$b \to s l^+ l^-$ LFU measurements at LHCb

10th International Workshop on the CKM Unitarity Triangle

Heidelberg, 20 September 2018

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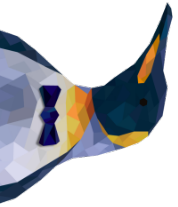
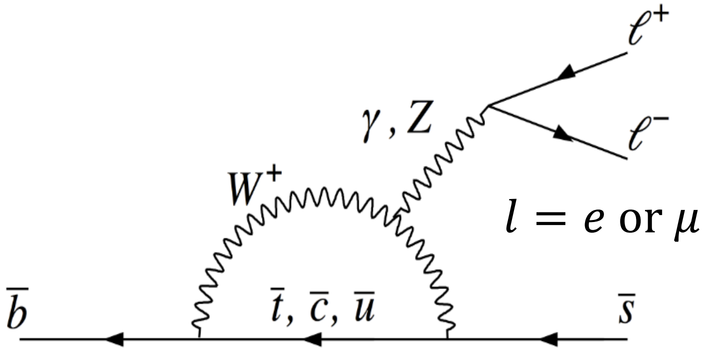
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

LHCb

What is LFU?

- **L**epton **F**lavor **U**niversality: couplings of electroweak bosons to different leptons are independent of their flavor.
  - The only difference can emerge from the lepton masses.
- LFU tested up to a percent precision in $Z \rightarrow l^+l^-, J/\psi \rightarrow l^+l^-$ decays, etc. [PRD **98**, 030001 (2018)]
- **What keeps us awake at night: LFU tests in B decays**
- There are two areas of recent interest:
  - Charged LFU ($b \rightarrow cl^-\overline{\nu_l}$): see previous talk by Adam
  - **Neutral LFU ($b \rightarrow sl^+l^-$): now**
    - **FCNC, loop only in the SM**





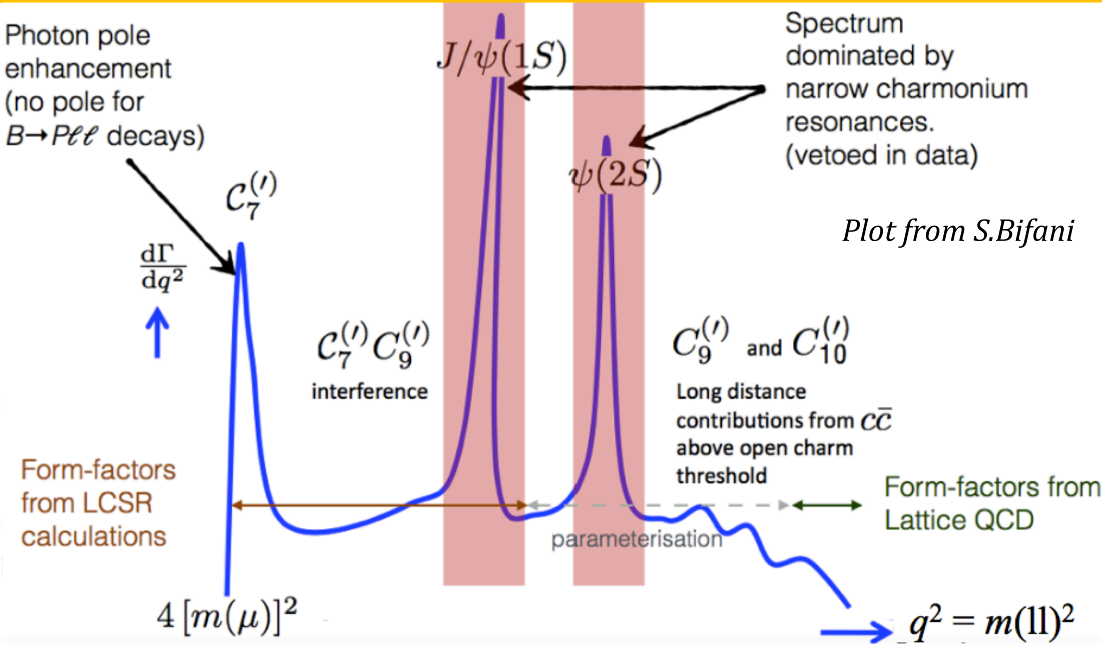
Focus on the experimental aspects, see theory talks for proposed models

Why rare decays?

- If New Physics is there, its effects are most probably tiny
- **Rare decays $b \to sl^+l^-$: $BR \sim 10^{-8} \ldots 10^{-6}$**
  - e.g. $BR(B^+ \to K^+l^+l^-) = (4.51 \pm 0.23) \cdot 10^{-7}$ [PDG average PRD **98**, 030001 (2018)]
- How many events do we expect?
  - $\sigma_{b\bar{b}} \approx 72\mu b$ at 7 TeV [PRL 118, 052002 (2017)], twice more at 13 TeV
  - **Luminosity**: 3 fb^{-1} in Run I → $\sim 2.6 \cdot 10^{11}$ $b\bar{b}$ pairs produced
  - **Hadronisation fraction**: $f_{u,d} \approx 0.4$, $f_s \approx 0.1$, $f_{\Lambda_b} \approx 0.08$ [Eur. Phys. J. C77 (2017) 895]
  - So, we have ~ 47000 $B^+ \to K^+l^+l^-$ decays happened in the LHCb acceptance
- But: trigger, reconstruction, offline selection
  - → O(200) $B^+ \to K^+e^+e^-$ and O(1200) $B^+ \to K^+\mu^+\mu^-$ events

So, how do we test LFU?

- $R_X[q^2_{min}, q^2_{max}] = \dfrac{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B\to X\mu^+\mu^-)}{dq^2}}{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B\to Xe^+e^-)}{dq^2}}$
- in certain ranges of $q^2 = m^2(l^+l^-)$
    - Avoid contamination from resonances
    - Avoid getting close to the mass threshold



Plot from S.Bifani

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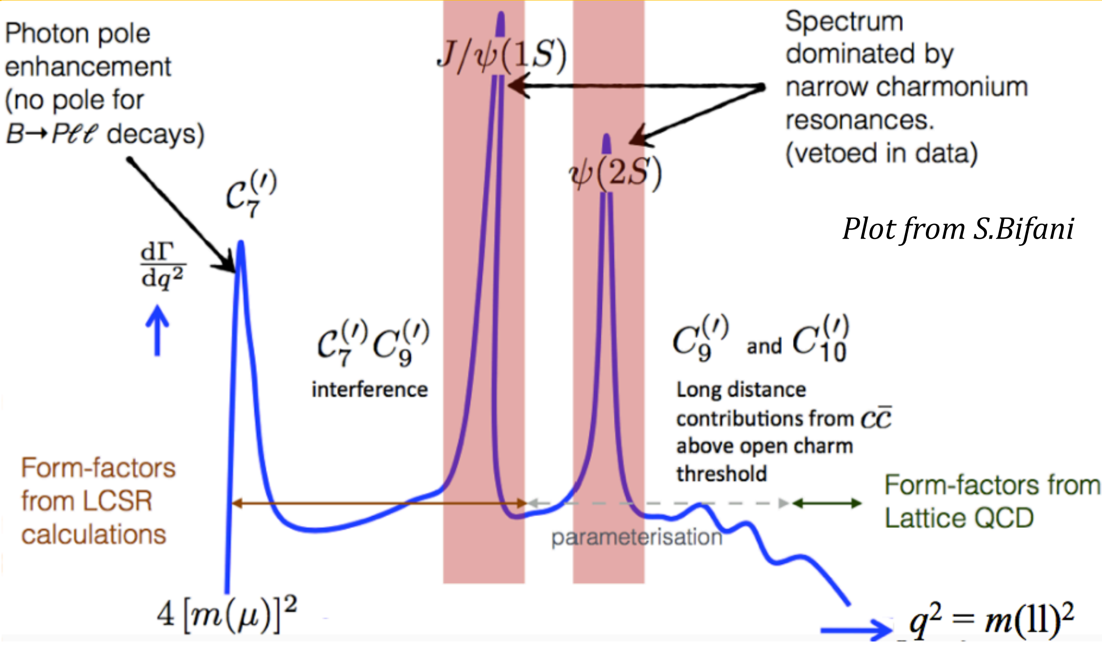

