# Test of Lepton Universality using $\Lambda_b$ decays

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# What is Lepton Universality?

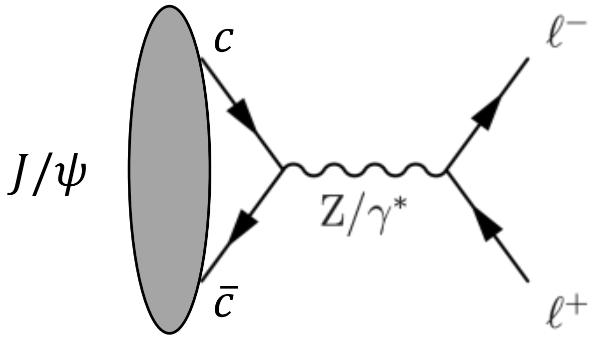


- **SM: couplings of all (charged) leptons to the gauge bosons should be identical**
  - (up to the order of mass/phase-space corrections)
- This means e.g. $\frac{BR(Z\to\mu^+\mu^-)}{BR(Z\to e^+e^-)} = 1$

**Decay Modes**

| Mode | | Fraction ($\Gamma_i / \Gamma$) |
|---|---|---|
| $\Gamma_1$ | $e^+e^-$ | $(3.363 \pm 0.004)\%$ |
| $\Gamma_2$ | $\mu^+\mu^-$ | $(3.366 \pm 0.007)\%$ |
| $\Gamma_3$ | $\tau^+\tau^-$ | $(3.370 \pm 0.008)\%$ |

- Should be also true for virtual off-shell $Z$ or $\gamma$
- This implies e.g. $\frac{BR(J/\psi\to\mu^+\mu^-)}{BR(J/\psi\to e^+e^-)} = 1$




$l = e$ or $\mu$

- This property is called **Lepton Universality**
- Nice summary of previous tests: [arXiv:1809.06229](arXiv:1809.06229)

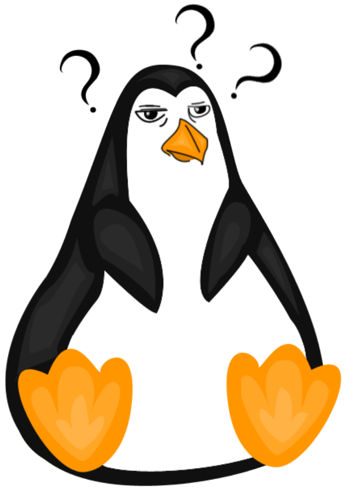
# What keeps us awake at night?



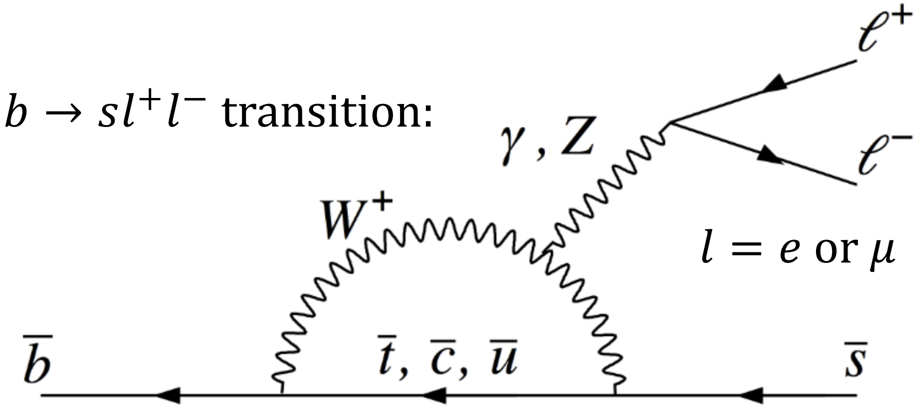
- **Penguins.**

Wake up at 6 AM and go to Arles.

- Are $b \rightarrow s l^+ l^-$ transitions lepton-universal?
  - SM: yes sure
  - Penguin: wait a second…



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



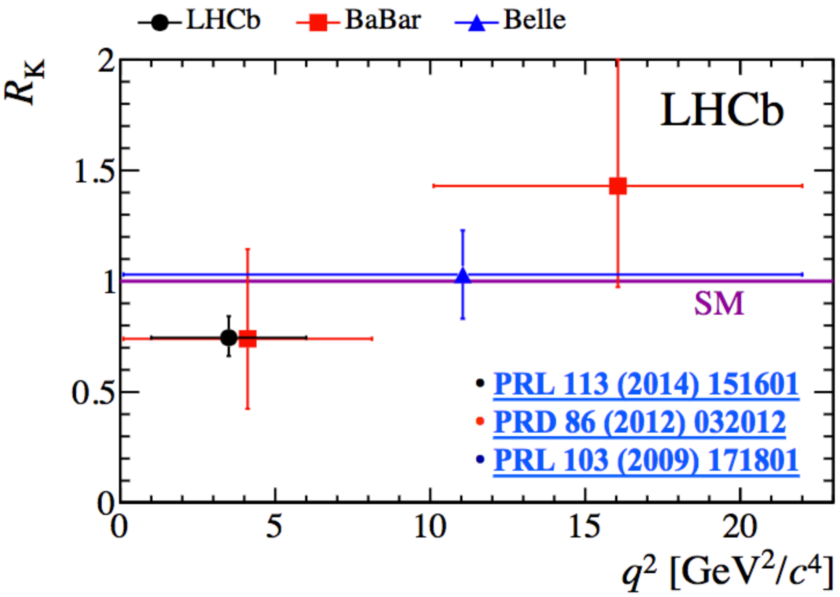

Very rare (BR~10$^{-7}$)
Sensitive to New Physics contributions

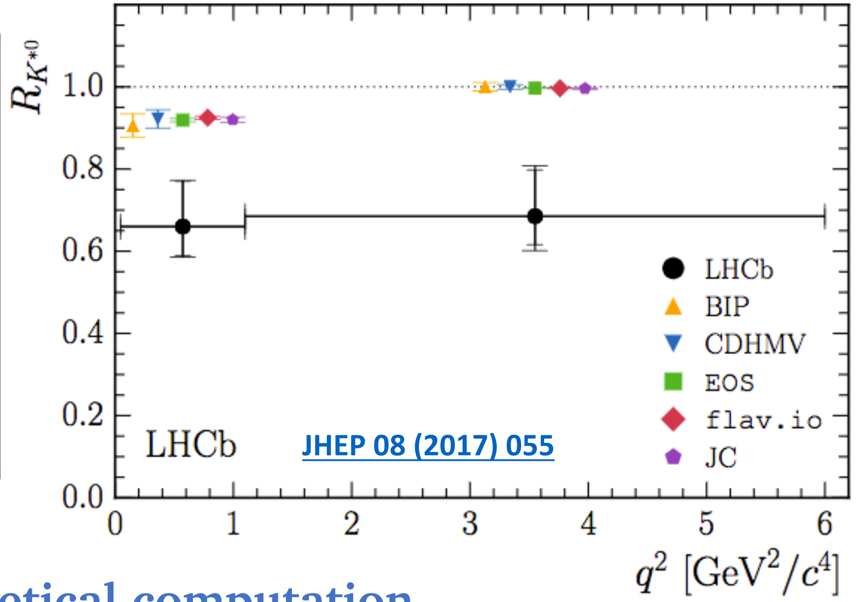
# Ratios of ratios of ratios…

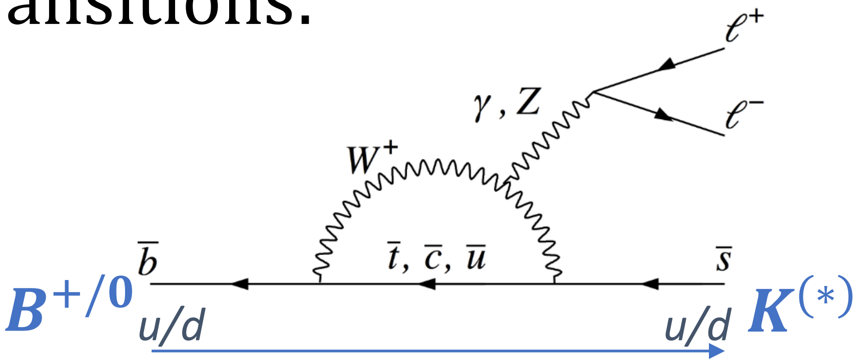


- Few remarkable measurements in the $b \to s l^+ l^-$ transitions:

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




**Q: is it a real thing?**

Ratios: precise theoretical computation
Cancellation of theoretical and experimental uncertainties

- Additional anomalies in angular analyses and absolute BR values

# Penguins or...?



Standard Model penguins

# Penguins or...?

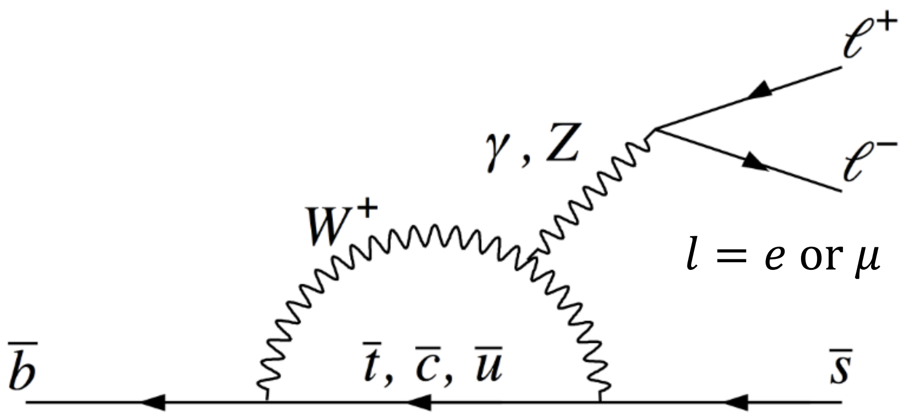


Standard Model penguins

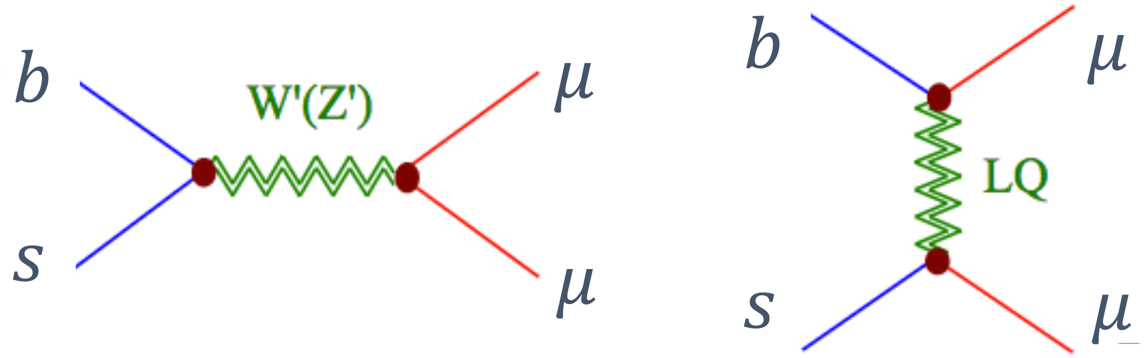

New Physics

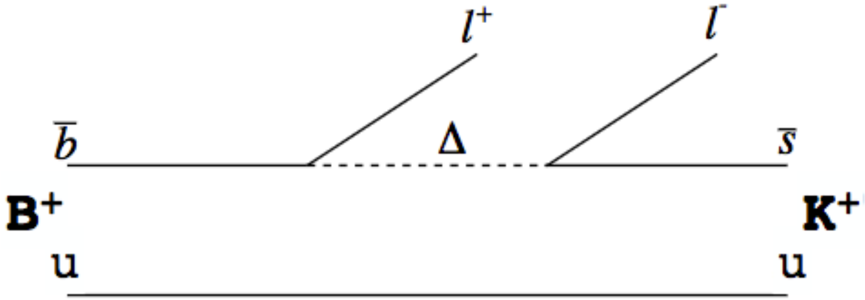
# Power of indirect searches

Standard Model penguins




New Physics




Q: is it a real thing?

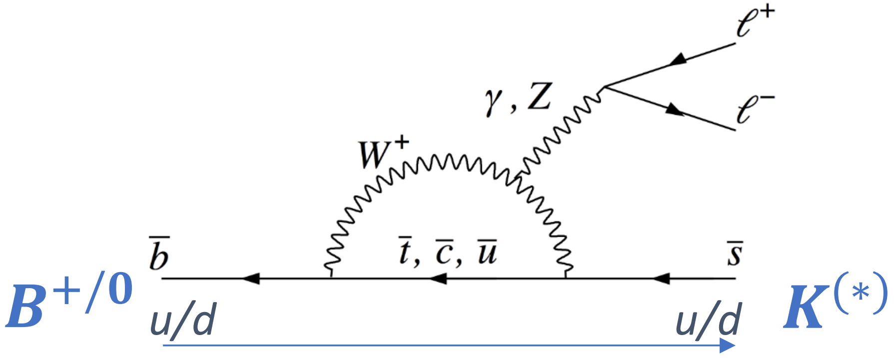
**A: Need more measurements!**

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

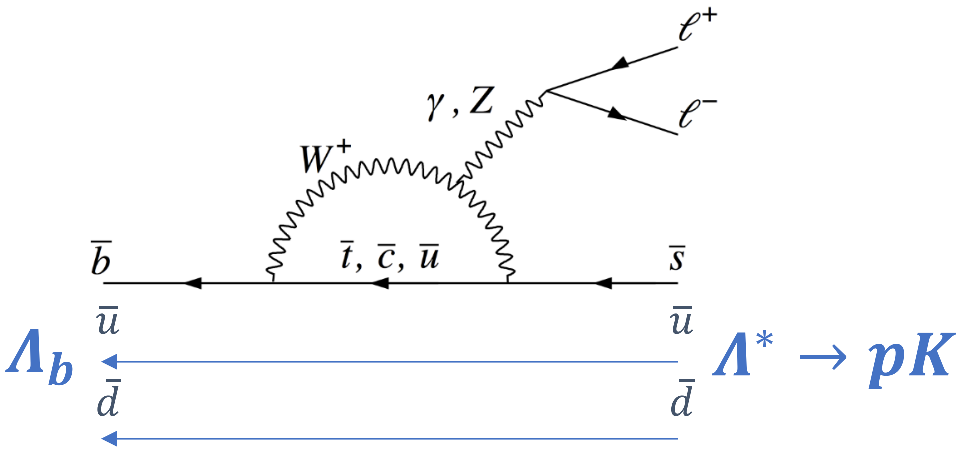
# Don't forget the baryons!



