Lepton universality tests with b-baryons

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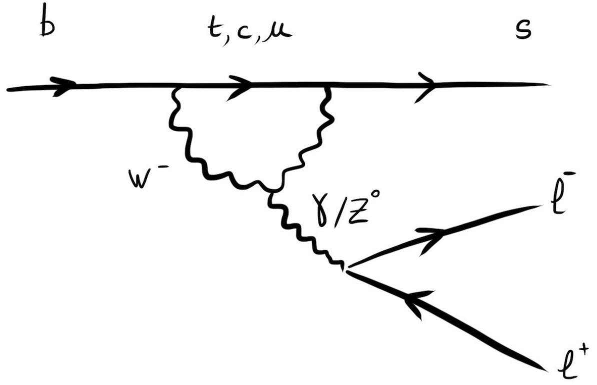


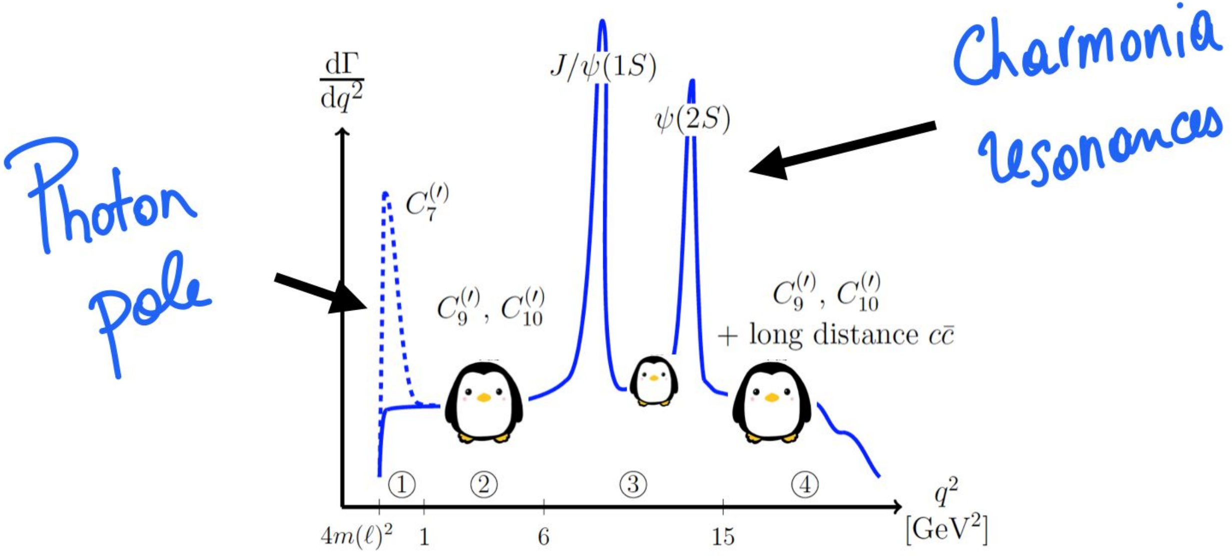
Lepton Universality tests

$$R_\phi(B_s) \approx R_{\pi K}(B) \approx R(\Lambda_b)_\Lambda \approx R(\Lambda_b)_{pK} \approx \ldots \approx R_K \ .$$

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

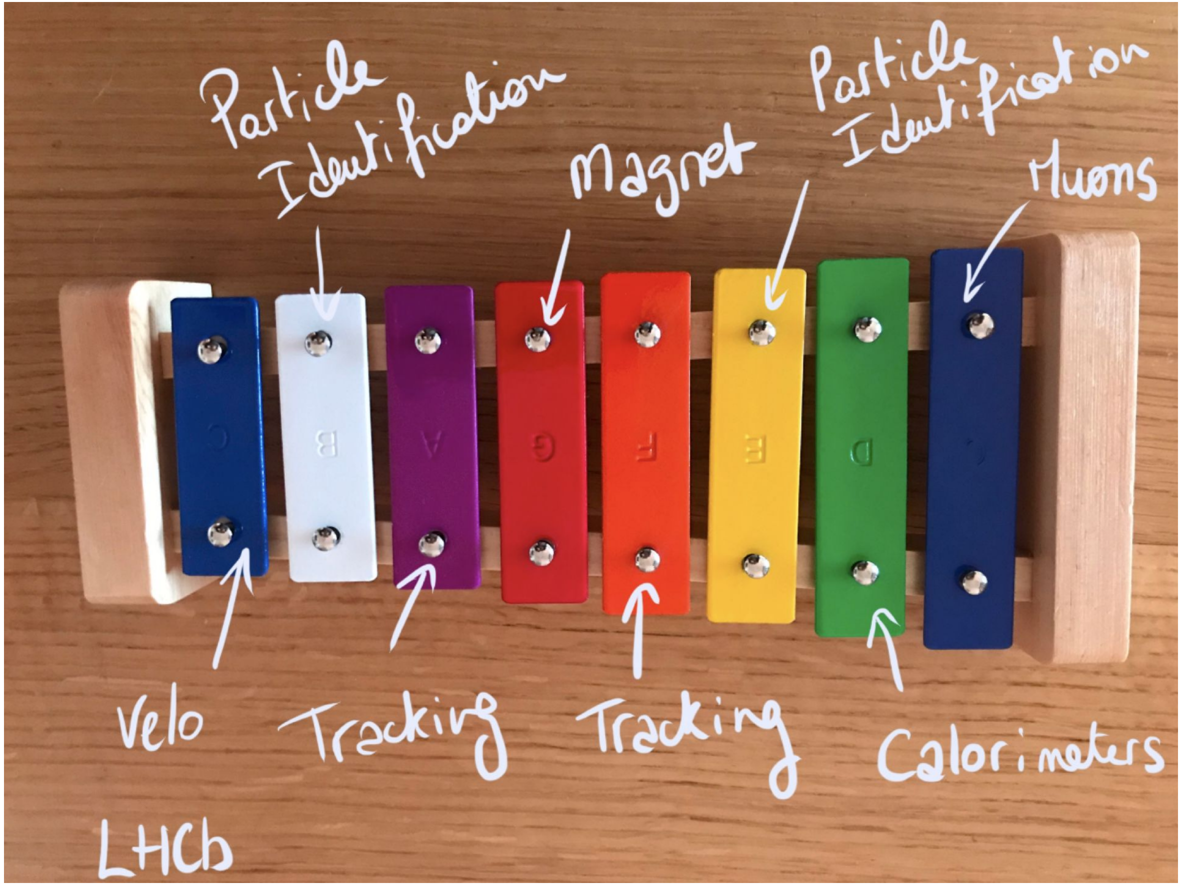
arXiv:1710.01335, arXiv:1909.02519

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \lambda^{\text{CKM}} \sum_i C_i \mathcal{O}_i + h.c,$$



