Lepton Flavour Universality tests with $R_{K\pi\pi}$

Jahrestreffen der deutschen LHCb-Gruppen

J. Heuel, C. Langenbruch, S. Schael

October 5th, 2020

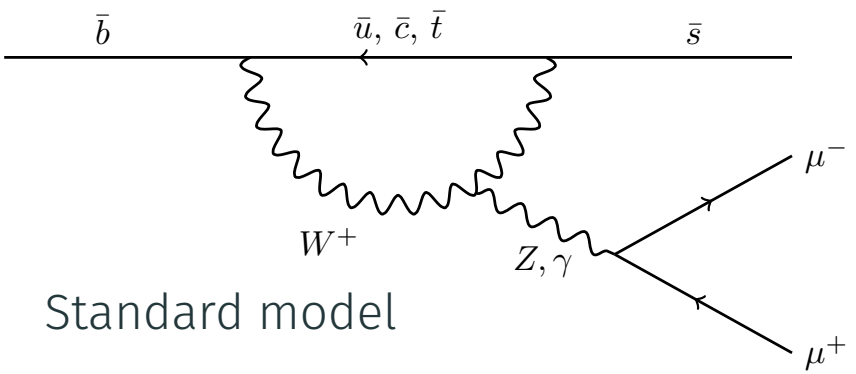
RWTH AACHEN UNIVERSITY

Bundesministerium
für Bildung
und Forschung

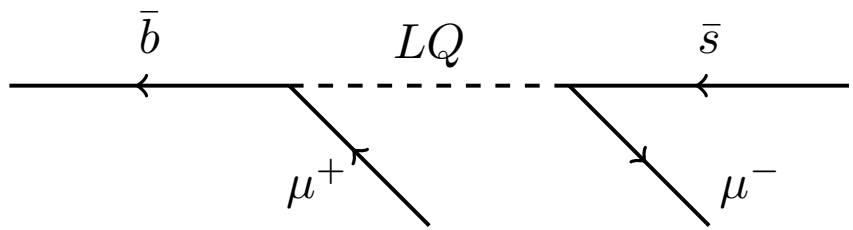
Motivation

- SM: Electroweak interaction couples in the same way to all charged leptons
  - Well tested in K and π decays (e.g. $K \to \ell\nu$ [JHEP 1302 (2013) 048])
- Flavor changing neutral currents (FCNC) $b \to s\ell\ell$
  - Forbidden in tree-level decays in the SM
  - Loop diagrams heavily suppressed
  - Highly sensitive to the presence of new heavy virtual particles

  $\Rightarrow$ Good probe for New Physics



Standard model



possible new physics contribution

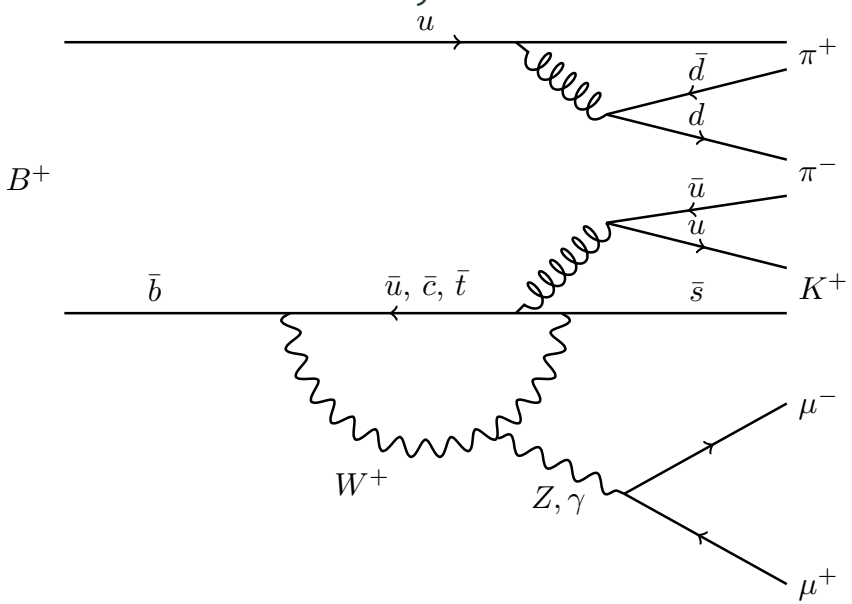
Motivation for R_H

A precise test of LFU in the SM is the ratio

$$R_H = \frac{\mathcal{B}(B \to H\mu\mu)}{\mathcal{B}(B \to Hee)}, \text{ with } H = K^+, K^{*0}, \phi, \ldots K^+\pi^+\pi^-$$

[Phys.Rev. D69 (2004) 074020]

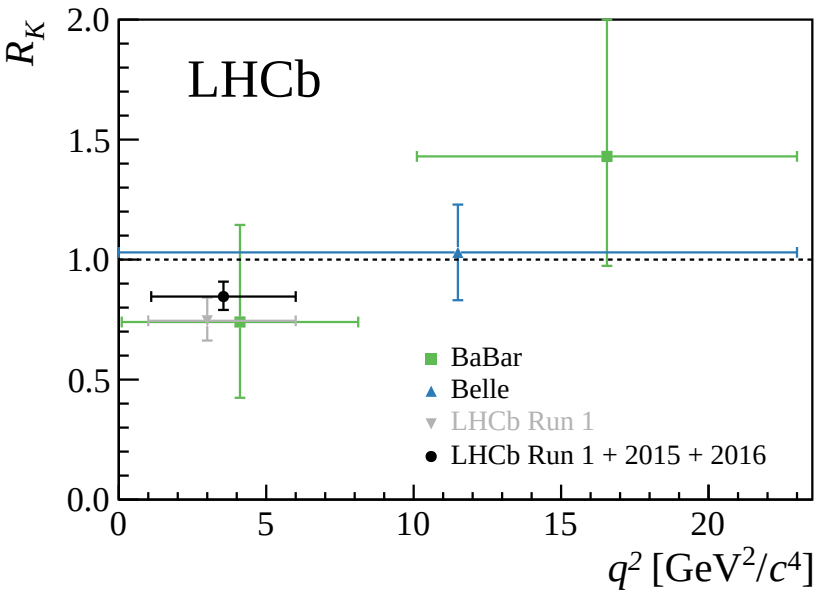
- R_H expected to be close to unity in the SM [JHEP 0712 (2007) 040]
- Theoretically clean as hadronic uncertainties cancel

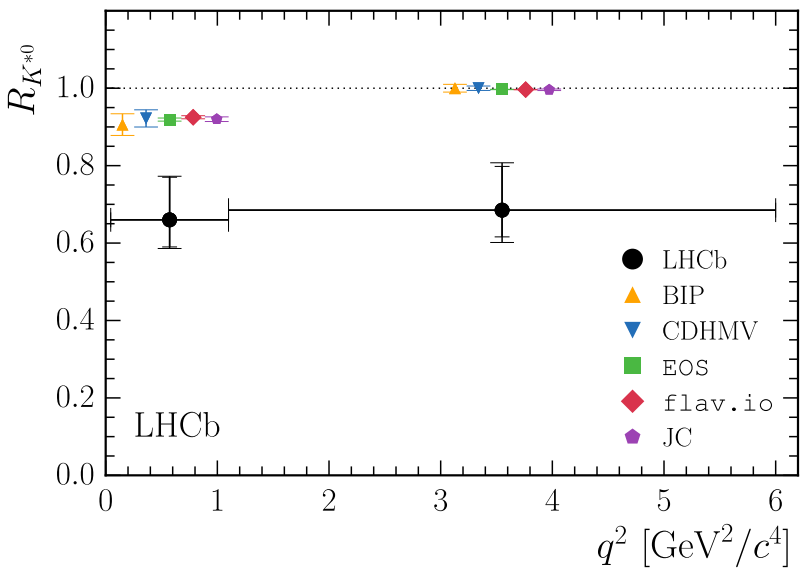


$R_{K\pi\pi}$

- Ratio of branching fractions of $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$
- Control channel: $B^+ \to K^+\pi^+\pi^- J/\psi\,(\to \ell^+\ell^-)$
- $q^2 = m(\ell^+\ell^-)^2$