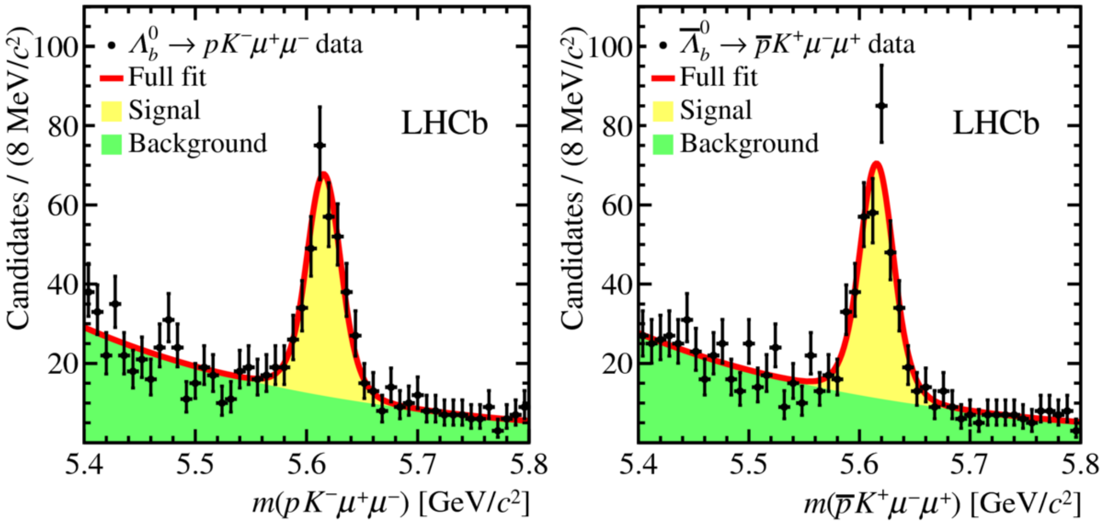
- We live in a world made of ~~love and cats~~ baryons
  - However, baryons are less explored than mesons
  - Exploring another spin configuration, possible surprises?
  - Laws in the baryon system are not always similar to mesons




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



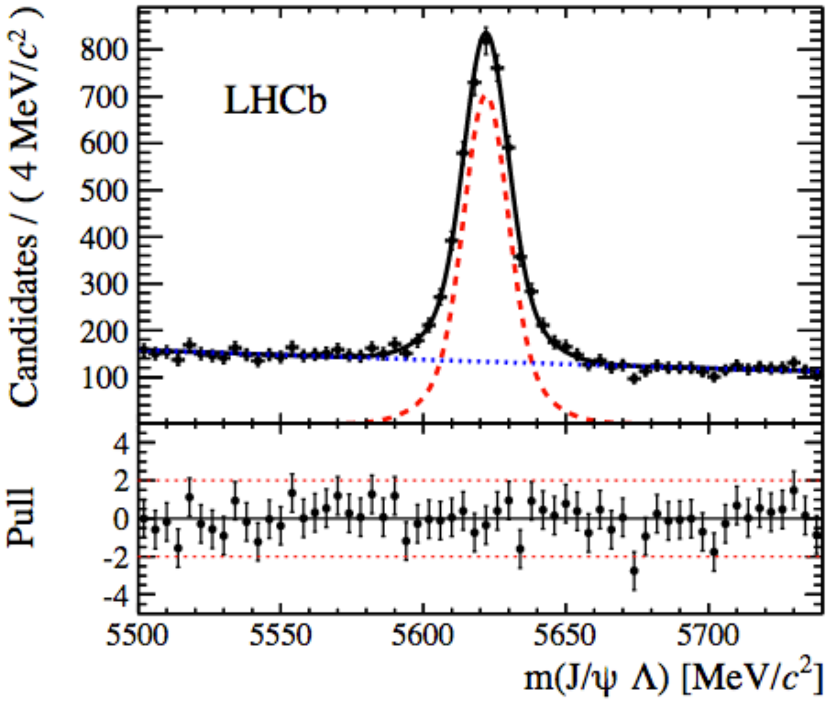

- $\Lambda_b^0 \to pK\mu^+\mu^-$ was observed [JHEP 06 (2017) 108]

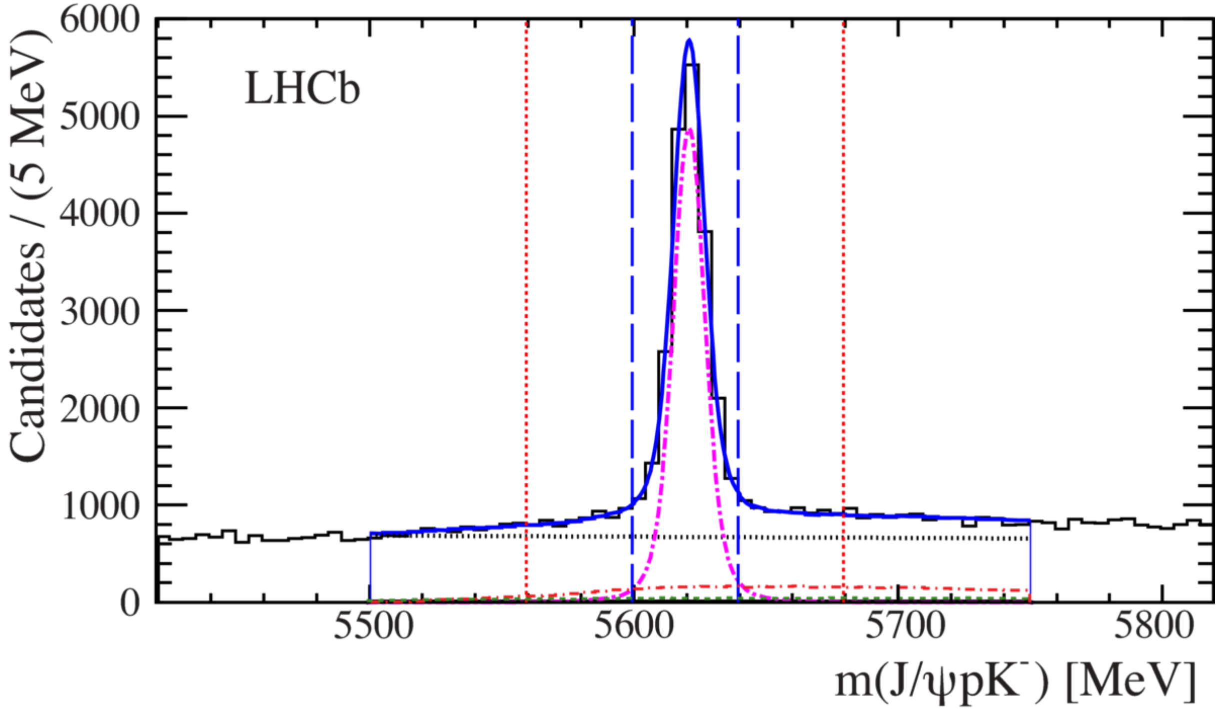


# Excited lambdas are so exciting



- Why this final state: easier experimentally than long-lived $\Lambda^0$
  - Develop a pilot analysis on higher-statistics inclusive mode, then catch up with others (also ongoing)
- LHCb used two channels to measure the $\Lambda_b^0$ lifetime with 2011 data (1fb$^{-1}$):
  - **JHEP04(2014)114** uses $\Lambda^0 J/\psi$ decay and has about 4k $\Lambda_b^0$ events
  - **Phys. Rev. Lett. 111, 102003 (2013)** uses $pKJ/\psi$ and has about 15.5k $\Lambda_b^0$ events

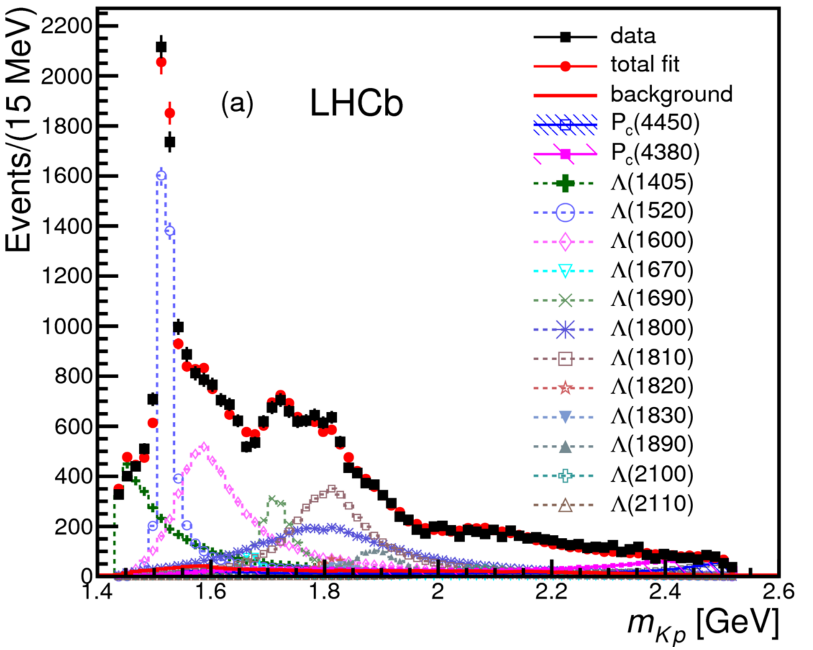


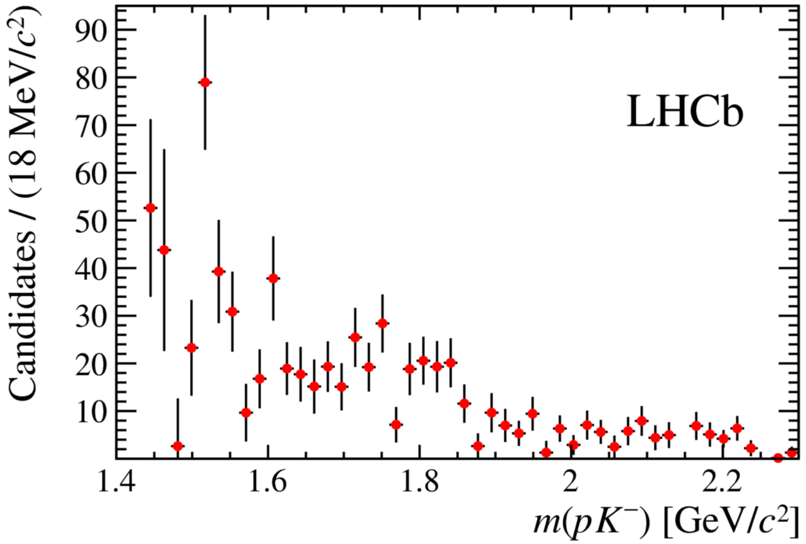



# Theorist’s nightmare



- What is easier for experimentalists, is not always the best from theory point of view
- Very complicated $pK$ spectrum: e.g. $\Lambda_b^0 \to pKJ/\psi$ [PRL 115, 072001 (2015)]
- No guarantee that the spectrum is exactly the same in rare modes [**JHEP 06 (2017) 108**]
- Makes theory predictions complicated (*see talk by Martín tomorrow*)
- We are still rather confident that **in the SM $R_{pK} \approx 1$,** but in New Physics models…
  - A) if NP is V-A only, all $R_X$ are similar [arXiv:1411.4773]
  - B) if NP has V+A currents, we have spin dependency, might have some fun
    - PhD topic in 2035: Measurement of $R_{pK}$ as a function of $m(pK)$



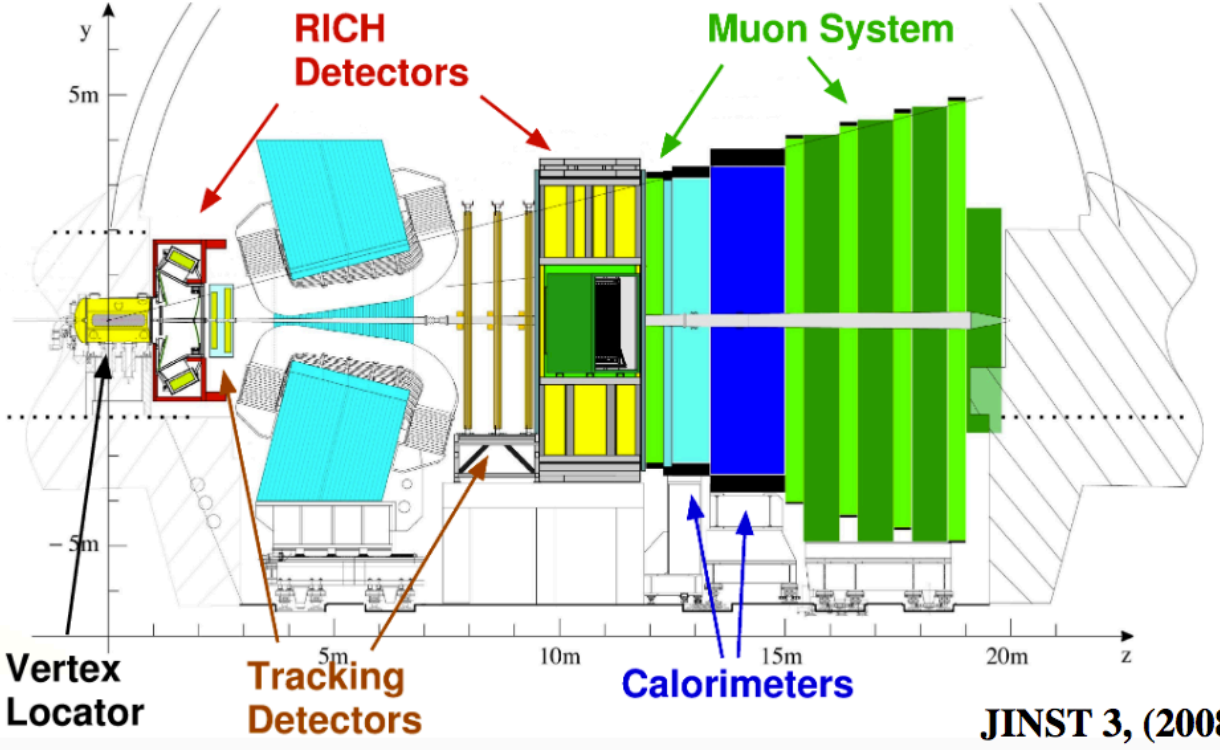



# The lowcost penguin laboratory



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

- **Our wish list:**
- Large $\Lambda_b^0$ production rate
- 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

