Test of Lepton Universality using Λ_b decays

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LHCb experiment

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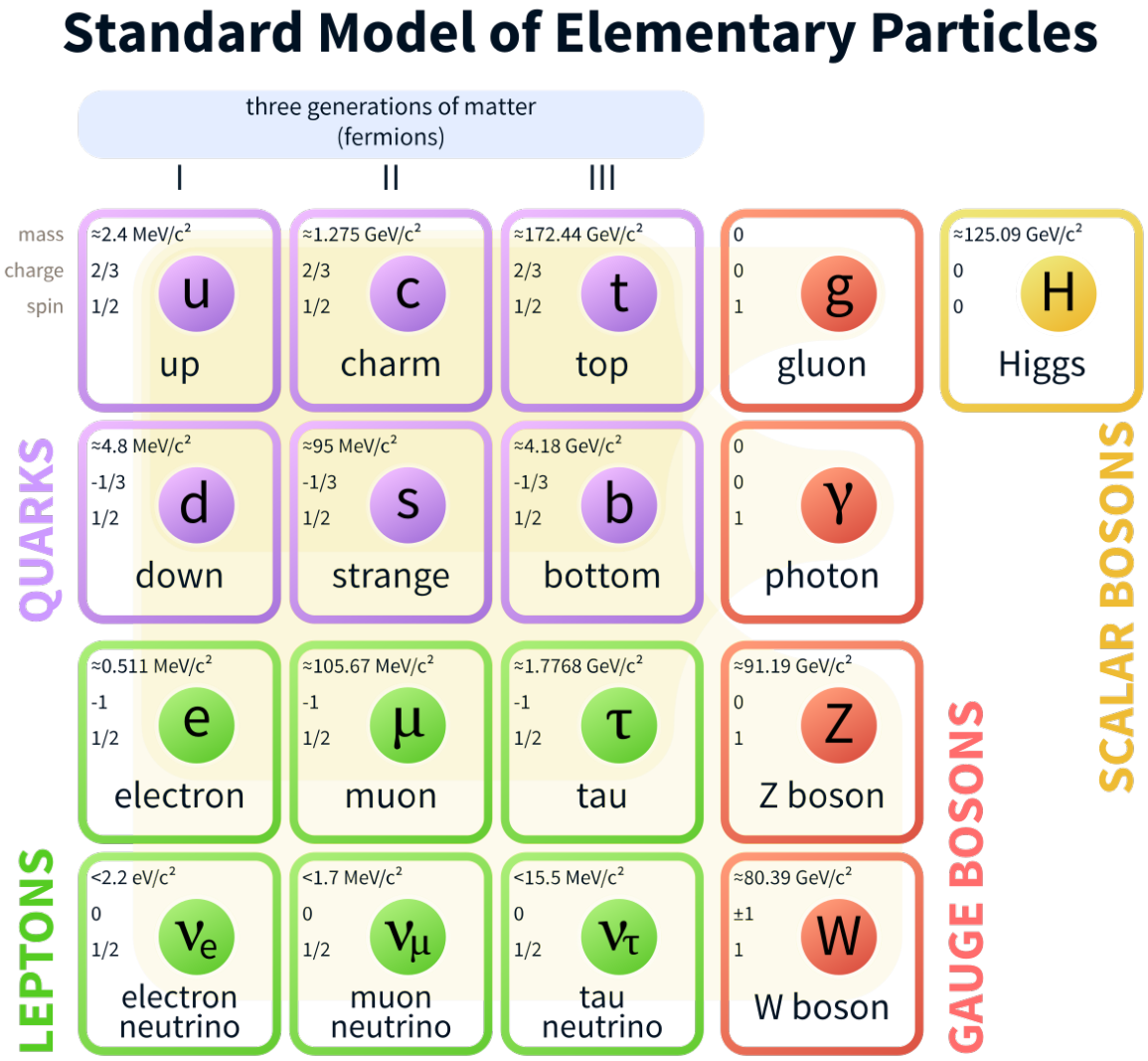
The Standard Model



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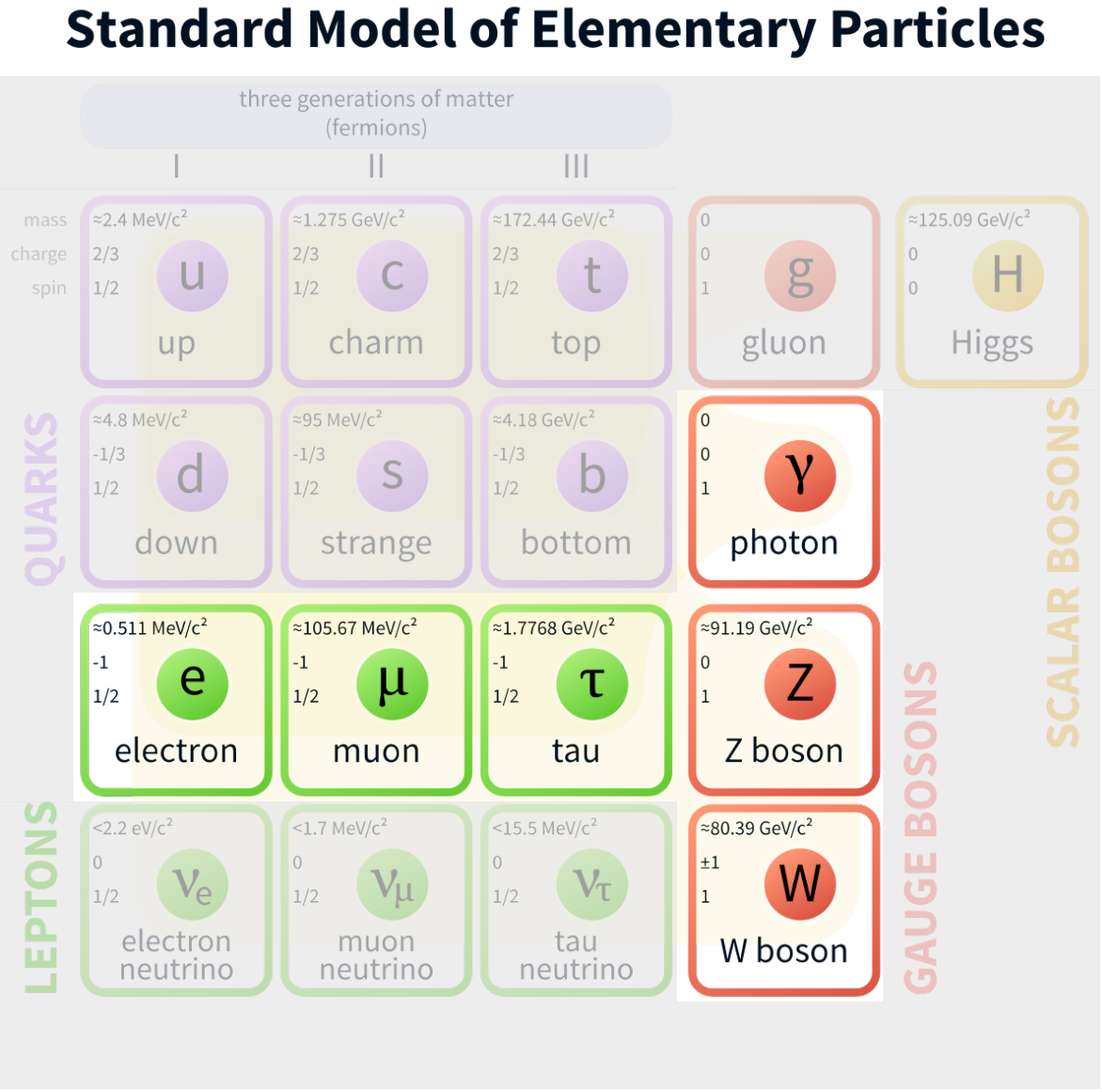
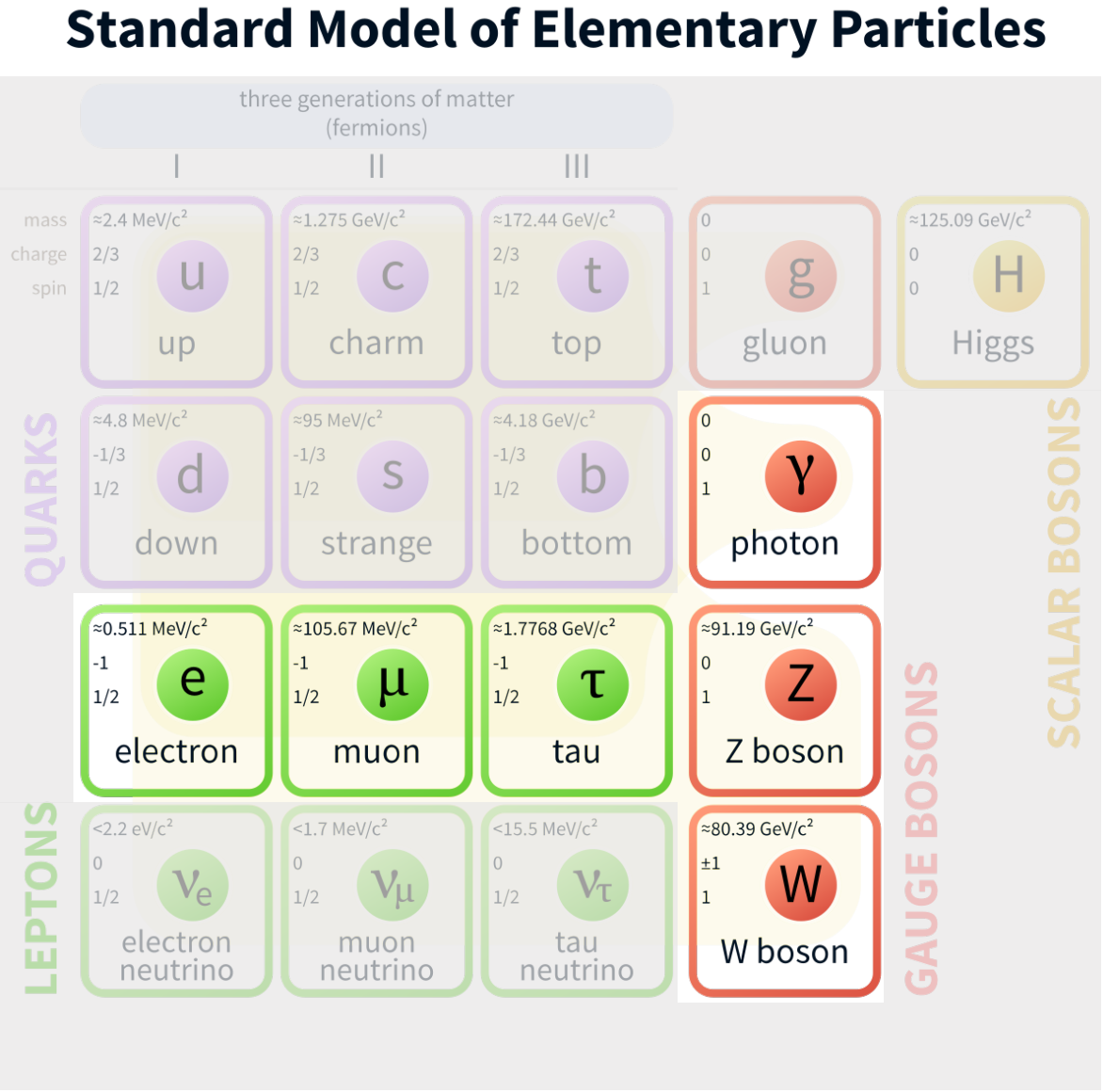


- **SM: couplings of all (charged) leptons to the gauge bosons should be identical**
  - (up to the order of mass/phase-space corrections)
- This means e.g. $\frac{BR(Z\to\mu^+\mu^-)}{BR(Z\to e^+e^-)} = 1$
  - Here, BR is 'branching ratio' – probability of such a decay to occur

Decay Modes

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



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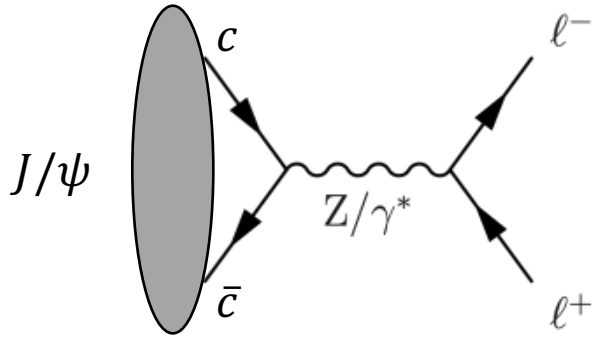
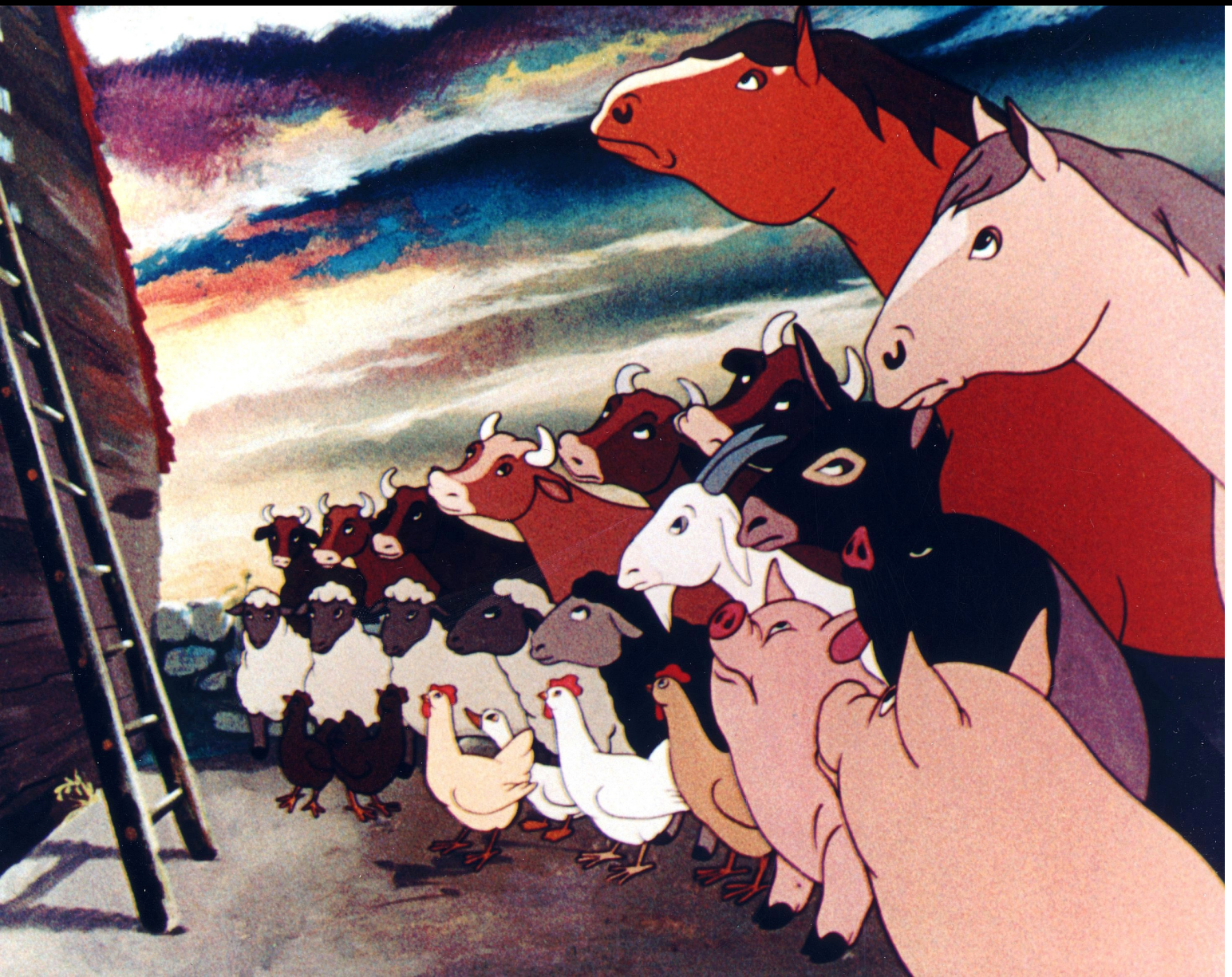
- This means e.g. $\frac{BR(Z\to\mu^+\mu^-)}{BR(Z\to e^+e^-)} = 1$
  - Here, BR is 'branching ratio' – probability of such a decay to occur
  - Should be also true for virtual off-shell Z or γ
  - This implies e.g. $\frac{BR(J/\psi\to\mu^+\mu^-)}{BR(J/\psi\to e^+e^-)} = 1$



$l = e$ or μ

- This property is called **Lepton Universality**

So, the Standard Model works?



