Electroweak penguin decays at LHCb
and tests of Lepton Flavor Universality

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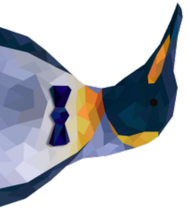
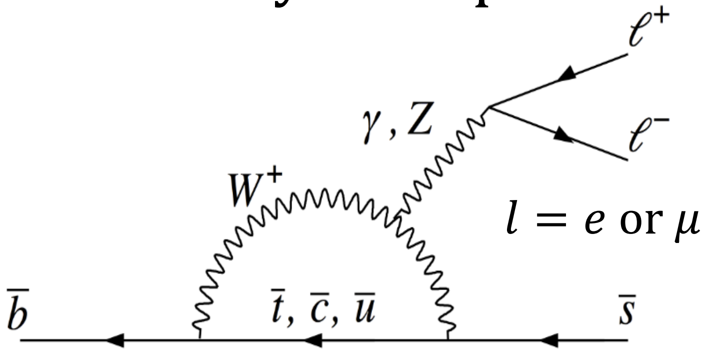
EPS-HEP, Ghent, 10-17 July 2019

Collage based on pictures from Wikimedia Commons

Why EWP decays?

- **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)]
- Flavor Changing Neutral Current: only at loop level in the SM





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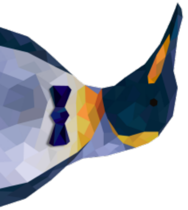
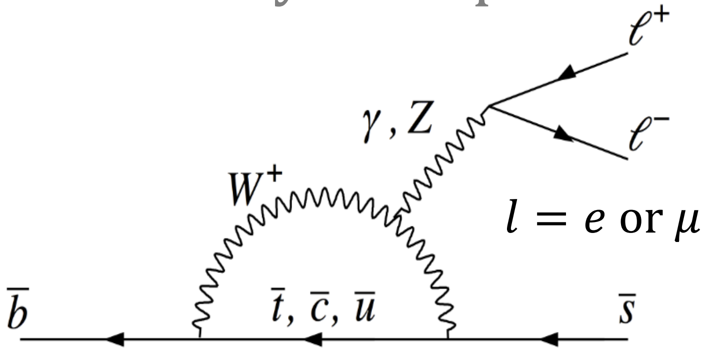




- If New Physics is there, its effects are most probably tiny
- How many events do we expect?
  - $\sigma_{b\bar{b}} \approx 72\mu b$ at 7 TeV [PRL 118, 052002 (2017)], twice more at 13 TeV
  - **Luminosity**: 3 fb^{-1} in Run 1 → $\sim 2.2 \cdot 10^{11}$ $b\bar{b}$ pairs produced
  - **Hadronisation fraction**: $f_{u,d} \approx 0.4$ [Eur. Phys. J. C77 (2017) 895]
  - So, we have $\sim 80000\ B^+ \to K^+l^+l^-$ 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 [**PRL113 (2014) 151601**]

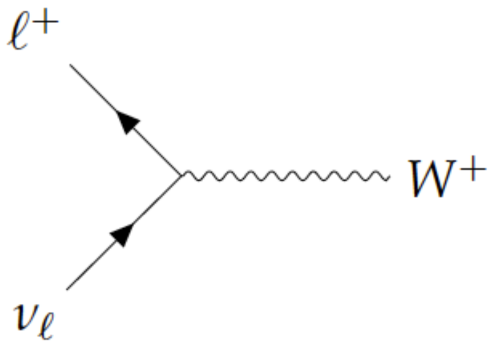
What can we measure?

- Observation of **new decay modes**
  - $\boldsymbol{b \to s l^+ l^-}$ transitions with $B, B_s, \Lambda_b, \ldots$ and various final states
  - CKM-suppressed $\boldsymbol{b \to d l^+ l^-}$ transitions
  - Charm and strange FCNC decays ($\boldsymbol{c \to u l^+ l^-, s \to d l^+ l^-}$)
- **Differential branching fractions**
- **Angular observables**

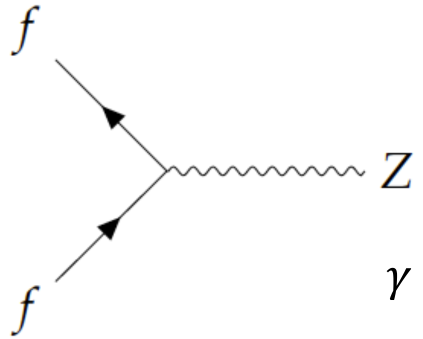
- **Tests of Lepton Flavor Universality**: are the rates of $\boldsymbol{b \to s e^+ e^-}$ and $\boldsymbol{b \to s \mu^+ \mu^-}$ the same?
  - This talk:
    Search for lepton-universality violation in $B^+ \to K^+ l^+ l^-$ decays: [Phys. Rev. Lett. 122 (2019) 191801]

What's up?

- **L**epton **F**lavor **U**niversality: couplings of electroweak bosons to different leptons (e, μ, τ) are independent of their flavor.
  - The only difference in decay rate can emerge from the **phase-space factor** (lepton masses).



$$-i\frac{g_W}{\sqrt{2}}\gamma_\mu P_L$$



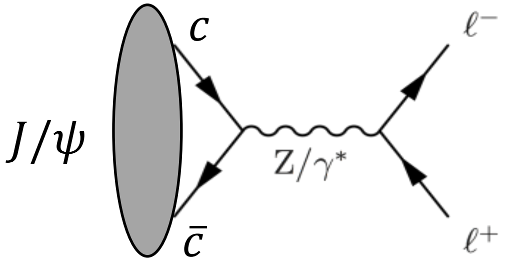
$$-i\frac{g_Z}{2}\gamma_\mu\left(\frac{1}{2}T_3 - Q\sin^2\theta_W - \frac{1}{2}T_3\gamma_5\right)$$

γ $\quad -iQe\gamma_\mu$

- LFU tested up to a sub-percent precision in $Z \to l^+l^-, J/\psi \to l^+l^-$ decays, etc. [PRD **98**, 030001 (2018)]

$$\frac{\Gamma_{Z\to\mu^+\mu^-}}{\Gamma_{Z\to e^+e^-}} = 1.0009 \pm 0.0028;$$

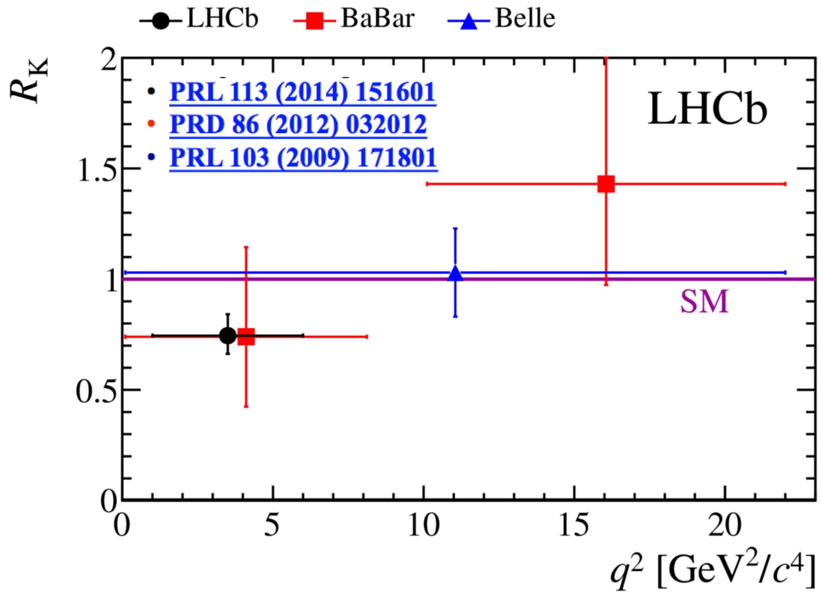
$$\frac{\Gamma_{Z\to\tau^+\tau^-}}{\Gamma_{Z\to e^+e^-}} = 1.0029 \pm 0.0032.$$

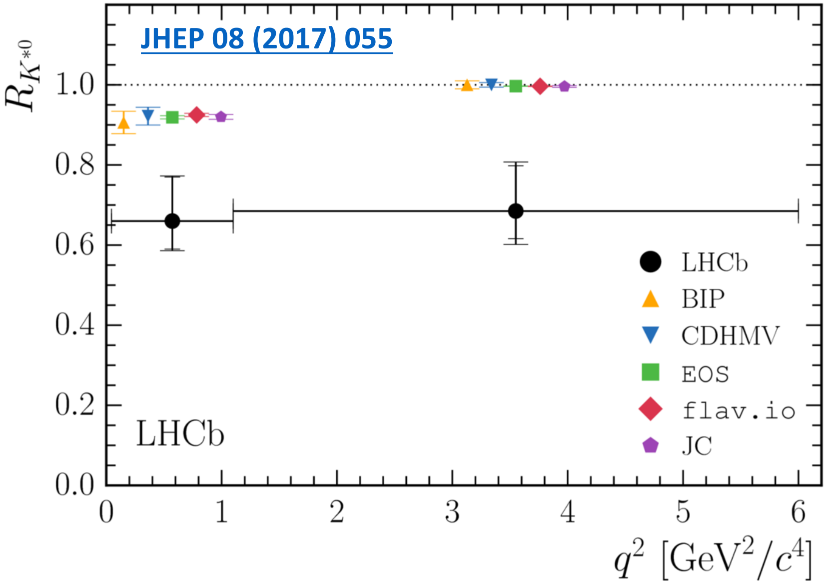


$$\frac{\Gamma_{J/\psi\to e^+e^-}}{\Gamma_{J/\psi\to\mu^+\mu^-}} = 1.0016 \pm 0.0031$$

What keeps us awake at night?