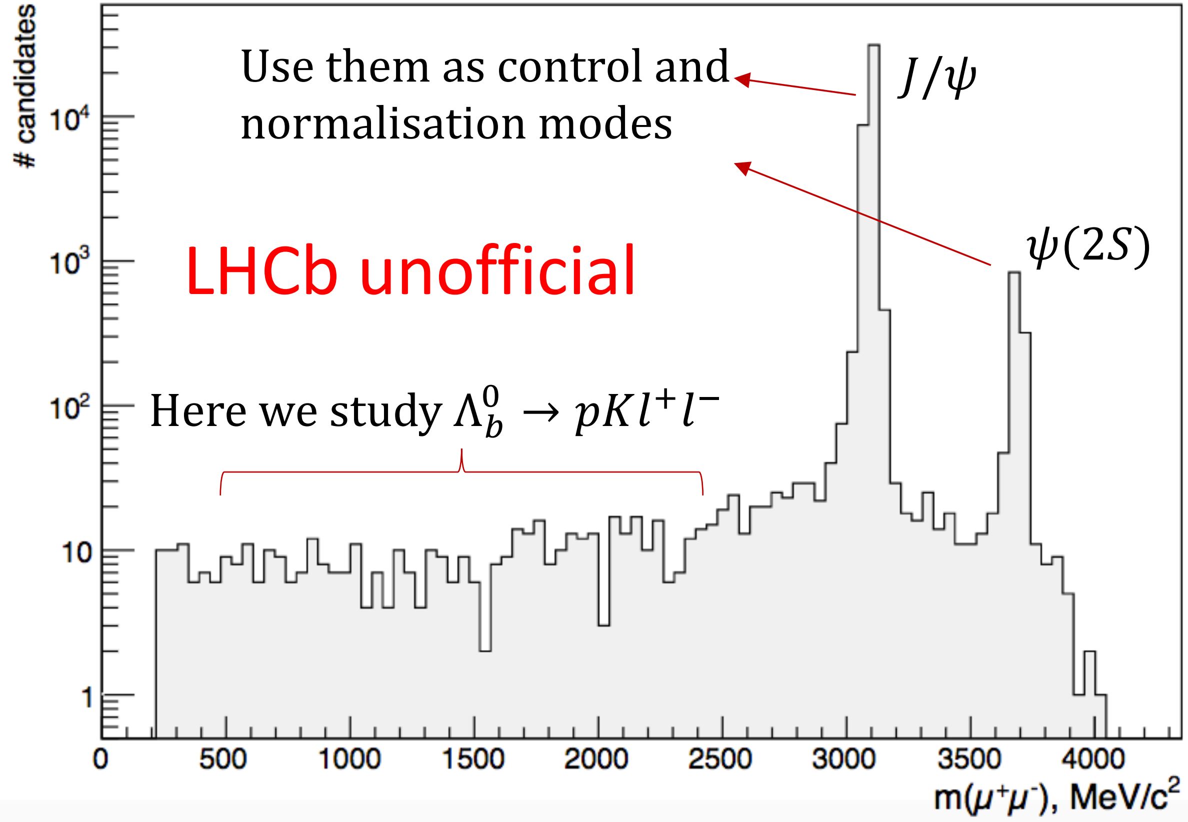



JINST 3, (2008) S08005

# 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: these are backgrounds
  - But they are *useful* backgrounds!




*How can backgrounds be useful?*

*Alright, mute your nonsense alarm!*

(me)

**What's important, these tree-level decays are lepton-universal!**

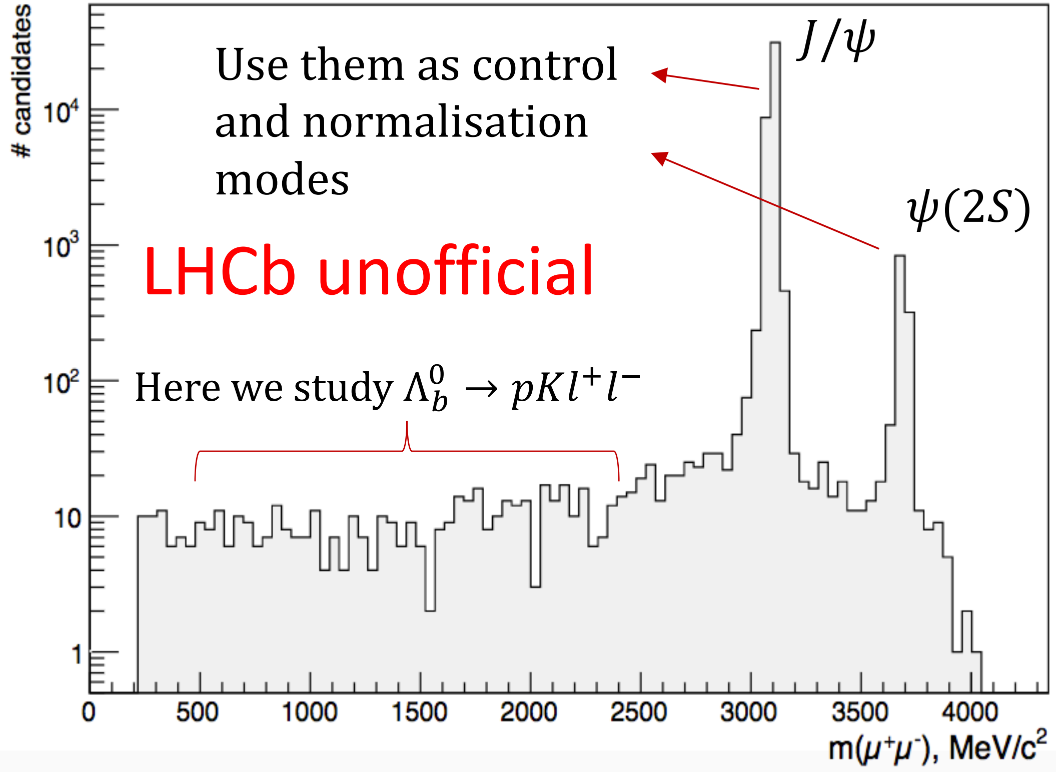
# The global strategy of the analysis



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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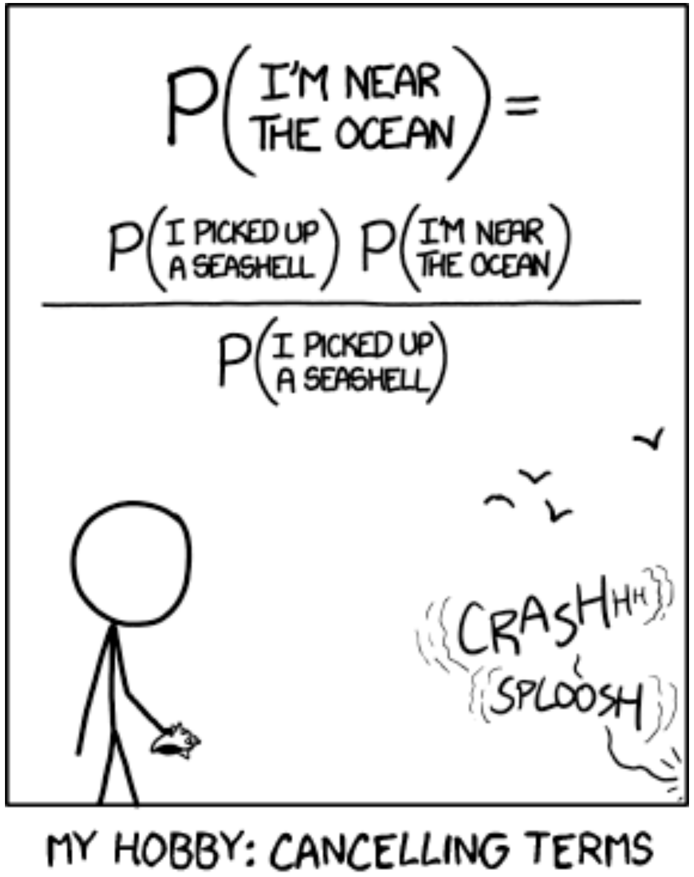
3) Compute the double ratio

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

- Normalize to high-statistics modes
- Cancel some uncertainties




**Easy? Well, not so much**

# Troubles on our way

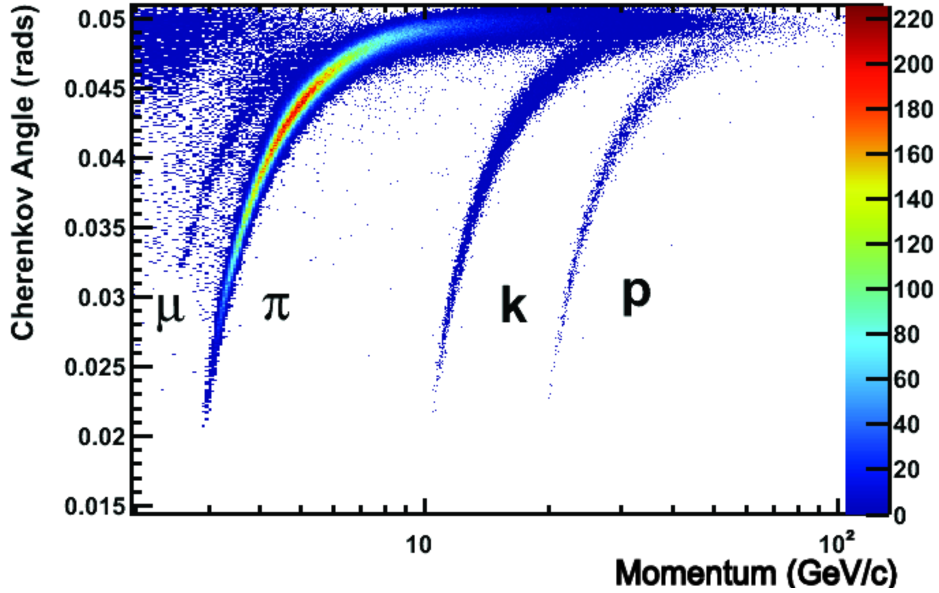


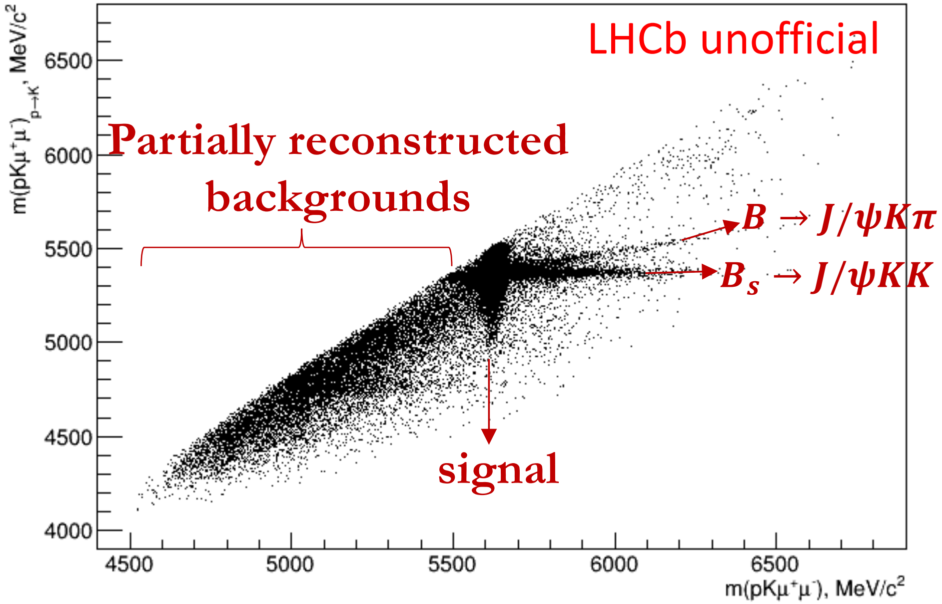

Some key beasts to fight:

- Systematic uncertainties
- Corrections to the simulation
- **Electron reconstruction** and trigger
- 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