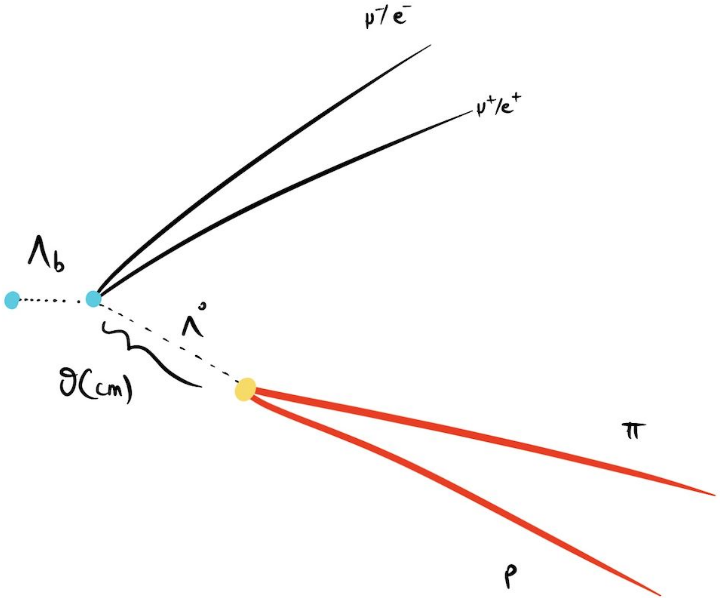
R_{pK} is measured between $[0.1, 6]$ GeV^2

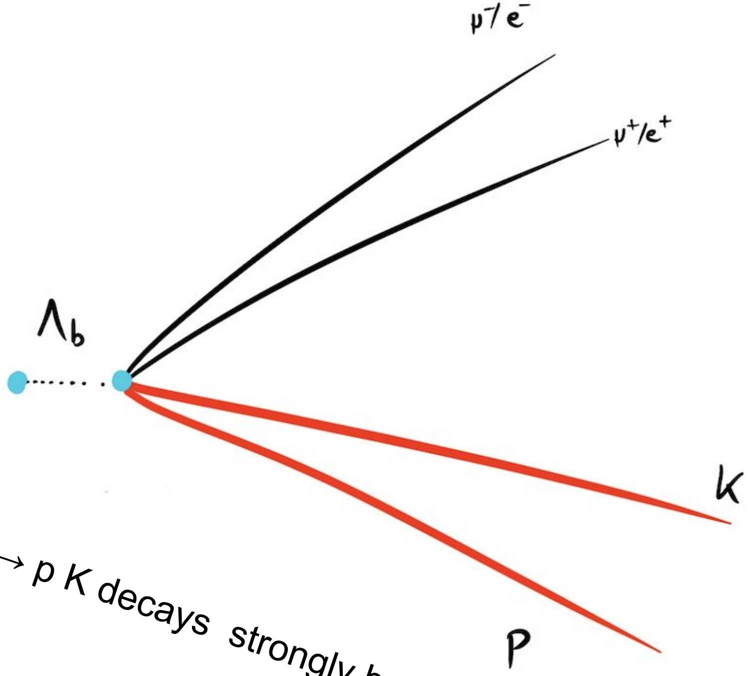
R_Λ will be measured between $[0.1, 6]$ and $[15, 20]$ GeV^2


Particle Identification
Magnet
Particle Identification
Muons
Velo
Tracking
Tracking
Calorimeters
LHCb

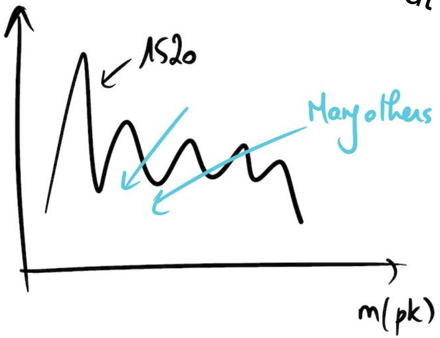
Topologies of the two decays

Λ→ pπ is well defined and long lived.





Λ*→ p K decays strongly but are messy.

