Binned $B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}$ Charge-Parity Asymmetry Measurement

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Background: The $B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}$ Decay

- $B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}$ is an electroweak penguin.
- A flavour changing neutral current (FCNC)
- Can only occur through a loop diagram, greatly is suppressed in the standard model (SM).
- Highly sensitive to New Physics (NP) contributions.
- **Can also proceed through** an intermediate vector meson, mainly $c\bar{c}$ **mesons**.
  - Much higher branching fractions, tree level decay.
  - ~ 130 larger for J/ψ intermediate meson.

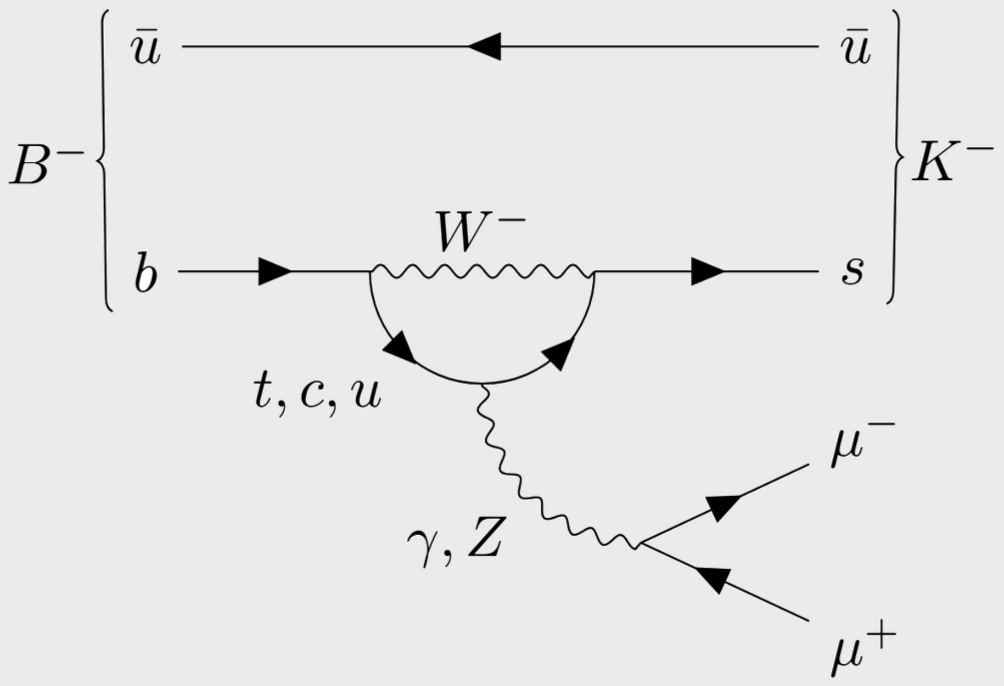


Diagram of $B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}$, top quark diagram dominates

Background: CPV in the $B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}$ Decay

- Charged meson decay, **only** subject to **direct CP-violation** (CPV).

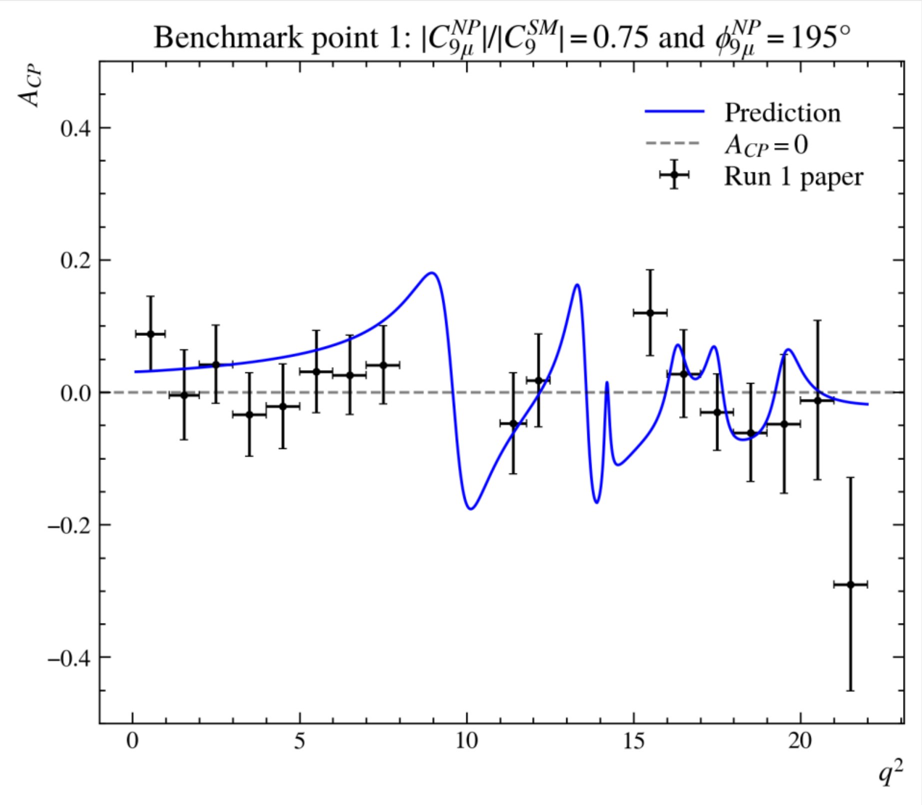
$$A_{CP} = \frac{\Gamma(B^{-} \to K^{-}\mu^{+}\mu^{-}) - \Gamma(B^{+} \to K^{+}\mu^{+}\mu^{-})}{\Gamma(B^{-} \to K^{-}\mu^{+}\mu^{-}) + \Gamma(B^{+} \to K^{+}\mu^{+}\mu^{-})}$$

- In the **SM, A_{CP} predicted to be negligible**.

- Influence of **CP-violating new physics (NP) could induce CPV**.
- Requires interference with a **CP-conserving phase.**
  - In this decay $\to$ charmonium resonances.
  - CPV **enhanced near** the $c\bar{c}$, mainly J/ψ and $\psi(2s)$.
  - Exactly zero at the resonance.
- CPV would vary as a function of $m_{\mu\mu}$.
  - Analysis binned in $m_{\mu\mu}^{2}$ (q^{2})
- In the effective Hamiltonian framework CPV probes the complex component of the Wilson coefficients.

Motivation for the Analysis

- **Significant CPV** in this decay
  - **Evidence of NP**.
- **Lack of CPV**
  - Set strong(er) **constraints** on **complex part** of **Wilson coefficients**.
- Previous LHCb measurement (run 1) found no evidence of CPV [1].
- Aim for **combined run 1, run 2 and run 3** measurement, **increase the precision**.
  - Run 3 data considered will be 2024 and 2025.
- Intend to get closer to the resonant peaks.
  - Excluded in the run 1 analysis.



Replica of the plot from [2]. The data shown is that from [1].

[1] The LHCb collaboration, Aaij, R. et al. , "Measurement of CP asymmetries in the decays B 0 → K *0 μ + μ − and B + → K + μ + μ − " (2014) https://doi.org/10.1007/JHEP09(2014)177.

[2] R. Fleischer et al., "Fingerprinting CP-violating New Physics with B → Kμ+μ−" (2023), https://doi.org/10.1007/JHEP03%282023%29113.

Analysis Overview

- **Binning** similar to **run 1 analysis** plus two extra **bins around** J/ψ peak.
- **BDT** used to **discriminate** the **combinatorial** background from the **signal** mode.

- Asymmetry seen in data is the **"raw" asymmetry**:

$$A_{raw}(B^\pm \to K^\pm \mu^+\mu^-) = \frac{Y(B^- \to K^-\mu^+\mu^-) - Y(B^+ \to K^+\mu^+\mu^-)}{Y(B^- \to K^-\mu^+\mu^-) + Y(B^+ \to K^+\mu^+\mu^-)}$$

- Need to correct for the **asymmetry in** the **production of** $\boldsymbol{B}$ mesons **and** the **detection efficiencies.**

$$A_{CP}(B^\pm \to K^\pm \mu^+\mu^-) = A_{raw}(B^\pm \to K^\pm \mu^+\mu^-) - A_P - A_D$$

- Will **utilise** $B^\pm \to (J/\psi \to \mu^+\mu^-)K^\pm$ (**control mode**) to estimate A_P and A_D.
- **Split data by charge, fit** run 1 + run 2 + run 3 **simultaneously** to extract A_{CP}.
- **Total** $\boldsymbol{A_{CP}}$ computed through a **weighted sum** over each run (r) and q^2 bin (i):

$$A_{CP} = \frac{\sum_{r,i} \left(S_{r,i}\, A_{CP_i}\right)/\epsilon_{r,i}}{\sum_{r,i} S_{r,i}/\epsilon_{r,i}}$$ where S is the signal yield and ϵ the efficiency

q^2 [GeV^2/c^4]
$0.1 < q^2 < 0.98$
$1.1 < q^2 < 2$
$2.0 < q^2 < 3.0$
$3.0 < q^2 < 4.0$
$4.0 < q^2 < 5.0$
$5.0 < q^2 < 6.0$
$6.0 < q^2 < 7.0$
$7.0 < q^2 < 8.0$
$8.0 < q^2 < 8.8$
$10.0 < q^2 < 11.0$
$11.0 < q^2 < 11.8$
$11.8 < q^2 < 12.5$
$15.0 < q^2 < 16.0$
$16.0 < q^2 < 17.0$
$17.0 < q^2 < 18.0$
$18.0 < q^2 < 19.0$
$19.0 < q^2 < 20.0$
$20.0 < q^2 < 22.0$

Production and Detection Asymmetries

- **Control mode used** to estimate A_P and A_D.
- **Not** use **a single value** for all bins.
  - Reweight the control data to the signal on each bin.
  - The $\boldsymbol{A_{raw}}$ of the reweighted control data provides an estimate of $A_P^{q^2} + A_D^{q^2}$ (or $A_{PD}^{q^2}$).
- The individual steps are outlined in this diagram.

