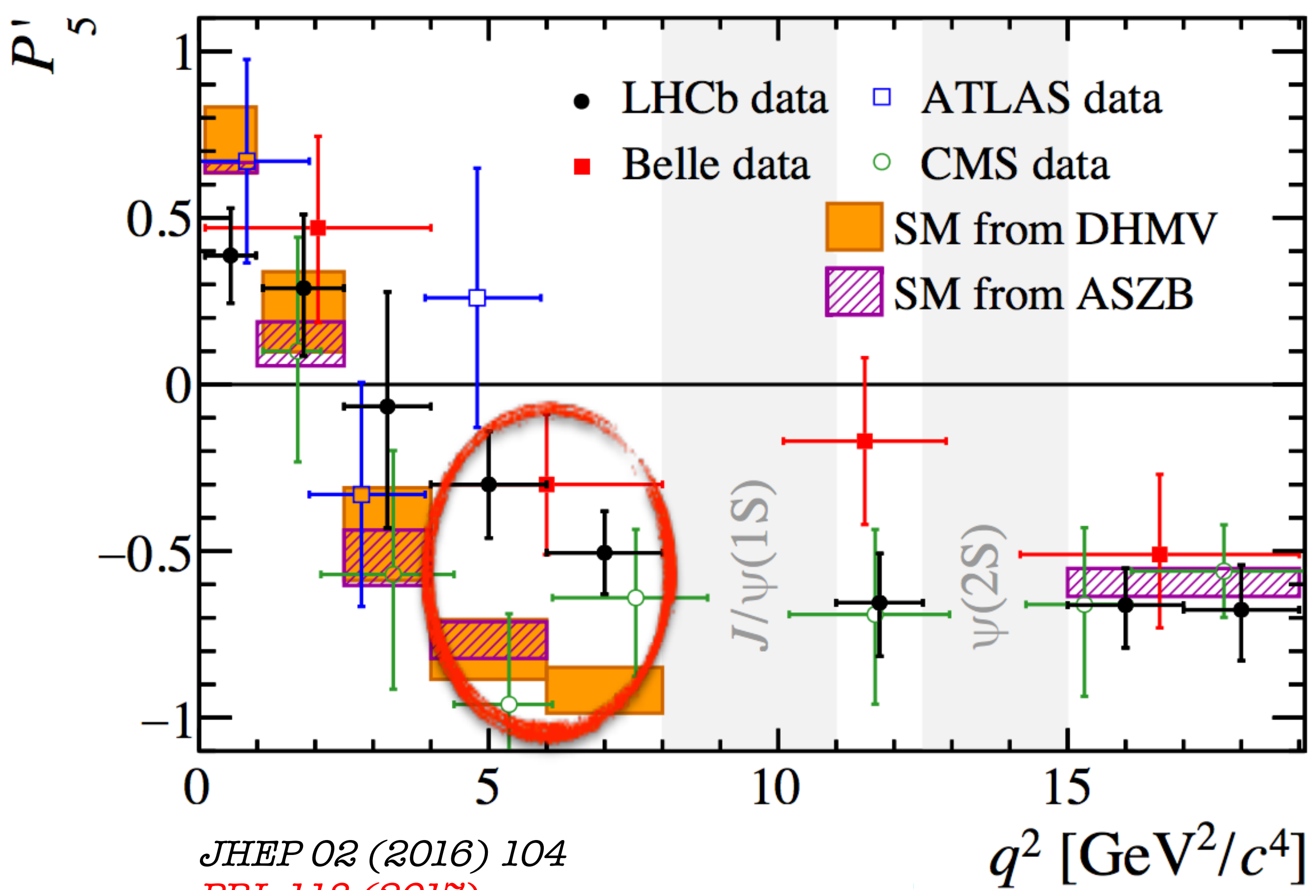


arXiv:1606.04731



OTHER b->sll RESULTS: angular observables

Angular observables in $B \to K^*\mu\mu$ show about 3.4σ discrepancy



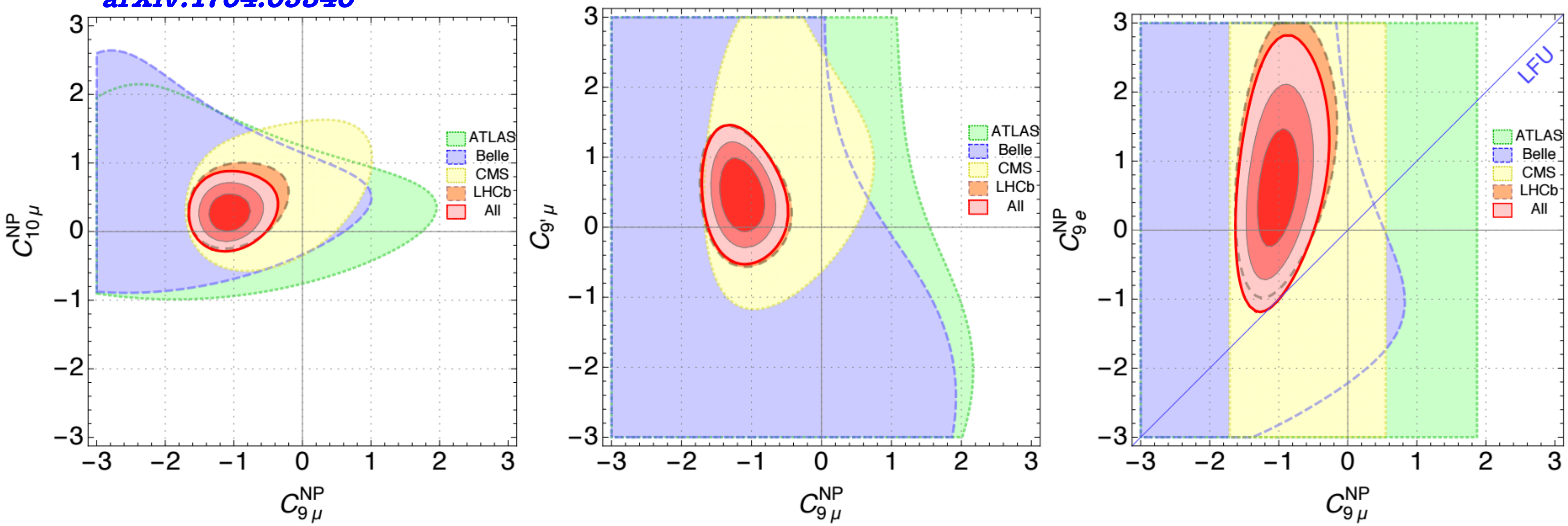
JHEP 02 (2016) 104
PRL 118 (2017)
ATLAS-CONF-2017-023
CMS-PAS-BPH-15-008

THE GLOBAL PICTURE

- Adding BRs and angular observables of *b->μμ, b->sll, b->sγ* => up to 5σ deviation from the SM (but QCD effects?)

- Mostly affecting $C_{9\mu}$ and $C_{10\mu}$ Wilson coefficients

arXiv:1704.05340



THE GLOBAL PICTURE

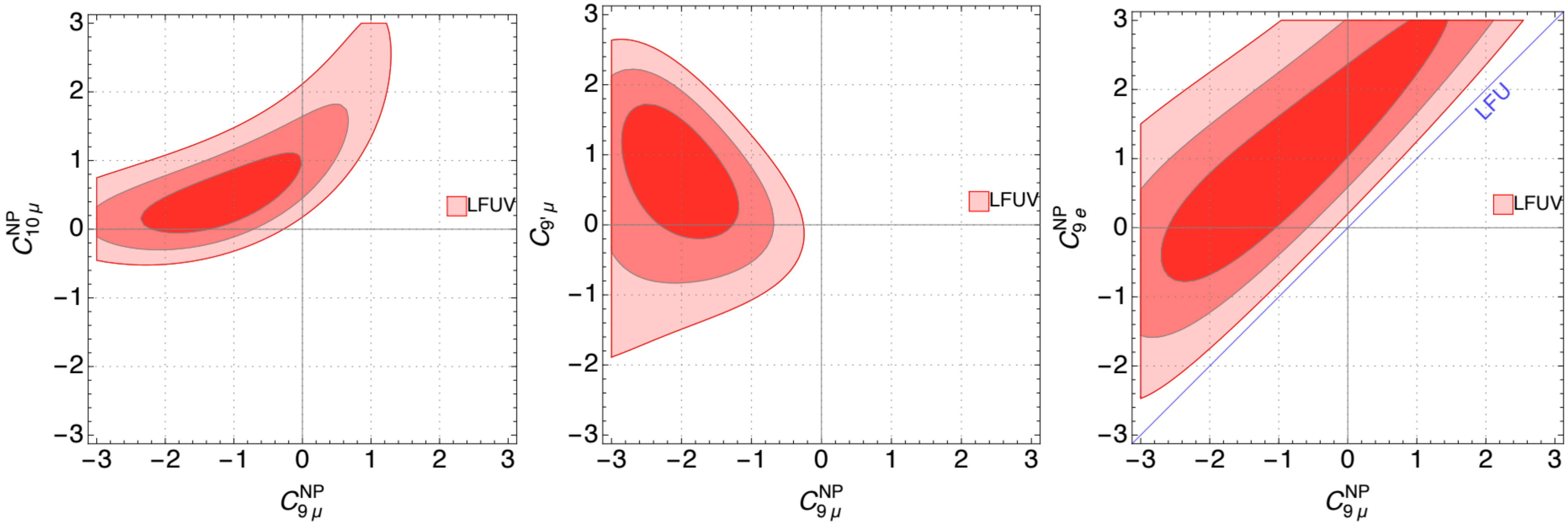
- Adding BRs and angular observables of *b->μμ, b->sll, b->sγ*
  => up to 5σ deviation from the SM (but QCD effects?)

- Mostly affecting $C_{9\mu}$ and $C_{10\mu}$ Wilson coefficients

- **Global fits of LFU only shows about 3σ discrepancy from SM**

- Remember: LFU tests are not affected by QCD effects (ex: charms loops)

arXiv:1704.05340



THE GLOBAL PICTURE

Many other theoretical papers:
arXiv:1704.05438v1
arXiv:1704.05444v1
arXiv:1704.05446v1
arXiv:1704.05447v1
arXiv:1704.05672v1
arXiv:1704.05835v1
arXiv:1704.05849v1
arXiv:1704.06005v1
arXiv:1704.06188v1
arXiv:1704.06200v1
arXiv:1704.06240v1
arXiv:1704.06659v1
arXiv:1704.07347v1
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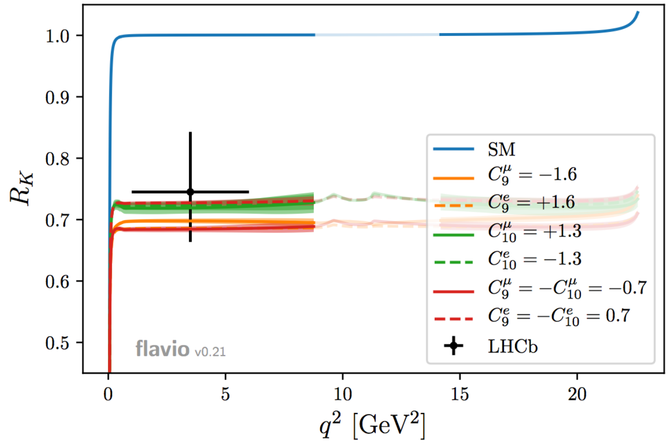
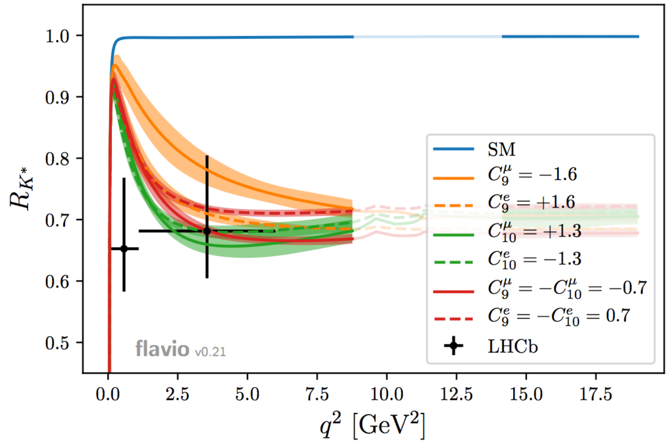
arXiv:1704.05435

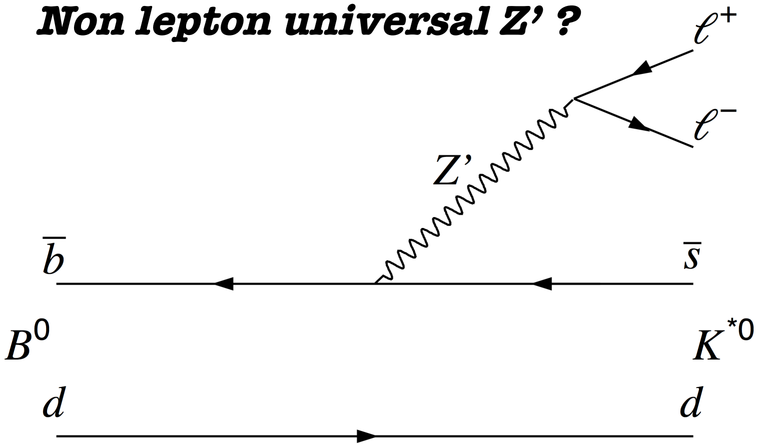




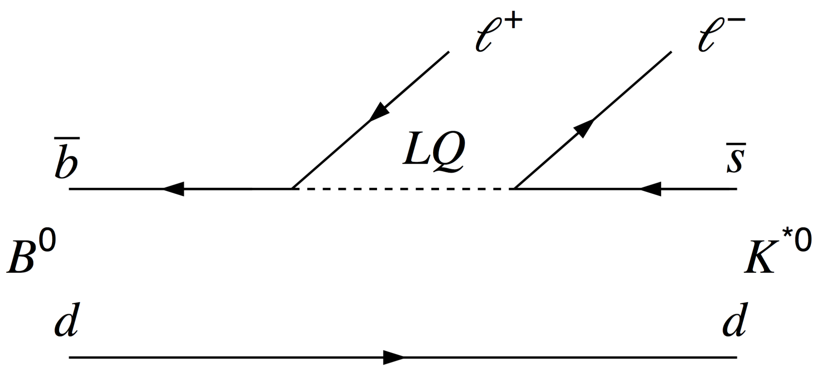
Some NP hypotheses mentioned

arXiv:1704.05435

Non lepton universal Z' ?



