Rare decays at LHCb: an overview of recent results

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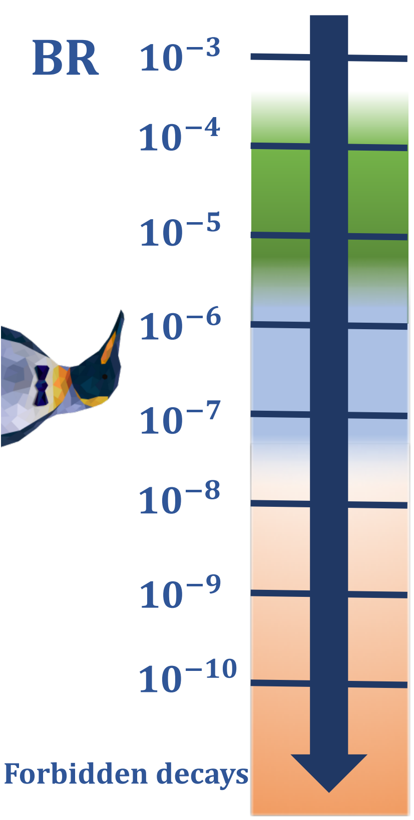
LHCb

Implications of LHCb measurements and future prospects
16 October 2019

Why rare decays?

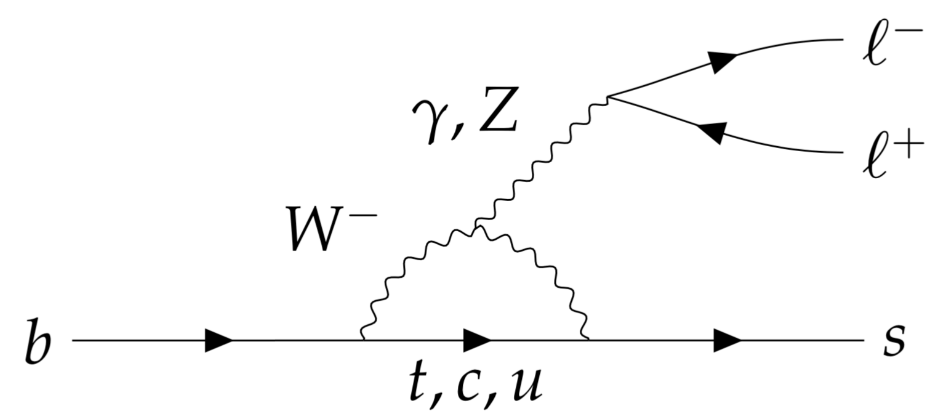
- **Rare decays:** electroweak transitions with leptons or photons in final state
- In the SM: Flavor Changing Neutral Currents, only at the loop level
- Sensitive to potential New Physics effects:
  - can affect branching fractions, angular distributions, lepton universality…
- At LHCb, we study rare decays of beauty, charm and strange hadrons



Radiative decays

Electroweak penguin transitions

Very rare and forbidden (in the SM) decays

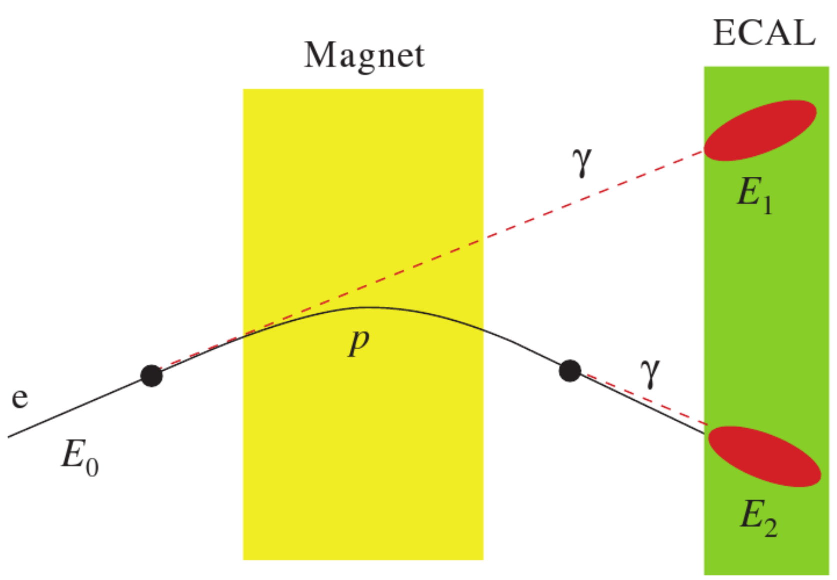


Experimental challenges: resolution

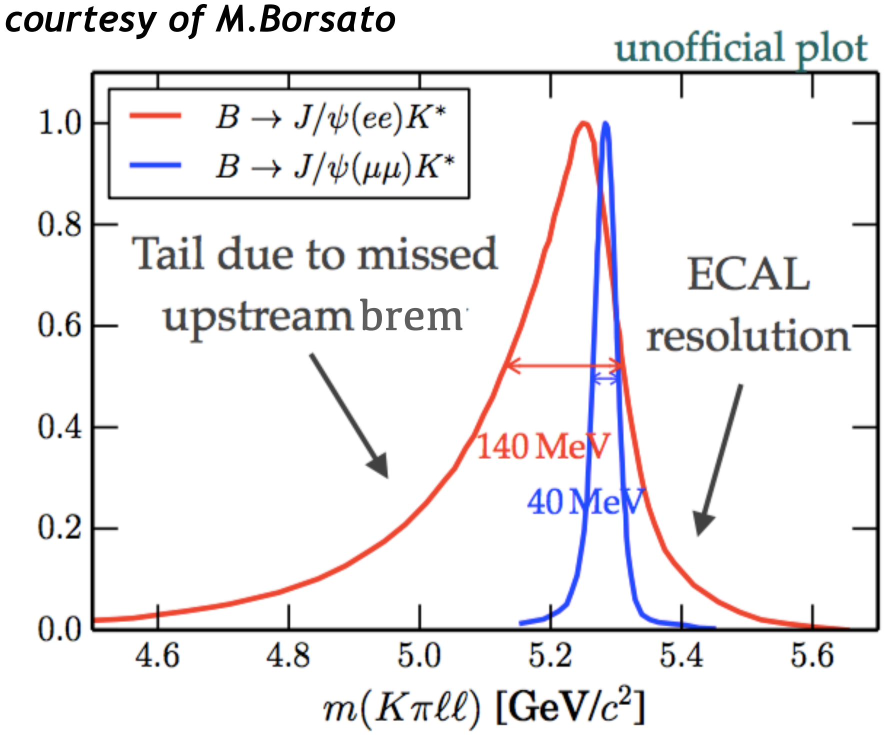
- Decay modes with photons: resolution driven by the ECAL resolution (~90 MeV for B hadrons)

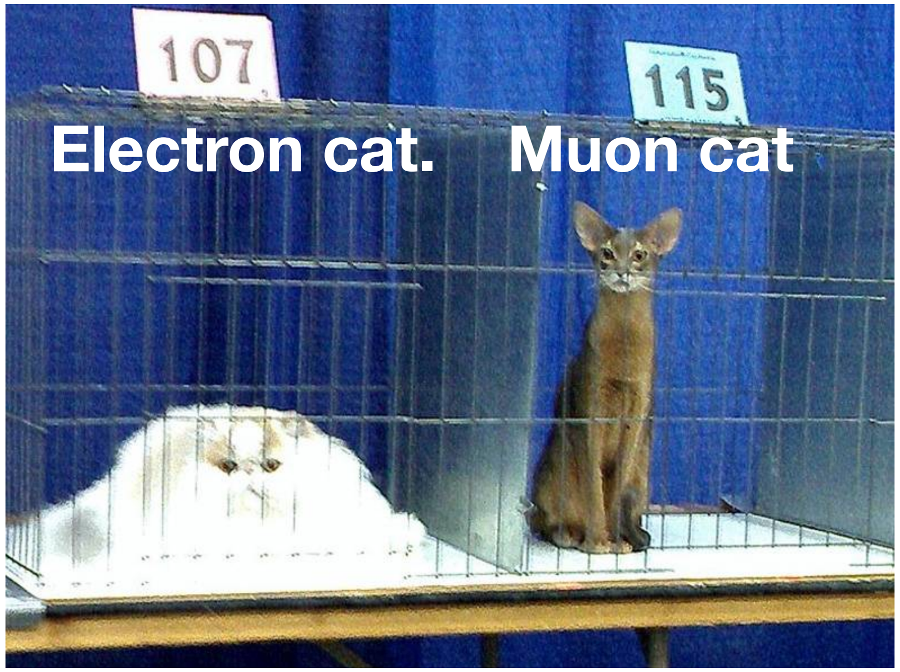
- Decay modes with electrons and muons: rely on the tracking, but…
  - Electrons **emit bremsstrahlung photons** in interactions with material
  - We **match electron tracks** to **photon clusters** in the ECAL
  - Correct electron momenta by energies of photons

- Resolution for decay modes with electrons is worse than for the muonic modes
  - Long bremsstrahlung tails



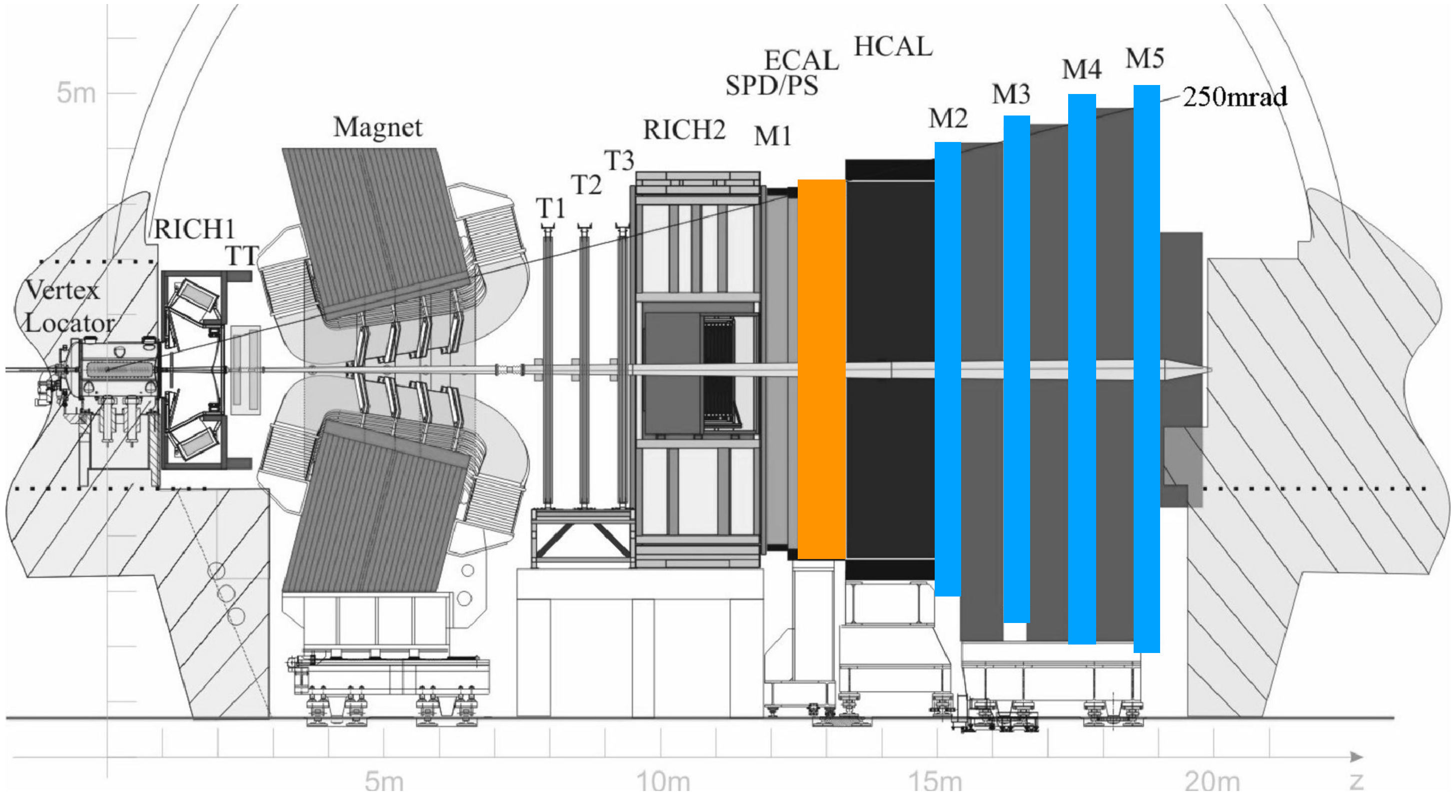
courtesy of M.Borsato





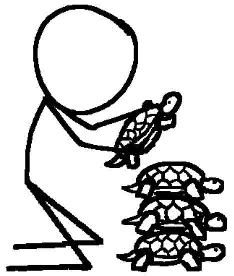
Experimental challenges: trigger

- We trigger on electrons and photons by the calorimeter
- And on muons using the muon stations



