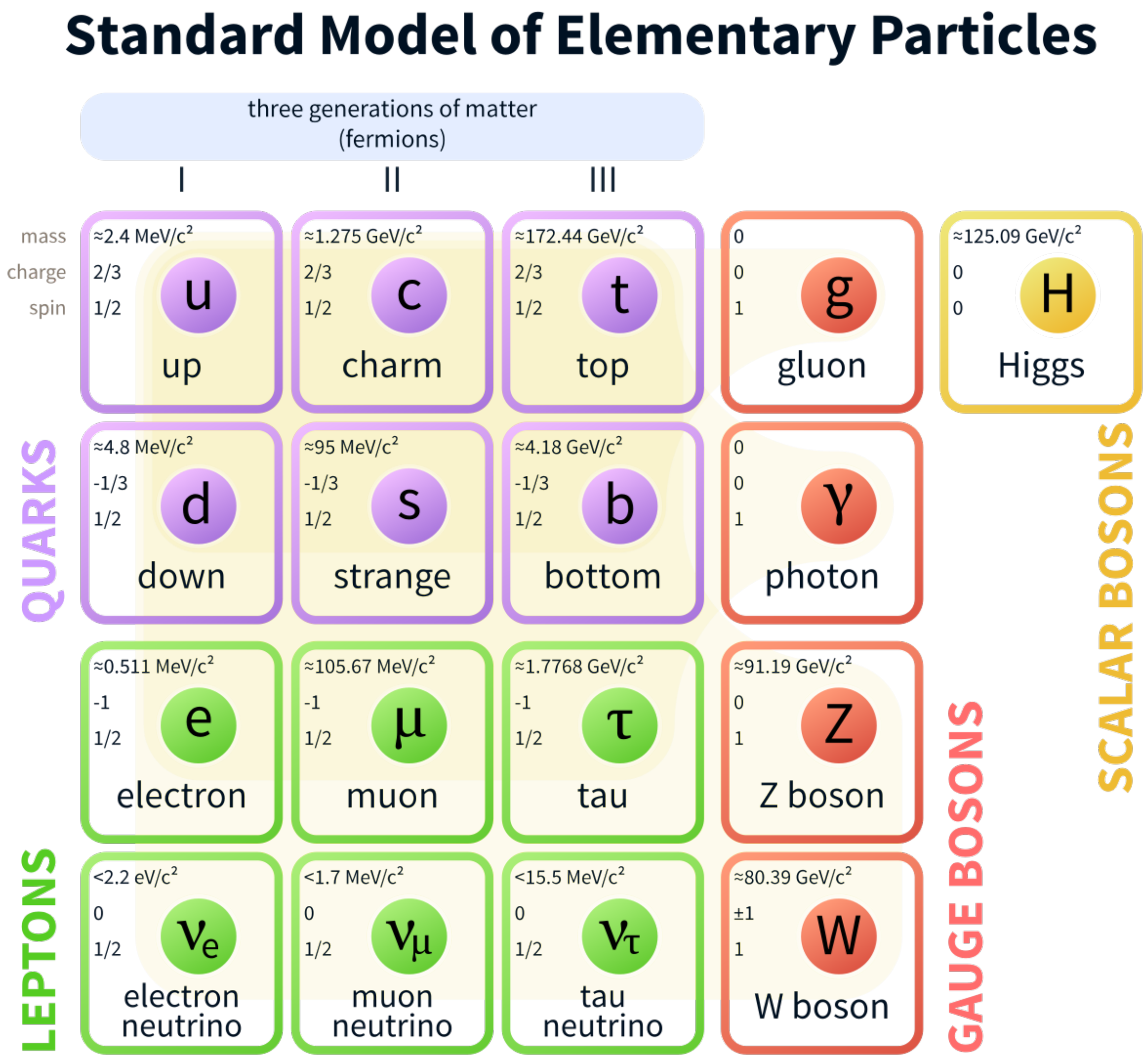
Search for Lepton Universality Violation using Λ_b decays

Vitalii Lisovskyi

Laboratoire de l'Accélérateur Linéaire, Orsay

LHCb experiment

The Standard Model

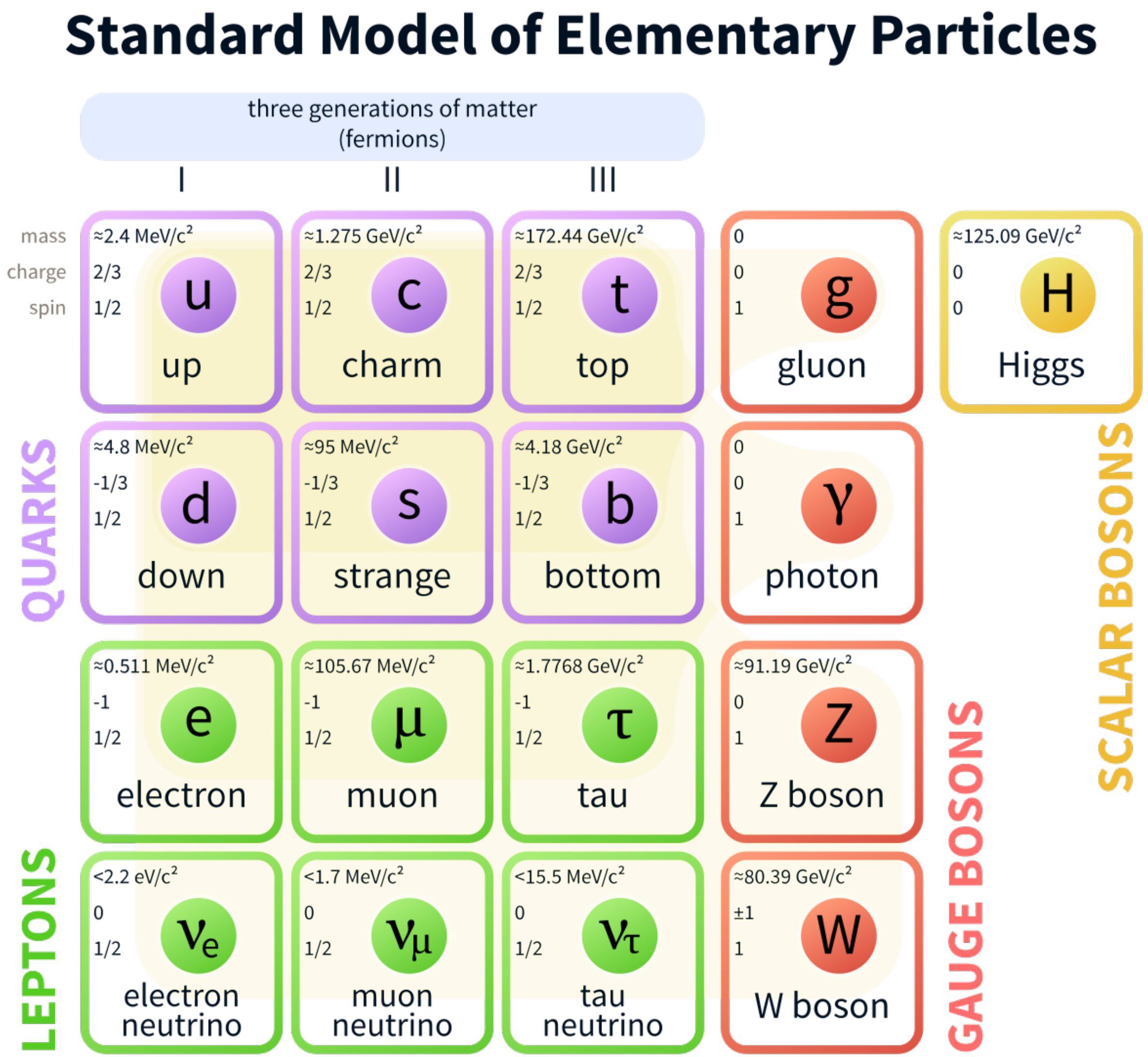


- SM: couplings of all (charged) leptons to the gauge bosons should be identical
  - (up to the order of mass/phase-space corrections)
- This means e.g. $\frac{BR(Z \to \mu^+\mu^-)}{BR(Z \to e^+e^-)} = 1$
  - Here, BR is ‘branching ratio’ – probability of such a decay to occur

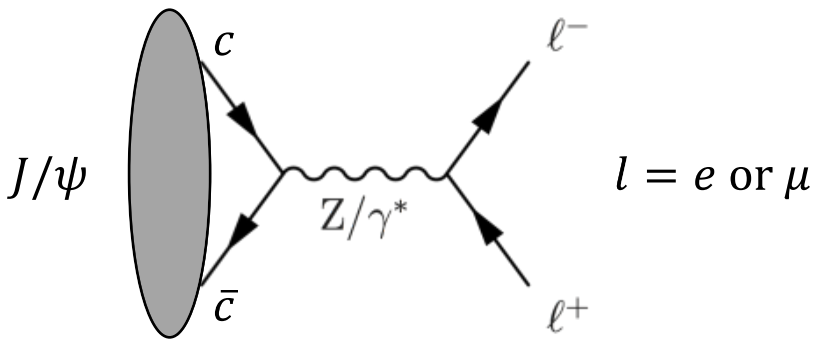
Decay Modes **Z**

Mode		*Fraction* (Γ_i/Γ)
Γ_1	e^+e^-	$(3.363 \pm 0.004)\%$
Γ_2	$\mu^+\mu^-$	$(3.366 \pm 0.007)\%$
Γ_3	$\tau^+\tau^-$	$(3.370 \pm 0.008)\%$

The Standard Model

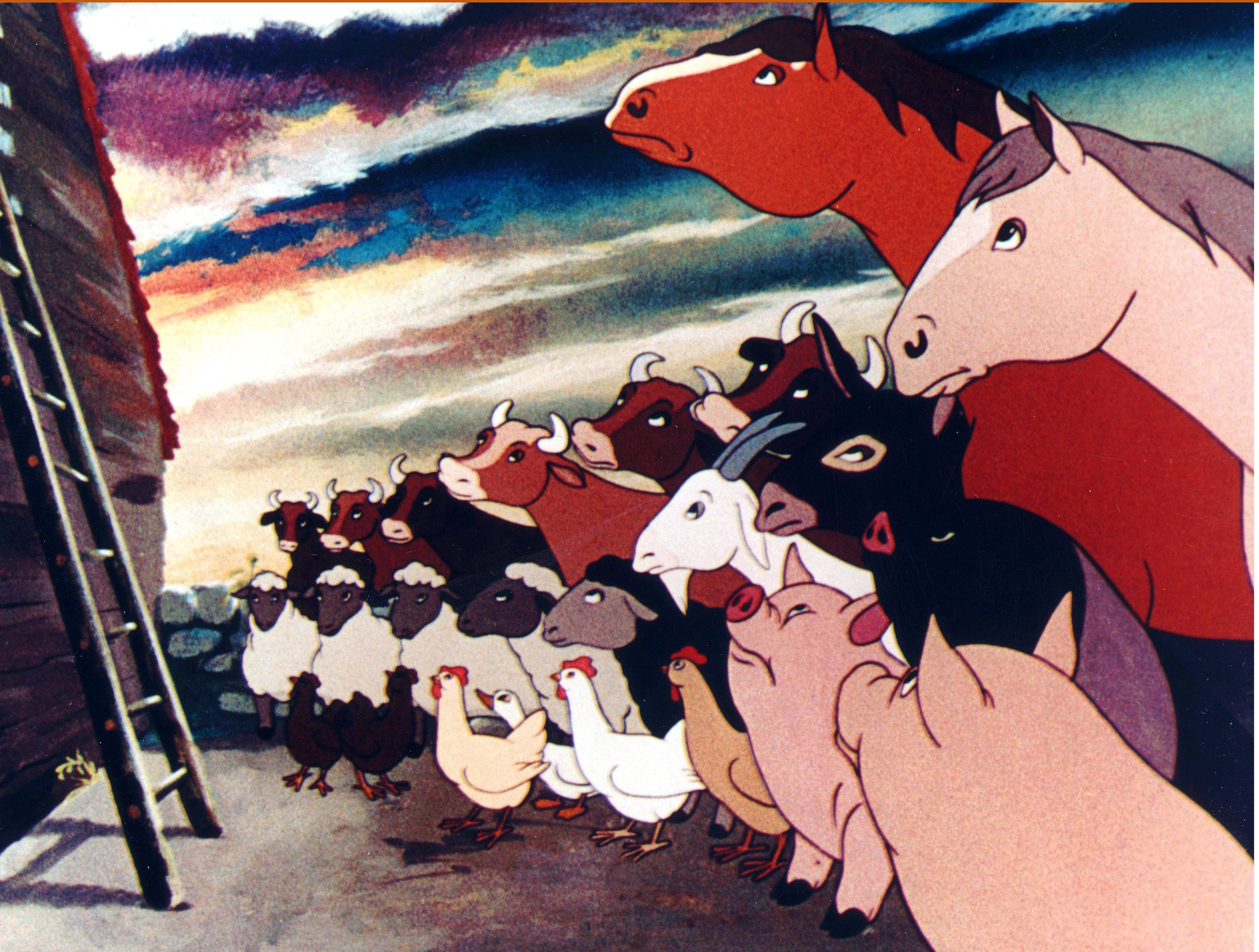


- **SM: couplings of all (charged) leptons to the gauge bosons should be identical**
  - (up to the order of mass/phase-space corrections)
- This means e.g. $\frac{BR(Z \to \mu^+ \mu^-)}{BR(Z \to e^+ e^-)} = 1$
  - Here, BR is 'branching ratio' – probability of such a decay to occur
  - Should be also true for virtual off-shell Z or γ
  - This implies e.g. $\frac{BR(J/\psi \to \mu^+ \mu^-)}{BR(J/\psi \to e^+ e^-)} = 1$



- This property is called **Lepton Universality**

So, the Standard Model works?