Published measurements of R_H





- Tensions with LFU measured by the LHCb collaboration
  - Measurement of R_K (2.5σ tension with SM) [Phys. Rev. Lett. 122 (2019) 191801]

$$R_K = 0.846^{+0.060}_{-0.054}\,(\text{stat})^{+0.016}_{-0.014}\,(\text{syst}) \quad \text{for } 1 < q^2 < 6.0\,\text{GeV}^2$$

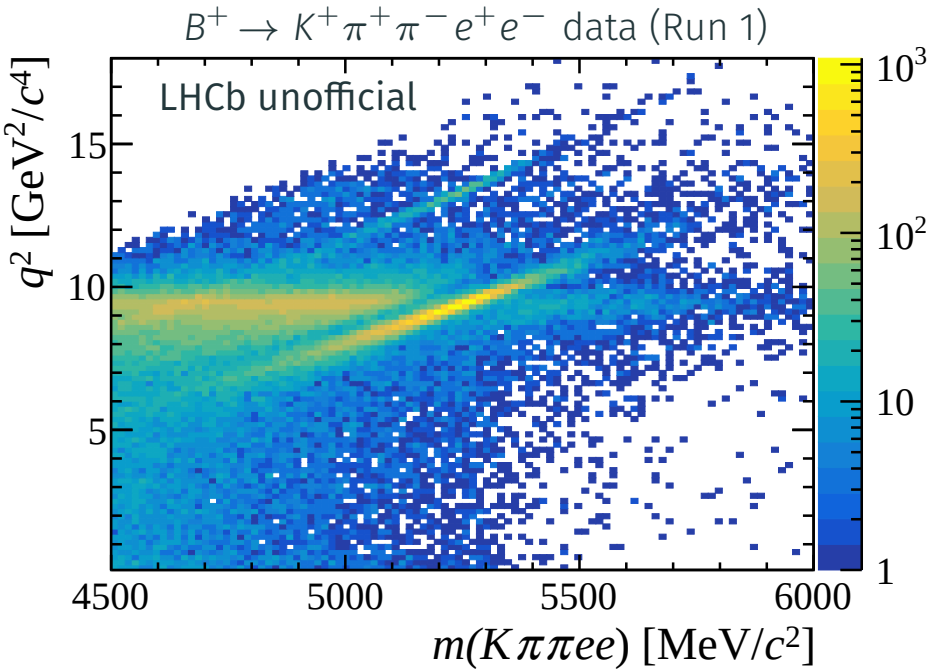
  - Measurement of $R_{K^{*0}}$ (2.1σ-2.5σ tension with SM) [JHEP 08 (2017) 055]

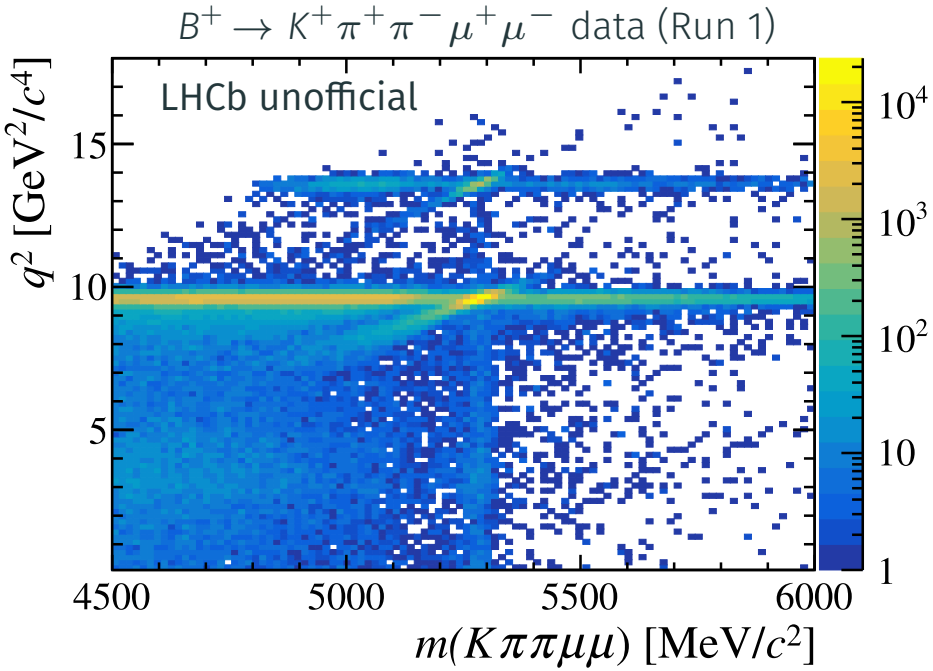
$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\,\text{GeV}^2 \\ 0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 < q^2 < 6.0\,\text{GeV}^2 \end{cases}$$

Analysis strategy

Perform double ratio

$$R_{K\pi\pi} = \underbrace{\frac{N_{K\pi\pi\mu\mu}}{N_{K\pi\pi(J/\psi\to\mu\mu)}} \cdot \frac{N_{K\pi\pi(J/\psi\to ee)}}{N_{K\pi\pi ee}}}_{\text{determined by fit to selected data}} \cdot \underbrace{\frac{\epsilon_{K\pi\pi(J/\psi\to\mu\mu)}}{\epsilon_{K\pi\pi\mu\mu}} \cdot \frac{\epsilon_{K\pi\pi ee}}{\epsilon_{K\pi\pi(J/\psi\to ee)}}}_{\text{calculated from corrected simulation}}$$



