Measurement of $\mathscr{B}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-)$

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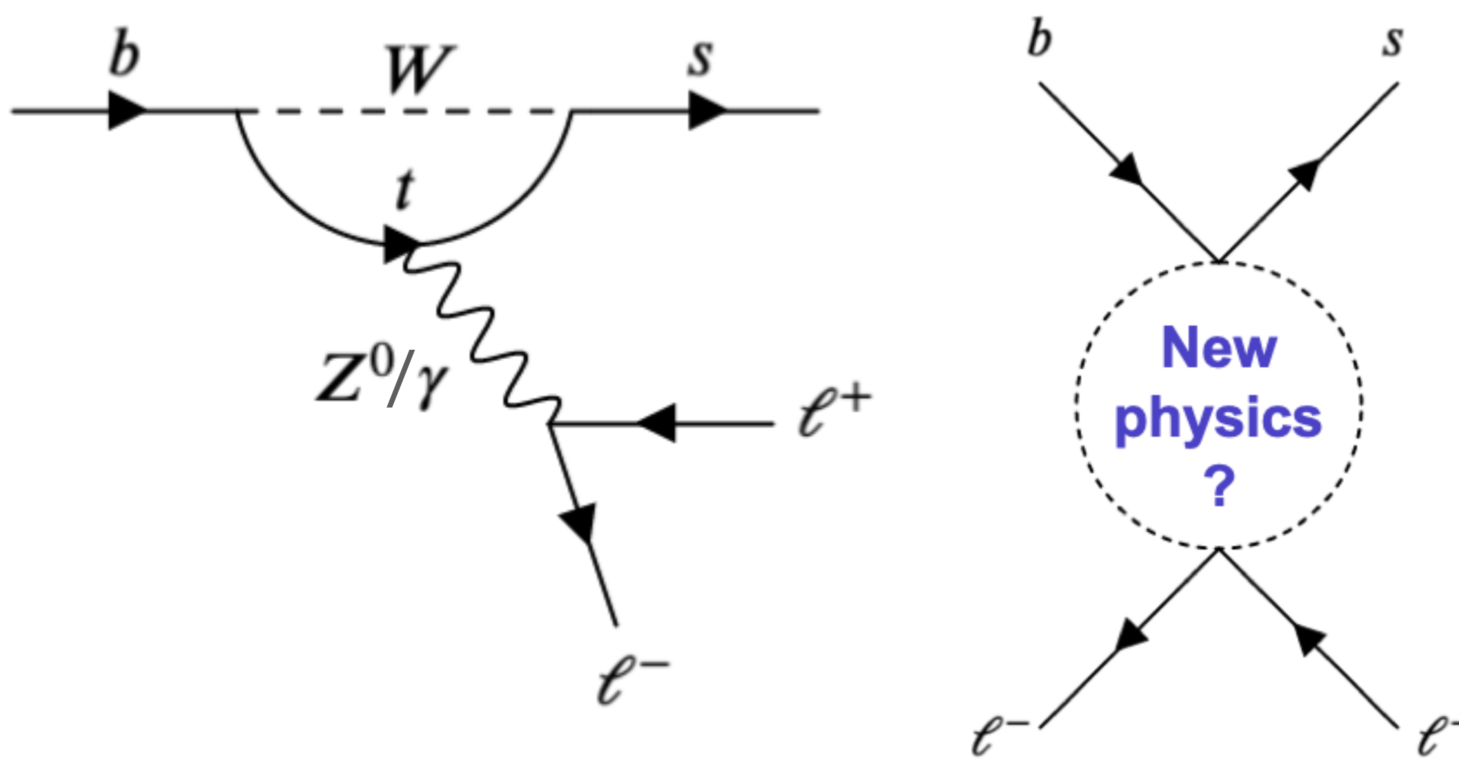
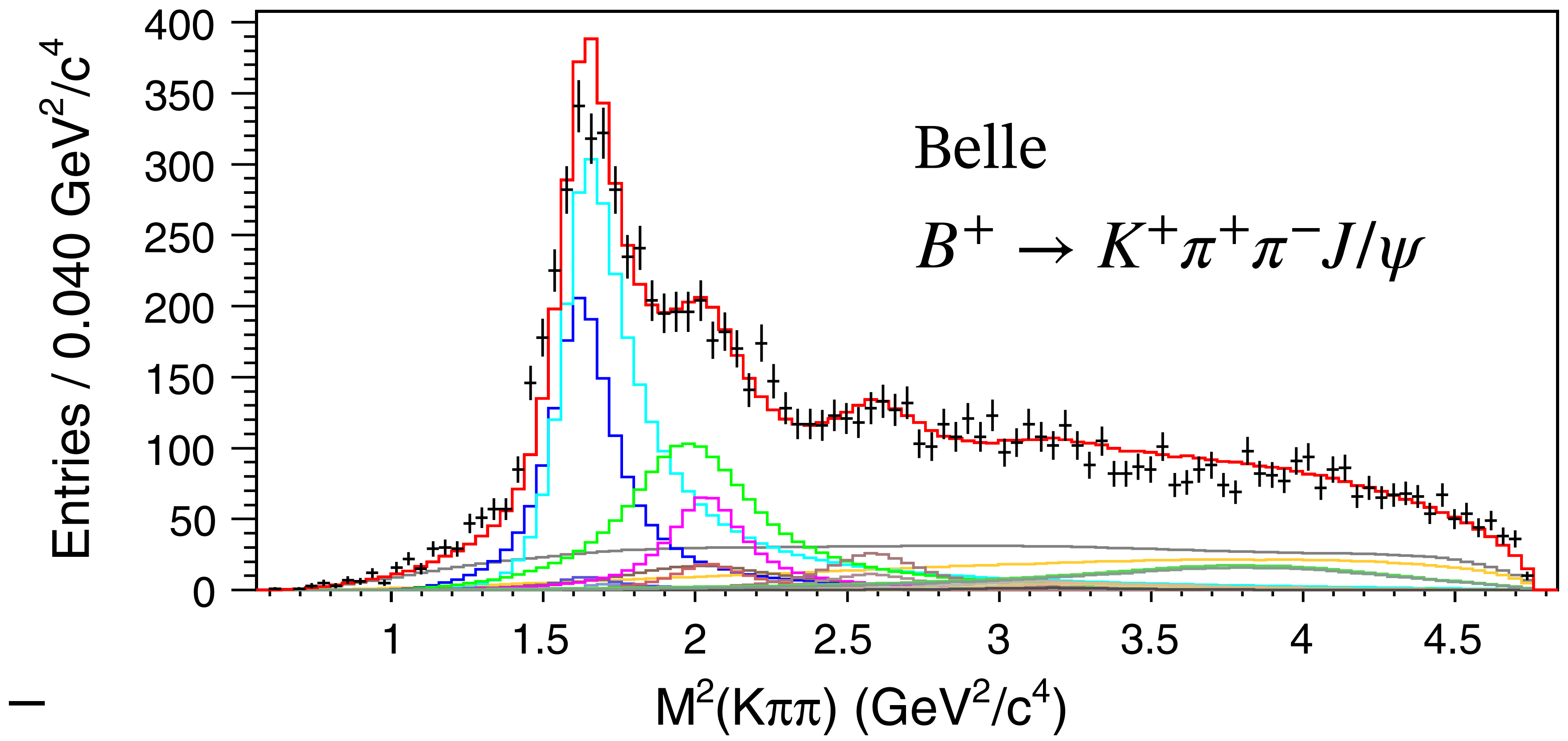
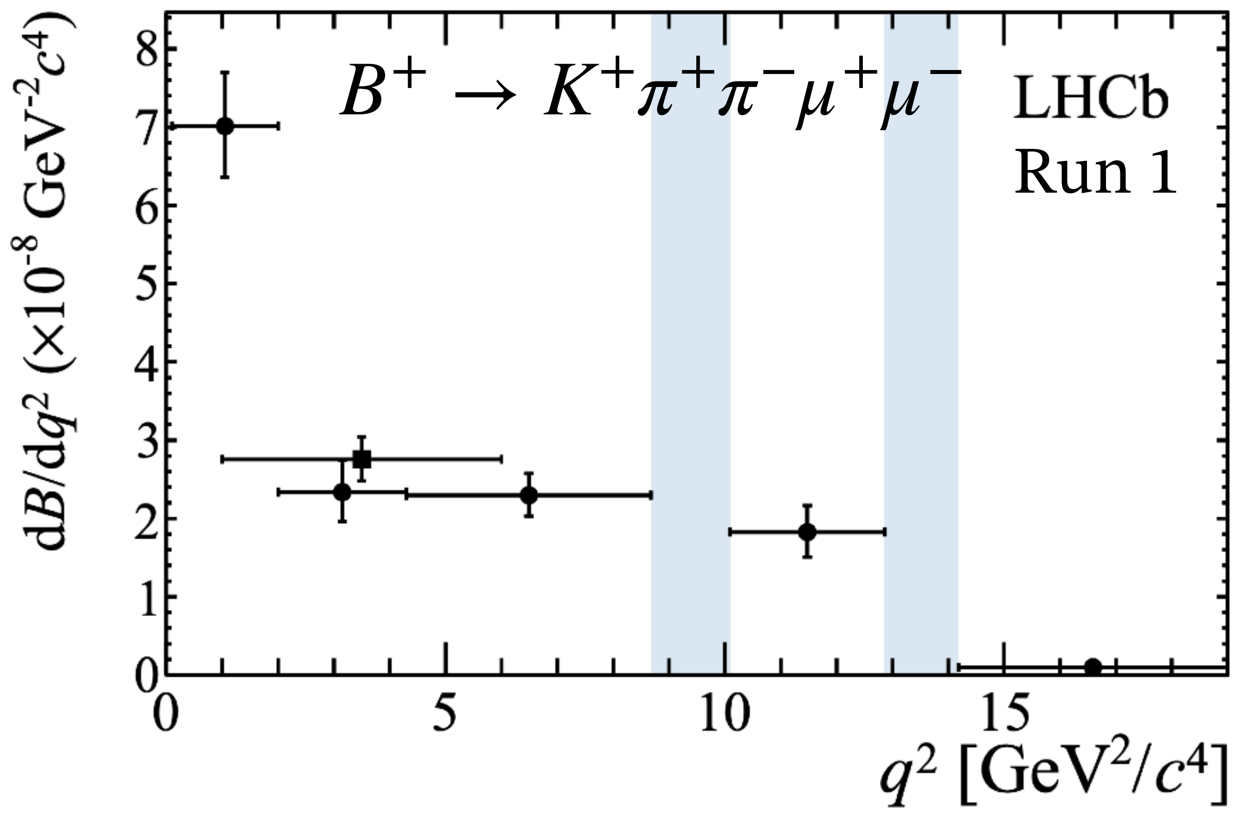
Why $B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$?

