Test of Lepton Universality with $\Lambda_b \rightarrow pK^- ll$ decays

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on behalf of the LHCb collaboration

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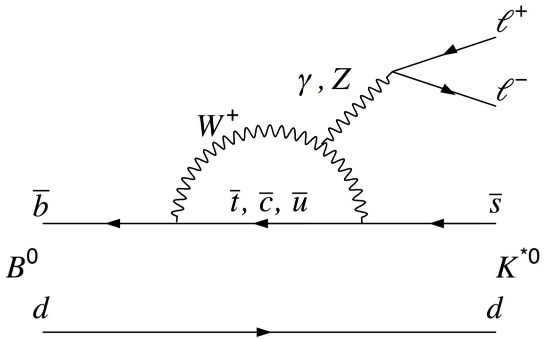
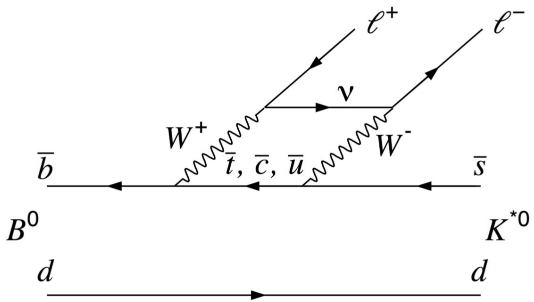
Introduction

Rare b-hadron decays

- FCNC sensitive to indirect effects of New Physics (NP) in loops
  - branching fractions, angular distributions, etc.
- Access to much larger scales than direct searches

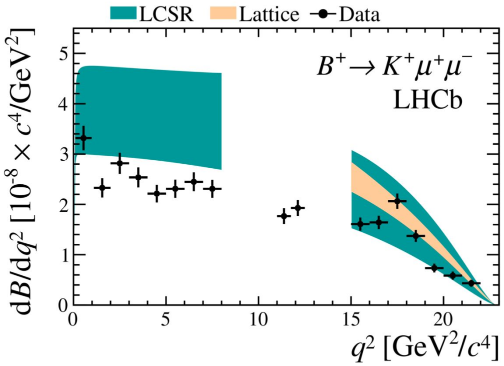




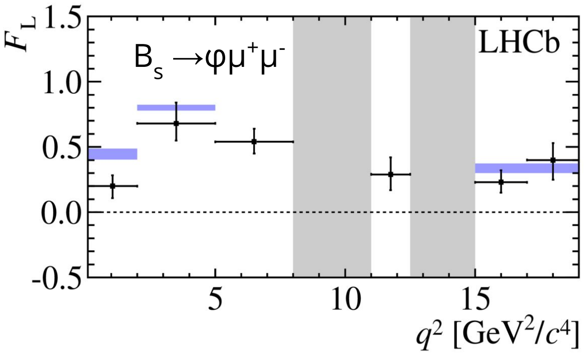
Intriguing deviations in rare B decays

See talk by M. Patel

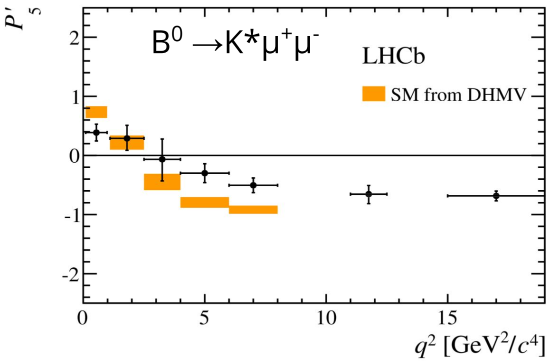
Differential BR and angular distributions



[JHEP 06 (2014) 133]



[JHEP 09 (2015) 179]



[JHEP 02 (2016) 104]

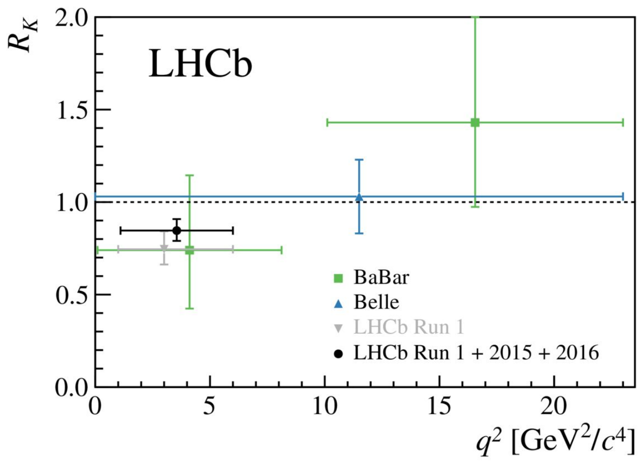
Intriguing deviations in rare B decays

See talk by M. Patel

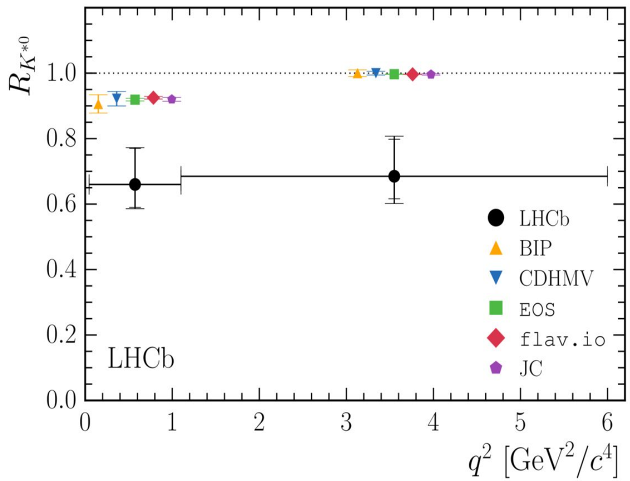
Lepton Universality (LU) tests

$$R_H \equiv \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\, dq^2}$$

PRL 122 (2019) 191801



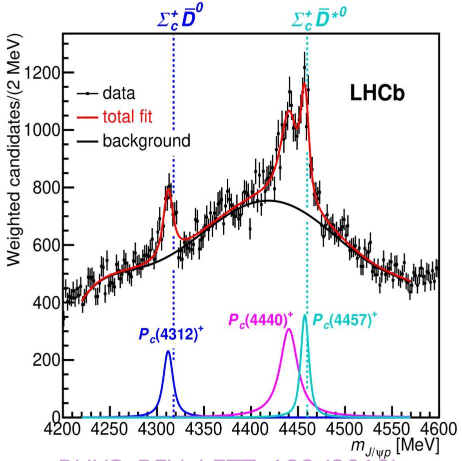
JHEP 08 (2017) 055



Crucial to add more data and measure LU in other modes

Λ_b decays at LHCb

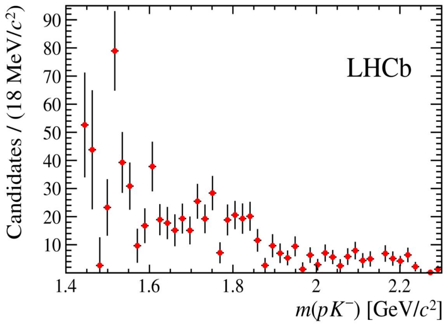
$\Lambda_b \rightarrow pKJ/\psi$



PHYS. REV. LETT. 122 (2019) 222001

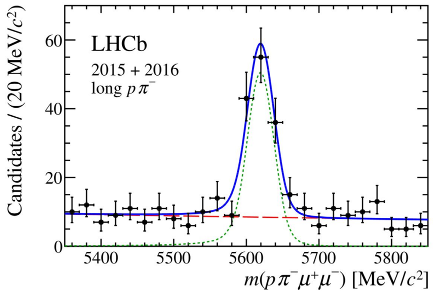
Rare decays

$\Lambda_b \rightarrow pK\mu^+\mu^-$



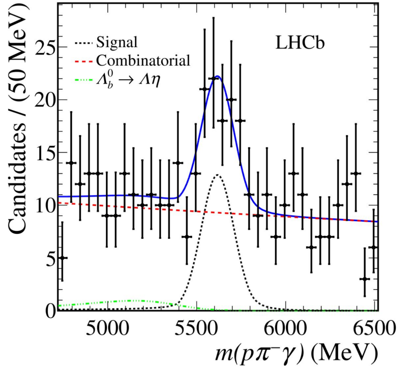
JHEP 06 (2017) 108

$\Lambda_b \rightarrow \Lambda^0\mu^+\mu^-$



JHEP 09 (2018) 146

$\Lambda_b \rightarrow \Lambda^0\gamma$



PHYS. REV. LETT. 123 (2019) 031801

pK final state provides large stats and clean signature
→ test LU here!

Experimental measurement

How do we measure LU?

In the SM:

$$R_H = \frac{BR(B\to H\mu^+\mu^-)}{BR(B\to He^+e^-)} = 1$$

[Fuentes-Martin, et al.]