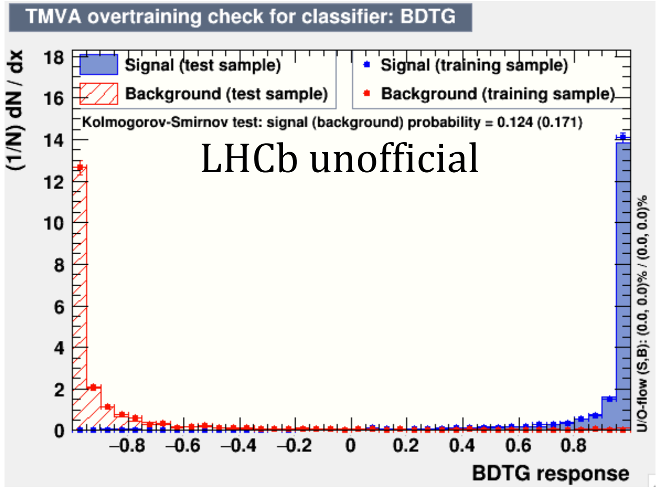


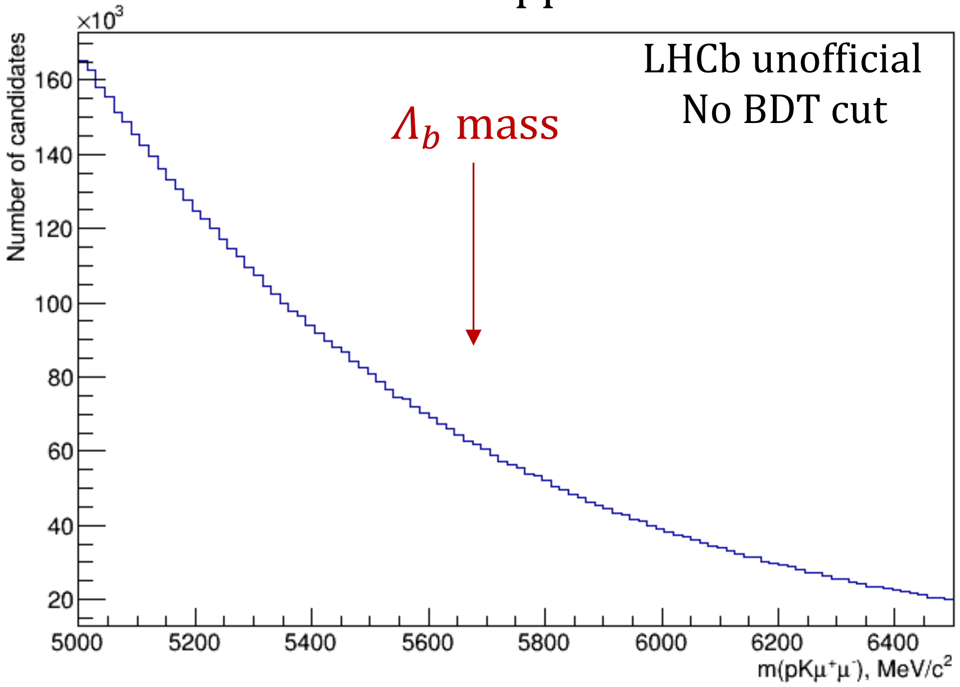
# But there's an elephant in the room



- 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

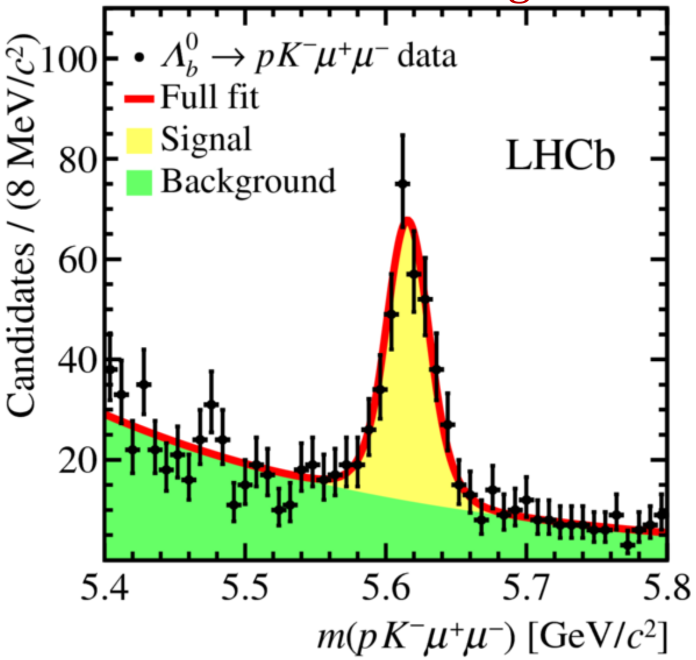



No BDT applied




BDT applied

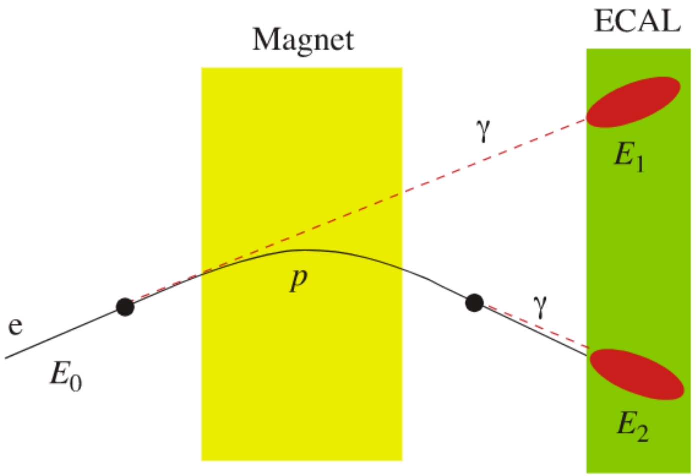
1000 times less background!

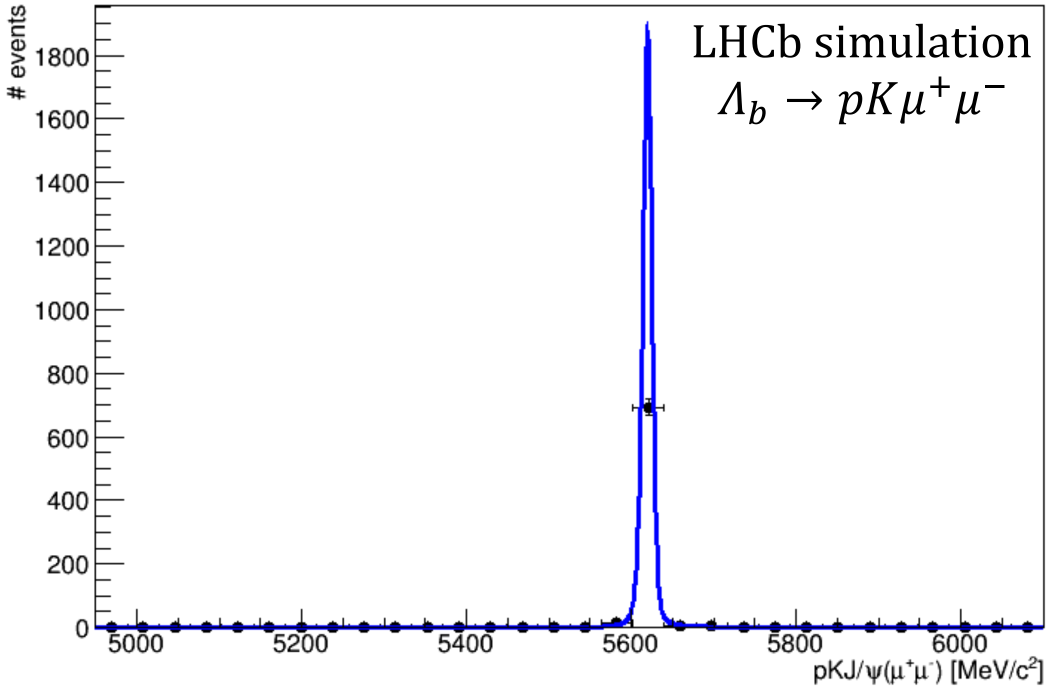


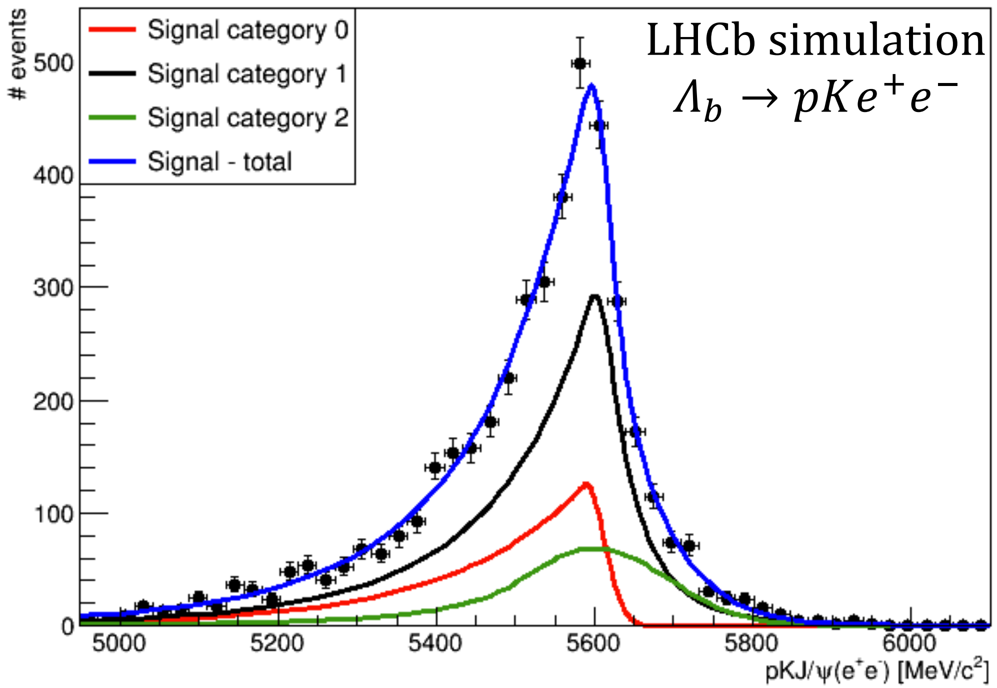

# Electron reconstruction and bremsstrahlung



- **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**



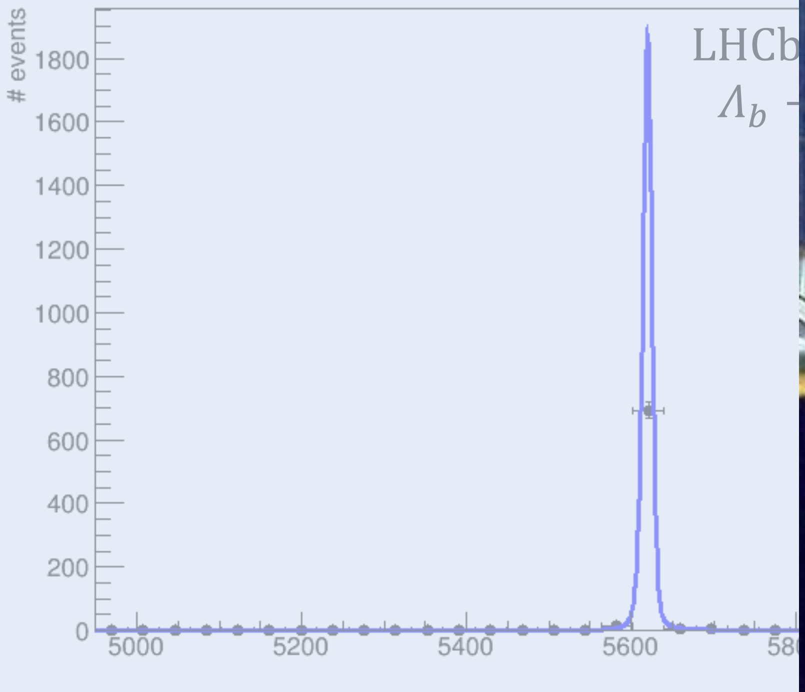



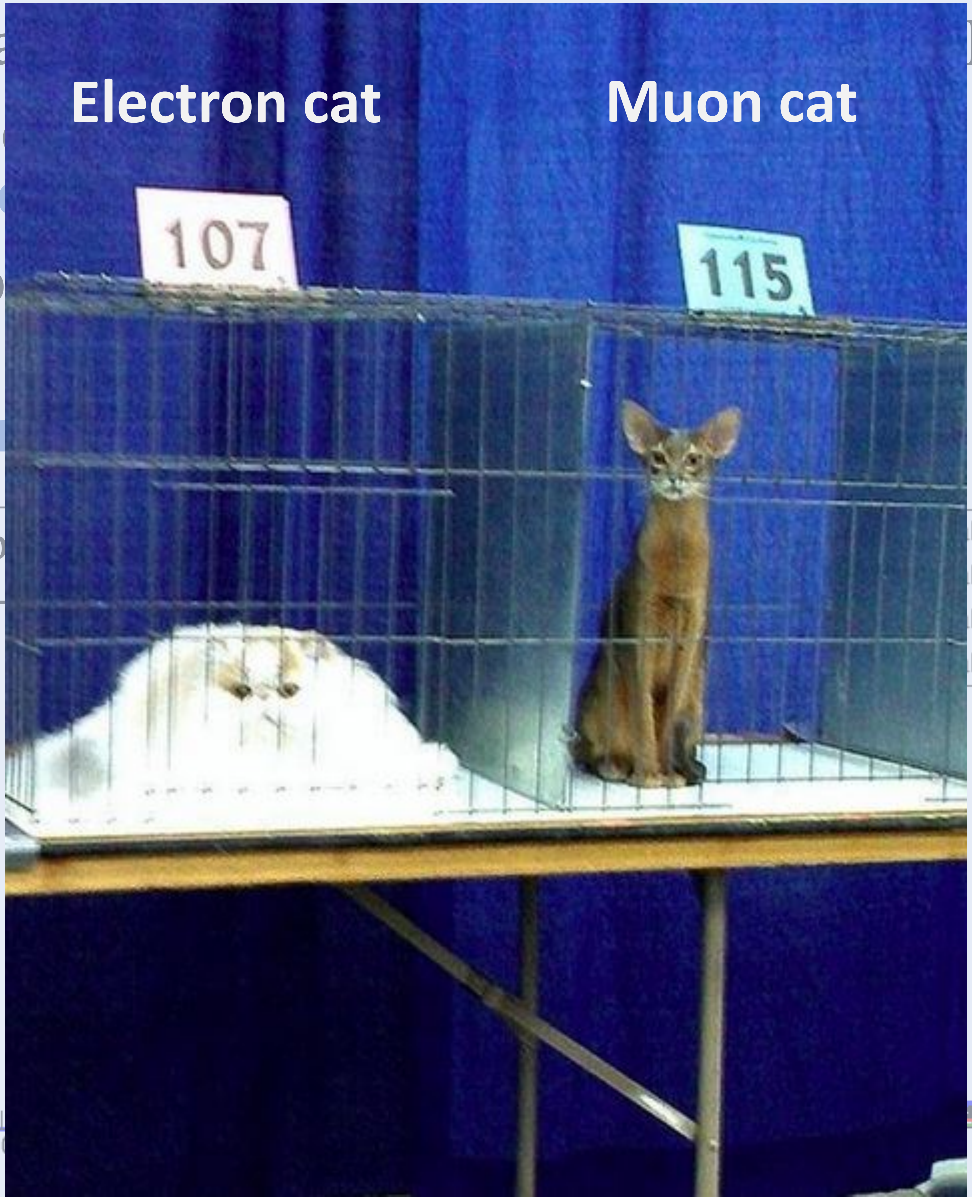



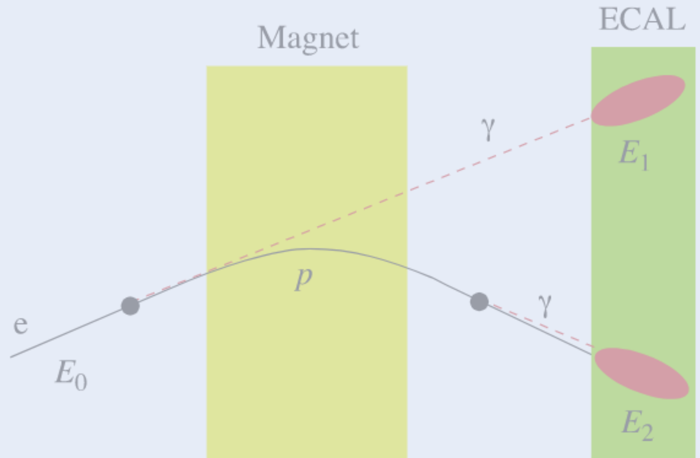
# Electron reconstruction and bremsstrahlung

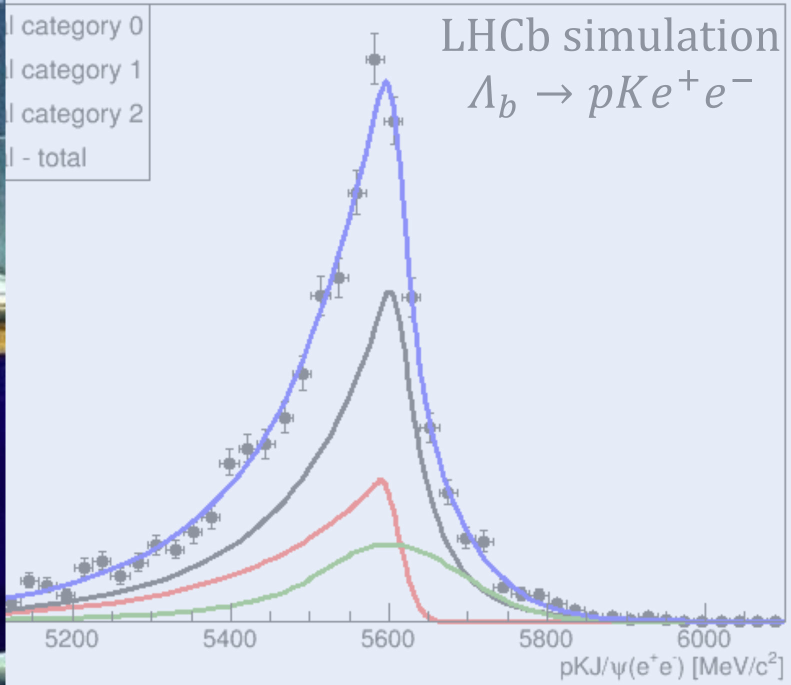


- **Electrons** emit **bremsstra** ... l
- To reconstruct the true en... emitted photons and **corr**...
- It is not always possible to ... too busy
- **Poor resolution on electr**...