- Well, all the ~~animals~~ leptons are equal, but some leptons…
- …are more equal than others?

Slide credits: V.Gligorov

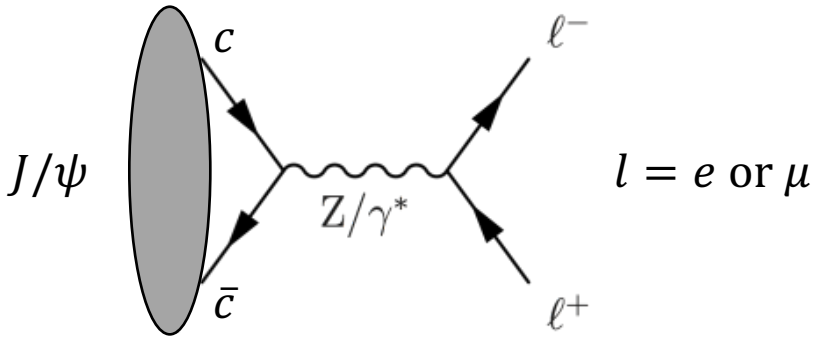
Insidious penguins

Tree-level decays

Very abundant (BR=10^{-2})

In excellent agreement with SM

Lepton-universal



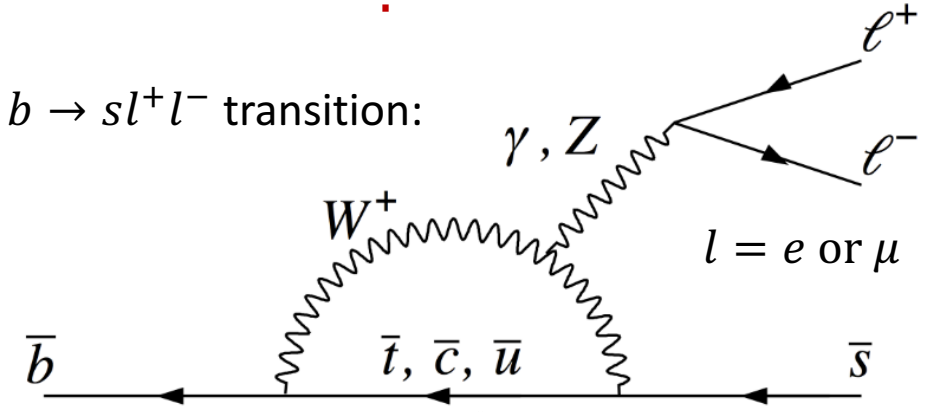
Penguin decays

Very rare (BR=10^{-7})

Sensitive to New Physics contributions

?

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

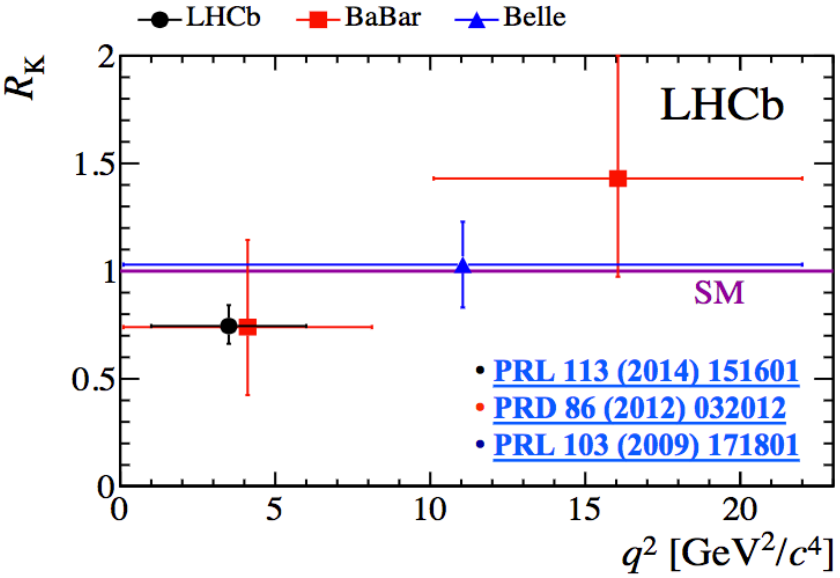


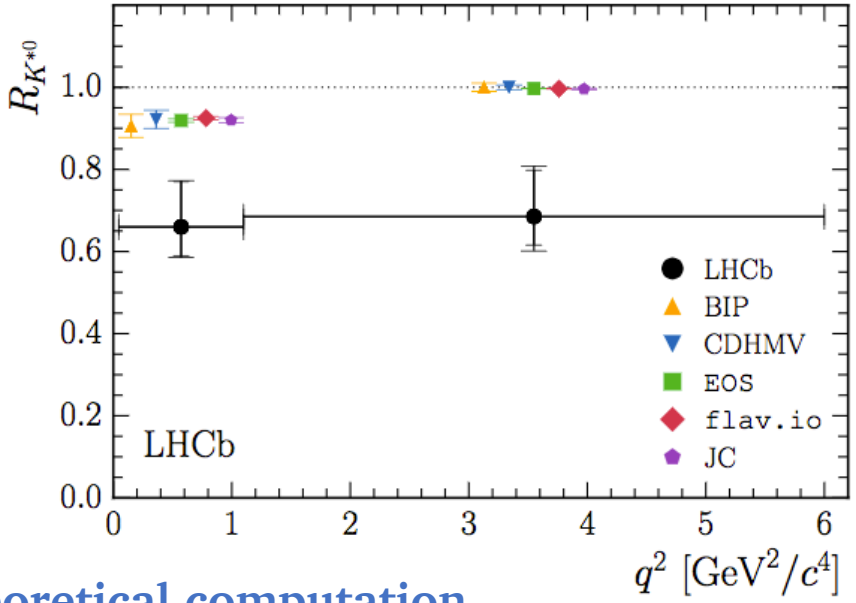
Ratios of ratios of ratios…

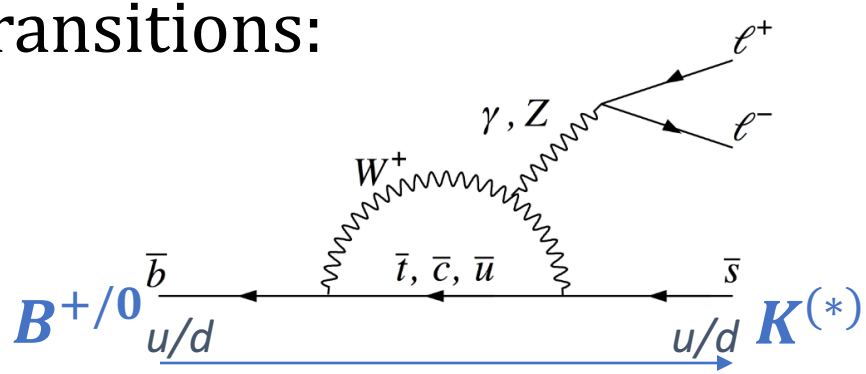
- Few remarkable measurements in the $b \to s l^+ l^-$ transitions:

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

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





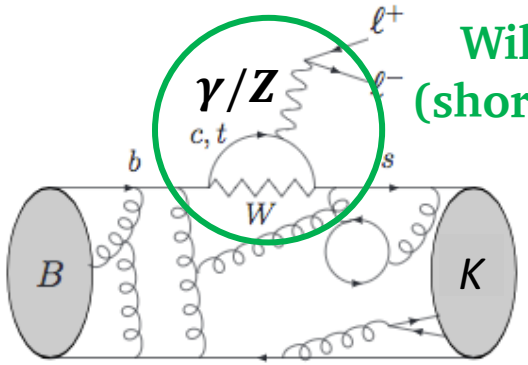


Ratios: very precise theoretical computation
Cancellation of theoretical and experimental uncertainties

- Additional anomalies in angular analyses and absolute BR values
- New measurements from LHCb and BELLE II awaited

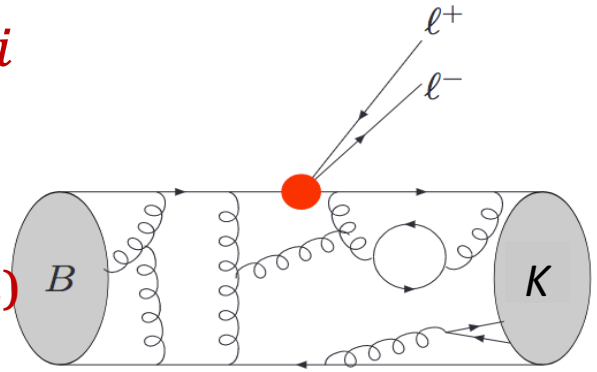
Theorist's point of view

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



Wilson coefficients
(short-distance effects)

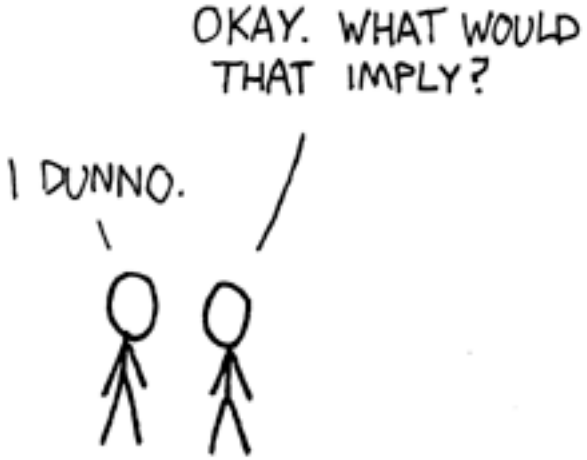
Local operators
(long-distance hadronic effects)



- Precise predictions in the SM:

Soft photon photon/Z Z

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



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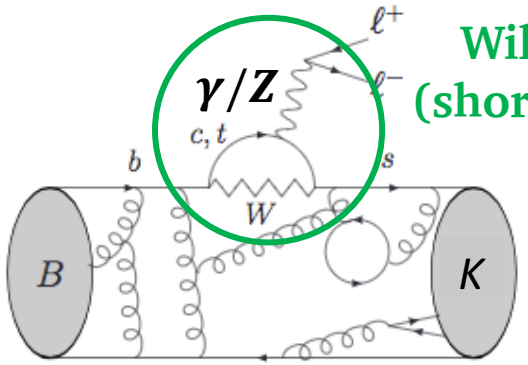

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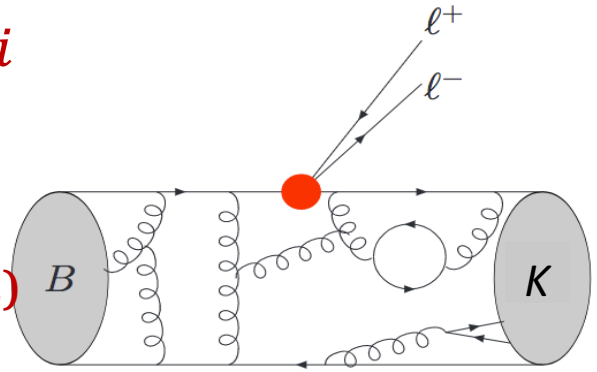


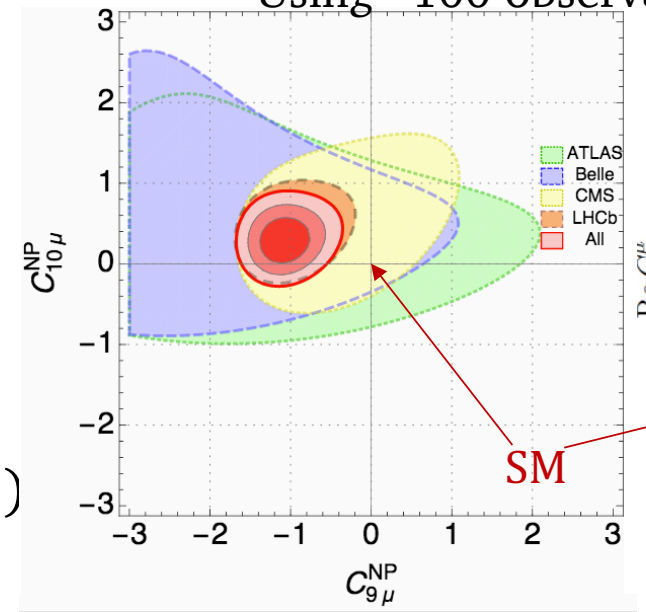
- Precise predictions in the SM:

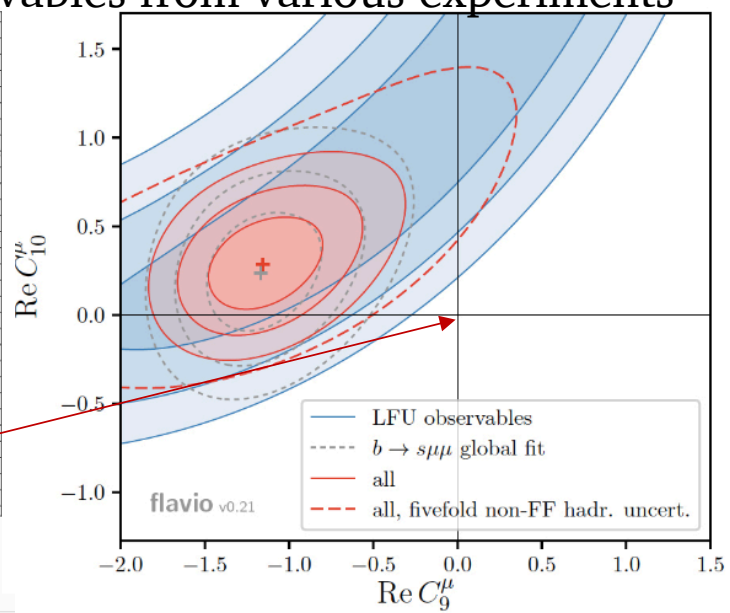
Soft photon photon/Z Z

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

- To describe New Physics:
  - $C_{i(exp)} = C_{i(SM)} + C^{l}_{i(NP)}$
- These effects look **coherent**
- Strong evidence for non-zero $C^{\mu}_{9(NP)}$

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





Penguins or...?