- Precision measurements of Standard Model (SM) processes offer an indirect window to new physics
- $b \to s\ell\ell$ transitions suppressed in the SM: new physics could contribute at a similar scale
- $B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$ decay channel:
  - Rich structure in $K^+\pi^+\pi^-$ system
  - Studied previously at LHCb in the branching ratio measurement using Run 1 (2011-2012) data: [arXiv:1408.1137], and Lepton Flavour Universality tests with $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$
  - Angular structure and CP-violation remain unexplored
  - High momentum transfer ($q^2 = m^2(\mu^+\mu^-) > 15$ GeV^2) region could provide information to recent theoretical calculations [arXiv:2305.03076]





[PhysRevD.83.032005]



[JHEP10(2014)064]

Objectives

- Update the measurement of the branching ratio $\mathscr{B}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-)$ using the full LHCb Run 1 and 2 dataset (2011-2018) in bins of q^2 } Current work
- Search for CP-violation effects
- Perform angular analysis of $B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$ } Longer-term plans

Analysis strategy

- The branching ratio (BR) can be computed experimentally as

$$\mathscr{B}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-) = \frac{N_{observed}}{\epsilon \times \mathscr{L} \times \sigma_{B-prod}}$$

$N_{observed}$: measured yield

ϵ : detection efficiency

$\mathscr{L}$: integrated luminosity

σ_{B-prod} : $B^{\pm}$ production cross section

but $\mathscr{L}$ and σ_{B-prod} are not known with high precision at the LHC

→ In practice, better to measure with respect to a normalisation channel with a well-known BR

Analysis strategy

- Measure $\mathscr{B}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-)$ with

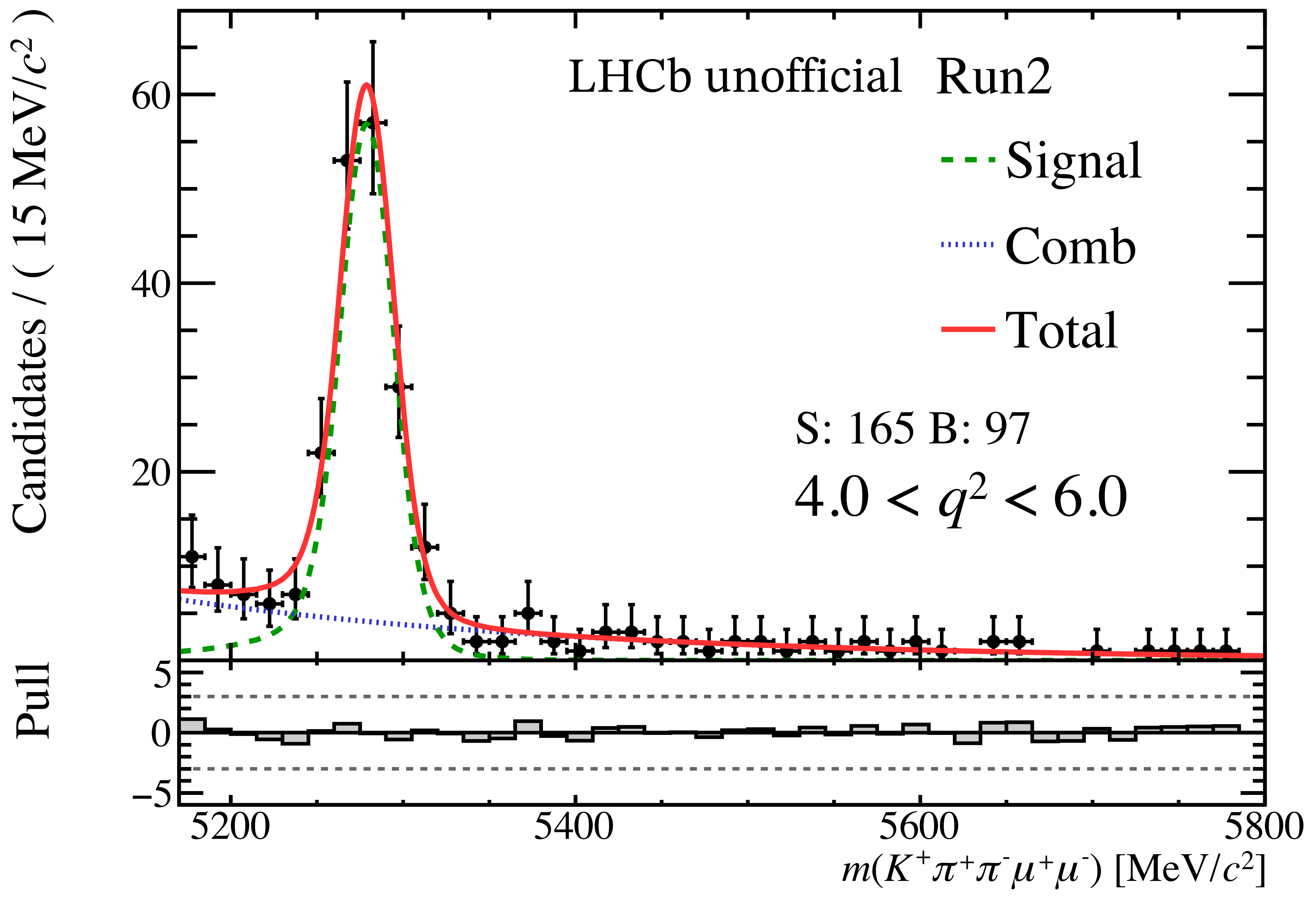
$$\mathscr{B}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-) = \mathscr{B}(normalisation) \times \frac{\sum_i^{N_{K\pi\pi\mu\mu}} \frac{s^i_{K\pi\pi\mu\mu}}{\epsilon^i_{K\pi\pi\mu\mu}}}{\sum_i^{N_{norm}} \frac{s^i_{norm}}{\epsilon^i_{norm}}}$$

$B^+ \to K^+\psi(2S)(\to \pi^+\pi^- J/\psi(\to \mu^+\mu^-))$

in the following bins:

q^2 [GeV^2]	0.1 — 0.98	1.1 — 2.5	2.5 — 4.0	4.0 — 6.0	6.0 — 8.0	11.0 — 12.5	15.0 —19.0

Analysis strategy



- Measure $\mathscr{B}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-)$ with

Weights from fits to data

$$\mathscr{B}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-) = \mathscr{B}(normalisation) \times \frac{\sum_i^{N_{K\pi\pi\mu\mu}} \frac{s^i_{K\pi\pi\mu\mu}}{\epsilon^i_{K\pi\pi\mu\mu}}}{\sum_i^{N_{norm}} \frac{s^i_{norm}}{\epsilon^i_{norm}}}$$

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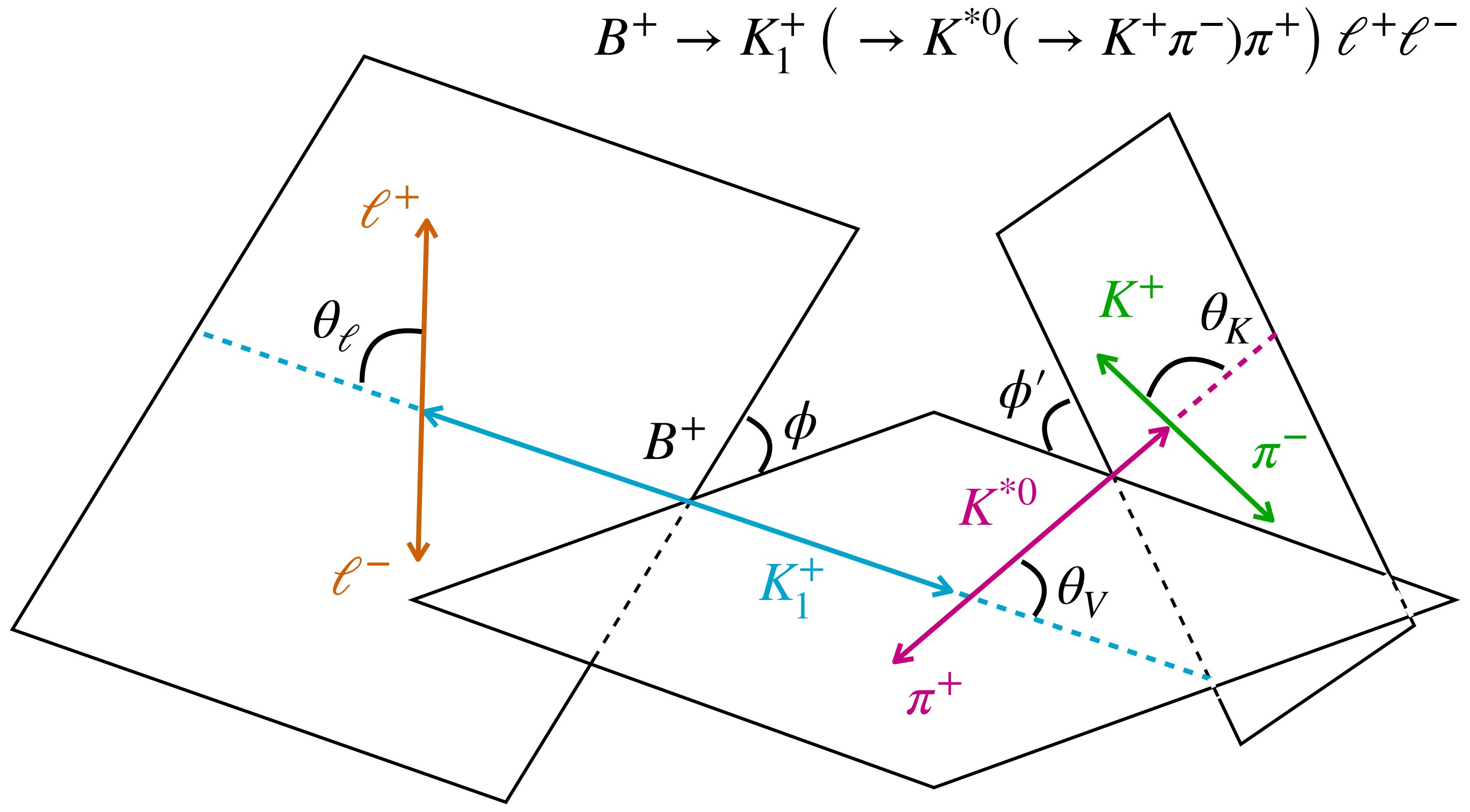
Analysis strategy



$\{\cos\theta_K, \cos\theta_L, \cos\theta_V, \phi, m^2(\pi\pi), m^2(\pi K), m(K\pi\pi), q^2\}$

- Measure $\mathscr{B}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-)$ with

Efficiencies parametrised in terms of phase space and decay angles

$$\mathscr{B}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-) = \mathscr{B}(normalisation) \times \frac{\sum_i^{N_{K\pi\pi\mu\mu}} \frac{s^i_{K\pi\pi\mu\mu}}{\epsilon^i_{K\pi\pi\mu\mu}}}{\sum_i^{N_{norm}} \frac{s^i_{norm}}{\epsilon^i_{norm}}}$$

$B^+ \to K^+\psi(2S)(\to \pi^+\pi^- J/\psi(\to \mu^+\mu^-))$

in the following bins:

q^2 [GeV^2]	0.1 — 0.98	1.1 — 2.5	2.5 — 4.0	4.0 — 6.0	6.0 — 8.0	11.0 — 12.5	15.0 —19.0

Analysis strategy

- Measure $\mathcal{B}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-)$ with

$$\mathcal{B}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-) = \mathcal{B}(normalisation) \times \frac{\sum_i^{N_{K\pi\pi\mu\mu}} \frac{s^i_{K\pi\pi\mu\mu}}{\epsilon^i_{K\pi\pi\mu\mu}}}{\sum_i^{N_{norm}} \frac{s^i_{norm}}{\epsilon^i_{norm}}}$$

$B^+ \to K^+\psi(2S)(\to \pi^+\pi^- J/\psi(\to \mu^+\mu^-))$

in the following bins:

							Blinded
q^2 [GeV^2]	0.1 — 0.98	1.1 — 2.5	2.5 — 4.0	4.0 — 6.0	6.0 — 8.0	11.0 — 12.5	

Analysis overview

Trigger & preselection

Multivariate selection

Corrections to simulation

Fits to $B-$mass

Modelling of efficiency in terms of phase space

Trigger & preselection

Trigger & preselection

Multivariate selection

Corrections to simulation

Fits to $B-$mass

Modelling of efficiency in terms of phase space

Due to the messy hadron collider environment, the reconstructed data from LHCb is largely dominated by random combinations of tracks. **Effective background suppression and signal selection are required.**

