Journées de Rencontre des Jeunes Chercheurs 2019, Centre Moulin Mer

Testing Lepton Flavor Universality with the $B^0 \to K^* \tau^+ \tau^-$ decay at the LHCb experiment

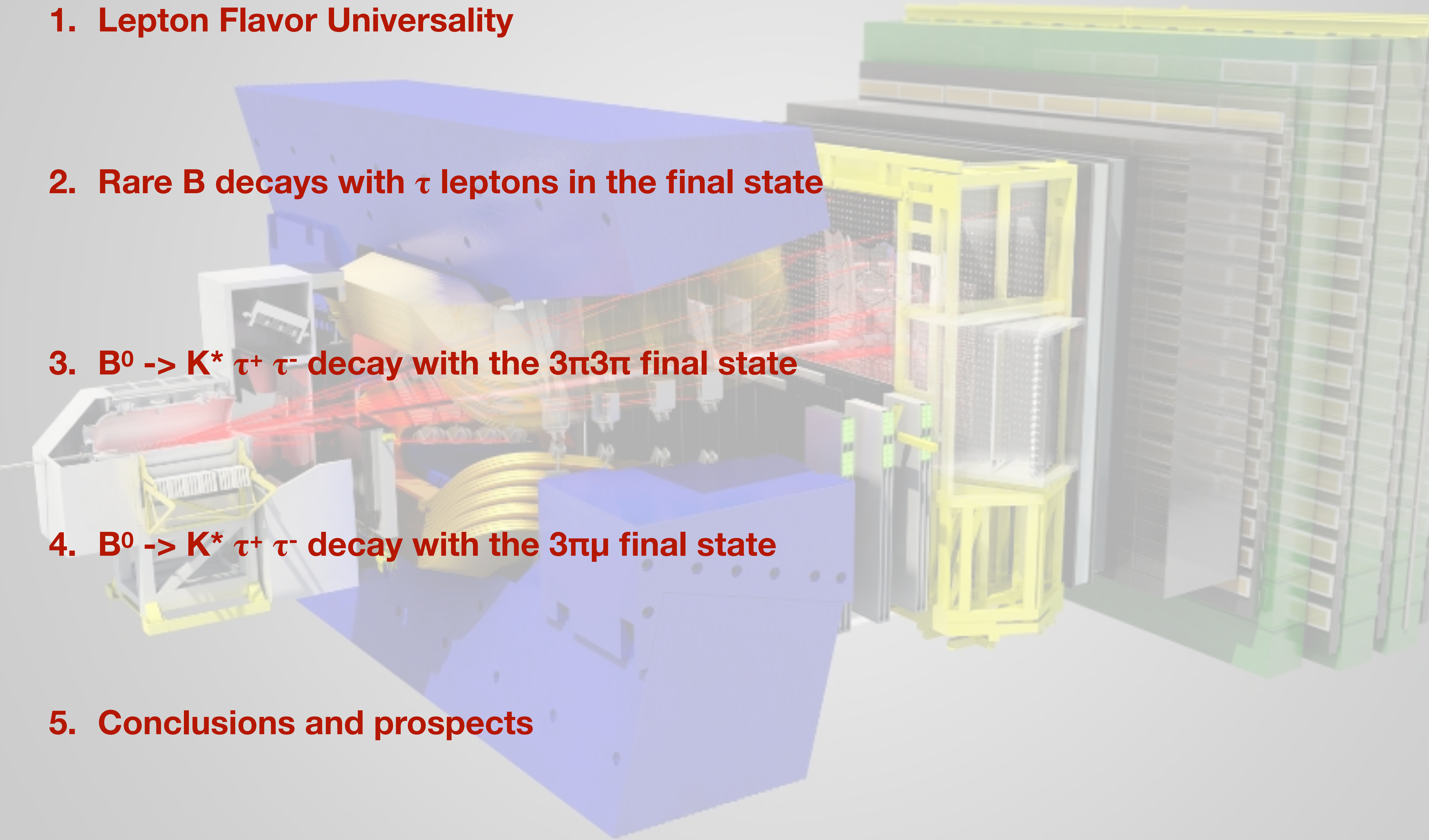
Jacopo Cerasoli

Supervisors: Giampiero Mancinelli, Julien Cogan

Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

25/11/2019

Outline



1. **Lepton Flavor Universality**

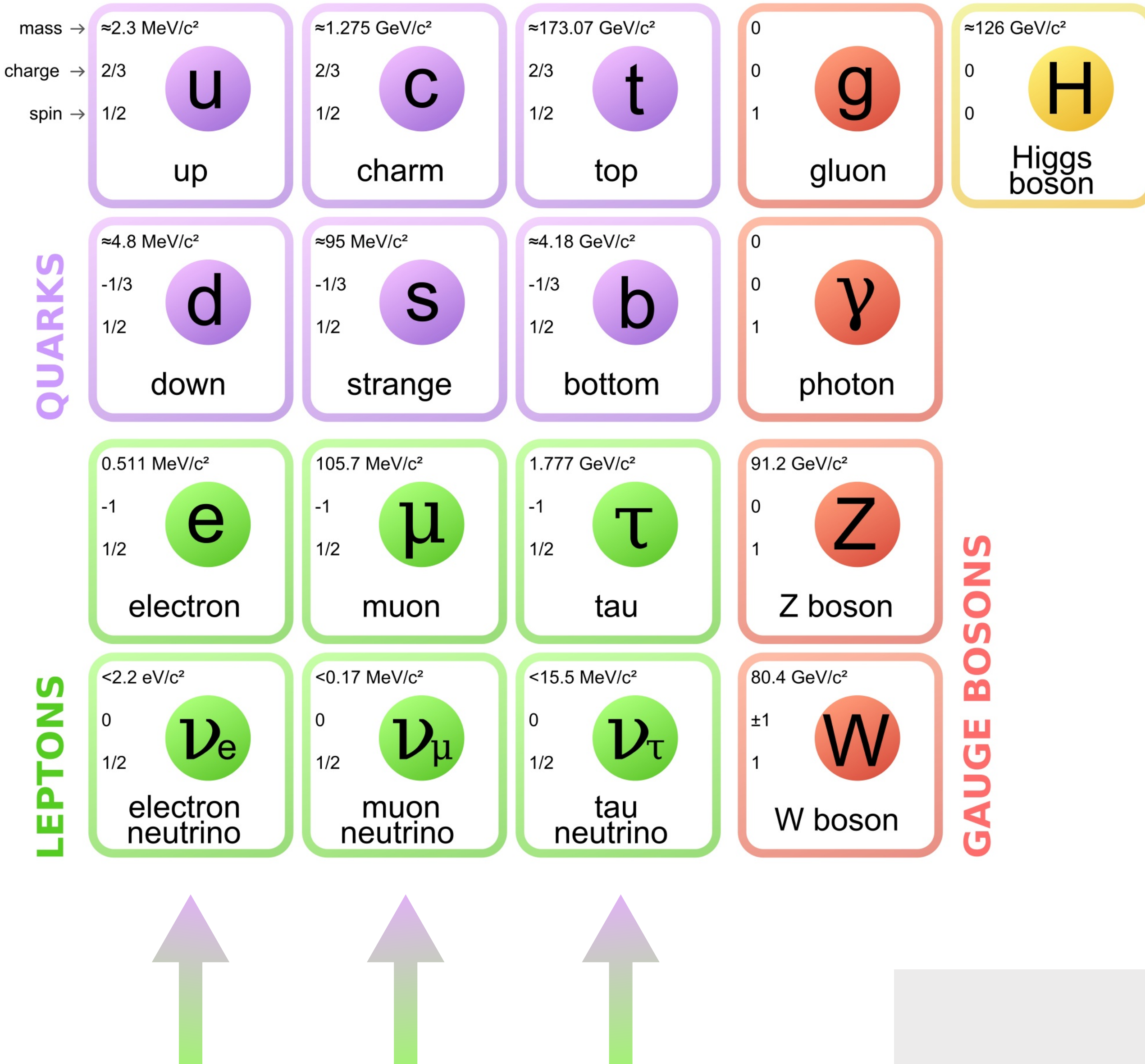
2. **Rare B decays with τ leptons in the final state**

3. **$B^0 \to K^* \tau^+ \tau^-$ decay with the 3π3π final state**

4. **$B^0 \to K^* \tau^+ \tau^-$ decay with the 3πμ final state**

5. **Conclusions and prospects**

Lepton Flavor Universality



- 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, dark energy, neutrino masses, matter-antimatter asymmetry…

Three families of fermions

Different species called “flavors”