Standard Model penguins

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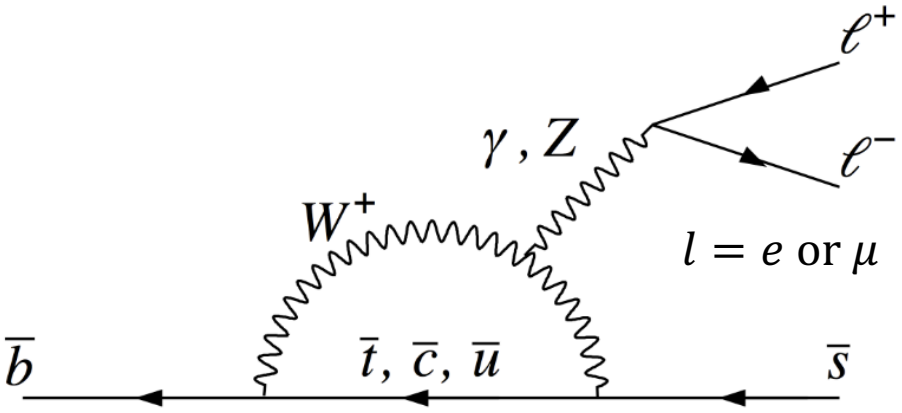
Standard Model penguins

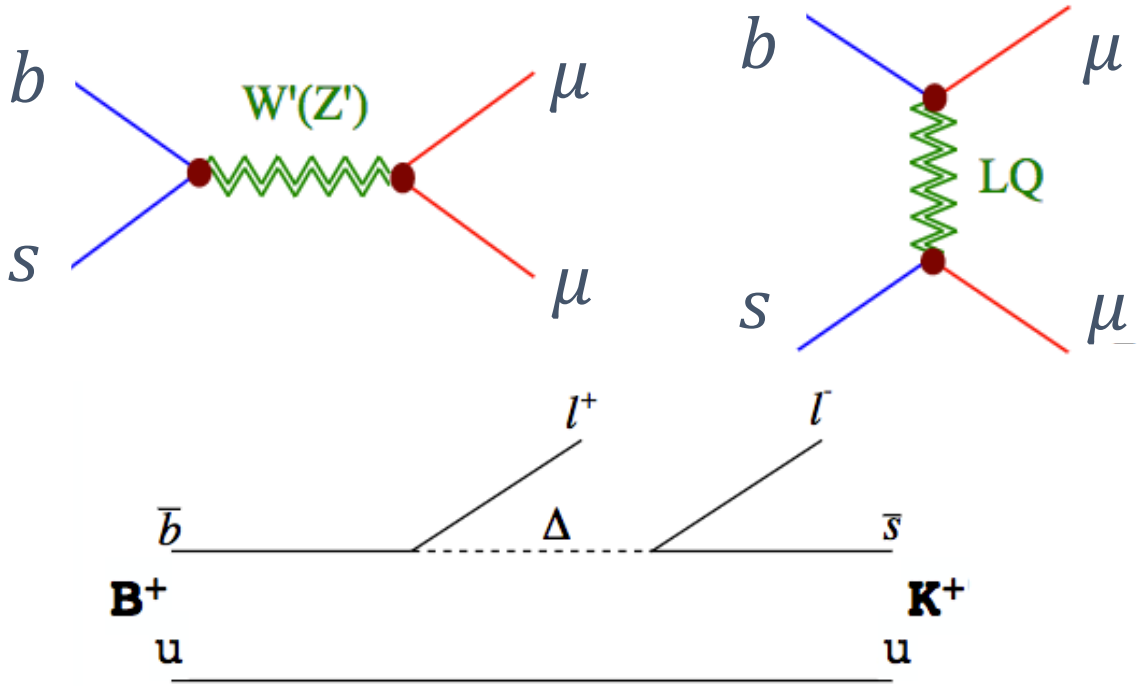
New Physics

Power or indirect searches

Standard Model penguins



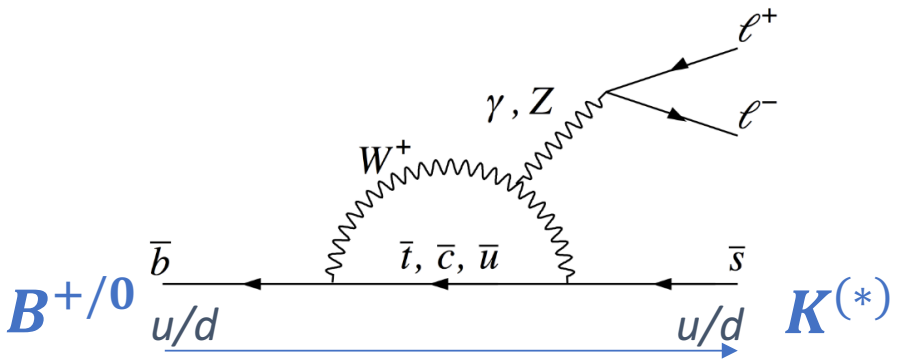
New Physics

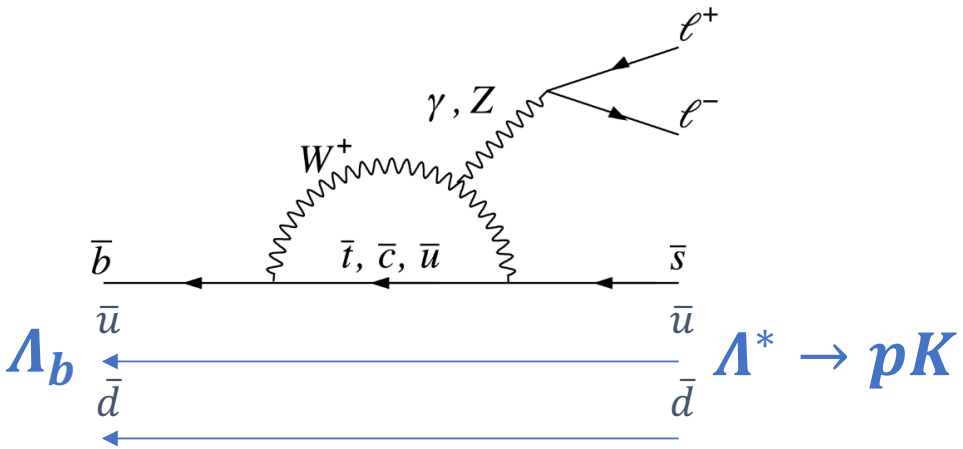


- Most popular scenarios:
  - Z'
  - Leptoquarks
- In any case, these new particles should be accessible for direct observation at ATLAS and CMS in near future

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
- **We want to measure $R_{pK} = \frac{BR(\Lambda_b \to pK\mu^+\mu^-)}{BR(\Lambda_b \to pKe^+e^-)}$**

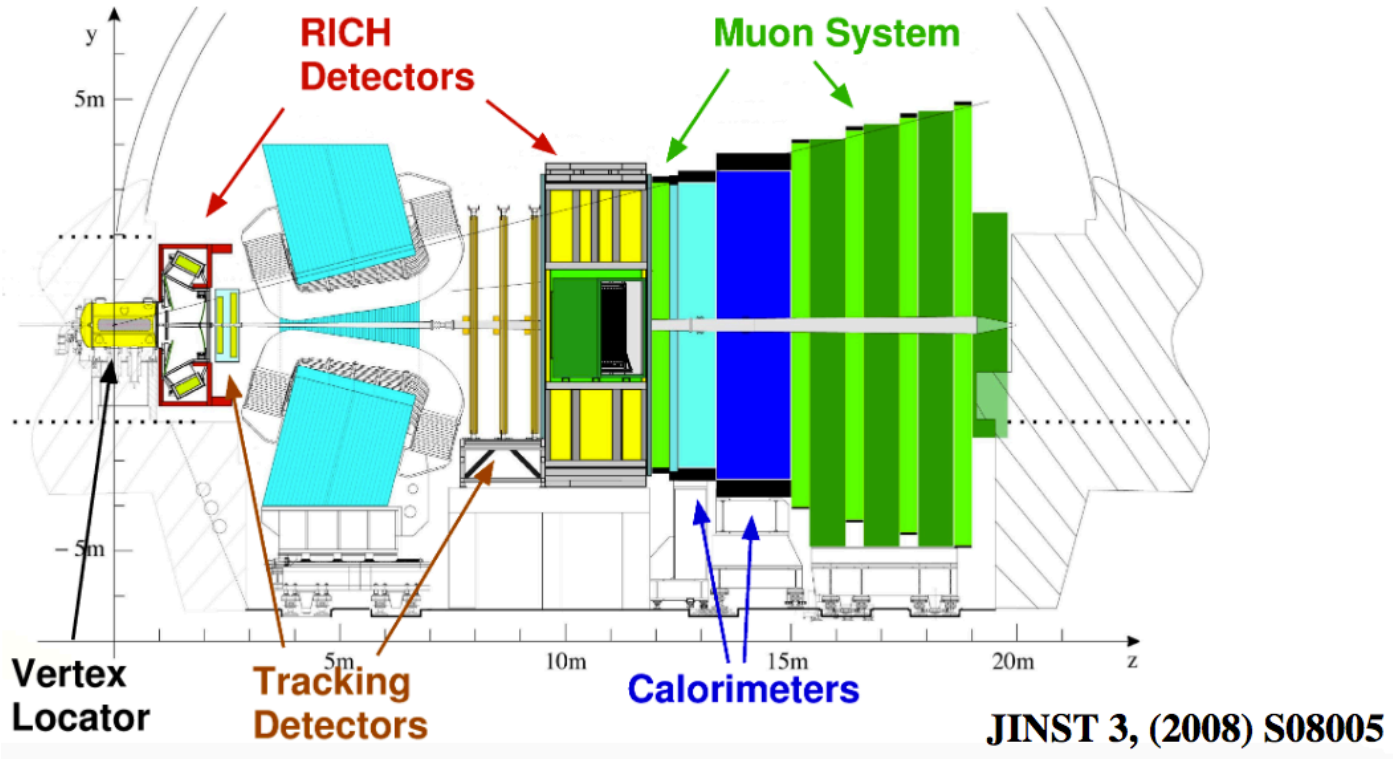




The penguin laboratory

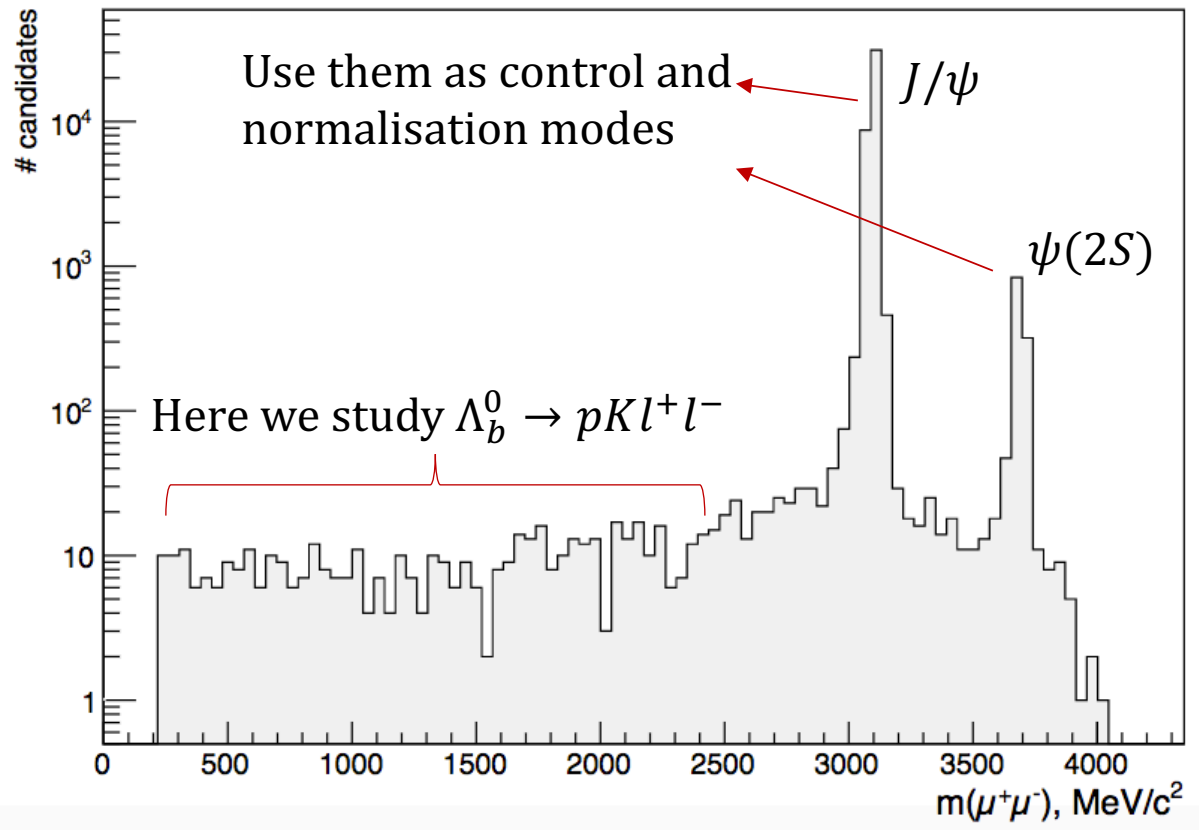
- How to build a proper detector to study $\Lambda_b^0 \to pKl^+l^-$ decays?