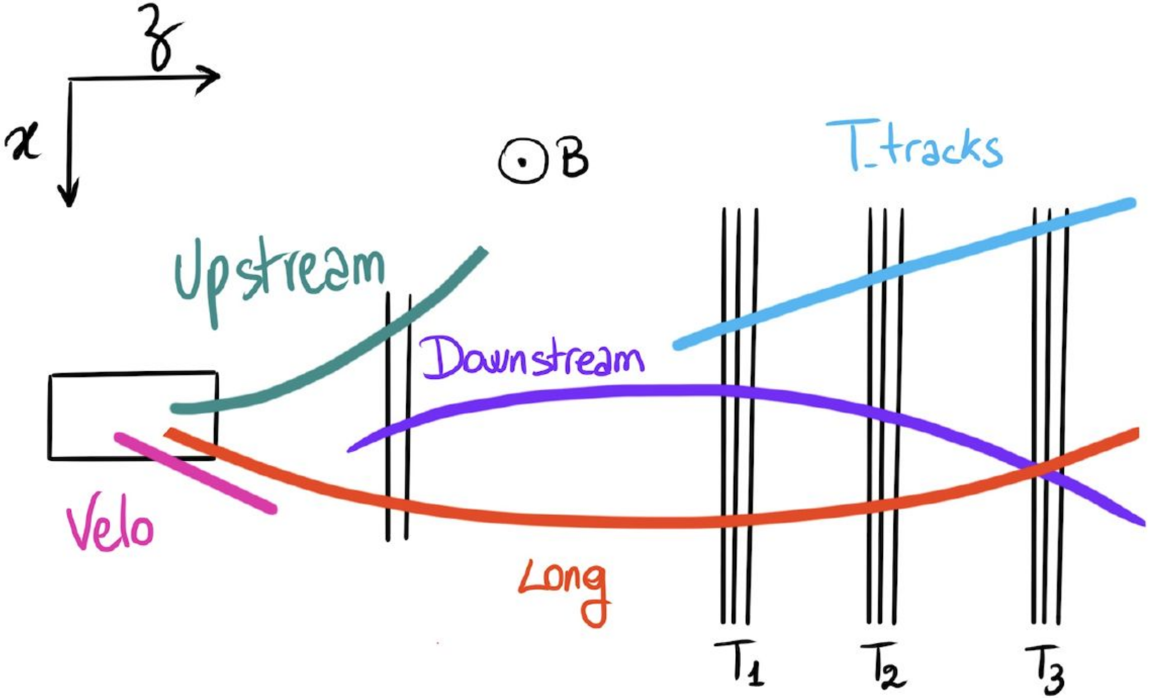


Reconstructing □^{0}’s

At LHCb, □^{0} decay to pπ
after few ns, few m

Reconstruct p and π as pairs of
Long tracks (including VELO)
or Downstream tracks
(only TT and T stations)

Reconstructed □^{0} are
~⅓ LL, ~⅔ DD;
however, LL □^{0} candidates have
less background, better resolution



Electrons

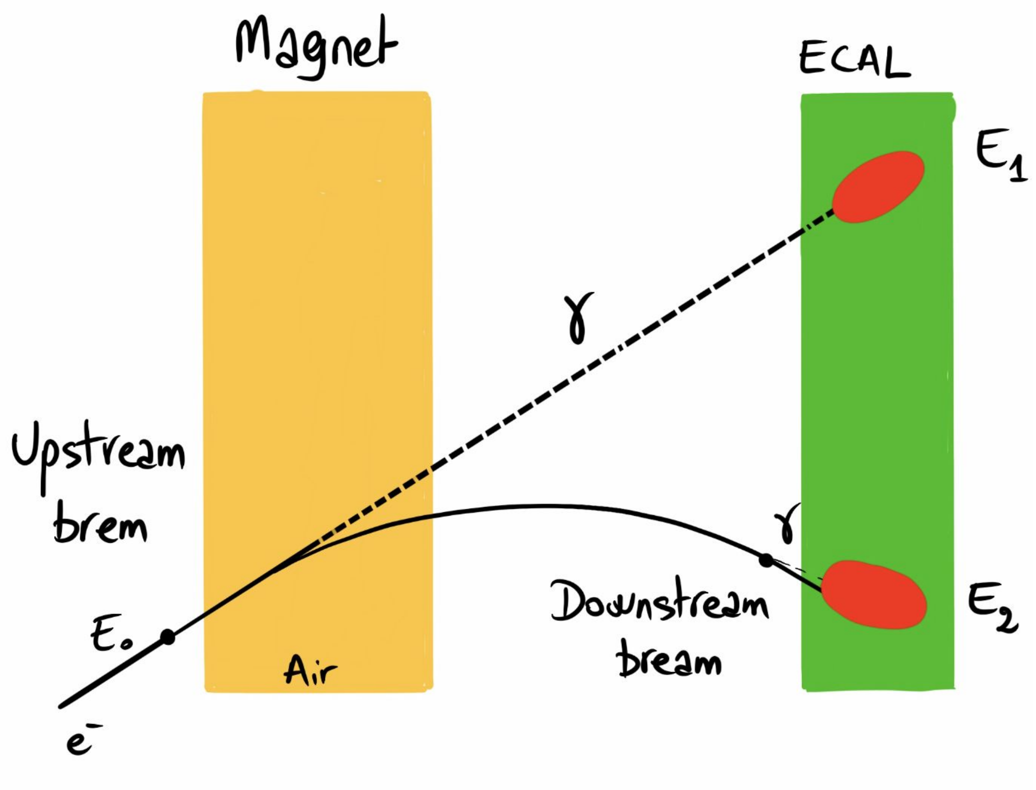
Electrons differ from muons due to material interactions (bremsstrahlung)

Energy loss of electron of ~ 30%:

- Track momentum != electron momentum
- Lower reconstruction efficiency

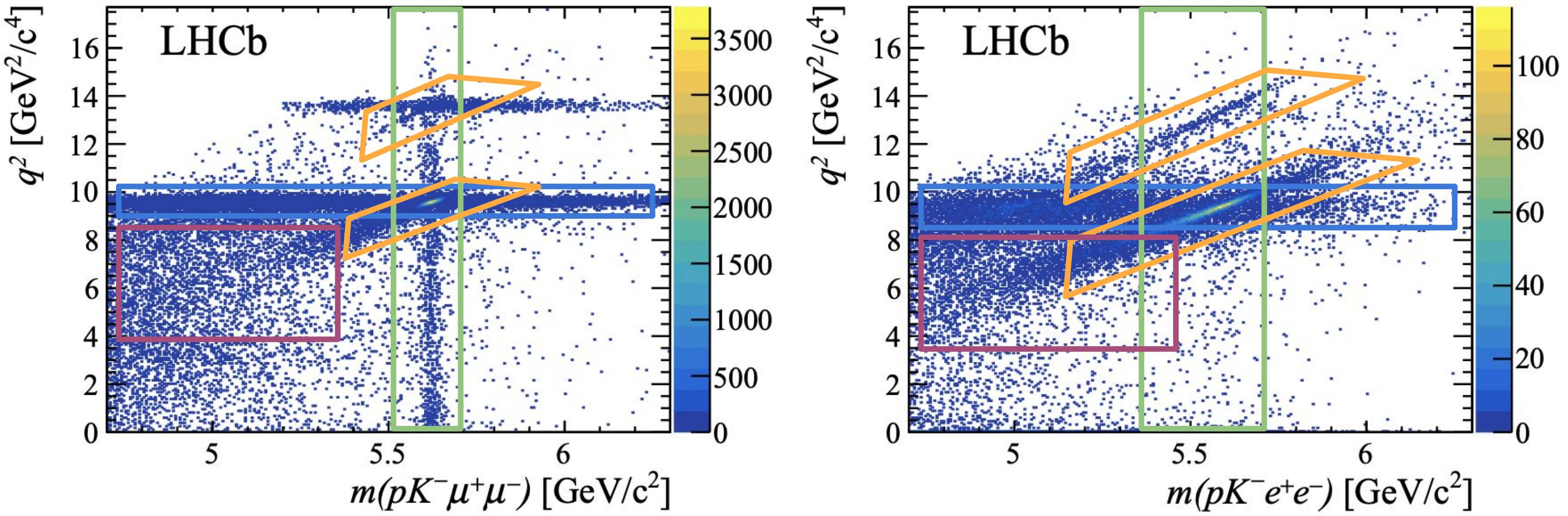
Reconstruct upstream brem cluster to recover lost energy:
Not easy in busy pp events!

