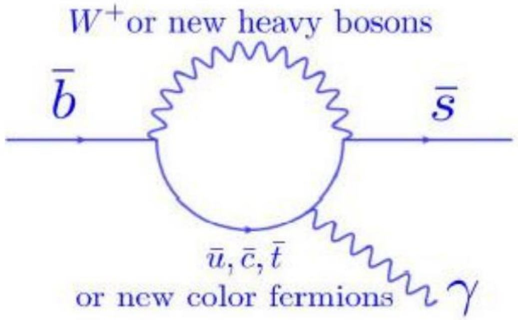
Measurement of time-dependent CP asymmetry using $B^0 \to K_S^0 \pi^+\pi^-\gamma$ decays in Belle II

Petros Stavroulakis, on behalf of the IPHC Strasbourg Belle II group

GDR-InF annual workshop at Mont Sainte-Odile, November 8th 2023

Photon polarization in $b \to s\,\gamma$



- In the Standard Model (SM) the polarization of the photon in $b \to s\gamma$ transitions is predominantly left-handed but New Physics (NP) may modify this
  - Atwood et al., Phys. Rev. Lett. 79, 185
  - E. Kou et al., JHEP 12 (2013) 102 [1305.3173]
  - N. Haba et al., JHEP 03 (2015) 160 [1501.00668]
- This polarization can be tested through a measurement of the time-dependent CP asymmetry of $B \to K_{\text{res}}\,\gamma$ decays

$$\mathcal{M} \simeq -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left[\left(C_{7\gamma}^{SM} + C_{7\gamma}^{NP} \right) \langle \mathcal{O}_{7\gamma} \rangle + C_{7\gamma}^{\prime NP} \langle \mathcal{O}_{7\gamma}^{\prime} \rangle \right]$$

TDCP asymmetry of $B^0 \to K_{res}\gamma \to K_S^0\pi^+\pi^-\gamma$ decays

$$\mathcal{A}_{CP}(\boldsymbol{\Delta t}) = \frac{\Gamma\left(B_{\mathrm{tag}=\bar{B}^0}(\boldsymbol{\Delta t}) \to f_{CP}\right) - \Gamma\left(B_{\mathrm{tag}=B^0}(\boldsymbol{\Delta t}) \to f_{CP}\right)}{\Gamma\left(B_{\mathrm{tag}=\bar{B}^0}(\boldsymbol{\Delta t}) \to f_{CP}\right) + \Gamma\left(B_{\mathrm{tag}=B^0}(\boldsymbol{\Delta t}) \to f_{CP}\right)} = \boldsymbol{S} \cdot \sin(\Delta m_d \Delta t) - \boldsymbol{C} \cdot \cos(\Delta m_\mathrm{d} \Delta t)$$

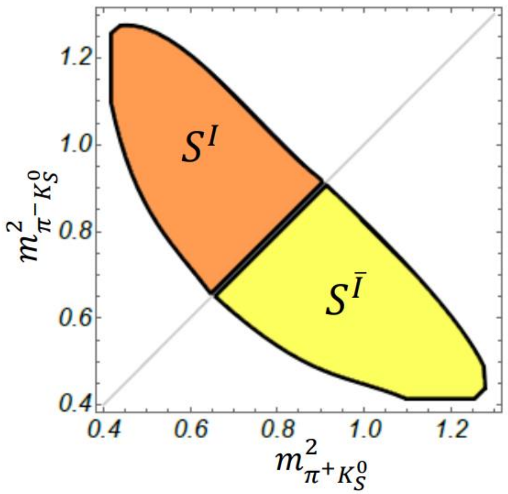
- We are interested in measuring $\boldsymbol{S}$ of the CP-eigenstate: $B^0 \to K_{res}\gamma \to K_S^0\rho^0\gamma \to K_S^0\pi^+\pi^-\gamma$
- A dilution factor is needed to properly account for non-CP-eigenstates resulting from various interfering kaonic resonances:

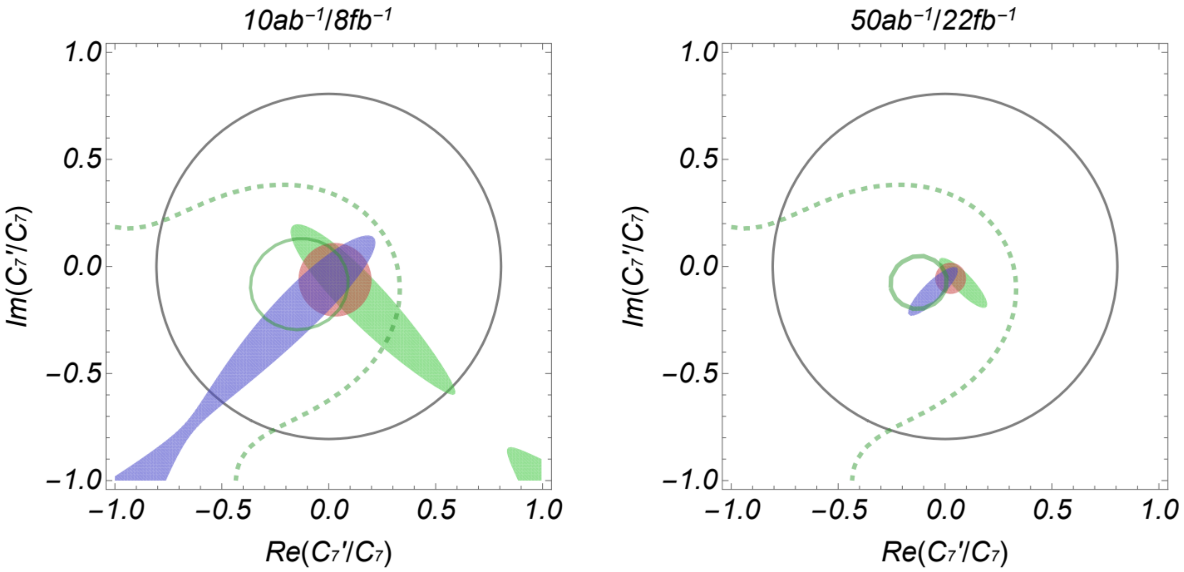
$$\mathcal{D} = \frac{S_{K_S^0\pi^+\pi^-\gamma}}{S_{K_S^0\rho^0\gamma}}$$

- Previous measurements:
  - BaBar PRD93 (2015) : $S_{K_S^0\,\pi^+\pi^-\gamma} = 0.14 \pm 0.25 \pm 0.03$ (using 471×10^6 $B\bar{B}$ pairs)
  - Belle PRL101 (2008) : $S_{K_S^0\,\pi^+\pi^-\gamma} = 0.09 \pm 0.27 \pm 0.07$ (using 657×10^6 $B\bar{B}$ pairs)
- We plan to do a combined measurement using the entire Belle (711 fb^{-1}) and current Belle II datasets (362 fb^{-1})

New constraints on C_7

- Work by $S. Akar, et\ al.$, proposes new observables by dividing the dataset in the Dalitz-plane
- The two new observables will provide orthogonal constraints to the real and imaginary parts of C_7'/C_7 in the complex plane



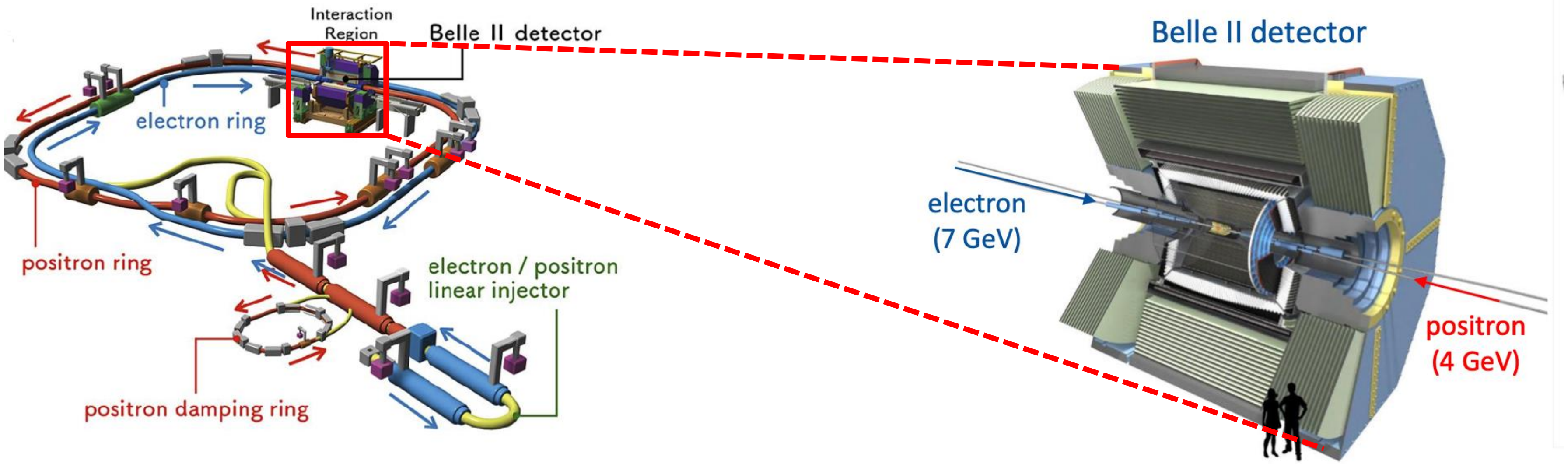


- New observables:

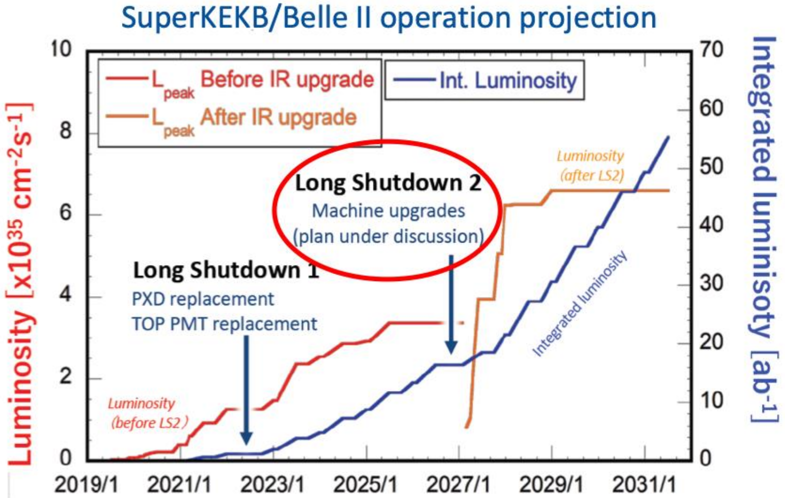
$$S^+_{K^0_S \rho^0 \gamma} = S^I + S^{\bar{I}}$$

$$S^-_{K^0_S \rho^0 \gamma} = S^I - S^{\bar{I}}$$

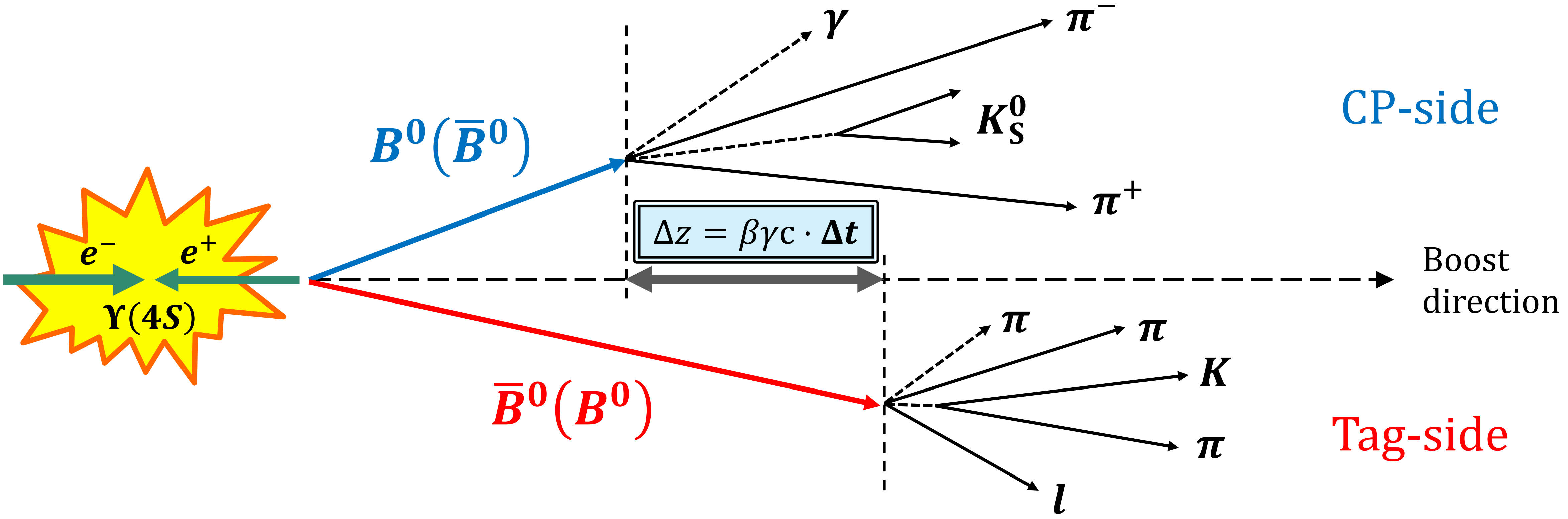
SuperKEKB & Belle II



- SuperKEKB: the "brightest" e^+e^- collider:
  - Current peak instantaneous luminosity: 4.7×10^{34} $\text{cm}^{-2}\text{s}^{-1}$ (**WR**)
  - Target instantaneous luminosity: 6×10^{35} $\text{cm}^{-2}\text{s}^{-1}$ ($\sim$30 times larger than at KEKB) achieved by **nano-beam scheme**
  - Already at 427 fb^{-1} $\approx$ BaBar dataset