- Well, all the ~~animals~~ leptons are equal, but some leptons…
- …well, they pretend to be more equal than others

Slide credits: V.Gligorov

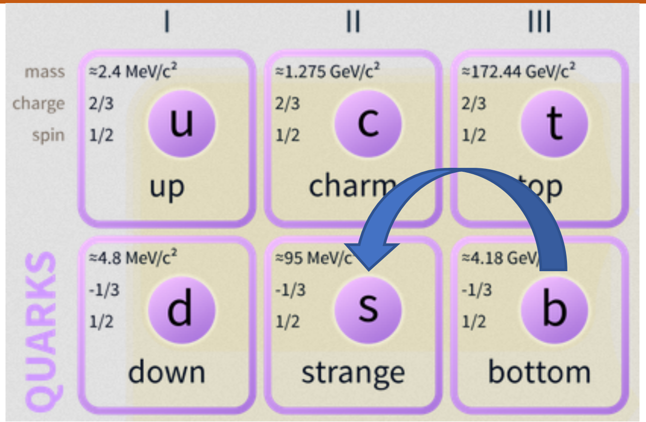
Insidious penguins

- The transitions between same-charge quarks – FCNC* – are forbidden *at the tree level*

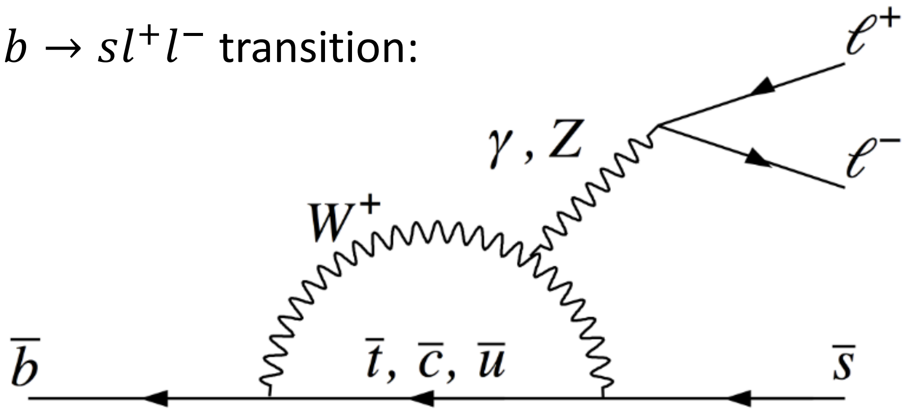
- They proceed via **penguin diagrams**

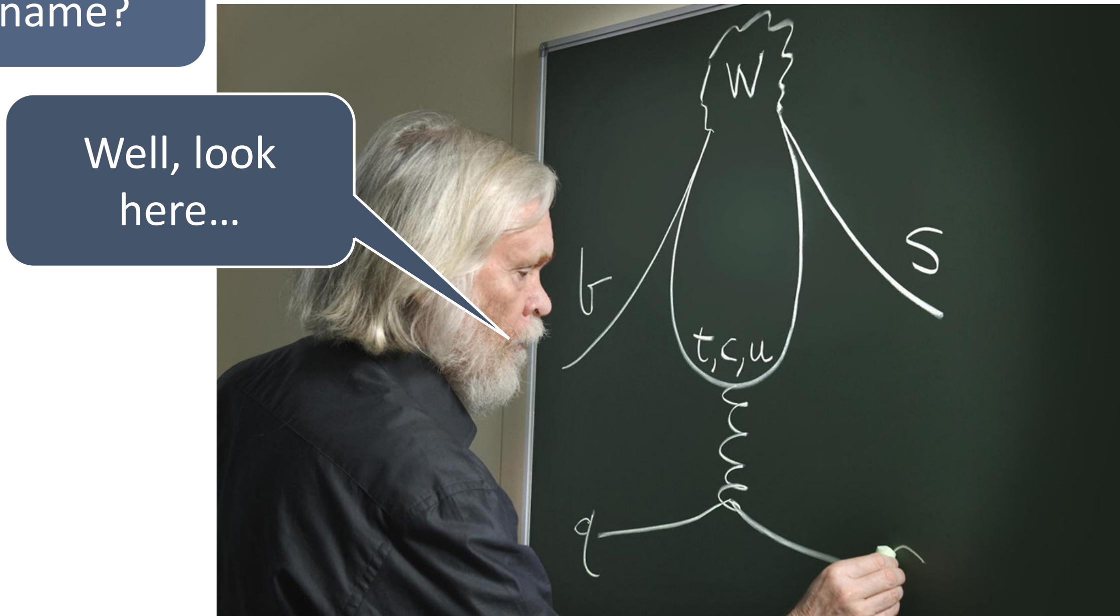
- This makes these processes **very rare**, but also **sensitive** to the possible New Physics contributions

- *And this is where we observe something intriguing…*



$b \to s l^+ l^-$ transition:



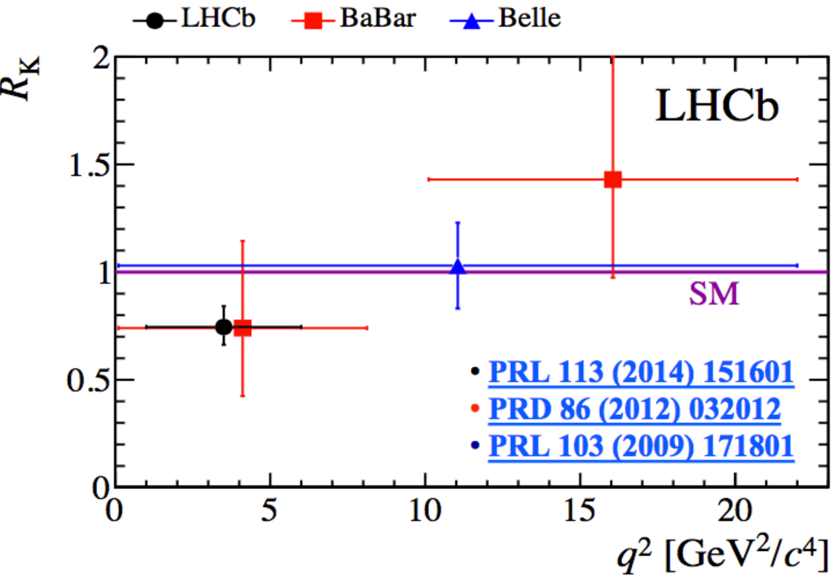


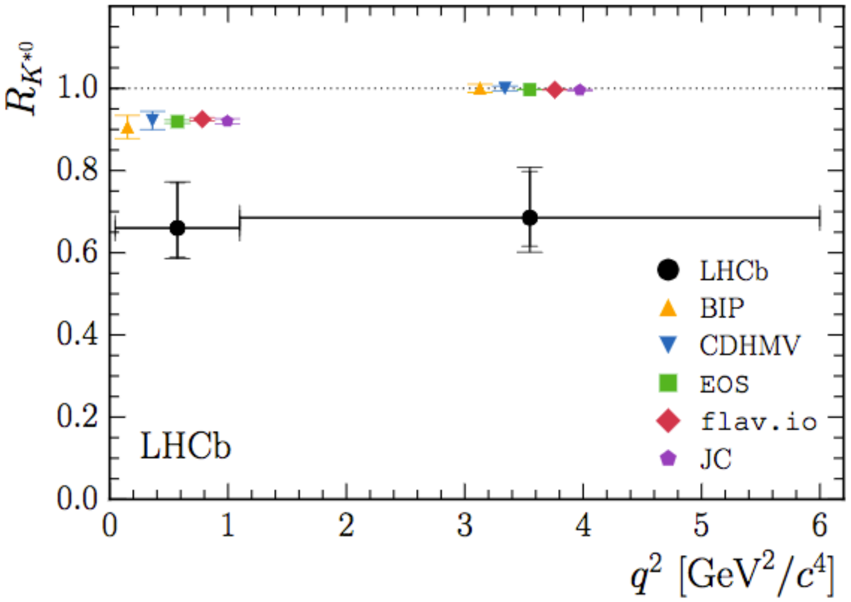
* FCNC = Flavor Changing Neutral Currents

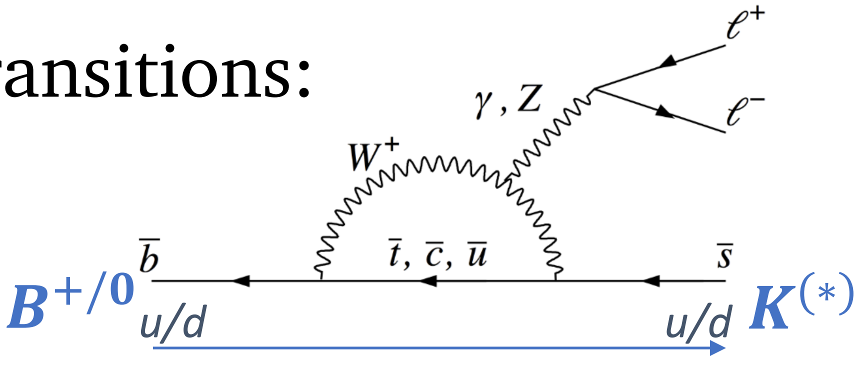
Ratios of ratios of ratios … 6

- Few remarkable measurements in the $b \to s l^+ l^-$ transitions:

$$R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)} \qquad R_{K^{*0}} = \frac{BR(B^0 \to K^{*0} \mu^+ \mu^-)}{BR(B^0 \to K^{*0} e^+ e^-)}$$



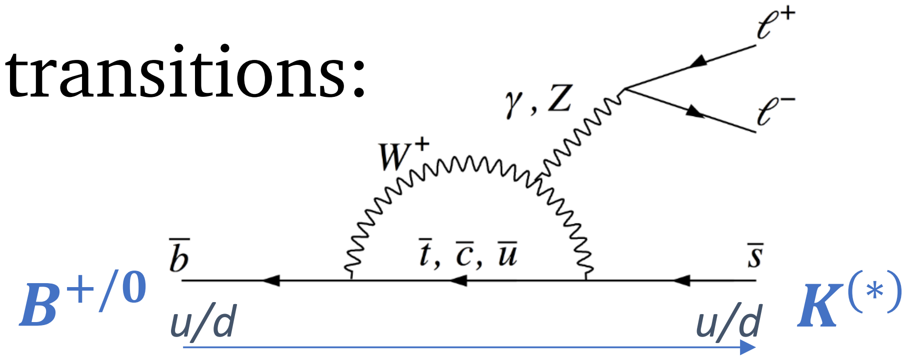




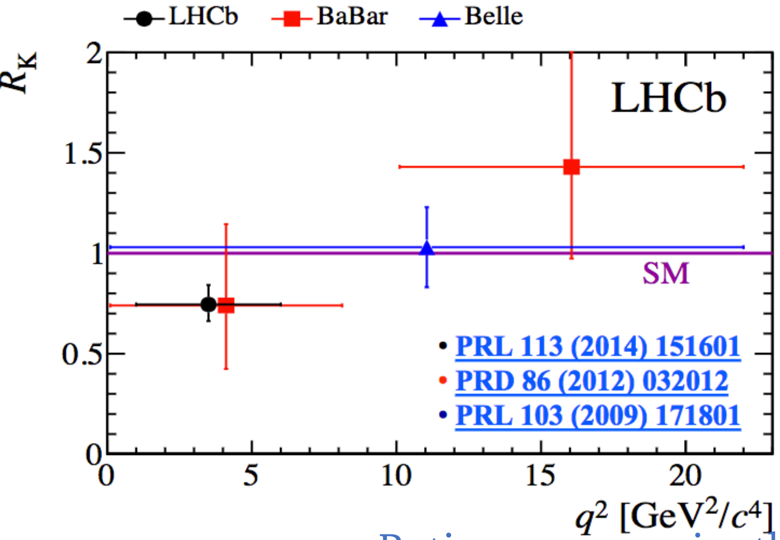
Ratios: very precise theoretical computation
Cancellation of theoretical and experimental uncertainties

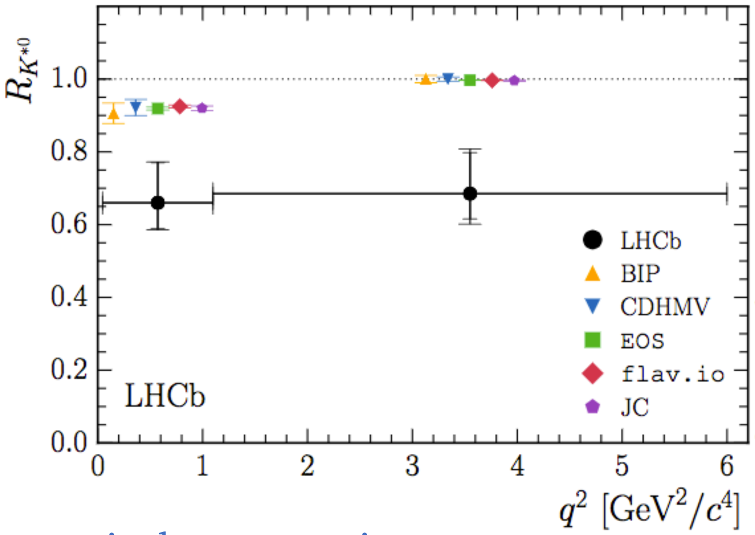
Ratios of ratios of ratios …

- Few remarkable measurements in the $b \to s l^+ l^-$ transitions:



$$R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)} \qquad R_{K^{*0}} = \frac{BR(B^0 \to K^{*0} \mu^+ \mu^-)}{BR(B^0 \to K^{*0} e^+ e^-)}$$