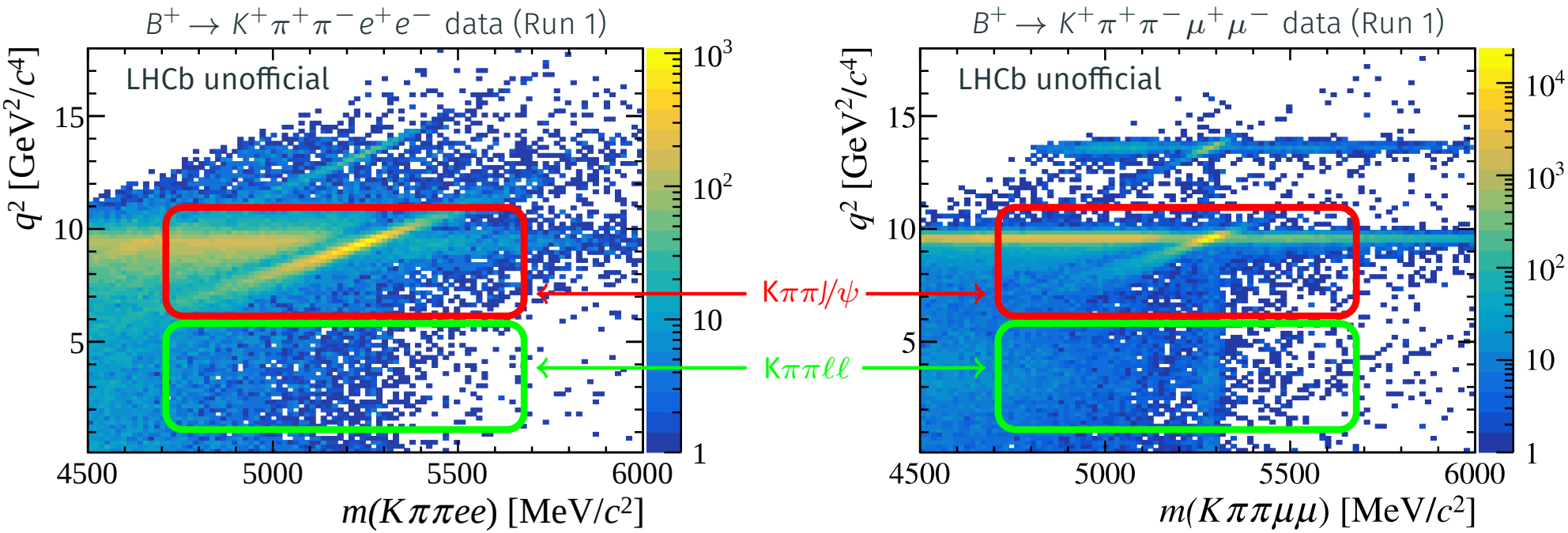


- Resolution in electron mode deteriorated by Bremsstrahlung

Analysis strategy

Perform double ratio

$$R_{K\pi\pi} = \underbrace{\frac{N_{K\pi\pi\mu\mu}}{N_{K\pi\pi(J/\psi\to\mu\mu)}} \cdot \frac{N_{K\pi\pi(J/\psi\to ee)}}{N_{K\pi\pi ee}}}_{\text{determined by fit to selected data}} \cdot \underbrace{\frac{\epsilon_{K\pi\pi(J/\psi\to\mu\mu)}}{\epsilon_{K\pi\pi\mu\mu}} \cdot \frac{\epsilon_{K\pi\pi ee}}{\epsilon_{K\pi\pi(J/\psi\to ee)}}}_{\text{calculated from corrected simulation}}$$



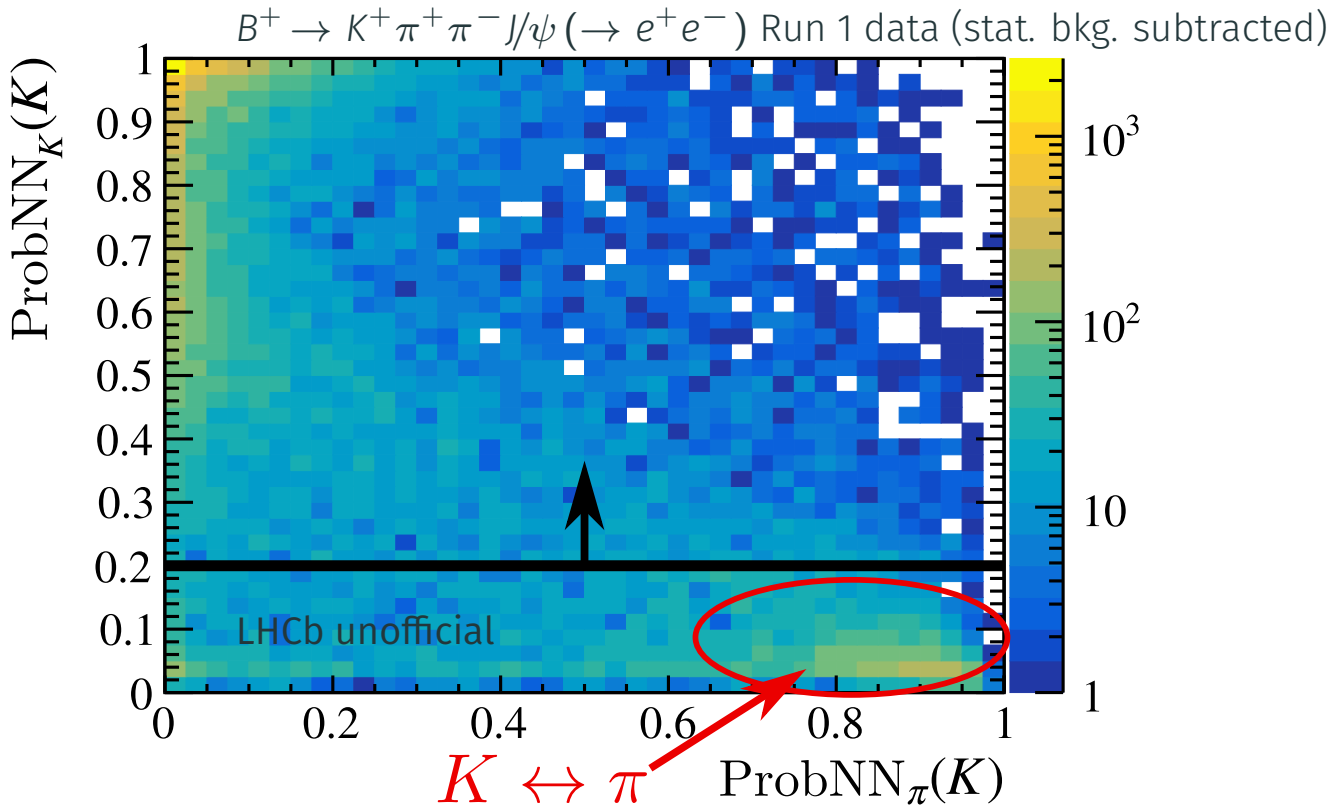
- Resolution in electron mode deteriorated by Bremsstrahlung

Selection

$$R_{K\pi\pi} = \underbrace{\frac{N_{K^+\pi^+\pi^-\mu^+\mu^-}}{N_{K\pi\pi(J/\psi\to\mu^+\mu^-)}} \cdot \frac{N_{K\pi\pi(J/\psi\to e^+e^-)}}{N_{K^+\pi^+\pi^-e^+e^-}}}_{\text{determined by fit to selected data}} \cdot \underbrace{\frac{\epsilon_{K\pi\pi(J/\psi\to\mu^+\mu^-)}}{\epsilon_{K^+\pi^+\pi^-\mu^+\mu^-}} \cdot \frac{\epsilon_{K^+\pi^+\pi^-e^+e^-}}{\epsilon_{K\pi\pi(J/\psi\to e^+e^-)}}}_{\text{calculated from corrected simulation}}$$

Pre-selection

- Fiducial cuts to exclude regions in which efficiency calculations are difficult ($p_{(T)}$, $m(K\pi\pi)$, ECAL regions)
- Require tracks of good quality
- PID variables are used to suppress mis-identified particles