Still, ½ of electrons have brem recovered! (but worse resolution than regular tracks, ie muons)



Mass versus q^2

Identify □$_b^0$ contributions from **charmonium** modes and **rare** mode; backgrounds exist from **partially reconstructed** and **charmonium + hadron** combinations



Analysis strategy

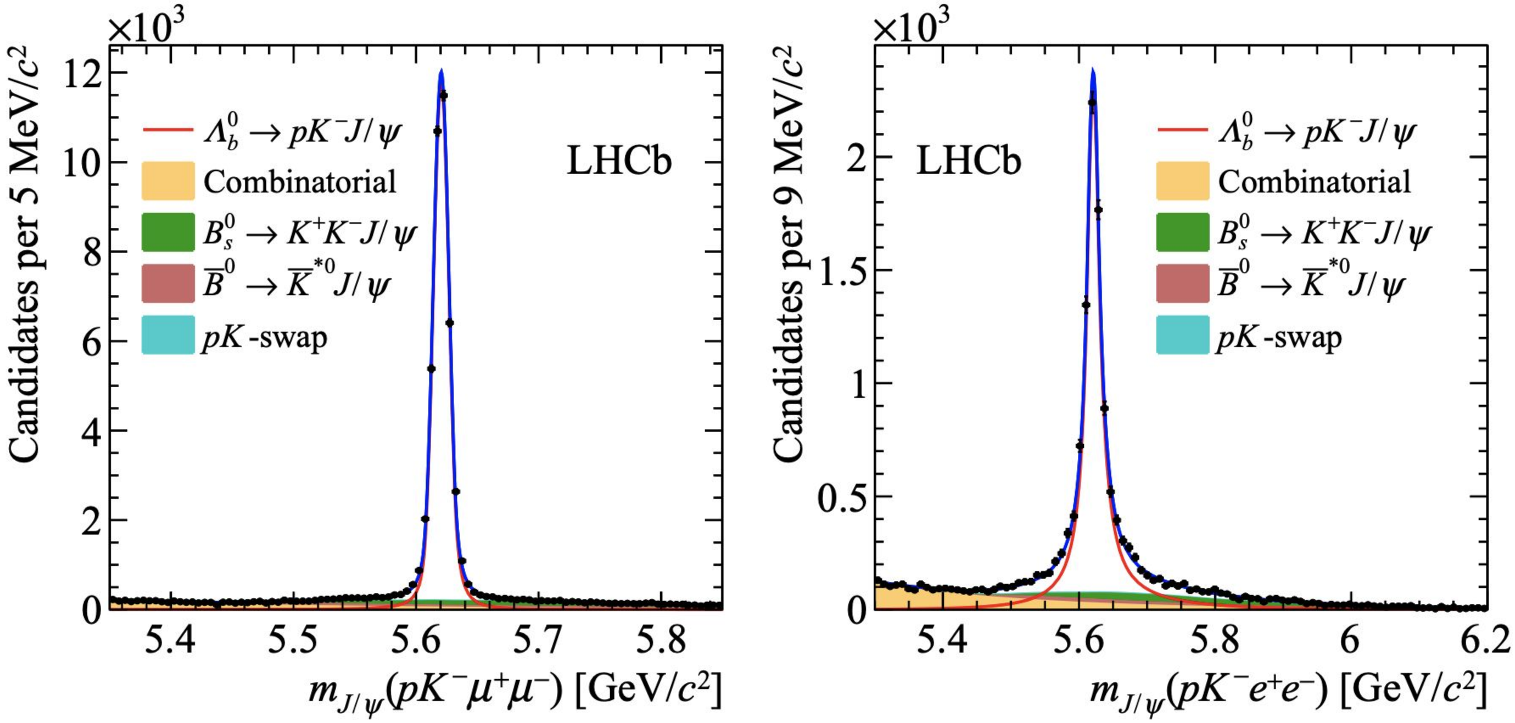
$$R_H \propto \boxed{\frac{N(B\to H\mu^+\mu^-)}{N(B\to He^+e^-)}} \times \boxed{\frac{\epsilon(B\to He^+e^-)}{\epsilon(B\to H\mu^+\mu^-)}}$$

