LEPTON FLAVOUR UNIVERSALITY TESTS

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on behalf of the LHCb collaboration

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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:

$$Z \to \ell\ell \qquad J/\psi \to \ell\ell \qquad \tau \to \ell\nu\bar{\nu}$$

$$W \to \ell\nu \qquad \psi(2s) \to \ell\ell \qquad \pi \to \ell\nu$$

$$\Upsilon \to \ell\ell \qquad K \to \pi\ell\nu$$

Now LHC is allowing a new bunch of LFU tests to be performed!

OUTLINE

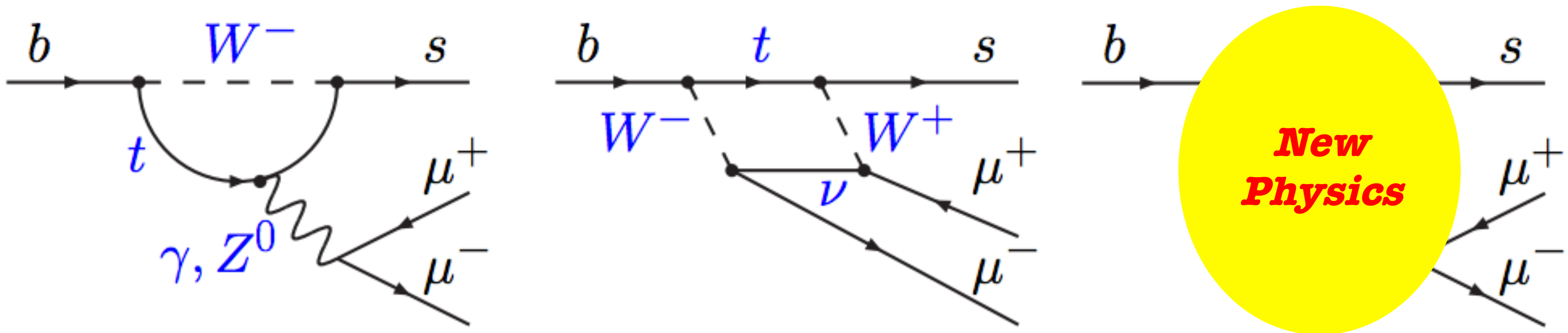
- Lepton universality tests in b->sll
- Lepton universality tests in b->clν
- Lepton universality test in W->lν
- Conclusion

OUTLINE

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

b->sll AS PROBES FOR NP

- *b->sll* transitions are powerful probe of New Physics:
  - FCNC proceeding via loop diagrams only;
  - suppressed in the SM, so more sensitive to NP;
  - rich phenomenology and many precise SM predictions available;
  - explore higher mass scales than the current collider energies.



- *New particles in the loop could enhance/suppress decay rates, introduce new sources of CP violation, modify angular distributions.*

- ***NP could couple differently to different lepton families***

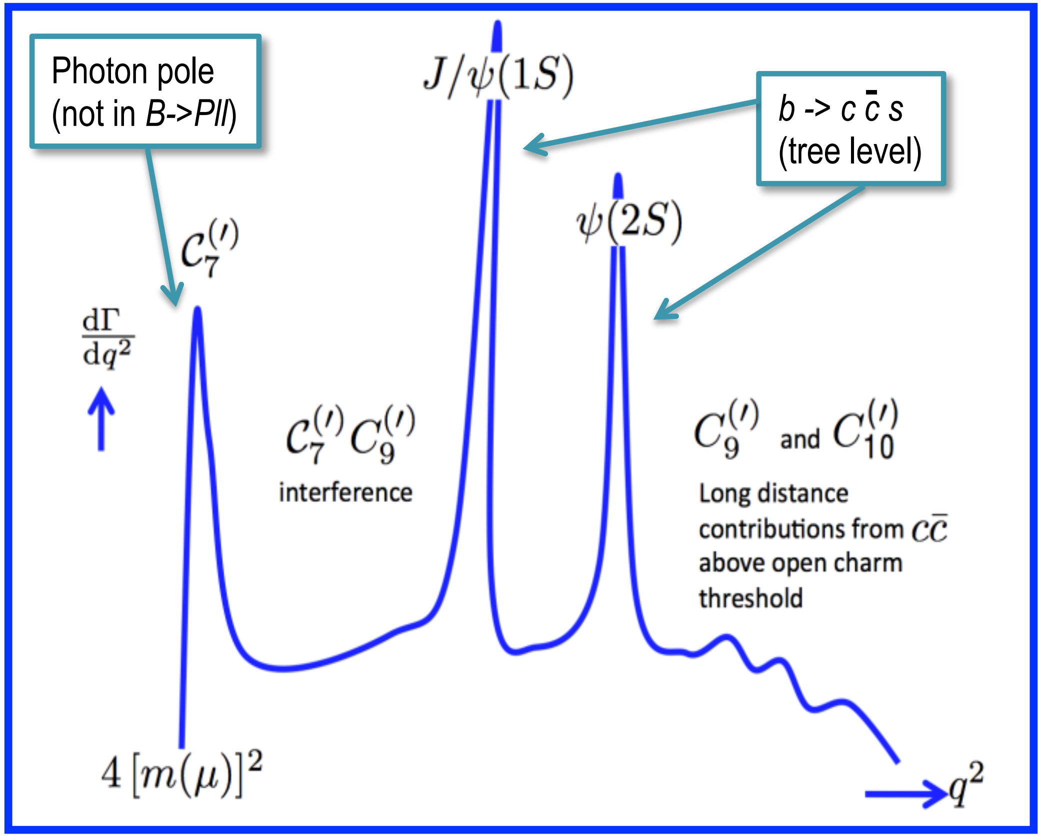
EFFECTIVE THEORY APPROACH

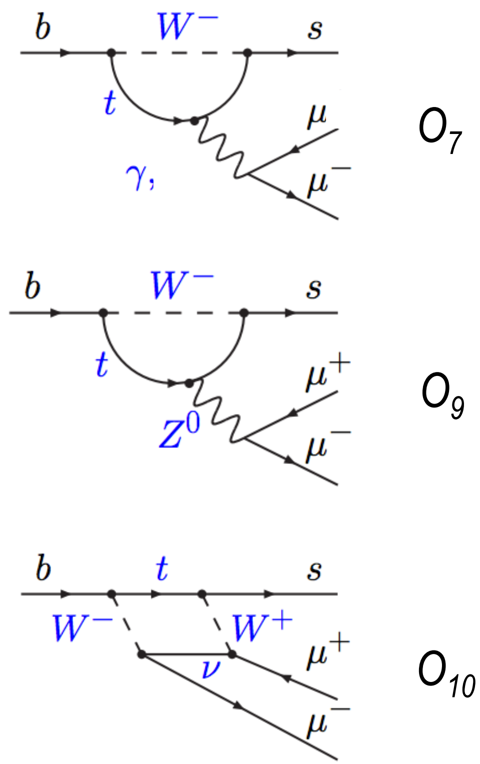
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}} \Big]$$

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: non-perturbative long-distance effects

Wilson coefficients C_i: perturbative short-distance effects



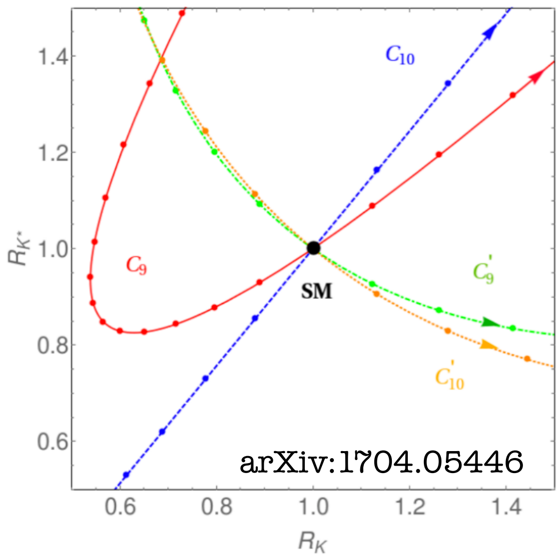


THE LU TEST R_H

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

(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:



THE R_{K^*} MEASUREMENT

NEW
arXiv:1705.05802

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

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

- The measurement boils down to precisely determining:
  - yields for each channel
  - efficiencies for each channel

- All other factors (luminosity, cross section) cancel in the ratio

- Most of difficulties are on the electron channel side

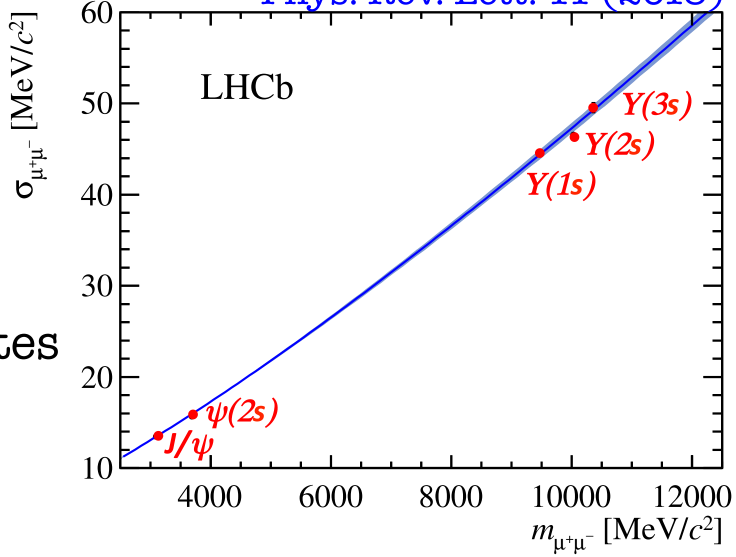
MUON RECONSTRUCTION

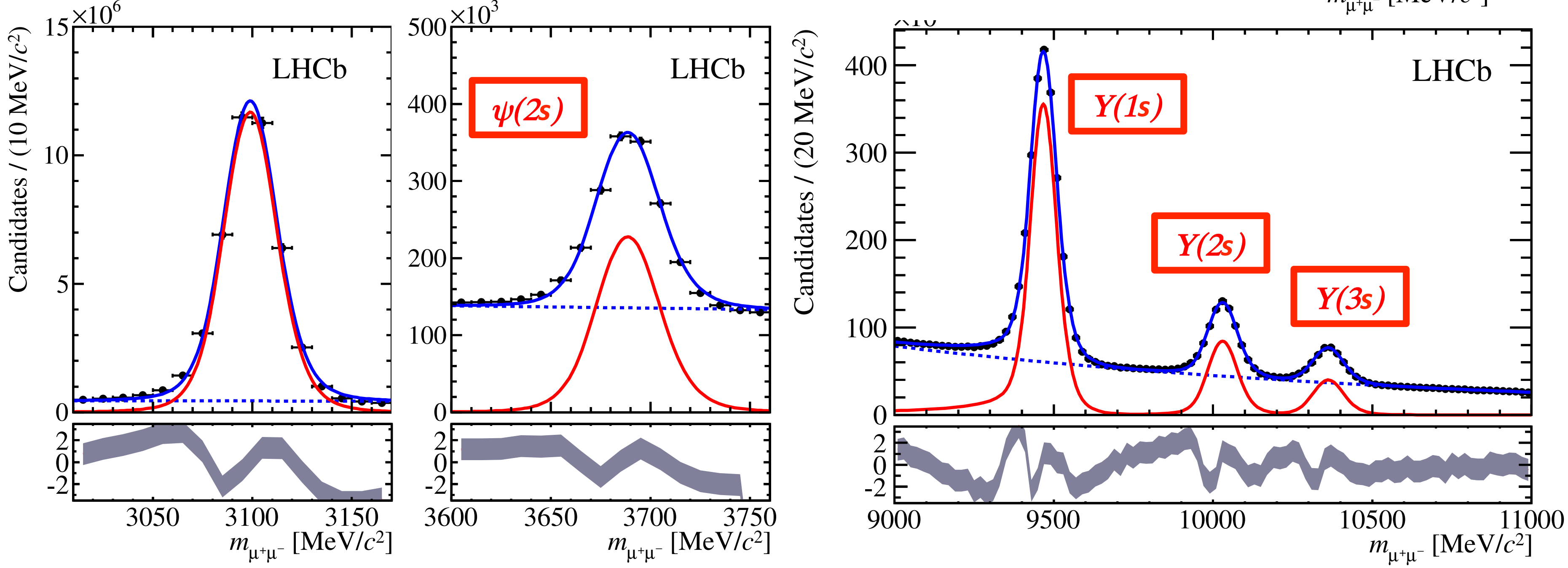
- **Extremely performant in LHCb**:
  - dedicated muon chambers
  - very efficient tracking system.