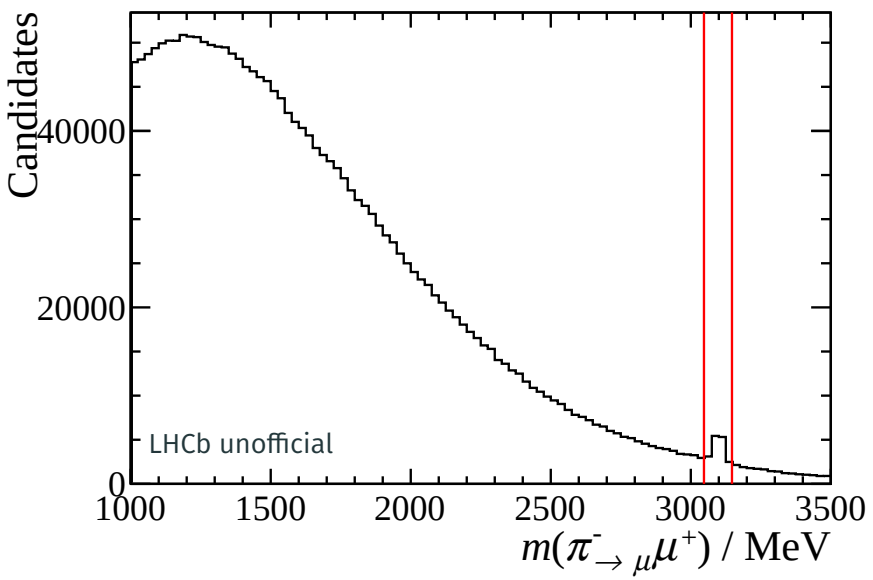
Peaking backgrounds

Background from physical processes

- Partially reconstructed decays
- Decays with one or two mis-identified particles

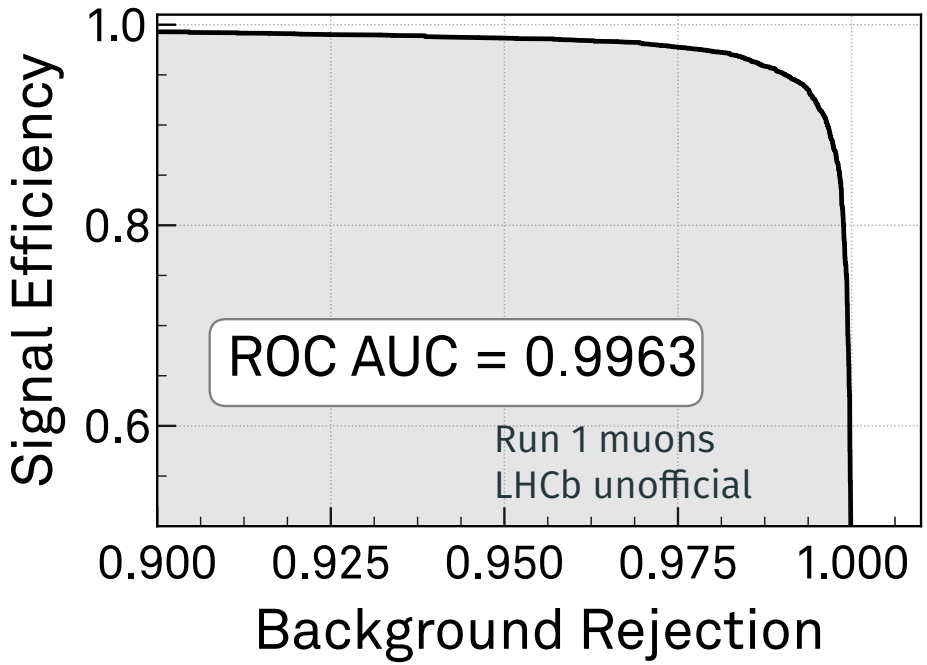
For example: Peaking background from $B^+ \to K^+\pi^+\pi^- J/\psi$ decays

- Double mis-identification of one hadron and one lepton, e.g. $B^+ \to K^+ \pi^+_{\to \mu^+} \pi^- (J/\psi \to \mu^+_{\to \pi^+} \mu^-)$
- Escapes charmonium veto on q^2
- Vetoes on $m(K^+\ell^-)$, $m(\pi^\pm \ell^\mp)$ with K^+ or the $\pi^\pm$ reconstructed as lepton



Combinatorial background suppression

- Multivariate analysis
- Boosted Decision Tree (LightGBM)
- Cross-validation ($n = 10$)
- Select input variables from set of well-simulated features by backward elimination
- Separate BDTs for electron and muon mode



Training data

- Signal: $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$ simulation (corrected)
- Background: Upper sideband $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$ data
  Only combinatorial background, no significant contribution from physical background sources

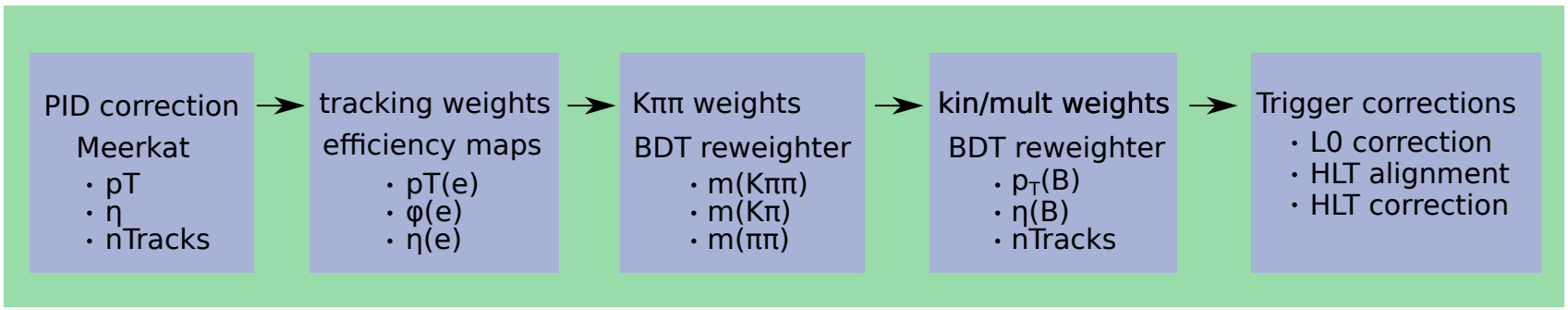
Corrections to simulation and efficiencies

$$R_{K\pi\pi} = \underbrace{\frac{N_{K^+\pi^+\pi^-\mu^+\mu^-}}{N_{K\pi\pi(J/\psi\to\mu^+\mu^-)}} \cdot \frac{N_{K\pi\pi(J/\psi\to e^+e^-)}}{N_{K^+\pi^+\pi^-e^+e^-}}}_{\text{determined by fit to selected data}} \cdot \underbrace{\frac{\epsilon_{K\pi\pi(J/\psi\to\mu^+\mu^-)}}{\epsilon_{K^+\pi^+\pi^-\mu^+\mu^-}} \cdot \frac{\epsilon_{K^+\pi^+\pi^-e^+e^-}}{\epsilon_{K\pi\pi(J/\psi\to e^+e^-)}}}_{\text{calculated from corrected simulation}}$$