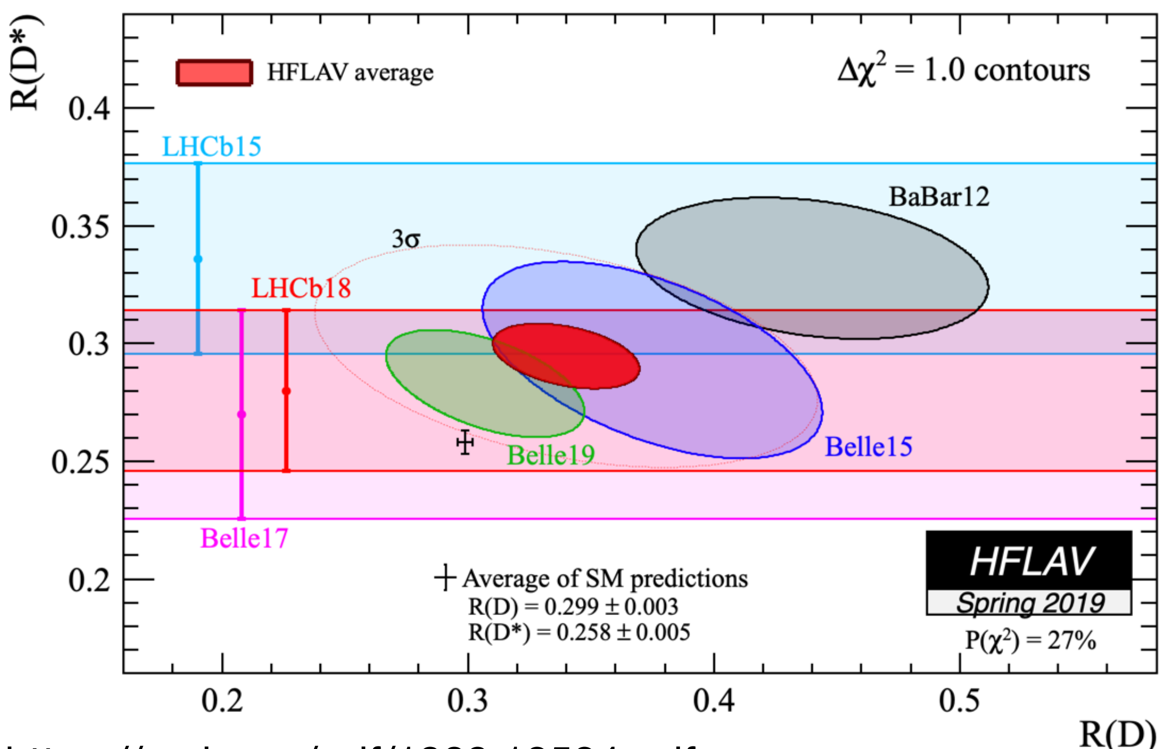
Lepton Flavor Universality (LFU):

Same electroweak coupling to the three charged leptons

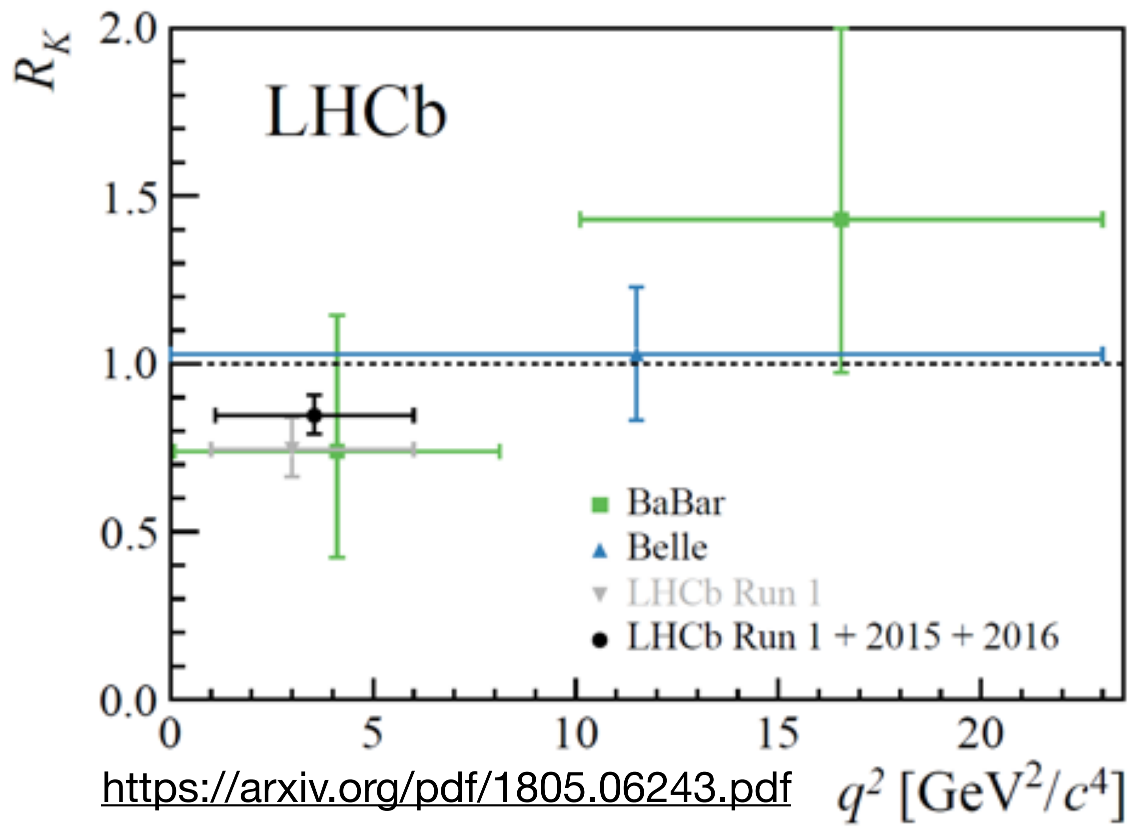
⟶ Differences in *branching fractions* for processes involving e, μ or τ in the final state are due only to their different masses

Is LFU a correct assumption?

- Standard Model prediction based on LFU assumption, but…
- …some tensions are observed in experimental measurements involving leptons in the final state



https://arxiv.org/pdf/1909.12524.pdf



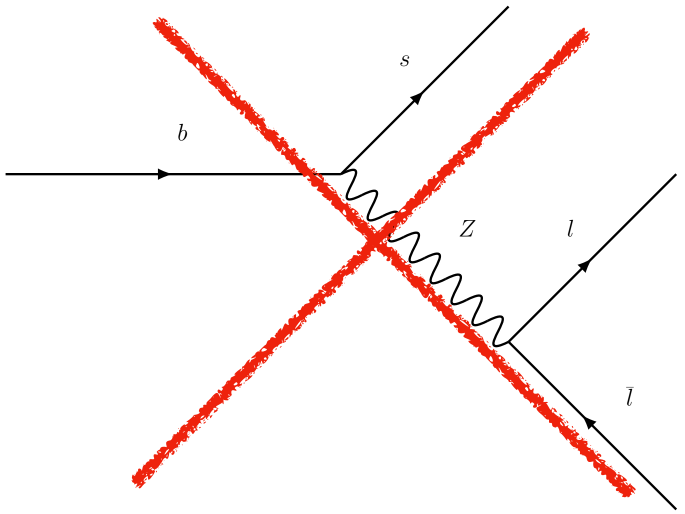
https://arxiv.org/pdf/1805.06243.pdf

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

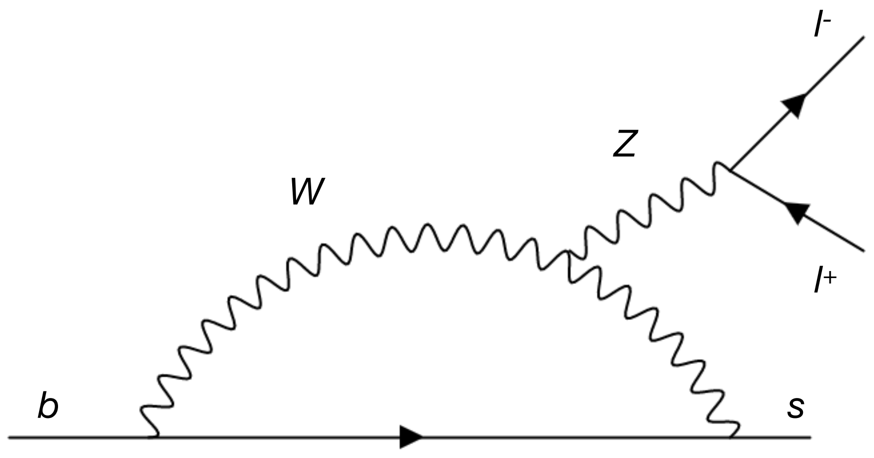
$$R(K) = \frac{\mathscr{B}(B^+ \to K^+\mu^-\mu^+)}{\mathscr{B}(B^+ \to K^+e^-e^+)}$$

- Very exciting times! Need more data and measurements to shed light on these “anomalies”.
- Why not doing it in rare B decays with τ leptons in the final state?

