Measurement of the time–dependent CP asymmetry in $B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma$ decays in the Belle II experiment

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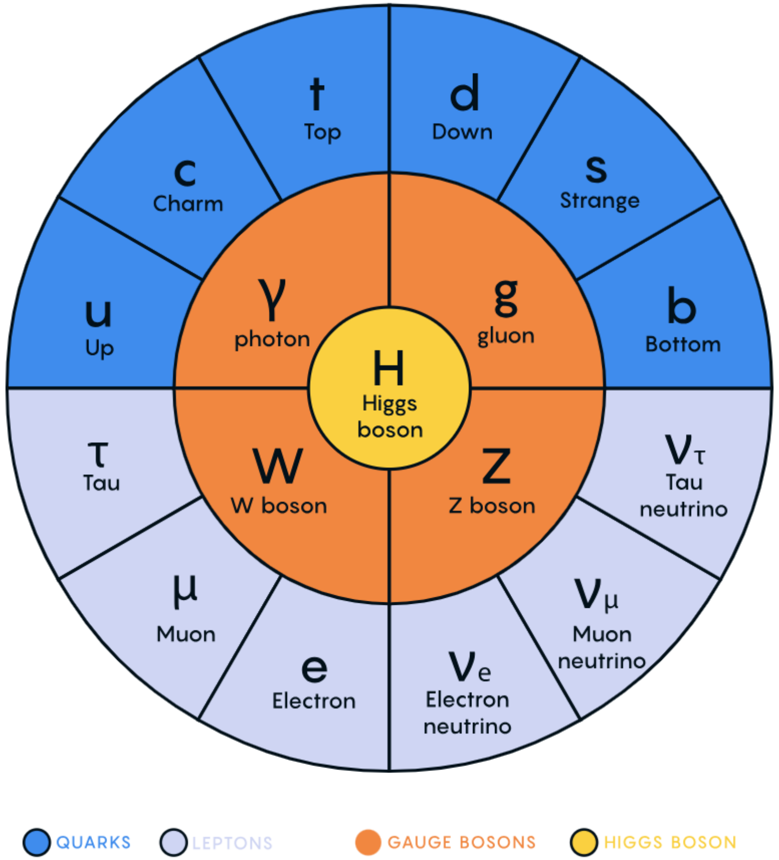
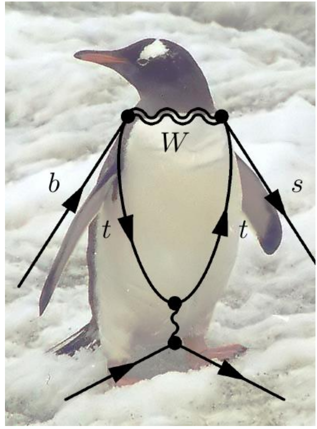
The Standard Model

- Standard Model (SM) of Particle Physics: most successful theory of fundamental particle interactions to date
- Interactions between fermions mediated by exchange of bosons
- **Effective theory**: valid up to an energy scale – $\mathcal{O}(100 \text{ GeV})$
- Some shortcomings:
  - No description of gravity
  - Why 3 families of quarks and leptons?
  - Origin of neutrino masses?
  - Dark matter composition?
  - Matter-antimatter asymmetry?



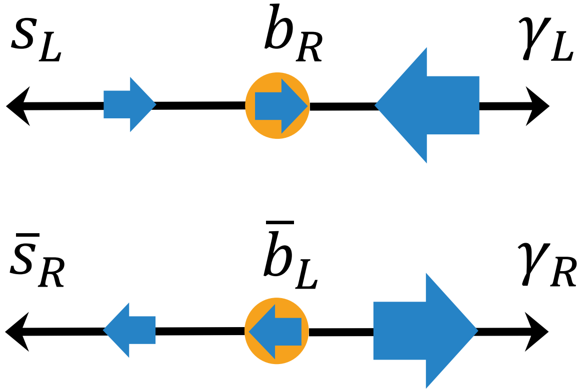
Possible answers in physics **Beyond the Standard Model** (BSM)

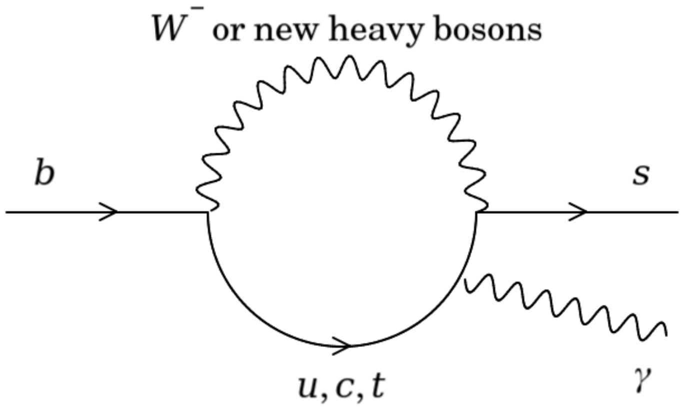
$b \to s\,\gamma$ penguin transitions



- $b \to s\,\gamma$ transitions are **Flavor Changing Neutral Currents** (FCNC)
  $\Rightarrow$ highly suppressed in the SM
- Photon in $b \to s\,\gamma$ predominantly **left-handed** in the SM
  $\Rightarrow$ right-handed contribution suppressed by $m_s^2/m_b^2 \sim 0.0005$
- BSM processes may **enhance** the right-handed polarization
- Description in **Effective Field Theory**:

$$\mathcal{H}_{\rm eff} \simeq -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb}\left[\left(C_7^{\rm SM} + \boldsymbol{C_7^{\rm NP}}\right)\langle\mathcal{O}_7\rangle + \boldsymbol{C_7^{\prime\rm NP}}\langle\mathcal{O}_7^\prime\rangle\right]$$

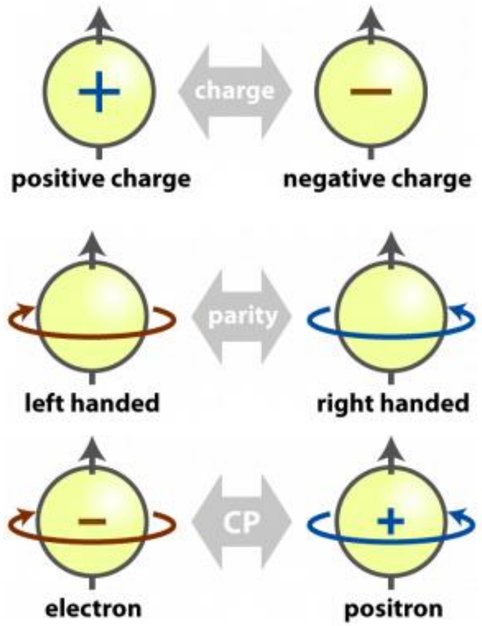


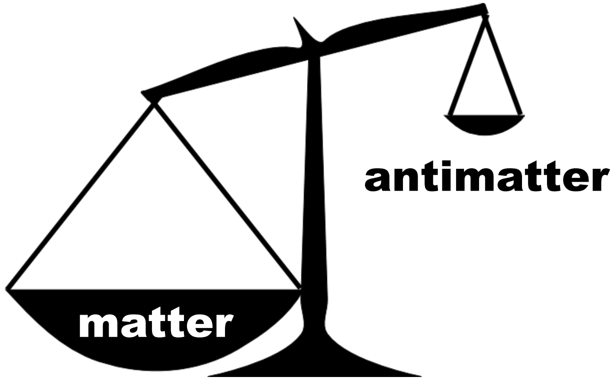


How can we probe the photon polarization?

CP symmetry and CP violation

- **Charge-Parity** (CP): fundamental **discrete symmetry** of the SM
- Conditions by A. Sakharov in 1967 require ***CP* violating** processes to explain **matter-antimatter asymmetry** in our Universe
- CP violation (CPV) observed in **weak interactions** of **quarks** by Belle and BaBar experiments
- CPV can also manifest in BSM physics processes

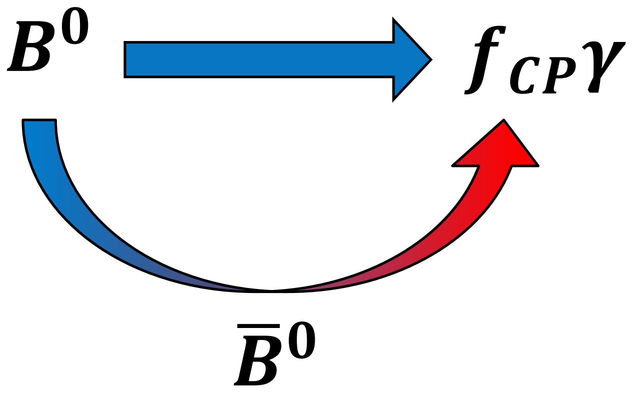




Investigate decays with almost no expected CPV for possible **New Physics (NP) enhancements**

CP violation in radiative B decays

- **Radiative** $B \to X\gamma$ decays proceed through $b \to s\gamma$ transitions
- Photon polarization in SM ⇒ **no interference** between $B^0 \to f_{CP}\gamma_R$ and $\bar{B}^0 \to f_{CP}\gamma_L$ ⇒ no CP violation at 1st order
- BSM processes may contribute to opposite photon polarization ⇒ non-zero CPV in radiative B meson decays
- Search for NP by measuring **mixing-induced CPV** in $B \to f_{CP}\gamma$ processes [PRL 79, 185-188 (1997)]
- **Indirect approach** to discovering NP; look for discrepancies between theoretical predictions and precise measurements



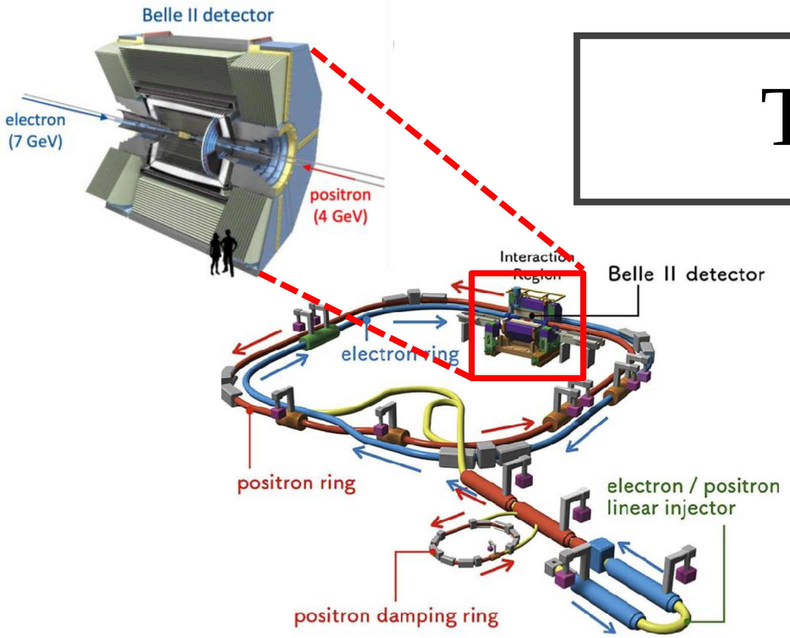
Where to find abundant source of B mesons?

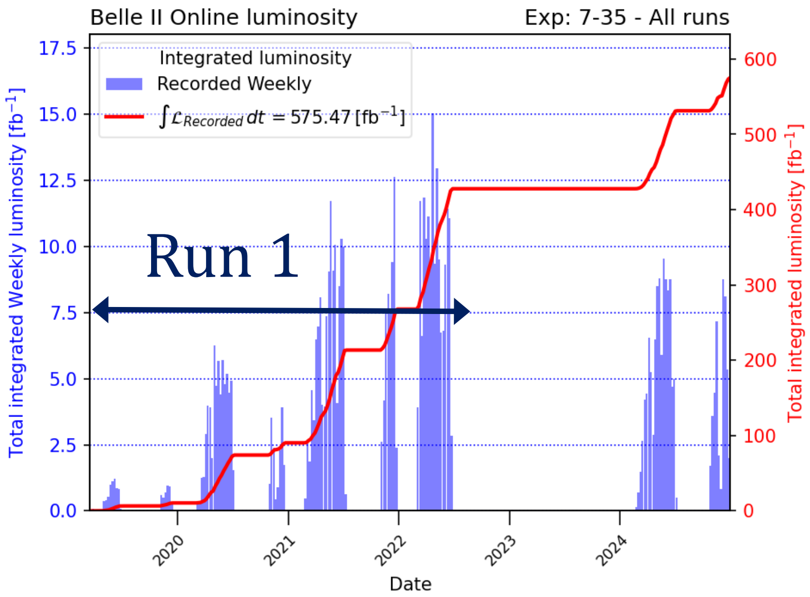
CP violation when:

$$\Gamma\left(B^0(\to \bar{B}^0) \to f_{CP}\gamma\right)$$
$$\neq$$
$$\Gamma\left(\bar{B}^0(\to B^0) \to f_{CP}\gamma\right)$$

Contents

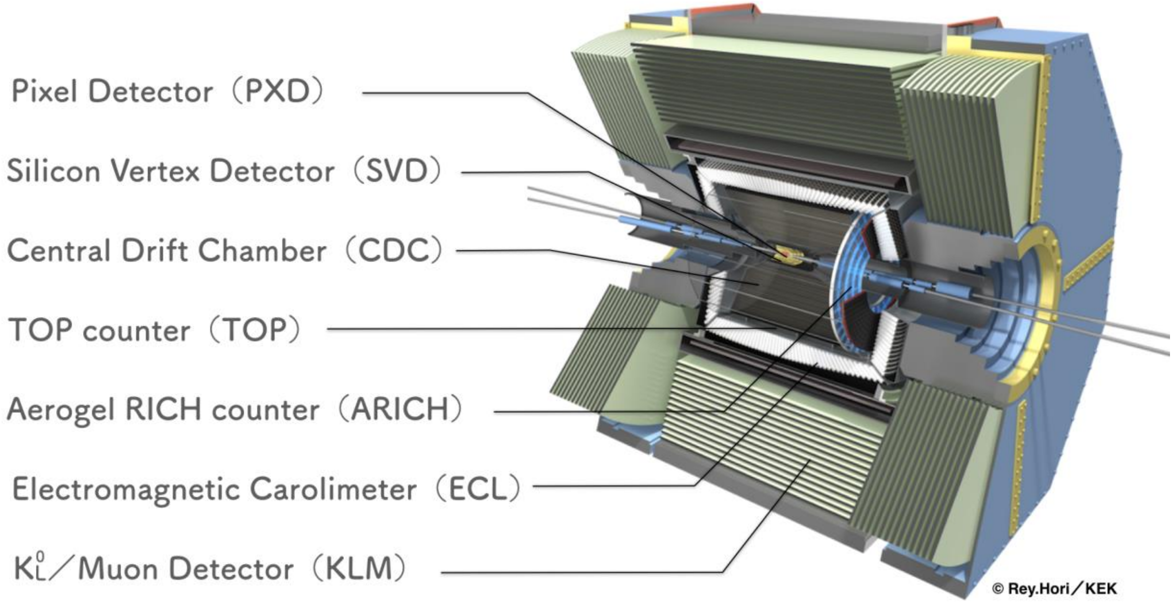
The Belle II experiment





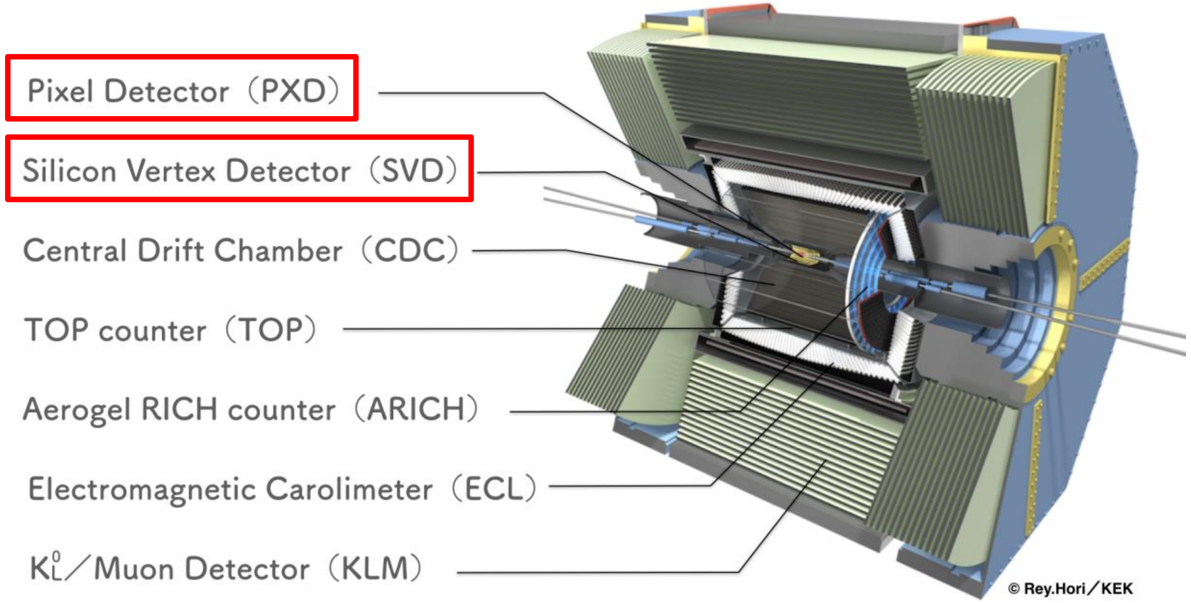
- International collaboration with experiment based in Japan
- Collecting physics data since 2019
- **SuperKEKB**: the world's "brightest" e^+e^- collider:
  - **World record** instantaneous luminosity: 5.1×10^{34} cm^{-2}s^{-1}
  - Asymmetric $\boldsymbol{e^+e^-}$ **collisions** at the $\boldsymbol{\Upsilon(4S)}$ **resonance** rest mass (10.58 GeV)
  - Total data collected in Run 1 + Run 2: **575 fb^{-1}**
  - Goal: collect **50 ab^{-1}** via >10 × collision rate achieved with collider **nano-beam scheme**
- Run 1 data analyzed in this thesis: **365 fb^{-1}** at the $\Upsilon(4S)$ + **68 fb^{-1}** slightly below the $\Upsilon(4S)$

Belle II detector



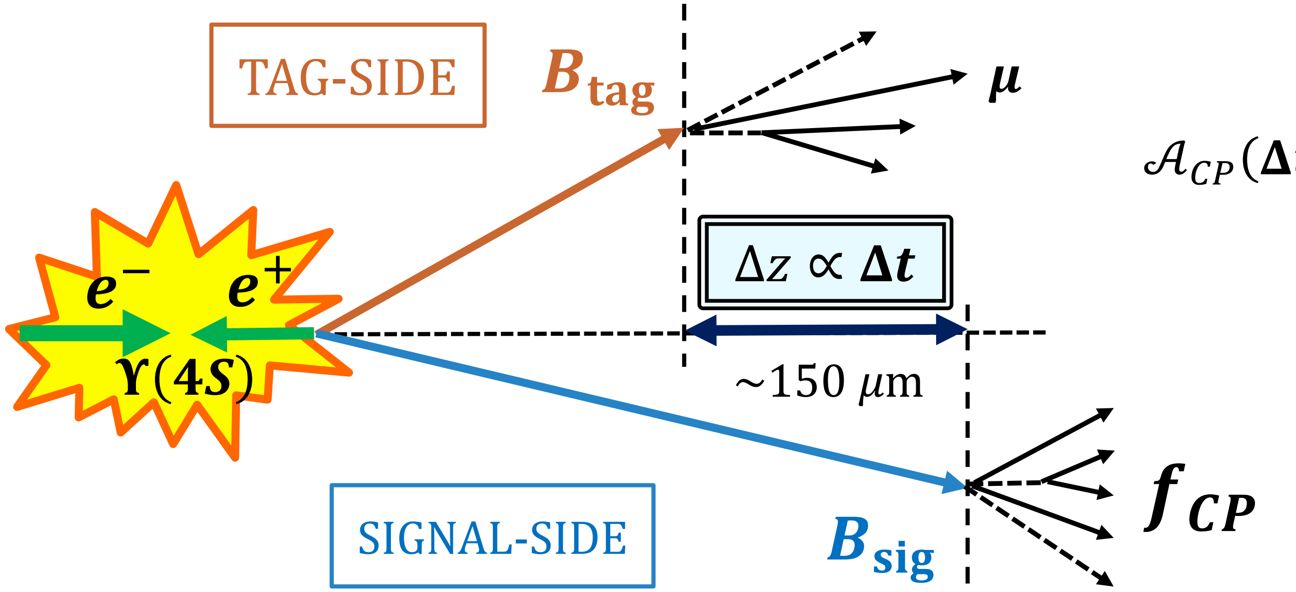
- State-of-the-art barrel-shaped spectrometer with excellent **tracking** efficiency ($\sim$95% for high-p_T tracks) and **energy resolution** ($\sim$1% for high energy photons)
- **Particle identification** via dE/dx, time-of-propagation measurements and Cerenkov radiation

Belle II detector



- State-of-the-art barrel-shaped spectrometer with excellent **tracking** efficiency ($\sim$95% for high-p_{T} tracks) and **energy resolution** ($\sim$1% for high energy photons)
- **Particle identification** via dE/dx, time-of-propagation measurements and Cerenkov radiation
- **Particle decay position reconstruction** using innermost sub-detectors (vertexing)