- **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**

Phys. Rev. Lett. 11 (2013)





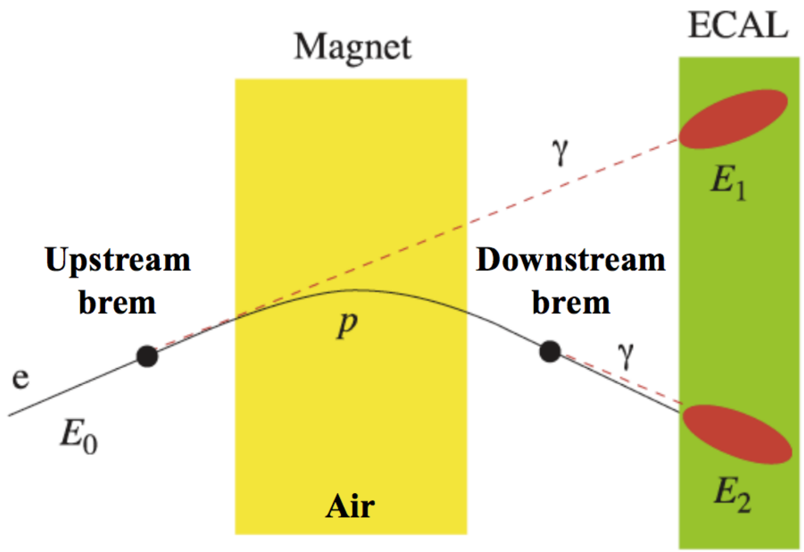
ELECTRON RECONSTRUCTION

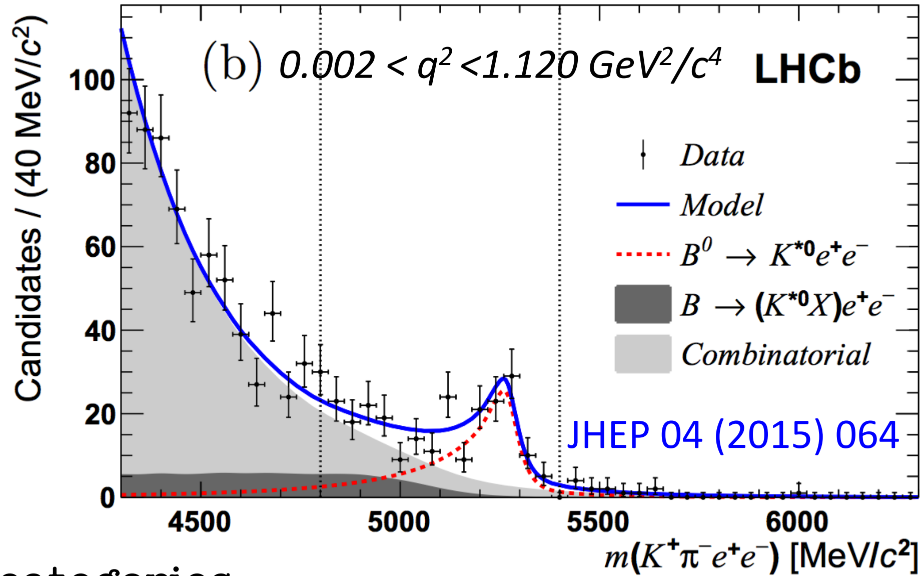
- Identified through the electromagnetic calorimeter:

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

(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



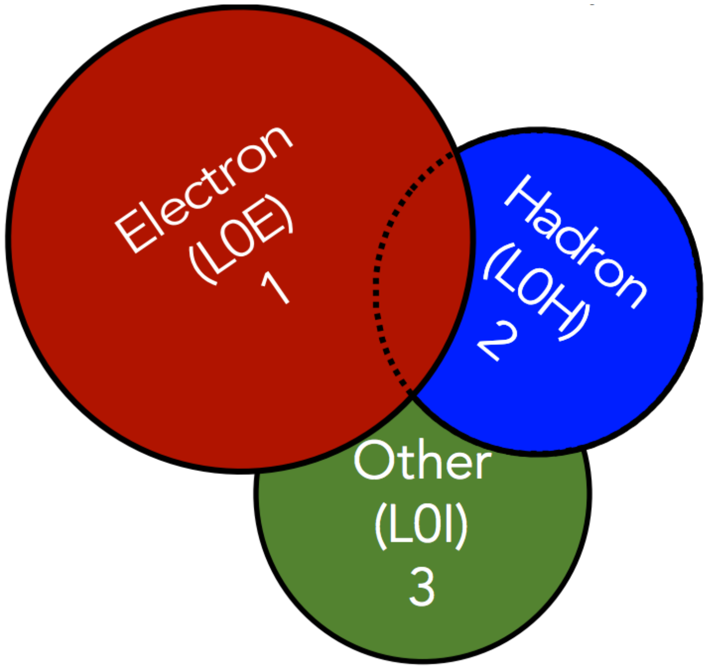


JHEP 04 (2015) 064

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

TRIGGER FOR ELECTRON CHANNELS

- High occupancy of calorimeters
  => **hardware thresholds on electron E_T higher than on muon p_T**
- Use different triggers to increase the yields:



L0E: trigger fired by one of the electrons (E_T>2.5GeV)

L0H: trigger fired by the K or the π (E_T>3.5GeV)

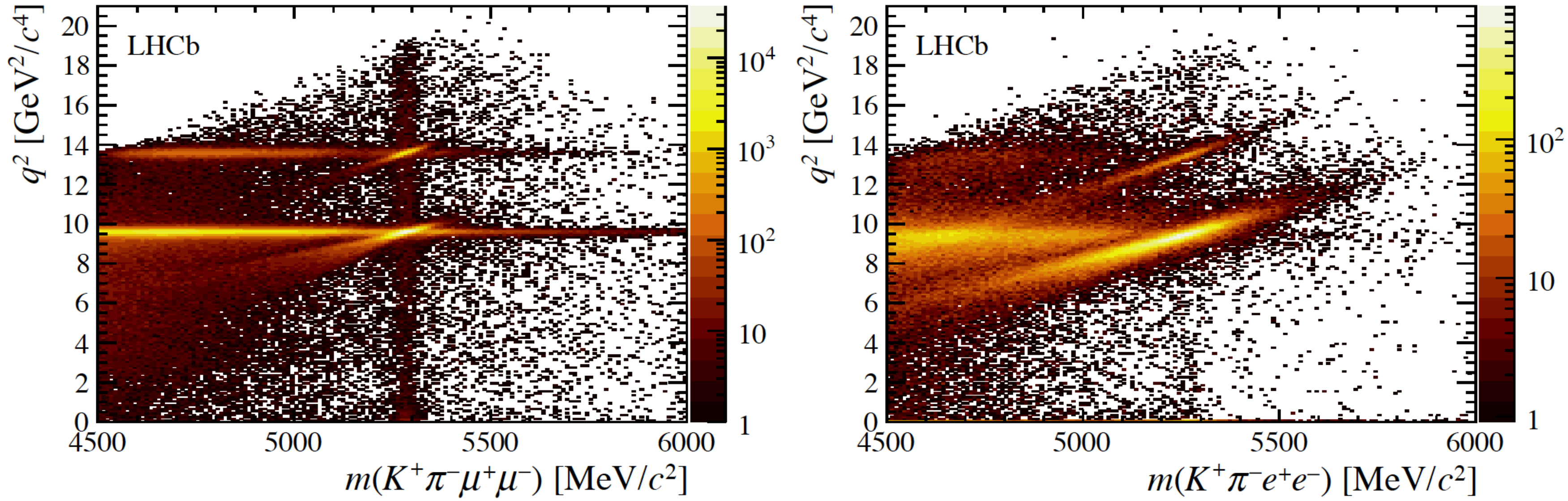
L0I: trigger fired by particles not associated to the signal candidate

- Study in exclusive trigger categories:
  - different resolutions
  - different purities

R_{K^*} DATASET AFTER PRESELECTION

- 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



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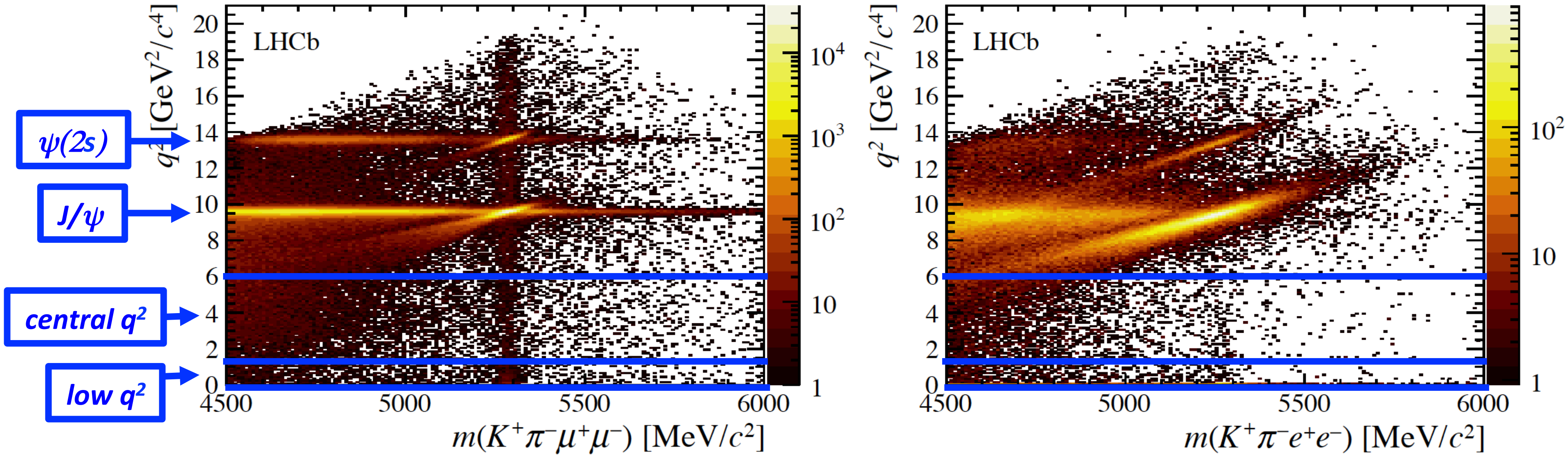

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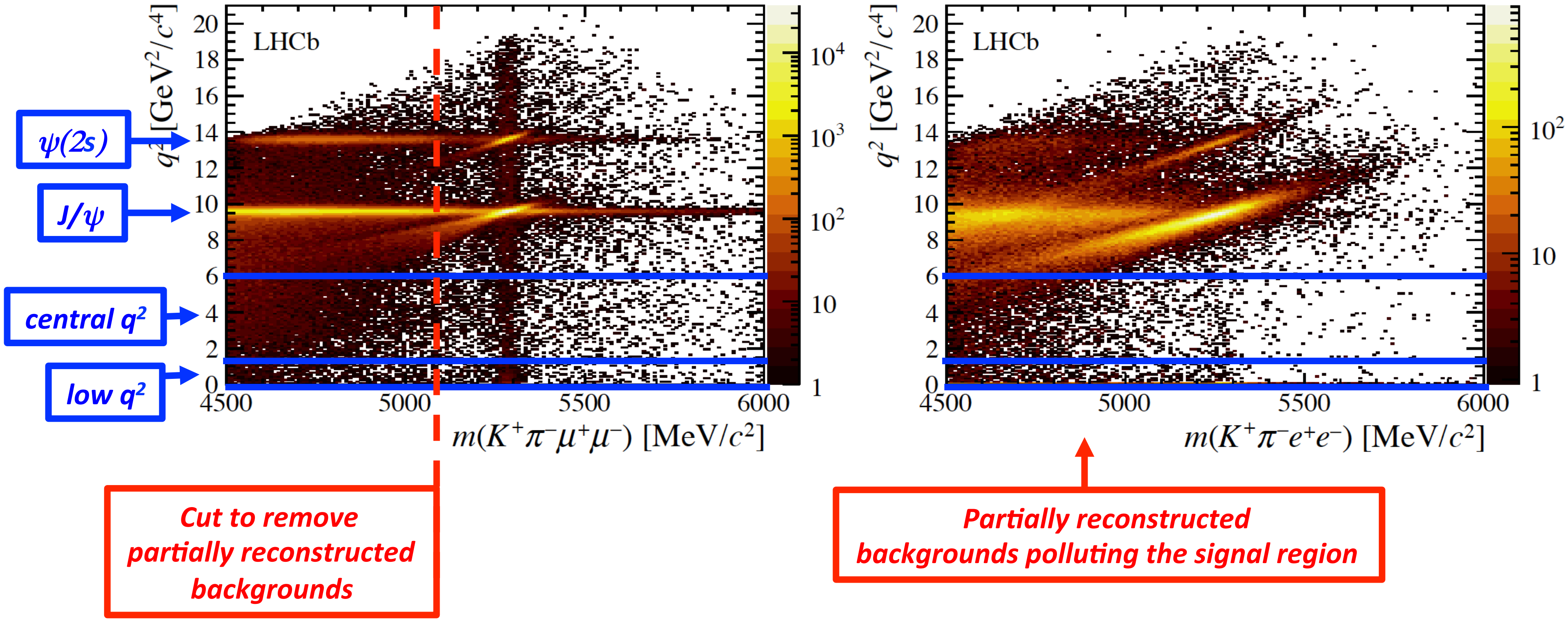