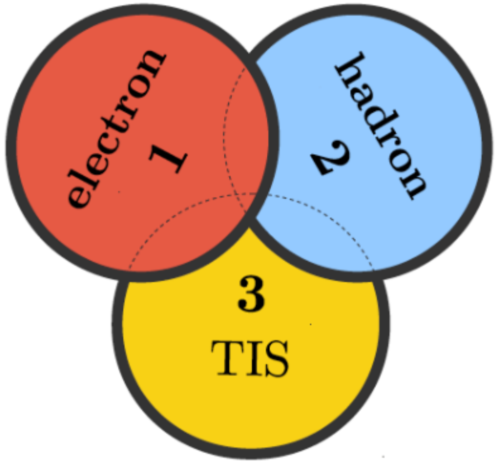



# Trigger categories



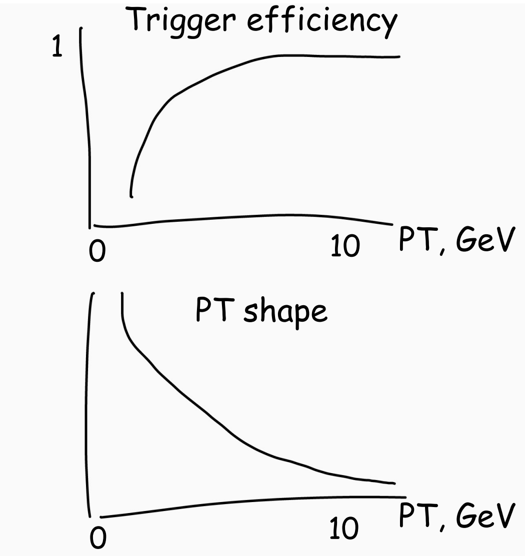
- As I just said, ECAL is very busy – plenty of electrons and photons (incl. from $\pi^0$)
- Thus, it is hard to trigger on electrons
  - Compare with super-easy triggering on muons: only muons fly through the muon chamber
- To gain more statistics, we can trigger on
  - Leptons – electron or muon (L0Lepton = 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

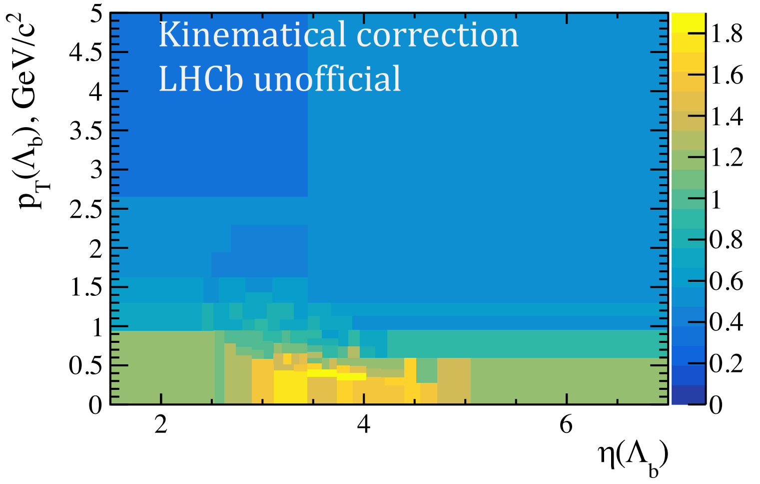


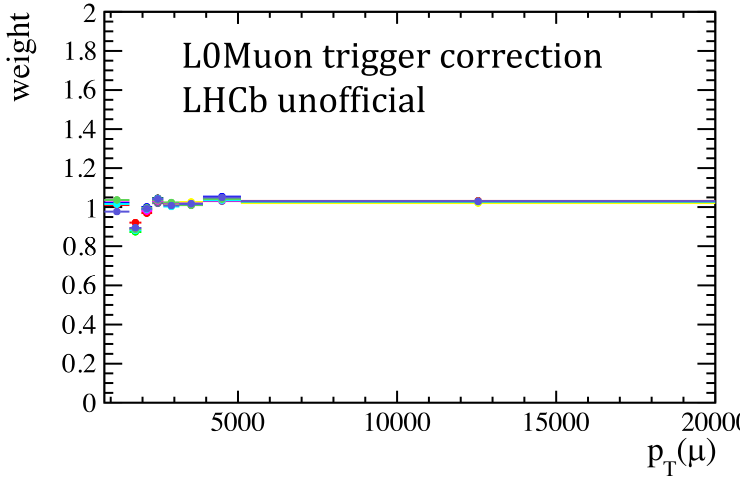
- $R_{pK} = \frac{BR(\Lambda_b \to pK\mu^+\mu^-)}{BR(\Lambda_b \to pKJ/\psi(\mu^+\mu^-))} * \frac{BR(\Lambda_b \to pKJ/\psi(e^+e^-))}{BR(\Lambda_b \to pKe^+e^-)}$
- What we really measure is a number of events ($N$)
- $R_{pK} = \frac{N(\Lambda_b \to pK\mu^+\mu^-)}{\varepsilon(\Lambda_b \to pK\mu^+\mu^-)} * \frac{\varepsilon(\Lambda_b \to pKJ/\psi(\mu^+\mu^-))}{N(\Lambda_b \to pKJ/\psi(\mu^+\mu^-))} * \frac{N(\Lambda_b \to pKJ/\psi(e^+e^-))}{\varepsilon(\Lambda_b \to pKJ/\psi(e^+e^-))} * \frac{\varepsilon(\Lambda_b \to pKe^+e^-)}{N(\Lambda_b \to pKe^+e^-)}$
- Efficiencies ($\varepsilon$) 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