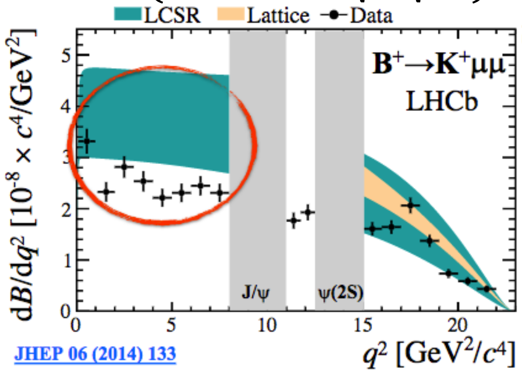


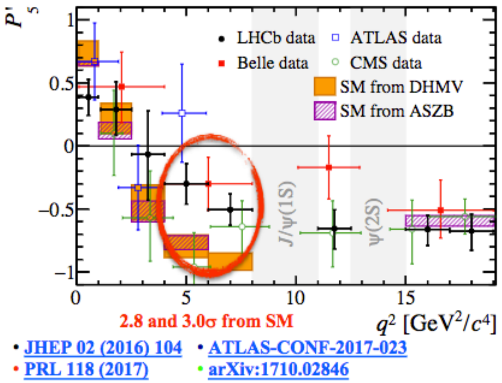


Ratios: very precise theoretical computation
Cancellation of theoretical and experimental uncertainties

Additional input:

$BR(B^0 \to K^{*0} \mu^+ \mu^-)$ Angular analysis

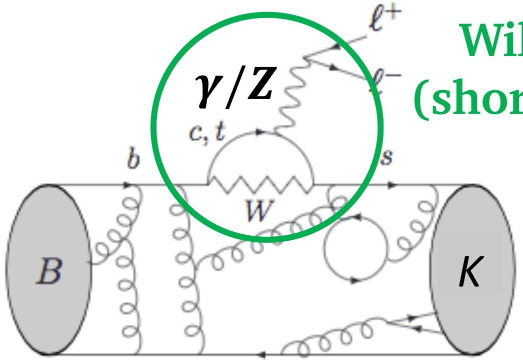




- Also some anomalies in the $b \to c l^+ \nu_l$ transitions
- New/updated measurements expected from LHCb and BELLE-II

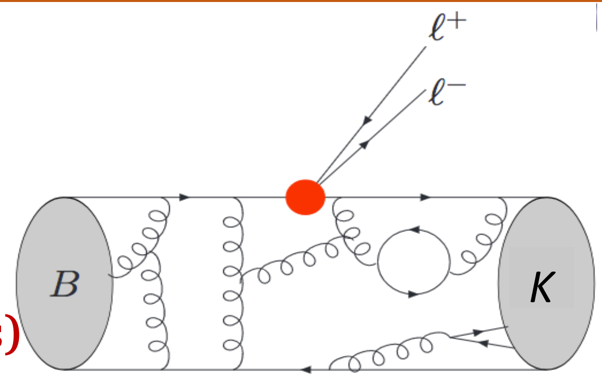
Theorists’ point of view

- Model-independent effective approach: $\mathcal{H}_{eff}(SM) \sim \sum C_i O_i$



Wilson coefficients
(short-distance effects)

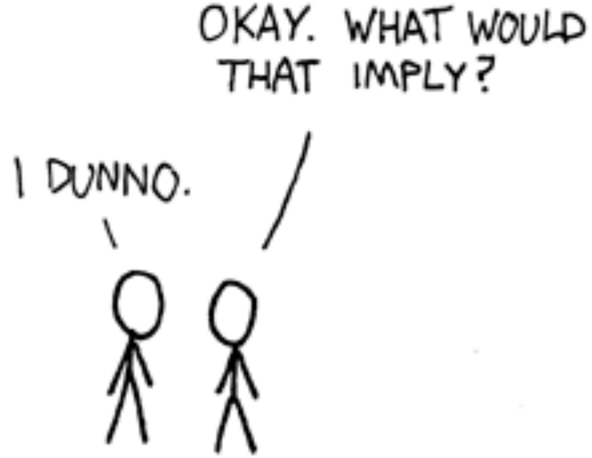
Local operators
(long-distance hadronic effects)



- Precise predictions in the SM:

Soft photon, photon/Z, Z

$C_7^{\mathrm{SM}} = -0.29,\; C_9^{\mathrm{SM}} = 4.1,\; C_{10}^{\mathrm{SM}} = -4.3$



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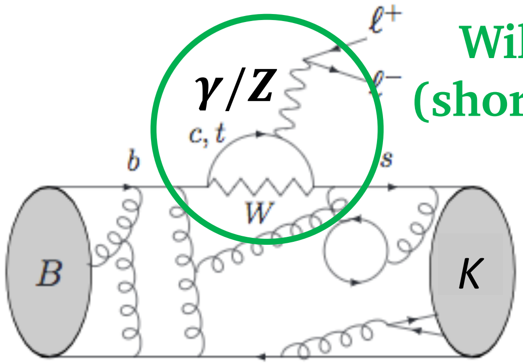

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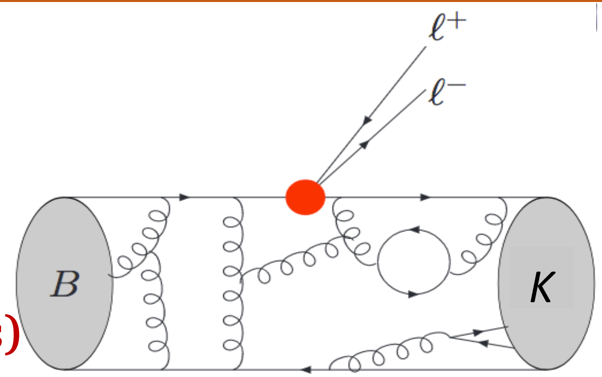


- Precise predictions in the SM:

Soft photon photon/Z Z

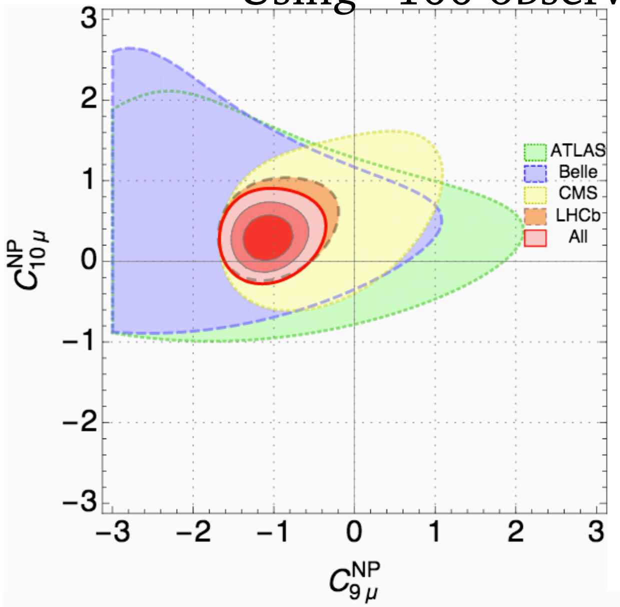
$C_7^{SM} = -0.29,\ C_9^{SM} = 4.1,\ C_{10}^{SM} = -4.3$

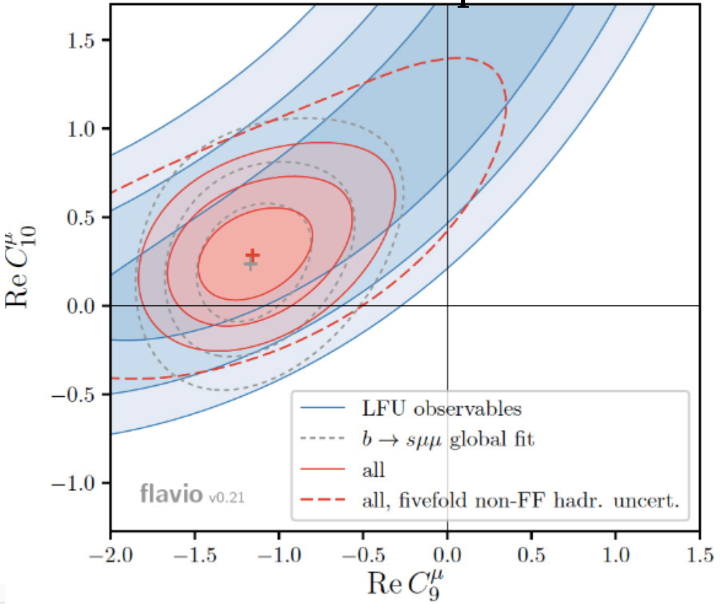
- To describe New Physics:

$C_i \rightarrow C_{i(SM)} + C_{i(NP)}^{l}$

- These effects look **coherent**
- Strong evidence for non-zero $C_{9(NP)}^{\mu}$

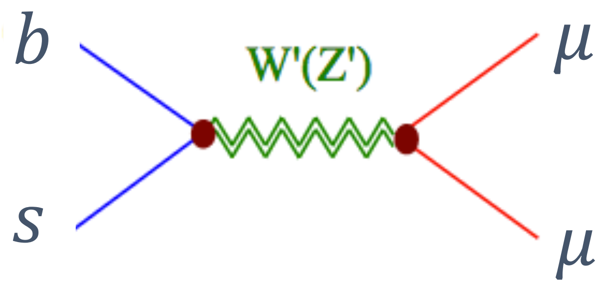
Fits of theory to the experimental data for $b \rightarrow s l^+ l^-$
Using ~100 observables from various experiments

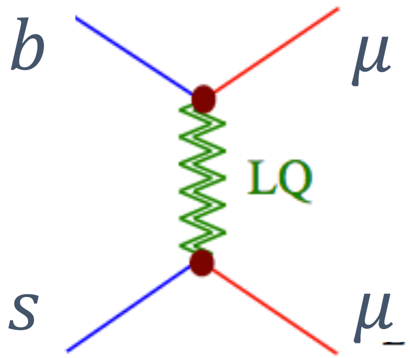




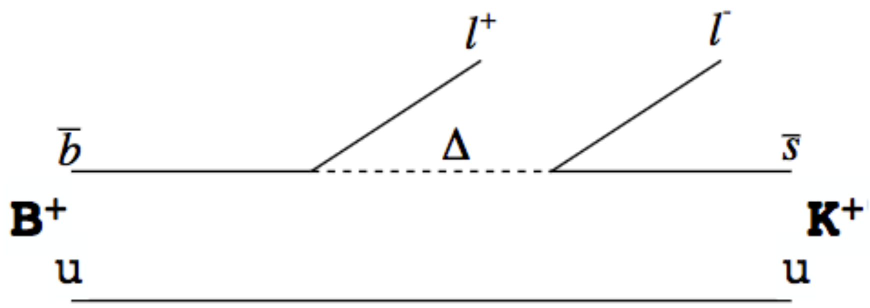
Possible explanations

- Well, it still may be a statistical fluctuation or an experimental error
- However, theorists actively propose models attempting to explain these effects
  - At the current level of knowledge, it is hard to distinguish between different scenarios
- Most popular scenarios:
  - Z'
  - Leptoquarks



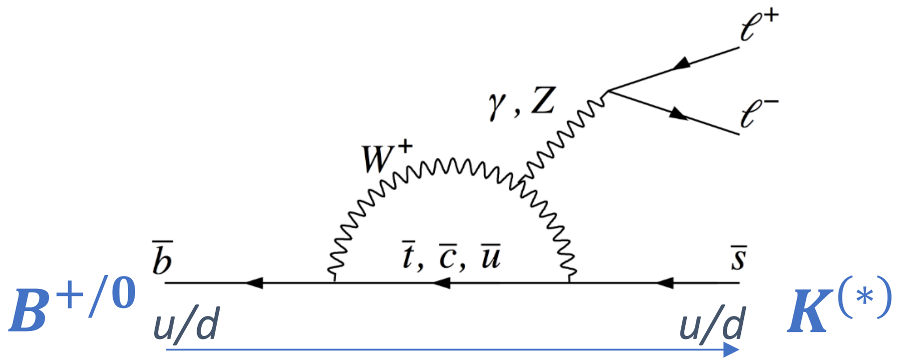


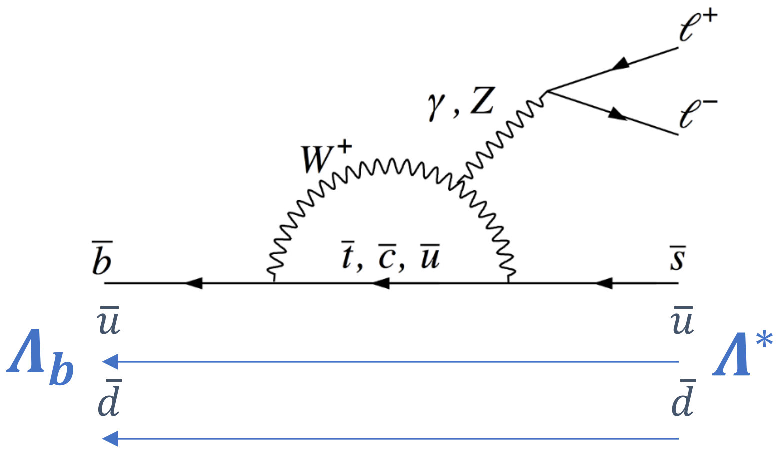
- In any case, these new particles should be accessible for direct observation at ATLAS and CMS in near future