Fit the control data

- Extract the total yield of $J/\psi\ K$ events
- sWeight the data to extract the control mode distributions

↓

Reweigh the control MC to the sWeighted control data

- In $\boldsymbol{B_{PT}}$ and $\boldsymbol{B_\eta}$
- Apply the reweighter to signal MC

↓

Reweigh the sWeighted control data to the signal MC in each q^2 bin

- Reweigh in $\boldsymbol{B_\eta}$, $\boldsymbol{K_{PT}}$ **and** $\boldsymbol{K_\eta}$
- Apply reweighter to the unweighted control data

↓

Fit the reweighted control data (with no sWeights)

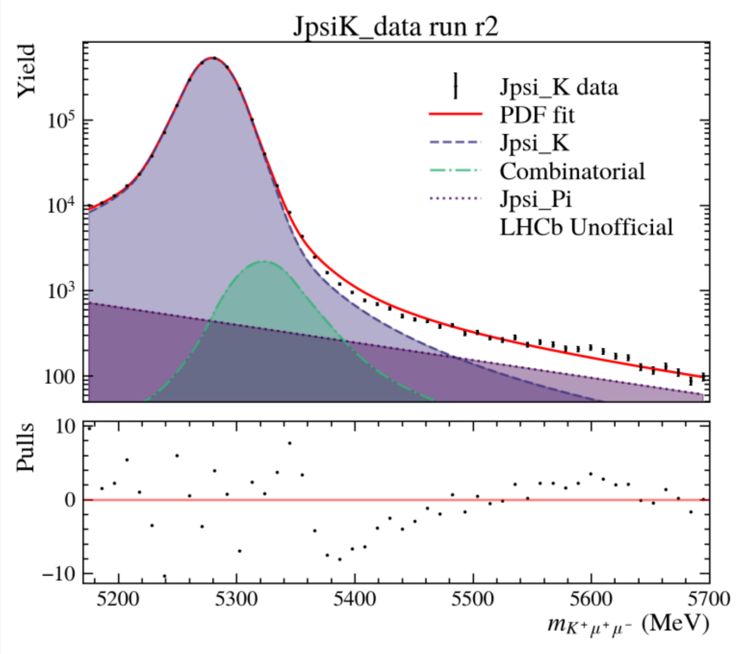
- Simultaneous fit split by charge
- Extract A_{raw} and its uncertainty

↓

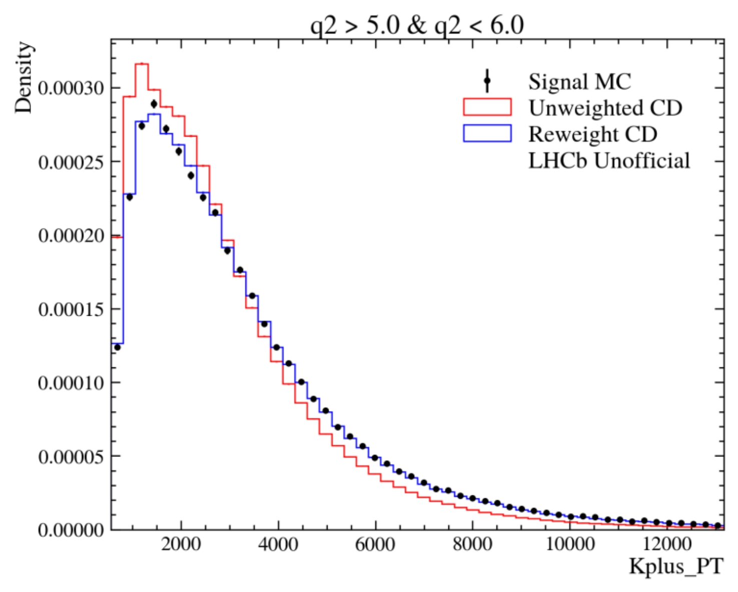
A_{raw} provides the estimate for A_{PD}

Production and Detection Asymmetries

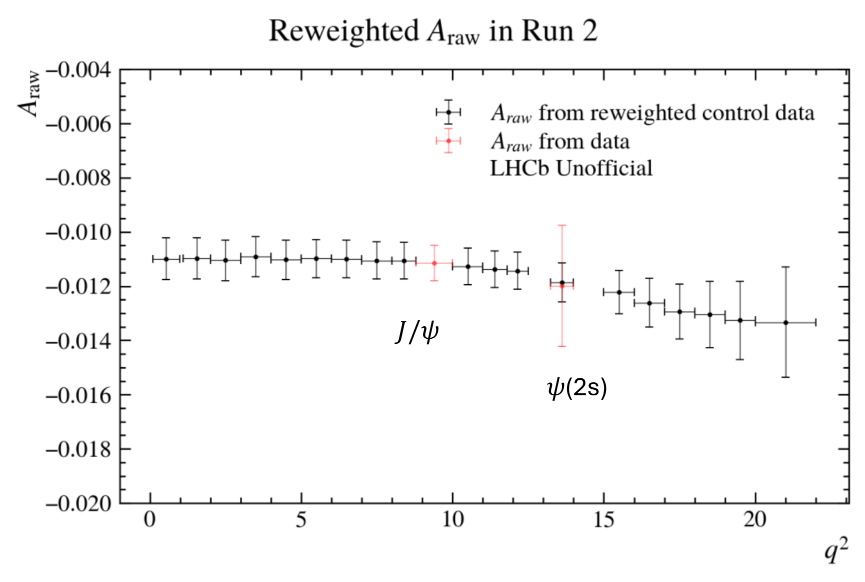
- Control mode fit:
  - **Shape** parameters for J/ψ modes **fixed** using **fits to MC**.
  - Extended **fit to** the **control data to extract** the **yields.** Allows a mean shift and width scale to float.
- Evaluated asymmetries:
  - Show clear trend of increasing magnitude at high q^2.
  - $\psi(2s)$ asymmetry computed using this method. Computed directly from data as crosscheck.



Run 2 fit to the control data



Example of the reweighter in one of the bins



Run 2 production and detection asymmetries.

Toy Study

- **Toy study** to **estimate** the **precision** and **sensitivity to A_{CP}**.
  - Pull study check for bias in fit and for correct coverage.
- Main components: **signal** (Double Crystallball+Gaussian), J/ψ **leakage** (Gaussian KDE), and **combinatorial background** (Exponential).
- **Signal and resonant leakages**:
  - Fits to MC in all bins to get the shape for each component.
  - Yields estimated **using the number of control** events in the data.
- **Combinatorial:**
  - Shape from Upper Mass Sideband **(UMS) fit** (B mass **5700-6000 MeV**). Same shape for all bins.
  - Yield estimated by **extrapolating full UMS** into fit window and **applying q^2 efficiency** for bin.