- The blue part is what we *want* to measure, red part should be exactly one
  - Cancellation of efficiencies and systematic uncertainties (electron tracking, trigger *etc.*)

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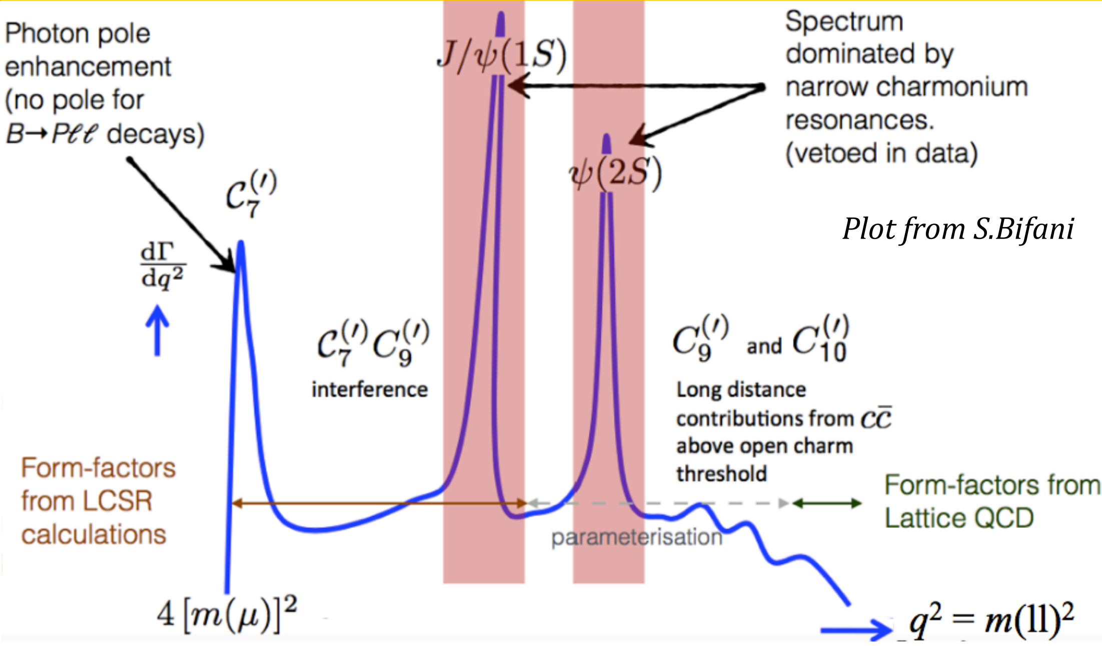
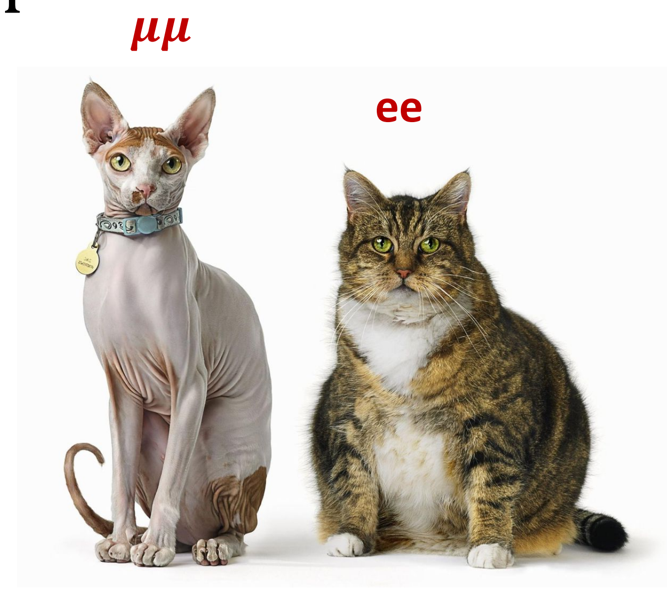


Plot from S.Bifani

- What we *really* measure is the number of events (N)
- $R_X = \frac{N(B\to X\mu^+\mu^-)}{\varepsilon(B\to X\mu^+\mu^-)} * \frac{\varepsilon(B\to XJ/\psi(\mu^+\mu^-))}{N(B\to XJ/\psi(\mu^+\mu^-))} * \frac{N(B\to XJ/\psi(e^+e^-))}{\varepsilon(B\to XJ/\psi(e^+e^-))} * \frac{\varepsilon(B\to Xe^+e^-)}{N(B\to Xe^+e^-)}$
  - Efficiencies (ε) are taken from the simulation

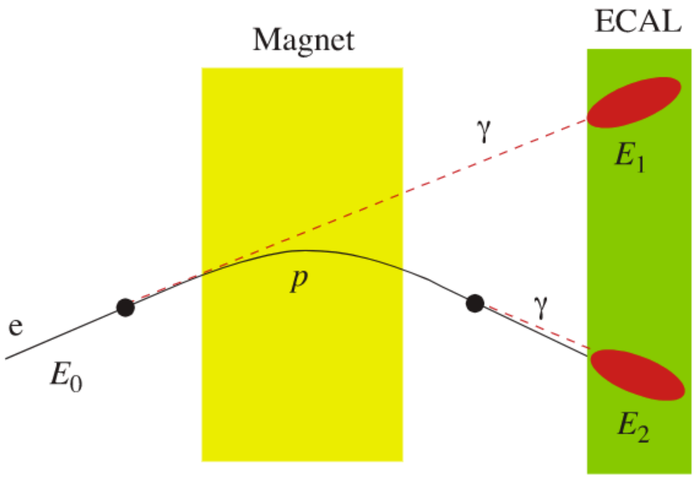
Main complications

- Electrons and muons have very different signatures in our detector
  - Bremsstrahlung
  - Trigger
  - Resolution
  - Tracking
  - Bin migration
- Backgrounds:
  - Combinatorial
  - Misidentifications
  - Partially reconstructed
  - ...
- Validation of simulation using real data

