Testing lepton flavor universality with the $B^0 \to K^* \tau^+ \tau^-$ decay at the LHCb experiment

CPPM Ph.D. students' seminars

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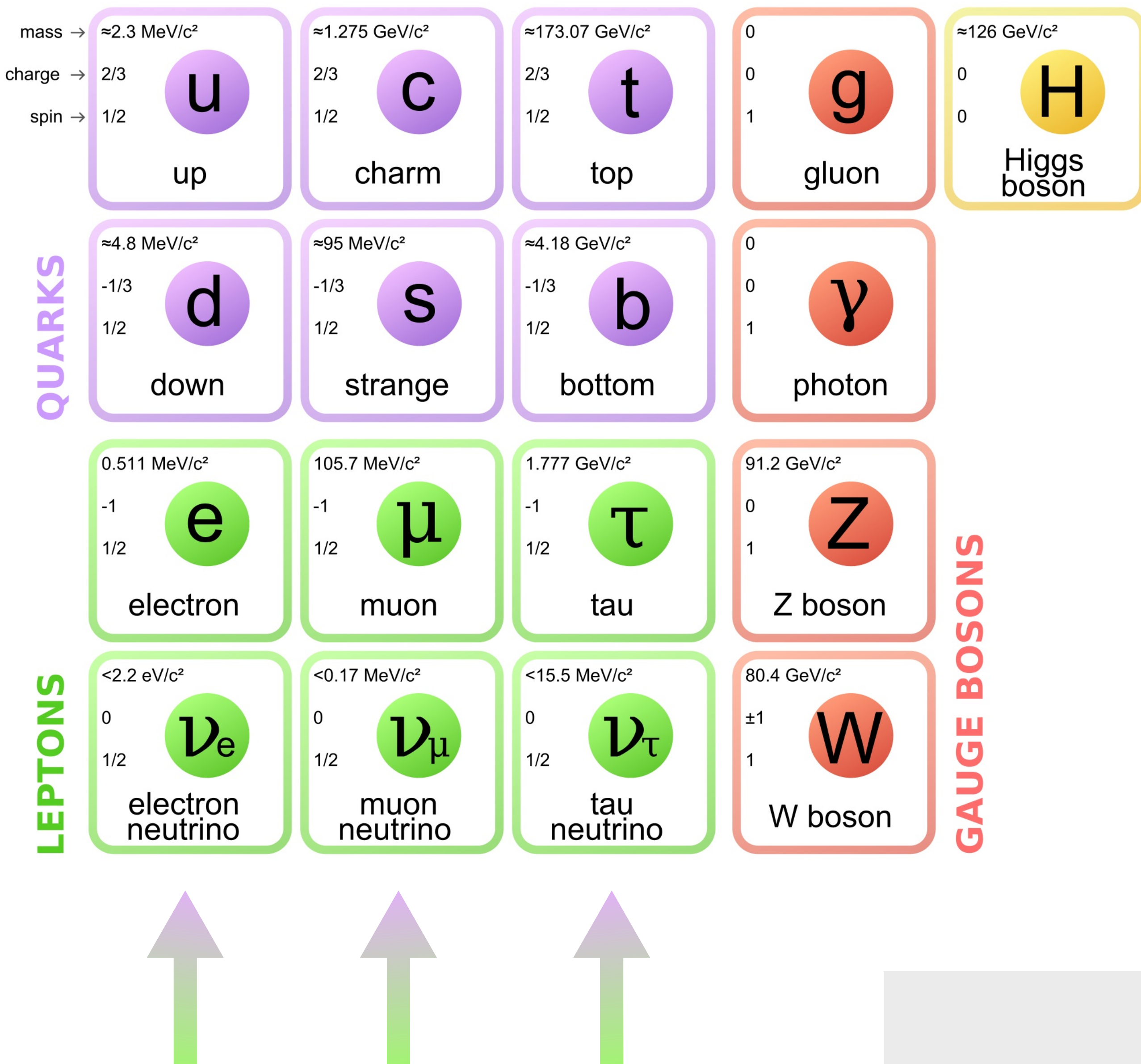
Lepton Flavor Universality in the Standard Model



Three families of fermions called "flavors"

- **Standard Model**: the theory describing elementary particles and their interactions
- Extremely powerful: experimentally tested from low-energy phenomena (~ 1 eV) up to the electroweak scale (~100 GeV)…
- …but incomplete: describes only ~5% of the universe
- **Many unsolved questions**:
  - Dark matter and dark energy
  - Neutrino mass
  - Matter-antimatter asymmetry
  - Higgs mass fine-tuning problem
  - …

Lepton Flavor Universality (LFU):

The three charged leptons have the same weak coupling constant

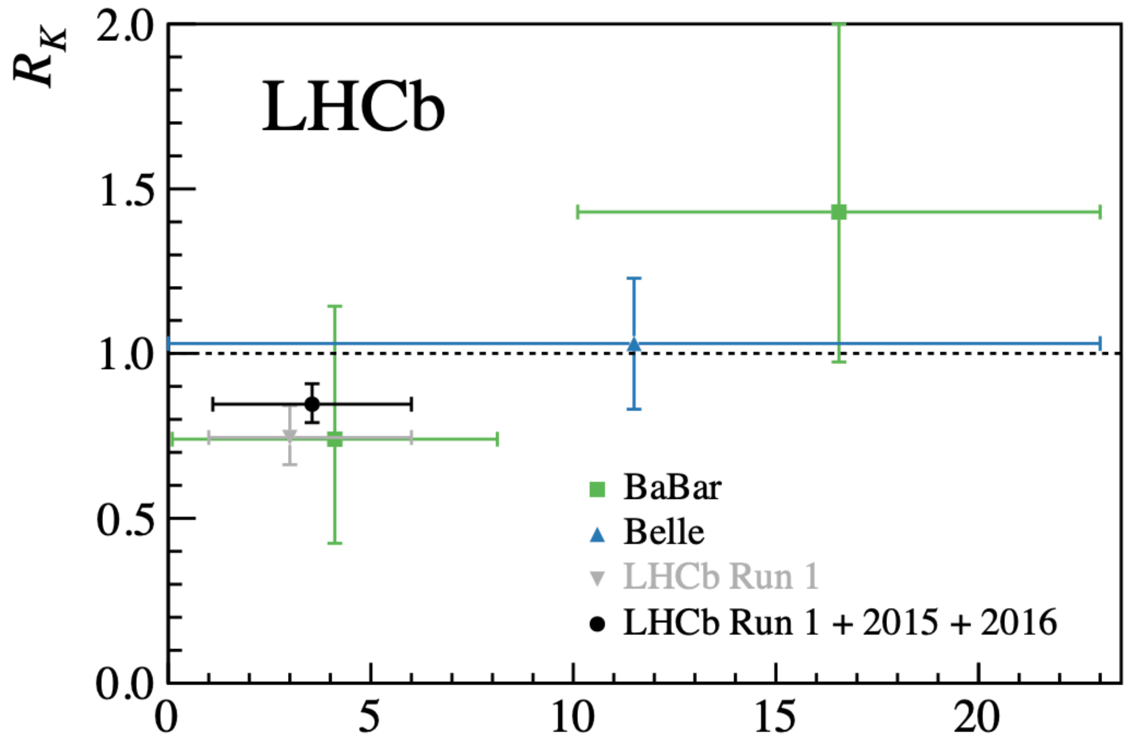
→ Differences in *branching ratios* for processes involving *e*, *μ* or **τ** in the final state are due only to their different masses

Is LFU correct?