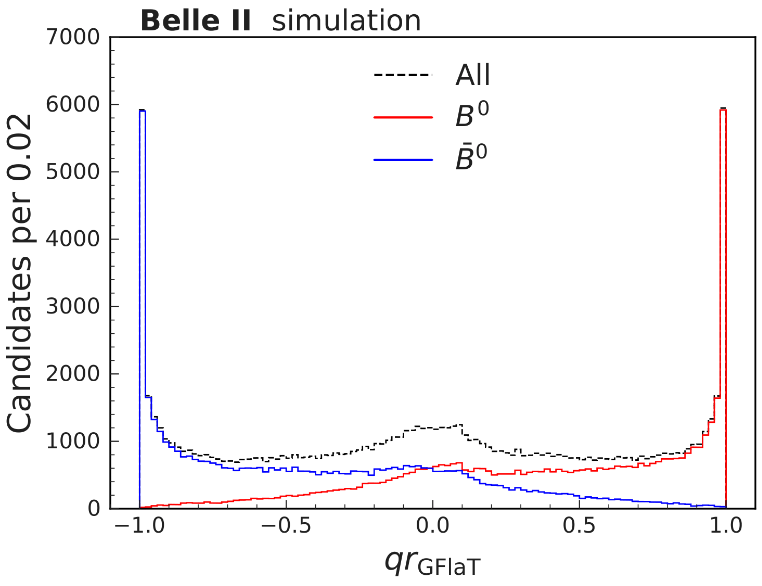
Event Reconstruction



- After fully reconstructing and vertexing the CP-side B candidate, the tracks from the rest of the event are used to vertex the tag-side ⇒ $\boldsymbol{\Delta t}$ measured indirectly using vertex positions
- Then the **Flavor Tagger** is run on the rest of the event to determine the B flavor at the time of decay

Flavor Tagging at Belle II

- B flavor currently estimated with a BDT classifier based on individual flavor estimators (i.e. high-p_T leptons, Kaons, etc.)
- The **Flavor Tagger** provides the tag-B flavor $\boldsymbol{q} = \pm 1$ and a confidence factor $\boldsymbol{r} = 1 - 2w$, where w is the mistag fraction
- 7 intervals of r: [0.0, 0.1, 0.25, 0.45, 0.6, 0.725, 0.875, 1.0] with the last bin corresponding to best flavor assignment
- Ongoing development to improve the Flavor Tagger based on deep learning techniques
- Expected improvement on statistical uncertainty of S: ~10%



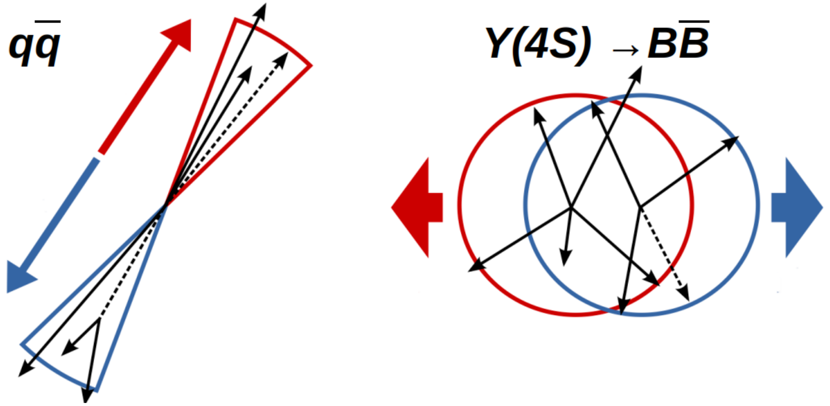
r-bin	$w(\%)$	$\Delta w(\%)$	$\mu(\%)$
0	48.29	0.78	−1.72
1	42.07	−1.41	−0.94
2	34.63	−0.04	−0.28
3	24.17	1.64	3.21
4	16.98	1.36	1.17
5	11.50	−0.26	−1.13
6	2.62	0.75	−0.18

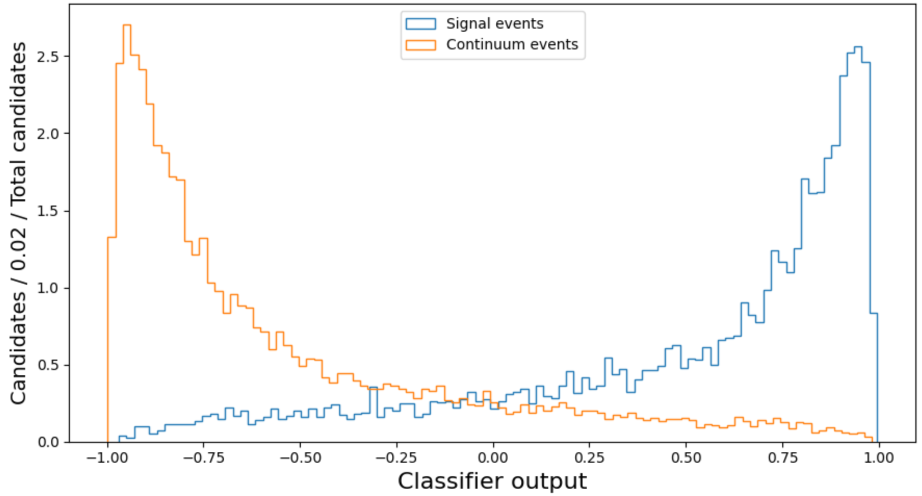
Calibrated Flavor Tagger parameters using 362 fb^{-1} data

Continuum Suppression

- Most dominant source of background is due to non-resonant $e^+e^- \to q\bar{q}$ events, with $q \in \{u, d, c, s\}$
- Has a jet-like topology as opposed to $\Upsilon(4S) \to B\bar{B}$ events which have a spherically symmetric topology
- Train a BDT classifier to suppress continuum background using event-shape variables as inputs:
  - Cosine of the angle between the thrust axes of the event
  - Cosine of the B-momentum polar angle in the CMS
  - Fox-Wolfram moments

$$H_l = \sum_{i,j} \frac{|p_i||p_j|}{E^2_{\text{event}}} P_l(cos\theta_{i,j})$$





Selection Criteria

- Pre-selection:
  - $1.4 < E_\gamma < 4$ GeV
  - Loose event-level cuts regarding no. of tracks & calorimeter clusters
  - Rest-of-Event (RoE) cuts to remove tracks & clusters due to beam background
- Additional selections:
  - π^0 likeness of photon < 0.7
  - Prompt $\pi^\pm$ pionID > 0.1
  - $\mathrm{M}_{K_S\pi\pi} < 1.8$ GeV/c^2
  - $0.6 < \mathrm{M}_{\pi\pi} < 0.9$ GeV/c^2 (ρ mass window)
  - "K_S selector" MVA classifier > 0.95 (optimised)
  - Continuum Suppression MVA classifier > 0.28 (optimised)
  - Single Candidate Selection (random)

Cut	Signal Efficiency (%)
$\pi^\pm$ pionID > 0.1	91.6 (91.6)
π^0 likeness < 0.7	80.8 (74.0)
$\mathrm{M}_{K_S\pi\pi} < 1.8$	78.9 (58.4)
$0.6 < \mathrm{M}_{\pi\pi} < 0.9$	52.6 (30.7)
K_S MVA > 0.95	92.0 (28.3)
CSMVA > 0.28	73.1 (20.7)
Single Candidate	84.1 (17.4)

*cumulative efficiencies in parentheses

Fit Strategy

- Four separate fit components: signal, self crossfeed (SCF), continuum and $B\bar{B}$ background → shape parameters of fit components obtained from fit to simulated $\mathrm{M_{bc}}$ and ΔE distributions

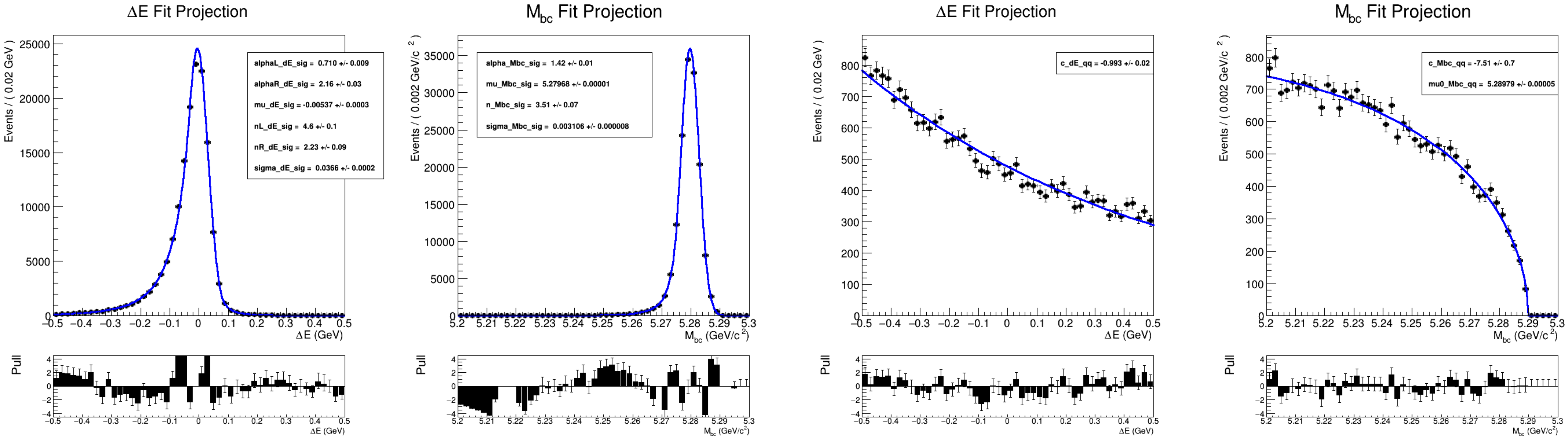
- Δt resolution model parameters determined from fit to Δt residual distribution of pure signal MC sample (more details on this shortly)

- Signal and background yields extracted via a 2D fit to $\mathrm{M_{bc}}$ and ΔE

- Subtract background in Δt using $sPlot$ [arxiv.org/abs/physics/0402083] and then fit resulting Δt distribution for S and C

$$\mathrm{M_{bc}} = \sqrt{{E_{\mathrm{beam}}/_{2}}^{2} - {p_{\mathrm{B}}^{*}}^{2}}$$
$$\Delta E = E_{\mathrm{B}}^{*} - \sqrt{s}/2$$

Shape parameters extraction



Signal:

- ΔE : Double-sided Crystal Ball
- M_{bc} : Crystal Ball

Continuum:

- ΔE : Exponential
- M_{bc} : Argus

Δt Model

- The signal Δt model can be written as:

$$\mathcal{P}(\Delta t, q = \pm 1) = \frac{e^{-|\Delta t|/\tau_{B0}}}{2\tau_{B0}}\{1 - q\Delta w + q\mu(1 - 2w) + \\ + [q(1 - 2w) + \mu(1 - q\Delta w)][\,\boldsymbol{S}\sin(\Delta m_{\mathrm{d}}\Delta t) - \boldsymbol{C}\cos(\Delta m_{\mathrm{d}}\Delta t)]\} \otimes \boldsymbol{\mathcal{R}}_{\mathbf{det}}$$

Δt Model

- The signal Δt model can be written as:

$$\mathcal{P}(\Delta t, q = \pm 1) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}}\{1 - q\Delta w + q\mu(1 - 2w) + \\ + [q(1 - 2w) + \mu(1 - q\Delta w)][\boldsymbol{S}\sin(\Delta m_{\rm d}\Delta t) - \boldsymbol{C}\cos(\Delta m_{\rm d}\Delta t)]\} \otimes \boldsymbol{\mathcal{R}}_{\mathbf{det}}$$

CP violation parameters

Δt Model

- The signal Δt model can be written as:

$$\mathcal{P}(\Delta t, q = \pm 1) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}} \{1 - q\Delta w + q\mu(1 - 2w) + [q(1 - 2w) + \mu(1 - q\Delta w)][\boldsymbol{S}\sin(\Delta m_{\mathrm{d}}\Delta t) - \boldsymbol{C}\cos(\Delta m_{\mathrm{d}}\Delta t)]\} \otimes \boldsymbol{\mathcal{R}}_{\mathbf{det}}$$

Flavor Tagger parameters

Δt Model

➢ The signal Δt model can be written as:

$$\mathcal{P}(\Delta t, q=\pm 1) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}}\{1 - q\Delta w + q\mu(1-2w) + \\ + [q(1-2w) + \mu(1-q\Delta w)][\,\boldsymbol{S}\sin(\Delta m_{\mathrm{d}}\Delta t) - \boldsymbol{C}\cos(\Delta m_{\mathrm{d}}\Delta t)]\} \otimes \boldsymbol{\mathcal{R}}_{\mathbf{det}}$$

where $\mathcal{R}_{\mathrm{det}}$ is the Δt resolution function, which models smearing effects due to the finite resolution of the detector in measuring the CP-side and tag-side B vertex positions, which are used to determine Δt

