# Measuring CP Violation in $B_s^0 \to J/\psi\eta(\eta')$ Decays at LHCb and 1st Year Work on Photon Reconstruction Calibration

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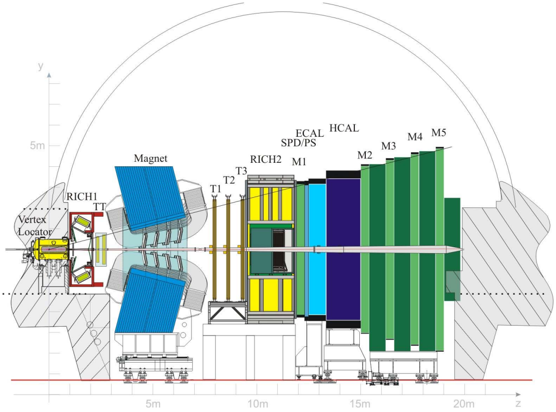
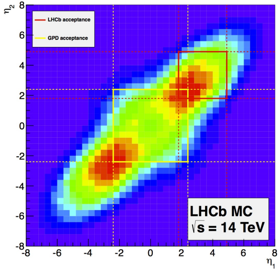
# LHCb and Thesis Project

# The LHCb Experiment

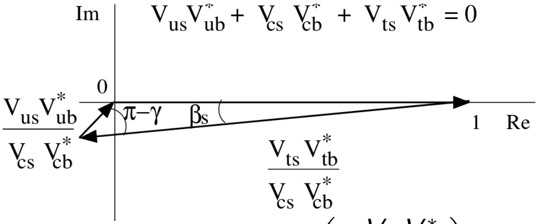



- Primarily dedicated to studying beauty and charm hadrons.
- For precision measurement of CKM parameters and *CP* violation.
- Rare processes in search of new physics.
- Hadron spectroscopy and heavy ions

# The Cabbibo-Kobayashi-Maskawa matrix and *CP* Violation

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

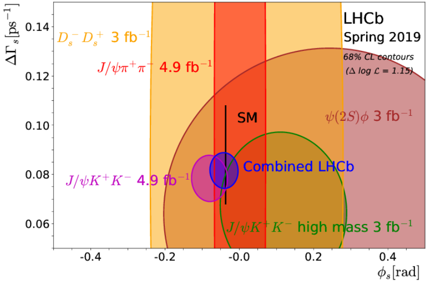



$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

$$\frac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*} \qquad \frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}$$

$$\phi_s = -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

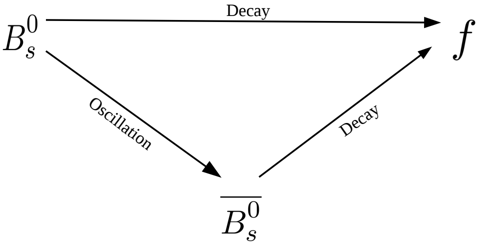
$$\phi_s^{SM} = 0.03686^{+0.00096}_{-0.00068}\,\text{rad}$$




$$\phi_s^{LHCb} = 0.041 \pm 0.025\,\text{rad}$$

# Motivation for measuring *CP* violation via $B_s^0 \to J/\psi\eta(\eta')$

- Neutral mesons oscillate between particle and antiparticle ($\to$ two propagating states with different masses $\Delta m$ and lifetimes $\Delta\Gamma$)
- Interference between decays w/ & w/o oscillation
  - Total amplitude is different for $B_s^0$ and $\overline{B}_s^0$ $\Rightarrow$ CP Violation!




- We'll look at $B_s^0 \to J/\psi\ \eta\ (\eta')$ vs. $\overline{B}_s^0$
- Several final states:
  $\eta \to \gamma\gamma, \pi^+\pi^-\pi^0, \pi^+\pi^-\gamma$ and
  $\eta' \to \rho^0\gamma, \pi^+\pi^-\eta$
- to maximise the precision on $\phi_s$