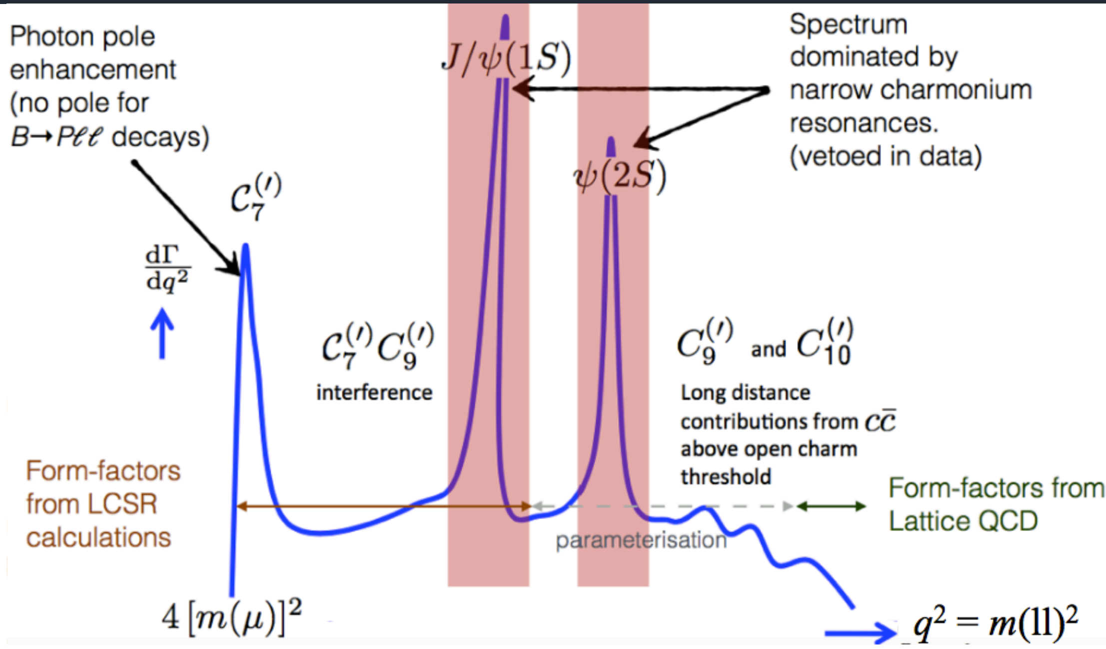
- Two results published by LHCb in the past
  - Dominant uncertainty: $N(B \rightarrow Xe^{+}e^{-})$
- R_K using $B^{+} \rightarrow K^{+}l^{+}l^{-}$ decays, Run I data
  - [Phys. Rev. Lett. 113, 151601 (2014)]
  - $q^2 = 1 \ldots 6\ GeV^2$
  - $R_K = 0.745^{+0.090}_{-0.074}(stat) \pm 0.036(syst)$
  - **$\sim 2.6\sigma$ deviation from unity**
- R_{K^*} using $B^{0} \rightarrow K^{*0}l^{+}l^{-}$ 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**





Hitchhiker's guide to LU tests

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



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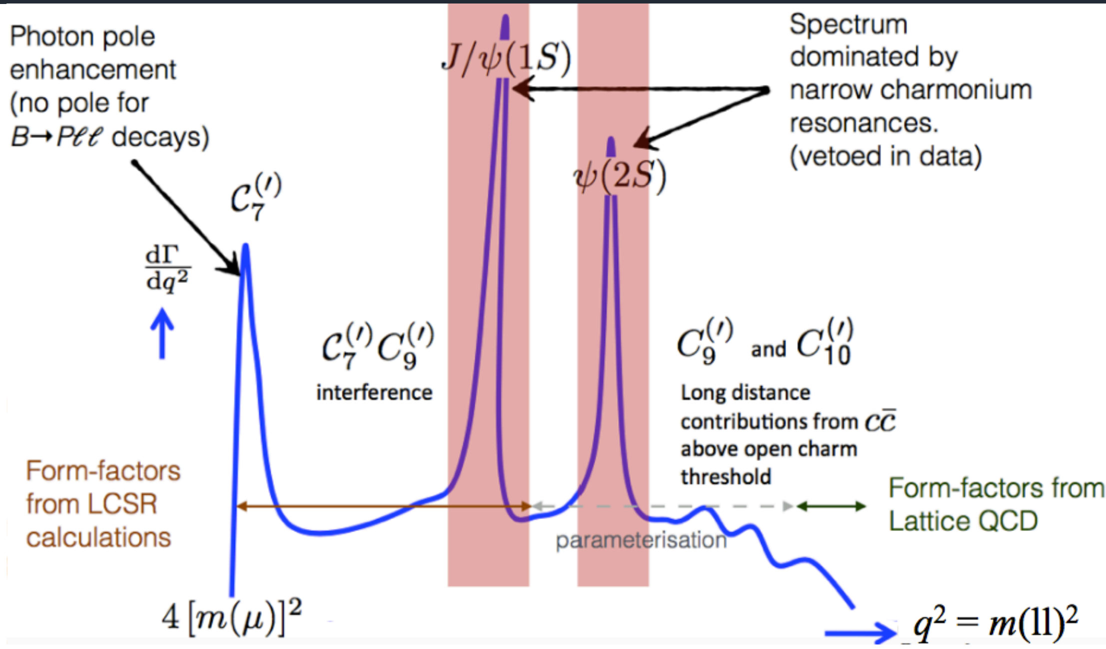
- *On practice: measure double ratio*
  - $R_K = \frac{BR(B\to K\mu^+\mu^-)}{BR(B\to Ke^+e^-)} \cdot \frac{BR(B\to KJ/\psi(e^+e^-))}{BR(B\to KJ/\psi(\mu^+\mu^-))}$
- The blue part is what we *want* to measure, red part should be exactly one
  - Cancellation of efficiencies and systematic uncertainties (electron tracking, trigger *etc.*)



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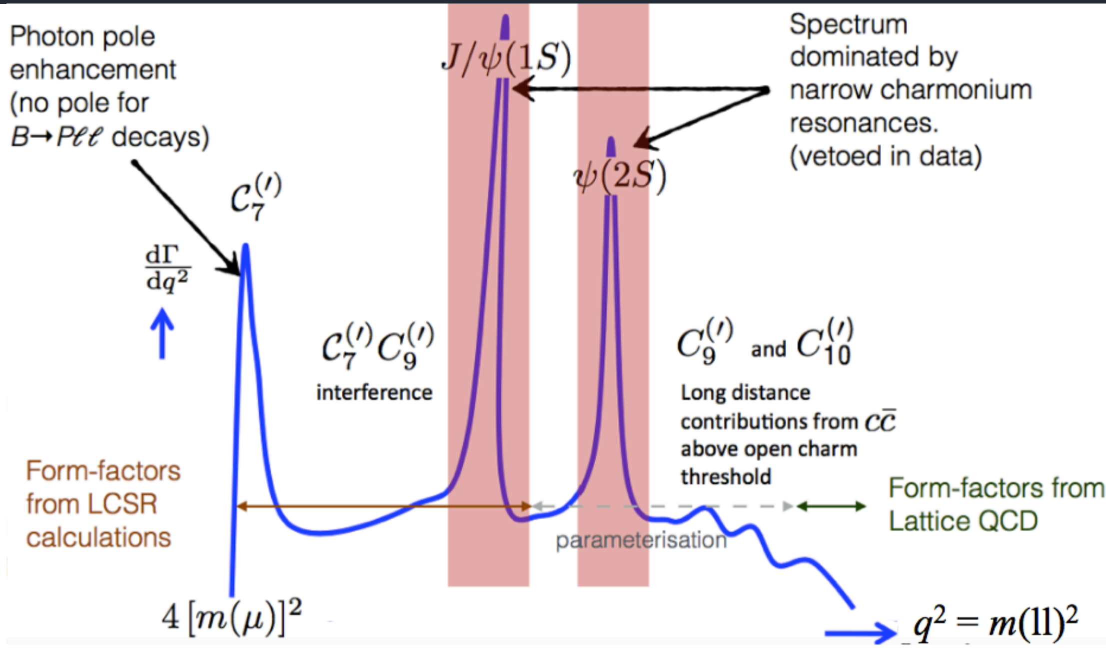


- The blue part is what we *want* to measure, red part should be exactly one
  - Cancellation of efficiencies and systematic uncertainties (electron tracking, trigger *etc.*)
- What we *really* measure is the number of events (N)
- $R_K = \frac{N(B\to K\mu^+\mu^-)}{\varepsilon(B\to K\mu^+\mu^-)} * \frac{\varepsilon(B\to KJ/\psi(\mu^+\mu^-))}{N(B\to KJ/\psi(\mu^+\mu^-))} * \frac{N(B\to KJ/\psi(e^+e^-))}{\varepsilon(B\to KJ/\psi(e^+e^-))} * \frac{\varepsilon(B\to Ke^+e^-)}{N(B\to Ke^+e^-)}$
  - Efficiencies (ε) are taken from the **simulation**

Do we control our efficiencies?