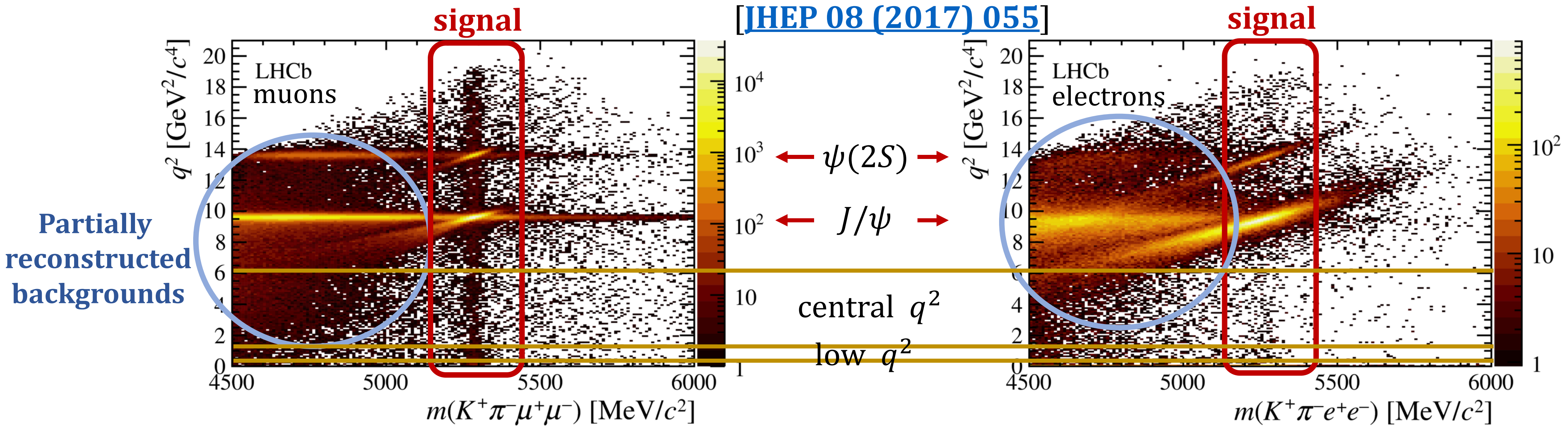


Electrons vs muons: bremsstrahlung

- Electrons emit bremsstrahlung photons when cross the material
- Match electron tracks to photon clusters in the ECAL
  - Correct electron momenta by "attaching" photons
  - 3 categories of events: 0, 1, >1 photons attached to dielectron pair
  - Different invariant mass shapes due to under- or over-correcting
- ECAL resolution is worse than tracker
- Bin migration included in systematics

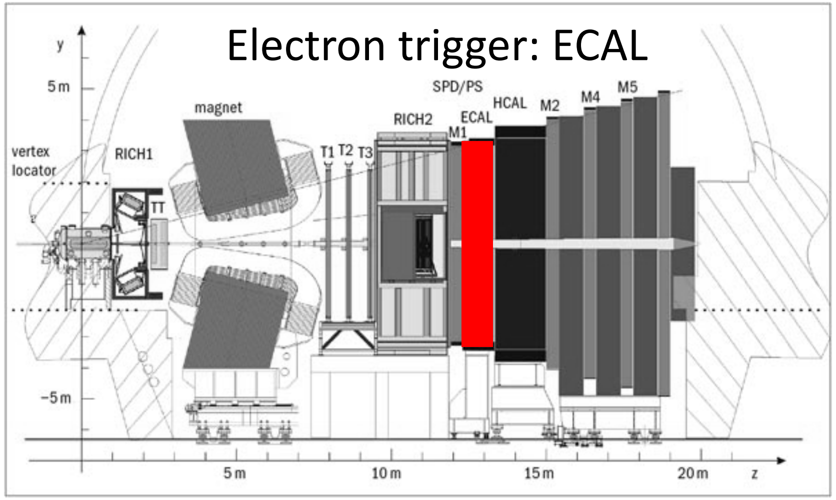


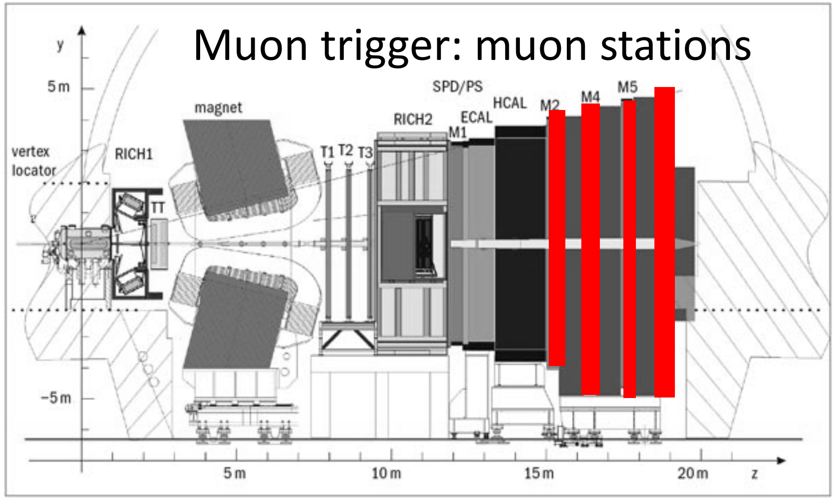
[JHEP 08 (2017) 055]

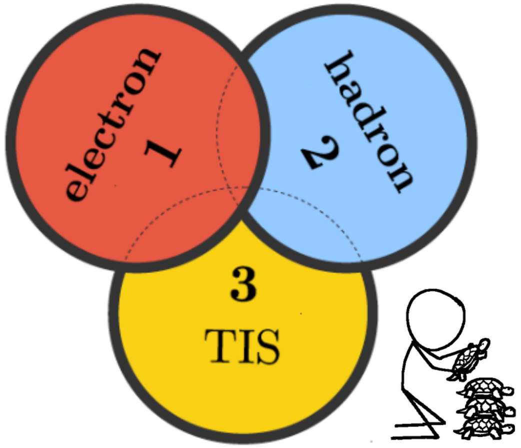


Electrons vs muons: trigger

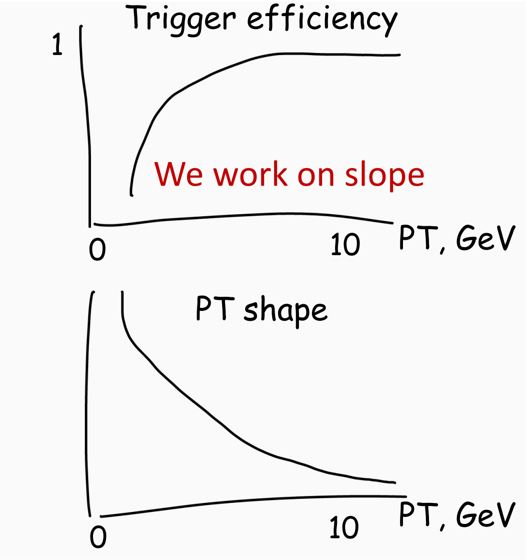
- Trigger on e and μ is done in a different way:





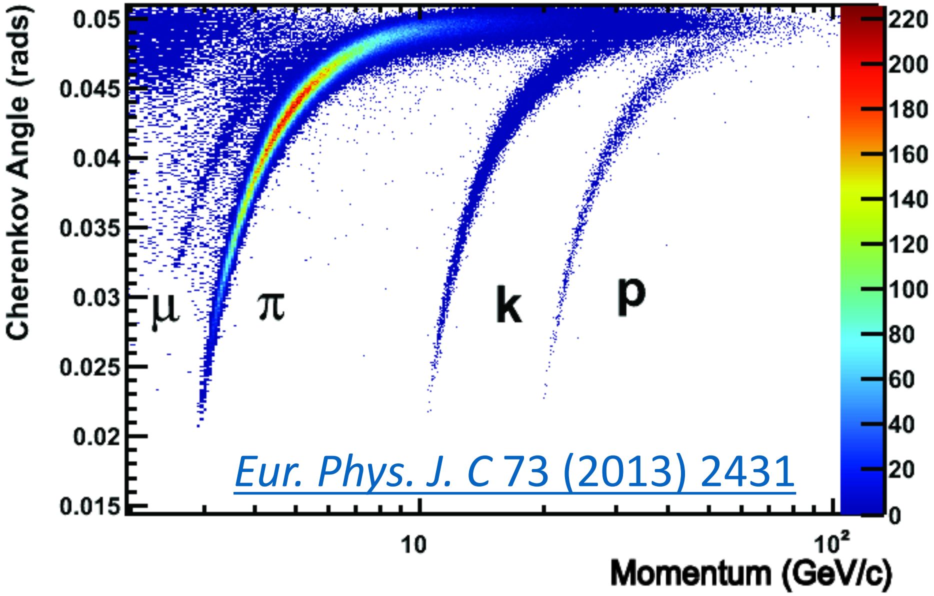


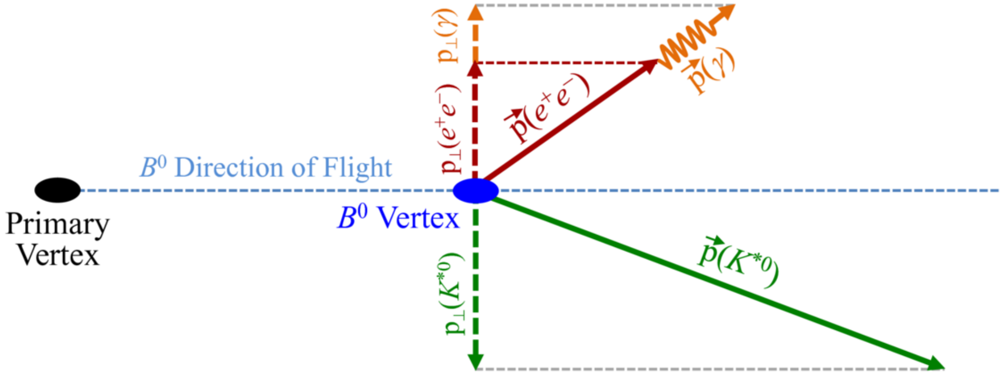
- ECAL is very busy: plenty of photons (incl. from π^0s)
  - High thresholds (E_T~3GeV) → lower statistics
- But: can trigger on **hadron**, or the **rest of event**
  - Add "Hadron" and "TIS" trigger categories to electron sample
- Need a strong control of trigger efficiencies
  - Use data-driven techniques



Backgrounds

- **Misidentifications:** exploit LHCb's PID system
  - PID efficiencies measured using high-purity calibration samples
  - Tag & probe technique
- **Partially reconstructed backgrounds:**
  - In particular, semileptonic decays having same *visible* final state
  - Or from excited states of final state hadrons…
  - Usually located below the signal peak so of less concern for muon mode
  - Use the momentum balance for electron mode to reduce the background
- **Combinatorial background**: train an MVA against it



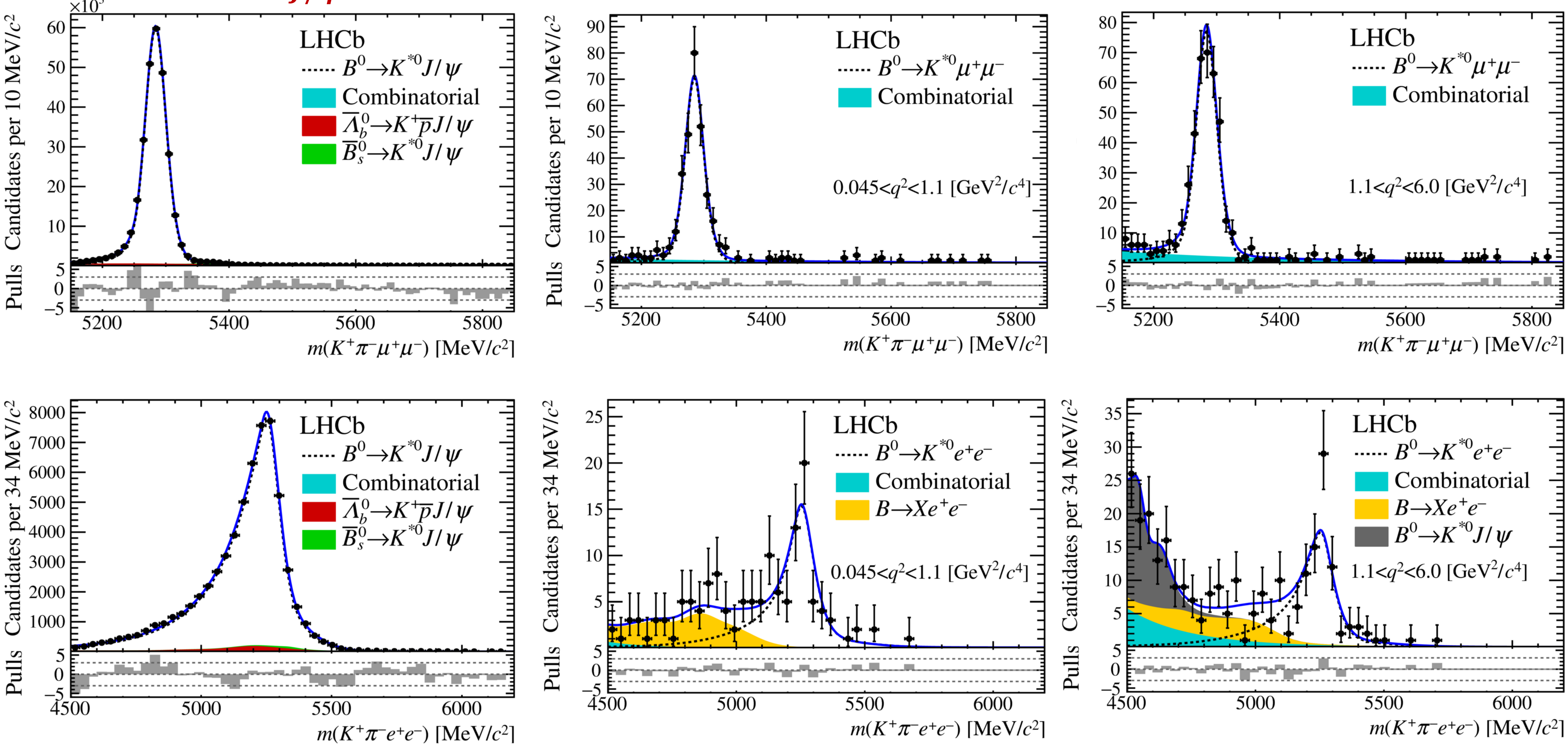


Fits: R_{K^*}

[JHEP 08 (2017) 055]