- But: ECAL is very busy (plenty of photons, also from π^0)
  - High thresholds → lower statistics

- Trick: can trigger on the hadron part, or on the rest of the event (the other B)



Radiative decays

$$b \to s\gamma$$

Radiative decays at LHCb

PRL 123 (2019) 081802
PRL 123 (2019) 031801

- Results in B-meson sector available from B-factories and LHCb, B_s mainly from LHCb
  - See the talk of Katya regarding the latest results in $B_s^0 \to \phi\gamma$ where we test CP observables

$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11$ **sensitive to CPV in decay**

$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11$

$A^{\Delta}_{\phi\gamma} = -0.67^{+0.37}_{-0.41} \pm 0.17$

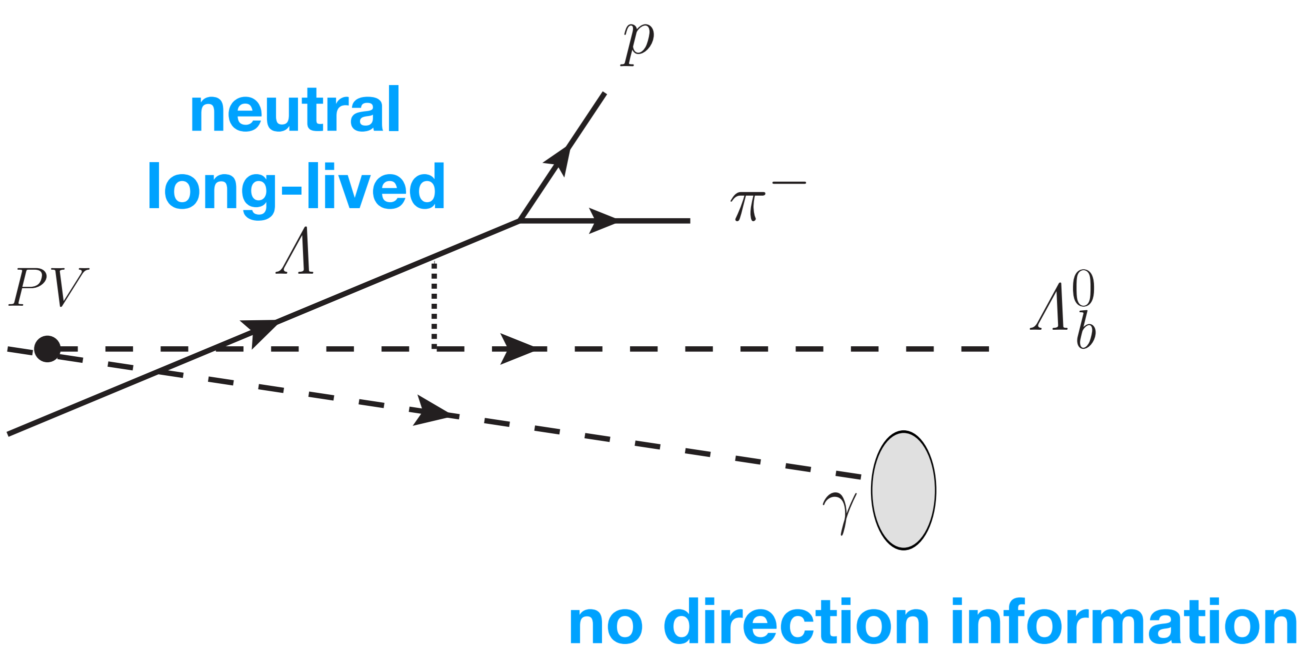
sensitive to photon helicity amplitudes

$\rightarrow$ set constraints on right-handed currents in $b \to s\gamma$

SM: all three close to zero [PLB664(2008) 174]

- Baryon sector provides a unique opportunity: non-zero spin of initial and final state particles
  - Direct access to the photon polarisation: predominantly left-handed in the SM
  - Weak decay of the Λ baryon allows to access the helicity structure of the $b \to s\gamma$ transition [PRD 65(2002) 074038]

- Very challenging at LHCb: no Λ_b^0 decay vertex!
  - Harsh background conditions

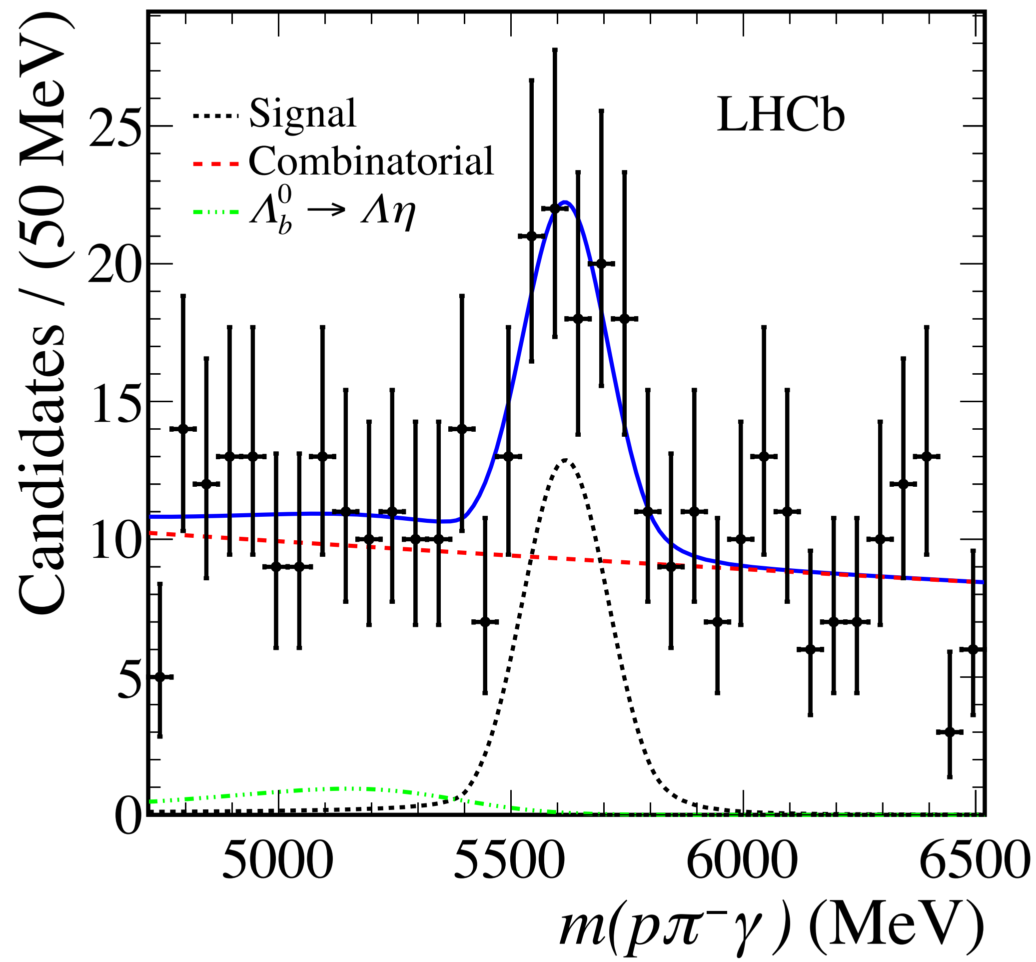


- Dedicated software trigger put in place in Run2
  - 2016 data was used for this pilot analysis: 1.7fb^{-1} at 13 TeV

- High-performance MVA classifier trained to reject the combinatorial background (99.8% rejection, 33% signal eff.)

First observation of $\Lambda_b^0 \to \Lambda\gamma$

- First observation: 5.6σ



- BR measured relatively to $B^0 \to K^{*0}\gamma$

$$BR(\Lambda_b^0 \to \Lambda\gamma) = (7.1 \pm 1.5(stat) \pm 0.6(syst) \pm 0.7(ext)) \times 10^{-6}$$

- In agreement with SM (predictions have broad range)
- Largest systematics: Λ_b^0 production fraction

- Full Run2 dataset is currently analysed to measure the photon polarisation
- Other radiative baryon decays are being explored as well

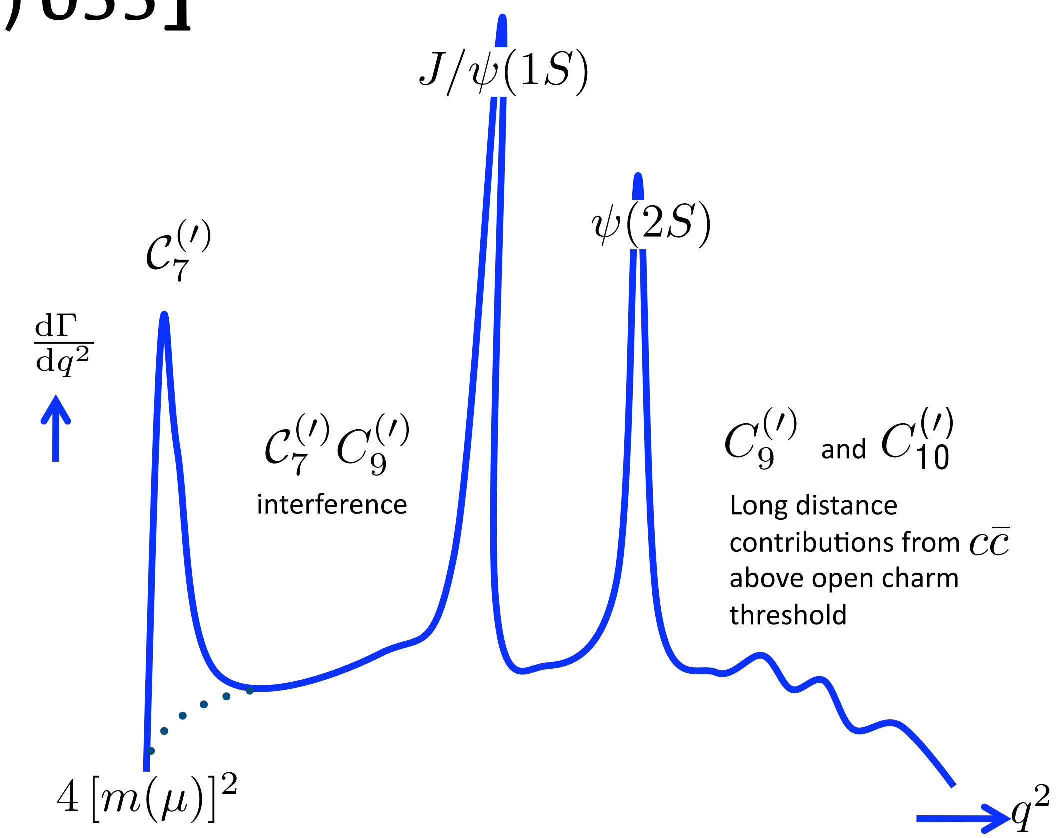
Electroweak penguin decays

$$b \to s\ell^+\ell^-$$

- Lepton Flavor Universality: couplings of EW bosons are same for all charged leptons
  - Tested to sub-percent precision in $Z \to \ell^+\ell^-, J/\psi \to \ell^+\ell^-$ decays, etc
- Hints of deviations from the SM seen in $b \to s\ell^+\ell^-$ transitions by LHCb [PRL 113, 151601 (2014); JHEP 08 (2017) 055]