Counting from mass fits **From simulation**

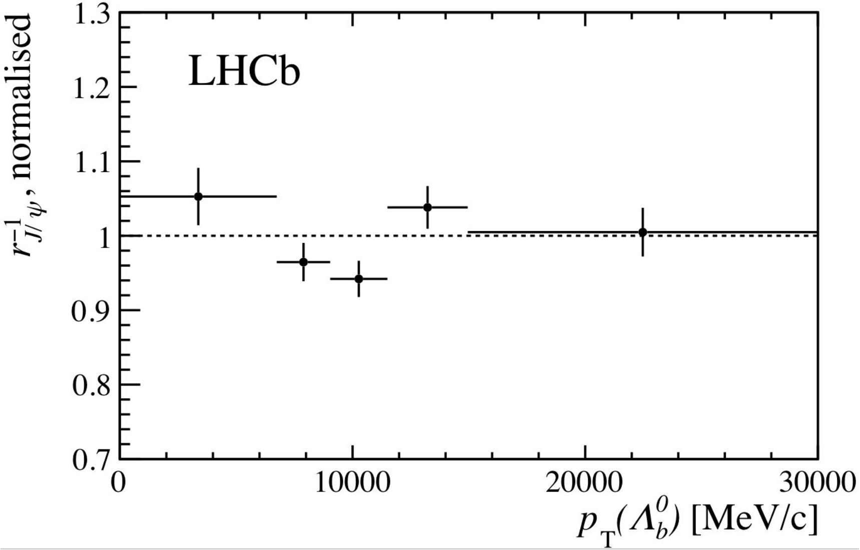
$$r_{J/\psi} = \frac{BR(B\to HJ/\psi(\mu^+\mu^-))}{BR(B\to HJ/\psi(e^+e^-))} = 1$$

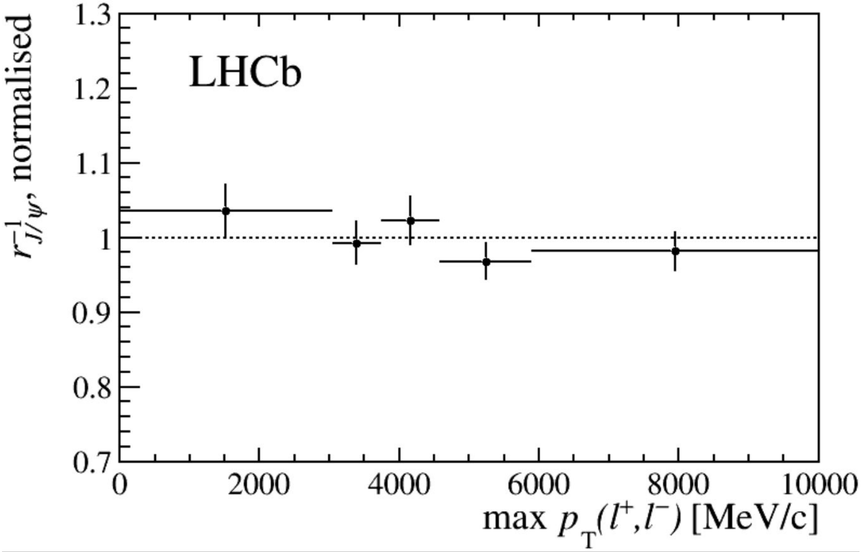
$$\boxed{R_H = \frac{\frac{N(B\to H\mu^+\mu^-)}{N(B\to HJ/\psi(\mu^+\mu^-))}}{\frac{N(B\to He^+e^-)}{N(B\to HJ/\psi(e^+e^-))}} \times \frac{\frac{\epsilon(B\to He^+e^-)}{\epsilon(B\to HJ/\psi(e^+e^-))}}{\frac{\epsilon(B\to H\mu^+\mu^-)}{\epsilon(B\to HJ/\psi(\mu^+\mu^-))}}}$$