Experimentally:

$$R_H \propto \boxed{\frac{N(B\to H\mu^+\mu^-)}{N(B\to He^+e^-)}} \times \boxed{\frac{\epsilon(B\to He^+e^-)}{\epsilon(B\to H\mu^+\mu^-)}}$$

from mass fit

from MC and calibration samples

Exploit the well tested LU in J/ψ modes

$$r_{J/\psi} = \frac{BR(B\to HJ/\psi(\mu^+\mu^-))}{BR(B\to HJ/\psi(e^+e^-))} = 1$$

- as stringent cross-check
- to build double ratio → cancel systematic effects

$$R_H = \frac{\frac{N(B\to H\mu^+\mu^-)}{N(B\to HJ/\psi(\mu^+\mu^-))}}{\frac{N(B\to He^+e^-)}{N(B\to HJ/\psi(e^+e^-))}} \times \frac{\frac{\epsilon(B\to He^+e^-)}{\epsilon(B\to HJ/\psi(e^+e^-))}}{\frac{\epsilon(B\to H\mu^+\mu^-)}{\epsilon(B\to HJ/\psi(\mu^+\mu^-))}}$$

Observables of interest

First test of LU with b-baryons, using $\mathbf{\Lambda_b \to pK^-\mu^+\mu^-}$ and $\mathbf{\Lambda_b \to pK^-e^+e^-}$ decays:

$$R_{pK}^{-1} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^- e^+ e^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to e^+ e^-))} \Bigg/ \frac{\mathcal{B}(\Lambda_b^0 \to pK^- \mu^+ \mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+ \mu^-))}$$

in the region:

- $0.1 < q^2 < 6$ GeV/c^4
- m(pK) < 2.6 GeV/c^2

* Inverse definition due to expected small yields in rare electron mode

- R_{pK} is expected to be unity in the SM [Fuentes-Martin et al.]
- Complementary to $R_{K(*)}$ due to fractional baryon spin

Observables of interest

First test of LU with b-baryons, using $\mathbf{\Lambda_b \to pK^-\mu^+\mu^-}$ and $\mathbf{\Lambda_b \to pK^-e^+e^-}$ decays:

$$R_{pK}^{-1} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)}{\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi(\to e^+e^-))} \Big/ \frac{\mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi(\to \mu^+\mu^-))}$$

in the region:

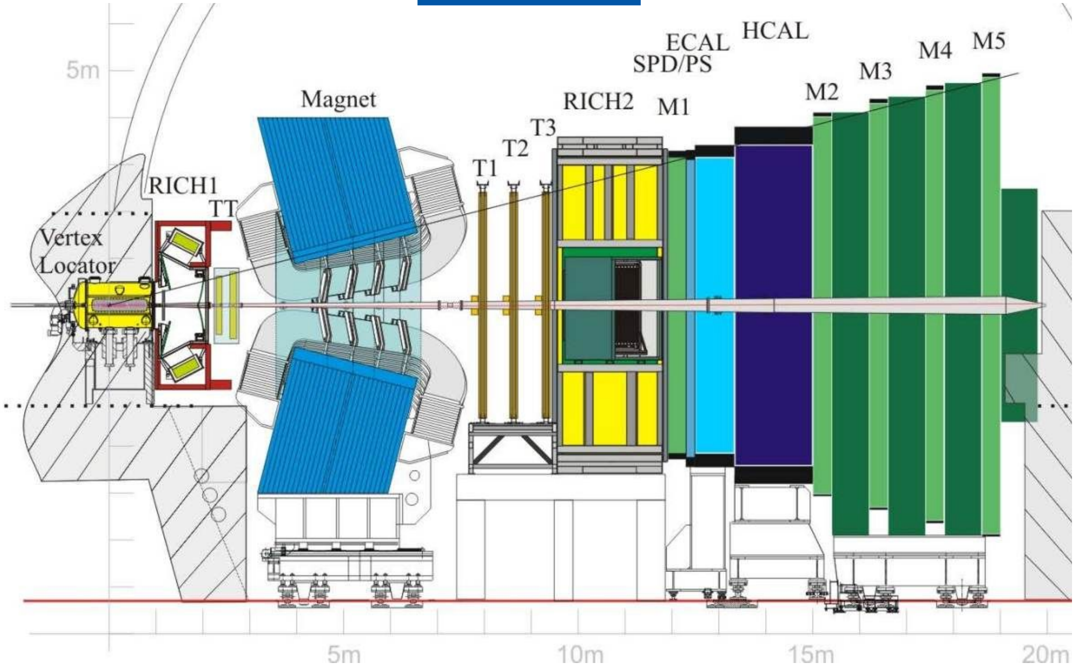
- $0.1 < q^2 < 6$ GeV/c^4
- $m(pK) < 2.6$ GeV/c^2

* Inverse definition due to expected small yields in rare electron mode

- $\Lambda_b \to pK^-e^+e^-$ never observed before → first observation
- $B(\Lambda_b \to pK^-\mu^+\mu^-)$ never measured before → first measurement

JINST 3 (2008) S08005

Experimental setup



$\Delta p / p$ = 0.5 - 1.0%

$\Delta IP = (15 + 29/p_T[GeV])\ \mu m$

$\Delta E/E_{ECAL} = 1\% + 10\% / \sqrt{(E[GeV])}$

Electron ID ~90% for ~5% e→h mis-id probability

Muon ID ~ 97% for 1-3% π→μ mis-id probability

Electrons at LHCb

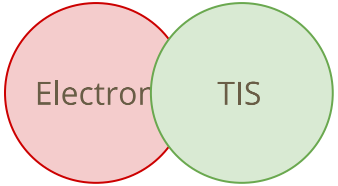
Hardware trigger

Larger ECAL occupancy → tighter thresholds for electrons:

- e p_T > 2700/2400 MeV in 2012/2016
- μ p_T > 1700/1800 MeV in 2012/2016

[LHCb-PUB-2014-046, 2019 JINST 14 P04013]

Mitigated by including events triggered independently of the signal (TIS)

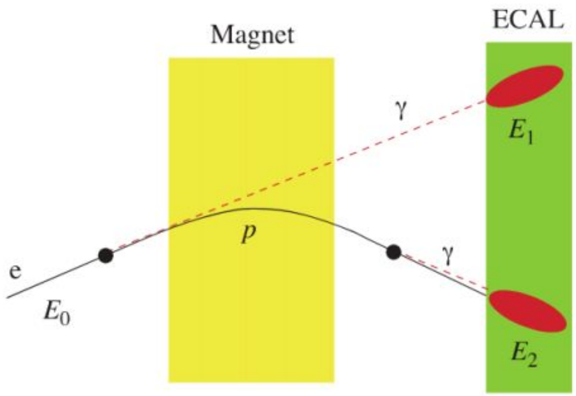


→ analysis performed in 2 trigger categories

Interaction with detector material

Electrons radiate much more Bremsstrahlung

Recovery procedure in place



- miss some photons and add fake ones
- ECAL resolution worse than tracking

→ worse mass resolution for electron modes

arXiv:1912.08139

Datasets and simulation

Datasets:

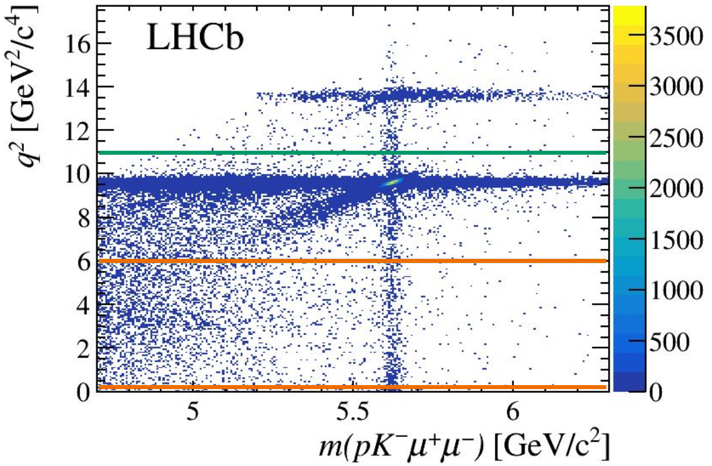
- 3 fb^{-1} at 7 and 8 TeV (Run 1)
- 1.7 fb^{-1} at 13 TeV (Run 2)

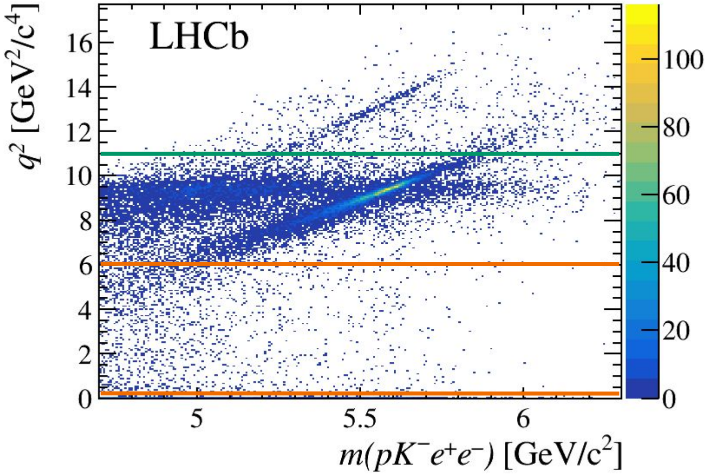
Region of interest:

- resonant: $6 < q^2 < 11$ GeV^2/c^4
- nonresonant: $0.1 < q^2 < 6$ GeV^2/c^4

Simulation:

- phase-space signal samples
- final-state radiation by PHOTOS
  - agrees with full QED [Bordone et al.]