NORMALIZATION MODE $B^0 \to J/\psi K^{*0}$ | **LOW q^2** | **CENTRAL q^2**

MUON MODES / **ELECTRON MODES**



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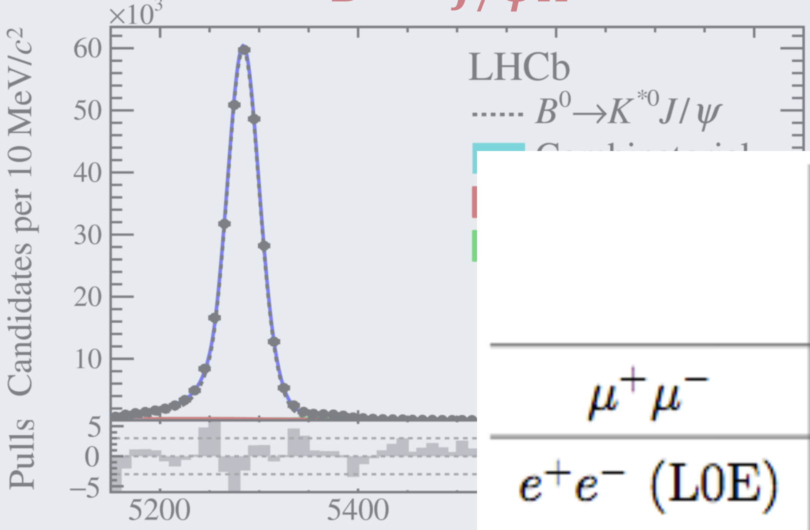
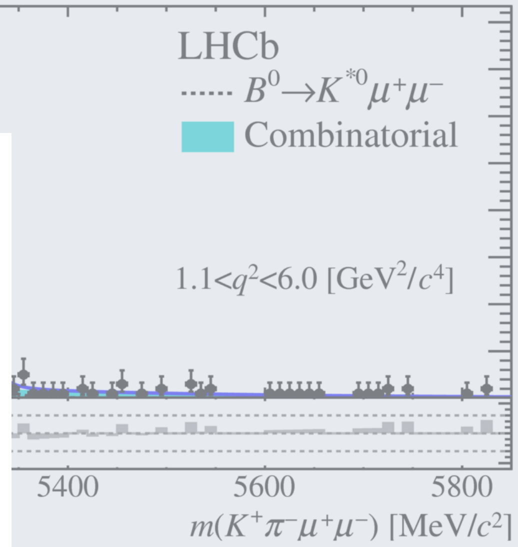
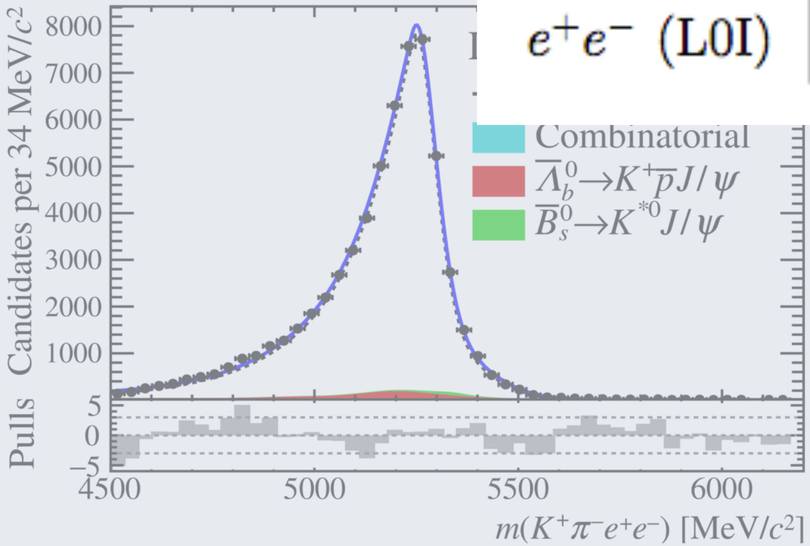


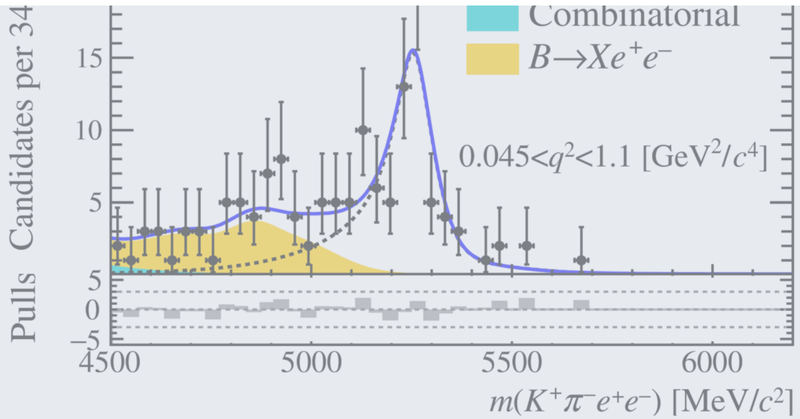


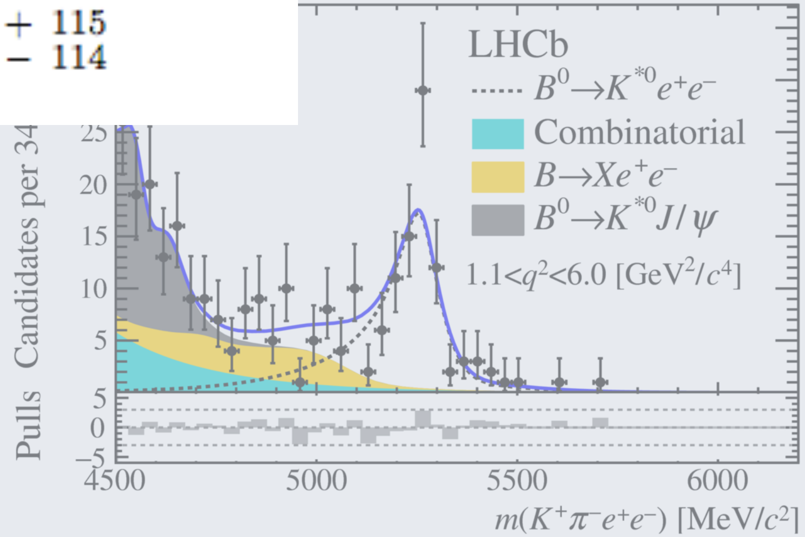
Rare decays | Normalization mode

	$B^0 \to K^{*0}\ell^+\ell^-$		$B^0 \to K^{*0} J/\psi (\to \ell^+\ell^-)$
	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)	$21\ ^{+\ 5}_{-\ 4}$	$25\ ^{+\ 7}_{-\ 6}$	$11505\ ^{+\ 115}_{-\ 114}$

ELECTRON MODES







Cross-checks

- Before testing the LFU in rare decays, could we confirm LFU in the decays precisely measured in the past?
- $R_{K^*} = \frac{N(B\to K^*\mu^+\mu^-)}{\varepsilon(B\to K^*\mu^+\mu^-)} * \frac{\varepsilon(B\to K^* J/\psi(\mu^+\mu^-))}{N(B\to K^* J/\psi(\mu^+\mu^-))} * \frac{N(B\to K^* J/\psi(e^+e^-))}{\varepsilon(B\to K^* J/\psi(e^+e^-))} * \frac{\varepsilon(B\to K^* e^+e^-)}{N(B\to K^* e^+e^-)}$
  - Check that the red part is indeed compatible with unity!
  - $r_{J/\psi} = 1.043 \pm 0.006 \pm 0.045$
  - Very stringent test of absolute efficiency control
  - Check stability of this ratio as function of kinematics, geometry *etc*.
- Also in agreement with expectations:
  - Double ratio $R_{\psi(2S)}$ (replace $B \to K^* l^+ l^-$ by $B \to K^* \psi(2S)(l^+ l^-)$)
  - $BR(B \to K^* \mu^+ \mu^-)$
  - $r_\gamma = \frac{BR(B\to K^*\gamma)}{BR(B\to K^* J/\psi)}$ with photon conversions

Results (which you already know by heart)

- Two results published so far
  - Dominant uncertainty: $N(B \to Xe^+e^-)$
- R_{K^*} using $B^0 \to K^{*0}l^+l^-$ decays, Run I data
  - [JHEP 08 (2017) 055]
  - Two bins: $q^2 = 0.045 \ldots 1.1\ GeV^2$ and $1.1 \ldots 6\ GeV^2$
  - $R_{K^*}^{low} = 0.66^{+0.11}_{-0.07}(stat) \pm 0.03(syst)$
  - $R_{K^*}^{central} = 0.69^{+0.11}_{-0.07}(stat) \pm 0.05(syst)$
  - $\sim 2.2\sigma$ and $\sim 2.4\sigma$ deviations, respectively
- R_K using $B^+ \to K^+l^+l^-$ decays, Run I data
  - [Phys. Rev. Lett. 113, 151601 (2014)]
  - $q^2 = 1 \ldots 6\ GeV^2$
  - $R_K = 0.745^{+0.090}_{-0.074}(stat) \pm 0.036(syst)$
  - $\sim 2.6\sigma$ deviation from unity