- **Generate 1800** toys **per bin per run**.
  - **MC shapes are corrected using** the shift and scale obtained from the **control data fit**.
- Signal yields parametrised in terms of A_{CP} and A_{PD}:

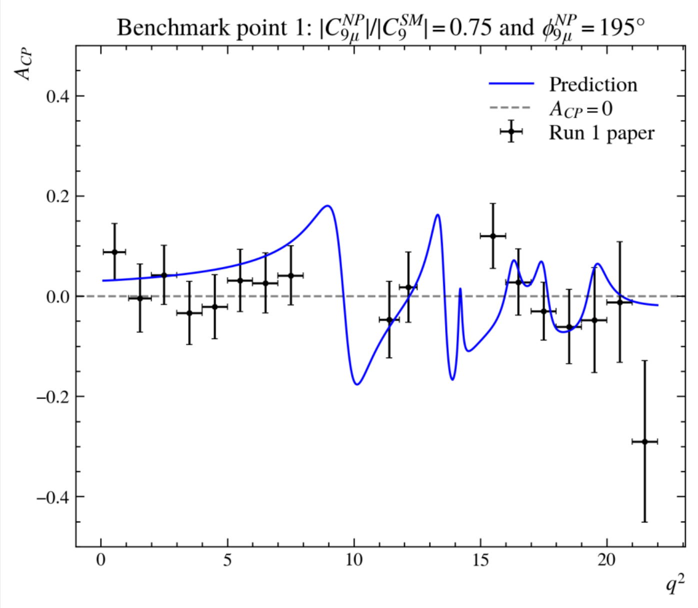
$$S_{r_i}^{\pm} = \frac{1 \mp \left(A_{CP} + A_{PD,r_i}\right)}{2} S_{r_i}^{T}$$

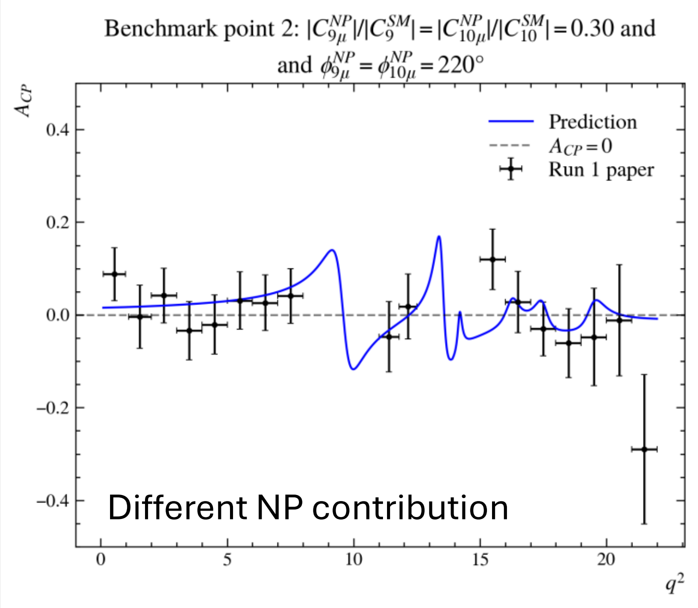
Toy Study: ACP Modelling

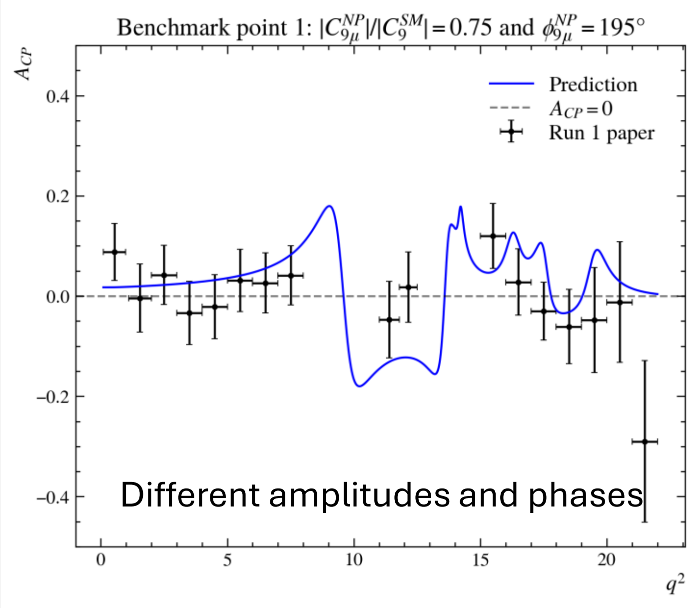
- To **induce A_{CP}** in the toy generation, a **theoretical model** was implemented. Based on [2] and [3].
- Contributions from $\bar{c}c$ are modelled as the **sum of Breit-Wigner** distributions:

$$Y(q^2) = \sum_j \eta_j e^{i\delta_j} A_j^{res}(q^2) \text{ with } A_j^{res}(q^2) = \frac{m_{0j}\Gamma_{0j}}{\left(m_{0j}^2 - q^2\right) - i m_{0j}\Gamma_j(q^2)}$$

- Can pick different configurations of phases and amplitudes [4]:







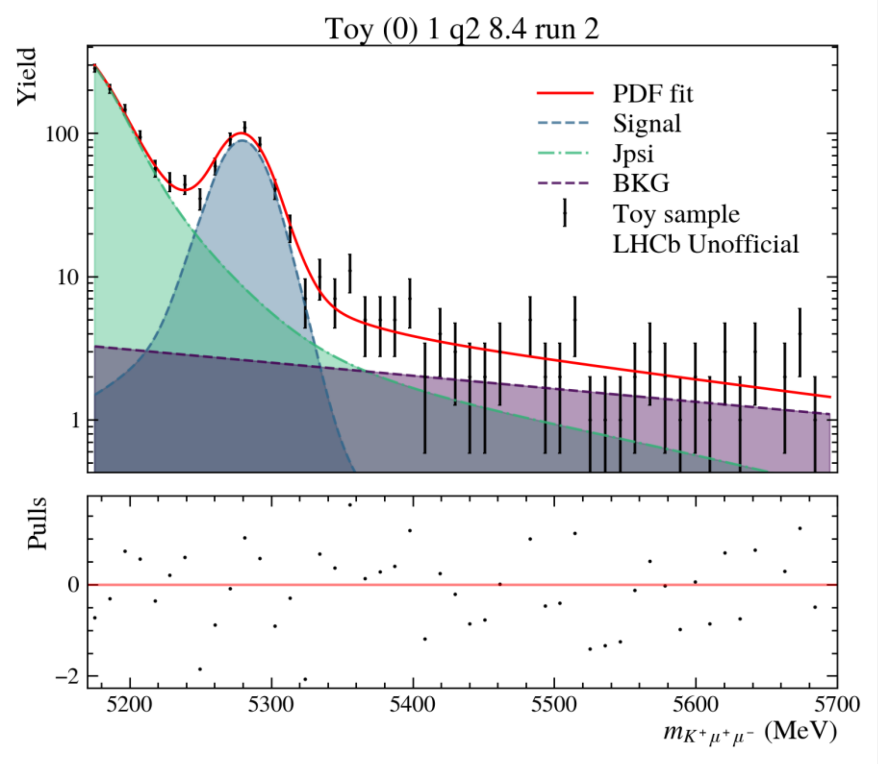
[2] R. Fleischer et al., "Fingerprinting CP-violating New Physics with B → Kμ+μ−" (2023), https://doi.org/10.1007/JHEP03%282023%29113.
[3] LHCb Collaboration, "Measurement of the phase difference between short- and long-distance amplitudes in the B → Kμμ decay" (2016), https://arxiv.org/abs/1612.06764.
[4] LHCb Collaboration (unpublished), Measurements of the local and non-local contributions in B → Kμμ decays with Run1 and Run2 data *https://twiki.cern.ch/twiki/bin/viewauth/LHCbPhysics/UnbinnedBuToKmumuRun1Run2.*

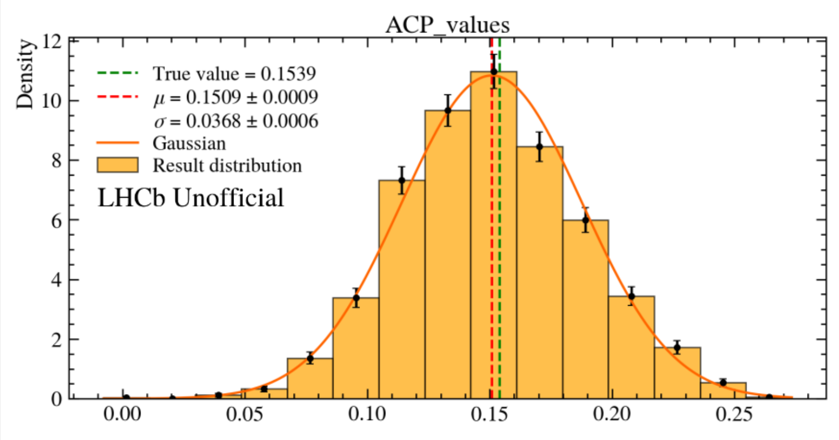
Toy Study: ACP Modelling

- **Events in one bin of q^2 reconstructed** into a **different bin**
  - Referred to as "**migrating**" → **could bias** the **measurement**.
- A_{CP} changes more quickly closer to the charmonium resonances.
  - **Bins near resonances more sensitive to this** type of effect.
  - Investigate extent of this.