Δt Model

- The signal Δt model can be written as:

$$\mathcal{P}(\Delta t, q = \pm 1) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}} \{1 - q\Delta w + q\mu(1-2w) + \\ + [q(1-2w) + \mu(1 - q\Delta w)][\, \boldsymbol{S} \sin(\Delta m_{\mathrm{d}} \Delta t) - \boldsymbol{C} \cos(\Delta m_{\mathrm{d}} \Delta t)]\} \otimes \boldsymbol{\mathcal{R}_{\mathrm{det}}}$$

where $\mathcal{R}_{\mathrm{det}}$ is the Δt resolution function, which models smearing effects due to the finite resolution of the detector in measuring the CP-side and tag-side B vertex positions, which are used to determine Δt

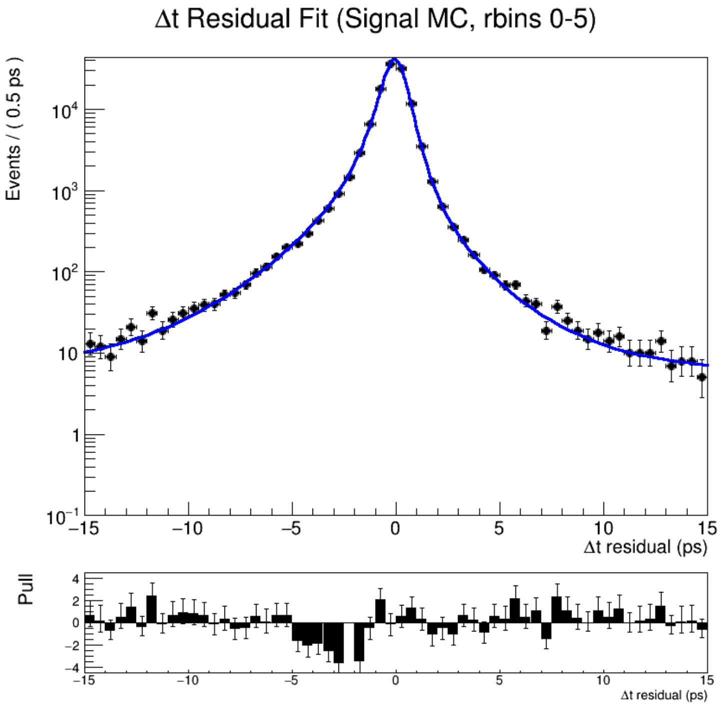
- Similar model for $\mathcal{R}_{\mathrm{det}}$ to the one used in BaBar to account for detector resolution effects:

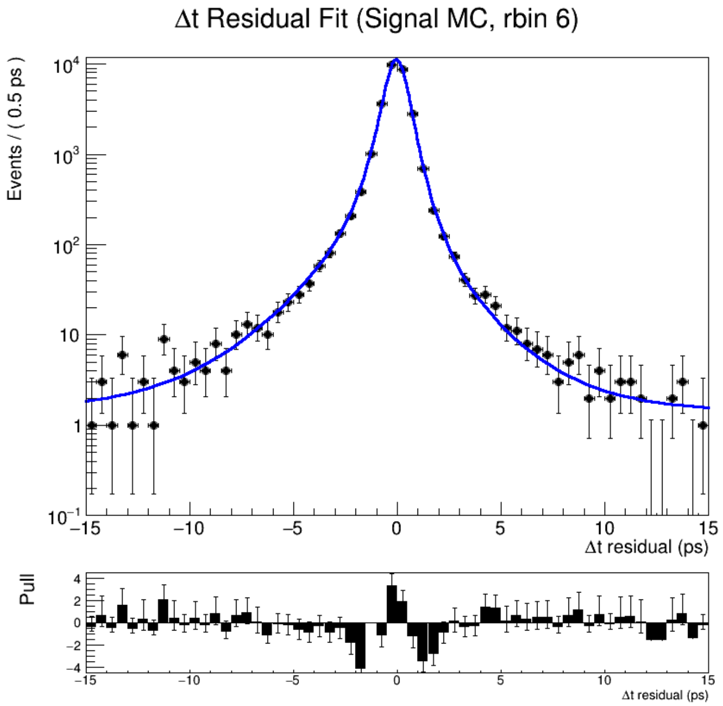
$$\mathcal{R}(\delta\Delta t; \sigma) = (1 - f_{\mathrm{OL}})\mathcal{R}_{\mathrm{core}}(\delta\Delta t; \sigma) + f_{\mathrm{OL}}\mathcal{R}_{\mathrm{OL}}(\delta\Delta t; \sigma)$$

$$\begin{aligned} \mathcal{R}_{\mathrm{core}}(\delta\Delta t; \sigma) = & (1 - f_{\mathrm{tail}}) \cdot G(\delta\Delta t; \mu_{\mathrm{main}} \cdot \sigma, s_{\mathrm{main}} \cdot \sigma) \\ & + (1 - f_{\mathrm{exp}}) \cdot f_{\mathrm{tail}} \cdot G(\delta\Delta t; \mu_{\mathrm{tail}} \cdot \sigma, s_{\mathrm{tail}} \cdot \sigma) \\ & + f_{\mathrm{tail}} \cdot f_{\mathrm{exp}} \cdot G(\delta\Delta t; \mu_{\mathrm{tail}} \cdot \sigma, s_{\mathrm{tail}} \cdot \sigma) \\ & \quad \otimes \left((1 - f_{\mathrm{R}}) \exp\_(\delta\Delta t / c \cdot \sigma) + f_{\mathrm{R}} \exp_{+}(-\delta\Delta t / c \cdot \sigma)\right) \end{aligned}$$

Δt Residual fits

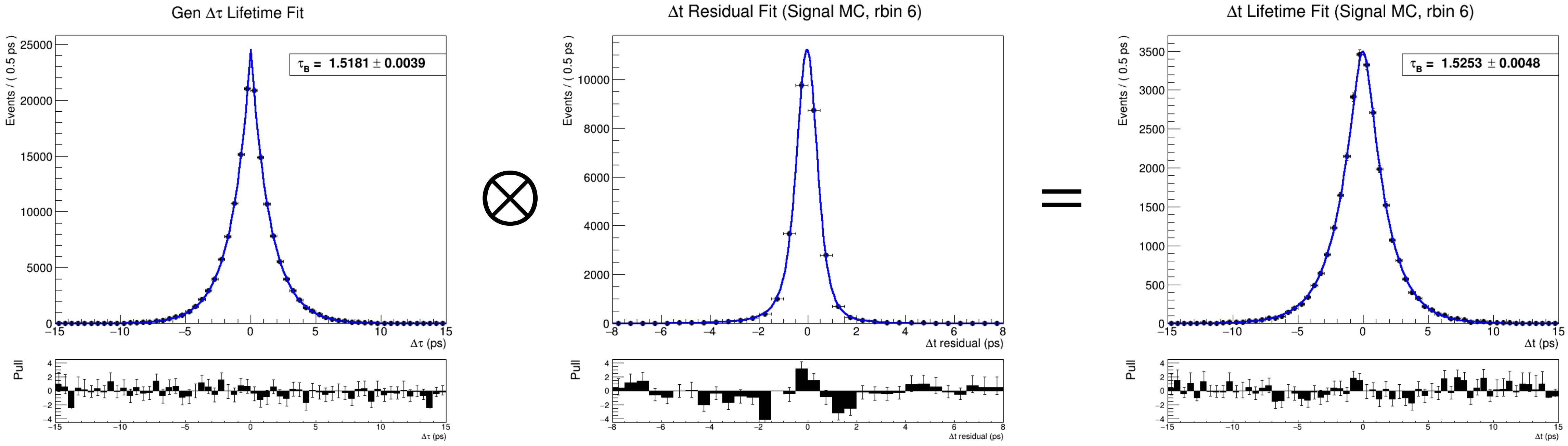
- Δt resolution parameter values determined by fitting the distribution of $\delta\Delta\text{t} = \Delta t^{\text{reco}} - \Delta t^{\text{true}}$ in the pure signal MC sample simultaneously in r-bins 0-5 and 6
- Resolution model parameter values noticeably different in two r-bin categories





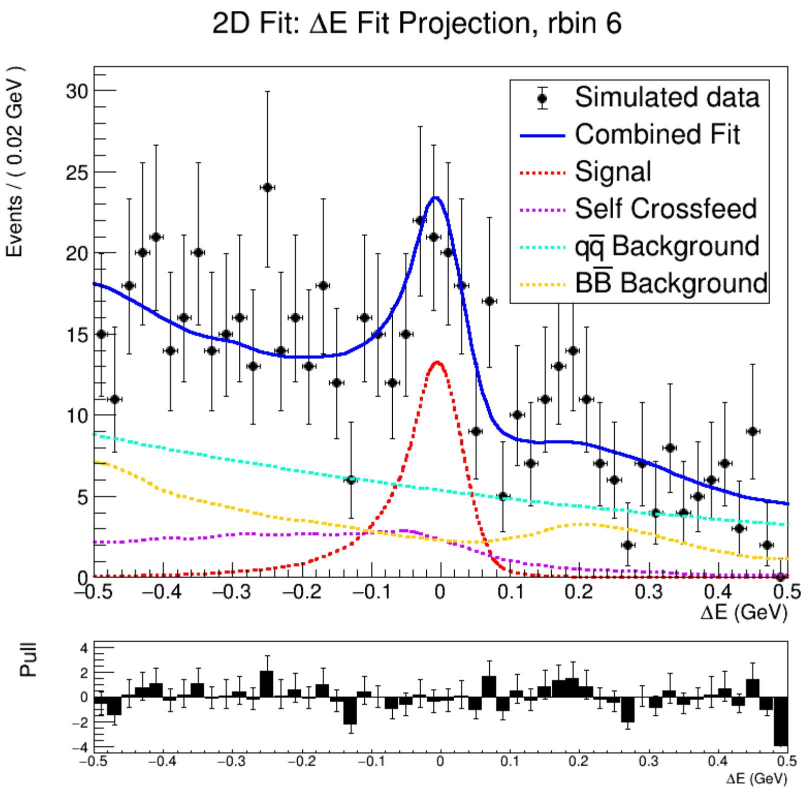
Lifetime fits

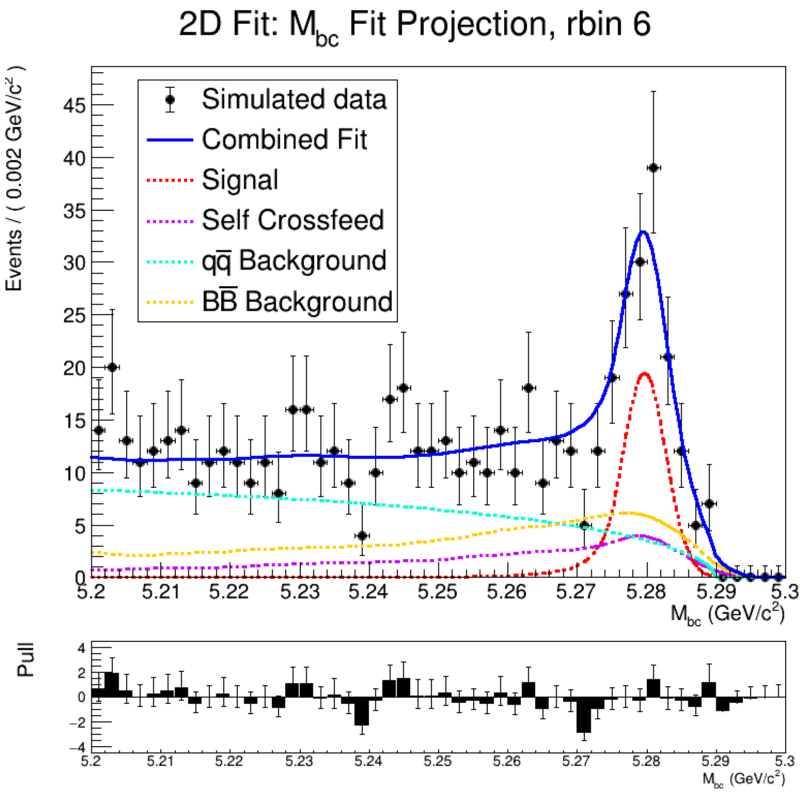
- One important check is to fit for the B lifetime (τ_{B^0}) without taking into account information on the B flavor
- The Δt resolution model is convolved with the pure physics Δt model



Yield extraction

- We fit the product of M_{bc} and ΔE to extract the signal and background yields