- Definition:

$$R_K[q^2_{min}, q^2_{max}] = \frac{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B \to K\mu^+\mu^-)}{dq^2}}{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B \to Ke^+e^-)}{dq^2}}$$



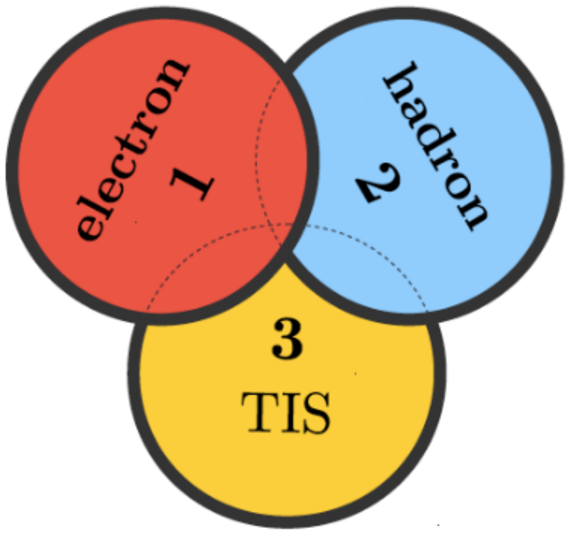
- At LHCb, we measure the double ratio

$$R_K = \frac{N(B^+ \to K^+\mu^+\mu^-)}{\epsilon(B^+ \to K^+\mu^+\mu^-)} \times \frac{\epsilon(B^+ \to K^+e^+e^-)}{N(B^+ \to K^+e^+e^-)} \times \frac{\epsilon(B^+ \to K^+J/\psi(\mu^+\mu^-))}{N(B^+ \to K^+J/\psi(\mu^+\mu^-))} \times \frac{N(B^+ \to K^+J/\psi(e^+e^-))}{\epsilon(B^+ \to K^+J/\psi(e^+e^-))}$$

Test of LFU: R_K

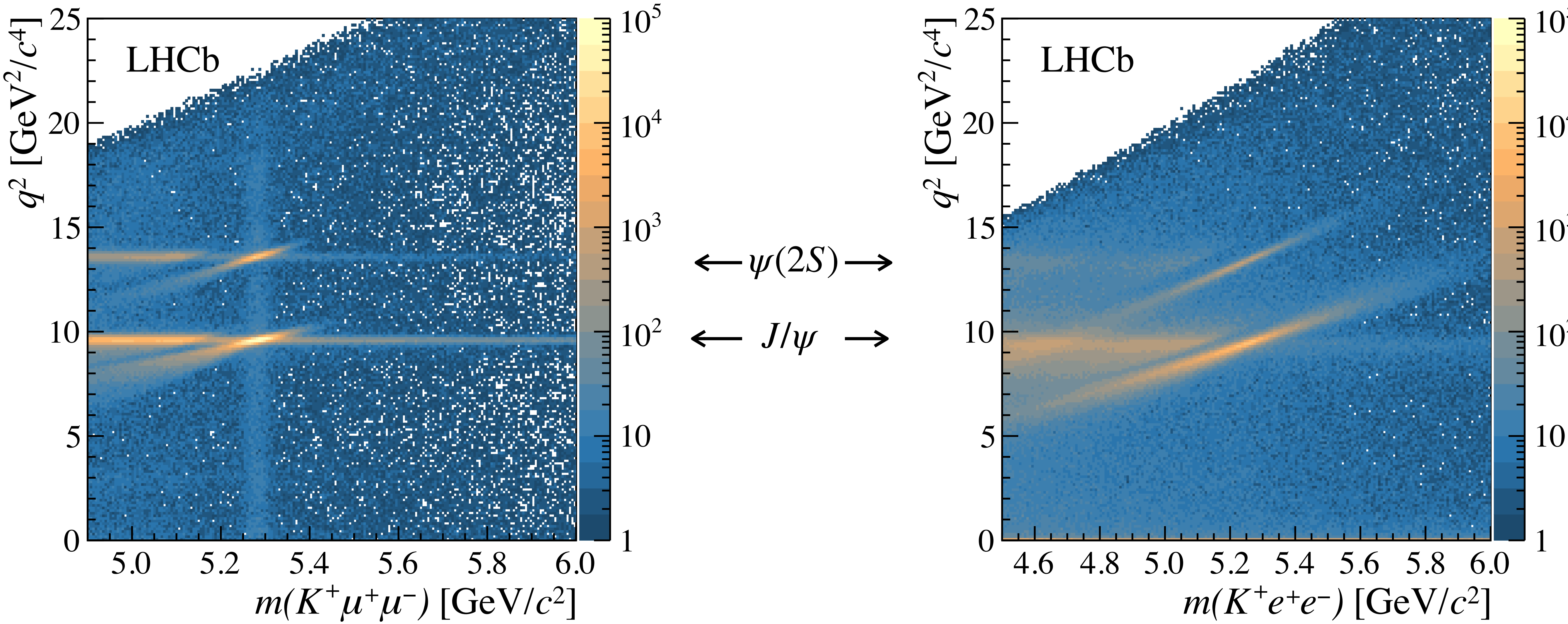
- This analysis: LHCb data up to 2016 (5fb^{-1} at 7-8-13 TeV)
- Only central-q^2 bin considered: $1.1 < q^2 < 6$ GeV^2/c^4.

- Different treatment of the final states:
  - $B^+ \to K^+\mu^+\mu^-$: trigger on muons
  - $B^+ \to K^+e^+e^-$: three exclusive categories:



- Backgrounds:
  - Combinatorial: suppressed by the MVA classifier
  - Misidentifications: suppressed by PID requirements
  - Semileptonic: mass veto
  - The most important remaining: $B^0 \to K^{*+}(K^+\cancel{\pi^0})e^+e^-$ part.-reco.

Backgrounds are more important for the dielectron mode: due to the worse resolution

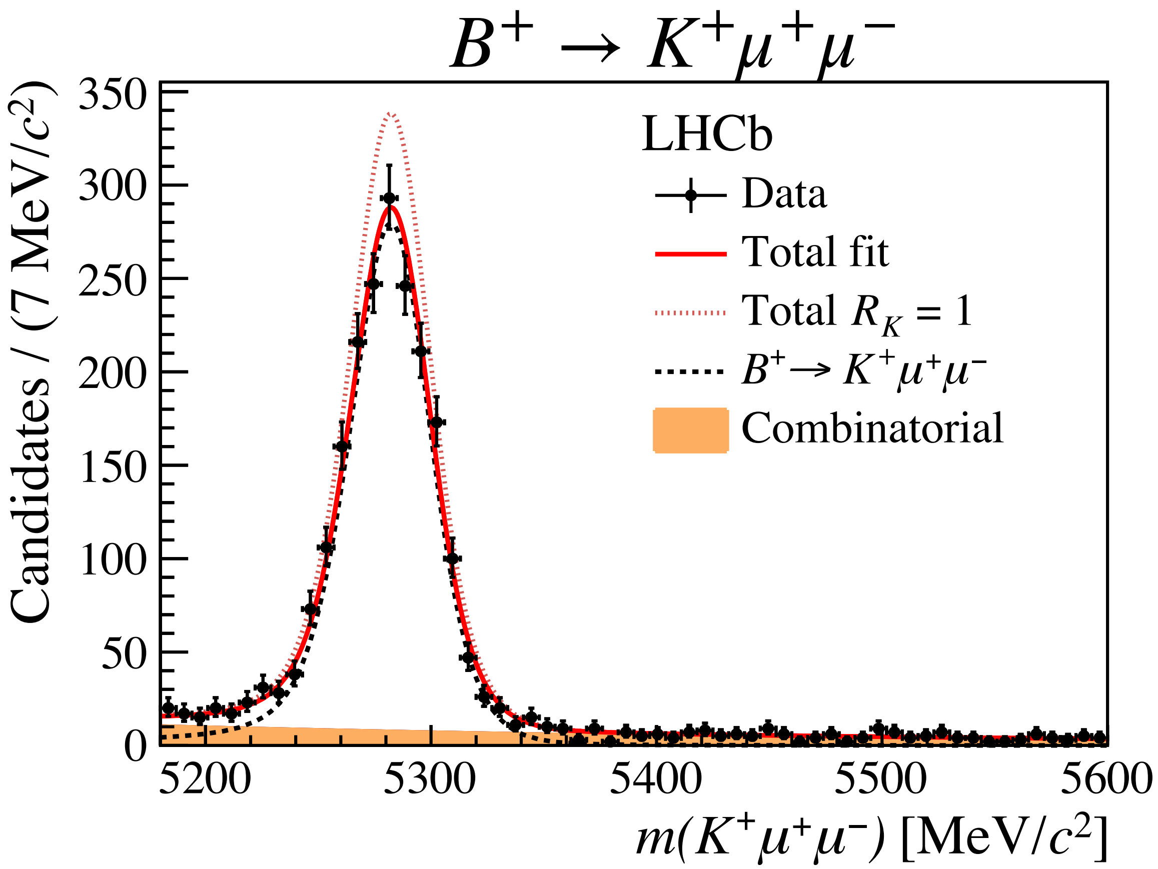


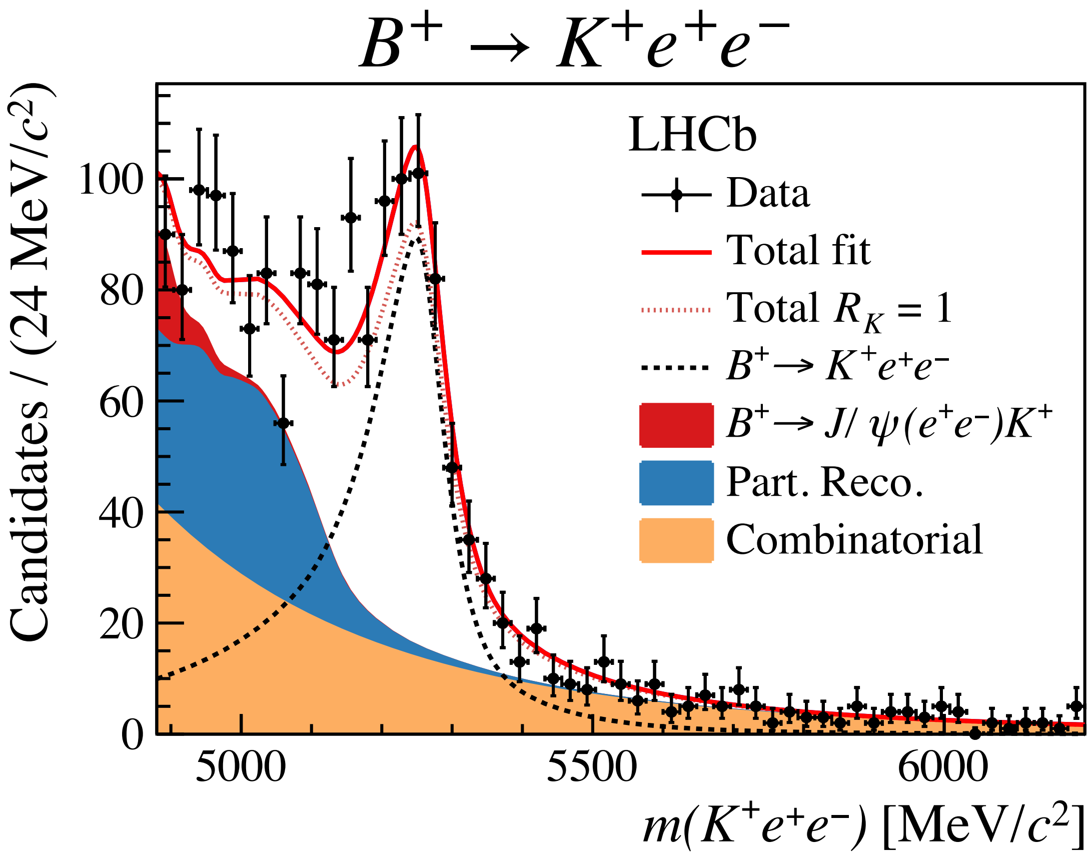
- The J/ψ region is used to validate the simulation:

$$r_{J/\psi} = \frac{N(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{\epsilon(B^+ \to K^+ J/\psi(\mu^+\mu^-))} \times \frac{\epsilon(B^+ \to K^+ J/\psi(e^+e^-))}{N(B^+ \to K^+ J/\psi(e^+e^-))} = 1.014 \pm 0.035$$