Expanding our knowledge

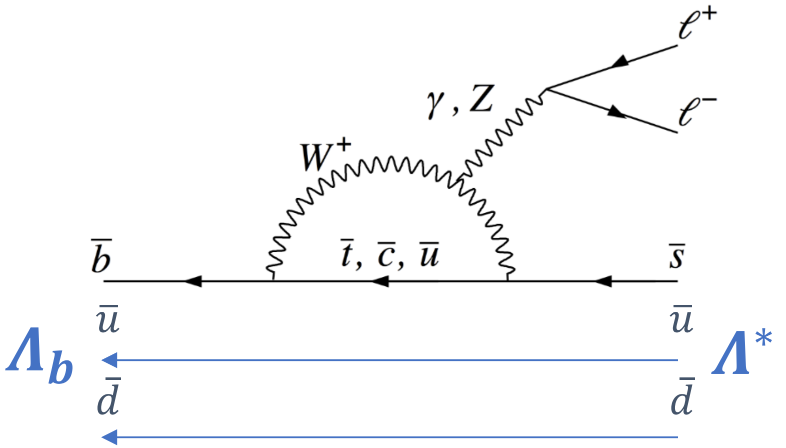
- There is another way of hadronisation for the $b \to sl^+l^-$ transition
- Not explored before

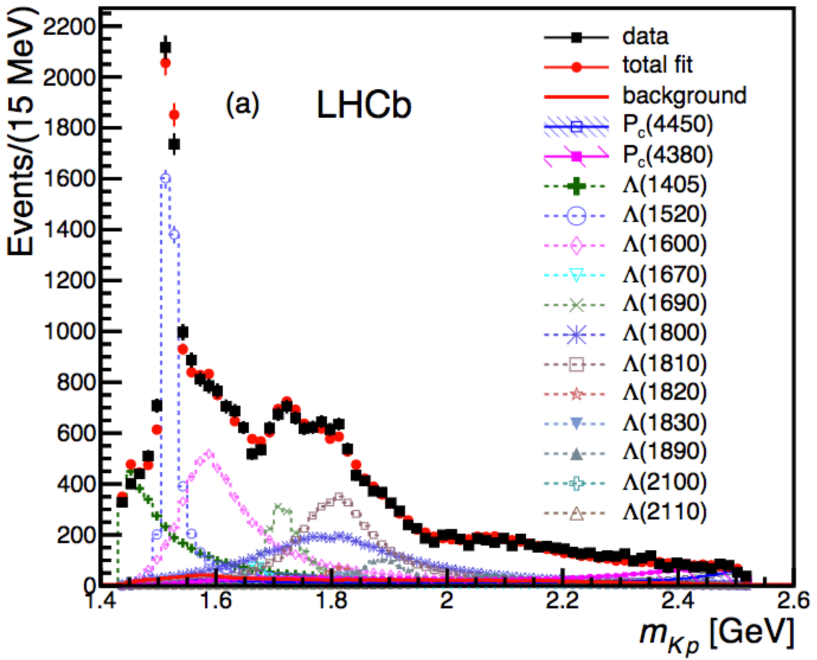




What about baryons?

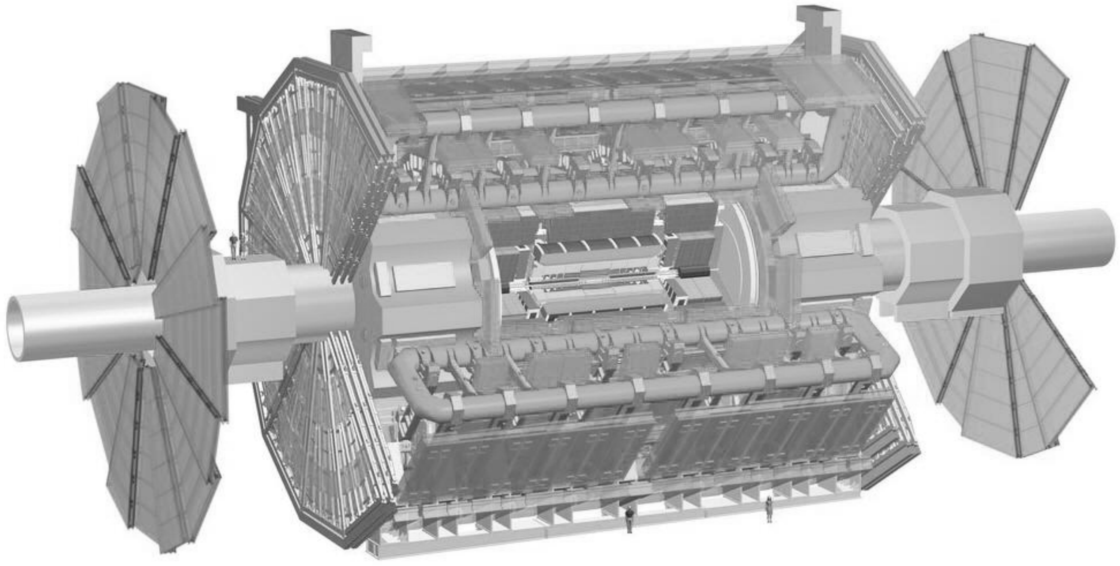
- We live in a world made of ~~love~~ baryons
  - However, baryons are less explored than mesons
- Exploring another spin configuration
- Laws in the baryon system are not always similar to mesons
  - E.g. charmonia ($c\bar{c}$) states production
  - $\frac{BR(\Lambda_b \to pK\psi(2S))}{BR(\Lambda_b \to pKJ/\psi)} = 0.21$, $\frac{BR(\Lambda_b \to pK\chi_{c2})}{BR(\Lambda_b \to pK\chi_{c1})} = 1.02$, while $\frac{BR(B^0 \to K^*\psi(2S))}{BR(B^0 \to K^*J/\psi)} = 0.46$, $\frac{BR(B^0 \to K^*\chi_{c2})}{BR(B^0 \to K^*\chi_{c1})} = 0.20$
- **We want to measure $R_{pK} = \frac{BR(\Lambda_b \to \Lambda^* \mu^+ \mu^-)}{BR(\Lambda_b \to \Lambda^* e^+ e^-)}$ with $\Lambda^* \to pK$**



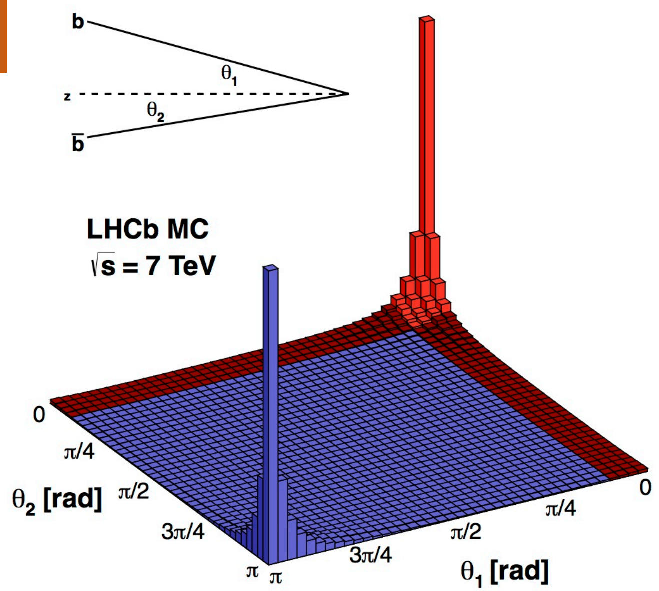


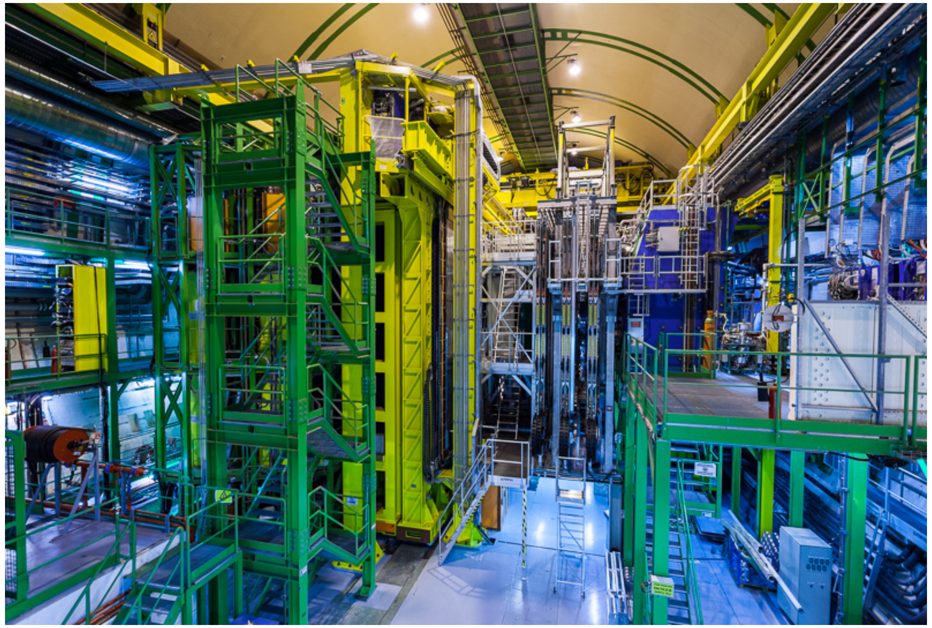
A perfect device

- Most people in this room are used to particle detectors looking like this
- 4π hermetic geometry
- Huge size (and cost)

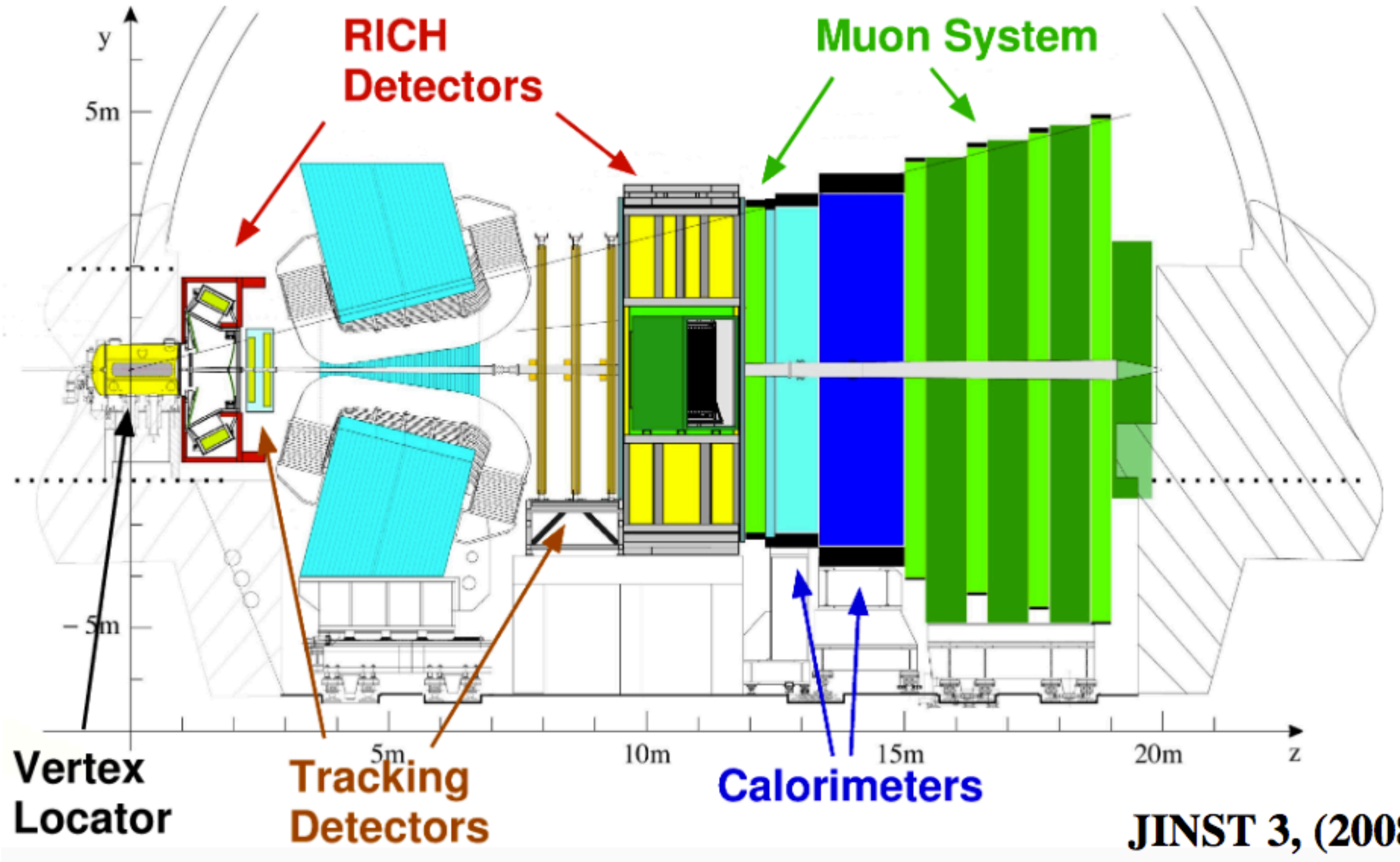


- But not LHCb
- It is a detector in the forward region
- Oriented to studies of the B-physics