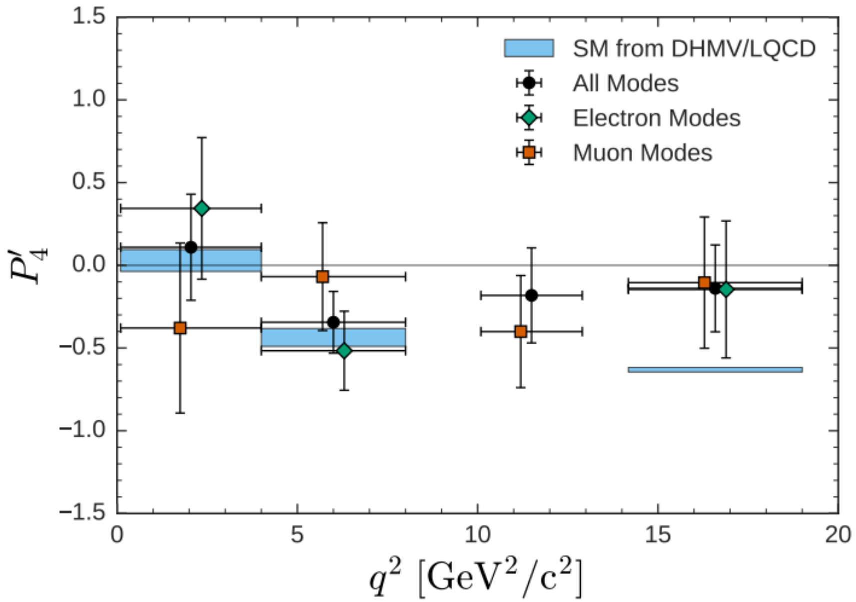
Leptoquarks?

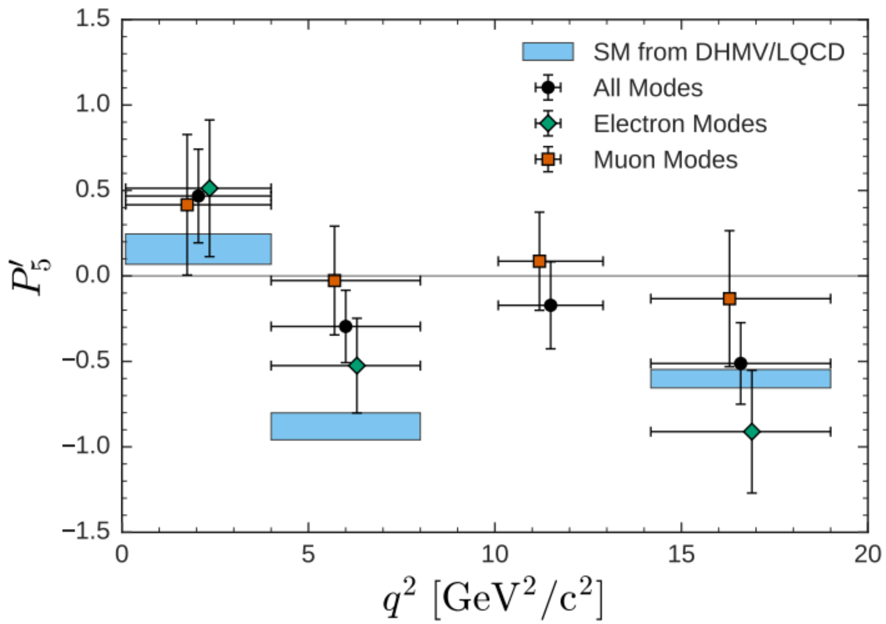


PROSPECTS FOR LFU TESTS IN b->sll

- $\mathbf{R_K}$, $\mathbf{R_{K^*}}$, $\mathbf{R\phi}$ and similar ratios need to be measured using the full run1+run2 statistics, and in all the q^2 bins.

- Perform LFU angular tests [as from Belle: Phys.Rev.Lett.118, 111801 (2017)].





- Also search for LFV decays:

  $B_{(s)} \to \tau\,\mu$, $B_{(s)} \to e\,\mu$,
  $B^+ \to K^+\,\tau\,\mu$, $B^0 \to K^{*0}\,\tau\,\mu$,
  $B^+ \to K^+\,e\,\mu$, $B^0 \to K^{*0}\,e\,\mu$,
  $B_s \to \phi\,\tau\,\mu$, $B_s \to \phi\,e\,\mu$, etc…

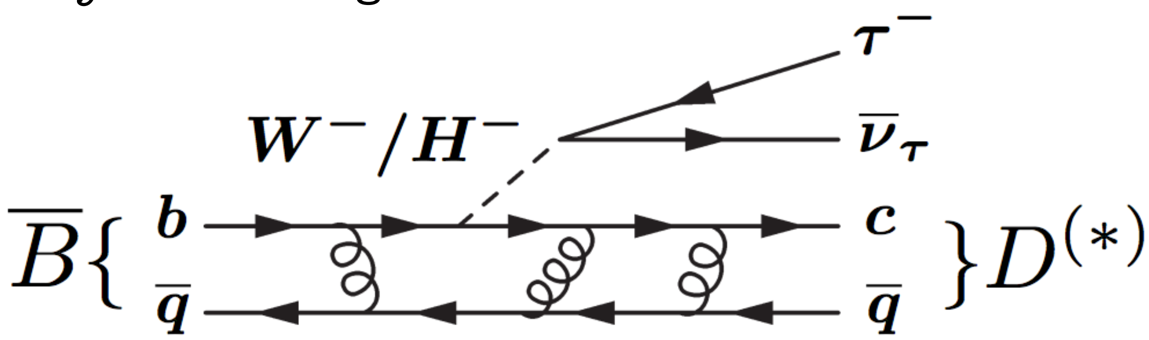
OUTLINE

- Lepton universality tests in b->sll
- **Lepton universality tests in b->clν**
- Lepton universality test in W->lν
- Conclusion

THE R_{D^*} MEASUREMENT

$$R_{D^*} = \frac{\Gamma(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu_\tau})}{\Gamma(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu_\mu})}$$

- SM expectation: 0.252+/- 0.003 [PRD85 (2012) 094025]
- Sensitive, for ex., to charged Higgs or non minimal flavor violating couplings favoring the tau, or leptoquarks
- NP could modify BR and angular distributions



R_{D^*} WITH LEPTONIC τ IN LHCb

$\tau \to \mu \nu_\mu \nu_\tau$

- Neutrinos => **no narrow peak to fit in any distribution**
- 3D template fit. Use discriminating variables calculated in the B rest frame:

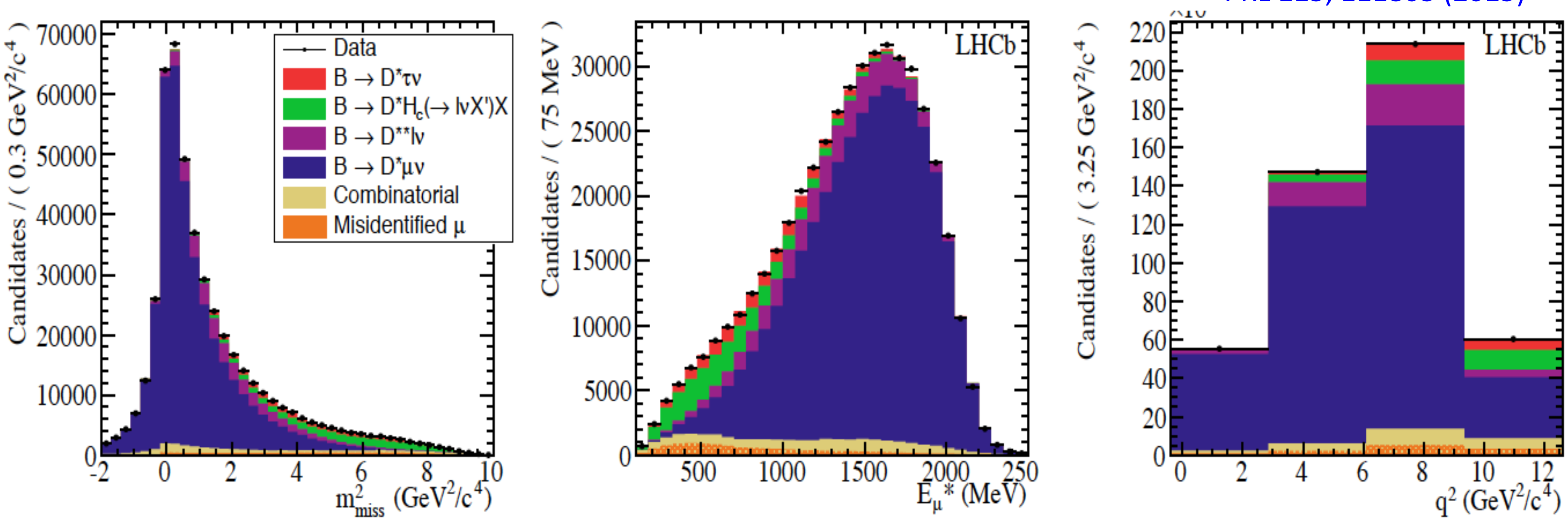
  - the missing mass squared: $m^2_{\text{miss}} = (p^\mu_B - p^\mu_D - p^\mu_\mu)^2$

  - the muon energy in c.o.m. frame: $E_\mu{}^*$

  - the squared four momentum transferred to the di-lepton system: q^2

Run1 dataset: 3 fb^{-1}

PRL 115, 111803 (2015)



$$R(D^*) = 0.336 \pm 0.027(stat) \pm 0.030(syst)$$

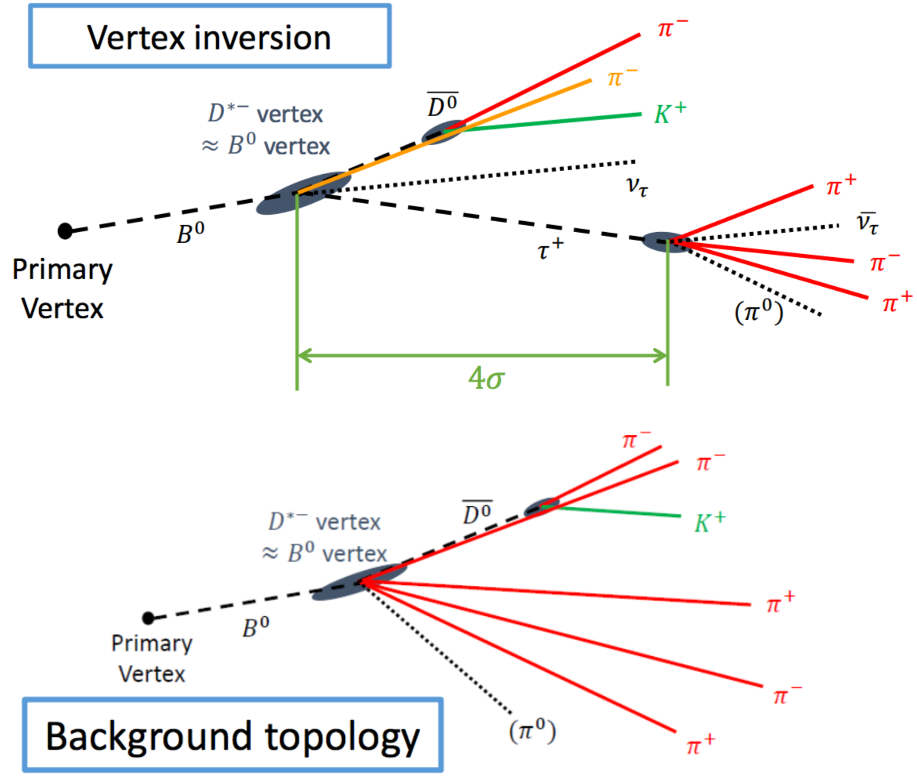
2.1 σ larger than the SM expectation

R_{D^*} HADRONIC IN LHCb $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$

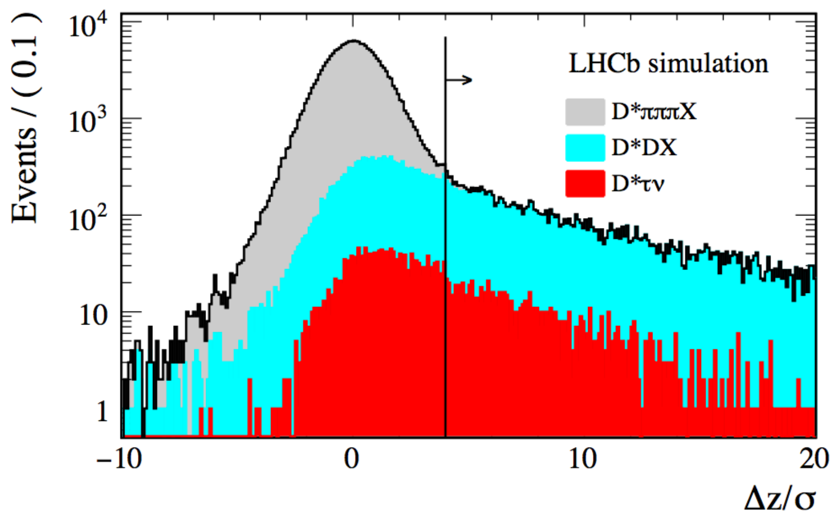
$$R_{D^*}^{HAD} = \frac{BR(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu_\tau})}{BR(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)} \frac{BR(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}{BR(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu_\mu})}$$

Same final state: systematics cancels — *External input*

- Good vertex reconstruction, but large hadronic backgrounds.
- Specific tools needed to reduce it, for ex: cut on vertex displacement.