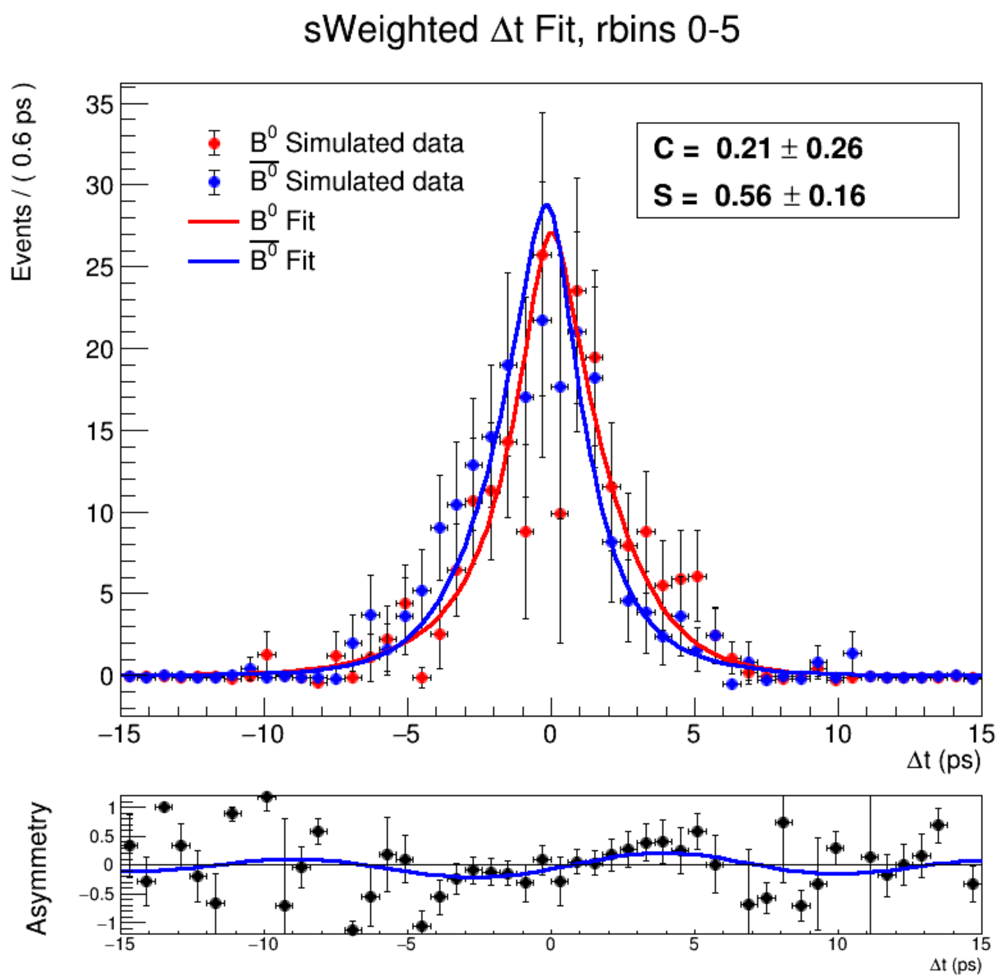


Yields (expected)	r-bins 0-5	r-bin 6
Signal	390 ± 30	90 ± 10
Background	10800 ± 110	540 ± 20

* MC sample equivalent in size to the 362 fb^{-1} real data sample

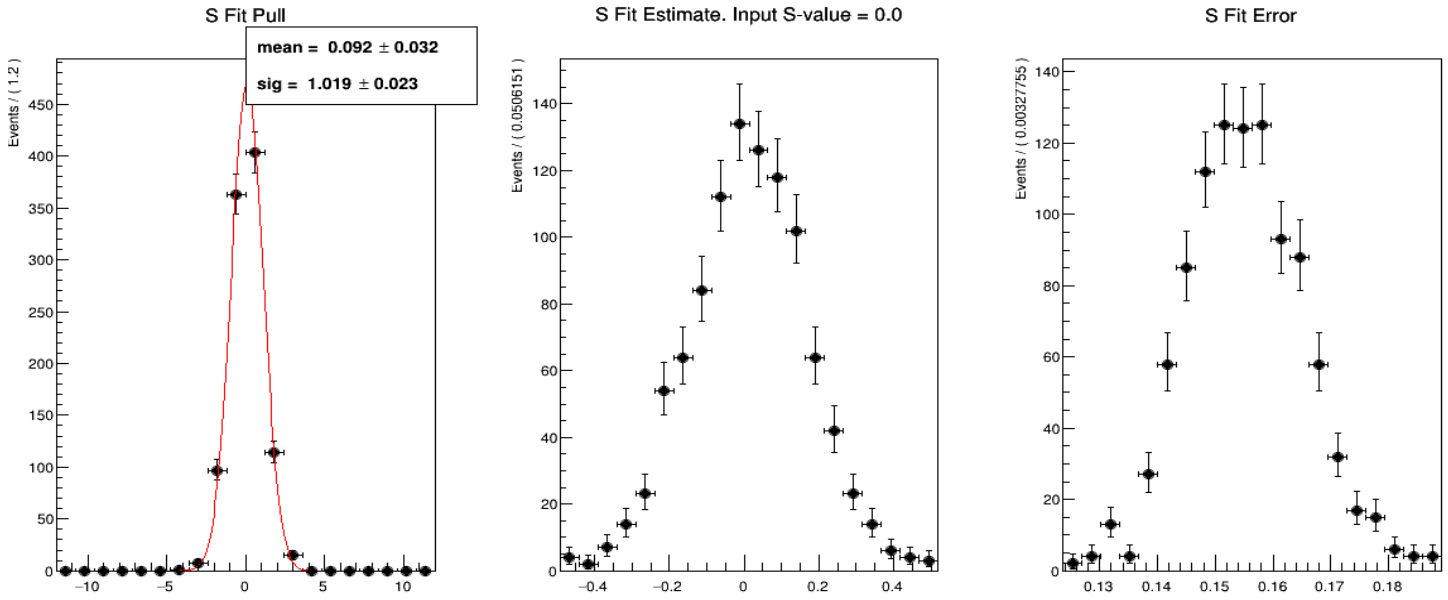
Δt fit

- *sPlot* is used to subtract background in Δt
- We fit the sWeighted Δt distribution of a sample that contains signal events generated with inputs $(C, S) = (0, 0.6)$
- Procedure to fit for $S^{\pm}$ already in place

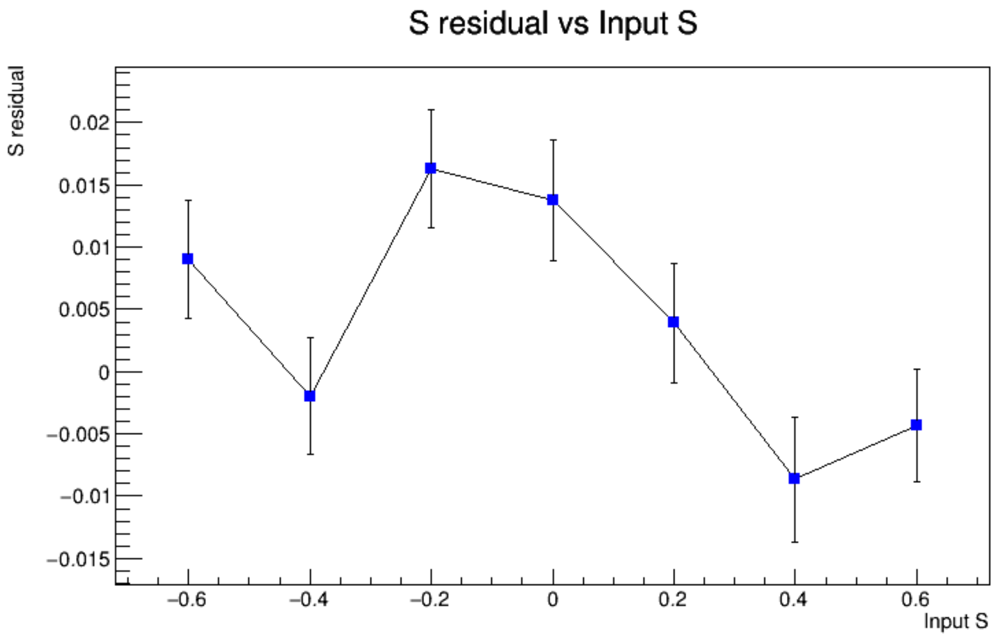


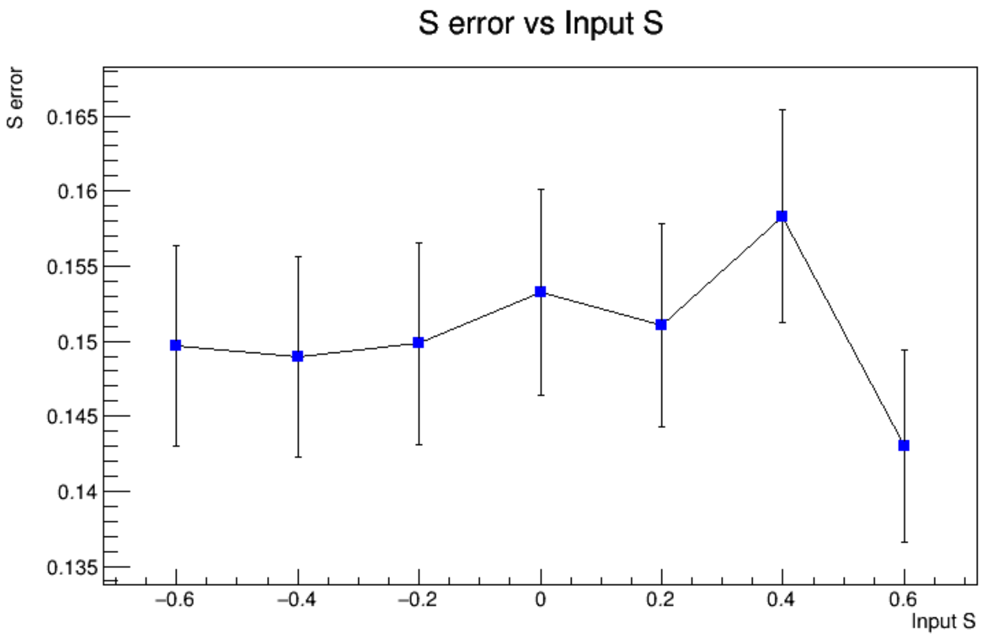
Linearity studies

- ➢ We generate 1 million signal events with $C = 0$ and $S = [-0.6, -0.4, -0.2, 0.0, 0.2, 0.4, 0.6]$ using an implementation of SVP_CP model from EvtGen in the Belle II software
- ➢ We make 1000 bootstrapped replicas using our simulated sample and perform the full fit on each of them to try and identify potential biases in the fit procedure



Linearity studies

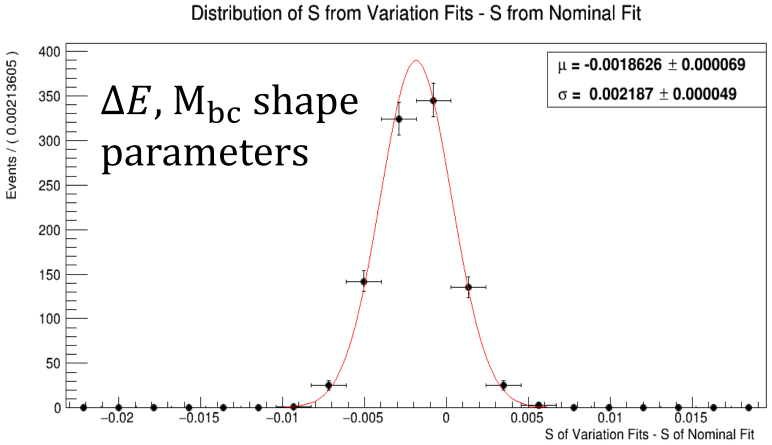


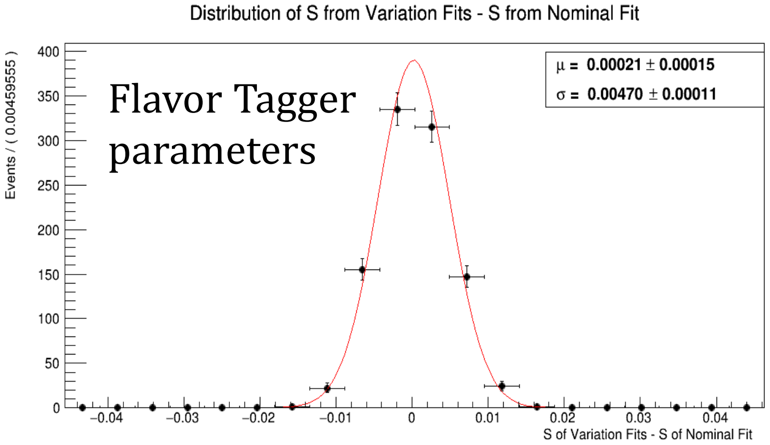


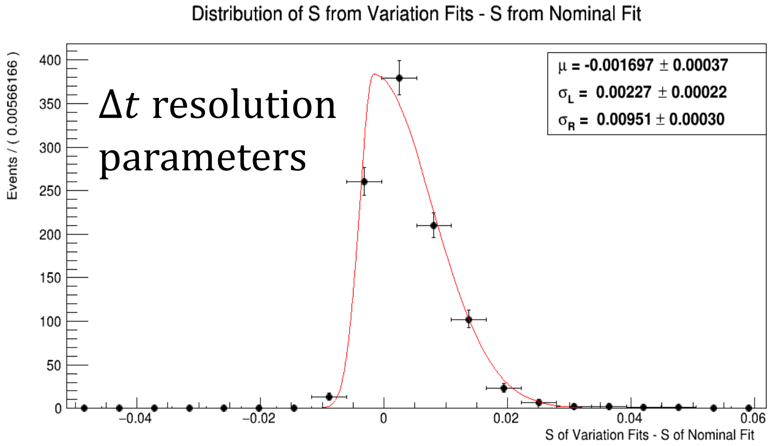
- No particular trend observed in the residual of $S = S^{\text{fit}} - S^{\text{true}}$
- Expected uncertainty on $\boldsymbol{S}$ is ~ 0.15, which is $\sim 36\%$ larger than the one expected from the Belle analysis with half the dataset size