The LHCb detector



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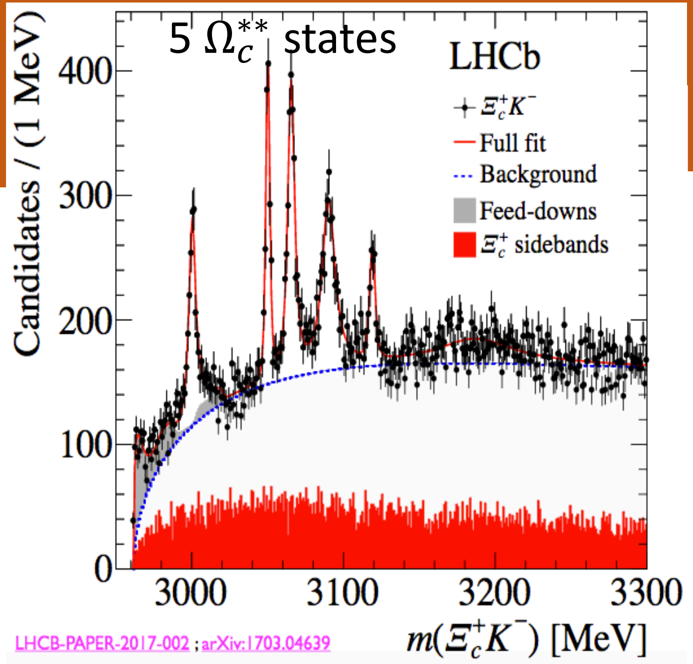
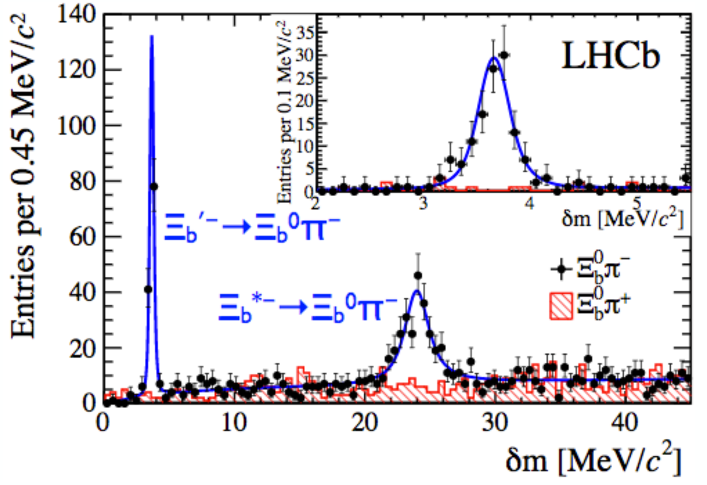
LHCb highlights

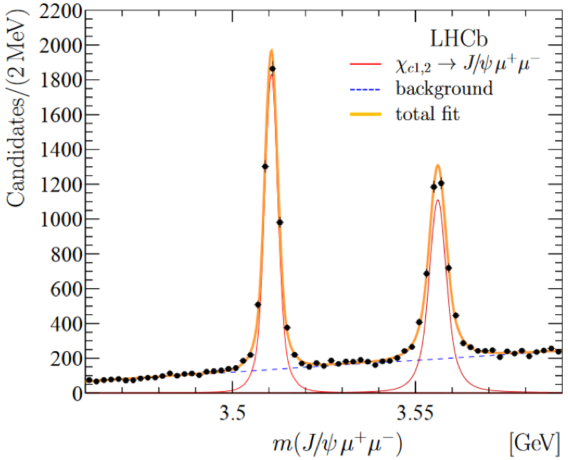
- We are good at searching for excited states of known particles

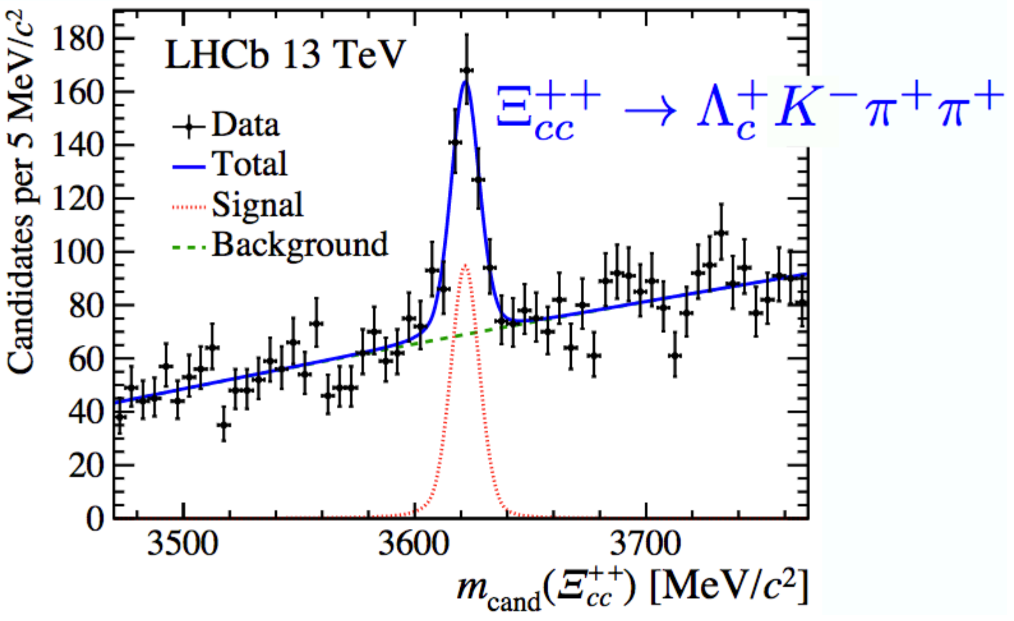


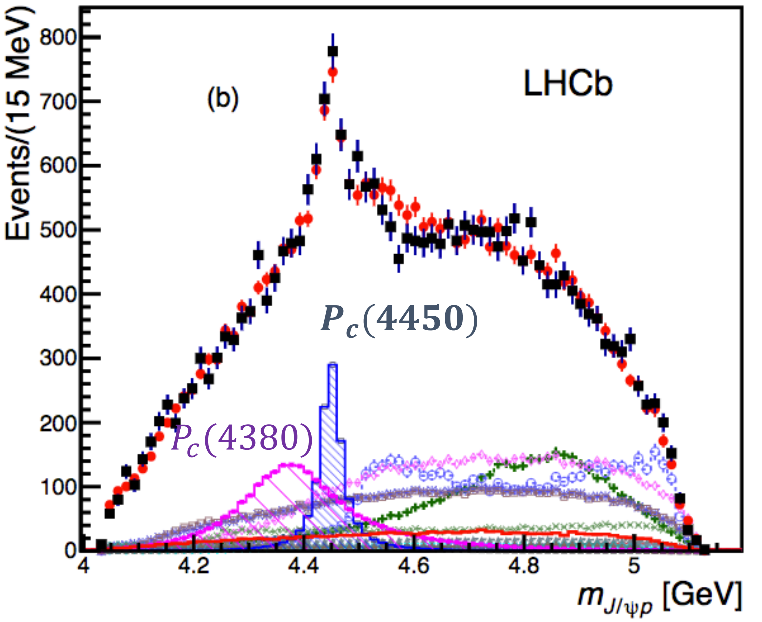


- Or at finding new particles

- And precise mass measurements

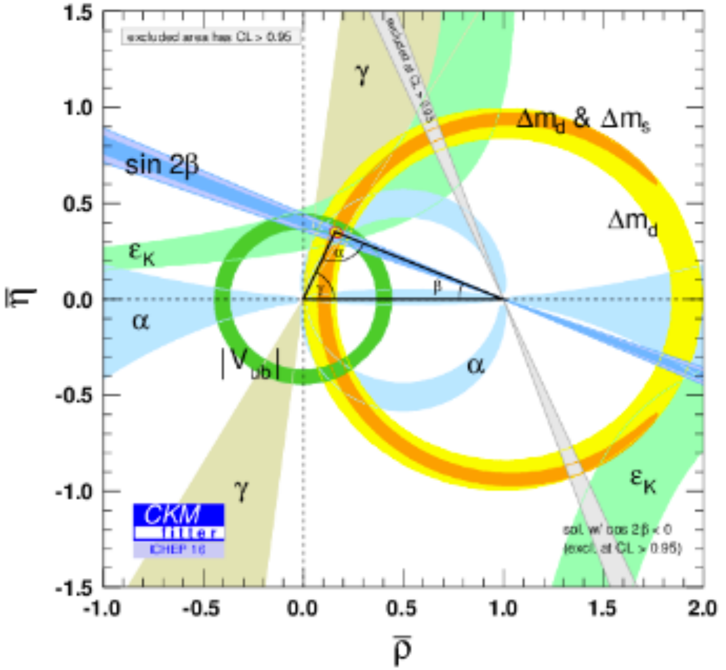


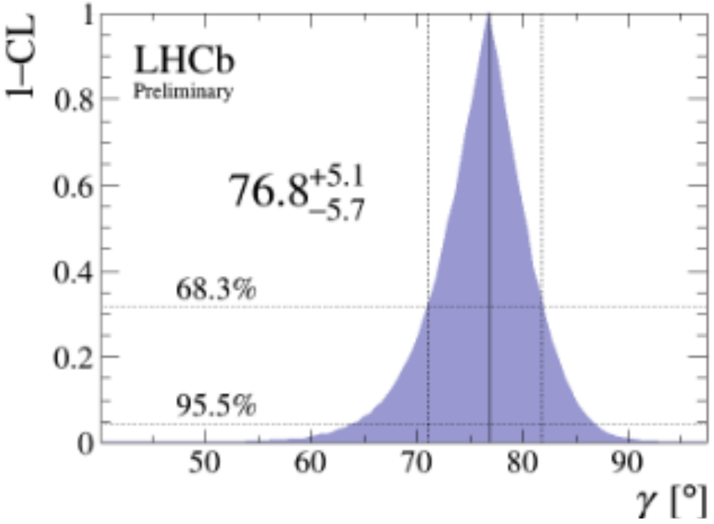


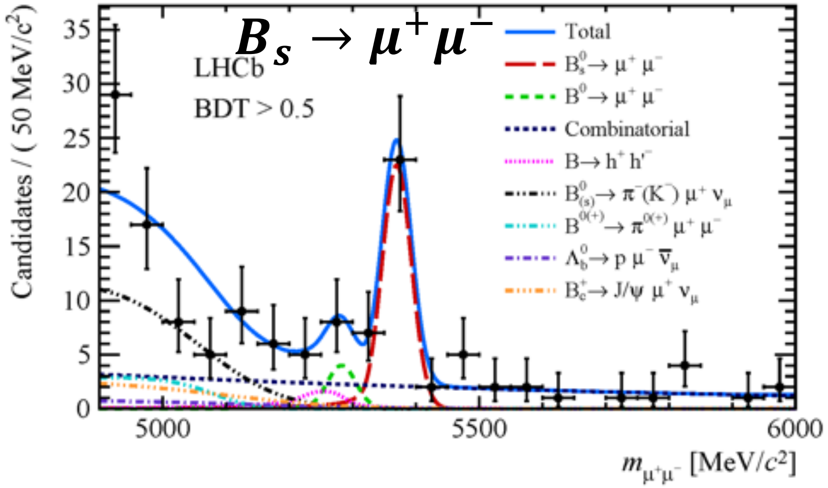


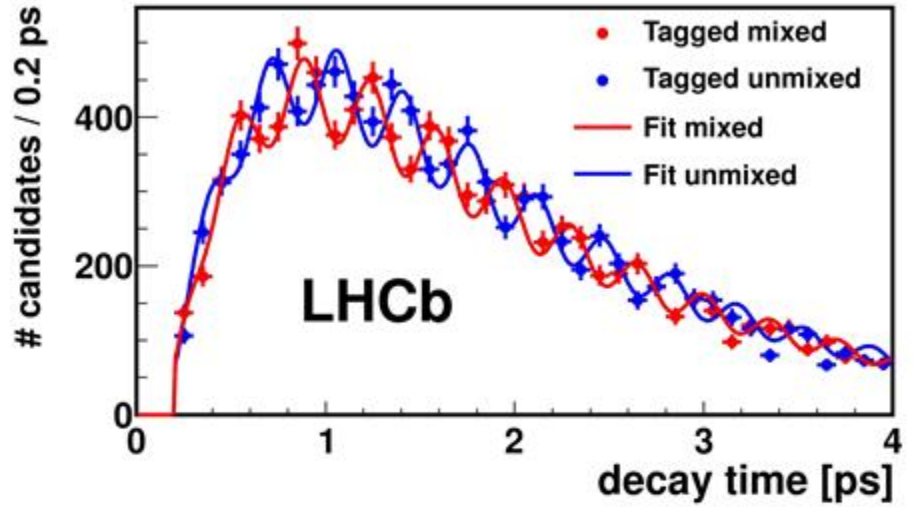
LHCb highlights

- Of course, the CKM unitarity triangle studies
- And particle-antiparticle oscillations of mesons
- Observing very rare decays
- We do also heavy-ion and even fix-target physics, and plenty more…