Calibration



Move across the phase space

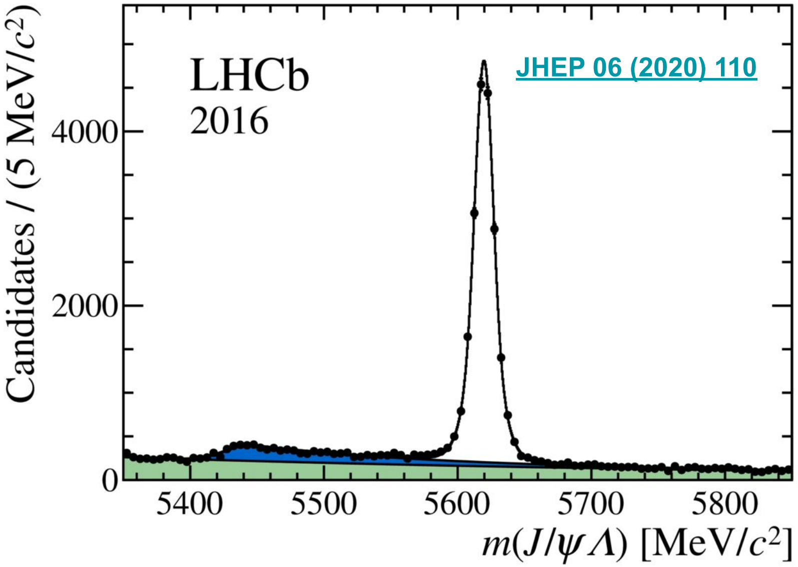


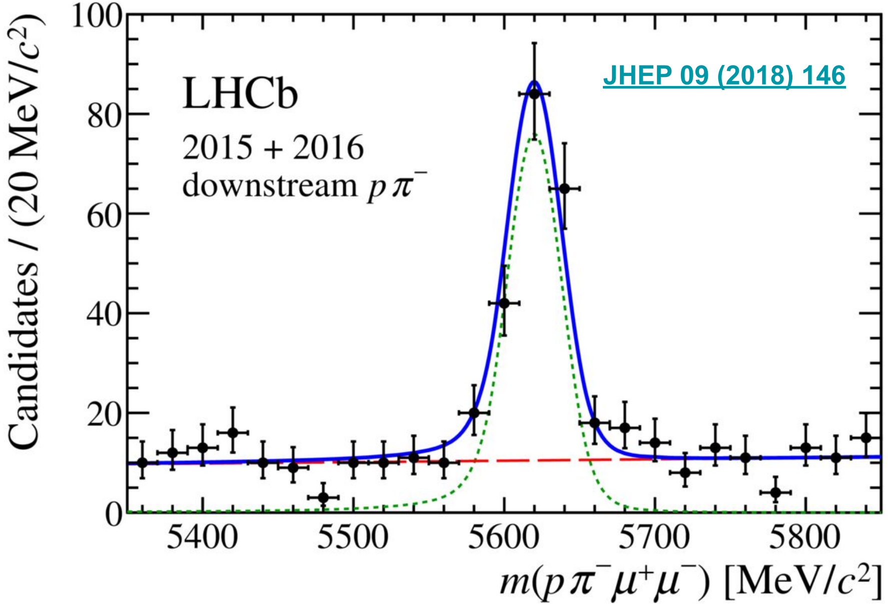


$$r^{-1}_{J/\psi} = 0.96 \pm 0.05$$

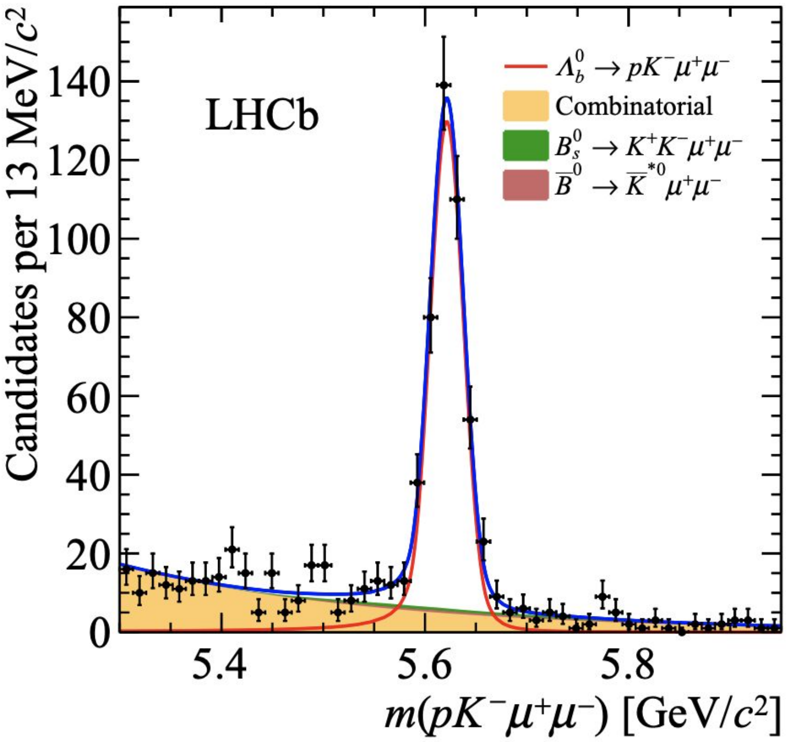
$\square_b^0 \to J/\psi\,\square^0$ + rare mode

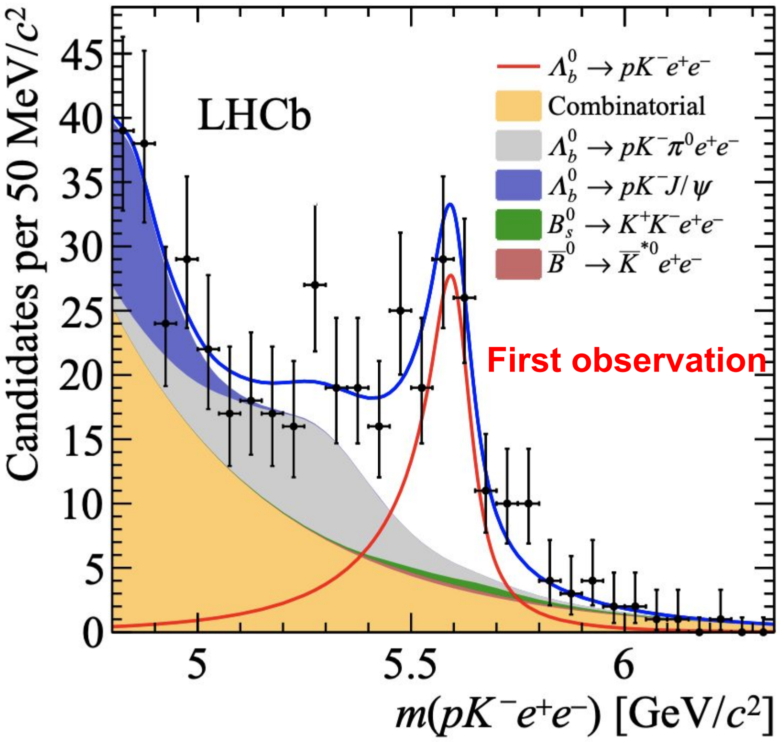
Fits from angular analyses to both modes