Corrections to simulation and efficiencies

Need to calculate accurate efficiencies

$\Rightarrow$ Correct some distributions in simulation

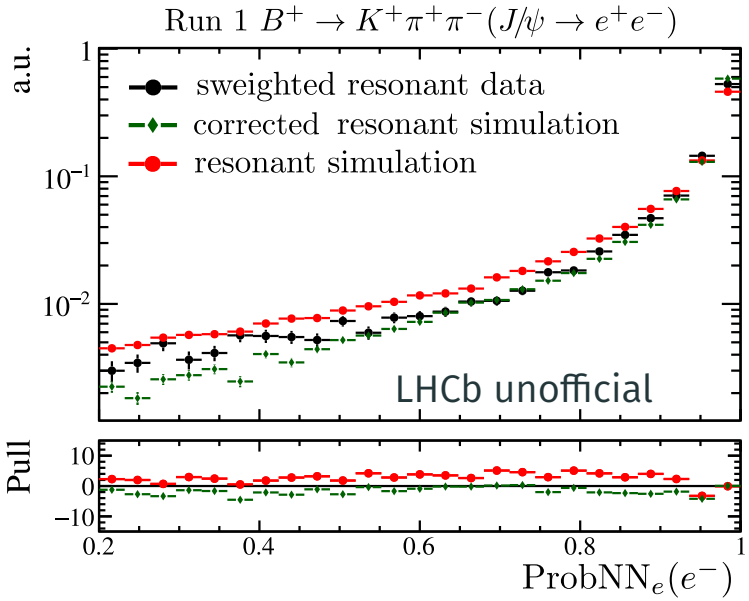


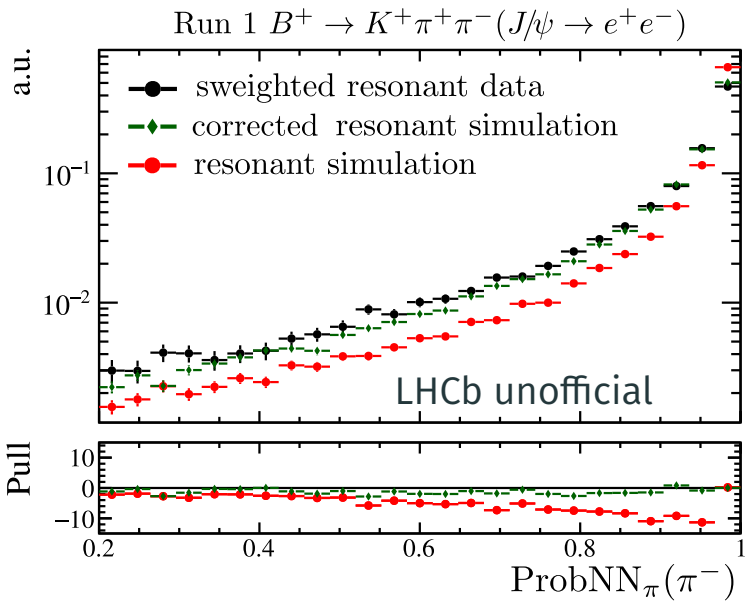
Correction of PID variables

- Known differences between data and simulation
- Corrected taking clean distributions from data
- Computed as function of p_{T}, η and nTracks

Calibration samples

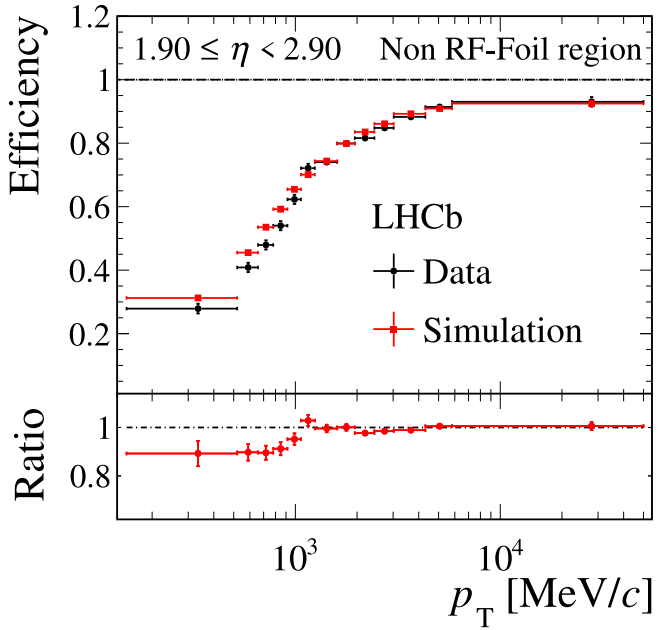
- Leptons from $J/\psi \to \ell^+\ell^-$
- K, π from $D^* \to \pi(D_0 \to K\pi)$

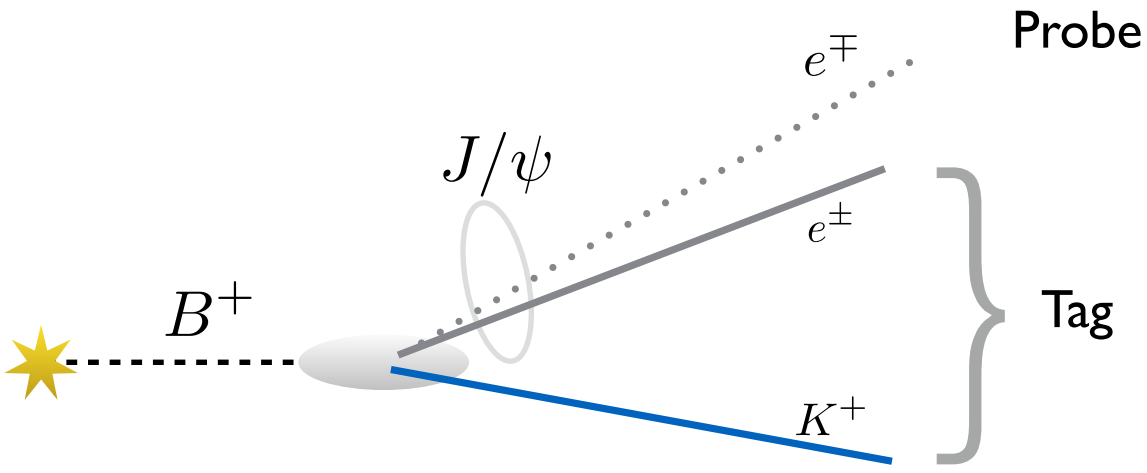




Tracking corrections

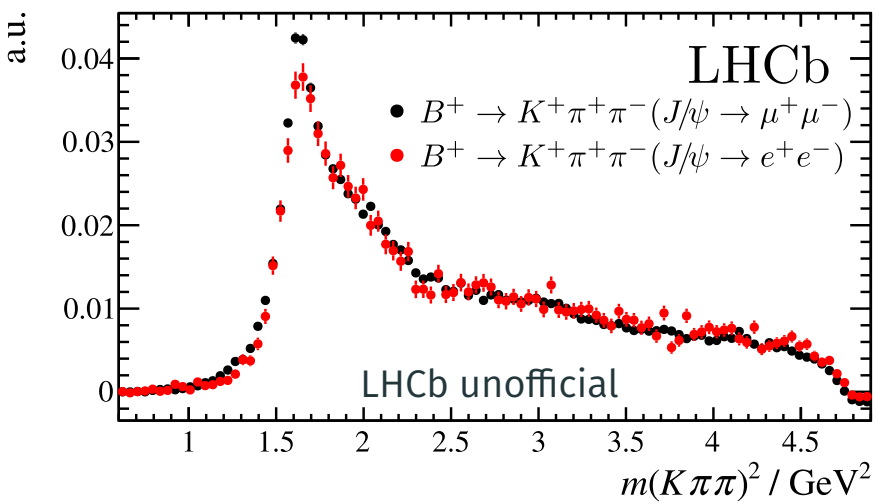
- Tracking efficiency controlled using tag & probe method on data
  - binned in p_{T}, η and ϕ
- Correction tables provided by tracking and alignment group [arXiv:1909.02957 hep-ex]