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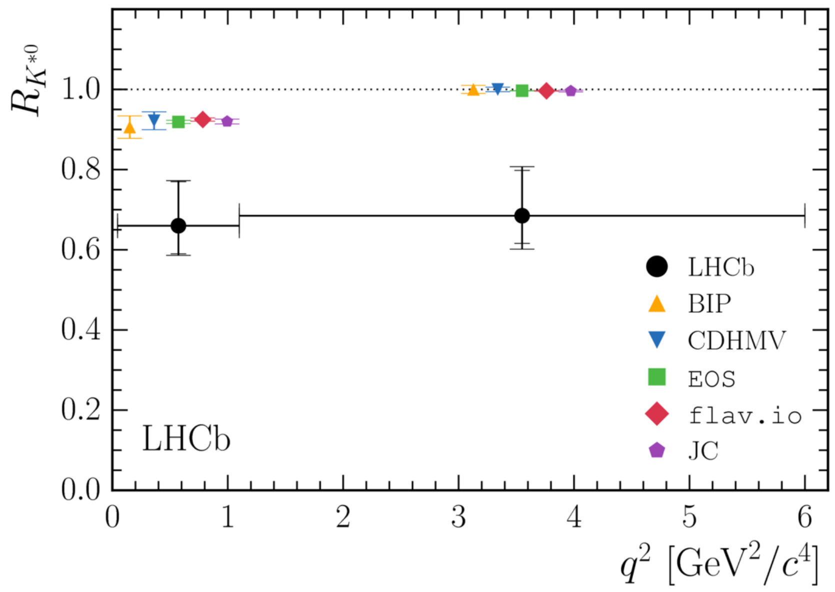
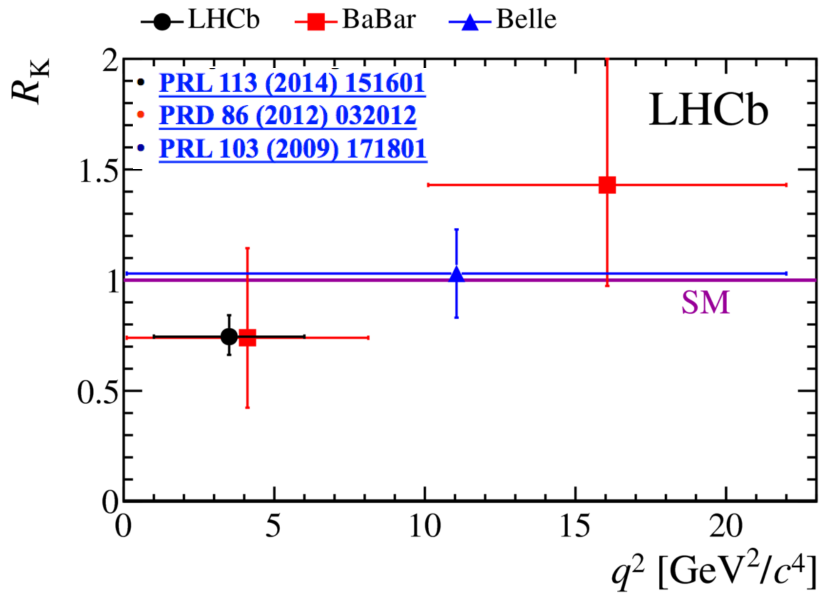
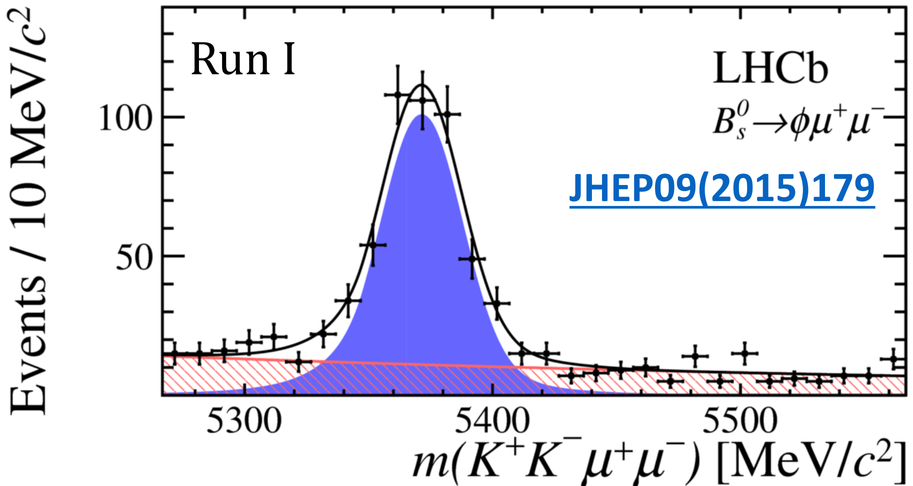
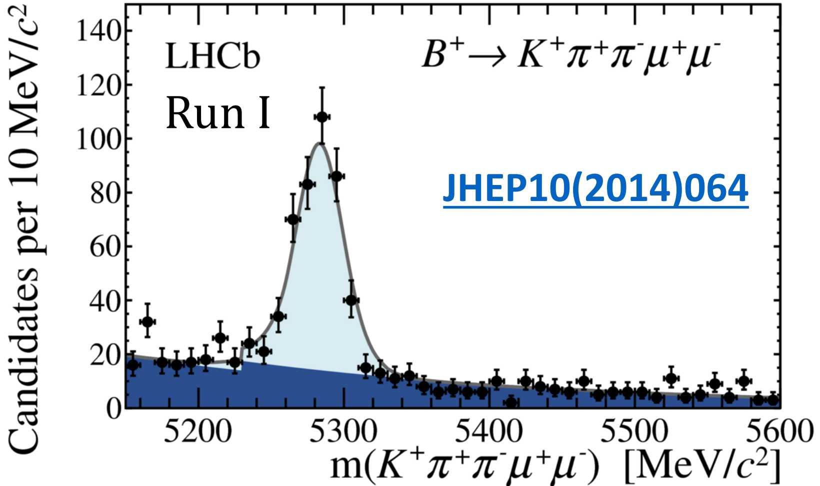




What's coming next?

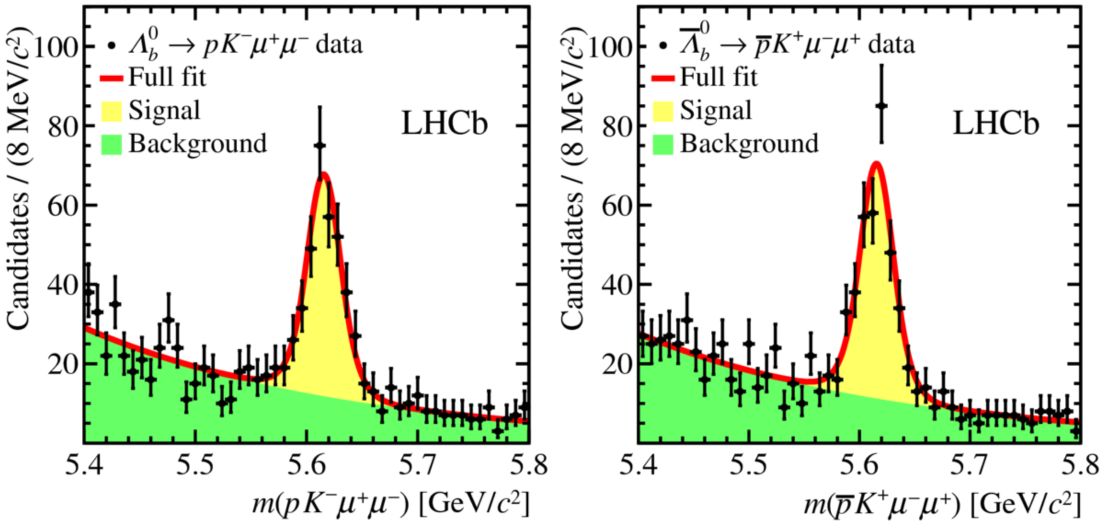
- Update of the R_K measurement with 2011… 2016 data [now in review]
  - Run I sample: improved electron reconstruction; updated strategy
  - Run II sample: lower electron trigger thresholds, so larger electron statistics
  - Many cross-checks currently ongoing
- Update of the R_{K^*} with 2011… 2016 data also in the pipeline
- Many various other R_X analyses ongoing
  - So far, all the LFU tests were performed with B mesons only
  - LHCb has also collected large samples of B_s^0 mesons and Λ_b^0 baryons