- **Our wish list:**
- Good acceptance of b-hadrons
- Good primary vertex resolution
- Good hadron PID
- Muon and electron PID
- Good invariant mass resolution
- Trigger on these events
- Reasonable size and cost



Backgrounds which help

- This is how the di-muon invariant mass looks in the $\Lambda_b^0 \to pK\mu^+\mu^-$ decay
- Two peaks are due to tree-level $\Lambda_b^0 \to pKJ/\psi(\to \mu^+\mu^-)$ and $\Lambda_b^0 \to pK\psi(2S)(\to \mu^+\mu^-)$ decays
  - Have nothing to do with penguins
  - Still, they are a nice reference for cross-checks
  - Most importantly, they are lepton-universal

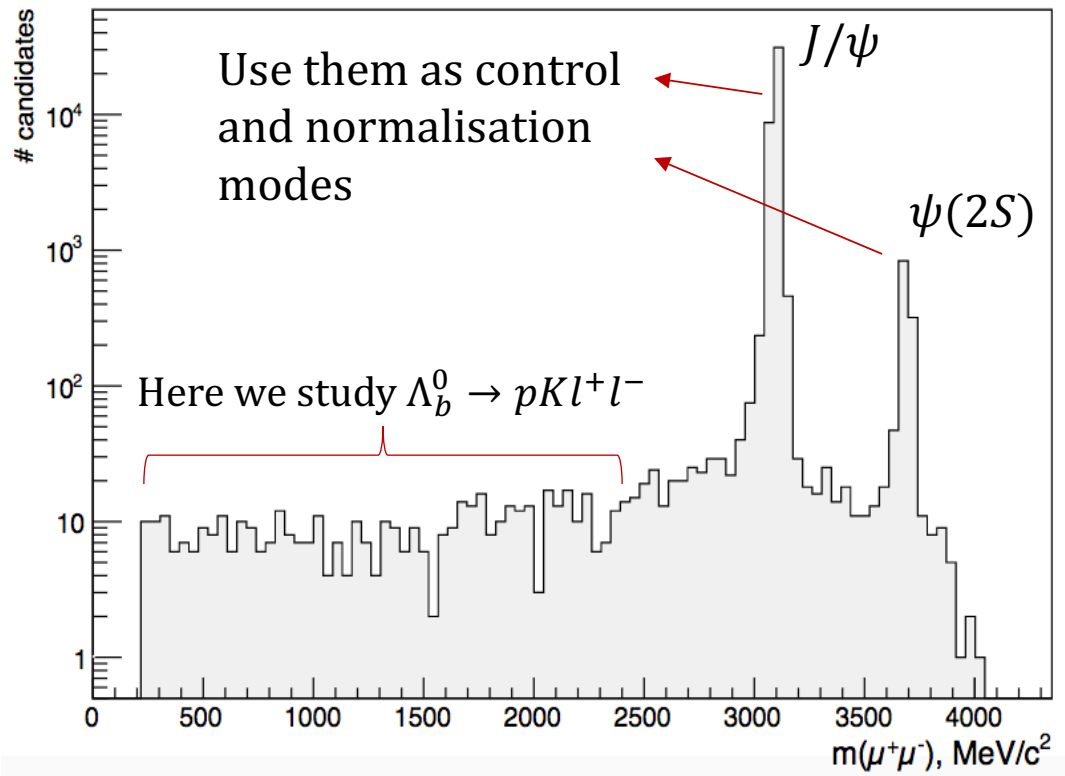


The global strategy of the analysis

1) Compute $r_{J/\psi} = \frac{BR(\Lambda_b^0 \to pKJ/\psi(\to e^+e^-))}{BR(\Lambda_b^0 \to pKJ/\psi(\to \mu^+\mu^-))}$

- It should be a) equal to one and b) independent of the kinematical variables
- Very strong control of efficiencies, powerful cross-check

2) Same for $r_{\psi(2S)} = \frac{BR(\Lambda_b^0 \to pK\psi(2S)(\to e^+e^-))}{BR(\Lambda_b^0 \to pK\psi(2S)(\to \mu^+\mu^-))}$



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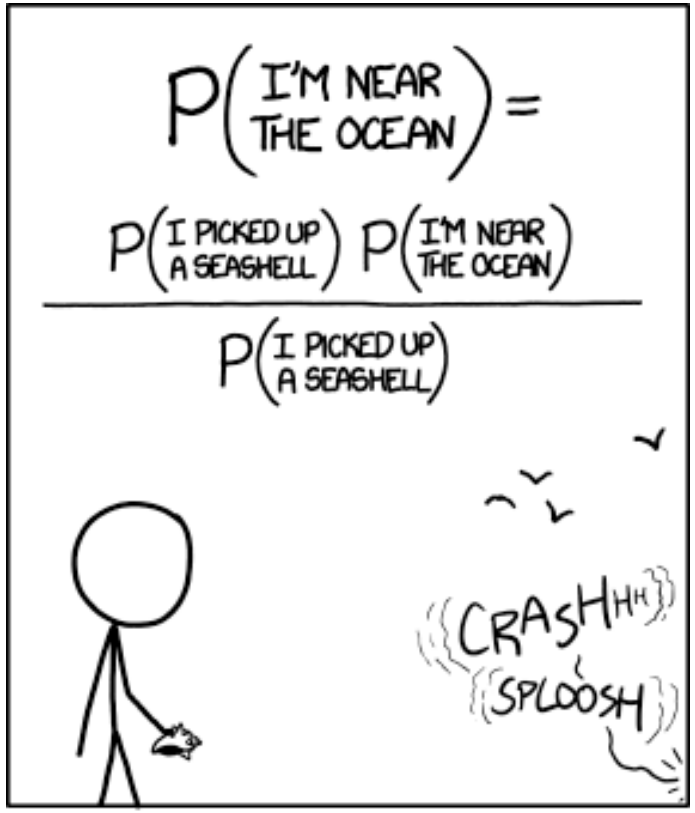
3) Compute the double ratio

$$R_{pK} = \frac{BR(\Lambda_b \to pK\mu^+\mu^-)}{BR(\Lambda_b \to pKJ/\psi(\mu^+\mu^-))} * \frac{BR(\Lambda_b \to pKJ/\psi(e^+e^-))}{BR(\Lambda_b \to pKe^+e^-)}$$

- Normalize to high-statistics modes
- Cancel some uncertainties



MY HOBBY: CANCELLING TERMS

Easy? Well, not so much

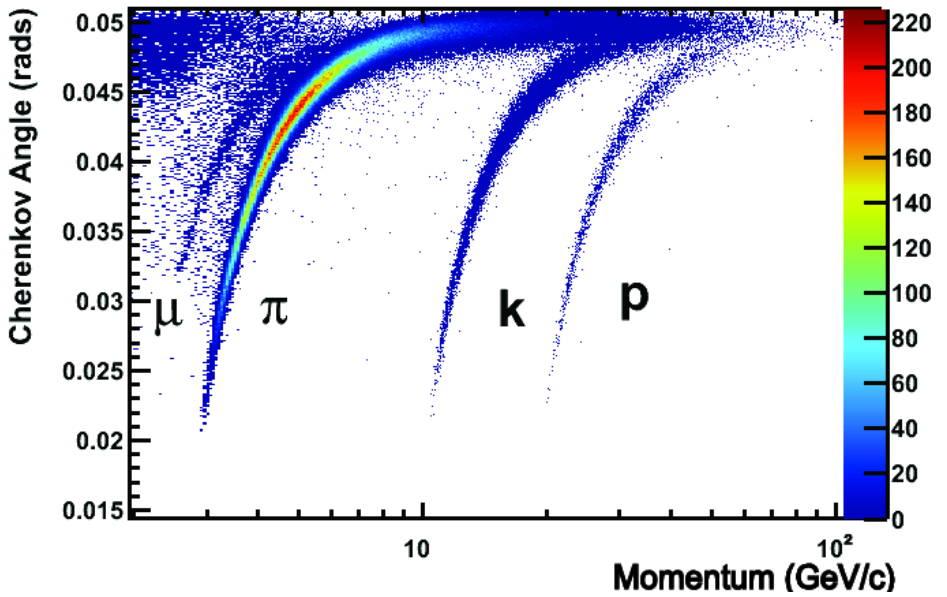
Troubles on our way

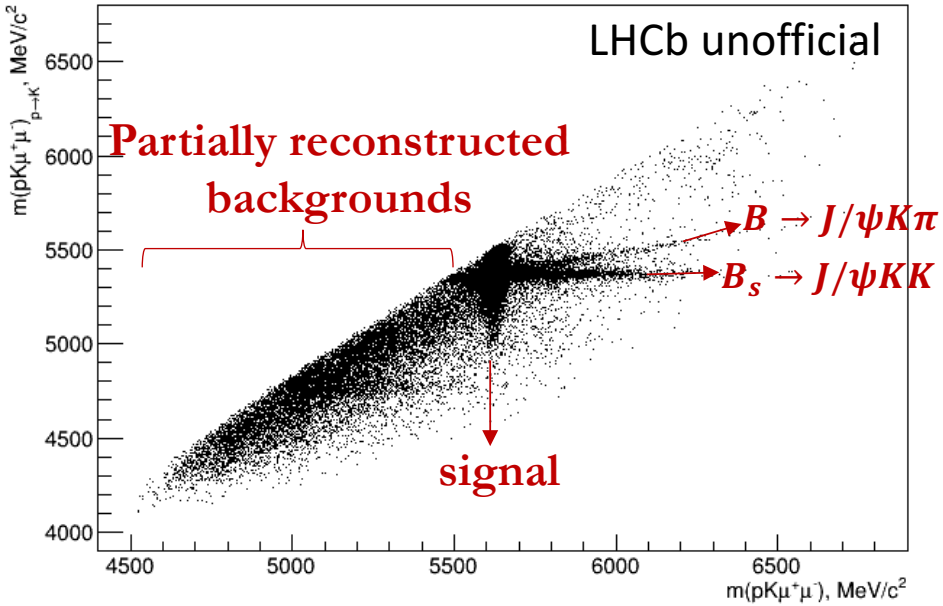
Some key beasts to fight:

- Systematic uncertainties
- Corrections to the simulation
- Electron reconstruction and trigger categories
- Bremsstrahlung
- Partially reconstructed backgrounds
- misID backgrounds
- Combinatorial background

Backgrounds which are not nice

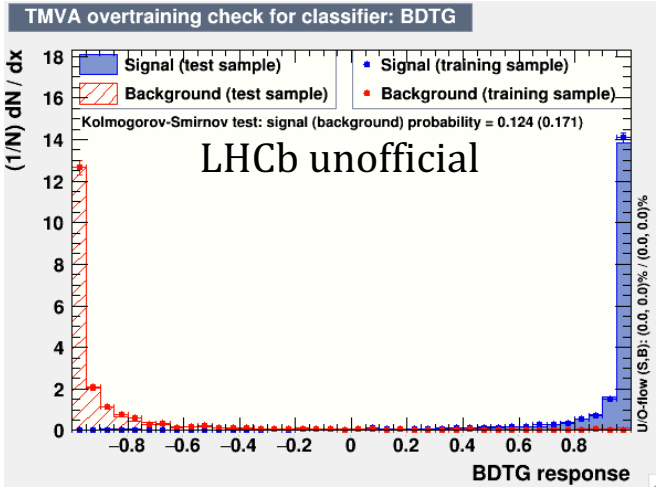
- Misidentifications
  - Region of proton momentum lower than 20 GeV does not have a good PID
  - Apply a cut above 10 GeV
  - Include the rest into the fit
  - $B_s \to KKl^+l^-$, $B^0 \to \pi Kl^+l^-$, swaps…
- Partially reconstructed backgrounds
  - One or more particles can be lost
  - In particular, 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
- Combinatorial background

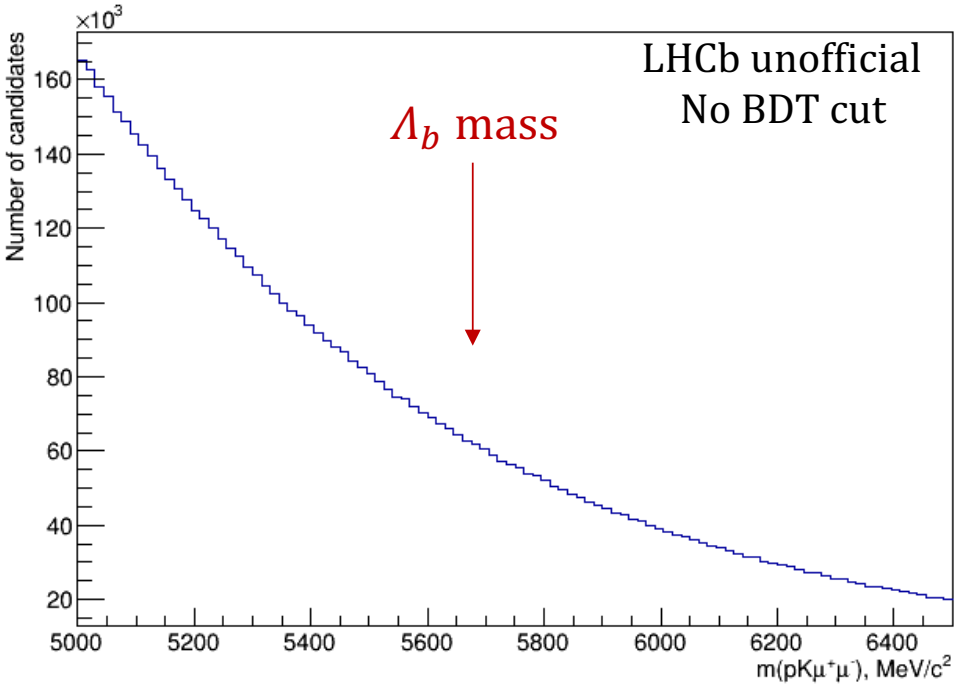


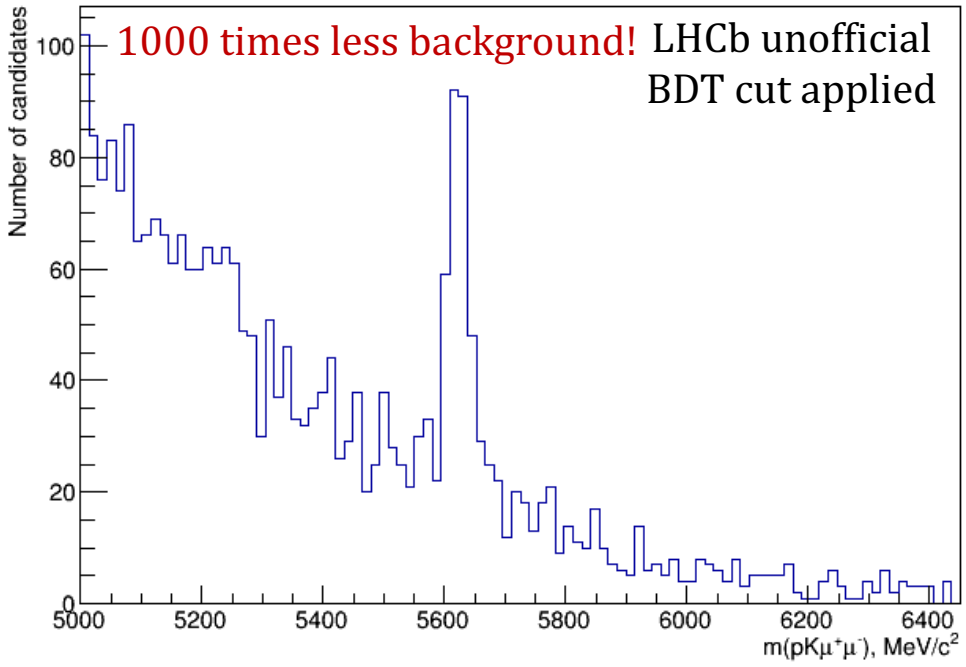


But there's an elephant in the room

- The most significant background is coming from **combining the random tracks**
- We train a Boosted Decision Tree to distinguish between signal and combinatorial background
- Exploit the difference in kinematics and geometry