Time–dependent CP asymmetry



$$\mathcal{A}_{CP}(\Delta t) = \frac{\Gamma\left(B_{\text{tag}=B^0}(\Delta t) \to f_{CP}\right) - \Gamma\left(B_{\text{tag}=\bar{B}^0}(\Delta t) \to f_{CP}\right)}{\Gamma\left(B_{\text{tag}=B^0}(\Delta t) \to f_{CP}\right) + \Gamma\left(B_{\text{tag}=\bar{B}^0}(\Delta t) \to f_{CP}\right)}$$

$$= S \cdot \sin(\Delta m_d \Delta t) - C \cdot \cos(\Delta m_d \Delta t)$$

Mixing-induced CP violation

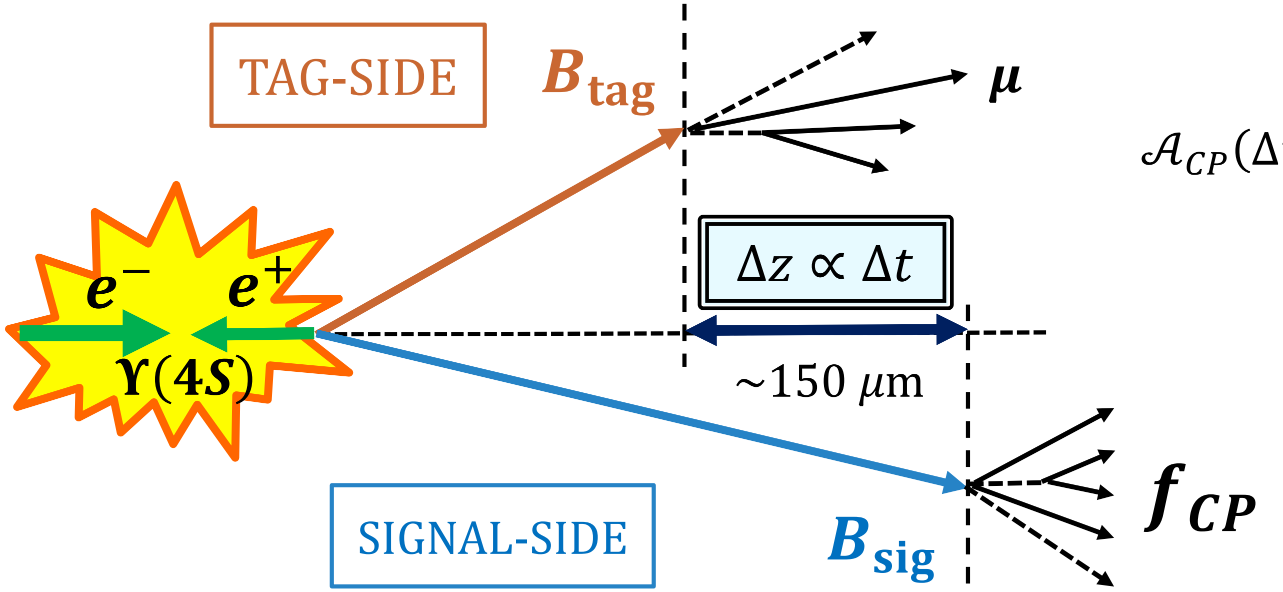
Direct CP violation

- Time-dependent CP (TDCP) asymmetry sensitive to **mixing-induced CP violation** effects
- $\Upsilon(4S)$ boosted in lab frame ⇒ determine Δt by measuring distance between B decay positions
- Determine B_{sig} meson **flavor** (B^0 or $\bar{B}^0$) from decay of B_{tag} meson ⇒ **Flavor Tagging**
- **Precision** on S and C driven by **statistics** + **Δt resolution** + **Flavor Tagging**

Contents

1. Phenomenological context
2. Experimental setup
3. Flavor Tagger calibration
4. Time-dependent CP asymmetry measurement

Flavor Tagging at Belle II



$$\mathcal{A}_{CP}(\Delta t) = \frac{\Gamma\left(B_{\mathbf{tag}=B^0}(\Delta t) \to f_{CP}\right) - \Gamma\left(B_{\mathbf{tag}=\bar{B}^0}(\Delta t) \to f_{CP}\right)}{\Gamma\left(B_{\mathbf{tag}=B^0}(\Delta t) \to f_{CP}\right) + \Gamma\left(B_{\mathbf{tag}=\bar{B}^0}(\Delta t) \to f_{CP}\right)}$$

$$= -\boldsymbol{\Delta w} + (1 - 2\boldsymbol{w})[S \cdot \sin(\Delta m_d \Delta t) - C \cdot \cos(\Delta m_d \Delta t)]$$

$\boldsymbol{w}$: wrong tag fraction

$\boldsymbol{\Delta w}$: asymmetry in wrongly tagging B^0 and $\bar{B}^0$

- Flavor Tagging essential in (time-dependent) CP asymmetry measurements
- Flavor of tag-side $B \Rightarrow$ signal-side B flavor **at time of B_{tag} decay**
- **Flavor-specific** B decay modes, i.e. $\boldsymbol{B^0} \to D^- \boldsymbol{\mu^+} \nu_\mu$ and $\boldsymbol{\bar{B}^0} \to D^+ \boldsymbol{\mu^-} \bar{\nu}_\mu$

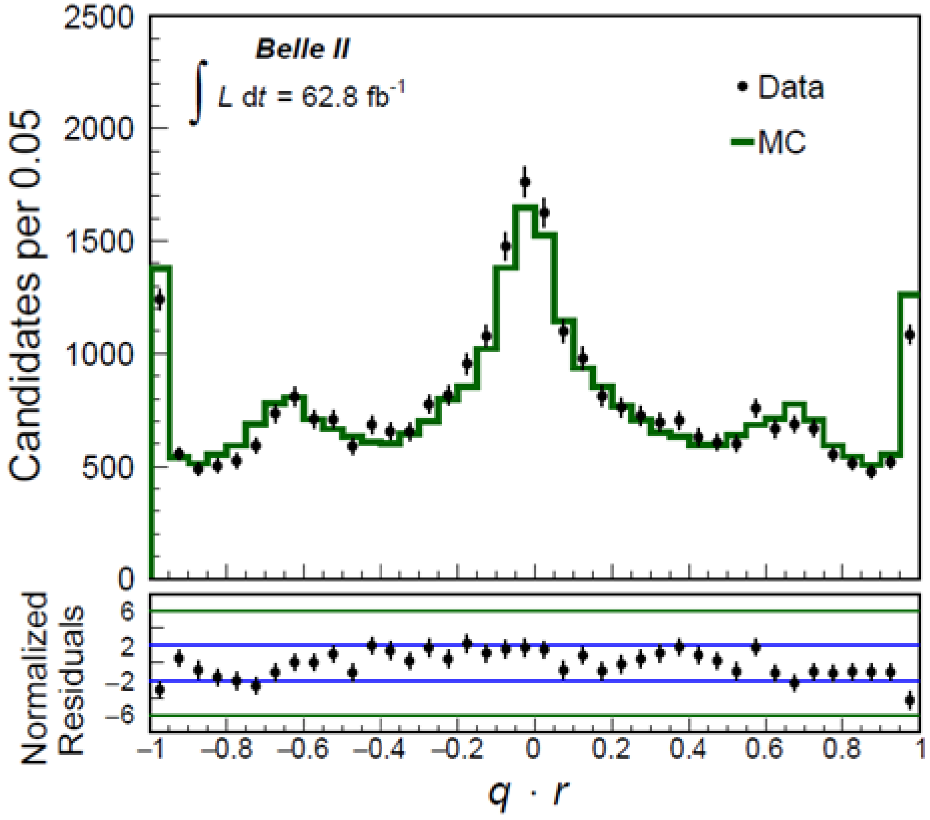
Category–based Flavor Tagger

- Kinematics, topology and particle identification information → identify category of flavor-specific B decay → tag B flavor
- Flavor Tagger output: $\boldsymbol{q} \cdot \boldsymbol{r}$ → confidence of flavor prediction
- Performance metric → **effective tagging efficiency**:

$$\varepsilon_{\text{tag}} = \sum_i \varepsilon_i \underbrace{(1 - 2w_i)}_{r}{}^2$$

- Better tagging efficiency ⇒ higher statistical precision on time-dependent CP asymmetry measurement

$$\sigma_S \propto \frac{1}{\sqrt{\varepsilon_{\text{tag}}}}$$



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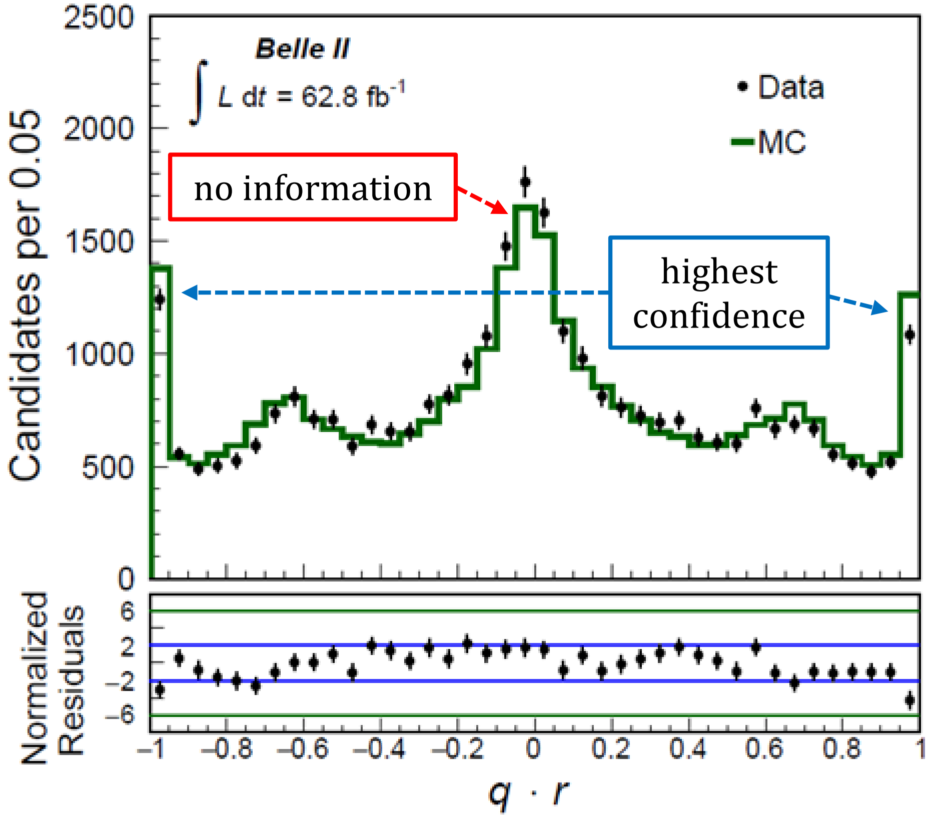

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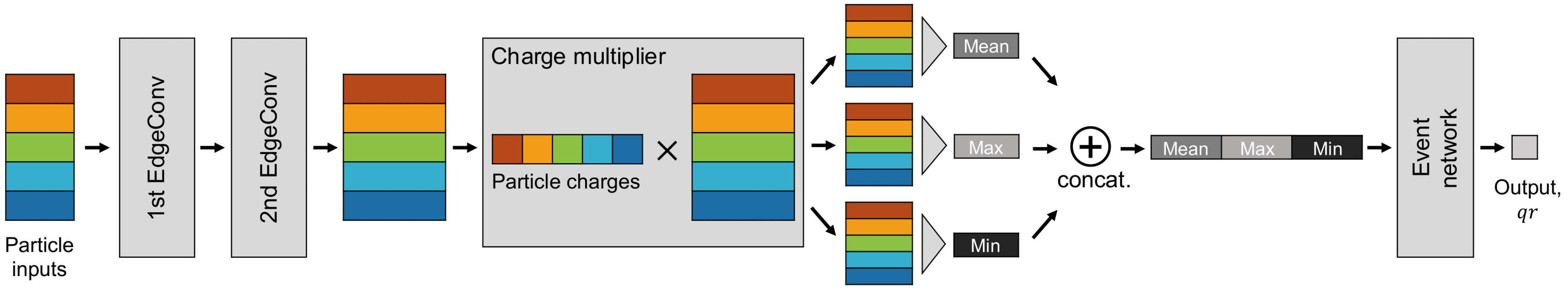
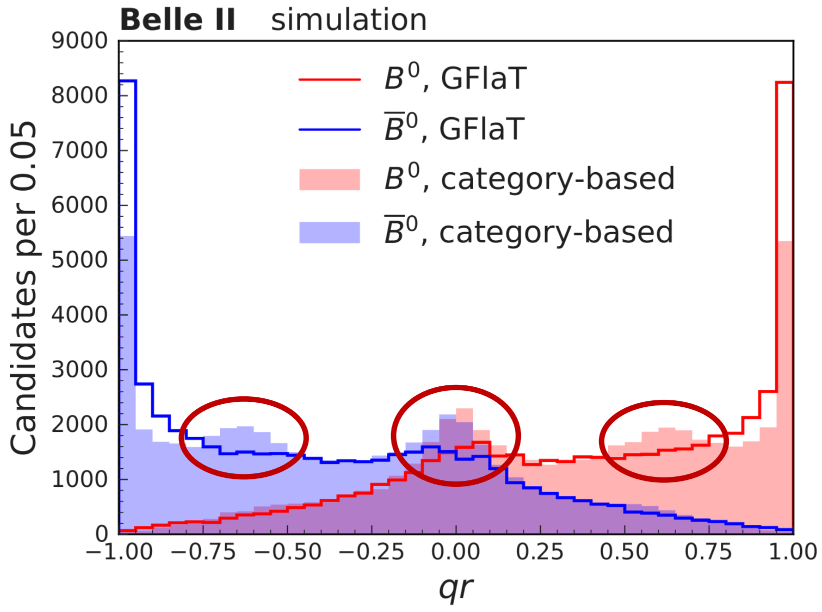
New GNN–based Flavor Tagger





- New Flavor Tagger, **GFlaT**, based on graph-neural-networks
- Accounts for relations between final-state particles
- Better tagging of events not containing charged leptons
  → smaller bump at $|qr| \approx 0$ and no bump at $|qr| \approx 0.65$
- Relative improvement of **20%** in effective tagging efficiency (from simulation)

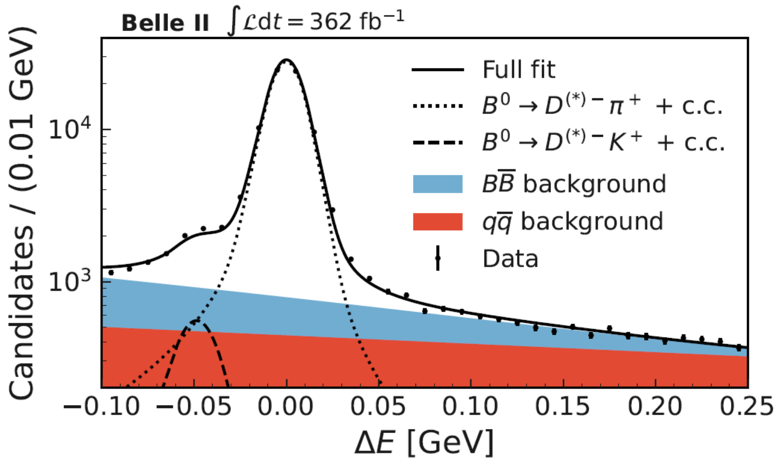
Calibration with data

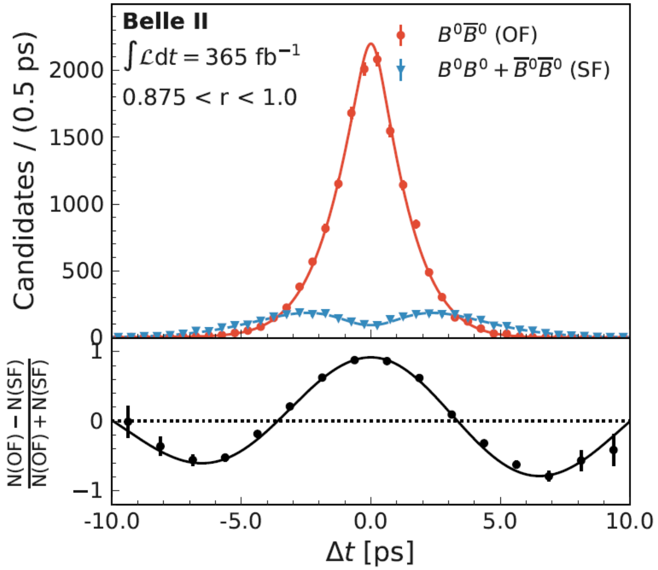
Energy difference:
$\Delta E = E_B^* - \sqrt{s}/2$

- Calibrate Flavor Tagger and Δt Resolution Function parameters using flavor-specific B decays:
  - $B^0 \to D^-\pi^+ \to K^+\pi^-\pi^-\pi^+$
  - $B^0 \to D^{*-}\pi^+ \to \bar{D}^0\pi^-\pi^+ \to K^+\pi^-\pi^-\pi^+$
  - $B^0 \to D^{*-}\pi^+ \to \bar{D}^0\pi^-\pi^+ \to K^+\pi^0\pi^-\pi^-\pi^+$
  - $B^0 \to D^{*-}\pi^+ \to \bar{D}^0\pi^-\pi^+ \to K^+\pi^+\pi^-\pi^-\pi^-\pi^+$
- Extract yields from fit to ΔE distribution and subtract Δt background from sideband using sPlot (NIMA 555, 356-369)
- Fit background-free Δt to obtain parameters of interest
- Relative improvement of **18%** in effective tagging efficiency:

Category-based: $\varepsilon_{\text{tag}} = (31.68 \pm 0.45\ (\text{stat}))\ \%$

GFlaT: $\varepsilon_{\text{tag}} = (\mathbf{37.40} \pm 0.43\ (\text{stat}) \pm 0.36\ (\text{syst}))\ \%$





Calibration with data

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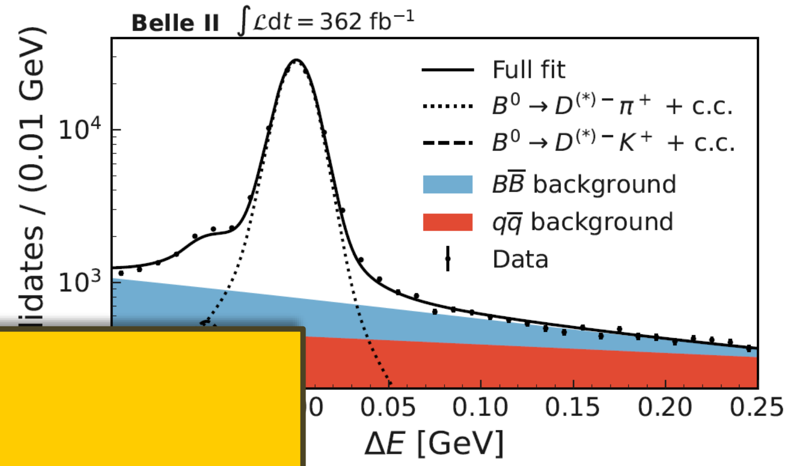
  - $B^0 \to D^{*-}\pi^+ \to \bar{D}^0\pi^-\pi^+ \to K^+\pi^-\pi^-\pi^+$
  - $B^0 \to D^{*-}\pi^+ \to \bar{D}$
  - $B^0 \to D^{*-}\pi^+ \to \bar{D}$



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- Extract yields from fi… Δt background from s…
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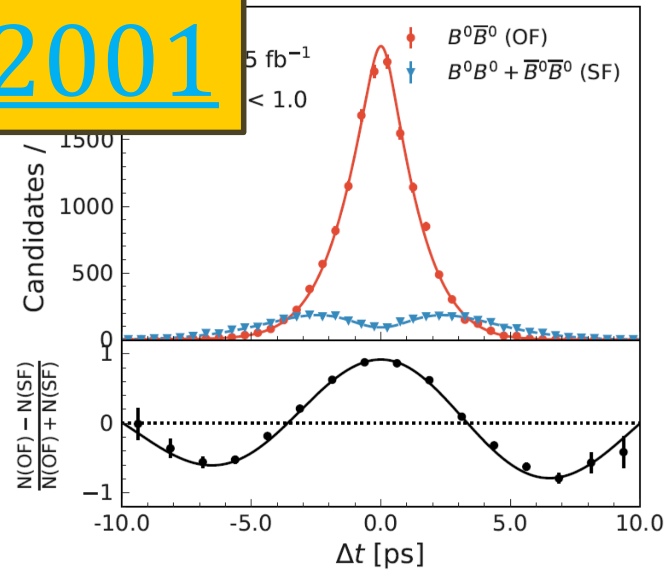

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TDCP asymmetry measurement

- Motivation & status
- Reconstruction & selection
- Fit strategy
- Validation
- Systematic uncertainties
- Results

TDCP asymmetry of $B^0 \to K_S^0 \pi^+ \pi^- \gamma$ decays

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

TDCP asymmetry of $B^0 \to K_S^0\pi^+\pi^-\gamma$ decays

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

- Goal: Measure S and C of the $\boldsymbol{CP}$ **eigenstate**: $B^0(\bar{B}^0) \to K_{res}\gamma \to$

$$\begin{array}{ccccc} & \nearrow & K^*\pi\,\gamma & \searrow & \\ K_{res}\gamma & \to & \boldsymbol{K_S^0\rho^0}\gamma & \to & K_S^0\pi^+\pi^-\gamma \\ & \searrow & (K_S^0\pi)\pi\,\gamma & \nearrow & \end{array}$$

- Disentangle non-CP eigenstate contributions via amplitude analysis of $B^+ \to K^+\pi^+\pi^-\gamma$ decays assuming isospin symmetry → here only measure **effective** $\boldsymbol{S}$ or $\boldsymbol{S_{\text{eff}}}$

TDCP asymmetry of $B^0 \to K_S^0 \pi^+ \pi^- \gamma$ decays

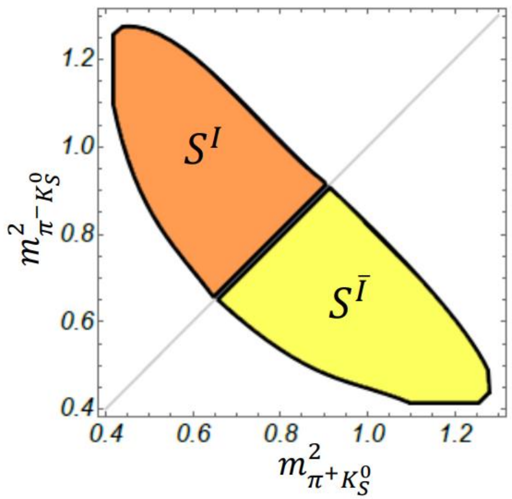
$$\mathcal{A}_{CP}(\Delta t) = \frac{\Gamma\left(B_{\text{tag}=B^0}(\Delta t) \to f_{CP}\gamma\right) - \Gamma\left(B_{\text{tag}=\bar{B}^0}(\Delta t) \to f_{CP}\gamma\right)}{\Gamma\left(B_{\text{tag}=B^0}(\Delta t) \to f_{CP}\gamma\right) + \Gamma\left(B_{\text{tag}=\bar{B}^0}(\Delta t) \to f_{CP}\gamma\right)}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