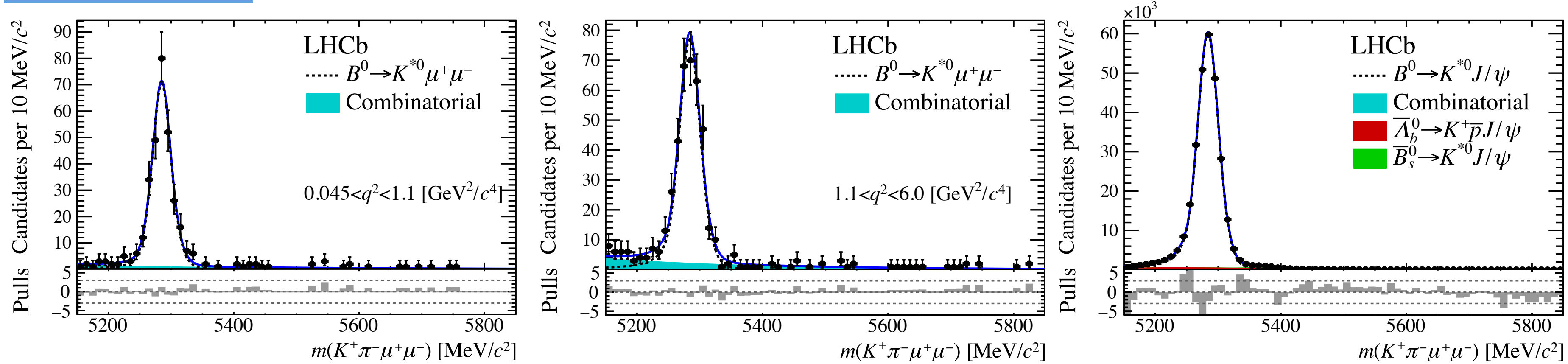
R_{K^*} ANALYSIS STRATEGY

- **Blind analysis**
- **Selection as similar as possible for the electron and muon channels:**
  - Quality of the candidates
  - Vetoes against peaking backgrounds
  - Particle identification
  - Multivariate classifier using quality of the candidates and kinematics
  - Kinematic discriminant to reduce partially reconstructed backgrounds
  - Random rejection of multiple candidates (1-2%)
- **Efficiencies determined using simulations, tuned with data**
- **Separate exclusive trigger categories and bremsstrahlung categories**
- **Simultaneous fit to resonant and non-resonant channels**

R_{K^*} YIELDS

arXiv:1705.05802

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

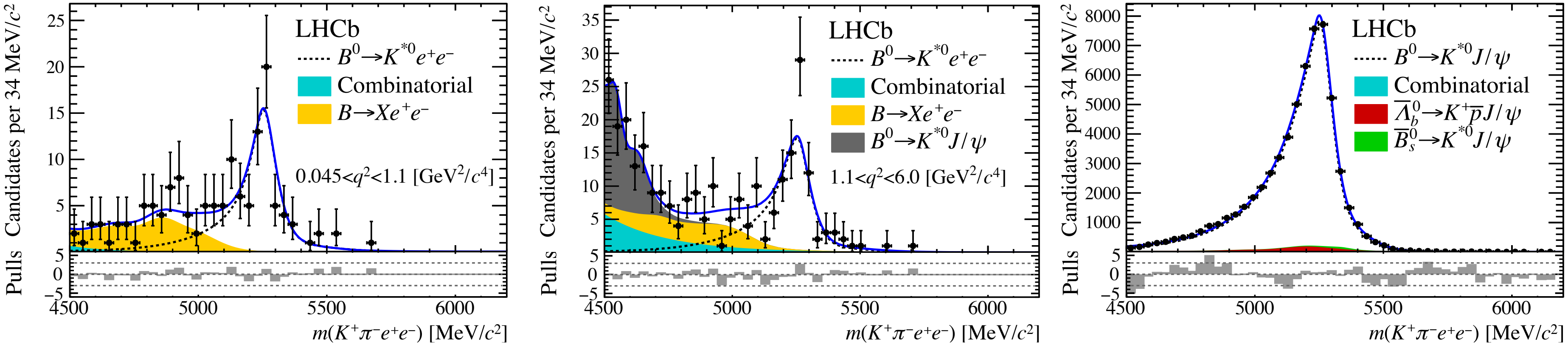


Low q^2 : 285 ± 18

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^*} SYSTEMATICS

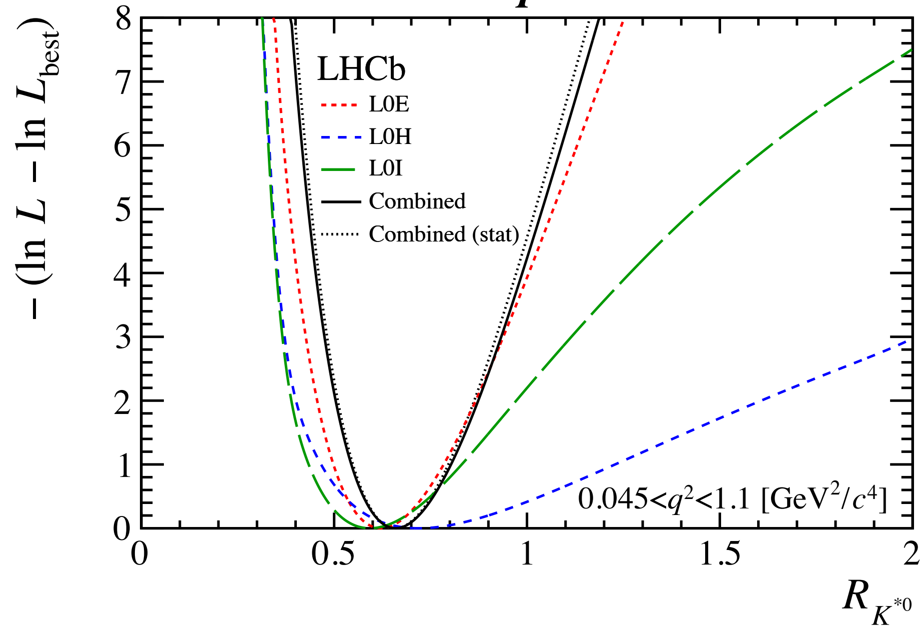
arXiv:1705.05802

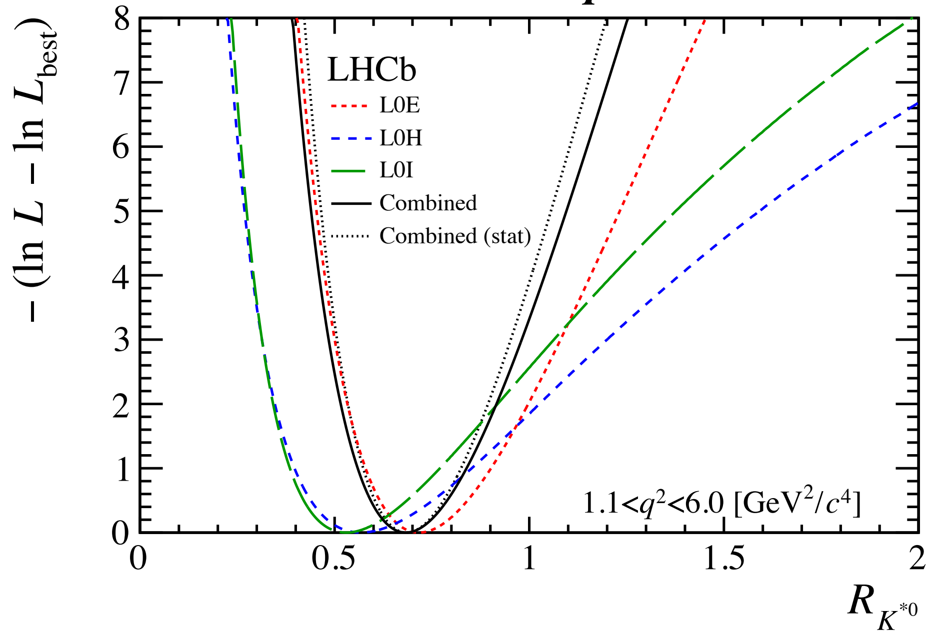
- **The double ratio cancels a lot of systematics**
- **The measurement is statistically dominated (15%)**

	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	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

R_{K^*} RESULTS

arXiv:1705.05802





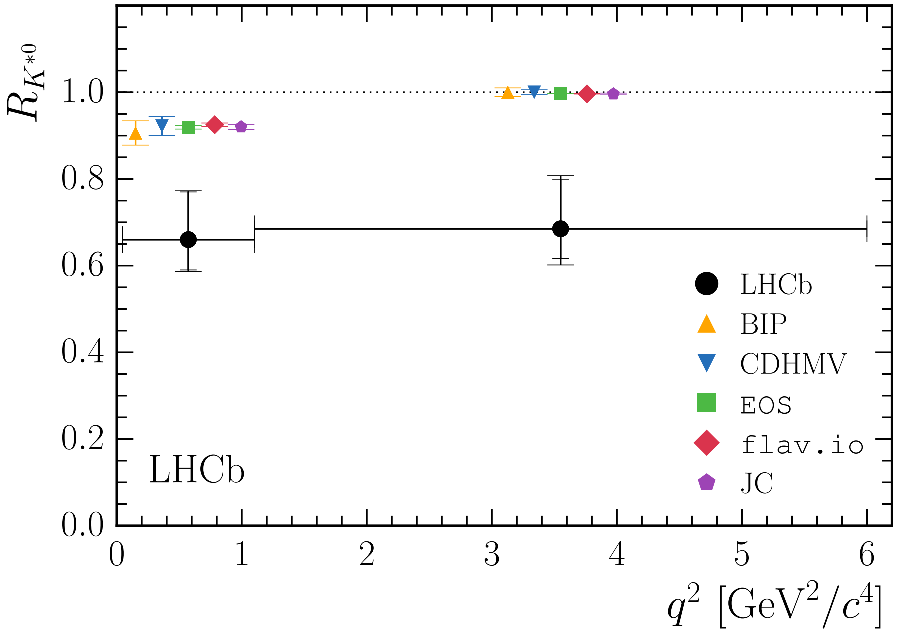
	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66\ ^{+\ 0.11}_{-\ 0.07} \pm 0.03$	$0.69\ ^{+\ 0.11}_{-\ 0.07} \pm 0.05$
95.4% CL	[0.52, 0.89]	[0.53, 0.94]
99.7% CL	[0.45, 1.04]	[0.46, 1.10]

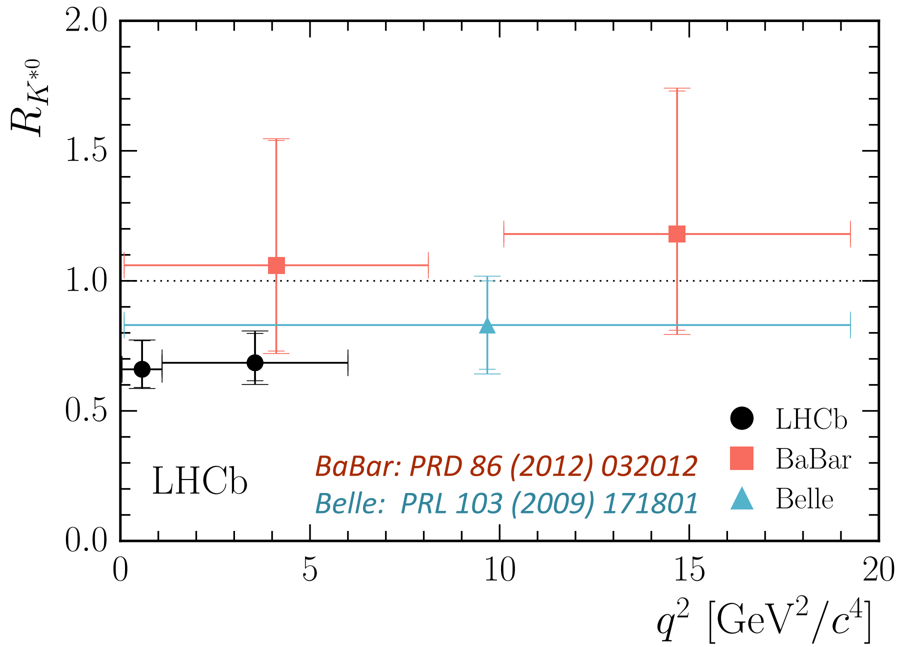
R_{K^*} RESULTS

Compatibility with the SM:

- **2.1-2.3 standard deviations (low-q^2)**
- **2.4-2.5 standard deviations (central-q^2)**

arXiv:1705.05802





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

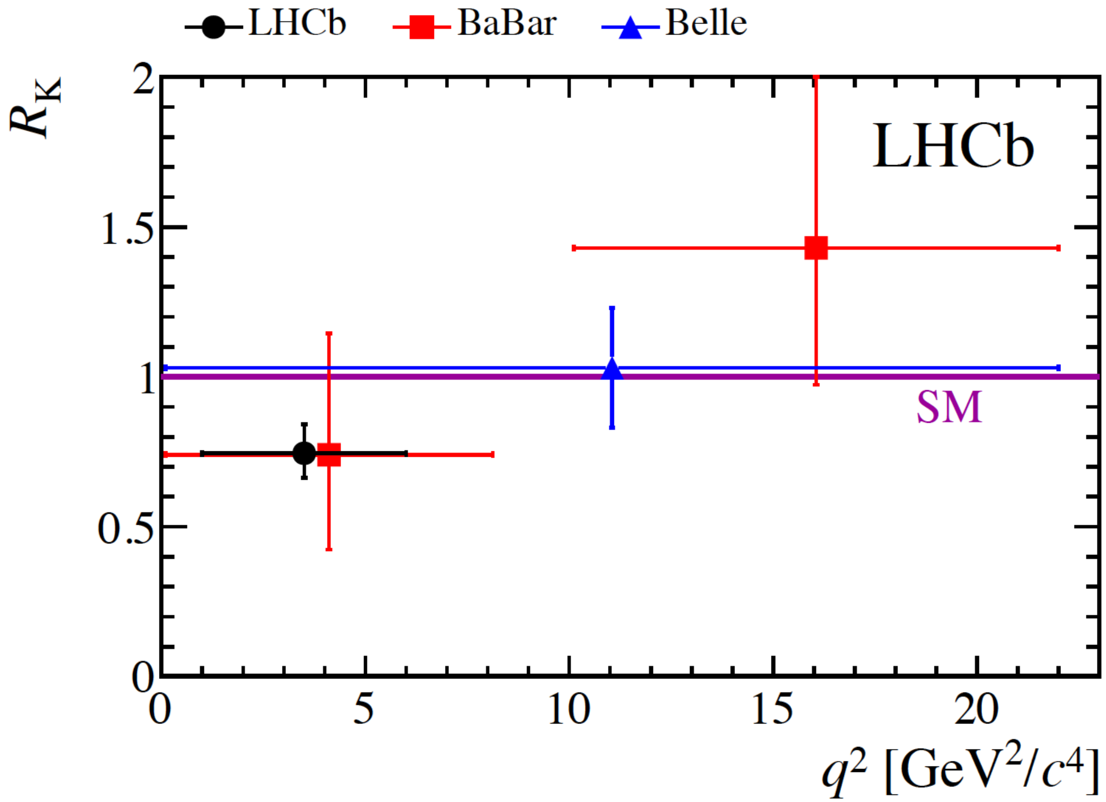
See G. Andreassi's talk (Heavy Flavors III)

R_K RESULT

- 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

REMINDER OF OTHER b->sll RESULTS

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

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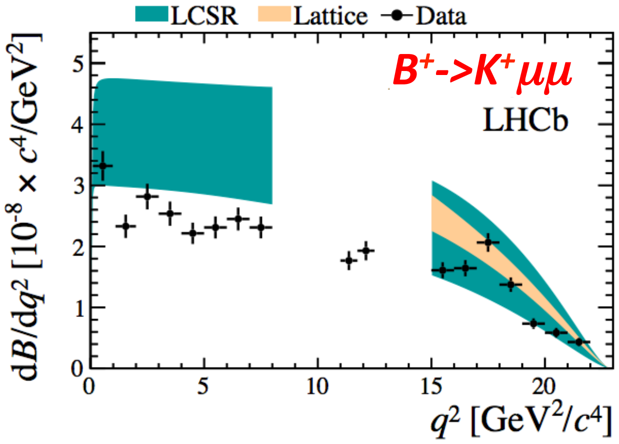
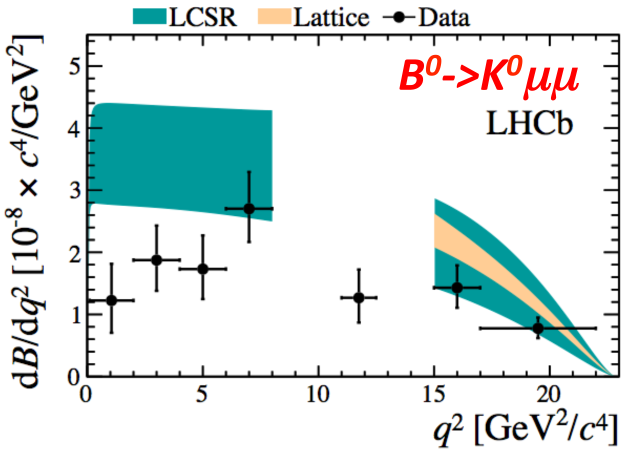
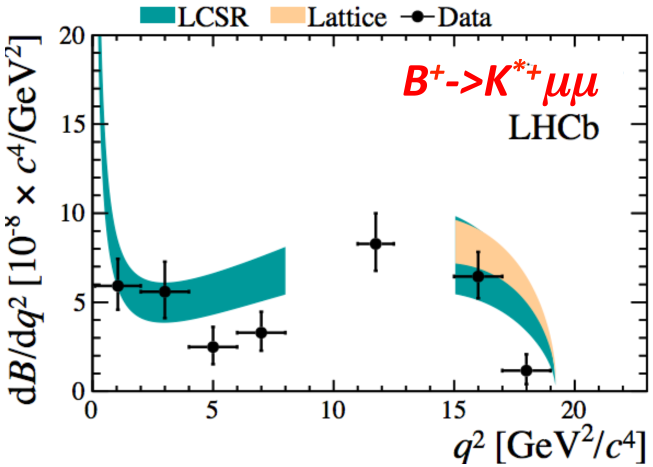
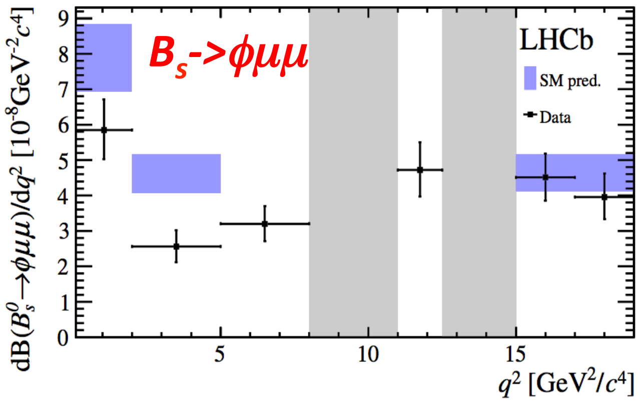


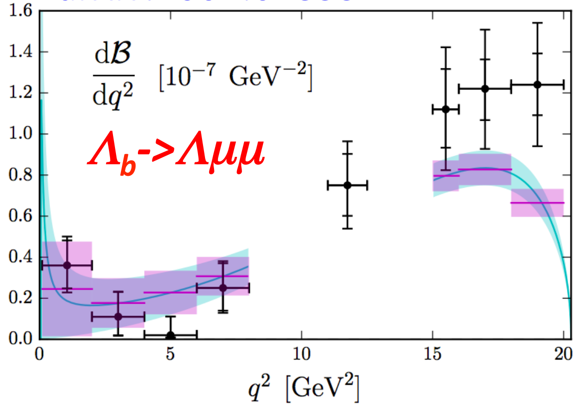




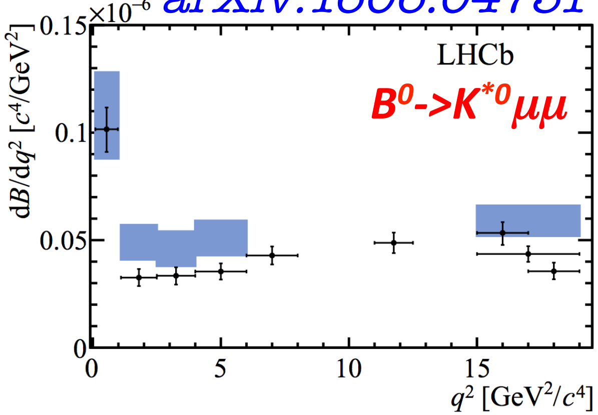
JHEP 09 (2015) 179



JHEP 06 (2015) 115 and
arXiv:1602.01399

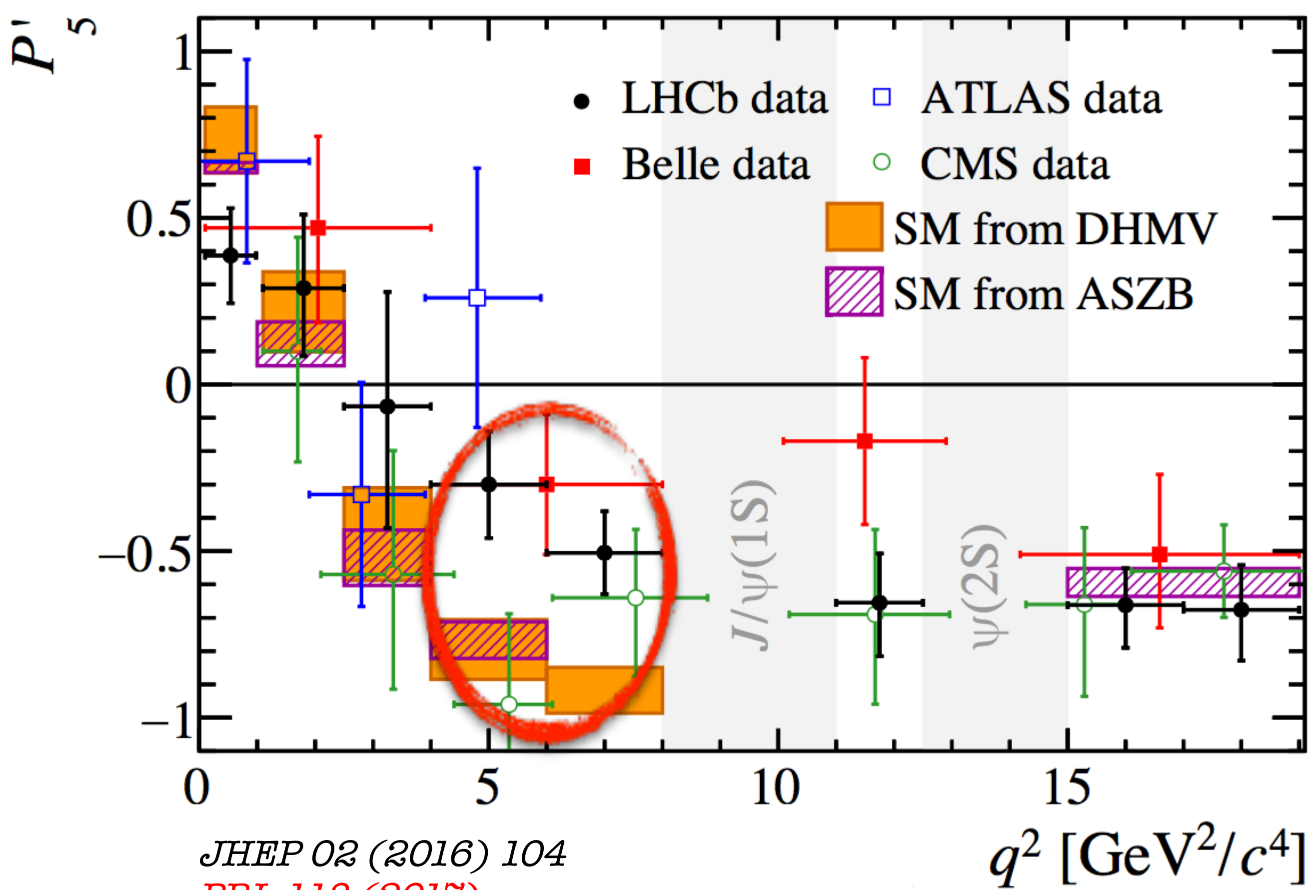


arXiv:1606.04731



REMINDER OF OTHER b->sll RESULTS

Angular observables in *B->K*μμ* show about 3.4σ discrepancy



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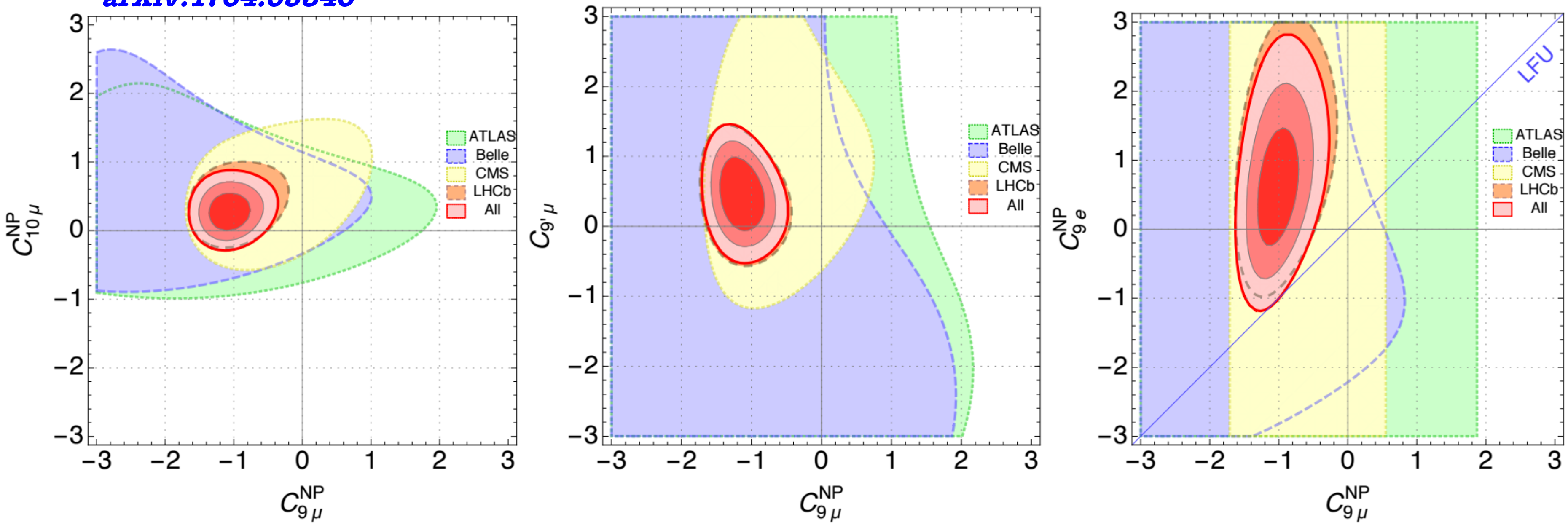
PRL 118 (2017)
ATLAS-CONF-2017-023
CMS-PAS-BPH-15-008

