Measurement of the ratio $R_{K\pi\pi}$ with the LHCb experiment

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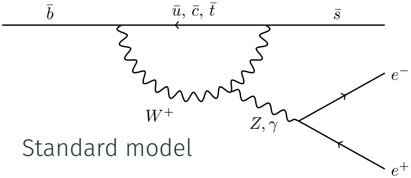
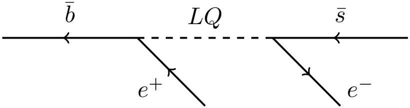
- SM: Electroweak interaction couples in the same way to all charged leptons
  - Well tested in K and π decays (e.g. $K \to \ell\nu$ [JHEP 1302 (2013) 048])
- Flavor changing neutral currents (FCNC) $b \to s\ell\ell$
  - Forbidden in tree-level decays in the SM
  - Loop diagrams heavily suppressed
 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

$\Rightarrow$ Good probe for new physics



Standard model



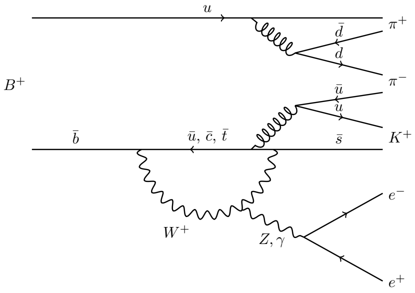
possible new physics contribution

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]

- The ratios R_H are expected to be close to unity in the SM [JHEP 0712 (2007) 040]
- Hadronic uncertainties cancel

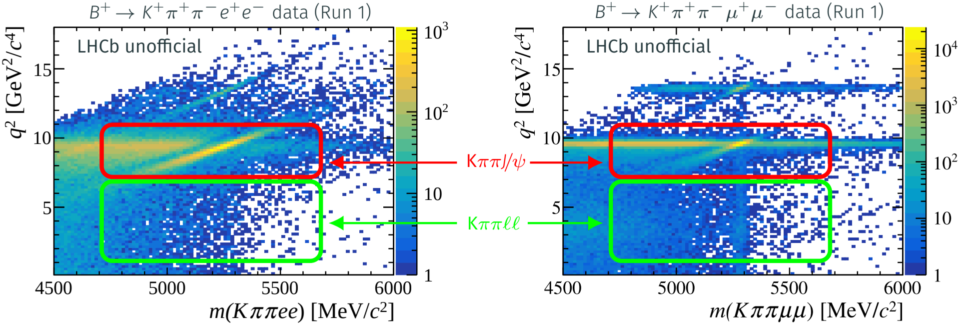


$R_{K\pi\pi}$

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

Perform double ratio

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

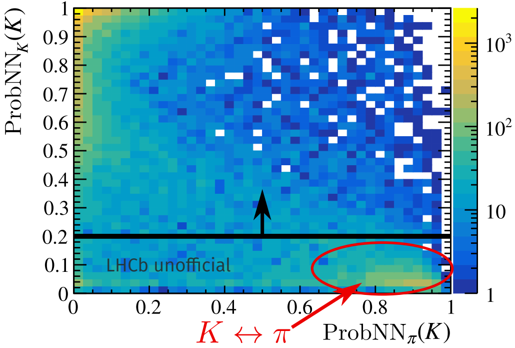


- Resolution in electron mode deteriorated by Bremsstrahlung
- Data from Run1: 2011–2012 ($3\,\text{fb}^{-1}$), and Run2: 2015–2018 ($6\,\text{fb}^{-1}$)

Selection

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

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



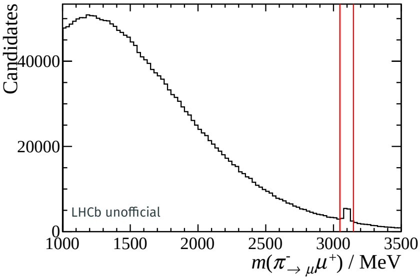
$B^+ \to K^+\pi^+\pi^- J/\psi(\to e^+e^-)$ Run 1 data
statistically background subtracted

Background from physical processes

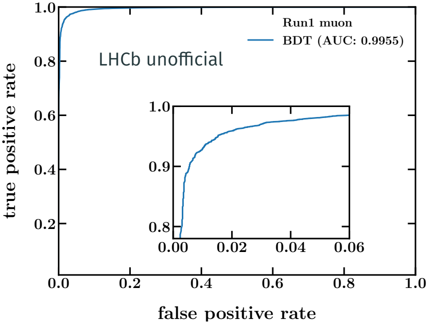
- Partially reconstructed decays
- Decays with one or two mis-identified particles