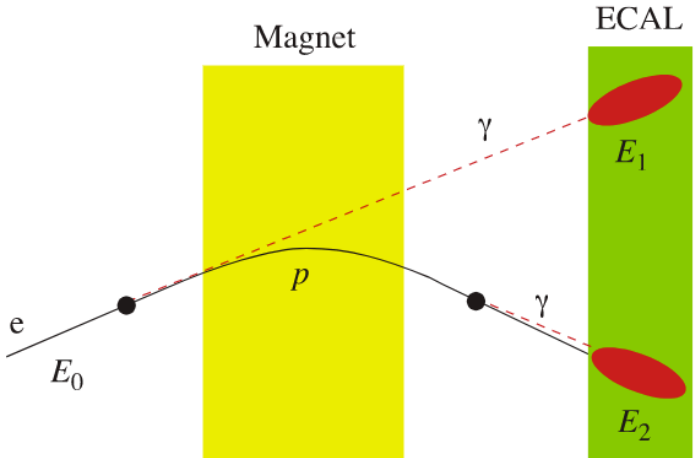


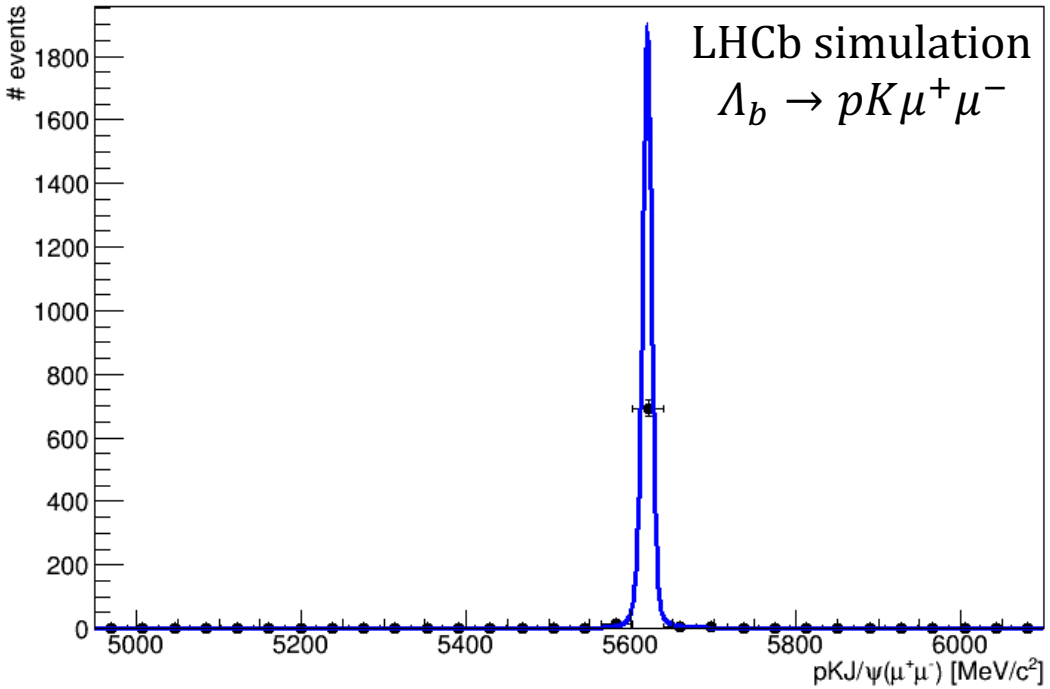


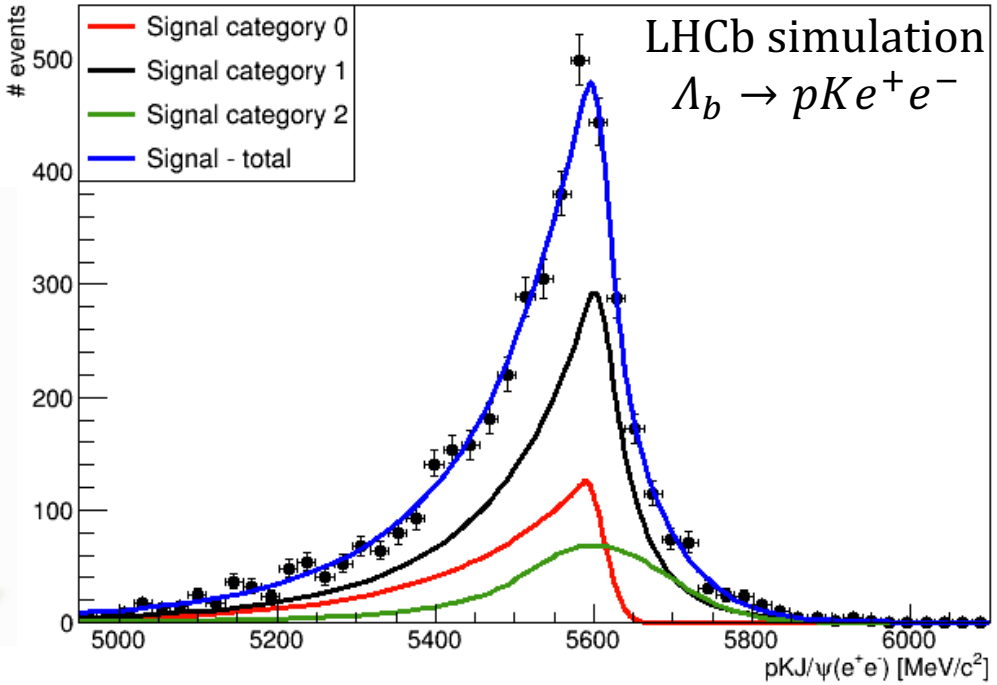


Electron reconstruction and bremsstrahlung

- **Electrons** emit **bremsstrahlung** in interactions with material
- To reconstruct the true energy of the electron, we 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**

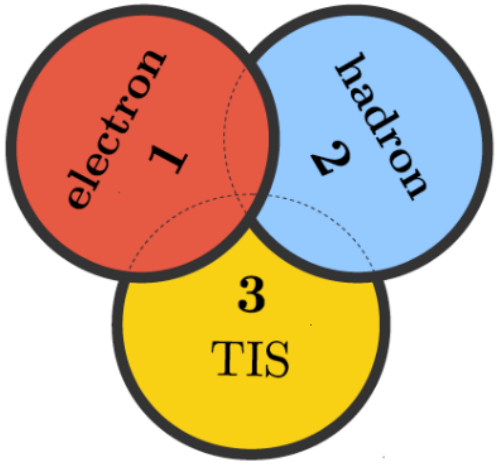






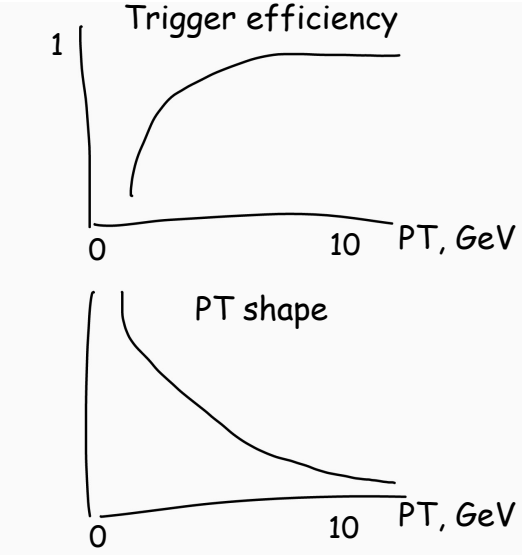
Trigger categories

- 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 gain more statistics, we can trigger on
  - Leptons – electron or muon (L0Lepton = L0L)
  - Hadrons – proton or kaon – too inefficient to be accounted for
  - Rest of the event (L0TIS = L0I)
- Trigger efficiencies in these cases are very different
  - So these 'trigger categories' are analyzed separately
  - Separate fits, separate results…
  - Only in the end, results are combined



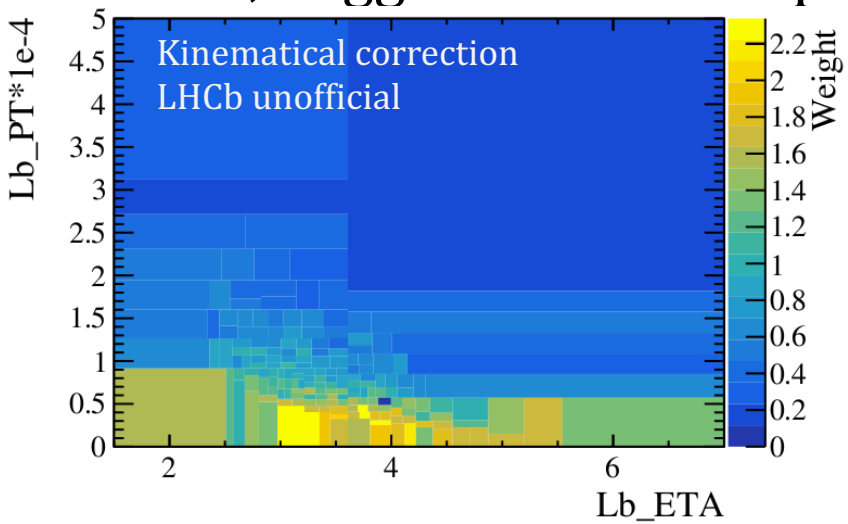
Efficiencies and corrections

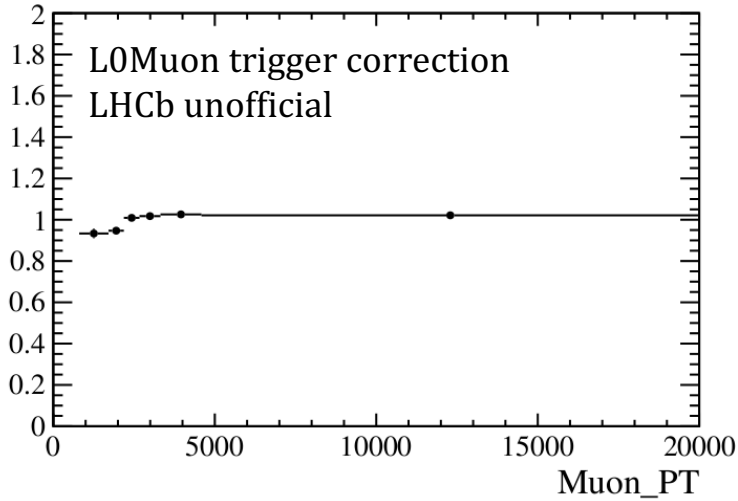
- $R_{pK} = \frac{BR(\Lambda_b \to pK\mu^+\mu^-)}{BR(\Lambda_b \to pKJ/\psi(\mu^+\mu^-))} * \frac{BR(\Lambda_b \to pKJ/\psi(e^+e^-))}{BR(\Lambda_b \to pKe^+e^-)}$
- What we really measure is a number of events (N)
- $R_{pK} = \frac{N(\Lambda_b \to pK\mu^+\mu^-)}{\varepsilon(\Lambda_b \to pK\mu^+\mu^-)} * \frac{\varepsilon(\Lambda_b \to pKJ/\psi(\mu^+\mu^-))}{N(\Lambda_b \to pKJ/\psi(\mu^+\mu^-))} * \frac{N(\Lambda_b \to pKJ/\psi(e^+e^-))}{\varepsilon(\Lambda_b \to pKJ/\psi(e^+e^-))} * \frac{\varepsilon(\Lambda_b \to pKe^+e^-)}{N(\Lambda_b \to pKe^+e^-)}$
- Efficiencies (ε) are taken from the simulation
  - An important step is to correct for possible data-simulation discrepancies
- Having a correct simulation is very important at LHCb
  - Work not on the trigger efficiency plateau
  - Ageing, different running conditions…
  - We are doing high-precision measurements
- Corrections are quite small but important though



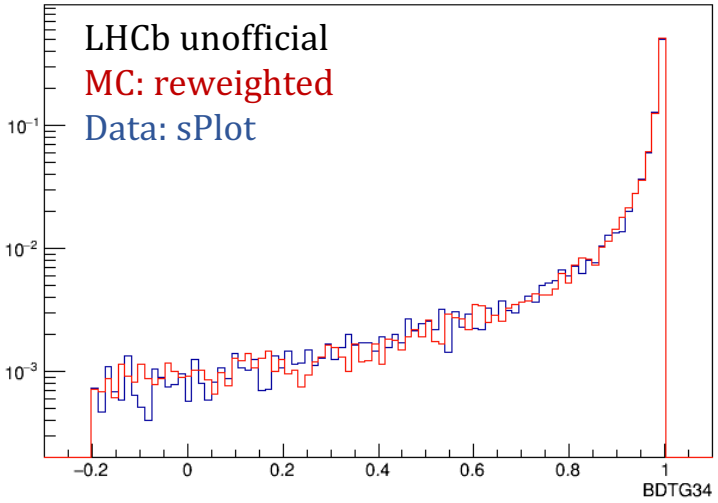
Corrections to the simulation

- Correct for event multiplicity, kinematics, trigger and PID response
- Corrections are data-driven