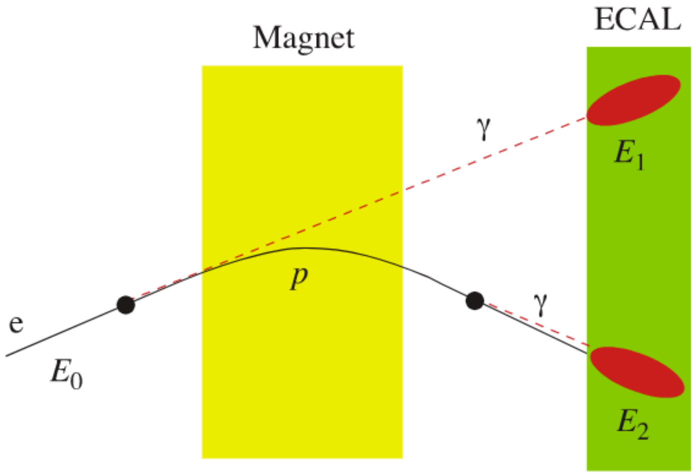
- A powerful cross-check:
- $r_{J/\psi} = \frac{N(B\to KJ/\psi(\mu^+\mu^-))}{\varepsilon(B\to KJ/\psi(\mu^+\mu^-))} * \frac{\varepsilon(B\to KJ/\psi(e^+e^-))}{N(B\to KJ/\psi(e^+e^-))}$
  - By definition, should be **equal to unity**
  - Should be **independent** of any kinematical / geometry variables
- This is a **stringent test of our control on signal efficiencies**
  - No cancellation of the leptonic part

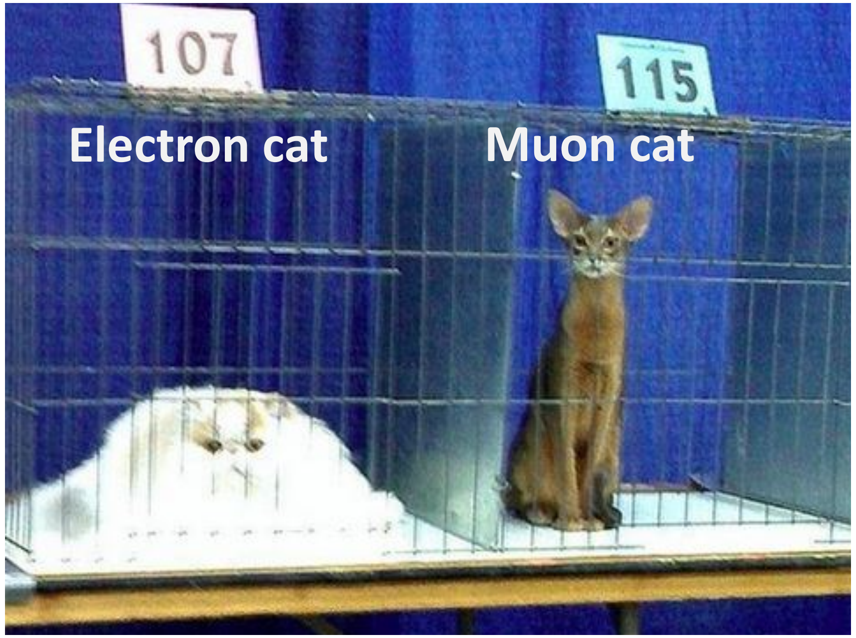
- Can also use $\psi(2S)$, but statistics is smaller
  - Test a double ratio:
  - $R_{\psi(2S)} = \frac{N(B\to K\psi(2S)(\mu^+\mu^-))}{\varepsilon(B\to K\psi(2S)(\mu^+\mu^-))} * \frac{\varepsilon(B\to KJ/\psi(\mu^+\mu^-))}{N(B\to KJ/\psi(\mu^+\mu^-))} * \frac{N(B\to KJ/\psi(e^+e^-))}{\varepsilon(B\to KJ/\psi(e^+e^-))} * \frac{\varepsilon(B\to K\psi(2S)(e^+e^-))}{N(B\to K\psi(2S)(e^+e^-))}$

Taming electrons

- Electrons emit **bremsstrahlung photons** when crossing the material
  - Emission before magnet is more dangerous
- We match electron tracks to photon clusters in the ECAL
  - Correct electron momenta by "attaching" photons
  - ECAL resolution is worse than tracking one

- The **resolution** for decay modes with electrons is much **worse** than for muonic modes
  - In addition, we get long bremsstrahlung tails

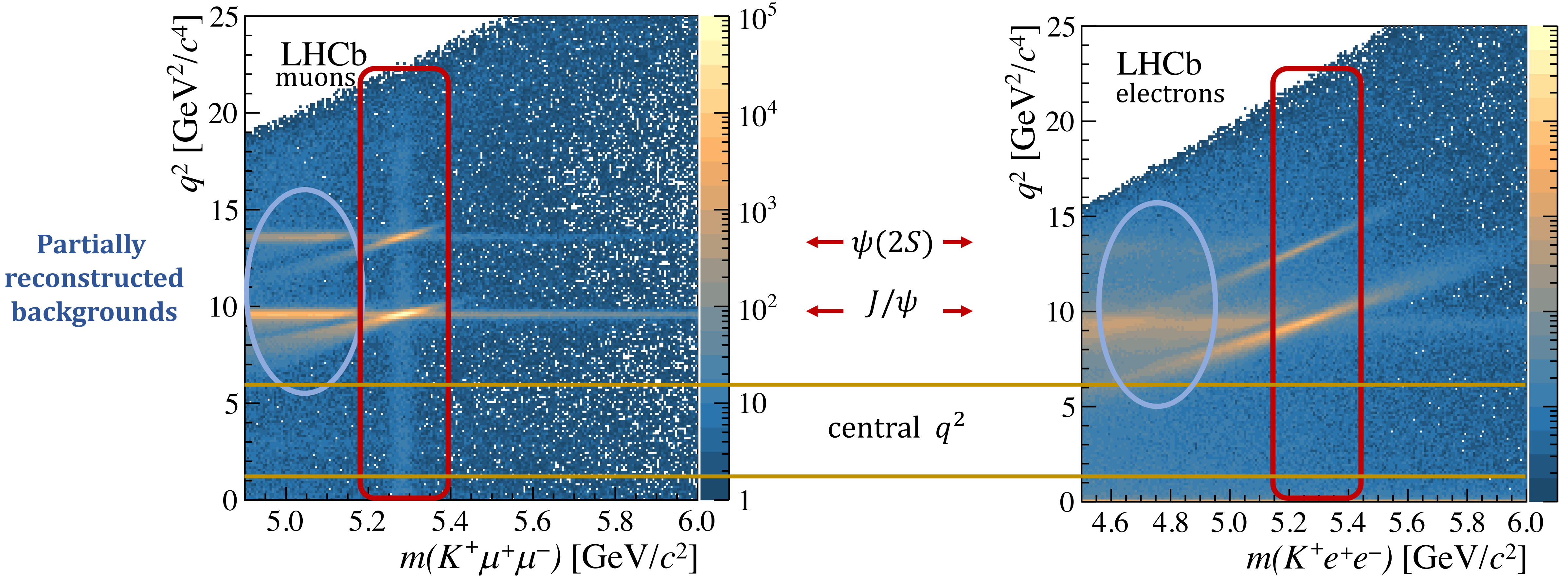




Taming electrons

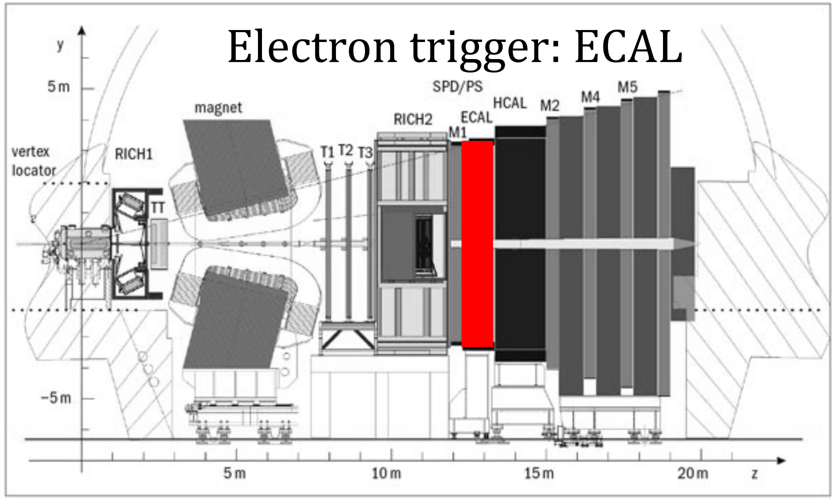
- 3 categories of events: 0, 1, >1 photons attached to a dielectron pair
  - Different invariant mass shapes due to under- or over-correcting
- Effect of resolution:

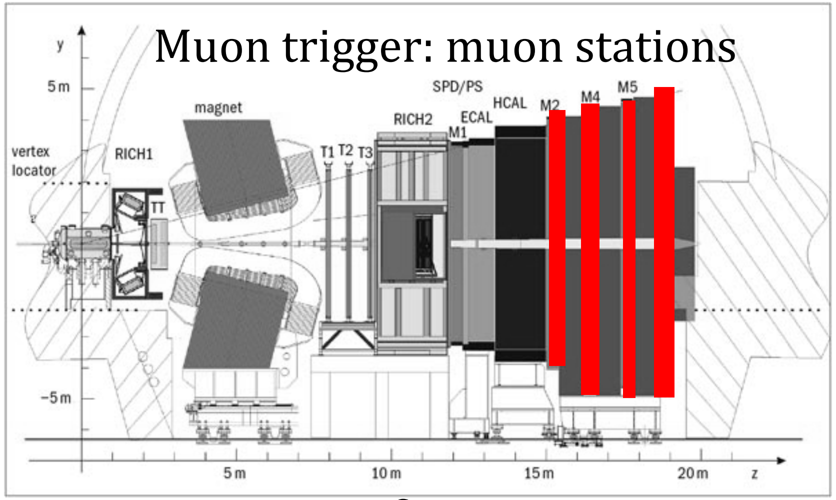
[PRL 122 (2019) 191801]