THE GLOBAL PICTURE

- Adding BRs and angular observables of *b->μμ*, *b->sll*, *b->sγ* => up to 5σ deviation from the SM
- Mostly affecting $C_{9\mu}$ and $C_{10\mu}$ Wilson coefficients

arXiv:1704.05340



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- **Global fits of LFU only shows about 3σ discrepancy from SM**
- Remember: LFU tests are not affected by QCD effects (ex: charms loops)

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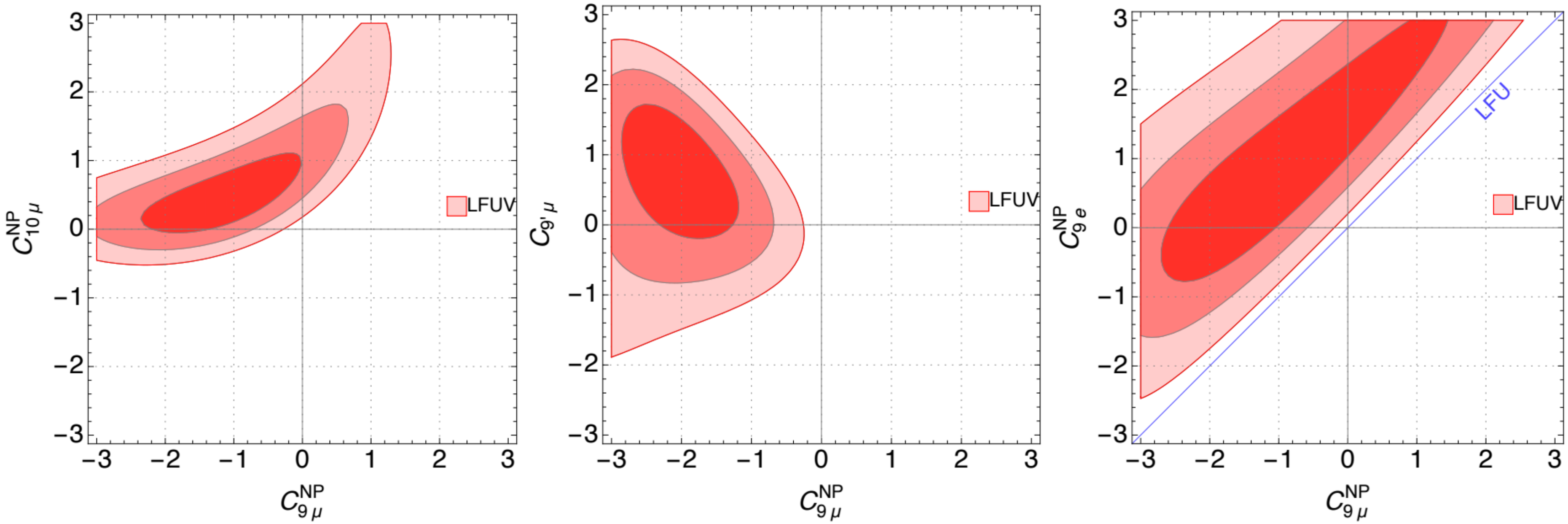

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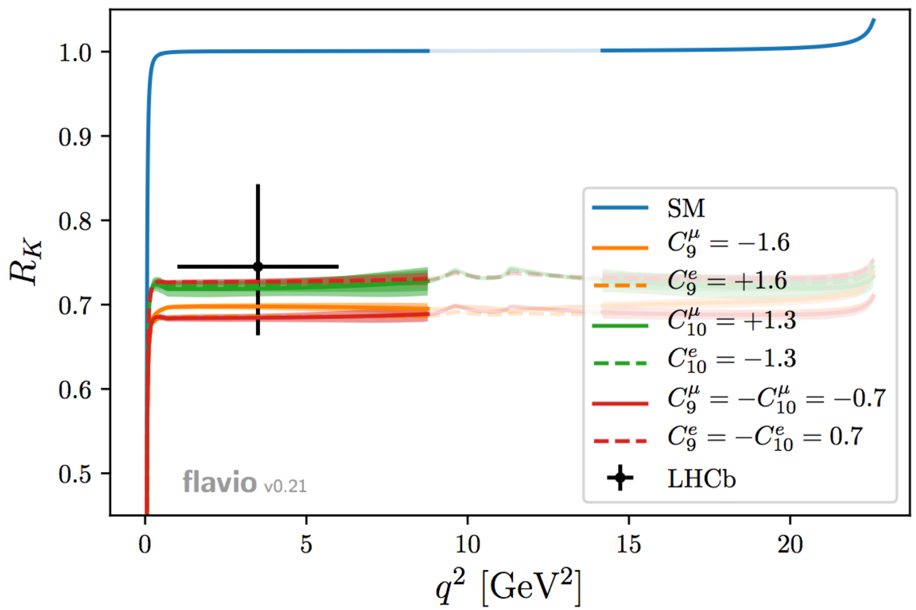
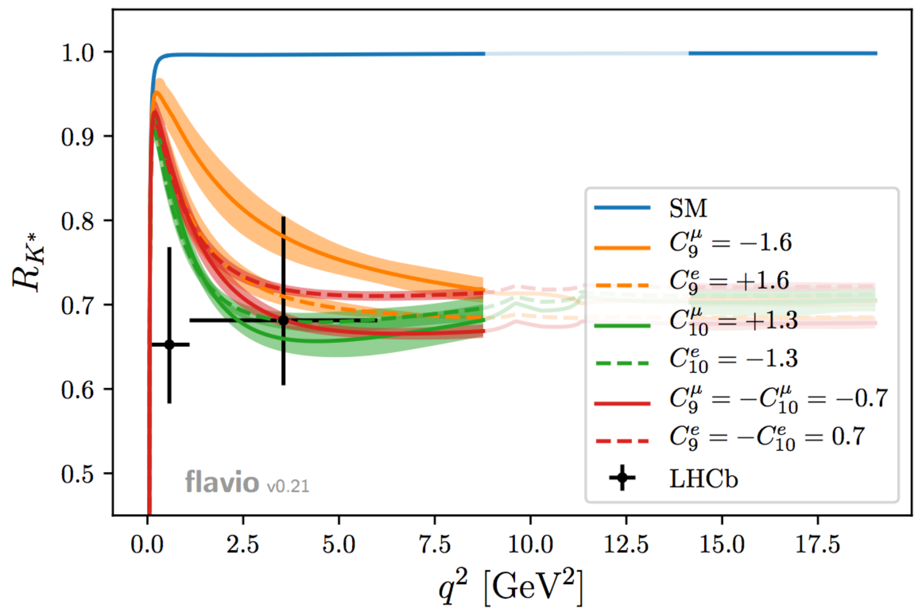
arXiv:1704.05435





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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
......

arXiv:1704.05435

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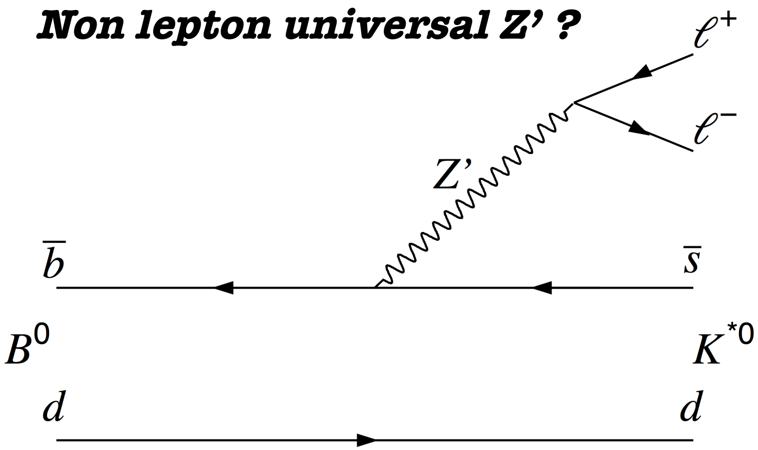
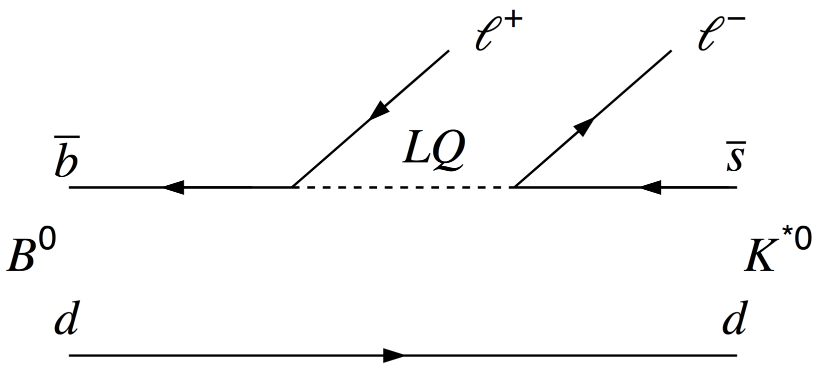
Some NP hypotheses mentioned

Non lepton universal Z' ?



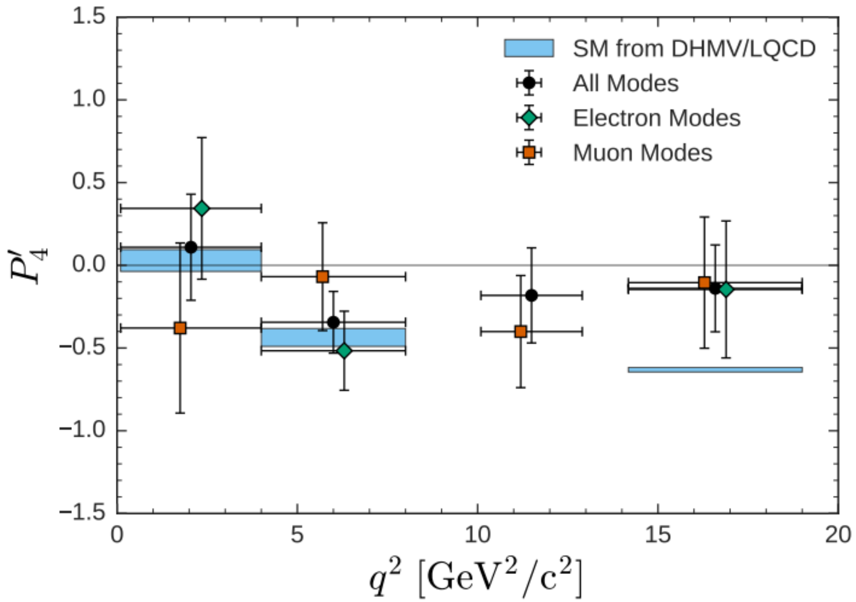
Leptoquarks?

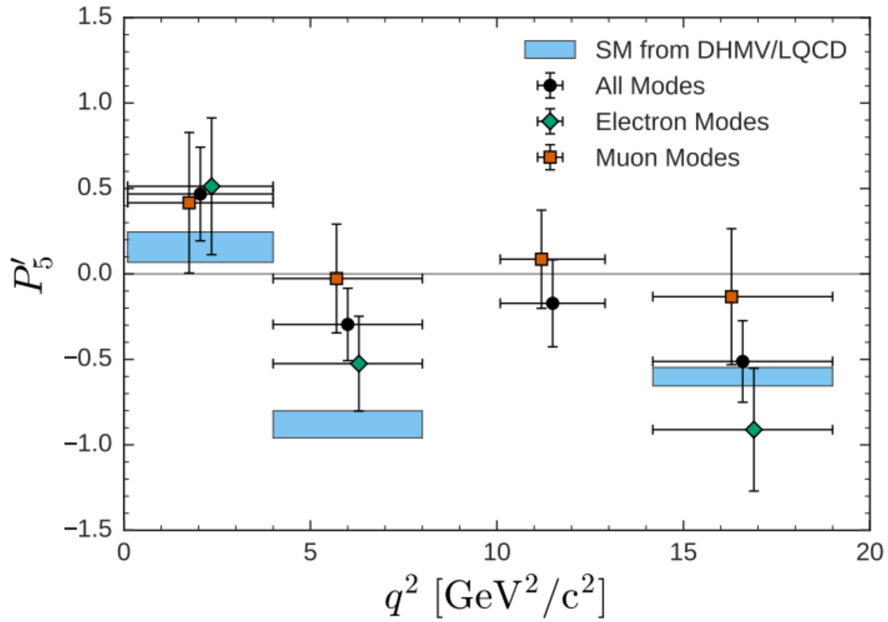


PROSPECTS FOR LFU IN b->sll

- $\mathbf{R_K}$, $\mathbf{R_{K^*}}$, $\mathbf{R\phi}$ 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...