- The phase is measured by a fit to time-dependent asymmetry of these decays

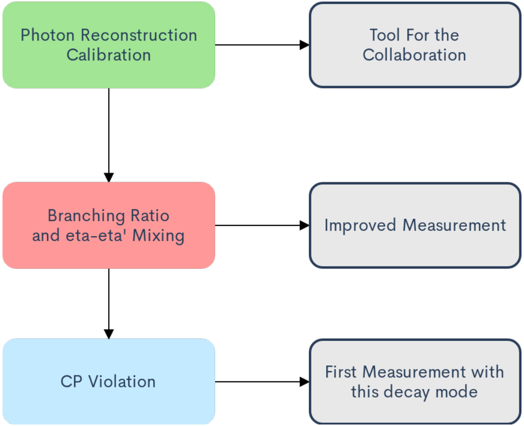
$$A_{CP}(t) = \frac{\Gamma(B_s^0(t)\to f) - \Gamma(\overline{B}_s^0(t)\to f)}{\Gamma(B_s^0(t)\to f) + \Gamma(\overline{B}_s^0(t)\to f)} = \frac{\sin\phi_s \sin\Delta m t}{\cosh\frac{\Delta\Gamma}{2}t - \cos\phi_s \sinh\frac{\Delta\Gamma}{2}t}$$

# Thesis Workflow

$$\eta_{\gamma}^{cor} = \frac{N^{s}_{B^+\to X\gamma}}{N^{s}_{B^+\to X}} \times \frac{\epsilon^{MC}_{B^+\to X}}{\epsilon^{MC}_{B^+\to X\gamma}} \times \frac{\mathcal{B}_{B^+\to X}}{\mathcal{B}_{B^+\to X\gamma}}$$

$$\mathcal{B}(B^0_s \to J/\psi\eta) = \frac{N_{B^0_s}}{N_{B^0}} \times \frac{\epsilon^{MC}_{B^0_s}}{\epsilon^{MC}_{B^0}} \times \mathcal{B}(B^0 \to X) \times \frac{f_s}{f_d}$$

$$A_{CP}(t) = \frac{\sin\phi_s \sin\Delta m t}{\cosh\frac{\Delta\Gamma}{2}t - \cos\phi_s \sin\frac{\Delta\Gamma}{2}t}$$



# 1st Year Work: Photon Reconstruction Calibration

# Motivation

- Potential source of systematics in many analyses at LHCb is the imperfect simulations. Data-MC discrepancies are not very well studied for neutral particles.
- It is crucial to have precise knowledge of the reconstruction and selection efficiencies determined by MC. $\rightarrow$ dedicated studies are needed to control them.
- This will be especially useful for *BR* measurements of decays with neutrals normalised to decays without neutrals $\rightarrow$ the reconstruction efficiency will not be cancelled in the ratios.
- I am producing a correction factors ($\eta_{\gamma}^{corr}$) in bins of $p_{\mathrm{T}}$ for different regions of the ECAL. So other analyses can benefit from them

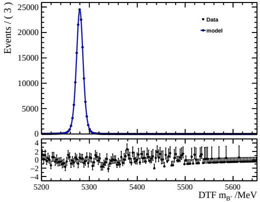
# Calculation of the correction factor

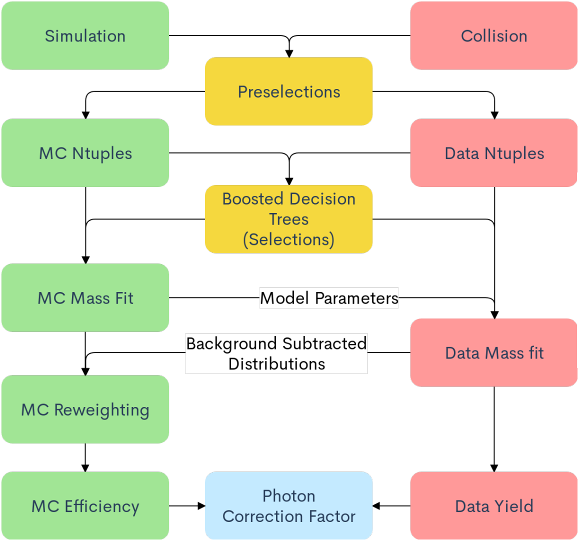
- Done by the comparison of two decay modes with similar topology
  - $B^+ \to \chi_{c1} K^+$ where $\chi_{c1} \to J/\psi\gamma$
  - $B^+ \to J/\psi K^+$ for normalisation and control of data-MC distributions
- Many systematics cancel in the ratios.