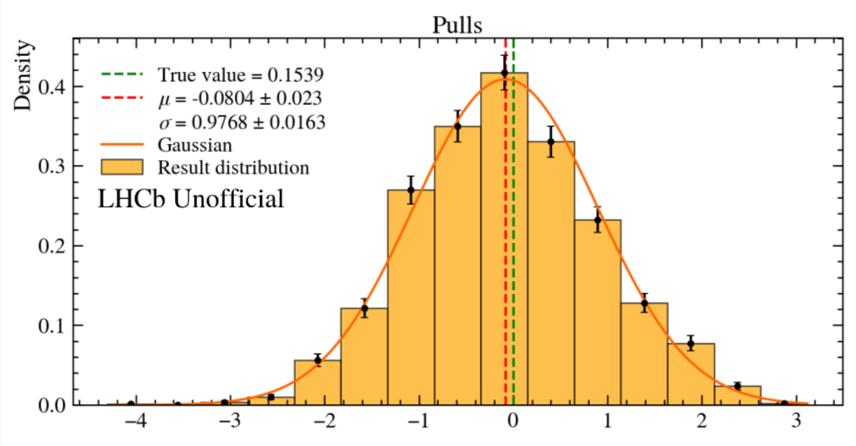
- Include our theoretical model and migrations in yield estimates. How?
- **Reweigh the truth signal MC in true q^2 to the model.**
  - Effectively **convolve the model with the experimental resolution.**
  - Accounts for bin migrations from other signal events.
- **Yields** for each CP mode **computed individually**.
- **Leakage contributions** only modelled when significant
  - Only around the J/ψ peak.

Toy Study: Results Near Resonance





b)

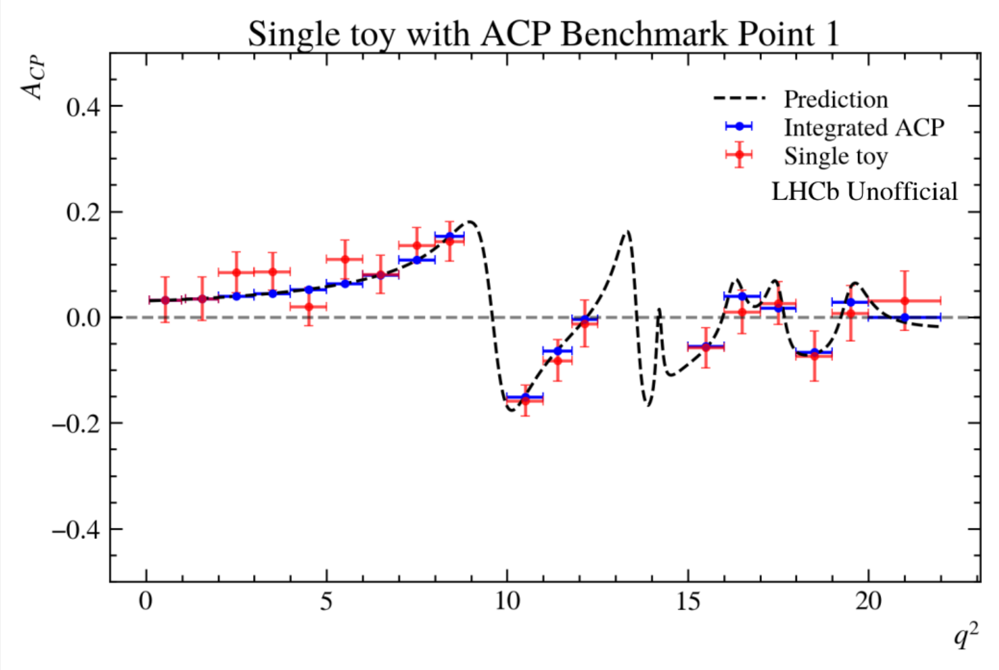


c)

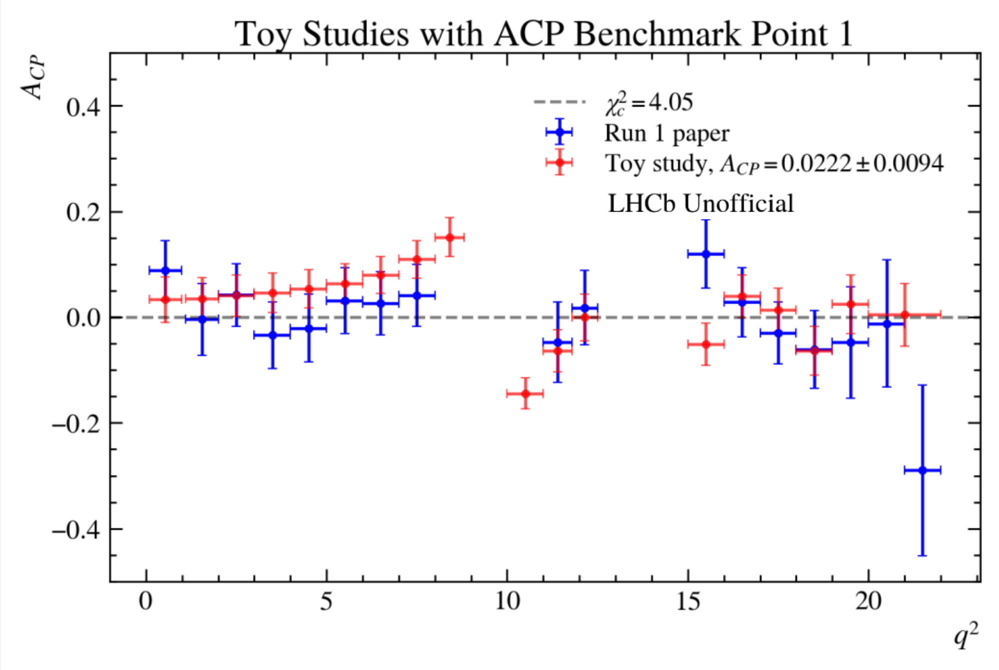
- Good fit convergence.
- Pulls show good coverage and a small bias that will be accounted for using a systematic.

Plots for $8 < q^2 < 8.8$: a) Fit for a single toy in run 2. b) Distribution of A_{CP} over all toys. c) Pull distribution over all toys.

Toy Study: Results



Single toy result compared with the predicted integrated value from the model.



Precision of the Run 1 results compared to the estimates from the toy study. The reduced χ^2 tests the compatibility with the "no A_{CP}" hypothesis.

- **Single toy experiment**:
  - Recover **correct integrated A_{CP}** within uncertainty, **despite migration** effects.
- Improvement on expected precision consistent with expectations. For Run1: 0.0130 ± 017 .
  - Considering we use a different selection working point and differential Br model.
- Here do not include systematics due to the shapes of components. These will vary across q^2.

Summary and Future Plans

- Binned analysis of CP-asymmetries in the $B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}$ decay.
- Aim to make a combined run 1, 2 and 3 measurement.
- Main challenge in analysis is getting closer to charmonium resonances.
- Status: completed selections (run 1 and 2), production and detection asymmetries, A_{CP} fit.
- Aim to be in WG review by end of year.

- Future plans:
  - **Optimise the binning** and add **bins near the $\psi(2s)$ peak**.
  - **More formal background study** needs to be performed.
  - **Assessment** of **systematic** uncertainties.
    - Methodology for computing A_P and A_D.
    - Mass shapes for signal and background.
  - Better optimise selections on **Run 3 data** and properly include 2025
    - Current implementation uses 2024 as proxy, preliminary estimate.

Questions?

Thanks a lot!

Backup: More $B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}$ Theory

- The decay **can also proceed through** an intermediate vector meson, mainly $\boldsymbol{c\bar{c}}$ **mesons**.
- This leads rise to **hadronic long-distance effects**, which can be modelled by replacing $\boldsymbol{C_{9\mu}}$ by and **effective coefficient** [2]:

$$C_{9\mu}^{eff} = C_{9\mu} + Y(q^2)$$

- With $Y \equiv |Y|e^{i\phi_Y}$, where $\boldsymbol{\phi_Y}$ is a charge-parity **(CP) conserving** strong **phase**.
- This is a function of q^2, the invariant mass of the muon pair.

- The **effective Hamiltonian** can be constructed with the dominating operators [1].

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^{*} \sum_{i=7,9\mu,10\mu} [C_i O_i + C'_i O'_i]$$

C^7 is the electromagnetic operator and $C^{9\mu,\,10\mu}$ are semileptonic operators. Primed operators correspond to right-handed currents and are suppressed

Backup: More CPV in $B^{\pm} \rightarrow K^{\pm}\mu^{+}\mu^{-}$

- This is a charged meson decay so **only** subject to **direct CP violation**.

$$A_{CP} = \frac{\Gamma(B^{-} \rightarrow K^{-}\mu^{+}\mu^{-}) - \Gamma(B^{+} \rightarrow K^{+}\mu^{+}\mu^{-})}{\Gamma(B^{-} \rightarrow K^{-}\mu^{+}\mu^{-}) + \Gamma(B^{+} \rightarrow K^{+}\mu^{+}\mu^{-})}$$

- Requires interference between **two** distinct **strong phases and two** distinct **weak phases**. The **amplitudes** of these phases must be **similar**.