  - Consistent with unity
  - Does not depend on kinematics / geometry

- Mass fits for nonresonant channels:

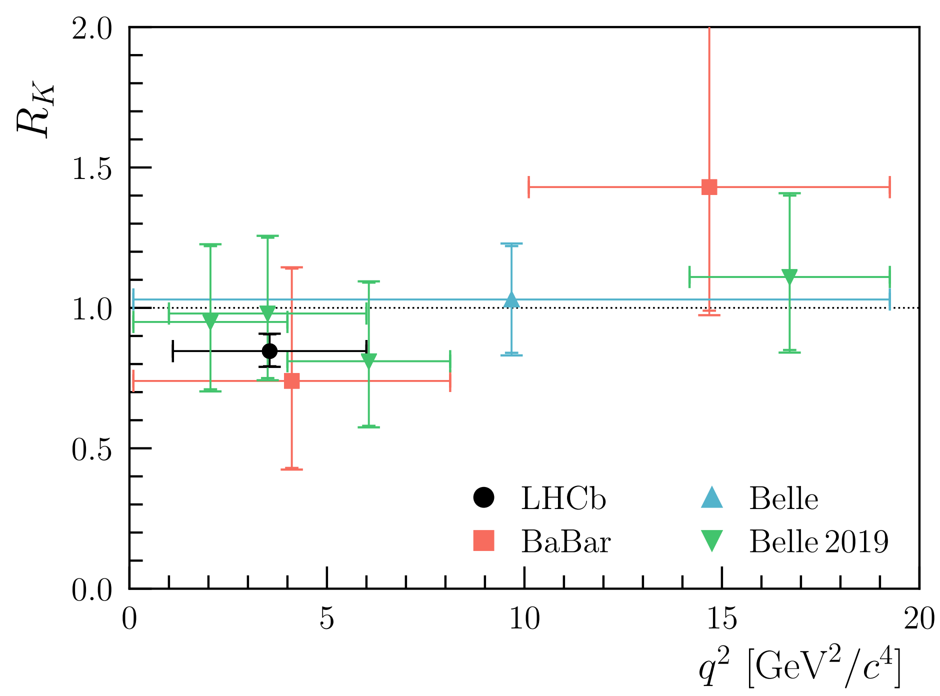




- Differential branching fraction of $B^+ \to K^+\mu^+\mu^-$ consistent with previous LHCb Run1 result

- Result: $R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$,
  - SM: $R_K = 1$, QED uncertainties ~1%
  - consistent with the SM at 2.5σ

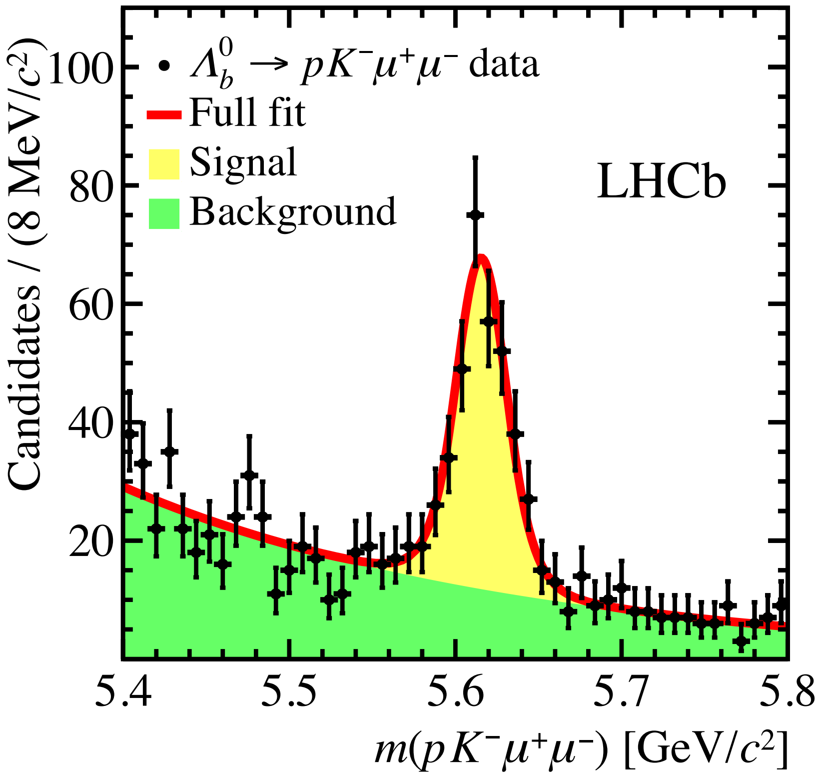
- Dominant systematics: trigger calibration, fit model



What's coming next?

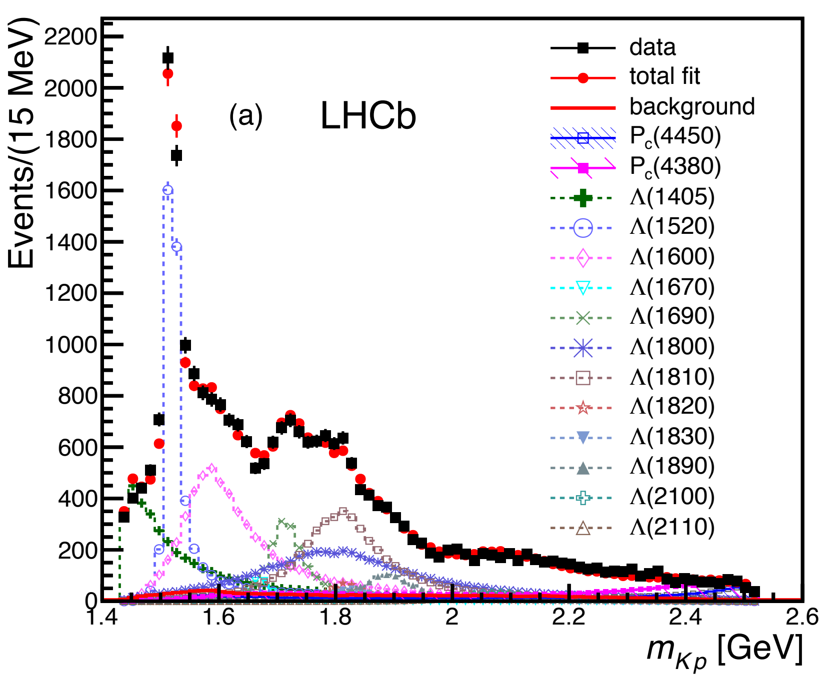
- We have tested LFU only with B mesons

- What about baryons?
- Measure the ratio with Run1+2016 data $R_{pK} = \frac{BR(\Lambda_b \to pK\mu^+\mu^-)}{BR(\Lambda_b \to pKe^+e^-)}$



- Muon mode seen by LHCb: [JHEP 06 (2017) 108]
- Electron mode not yet observed

- Main complication: (pK) system has a tricky resonant structure
- E.g., in the J/ψ window [PRL 115 (2015) 072001]:



- Results on R_{pK} expected soon.

Very rare decays

Many interpretations of 'flavor anomalies': covered in the theory talks, e.g.:

16:10 **New Physics interpretations (20+5)**

Speaker: Dr Olcyr Sumensari (INFN Padova)

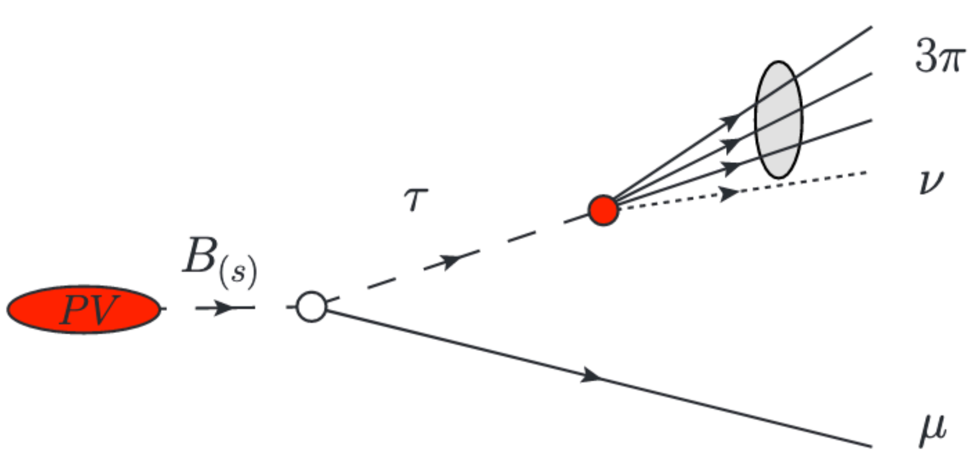
Most of the models predict measurable rate for certain decays which are extremely suppressed in the SM

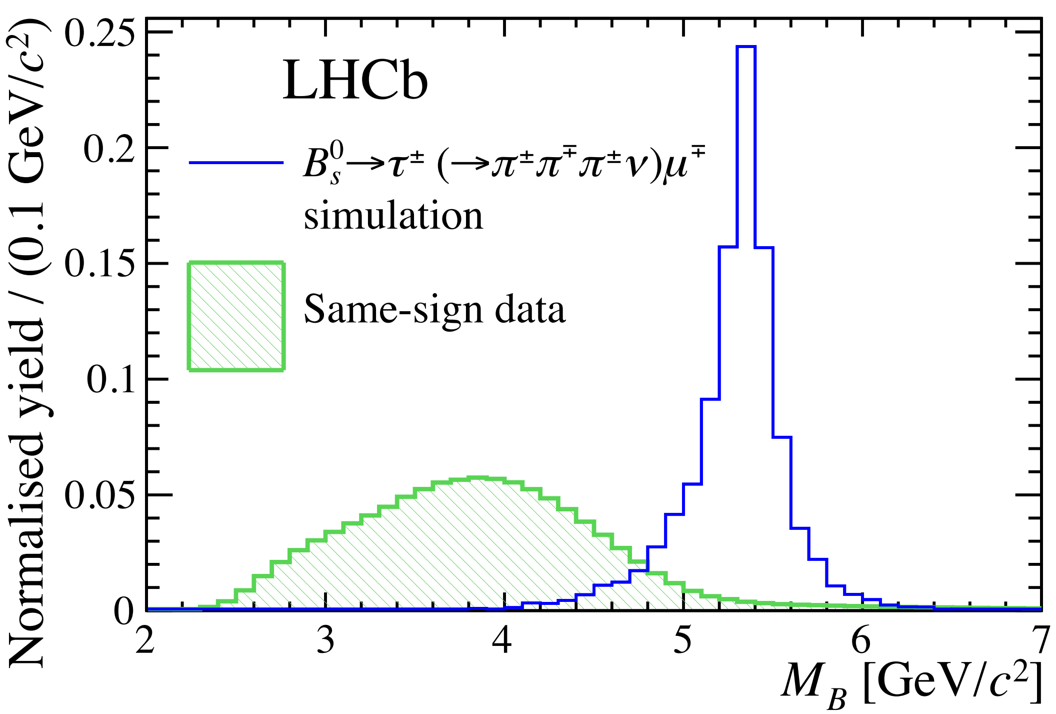
Search for $B^0_{(s)} \to \tau^\pm\mu^\mp$