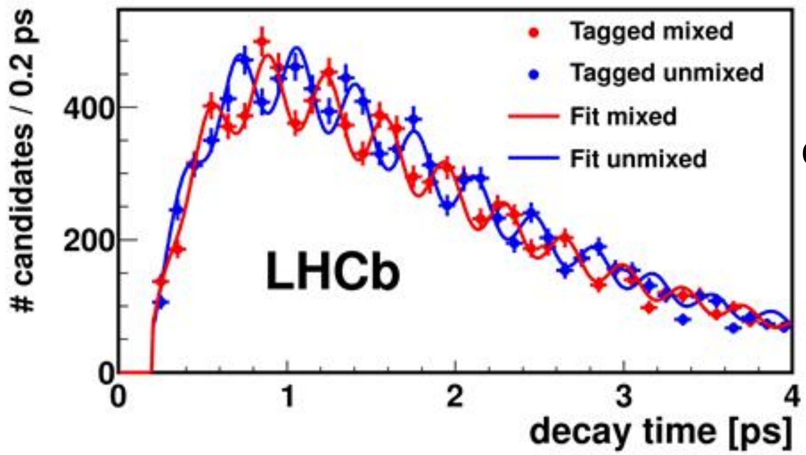




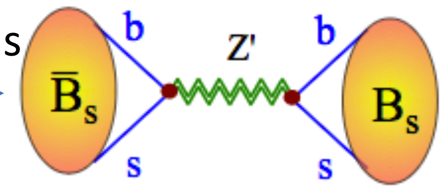


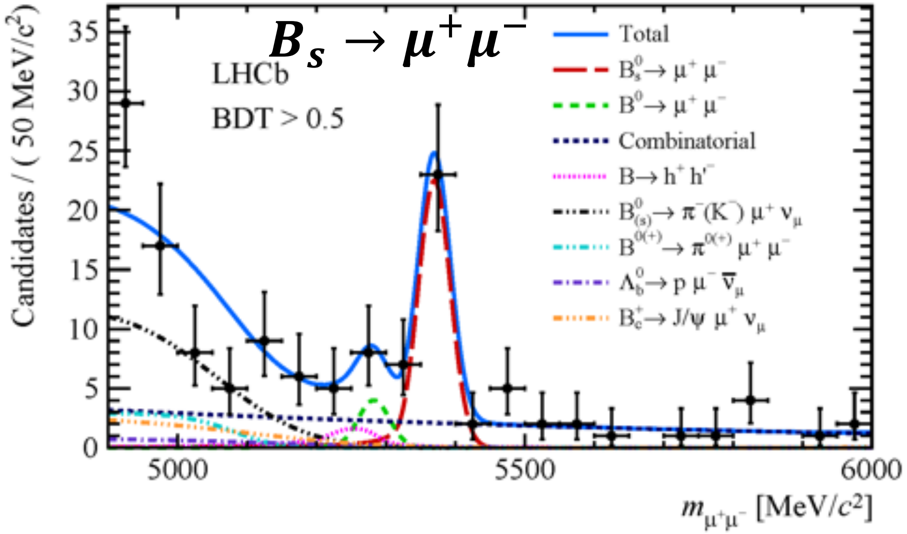


- Putting **indirect** constraints on New Physics models – reaching the scale higher than accessible for the LHC direct searches…



constrains





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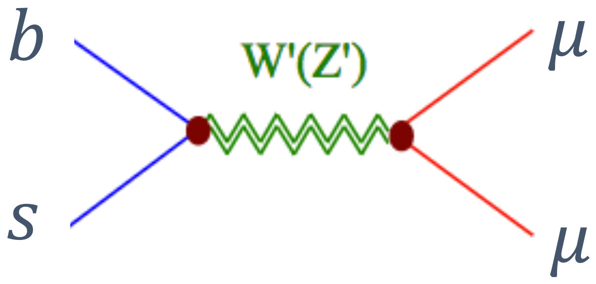
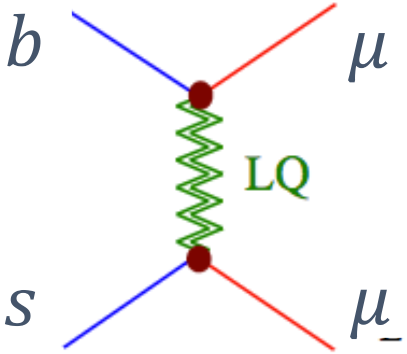




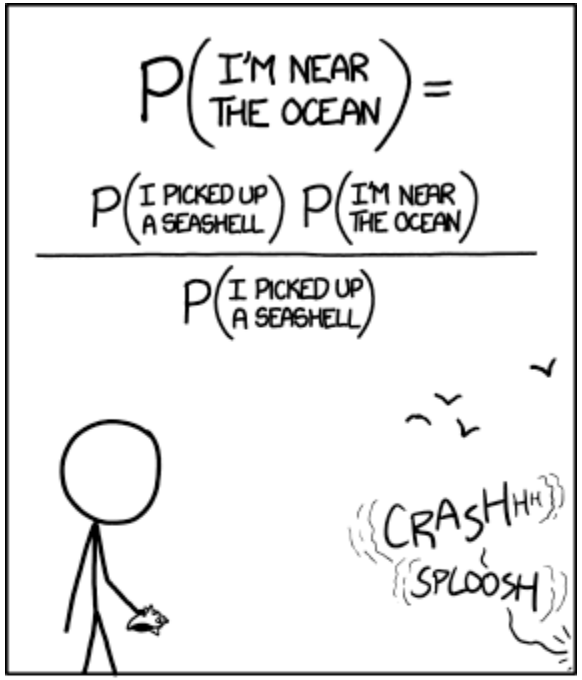
- … But also performing the direct seraches in the forward region

Analysis roadmap

- The decays we want to study are very rare: expect low statistics
- **Normalize** by the decay modes with high statistics to reduce uncertainties
- $R_{pK} = \frac{BR(\Lambda_b \to pK\mu^+\mu^-)}{BR(\Lambda_b \to pKJ/\psi(\mu^+\mu^-))} * \frac{BR(\Lambda_b \to pKJ/\psi(e^+e^-))}{BR(\Lambda_b \to pKe^+e^-)}$, assuming $\frac{BR(J/\psi \to \mu^+\mu^-)}{BR(J/\psi \to e^+e^-)} = 1$

Red: signal modes

Green: normalization modes



MY HOBBY: CANCELLING TERMS

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- What exactly we measure: numbers of events (N) and selection efficiencies (ε)
- $R_{pK} = \frac{N(\Lambda_b \to pK\mu^+\mu^-)}{\varepsilon(\Lambda_b \to pK\mu^+\mu^-)} * \boxed{\frac{\varepsilon(\Lambda_b \to pKJ/\psi(\mu^+\mu^-))}{N(\Lambda_b \to pKJ/\psi(\mu^+\mu^-))} * \frac{N(\Lambda_b \to pKJ/\psi(e^+e^-))}{\varepsilon(\Lambda_b \to pKJ/\psi(e^+e^-))}} * \frac{\varepsilon(\Lambda_b \to pKe^+e^-)}{N(\Lambda_b \to pKe^+e^-)}$

Should be 1 if everything is correct

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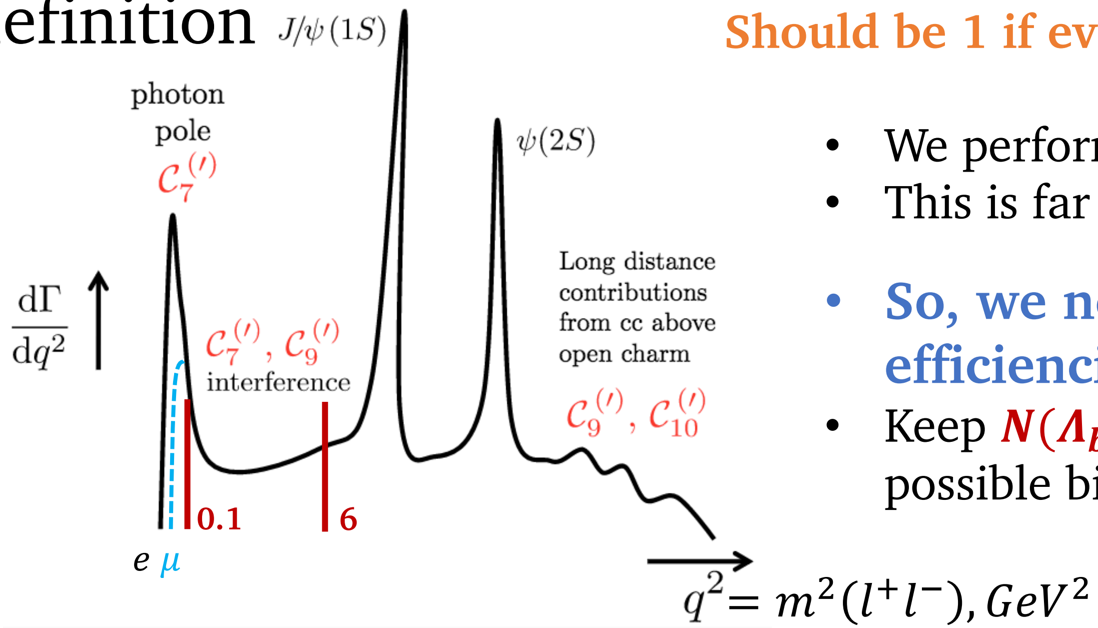
Should be 1 if everything is correct

- q^2 definition



- We perform our measurement in $q^2 = 0.1 \ldots 6\ GeV^2$
- This is far away from phase space edges and charmonia resonances
- **So, we need to measure BRs and corresponding efficiencies for 4 decay modes**
- Keep $N(\Lambda_b \to pKe^+e^-)$ blind until the end of the analysis to avoid possible bias

Way towards the measurement

- Looks simple? Well, not that much…
- Plenty troubles on our way:

Systematic uncertainties

Corrections to the simulation

Electron reconstruction and trigger categories

Bremsstrahlung

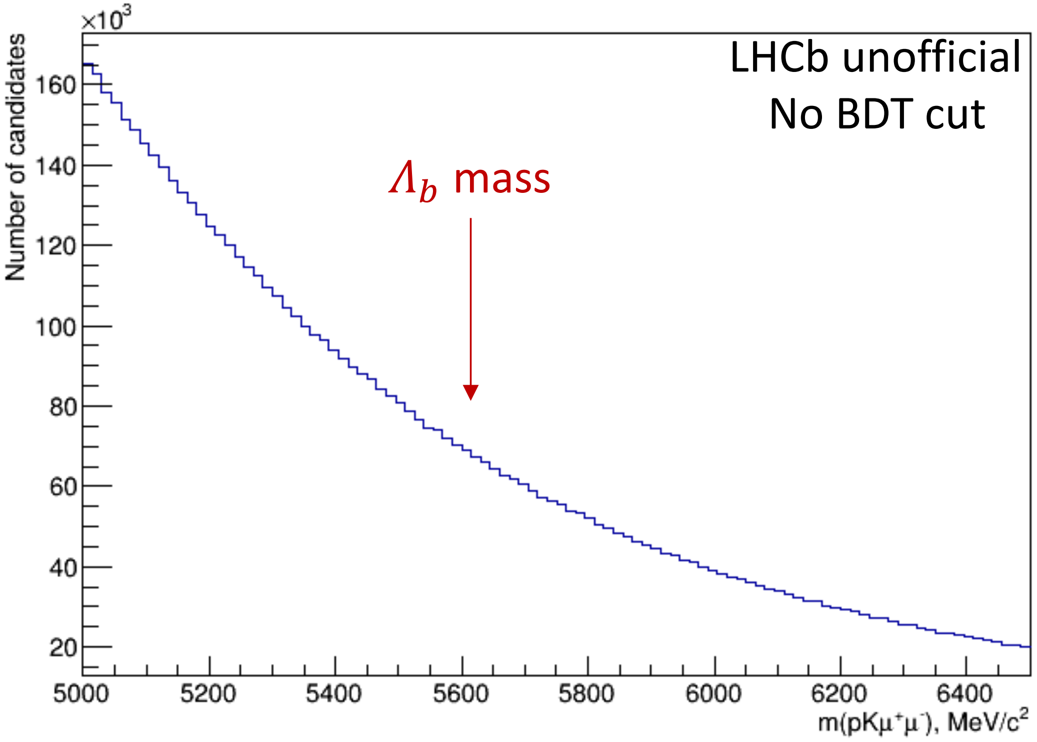
Partially reconstructed backgrounds

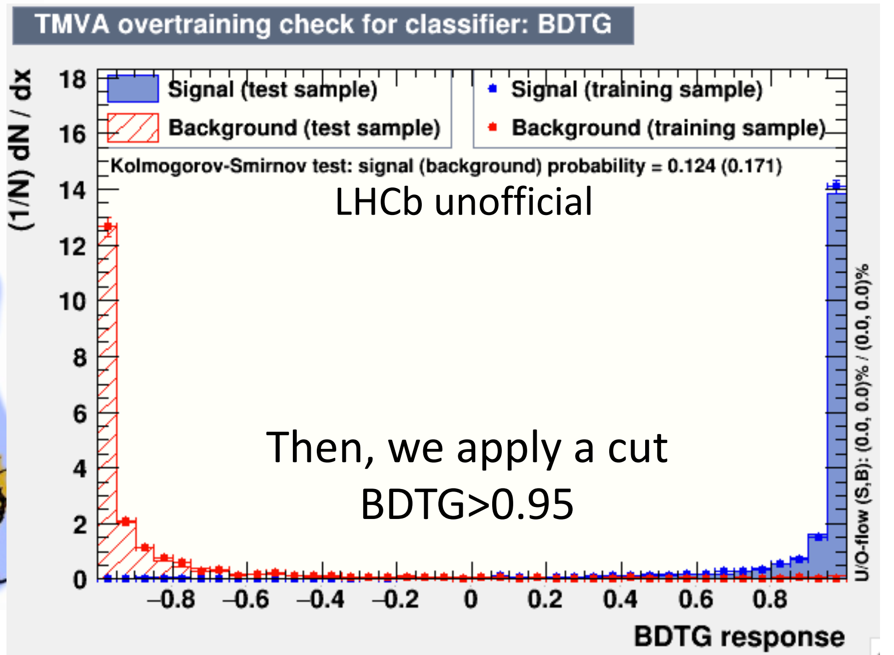
misID backgrounds

Combinatorial background

Problem 1: combinatorial background

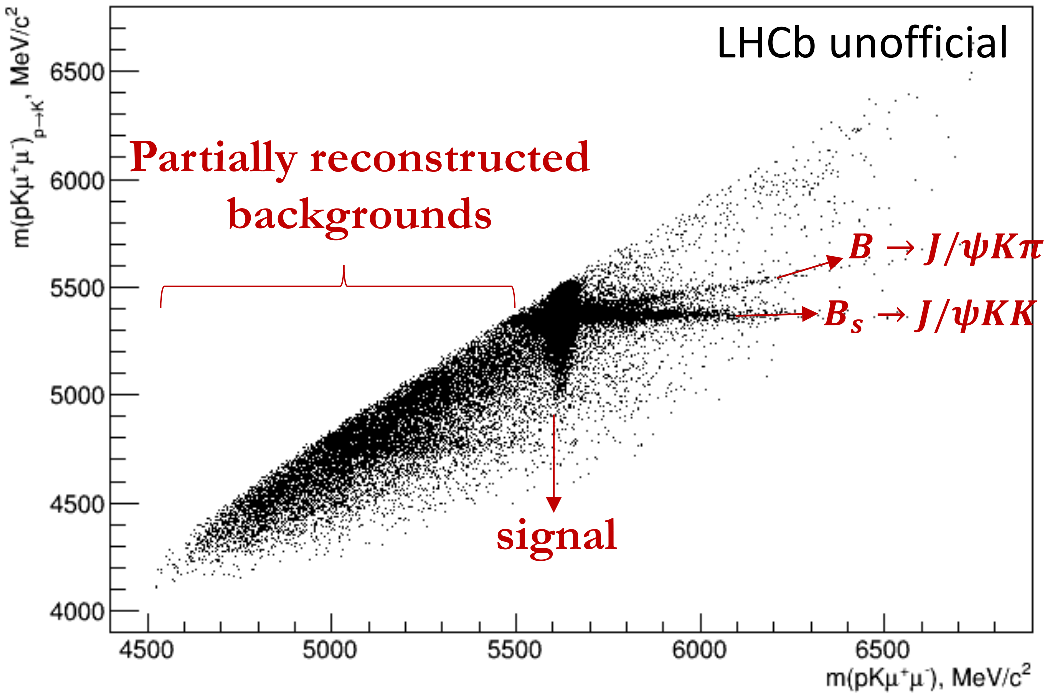
- The most significant background is coming from **combining the random tracks**
- We train a Boosted Decision Tree to distinguish between signal and combinatorial background: one for $\Lambda_b \to pK\mu^+\mu^-$ and another one for $\Lambda_b \to pKe^+e^-$
  - As a signal proxy, we use the signal simulation
  - As a background proxy, we use the upper sideband of the data
  - 21 variables (kinematics and geometry) are used

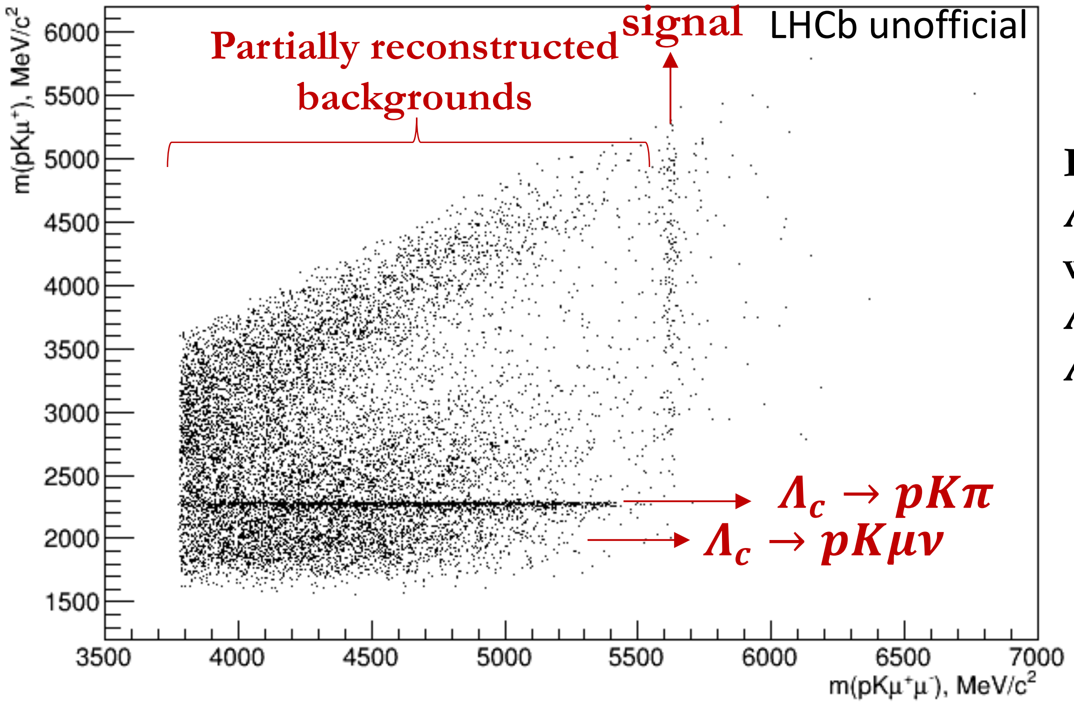




Problem 2: misID and part-reco backgrounds

- After fighting the combinatorial, we still have plenty of background due to misidentification of the final-state particles
  - Even after applying some PID requirements using information from RICH
- For example, misidentifying proton (left) or lepton (right):



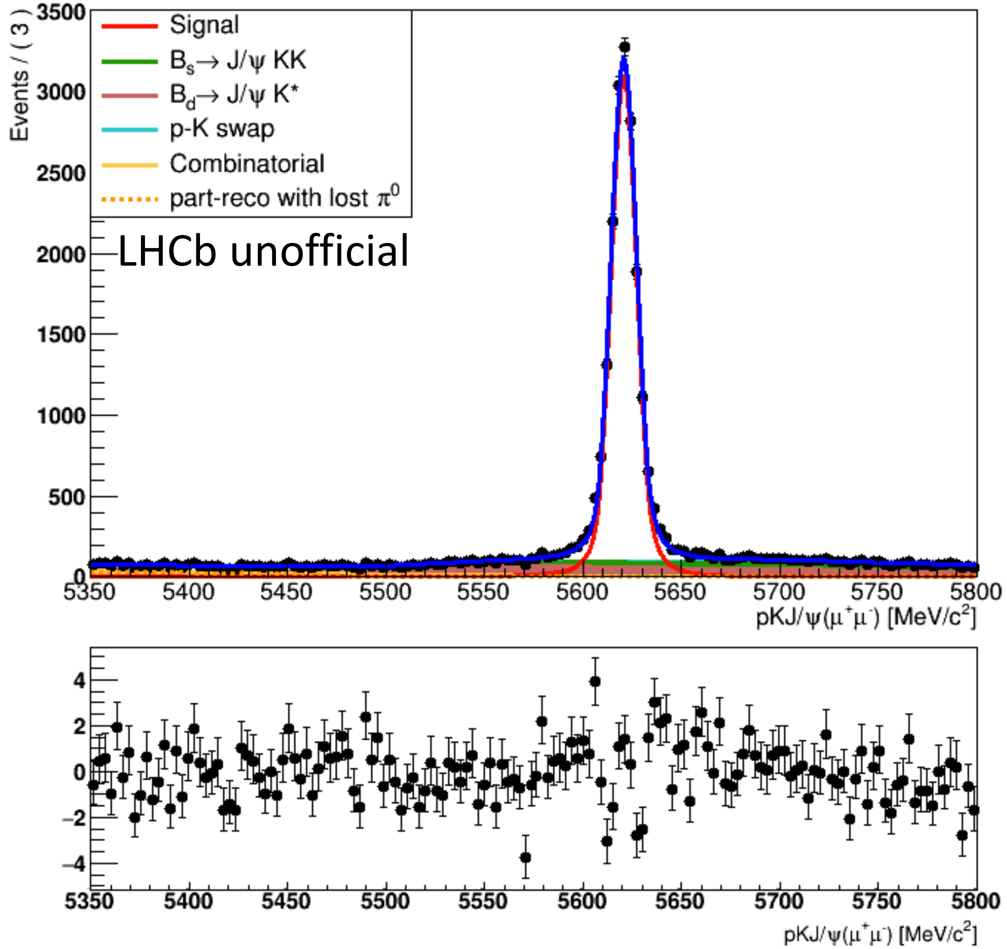


Full decay is $\Lambda_b \to \Lambda_c \mu\nu$ with $\Lambda_c \to pK\pi$ or $\Lambda_c \to pK\mu\nu$

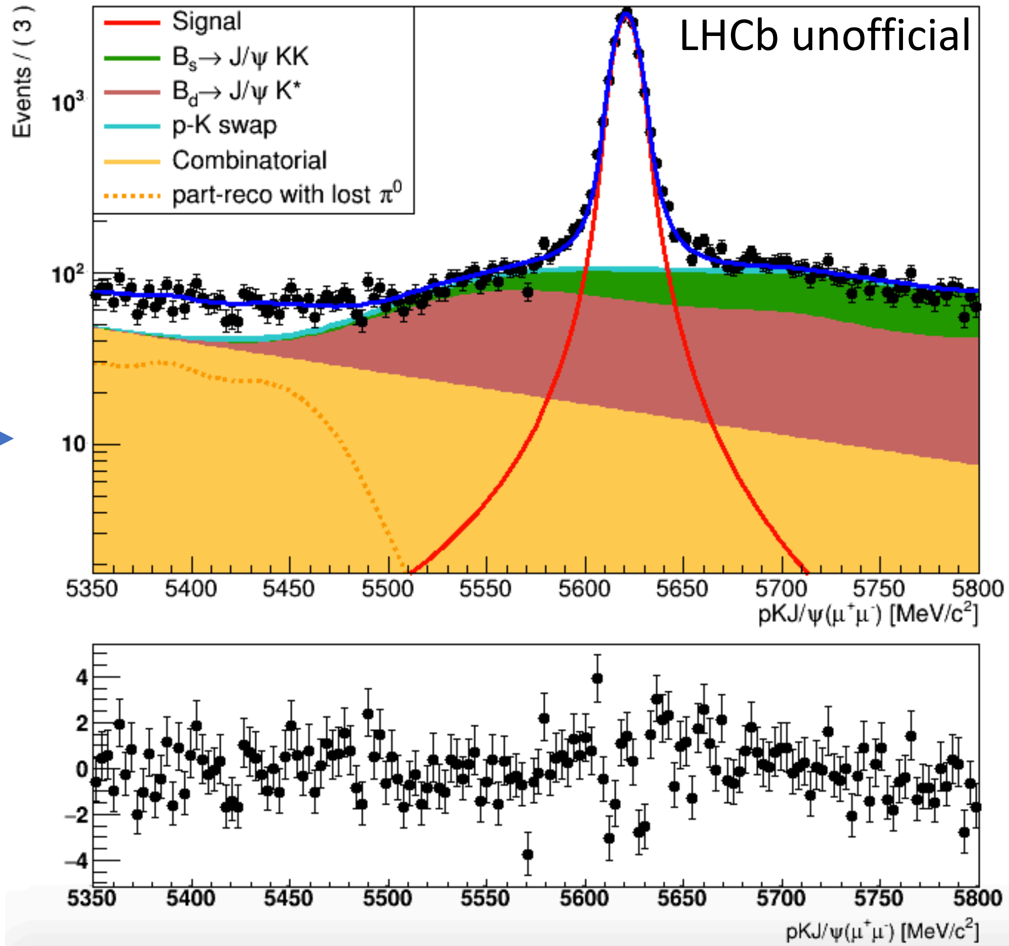
- We veto the backgrounds lying far away from the signal, and include others into the fit

Fitting to the real data

- In the fit, we include the components for the dominant background modes
- This is easy for muonic modes, while more complicated for electrons, because…