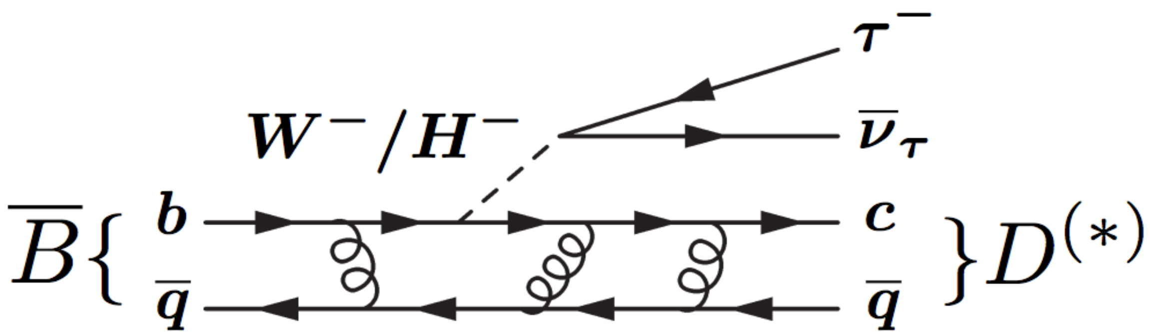
OUTLINE

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



RECONSTRUCTION OF τ

- Taus reconstructed through their decay products.
- Tau decay vertex not always identified.
- Neutrinos => missing energy and degradation of the mass resolution.
- Traditional and new reconstruction techniques based on the kinematics are explored.
- Approximations: $(p_B)_z = \dfrac{m_B}{m_{reco}} (p_{reco})_z$

Leptonic:

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

Hadronic:

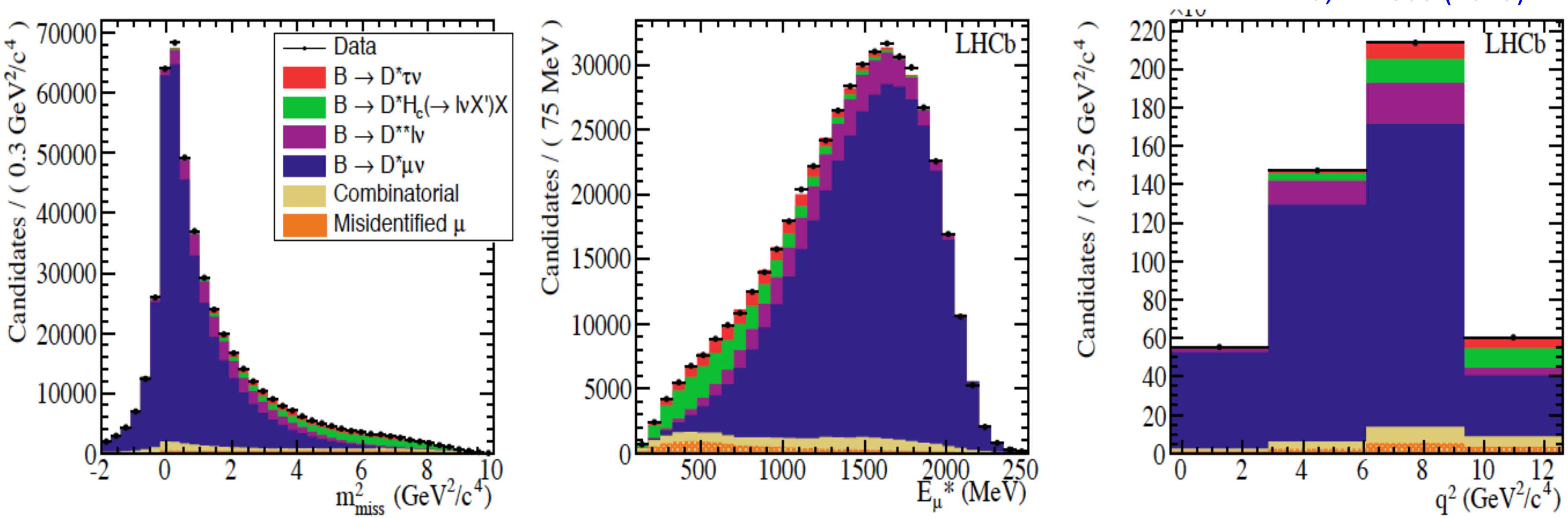
- BR($\tau^- \rightarrow \pi^- \nu$) = 10.83 ± 0.06 %
- BR($\tau^- \rightarrow \pi^- \pi^0 \nu$) = 25.52 ± 0.09 %
- BR($\tau^- \rightarrow \pi^- \pi^0 \pi^0 \nu$) = 9.30 ± 0.11 %
- BR($\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu$) = 9.31 ± 0.06 %
- BR($\tau^- \rightarrow \pi^- \pi^+ \pi^- \pi^0 \nu$) =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

R_{D^*} WITH LEPTONIC τ IN LHCb

- 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: $m^2_{\mathrm{miss}} = (p^\mu_B - p^\mu_D - p^\mu_\mu)^2$
  - the muon energy in c.o.m. frame: $E_\mu{}^*$
  - the squared four momentum transferred to the di-lepton system: q^2

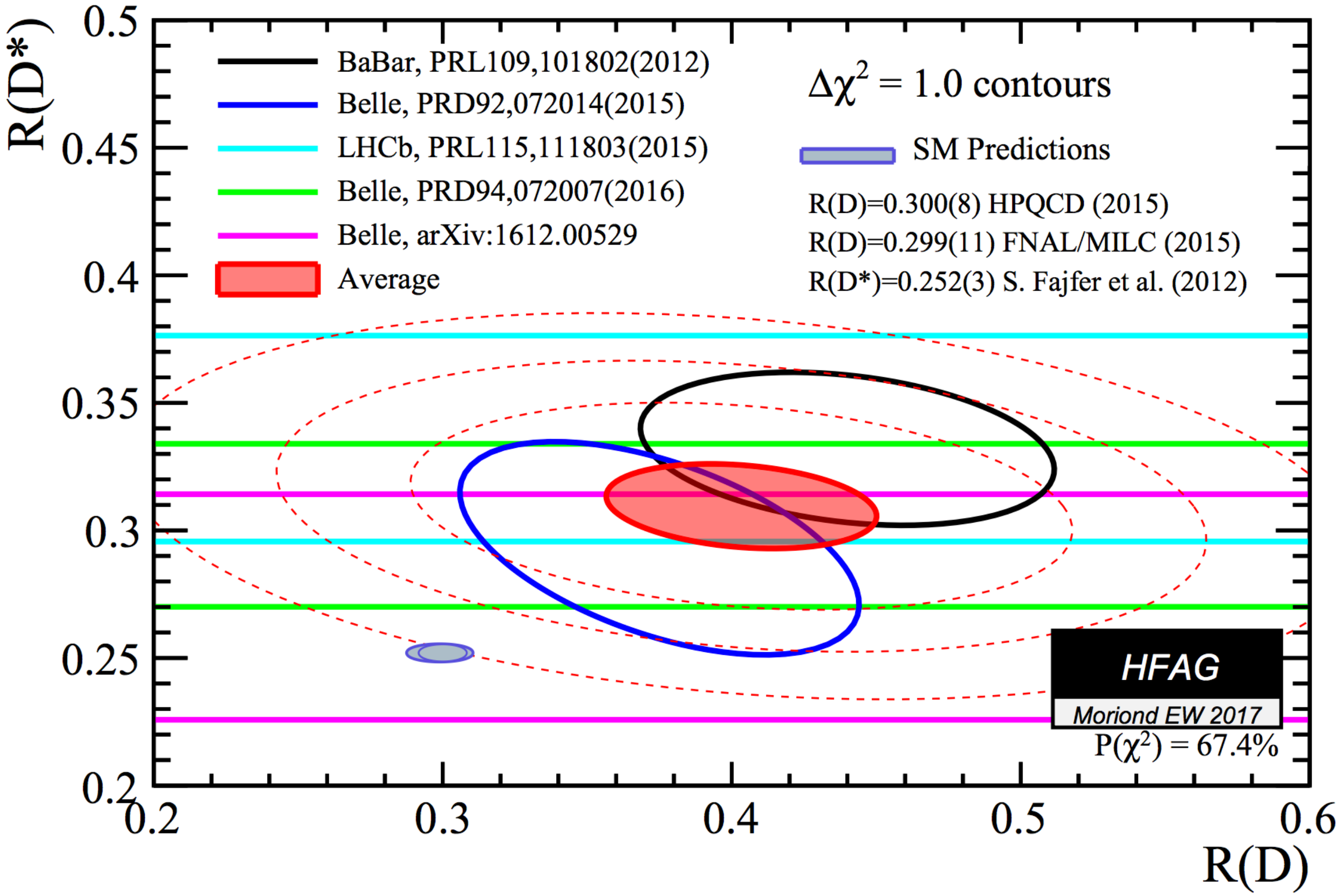
Run1 dataset: 3 fb^{-1}
PRL 115, 111803 (2015)



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

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

- 2.1 σ larger than the SM expectation
- In combination with other experiments and R_D ==> 3.9σ discrepancy



R_{D^*} HADRONIC IN LHCb

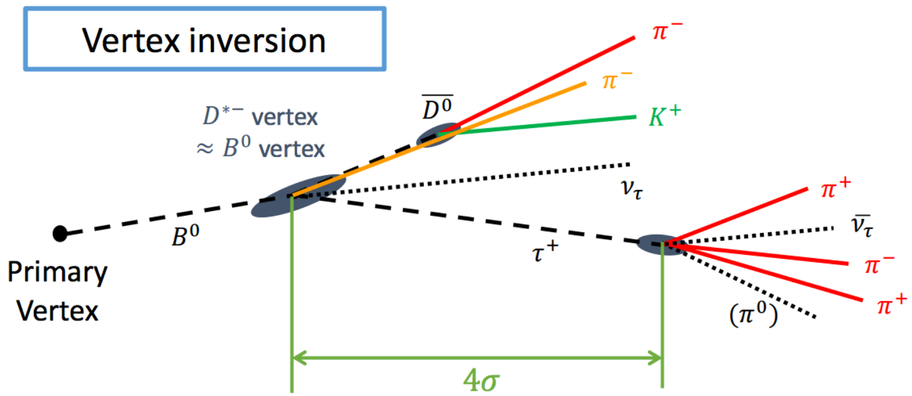
See F. Betti talk (Heavy Flavors III)

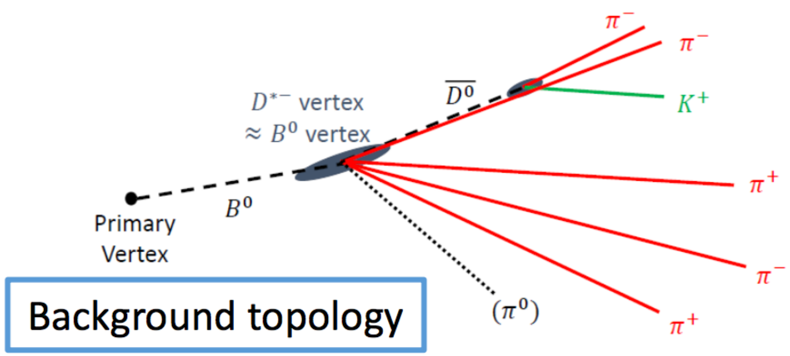
$$\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$$

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

Same final state: systematics cancels — *External input*

- Good vertex reconstruction, but large hadronic backgrounds. Specific tools needed to reduce it.





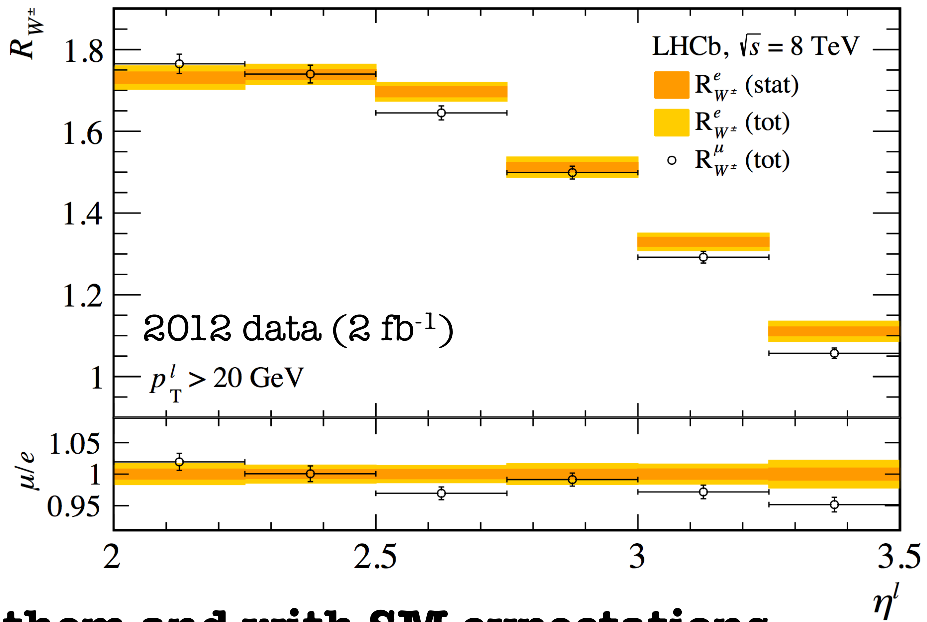
- Expected statistical precision: 7% with 3fb^{-1} (competitive with world average)
- Other analysis ongoing: R_D, $R_{J/\psi}$, R_{Ds}, $R_{\Lambda c}$