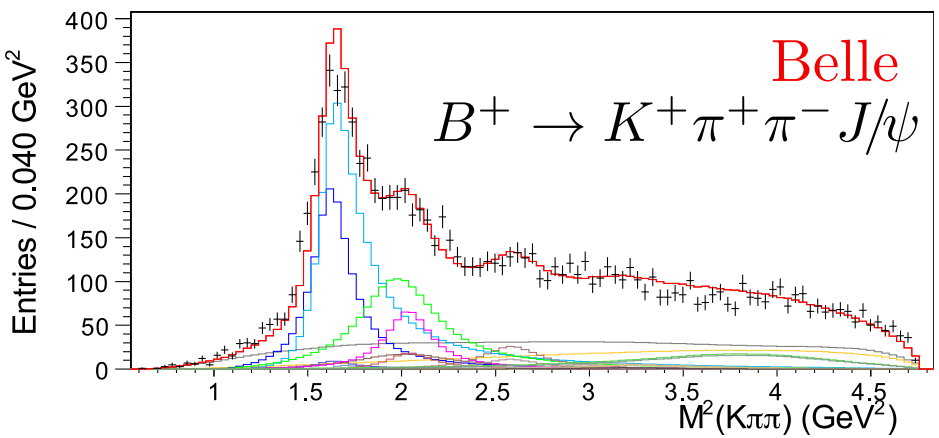




$K\pi\pi$ composition

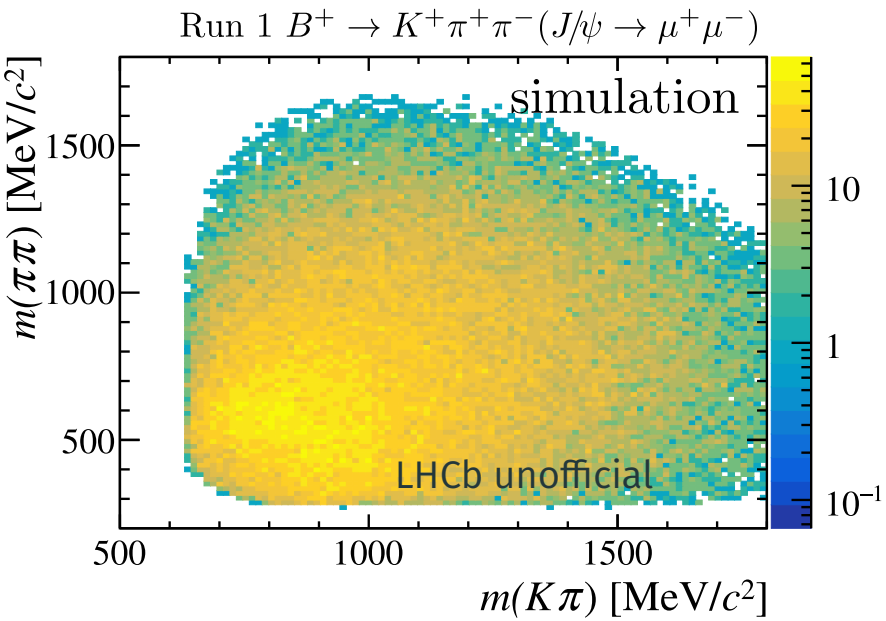
- Perform inclusive measurement of the $K^+\pi^+\pi^-$ system
- $K\pi\pi$ can originate from
  - $K_1(1270) \to K\rho$
  - $K_1(1270) \to K^*(892)\pi$
  - $K_1(1400) \to K^*(892)\pi$
  - $K_2(1430) \to K^*(892)\pi$
  - ...
- Difficult to model in simulation

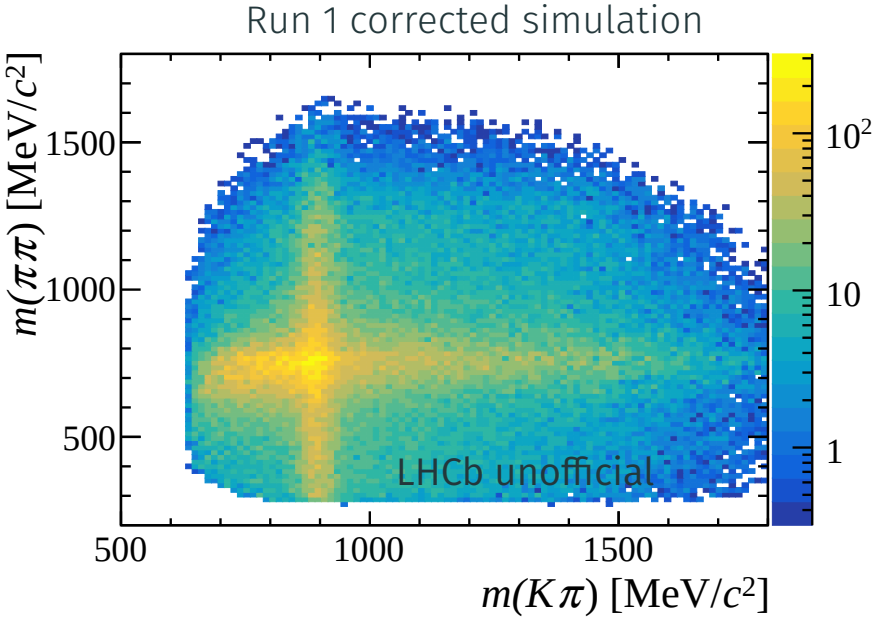




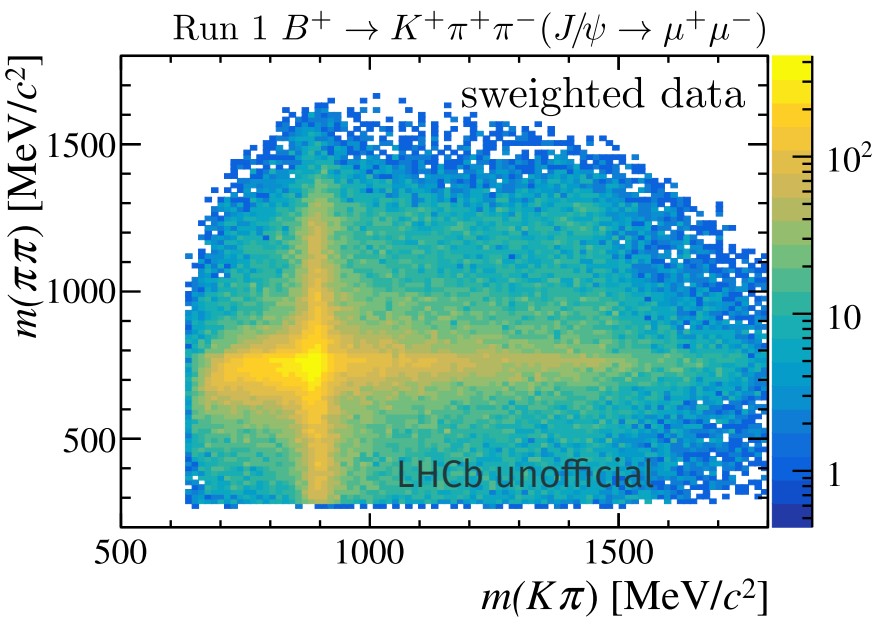
[Phys. Rev. D 83, 032005 (2011)]