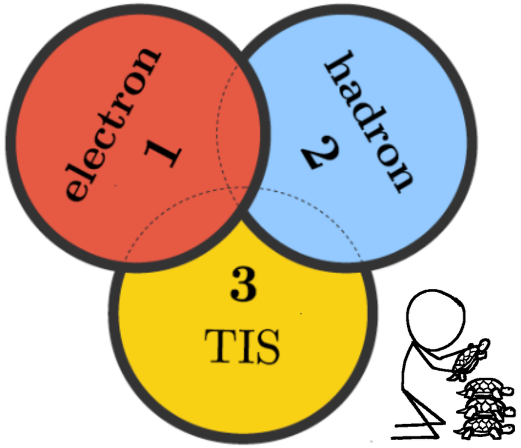
(Hardware) trigger

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



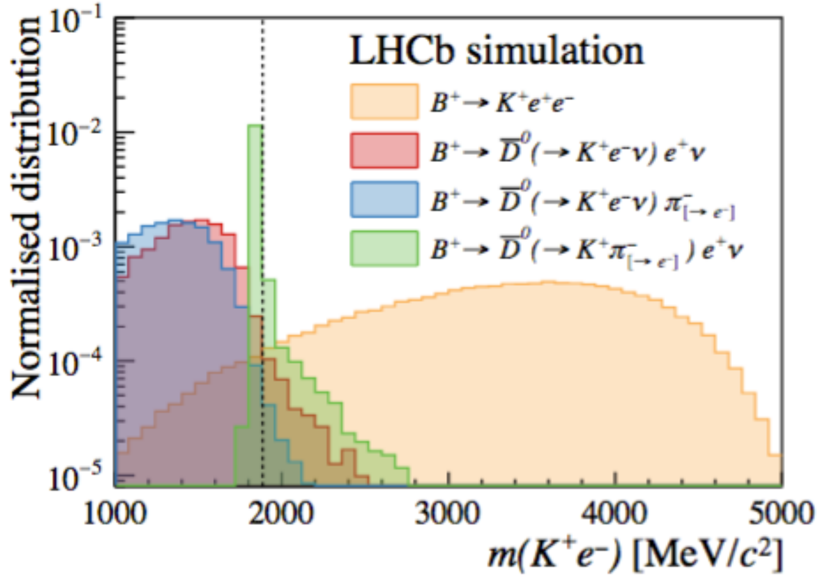


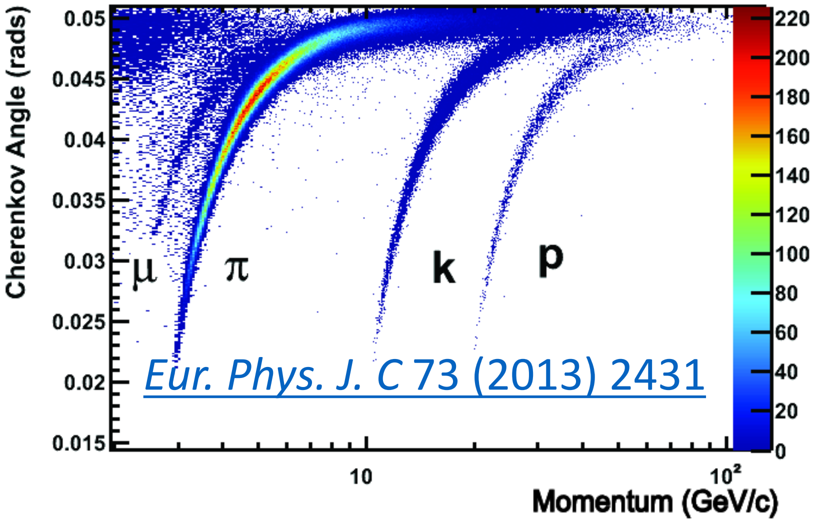
- ECAL is very busy: plenty of photons (incl. from π^0s)
  - High thresholds (E_T~3GeV) → lower statistics
- But: can trigger on the **hadron** part, or the **rest of event**
  - Add "hadron" and "TIS" trigger categories to electron sample
- Need a strong control of trigger efficiencies
  - Use data-driven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



Backgrounds

- Combinatorial: random track combinations
  - Reduced by a multivariate classifier
  - Separate for muons/electrons, trigger category, run period
- Partially reconstructed: $B \to K l^+ l^- X$
  - Semileptonic $B^+ \to D^0(K^+ l^- \overline{\nu_l}) l^+ \nu_l$: vetoed
  - Largest remaining: $B^0 \to K^{*0}(K^+ \pi^0) l^+ l^-$
- Misidentifications: exploit LHCb PID system
  - PID efficiencies measured using high-purity calibration samples
  - Tag & probe technique
- "Leakages" between q^2 regions (for electrons)





Eur. Phys. J. C 73 (2013) 2431

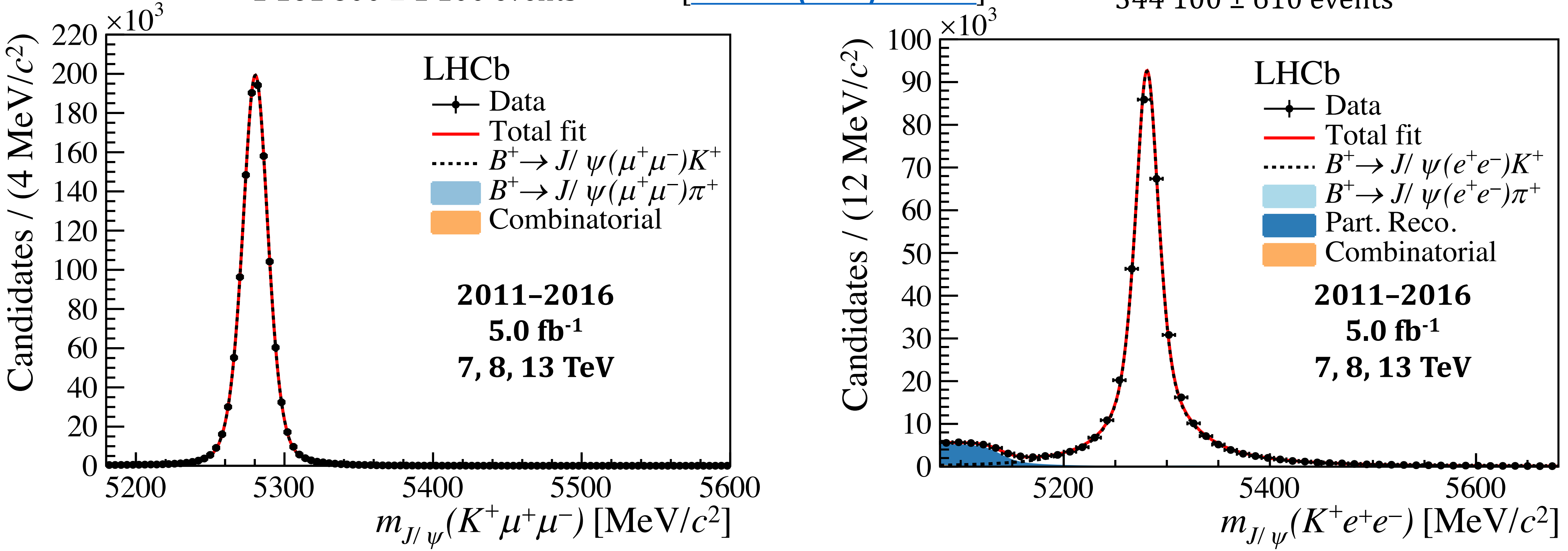
Counting the trees

- Exploit J/ψ mass constraint: improve the resolution
- Ratio ~3 between electron and muon yields