- **Trigger:** select events with at least one high-p_T muon
- **Preselection**: apply cuts on the track quality, particle identification, and kinematics of the signal candidates

Multivariate selection

Trigger & preselection

Multivariate selection

Corrections to simulation

Fits to $B-$mass

Modelling of efficiency in terms of phase space

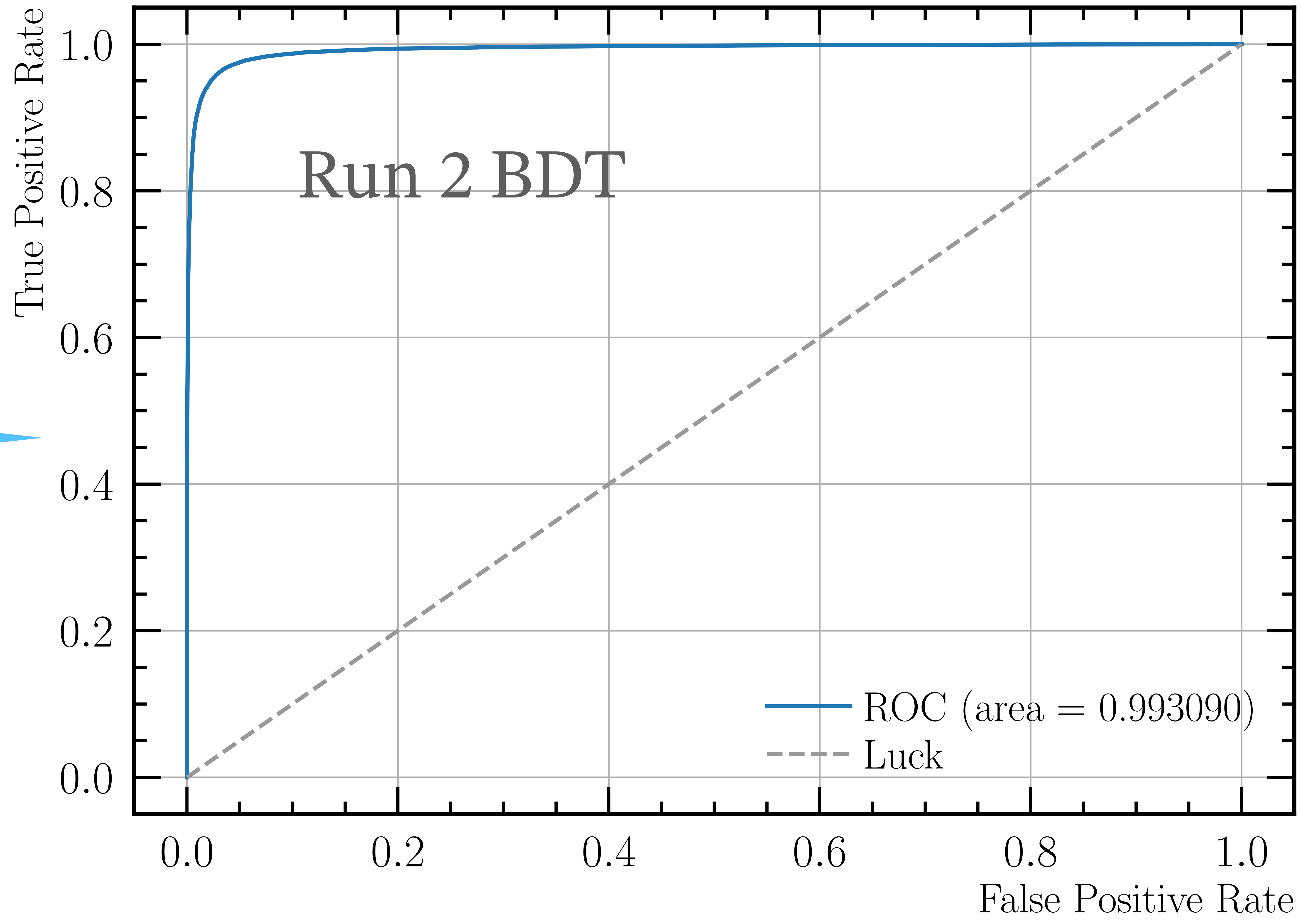
Cut-based preselection works as a first-stage data cleanup, but better results are achieved with the help of **machine learning**.

- **Train** Boosted Decision Trees (BDTs) to distinguish signal from background
  - Vertex quality and kinematic variables as BDT features
  - Separate BDTs trained for Run1, Run2 and the high-q^2
  - Simulation as signal proxy, data sideband at $M_B > 5450$ MeV and $1.1 < q^2 < 7$ GeV^2 ($15 < q^2 < 19$ for high-q^2 BDTs) as background proxy
- **Optimise** the selection by finding the cut on BDT response that maximises the signal significance $S/\sqrt{S+B}$

Multivariate selection

Performance

AUC > 0.99 for all classifiers



MC corrections

Trigger & preselection

Multivariate selection

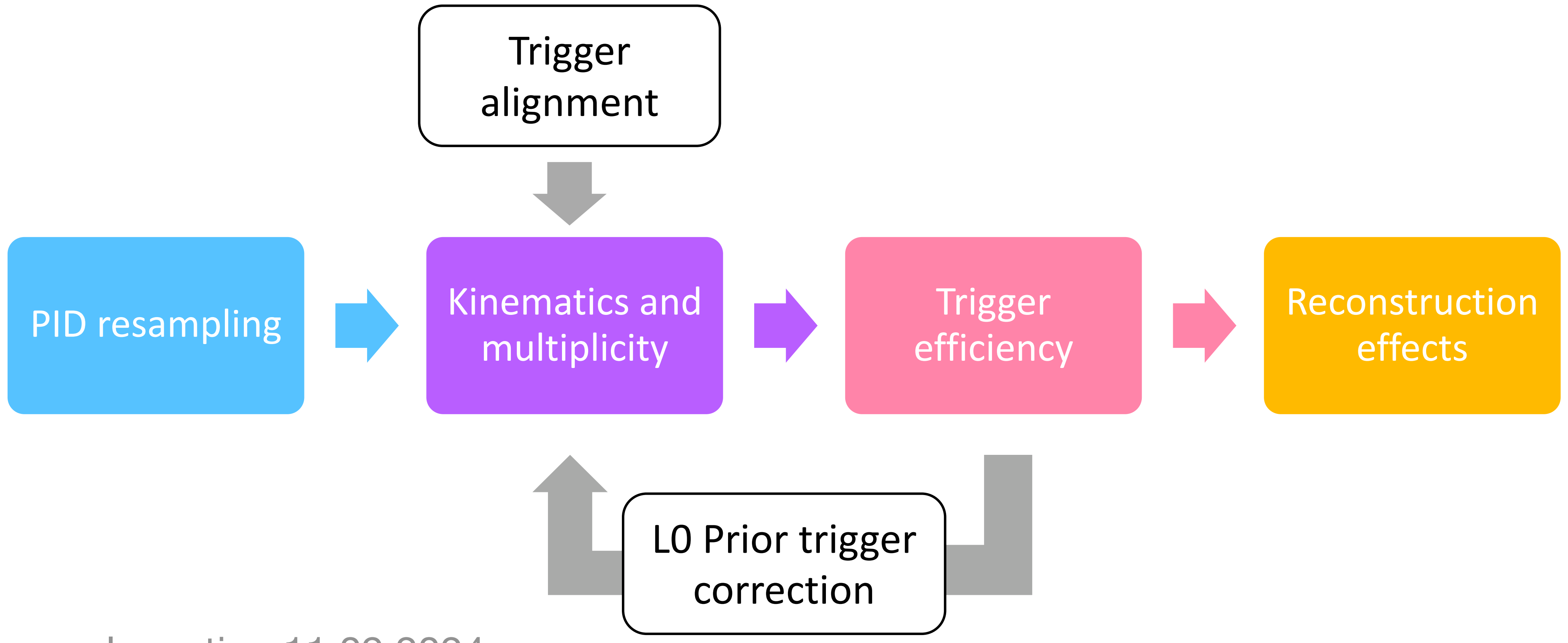
Corrections to simulation

Fits to $B-$mass

Modelling of efficiency in terms of phase space

Modelling of the pp collision, B-production and detector response in the simulation is imperfect → **apply a chain of statistical corrections to mitigate the data-simulation discrepancies**

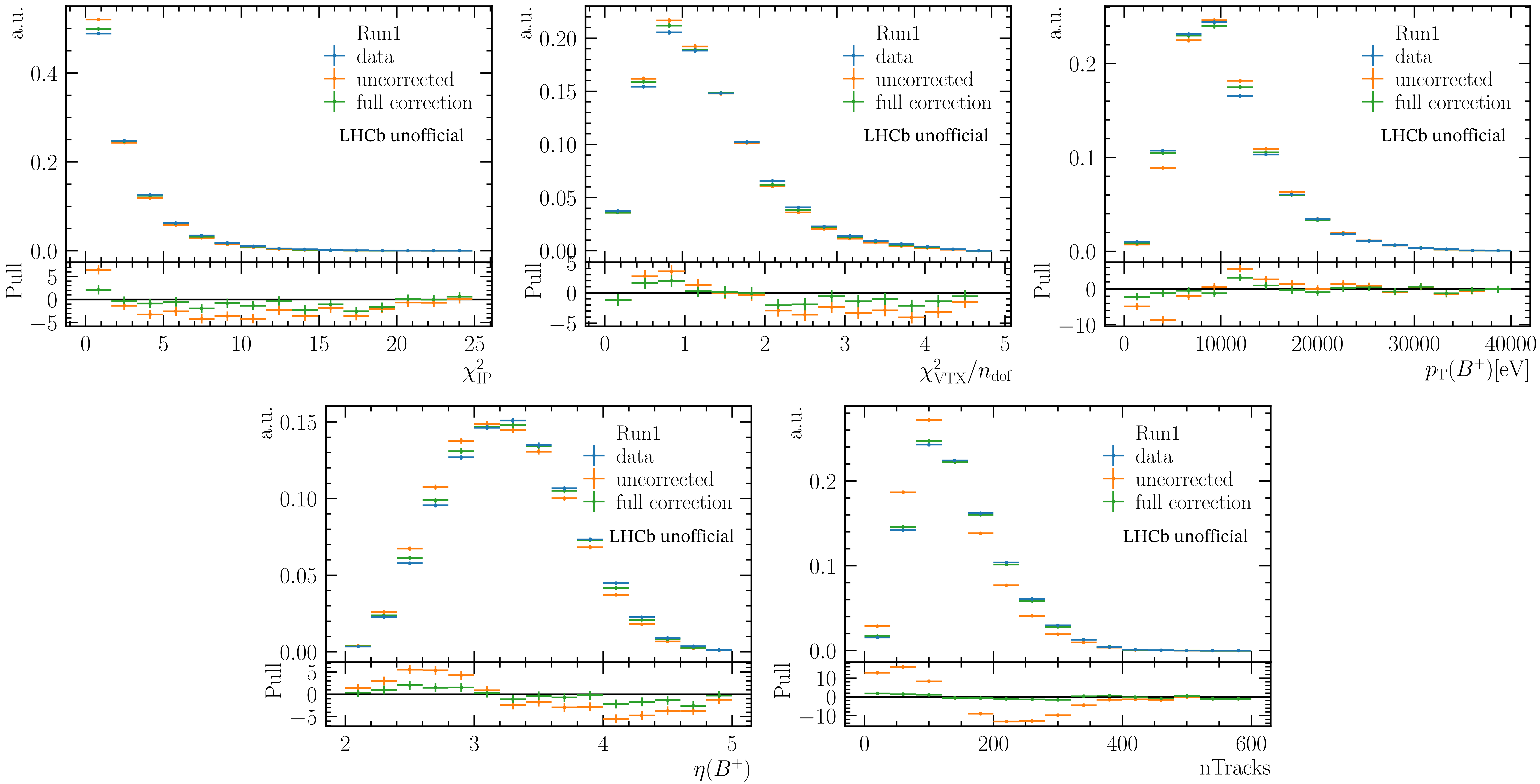
- **PID:** Resample particle identification response using pre-made calibration maps
- **Kin-mult:** Reweight the samples on kinematics and multiplicity variables using **Gradient Boosted Reweighter** (GBR) algorithm
- **Trigger:** Correct trigger efficiency using weights obtained by comparing trigger efficiencies in simulation and data
- **Reco:** Mitigate residual reconstruction effects by applying GBR on vertex quality and impact parameter