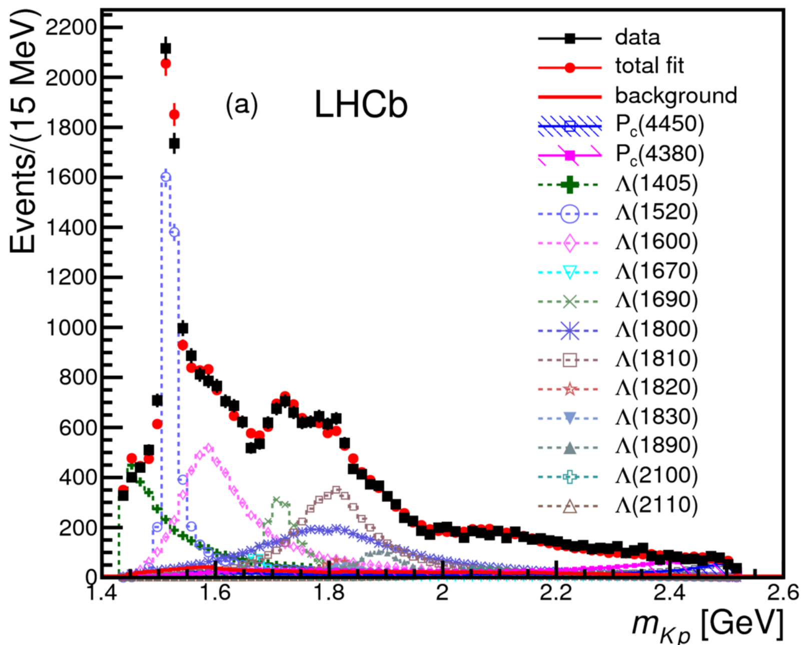




LFU with baryons?

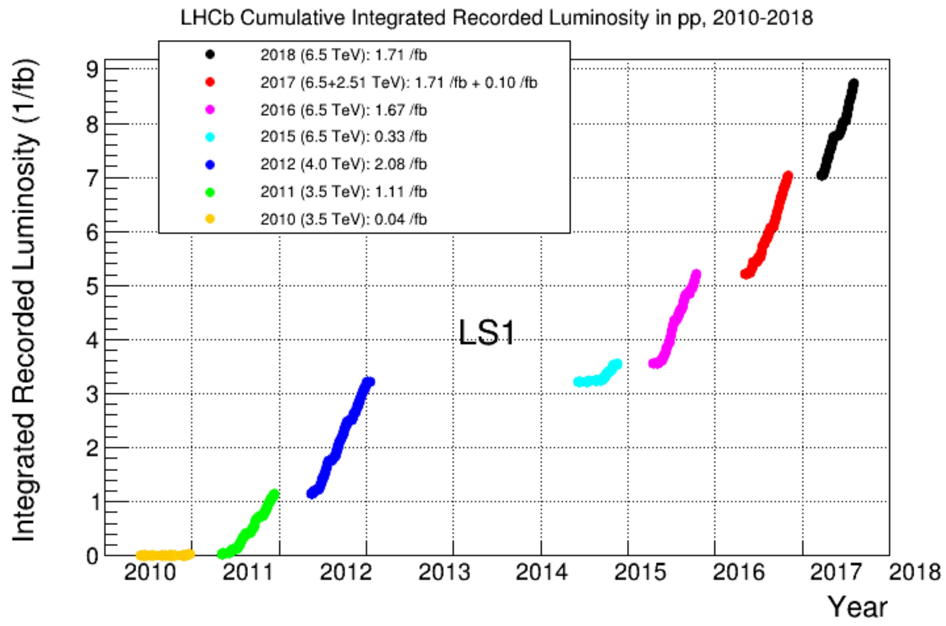
- One of ideas is the first LFU test with *b*-baryons
  - Different spin structure and phase space, possible surprises?
  - Do we see a deviation from unity also in baryonic mode?
- $R_{pK} = \frac{BR(\Lambda_b^0 \to pK\mu^+\mu^-)}{BR(\Lambda_b^0 \to pKe^+e^-)} \cdot \frac{BR(\Lambda_b^0 \to pKJ/\psi(e^+e^-))}{BR(\Lambda_b^0 \to pKJ/\psi(\mu^+\mu^-))}$
- Why this final state: easier experimentally than long-lived Λ
  - Develop a pilot analysis on higher-statistics inclusive mode, then catch up with others (also ongoing)
- Complication is the pK spectrum: e.g. $\Lambda_b^0 \to pKJ/\psi$ [PRL 115, 072001 (2015)]
  - How fair is to say the SM prediction for R_{pK} (with that complex resonant content) is equal to 1?
- $\Lambda_b^0 \to pK\mu^+\mu^-$ was observed [JHEP 06 (2017) 108]

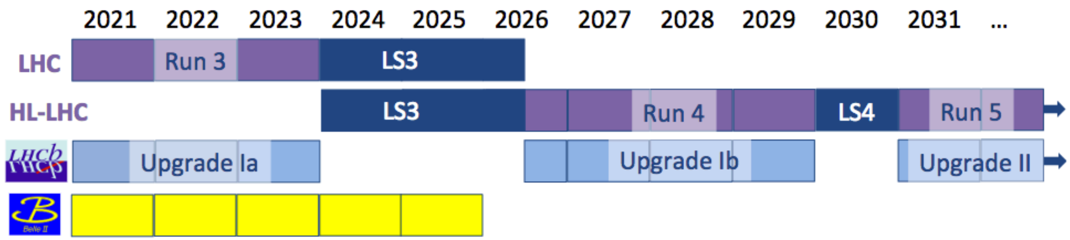




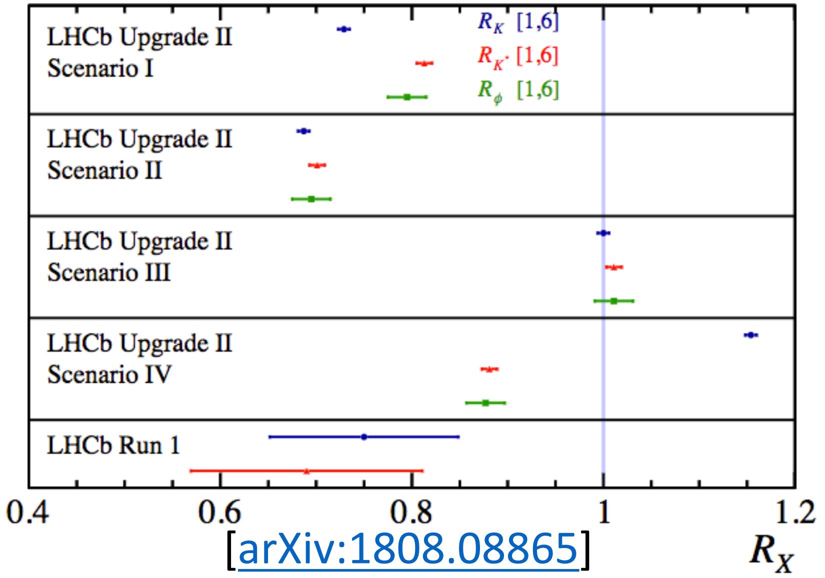
Longer-term prospects

- We are collecting data right now!
  - On track for about 9.5 fb^{-1} in Run I+II
  - To be analyzed during the LS2
- LHCb Upgrades are coming [arXiv:1808.08865]
  - Plan to collect up to 50 fb^{-1} until 2030
  - Proposal to reach 300 fb^{-1} until 2037
  - Exciting prospects for precision measurements
  - LFU tests with $b \to d l^+ l^-$ will be possible