Why rare decays?



- In SM some processes at quark level (FCNC) can not proceed in a “simple way” (first order in perturbation theory)

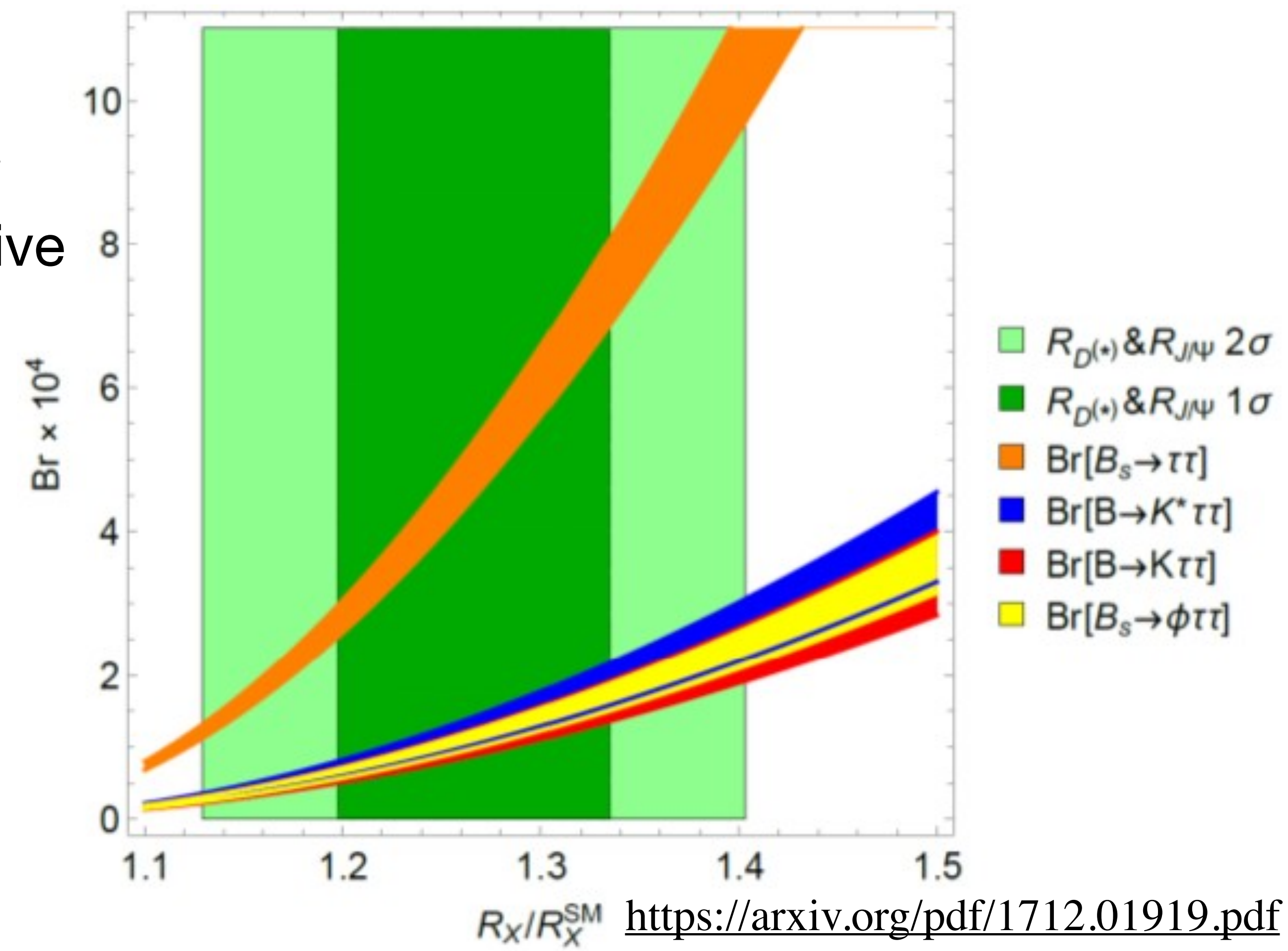


- Instead they proceed through loops or boxes diagrams

- More complex diagrams: less probable to happen
- Sensitive to hypothetical new particles entering the loop: branching ratio of the decay could be enhanced!

Why 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!

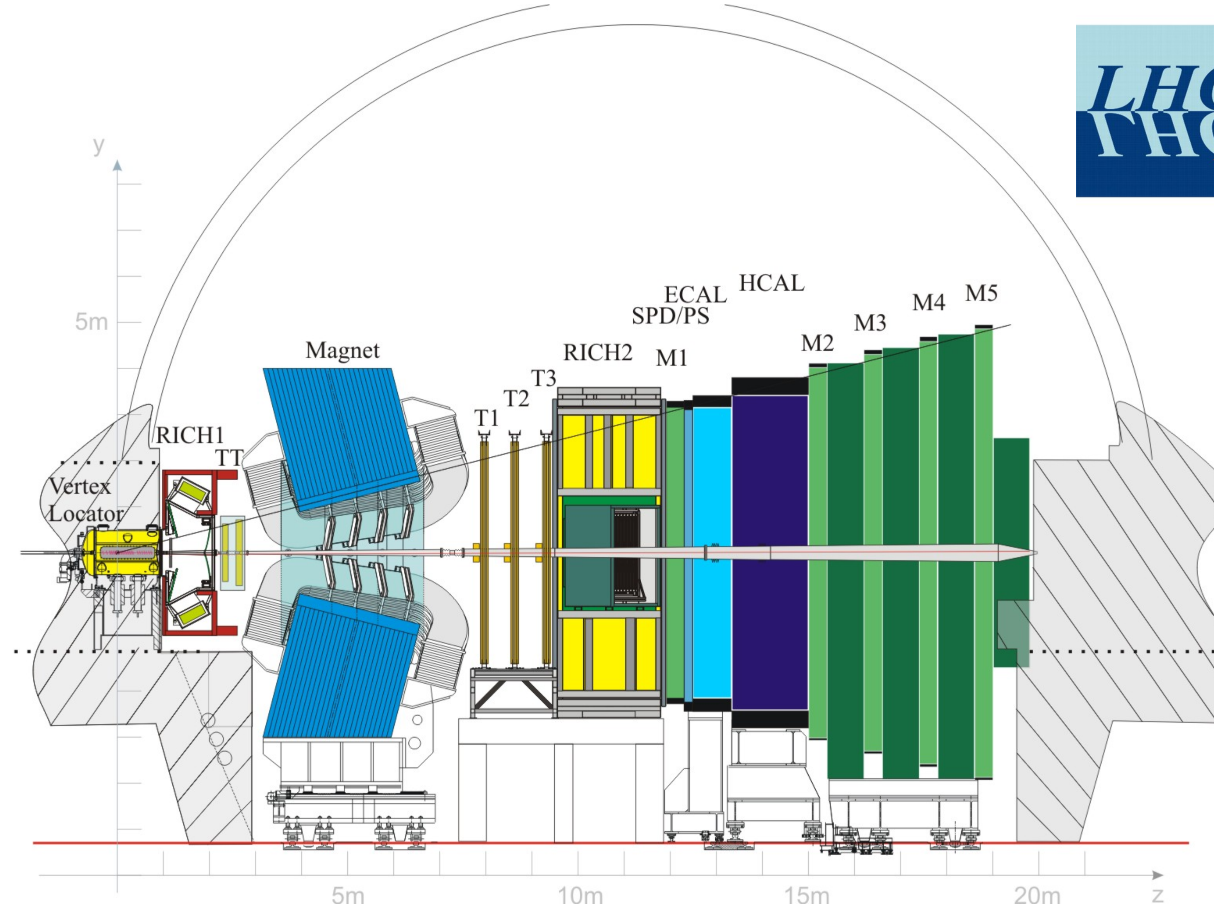


https://arxiv.org/pdf/1712.01919.pdf

Nice, but how?