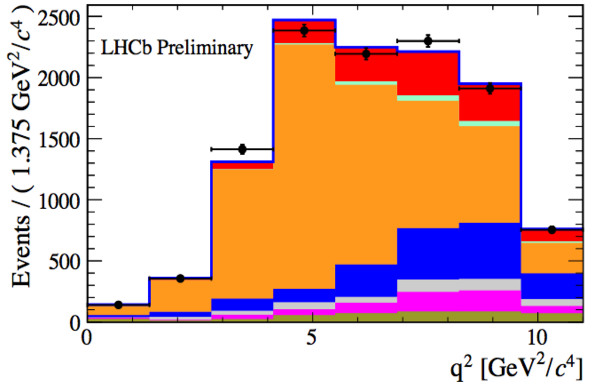


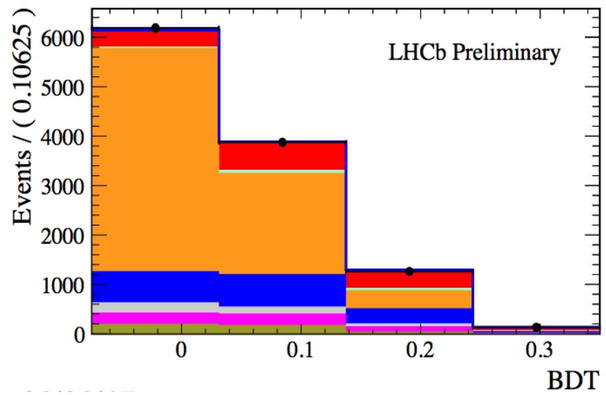
LHCb-PAPER-2017-017

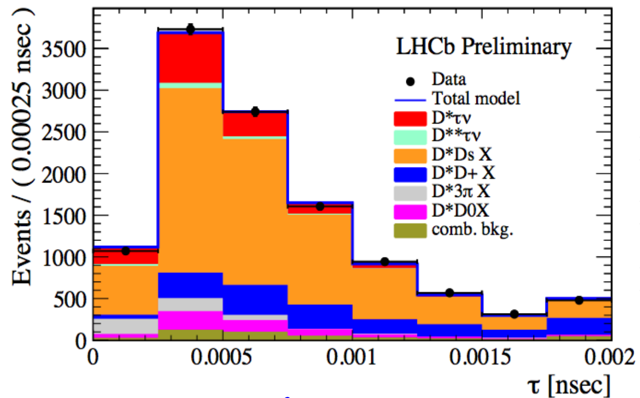


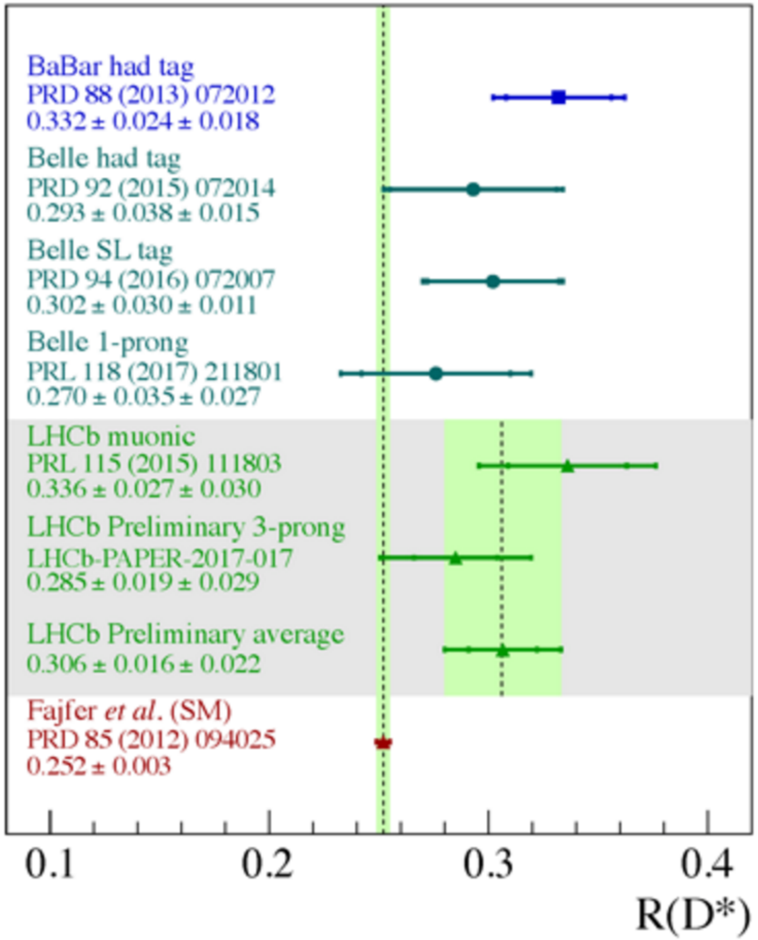
R_{D^*} HADRONIC IN LHCb: RESULTS

Signal yield: 1300 events









$R(D^*)_{had}$ = 0.285 ± 0.019(stat) ±0.025(syst)±0.014(ext)

$R(D^*)_{LHCb}$: 0.306 ± 0.016 ± 0.022 => 2.1 σ from SM

Naive R(D),R(D*) world average => 4.1 σ from SM

LHCb-PAPER-2017-017

PROSPECTS FOR LFU TESTS IN b->clv

- R(D*) will have 4 times the present dataset with Run2
- Other measurements ongoing:

Decay	Observable
$B^0 \to D^{*-} \tau^+ \nu_\tau$	$R(D^{*-})$
$B^0 \to D^- \tau^+ \nu_\tau$	$R(D^-)$
$B^+ \to D^0 \tau^+ \nu_\tau$	$R(D^0)$
$B_s^0 \to D_s^{(*)} \tau^+ \nu_\tau$	$R(D_s^{(*)})$
$B_c^+ \to J/\psi \tau^+ \nu_\tau$	$R(J/\psi)$
$\Lambda_b \to \Lambda_c^{(*)-} \tau^+ \nu_\tau$	$R(\Lambda_c^{(*)})$

OUTLINE

- Lepton universality tests in b->sll
- Lepton universality tests in b->clv
- **Lepton universality test in W->lv**
- Conclusion

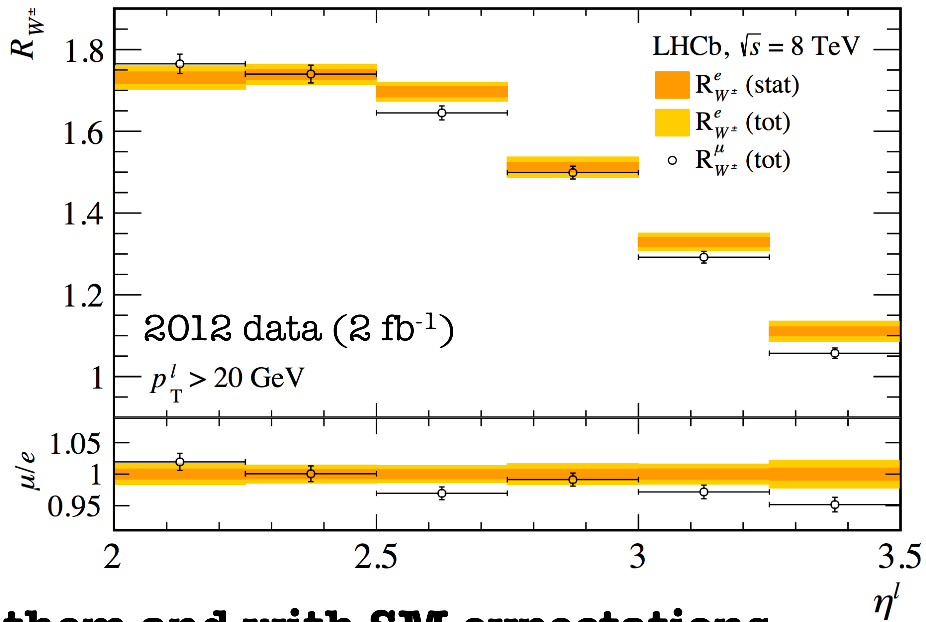
R_W MEASUREMENTS

R_W: ratio of forward production cross section $W \to e\nu$ (JHEP 10 (2016) 030) and $W \to \mu\nu$ (JHEP 01 (2016) 155)

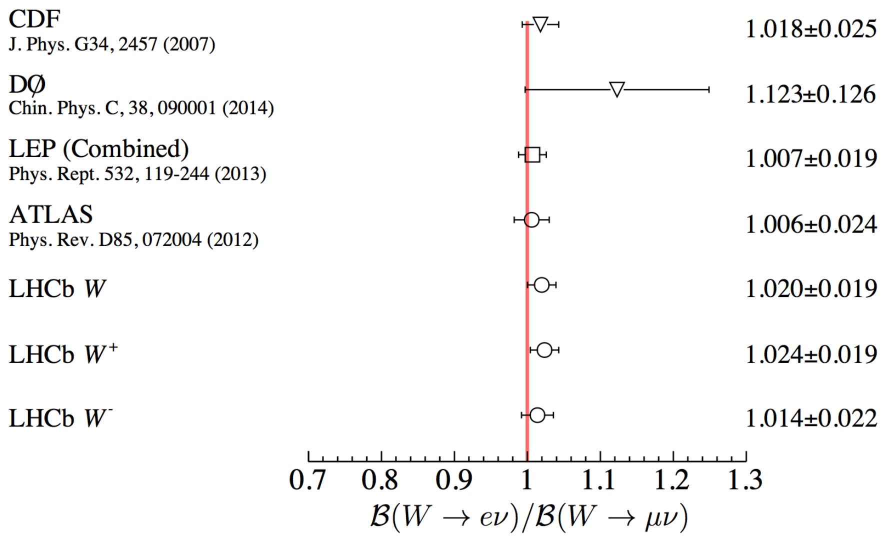
$$\frac{\mathcal{B}(W+ \to e^+\nu_e)}{\mathcal{B}(W+ \to \mu^+\nu_\mu)} = 1.024 \pm 0.003 \pm 0.019$$

$$\frac{\mathcal{B}(W- \to e^-\bar{\nu}_e)}{\mathcal{B}(W- \to \mu^-\bar{\nu}_\mu)} = 1.014 \pm 0.004 \pm 0.022$$

$$\frac{\mathcal{B}(W \to e\nu)}{\mathcal{B}(W \to \mu\nu)} = 1.020 \pm 0.002 \pm 0.019$$



All experiments in agreement among them and with SM expectations



New ATLAS result: Eur. Phys. J. C 77 (2017) 367

$$R_W = \frac{\sigma^{\text{fid},e}_{W\to e\nu}/E^e_W}{\sigma^{\text{fid},\mu}_{W\to\mu\nu}/E^\mu_W} = \frac{\sigma^{\text{fid}}_{W\to e\nu}}{\sigma^{\text{fid}}_{W\to\mu\nu}} = \frac{BR(W\to e\nu)}{BR(W\to\mu\nu)}$$
$$= 0.9967 \pm 0.0004\,(\text{stat}) \pm 0.0101\,(\text{syst})$$
$$= 0.997 \pm 0.010\,.$$

OUTLINE

- Lepton universality tests in b->sll
- Lepton universality tests in b->clv
- Lepton universality test in W->lv
- **Conclusion**

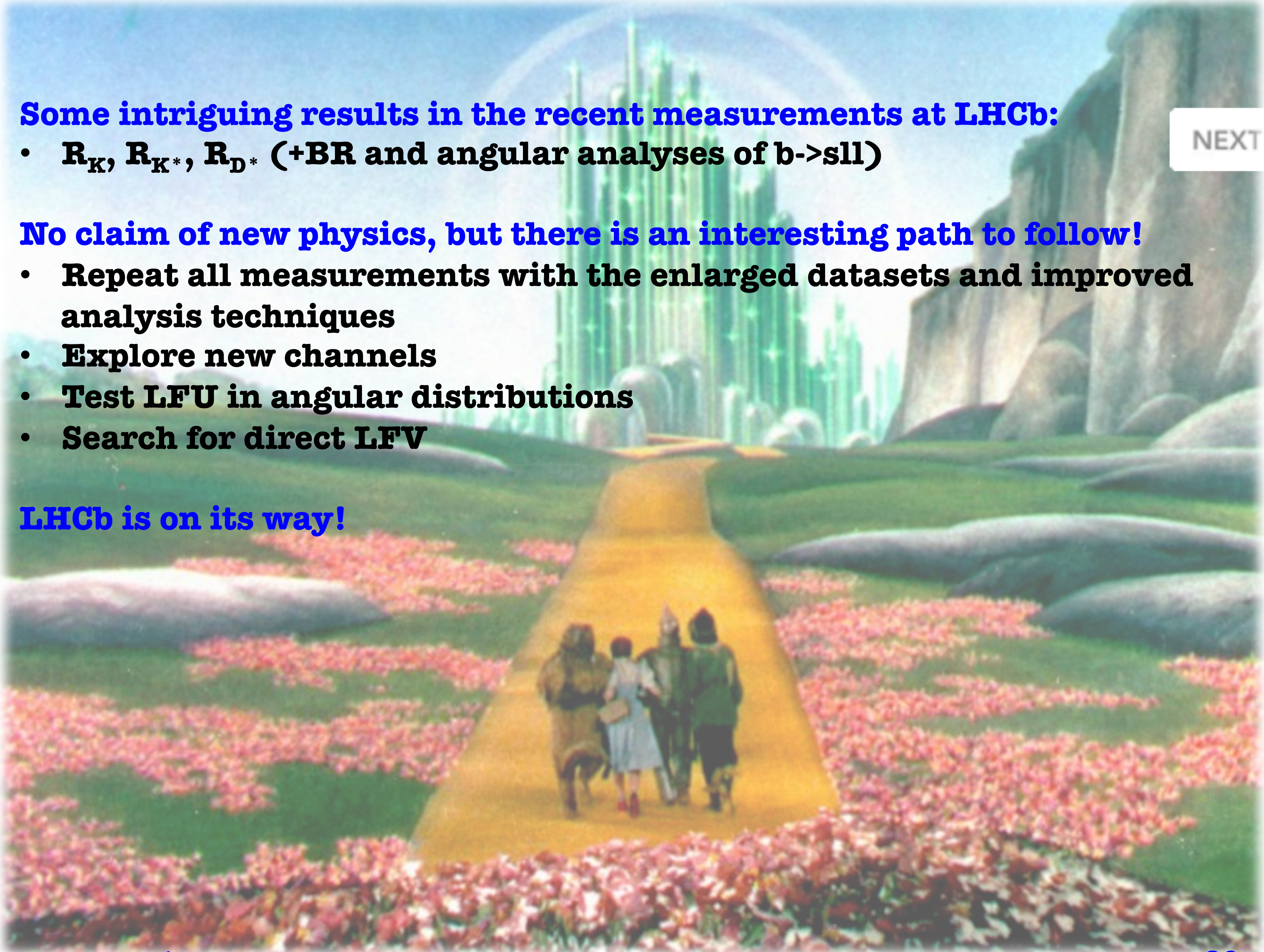
Some intriguing results in the recent measurements at LHCb:

- **R_K, R_{K^*}, R_{D^*} (+BR and angular analyses of b->sll)**

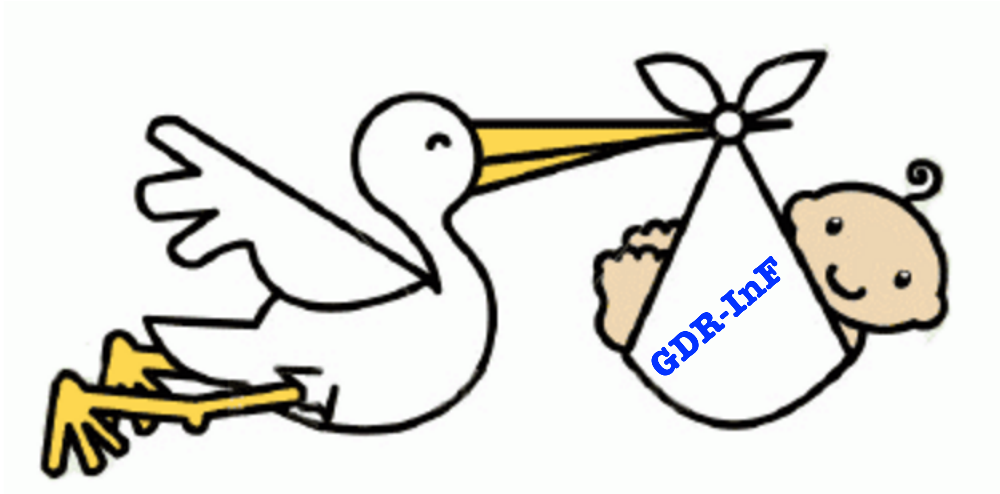
No claim of new physics, but there is an interesting path to follow!

- **Repeat all measurements with the enlarged datasets and improved analysis techniques**
- **Explore new channels**
- **Test LFU in angular distributions**
- **Search for direct LFV**

LHCb is on its way!



A new baby is born!