- **Strong phases** (ϕ) come from the $\boldsymbol{c\bar{c}}$ **resonance effects**. **Weak phases** (δ) come from the **penguin diagrams**.
- u diagram is heavily Cabibbo suppressed compared to the t. Thus **expect** this $\boldsymbol{A_{CP}}$ to be **negligible**.
- A new physics (**NP**) **CP-violating phase** can **enter** the Wilson coefficient $\boldsymbol{C_{9\mu}}$ as a **complex** term [2].

$$C_{9\mu}^{NP} = \left|C_{9\mu}^{NP}\right| e^{i\delta_{9\mu}^{NP}}$$

- This could result in **significant CPV** in this decay.
- Its size will be **proportional to** $\boldsymbol{\sin\phi\,(q^2)}$.

$$A_{CP} = \frac{\sum_i (S_i A_{CP,i})/\epsilon_i}{\sum_i S_i/\epsilon_i}$$

Benchmark Point 1: $\left|C_{9\mu}^{\rm NP}\right| / \left|C_9^{\rm SM}\right| = 0.75\,,\qquad \phi_{9\mu}^{\rm NP} = 195^\circ$

Backup: Selections and BDT Variables

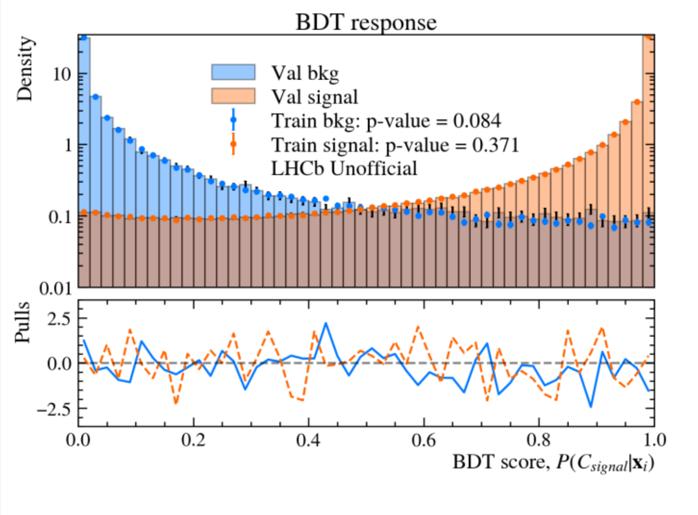
Selection purpose	Selection (in GeV)
L0 Run 1 and Run 2	L0Muon
HLT1 Run 1 (Run 2)	TrackMuon or TrackAll or DiMuonLow or DiMuonHigh (TrackMuon or TrackMVA)
HLT2 Run 1 (Run 2)	TopoMu 2/3 BodyBDT or Topo 2/3 BodyBDT or SingleMuon or DiMuonDetached or DiMuonDetachedHeavy (TopoMu 2/3 Body)
PID selections	(muplus_isMuon == True), (muminus_isMuon == True), (muplus_ProbNNmu > 0.1), (muminus_ProbNNmu > 0.1), (Kplus_ProbNNk > 0.1)
q^2 range	$0.1 < q^2 < 22.00$
Cut ϕ_{1020} resonance	not$(0.98 < q^2 < 1.10)$
Cut J/ψ resonance	not$(8.8 < q^2 < 10.0)$
Cut $\psi(2s)$ resonance	not$(13.24 < q^2 < 14.00)$
Remove $K\mu$ missID	Kplus_ProbNNk > 0.6 if $8.8 < m(K^{\pm}(\to \mu^{\pm})\,\mu^{\mp})^2 < 10$

Table of all current pre-selections for the analysis. All trigger requirements are trigger on signal (TOS).

Bplus ENDVERTEX CHI2
Bplus DIRA OWNPV
Bplus FDCHI2 OWNPV
Kplus IPCHI2 OWNPV
Bplus IPCHI2 OWNPV
muplus IPCHI2 OWNPV
muminus IPCHI2 OWNPV
Bplus P
Bplus PT
Kplus P
Jpsi IPCHI2 OWNPV

Backup: BDT for Removing Combinatorial Background

- An *Xgboost* **BDT** was trained to **separate signal** from **combinatorial** background.
  - **Signal** sample: **MC** in the fit B-mass region, **5170-5700 MeV**.
  - **Background** sample: upper mass sideband (**UMS**) **data 5700-6000 MeV**
- A mixture of **kinematic and geometric variables** was used for the training of the BDT.
- 5-fold cross validation used and each run utilised a different BDT.



- The **BDT** was **optimised** by **maximising** the significance, i.e. the **ratio** $\frac{S}{\sqrt{S+B}}$.
- The **number** of **signal** events (S), was estimated from the number of **control events** (C) seen in data.

$$S = C\,\frac{Br_S}{Br_C}\frac{\epsilon_S}{\epsilon_C}$$

- The **number of background** events (B), calculated by **fitting the UMS** and **extrapolating to** the **signal window**.

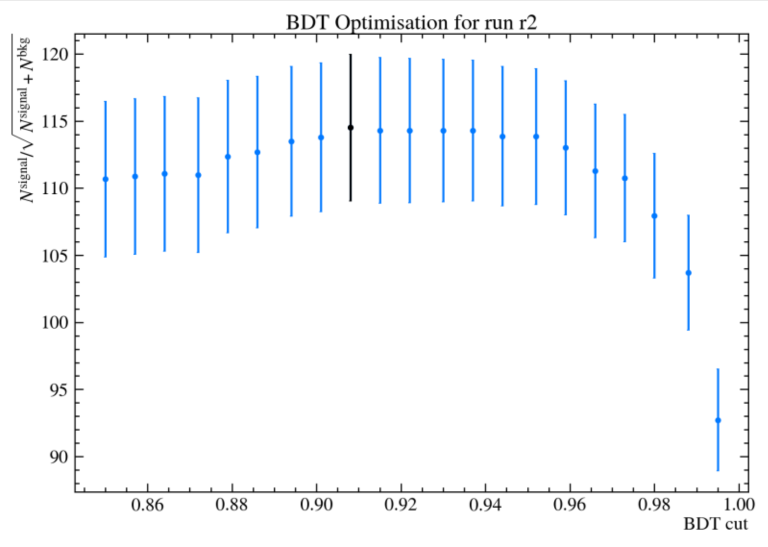
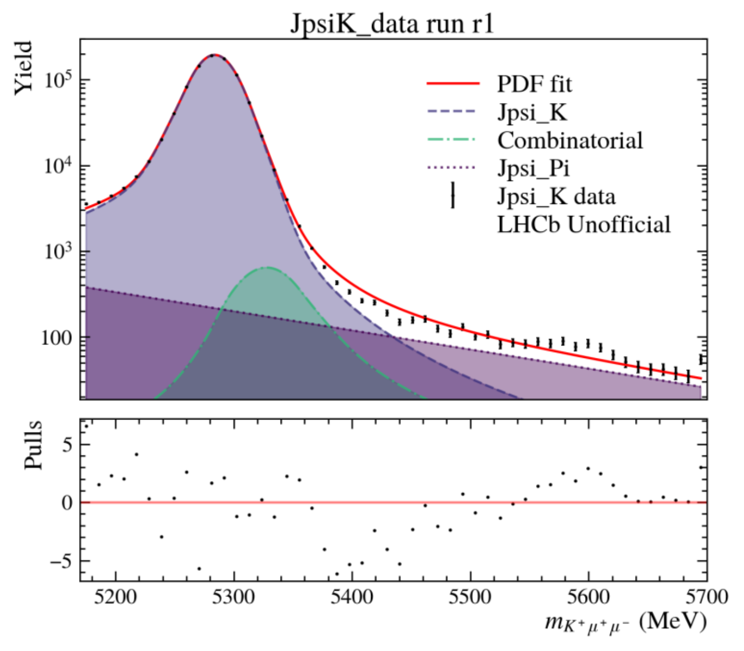