MC corrections

Total correction results - Run1

Tested on
$B^+ \to K^+\pi^+\pi^- J/\psi(\to \mu^+\mu^-)$
resonant mode



Fits

Trigger & preselection

Multivariate selection

Corrections to simulation

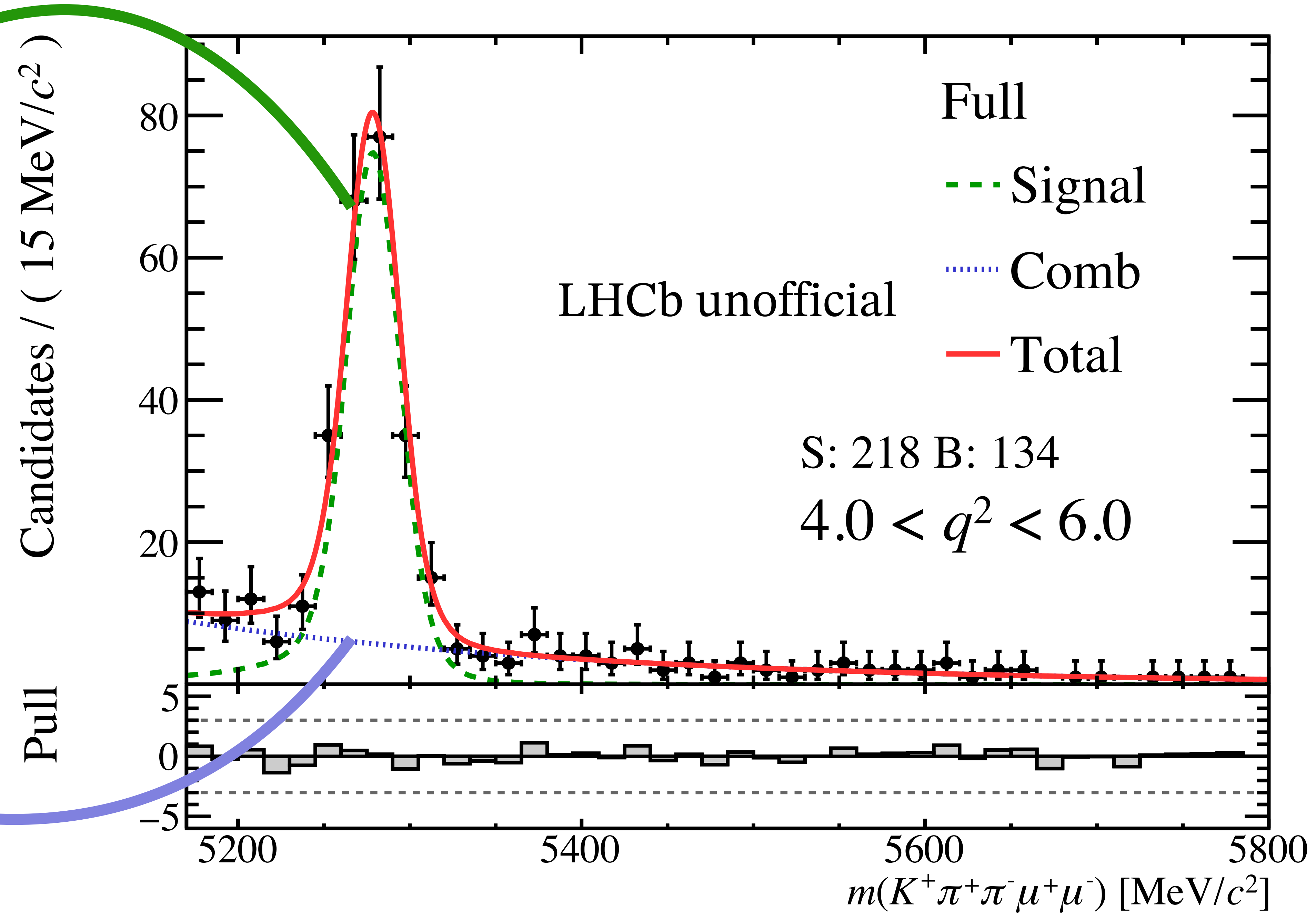
Fits to $B-$mass

Modelling of efficiency in terms of phase space

Fit to the rare mode B-mass distribution in **each q^2 bin**

Signal model: Double Crystal Ball

Background model: Exponential



- Signal shape parameters fixed from fits to simulation
- Signal model to rare mode data includes a **scale** and a **shift** parameter, fixed from $B^+ \to K^+\pi^+\pi^- J/\psi(\to \mu^+\mu^-)$ fits, to allow for data-MC differences

Fits range restricted to $M_{K\pi\pi\mu\mu} \in [5170,5800]$ to prevent leakage of partially reconstructed B decays into the fit region

Efficiency

Trigger & preselection

Multivariate selection

Corrections to simulation

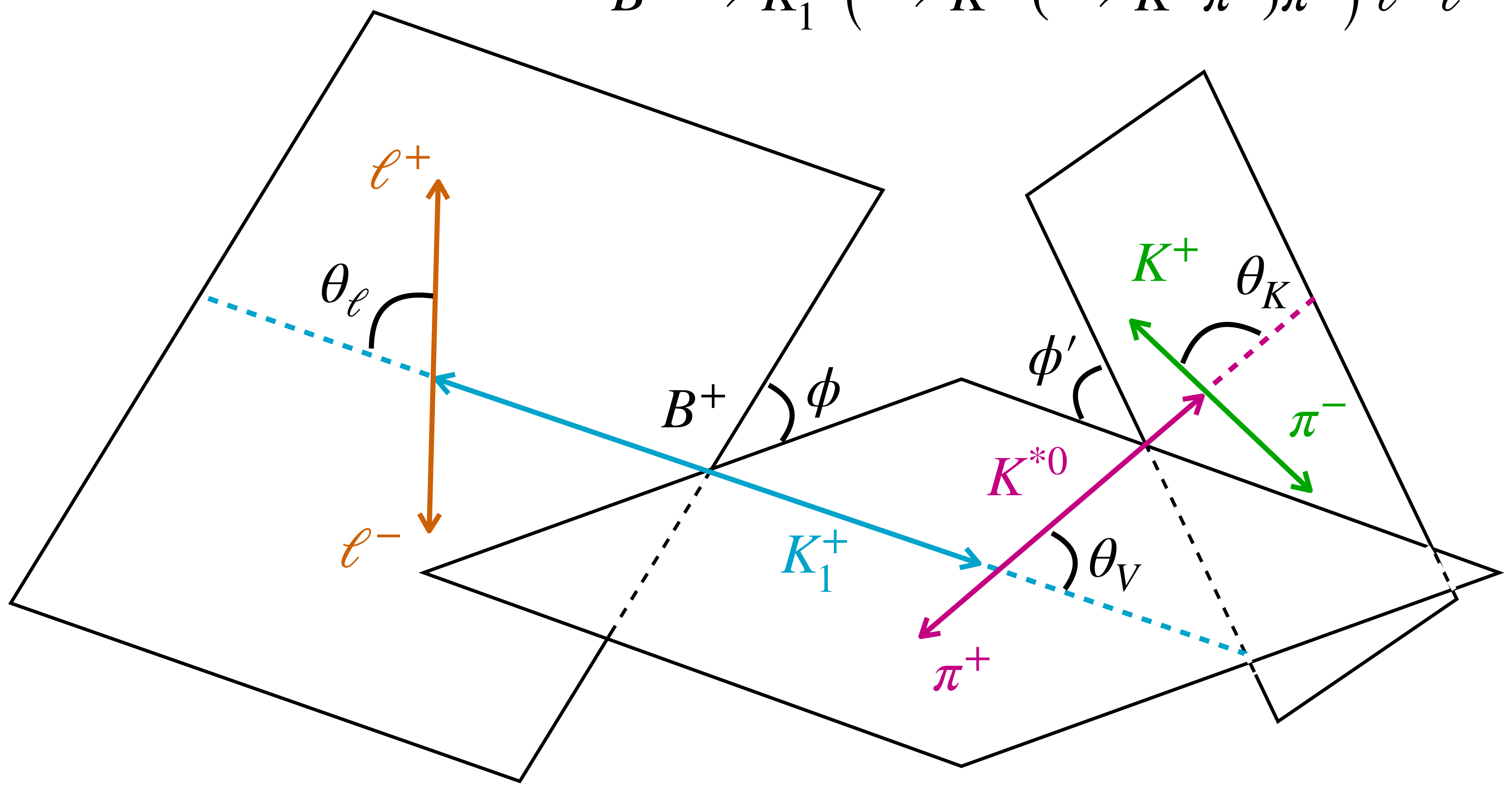
Fits to $B-$mass

Modelling of efficiency in terms of phase space

Parametrise the total efficiency in terms of $\cos\theta_K, \cos\theta_L, \cos\theta_V, \phi, m^2(\pi\pi), m^2(\pi K), m(K\pi\pi), q^2$

- Compute the branching ratios using the weights from fits and the per-event efficiencies