OUTLINE

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

R_W MEASUREMENTS

R_W: ratio of forward production cross section W->eν (JHEP 10 (2016) 030) and W->μν (JHEP 01 (2016) 155)

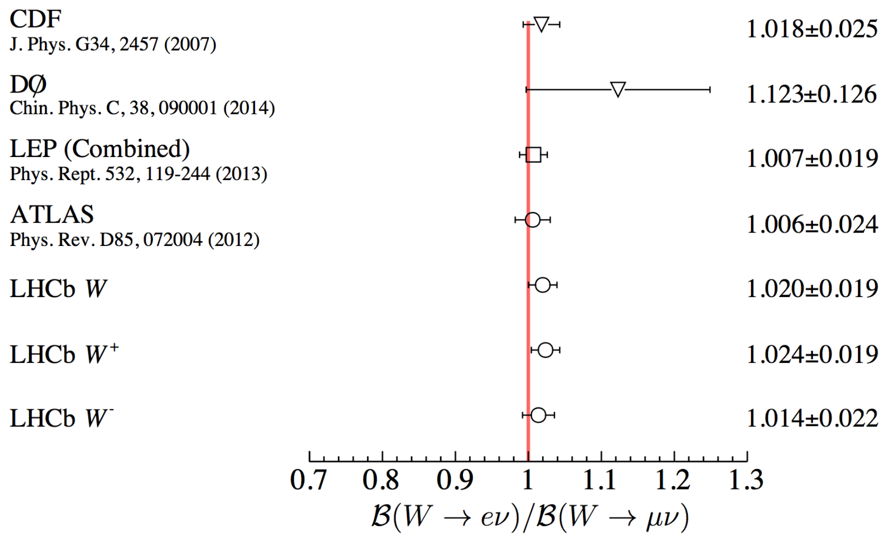


$$\frac{\mathcal{B}(W+\to e^+\nu_e)}{\mathcal{B}(W+\to \mu^+\nu_\mu)} = 1.024 \pm 0.003 \pm 0.019$$

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

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

All experiments in agreement among them and with SM expectations



OUTLINE

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

LFU tests are extremely clean probes for New Physics

Some intriguing discrepancies in the recent measurements:

- R_K, R_{K^*}, R_{D^*}

Follow the path!

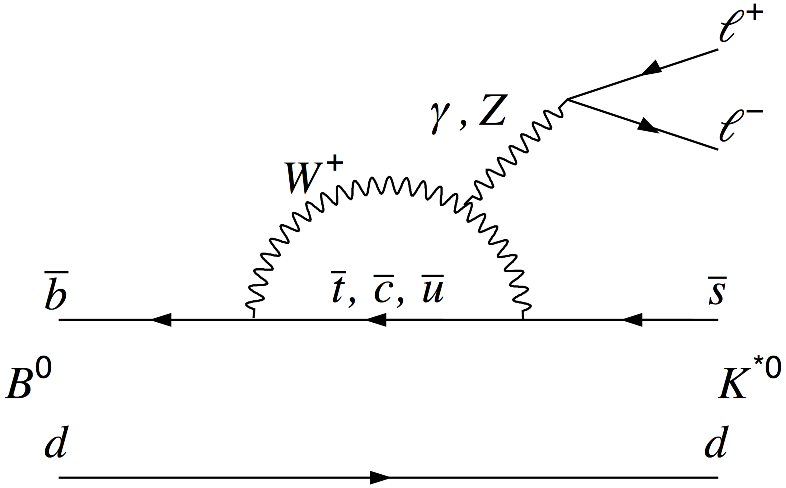
- Repeat all measurements with the enlarged datasets and improved analysis techniques
- Explore new channels
- Test LFU in angular distributions
- Search for direct LFV

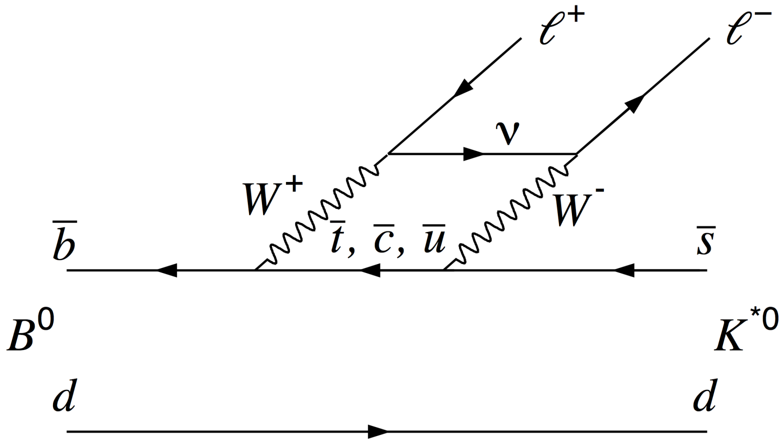
LHCb is on its way!

R_{K^*} FEYNMAN DIAGRAMS

arXiv:1705.05802

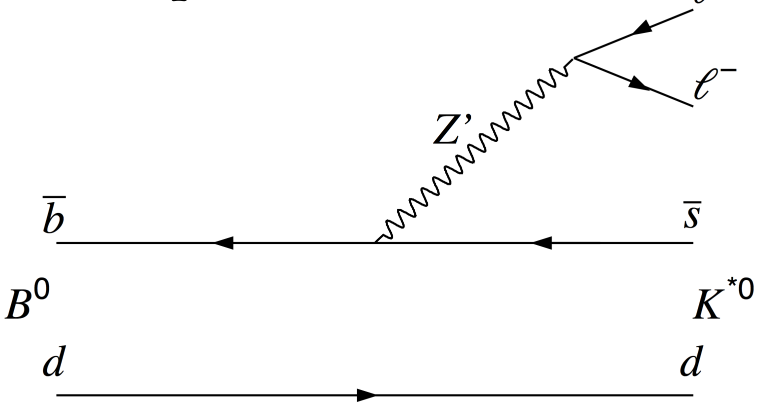
Standard Model



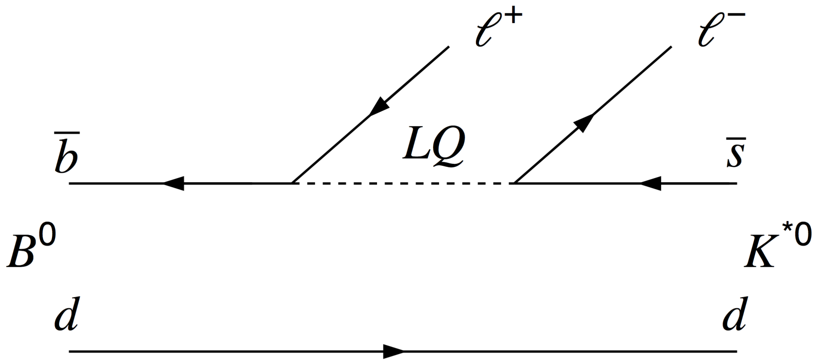


Some NP hypotheses mentioned

Non lepton universal Z' ?



Leptoquarks?

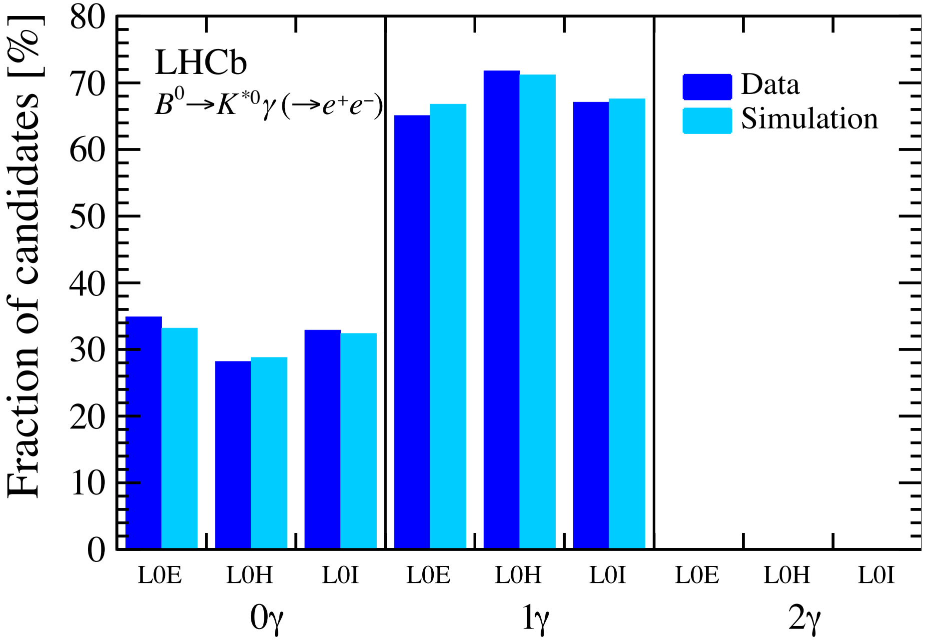


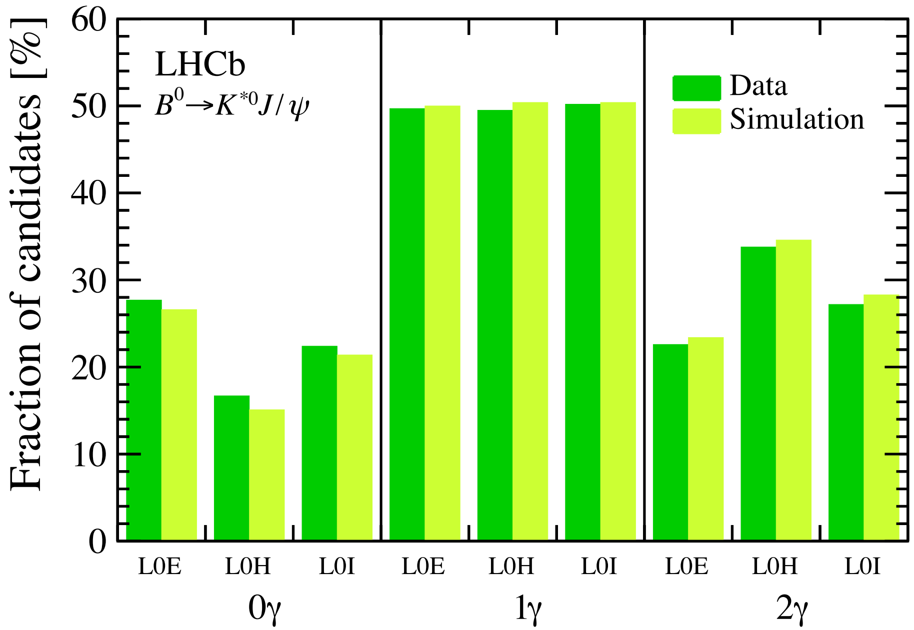
R_{K^*} YIELDS

	$B^0 \to K^{*0}\ell^+\ell^-$		$B^0 \to K^{*0} J/\psi(\to \ell^+\ell^-)$
	low-q^2	central-q^2	
$\mu^+\mu^-$	$285\,^{+\,18}_{-\,18}$	$353\,^{+\,21}_{-\,21}$	$274416\,^{+\,602}_{-\,654}$
e^+e^- (L0E)	$55\,^{+\,9}_{-\,8}$	$67\,^{+\,10}_{-\,10}$	$43468\,^{+\,222}_{-\,221}$
e^+e^- (L0H)	$13\,^{+\,5}_{-\,5}$	$19\,^{+\,6}_{-\,5}$	$3388\,^{+\,62}_{-\,61}$
e^+e^- (L0I)	$21\,^{+\,5}_{-\,4}$	$25\,^{+\,7}_{-\,6}$	$11505\,^{+\,115}_{-\,114}$