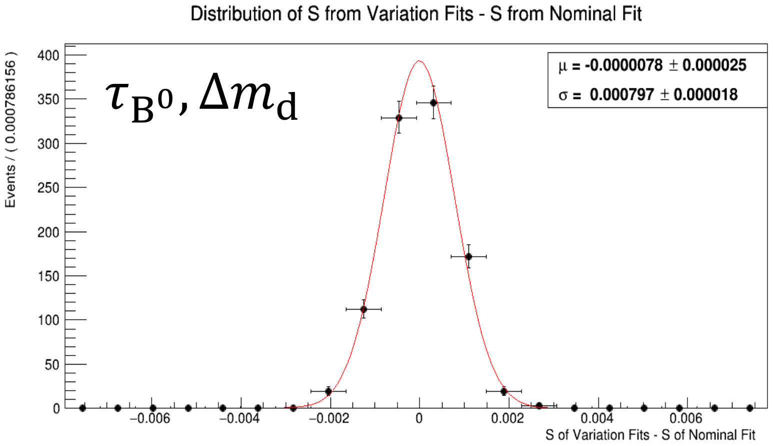
Systematics

- First few sources of systematic uncertainty already estimated (from MC)









Conclusion & prospects

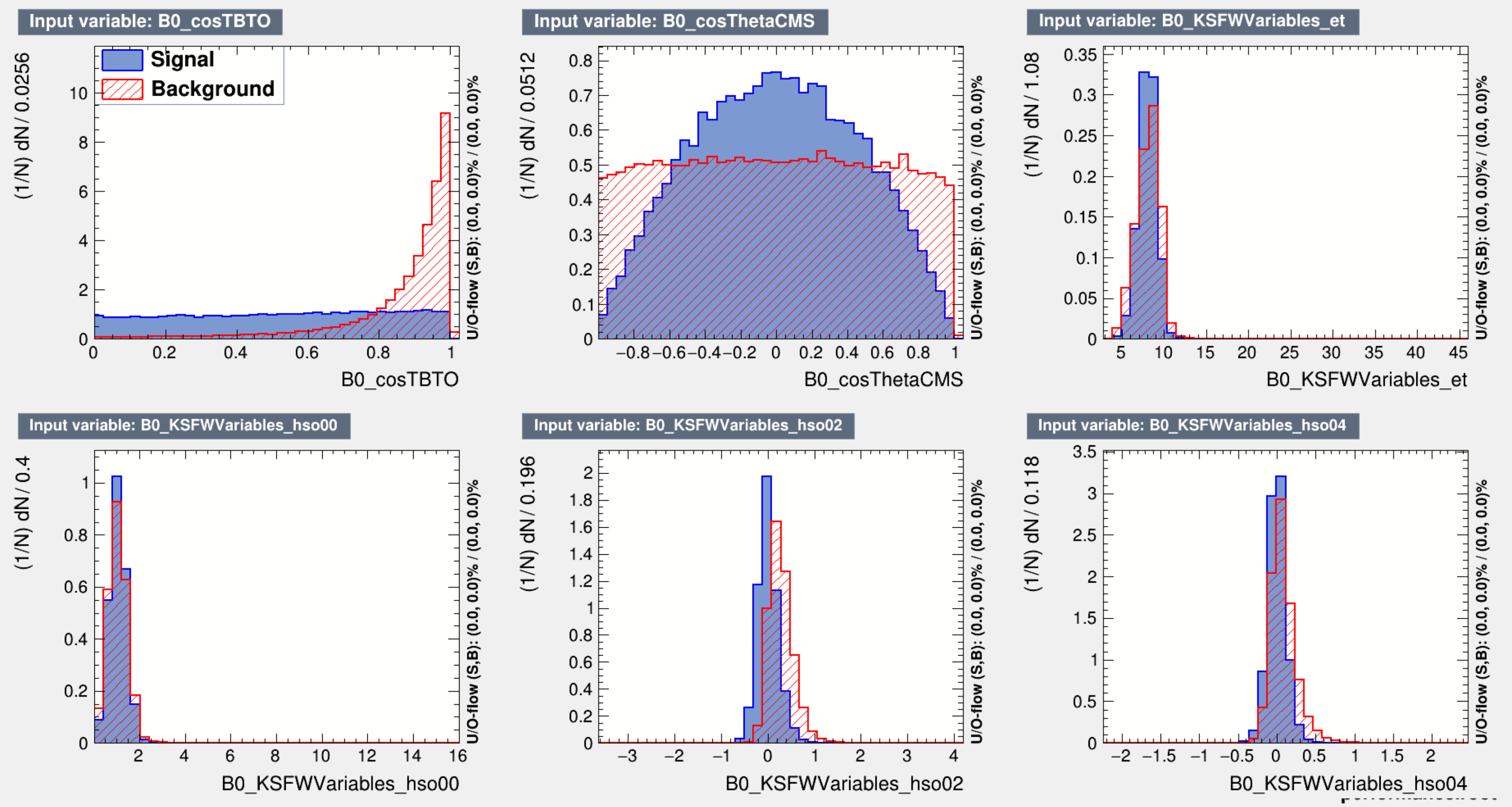
- ✓ Current fit strategy used for Belle II analysis seems robust
  - Belle analysis is already in a mature state (not shown here)
- ✓ Already started estimating systematics
- ➢ Next steps:
  - Control channel: $B^0 \to J/\psi\ K\pi$ for fit validation and data/MC corrections
  - Finish up systematics estimation (also for $S^{\pm}$)

Thank You!

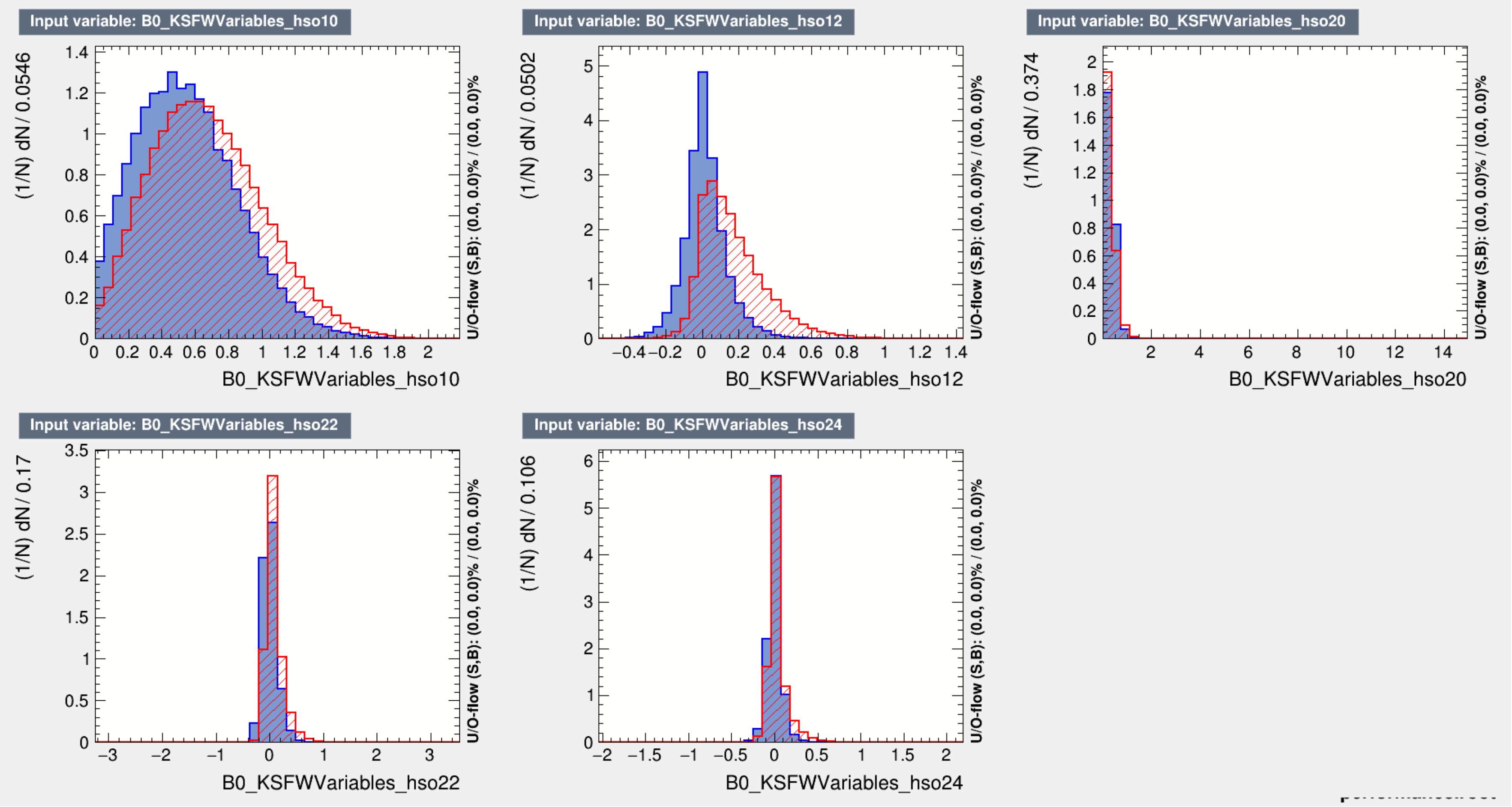
Questions?