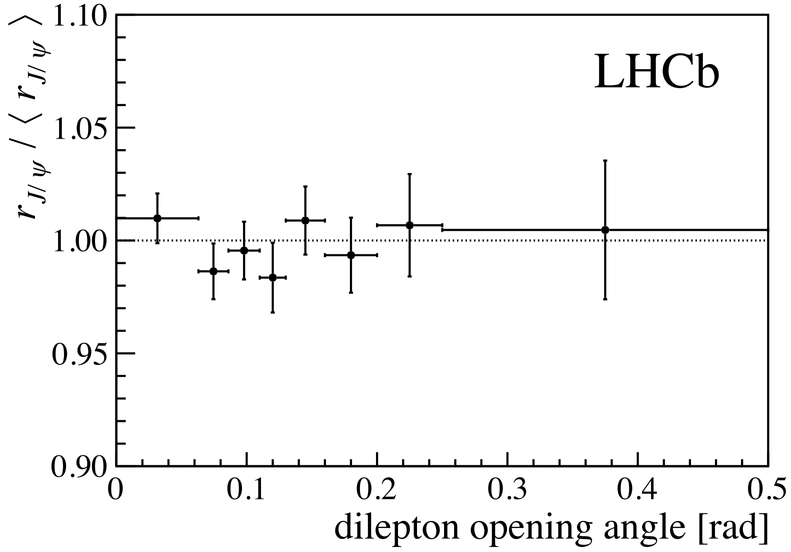
1 161 800 ± 1 100 events

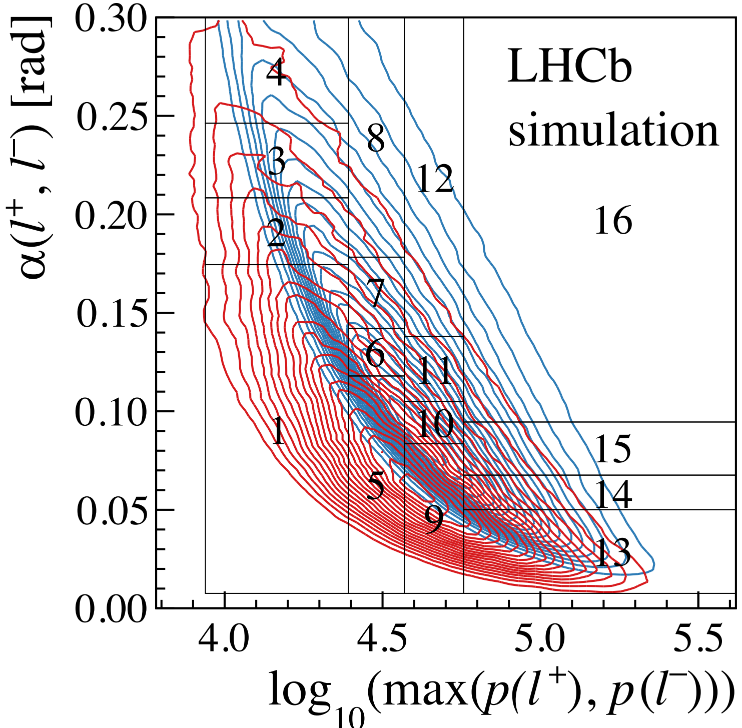
[PRL 122 (2019) 191801]

344 100 ± 610 events



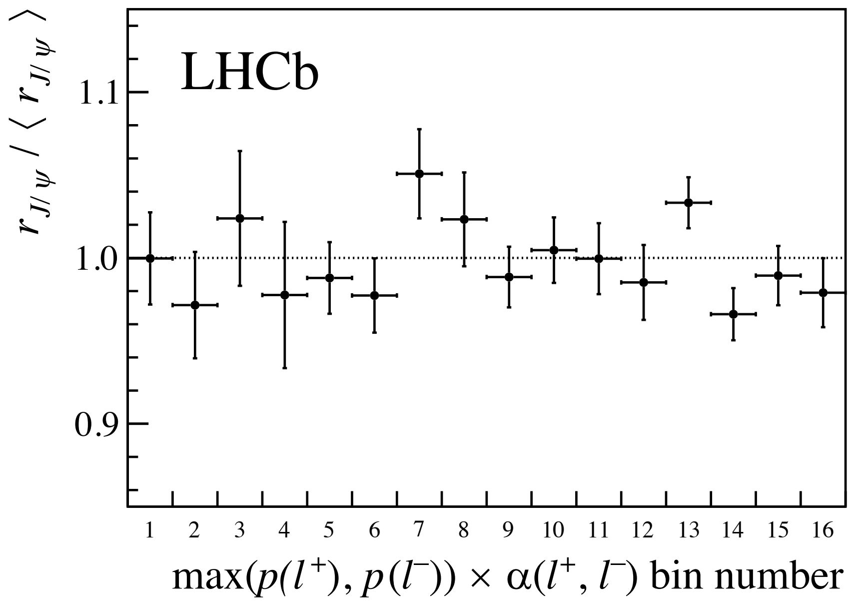
- $r_{J/\psi}$ average: $r_{J/\psi} = 1.014 \pm 0.035$
  - Uncertainty: stat. and syst. (relevant for R_K)
- Checked agreement between datasets
- Or absence of trends in important variables:
- 2D check





- Also:

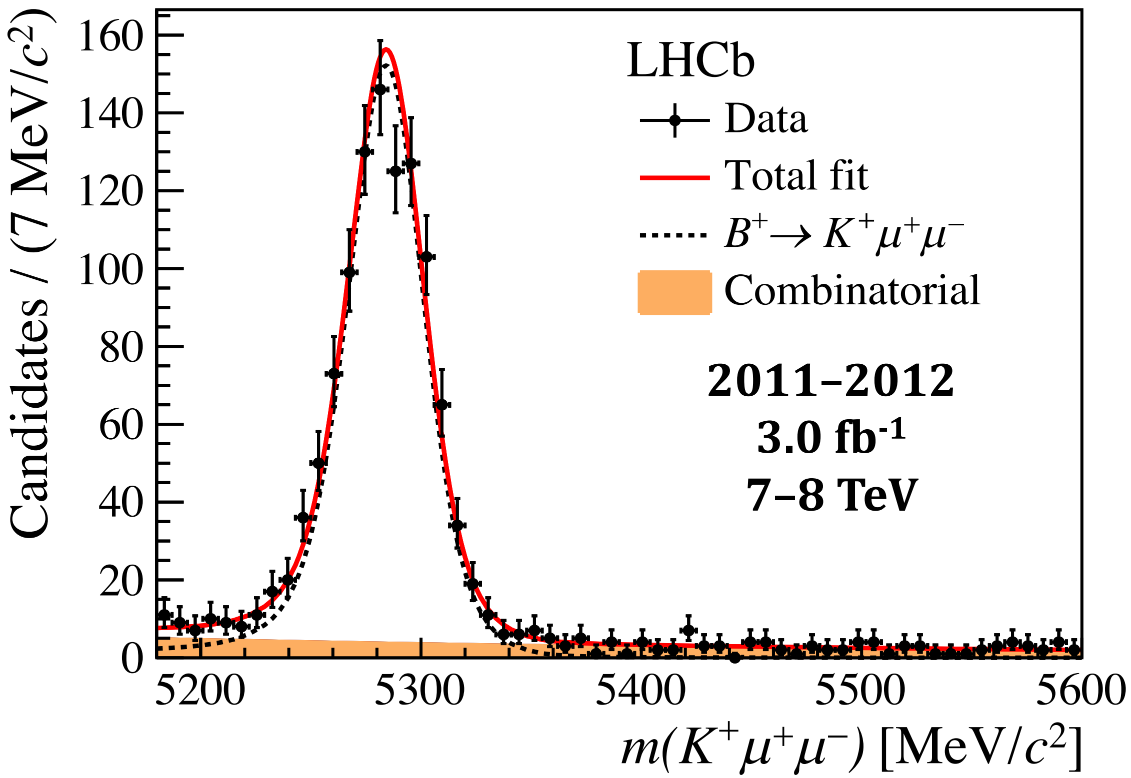
$R_{\psi(2S)}$ =0.986±0.013

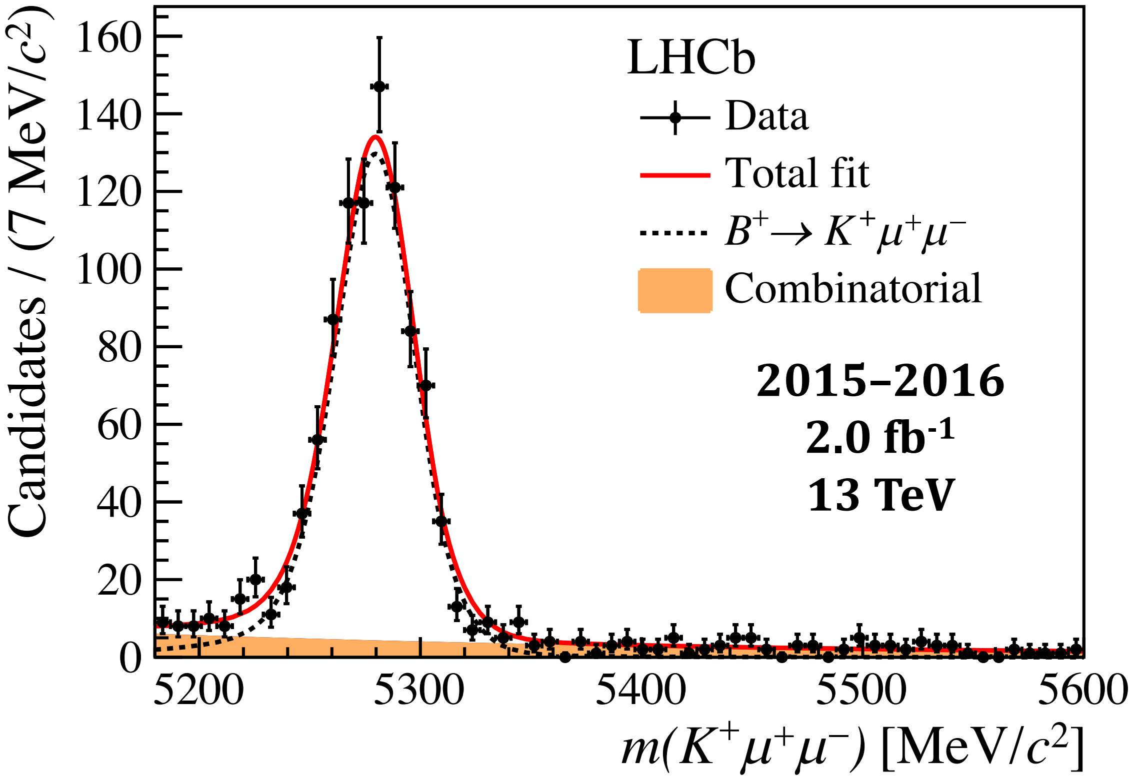


Counting the penguins: muons

- Very clean signal
  - In total, 1 943 ± 49 events
  - Fits for separately Run I / Run II shown below
- Differential BR in agreement with published LHCb measurement [JHEP 06 (2014) 133]

[PRL 122 (2019) 191801]