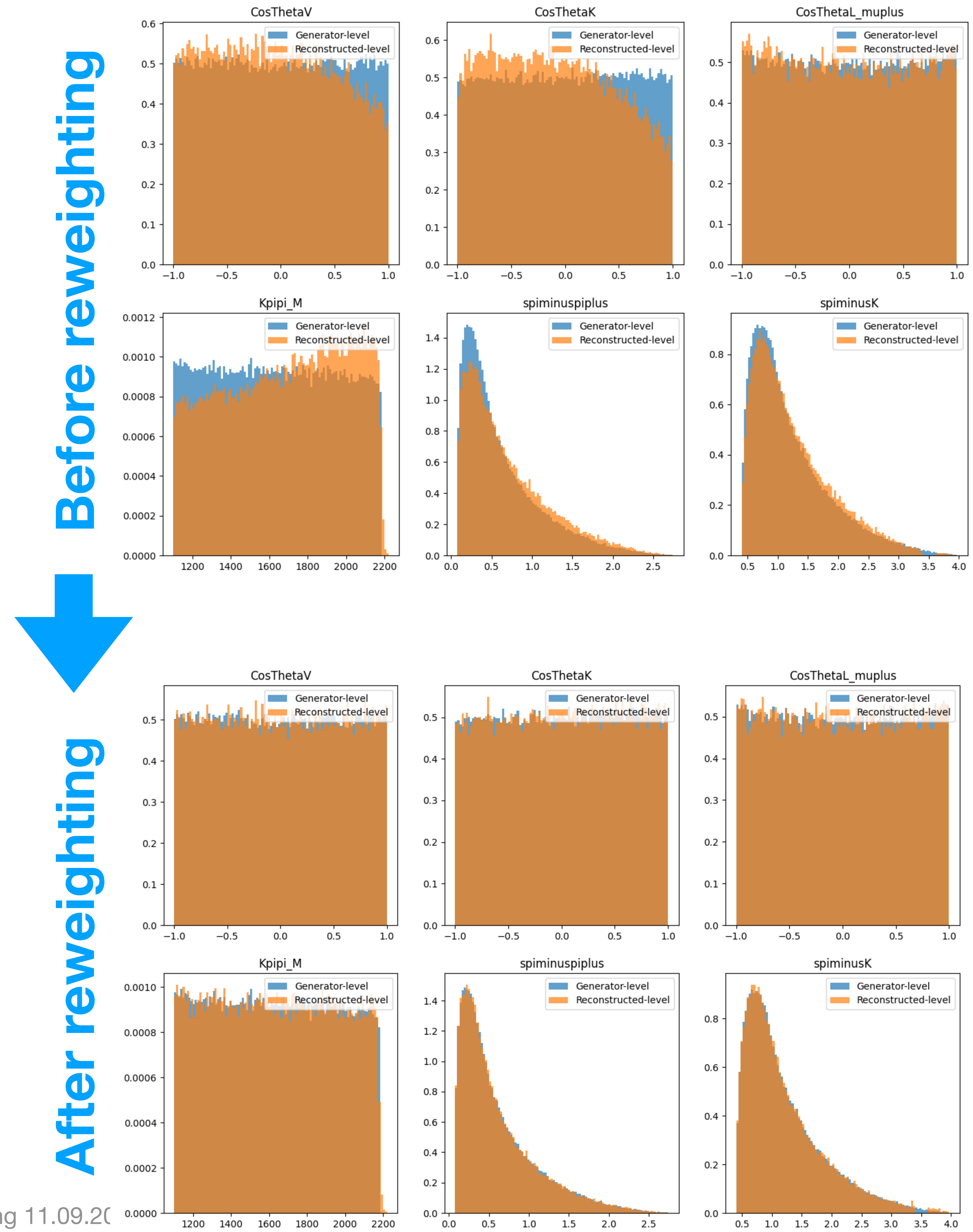
$B^+ \to K_1^+ \left(\to K^{*0}(\to K^+\pi^-)\pi^+ \right) \ell^+\ell^-$



Efficiency

With Gradient Boosted Reweighters

- Try a machine learning approach to the multi-dimensional task:
    - Train a GBR on generator-level and reconstructed, selected MC, using the degrees of freedom as training features
    - Use the obtained weights, normalised to total efficiency, as the per-event efficiencies
- Good results obtained with 6D&7D so far



Summary and outlook

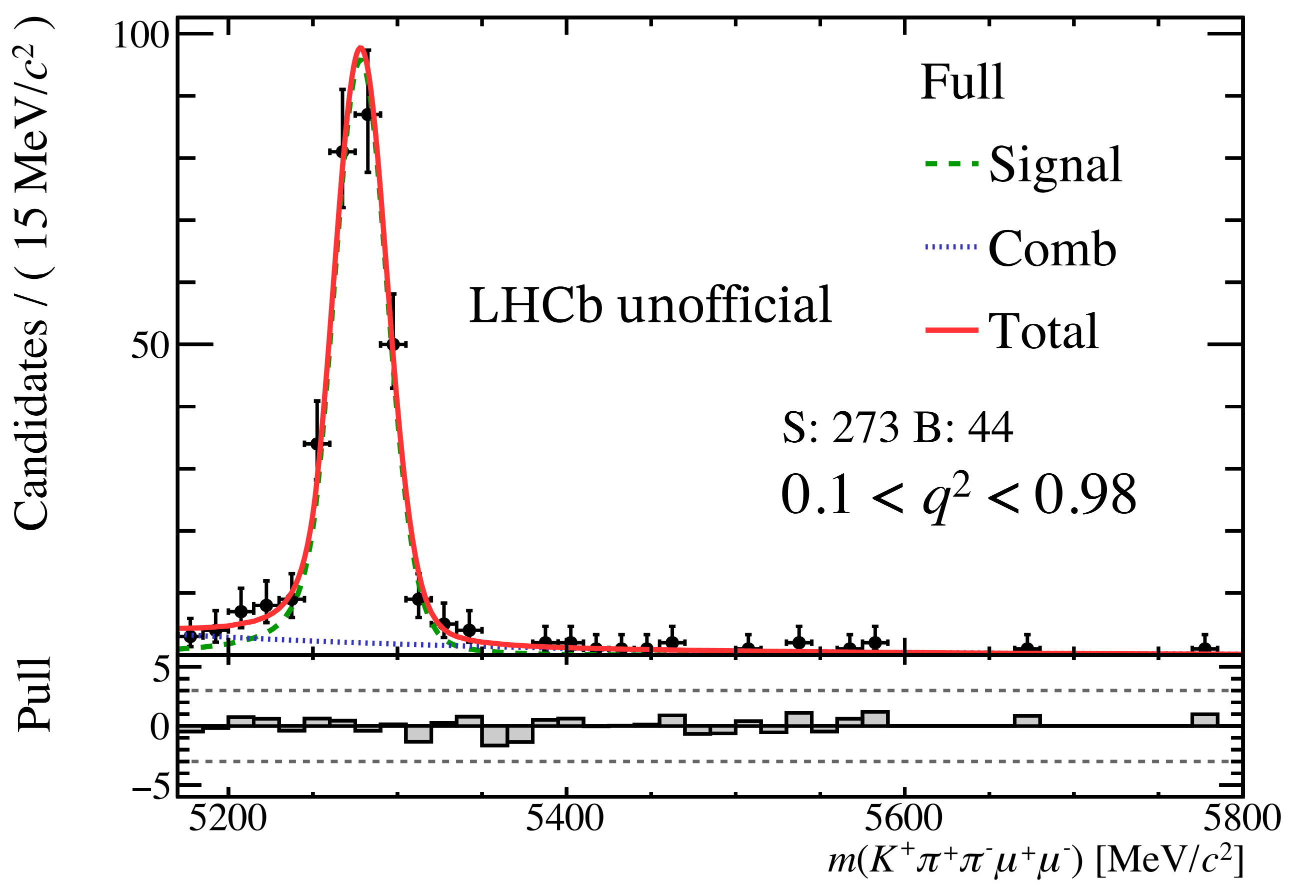
- Precision tests of rare decays involving $b \to s\ell\ell$ transitions can be used to indirectly search for new physics
- Ongoing measurement aims to improve the precision of $\mathscr{B}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-)$, and provide a measurement of the branching ratio in the high-q^2region
  - Analysis is moving towards completion, the missing links at the moment are the finalisation of the efficiency model and the measurement of the normalisation channel
- Longer-term plans include studying the previously unexplored angular structure and CP-violation of the $B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$ channel

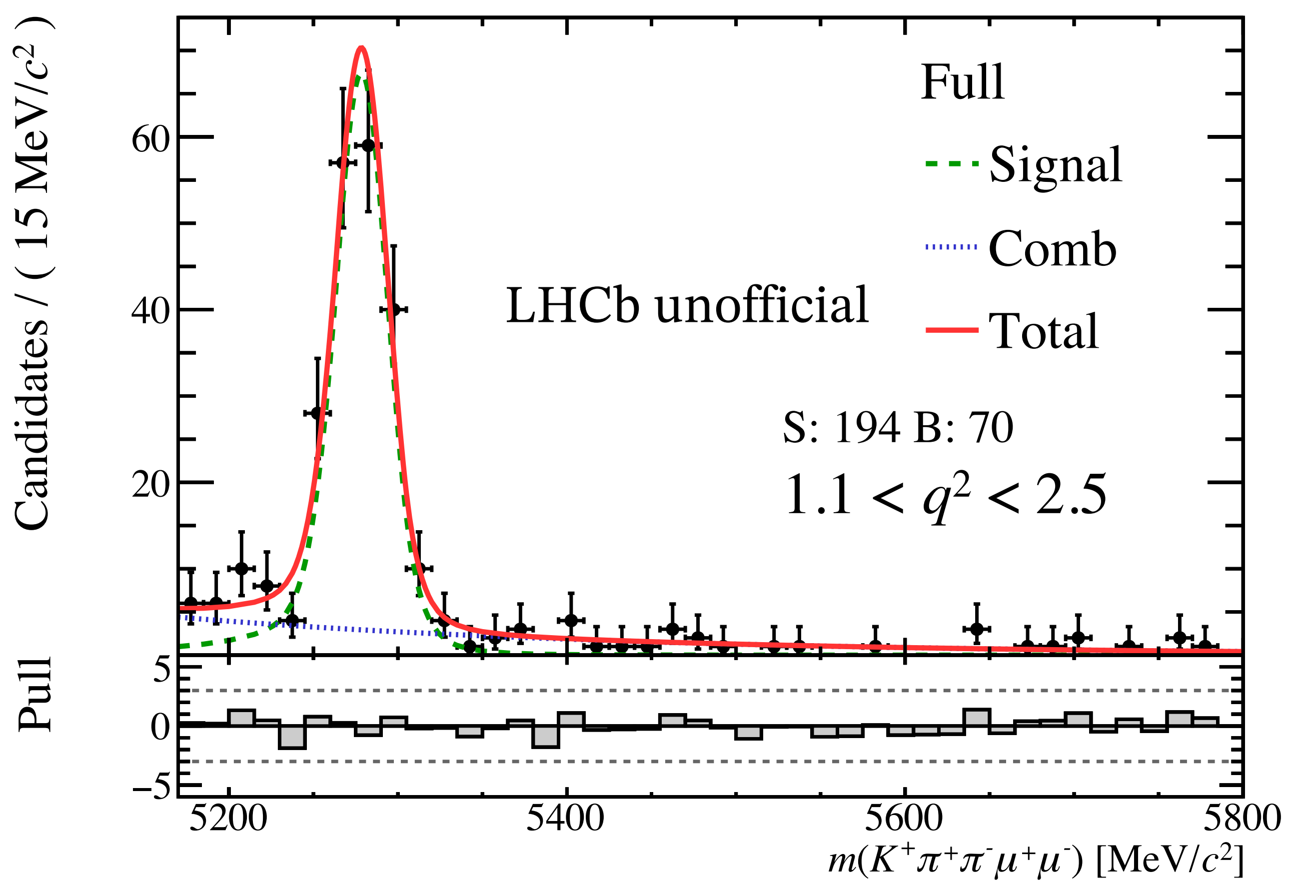
Thank you for you attention!