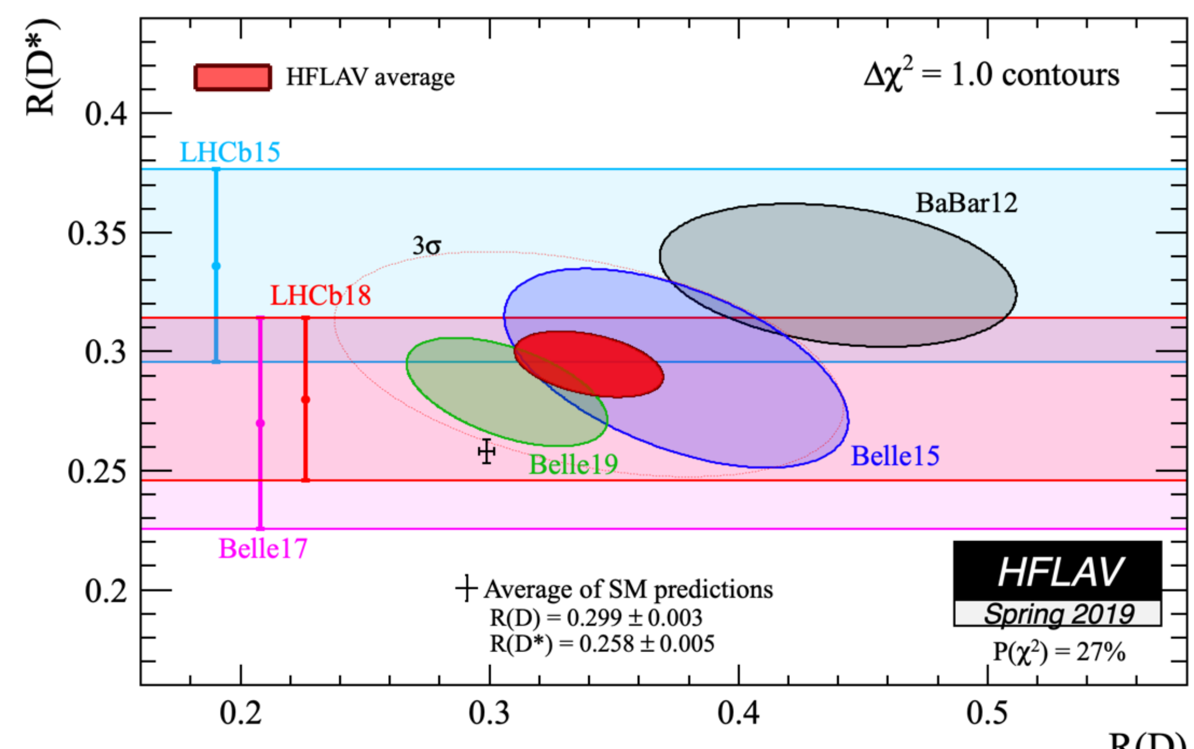
- Standard Model predictions based on LFU assumption
- Some tensions are observed in experimental measurements involving different leptons in the final state

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

$$R(D^{(*)}) = \frac{\mathscr{B}(\bar{B}^0 \to D^{(*)+} \tau^- \bar{\nu}_\tau)}{\mathscr{B}(\bar{B}^0 \to D^{(*)+} \mu^- \bar{\nu}_\mu)}$$



https://arxiv.org/pdf/1903.09252.pdf

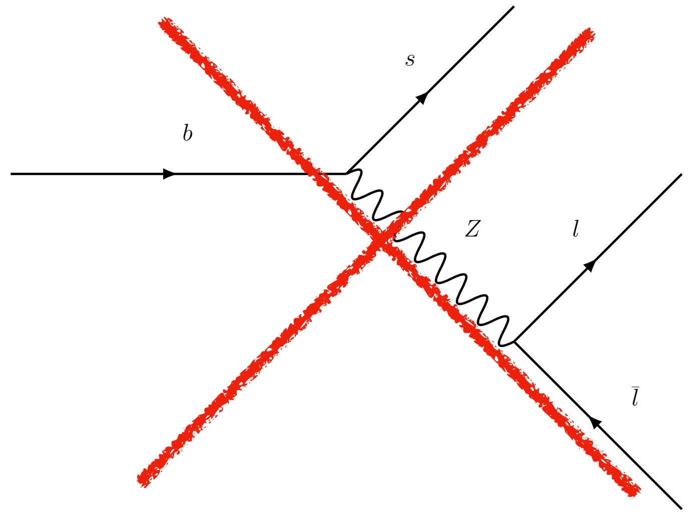


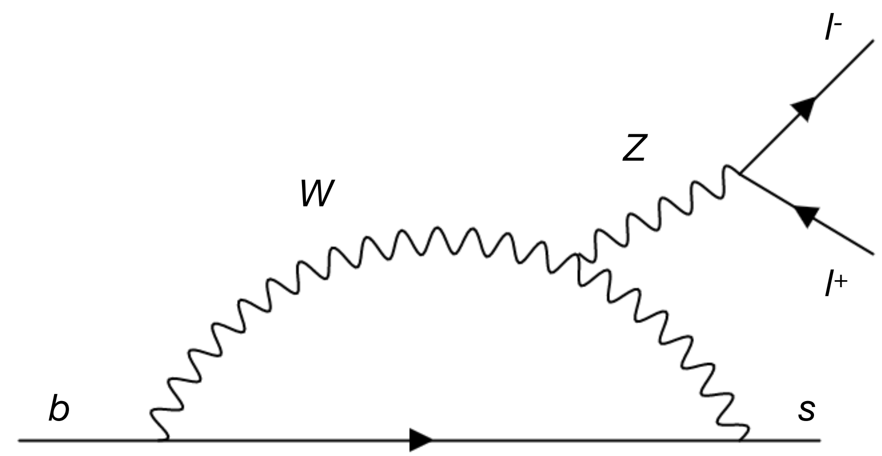
https://hflav.web.cern.ch

- Global fit with data from various experiments using EFT shows ~ 7σ deviation from SM (Eur. Phys. J. C (2019) 79 714)
- Need more data and measurements to shed light on these “anomalies”

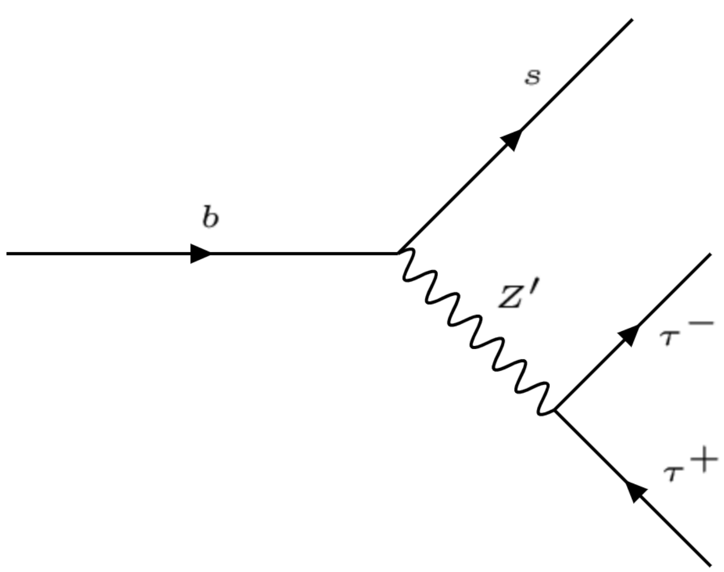
Rare B^0 decays…

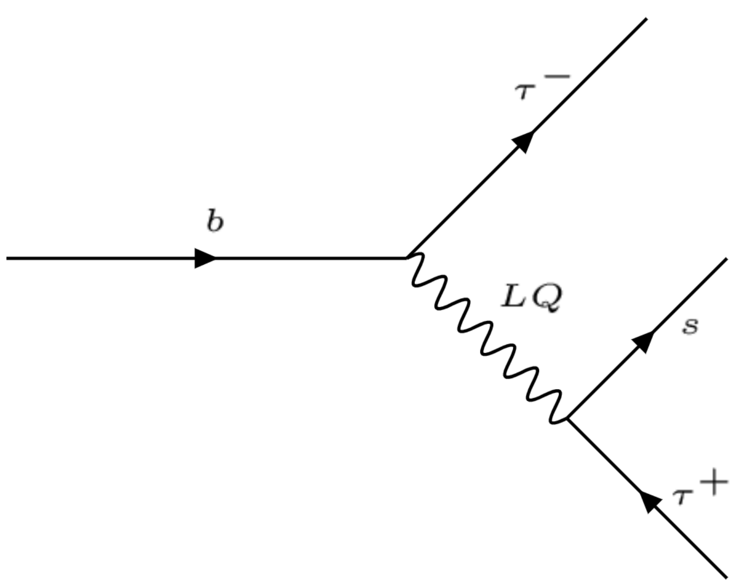
- B^0 mesons can decay via $b \to s\, l^+ l^-$ quark transitions
- These transitions are forbidden at three-level in the Standard Model
- Instead they proceed through loops or boxes diagrams at higher order