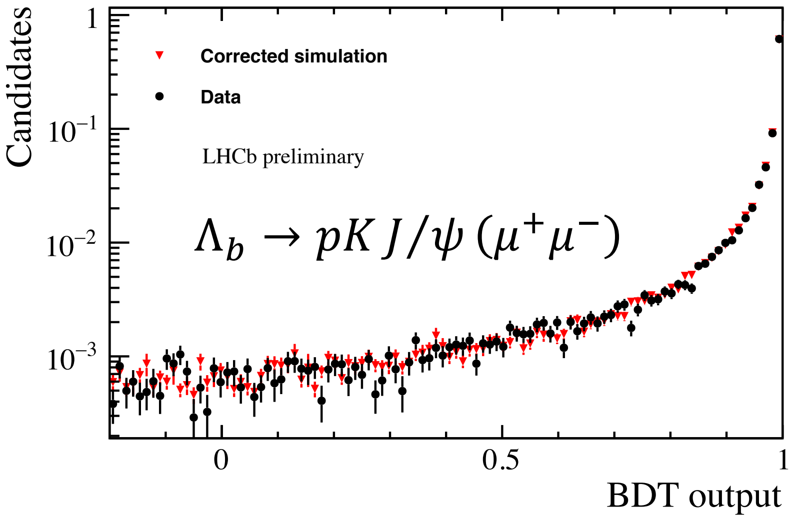
# Corrections to the simulation

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

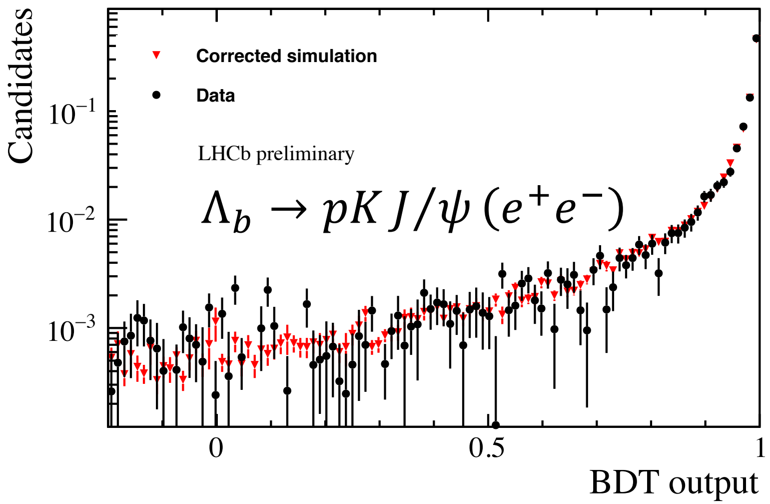



- When done, check the data-MC agreement in the BDT variable

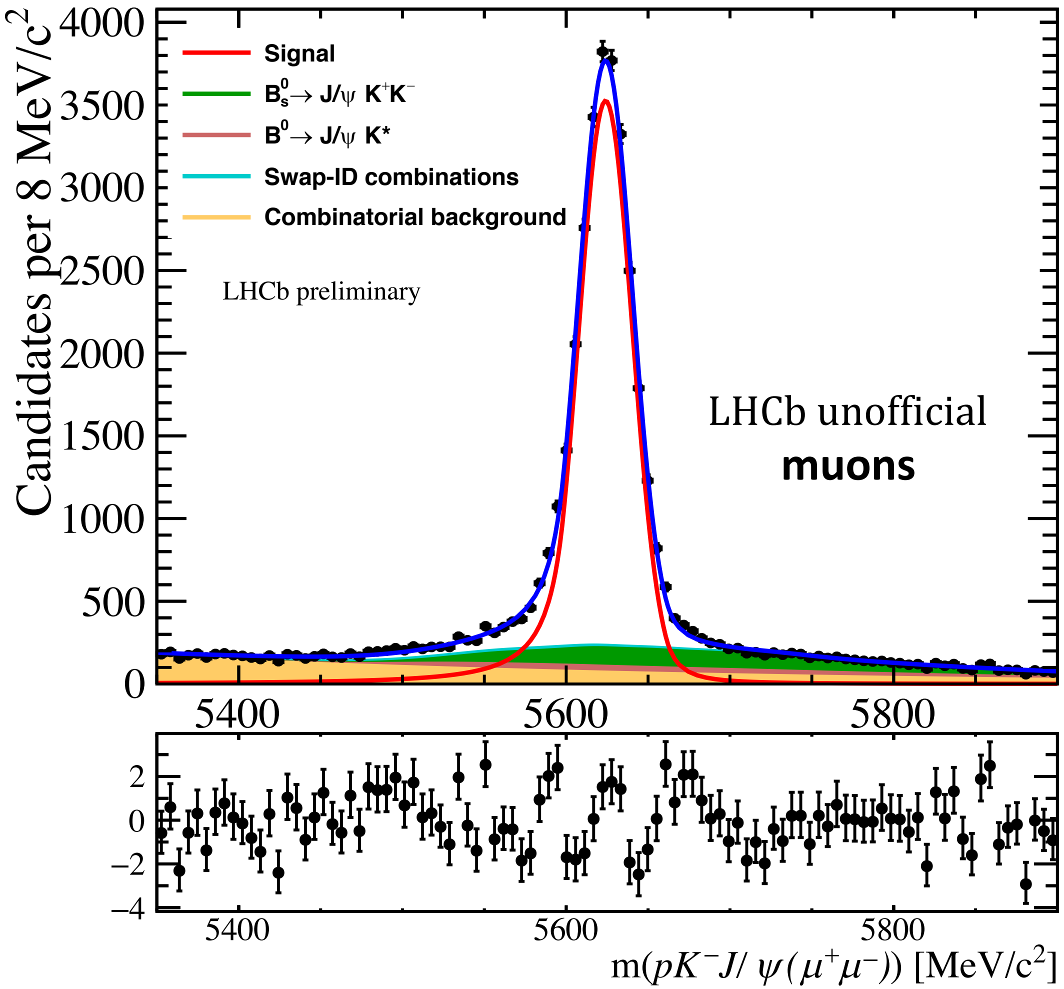


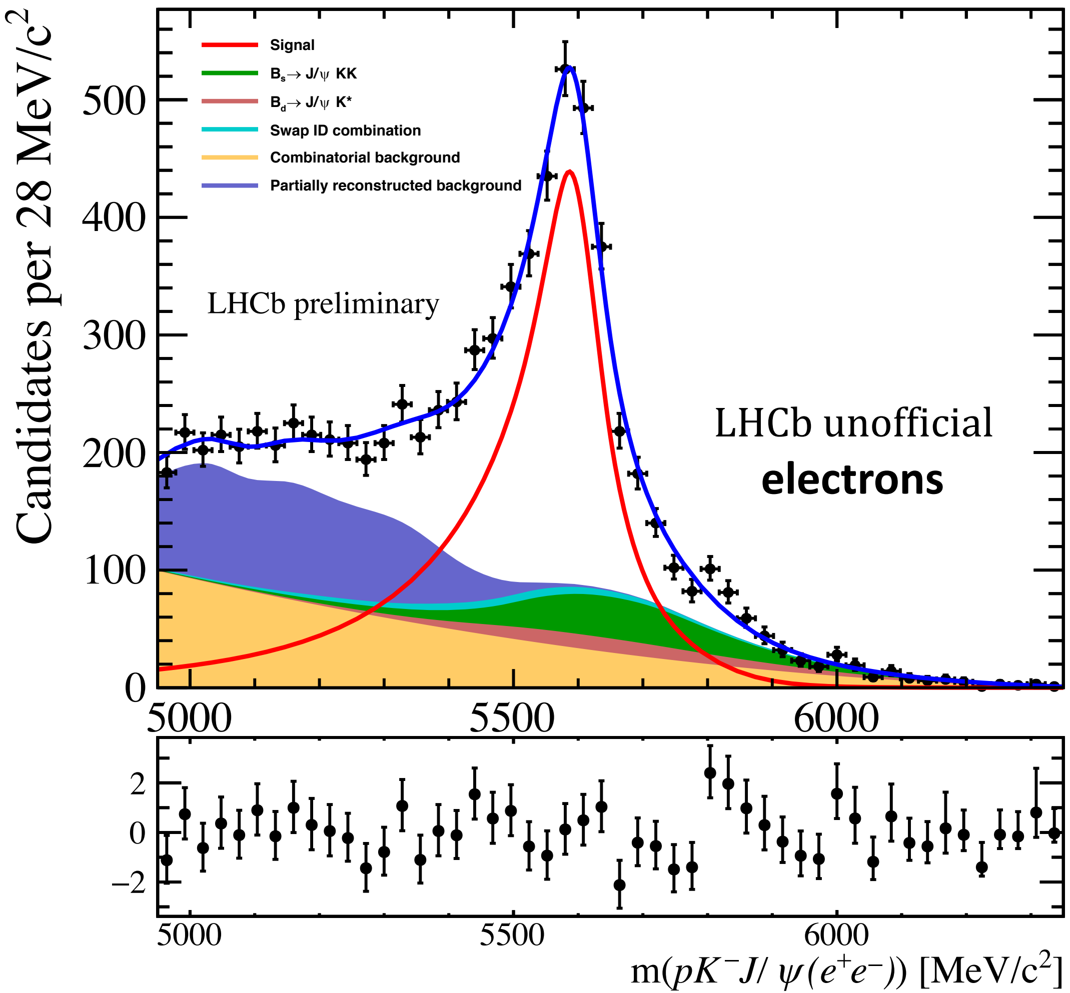

LHCb unofficial
MC: reweighted
Data: sPlot



# Fits to real data

- Include signal peak and background components
- Fits in the $J/\psi$ window:

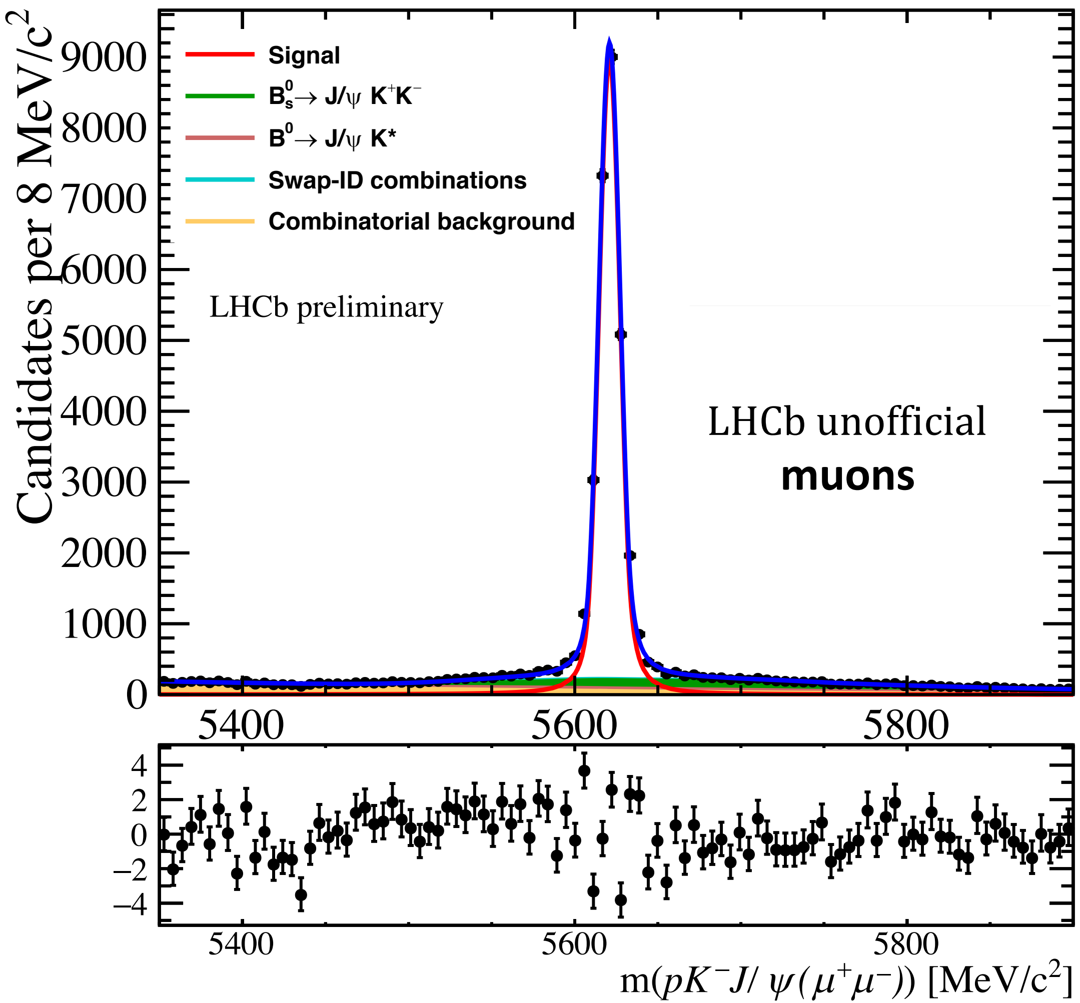


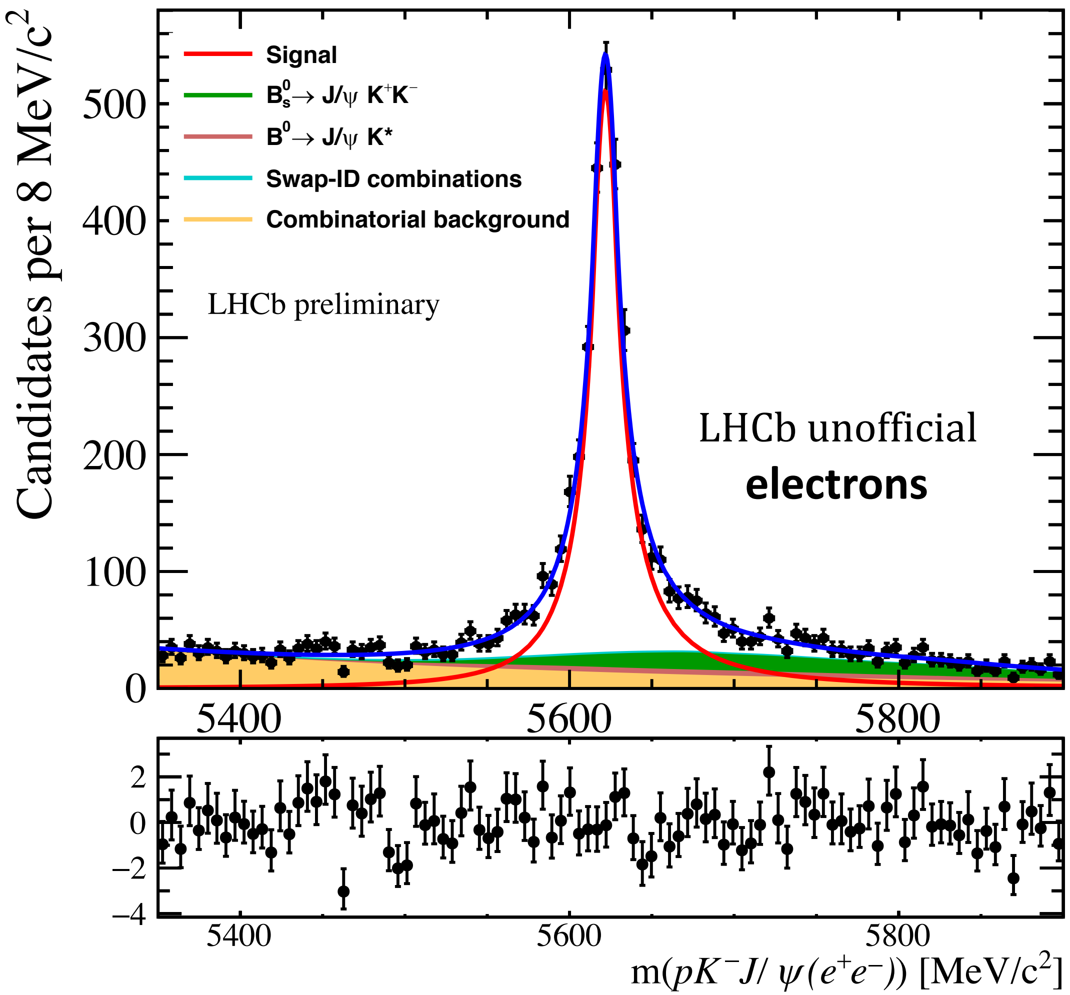



# Power of mass constraints




- We know the true mass of $J/\psi$
- Why not recompute the invariant mass using it?

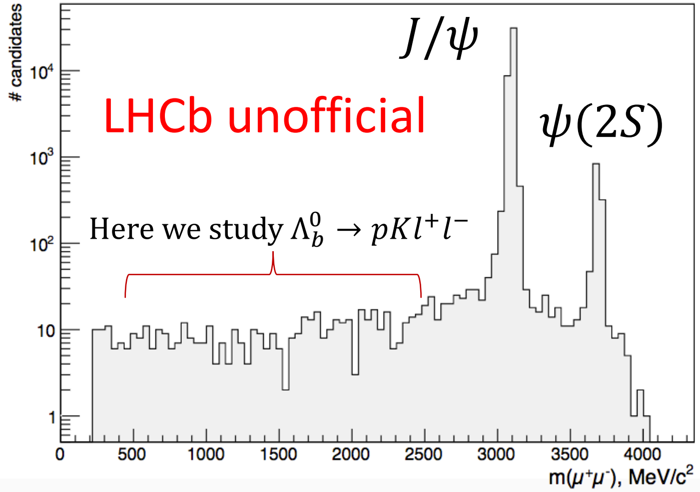


# Cross-checks: $r_{J/\psi}$ and friends



- 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
- Perform consistency cross-checks on $\Lambda_b \to pK\,\mu^+\mu^-$
- $\Lambda_b \to pK\,e^+e^-$ is kept blind!
  - (We should not know the $R_{pK}$ value before analysis framework settled!)
- Finally, the result: $R_{pK} =$


**Thank you for your attention!**
**Questions?**

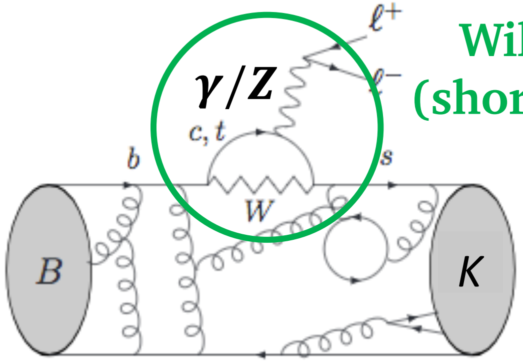
# Fin


Backup slides below

# Theorist's point of view

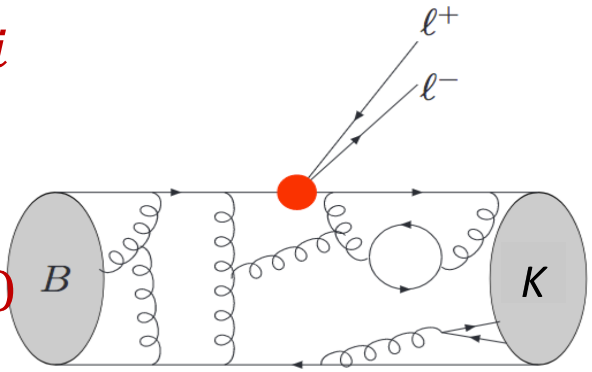


- Model-independent effective approach: $\mathcal{H}_{eff}(SM) \sim \sum C_i O_i$




**Wilson coefficients (short-distance effects)**

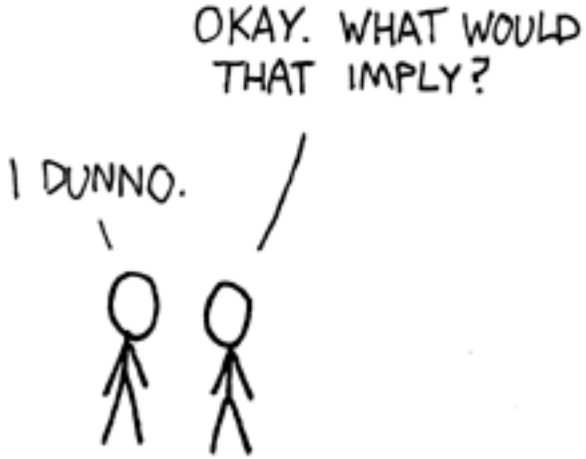
**Local operators (long-distance hadronic effects)**




- Precise predictions in the SM:

Soft photon — photon/Z — Z

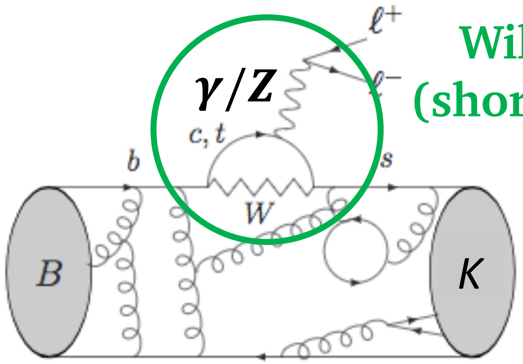
$C_7^{\mathrm{SM}} = -0.29, \; C_9^{\mathrm{SM}} = 4.1, \; C_{10}^{\mathrm{SM}} = -4.3$



# Theorist's point of view

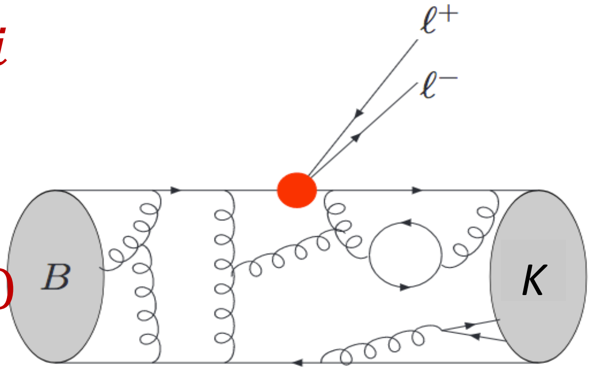


- Model-independent effective approach: $\mathcal{H}_{eff}(SM) \sim \sum C_i O_i$