Backup

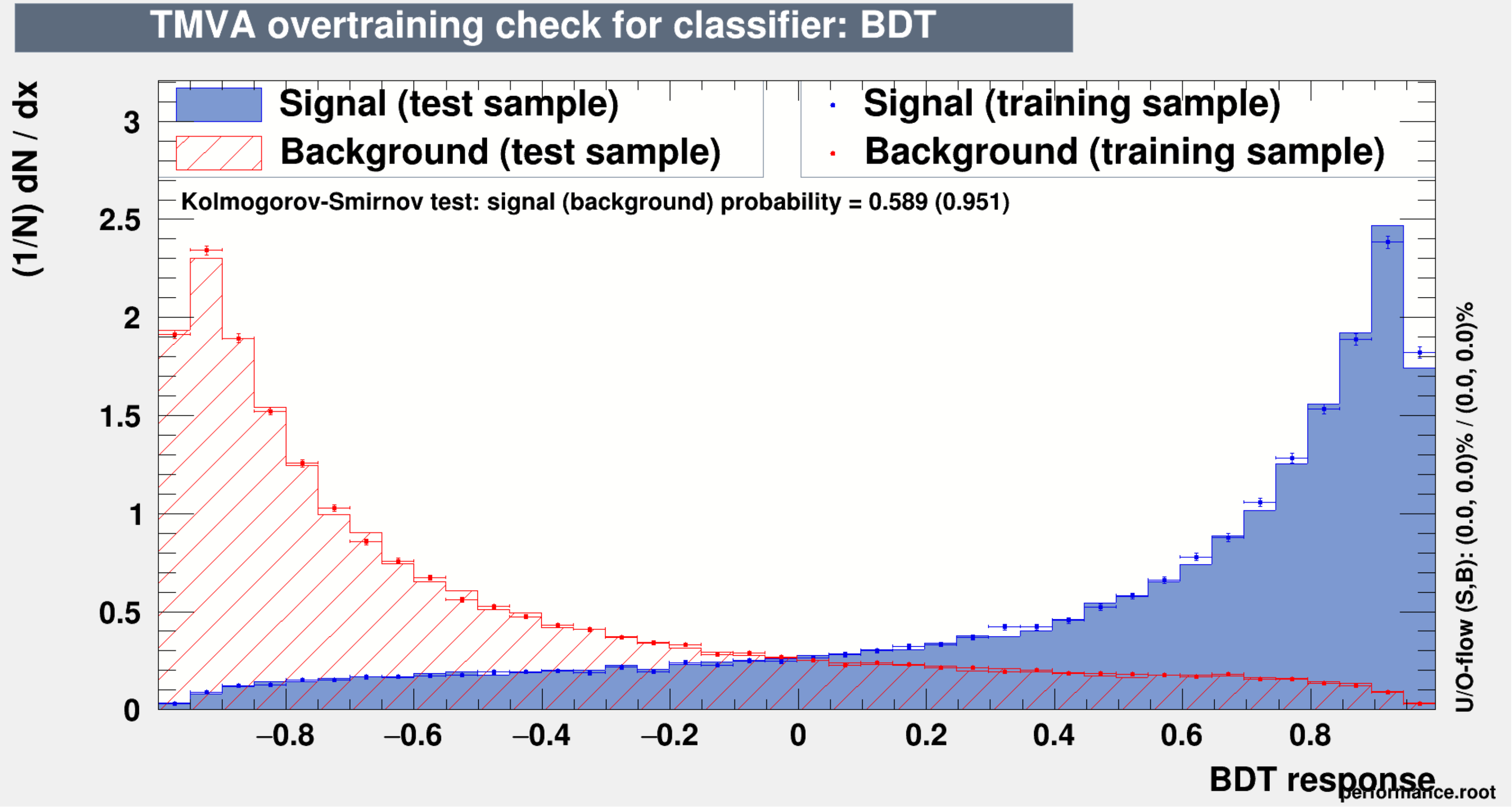
Continuum Suppression



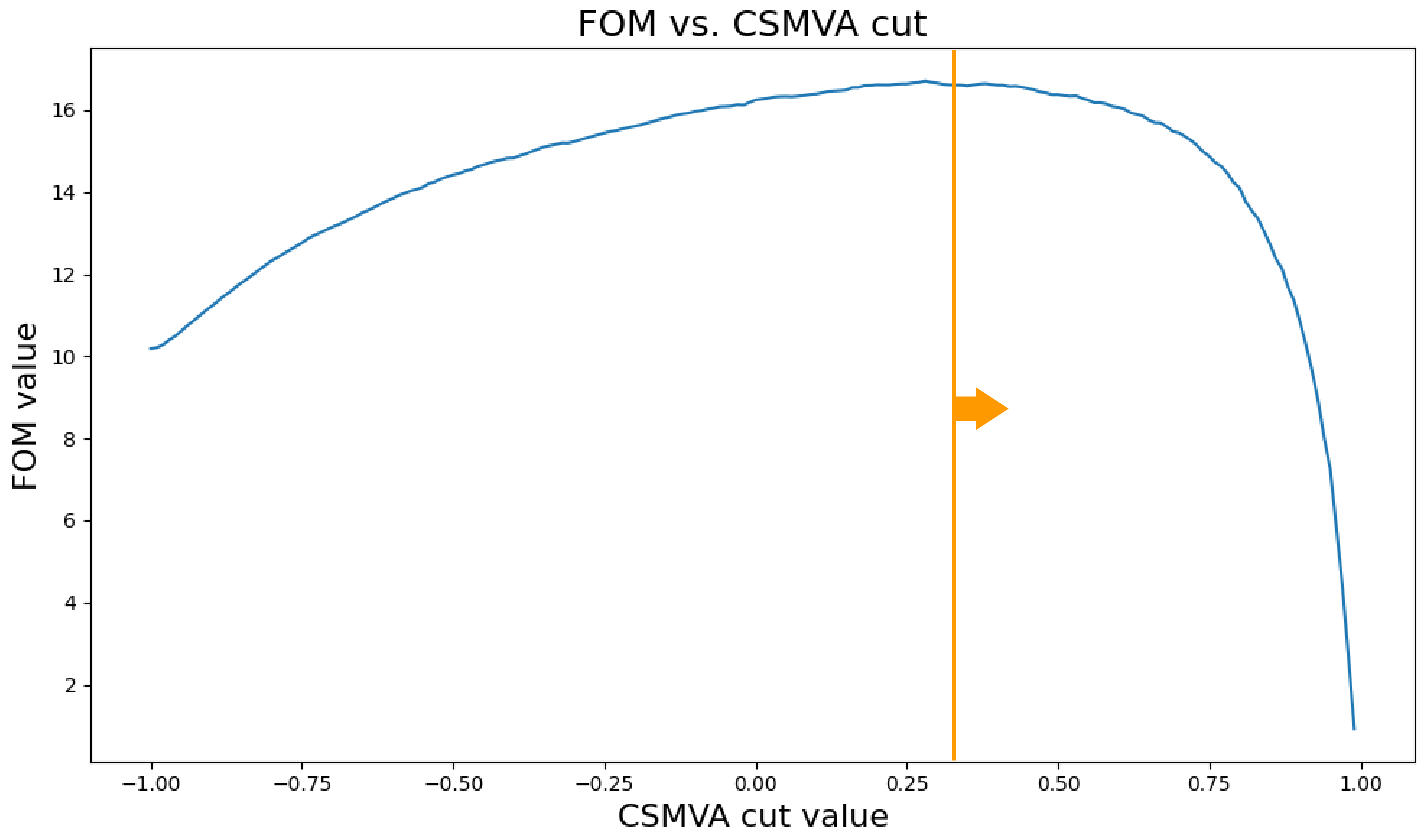
Continuum Suppression



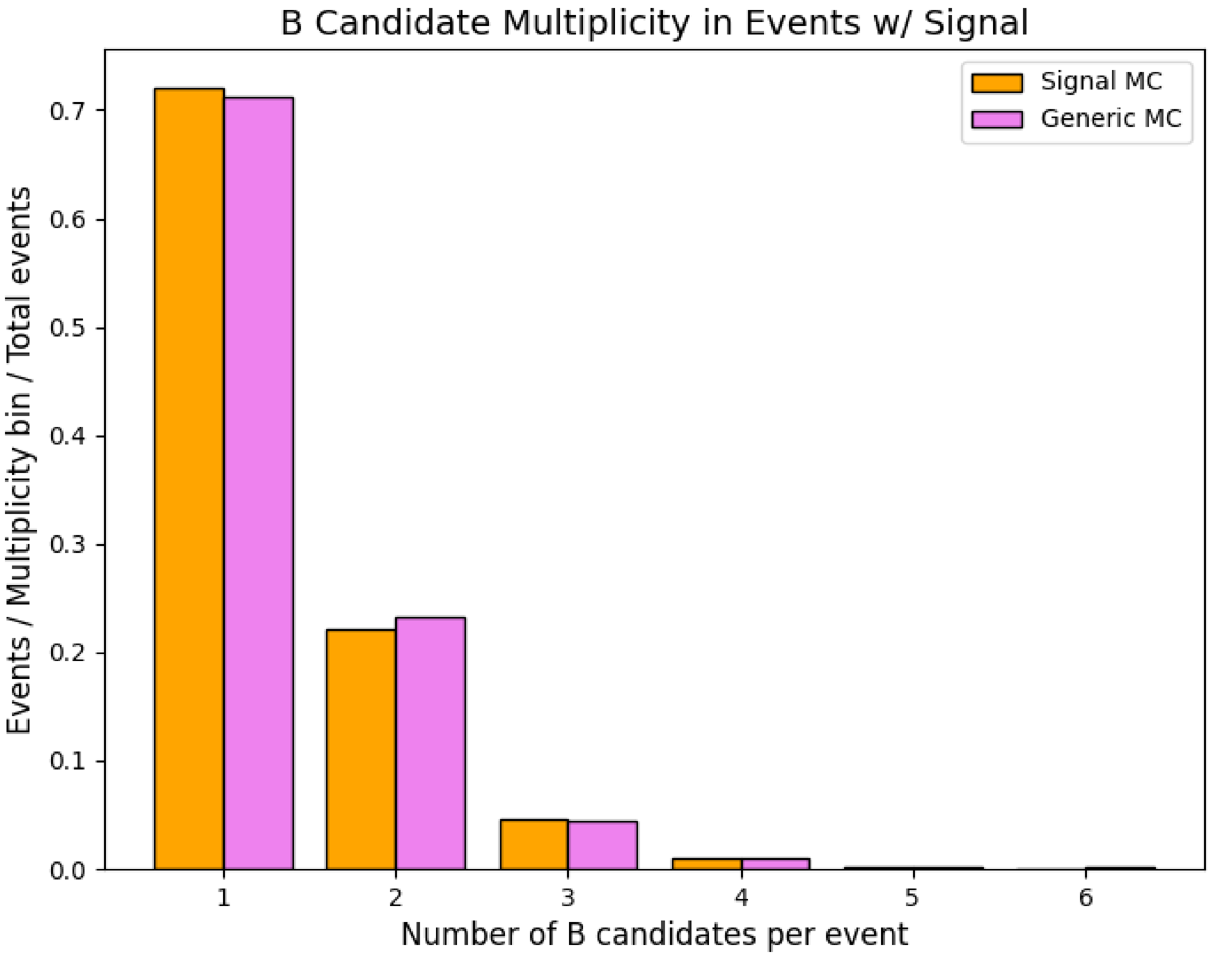
Continuum Suppression



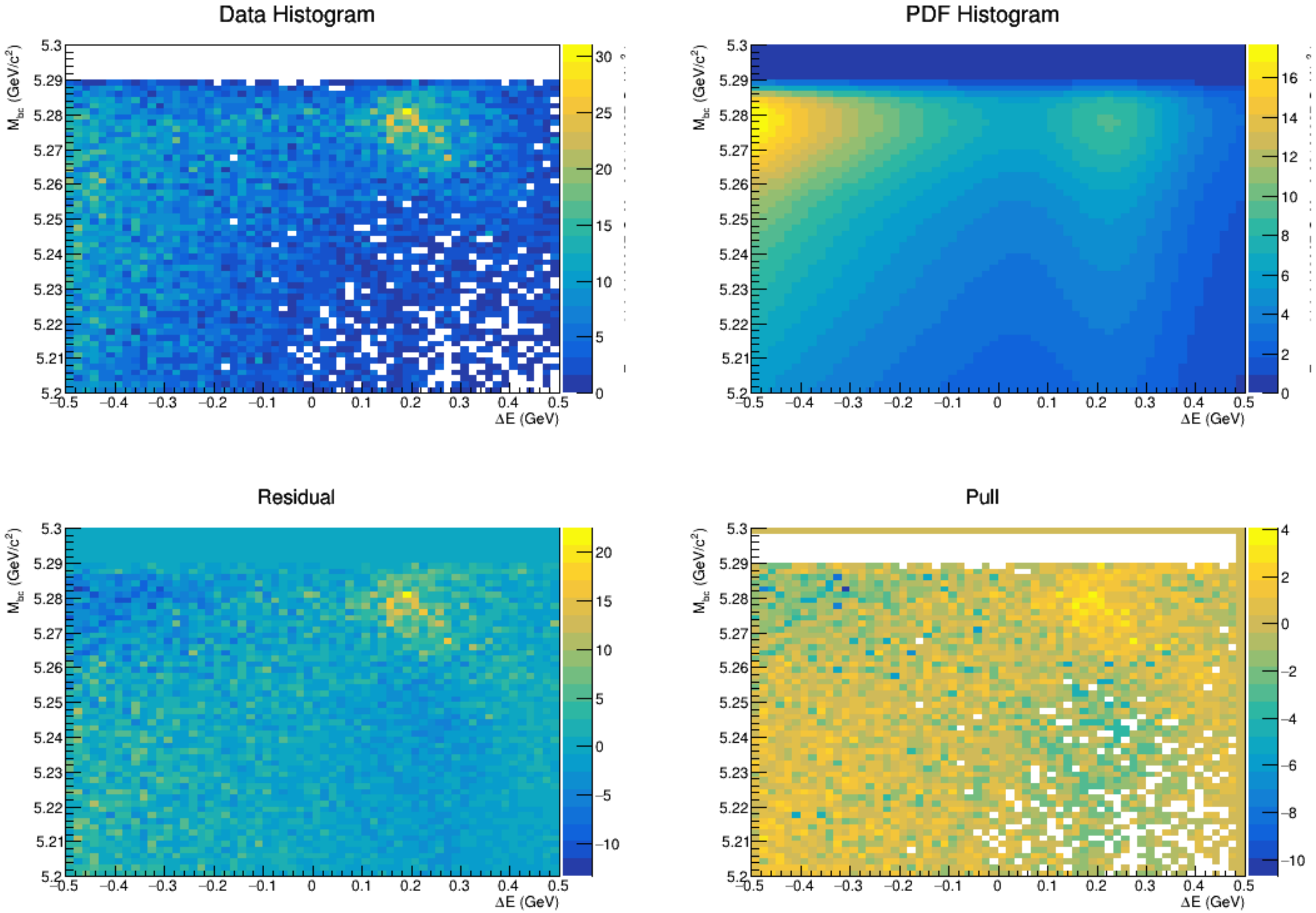
CSMVA cut optimisation



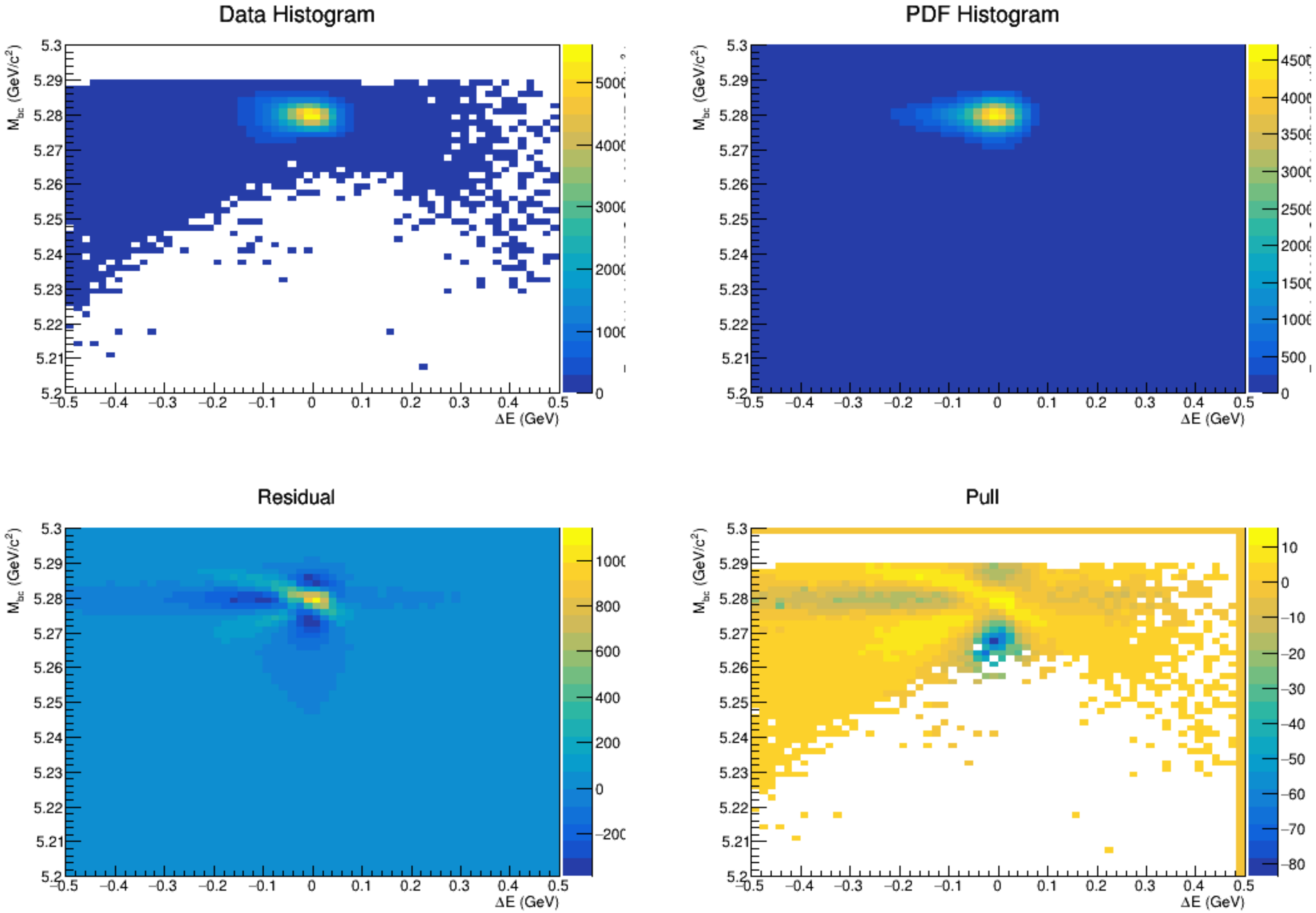