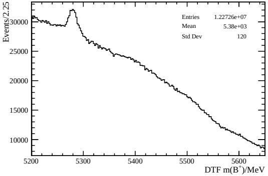
$$\eta_\gamma^{cor} = \frac{N^s_{B^+\to\chi_{c1}K^+}}{N^s_{B^+\to J/\psi K^+}} \times \frac{\epsilon^{MC}_{B^+\to J/\psi K^+}}{\epsilon^{MC}_{B^+\to\chi_{c1}K^+}} \times \frac{\mathcal{B}_{B^+\to J/\psi K^+}}{\mathcal{B}_{B^+\to\chi_{c1}K^+}\mathcal{B}_{\chi_{c1}\to J/\psi\gamma}}$$

- $N^s$: signal yield from data mass fits → needs background control (MVA)
- $\varepsilon^{MC}$: efficiencies from MC simulation → needs accurate simulation (GBReweighting)
- $\mathcal{B}$ taken from Particle Data Group → large uncertainty on $\mathcal{B}(B\to \chi_{c1}K^+)\mathcal{B}(\chi_{c1}\to J/\psi\gamma)$

# Photon reconstruction calibration analysis workflow



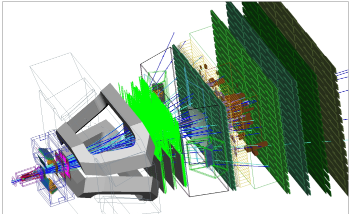
# Data samples and selections

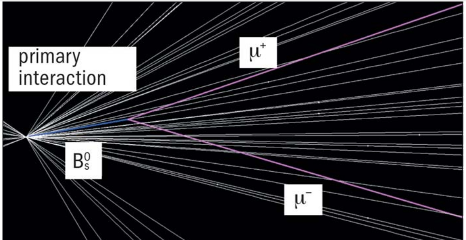
## Data samples

- Run-I : 2011 & 2012 $\sim 3\,\text{fb}^{-1}$ at $\sqrt{s} = 7\,\text{TeV}$ & $\sqrt{s} = 8\,\text{TeV}$ respectively
- Run-II: 2015-2018 $\sim 6\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$

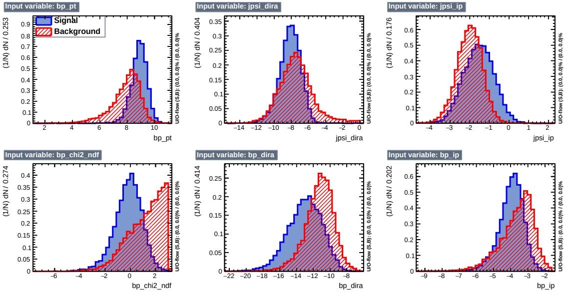
## Selections

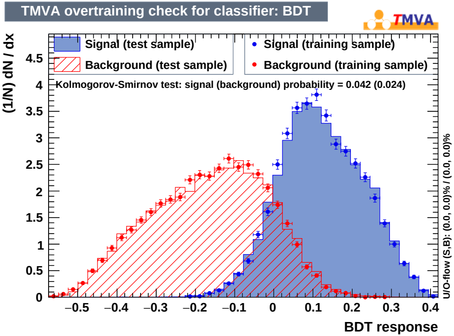
- Background reduction: mass windows and momentum cuts
- Track & vertex quality: $B$ decay vertex is displaced wrt primary interaction point
- PID: particle probability cuts





# BDT selection and optimisation



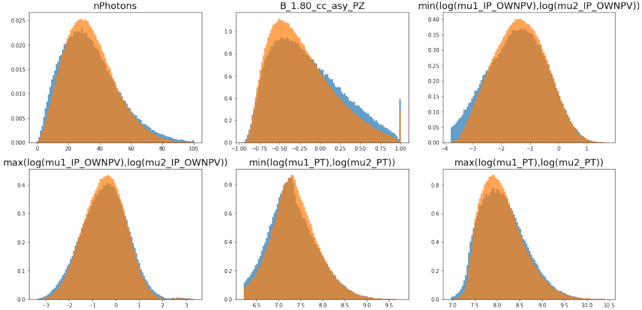




- Boosted Decision Trees for multivariate analysis.
- This uses 12 variables: signal (MC sample) vs. background (high mass data sample).
- Careful choice of inputs: Similar for $\chi_{c1}K^+$ and $J/\psi K^+$
- Outputs one variable which uses many distributions to improve signal purity.
- This is optimised by maximising $S/\sqrt{S+B}$ on $B^+ \to \chi_{c1}K^+$

# Data driven MC corrections (Gradient Boosted Reweighting)

- A new approach to reweighting samples using BDTs.
- Improves agreement between $J/\psi K^{+}$ MC and background subtracted data distributions
- Produces weights to be applied to $\chi_{c1} K^{+}$ MC before training the BDT and better control the efficiencies ($\epsilon^{MC}$)