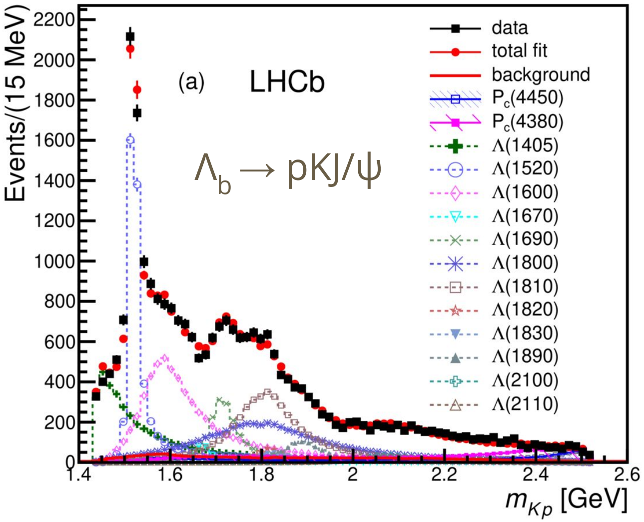


arXiv:1912.08139

Corrections to simulation

- Hadronic pK^- structure: phase-space in MC, rich structure in data
  - correct MC following amplitude analysis of $\Lambda_b \to pKJ/\psi$ in data (Pentaquark discovery)

- Λ_b kinematics and lifetime
- Particle identification (PID) response
- Event multiplicity
- Trigger response



Very good agreement between data and MC after all the corrections

Efficiency extraction from corrected MC

Phys. Rev. Lett. 115 (2015) 072001

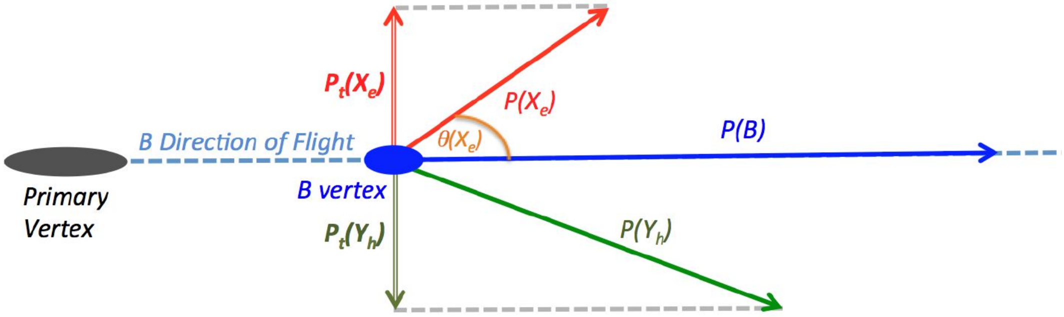
arXiv:1912.08139

Selection and backgrounds

- Preselection: p and p_T requirements, acceptance, PID
- Mass vetoes: Φ, Λ_c, D^0, $\gamma \to e^+e^-$, $B^+ \to K^+ll$ and $p \longleftrightarrow K^-$ swaps
- BDT against combinatorial background using kinematic information
    - trained on $\Lambda_b \to pK^-ll$ MC and data side-band: $m(pK^-ll) > 5825$ MeV/c^2
    - separated BDTs for e and μ final states and run periods
    - suppress ~97% of the background while retaining ~85% of the signal
- Corrected mass cut against partially reconstructed backgrounds
    - for rare electron mode only

$$\alpha = p_T(pK)/p_T(ee)$$
$$p_{corr}(ee) = \alpha \times p(ee)$$

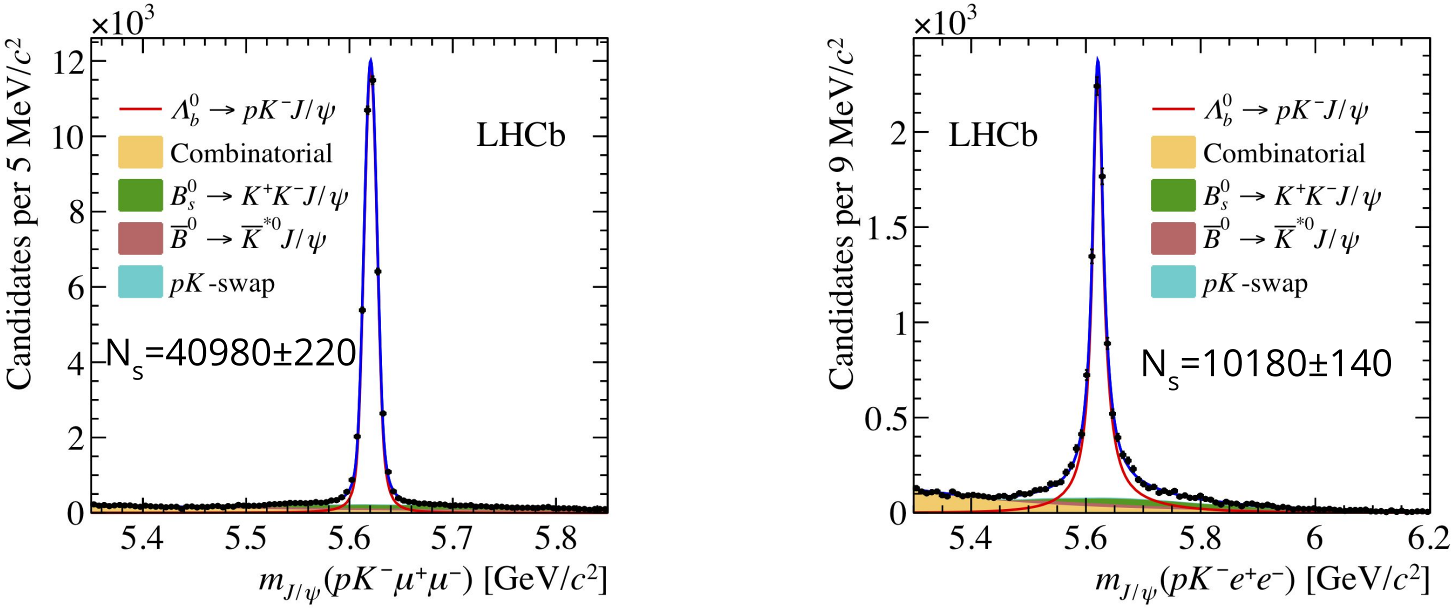
JHEP 08 (2017) 055



arXiv:1912.08139

Resonant modes: mass fit

Constrain m(ee/μμ) to known J/ψ mass → better mass resolution for $m_{J/\psi}$



arXiv:1912.08139

Resonant modes: $r_{J/\psi}$ cross-check

Efficiency cross-check: single ratio $r_{J/\psi}$ known to be LU

$$r^{-1}_{J/\psi} = \frac{N(\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-))}{N(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+\mu^-))} \times \frac{\epsilon(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+\mu^-))}{\epsilon(\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-))}$$

$r^{-1}_{J/\psi} = 0.96 \pm 0.05$ including stat. and syst.

Compatible with unity

arXiv:1912.08139

Resonant modes: $r_{J/\psi}$ cross-check

Efficiency cross-check: single ratio $r_{J/\psi}$ known to be LU

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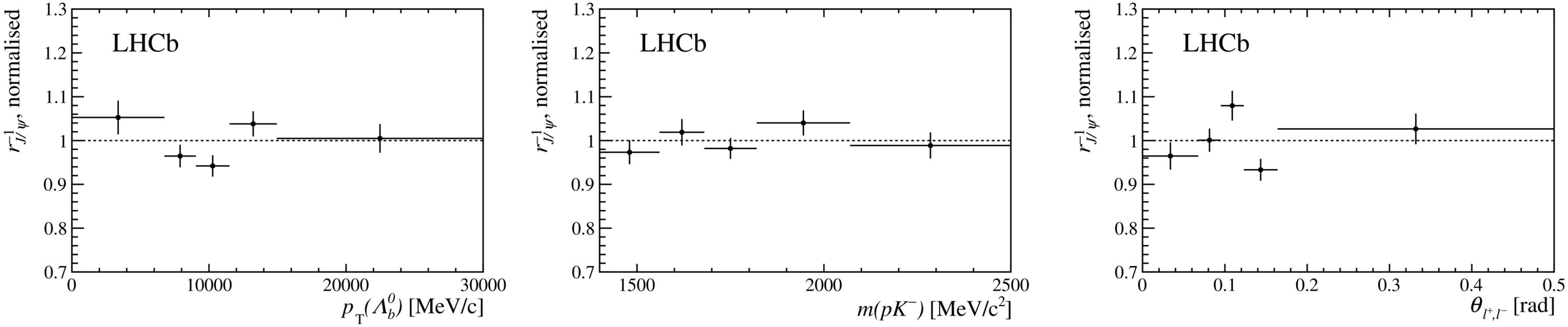