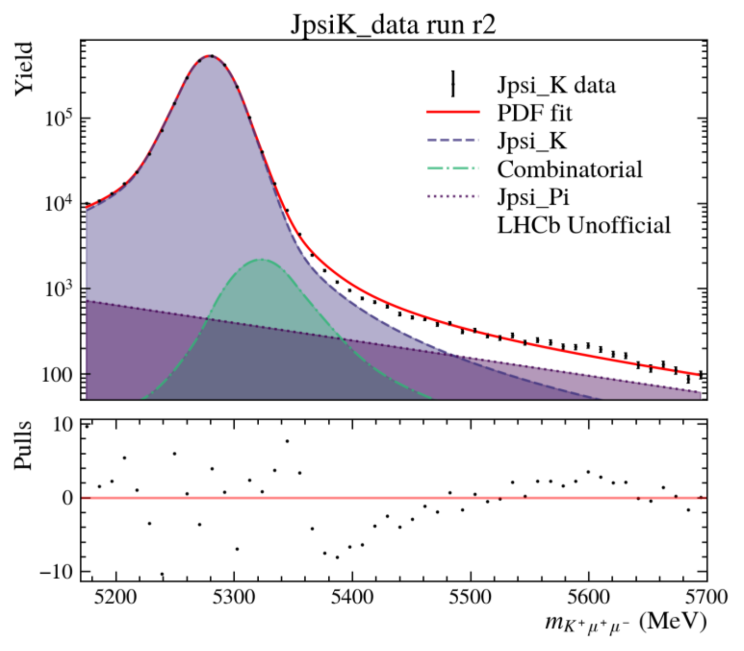
Fig a): BDT response for one fold of the run 2 BDT. KS-test p-value is also given.
*Fig b) BDT optimisation for run 2. **Run 2** optimal cut was **0.915** and for **run 1** it was **0.944.***

Backup: Fit to the Control Mode

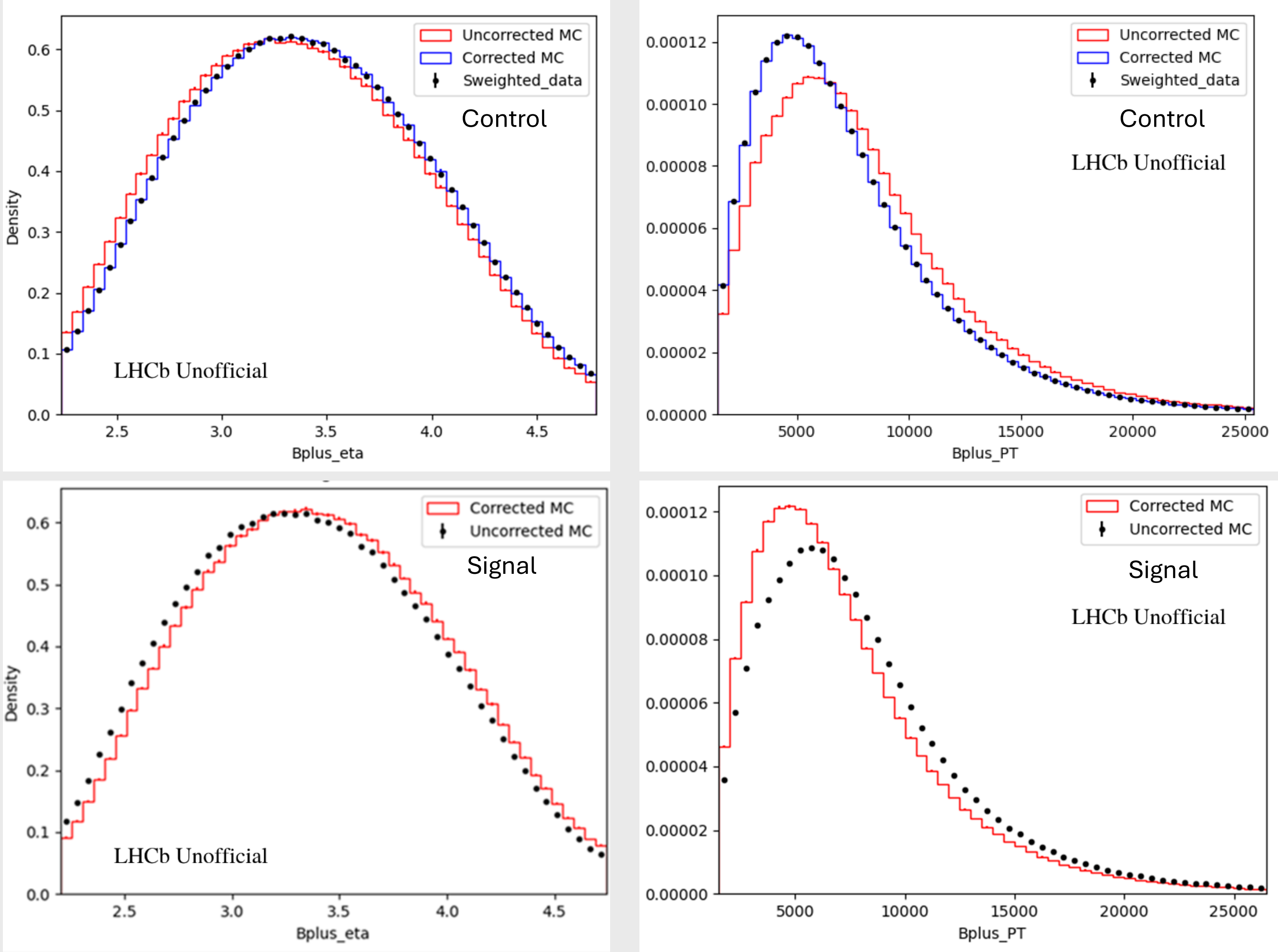
- Components in the fit: control mode, a $B^{\pm} \to (J/\psi \to \mu^{+}\mu^{-})\,\pi^{\pm}$ misID background and the combinatorial background.
- Shape **parameters** are **fixed** using **fits to MC**.
  - **Control mode** shape is the **sum** of a **Double Crystal Ball and** a **Gaussian**, with a shared mean. **Same for** $J/\psi\,\pi$ **misID**.
- Extended **fit to** the **data to extract** the **yields**.
  - Allows a mean shift and width scale to float.
  - **Combinatorial background** modelled **with** an **exponential**.



Component	Run 1	Run 2
$J\psi\ K$	911160 ± 1000	2403490 ± 1700
$J\psi\ \pi$	4479 ± 103	14667 ± 264
Combinatorial	7151 ± 370	13051 ± 600



Backup: Reweighting the MC Samples

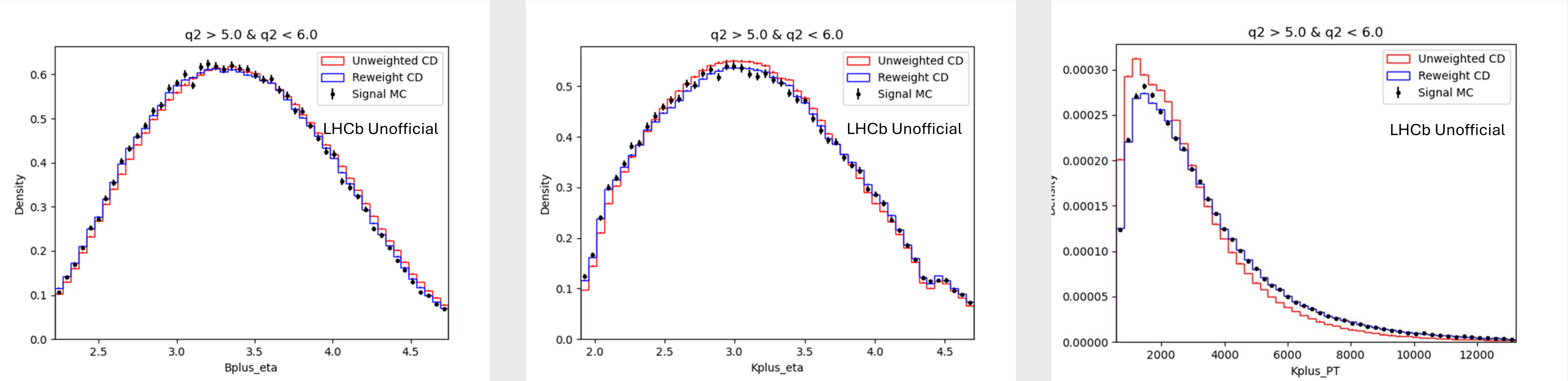


- **Reweighted** the **control MC to** the **sWeighted data** in B_{PT} and B_{η}.
- **Reweighter applied to** the **MC of** the **signal and** $J/\psi\ \pi$ **misID** to correct the samples for these modes as well.

Results of the reweighter on the Run 2 MC.

Backup: Reweighting the Control Data to Signal MC

- **Reweighted** the sWeighted data to signal MC in B_η, K_{PT} **and** K_η for each q^2 bin.
- **Applied** the reweighter **to the unweighted control data**.