Before



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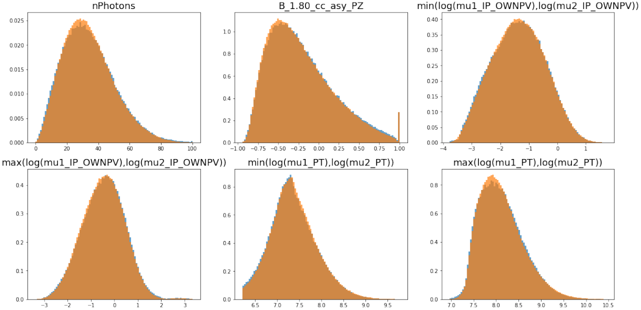
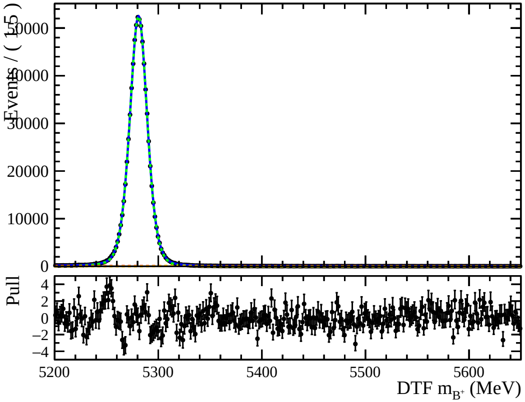
After



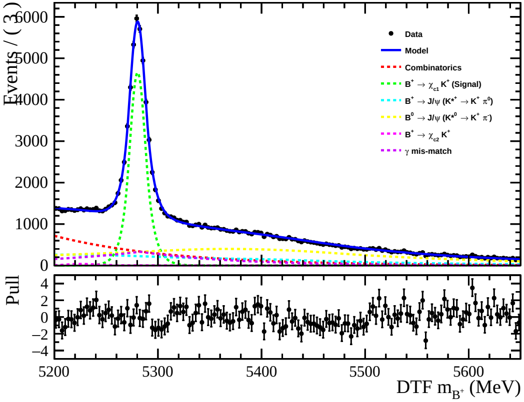
# Mass fits & data yields - 2012 (Run-I)

$B^+ \to J/\psi K^+$




$N_s = (7.844 \pm 0.009) \times 10^5$

$B^+ \to \chi_{c1} K^+$




$N_s = (3.338 \pm 0.018) \times 10^4$

# The correction factor — 2012

- $B \to J/\psi K$
  - $N_s = (7.844 \pm 0.009) \times 10^5$
  - $\epsilon^{reco+sel} = (16.78 \pm 0.01)\%$,
  - $\epsilon^{gen} = (16.280 \pm 0.018)\%$

- $B \to \chi_{c1} K$
  - $N_s = (3.338 \pm 0.018) \times 10^4$,
  - $\epsilon^{reco+sel} = (6.082 \pm 0.025)\%$,
  - $\epsilon^{gen} = (10.120 \pm 0.035)\%$

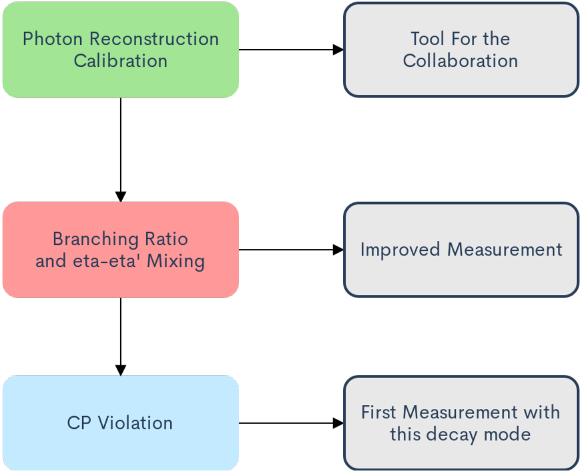
$$\eta_\gamma^{cor} = \frac{N^s_{B\to\chi_{c1}K}}{N^s_{B\to J/\psi K}} \times \frac{\epsilon^{MC}_{B\to J/\psi K}}{\epsilon^{MC}_{B\to\chi_{c1}K}} \times \frac{\mathcal{B}_{B\to J/\psi K}}{\mathcal{B}_{B\to\chi_{c1}K}\mathcal{B}_{\chi_{c1}\to J/\psi\gamma}} = 1.149 \pm 0.006 \pm 0.006 \pm 0.072$$