- <u>Goal</u>: Measure S and C of the ***CP* eigenstate**: $B^0(\bar{B}^0) \to K_{res}\gamma \to$ [$\nearrow K^*\pi\gamma \searrow$ / $\boldsymbol{K_S^0\rho^0}\gamma$ / $\searrow (K_S^0\pi)\pi\gamma \nearrow$] $\to K_S^0\pi^+\pi^-\gamma$
- Disentangle non-CP eigenstate contributions via amplitude analysis of $B^+ \to K^+\pi^+\pi^-\gamma$ decays assuming isospin symmetry → here only measure **effective $\boldsymbol{S}$** or $\boldsymbol{S_{\text{eff}}}$
- Previous measurements of S_{eff} in $B^0 \to K_S^0\pi^+\pi^-\gamma$:
  - BaBar PRD93 (2015) : $S_{K_S^0\pi^+\pi^-\gamma} = 0.14 \pm 0.25 \pm 0.03$ (using 424 fb^{-1})
  - Belle PRL101 (2008) : $S_{K_S^0\pi^+\pi^-\gamma} = 0.09 \pm 0.27 \pm 0.07$ (using 594 fb^{-1})
- **Combined measurement** using entire Belle (711 fb^{-1}) and current <u>Belle II datasets</u> (365 fb^{-1})

Novel additional observables

- Phenomenological work proposes **additional observables** by dividing the dataset in the **Dalitz plane**
- New observables ⇒ complementary constraints to real and imaginary parts of C_7'/C_7 in the complex plane

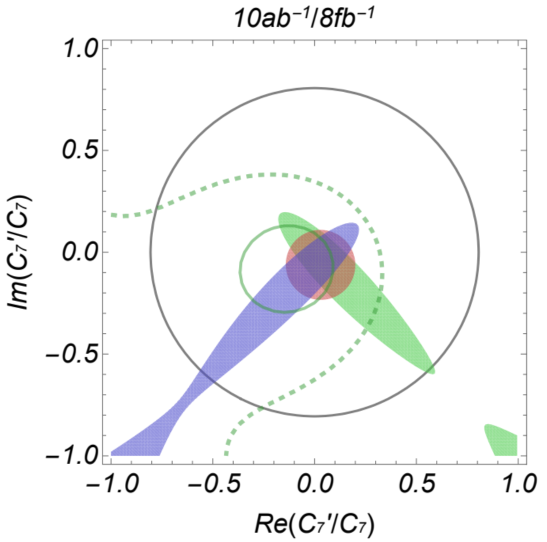
Dalitz plane



Prospective constraints

$B^0 \to K_S^0 \pi^+ \pi^- \gamma$ (Belle II)

$B^0 \to K^{*0} e^+ e^-$ (LHCb)



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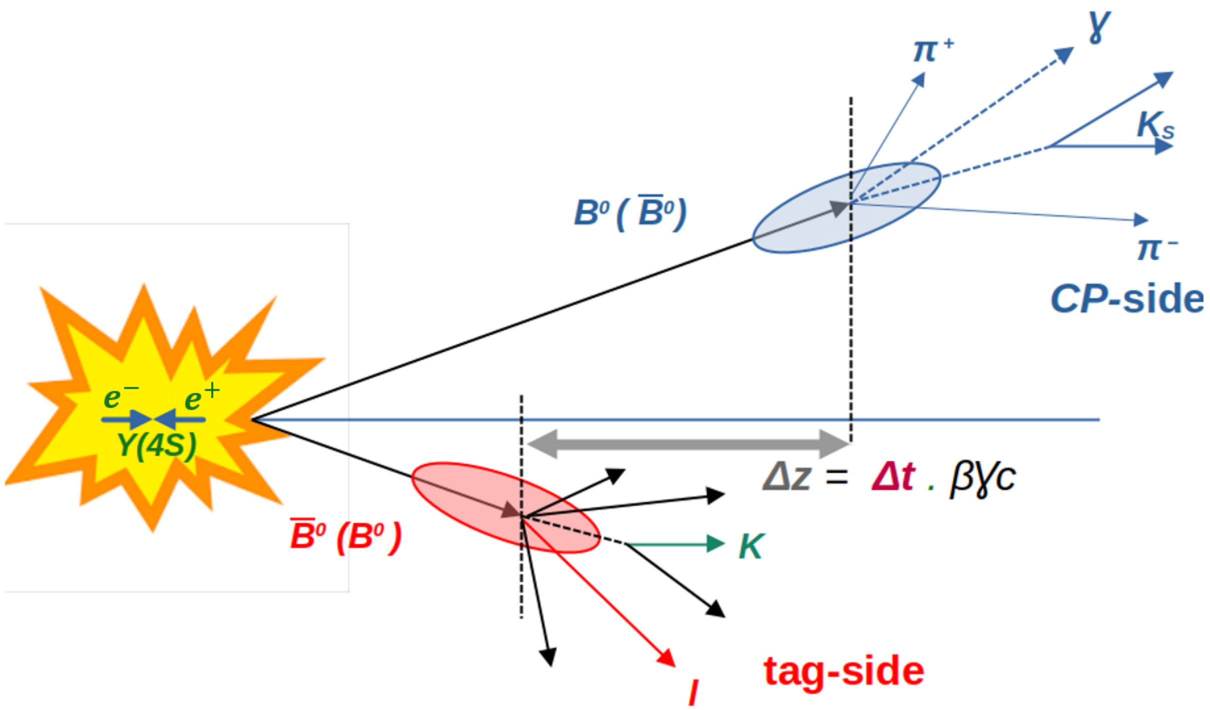
New observables:

$$S^+_{K_S^0\pi^+\pi^-\gamma} = S^I + S^{\bar{I}}$$

$$S^-_{K_S^0\pi^+\pi^-\gamma} = S^I - S^{\bar{I}}$$

Reconstruction & Selection



Event reconstruction:

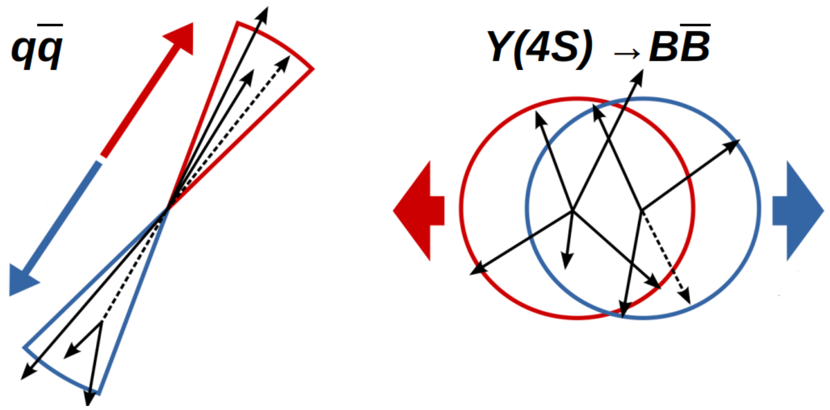
1. Fully reconstruct signal-side B decay
2. Fit B_{sig} vertex using only the two prompt $\pi^{\pm}$
3. Fit B_{tag} vertex using all other tracks in event
4. Tag the flavor of B_{tag} based on its daughters at the time of its decay

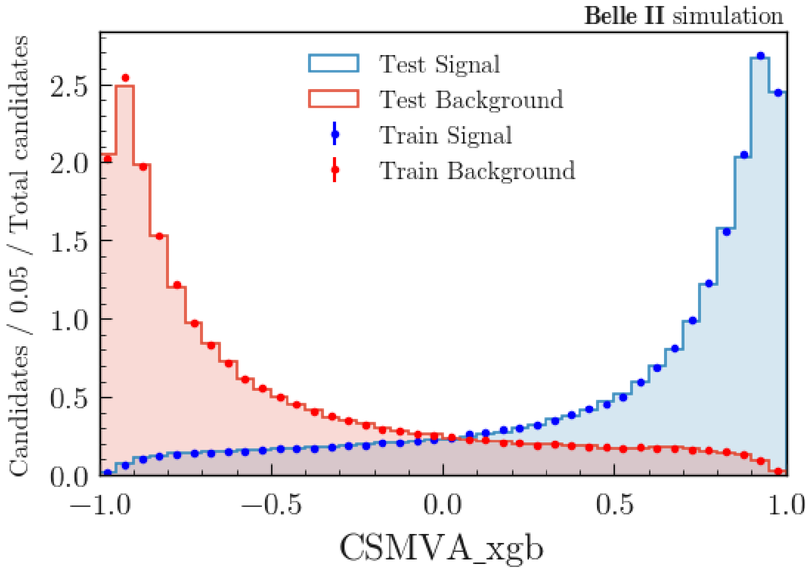
Selection criteria:

- **Veto** photon candidates coming from $\boldsymbol{\pi^0} \rightarrow \boldsymbol{\gamma\gamma}$
- Purify $\boldsymbol{K_S^0}$ **candidates** using a MVA classifier
- $\boldsymbol{\pi^+\pi^-}$ invariant mass window corresponding to $\boldsymbol{\rho^0}$ **mass**
- $\boldsymbol{K\pi\pi}$ invariant mass **upper limit**
- **Suppress continuum** background using a MVA
- Single B_{sig} candidate selection

Continuum Suppression

- Most dominant source of background due to non-resonant $e^+e^- \to q\bar{q}$ events
- **Jet-like** topology vs. $\Upsilon(4S) \to B\bar{B}$ events that have **spherically symmetric** topology
- Train **BDT classifier** (CSMVA) to suppress continuum background using event-shape variables as inputs
- Optimise cut on CSMVA classifier by maximising the **signal significance** $S/\sqrt{S+B}$
- Optimal cut:
  - $\sim$70% signal efficiency
  - $\sim$90% background rejection



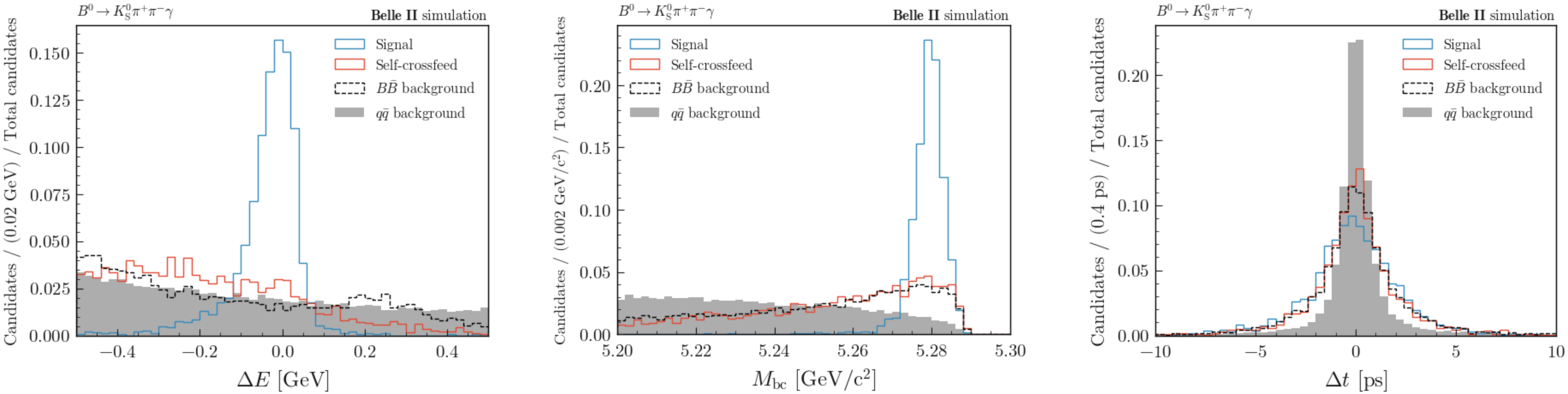


Fit Strategy

$$\Delta E = E_B^* - \sqrt{s}/2$$

$$M_{\rm bc} = \sqrt{(\sqrt{s}/2)^2 - {p_B^*}^2}$$

- 3D unbinned maximum likelihood fit in $\boldsymbol{\Delta E}$, $\boldsymbol{M_{\rm bc}}$ and $\boldsymbol{\Delta t}$ to extract $\boldsymbol{S}$ and $\boldsymbol{C}$
- Simultaneous fit in two Dalitz half-planes to extract $\boldsymbol{S}^{\pm}$
- Four separate components: signal, self-crossfeed (SCF), continuum and $B\bar{B}$ background
  $\Rightarrow$ shapes fixed from simulation



Δt Fit Model

- The full signal Δt PDF model is:

$$\mathcal{P}(\Delta t, q = \pm 1) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 - q\Delta w + q\mu(1-2w) + \\ + [q(1-2w) + \mu(1 - q\Delta w)][\boldsymbol{S}\sin(\Delta m_d \Delta t) - \boldsymbol{C}\cos(\Delta m_d \Delta t)]\} \otimes \boldsymbol{\mathcal{R}}_{\mathbf{det}}$$

CP violation parameters

Δt Fit Model

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Flavor Tagger parameters

Δt Fit Model

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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 signal- and tag-side B vertex positions

Δt Fit Model

- The full signal Δt PDF model is:

$$\mathcal{P}(\Delta t, q = \pm 1) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 - q\Delta w + q\mu(1-2w) + \\ + [q(1-2w) + \mu(1 - q\Delta w)][\boldsymbol{S}\sin(\Delta m_d \Delta t) - \boldsymbol{C}\cos(\Delta m_d \Delta t)]\} \otimes \boldsymbol{\mathcal{R}_{\mathrm{det}}}$$

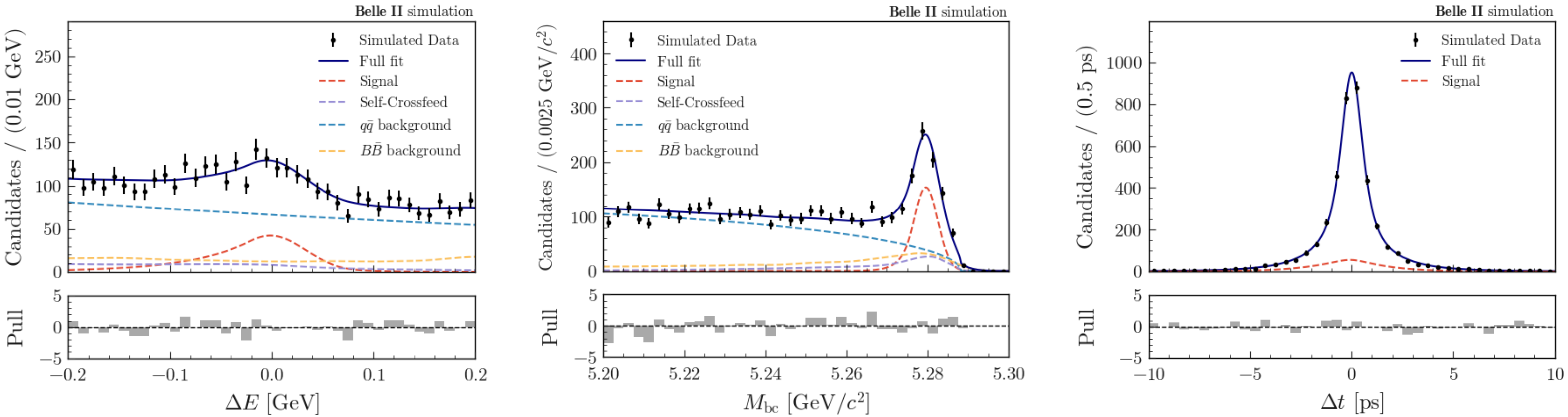
where $\mathcal{R}_{\mathrm{det}}$ is the Δt Resolution Function, which models smearing effects due to the finite resolution of the detector in measuring the signal- and tag-side B vertex positions

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

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

- Δt Resolution Function parameter values obtained from calibration using $B^0 \to D^{(*)-}\pi^+$ decays

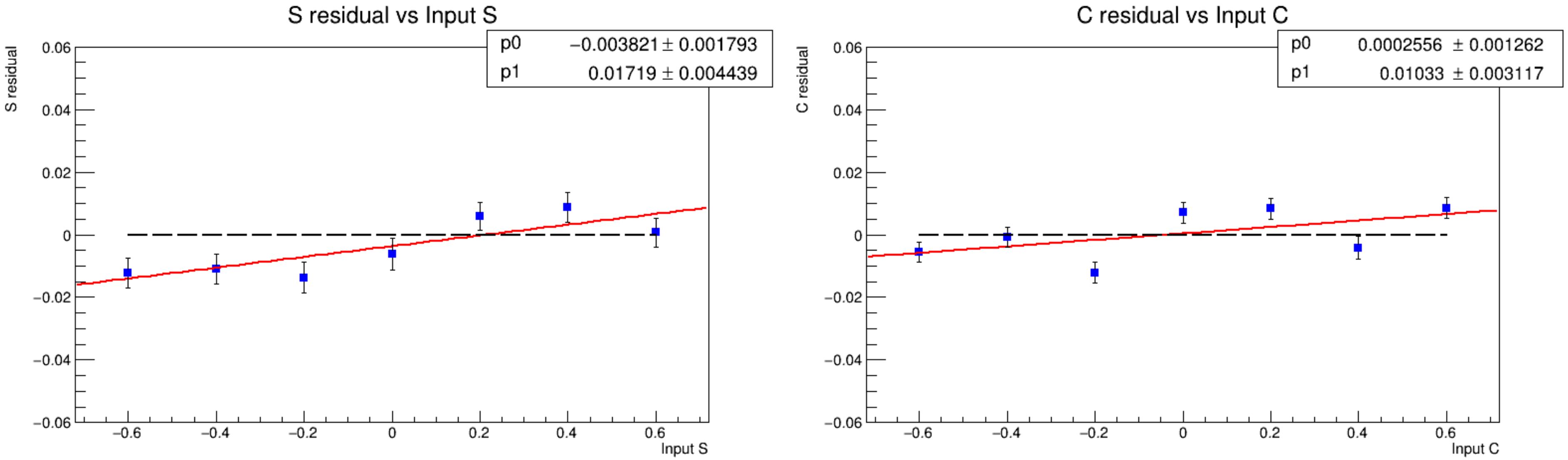
3D fit example



- 3D fit of data-like MC sample generated with $S = 0$ and $C = 0$
- Yields of signal+SCF, $B\bar{B}$ background and continuum free to float separately
- ✓ Fitted CP parameters: $S = -0.08 \pm 0.14$ and $C = 0.09 \pm 0.09$

Validation: Toys

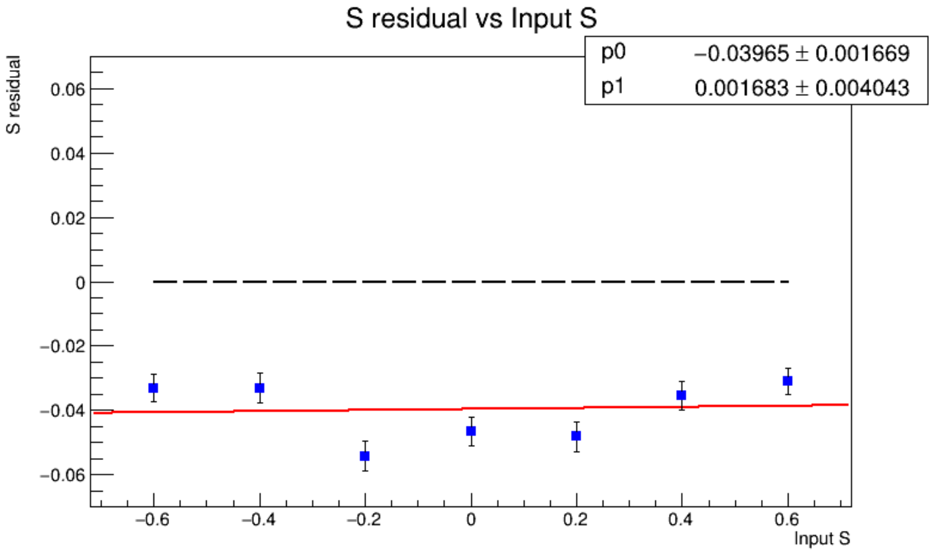
- Test fit stability by fitting data-like toy MC samples generated from PDF model
- Input S: {-0.6, -0.4, -0.2, 0.0, 0.2, 0.4, 0.6} and C: {-0.6, -0.4, -0.2, 0.0, 0.2, 0.4, 0.6}

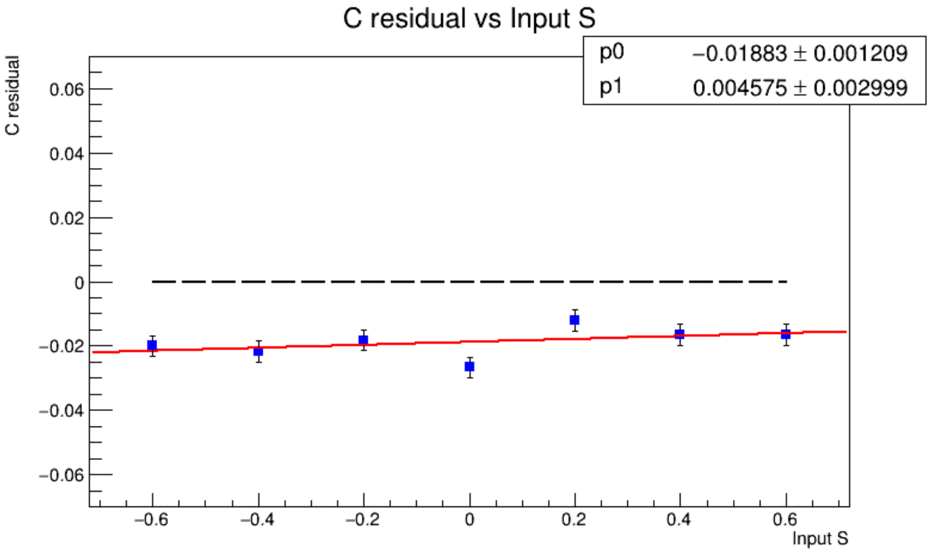


- Each point corresponds to average of fitted parameter across 1000 toy samples
- No bias on S or C but slight trend observed $\Rightarrow$ no glaring issues with PDF model
- Estimated uncertainties on S and C: $\sigma_S \sim 0.16$ and $\sigma_C \sim 0.11$