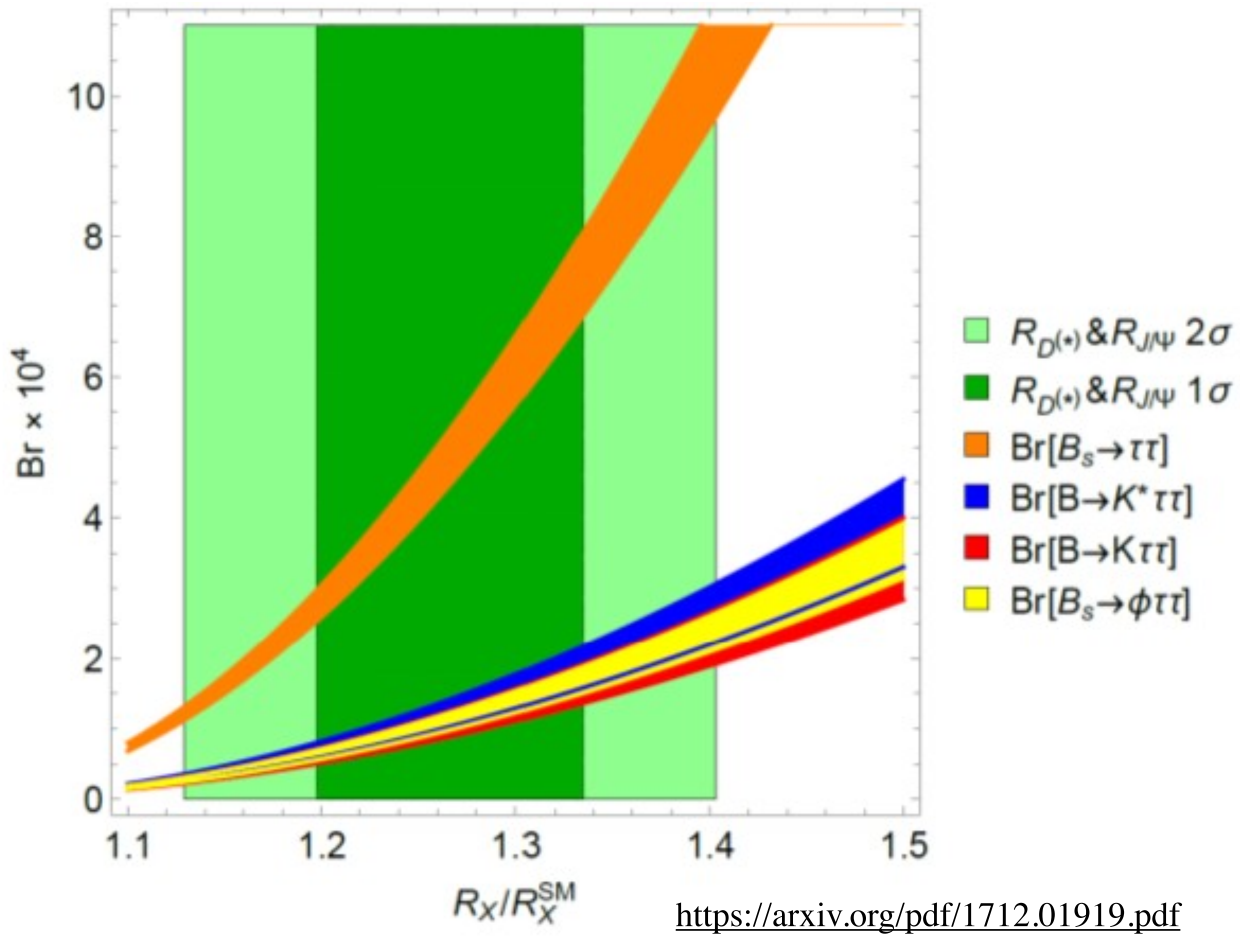
- The probability of the decay is suppressed
- Sensitive to hypothetical new particles entering the loop (Z’, leptoquarks, …)
- Branching ratio could be enhanced