- LF-violating, highly suppressed in the SM (BR~10^{-54} [Riv. Nuovo Cimento, Vol. 41 (2018) 71])
- Enhanced in many NP models (e.g. [JHEP11(2016) 035]) up to 10^{-5}

- Previous limit by BaBar: $BR(B^0 \to \tau^\pm\mu^\mp) < 2.2 \times 10^{-5}$ at 90% CL [PRD 77(2008)091104]
  - No limits for the B^0_s mode

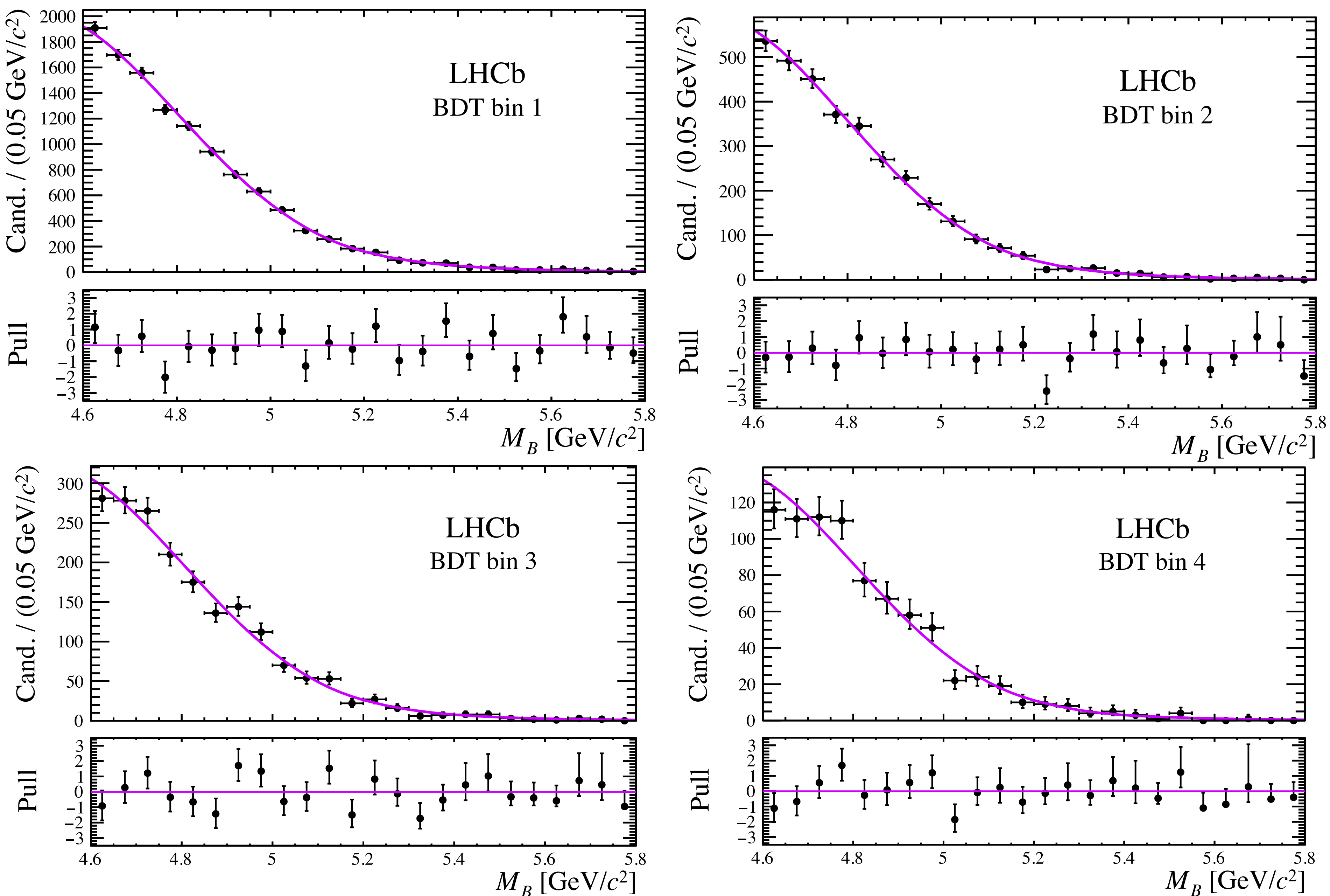
- LHCb analysis with Run1 data (3fb^{-1} at 7-8 TeV)
- Hadronic decay of the τ lepton: $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
  - Constrain the momentum of the neutrino from reconstructed tracks and vertices





Search for $B^0_{(s)} \to \tau^\pm\mu^\mp$

- Isolation criteria and mass vetoes against important backgrounds
- As the normalisation, $B^0 \to D^-(K\pi\pi)\pi^+$ was used
- MVA classifier; four bins of the classifier output analysed simultaneously
- Fit under hypotheses of B_s or B^0 signal only: no signal seen



$$N_{B^0_s \to \tau^\pm\mu^\mp} = -16 \pm 38$$

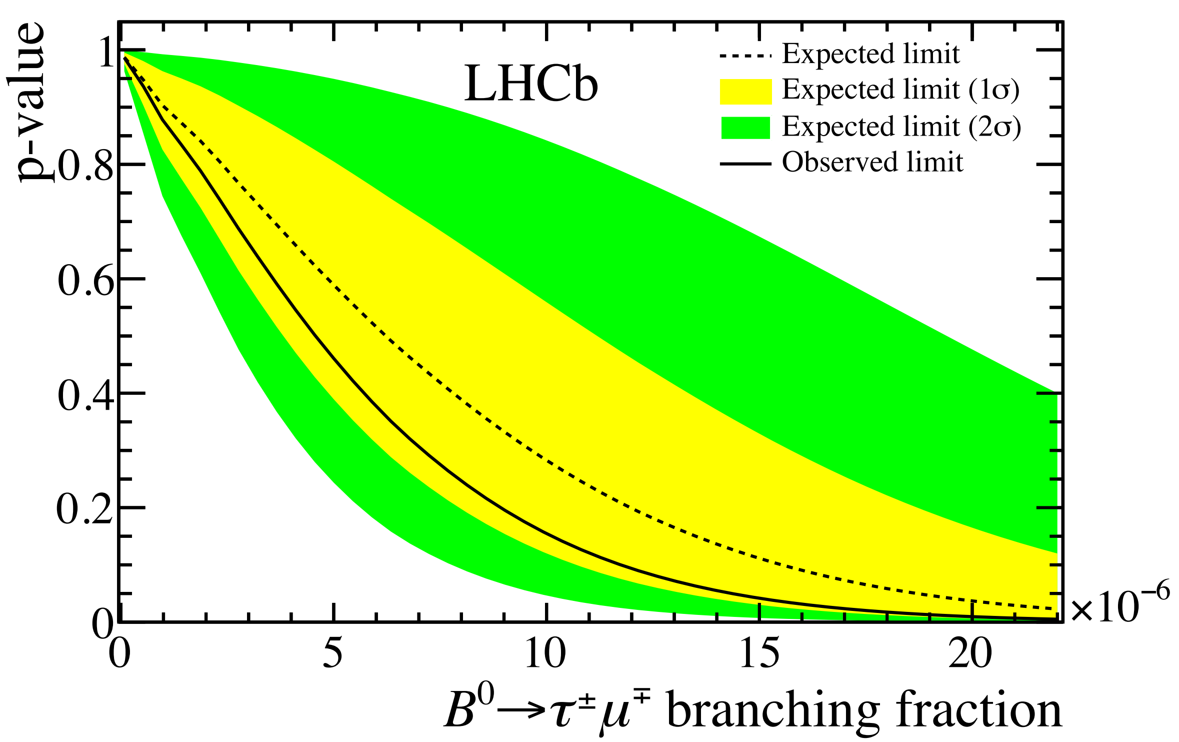
$$N_{B^0 \to \tau^\pm\mu^\mp} = -65 \pm 58$$

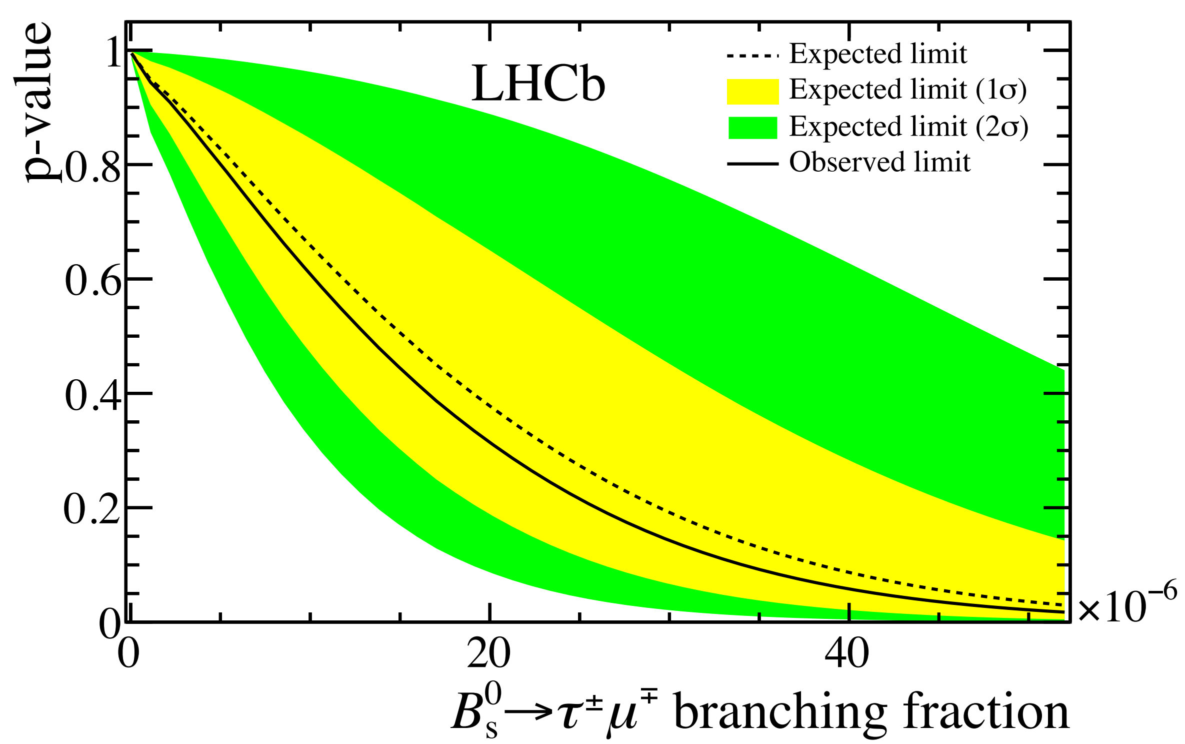
Search for $B^0_{(s)} \to \tau^\pm \mu^\mp$

- Limits set:

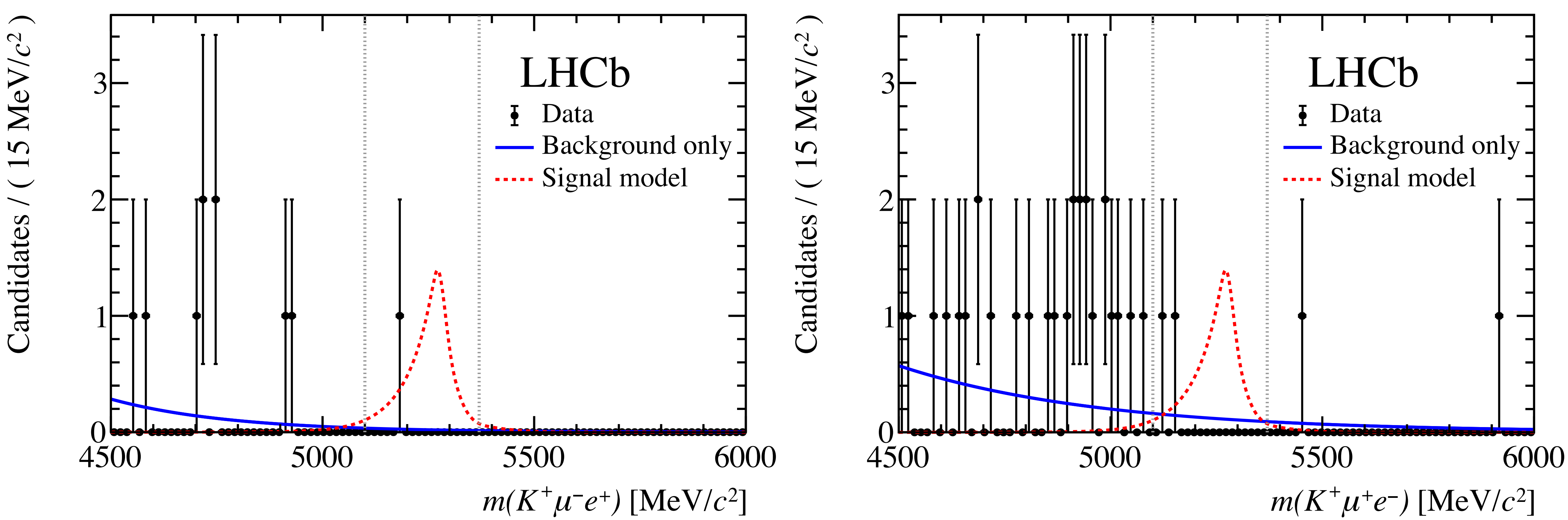
Mode	Limit	90% CL	95% CL
$B^0_s \to \tau^\pm \mu^\mp$	Observed	3.4×10^{-5}	4.2×10^{-5}
	Expected	3.9×10^{-5}	4.7×10^{-5}
$B^0 \to \tau^\pm \mu^\mp$	Observed	1.2×10^{-5}	1.4×10^{-5}
	Expected	1.6×10^{-5}	1.9×10^{-5}

- Dominant systematics: background model
- Factor 2 improvement of the BaBar limit; first limit for the B_s mode
- Enter the range allowing to constrain certain NP models!





- LFV decay, can be enhanced in NP models up to 10^{-8} level (e.g. [JHEP06(2015) 072])
- Best limits by BaBar: [PRD 73(2006) 092001] $BR(B^+ \to K^+\mu^- e^+) < 9.1 \times 10^{-8}$ $BR(B^+ \to K^+\mu^+ e^-) < 13 \times 10^{-8}$ at 90% CL
- LHCb analysis: Run1 data ($3fb^{-1}$ at 7-8 TeV)
  - Semileptonic backgrounds: removed by $m(K^+l^-) > 1885$ MeV
  - MVA against the combinatorial
- As a normalisation, $B^+ \to K^+J/\psi(\mu^+\mu^-)$ was used
- No signal seen in either of charge combinations:



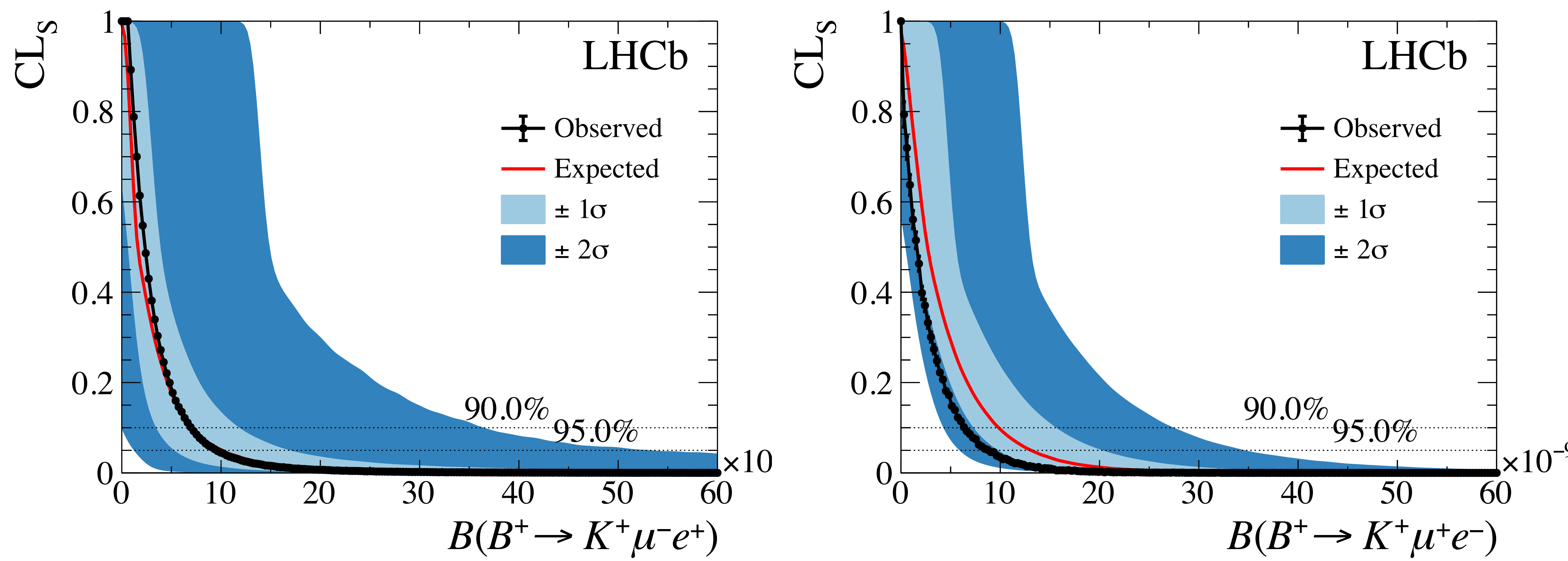
Search for $B^+ \to K^+\mu^\pm e^\mp$

LHCb-PAPER-2019-022

- Limits set:

	90% C. L.	95% C. L.
$\mathcal{B}(B^+ \to K^+\mu^- e^+)/10^{-9}$	7.0	9.5
$\mathcal{B}(B^+ \to K^+\mu^+ e^-)/10^{-9}$	6.4	8.8

- Dominant systematics: PID calibration for electrons, normalisation, background model



- Efficiency variation across the Dalitz plane is provided for model-dependent interpretation of the results

Search for $K_S \to \mu^+\mu^-$

- Very suppressed: SM prediction ~ 5×10^{-12} [JHEP01(2004) 009]
  - Can be enhanced in some NP models
- Related process $K_L \to \mu^+\mu^-$: BR=$(6.84\pm0.11) \times 10^{-9}$ [PDG] in agreement with SM predictions

- Current best limit: $BR(K_S \to \mu^+\mu^-) < 1.0 \times 10^{-9}$ at 95% CL (LHCb Run1) [Eur. Phys. J.C77(2017) 678]
  - Huge kaon production cross-section at LHCb, but low trigger efficiencies

- **New analysis:** 2016-2018 dataset (5.6 fb^{-1} at 13 TeV)
  - **Dedicated software triggers**, not present in Run1: an order of magnitude increase in efficiency
    - Limited by the hardware trigger

  - Consider only K_S decaying in VELO: about 22% of all prompt K_S
  - Remove background from inelastic interactions with VELO material

- Dominant backgrounds:
  - Misidentified $K_S \to \pi^+\pi^-$: shifted in invariant mass
  - Combinatorial: suppressed by the MVA algorithm
  - $K_L \to \mu^+\mu^-$: suppressed due to the longer lifetime