GDR Intensity Frontiers

- *CP violation*
- *Rare- radiative and semi-leptonic B decays*
- *Charm and Kaon physics*
- *Heavy flavour production and spectroscopy*
- *Interplay of quark and lepton flavour*
- *Future experiments*

Mailing list: GDR-INTENSITYFRONTIER-L@LISTSERV.IN2P3.FR
Website: http://gdrintensityfrontier.in2p3.fr/ (to be operational soon)
Contacts: Aoife Bharucha and Francesco Polci

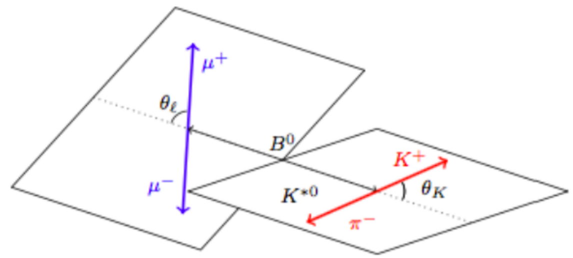
BACKUP

THE PRINCIPLE OF ANGULAR ANALYSES

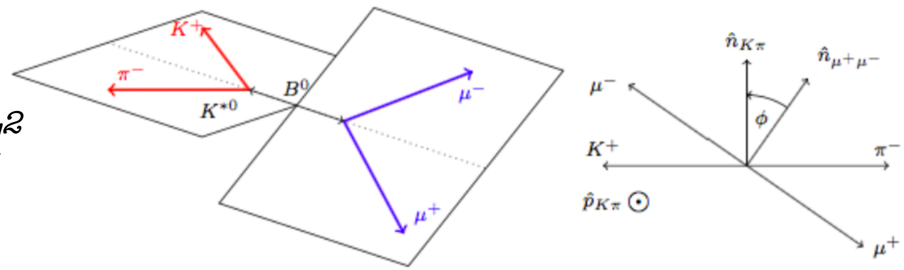
- Angular analyses are complex, but a rich framework to measure a variety of observables, sensitive to different sources of new physics depending on q^2

- Decays with four particles in the final state are described by:
  - three angles in the helicity basis;
  - the di-lepton invariant mass squared q^2

- **Observables depend on Wilson coefficients** (underlying short-distance physics) **and form-factors (hadronic matrix elements)**



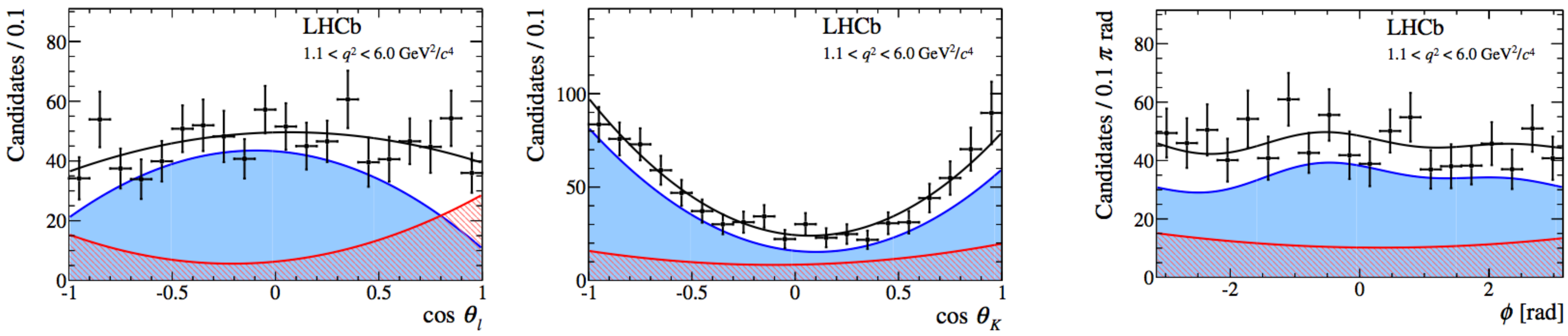
(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay

Example: ***B->K*μμ***

JHEP 02 (2016) 104



$B \to K^*\mu\mu$ ANGULAR ANALYSIS

Study the full angular distribution (θ_l, θ_K, ϕ) of the 4 final state particles.

Described by eight independent observables:

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

Observables (A_{FB}, F_L and S_j) are function of the Wilson coefficients.

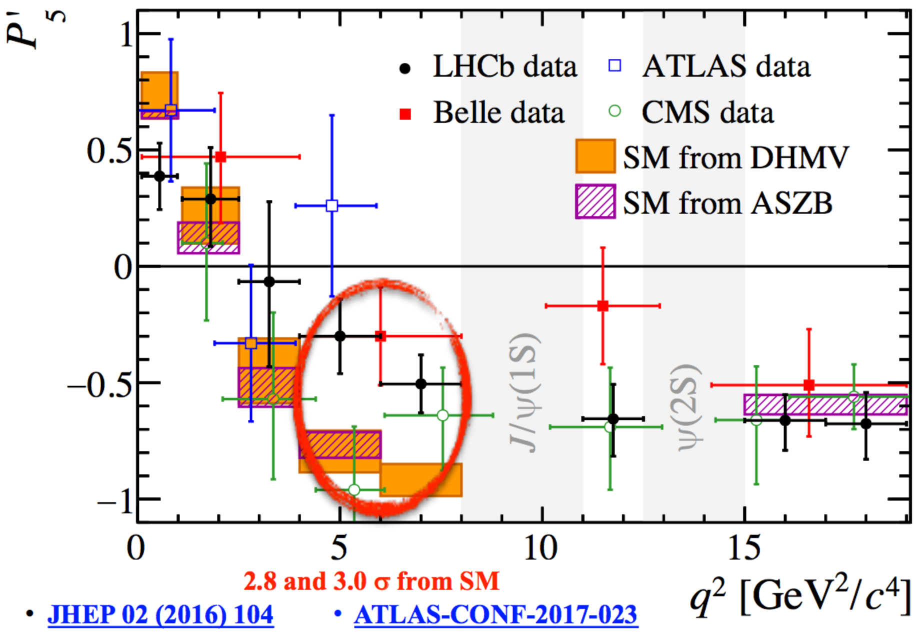
A cleaner set of observables, where hadronic form factor uncertainties cancels at the leading order, can be defined (*JHEP 1305(2013)137*), ex:

$$P'_5 \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

$B \to K^*\mu\mu$ ANGULAR ANALYSIS

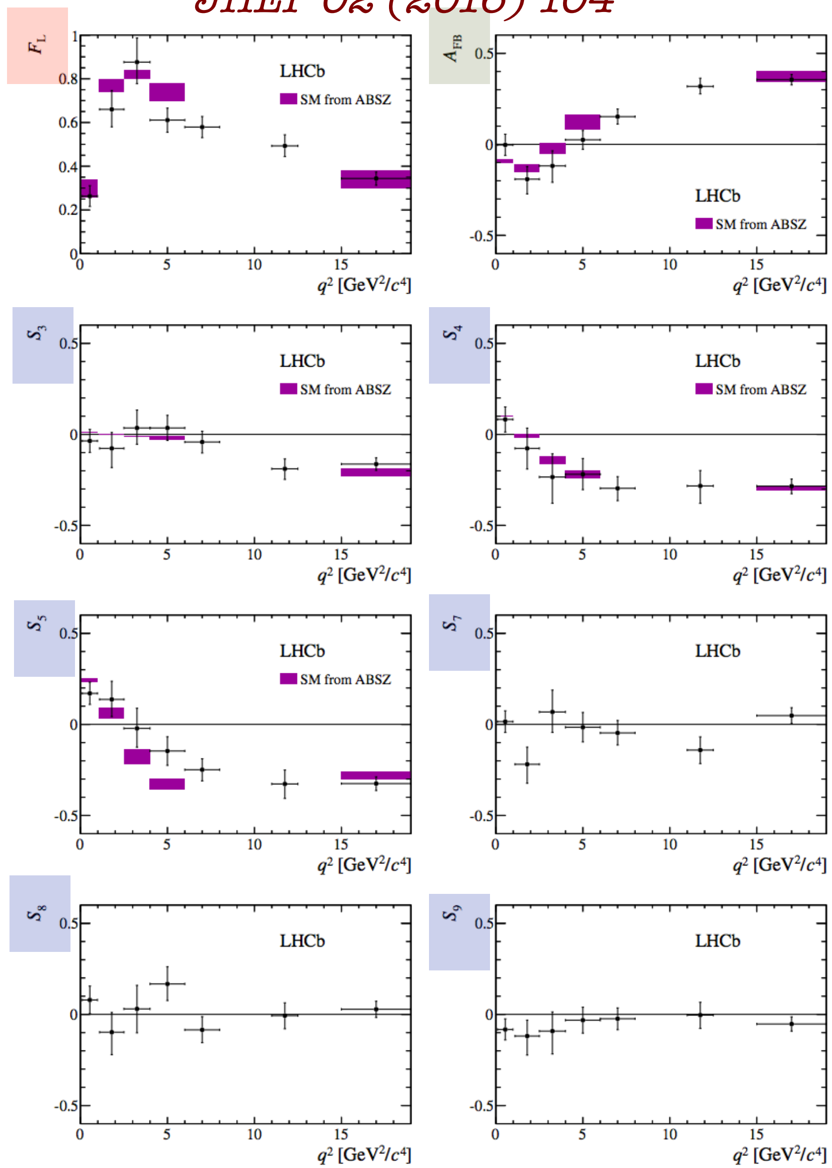
LHCb performed the first full angular analysis of $B \to K^*\mu\mu$, using Run1 (3 fb^{-1})

- full set of CP-averaged angular terms
- full set of CP-asymmetries
- correlation matrix published
- form-factor independent ratios of observables measured (P')



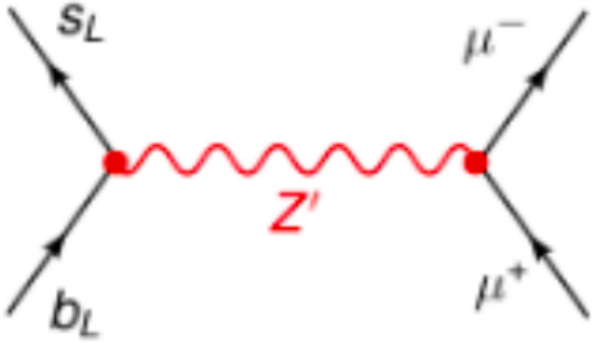
- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

JHEP 02 (2016) 104

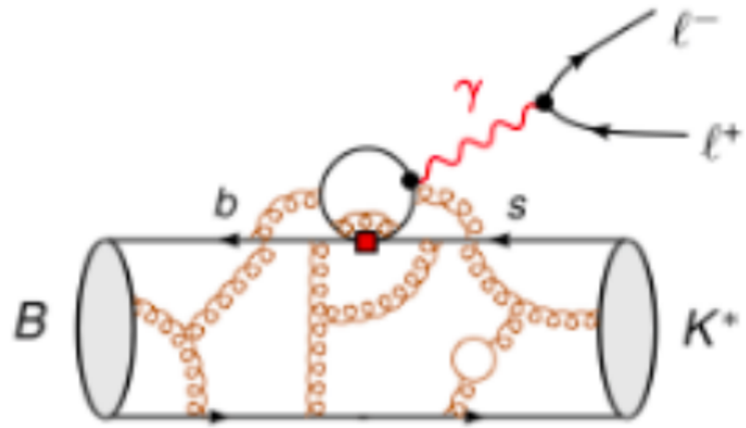


Global fit to $B \to K^*\mu\mu$ for LHCb is 3.4σ from SM.

What is this new vector-like contribution C_9^{NP}?



OR



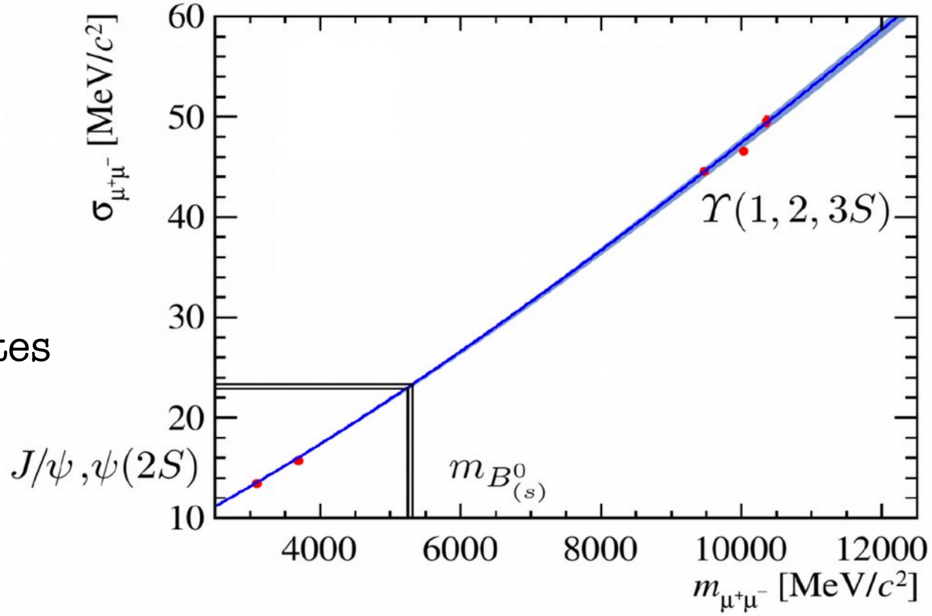
?

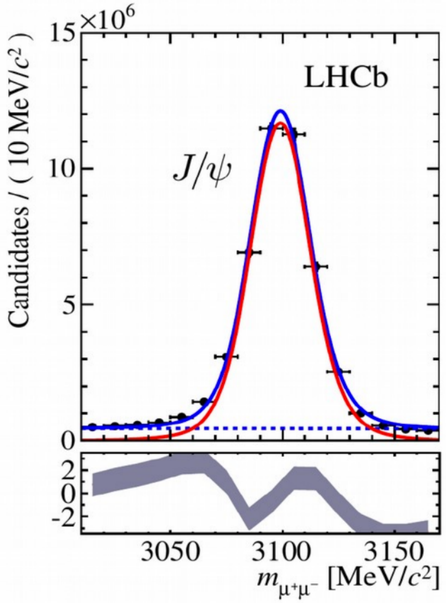
MUONS RECONSTRUCTION

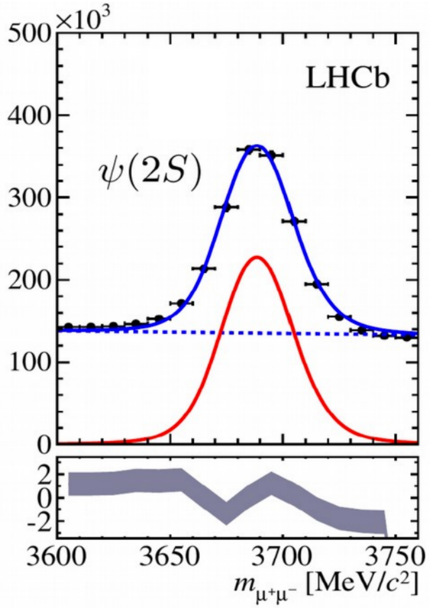
- Extremely performing in LHCb:
  - dedicated muon chambers
  - very efficient tracking system.