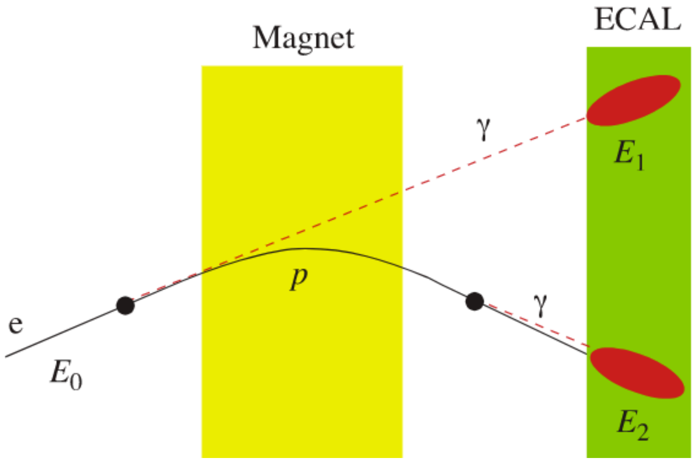


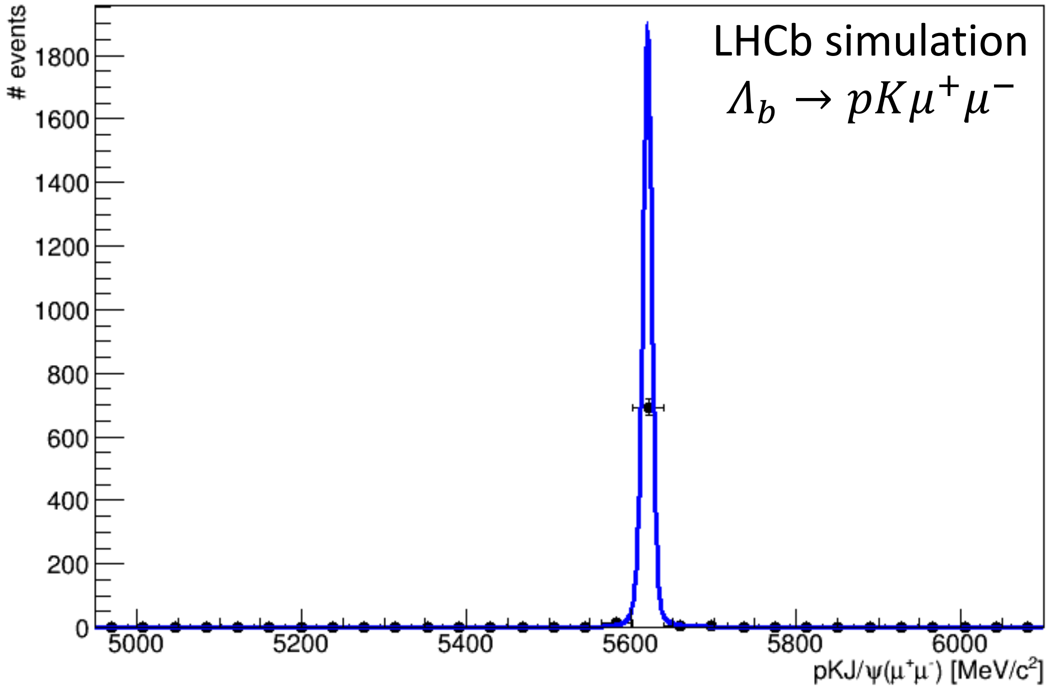
Log scale

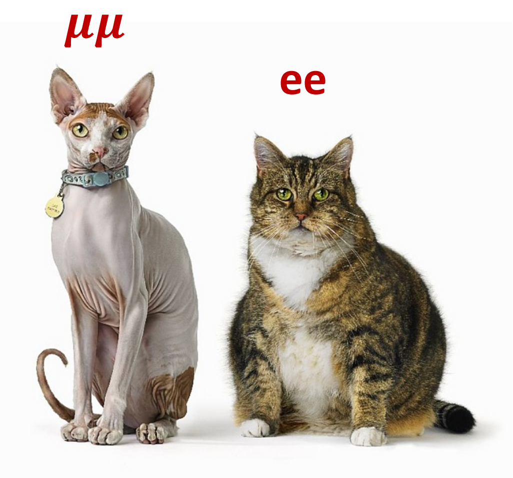


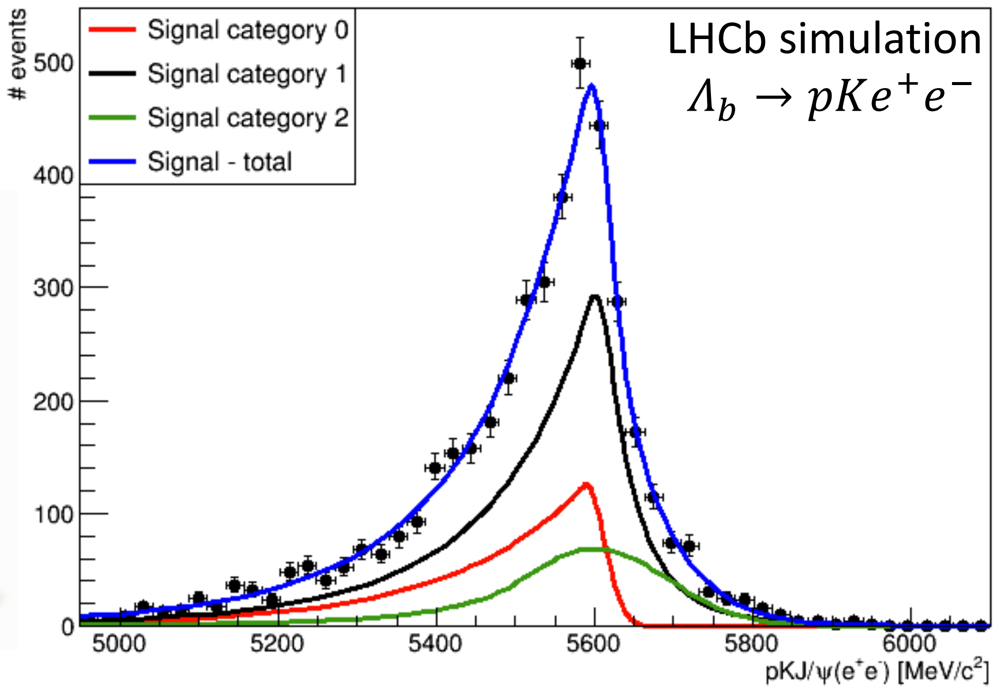
Problem 3: Bremsstahlung

- **Electrons** are very light, so they emit **bremsstrahlung** when travelling in the magnetic field
- To reconstruct the true energy of the electron, we should search for emitted photons and correct for their energy
- It is not always possible to find the 'proper' photon: ECAL is too busy
- Poor resolution on electron modes → study all the backgrounds using muons and transfer the knowledge



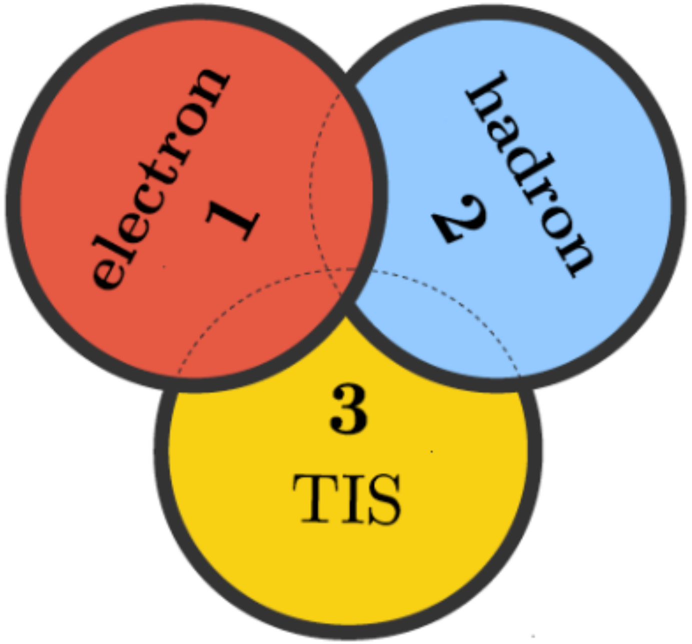






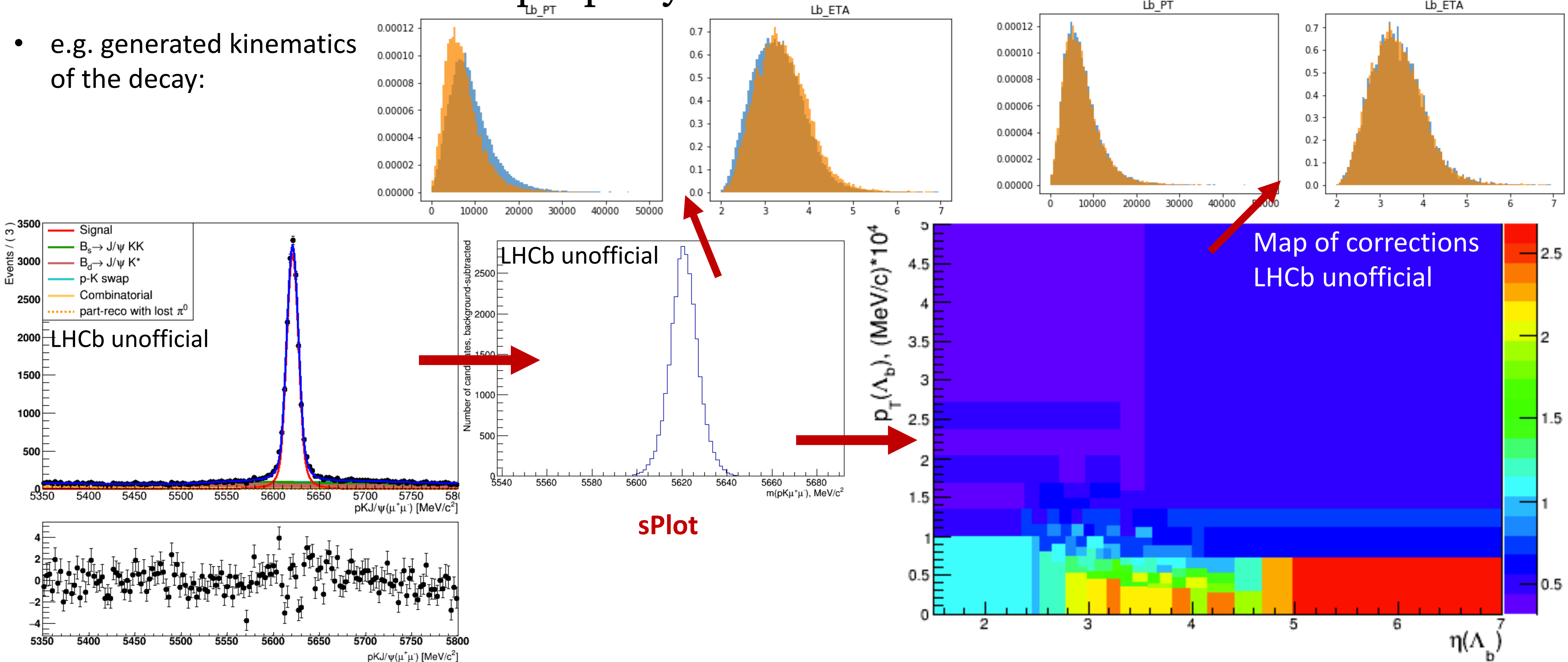
Problem 4: Trigger categories

- As I just said, ECAL is very busy – plenty of electrons, photons and π^0
- Thus, it is hard to trigger on electrons
  - Compare with super-easy triggering on muons: only muons fly through the muon chamber
- To compensate for this effect, we can also **trigger on the hadronic part of the decay** (proton/kaon)
  - or even **independent of signal** (another B, rest of the event)
- Various trigger categories have very different efficiencies
  - Should repeat the analysis 3 times – for each trigger category
  - Dealing with relatively low yields in each of them
  - This increases the systematic uncertainty



Problem 5: Simulation is not perfect

- Some variables are not properly modeled in the simulation:
  - e.g. generated kinematics of the decay:

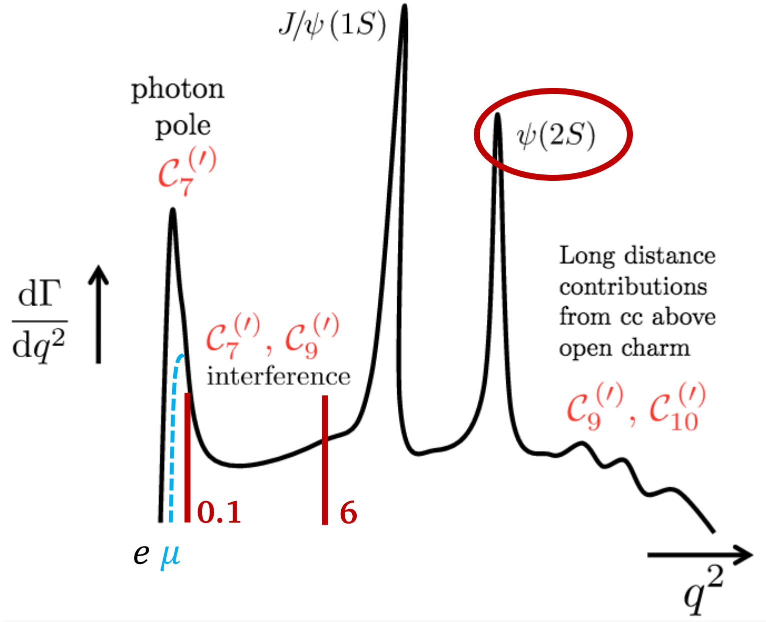


Cross-checks

- So, now we know how to get yields and efficiencies
- Various tests to be performed before unblinding the final result
- $R_{pK} = \frac{N(\Lambda_b \to pK\mu^+\mu^-)}{\varepsilon(\Lambda_b \to pK\mu^+\mu^-)} * \boxed{\frac{\varepsilon(\Lambda_b \to pKJ/\psi(\mu^+\mu^-))}{N(\Lambda_b \to pKJ/\psi(\mu^+\mu^-))} * \frac{N(\Lambda_b \to pKJ/\psi(e^+e^-))}{\varepsilon(\Lambda_b \to pKJ/\psi(e^+e^-))}} * \frac{\varepsilon(\Lambda_b \to pKe^+e^-)}{N(\Lambda_b \to pKe^+e^-)}$

  Should be 1 if everything is correct

  - Should not only be 1, but also independent of kinematical variables (e.g. flat in bins of $p_T(\Lambda_b)$)
- Evaluate separate BRs and compare to PDG
  - $BR(\Lambda_b \to pK\mu^+\mu^-)$
  - $BR(\Lambda_b \to pK\psi(2S))$ **with** $\psi(2S) \to \mu^+\mu^-$ **or** e^+e^-
  - $BR(\Lambda_b \to pK\gamma)$ **with conversions** $\gamma \to e^+e^-$
  - …



Conclusions

- LHCb is a perfect device to study the decays of B hadrons
- And this perfect device tells us that penguin decays with muons in the final state are **less abundant** than those with electrons
  - Which is in some contradiction with SM
  - And if confirmed, **requires new particles** to exist
- Additional measurements are needed to confirm or reject the current observations
  - On the LHCb side, we accumulate statistics to improve previous measurements, and explore new decay modes (of $B^{+/0}$,B_s^0, Λ_b^0)
  - **Performing a first ever search for LU violation in baryonic sector!**
  - Also waiting for an input from BELLE-II (only decay modes of $B^{+/0}$) – competition is coming!
- Stay tuned: new results are coming!