Wilson coefficients (short-distance effects)

Local operators (long-distance hadronic effects)



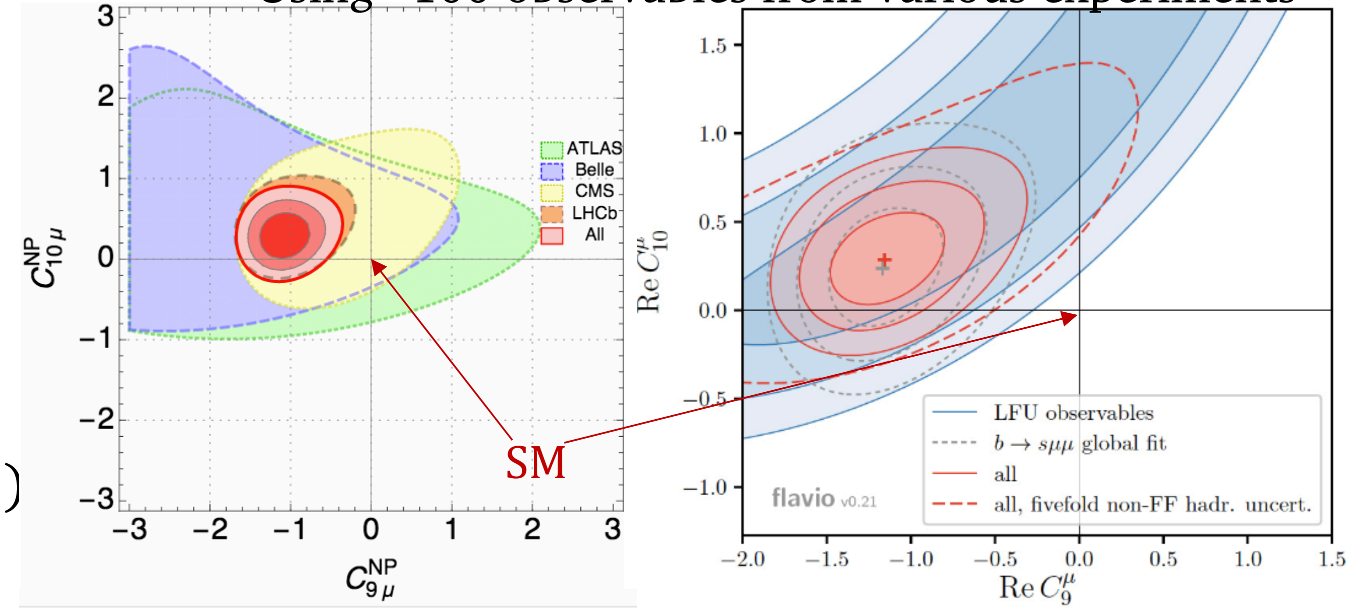

- Precise predictions in the SM:

Soft photon, photon/Z, Z

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

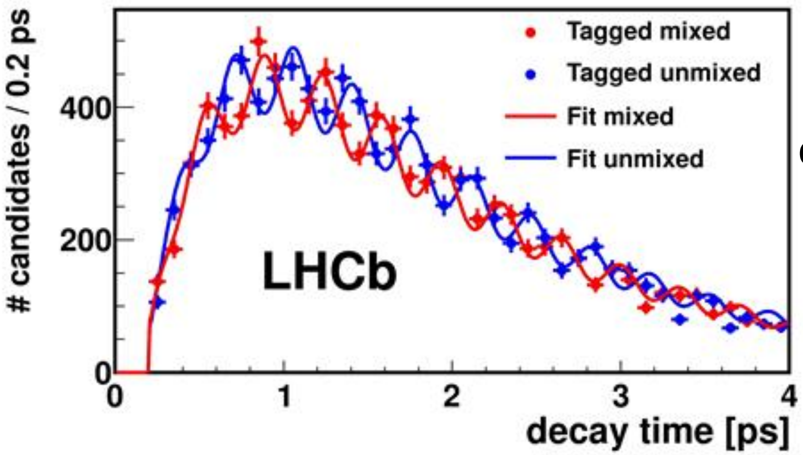
- To describe New Physics:
  - $C_{i(exp)} = C_{i(SM)} + C_{i(NP)}^{l}$
- These effects look **coherent**
- Strong evidence for non-zero $C_{9(NP)}^{\mu}$

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

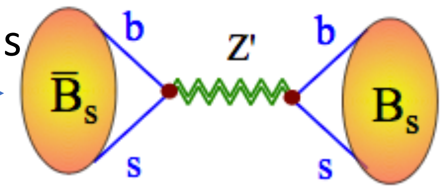


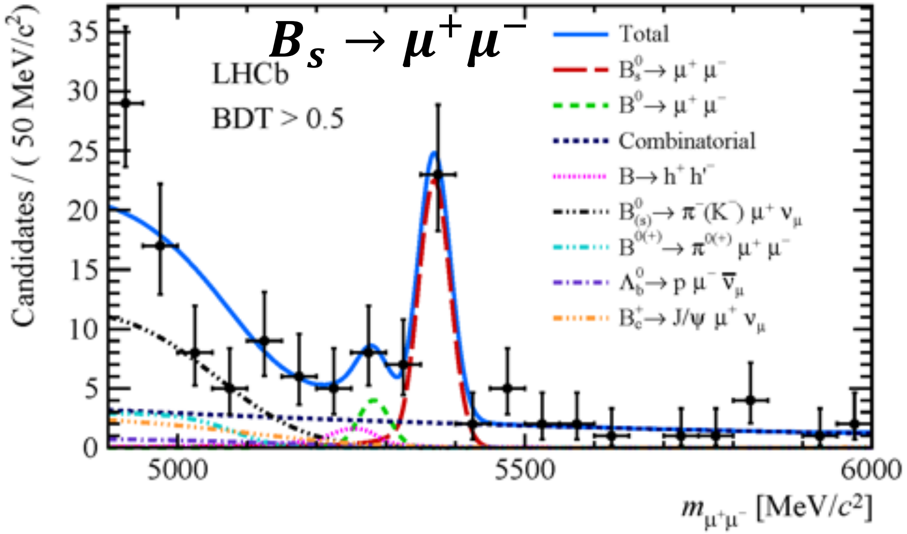
# Constraining New Physics models

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

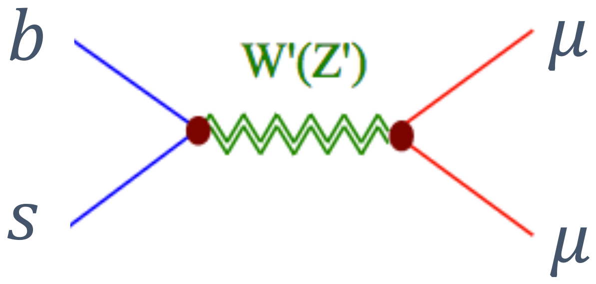


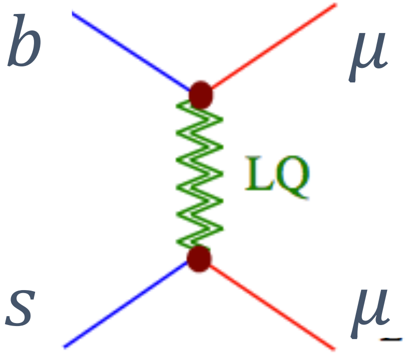

constrains




constrains



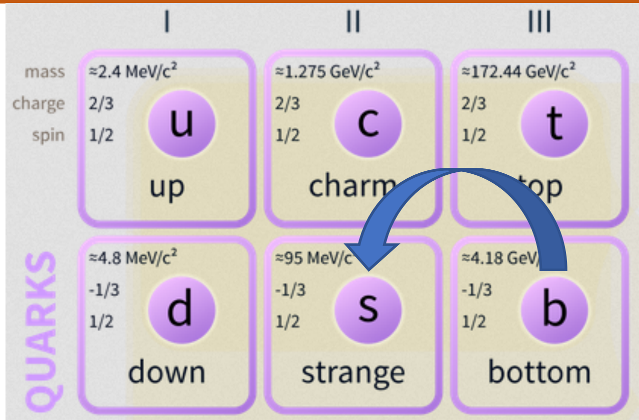




- ... But also performing the direct seraches in the forward region

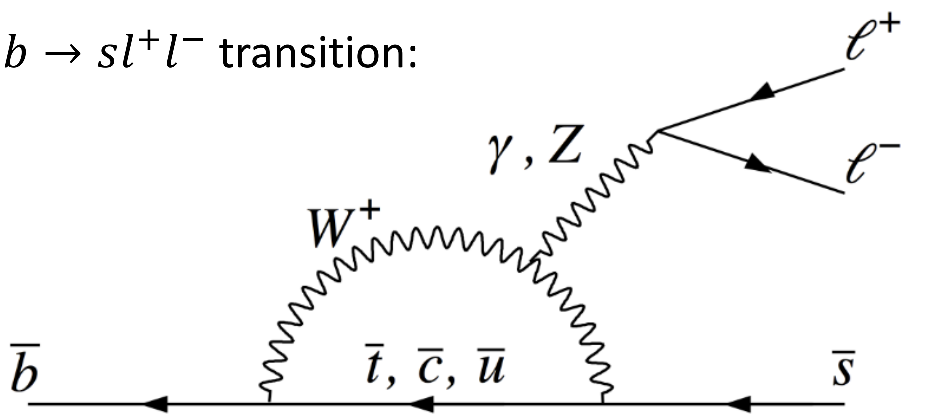
# Insidious penguins

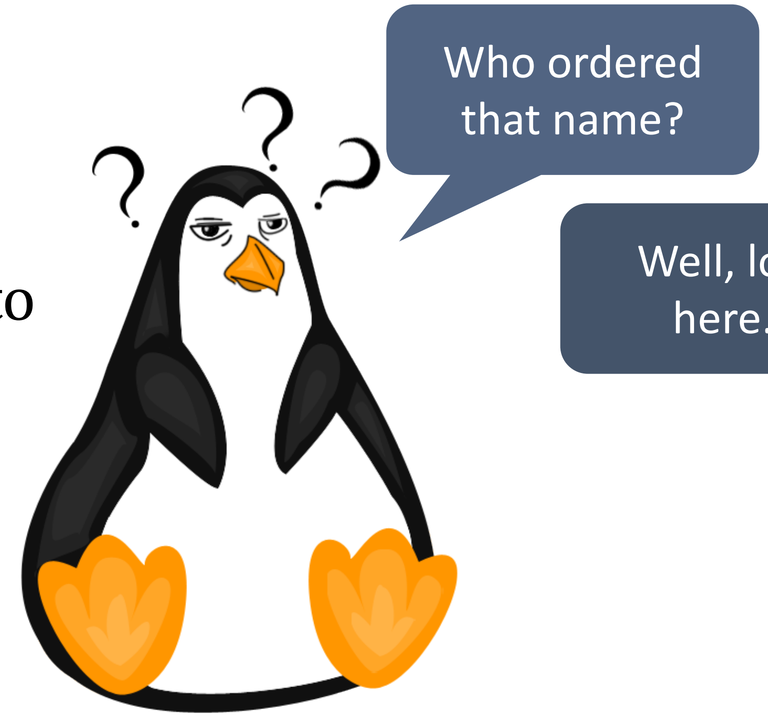


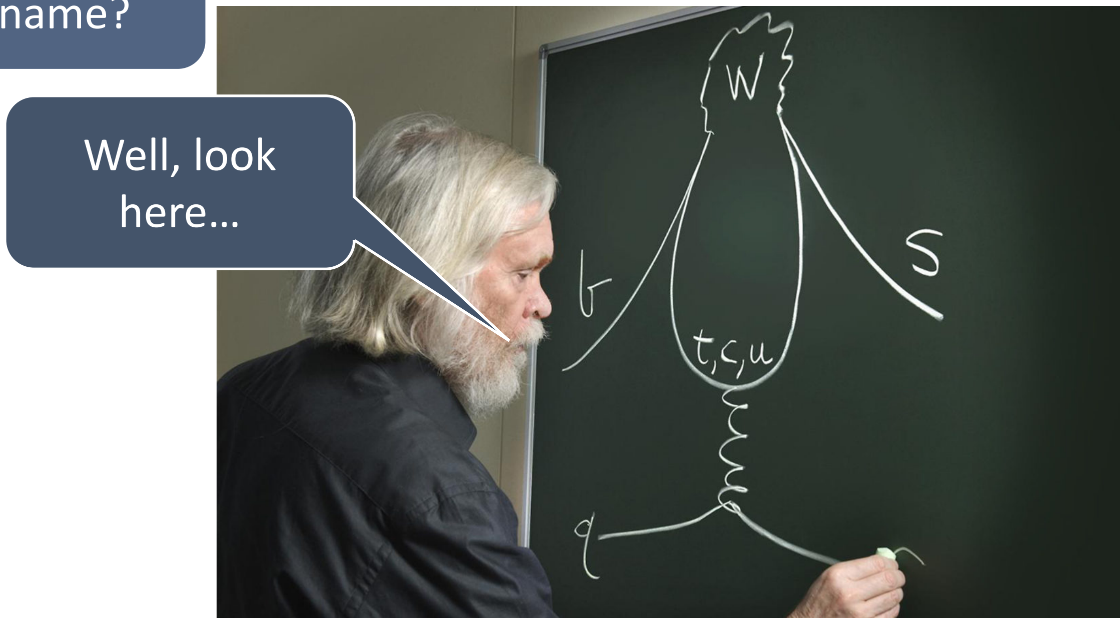
- The transitions between same-charge quarks – FCNC* – are forbidden *at the tree level*
- They proceed via **penguin diagrams**
- This makes these processes **very rare**, but also **sensitive** to the possible New Physics contributions
- *And this is where we observe something intriguing…*