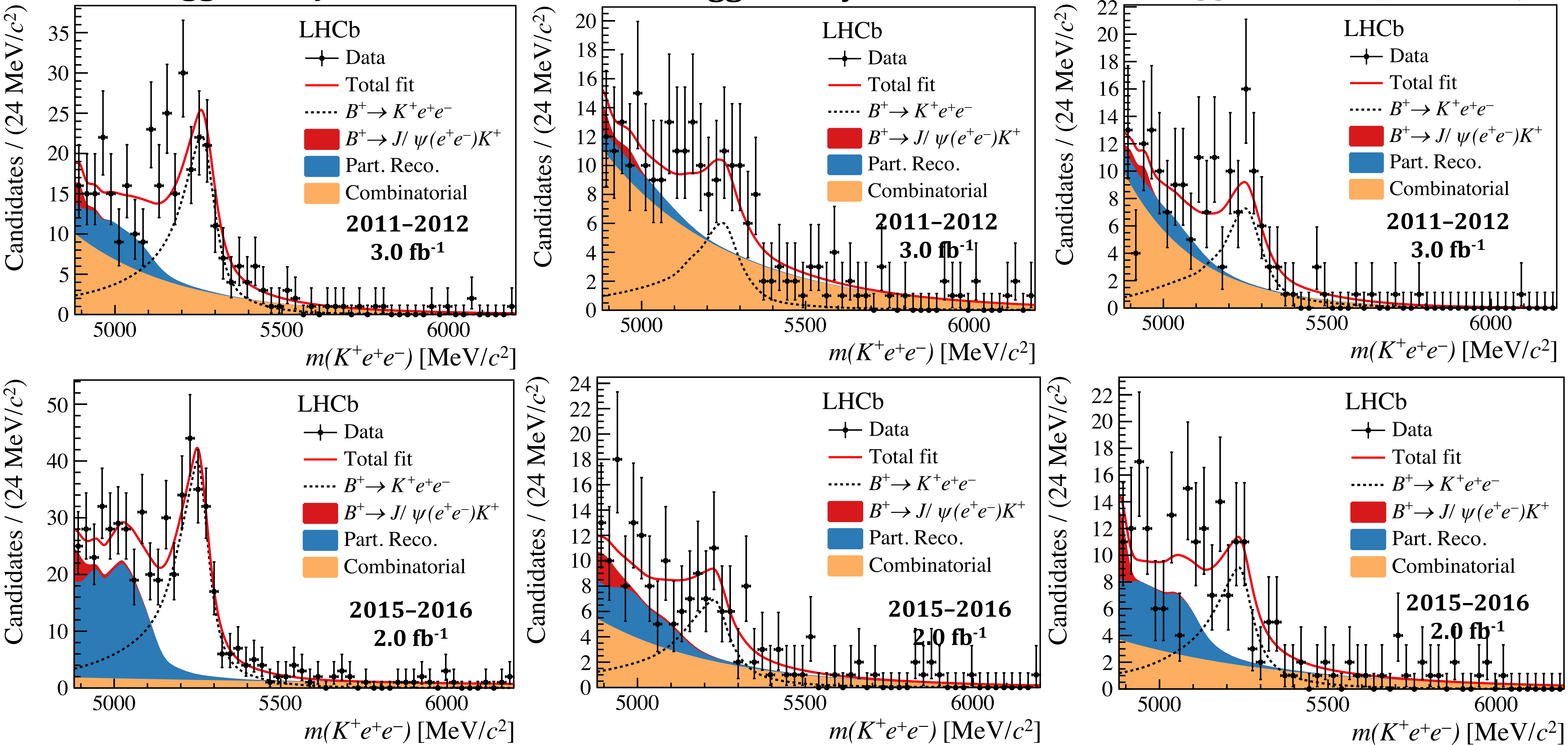
Counting the penguins: electrons

[PRL 122 (2019) 191801]

Triggered by electron | Triggered by hadron | Triggered independently

RUN I

RUN II



Result

- R_K is extracted through simultaneous fit to 8 datasets: muons/electrons (3 trigger categories) Run1/Run2

$$\boldsymbol{R_K = 0.846\ ^{+0.060}_{-0.054}\ ^{+0.016}_{-0.014}}\ \text{(stat., syst.)}$$

  - Consistent with the SM at 2.5 standard deviations
  - Dominated by statistics of the rare electron mode
  - Dominant systematics: corrections to the simulation (trigger), fit model

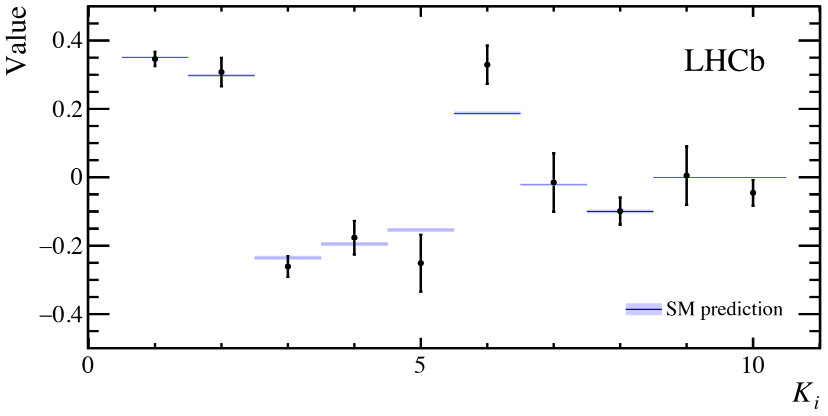
- Updated measurement of dielectron differential branching fraction

$$\frac{d\mathcal{B}(B^+ \to K^+ e^+ e^-)}{dq^2}(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = (28.6\,^{+2.0}_{-1.7} \pm 1.4) \times 10^{-9}\,c^4/\mathrm{GeV}^2\,.$$

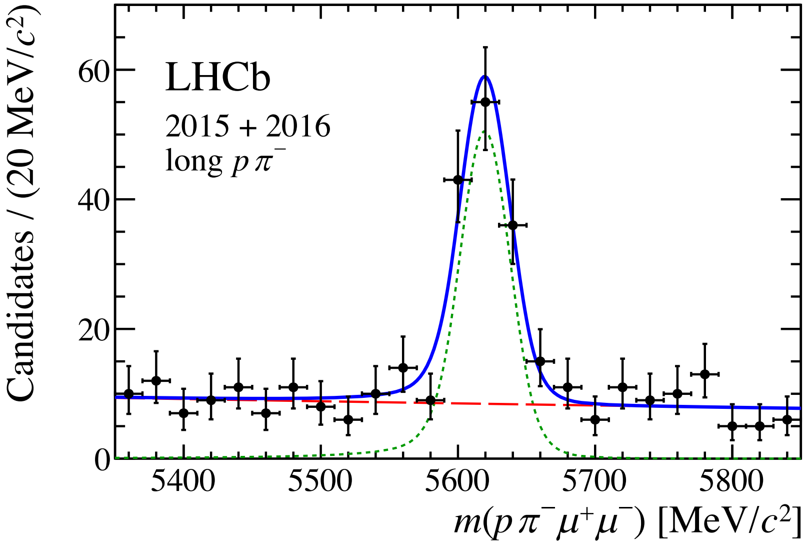
  - Consistent with the SM predictions

Other recent measurements

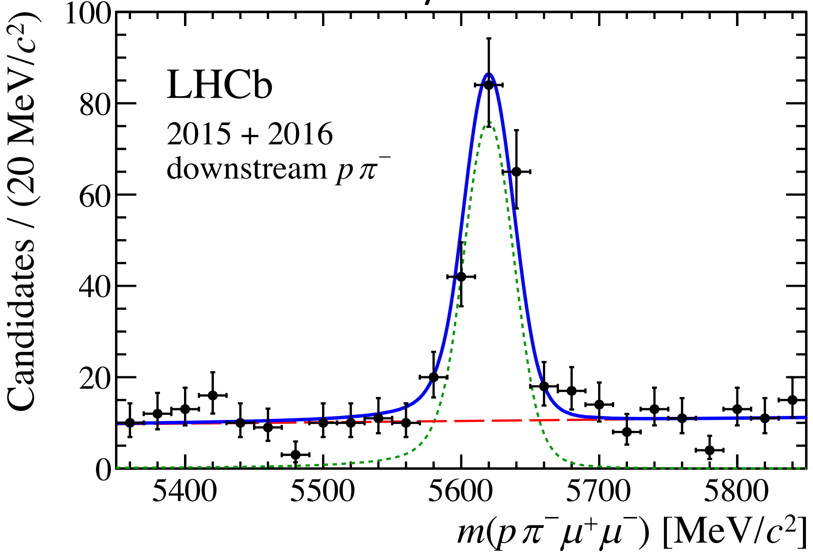
- **Angular moments of the decay $\Lambda_b \to \Lambda\mu^+\mu^-$ at low hadronic recoil: [JHEP 09 (2018) 146]**
  - Analysis using method of moments, first measurement of full set of observables
  - Results compatible with SM (and NP models)