Validation: Bootstrapping

- Same test using bootstrapped datasets sampled from simulation
- Input S: {-0.6, -0.4, -0.2, 0.0, 0.2, 0.4, 0.6} and C=0

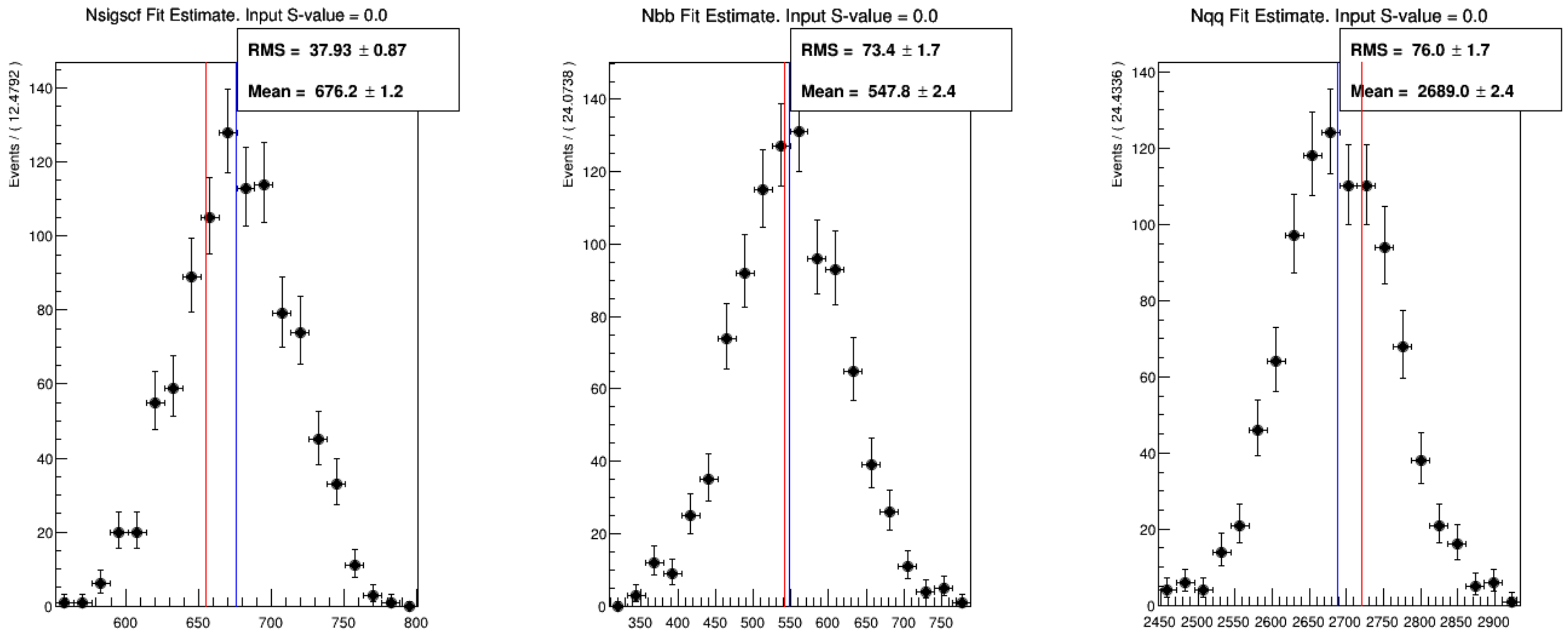




- Small bias observed in S and C $\Rightarrow$ possibly due to background mismodeling or repetition of events during bootstrapping process
- Assign conservative systematic uncertainty

Validation: Bootstrapping

- Same test using bootstrapped datasets sampled from simulation
- Input S: {-0.6, -0.4, -0.2, 0.0, 0.2, 0.4, 0.6} and C=0



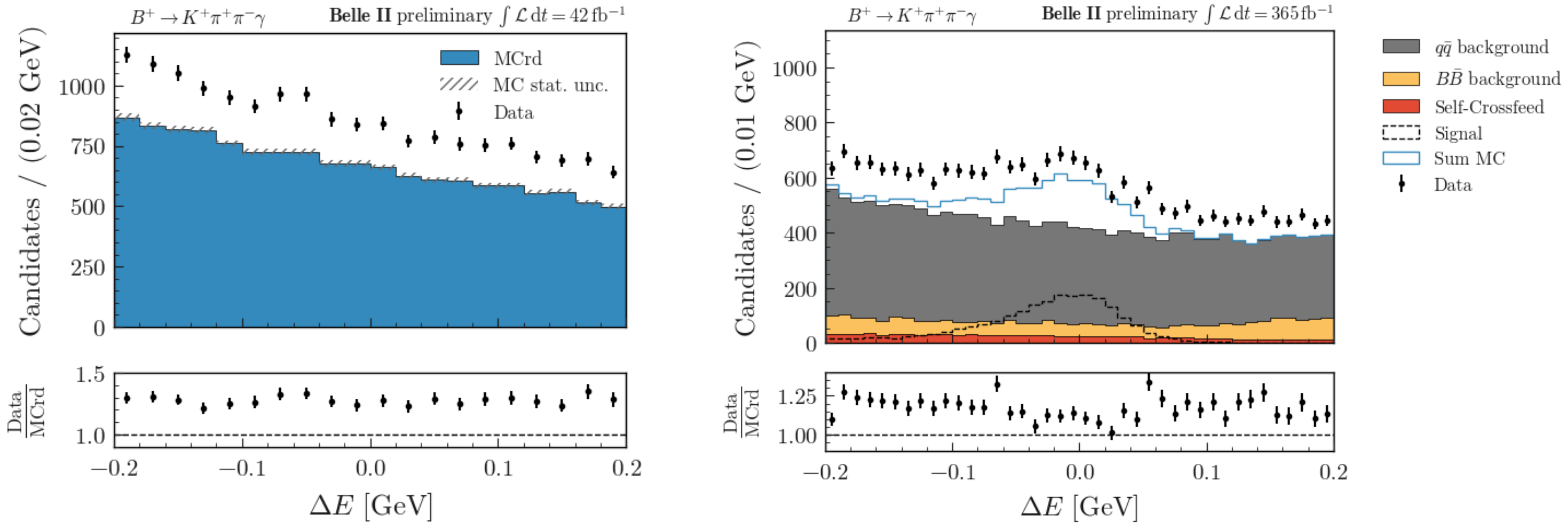
- Fitted yields slightly biased ⇒ negligible effect on CP parameters

Validation: Control mode

- Use isospin partner mode $B^+ \rightarrow K^+\pi^+\pi^-\gamma$ as **control mode**
- **No mixing** between B^+ and B^- $\Rightarrow S$ is expected to be 0
- Selection identical to signal mode except for $K^+ \leftrightarrow K_S^0$
  - Reconstruct B_{sig} vertex using only **two prompt pions**
  - Use Flavor Tagger in the **same way** as with signal mode
  - **Same BDT** for continuum suppression
- Expect $\sim 5\times$ signal events compared to signal mode

Validation: Control mode

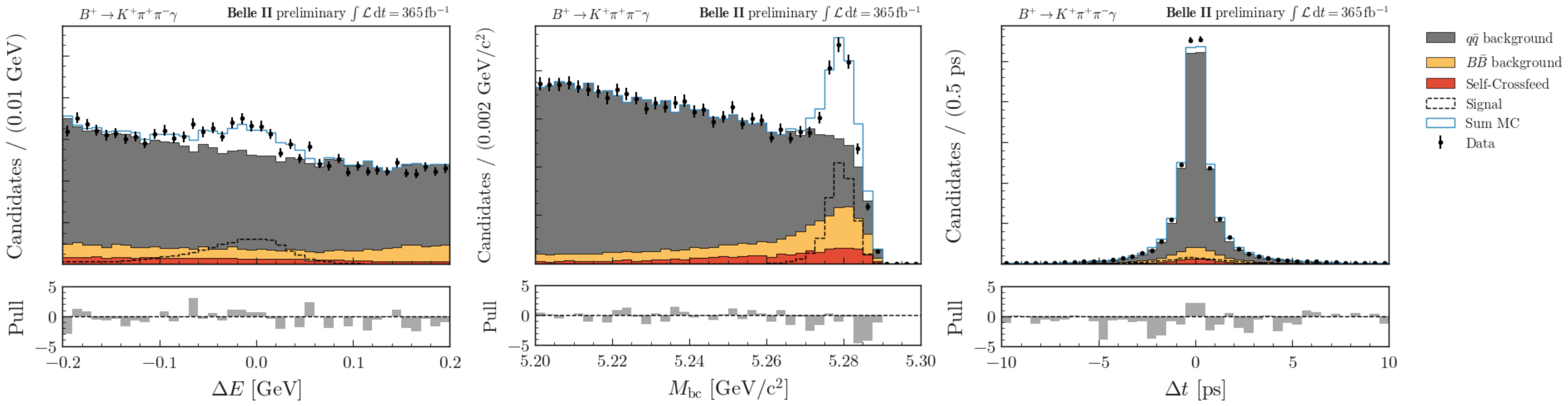
➢ Check data/MC agreement in off-resonance and on-resonance samples



➢ ~30% more continuum and ~30% less signal in data compared to MC
⇒ no problem since signal and continuum yields float separately in the fit

Validation: Control mode

- Apply overall correction factor and check agreement between shapes



✓ ΔE, M_{bc} & Δt shapes consistent between data and MC

Systematic uncertainties

- Estimate systematic uncertainties due to various sources

Source of uncertainty	C	S	S^+	S^-
Fixed shape parameters	0.003	0.005	0.005	0.004
Flavor Tagger parameters	0.018	0.007	0.014	0.012
Δt Resolution Function parameters	0.005	0.014	0.023	0.018
τ_{B^0} & Δm	< 0.001	0.001	0.001	0.003
Fixed SCF background fractions	0.006	0.004	0.008	0.011
CP violation in $B\overline{B}$ background	0.019	0.017	0.034	0.001
Yield bias	0.005	0.004	0.008	0.014
Bootstrapping bias	0.027	0.054	0.110	0.033
Detector misalignment	0.005	0.003	0.006	0.012
Tag-side interference	0.028	< 0.001	< 0.001	< 0.001
Total systematic uncertainty	0.048	0.059	0.119	0.045
Expected statistical uncertainty	0.110	0.160	0.310	0.300

- Most systematics evaluated on the real data sample
- Dominant systematic on S (bootstrapping bias) amounts to $\sim 1/3$ of stat. uncertainty
- Measurement is **statistically dominated**

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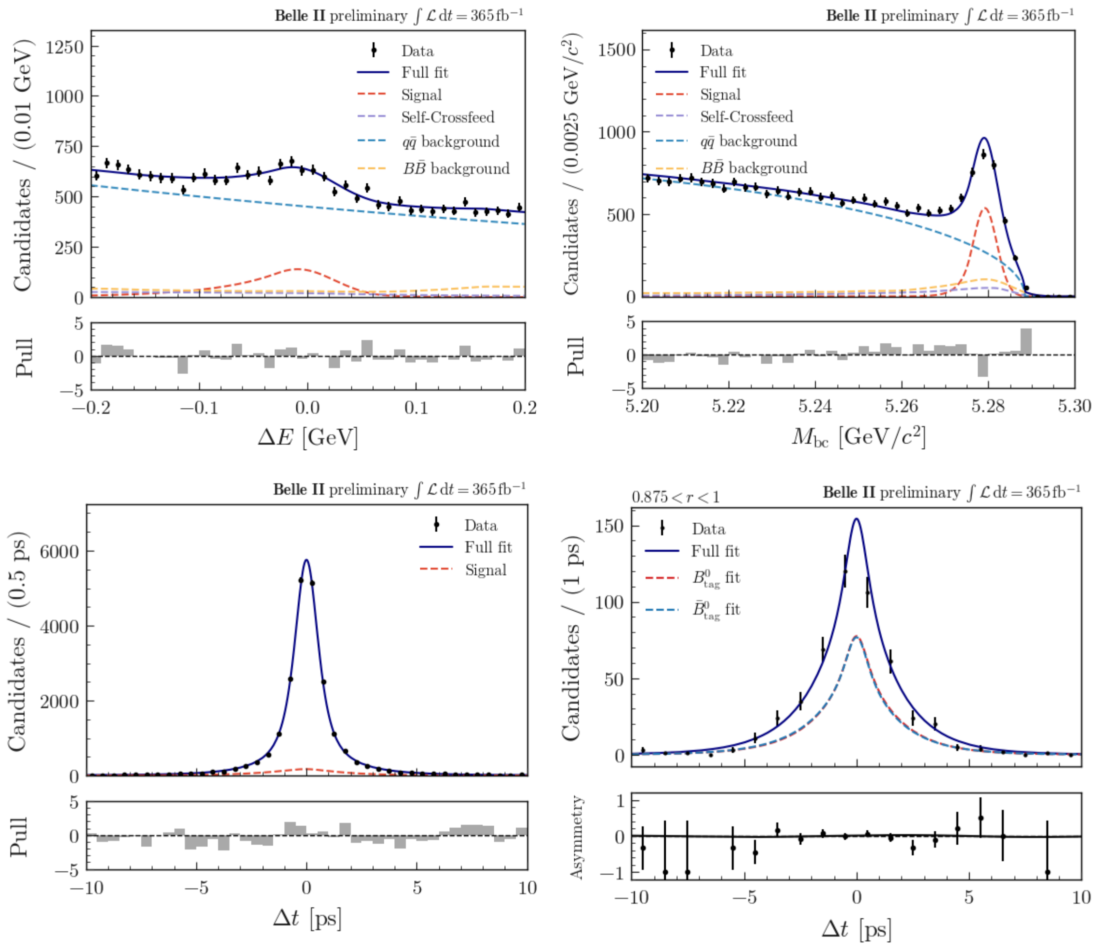
- Dominant systematic on S (bootstrapping bias) amounts to $\sim 1/3$ of stat. uncertainty
- Measurement is **statistically dominated**

Further tests before measurement

1. Fit control mode to extract B^+ lifetime
2. Fit control mode to extract CP parameters
3. Fit signal mode to extract B^0 lifetime
4. Fit signal mode randomizing Flavor Tagger prediction (q) in each event
5. Fit signal mode to extract CP parameters

Control mode fit



Fitted yields:

$N_{sig-like} = 2240 \pm 70$

$N_{B\bar{B}} = 1425 \pm 110$

$N_{q\bar{q}} = 18075 \pm 165$

B^+ lifetime:

$\tau_{B^+} = 1.62 \pm 0.06$ ps

PDG: 1.638 ± 0.004 ps

CP parameters:

$C = -0.02 \pm 0.06$

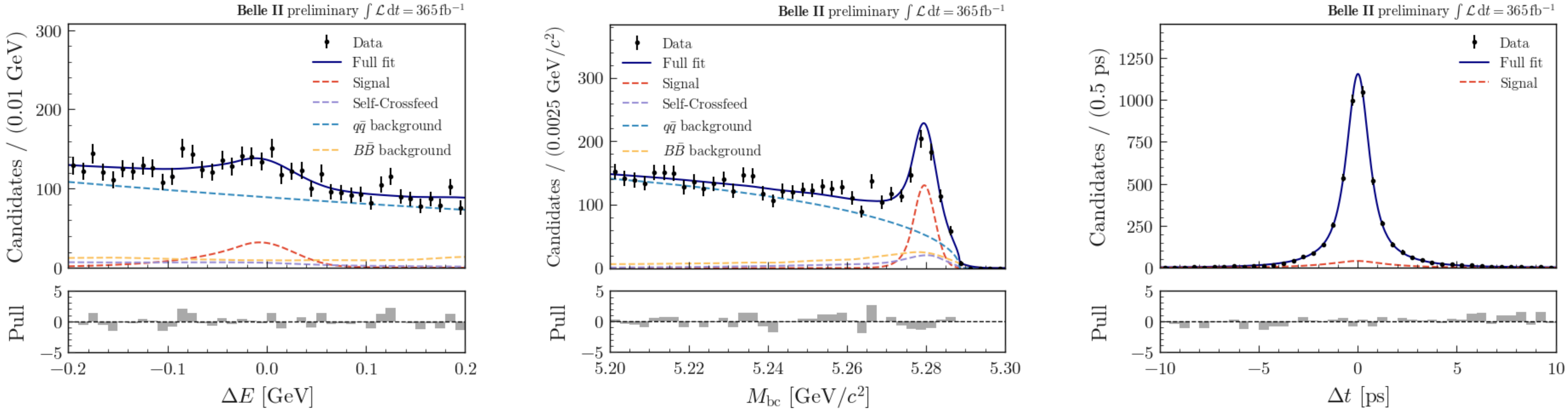
$S = 0.03 \pm 0.08$

$S^+ = 0.06 \pm 0.15$

$S^- = -0.03 \pm 0.15$

- ✓ Good overall agreement between model and data
- ✓ Fitted lifetime value compatible with world average
- ✓ Fitted CP parameters all compatible with 0

Results: Dalitz-integrated fit



- ✓ Good overall agreement between model and data
- ✓ Fitted yields within expectations from simulation studies
- ✓ Fitted lifetime value compatible with world average

Fitted yields:

$N_{\text{sig-like}} = 535 \pm 35$

$N_{B\bar{B}} = 435 \pm 65$

$N_{q\bar{q}} = 3605 \pm 80$

B^0 lifetime:

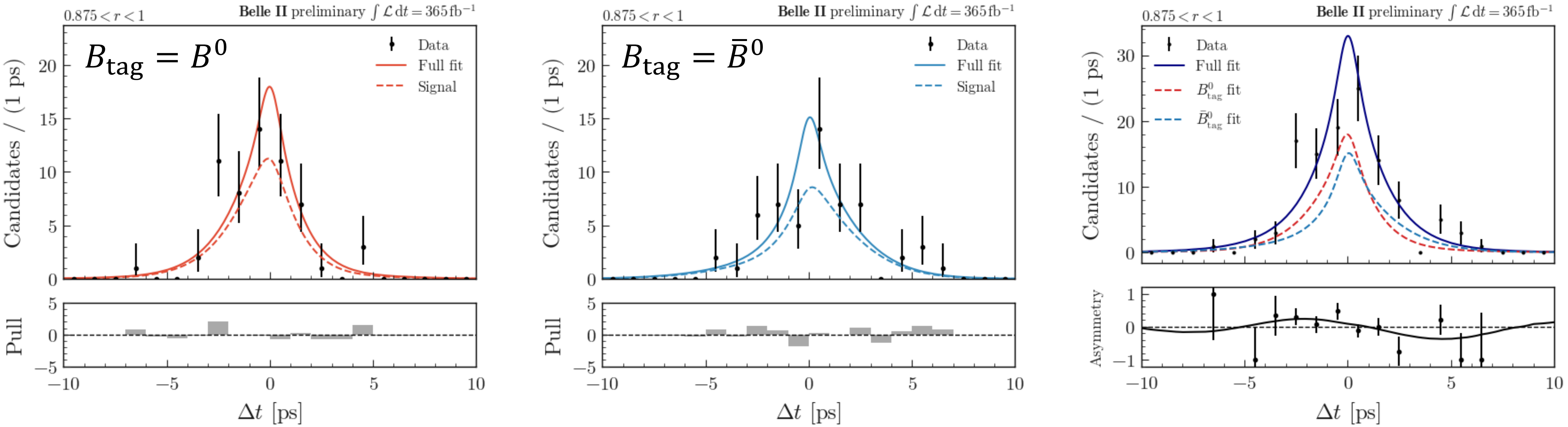
$\tau_{B^0} = 1.52 \pm 0.11$ ps

PDG: 1.517 ± 0.004 ps

Results: Dalitz-integrated fit

Signal-enhanced region:

$|\Delta E| < 0.1$ GeV &
$M_{\text{bc}} > 5.27$ GeV$/c^2$ &
$r > 0.875$ (best r-bin)



- Δt projections in a signal-enhanced region in ΔE, M_{bc} and r
- Slight deviation from SM expectation observed (2.3σ)

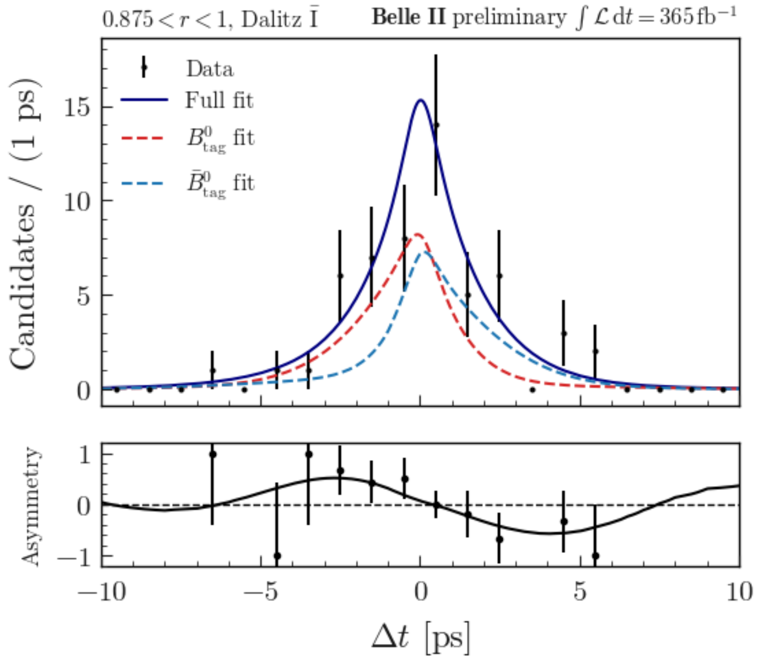
CP parameters:

$S = -0.36 \pm 0.16$

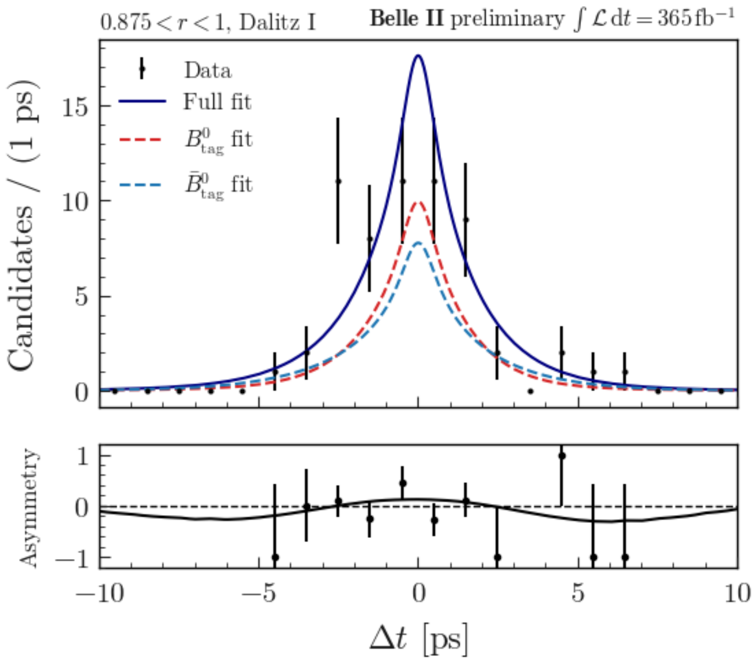
$C = -0.29 \pm 0.13$

Results: Dalitz-split fit

$m^2_{K_S\pi^+} > m^2_{K_S\pi^-}$



$m^2_{K_S\pi^+} < m^2_{K_S\pi^-}$



CP parameters:

$S^+ = -0.72 \pm 0.31$

$S^- = \ \ 0.70 \pm 0.30$

or equivalently:

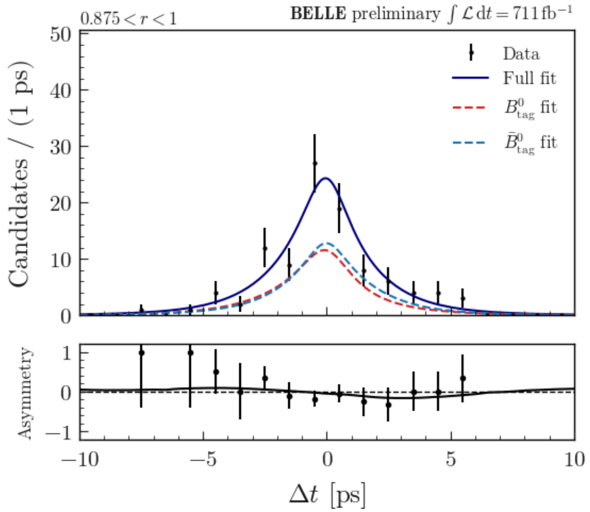
$S^I = -0.01 \pm 0.22$

$S^{\bar{I}} = -0.70 \pm 0.22$

- Similar deviation from SM expectation as with Dalitz-integrated fit
- Observed *CP* violation seems to originate from one half of the Dalitz plane (Dalitz $\bar{I}$)

Belle results

- Analysis of the full Belle dataset (711 fb^{-1}) performed in parallel
- Measurement strategies as similar as possible with irreducible differences due to different detectors and software frameworks
- **Similar precision** between Belle and Belle II despite the difference in dataset size due to improved detector and better flavor tagging
- Belle results within 1σ from SM expectation while being mostly in agreement with Belle II results



Belle results:

$$C = -0.04 \pm 0.11 \pm 0.07$$
$$S = -0.18 \pm 0.17 \pm 0.08$$

$$S^+ = -0.33 \pm 0.34 \pm 0.15$$
$$S^- = -0.36 \pm 0.38 \pm 0.11$$

Combination

- Combine results following HFLAV method
- Systematics considered as uncorrelated except for tag-side interference
- Resulting precision on S and C is the world's best for this mode

Belle results:

$C \;\; = -0.04 \pm 0.11 \pm 0.07$

$S \;\; = -0.18 \pm 0.17 \pm 0.08$

$S^+ = -0.33 \pm 0.34 \pm 0.15$

$S^- = -0.36 \pm 0.38 \pm 0.11$

$\oplus$

Belle II results:

$C \;\; = -0.29 \pm 0.13 \pm 0.06$

$S \;\; = -0.36 \pm 0.16 \pm 0.05$

$S^+ = -0.72 \pm 0.31 \pm 0.12$

$S^- = \;\; 0.70 \pm 0.30 \pm 0.05$

$=$

Combined results:

$C \;\; = -0.17 \pm 0.09 \pm 0.04$

$S \;\; = -0.29 \pm 0.11 \pm 0.05$

$S^+ = -0.57 \pm 0.23 \pm 0.10$

$S^- = \;\; 0.31 \pm 0.24 \pm 0.05$

Discussion

- Combined result exhibits a $1.3\sigma - 2.4\sigma$ tension with the SM expectation
- Extensive tests of the fit strategy did not reveal any major issues
- Precision still statistically limited
- No New Physics has been observed

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Submitted to JHEP
arXiv:2510.01331

Conclusions and Prospects

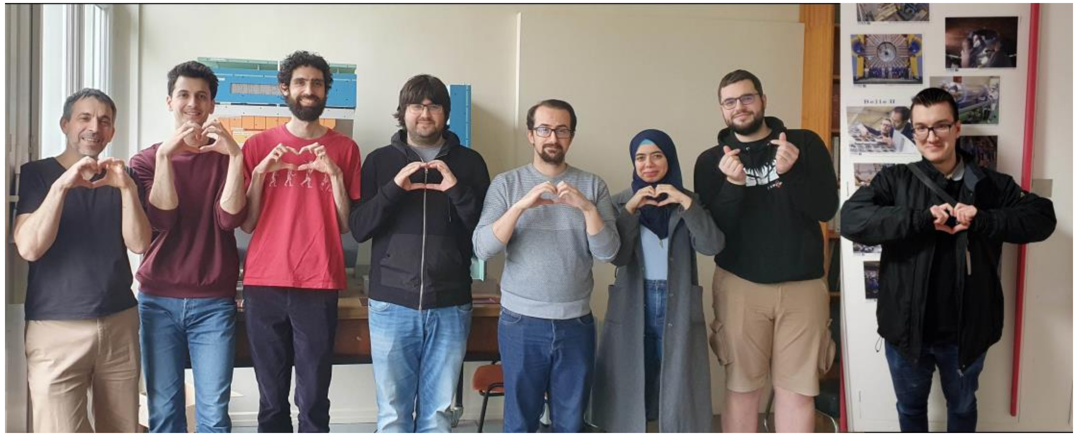
- ✓ Calibrated Flavor Tagger and Δt Resolution Function parameters
  → PRD 110, 012001
- ✓ Measured time-dependent CP asymmetry in $B^0 \to K_S^0 \pi^+\pi^-\gamma$ decays
  → arXiv:2510.01331

- ➢ Growing Belle II dataset + further improvements in Flavor Tagging
  ⇒ **higher precision** measurements
- ➢ **Vertex detector upgrade** ⇒ ~20% gain in precision expected; demonstrated in **benchmark study** using simulated $B^0 \to K_S^0 \pi^+\pi^-\gamma$ decays
- ➢ Ongoing **amplitude analysis** in $B^+ \to K^+\pi^+\pi^-\gamma$ by Strasbourg group
  ⇒ new constraints on C_7'/C_7 complex plane


KEK


KEK

Thank You!

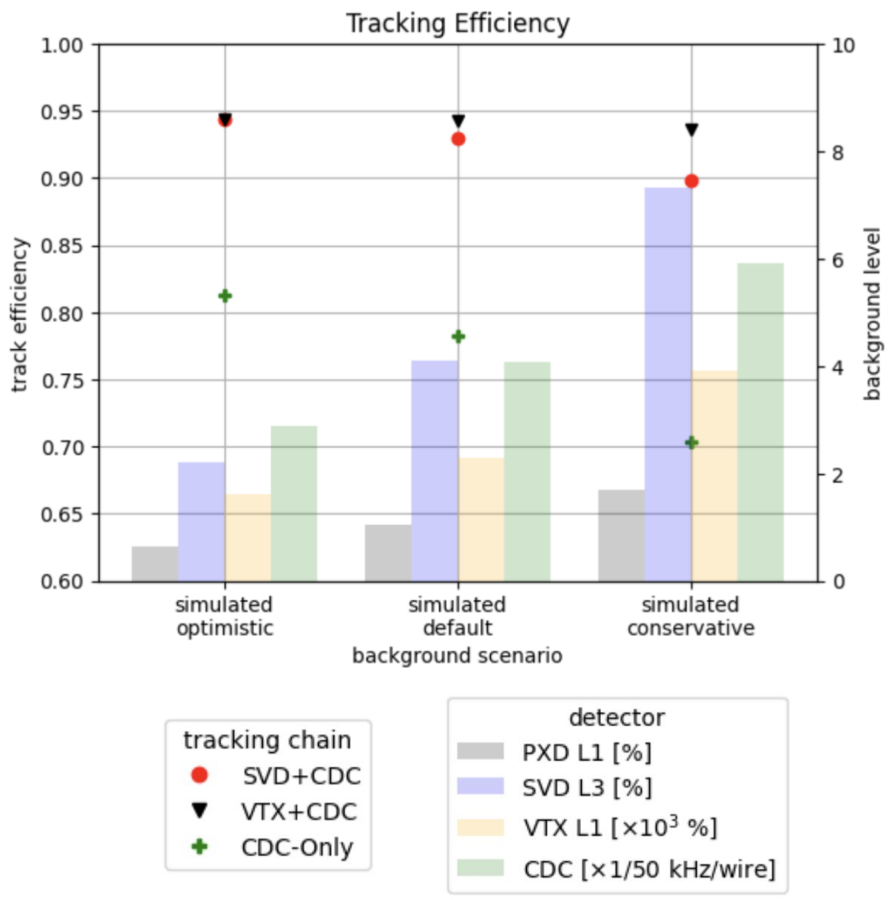



Graph Neural
Measure
Petros Stavroulakis (IP
58th Rencontres de Mor
La Thuile, March 27th 2
Belle II

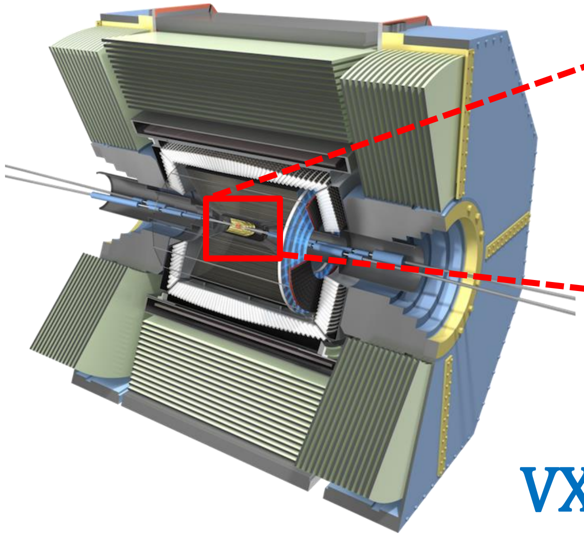
Backup

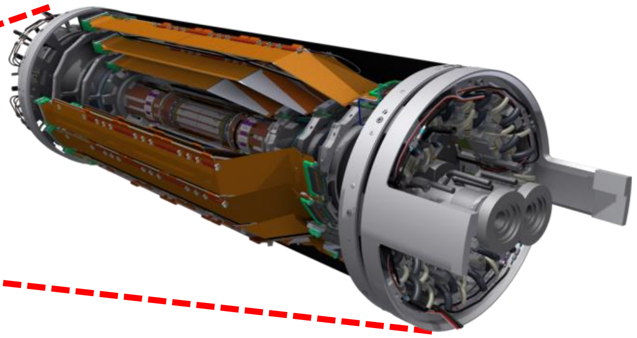
The need for an upgrade

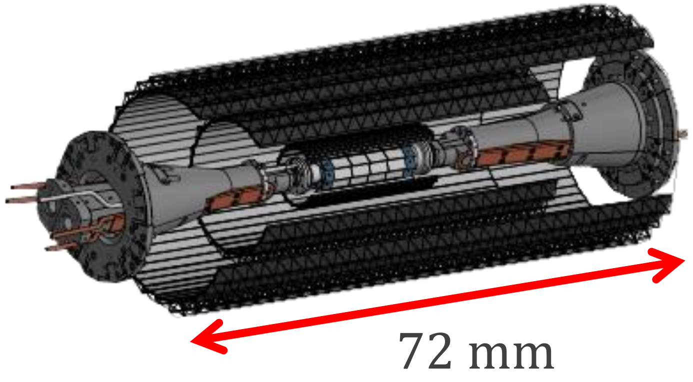
- **Experimental challenge** posed by extremely high luminosity
  ⇒ parasitic particles generated by **beam-induced backgrounds**
- **Touschek scattering** expected to be a major source of beam-induced background at nominal SuperKEKB luminosity
- CDC and VXD will struggle to keep up with increased hit rate
- Detector upgrade expected during Long Shutdown 2



Vertex Detector Upgrade







VXD
- 2 layers: DEPFET pixel sensors
- 4 layers: 2-sided strip detectors

VTX: 5 layers of CMOS pixel sensors

- ✓ Decrease **occupancy** by increasing granularity (30 → 40 μm pitch) and reducing integration time (≤ 100 ns)
- ➢ Are the upgraded geometries **optimised** for physics?
- ➢ Is the **sensitivity** of Belle II to new physics improved?

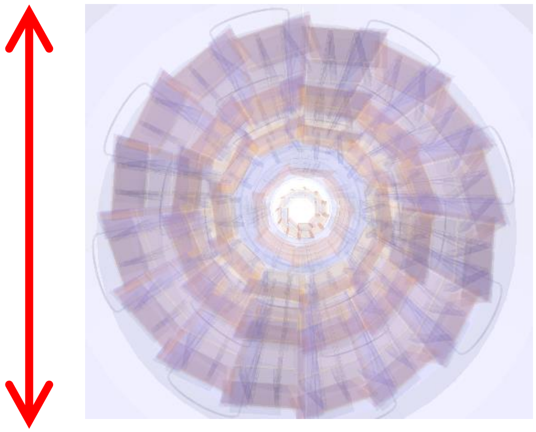
$$\text{Occupancy} \propto \frac{\text{integration time}}{\text{granularity}}$$

Simulated geometries

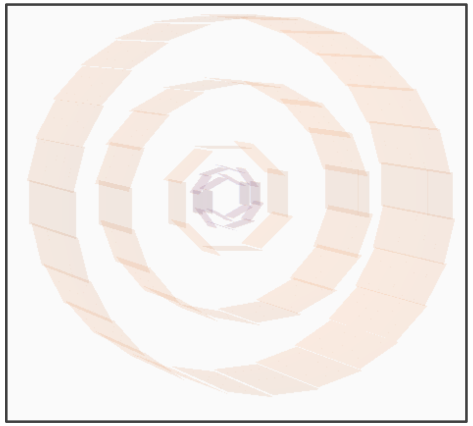
- Study VTX performance using simulated $B^0 \to K_S^0 \pi^+\pi^-\gamma$ decays
- Ideal **benchmark** for studying prompt (B^0) and displaced (K_S^0) vertices + high energy photons
- Specifically study B^0 & K_S^0 **reconstruction efficiency** and B^0 **decay vertex resolution**
- 3 geometries available in the Monte Carlo (MC) simulation (1 current + 2 upgrade)

Current VXD

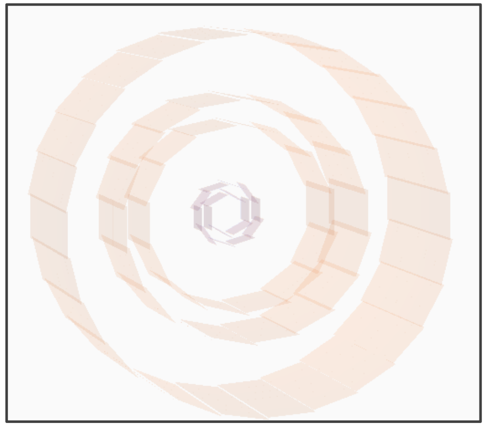
28 mm



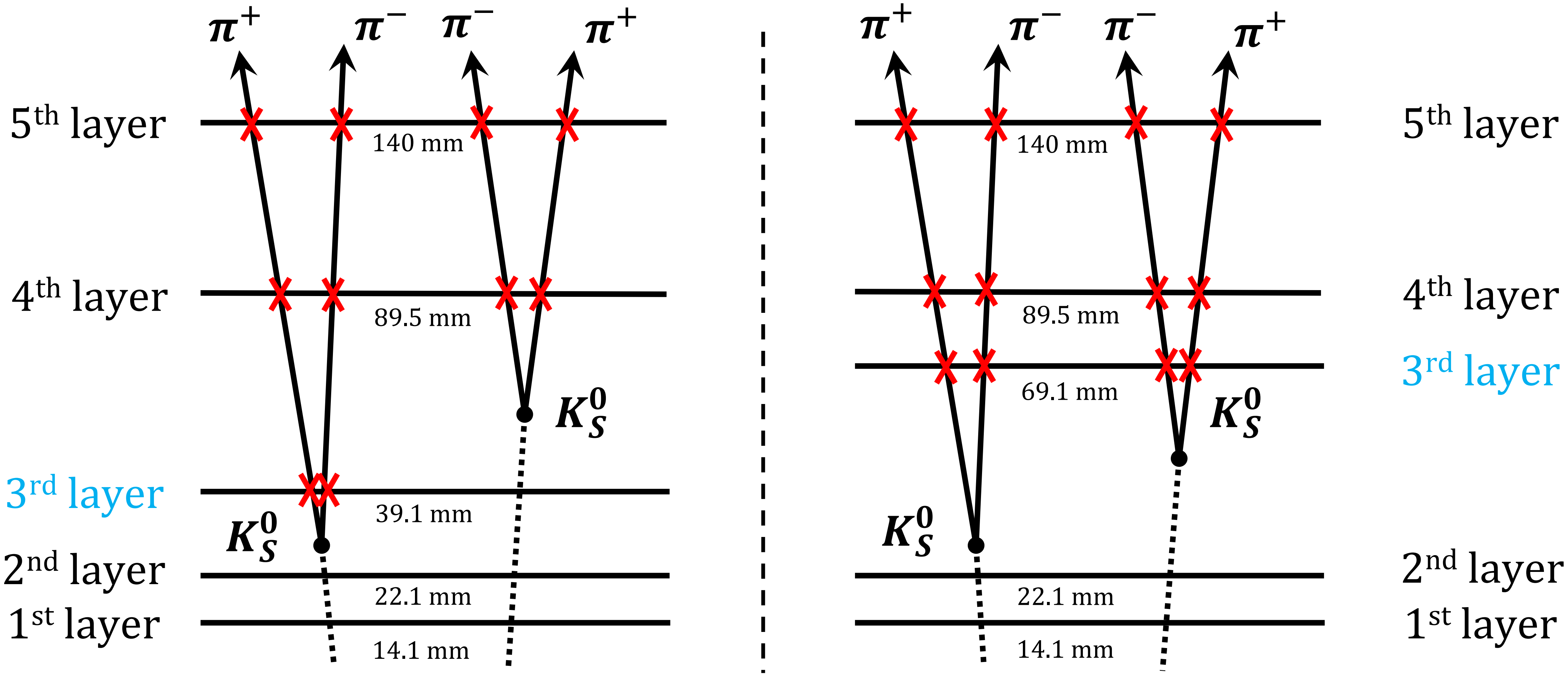
VTX 5 layers



VTX 5 layers
w/ modified L3



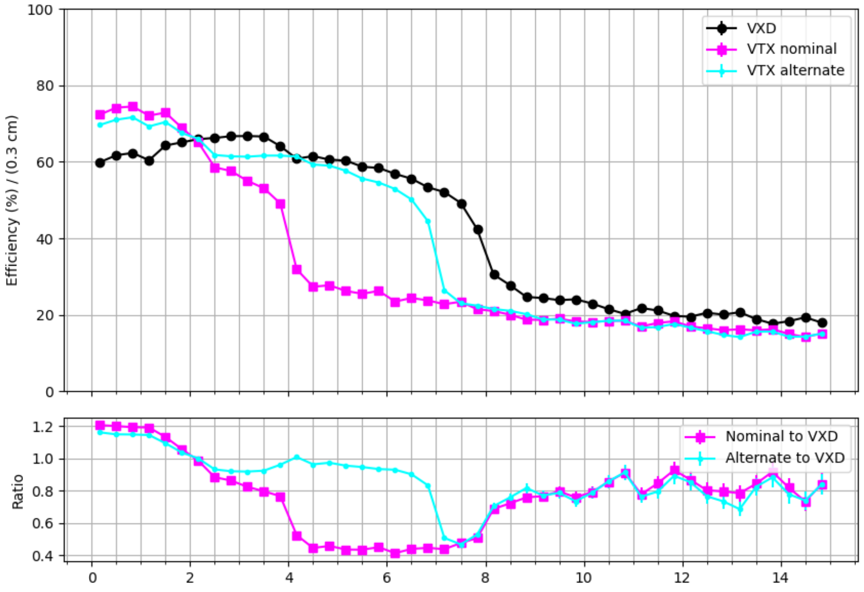
Motivation for modifying L3



Reconstruction Efficiency

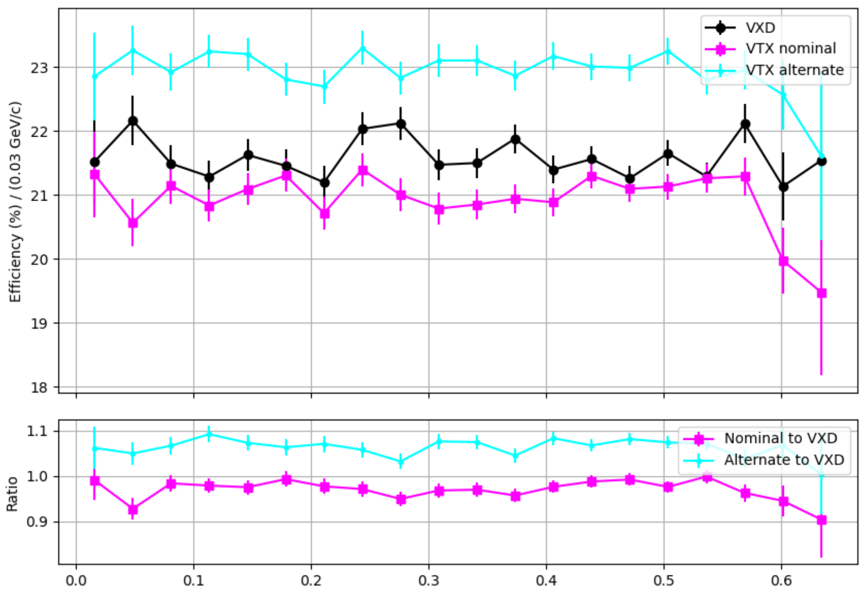
ρ: transverse decay length
p_T: transverse momentum