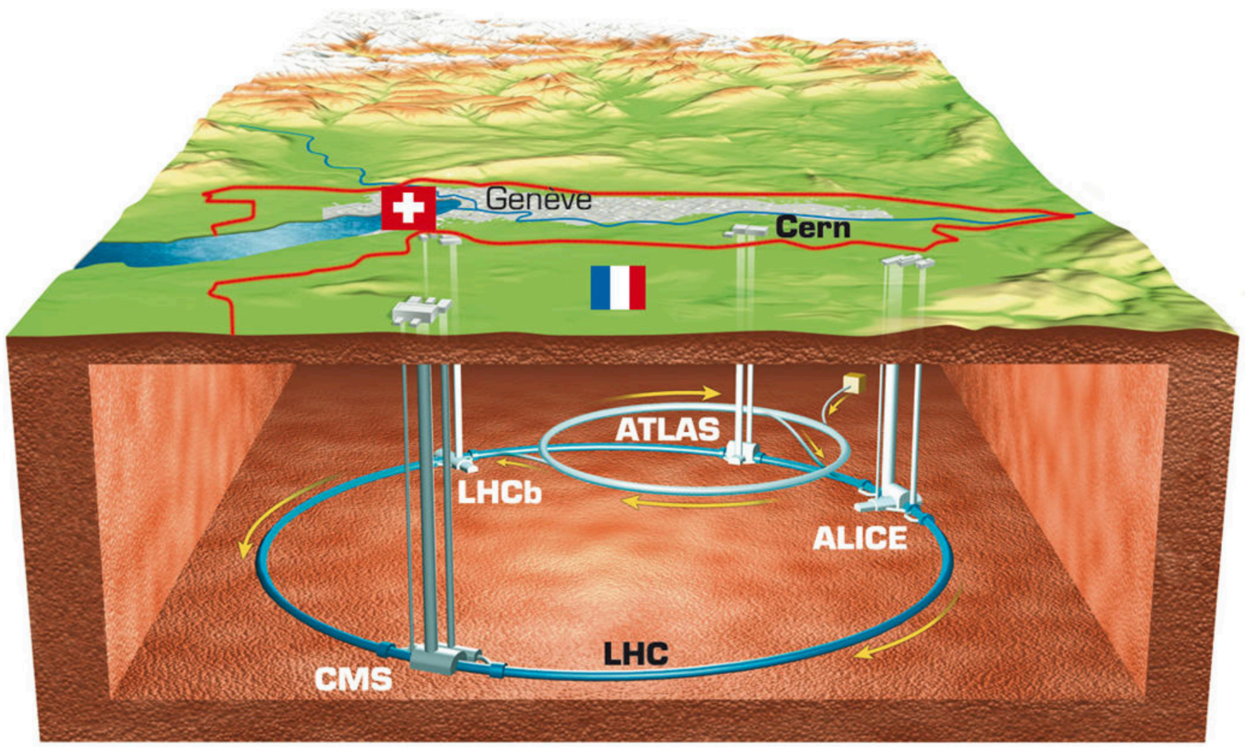


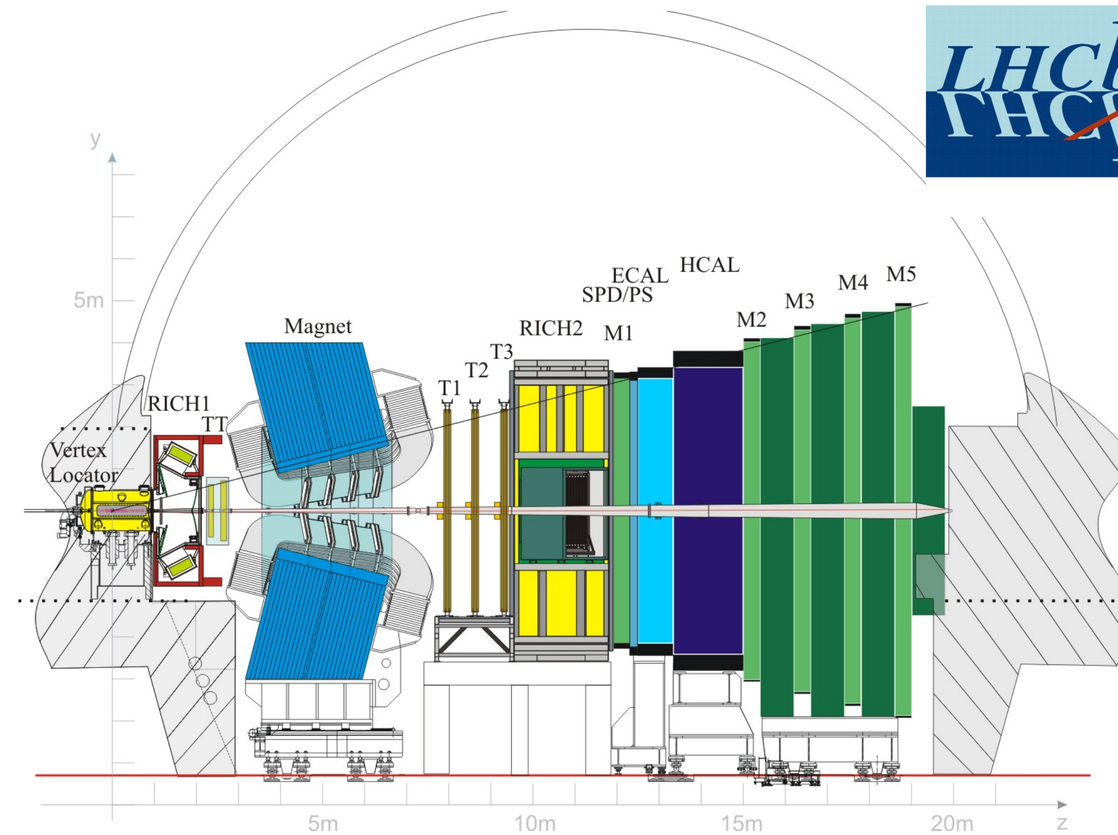
...with τ leptons in the final state

- τ is the heaviest lepton: $m_\tau \sim 17 \cdot m_\mu \sim 3500 \cdot m_e$
- Because of its mass it could be the most sensitive to new physics effects ✓
- τ modes still largely unexplored ✓
- More complex experimentally: ✗
  - It decays before it is detected
  - Neutrinos in the final state: missing energy



https://arxiv.org/pdf/1712.01919.pdf





https://iopscience.iop.org/article/10.1088/1748-0221/3/08/S08005/pdf

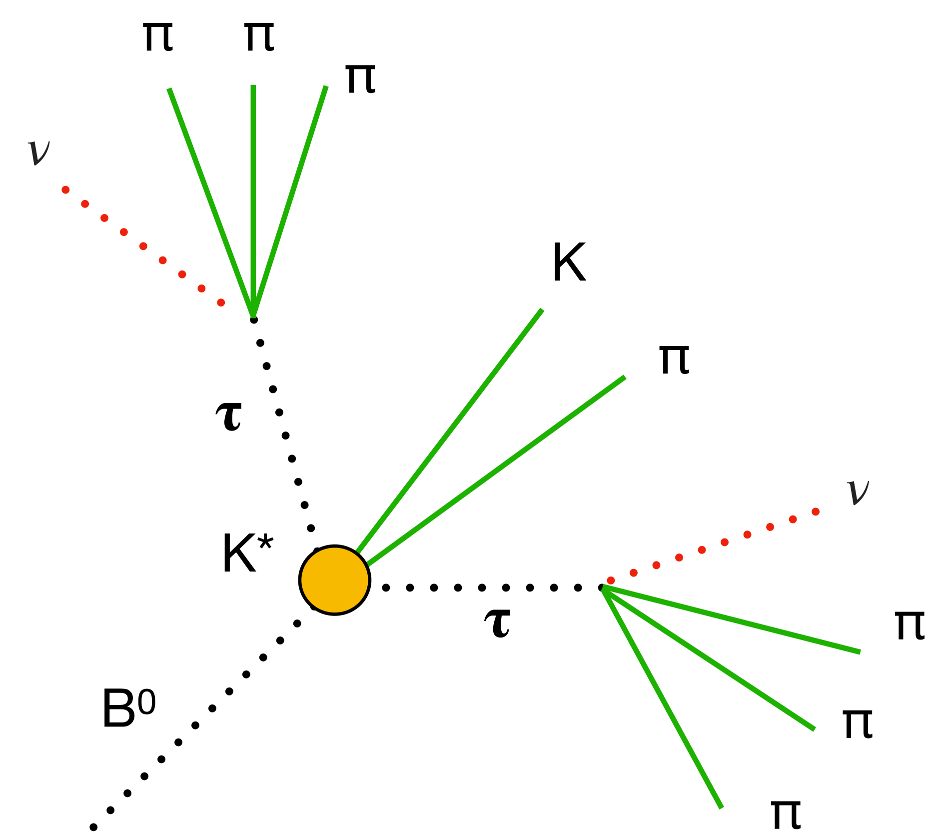
- ~~Precision experiment to study CP violation in B hadron decays~~

  General purpose experiment optimized for detecting beauty and charm hadrons
- Peculiar features for rare B decays studies:
  - **Vertex Locator (VELO)**: Precise measurement of displaced vertex positions (~13μm vertex resolution in transverse plane, ~70μm along beam axis)
  - **RICH detectors**: identification of charged hadrons via Cherenkov effect (over ~ 2-100 GeV range)
  - **Tracking system**: good momentum resolution (~0.8 % for 100 GeV particles)
  - **Muon stations**: muon identification and trigger

The B^0 -> $K^*\,\tau^+\,\tau^-$ decay

- $b \to s\, l^+\, l^-$ transition, **expected BR(B^0 -> $K^*\,\tau^+\,\tau^-$) ~ 10^{-7}** *
- The search is performed using full LHCb dataset (9 fb^{-1}), using the channel:

$$B^0 \to K^*(\to K^-\pi^+)\,\tau^+(\to \pi^+\pi^+\pi^-\bar{\nu}_\tau)\,\tau^-(\to \pi^+\pi^-\pi^-\nu_\tau)$$



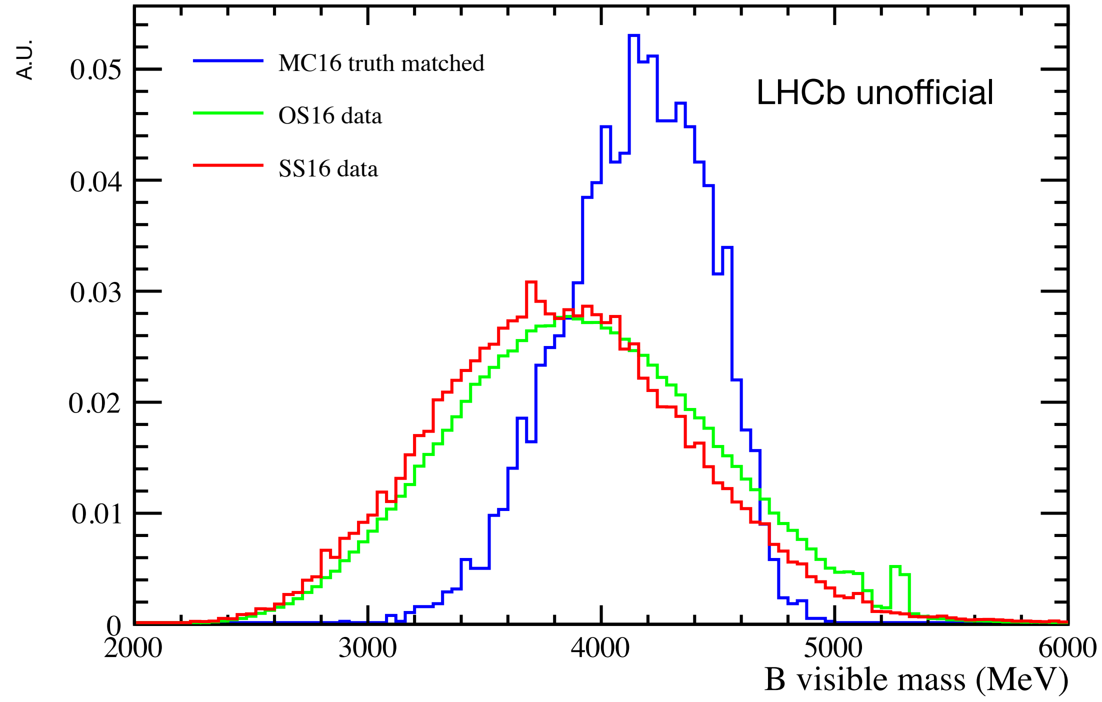
- A second final state has been considered, less advanced state:

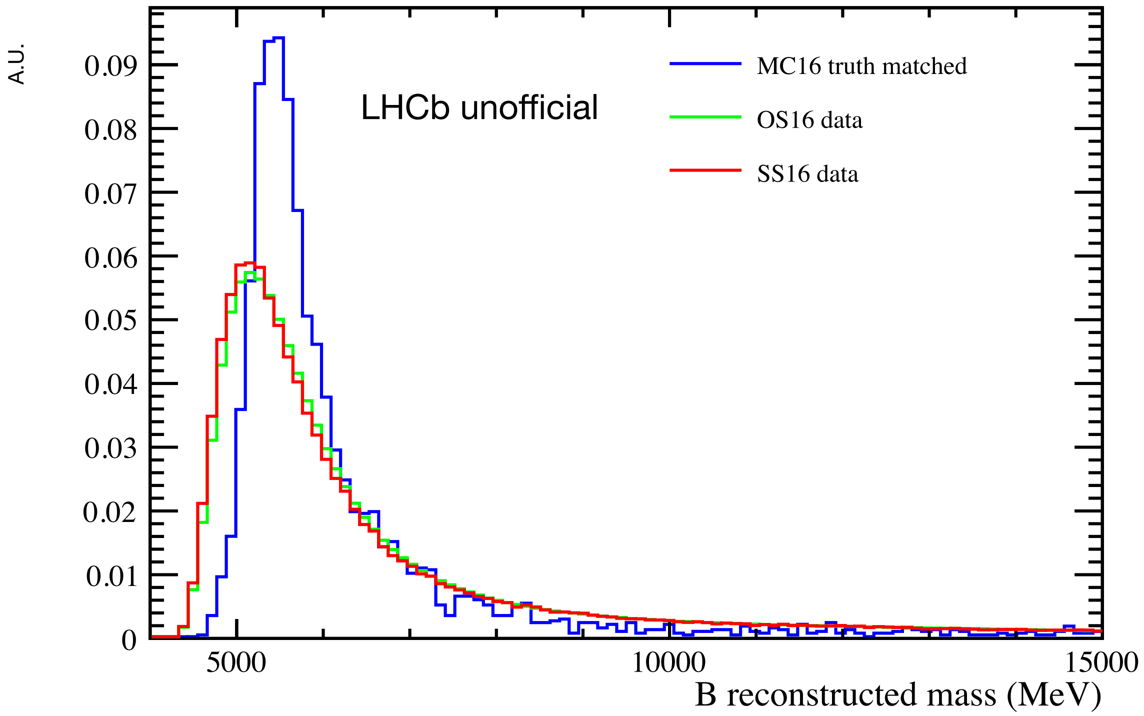
$$B^0 \to K^*(\to K^-\pi^+)\,\tau^+(\to \pi^+\pi^+\pi^-\bar{\nu}_\tau)\,\tau^-(\to \mu^-\nu_\tau\bar{\nu}_\mu)$$

*https://arxiv.org/abs/1712.01919v1

Strategy

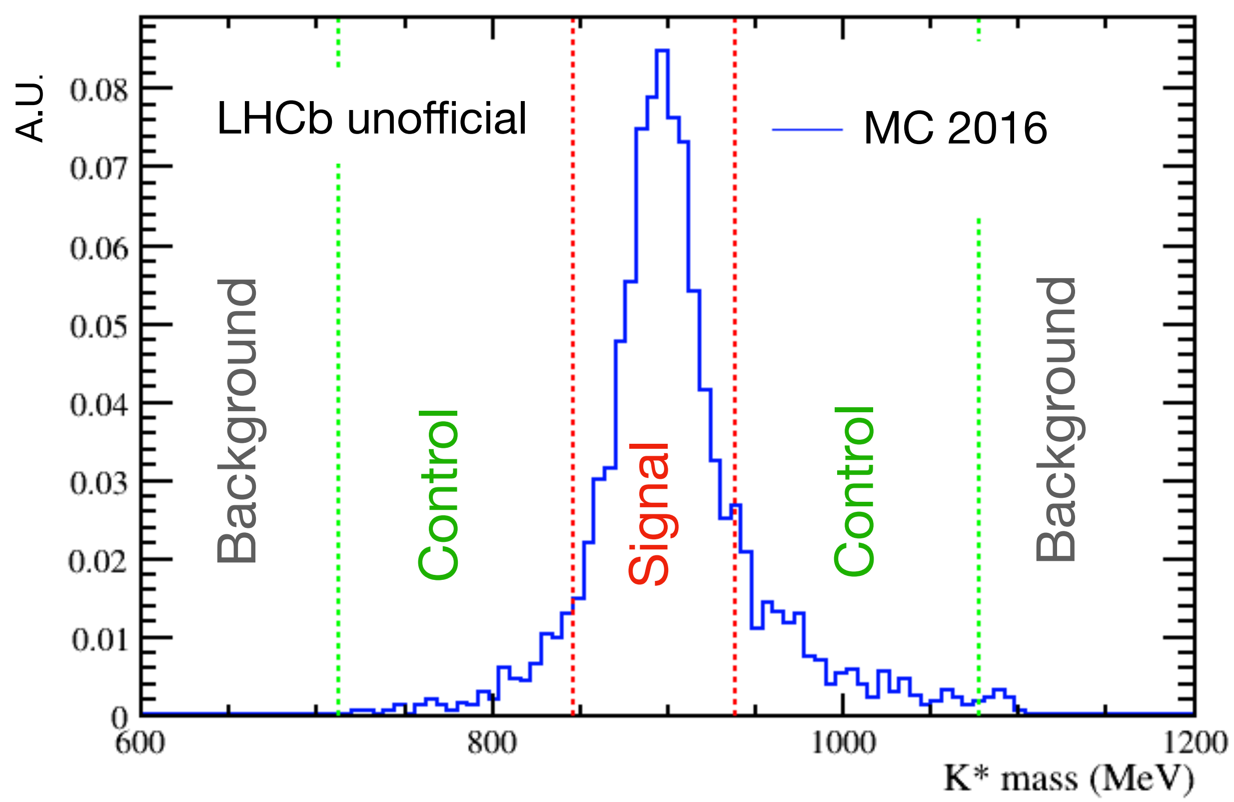
- Very challenging analysis:
    1. **High event multiplicity**: ~ 10 candidates per event on average after trigger requirements, need to use multivariate algorithms to reduce background: **selection done using a Boosted Decision Tree (BDT)**
    2. **Two neutrinos in the final state**: LHCb has not full solid angle coverage, can not reconstruct missing energy
    3. **B mass can not be used to fit**: Visible and analytically reconstructed B mass (computed applying tau mass constraints) have poor discriminating power. The **fit is performed on the output of a second BDT**
    4. There is **no obvious background template** which provides a **good description of the BDT distribution in the fit region**