Distinguish between NP scenarios



[arXiv:1808.08865]

Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to K^+ e^+ e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0} e^+ e^-$	111 ± 14 [275]	490	1 400	3 300	20 000
$B^0_s \to \phi e^+ e^-$	–	80	230	530	3 300
$\Lambda^0_b \to pK e^+ e^-$	–	120	360	820	5 000
$B^+ \to \pi^+ e^+ e^-$	–	20	70	150	900
R_X precision (stat.only)	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
R_K	$0.745 \pm 0.090 \pm 0.036$ [274]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [275]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

Conclusions

- Intriguing measurements by LHCb: hints of lepton non-universality?

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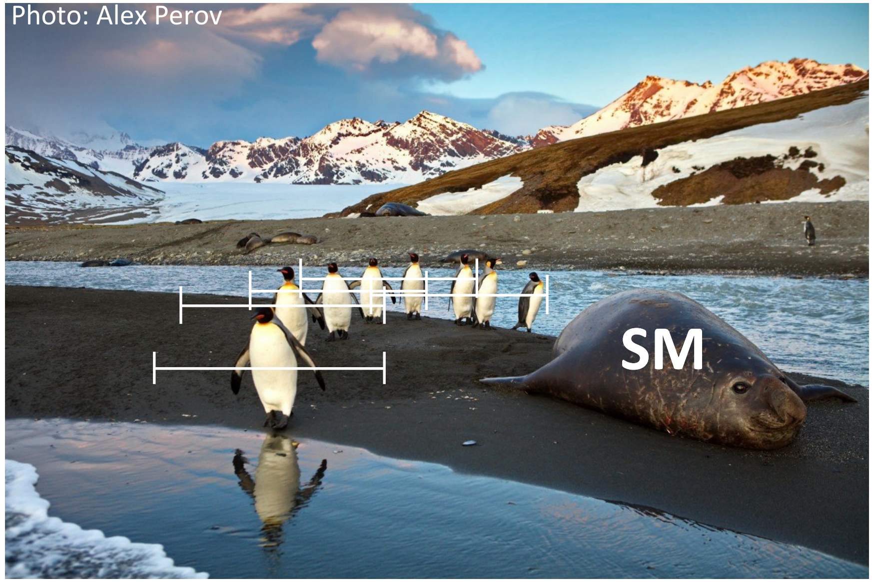


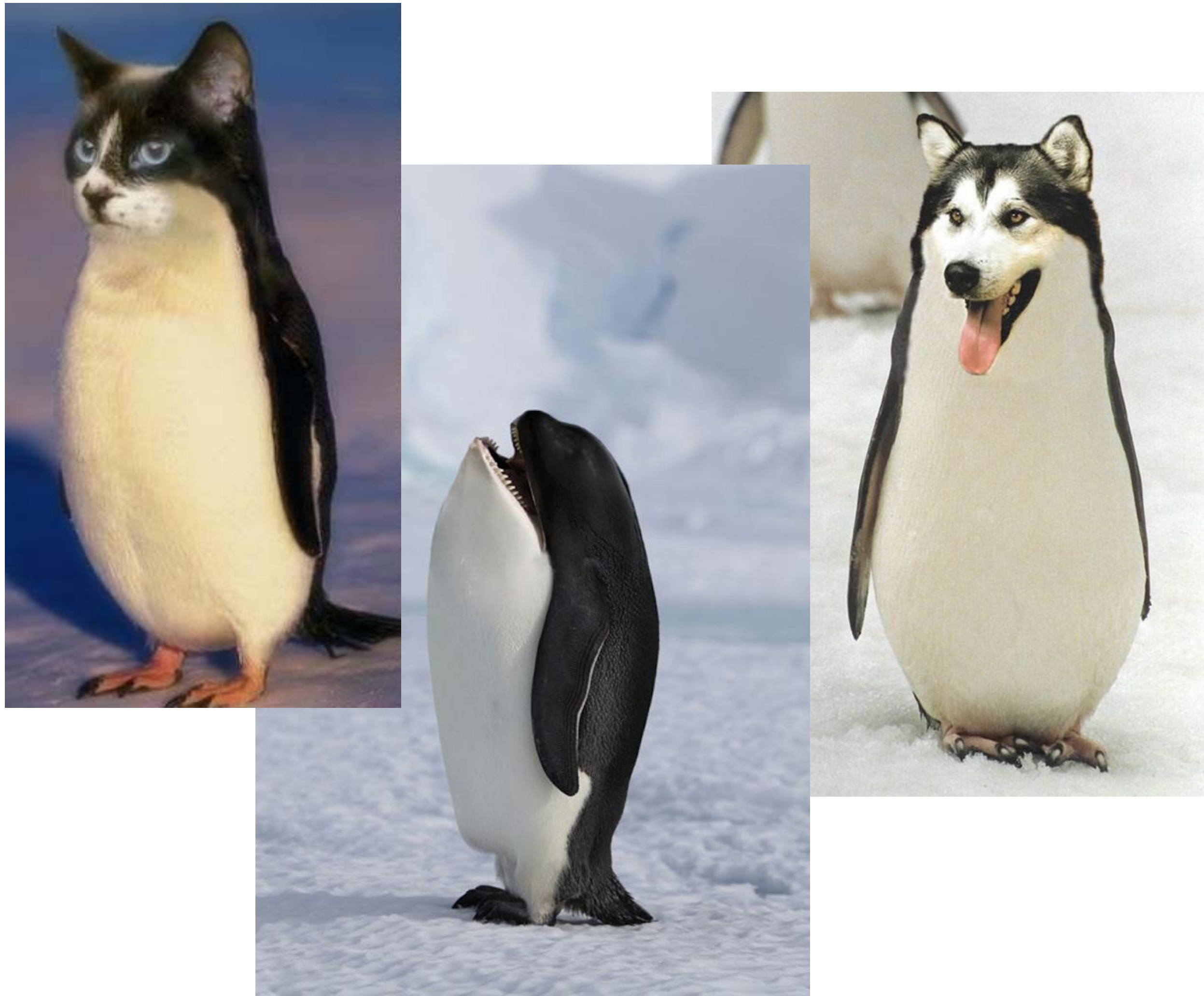
- New ideas & updated measurements are coming
- LHCb will become even more powerful soon!
- These related talks might be interesting:
  - *b -> sll results from LHCb* by Gabriela Pomery
  - *Experimental Status of B anomalies* by Tom Blake
  - *LVF and other very rare decay searches at LHCb* by Giulio Dujany
  - *LFU tests with semitauonic decays at LHCb* by Adam Morris

Stay tuned!

One day we will be able to distinguish between various species:

Standard Model penguins

New Physics



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