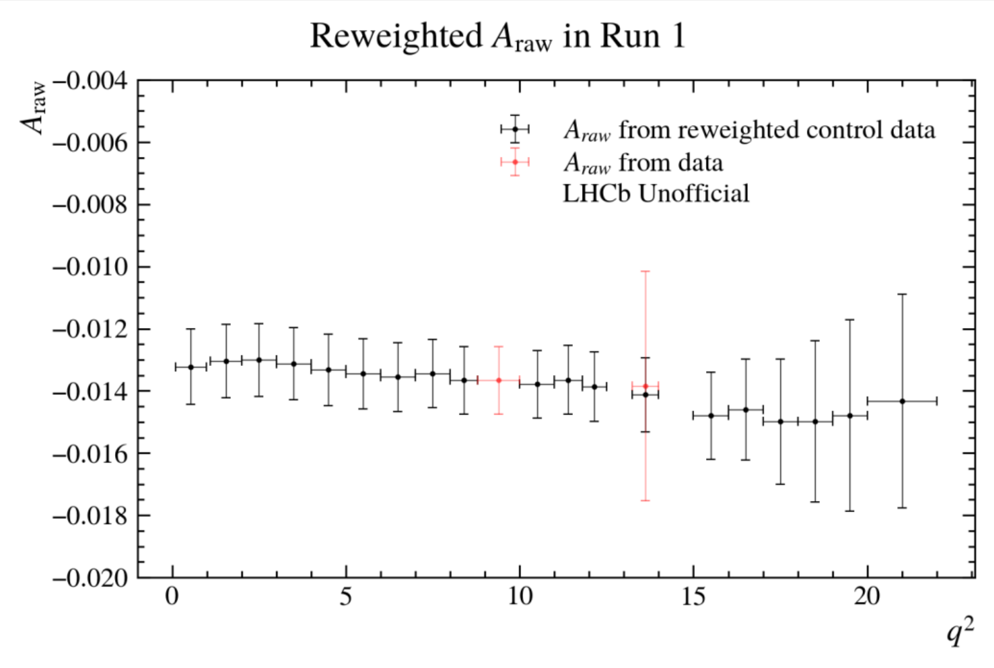


Results of the reweighter on the Run 2 control data for one bin.

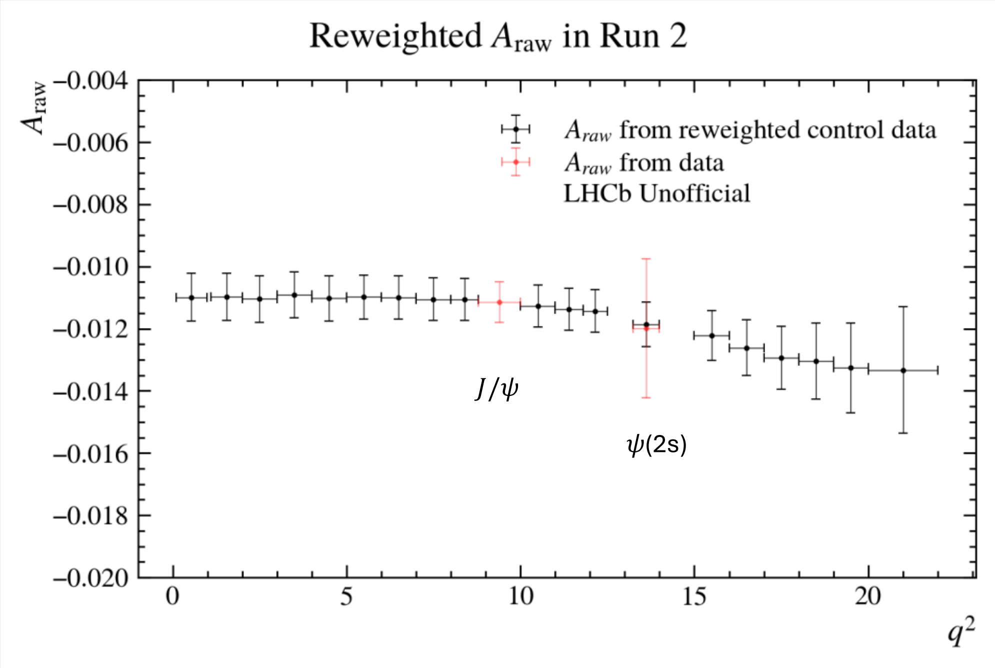
A_{PD} Results for Run 1 and Run 2

- **For each q^2 bin**, the corresponding reweighted **data is split by charge**.
- A **simultaneous fit** is performed to **measure A_{raw}**.

- **A_{PD} for the $\psi(2s)$** mode is also estimated **using this method**.
- Should be **equal to the A_{raw}** measured **from the $\psi(2s)$ data** directly.
- Good test for the validity of the method.



Production and detection asymmetry results for Run 1.



Production and detection asymmetry results for Run 2.