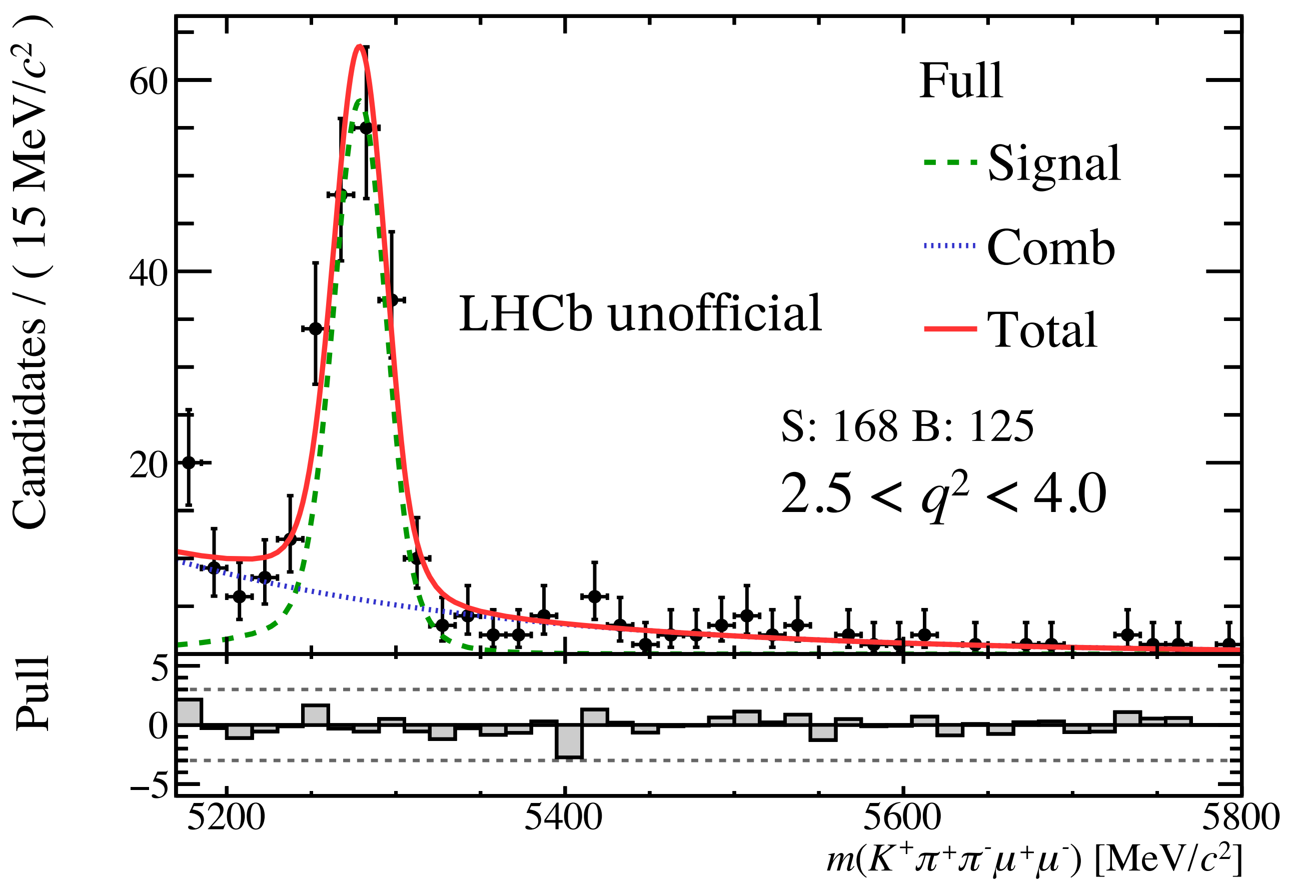
Backup

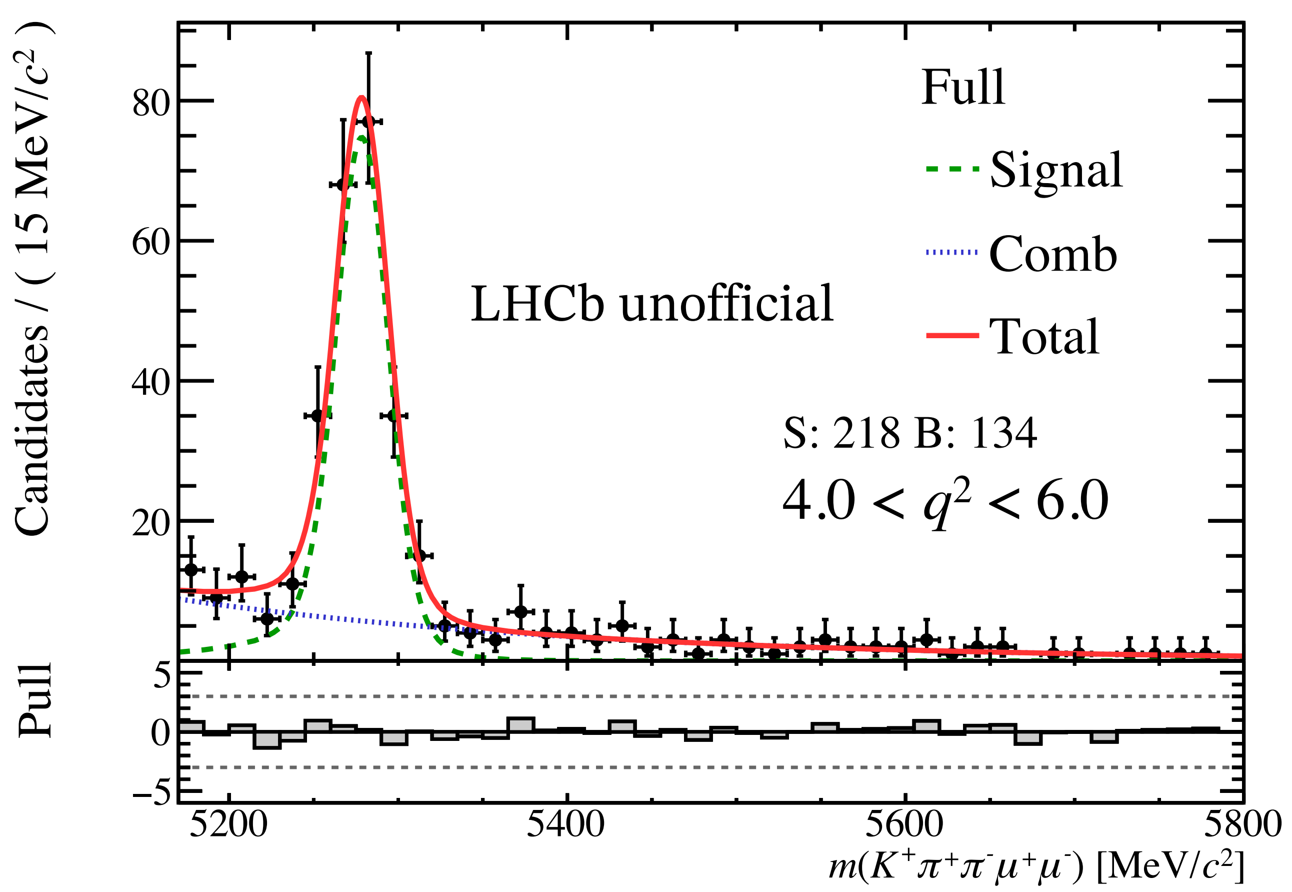
Fits

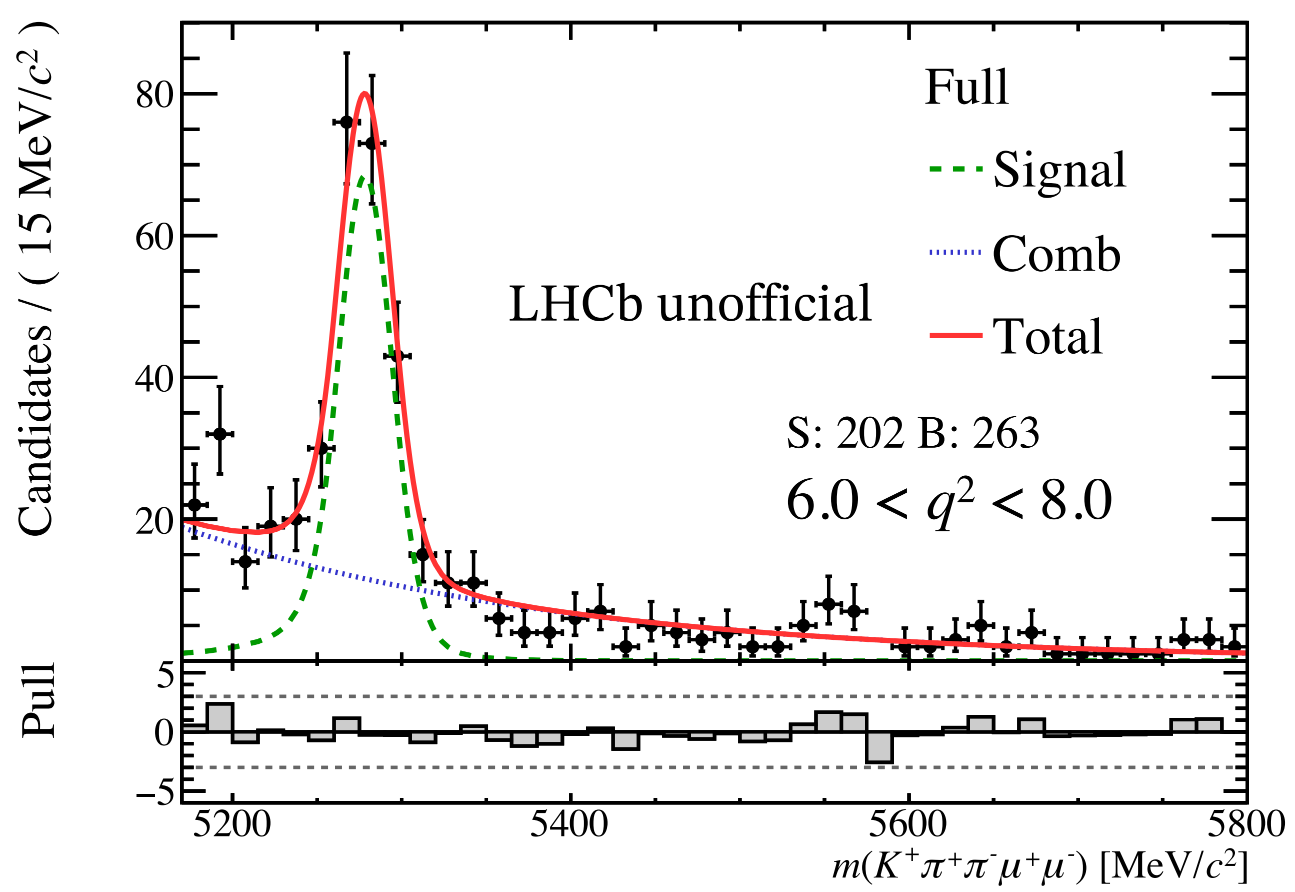
Results

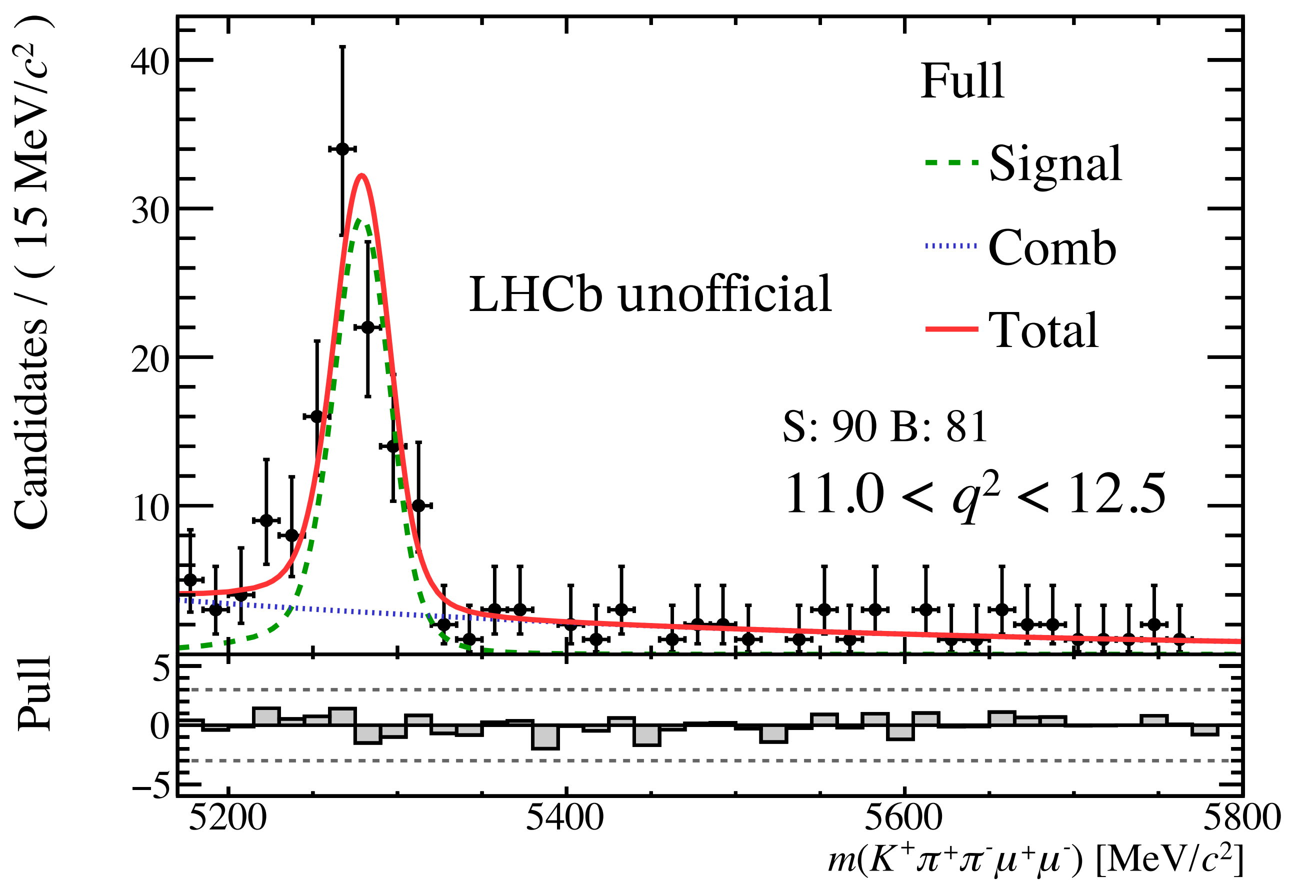


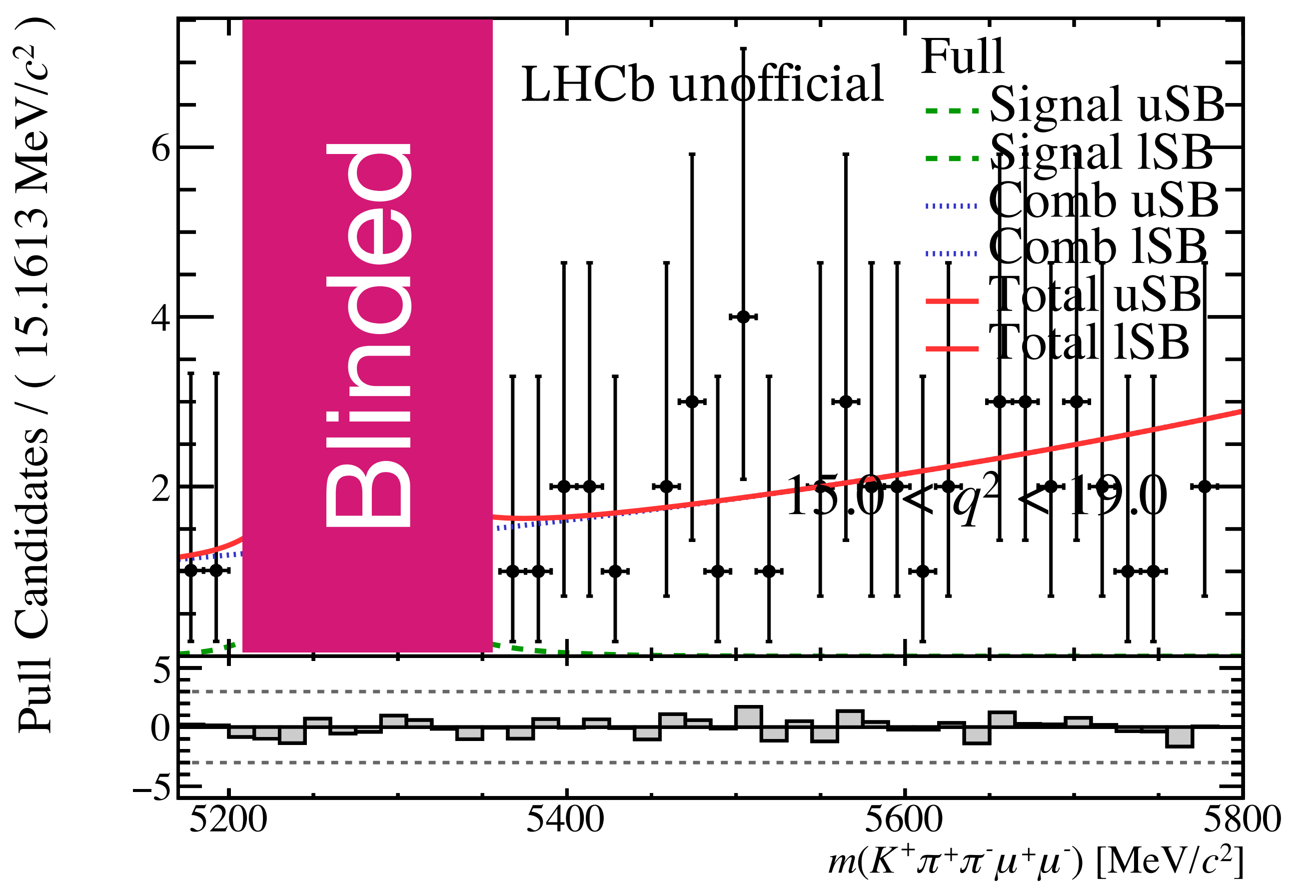












Run 1 + Run 2

nua

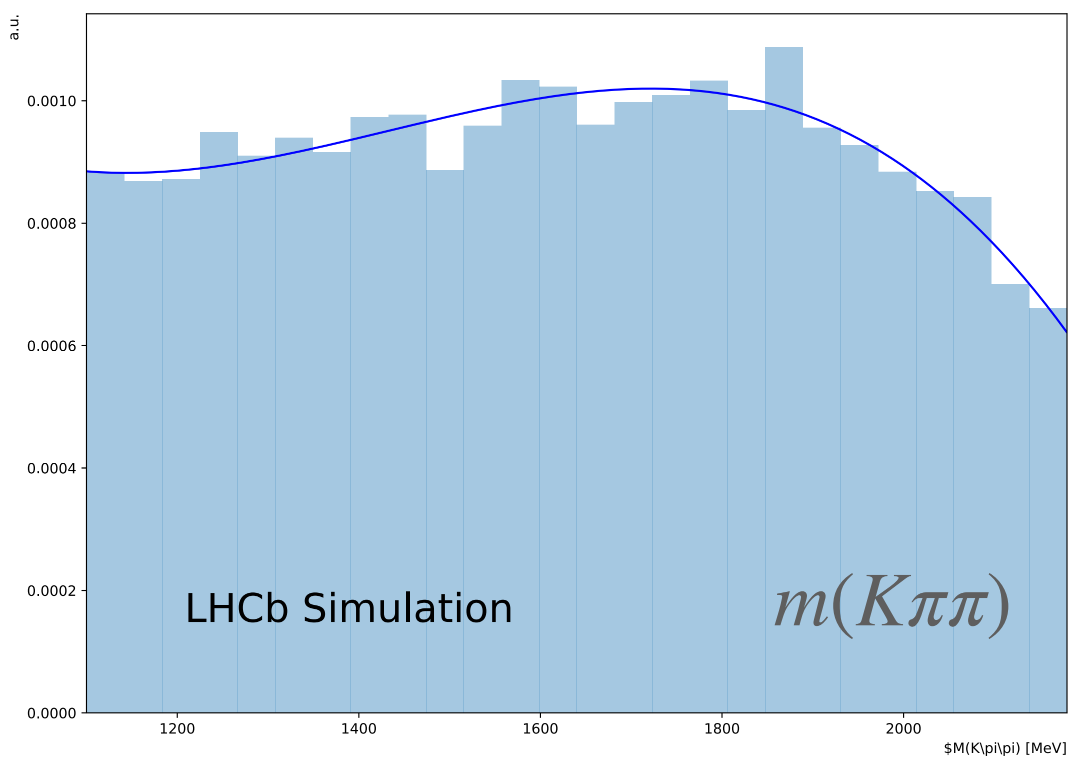
Efficiency

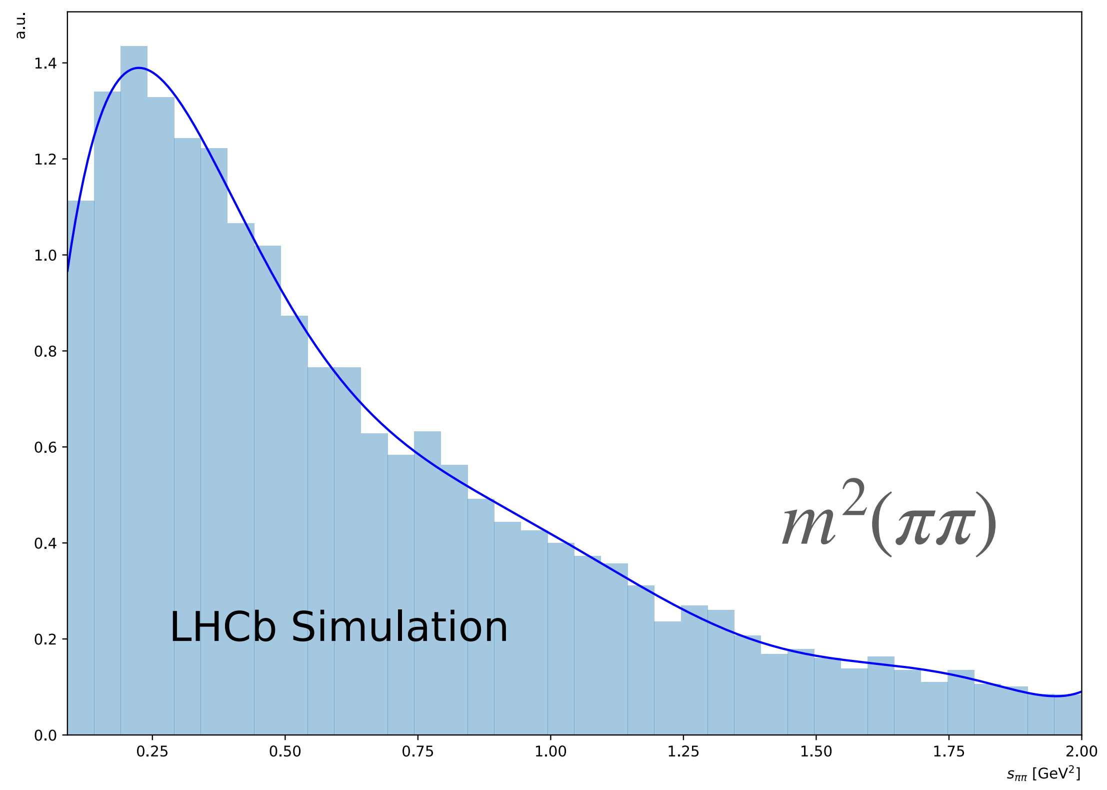
With Legendre polynomials

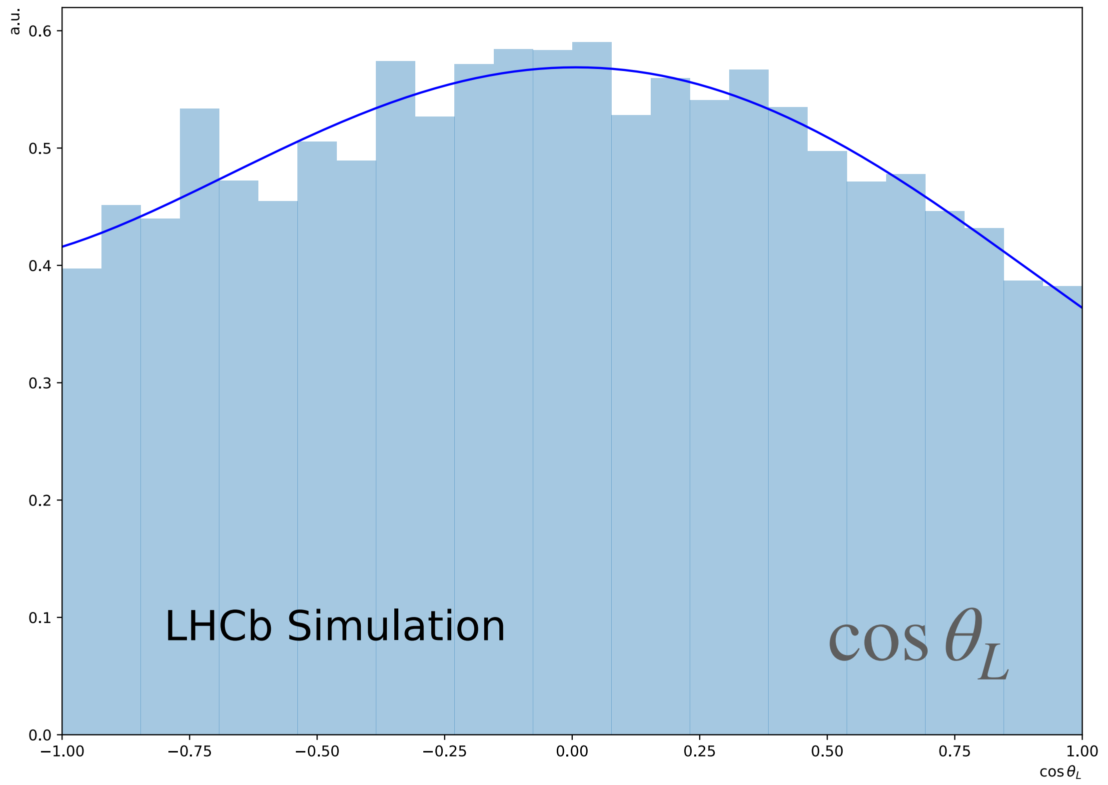
- Use Legendre polynomials to model the efficiency in terms of the Dalitz masses and decay angles
  - Fit the polynomials to both generator-level and reconstructed, selected MC
- Fitting in 8D is computationally very intensive, requires > 500GB RAM

➡ Not technically feasible

  - Cannot factorise due to correlations between the variables