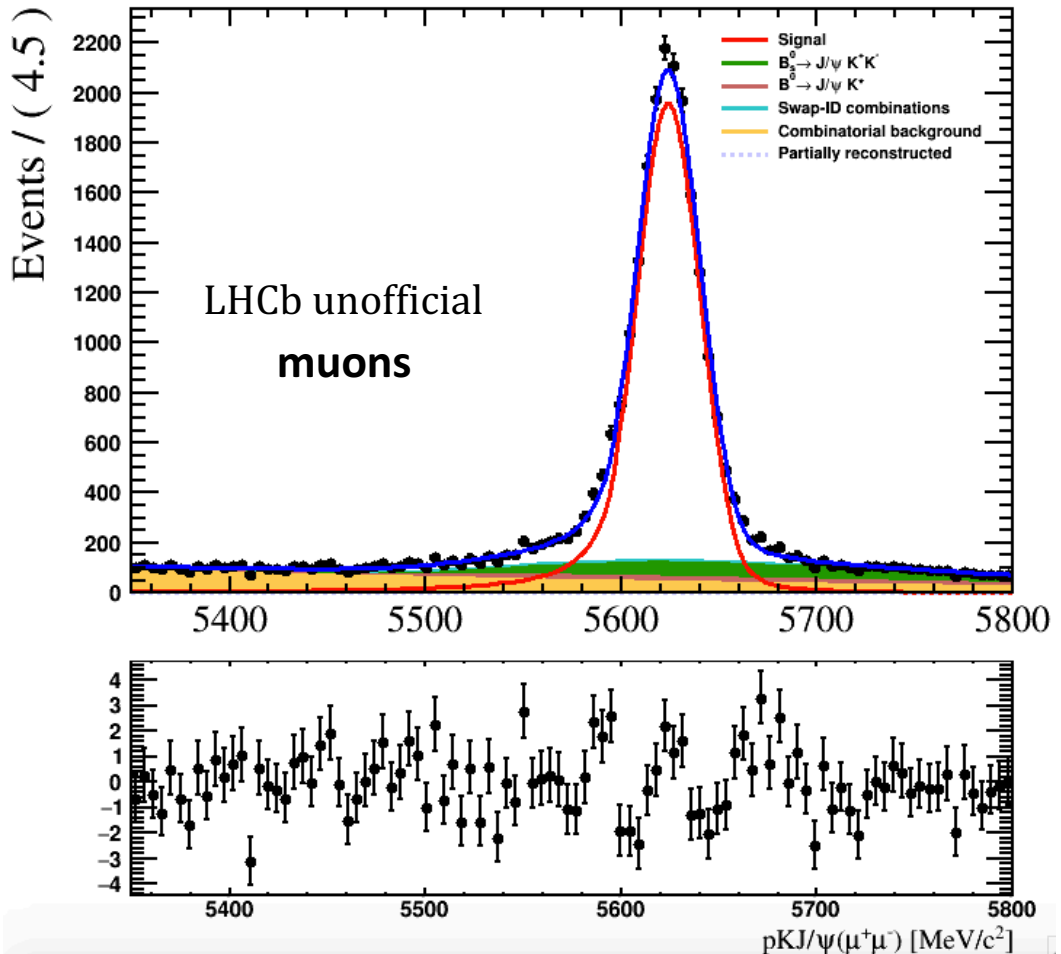


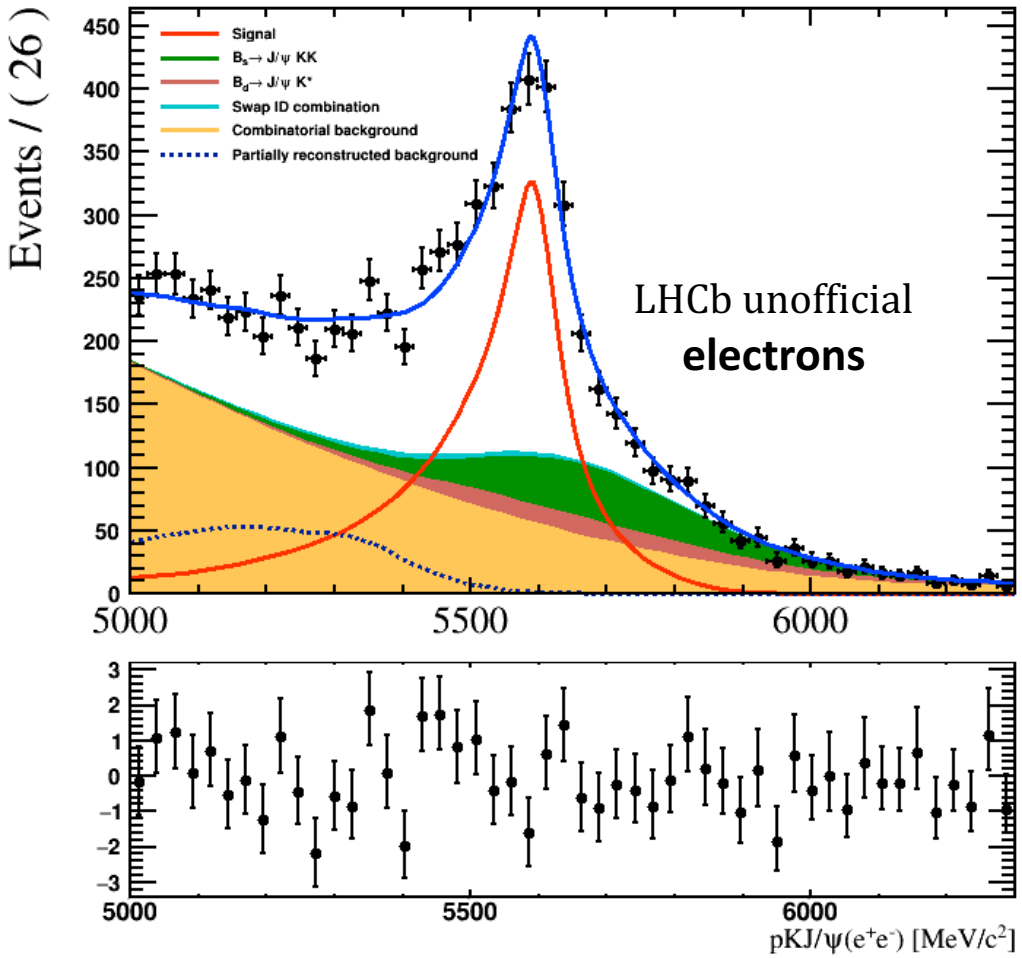
- When done, check the data-MC agreement in the BDT variable



Fits to real data

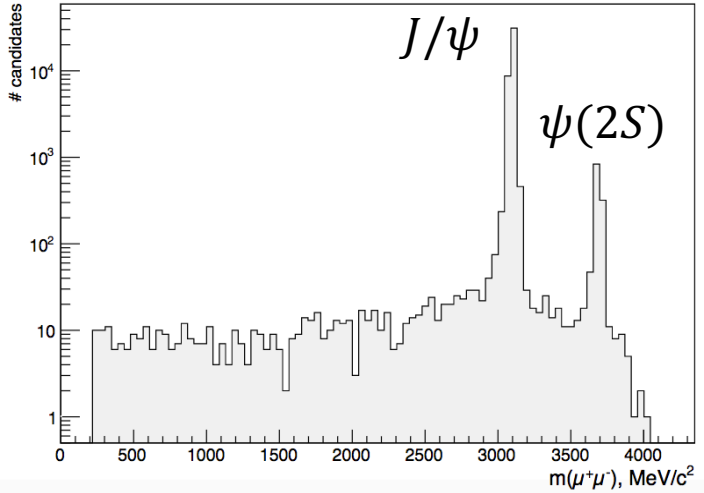
- Include signal peak and background components
- Fits in the J/ψ window:

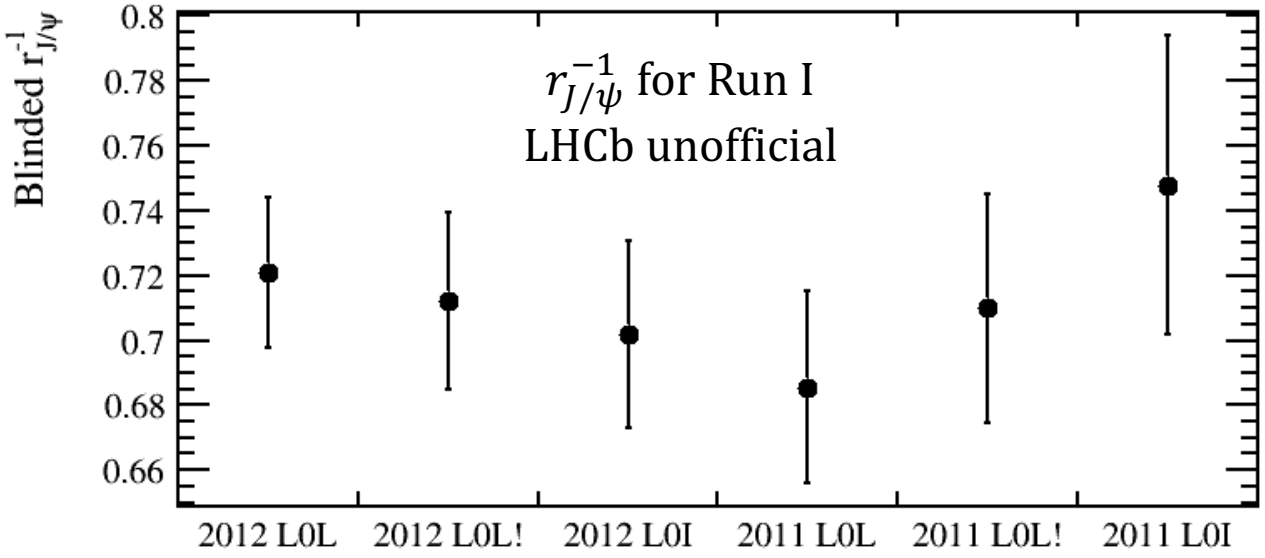




Cross-checks: $r_{J/\psi}$

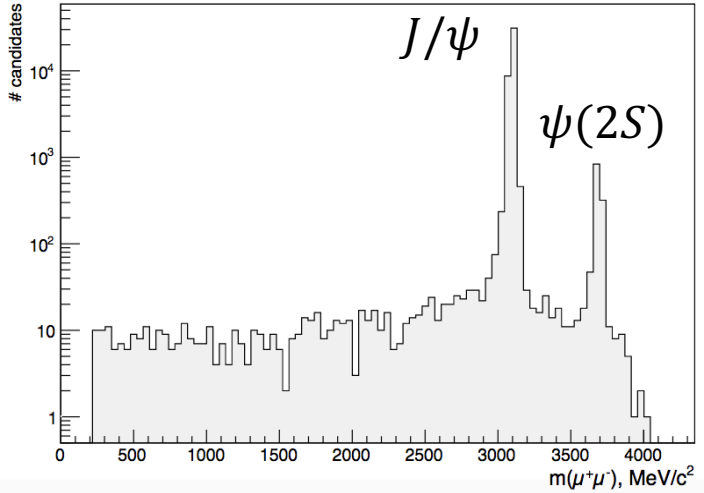
- Single ratio $BR(\Lambda_b \to pKJ/\psi(e^+e^-))/BR(\Lambda_b \to pK\,J/\psi\,(\mu^+\mu^-))$: requires full efficiency control
- Blind: multiplied by a blinding factor [equal for all categories]
- 1) compare blinded **central value** per dataset

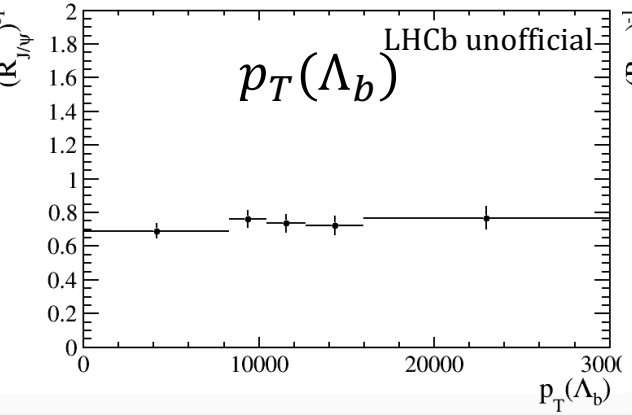


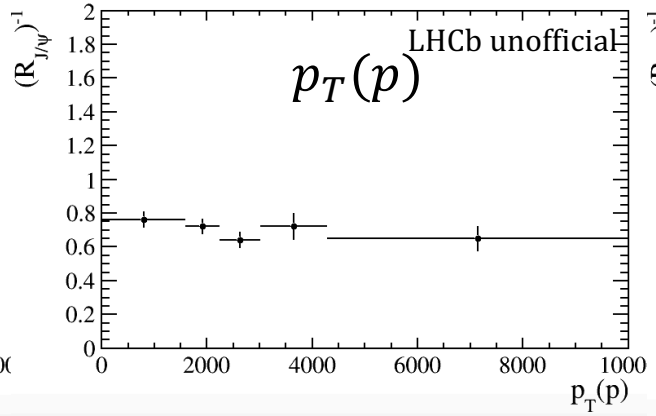


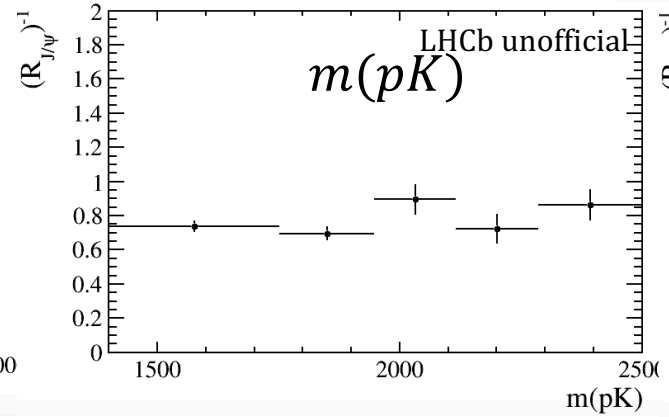
Cross-checks: $r_{J/\psi}$

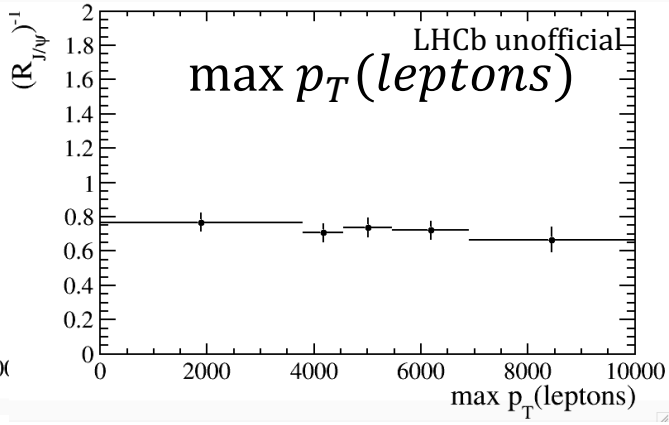
- Single ratio $BR(\Lambda_b \to pKJ/\psi(e^+e^-))/BR(\Lambda_b \to pK\,J/\psi\,(\mu^+\mu^-))$: requires full efficiency control
- Blind: multiplied by a blinding factor [equal for all categories]
- 1) compare blinded **central value** per dataset
- 2) check the **trend** in various variables in each category







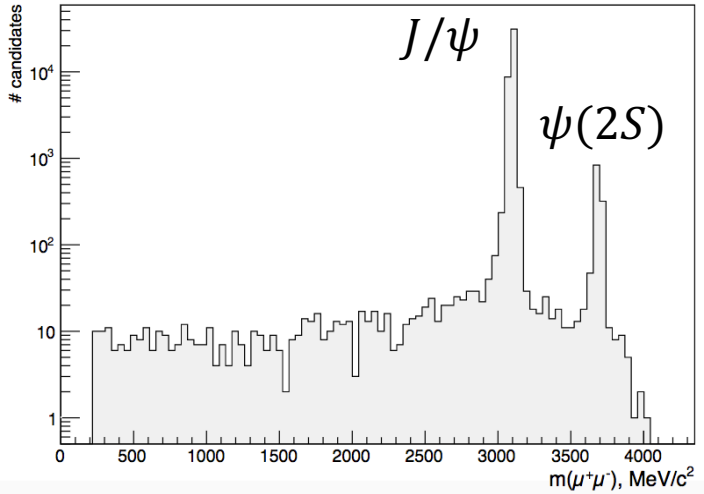


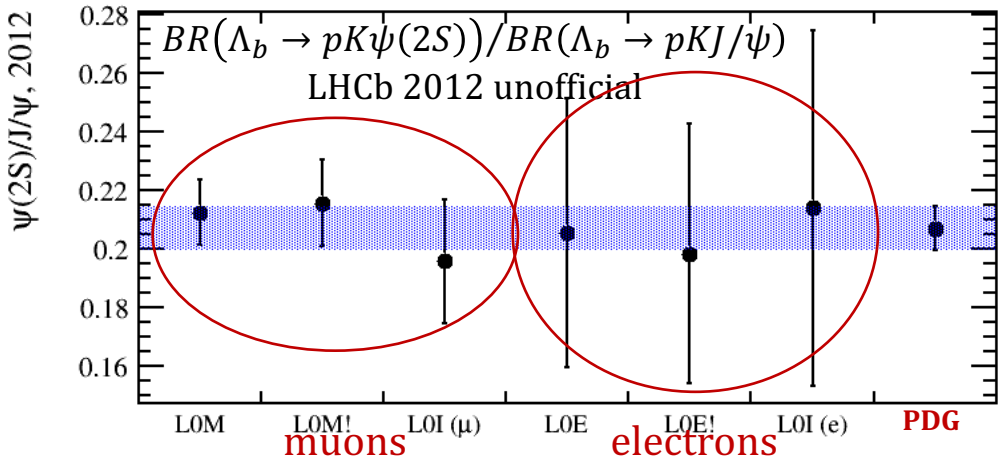


(and 82374659834769 similar plots)