- $\mathcal{B}(B \to \chi_{c1} K) = (4.84 \pm 0.23) \times 10^{-4}$
- $\mathcal{B}(\chi_{c1} \to J/\psi\gamma) = (34.3 \pm 1.0)\%$
- $\mathcal{B}(B \to J/\psi K) = (1.010 \pm 0.029) \times 10^{-3}$

Currently working on the systematics

# Future Work: Branching Ratio and CP Violation Measurements

# Thesis Workflow

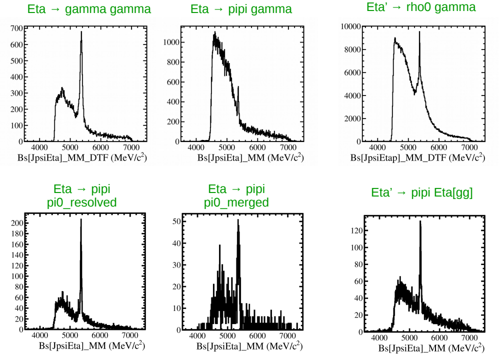


# Branching Ratio of $B_s^0 \to J/\psi\eta(\eta')$

Very similar workflow to Photon Reconstruction Calibration

$$\mathcal{B}(B_s^0 \to J/\psi\eta) = \frac{N_{B_s^0}}{N_{B^0}} \times \frac{\epsilon^{MC}_{B_s^0}}{\epsilon^{MC}_{B^0}} \times \mathcal{B}(B^0 \to X) \times \frac{f_s}{f_d} \times \frac{1}{\eta_\gamma^{cor}}$$

$$= (3.79 \pm 0.31(\text{stat})^{+0.20}_{-0.41}(\text{syst})^{+0.29}_{-0.27} \pm 0.56(\mathcal{B}(B \to J/\psi\rho^0))) \times 10^{-4}$$



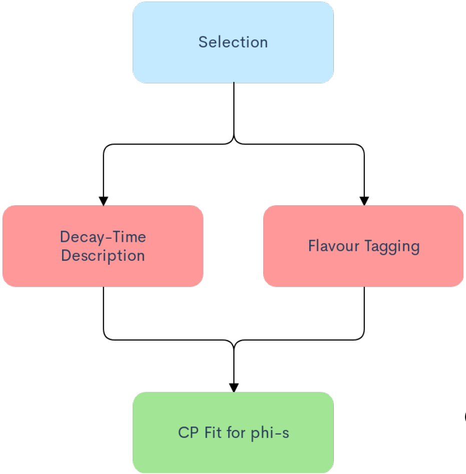

[Nucl. Phys. B867 (2013) 547]

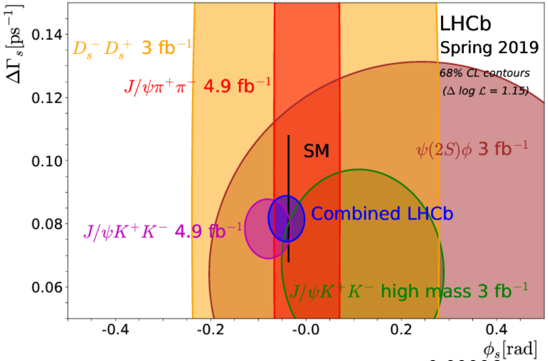
| Channel | $R_{\eta'}$ | $R_\eta$ | $R_s$ | R | $R_{\psi(2S)}$ |
|---|---|---|---|---|---|
| Photon reconstruction | — | — | 2.1 | 2.1 | — |
| Fit model | 2.9 | 2.9 | 0.8 | 2.6 | 1.2 |
| Data-simulation agreement | 2.9 | 3.7 | 3.7 | 3.7 | 2.9 |
| Trigger | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Simulation conditions | 1.4 | 1.5 | 0.8 | 1.1 | 0.9 |
| Total | 4.5 | 5.1 | 4.5 | 5.2 | 3.4 |

**Table 5**. Systematic uncertainties (in %) of the ratios of the branching fractions.

[JHEP 01 (2015) 024]

# $\phi_s$ Measurement




Current SM prediction: $\phi_s^{SM} = 0.03686^{+0.00096}_{-0.00068}\ rad$

# Overview

- I am completing the work on Photon Reco. Calibration
  - This will be published as a public note and a tool for the collaboration.
  - Given two talks around the subject (to Run-1&2 Performance WG and to LHCb's 77th Analysis & Software & Computing Week).
  - Will get involved in Run-III early measurements campaign.
- Branching Ratio measurement is a very similar process, but will have its own challenges
  - The analysis is starting now.
  - Target: publication in a physics journal in Summer 2021.
- In the beginning of next year I will move on to the work that is the namesake of my thesis: Measuring the CP violation in the decay of $B_s^0 \to J/\psi\eta(\eta')$.