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

- Mis-identification of one hadron and one lepton, e.g. $B^+ \to K^+\pi^+_{\to\mu^+}\pi^-(J/\psi \to \mu^+_{\to\pi^+}\mu^-)$
- Vetoes on $m(K^+\ell^-)$, $m(\pi^\pm\ell^\mp)$ with K^+ or the $\pi^\pm$ reconstructed as muon or electron



- Suppress combinatorial background
- 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

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

Need to calculate accurate efficiencies

$\Rightarrow$ Correct necessary distributions in simulation

Types of corrections to simulation

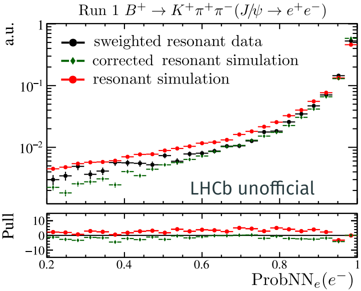
1. Correction of PID variables
2. Tracking efficiency correction
3. Reweighting of the $K^+\pi^+\pi^-$ system
4. Reweighting of B^+ production kinematics and multiplicity
5. Trigger efficiency corrections
6. Residual reconstruction differences
7. q^2 resolution correction

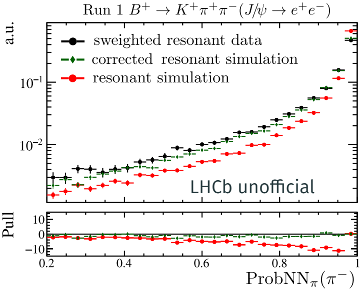
$\Rightarrow B^+ \to K^+\pi^+\pi^- J/\psi$ as proxy for signal in data/MC comparison

- Difficult/computationally expensive to simulate because of large number of low momentum photons
- Take from clean data samples

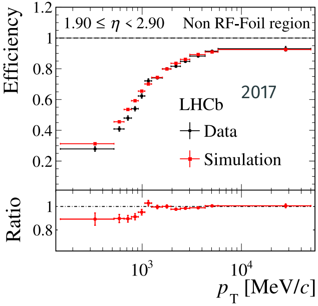
Calibration samples

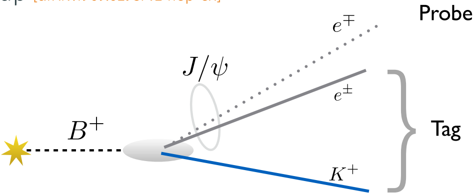
- Leptons from $J/\psi \to \ell^+\ell^-$
- K, π from $D^* \to \pi(D_0 \to K\pi)$





- Detector material not perfectly modeled
- Electron tracking efficiency controlled using tag & probe method on data
  - Channel: $B^+ \to K^+(J/\psi \to e^+e^-)$
  - Tag: electron and Kaon (long-tracks)
  - Probe: other electron reconstructed in the VELO
  - binned in p_T, η and ϕ
- Correction tables provided by tracking and alignment group [arXiv:1909.02957v2 hep-ex]



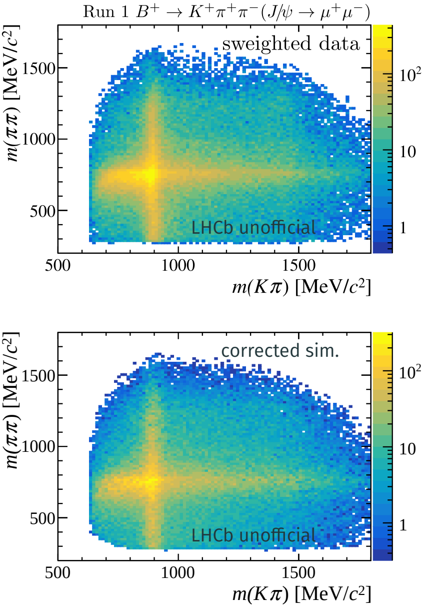


Simulation generated using generic phase space model

Data-driven correction

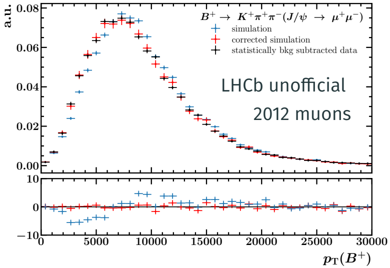
1. Calculate efficiency maps from simulation
2. Unfold data to account for efficiency
3. Train BDT reweighter

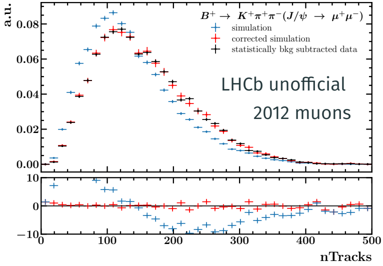
$\Rightarrow$ 4. Accurately reproduce $K\pi\pi$ resonance structure in data