Candidate Multiplicity



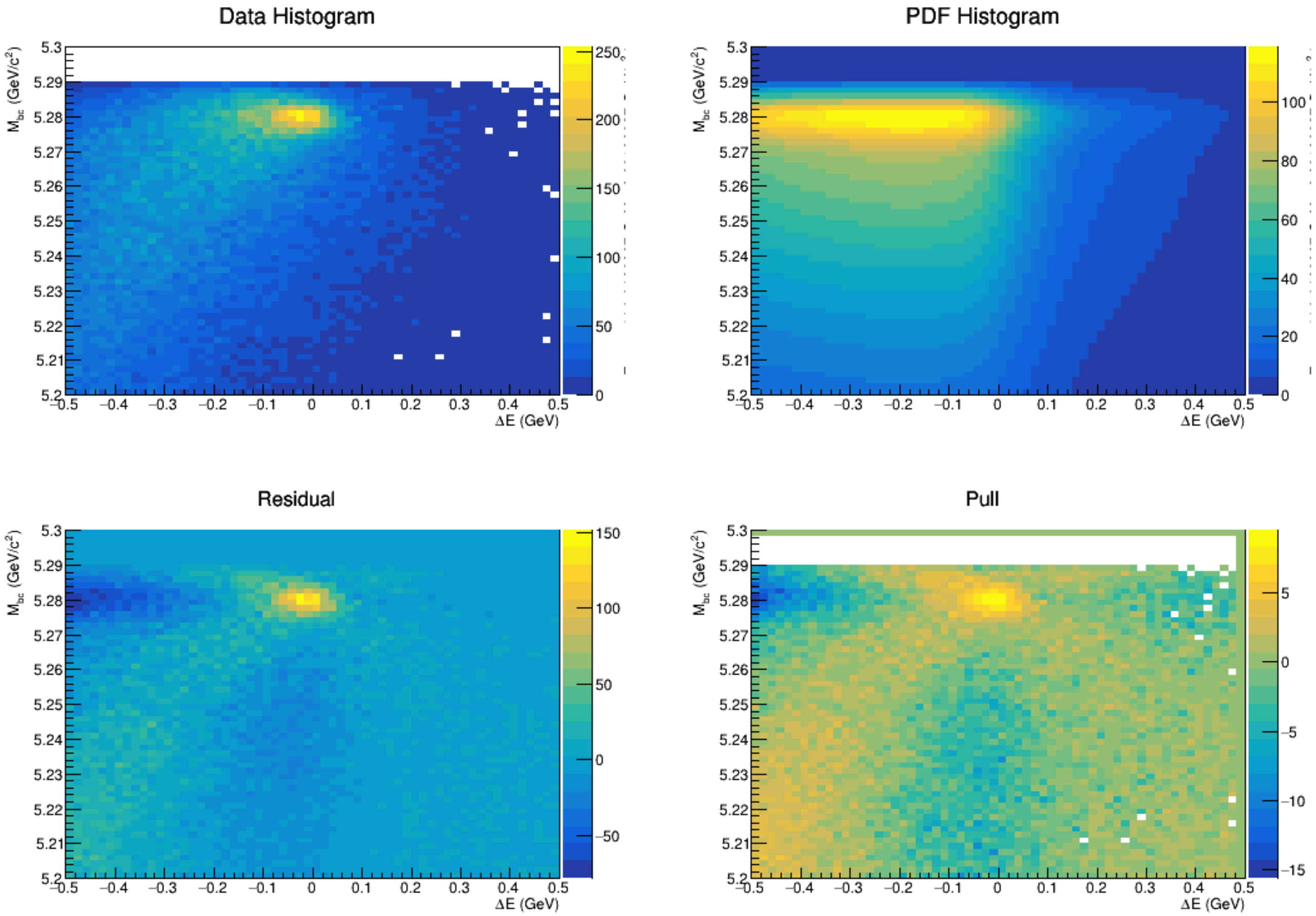
2D residual – $B\bar{B}$ bkg



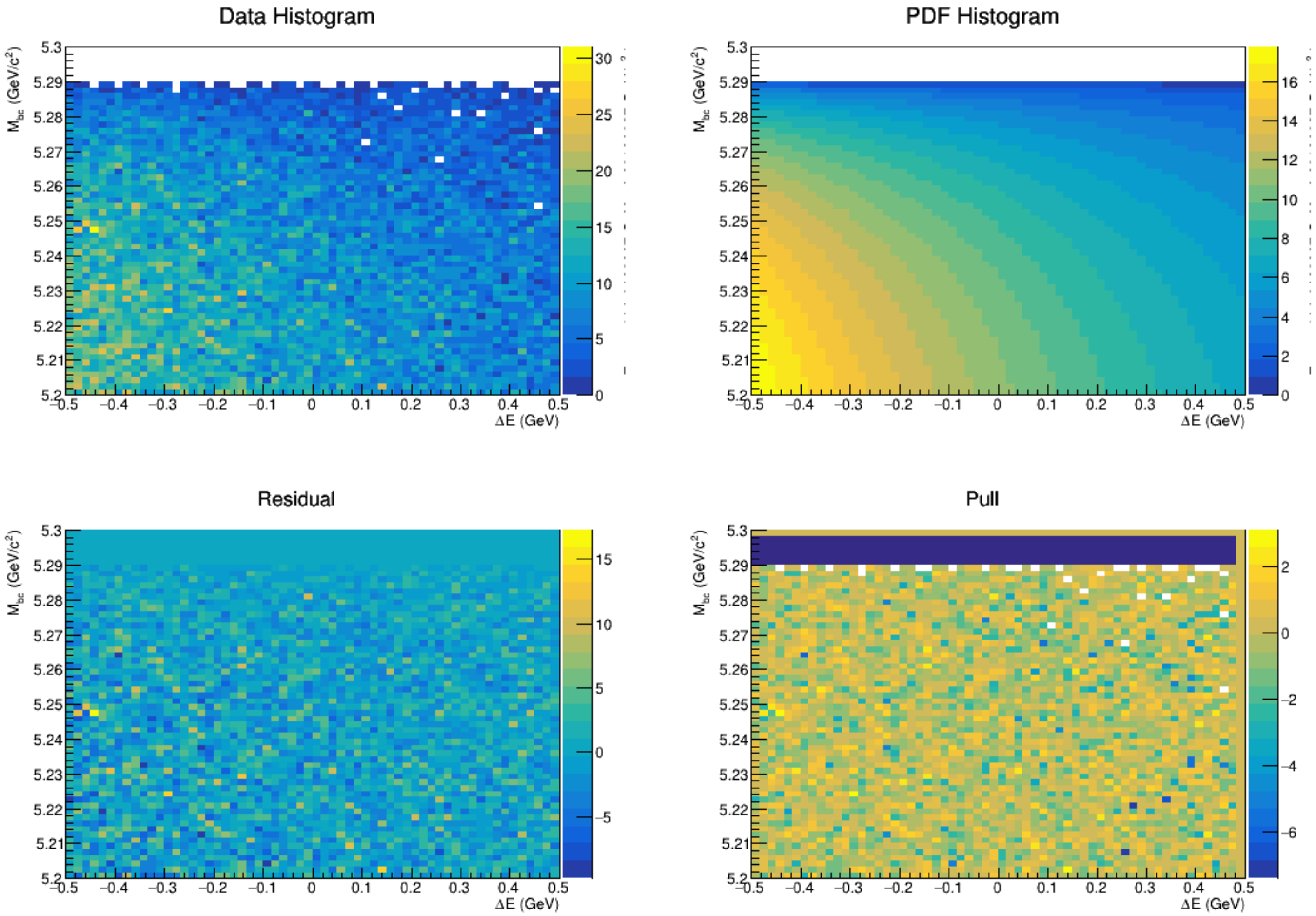
2D residual – Signal



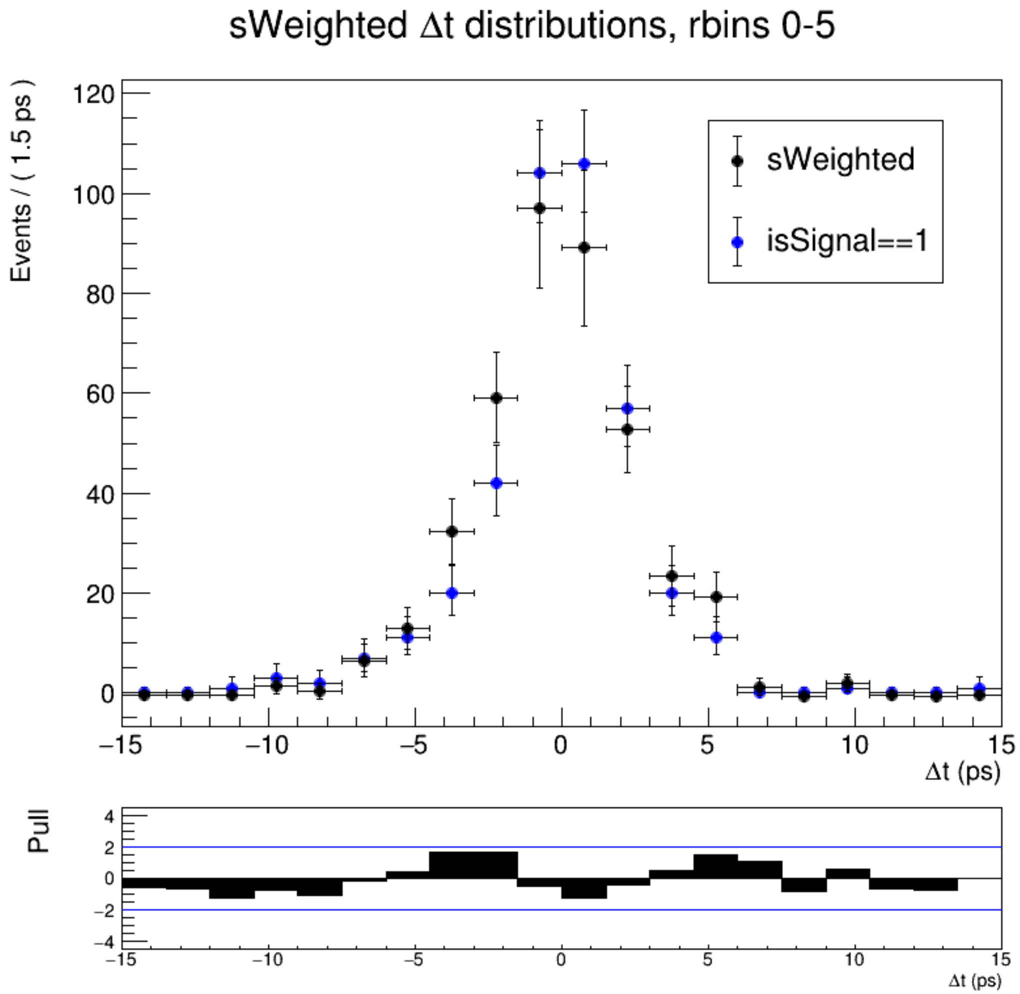
2D residual – SCF

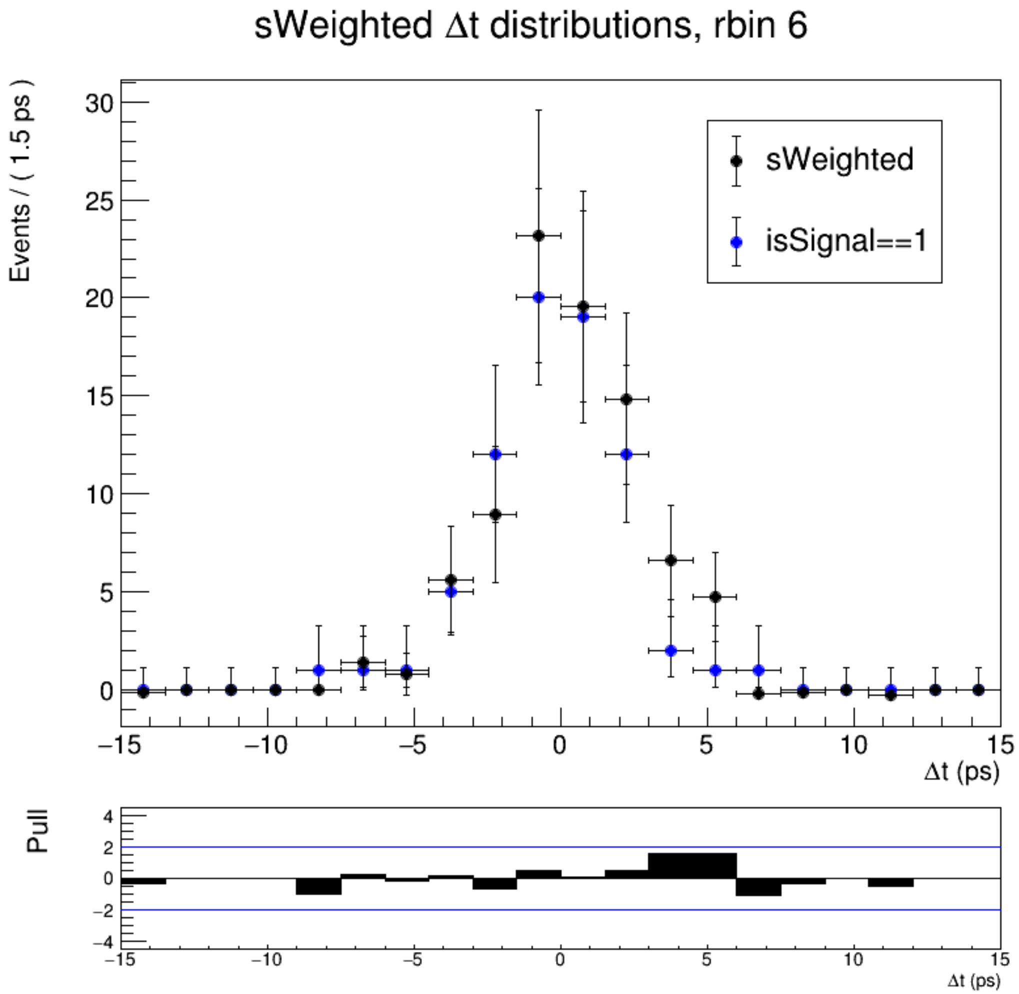


2D residual – Continuum