Compatible with unity and flat on kinematic and topological variables

arXiv:1912.08139

Nonresonant modes: extracting R^{-1}_{pK}

Simultaneous fit to electron and muon mode, in various data-taking and trigger categories. Observables are fit parameters:

$$N^i(\Lambda_b^0 \to pK^-\mu^+\mu^-) = r_{\mathcal{B}} \times \frac{N^i(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(J/\psi \to \ell^+\ell^-)} \times \frac{\epsilon^i(\Lambda_b^0 \to pK^-\mu^+\mu^-)}{\epsilon^i(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+\mu^-))}$$

$$N^i(\Lambda_b^0 \to pK^-e^+e^-) = R_{pK}^{-1} \times r_{\mathcal{B}} \times \frac{N^i(\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-))}{\mathcal{B}(J/\psi \to \ell^+\ell^-)} \times \frac{\epsilon^i(\Lambda_b^0 \to pK^-e^+e^-)}{\epsilon^i(\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-))}$$

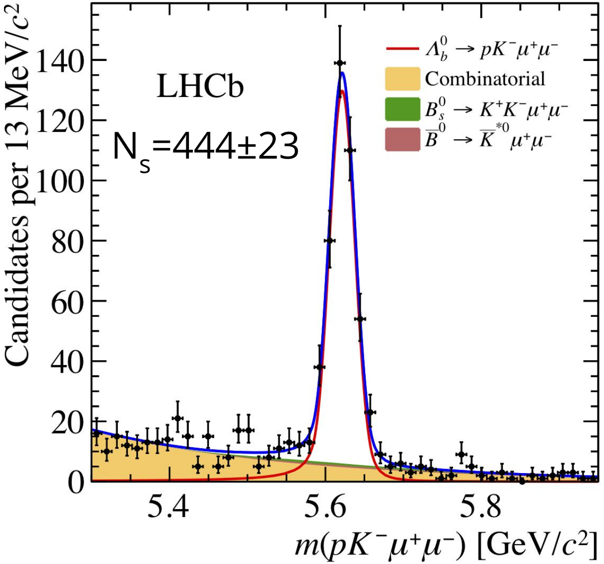
observables
from resonant-mode fit
from corrected MC
from PDG

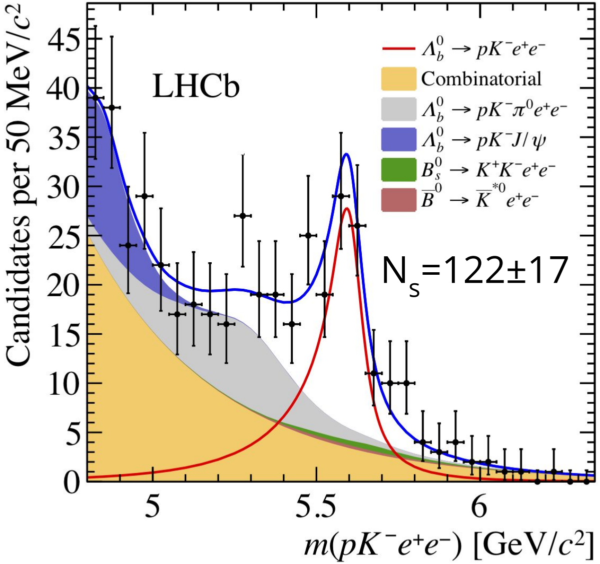
$$r_{\mathcal{B}} \equiv \mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)/\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi)$$

arXiv:1912.08139

Nonresonant modes: mass fit

Mass constraint not possible → larger mass ranges, degradation for electrons





arXiv:1912.08139

Systematic uncertainties

R^{-1}_{pK} measurement statistically dominated, main systematic uncertainties:

- Fit model (5.2%): partially reconstructed background shape in $\Lambda_b \to pK^- ee$
  - nominal: $\Lambda_b \to pK^{*-} ee$, $K^{*-} \to K^- \pi^0$; alternative: nonresonant $\Lambda_b \to pK^- \pi^0 ee$ decay
- Normalisation mode (~3.5%): uncertainties on yields and efficiencies
- Decay model (1.9%): alternative corrections from $\Lambda_b \to pK^- \mu\mu$ data
- Others: other corrections to simulation, m_{corr} cut efficiency, q^2 migration

arXiv:1912.08139

Systematic uncertainties

Uncertainty treatment depending on whether there is correlation between data taking and trigger categories:

- uncorrelated: gaussian constraints included in the mass fit
  - MC corrections, normalisation mode uncertainties
- correlated: gaussian smearing of likelihood profile
  - decay model corrections, fit model, m_{corr} cut efficiency, q^2 migration

arXiv:1912.08139

Results

In $0.1 < q^2 < 6\ \mathrm{GeV}^2/c^4$ and $m(pK^-) < 2.6\ \mathrm{GeV}/c^2$:

- First observation of $\Lambda_b \rightarrow pK^-ee$ decay mode: significance >7σ
- First measurement of $\Lambda_b \rightarrow pK^-\mu\mu$ branching fraction:

$$\mathcal{B}(\Lambda_b^0 \rightarrow pK^-\mu^+\mu^-)\big|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = (2.65 \pm 0.14 \pm 0.12 \pm 0.29\,^{+0.38}_{-0.23}) \times 10^{-7}$$

uncertainty dominated by knowledge of $\Lambda_b \rightarrow pK^-J/\psi$ (hadronisation fraction)

arXiv:1912.08139

Results 2

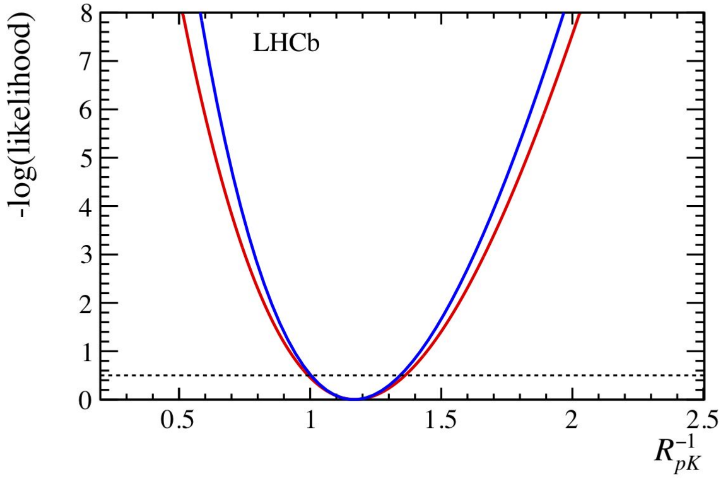
In $0.1 < q^2 < 6$ GeV/c^4 and m(pK$^-$) < 2.6 GeV/c^2:

- first test of LU in b-baryons:

$$R^{-1}_{pK}\Big|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = 1.17^{+0.18}_{-0.16} \pm 0.07$$

- inverting likelihood profile:

$$R_{pK}\Big|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = 0.86^{+0.14}_{-0.11} \pm 0.05$$



compatible with unity and previous R_H measurements

arXiv:1912.08139

Results 3

In $0.1 < q^2 < 6$ GeV/c^4 and $m(pK^-) < 2.6$ GeV/c^2:

- First observation of $\Lambda_b \rightarrow pK^-ee$ decay mode: significance >7σ
- Derived result from $B(\Lambda_b \rightarrow pK^-\mu\mu)$ and R^{-1}_{pK}:

$$\mathcal{B}(\Lambda_b^0 \rightarrow pK^-e^+e^-)\big|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = \left(3.1 \pm 0.4 \pm 0.2 \pm 0.3^{+0.4}_{-0.3}\right) \times 10^{-7}$$

uncertainty dominated by knowledge of $\Lambda_b \rightarrow pK^-J/\psi$ (hadronisation fraction)

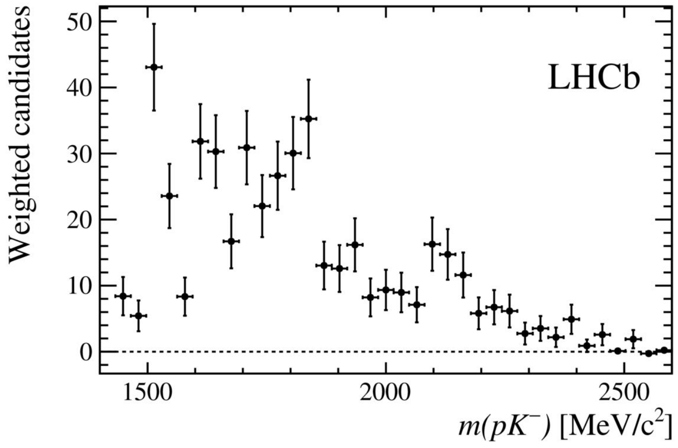
Future prospects

LU result dominated by statistical uncertainty (~15%):

- LHCb has x2 Λ_b decays on tape → ~11% uncertainty
- LHCb will collect 50 fb^{-1} during Run 3 & 4 → ~6% uncertainty