$$\{v\} = \{\cos\theta_K, \cos\theta_L, \cos\theta_V, \phi, m^2(\pi\pi), m^2(\pi K), m(K\pi\pi), q^2\}$$

$$\epsilon(\{v\}) = \sum_{i_1, i_2, \ldots, i_8} c_{i_1 i_2 \ldots i_8} \prod_{j=1}^{8} L_{i_j}(v_j)$$

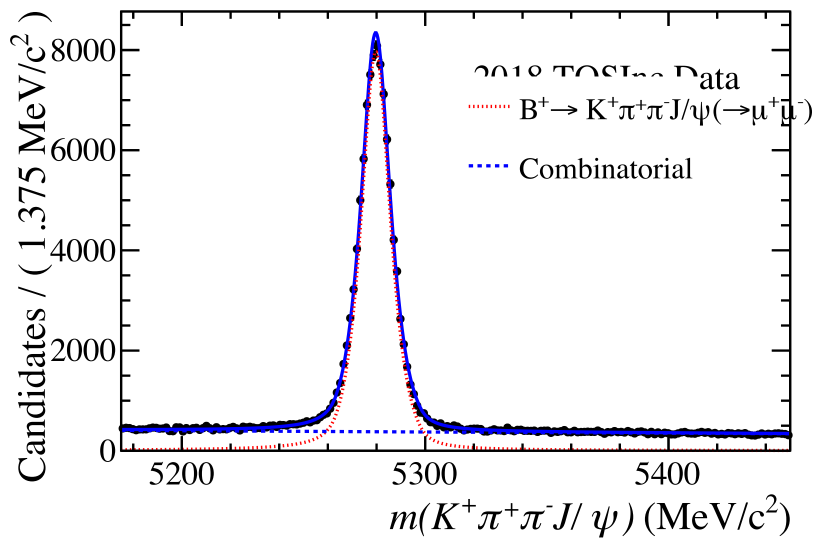
Legendre polynomials

Multivariate selection

Cut optimisation

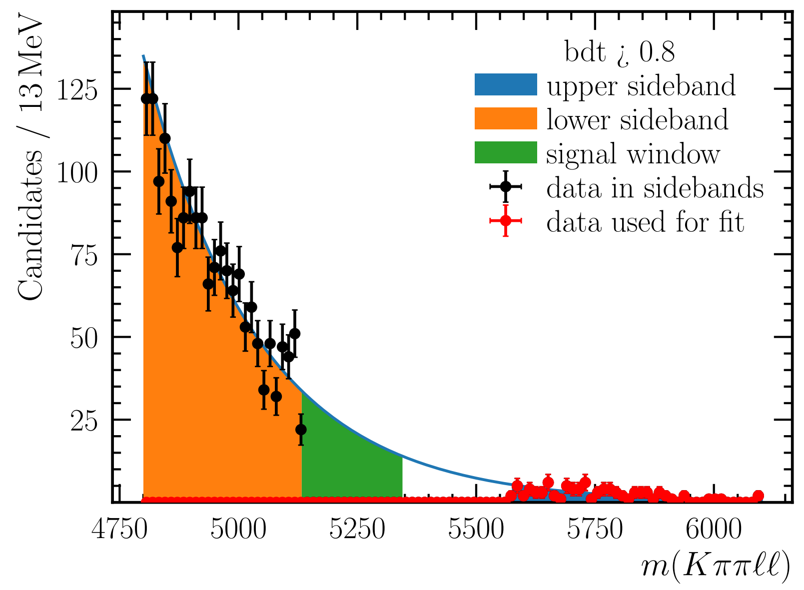
Signal estimated as

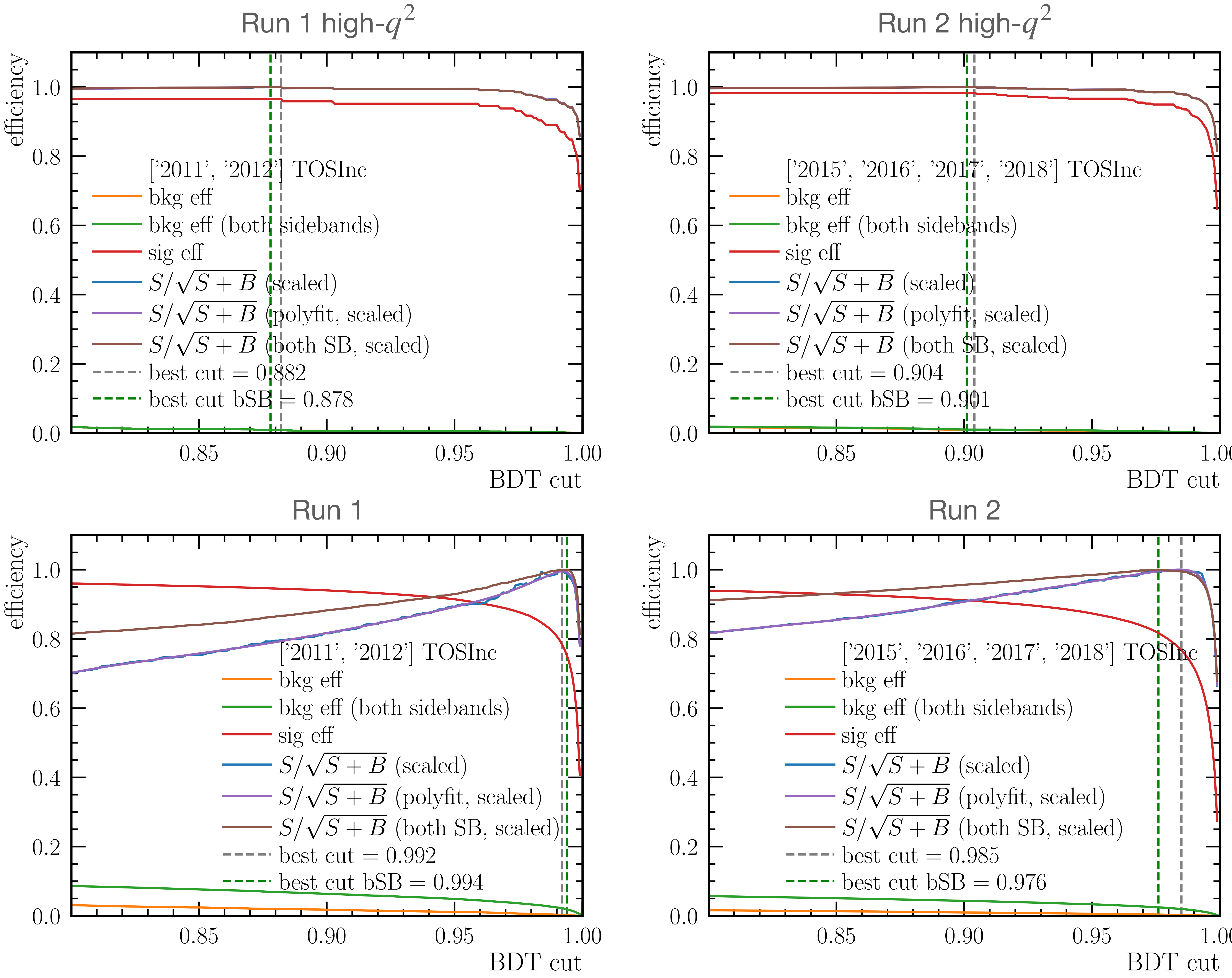
$$S = N_{reso} \times \frac{\epsilon_{rare}}{\epsilon_{reso}} \times \frac{\mathcal{B}_{rare}}{\mathcal{B}_{reso}} \times \epsilon_{BDT}$$



where N_{reso} is from a fit to J/ψ

Background estimated from fits to rare mode sideband(s)





Choice of normalisation channel

- Three options
  - $B^+ \to K^+\pi^+\pi^- J/\psi(\to \mu^+\mu^-)$
    - $\mathscr{B} \approx 5 \times 10^{-5}$
    - High statistics, but large discrepancies in BR value
  - $B^+ \to K^+\pi^+\pi^- \psi(2S)(\to \mu^+\mu^-)$
    - $\mathscr{B} \approx 3 \times 10^{-6}$
    - Previous BR measurements more consistent, but less statistics in our samples
  - $B^+ \to K^+\psi(2S)(\to \pi^+\pi^- J/\psi(\to \mu^+\mu^-))$
    - $\mathscr{B} \approx 1 \times 10^{-5}$
    - Cannot use the same efficiency model due to different decay topology

$\Gamma(\ B^+ \to J/\psi(1S)K^+\pi^+\pi^-\ )/\Gamma_{total}$

VALUE (10^{-3})	
0.81 ± 0.13	OUR AVERAGE Error
$0.716 \pm 0.010 \pm 0.060$	Belle
$1.16 \pm 0.07 \pm 0.09$	BaBar
$0.69 \pm 0.18 \pm 0.12$	
$(139 \pm 81 \pm 1) \times 10^{-2}$	
$(139 \pm 91 \pm 1) \times 10^{-2}$	