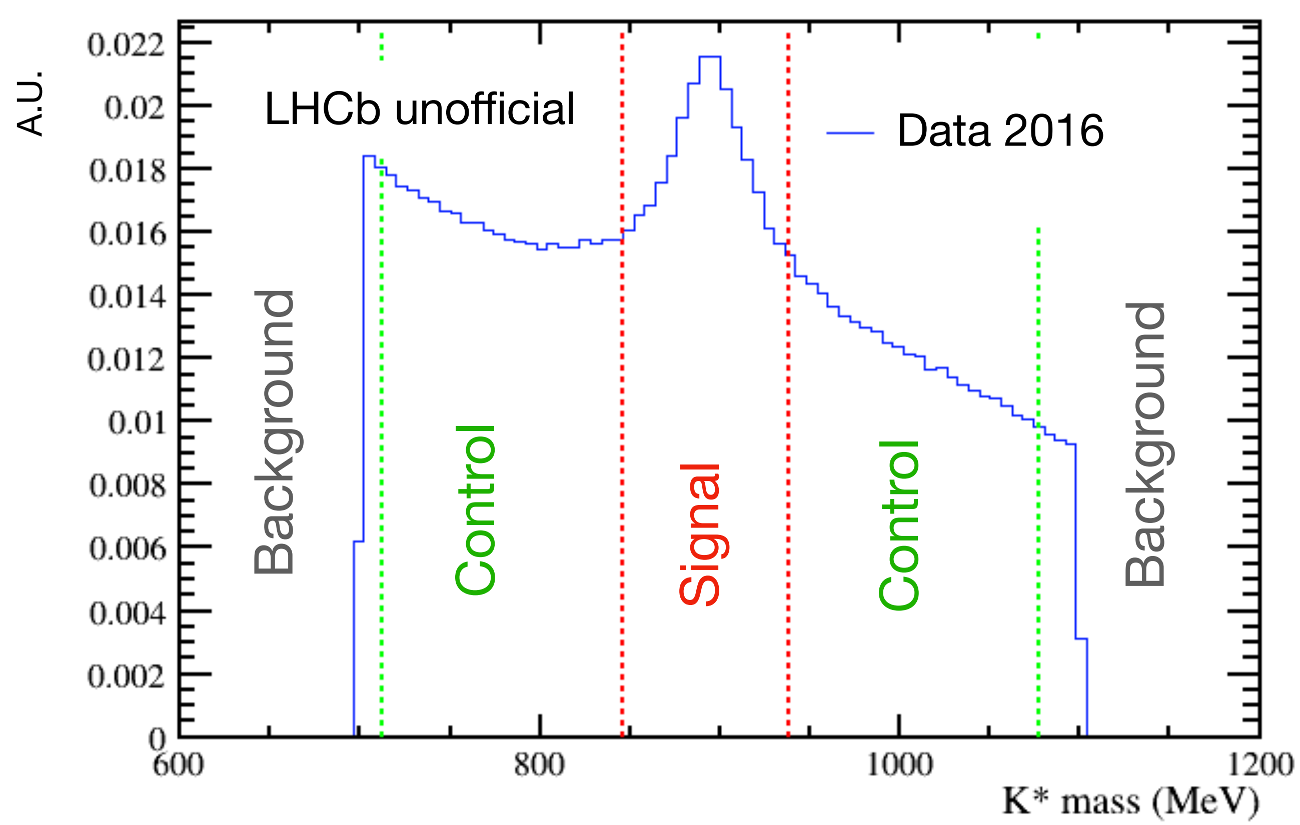




Background template

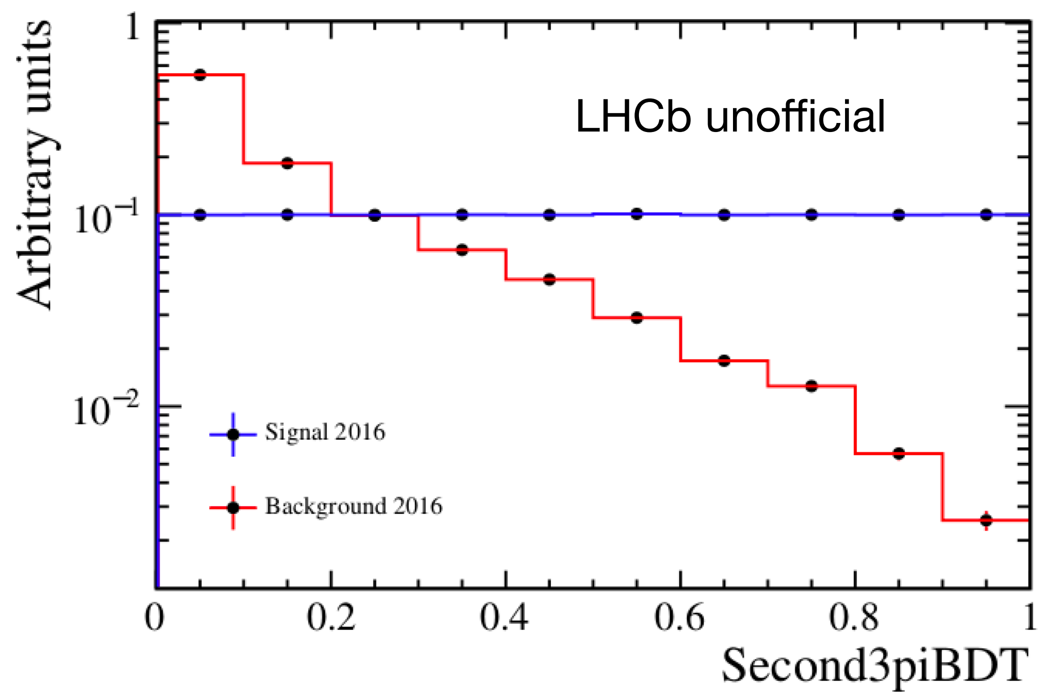
- The background template is built with a data-driven method using **K* mass distribution**:
  - **Fit is done selecting events close to the K* mass peak**, ~ **75% efficiency on signal**
  - Data from background regions are used as background proxy for BDT training
  - **Control regions are used to get background template** in the fit
  - The **background template provides good description of BDT distribution** in signal region if there's **no correlation with K* mass for the variables used in the BDT**



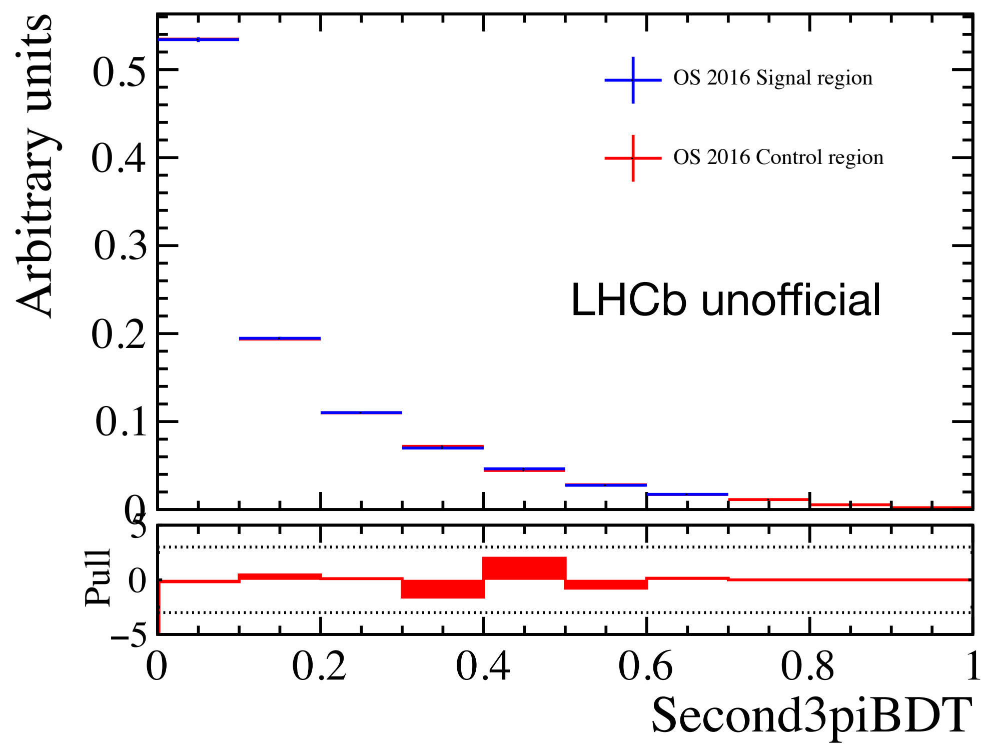


Quality checks: signal - control region agreement

- **Flatten transformation applied on fit BDT:** signal distribution appears flat, background peaks at BDT = 0



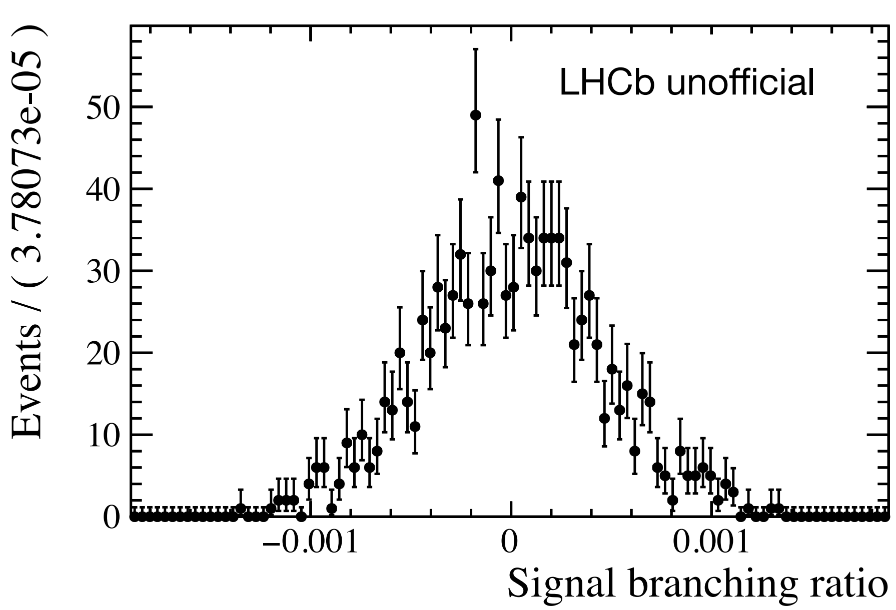
- **Blind analysis**: last three bins are the most sensitive to the signal, they are set to 0 for events close to the K* mass peak
- It is crucial to have a **good agreement of fit BDT distribution in signal and control region**:

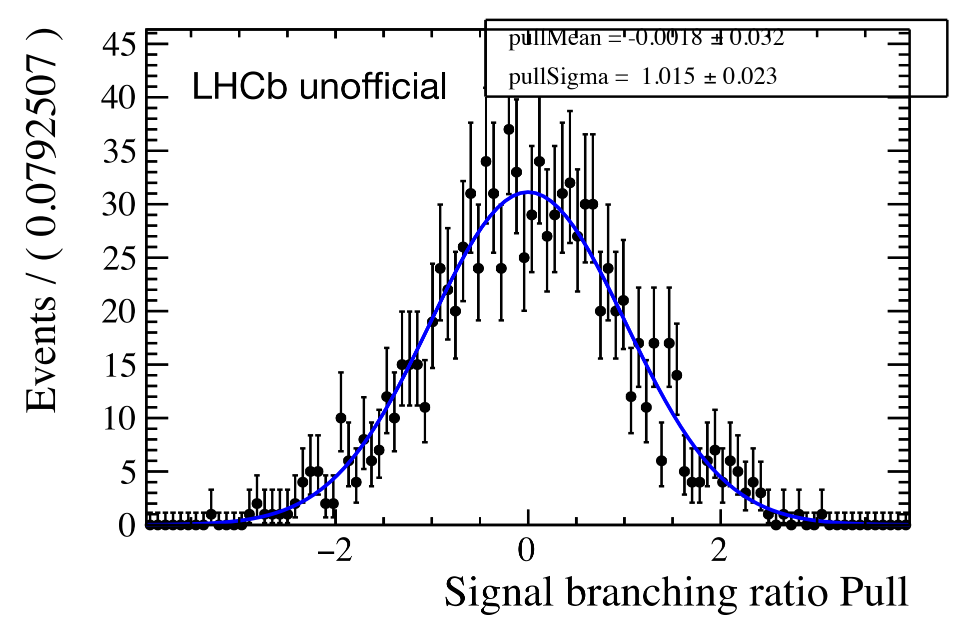


- Branching ratio is measured relative to the one of a **normalization channel** $B^0 \to D^+ \ (\to \pi^+\pi^+K^-) \ D_s^- \ (\to K^+K^-\pi^+)$
- Systematics due to luminosity and cross-section measurements cancel out:

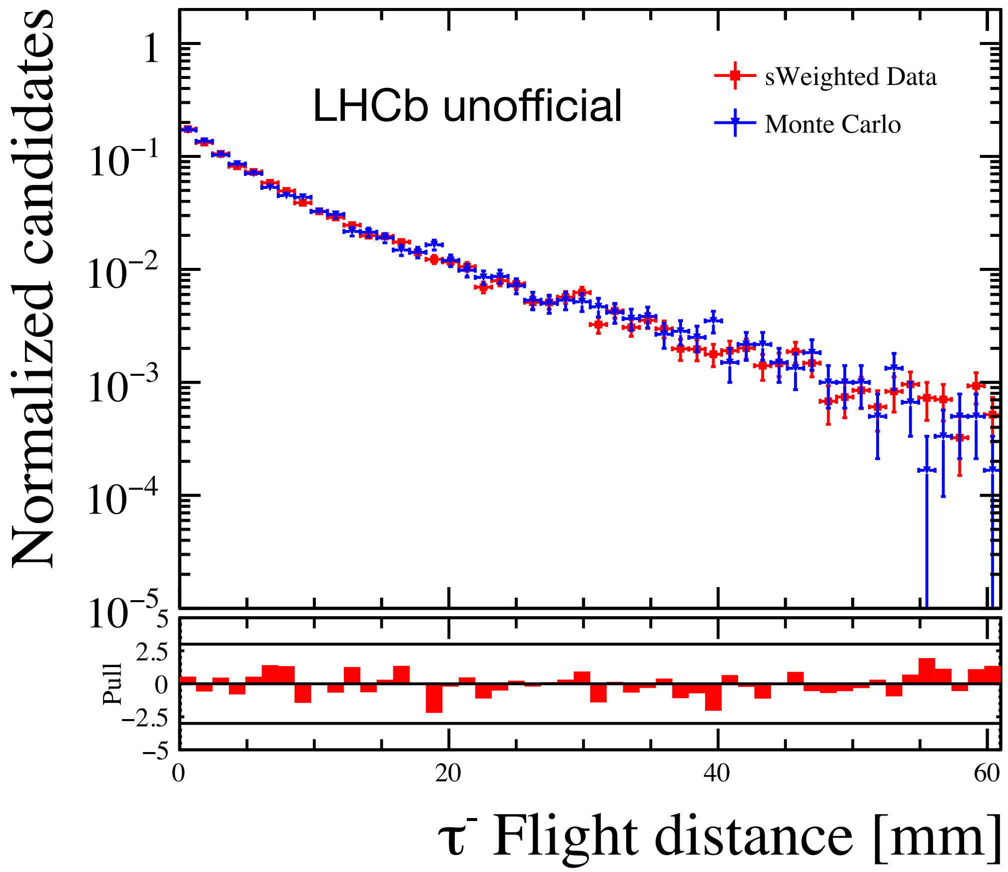
$$\frac{\mathcal{B}(B^0 \to K^*\tau^+\tau^-)}{\mathcal{B}(B^0 \to D^+D_s^-)} = \frac{N_{obs}^{K^*\tau\tau}}{\epsilon_{K^*\tau\tau} \cdot \sigma \cdot L} \cdot \frac{\epsilon_{DD_s} \cdot \sigma \cdot L}{N_{obs}^{DD_s}}$$

- The fit model contains three components: $\textbf{DATA} = f\,BR \cdot \textbf{SIG} + \frac{N_{bkg}^{sig}}{N_{bkg}^{ctl}} N_{tot}^{ctl} \cdot \textbf{CTL} - f\,BR\,\frac{\epsilon_{ctl}}{\epsilon_{sig}} \frac{N_{bkg}^{sig}}{N_{bkg}^{ctl}} \cdot \textbf{CONT}$
  - **SIG** : **template from signal region in simulation**
  - **CTL** : **background template from data in K* mass sidebands**
  - **CONT** : **template from sidebands in simulation** ("contamination" of signal in control region)
  - **BR** : **branching ratio**
- Information on the normalization channel encoded in *f* factor
- The fit is performed simultaneously on the data-taking years
- The fit model has been validated using toy studies: **no bias observed**





- **Systematic uncertainties** are being investigated:
  - **Data-MC agreement** is checked on normalization channel

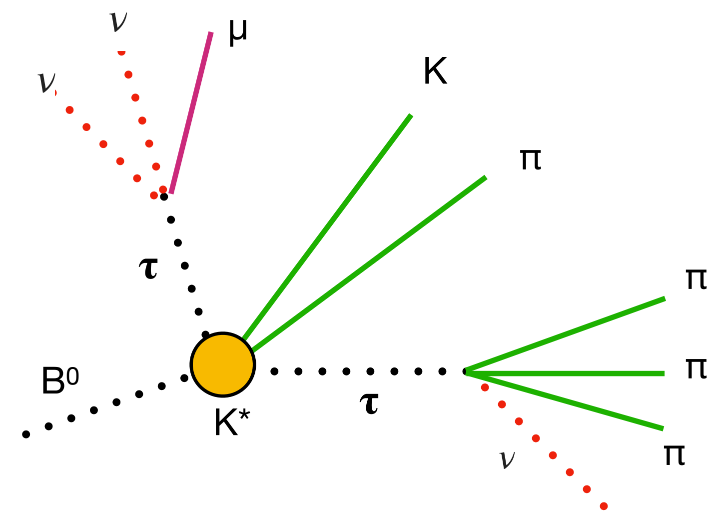


  - **Particle identification efficiency correction**
    - PID variables are not well simulated, efficiency of PID cuts estimated with data-driven method
    - π and K high-purity samples used to determine an efficiency map, per-event efficiency assigned on signal candidates
  - **Fit template shape**
    - Bin contents of signal and background templates are varied to asses a systematic on the statistical fluctuation of the model
  - **More to be investigated**: trigger efficiency, track reconstruction correction, …