R_{K^*} BREMSSTRAHLUNG

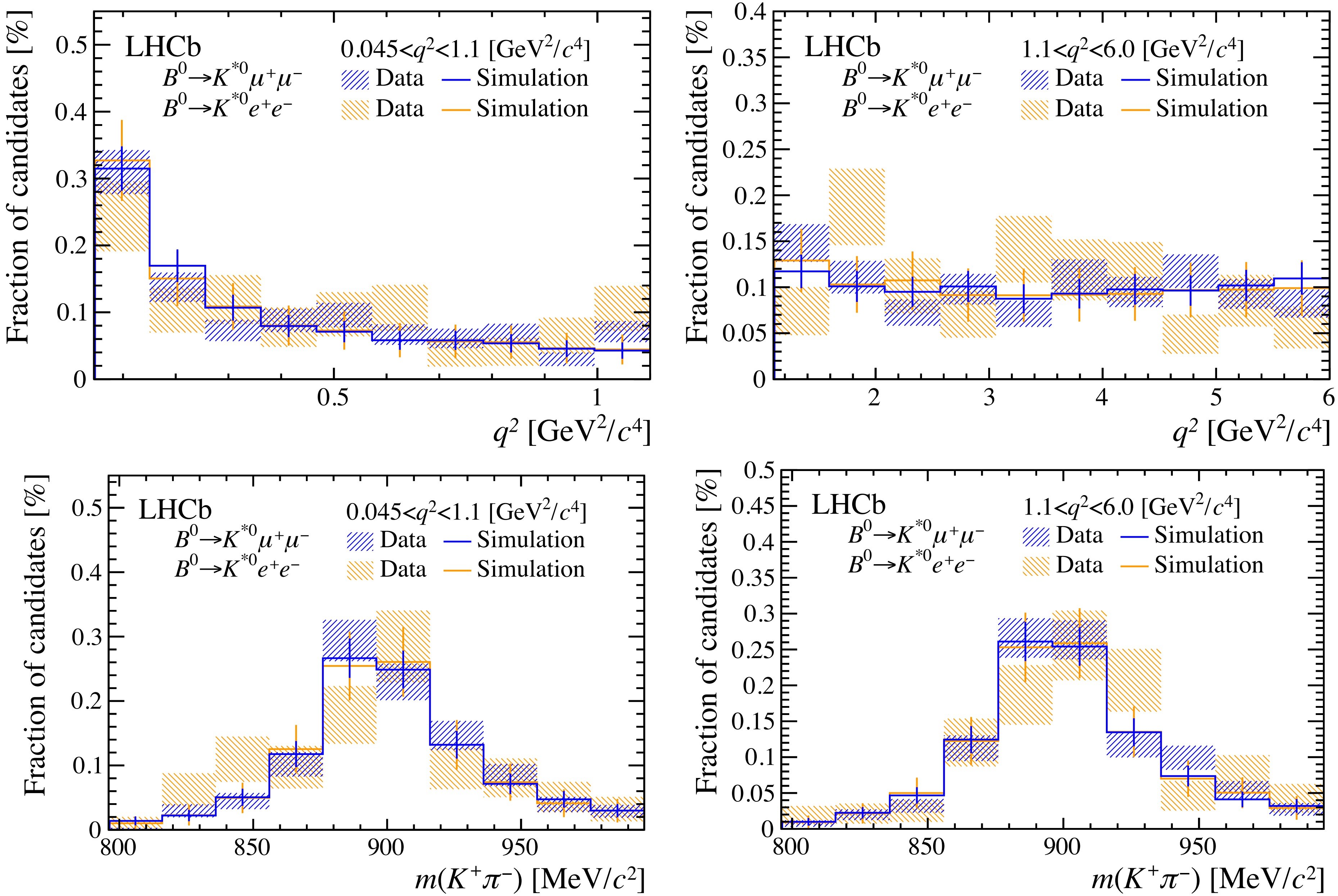
arXiv:1705.05802





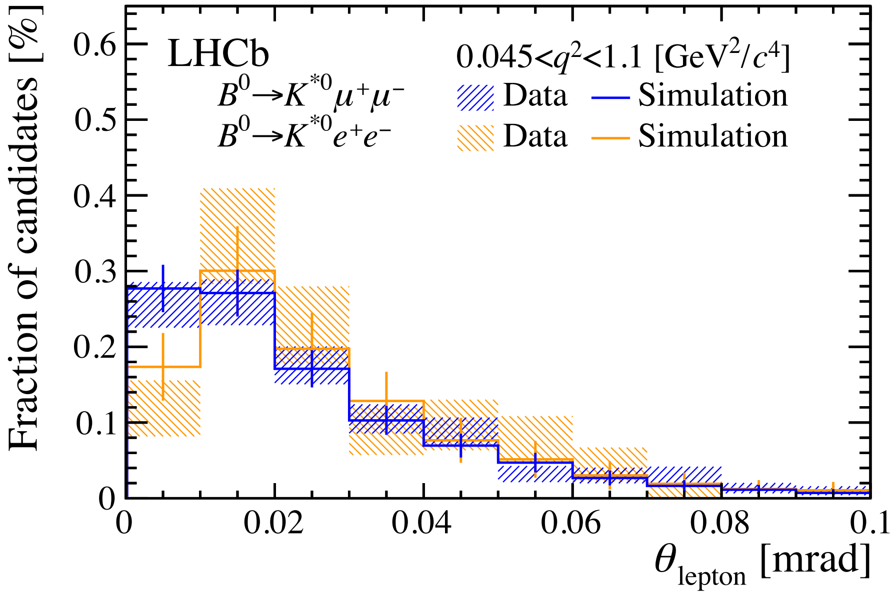
R_{K^*} CROSSCHECKS

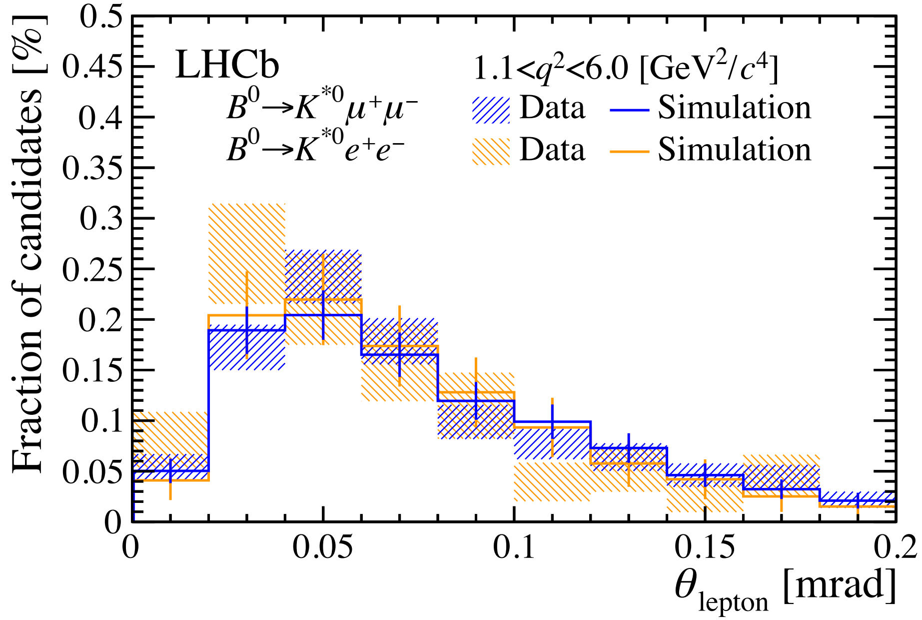
arXiv:1705.05802

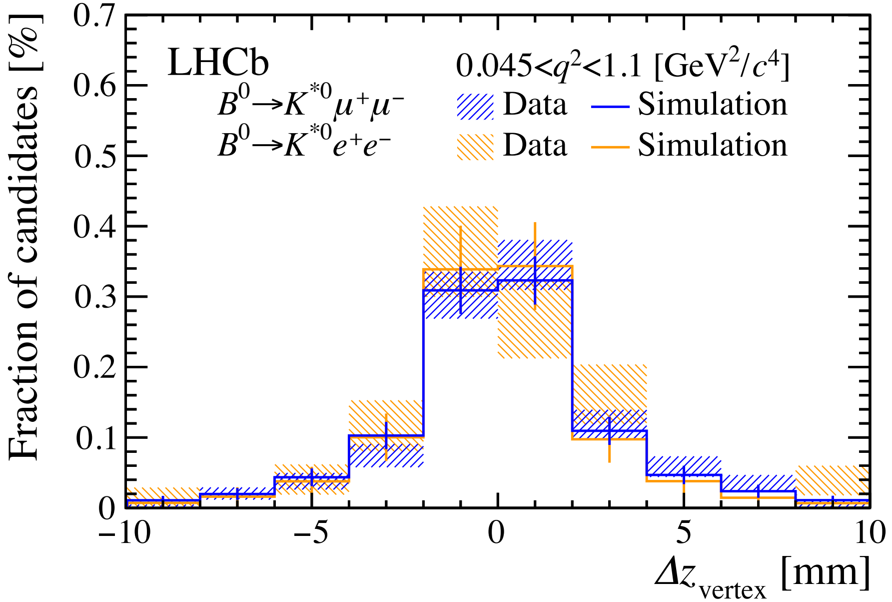


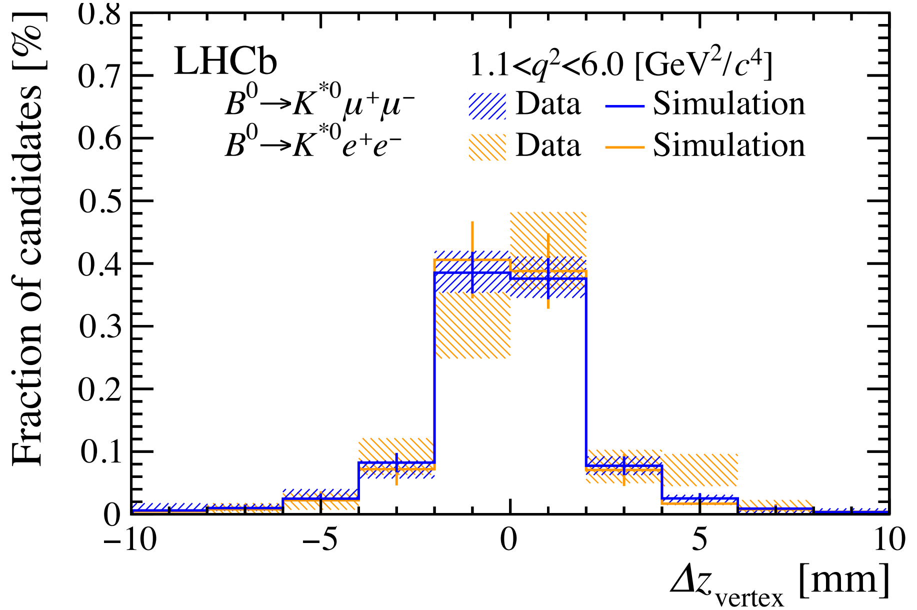
R_{K^*} CROSSCHECKS

arXiv:1705.05802





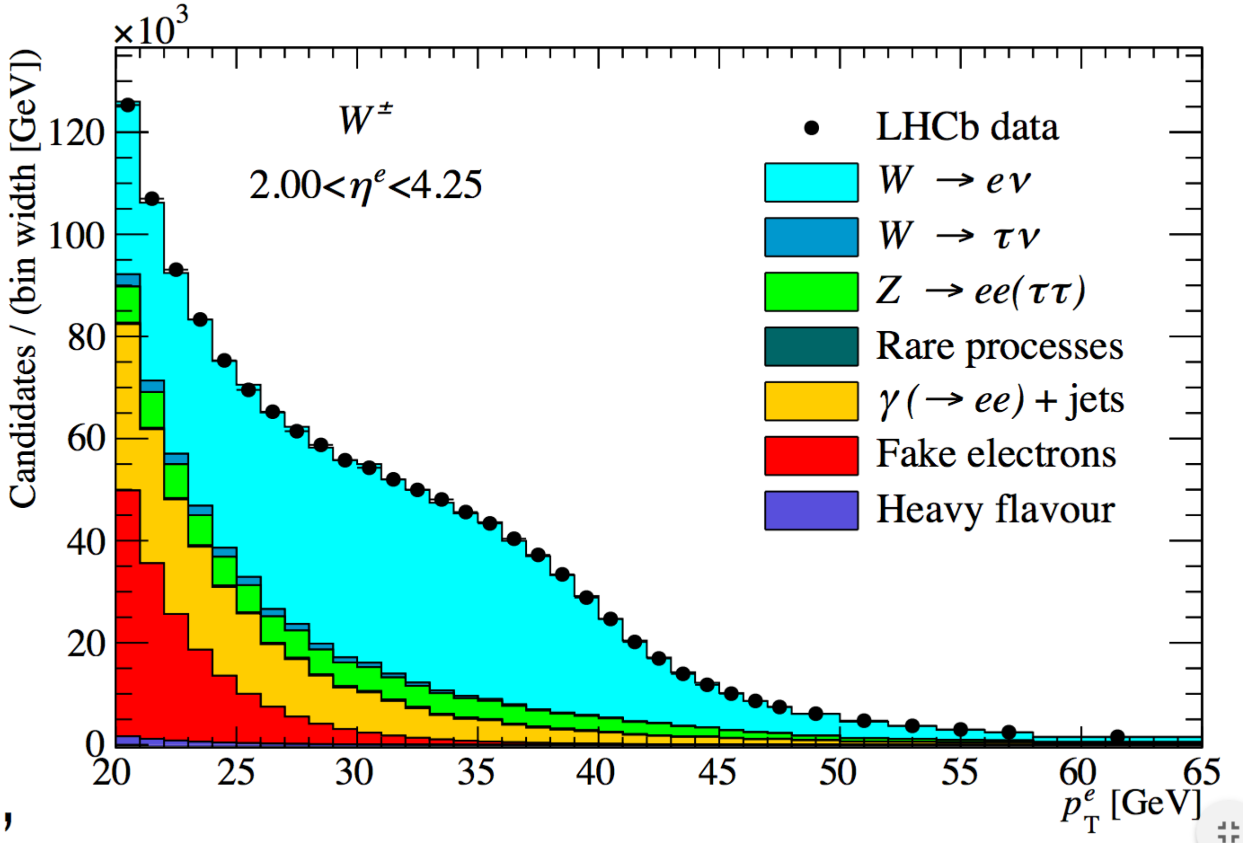




W->lν IN LHCb

Forward W->eν (JHEP 10 (2016) 030) and W->μν (JHEP 01 (2016) 155) production cross section in 2012 at 8TeV (2 fb^{-1})

- Sensitive to NP in trees and loops
- Measured in 8 bins of pseudo-rapidity, separately per lepton charges
- Binned template fits to the lepton p_T
- Data driven methods for fake electrons and heavy flavour decays



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