Cross-checks: $r_{J/\psi}$ and friends

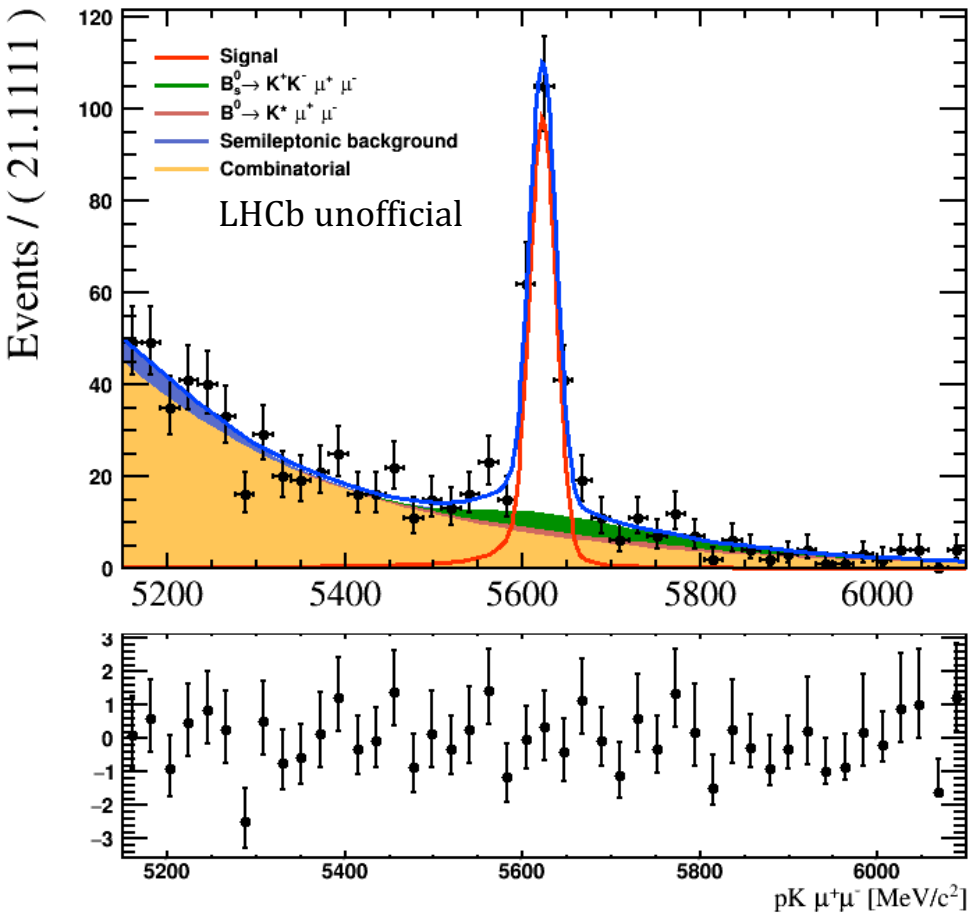
- Single ratio $BR(\Lambda_b \to pKJ/\psi(e^+e^-))/BR(\Lambda_b \to pK\,J/\psi\,(\mu^+\mu^-))$: requires full efficiency control
- Blind: multiplied by a blinding factor [equal for all categories]
- 1) compare blinded **central value** per dataset
- 2) check the **trend** in various variables in each category
- … (tens of other cross-checks inbetween…)
- N) **unblind** and check if the central value is compatible with 1
- Then perform similar studies for $\Lambda_b \to pK\psi(2S)$:



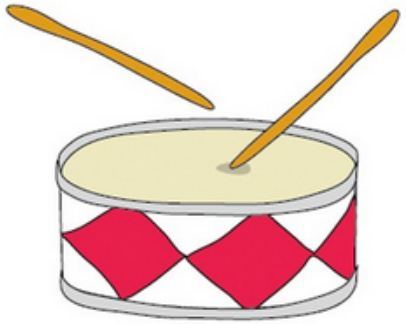


R_{pK}

- When we are happy with all the cross-checks, we can study the non-resonant mode
- Fit shown for non-resonant $\Lambda_b \to pK\ \mu^+\mu^-$
- $\Lambda_b \to pK\ e^+e^-$ is kept blind!
  - (We should not know the R_{pK} value before all the cross-checks passed!)

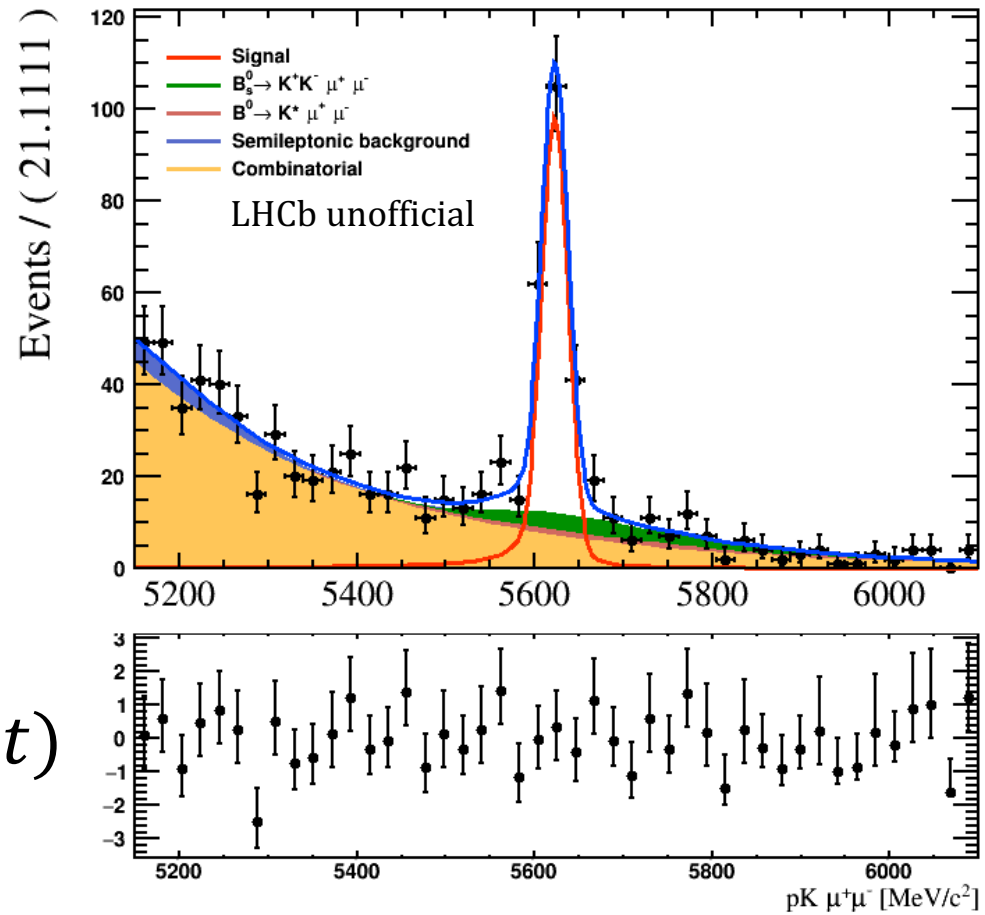


- Finally, the result:



R_{pK}

- When we are happy with all the cross-checks, we can study the non-resonant mode
- Fit shown for non-resonant $\Lambda_b \to pK\ \mu^+\mu^-$
- $\Lambda_b \to pK\ e^+e^-$ is kept blind!
  - (We should not know the R_{pK} value before all the cross-checks passed!)



- Finally, the result: $R_{pK} = X \pm Y(stat) \pm Z(syst)$

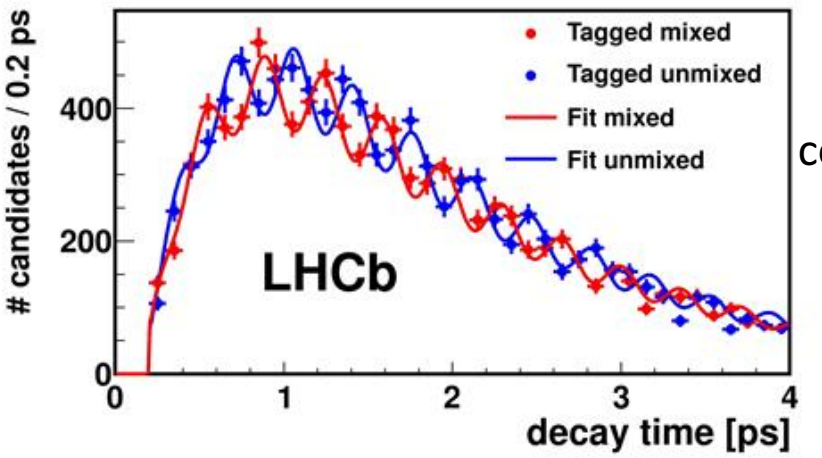
Thank you for your attention!
Questions?

Fin

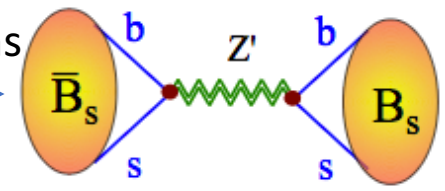
Backup slides below

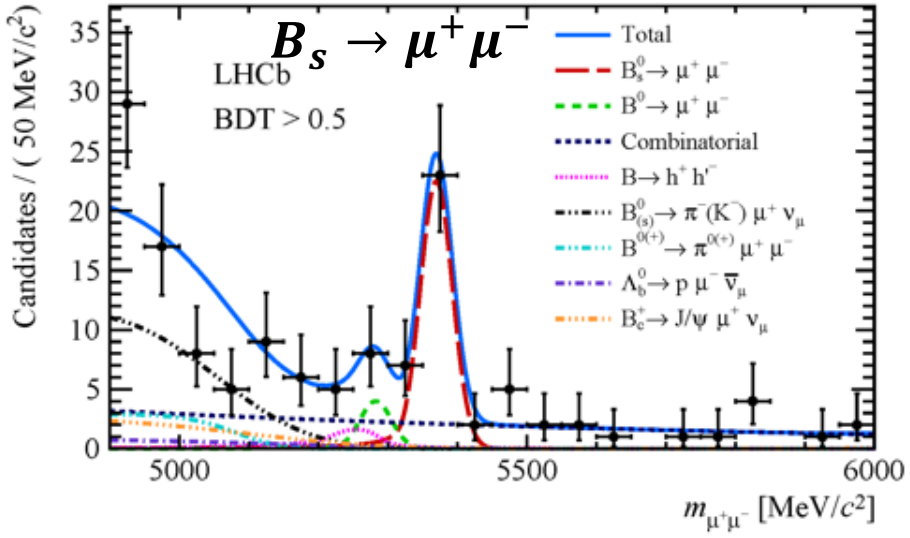
Constraining New Physics models

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

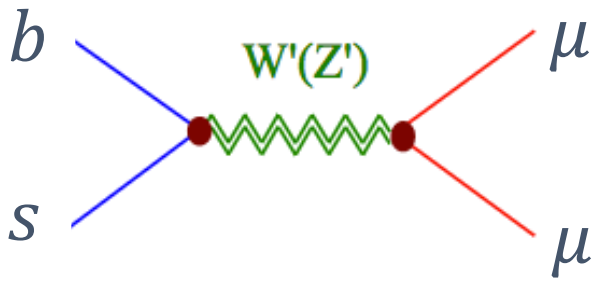


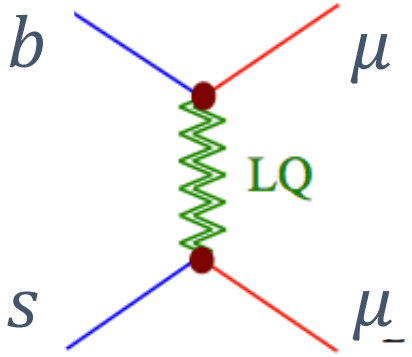
constrains





constrains





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

Insidious penguins

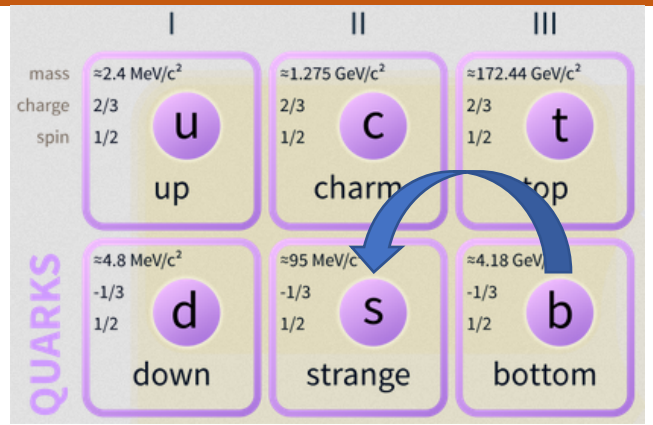
- The transitions between same-charge quarks – FCNC* – are forbidden *at the tree level*

- They proceed via **penguin diagrams**

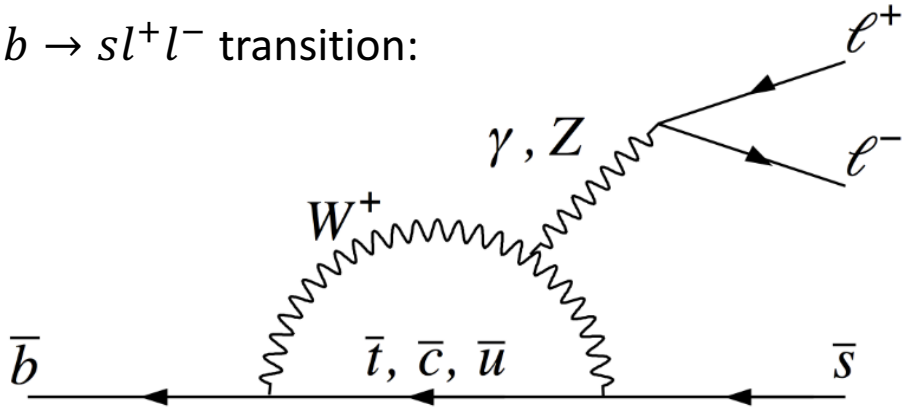
- This makes these processes **very rare**, but also **sensitive** to the possible New Physics contributions

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

* FCNC = Flavor Changing Neutral Currents



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

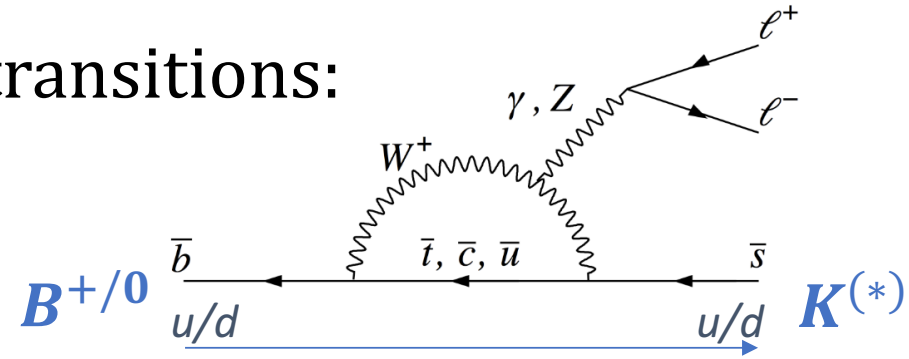


Who ordered that name?