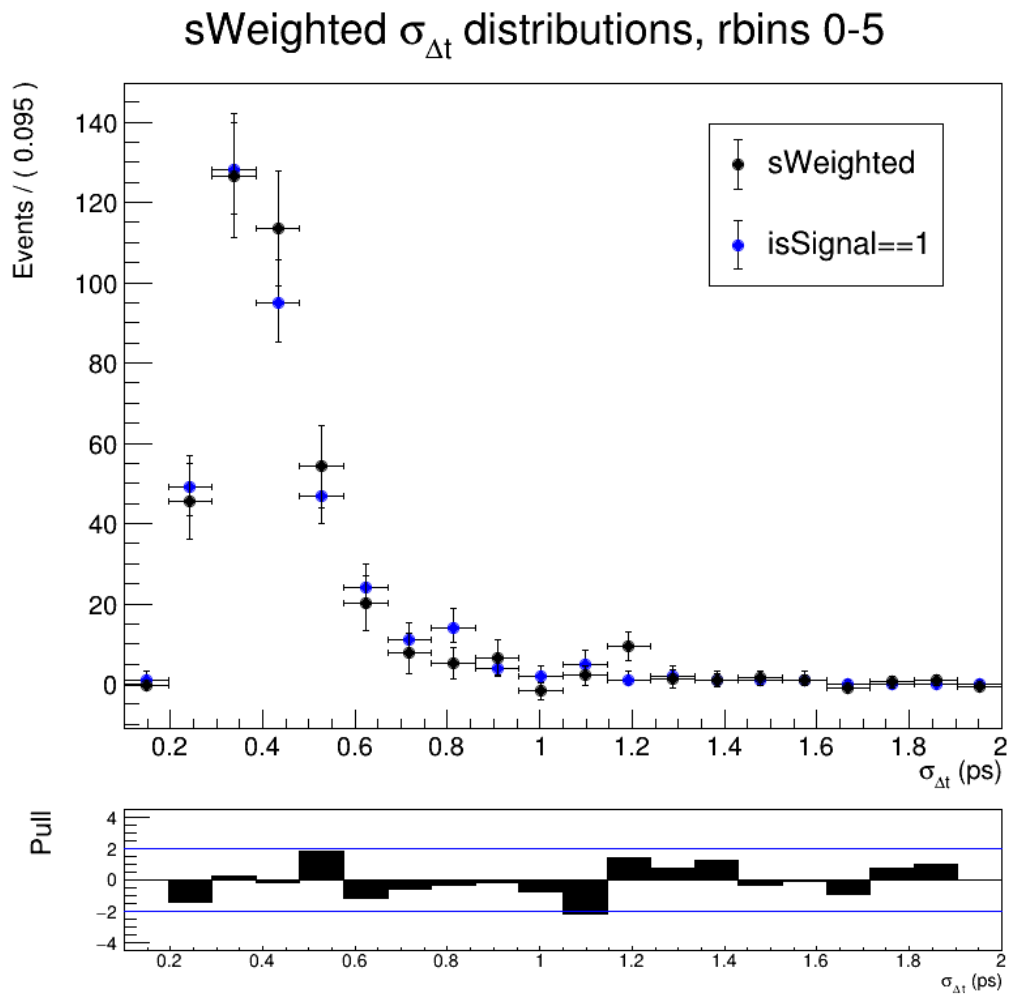


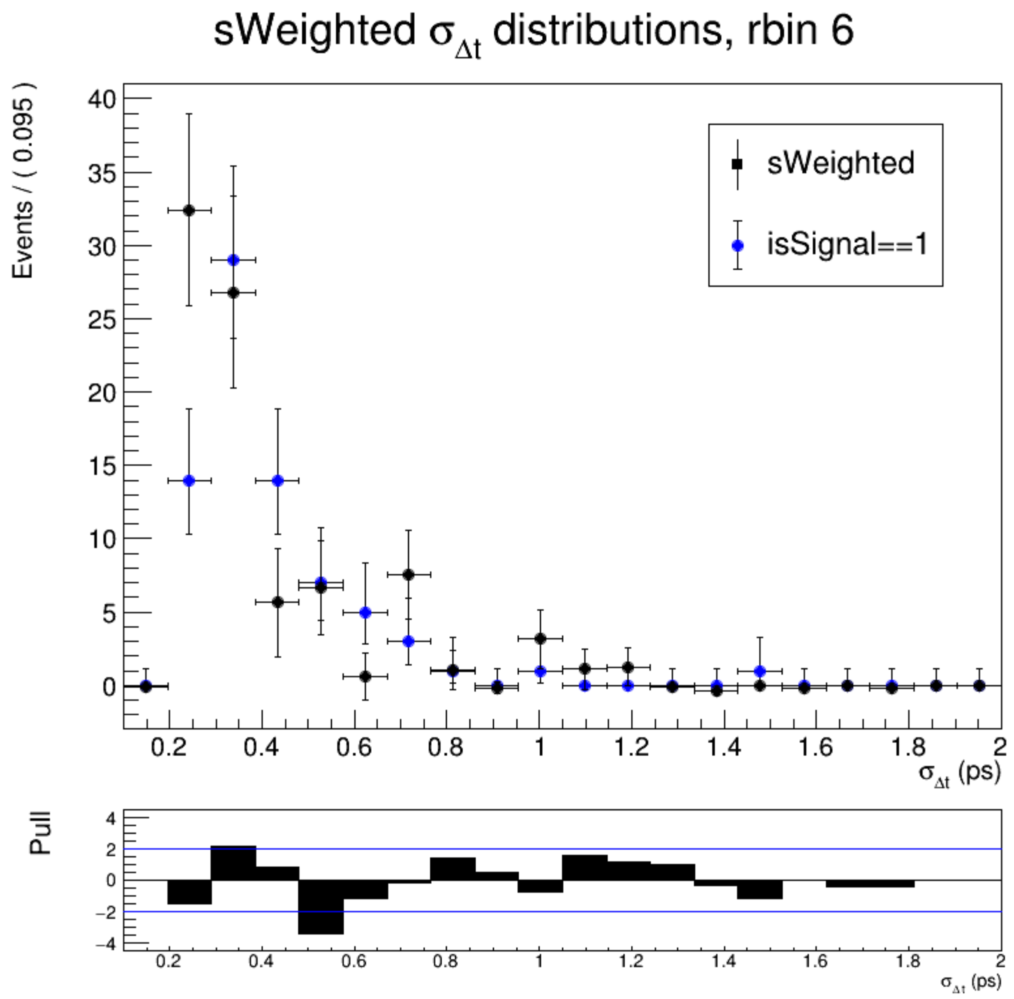
sWeights validation – Δt



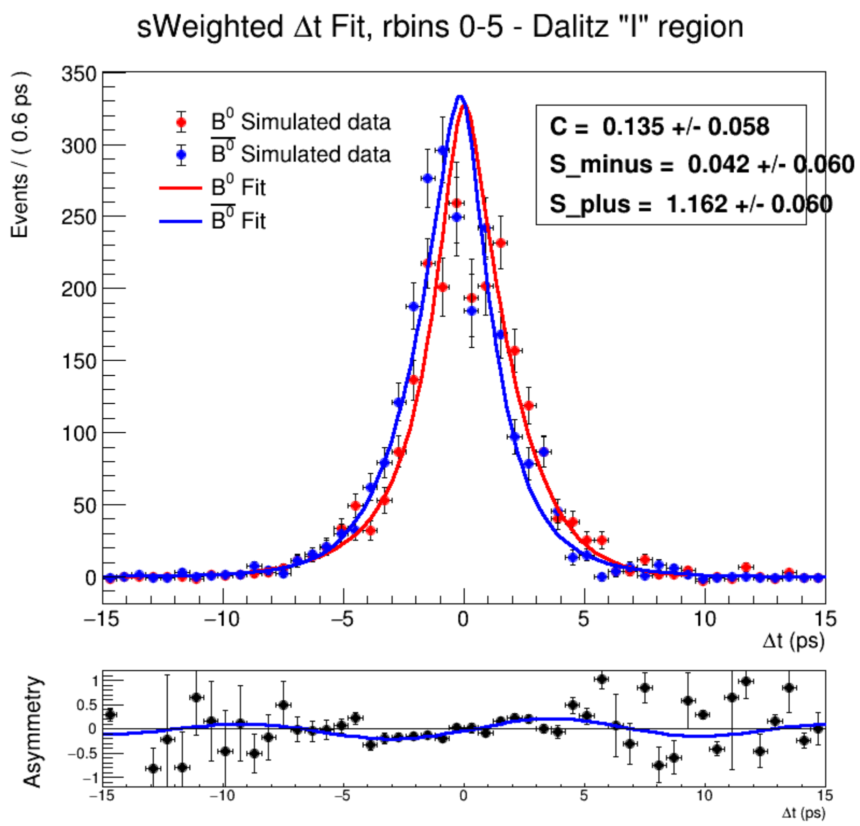


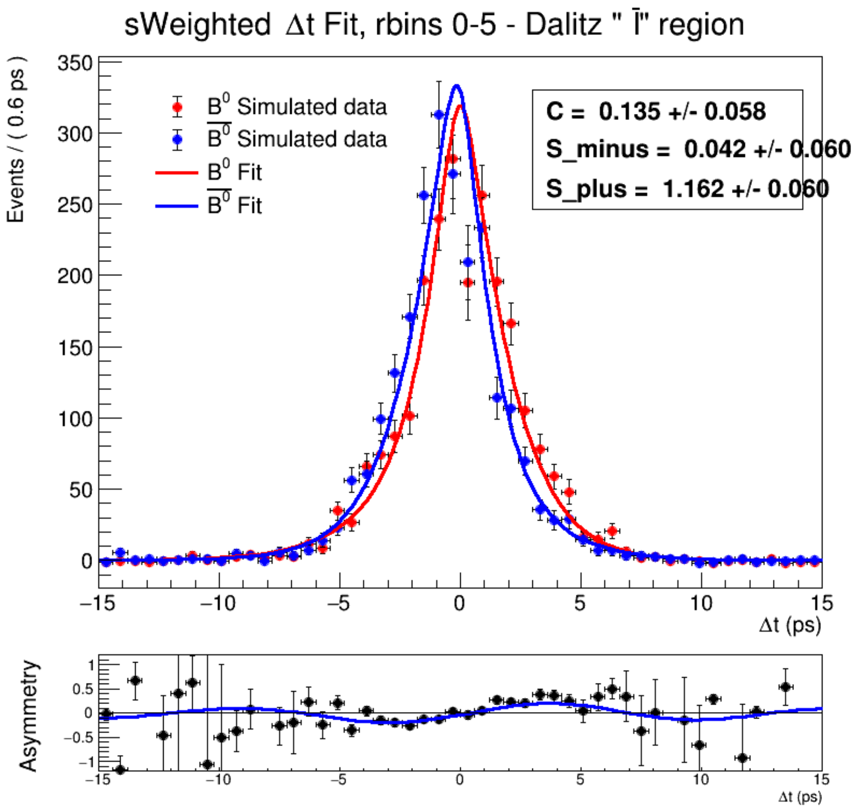
sWeights validation – $\sigma_{\Delta t}$





Dalitz plane halves Δt fits





Dalitz plane halves Δ*t* fits