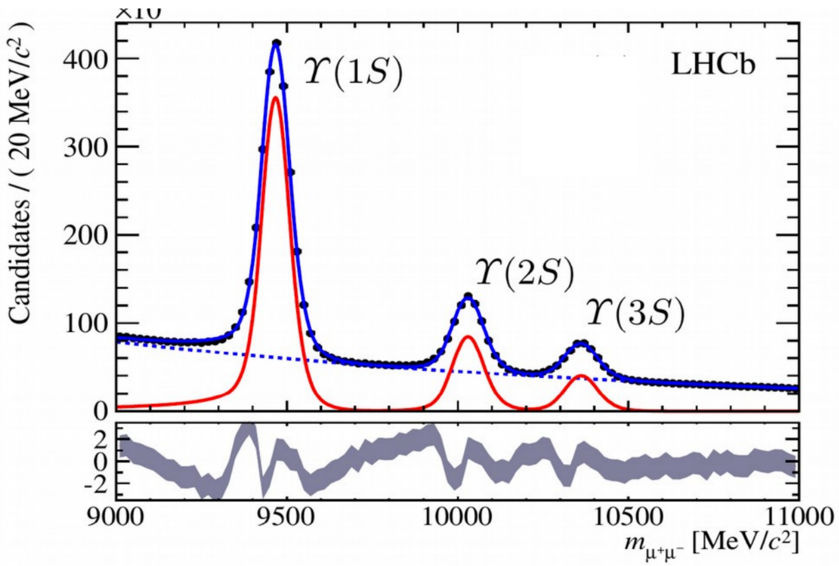
- A muon is a clear trigger signature:
  ε(L0+HLT)= ~90% for di-muon channels
  ε(L0+HLT)= ~30% for multibody hadronic states

- Very good di-muon resolution







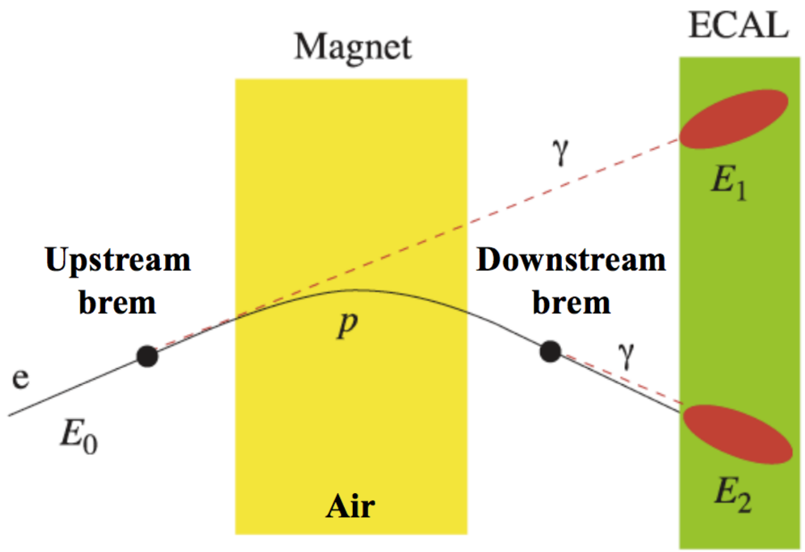


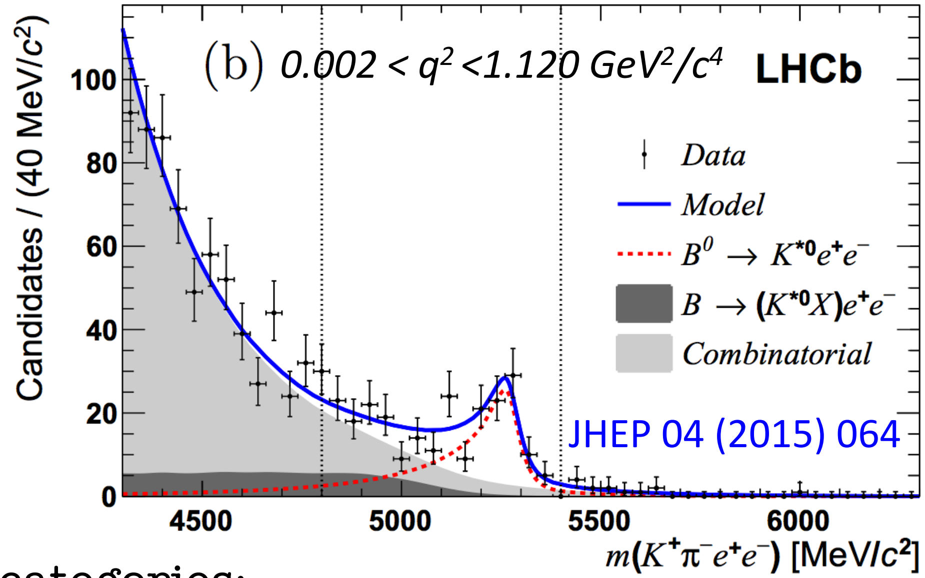
- Identified through the electromagnetic calorimeter:

$$ECAL: \frac{\sigma_E}{E} \sim 1\% \otimes \frac{10\%}{\sqrt{E(GeV)}}$$

(Int. J. Mod. Phys. A 30 (2015) 1530022)

- Resolution degraded by energy loss from **bremsstrahlung**:
  - **recovery of bremsstrahlung photons** can not be 100% efficient
  - significant **degradation of the *B* mass resolution** with a tail on the left
  - **large contribution from partially reconstructed** backgrounds





- Study in exclusive bremsstrahlung categories:
  - different resolutions, different purities

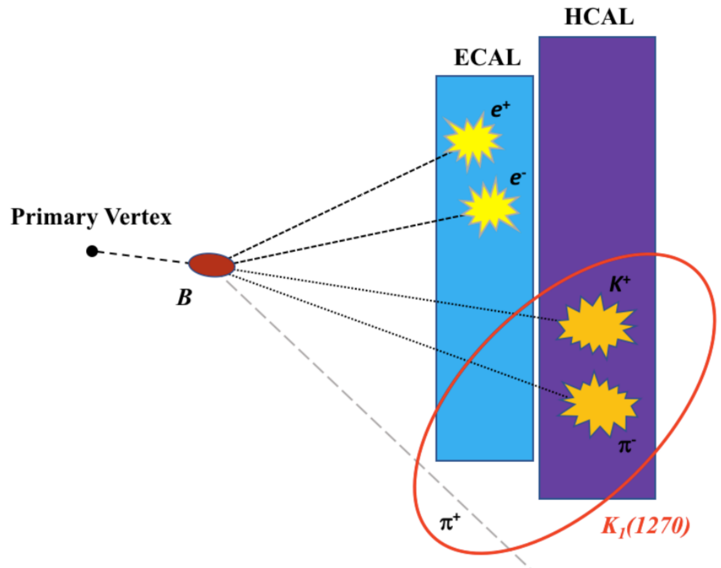
ELECTRON RECONSTRUCTION

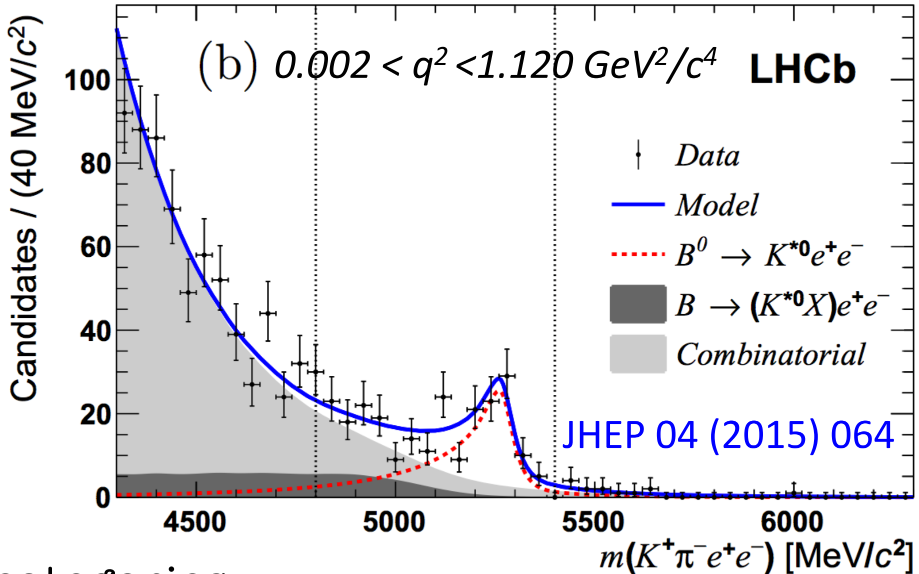
- Identified through the electromagnetic calorimeter:

$$ECAL: \frac{\sigma_E}{E} \sim 1\% \otimes \frac{10\%}{\sqrt{E(GeV)}}$$

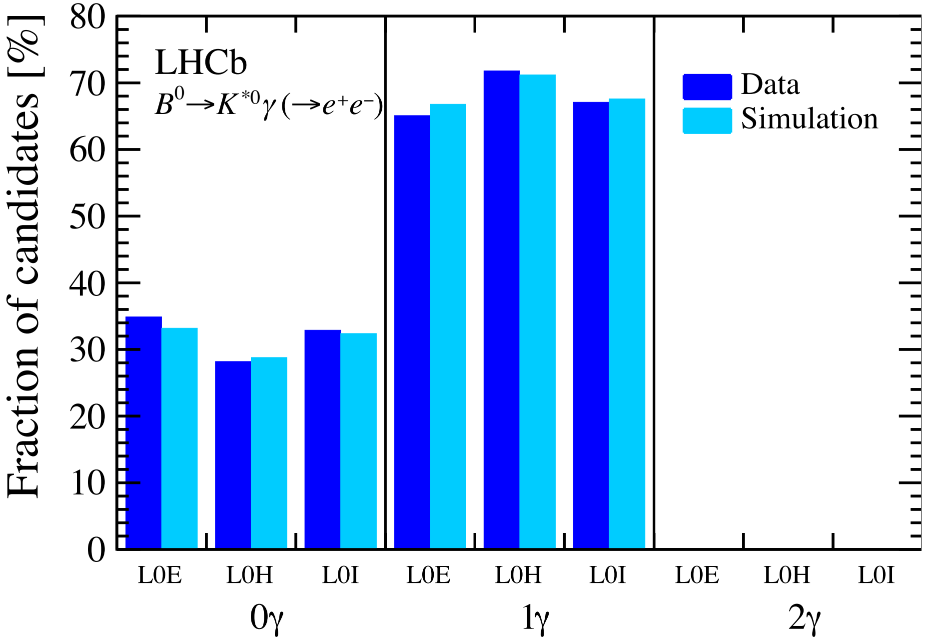
(Int. J. Mod. Phys. A 30 (2015) 1530022)

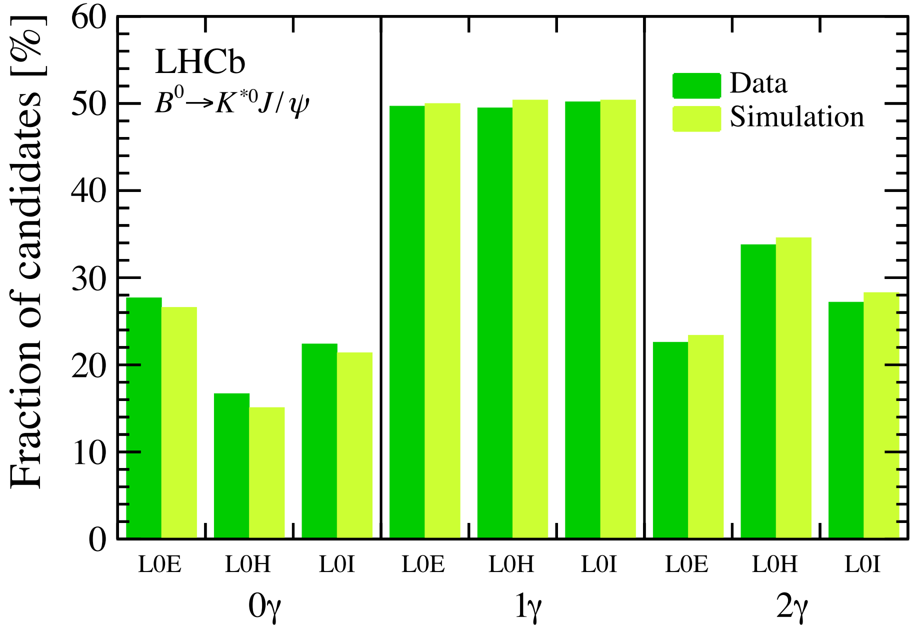
- Resolution degraded by energy loss from **bremsstrahlung**:
  - **recovery of bremsstrahlung photons** can not be 100% efficient
  - significant **degradation of the *B* mass resolution** with a tail on the left
  - **large contribution from partially reconstructed** backgrounds





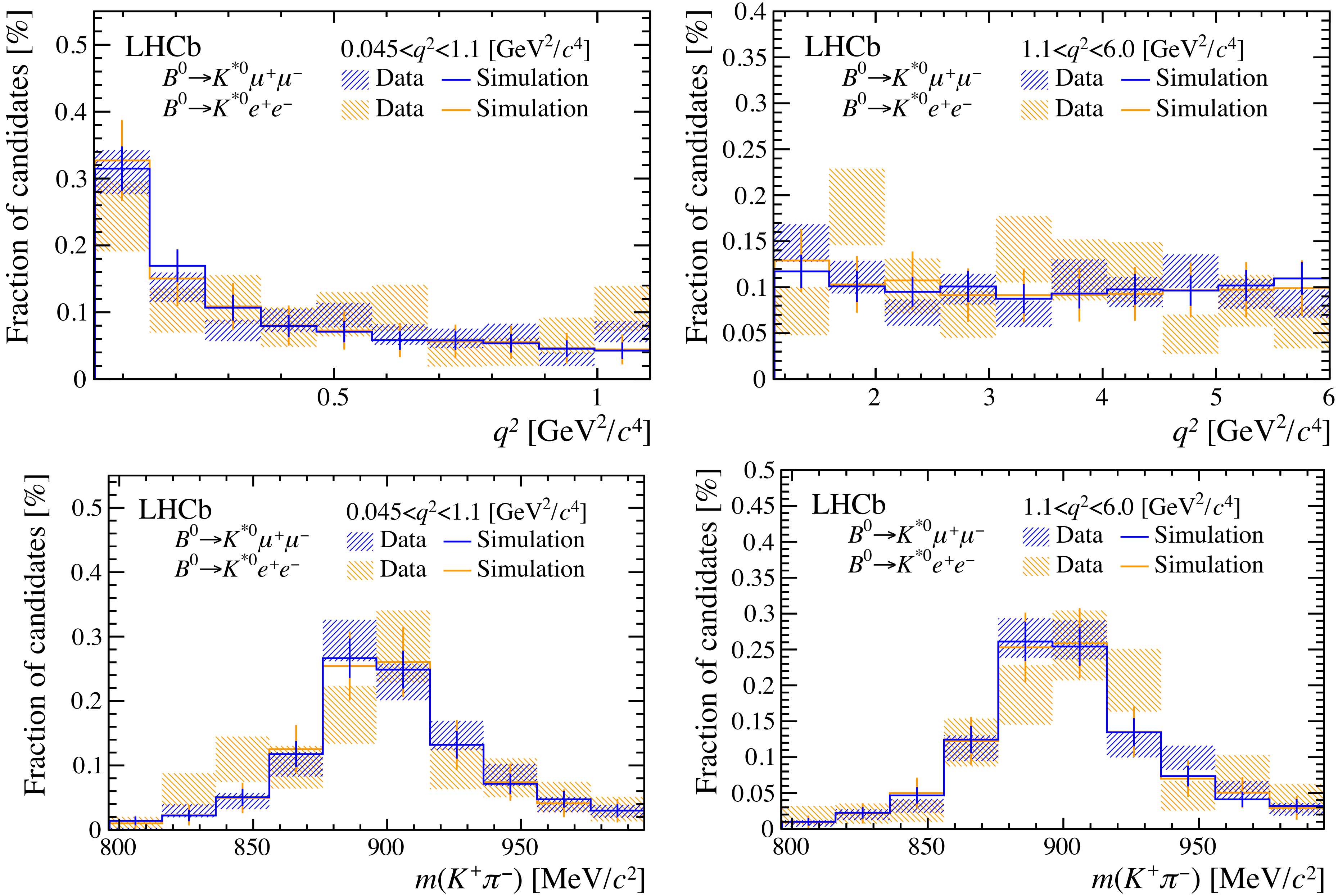
- Study in exclusive bremsstrahlung categories:
  - different resolutions, different purities