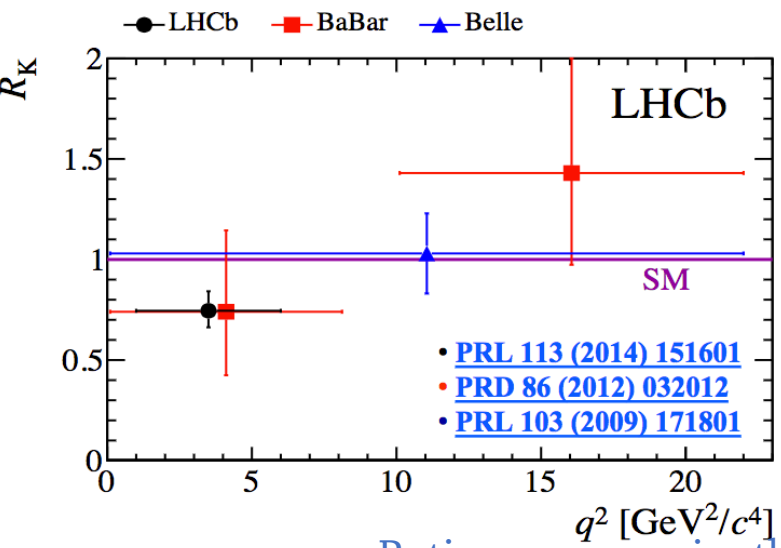
Well, look here…

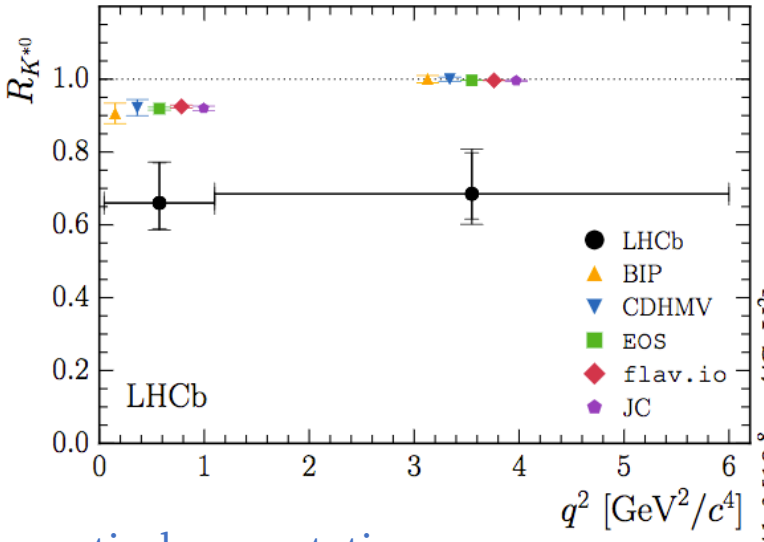
Ratios of ratios of ratios ...

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



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

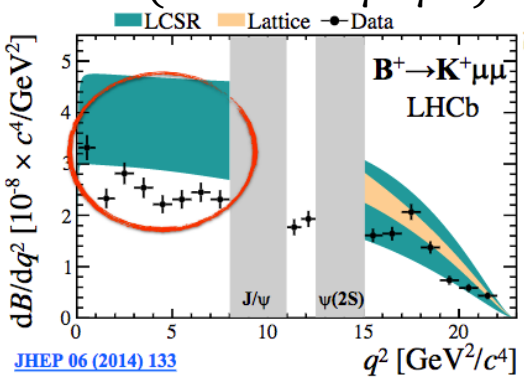




Ratios: very precise theoretical computation
Cancellation of theoretical and experimental uncertainties

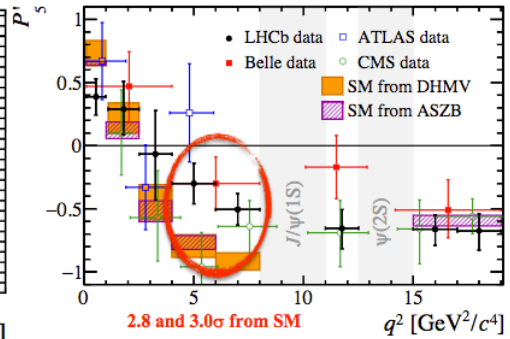
Additional input:

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



JHEP 06 (2014) 133

Angular analysis

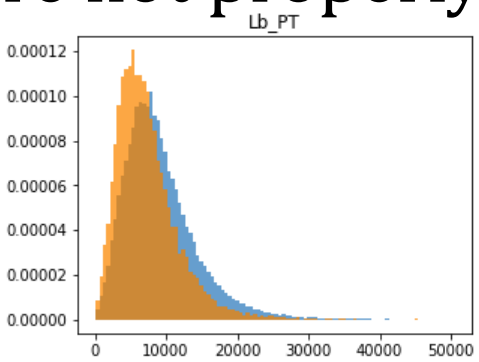


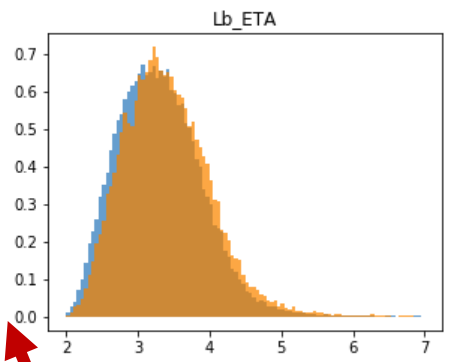
JHEP 02 (2016) 104
PRL 118 (2017)
ATLAS-CONF-2017-023
arXiv:1710.02846

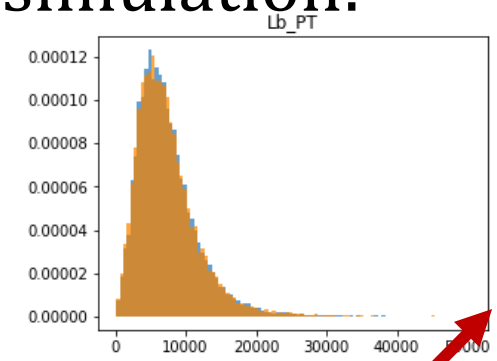
- Also some anomalies in the $b \to c l^+ \nu_l$ transitions
- New/updated measurements expected from LHCb and BELLE-II

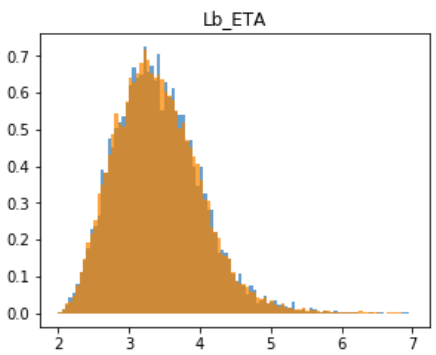
Corrections in work

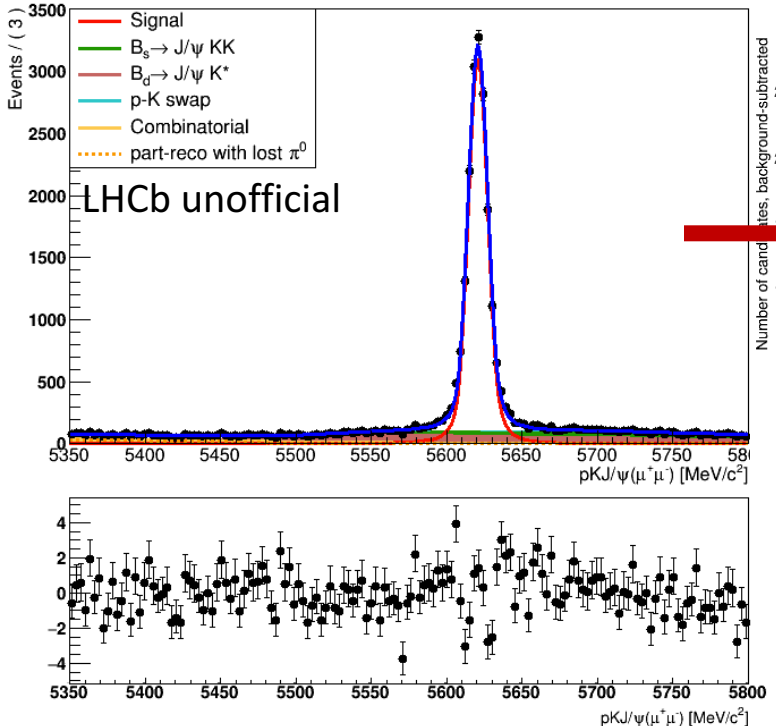
- Some variables are not properly modeled in the simulation:
  - e.g. generated kinematics of the decay:

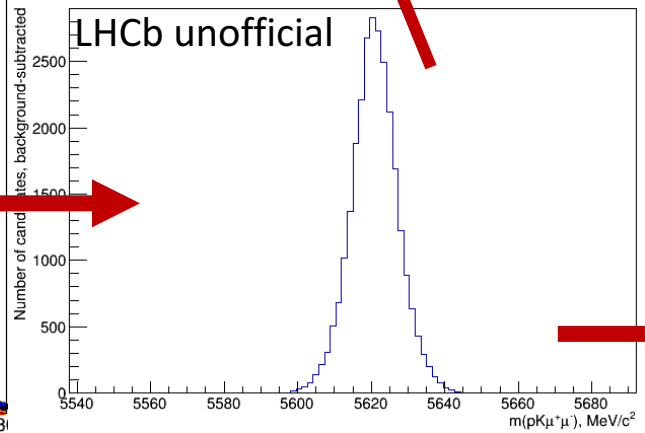




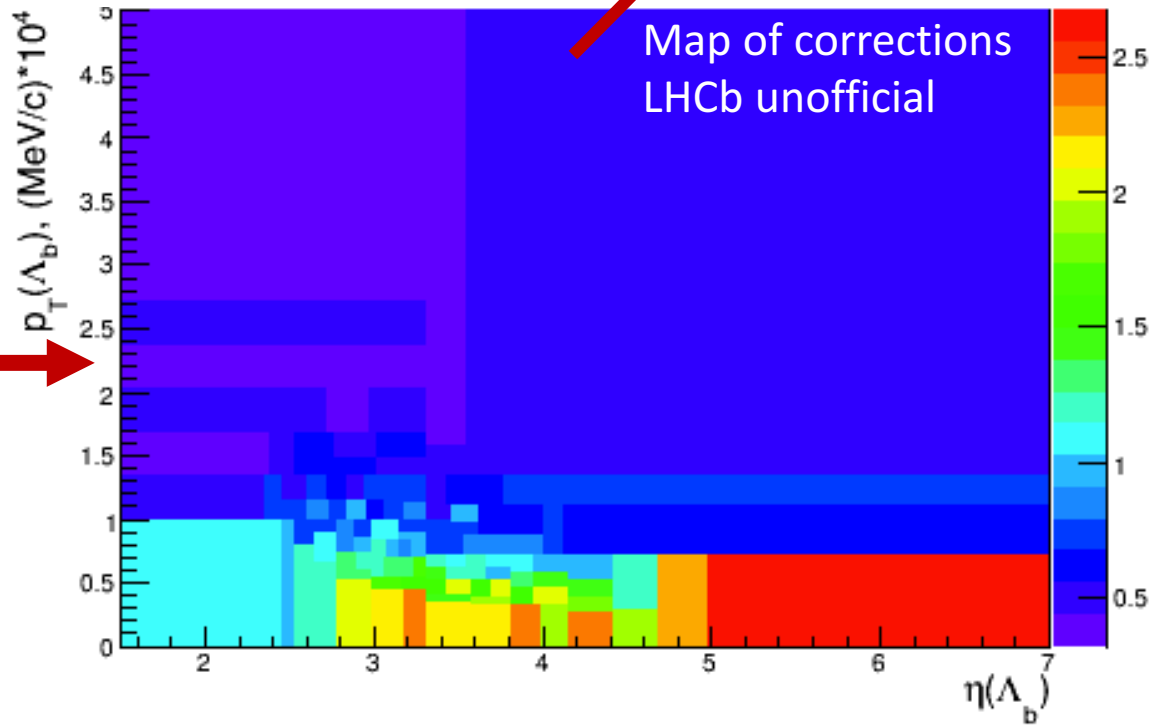








sPlot

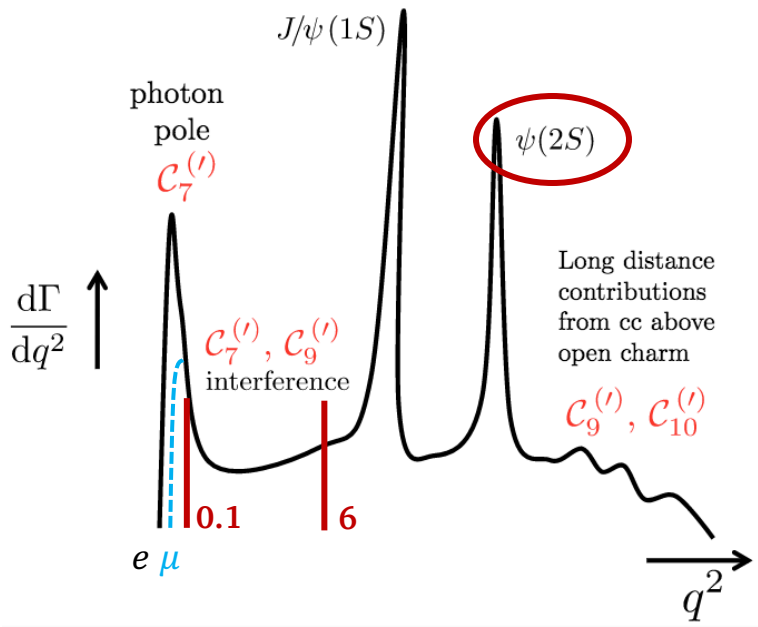


Cross-checks

- 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 $\gamma \to e^+e^-$
  - ...



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 $\Lambda^* \to pK$**