Correct $K\pi\pi$ model in simulation



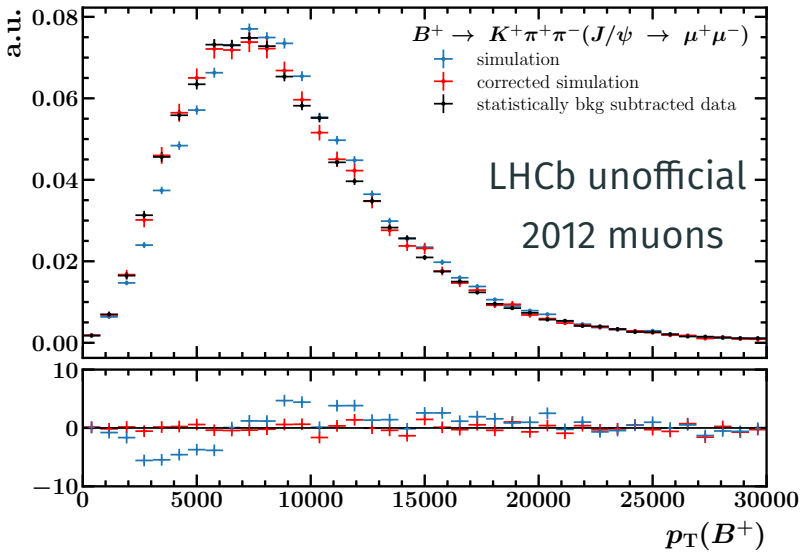


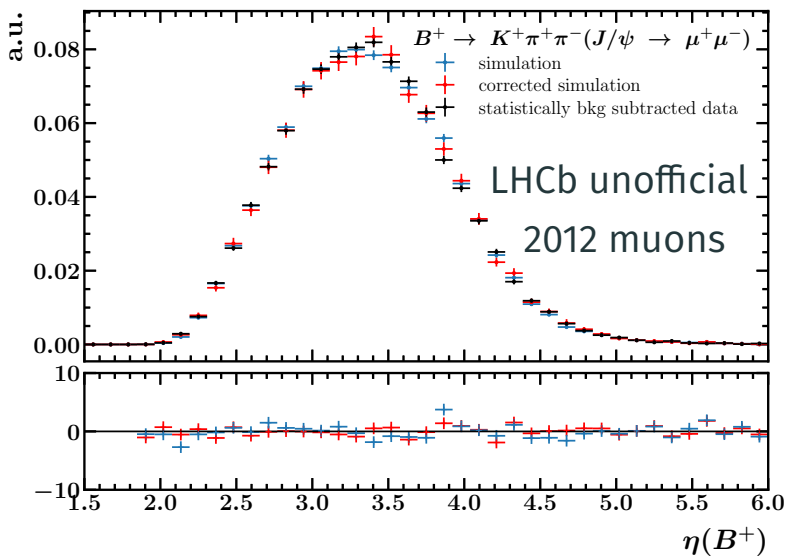
- Simulation generated using generic phase space model
- Calculate weight as function of $m(K^+\pi^-)$, $m(\pi^-\pi^+)$ and $m(K^+\pi^+\pi^-)$
- Accurately reproduce $K\pi\pi$ resonance structure in data

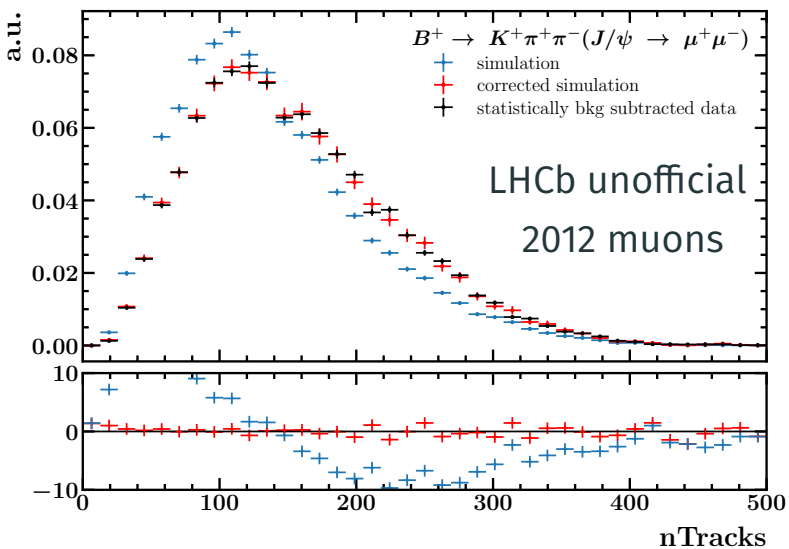


Reweighting of the B^+ production kinematics and multiplicity

- Correct B^+ production kinematics and multiplicity
- Weights are calculated on trigger corrected muonic control channel data
- Observables
  - $p_T(B^+)$
  - $\eta(B^+)$
  - nTracks

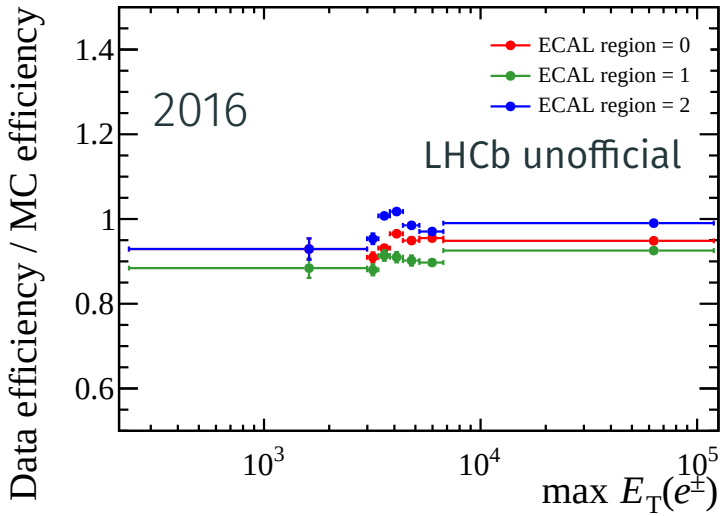


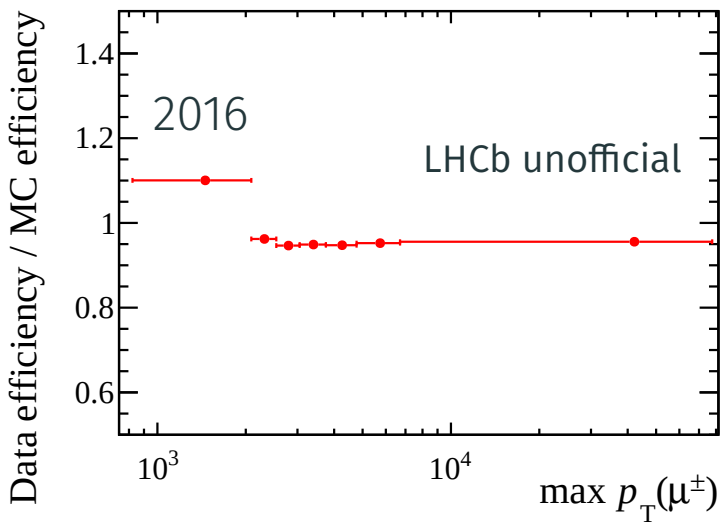




Trigger corrections

- Tag and probe approach
- Ratios of efficiencies on data and simulation
- Example: Lepton triggers
  - Binned in $E_{T,max}(e^{\pm})$ and ECAL region or $p_{T,max}(\mu^{\pm})$
  - Determine efficiency using trigger independent of signal