INSTRUCTIONS

1. Take a plane to Geneva airport (GVA)
2. Take bus 57 and tram 18 to CERN
3. Go to the LHCb experiment



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

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

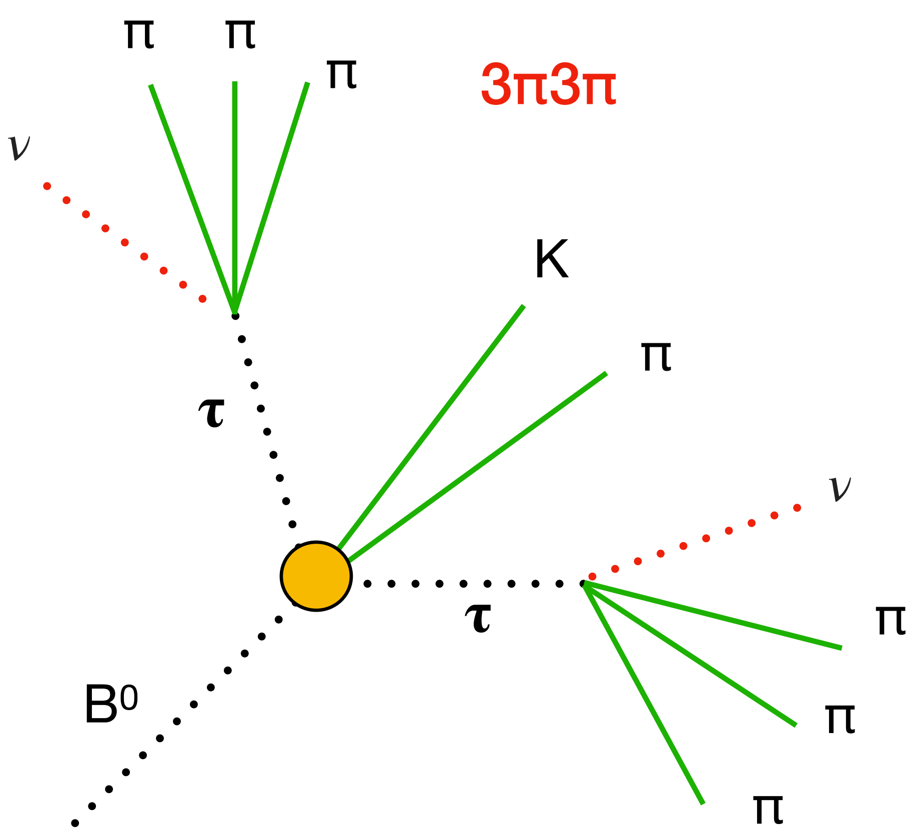
  General purpose experiment optimized for detecting beauty and charm hadrons
- Peculiar features for rare B decays studies:
  - Vertex Locator (VELO): Precise measurement of displaced vertex positions (~13μm vertex resolution in transverse plane, ~70μm along beam axis)
  - RICH detectors: identification 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

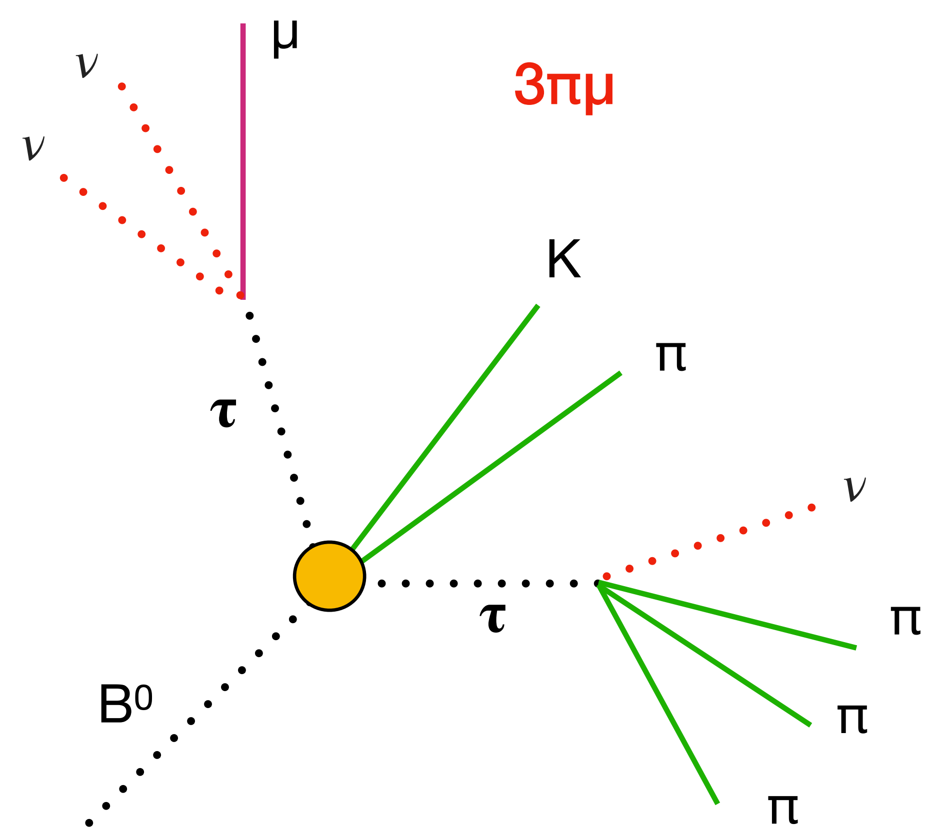
The $B^0 \to K^* \tau^+ \tau^-$ decay

- Let's focus on the $B^0 \to K^* \tau^+ \tau^-$ decay:
- $b \to s\, l^+ l^-$ quark level transition at second order, **expected BR($B^0 \to K^* \tau^+ \tau^-$) ~ 10^{-7} ***
- Goal: perform study in **two final states** using full dataset (2011-2012 + 2016-2018):

$$B \to K^*(\to K^-\pi^+)\tau^+(\to \pi^+\pi^+\pi^-\bar{\nu}_\tau)\tau^-(\to \pi^+\pi^-\pi^-\nu_\tau)$$ → **3π3π final state**

$$B \to K^*(\to K^-\pi^+)\tau^+(\to \pi^+\pi^+\pi^-\bar{\nu}_\tau)\tau^-(\to \mu^-\nu_\tau\bar{\nu}_\mu)$$ → **3πμ final state**





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

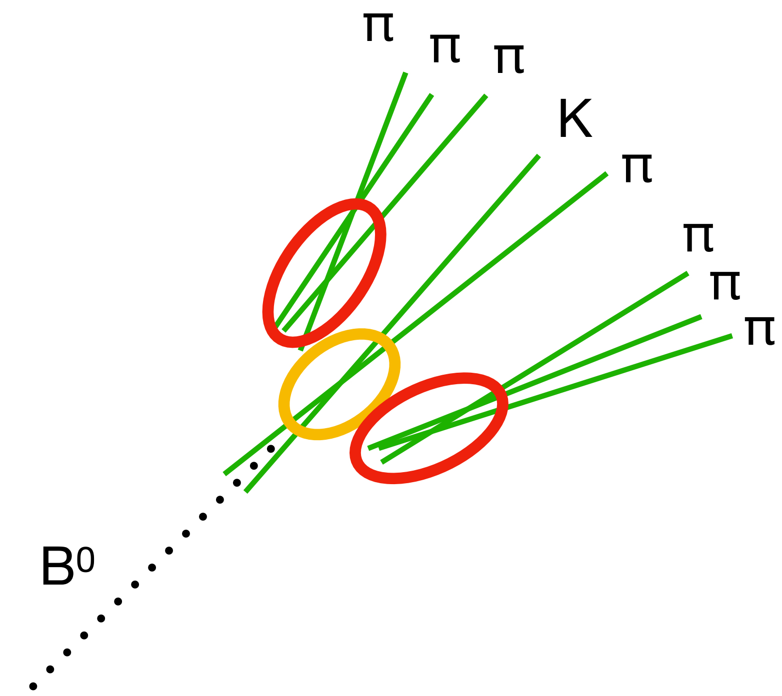
3π3π final state

Neutrinos and mass reconstruction

- Missing energy due to two neutrinos in final state!
- **Tau momentum can be reconstructed analytically** imposing its true mass:

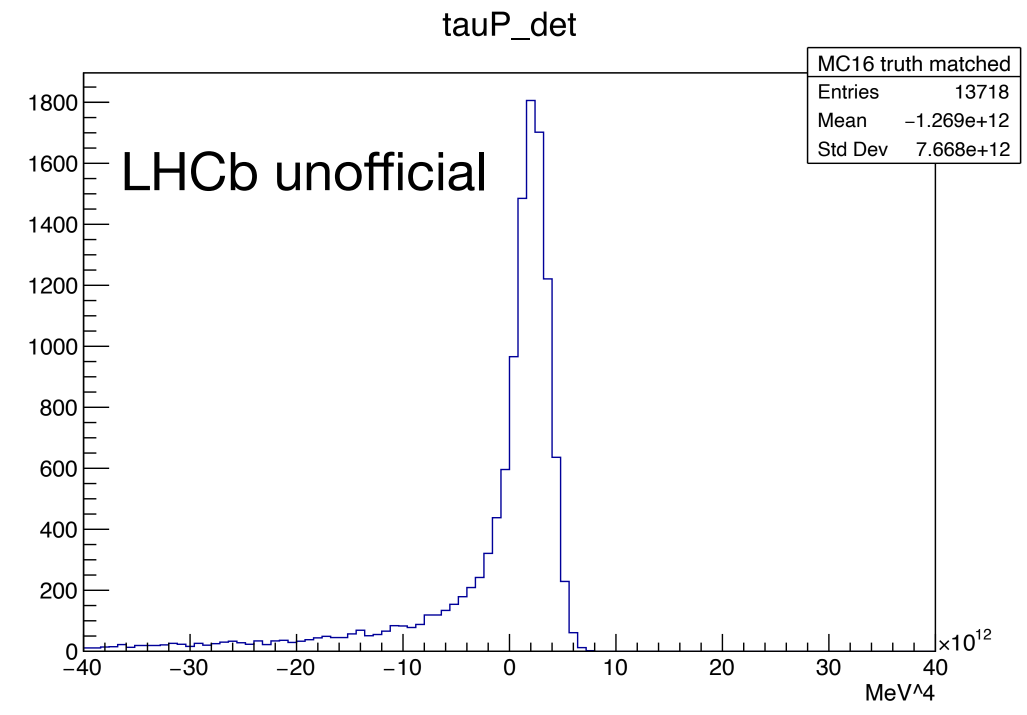
$$|\vec{p}_\tau| = \frac{(m_\tau^2 + m_{3\pi}^2)|\vec{p}_{3\pi}|\cos\theta \pm E_{3\pi}\sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2|\vec{p}_{3\pi}|^2\sin^2\theta}}{2(E_{3\pi}^2 - |\vec{p}_{3\pi}|^2\cos^2\theta)}$$

$$\vec{p}_\tau = |\vec{p}_\tau|\,\vec{u}_\tau\,, \quad \vec{u}_\tau = \frac{\vec{p}_{\tau V} - \vec{r}_{SV}}{|\vec{p}_{\tau V} - \vec{r}_{SV}|}$$

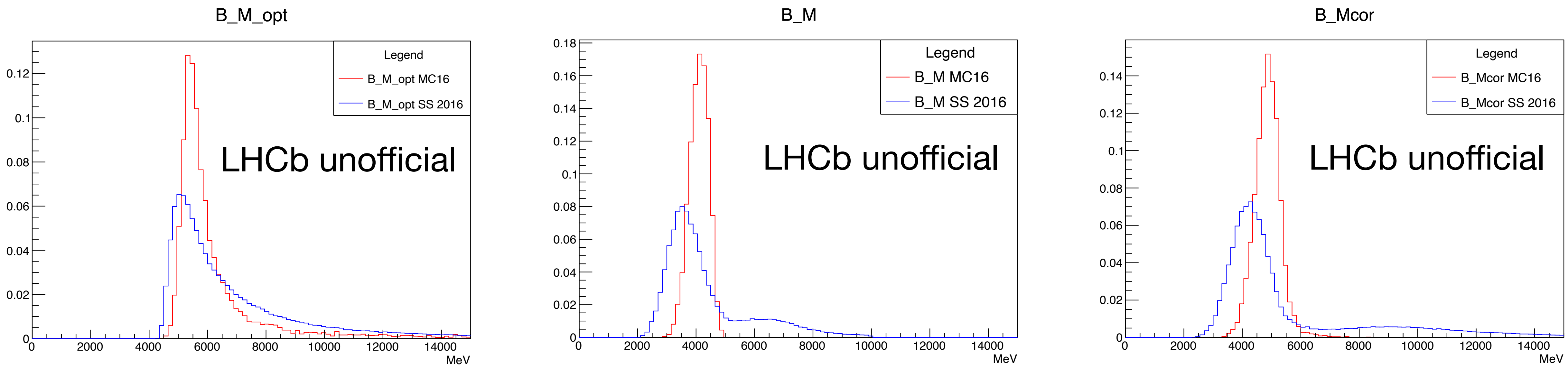


How it "looks like" in the detector!

- Due to vertex resolution the discriminant can be negative
- In signal sample only 33% candidates have positive discriminant for both taus, discriminant set to 0 if negative
- **Four-fold ambiguity on B mass.** "Optimal" solution is chosen as the one with minimum angle between reconstructed momentum and B direction (from primary and secondary vertices)



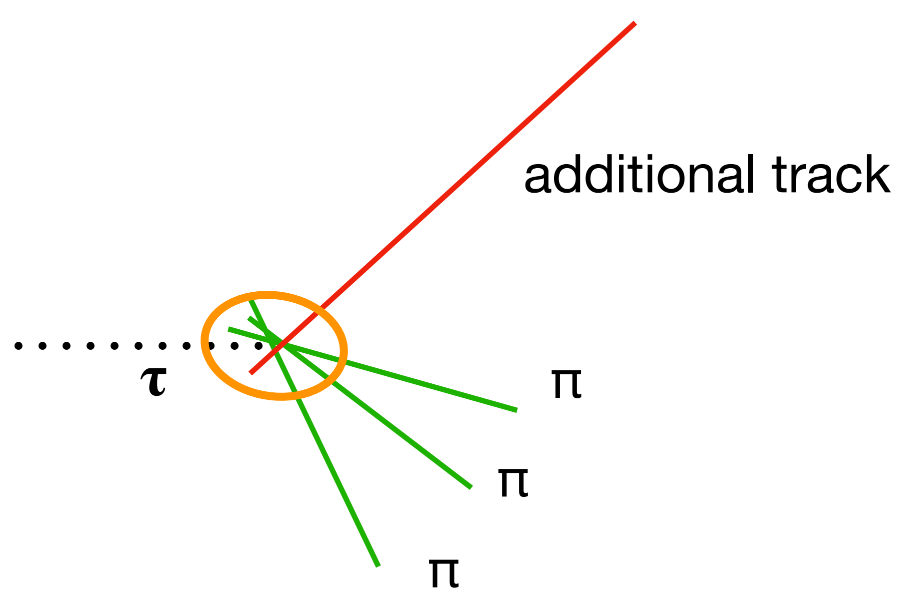
- Different masses can be defined:
  - Analytically reconstructed
  - Visible mass
  - “Corrected” mass $M_{cor} = \sqrt{P_T^2 + M_{vis}} + P_T^2$
- **None of them very discriminating** compared to background from same sign data (selected requiring both taus to have the same charge):