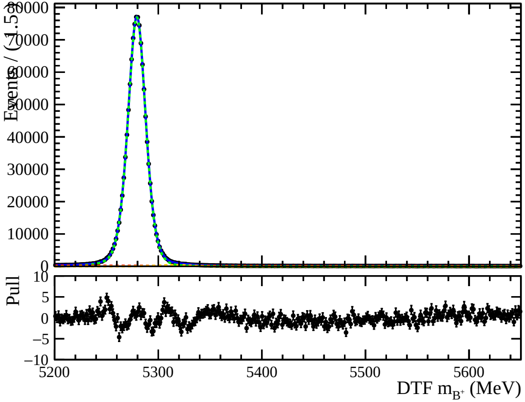
# Back Up Slides

# Selections

| Category | Particle | Cut |
|---|---|---|
| Background reduction | $B^+$ | $DIRA > 0.99755$, $IP < 0.2$, $5200\ MeV < DTF\ M < 5650\ MeV$ |
| | $J/\psi$ | $\|M - M_{J/\psi}\| < 38\ MeV$ |
| | $\chi_{c1}$ | $\|M - M_{\chi_{c1}}\| < 72\ MeV$ |
| | $\gamma$ | $p^T > 200\ MeV$ |
| Track & vertex quality | $B^+$ | $\chi^2(IP) < 20$, $\chi(vtx)^2/ndf < 3$ |
| | $\mu$ | $\chi^2(IP) > 4$ |
| PID | $K^+$ | $ProbNNk > 0.1$ |
| | $\gamma$ | $CL > 0.05$ |

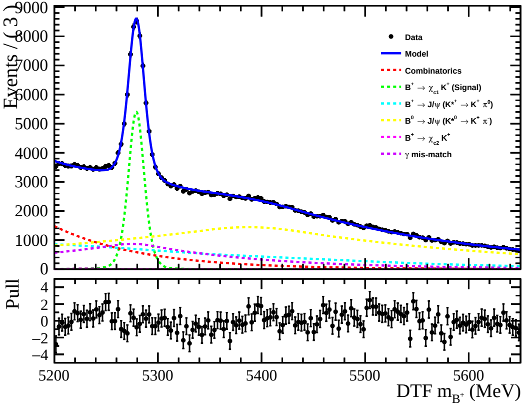
# Mass fits & data yields - 2016 (Run-II)

$B^+ \to J/\psi K^+$




$N_s = (1.17 \pm 0.12) \times 10^6$

$B^+ \to \chi_{c1} K^+$




$N_s = (3.665 \pm 0.016) \times 10^4$

# The correction factor — 2016 (WIP!)

- $B \to \chi_{c1} K$
  - $N_s = (3.665 \pm 0.016) \times 10^4$,
  - $\epsilon^{reco+sel} = (10.139 \pm 0.007)\%$,
  - $\epsilon^{gen} = (10.682 \pm 0.027)\%$
- $B \to J/\psi K$
  - $N_s = (1.17 \pm 0.12) \times 10^6$
  - $\epsilon^{reco+sel} = (20.27 \pm 0.05)\%$,
  - $\epsilon^{gen} = (17.36 \pm 0.04)\%$

$$\eta_\gamma^{cor} = \frac{N^s_{B\to\chi_{c1}K}}{N^s_{B\to J/\psi K}} \times \frac{\epsilon^{MC}_{B\to J/\psi K}}{\epsilon^{MC}_{B\to\chi_{c1}K}} \times \frac{BR_{B\to J/\psi K}}{BR_{B\to\chi_{c1}K} BR_{\chi_{c1}\to J/\psi\gamma}} = 0.62 \pm 0.04$$

- $BR(B \to \chi_{c1} K) = (4.84 \pm 0.23) \times 10^{-4}$
- $BR(\chi_{c1} \to J/\psi\gamma) = (34.3 \pm 1.0)\%$
- $BR(B \to J/\psi K) = (1.010 \pm 0.029) \times 10^{-3}$