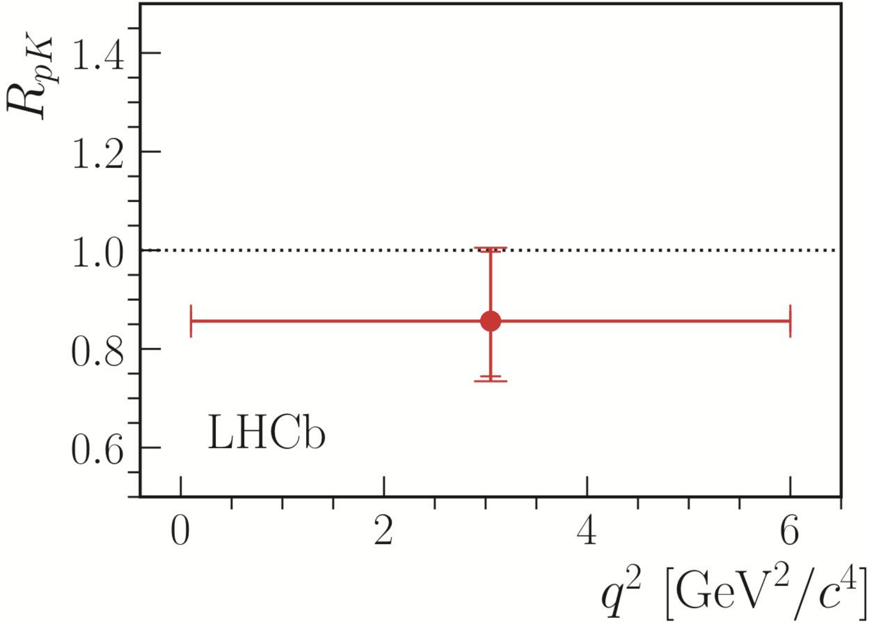
Rare modes





arXiv:1912.08139

The result

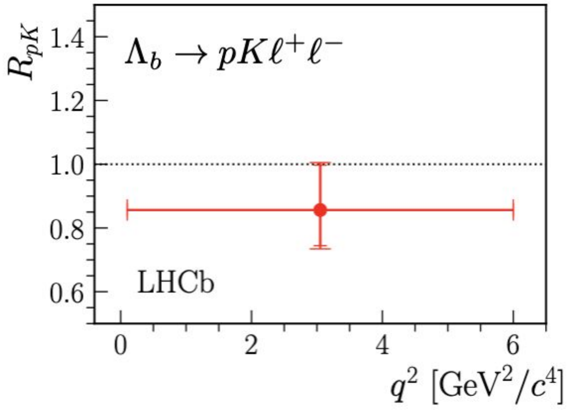


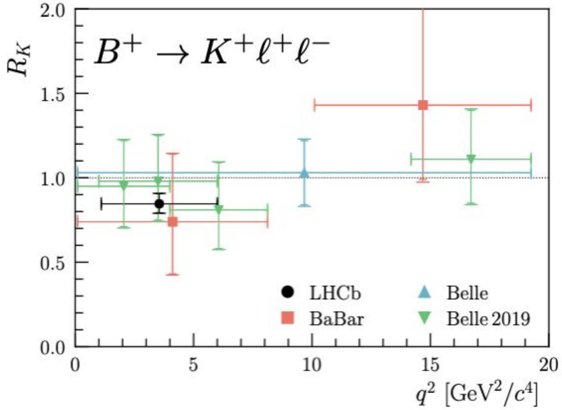
arXiv:1912.08139

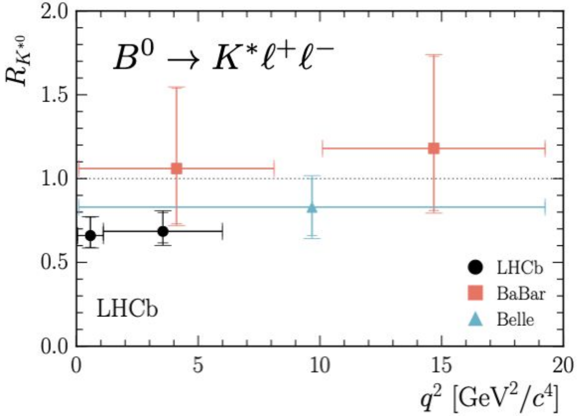
$$R_{pK}^{-1}\Big|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = 1.17^{\,+0.18}_{\,-0.16} \pm 0.07,$$

$R(\Lambda_b)_\Lambda$ Expect to observe $\Lambda_b \rightarrow \Lambda ee$ at high q^2, at best evidence at low q^2 (Run 1+2)

Are we seeing a coherent pattern in the data ?







$$R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

$0.1 < q^2 < 6$ GeV^2

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

$1.1 < q^2 < 6$ GeV^2

$$R_{K*} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

$1.1 < q^2 < 6$ GeV^2

1912.08139, 1903.09252, 1705.05802

Conclusions

- Lepton universality is an interesting test of the SM and beyond.
- Tests with *b*-baryons are complementary and probe separate degrees of freedom

- LHCb is well suited to study $R(\Lambda_b)_{\Lambda}$ and $R(\Lambda_b)_{pK}$

- Challenging experimental analyses (electrons, etc.)
- Calibration with charmonium modes essential.
- Looking forward to more fun with *b*-baryons :)

BEHIND THE SCENES

Decay mode	q^2 [GeV^2/c^4]	$pK^-\ell^+\ell^-$ invariant mass [GeV/c^2]
$\Lambda_b^0 \to pK^-e^+e^-$	0.1 – 6.0	4.80 – 6.32
$\Lambda_b^0 \to pK^-J/\psi(\to e^+e^-)$	6.0 – 11.0	5.30 – 6.20
$\Lambda_b^0 \to pK^-\mu^+\mu^-$	0.1 – 6.0	5.30 – 5.95
$\Lambda_b^0 \to pK^-J/\psi(\to \mu^+\mu^-)$	8.41 – 10.24	5.35 – 5.85

Table 2: Efficiency ratios between the nonresonant and resonant modes, $\epsilon(\Lambda_b^0 \to pK^-\ell^+\ell^-)/\epsilon(\Lambda_b^0 \to pK^-J/\psi(\to \ell^+\ell^-))$, for the muon final state and electron final state in the two trigger categories and data-taking periods. The uncertainties are statistical only.

Channel	Run 1	Run 2
$\mu^+\mu^-$	0.756 ± 0.010	0.796 ± 0.013
e^+e^- (L0I)	0.862 ± 0.017	0.859 ± 0.018
e^+e^- (L0E)	0.630 ± 0.013	0.631 ± 0.013