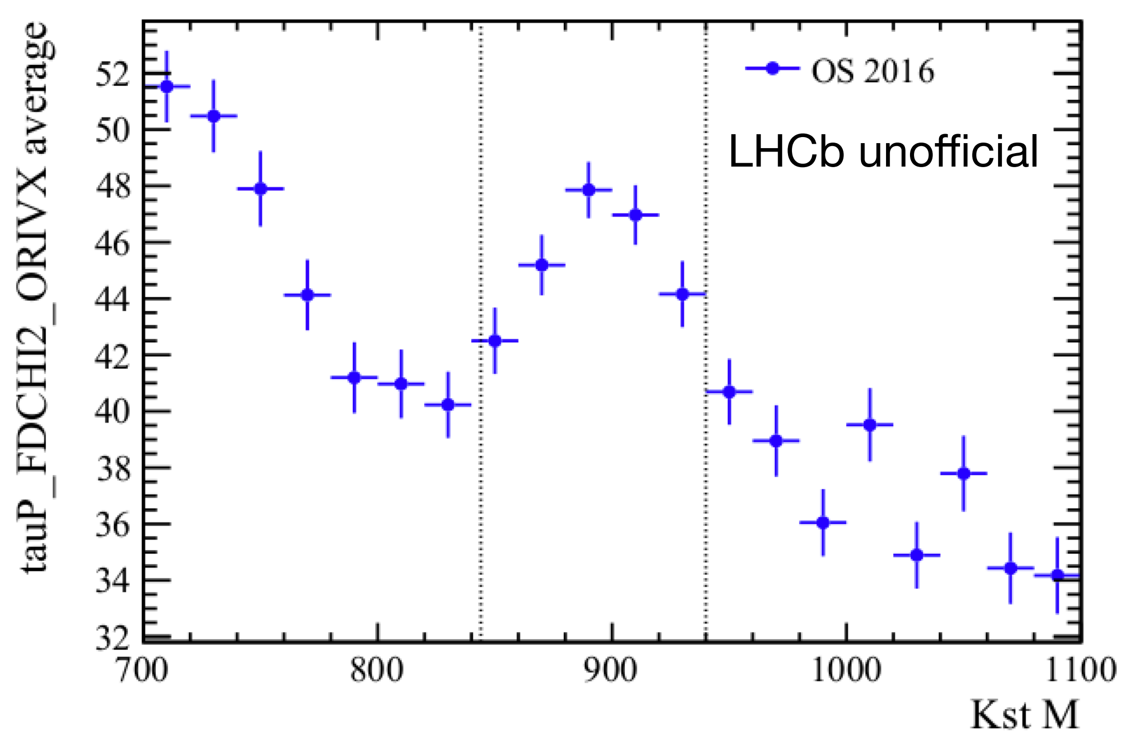
Semileptonic final state

- The semileptonic final state is also being investigated:

$$B \to K^*(\to K^-\pi^+)\tau^+(\to \pi^+\pi^+\pi^-\bar{\nu}_\tau)\tau^-(\to \mu^-\bar{\nu}_\mu\nu_\tau)$$



- Similar difficulties as for the hadronic final state: **high event multiplicity**, **poor mass discriminating power**, …
- **More background** due to semi-leptonic decays
- Didn't succeed in order to find a background template for the fit: in particular the **K* mass shows more correlation with other variables**



Conclusions

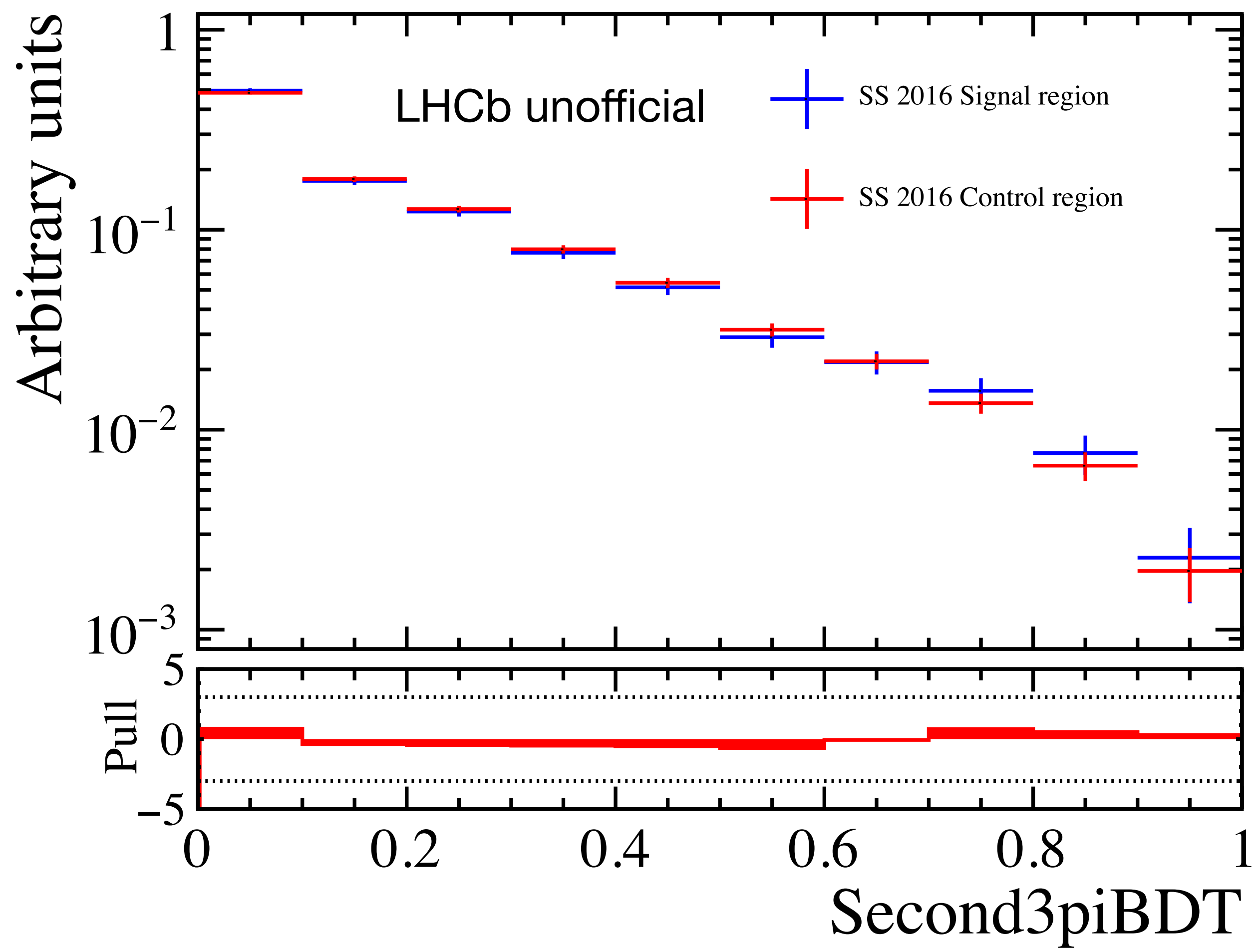
- Intriguing **deviations from the SM predictions** have arisen in flavor sector
- **Lepton flavor universality might be violated**
- Rare B decays with tau leptons in the final state are good probes for new physics beyond the SM
- **$B^0 \rightarrow K^* \tau^+ \tau^-$ analysis** ongoing in two different final states
- Challenging analysis, the **selection strategy and fit procedure have been finalized**
- Work on the estimation of **systematic uncertainties** is ongoing

Thanks!

From Facebook

Backup

- Same sign data (SS) used to validate the background template
- SS are selected requiring both tau’s to have the same charge
- Full selection has been applied on data and the signal-control regions agreement has been checked:



Global fit with EFT

- Global fit with data from various experiments using EFT shows ~ 7σ deviation from SM (Eur. Phys. J. C (2019) 79 714)
- New Physics LFU violating left-handed coefficients $C^V_{9\mu}$ (vector coupling) and $C^V_{10\mu}$ (axial-vector coupling)
- New physics LF universal right-handed coefficient C^U_9