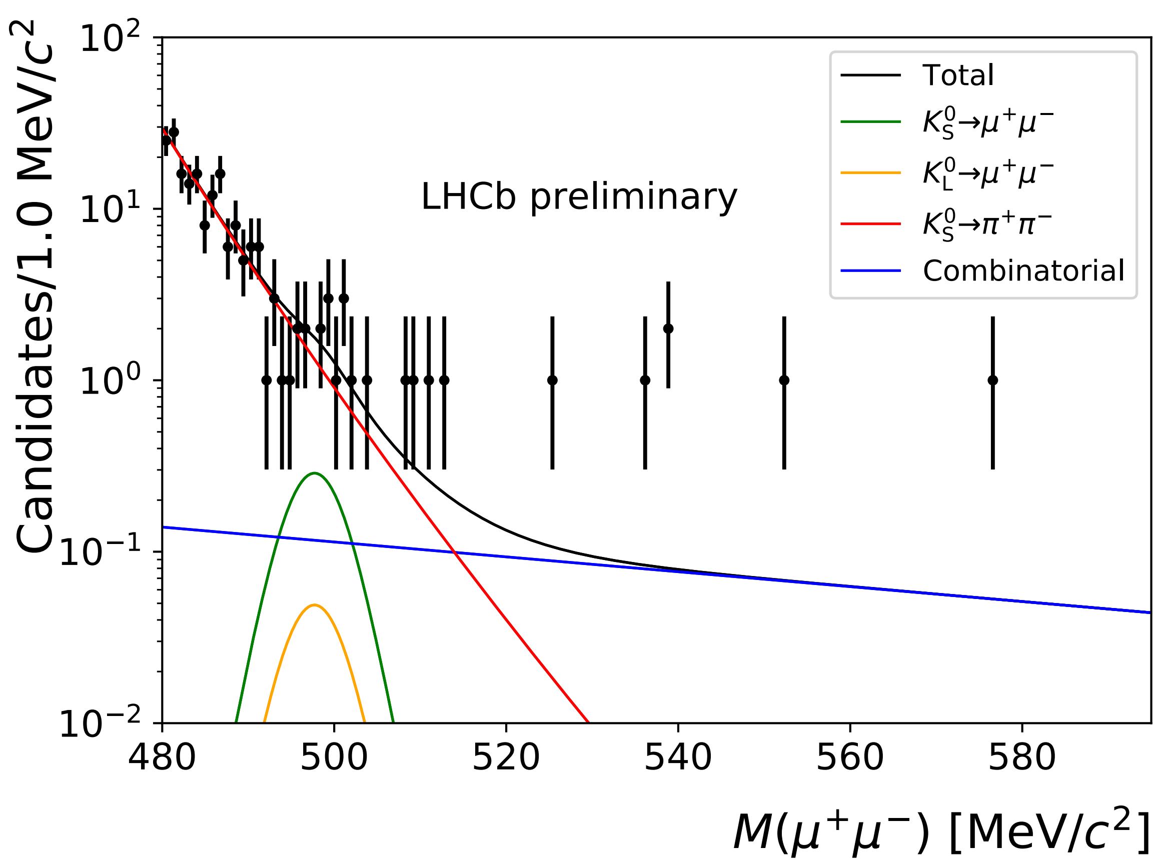
normalisation channel

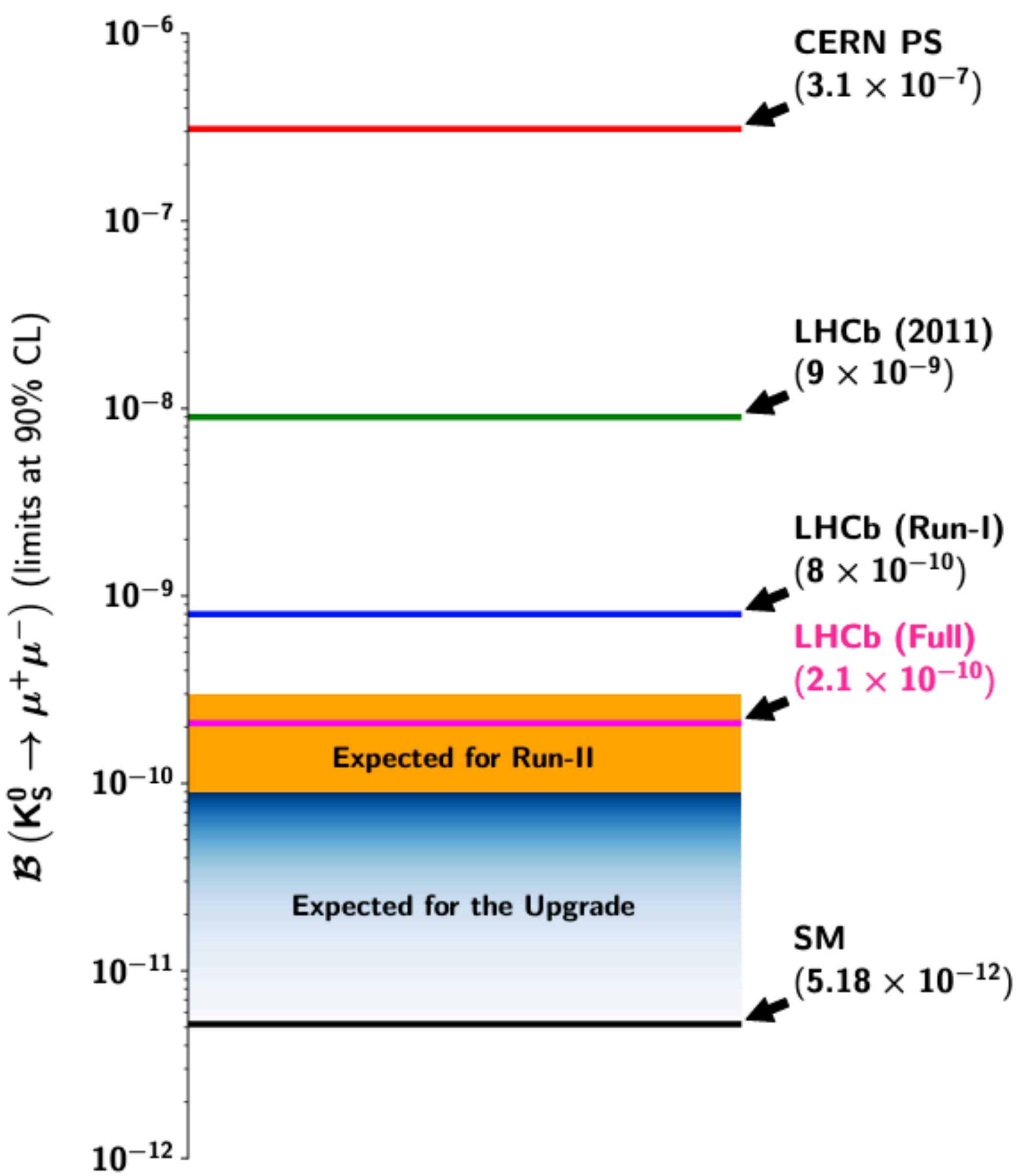
- No significant signal seen; limit set (combined with Run1):

$$BR(K_s \to \mu^+\mu^-) < 2.1(2.4) \times 10^{-10}$$

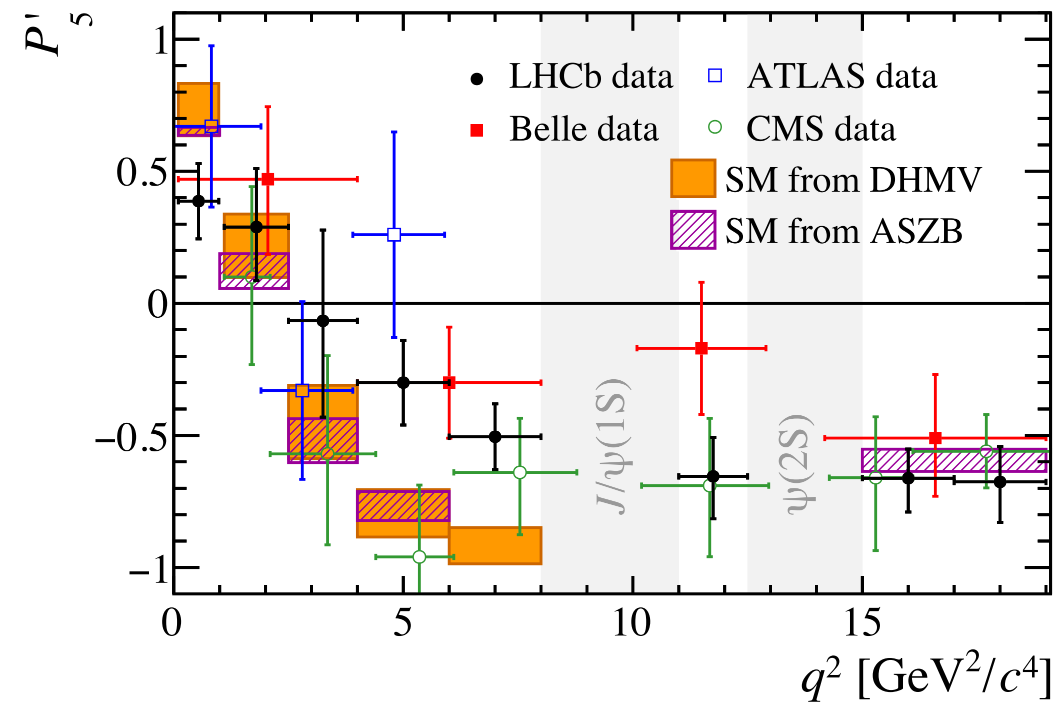
at 90 (95)% CL

Factor 4 lower than the previous limit





- Another puzzle: angular observables in $B^0 \to K^{*0}\mu^+\mu^-$
- Input from many experiments
- Update from LHCb (data up to 2016) expected soon.



LHCb: JHEP 02 (2016) 104 Atlas-Conf-2017-023
Belle: PRL 118 2017 CMS: PLB 781 (2018) 517541

- Also foreseen in next few months (mostly use a partial dataset):

R_{pK}, searches for $B^0_{(s)} \to e^+e^-, B^+ \to K^+\mu^-\tau^+$

- Work on legacy measurements with the full LHCb dataset (longer term):

$R_H, B^0_{(s)} \to \mu^+\mu^-$, angular analyses with muons and electrons, …

$H = K^+, K^*, K_S, K\pi\pi, \phi, \Lambda$

What else?

- Rare charm decays: probe up-type quarks
- A number of LHCb results with a (partial) Run1 dataset, probing BRs down to 10^{-8}
  - Best limits on $D^0 \to \mu^+\mu^-$ [PLB 725 (2013) 15], $D_{(s)}^+ \to \pi^\pm\mu^\mp\mu^+$ [PLB 724 (2013) 203], $D^0 \to e^+\mu^-$ [PLB 754 (2016) 167], $\Lambda_c^+ \to p\mu^+\mu^-$ [PRD 97 (2018) 091101].
  - First observation of $D^0 \to K^-\pi^+V(\to\mu^+\mu^-)$ [PLB 757 (2016) 558], $D^0 \to K^-K^+V(\to\mu^+\mu^-)$, $\pi^-\pi^+V(\to\mu^+\mu^-)$ [PRL 119 (2017) 181805], $\Lambda_c^+ \to pV(\to\mu^+\mu^-)$ [PRD 97 (2018) 091101]
- So far, no discrepancies with the SM
- Serious efforts ongoing for $D_{(s)}^+ \to h^\pm\ell^\pm\ell^\pm$, $D^0 \to \mu^+\mu^-$, $D^0 \to h^+h^-\mu^+\mu^-$ and other channels with a (partial) Run2 dataset

Conclusions

- LHCb is very active in exploring rare decays: we analyse new channels and update old results
  - Several first observations, or first limits
  - Most of the results still statistically dominated

- Sensitivity to the LFV channels enters the region interesting to probe some of the NP models

- No final word on the ‘flavor anomalies’ yet, but results coming

- LHCb Upgrade will open new horizons in few years

LHCb physicist

Data yet to be analysed

Stay tuned!

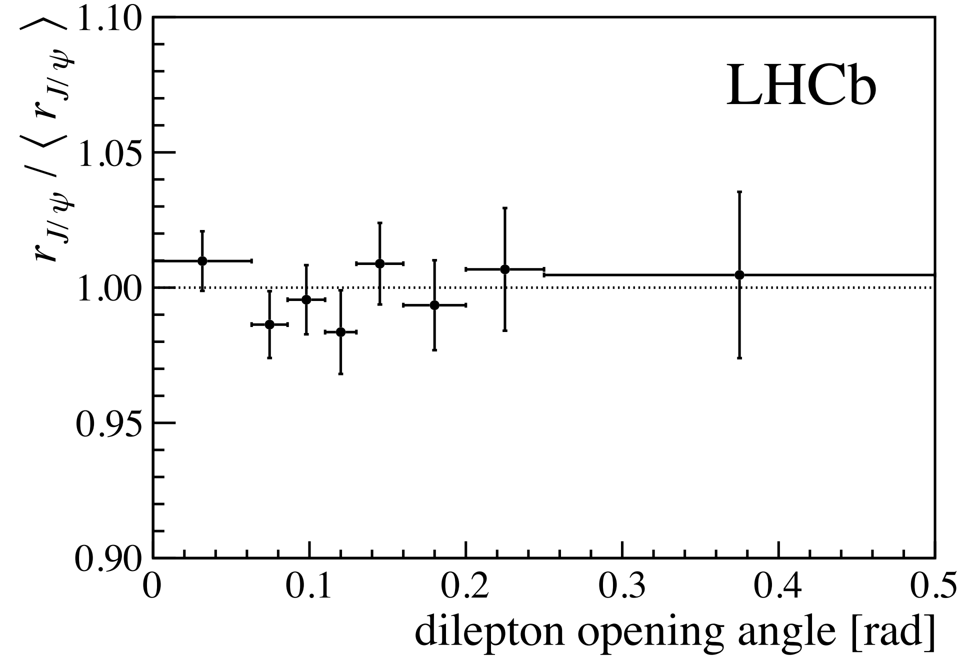
The End

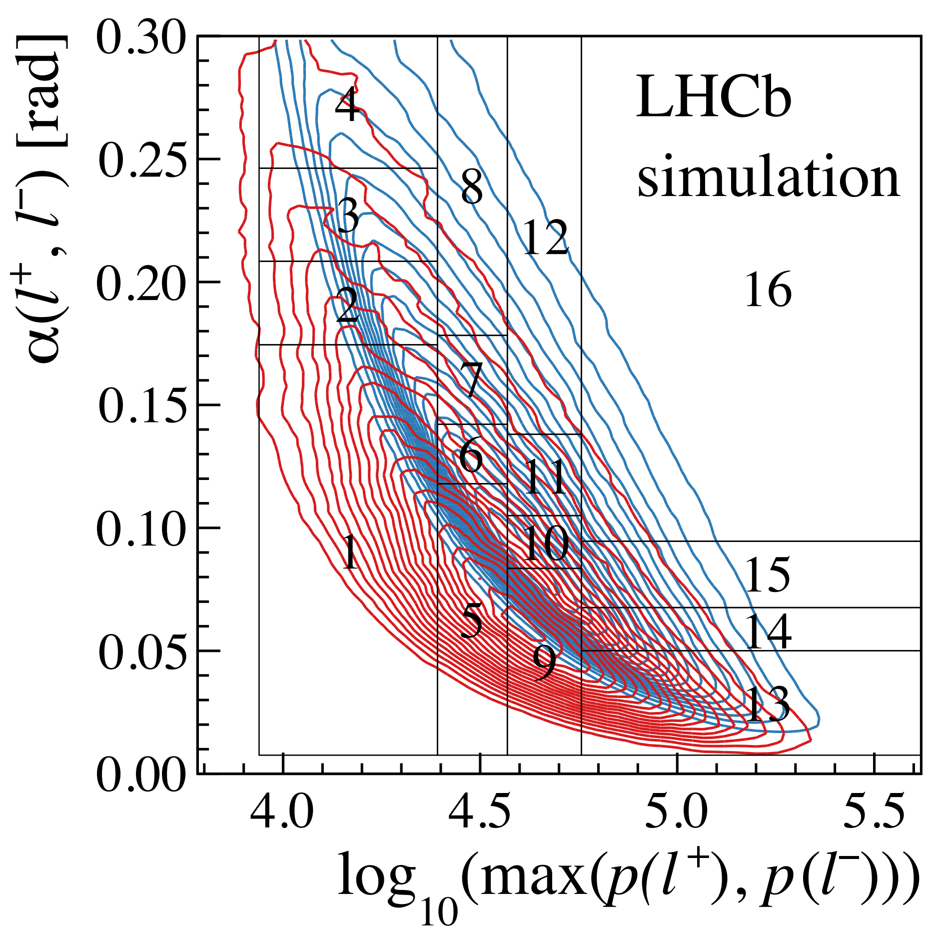
Thanks to all LHCb colleagues who helped to improve this talk!