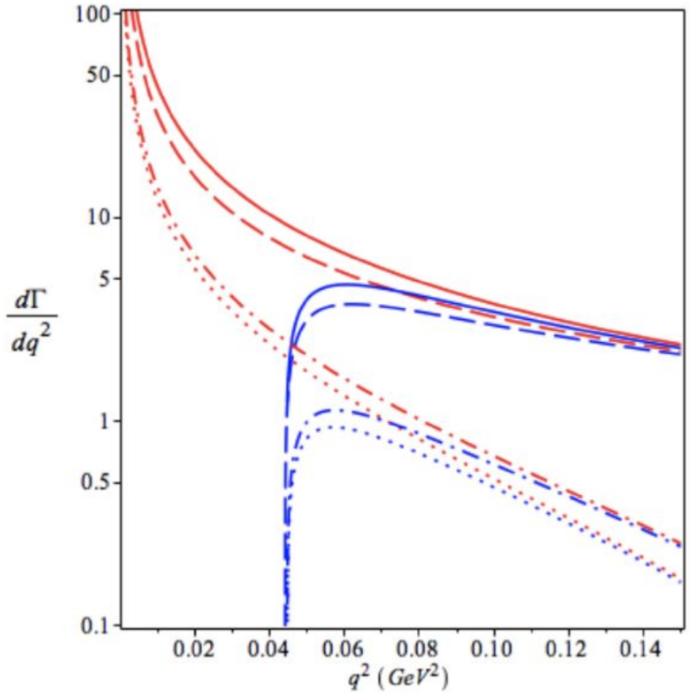
$$N^i(\mathit{\Lambda}_b^0 \to pK^-\mu^+\mu^-) = r_{\mathcal{B}} \times \frac{N^i(\mathit{\Lambda}_b^0 \to pK^- J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(J/\psi \to \ell^+\ell^-)} \times \frac{\epsilon^i(\mathit{\Lambda}_b^0 \to pK^-\mu^+\mu^-)}{\epsilon^i(\mathit{\Lambda}_b^0 \to pK^- J/\psi(\to \mu^+\mu^-))},$$

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

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

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

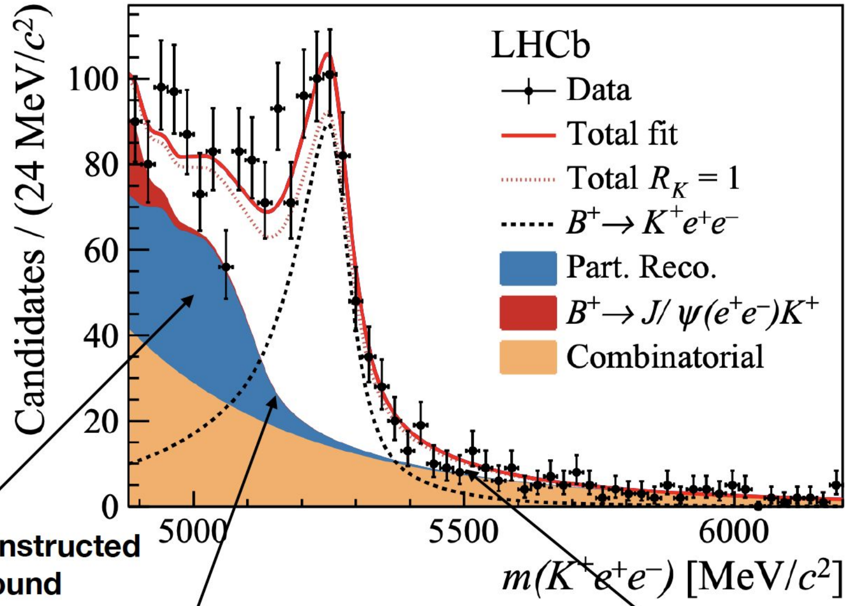
1605.07633



$$R_{K^*}[1.1,\ 6.0]^{\mathrm{SM}} = 1.00 \pm 0.01_{\mathrm{QED}}$$

$$R_{K^+}[1.0,\ 6.0]^{\mathrm{SM}} = 1.00 \pm 0.01_{\mathrm{QED}}$$

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

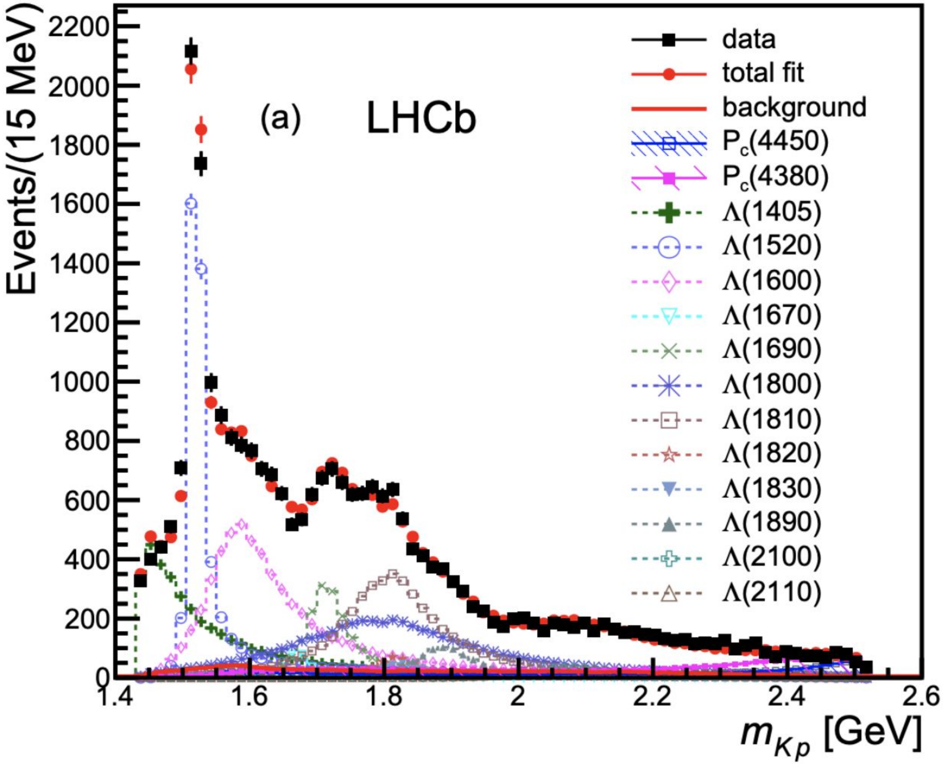


Partially reconstructed background

non trivial signal shape from simulation

When bremsstrahlung photons are added.

1507.03414



Events/(15 MeV)
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
(a)
LHCb
data
total fit
background
P_c(4450)
P_c(4380)
Λ(1405)
Λ(1520)
Λ(1600)
Λ(1670)
Λ(1690)
Λ(1800)
Λ(1810)
Λ(1820)
Λ(1830)
Λ(1890)
Λ(2100)
Λ(2110)
1.4
1.6
1.8
2
2.2
2.4
2.6
m_Kp [GeV]

The hadronic spectrum