B^+ production kinematics and multiplicity

- Weights are calculated on $B^+ \to K^+\pi^+\pi^- J/\psi(\to \mu^+\mu^-)$ after pre-selection
- Minimize dependency on trigger category
  - Train on aligned data and simulation samples
  - Prior trigger correction
- Observables
  - $p_{\mathrm{T}}(B^+)$
  - $\eta(B^+)$
  - nTracks





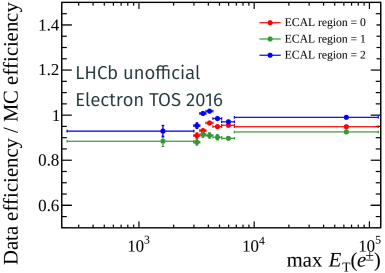
Trigger corrections

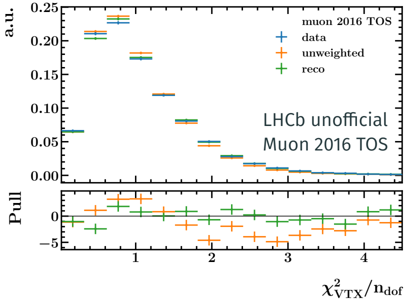
Trigger response not perfectly described in simulation

- Measure efficiencies on data and simulation of the resonant channel [LHCb-PUB-2014-039]
- Calculate ratios in bins
- Apply as weight to simulation
- Validated using more abundant $B^+ \to J/\psi K^+$

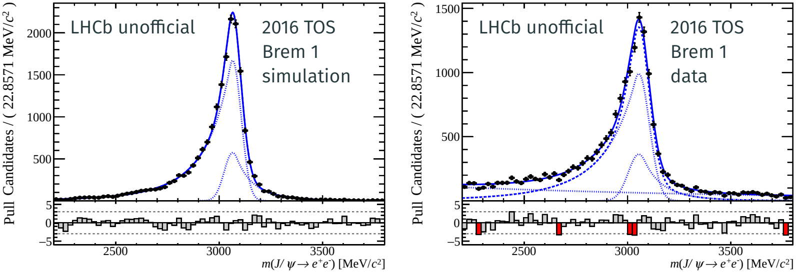
Residual reconstruction differences

- Calculated on full selection, trigger categories, electrons and muons
- Variables
  - $\chi^2_{\mathrm{IP}}(B^+)$
  - $\chi^2_{\mathrm{vtx}}(B^+)/\mathrm{ndof}$





- Detector material not perfectly modeled (Bremstrahlung)
- Resolution of m(J/ψ) differs between simulation and data, while q^2 cut efficiency must be evaluated carefully



- Fit simulation (double CB shape) in Bremstrahlung categories
- Fit data (float scale on width, shift on mean and yields)
- Calculate corrected mass $m^{\text{corr}}(J/\psi)$

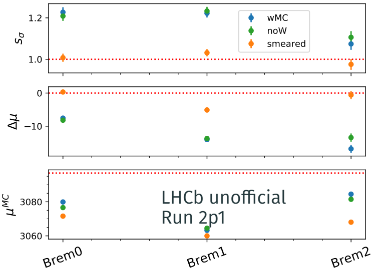
q^2 correction

- Calculate dilepton mass $m^{\text{corr}}(J/\psi)$ from fits to simulation and data

$$m^{\text{corr}}(J/\psi) = m^{\text{true}} + s_\sigma \cdot (m^{\text{reco}} - m^{\text{true}}) \\ + \Delta\mu + (1 - s_\sigma) \cdot \left(\mu^{\text{MC}} - m(J/\psi)_{\text{PDG}}\right)$$

- Crosscheck: Fit again using $m^{\text{corr}}(J/\psi)$ in q^2 selection

- μ^{MC} is the mean from a fit to simulation
- $\Delta\mu$ is the shift between means
- m^{true} is the generated dilepton mass
- m^{reco} is the reconstructed dilepton mass
- s_σ is the scale on the width



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

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

- Ratio of tree level branching fractions
- Powerful cross check for the efficiency calculations
- Calculate $r_{J/\psi}$ integrated and as a function of kinematic and other quantities
- Found $r_{J/\psi}$ flat and compatible with unity after corrections

Summary

- R_H ratios are a good probe of New Physics contributions
- This analysis adds a measurement in an additional channel
- Presented the precise control over efficiencies

Ongoing work

- Complete systematics
- Finalise fits of the rare modes
- Prepare internal documentation for working group review

Thank you!