K_S^0 Reconstruction Efficiency per ρ bin



ρ [cm]

B^0 Reconstruction Efficiency per p_T bin



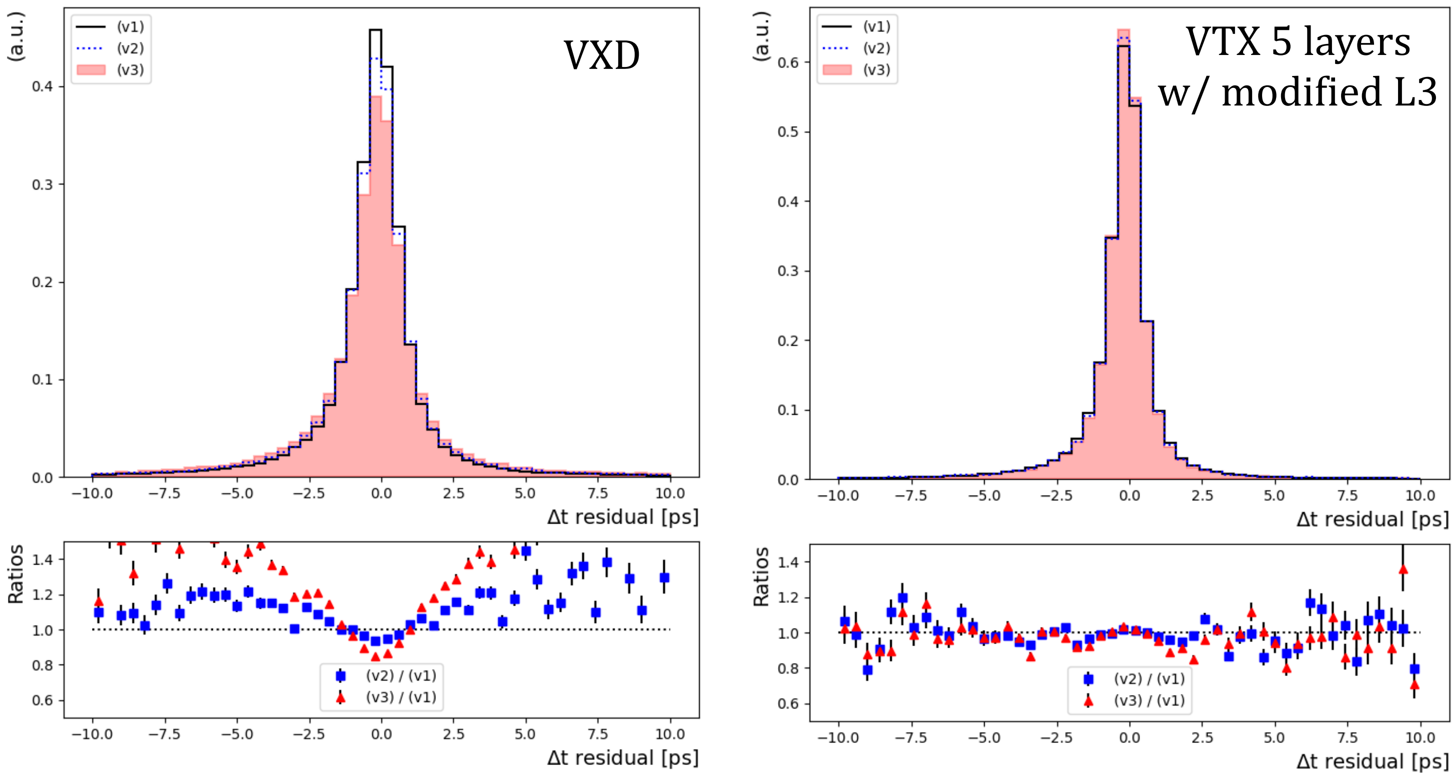
p_{T} [GeV/c]

Detector Geometry	Efficiency [%]
VXD	21.57 ± 0.06
VTX 5 layers	21.04 ± 0.06
VTX 5 layers L3 mod	$\mathbf{23.02 \pm 0.06}$

VTX reaches **better reconstruction efficiency** than VXD with high beam-induced backgrounds due to L3 modification

Δt residual: $\Delta t_{\text{reco}} - \Delta t_{\text{true}}$

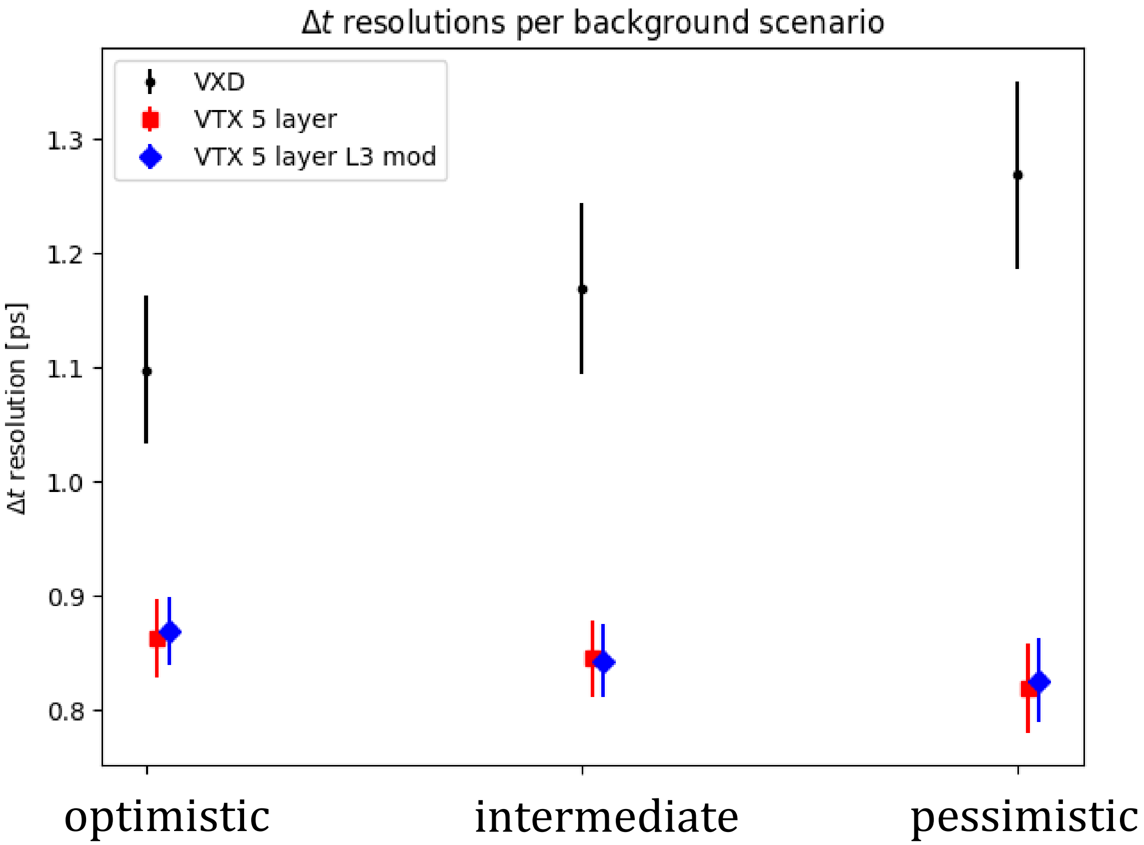
Decay Vertex Resolution



Background Scenario	Δt Resolution [ps]	
	VXD	VTX L3 mod
Optimistic	1.10 ± 0.05	0.87 ± 0.03
Intermediate	1.17 ± 0.06	0.84 ± 0.03
Pessimistic	1.27 ± 0.07	0.83 ± 0.04

VTX more **robust** than VXD against increasing beam-induced backgrounds and with **better vertex resolution** due to higher granularity achieved by CMOS pixels

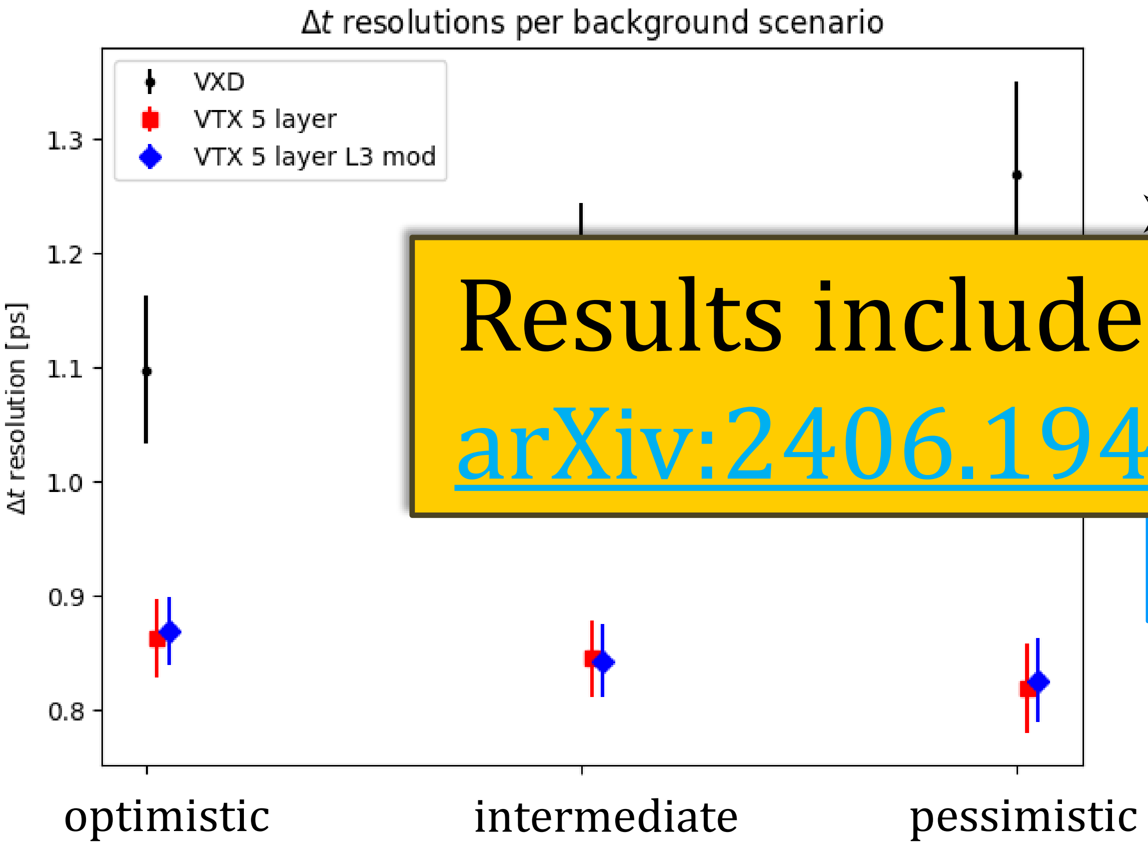
Effect on TDCP asymmetry



- Estimate sensitivity gain on the TDCP asymmetry measurement using pseudo-experiments
- Pessimistic background scenario, 50 ab^{-1} projection

✓ From VTX upgrade alone gain **~20%** on sensitivity $\Rightarrow$ **~40%** more data!

Effect on TDCP asymmetry

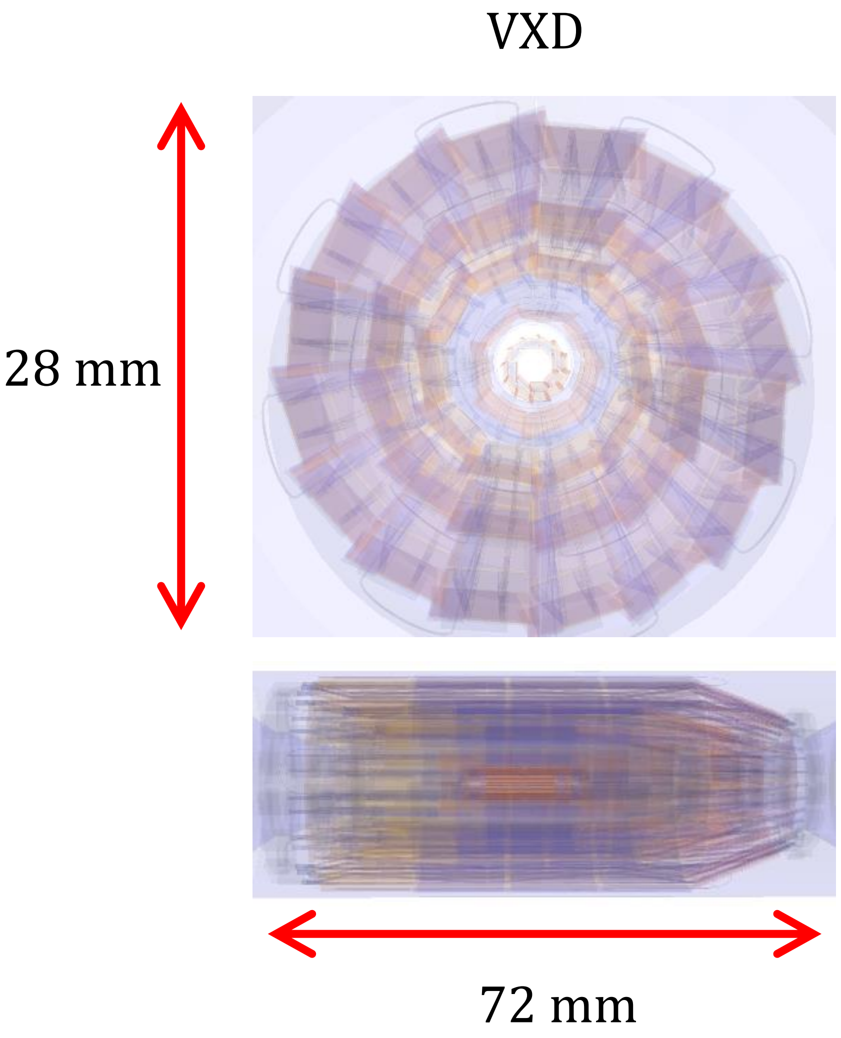


Results included in Upgrade CDR
arXiv:2406.19421

- Estimate sensitivity gain on the TDCP asymmetry
  ...ments
  ...0 ab^{-1} projection

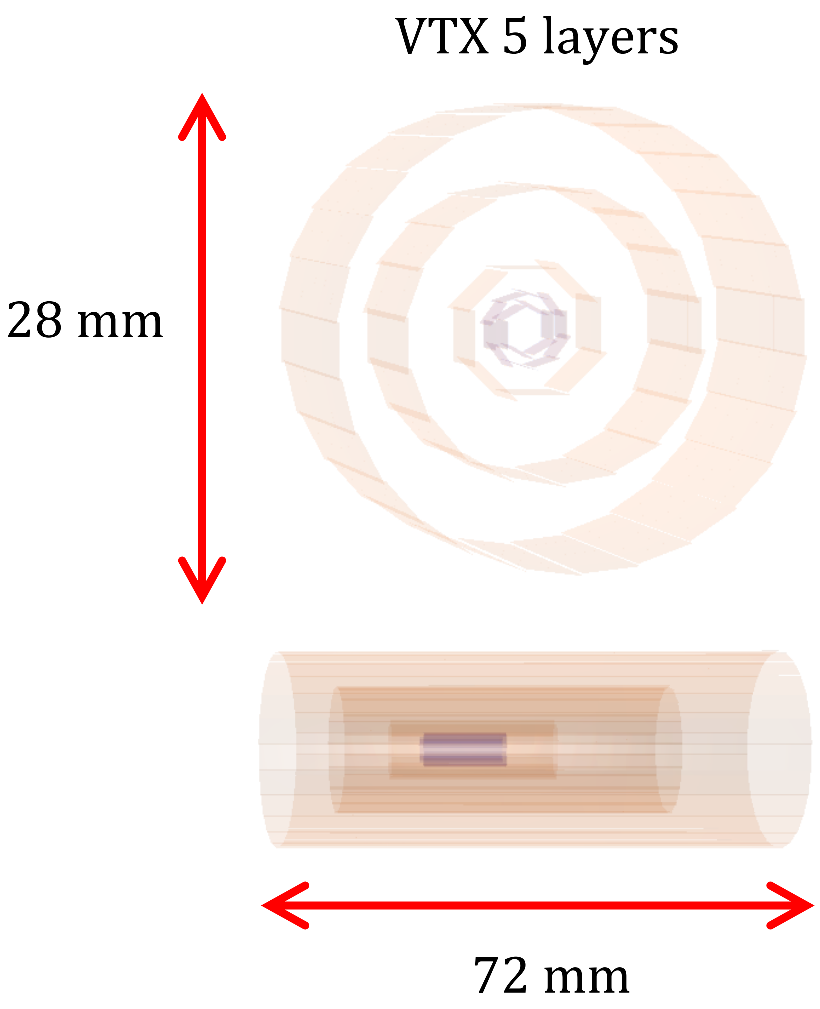
- From VTX upgrade alone gain ~**20%** on sensitivity
  ⇒ ~**40%** more data!

Vertex detector geometries



Layer no.	1	2	3	4	5	6
Radius (mm)	14.2	21.8	39.0	80.0	104.0	135.2
# Ladders	8	12	7	10	12	16
# Sensors per ladder	2	2	2	3	4	5
$(r-\phi, z)$ pitch (μm)	$(60, 50)$	$(60, 50)$	$(160, 50)$	$(160, 50)$	$(160, 50)$	$(160, 50)$

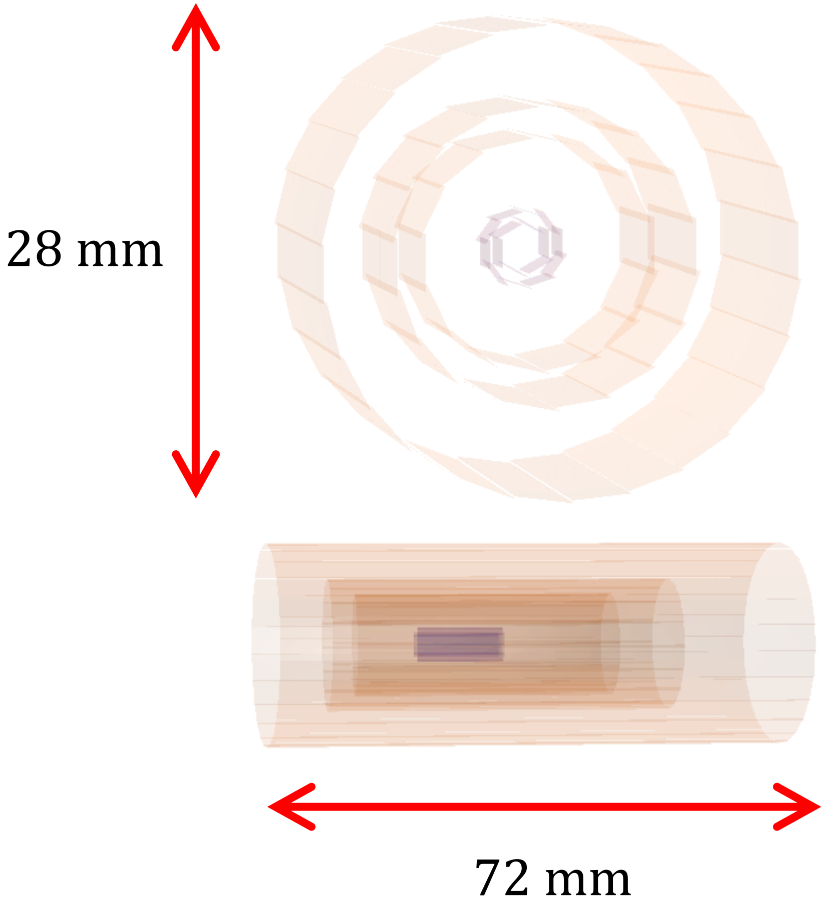
Vertex detector geometries



Layer no.	1	2	3	4	5
Radius (mm)	14.1	22.1	39.1	89.5	140.0
# Ladders	6	10	8	18	26
# Sensors per ladder	4	4	8	16	24
$(r-\phi, z)$ pitch (μm)	$(35, 35)$	$(35, 35)$	$(35, 35)$	$(35, 35)$	$(35, 35)$