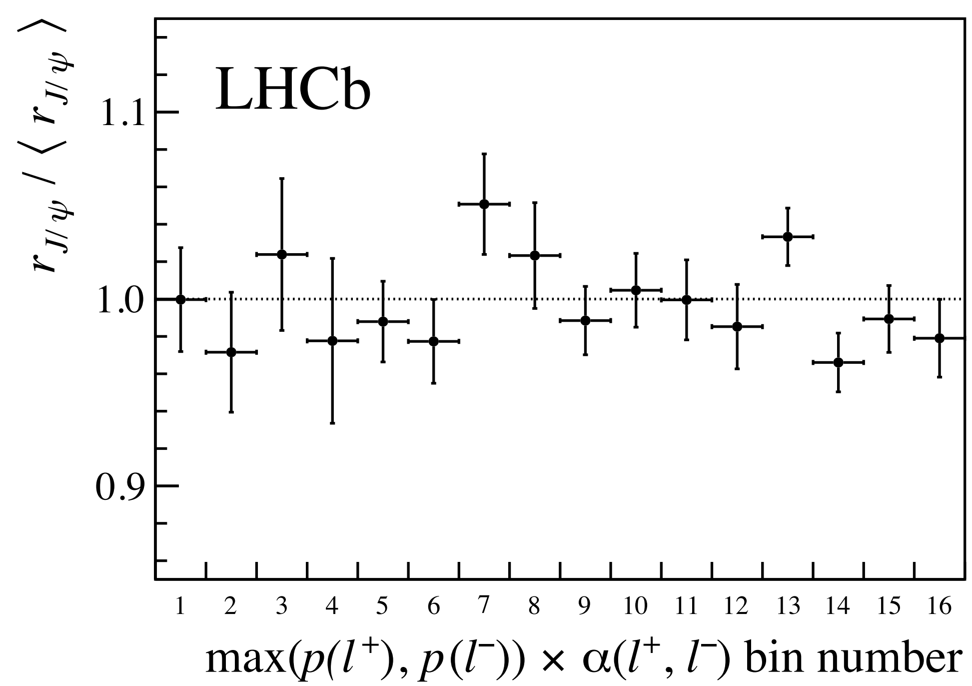
Extra penguins

$$r_{J/\psi} = \frac{N(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{\epsilon(B^+ \to K^+ J/\psi(\mu^+\mu^-))} \times \frac{\epsilon(B^+ \to K^+ J/\psi(e^+e^-))}{N(B^+ \to K^+ J/\psi(e^+e^-))}$$

- Average: $r_{J/\psi} = 1.014 \pm 0.035$
- Flat in important variables
- Flat in 2D phase-space

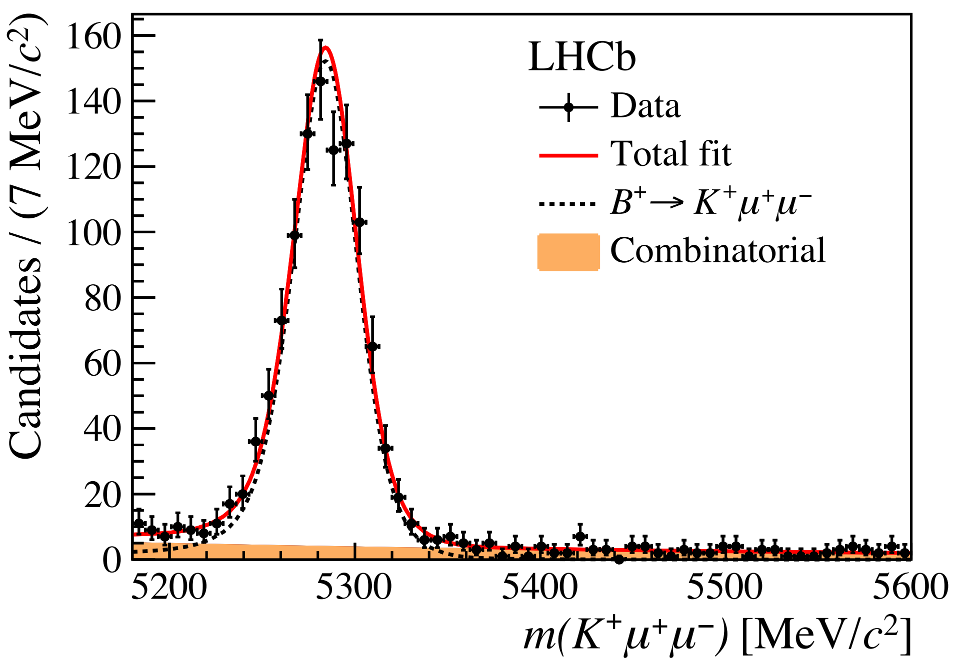


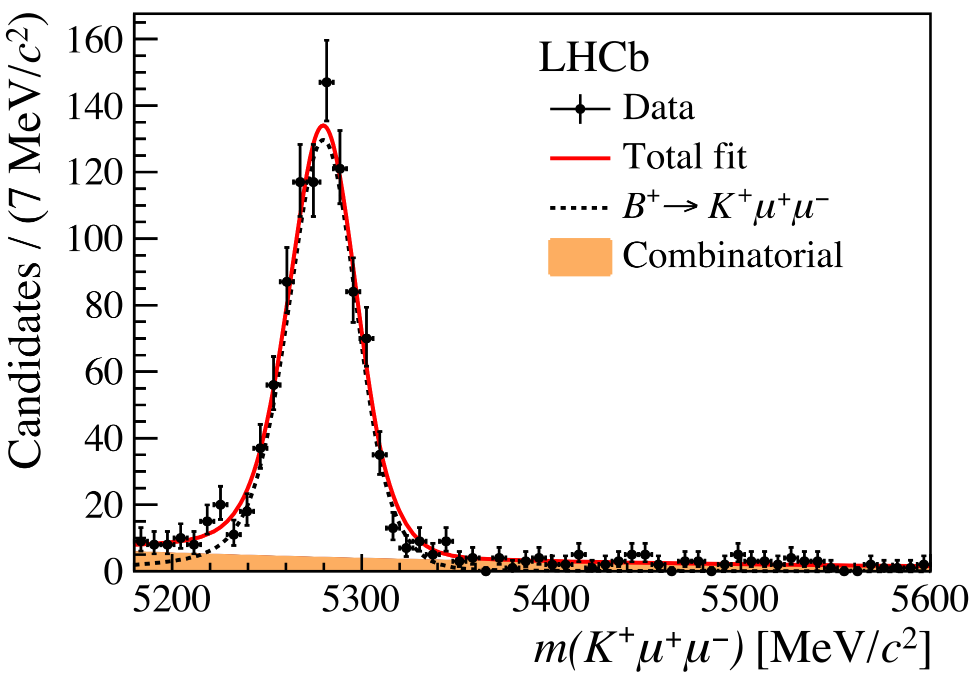




- Also: double ratio $R_{\psi(2S)} = 0.986 \pm 0.013$ also well consistent with unity

- Mass projections: muons R1 and R2

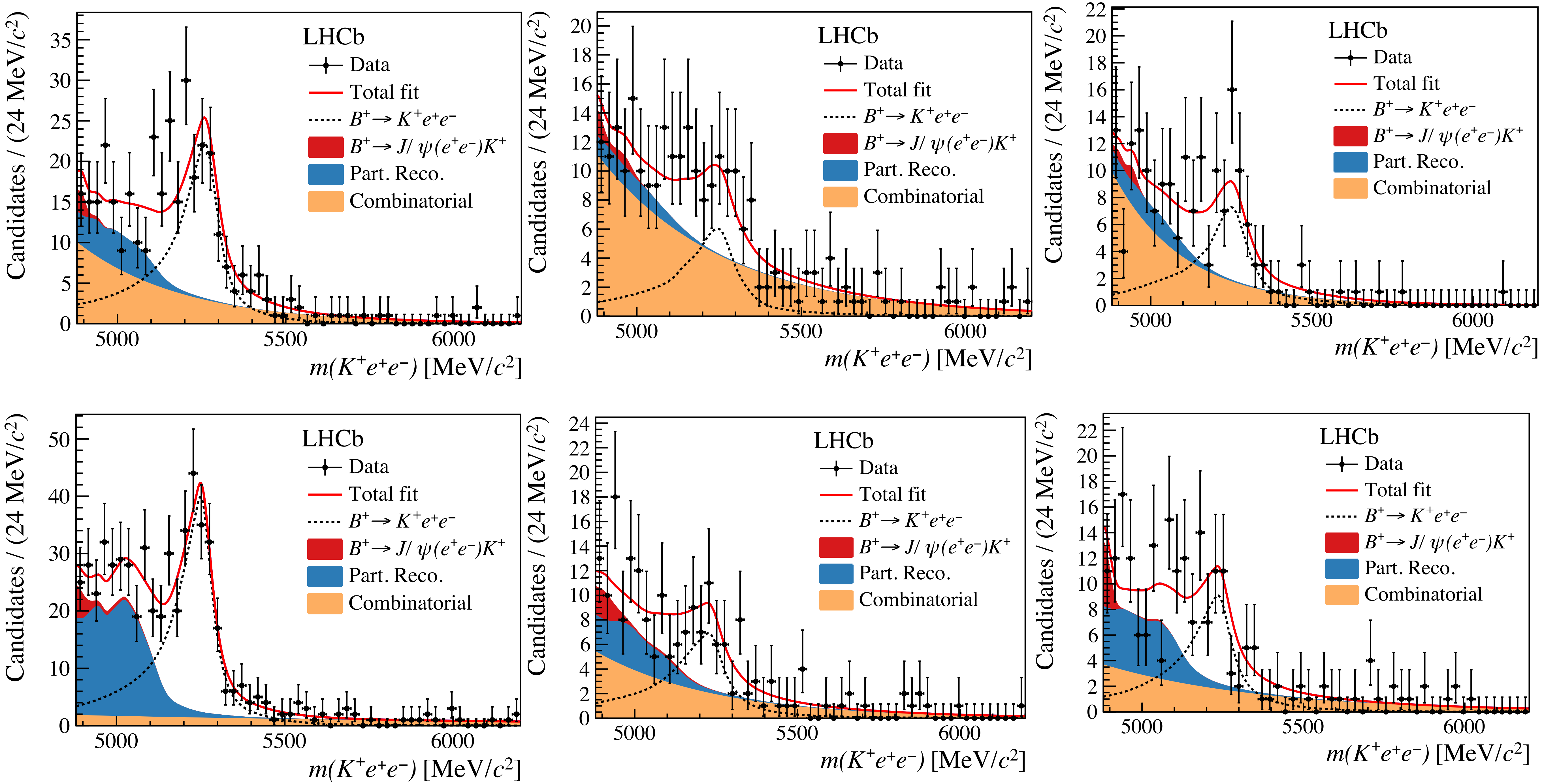




Test of LFU: R_K

- Mass projections: electrons R1 and R2, three trigger categories:

electron trigger | **kaon trigger** | **other tracks**



Test of LFU: R_K

- Run1 and Run2 compatible at 1.9σ

$$R_K^{7\text{ and }8\,\text{TeV}} = 0.717\,{}^{+0.083}_{-0.071}\,{}^{+0.017}_{-0.016}\,,$$
$$R_K^{13\,\text{TeV}} = 0.928\,{}^{+0.089}_{-0.076}\,{}^{+0.020}_{-0.017}\,,$$

- Run1 result in a good agreement with the previous analysis [PRL113 (2014) 151601]

$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst}).$$ **(old Run1)**