Λ decays in VELO



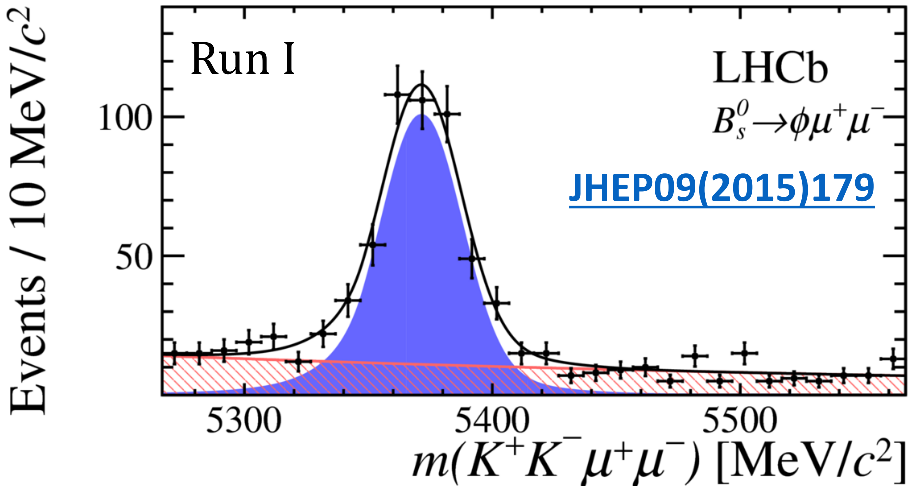
Λ decays after VELO

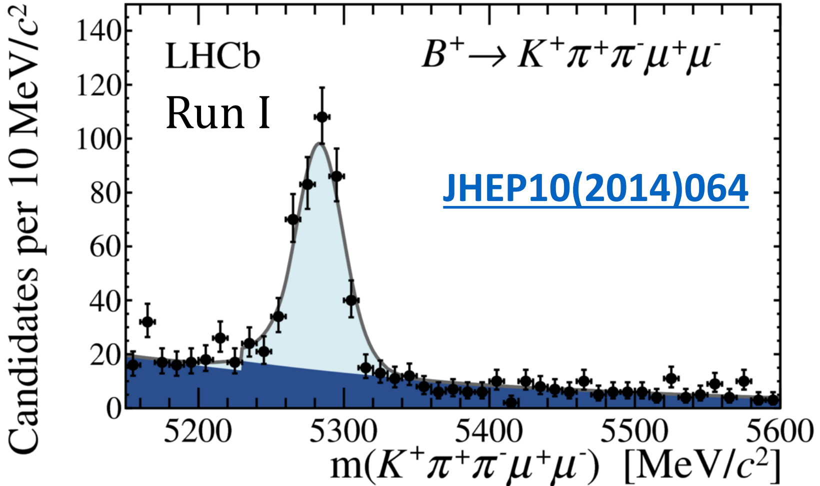


- See the talk of Luis Miguel Garcia Martin (today 3:50 PM in this room) for other results on rare decays!
- Also the talk by Dominik Mitzel for rare charm decays (yesterday 3:30 PM)

What's coming next?

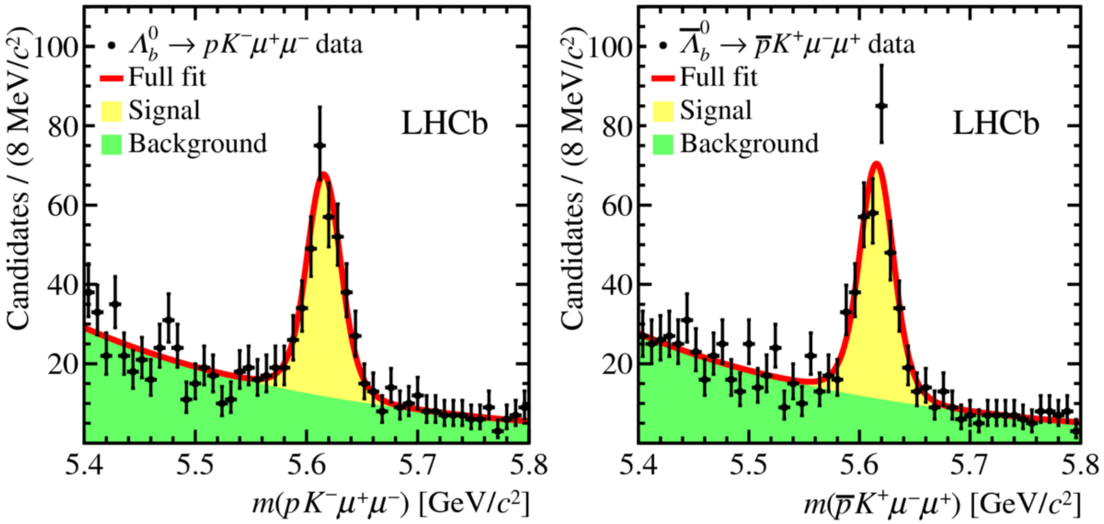
- Update of the angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ with a larger dataset
- Update of R_X measurements with larger datasets
- Some other R_X tests and angular analyses ongoing
  - So far, all the LFU tests were performed with B mesons only
  - LHCb has also collected large samples of B_s^0 mesons and Λ_b^0 baryons

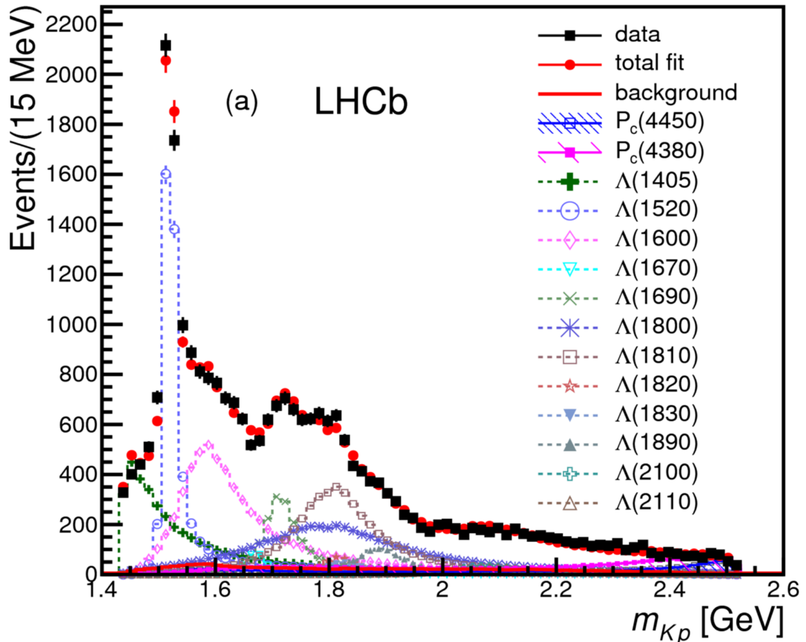




LFU with baryons?

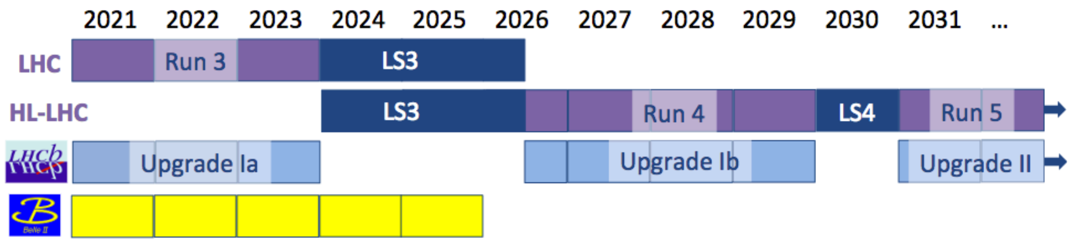
- One of ideas is the first LFU test with *b*-baryons
  - Different spin structure and phase space, possible surprises?
  - Do we see a deviation from unity also in baryonic mode?
- $R_{pK} = \frac{BR(\Lambda_b^0 \to pK\mu^+\mu^-)}{BR(\Lambda_b^0 \to pKe^+e^-)} \cdot \frac{BR(\Lambda_b^0 \to pKJ/\psi(e^+e^-))}{BR(\Lambda_b^0 \to pKJ/\psi(\mu^+\mu^-))}$
- 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)]
- $\Lambda_b^0 \to pK\mu^+\mu^-$ was observed [JHEP 06 (2017) 108]



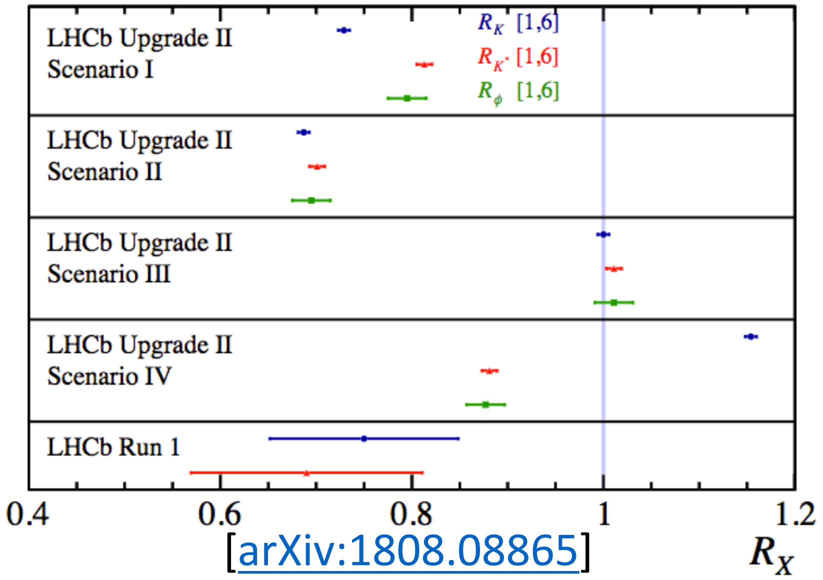


Longer-term prospects

- We have more data on tape!
  - **Collected about 9 fb^{-1} in Run 1+2**
  - 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 deviations from SM?