Interpretation of the result in terms of NP is hard with current setup, with more data:

- study rich structure in m(pK) spectrum
- split low and middle q^2 bins: [0.1, 1] and [1, 6] GeV/c^4



arXiv:1912.08139

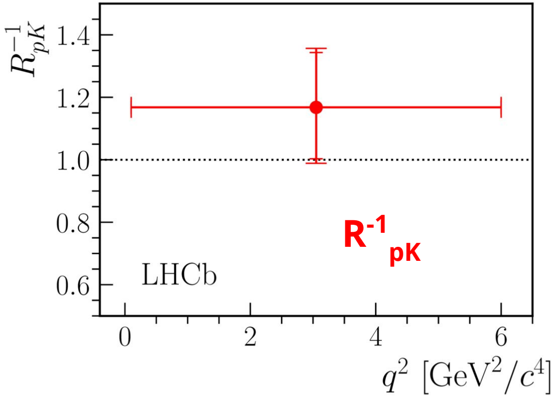
Summary & conclusions

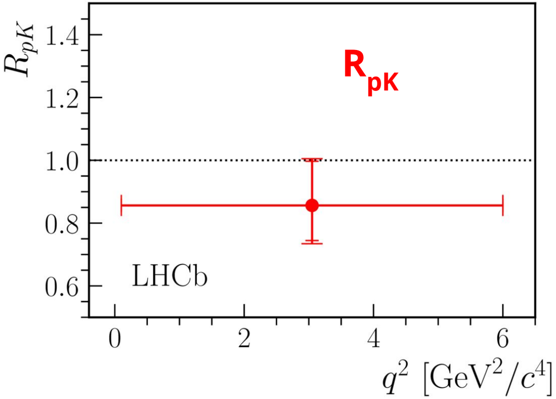
First test of LU performed with b-baryons R^{-1}_{pK}

- result compatible with unity
- and with previous R_H measurements
- null test of the SM → larger stats are needed

With more data:

- study m(pK) spectrum
- split q^2 ranges for higher sensitivity





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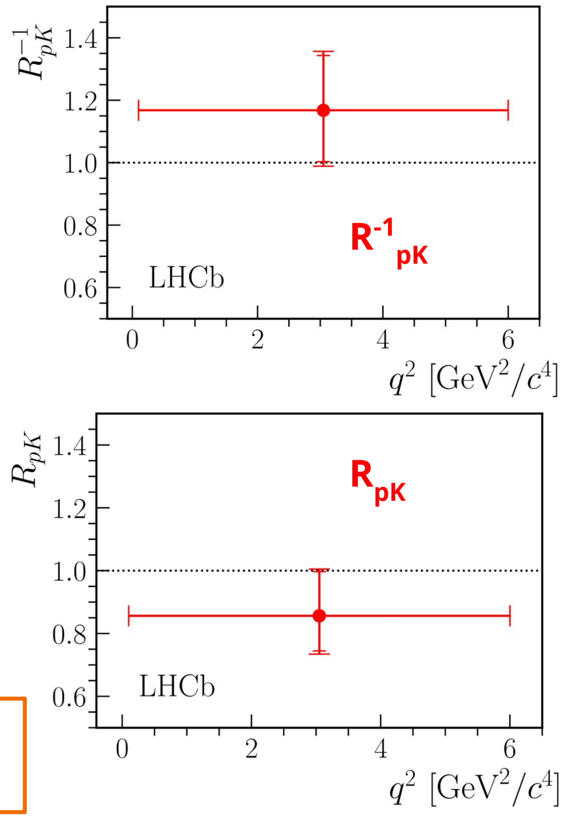
Stay tuned!



THANK YOU

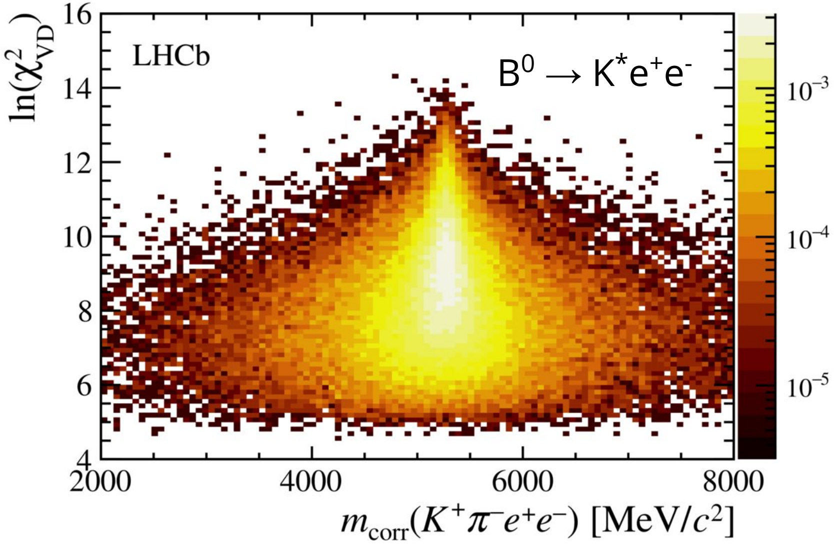
BACK-UP

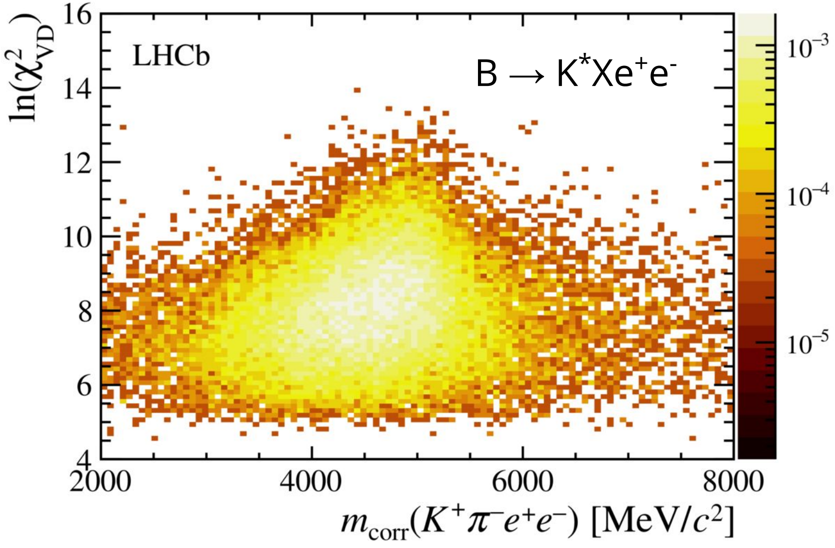
Background vetoes

B^+	$m(K\ell^+\ell^-) < 5200\ \text{MeV}/c^2$, $m(p\ell^+\ell^-)_{p\leftarrow K} < 5200\ \text{MeV}/c^2$	all
ϕ	$abs(m(pK)_{p\leftarrow K} - 1020) > 12$	all
Λ_c^+	$m(pK\ell^+) > 2320\ \text{MeV}/c^2$, $m(pK\ell^-)_{p\leftrightarrow K} > 2320\ \text{MeV}/c^2$	all
D^0	$abs(m(K^-\ell^+)_{\ell\leftarrow\pi} - 1865) > 20$	all rare
swaps	$abs(m(K^-\mu^+)_{K\leftarrow\mu} - 3097) > 35$	rare $\mu\mu$
	$m(K^-e^+)_{K\leftarrow e} < 2900$ or > 3150	rare ee
conversions	$m(K^-e^+)_{K\leftarrow e} > 10$, $m(pe^-)_{p\leftarrow e} > 10$	all ee
clones	$\theta(K,\ell) > 0.5$ mrad, $\theta(p,\ell) > 0.5$ mrad	all

Background rejection with m_{corr}

From R_{K*} analysis [JHEP 08 (2017) 055]:

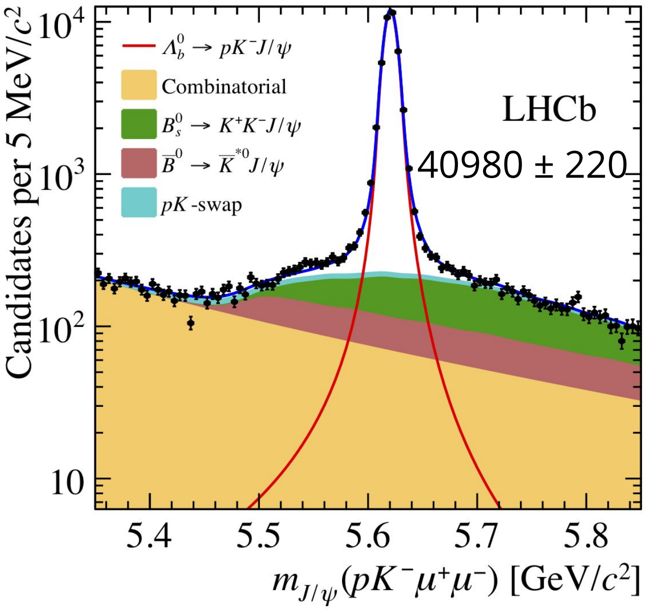


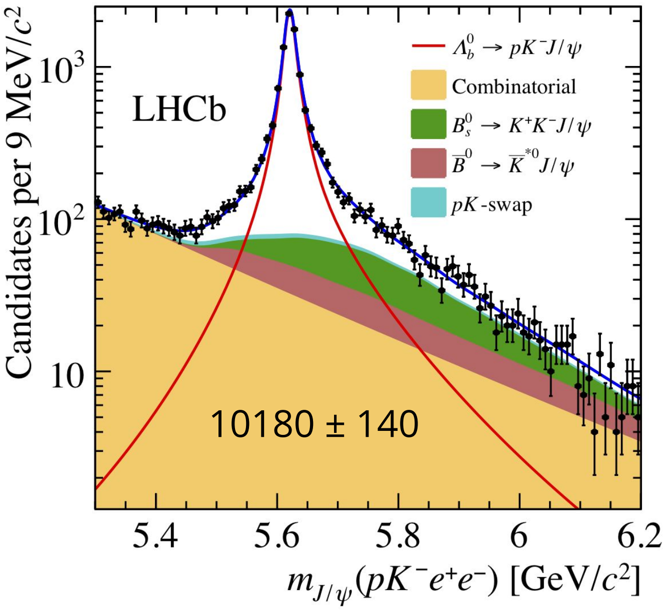


arXiv:1912.08139

Resonant modes: mass fit

Constrain m(ee/μμ) to known J/ψ mass → better mass resolution for $m_{J/\psi}$

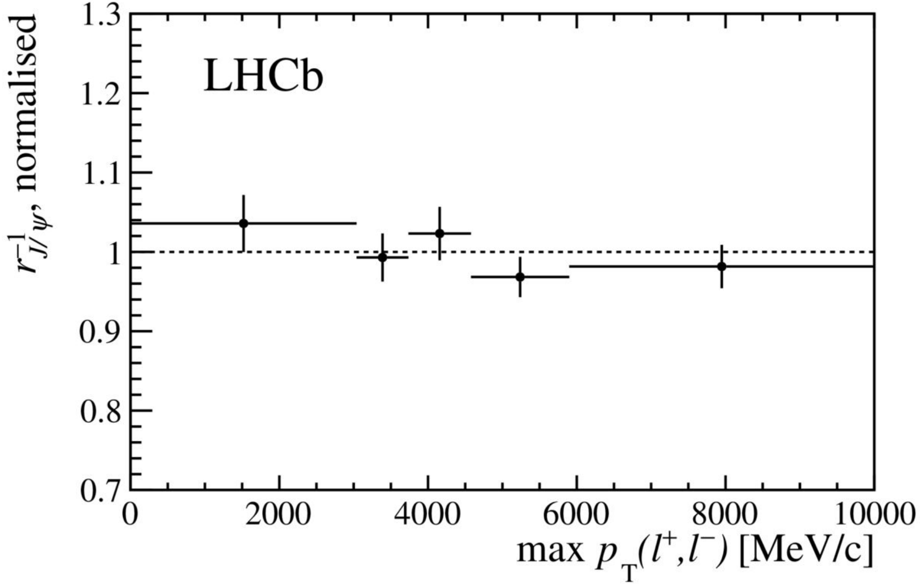




arXiv:1912.08139

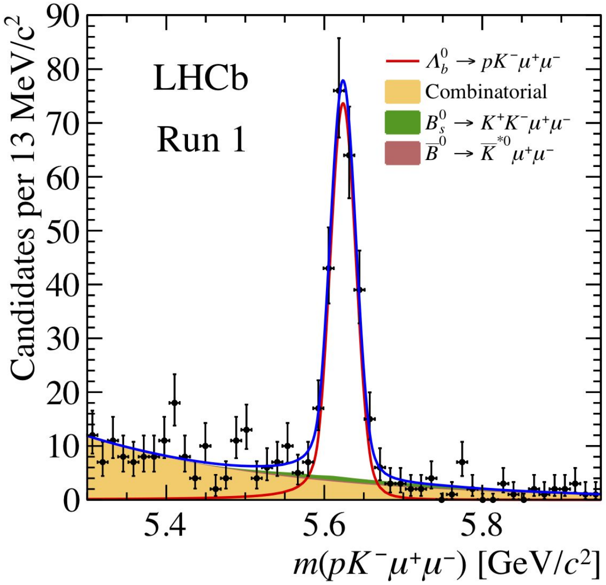
Resonant modes: $r_{J/\psi}$ test

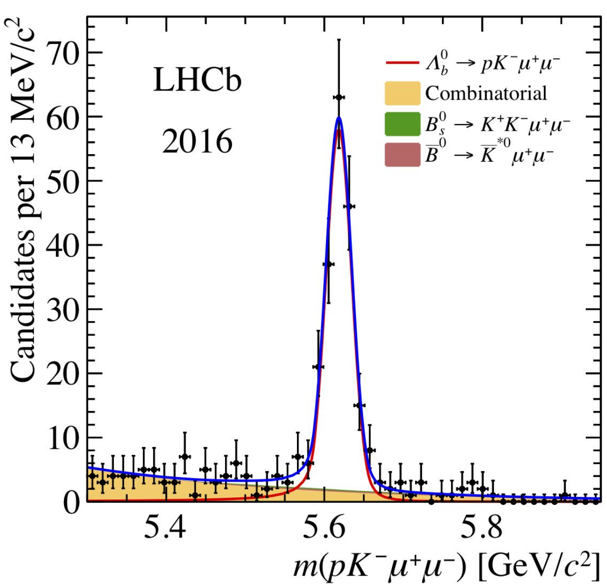
Trends in kinematic variables



[arXiv:1912.08139](https://arxiv.org/abs/1912.08139)