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



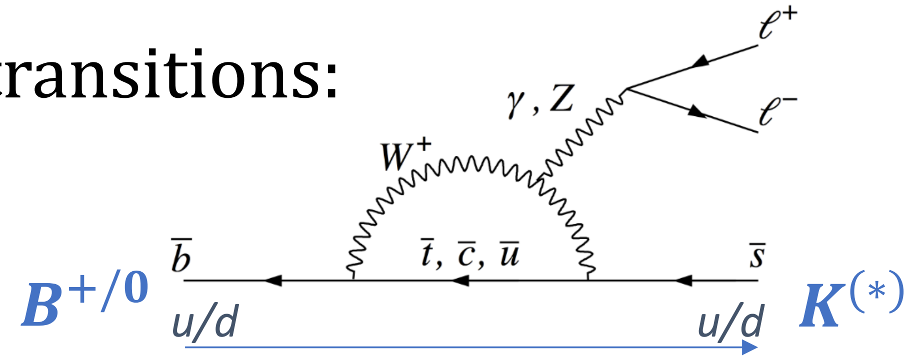




* FCNC = Flavor Changing Neutral Currents

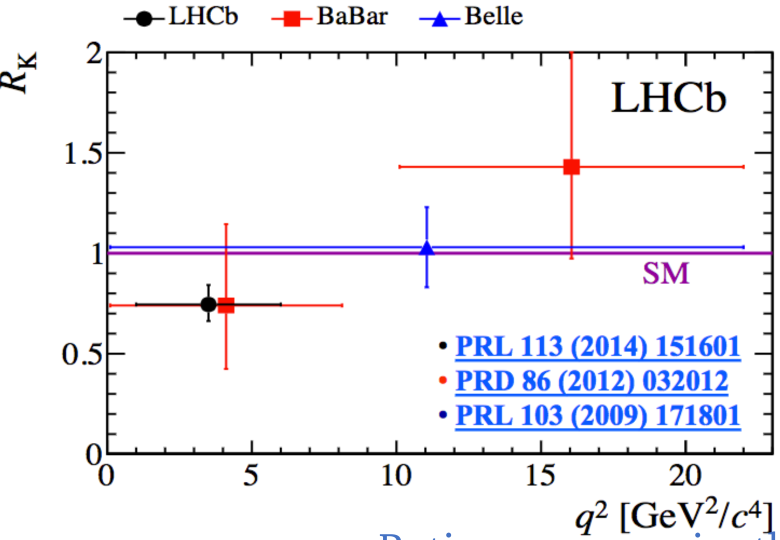
# Ratios of ratios of ratios …

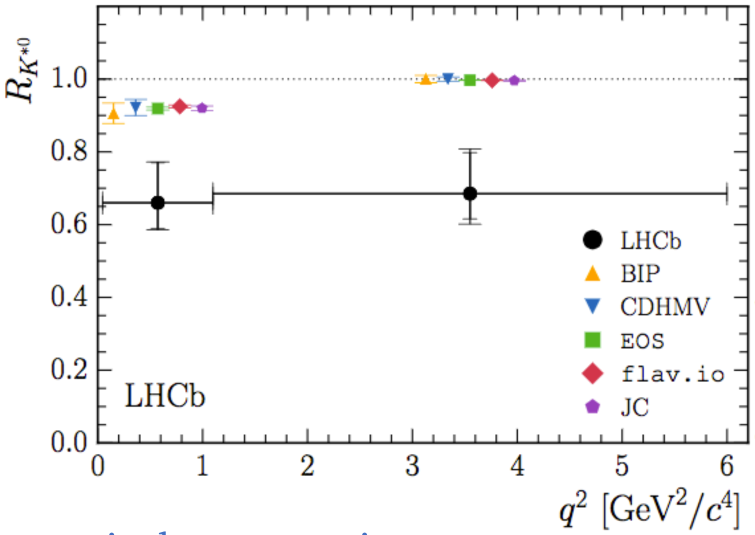


- Few remarkable measurements in the $b \to sl^+l^-$ transitions:




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

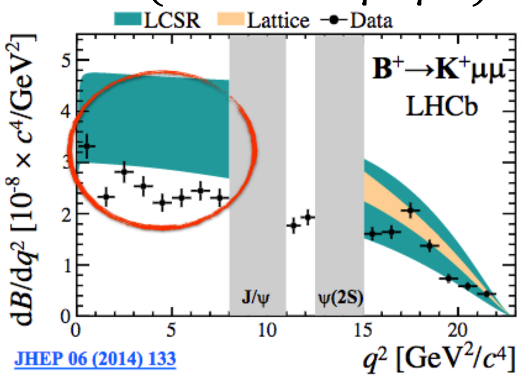


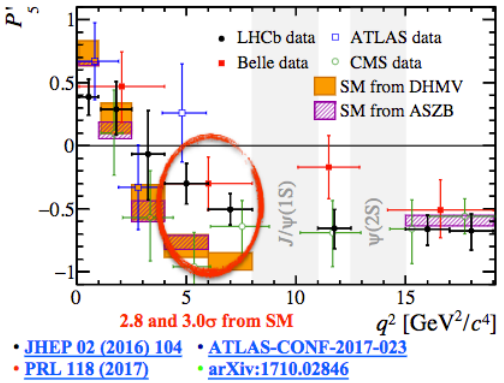

Ratios: very precise theoretical computation
Cancellation of theoretical and experimental uncertainties

Additional input:

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




Angular analysis

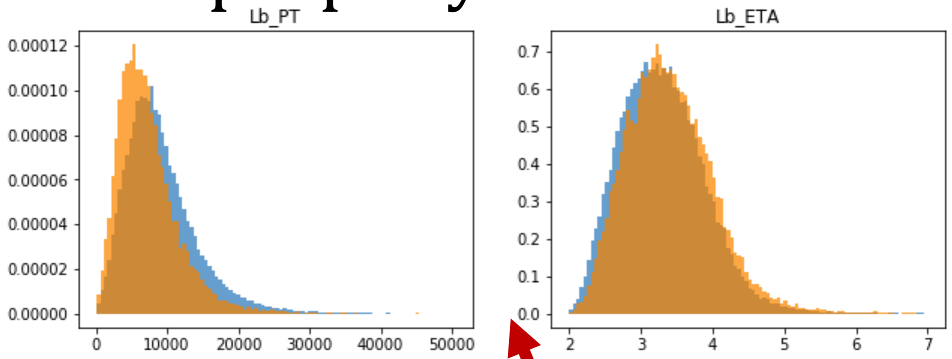


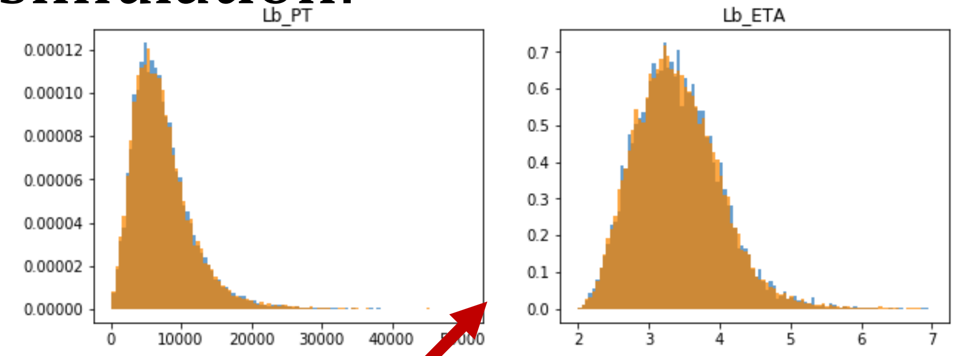

- Also some anomalies in the $b \to cl^+\nu_l$ transitions
- New/updated measurements expected from LHCb and BELLE-II

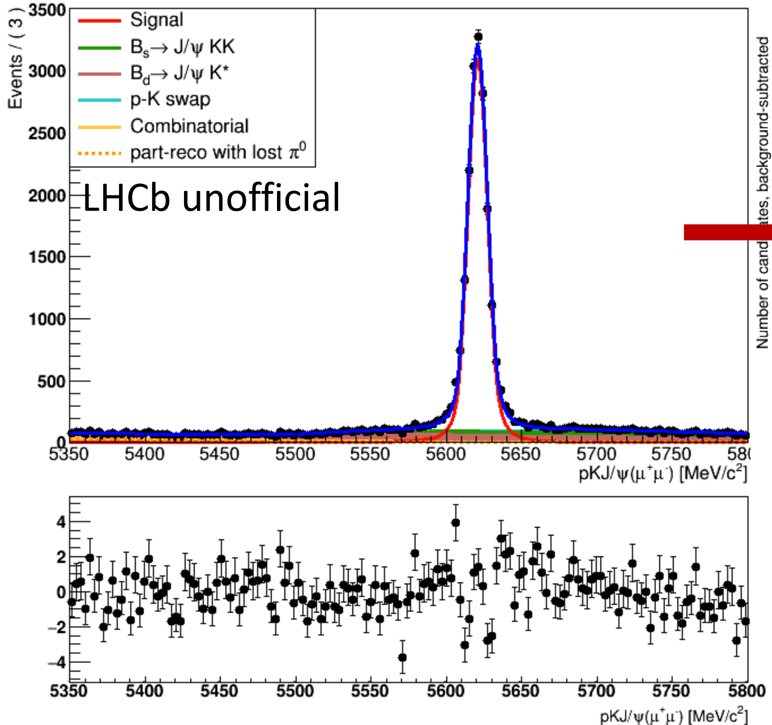
# Corrections in work

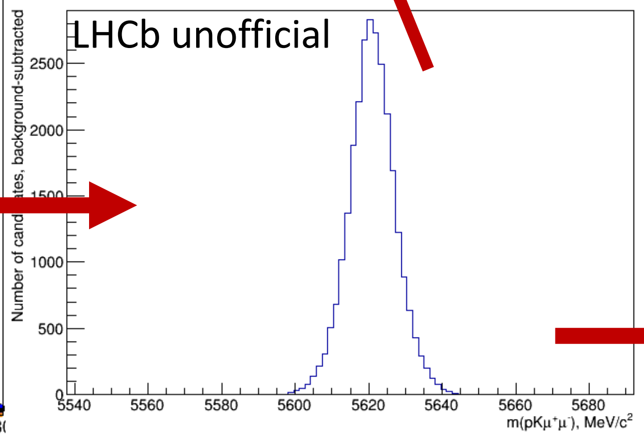


- Some variables are not properly modeled in the simulation:
  - e.g. generated kinematics of the decay:

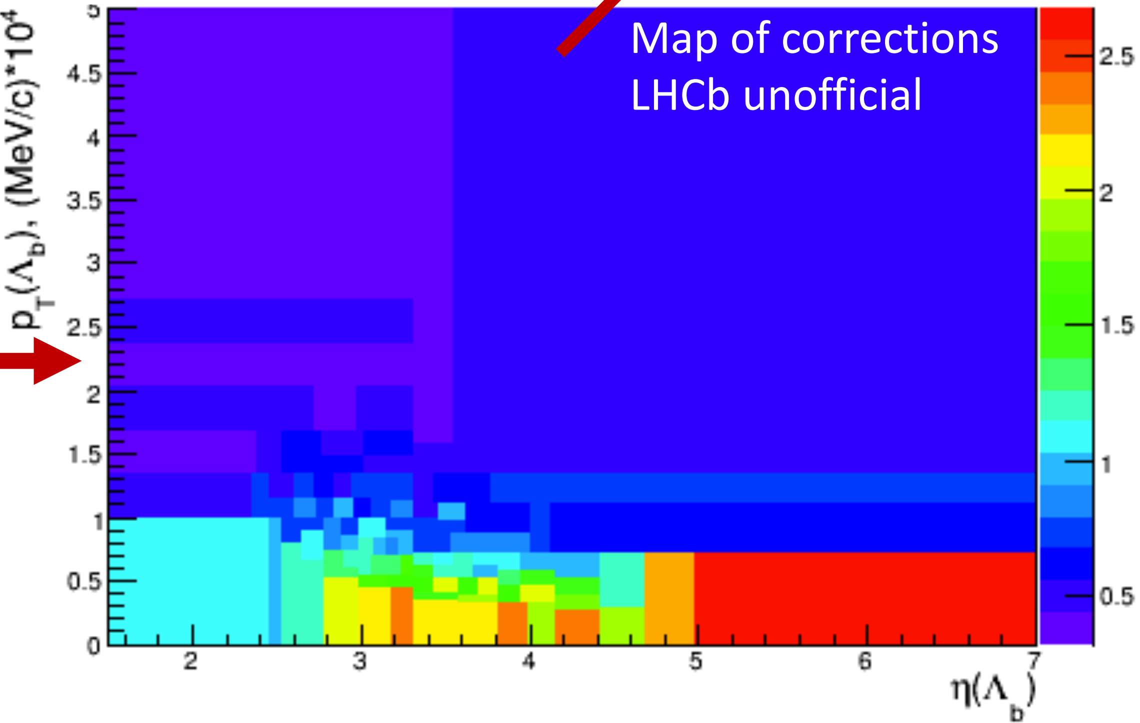



sPlot



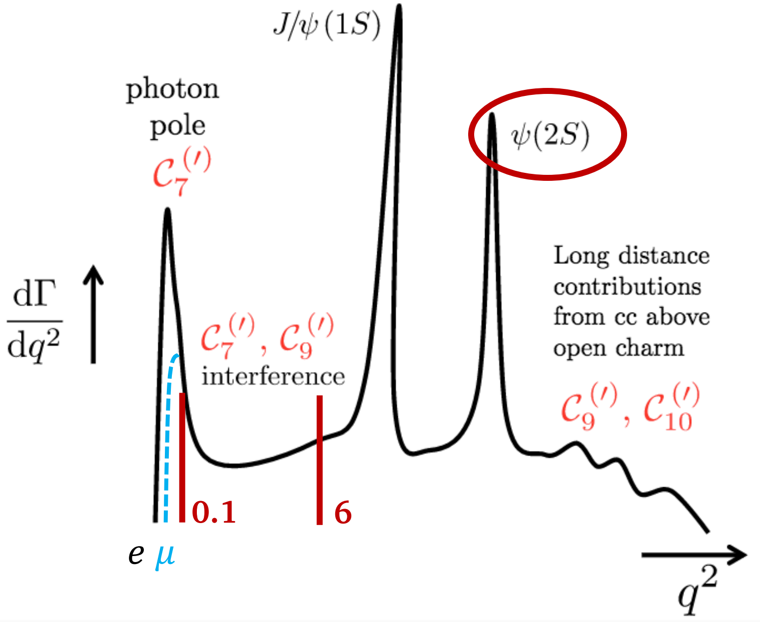
# Cross-checks



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

  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?



- 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
  - $\frac{BR(B^0 \to K^*\psi(2S))}{BR(B^0 \to K^*J/\psi)} = 0.46$, $\frac{BR(B^0 \to K^*\chi_{c2})}{BR(B^0 \to K^*\chi_{c1})} = 0.20$