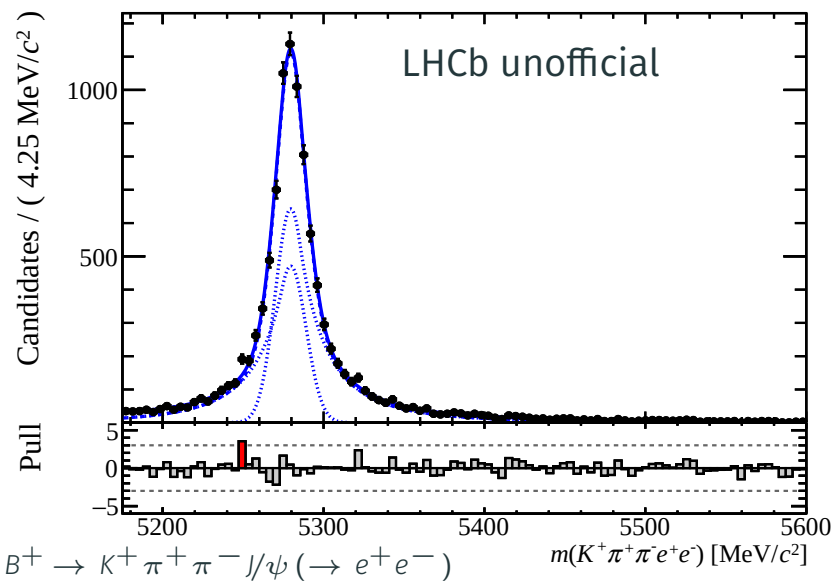


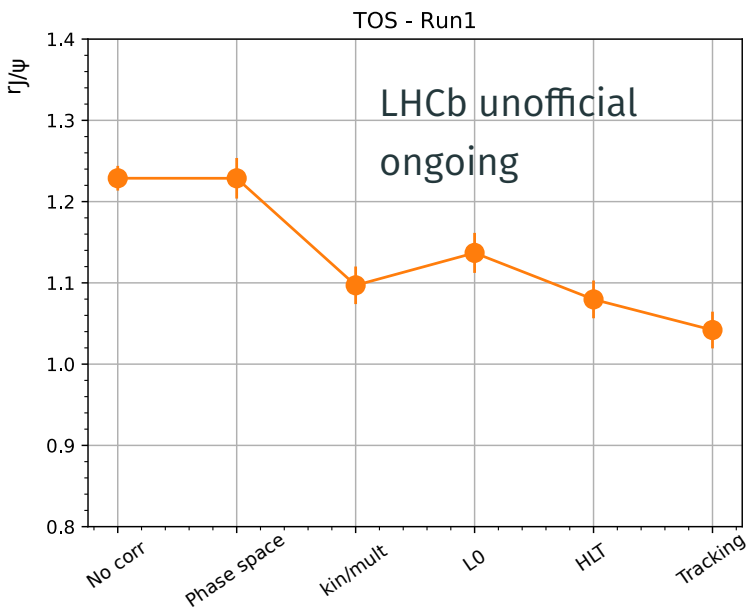


Test of the efficiency calculation - cross-check $r_{J/\psi}$

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+\pi^+\pi^- J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+\pi^+\pi^- J/\psi(\to e^+e^-))} = \frac{N_{K\pi\pi(J/\psi\to\mu\mu)}}{N_{K\pi\pi(J/\psi\to ee)}} \cdot \frac{\epsilon_{K\pi\pi(J/\psi\to ee)}}{\epsilon_{K\pi\pi(J/\psi\to\mu\mu)}} = 1$$

- Ratio of tree level decays
- Powerful cross check for the efficiency calculations
- Calculate $r_{J/\psi}$ as a function of kinematic and other quantities



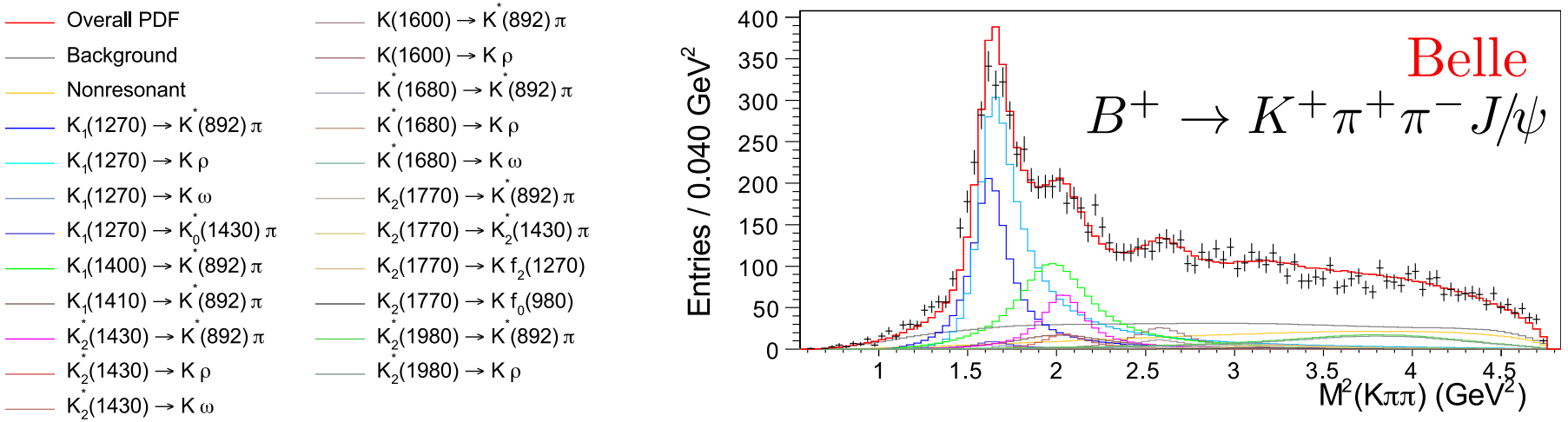


Conclusion

- R_H measurements are a good probe of New Physics contributions
- Recent measurements show tensions up to 2.5σ with SM
- This analysis adds measurement in an additional channel
- Presented
  - Overview over selection criteria
  - Corrections to simulation
- Work in progress
  - Finish studies of $r_{J/\psi}$ (flatness, value)
  - Study of systematic uncertainties

Thank you!

Backup



[Phys. Rev. D 83, 032005 (2011)]

Feynman diagrams