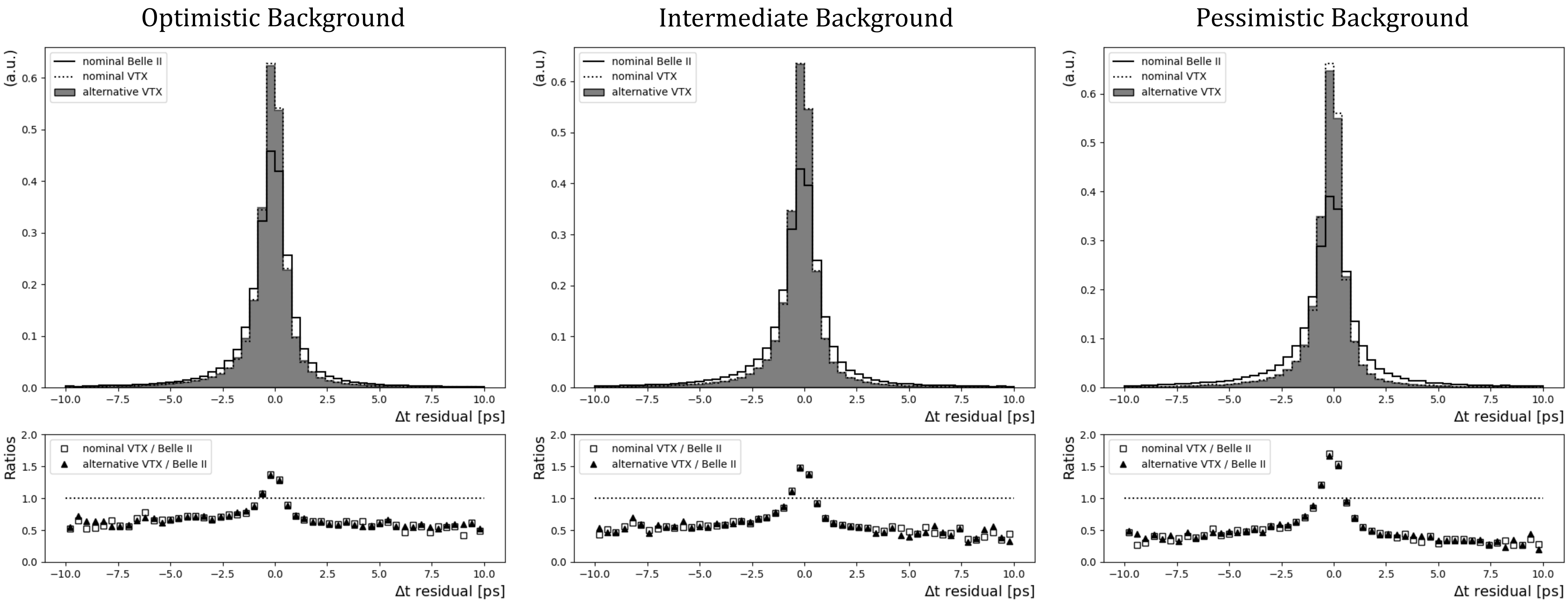
Vertex detector geometries

VTX 5 layers w/ modified L3



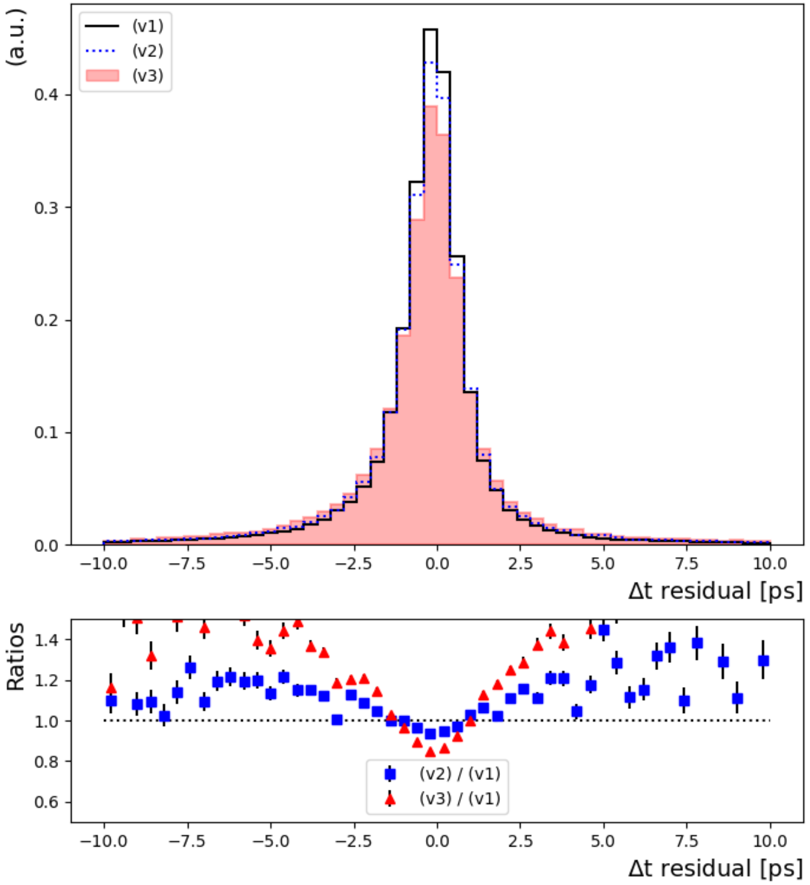
Layer no.	1	2	3	4	5
Radius (mm)	14.1	22.1	**69.1**	89.5	140.0
# Ladders	6	10	**12**	18	26
# Sensors per ladder	4	4	**12**	16	24
$(r-\phi, z)$ pitch (μm)	$(35, 35)$	$(35, 35)$	$(35, 35)$	$(35, 35)$	$(35, 35)$

Resolutions per detector geometry

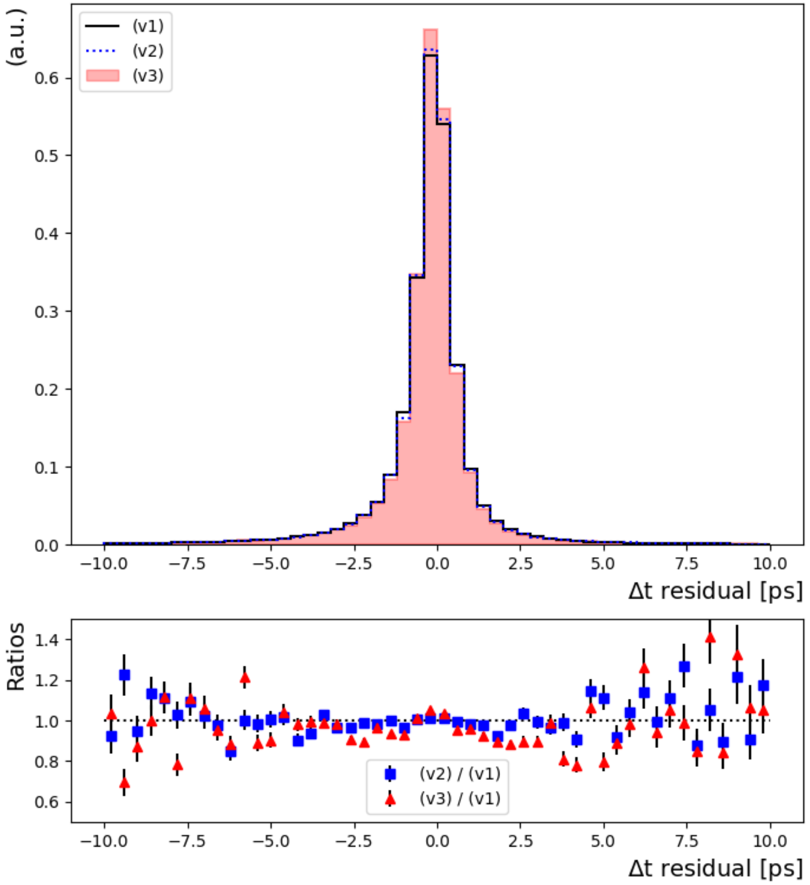


Resolutions per BG scenario

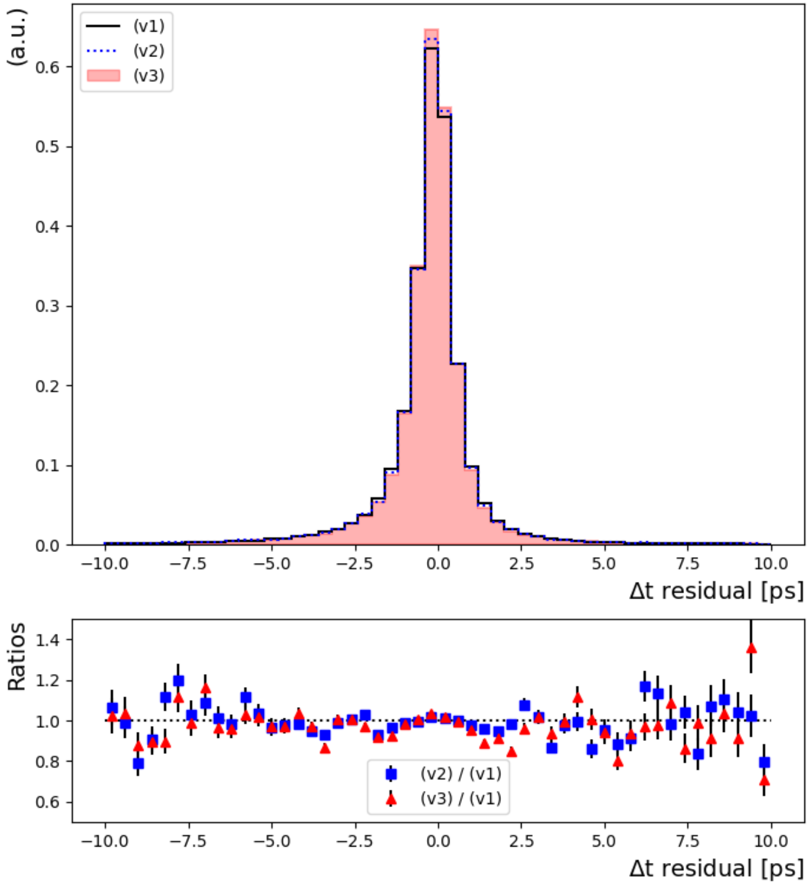
VXD



VTX 5 layers



VTX 5 layers modified L3



Flavor Tagging Categories

Categories	Targets for $\overline{B}^0$
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
Kinetic Lepton	ℓ^-
Intermediate Kinetic Lepton	ℓ^+
Kaon	K^-
Kaon-Pion	K^-, π^+
Slow Pion	π^+
Maximum p^*	ℓ^-, π^-
Fast-Slow-Correlated (FSC)	ℓ^-, π^+
Fast Hadron	π^-, K^-
Lambda	Λ

Underlying decay modes

$\overline{B}^0 \rightarrow D^{*+}\ \bar{\nu}_\ell\ \ell^-$

$\quad \hookrightarrow D^0\ \pi^+$

$\quad\quad \hookrightarrow X\ K^-$

$\overline{B}^0 \rightarrow D^+\ \pi^-\ (K^-)$

$\quad \hookrightarrow \overline{K}^0\ \nu_\ell\ \ell^+$

$\overline{B}^0 \rightarrow \Lambda_c^+\ X^-$

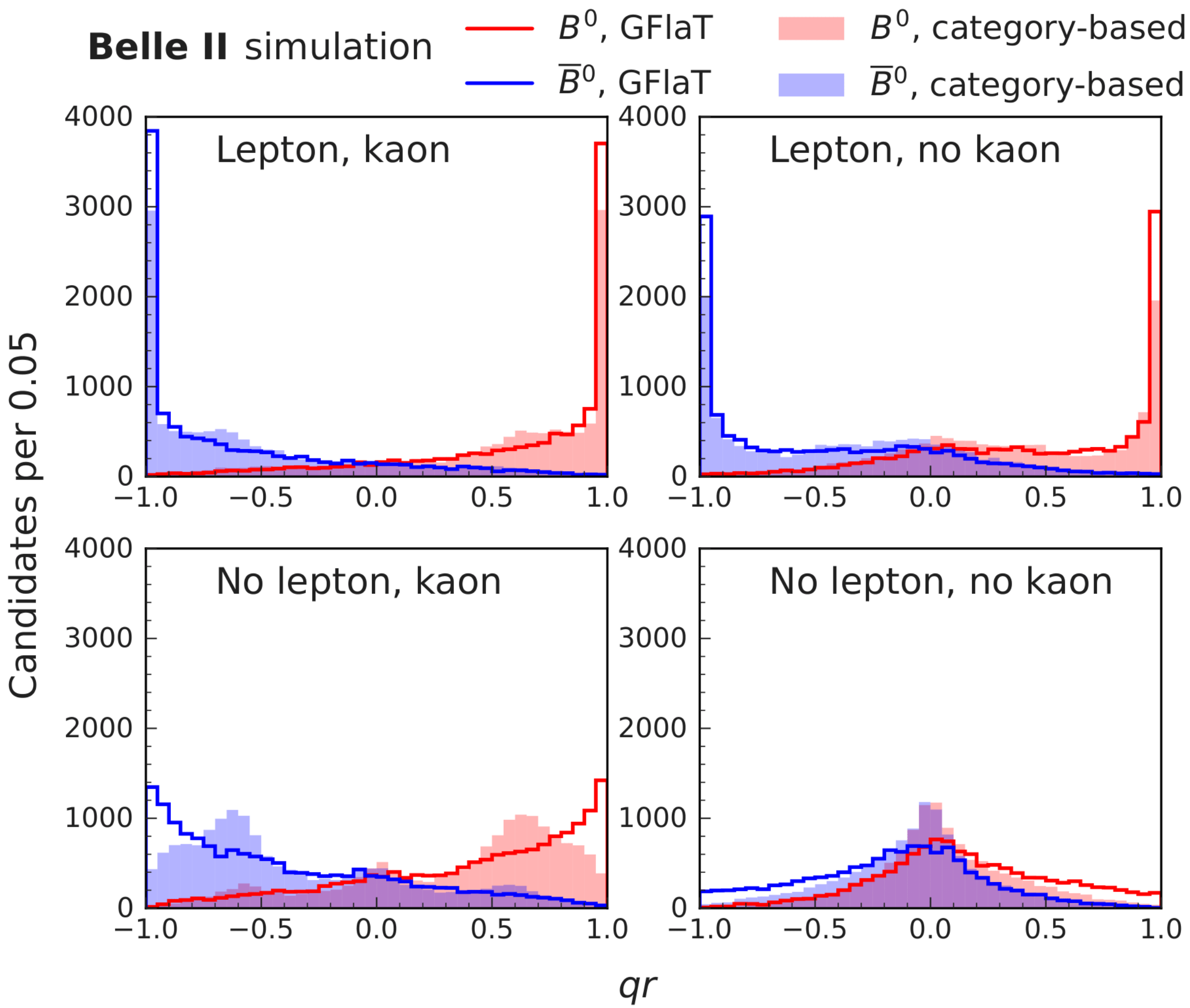
$\quad \hookrightarrow \Lambda\ \pi^+$

$\quad\quad \hookrightarrow p\ \pi^-$

GFlaT Input Variables

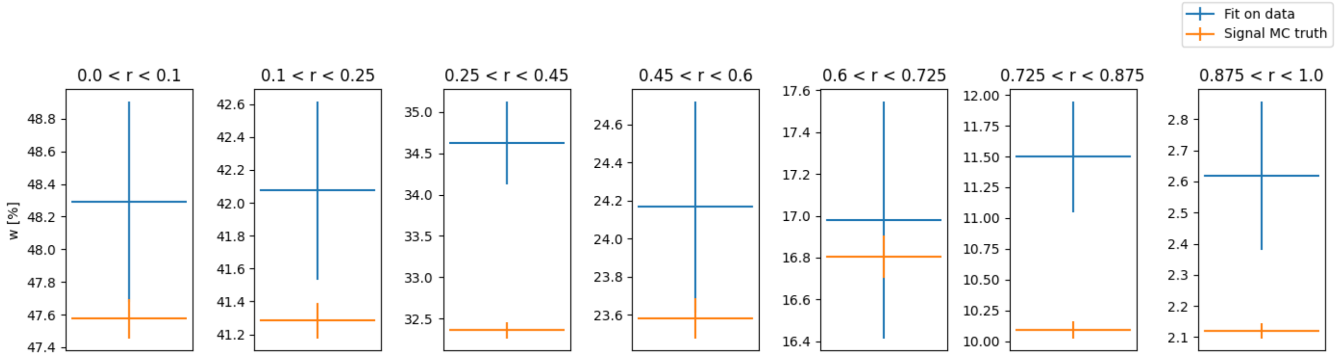
Variables	Usage	Descriptions
QpTrack(categoryName) * charge	Input features	multiplication of the charge of each particle by the category-baed Flavor Tagger output for each of the 13 categories;
p_x, p_y, p_z (px, py, pz)		momentum of a charged particle
electronID_noSVD_noTOP, muonID, pionID, kaonID, protonID, deuteronID		particle identification probability calculated from a global likelihood ratio of sub-detectors
x, y, z (dx, dy, dz)	Input coordinates, and edge-features $\boldsymbol{x}_{i_j} - \boldsymbol{x}_i$	distance of POCA to the interaction point
charge	Charge multiplier block	charge of a charged particle