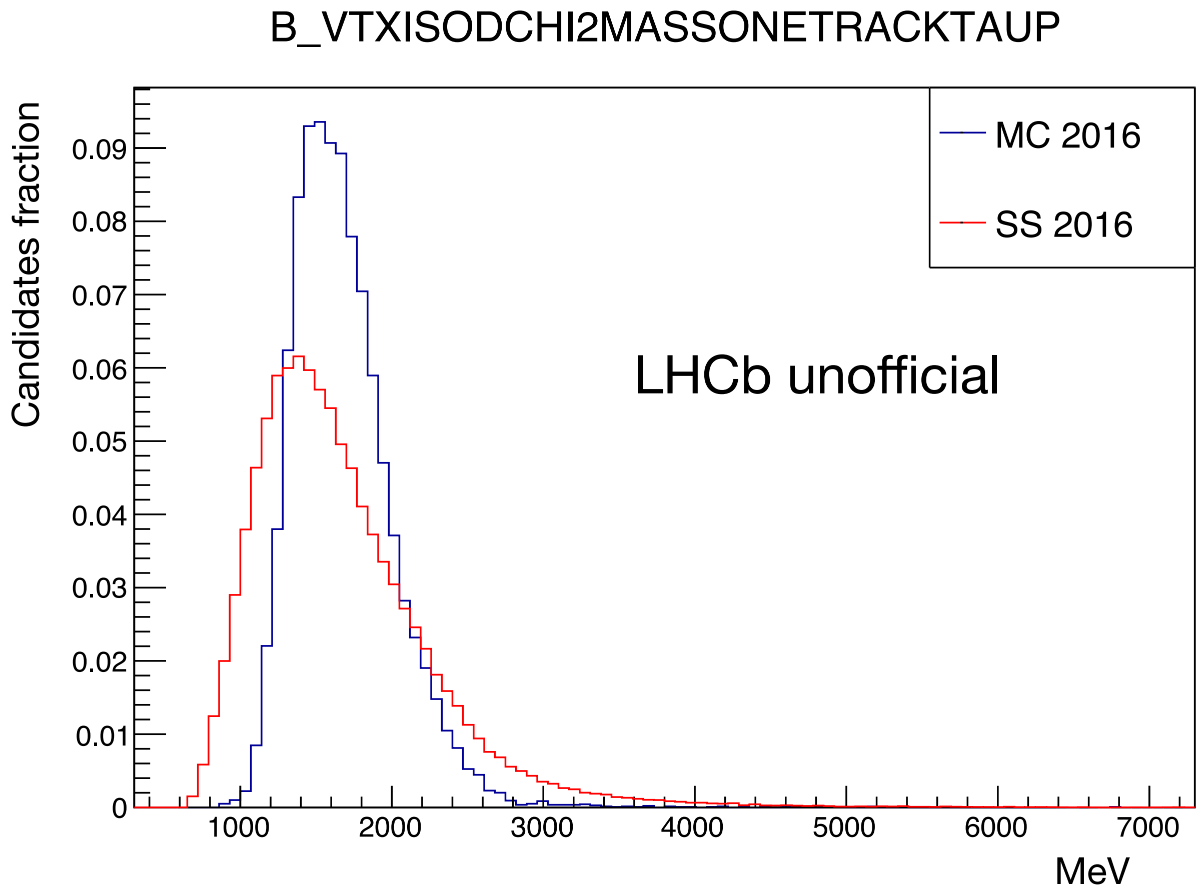


- Not enough mass discriminating power to fit, need to modify analysis strategy:
  - Loose cut-based preselection
  - MVA-based selection, 2 BDTs in sequence
  - **Fit on third BDT**
  - $B^0 \to D^+ \, (\to \pi^+\pi^+K^-) \, D_s^- \, (\to K^+K^-\pi^+)$ used as (preliminary) normalization channel to avoid introduction of uncertainty on luminosity and cross-section measurements

Selection tools

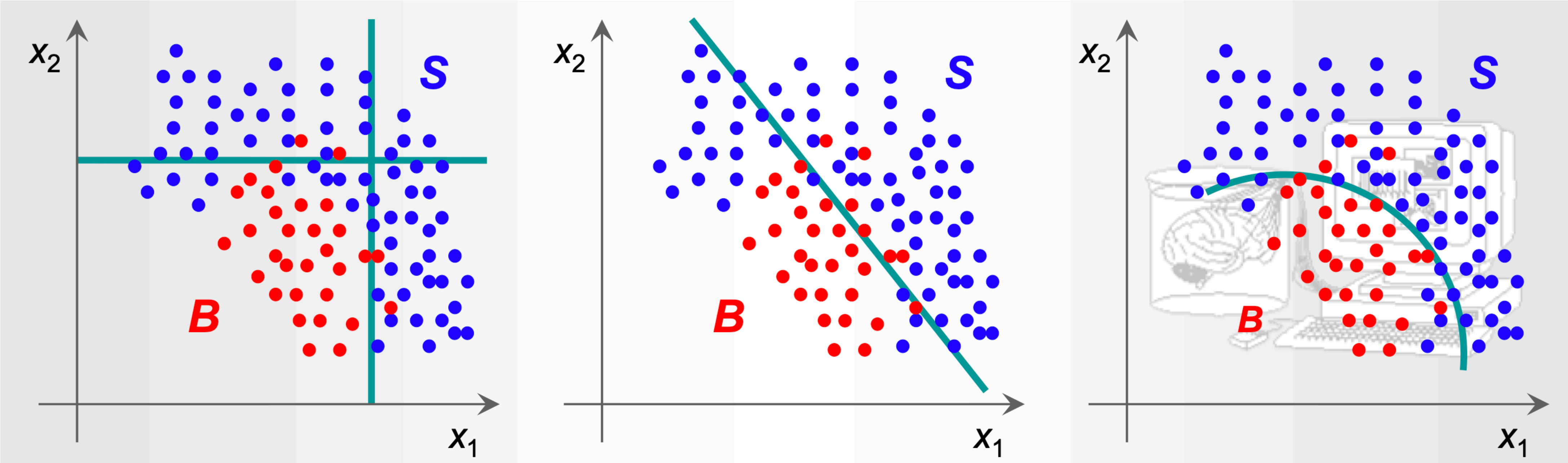
- Need to kill lots of background:
  - **Isolation variables**: quantify the probability of a track in proximity of the signal candidate to be part of the candidate itself
  - **Particle identification** requirements
  - **Multivariate analysis**: BDT-based selection
- Example of isolation variable: an additional track forming a good vertex is added to the signal candidate. The “new” mass is computed





Selection tools - What's a BDT?

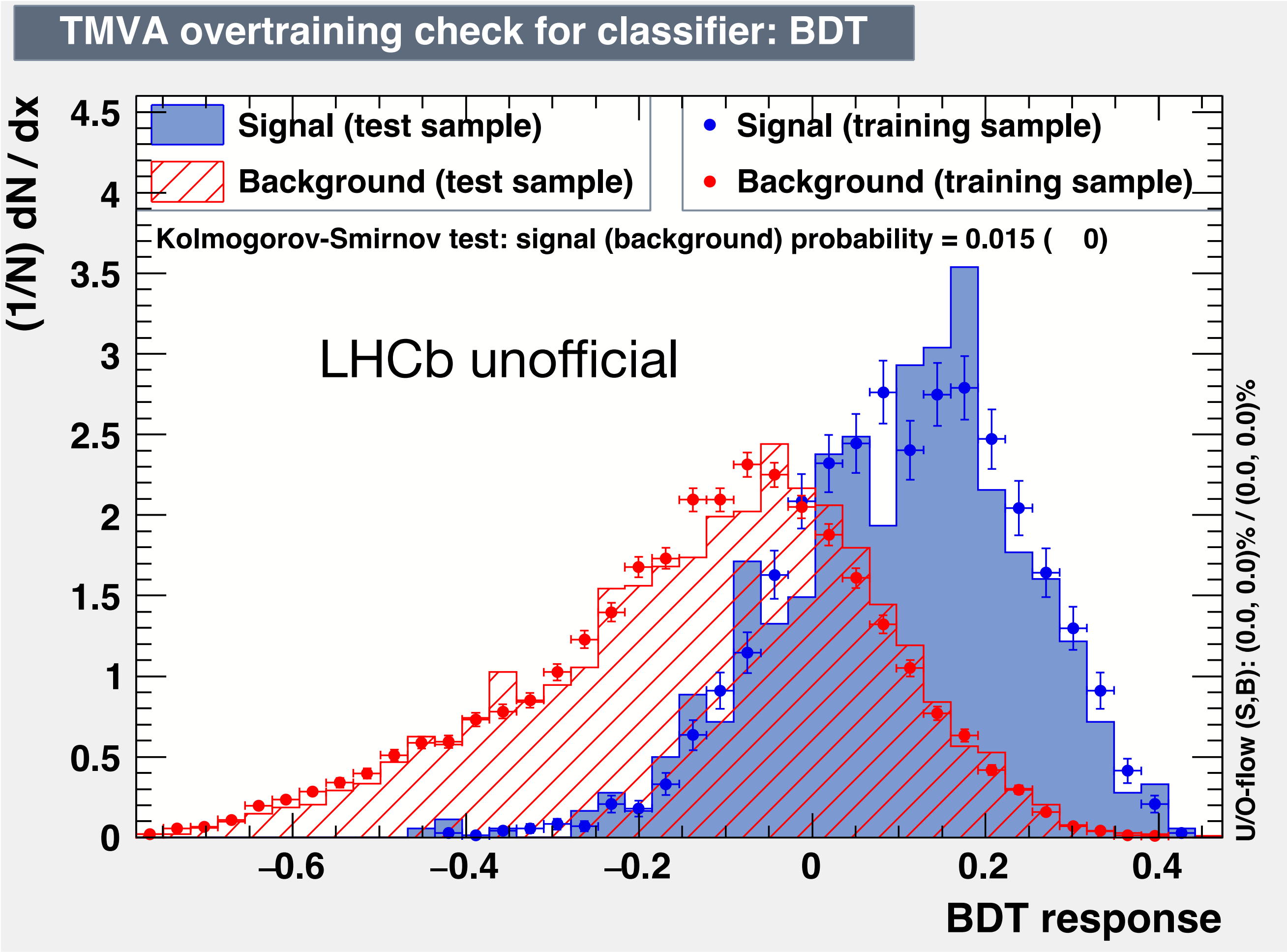
- BDT = "Boosted decision tree"
- Tool to combine information from several input variables into one single output variable
- Goal: optimize the "shape" of the cut in the n-dimensional space of the variables
- It needs to be "trained" on a signal and a background sample
- It applies cuts on the variables and labels phase space regions as "signal" or "background"



Helge Voss - Multivariate Data Analysis and Machine Learning in High Energy Physics

Selection

- **Loose cut-based preselection** on isolation variables
- **BDT-based selection**, trained against:
  - Fully matched and reconstructed **signal MC events**
  - **Same sign data** as background sample
- First BDT trained using isolation variables
- Second BDT trained after the first BDT cut, using flight distances and vertex information