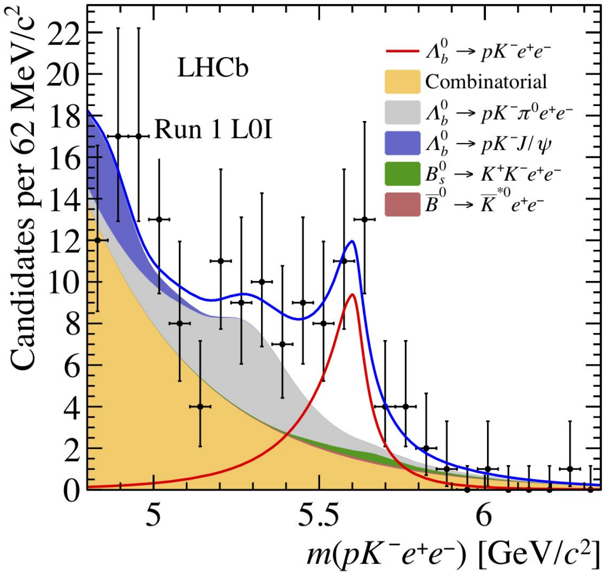
Nonresonant modes: mass fit for muons

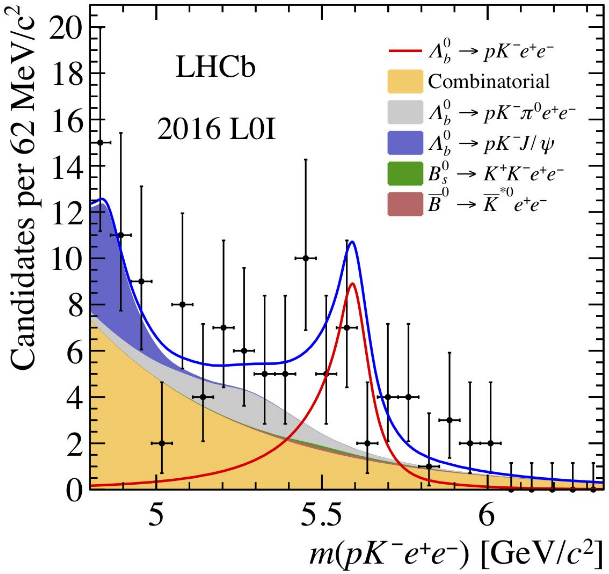




arXiv:1912.08139

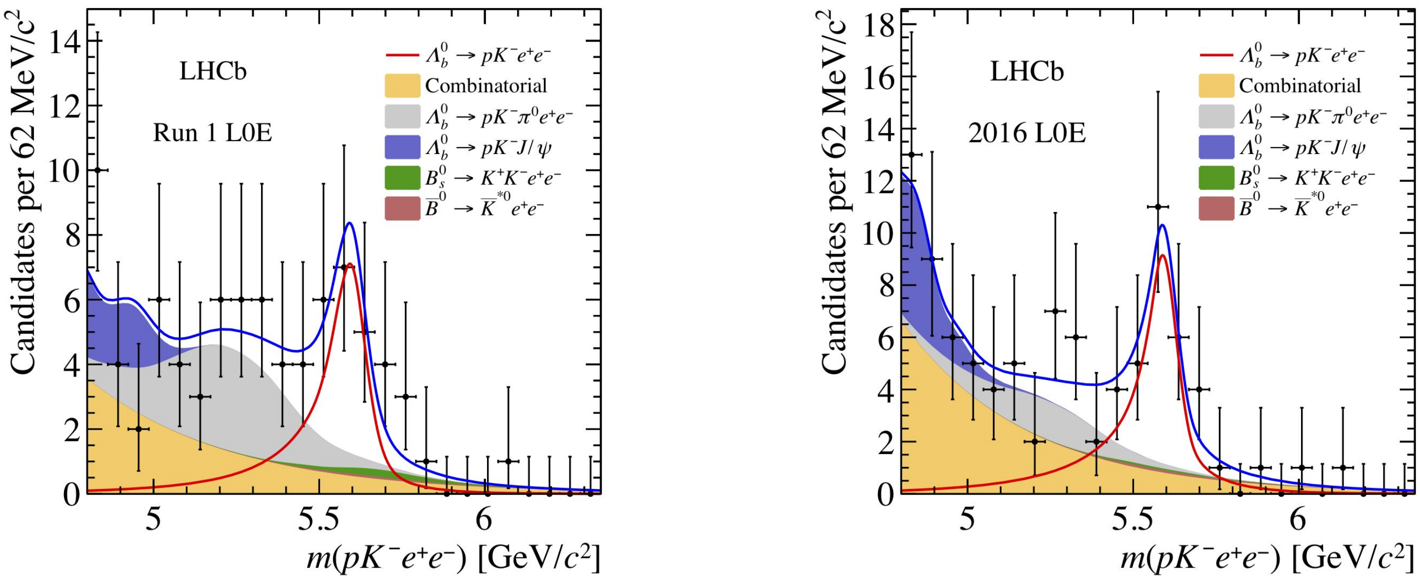
Nonresonant modes: mass fit for electrons L0I





arXiv:1912.08139

Nonresonant modes: mass fit for electrons L0E

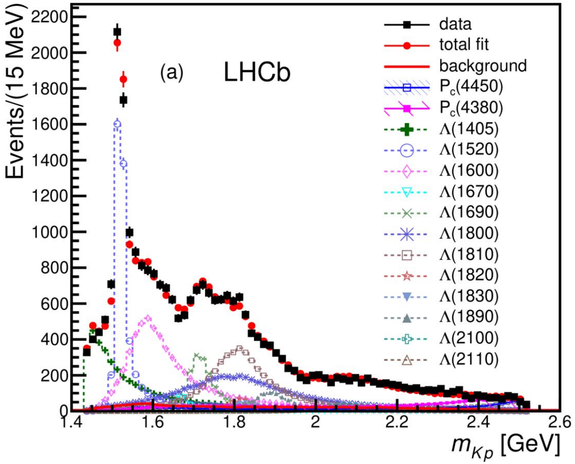


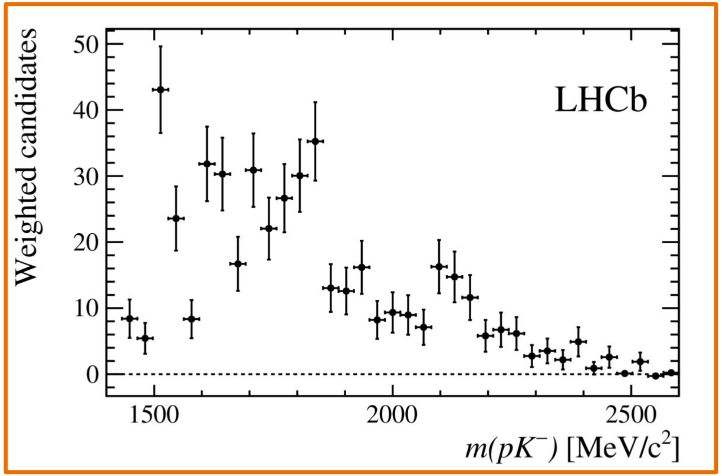
arXiv:1912.08139

Systematic uncertainties

Decay model systematics:

- use m(pK) spectrum from $\Lambda_b \to pK^-\mu\mu$ background-subtracted data instead of $\Lambda_b \to pK^-J/\psi$ amplitude model

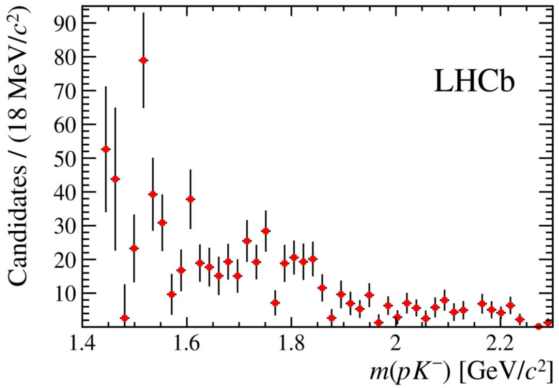




Phys. Rev. Lett. 115 (2015) 072001

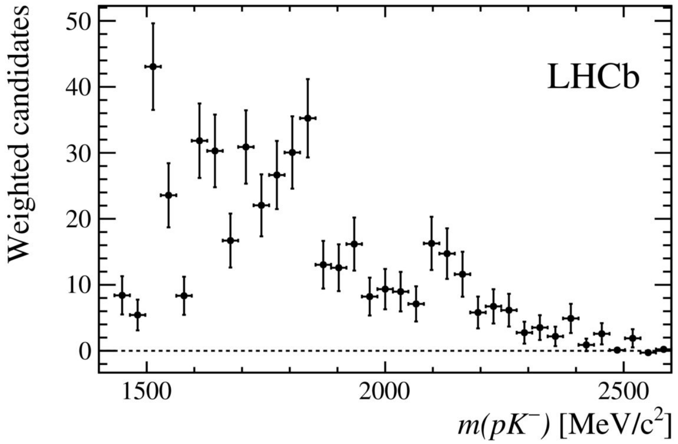
m(pK) in $\Lambda_b \to pK\mu\mu$

3 fb^{-1}, middle&high q^2, m(pK)<2.35, efficiency corrected



[JHEP 06 (2017) 108]

This analysis
not efficiency corrected



[arXiv:1912.08139]

arXiv:1912.08139

Systematic uncertainties: $B(\Lambda_b \to pK^-\mu\mu)$

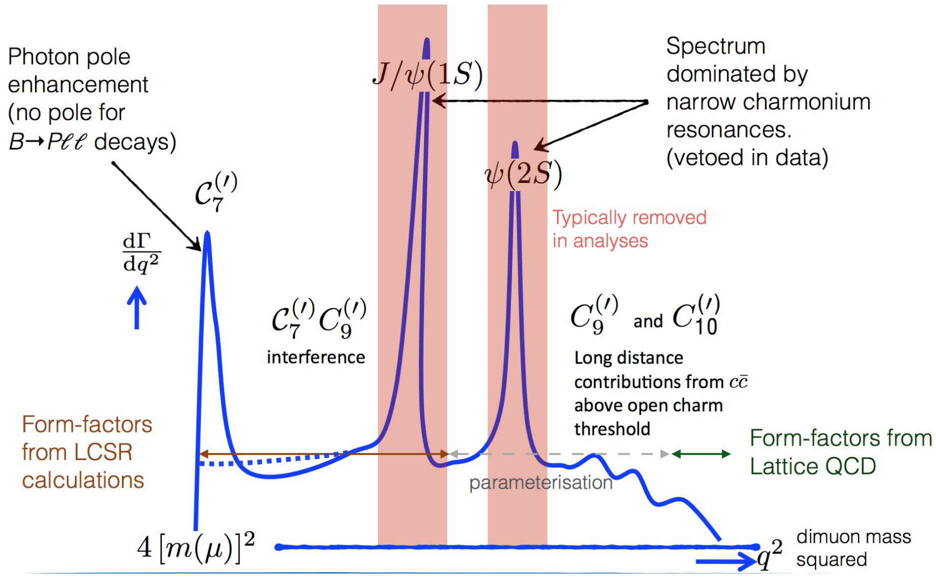
Source	Run 1	Run 2	Correlated
Decay model	–	–	3.6
Other corrections	2.5	3.3	–
Normalisation mode	0.9	1.4	–
Fit model	–	–	1.4
Total uncorrelated	2.6	3.6	–
Total correlated	–	–	3.9

arXiv:1912.08139

Systematic uncertainties: R^{-1}_{pK}

Source	Run 1 L0I	Run 1 L0E	Run 2 L0I	Run 2 L0E	Correlated
Decay model	–	–	–	–	1.9
Other corrections	3.4	3.6	3.6	3.2	–
m_{corr} cut efficiency	–	–	–	–	0.5
q^2 migration	–	–	–	–	2.0
Normalisation mode	3.7	3.7	3.5	2.7	–
Fit model	–	–	–	–	5.2
Total correlated	–	–	–	–	5.9
Total uncorrelated	5.0	5.2	5.0	4.2	–

b⟶sll q^2 spectrum



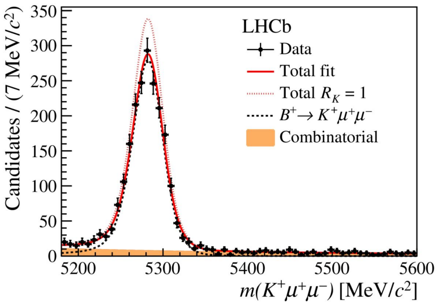
b ⟶ sll with electrons

Theoretically, same behaviour as for muons, but experimentally:

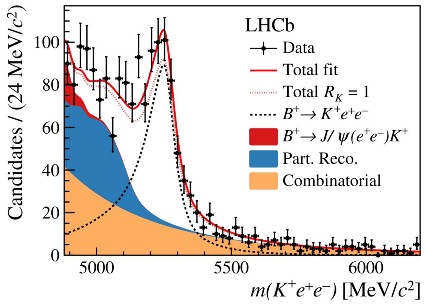
a challenge at LHCb:

PRL 122 (2019) 191801

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

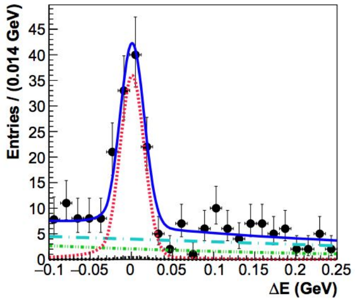


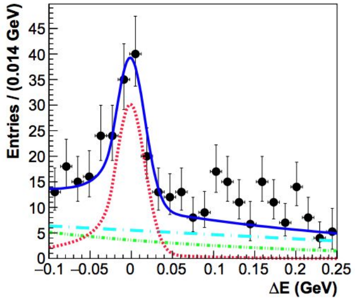
$B \to Ke^+e^-$



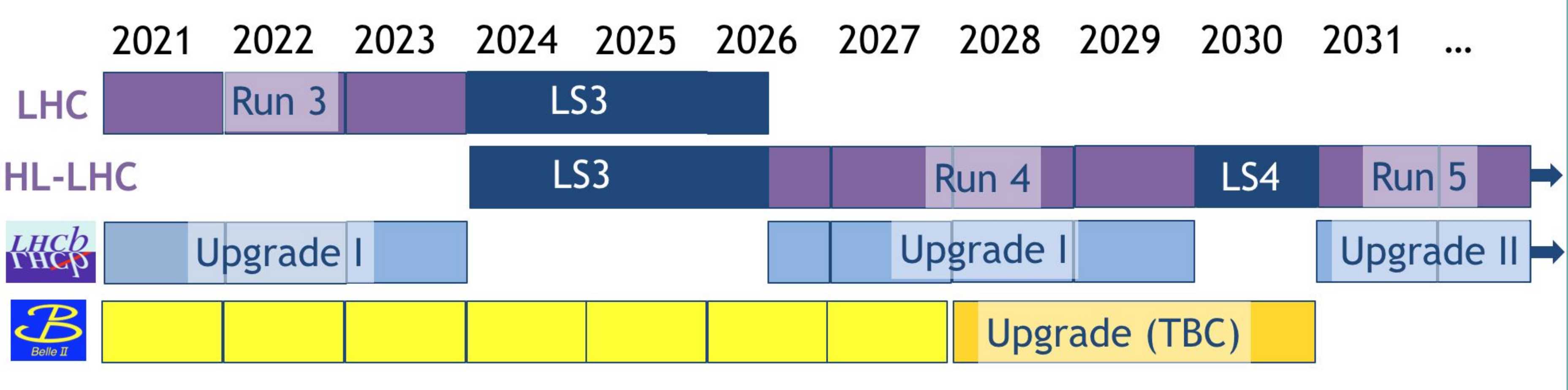
much more similar to muons at Belle:

arXiv:1908.01848





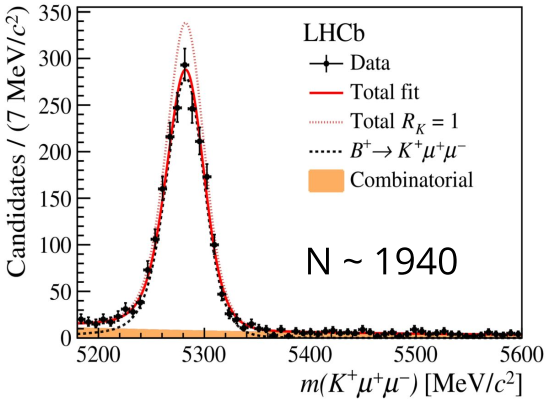
LHC schedule

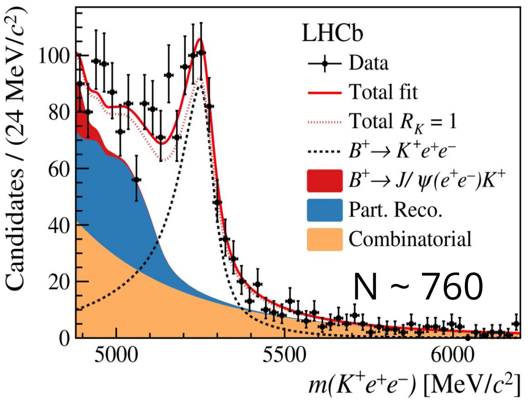


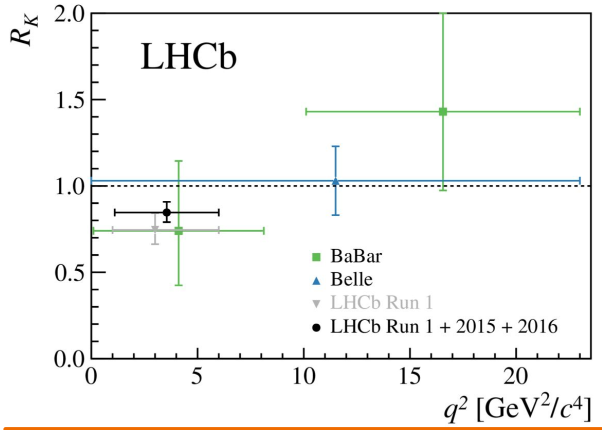
Updated R_K from LHCb

PRL 122 (2019) 191801

Factor 2 larger yields than in previous analysis still statistically dominated by electron mode







$$R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$$

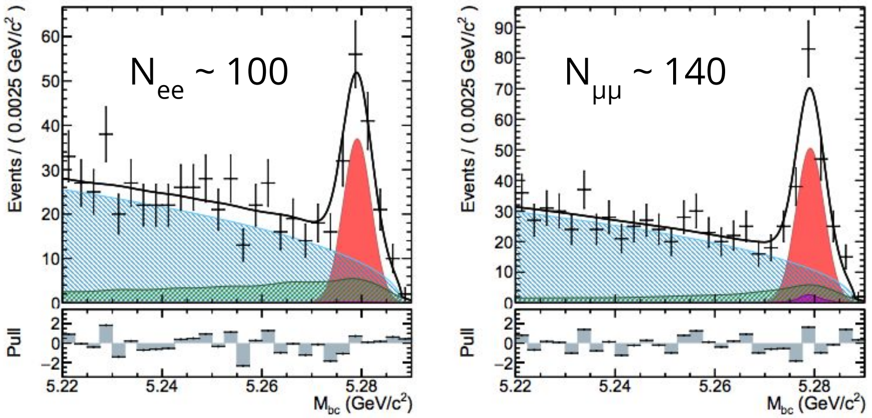
compatible with previous analysis and ~2.5σ from SM

Still x2 B decays recorded by LHCb to be analysed!

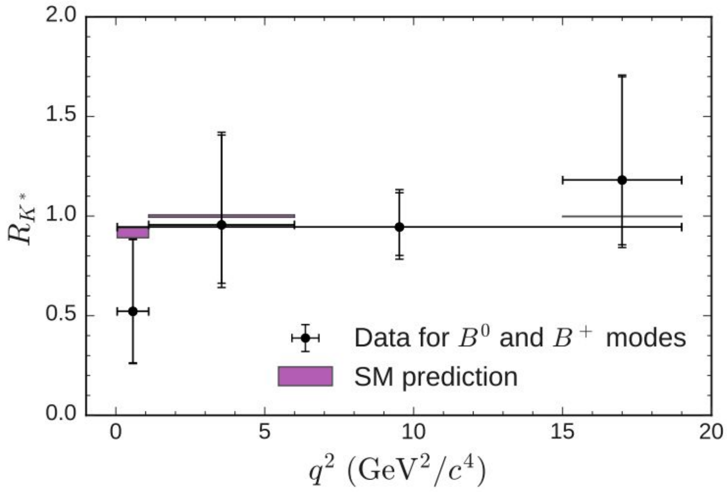
Updated R_{K^*} from Belle

arXiv:1904.02440

Main backgrounds: combinatorial, misidentification, charmonium and peaking



Measure charged and neutral modes separately and weighted average in various q^2 bins:



Results compatible with SM and LHCb measurement

Updated R_K from Belle

arXiv:1908.01848

Measure charged and neutral modes separately and weighted average in q^2 regions: [0.1 , 4.0], [4.0 , 8.12], > 14.18, [1.0 , 6.0], > 0.1