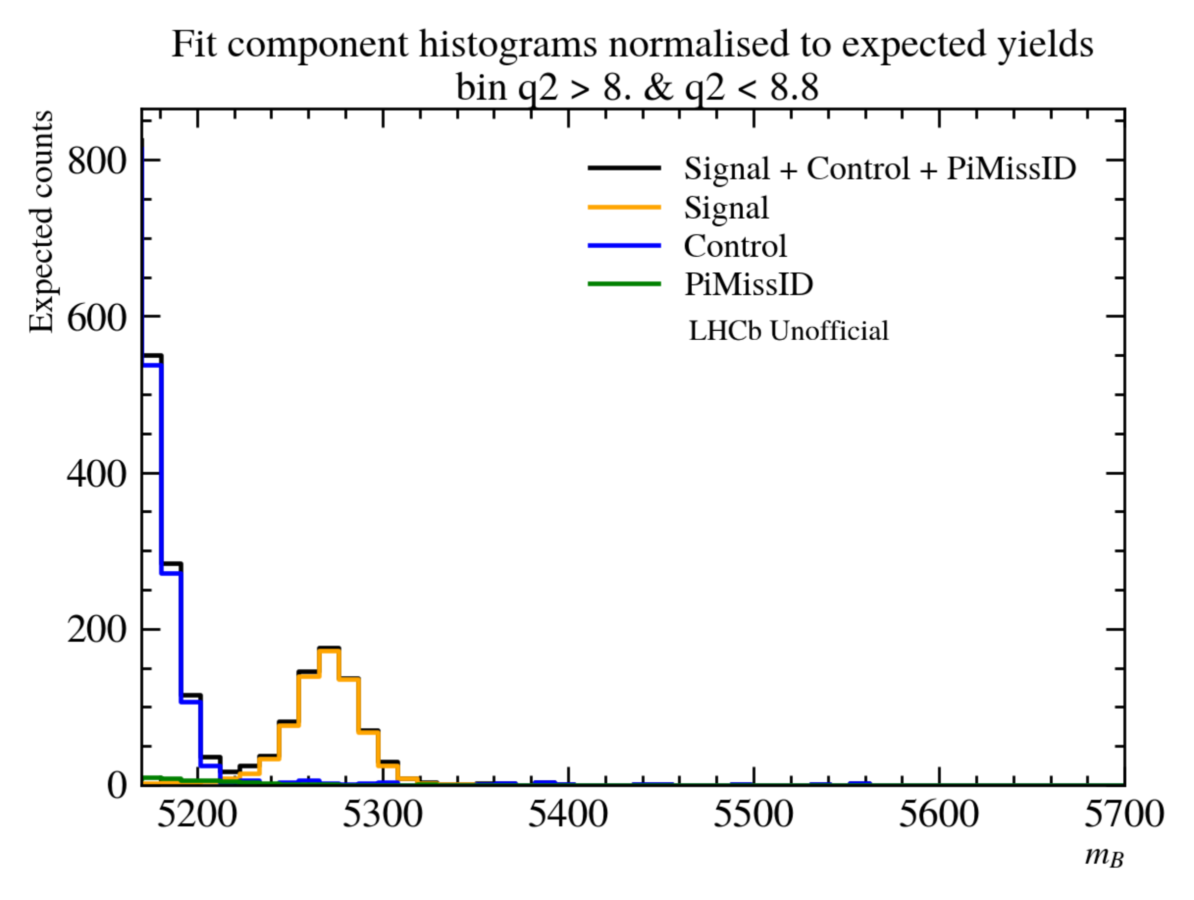
Toy Study: More Detailed Yield Approach

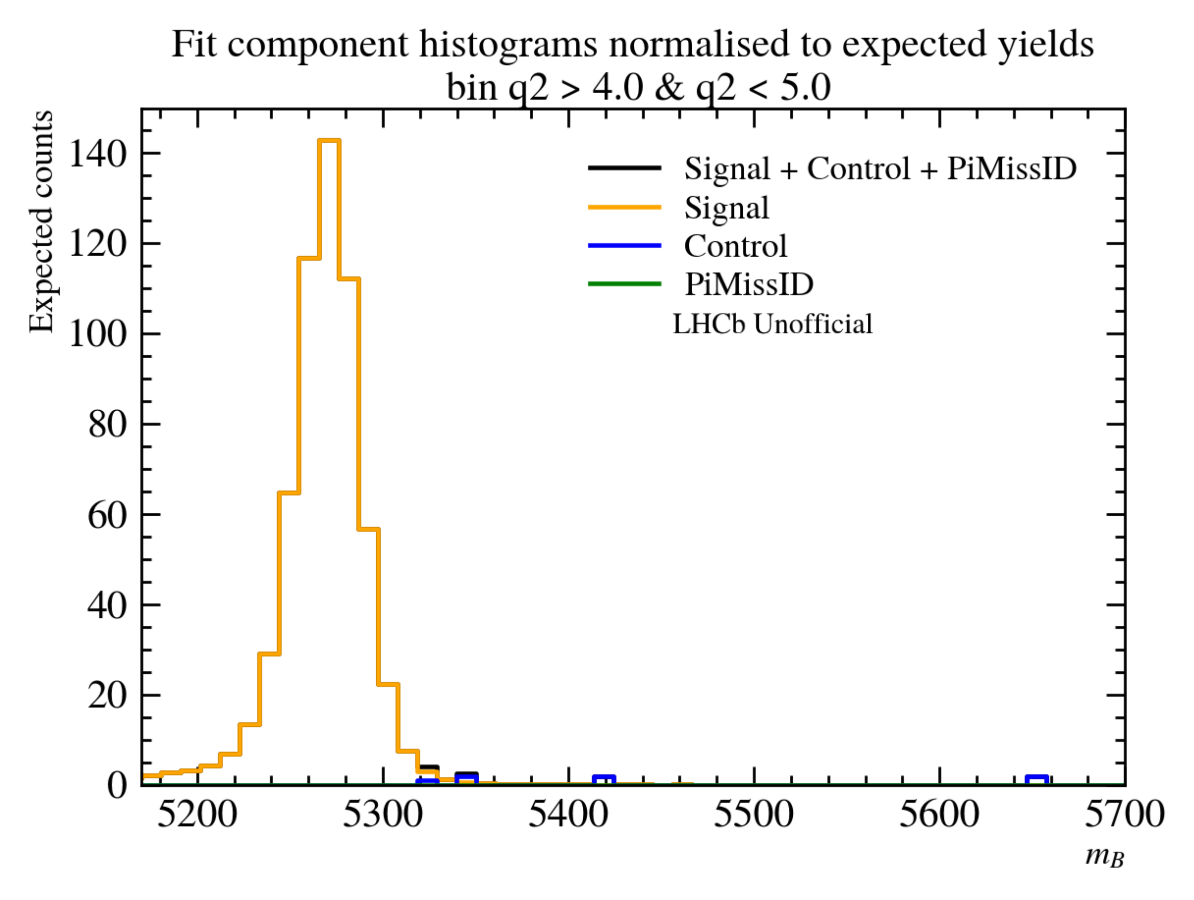
- **Reweight MC** into two separate samples:
  - One reweighted **to the particle model and** another to the **antiparticle model**.
- **Signal efficiency** now **includes all selection efficiencies** and $\boldsymbol{q^2}$ **bin efficiency**.
- **Don't reweight control** MC, efficiency only includes selections.
- Compute the **yields for each CP mode individually.**

$$S_i^{\pm} = C\,\frac{\epsilon^{\pm}{}_{iS}\, Br_S}{\epsilon_C\, Br_C}$$

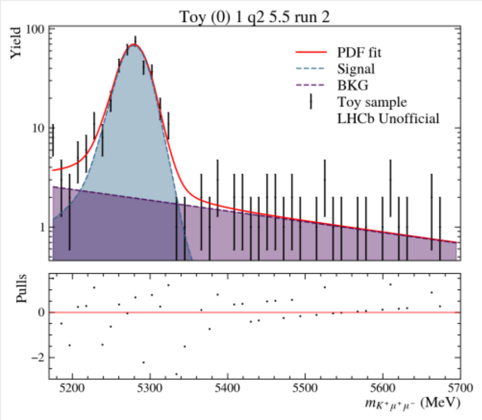
- Effectively we have **convolved the model with the experimental resolution**. This accounts for bin migrations from other signal events.

Expected leakage yields.

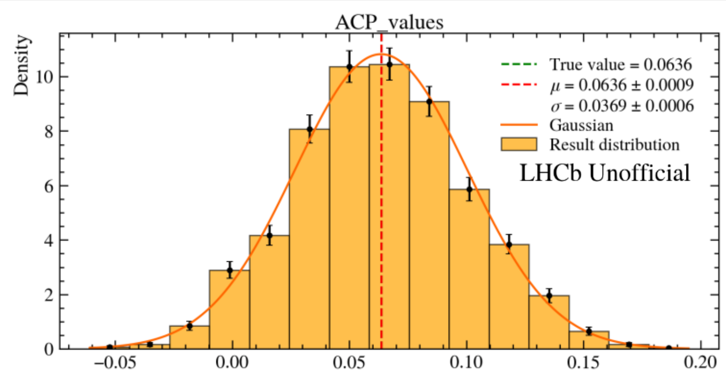




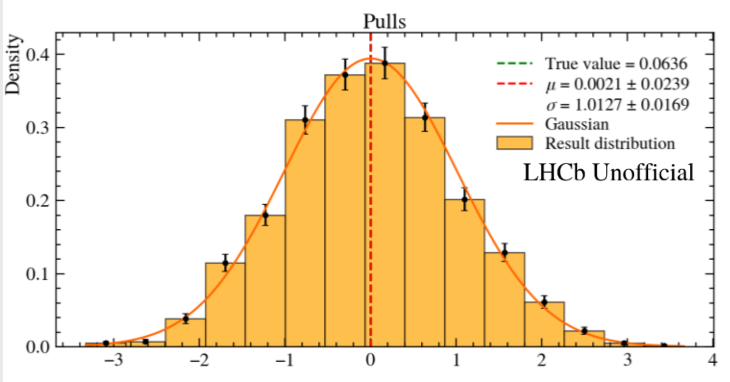
Toy Study: Results



a)



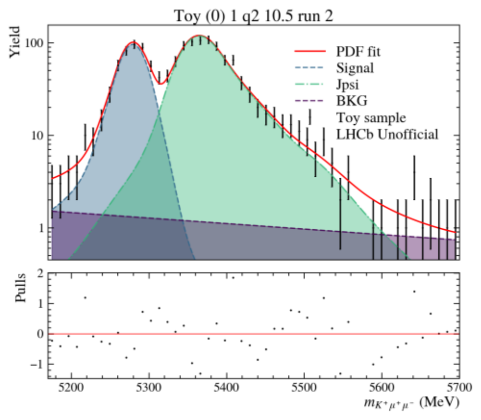
b)



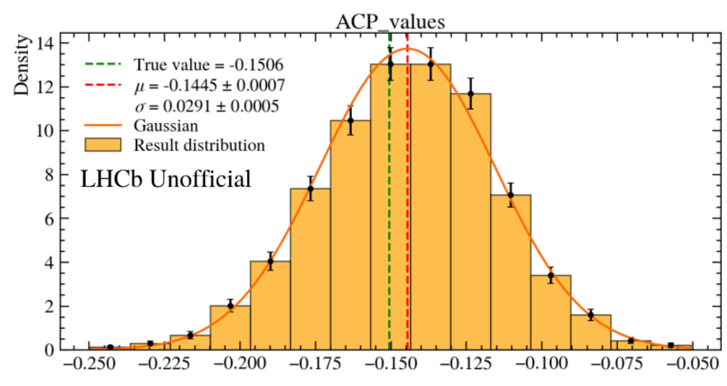
c)

Plots for $5 < q^2 < 6$: a) Fit for a single toy in run 2. b) Distribution of A_{CP} over all toys. c) Pull distribution over all toys.

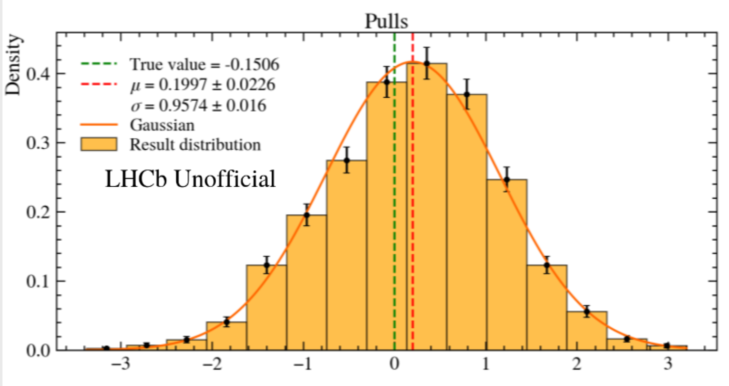
- Good fit convergence.
- Pulls show good coverage and no evidence of bias.



a)



b)



c)

Plots for $10 < q^2 < 11$: a) Fit for a single toy in run 2. b) Distribution of A_{CP} over all toys. c) Pull distribution over all toys.

- Good fit convergence.
- Bias due to migrations.
- Add a systematic