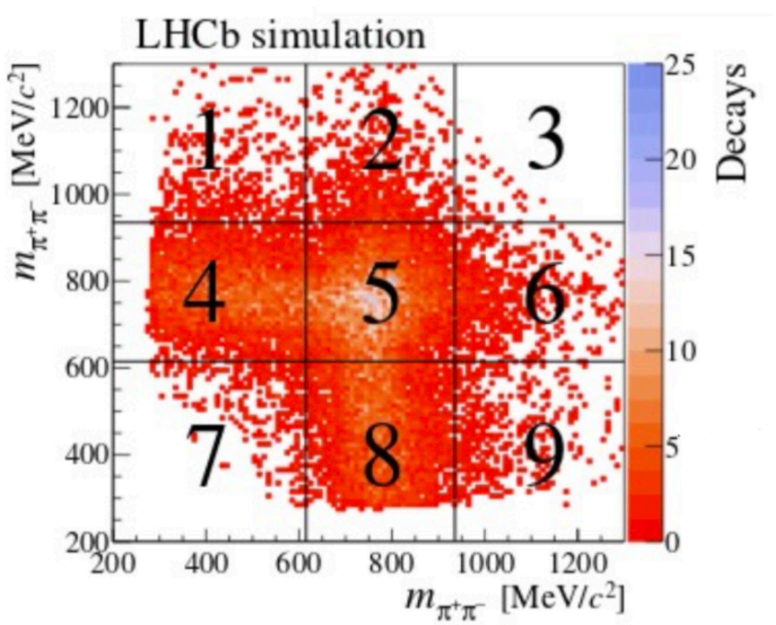


Background categorization

- **Same Sign data** used for BDT training
- **Simulated inclusive B sample**
  - Used to identify background from exclusive decays after selection
  - Expected backgrounds from B decaying into D mesons:

$$B^- \to D^*(2007)^0\ \pi^+\ \pi^+\ \pi^-\ \pi^-\ \pi^-$$
$$B^0 \to D^*(2010)^-\ D_s^{*+}$$
$$B^+ \to \bar{D}^0\ D_s^+\ \pi^+\ \pi^-$$
$$\ldots$$

  - Investigating vertex topology
  - Veto on D mass?
- Plan to consider other possibilities for background characterization:
  - Combinatorial background from K* mass sidebands
  - Background regions in “dalitz” plane (as done in $B_s \to \tau^+ \tau^-$)
  - Exclusive MC samples

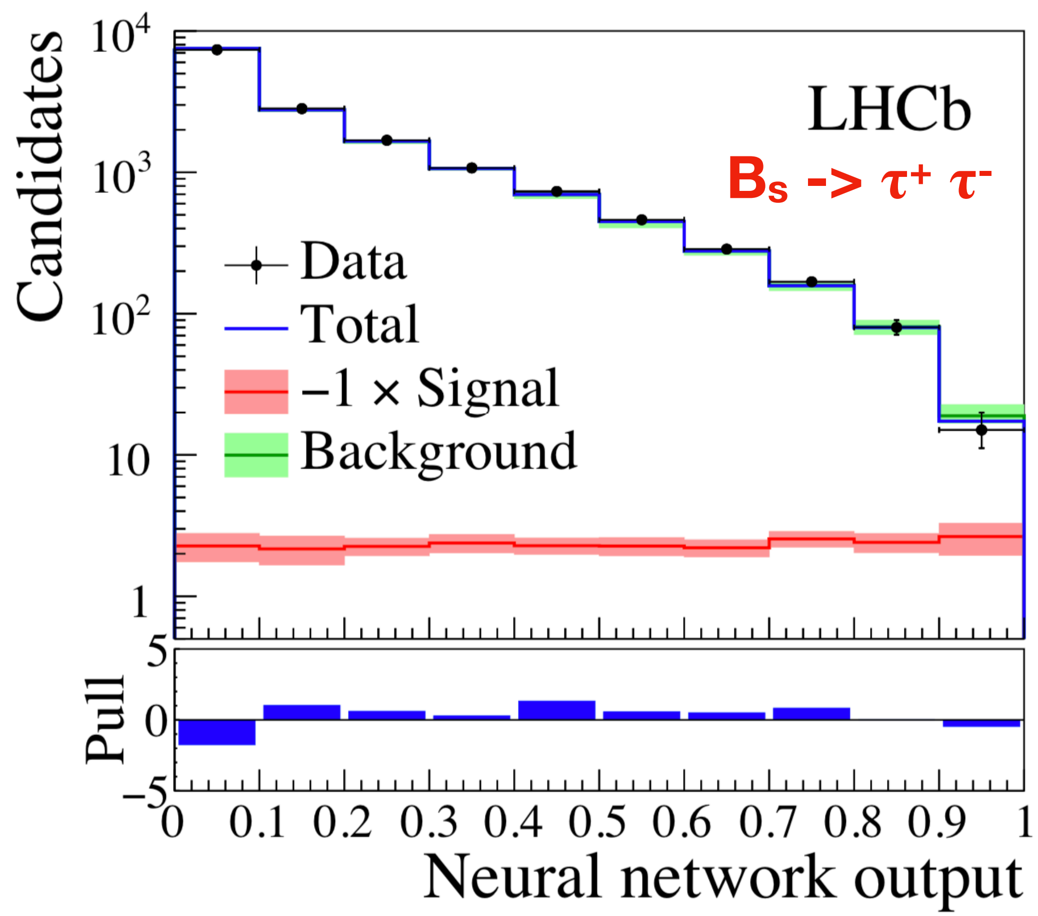


$B_s \to \tau^+ \tau^-$

https://arxiv.org/pdf/1703.02508.pdf

Fit BDT

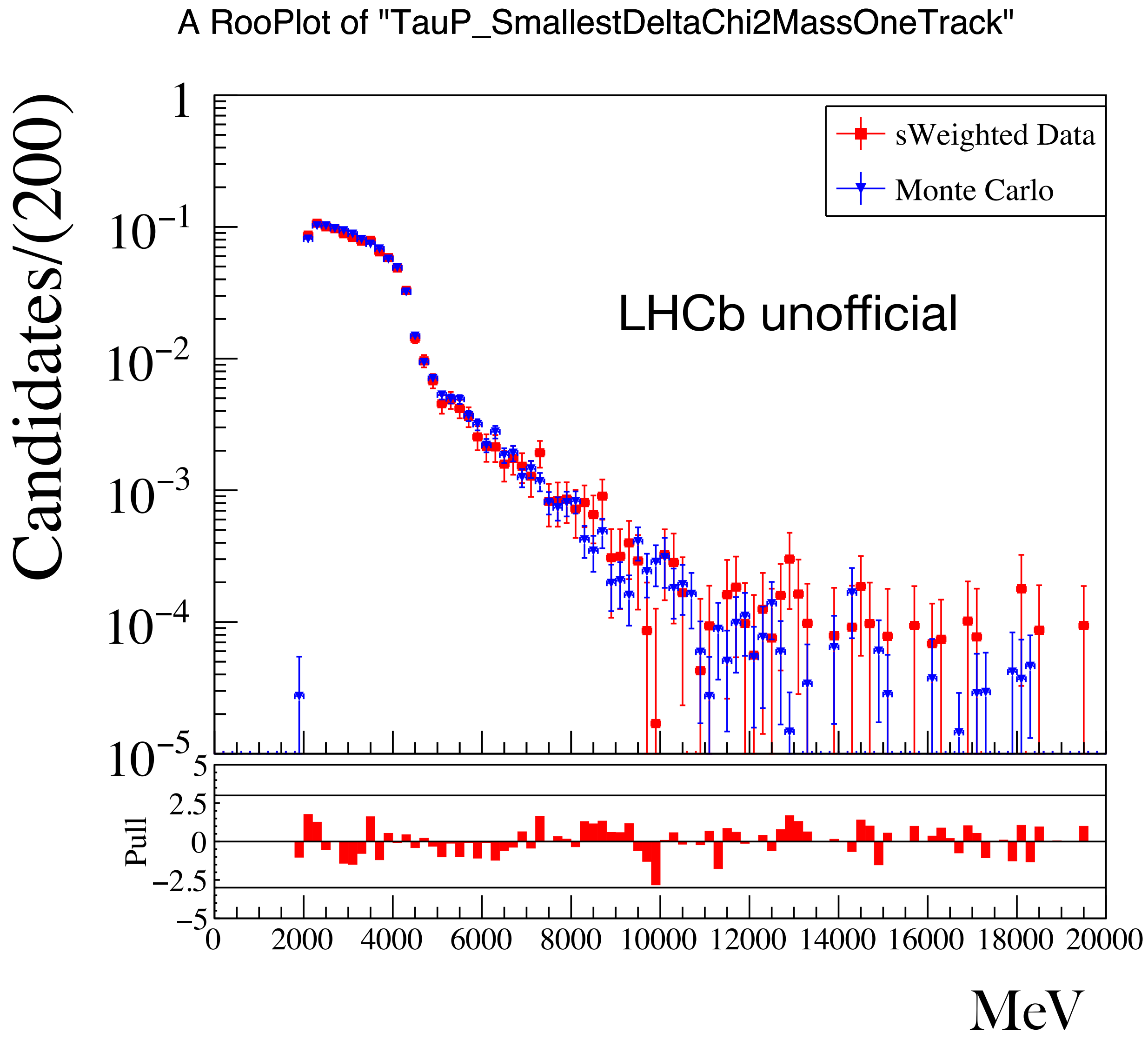
- Mass discriminating power not enough to perform a fit: **trained a third BDT** with masses and momenta
- Same samples used, after the first and second BDT cuts
- Fit strategy similar to the $B_s \to \tau^+ \tau^-$ case:



https://arxiv.org/pdf/1703.02508.pdf

Data-MC comparison

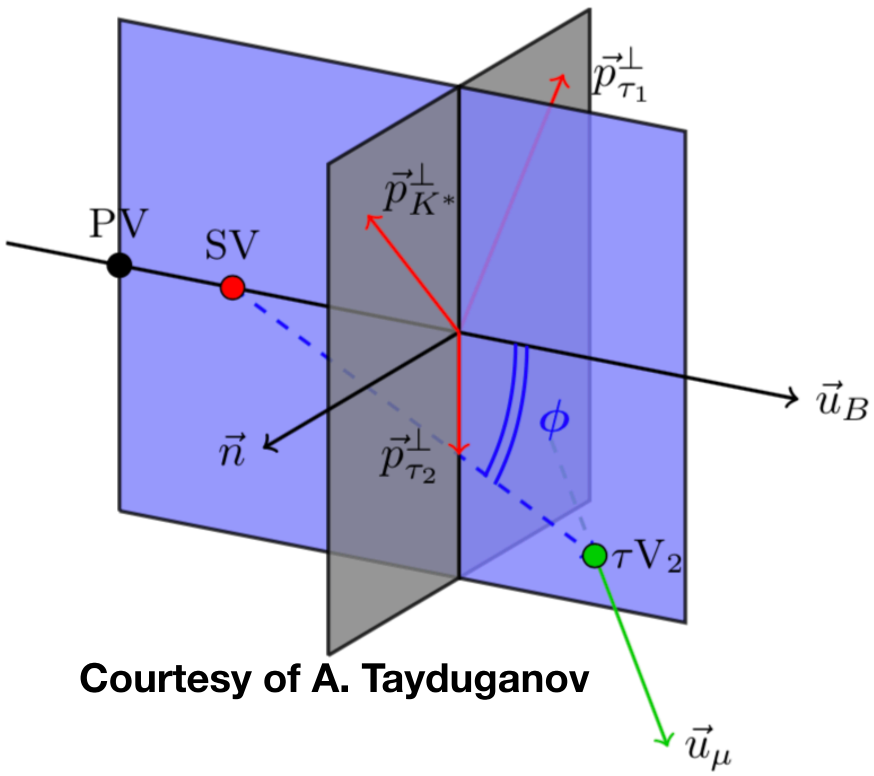
- Montecarlo simulation widely used in particle physics
- Not perfect replica of data! Need to spot differences wrt data and apply corrections
- Comparison data-MC ongoing using normalization channel



3πμ final state

Neutrinos and mass reconstruction

- Tau decaying into three pions (tau1) reconstructed analytically with two-fold ambiguity
- Information on decay vertex position for tau decaying into muon (tau2):
    1. tau2 transverse momentum wrt B flight direction: $\overrightarrow{p_T^{\tau_2}} = -\overrightarrow{p_T^{\tau_1}} - \overrightarrow{p_T^{K*}}$
    2. Plane containing tau2 transverse momentum and B flight direction
    3. Intersection between plane and muon track: **tau2 vertex**!

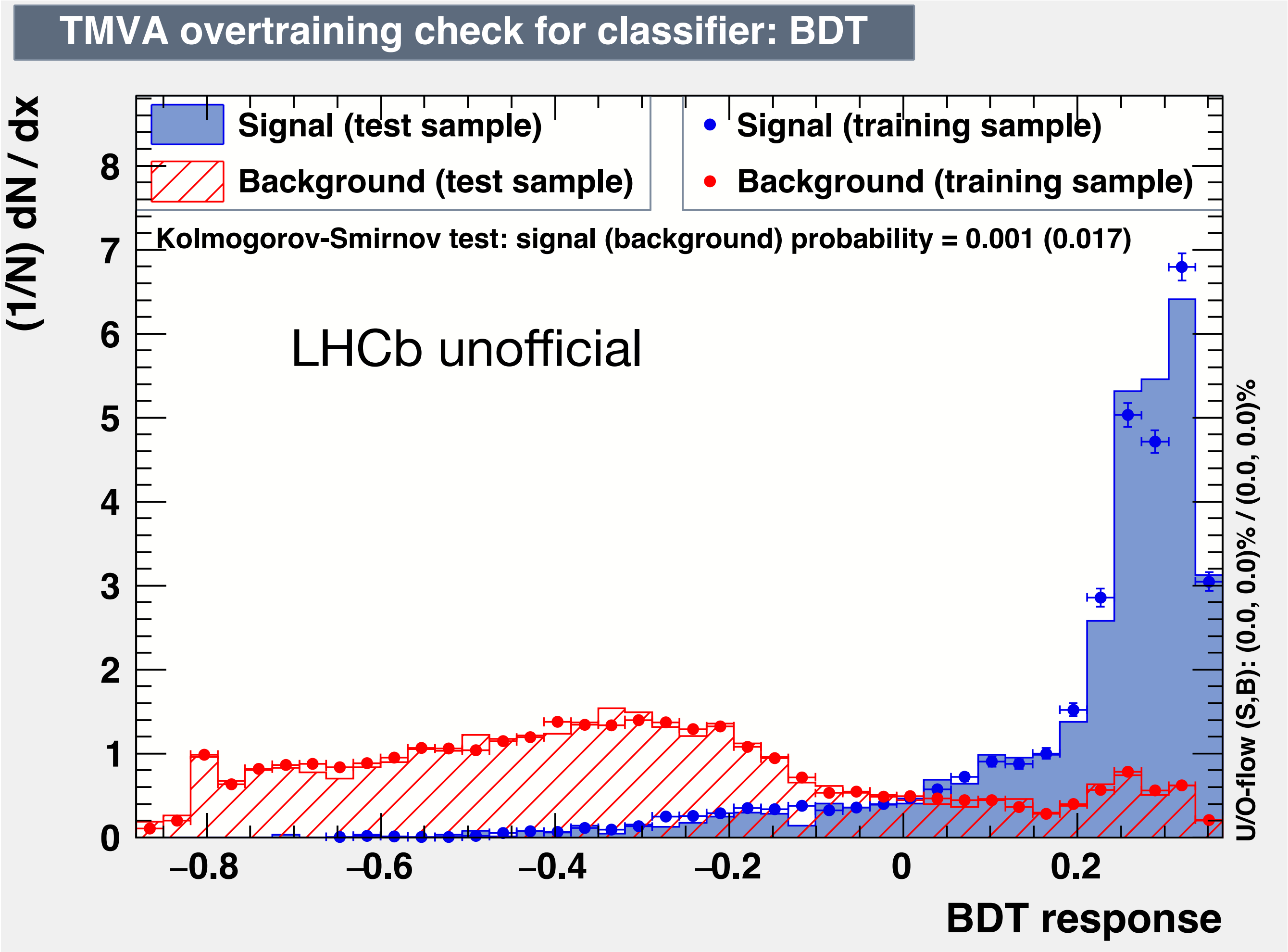


Courtesy of A. Tayduganov

- Using transverse momentum and angle between B flight direction and tau2 flight direction one gets tau2 momentum
- 54% of taus have positive discriminant, set to 0 if negative
- **Two-fold ambiguity on B mass**, constrain on B flight direction already used
- Higher fractions of true events in MC sample, less background
- Masses still not discriminating, strategy similar to the 3π3π case

Selection

- **Loose cut-based preselection** on isolation variables
- **BDT-based selection**, trained against MC signal sample and SS data
- First BDT trained using isolation variable
- Second BDT trained using isolation, flight distances and vertex information



Conclusions

- Interesting deviations suggesting lepton flavor non-universality observed
- B physics with taus in the final state very promising field
- $B^0 \to K^* \tau^+ \tau^-$ analysis: work in progress in two different final states
- Challenging analysis: multiple candidates, lots of background, poor mass discriminating power
- Selection almost completed, fit will be probably performed on BDT
- Background characterization and data-MC comparison ongoing
- Next step: define a fit strategy
- Many New Physics models, next few years will shed light on flavor anomalies!

Thanks!