LHCb
$B^0 \to K^{*0}\gamma(\to e^+e^-)$
Data
Simulation
Fraction of candidates [%]
L0E
L0H
L0I
0γ
1γ
2γ


LHCb
$B^0 \to K^{*0}J/\psi$
Data
Simulation
Fraction of candidates [%]
L0E
L0H
L0I
0γ
1γ
2γ

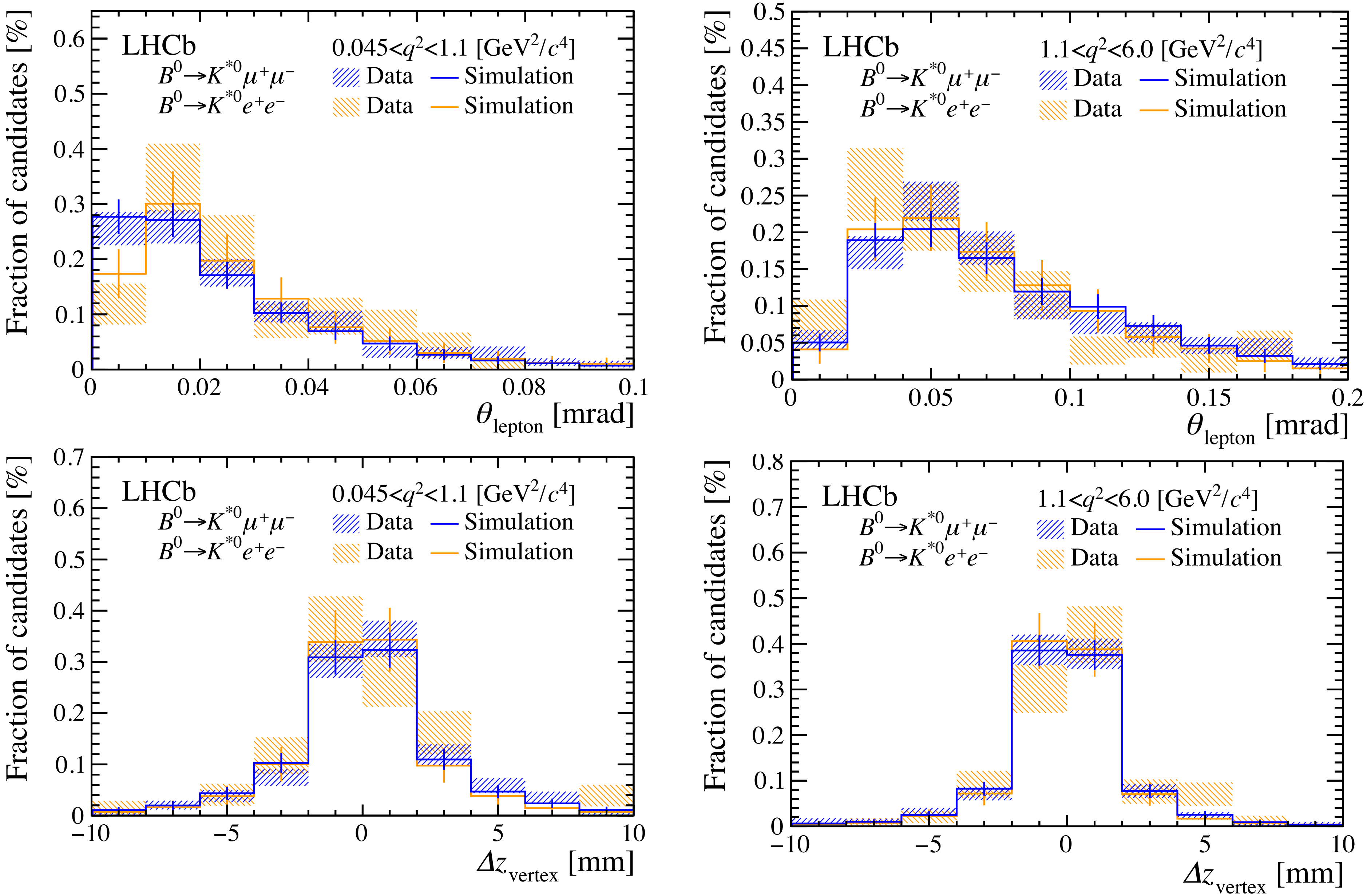
R_{K^*} CROSSCHECKS

arXiv:1705.05802



R_{K^*} CROSSCHECKS

arXiv:1705.05802



R_{K^*} SYSTEMATICS

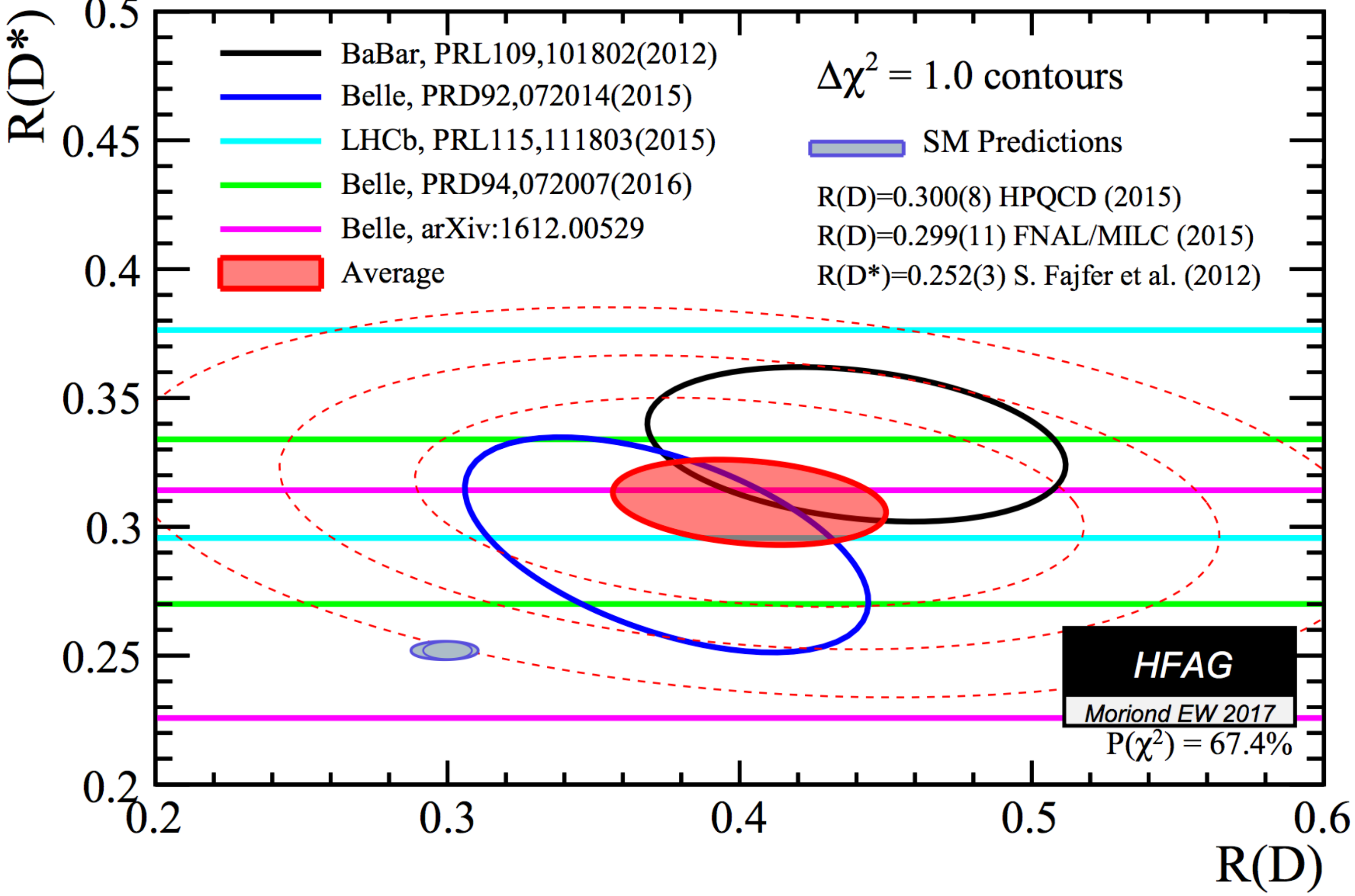
arXiv:1705.05802

- **The double ratio cancels a lot of systematics**
- **The measurement is statistically dominated (15%)**

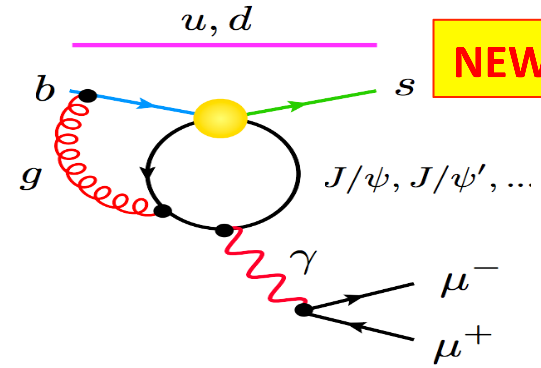
	$\Delta R_{K^{*0}} / R_{K^{*0}}$ [%]					
	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ ratio	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

STATUS OF THE $R_{D^{(*)}}$ MEASUREMENTS

BEFORE THE LHCb HADRONIC!!!
(but will globally not change a lot)

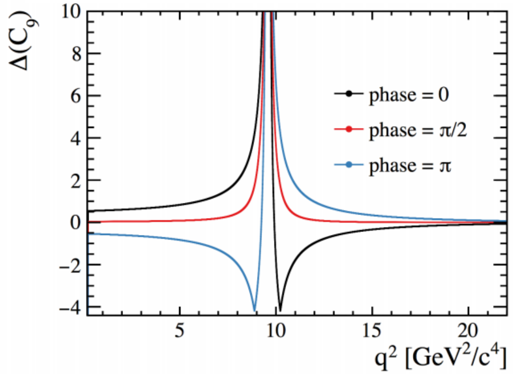


EVALUATING CHARM CONTRIBUTIONS IN $B^+ \to K^+\mu\mu$



NEW

Purpose: measure the phase difference between short- (FCNC) and long-distance amplitudes
- Sizeble effect of the long-distance contributions far from the resonances could explain the observed tensions



Method: analize the dimuon mass spectrum
- long-distance modeled as sum of BW
- magnitudes, phases, C_9, C_{10} floated
- C_7 fixed to SM
- hadronic form factors f_+ constrained
- crucial control of the **resolution function**

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{2^7\pi^5}|\boldsymbol{k}|\beta\left\{\frac{2}{3}|\boldsymbol{k}|^2\beta^2\left|C_{10}f_+(q^2)\right|^2 + \frac{4m_l^2(m_B^2-m_K^2)^2}{q^2}\left|C_{10}f_0(q^2)\right|^2 + |\boldsymbol{k}|^2\left[1-\frac{1}{3}\beta^2\right]\left|C_9^{\text{eff}}f_+(q^2) + 2C_7\frac{m_b+m_s}{m_B+m_K}f_T(q^2)\right|^2\right\},$$

$$C_9^{\text{eff}} = C_9 + \sum_j |\eta_j| e^{i\delta_j} A_j^{\text{res}}(q^2)$$

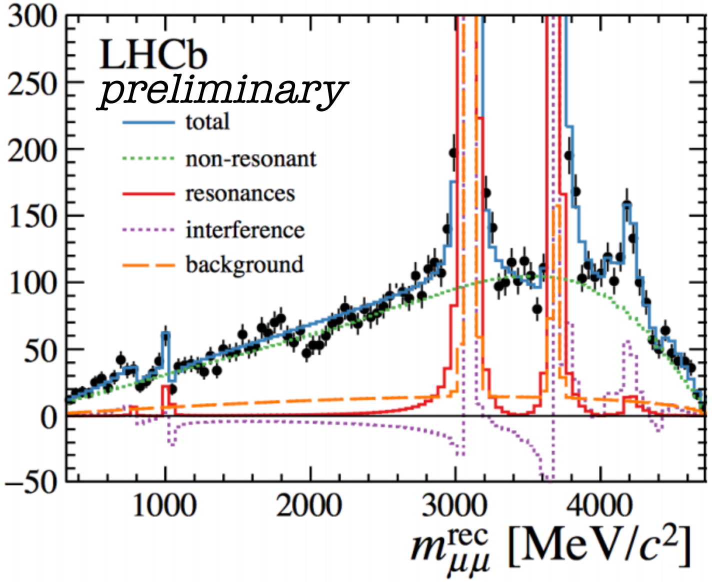
$$P_{\text{sig}}(m_{\mu\mu}^{\text{rec}}) \propto R(m_{\mu\mu}^{\text{rec}}, m_{\mu\mu}) \otimes \left(\varepsilon(m_{\mu\mu})\frac{\text{d}\Gamma}{\text{d}q^2}\frac{\text{d}q^2}{\text{d}m_{\mu\mu}}\right)$$

EVALUATING CHARM CONTRIBUTIONS IN $B^+ \to K^+\mu\mu$

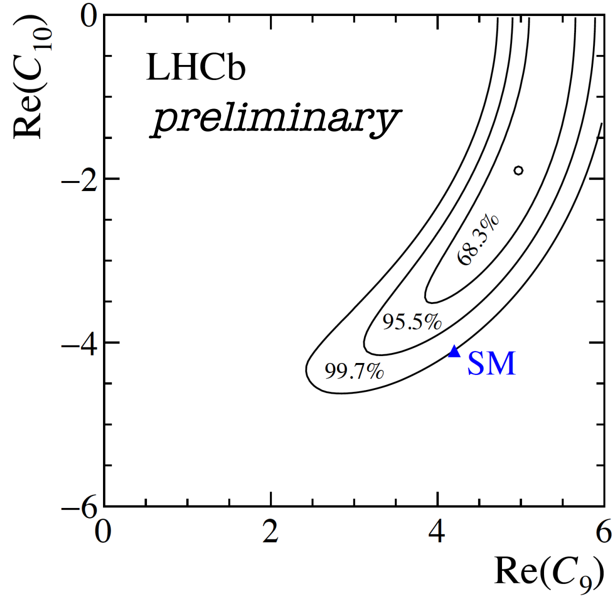
- Four degenerate solutions, corresponding to the ambiguities of J/Psi and Psi(2s) phases being negative or positive
- J/Psi phase is compatible with +/-π/2 => is small away from the pole
- Preferred values: $|C_{10}|<|C_{10}^{SM}|$ and $|C_9|>|C_9^{SM}|$
  If $C_{10} = C_{10}^{SM}$, $|C_9|<|C_9^{SM}|$

NEW

LHCb-PAPER-2016-045
COMING SOON



Resonance
$\rho(770)$
$\omega(780)$
$\phi(1020)$
J/ψ
$\psi(2S)$
$\psi(3770)$
$\psi(4040)$
$\psi(4160)$
$\psi(4415)$



- BF compatible with previous measurement and smaller than the SM:

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37 \pm 0.15\,(\text{stat}) \pm 0.23\,(\text{syst})) \times 10^{-7}$$

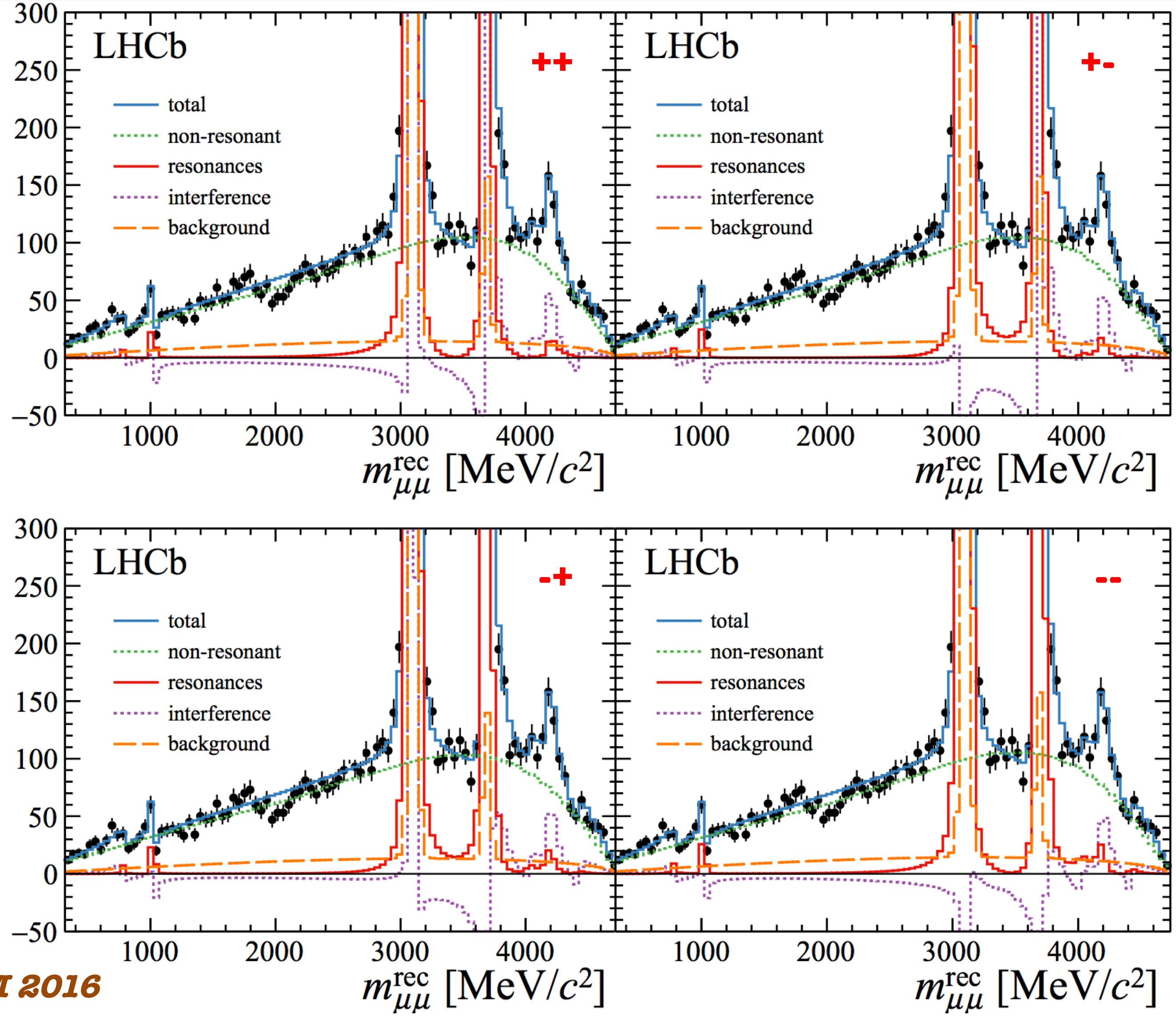
For the future: improved *B->K* form factors and more data needed.
More difficult for the *K**: helicity states can have different relative phases

EVALUATING CHARM CONTRIBUTIONS IN $B^+ \to K^+\mu\mu$

$$P_{\rm sig}(m_{\mu\mu}^{\rm rec}) \propto R(m_{\mu\mu}^{\rm rec}, m_{\mu\mu}) \otimes \left(\varepsilon(m_{\mu\mu})\frac{{\rm d}\Gamma}{{\rm d}q^2}\frac{{\rm d}q^2}{{\rm d}m_{\mu\mu}}\right)$$

LHCb-PAPER-2016-045
COMING SOON

Resonance
$\rho(770)$
$\omega(780)$
$\phi(1020)$
J/ψ
$\psi(2S)$
$\psi(3770)$
$\psi(4040)$
$\psi(4160)$
$\psi(4415)$



hep-ph arXiv:1704.05340

Patterns of New Physics in $b \to s\ell^+\ell^-$ transitions in the light of recent data

Bernat Capdevila[a], Andreas Crivellin[b], Sébastien Descotes-Genon[c], Joaquim Matias[a] and Javier Virto[d]

[a] Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Institut de Fisica d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain
[b] Paul Scherrer Institut, CH–5232 Villigen PSI, Switzerland
[c] Laboratoire de Physique Théorique, UMR 8627, CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay Cedex, France
[d] Albert Einstein Center for Fundamental Physics, Institute for Theoretical Physics, University of Bern, CH-3012 Bern, Switzerland

(Dated: April 19, 2017)

The $b \to s\ell^+\ell^-$ processes observed by the LHCb collaboration at 1 and 3 fb^{-1} have exhibited a coherent set of deviations from the Standard Model (SM) predictions, i.e., anomalies, most remarkably in the angular analysis of the $B \to K^*\mu^+\mu^-$ decay and in the Lepton Flavour Universality (LFU) violating ratios R_K and (very recently) R_{K^*}. All these anomalies are analysed consistently by fitting the Wilson coefficients of effective operators which encode the short-distance contributions to $b \to s\ell^+\ell^-$ transitions, pointing towards specific patterns of New Physics (NP). We include recent data presented by LHCb, CMS, ATLAS and Belle in our framework, finding several hypotheses with NP in one and two Wilson coefficients preferred at the 5 σ level compared to the SM. One of the most prominent patterns consist of large contributions to the coefficients $\mathcal{C}_{9\mu}$ ($\mathcal{C}_{10\mu}$) involving a left-handed quark current and a vector (axial) muon current while the effect in electrons is small, confirming the indications for LFU violation. We also perform an analysis allowing for New Physics in six Wilson coefficients (SM-like and chirally flipped), obtaining a pull for the SM at the level of 5 σ. Dedicated fits restricted to LFU-violating observables are also presented. We find that LFU violation is favoured with respect to LFU at 3.3σ level in the case of NP contributions to $\mathcal{C}_{9e}$ and $\mathcal{C}_{9\mu}$. Finally, we consider the implications of these results for specific models of NP and we discuss possible correlations to the LFU-violating ratios R_D and R_{D^*}.

hep-ph arXiv:1704.05340

Largest pulls	$\langle P_5' \rangle_{[4,6]}$	$\langle P_5' \rangle_{[6,8]}$	$R_K^{[1,6]}$	$R_{K^*}^{[0.045,1.1]}$	$R_{K^*}^{[1.1,6]}$	$\mathcal{B}^{[2,5]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[5,8]}_{B_s\to\phi\mu^+\mu^-}$
Experiment	-0.30 ± 0.16	-0.51 ± 0.12	$0.745^{+0.097}_{-0.082}$	$0.66^{+0.113}_{-0.074}$	$0.685^{+0.122}_{-0.083}$	0.77 ± 0.14	0.96 ± 0.15
SM prediction	-0.82 ± 0.08	-0.94 ± 0.08	1.00 ± 0.01	0.92 ± 0.02	1.00 ± 0.01	1.55 ± 0.33	1.88 ± 0.39
Pull (σ)	-2.9	-2.9	+2.6	+2.3	+2.6	+2.2	+2.2
Prediction for $\mathcal{C}_{9\mu}^{\rm NP} = -1.1$	-0.50 ± 0.11	-0.73 ± 0.12	0.79 ± 0.01	0.90 ± 0.05	0.87 ± 0.08	1.30 ± 0.26	1.51 ± 0.30
Pull (σ)	-1.0	-1.3	+0.4	+1.9	+1.2	+1.8	+1.6

TABLE I: Main anomalies currently observed in $b \to s\ell\ell$ transitions, with the current measurements, our predictions for the SM and the NP scenario $\mathcal{C}_{9\mu}^{\rm NP} = -1.1$, and the corresponding pulls. In addition, a deficit compared to the SM predictions has been observed at low and large recoils for $\mathcal{B}(B^{(0,+)} \to K^{(0,+)}\mu\mu)$ [13] and $\mathcal{B}(B^0 \to K^{*0}\mu\mu)$ [14], as well as at low recoil (above 15 GeV^2) for $\mathcal{B}(B^+ \to K^{*+}\mu^+\mu^-)$ [13] and $\mathcal{B}(B_s \to \phi\mu^+\mu^-)$ [7].

	All					LFUV				
1D Hyp.	Best fit	1 σ	2 σ	Pull_{SM}	p-value	Best fit	1 σ	2 σ	Pull_{SM}	p-value
$\mathcal{C}_{9\mu}^{\text{NP}}$	-1.10	$[-1.27, -0.92]$	$[-1.43, -0.74]$	5.7	72	-1.76	$[-2.36, -1.23]$	$[-3.04, -0.76]$	3.9	69
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$	-0.61	$[-0.73, -0.48]$	$[-0.87, -0.36]$	5.2	61	-0.66	$[-0.84, -0.48]$	$[-1.04, -0.32]$	4.1	78
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9\mu}'$	-1.01	$[-1.18, -0.84]$	$[-1.33, -0.65]$	5.4	66	-1.64	$[-2.12, -1.05]$	$[-2.52, -0.49]$	3.2	31
$\mathcal{C}_{9\mu}^{\text{NP}} = -3\mathcal{C}_{9e}^{\text{NP}}$	-1.06	[-1.23,-0.89]	[-1.39,-0.71]	5.8	74	-1.35	$[-1.82, -0.95]$	$[-2.38, -0.59]$	4.0	71

	All			LFUV		
2D Hyp.	Best fit	Pull_{SM}	p-value	Best fit	Pull_{SM}	p-value
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10\mu}^{\text{NP}})$	(-1.17,0.15)	5.5	74	(-1.13,0.40)	3.7	75
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_7')$	(-1.05,0.02)	5.5	73	(-1.75,-0.04)	3.6	66
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu})$	(-1.09,0.45)	5.6	75	(-2.11,0.83)	3.7	73
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10'\mu})$	(-1.10,-0.19)	5.6	76	(-2.43,-0.54)	3.9	85
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9e}^{\text{NP}})$	(-0.97,0.50)	5.4	72	(-1.09,0.66)	3.5	65
Hyp. 1	(-1.08,0.33)	5.6	77	(-1.74,0.53)	3.8	77
Hyp. 2	(-1.00, 0.15)	4.9	61	(-1.89,0.27)	3.1	39
Hyp. 3	(-0.65,-0.13)	4.9	61	(0.58,2.53)	3.7	73
Hyp. 4	(-0.65,0.21)	4.8	59	(-0.68,0.28)	3.7	72

TABLE II: Most prominent patterns of New Physics in $b \to s\mu\mu$ with high significances. The last four rows corresponds to hypothesis 1: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{\text{NP}} = \mathcal{C}_{10'\mu})$, 2: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{\text{NP}} = -\mathcal{C}_{10'\mu})$, 3: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = \mathcal{C}_{10'\mu})$ and 4: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$. The "All" columns include all available data from LHCb, Belle, ATLAS and CMS, whereas the "LFUV" columns are restricted to R_K, R_{K^*} and $Q_{4,5}$ (see text for more detail). The p-values are quoted in % and Pull_{SM} in units of standard deviation.

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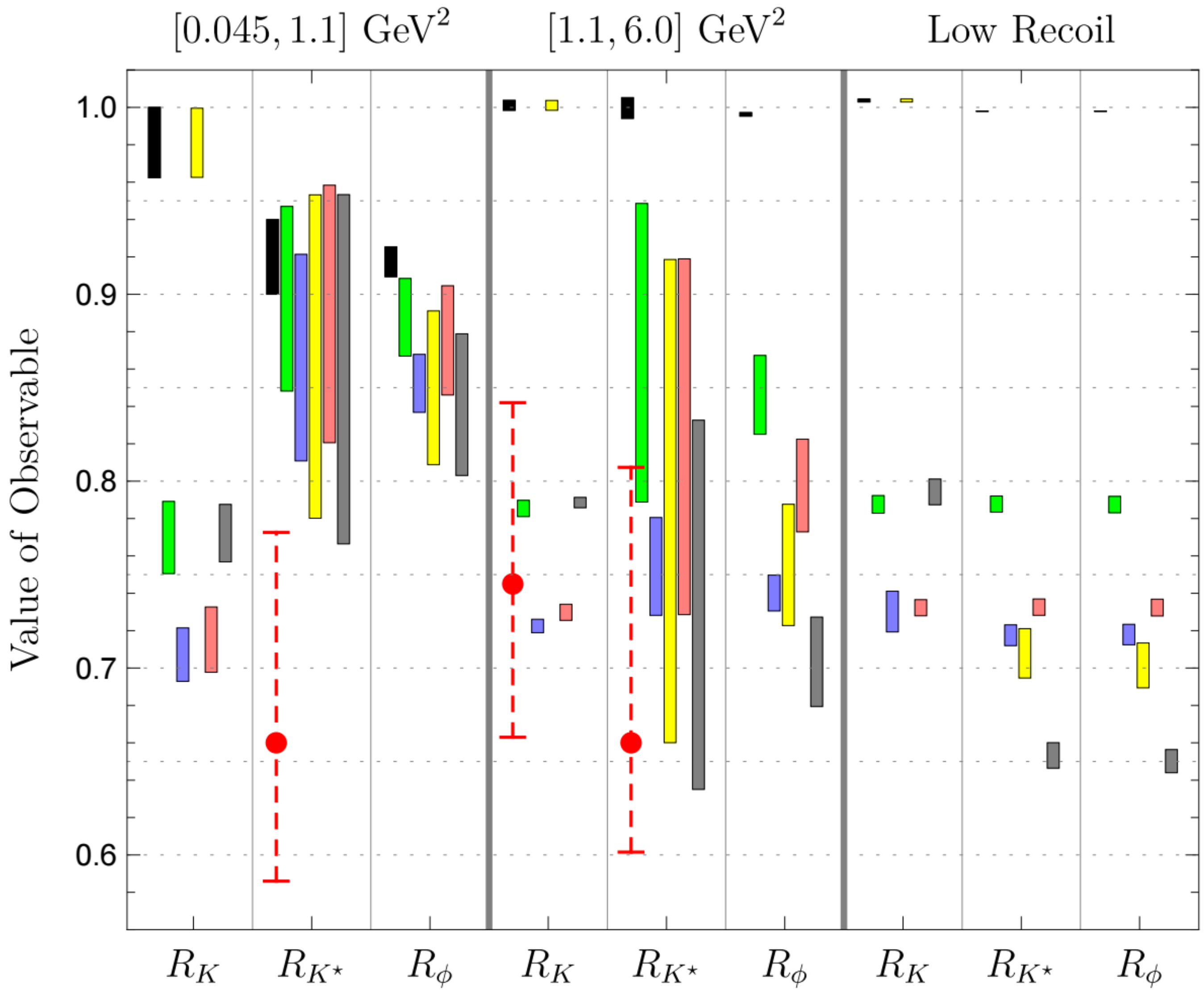