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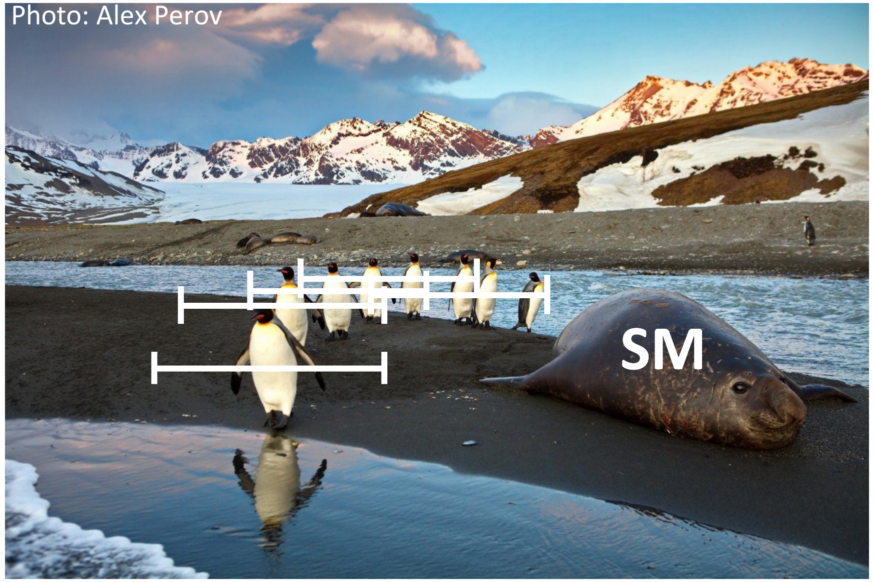
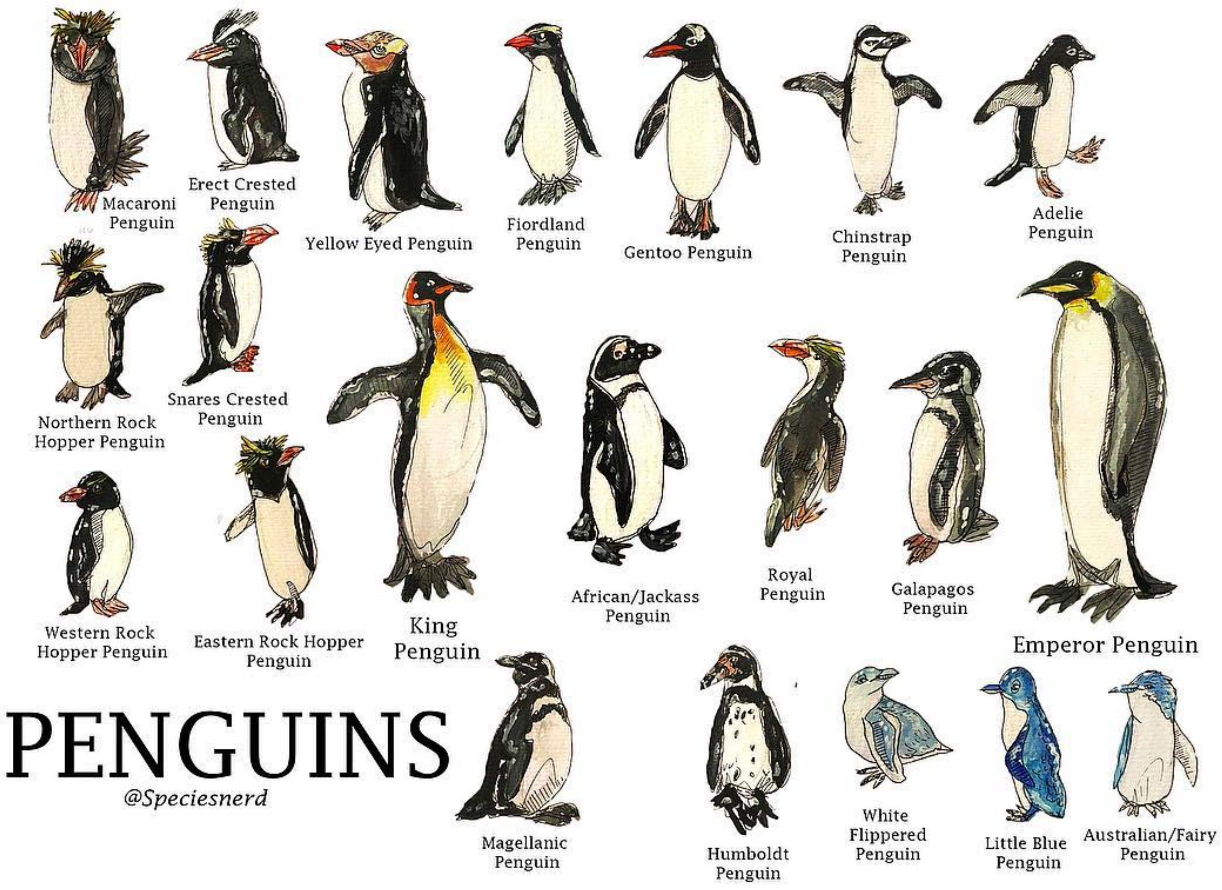


- New ideas & updated measurements are coming

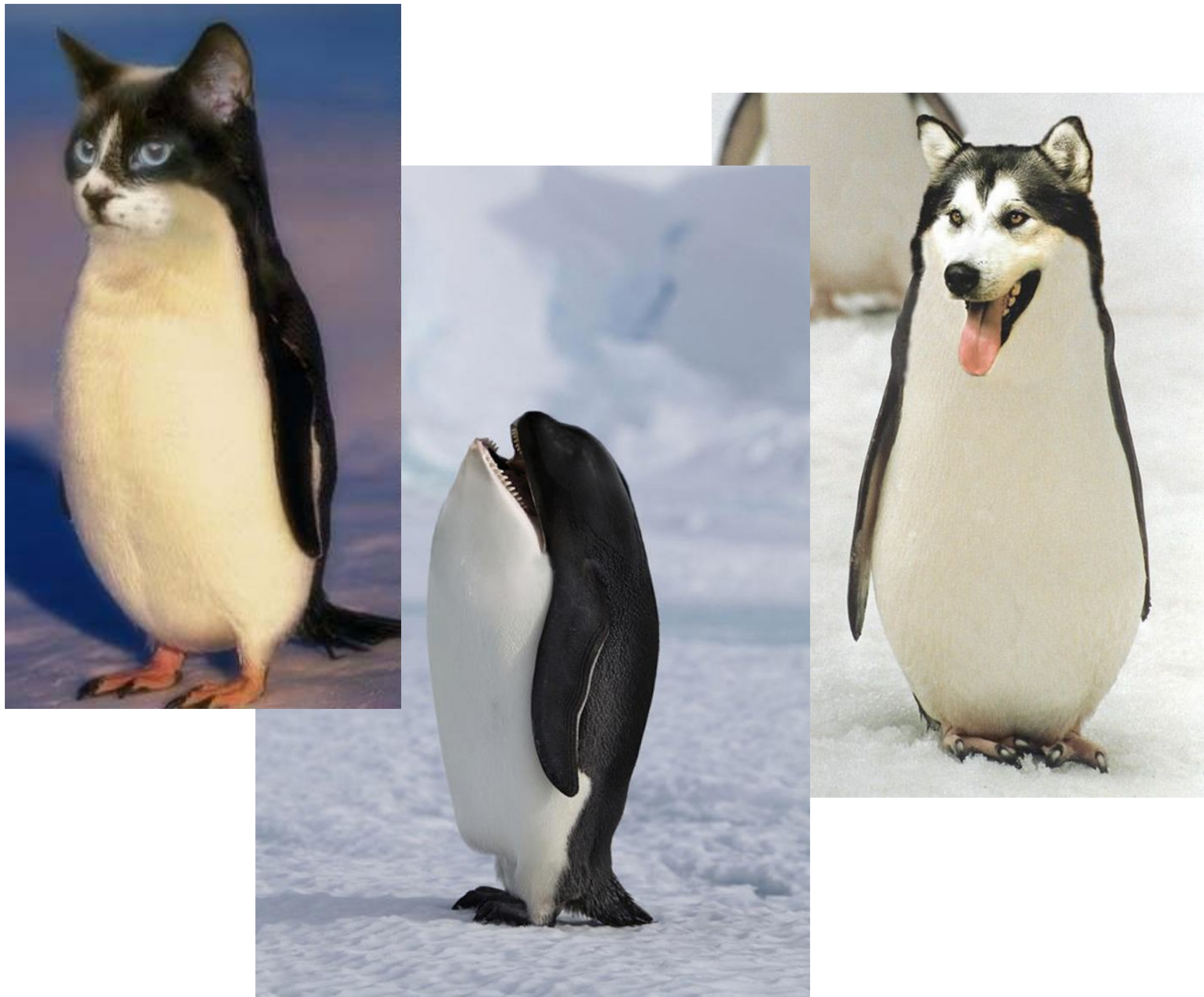
Stay tuned!

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

Standard Model penguins



New Physics



Comparison to the old result

- Old Run1 result: [PRL 113 (2014) 151601]
  $R_K(\text{old Run1}) = 0.745\,^{+0.090}_{-0.074} \pm 0.036$
- Updated Run1: improved reconstruction, re-optimized selection, … [PRL 122 (2019) 191801]
- Improved calibration of simulation (-> systematics)
- $R_K(\text{Run1}) = 0.717\,^{+0.083}_{-0.071}\,^{+0.017}_{-0.016}$
- $R_K(\text{Run2}) = 0.928\,^{+0.089}_{-0.076}\,^{+0.020}_{-0.017}$
- NB: take into account correlations for the combination