More conservative form factors for RK* => larger errors

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Interpreting Hints for Lepton Flavor Universality Violation

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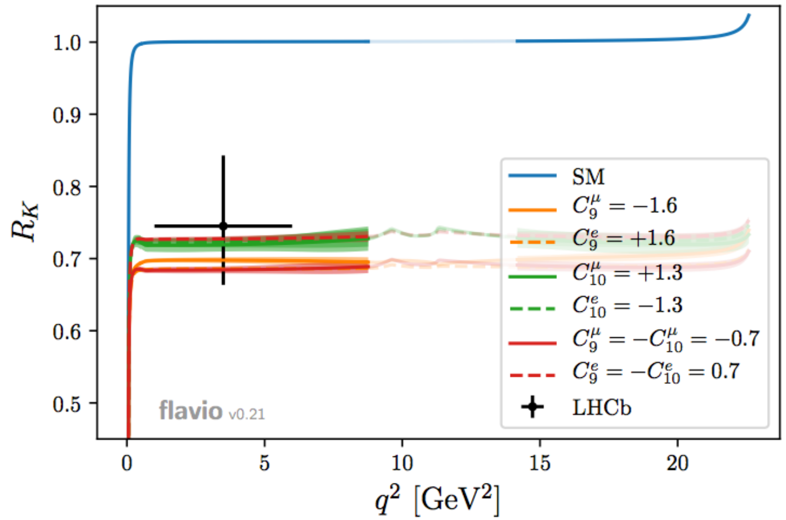
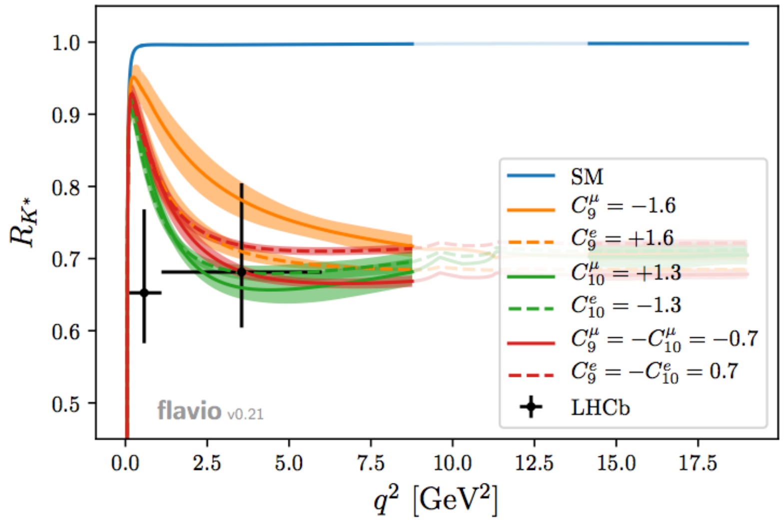
We interpret the recent hints for lepton flavor universality violation in rare B meson decays. Based on a model-independent effective Hamiltonian approach, we determine regions of new physics parameter space that give a good description of the experimental data on R_K and R_{K^*}, which is in tension with Standard Model predictions. We suggest further measurements that can help narrowing down viable new physics explanations. We stress that the measured values of R_K and R_{K^*} are fully compatible with new physics explanations of other anomalies in rare B meson decays based on the $b \to s\mu\mu$ transition. If the hints for lepton flavor universality violation are first signs of new physics, perturbative unitarity implies new phenomena below a scale of ~ 100 TeV.





arXiv:1704.05444

R_K and R_{K^*} beyond the Standard Model

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Measurements of the ratio of $B \to K^* \mu\mu$ to $B \to K^* ee$ branching fractions, R_{K^*}, by the LHCb collaboration strengthen the hints from previous studies with pseudoscalar kaons, R_K, for the breakdown of lepton universality, and therefore the Standard Model (SM), to $\sim 3.5\sigma$. Complementarity between R_K and R_{K^*} allows to pin down the Dirac structure of the new contributions to be predominantly SM-like chiral, with possible admixture of chirality-flipped contributions of up to $\mathcal{O}$(few10%). Scalar and vector leptoquark representations (S_3, V_1, V_3) plus possible $(\tilde{S}_2, V_2)$ admixture can explain R_{K,K^*} via tree level exchange. Flavor models naturally predict leptoquark masses not exceeding a few TeV, with couplings to third generation quarks at $O(0.1)$, implying that this scenario can be directly tested at the LHC.

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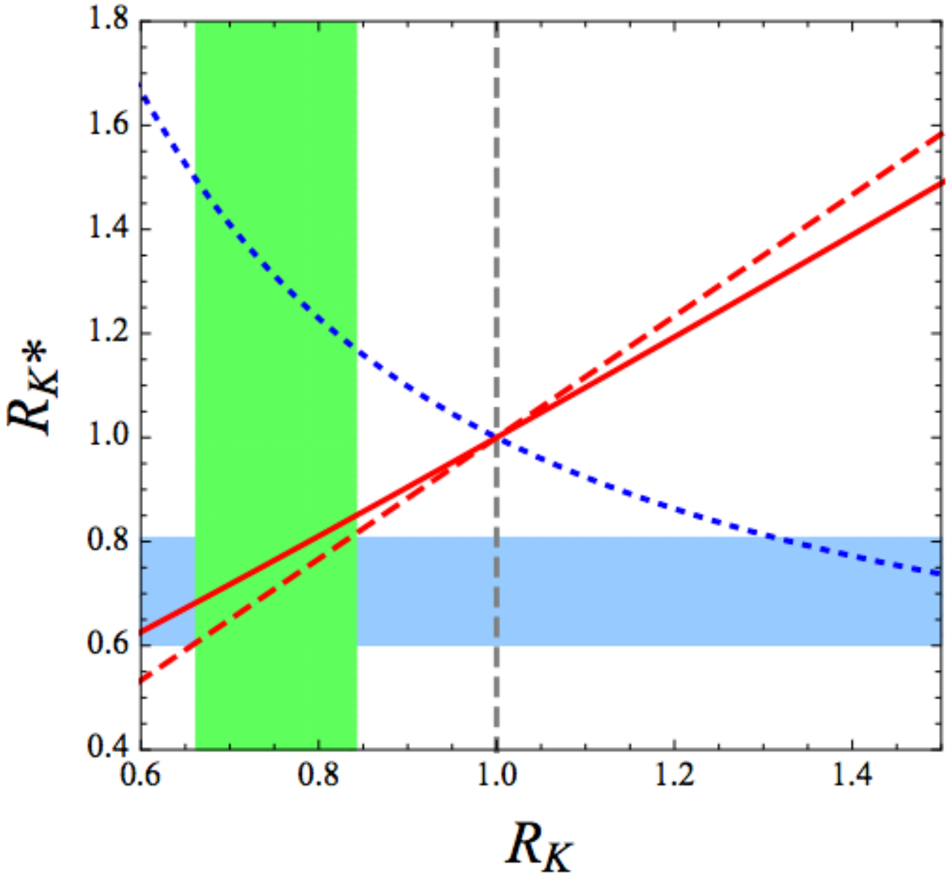

FIG. 2. Correlations between R_K and R_{K^*} (plot to the left) and R_K and the double ratio X_{K^*} (plot to the right) in BSM scenarios. Solid red curve: $C_{LL}^{\rm NP}$ ($C_9^{\rm NP} = -C_{10}^{\rm NP}$) corresponding to leptoquarks S_3, V_1 or V_3, blue dotted curve: C_{RL} (leptoquark $\tilde{S}_2$ or V_2), gray dashed curve: $C_{RL} = -C_{LL}^{\rm NP}$ (no single leptoquark), and red dashed curve: $C_{LL}^{\rm NP}$ and $C_{RL} = -1/10\, C_{LL}^{\rm NP}$ (for instance, S_3 plus 10% admixture of $\tilde{S}_2$). The colored bands correspond to the LHCb measurements of R_K (2) , R_{K^*} (3) and X_{K^*} (10).

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If leptoquarks, low masses preferred by data

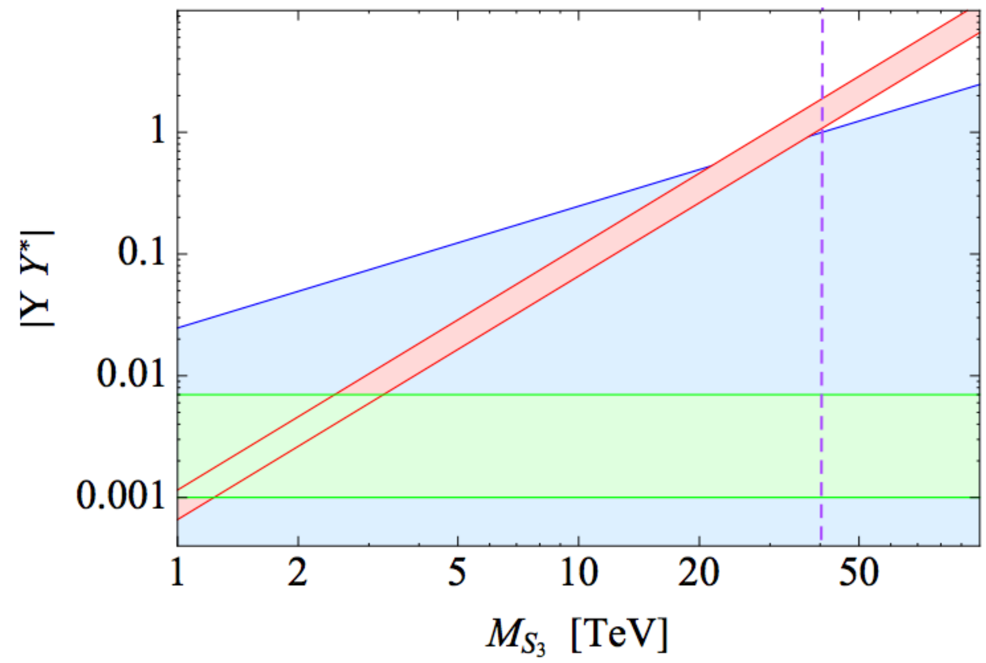

FIG. 3. Constraints in the $|(YY^*|, M_{S_3})$ plane: a) the allowed region by Δm_{B_s} (light blue), b) the allowed range for $R_{K^{(*)}}$ (light red) (12). The light green band corresponds to flavor model predictions (18). The dashed dark blue line corresponds to the upper limit on the mass of the S_3 leptoquark (19).

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Towards the discovery of new physics with lepton-universality ratios of $b \to s\ell\ell$ decays

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Tests of lepton-universality as rate ratios in $b \to s\ell\ell$ transitions can be predicted very accurately in the Standard Model. The deficits with respect to expectations reported by the LHCb experiment in muon-to-electron ratios of the $B \to K^{(*)}\ell\ell$ decay rates thus point to genuine manifestations of lepton non-universal new physics. In this paper, we analyse these measurements in the context of effective field theory. First, we discuss the interplay of the different operators in R_K and R_{K^*} and provide predictions for R_{K^*} in the Standard Model and in new-physics scenarios that can explain R_K. We also provide approximate numerical formulas for these observables in bins of interest as functions of the relevant Wilson coefficients. Secondly, we perform frequentist fits to R_K and R_{K^*}. The SM disagrees with these measurements at 3.7σ significance. We find excellent fits in scenarios with combinations of $\mathcal{O}^{\ell}_{9(10)} = \bar{s}\gamma^{\mu}b_L\, \ell\gamma_{\mu}(\gamma_5)\ell$ operators, with pulls relative to the Standard Model in the region of 4σ. An important conclusion of our analysis is that a lepton-specific contribution to $\mathcal{O}_{10}$ is essential to understand the data. Under the hypothesis that new-physics couples selectively to the muons, we also present fits to other $b \to s\mu\mu$ data with a conservative error assessment, and comment on more general scenarios. Finally, we discuss new lepton universality ratios that, if new physics is the origin of the observed discrepancy, should contribute to the statistically significant discovery of new physics in the near future.

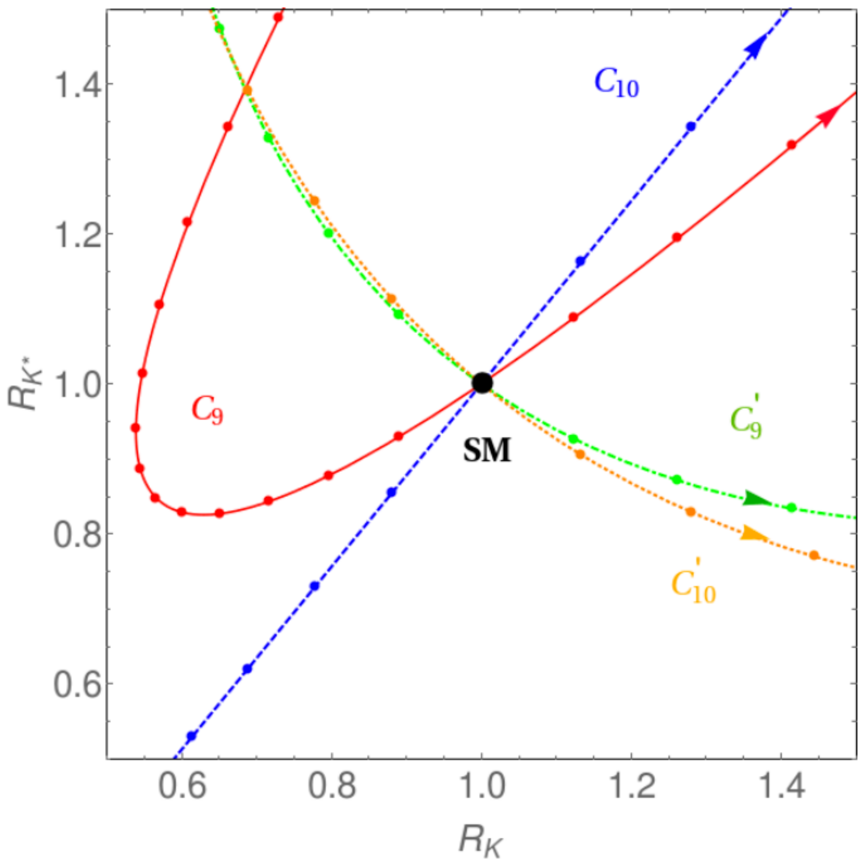

FIG. 1: R_K and R_{K^*} (in the $[1.1,\ 6]$ GeV^2 bin) parametric dependence on one Wilson coefficient where the nodes indicate steps of $\Delta C^\mu = +0.5$ from the SM point and in the direction of the arrows. The red solid line shows the dependence on δC_9^μ, dashed blue line on δC_{10}^μ, green dot-dashed on $\delta C_9'^\mu$ and orange dotted on $\delta C_{10}'^\mu$.

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On Flavourful Easter eggs for New Physics hunger and Lepton Flavour Universality violation

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In conclusion, while our global analysis confirms the need of NP sources to fully explain the current experimental situation in B physics, it clearly delineates the challenges and the subtleties present in the attempt to quantify the size and to identify the pattern of the underling BSM theory addressing the current experimental situation.