qr Breakdown

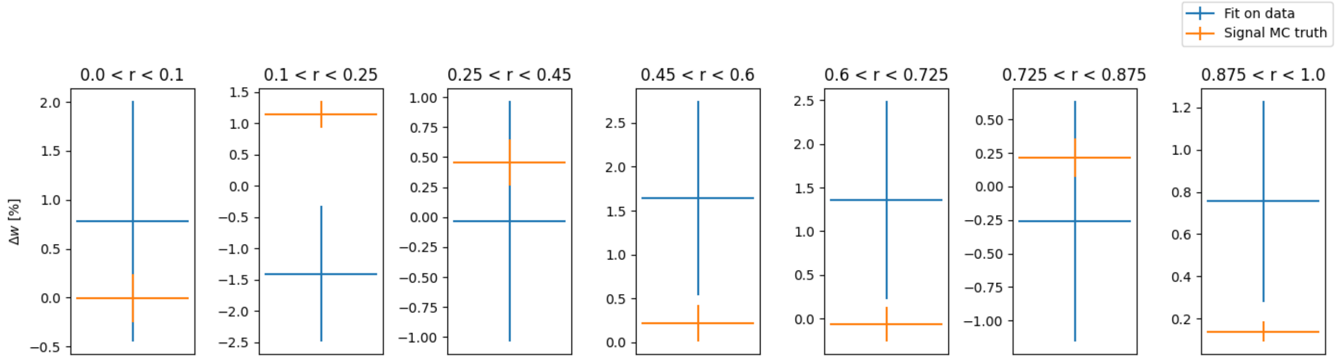


FT parameters Data/MC comparison

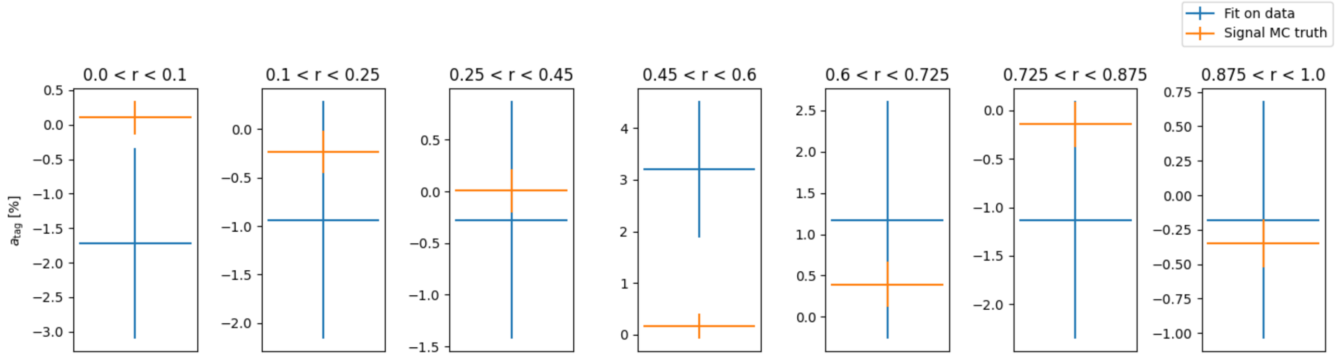
Wrong tag fraction



Wrong tag asymmetry

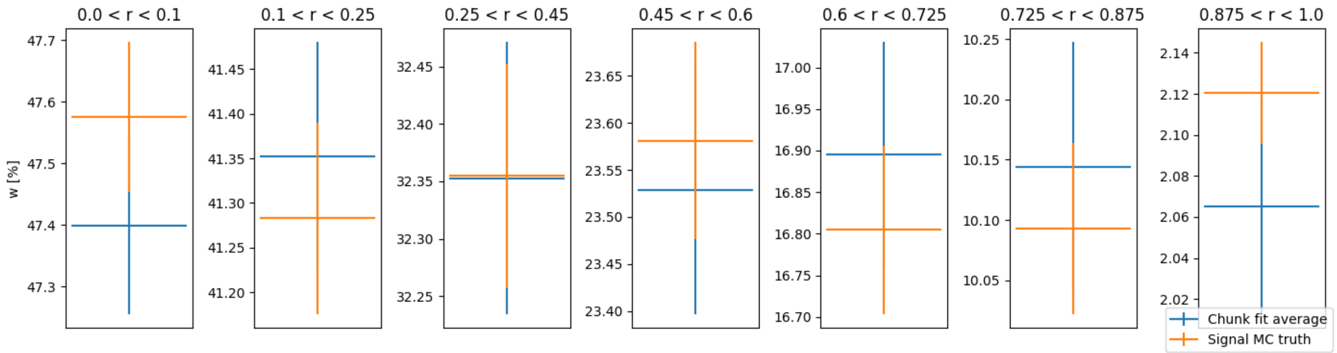


Tag efficiency asymmetry

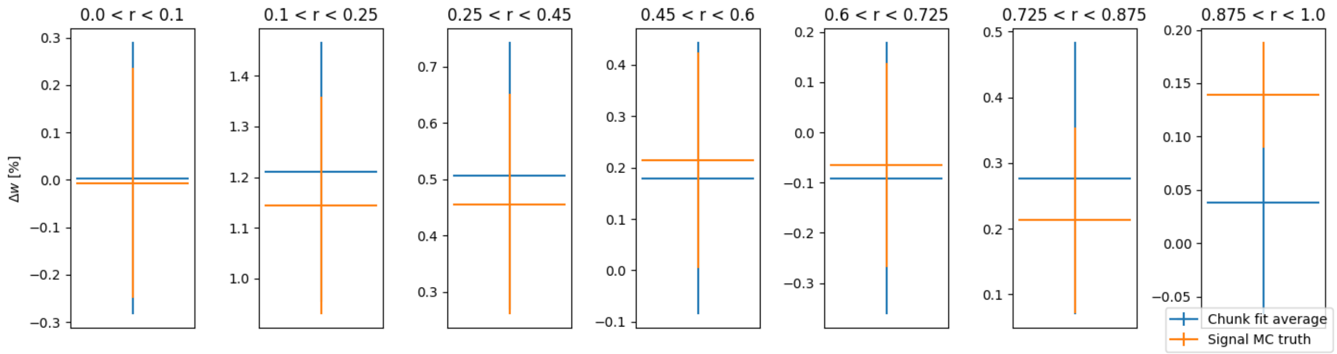


Signal MC fit/MC truth comparison

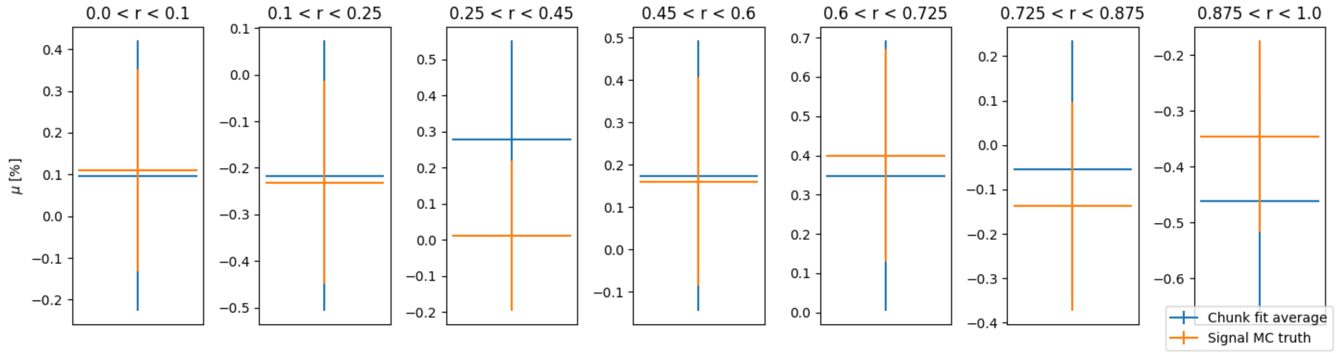
Wrong tag fraction



Wrong tag asymmetry

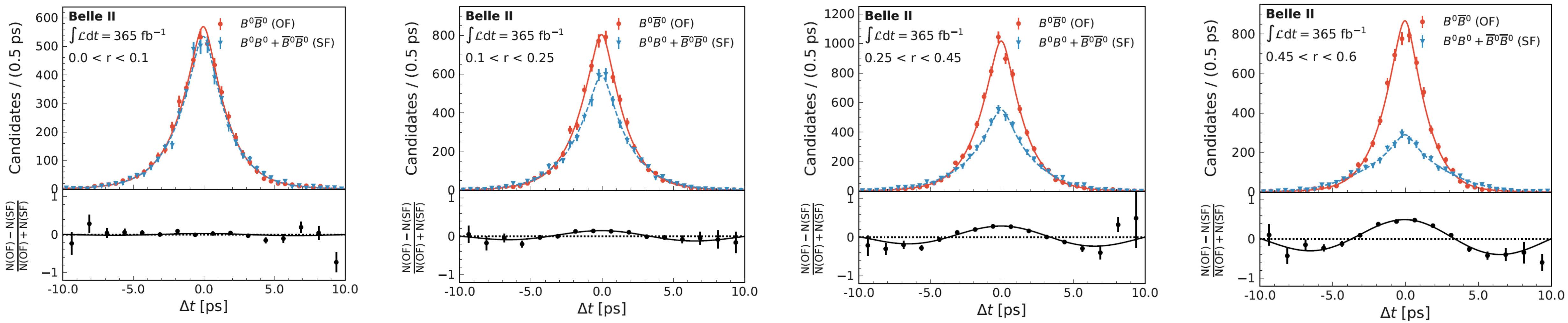


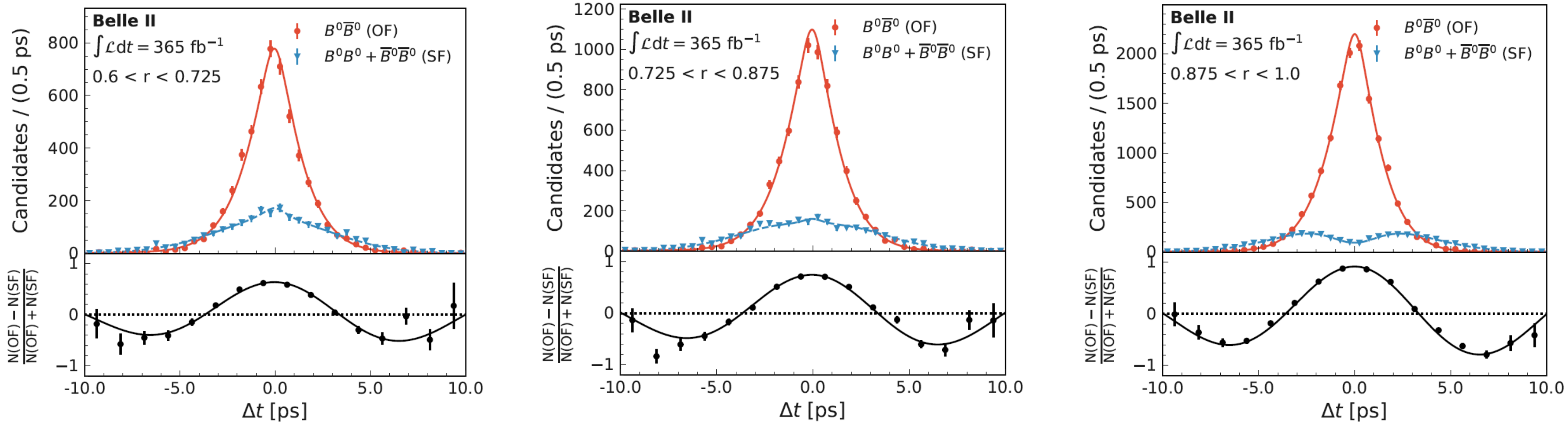
Tag efficiency asymmetry



FT calibration – Mixing fits

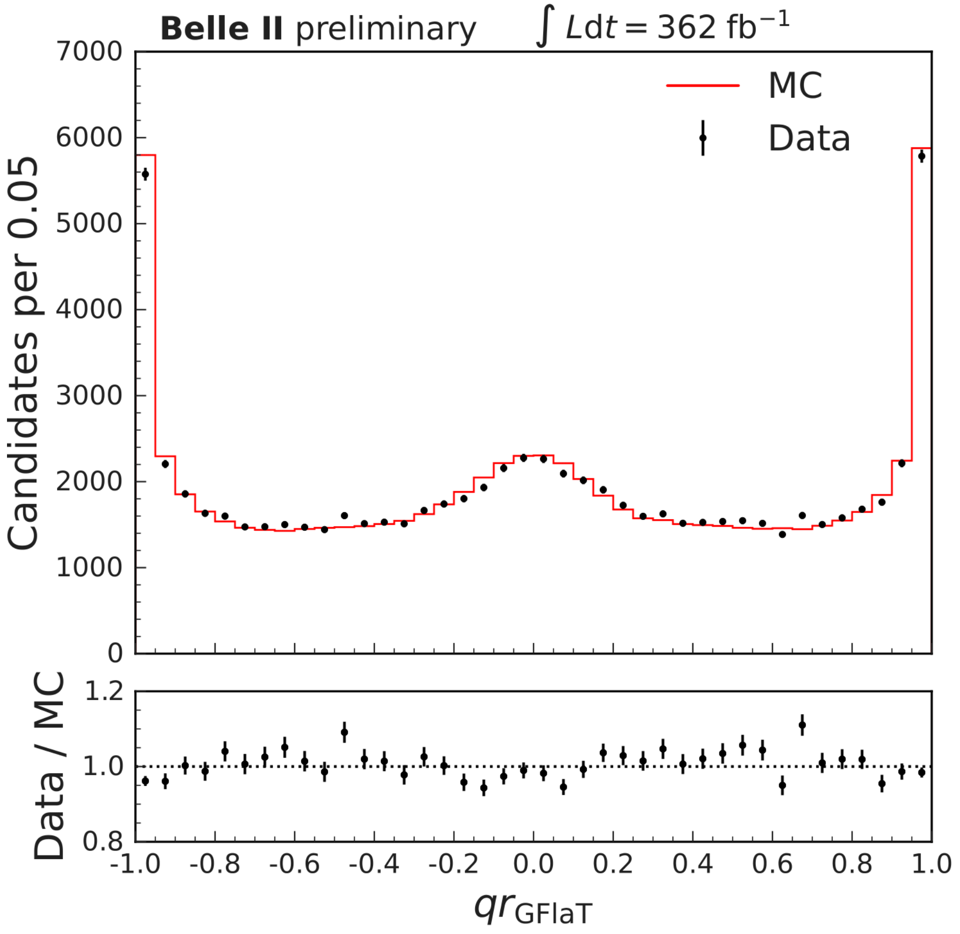
Lowest Confidence

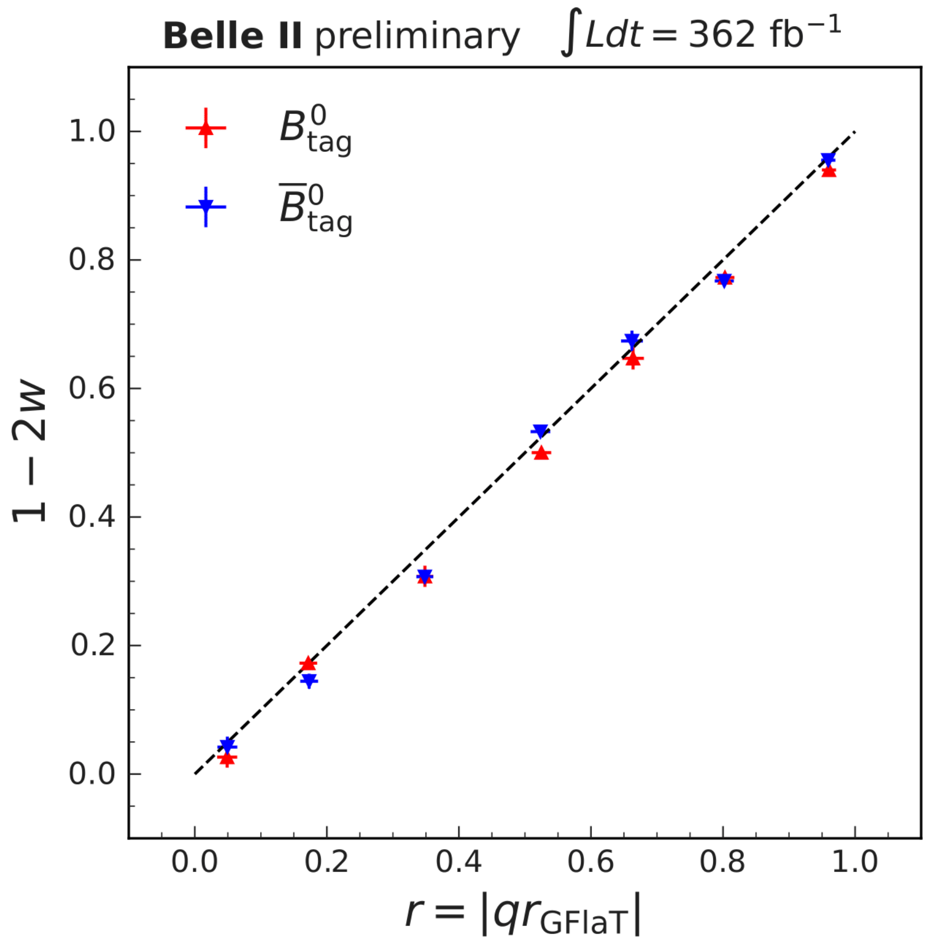




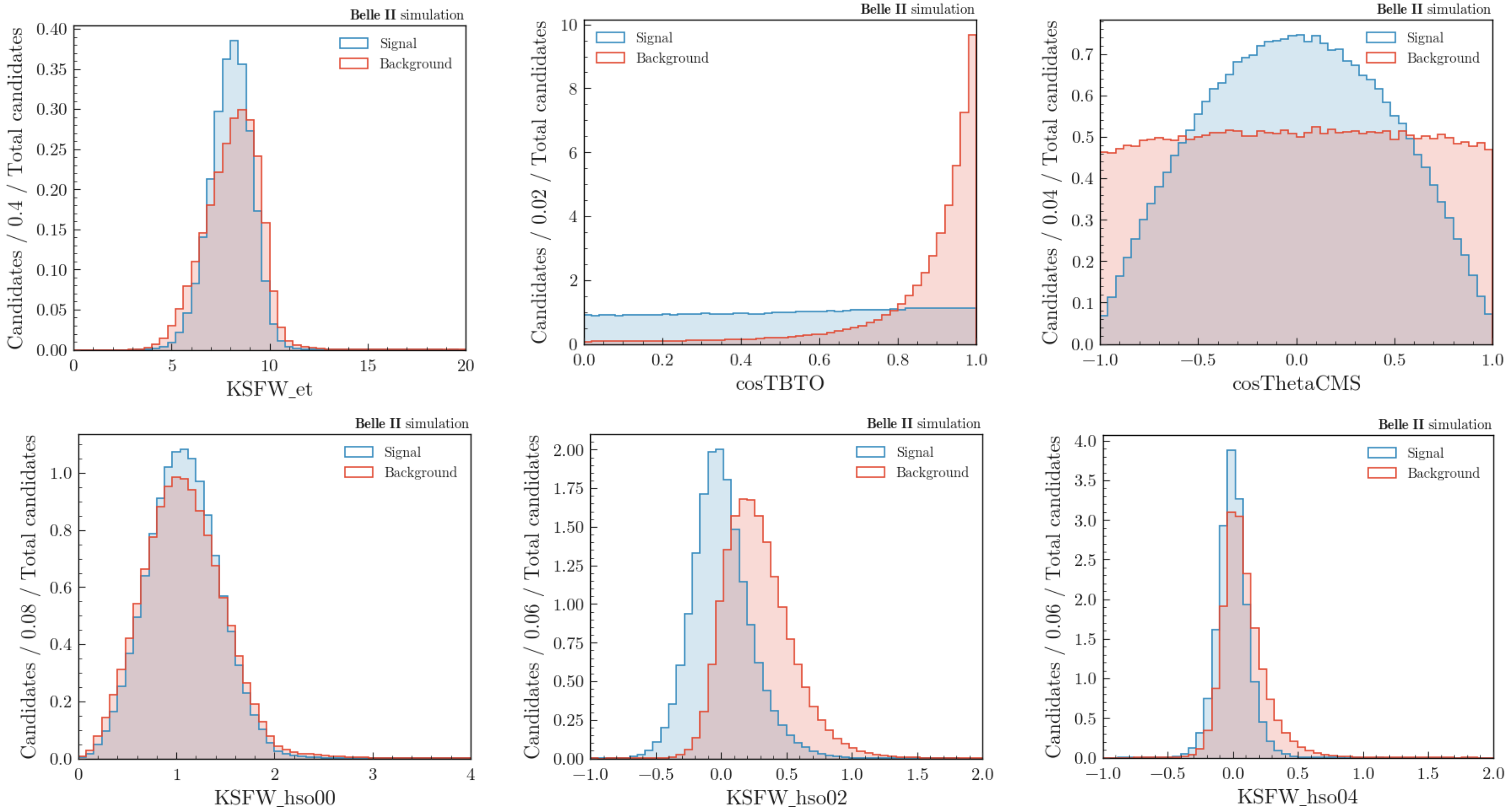
Highest Confidence

Data/MC & Linearity Checks

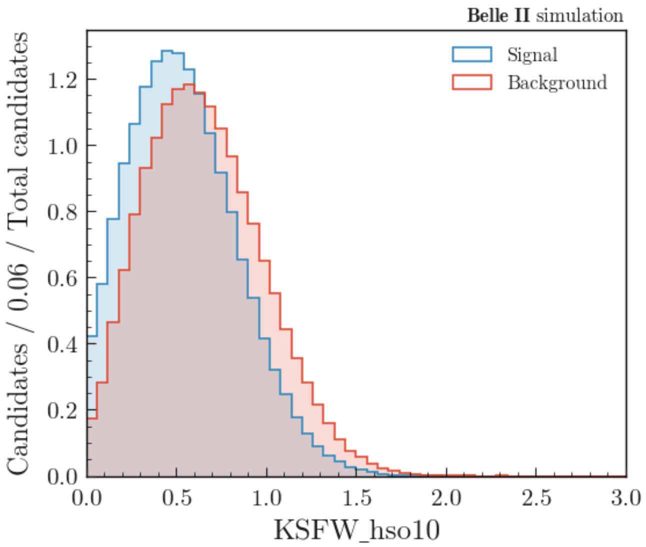


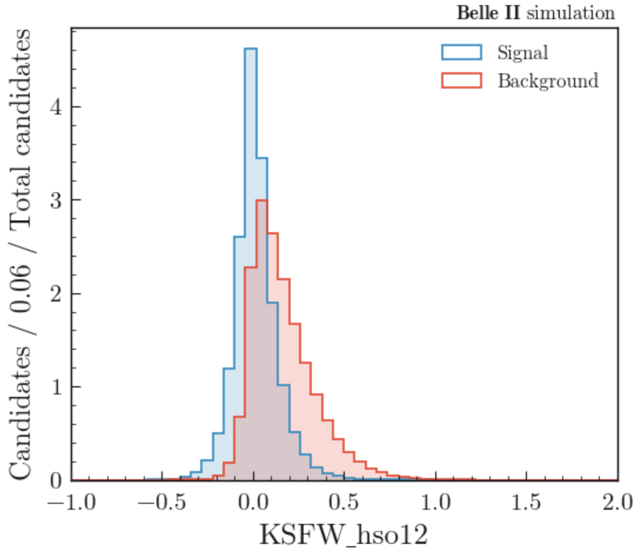


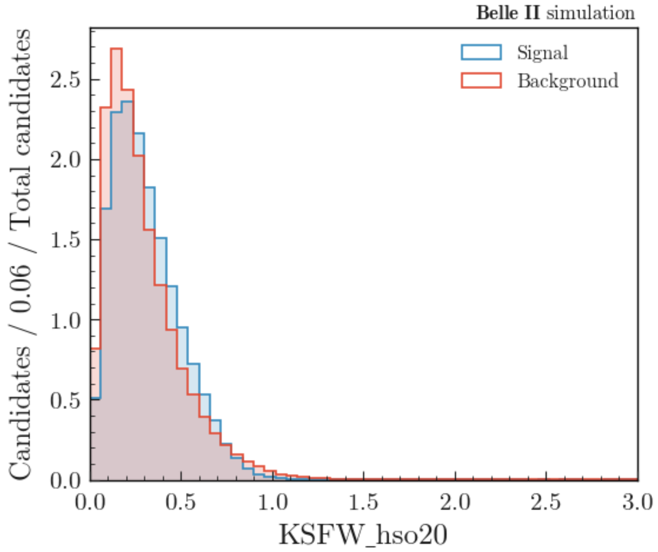
CSMVA input variables (1)

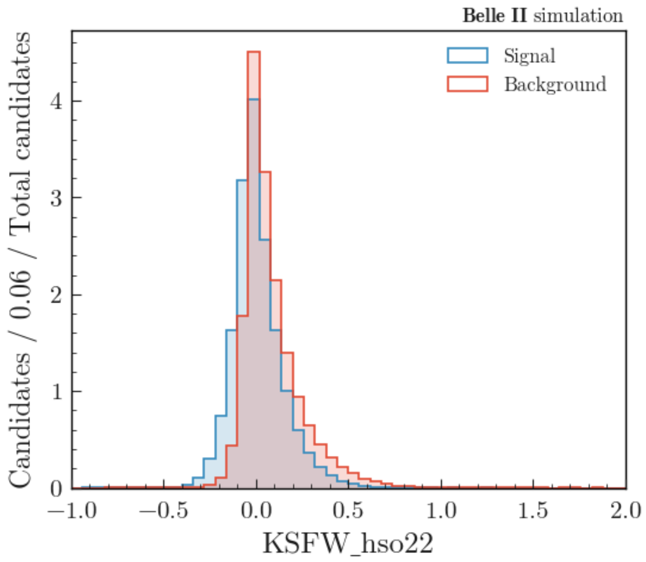


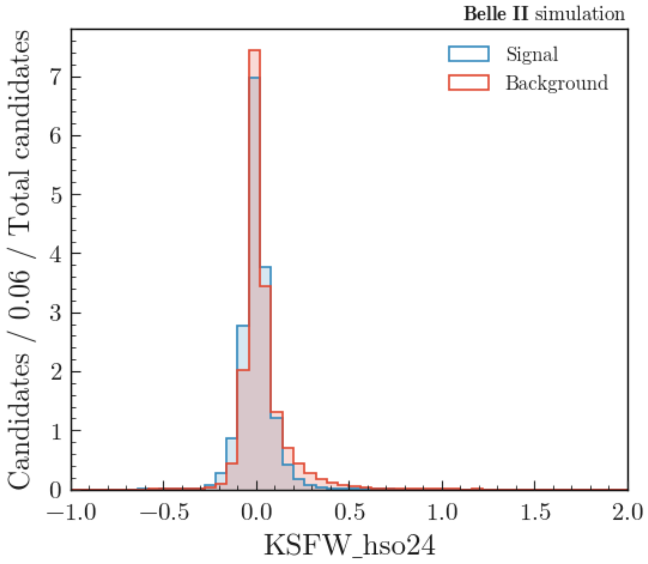
CSMVA input variables (2)



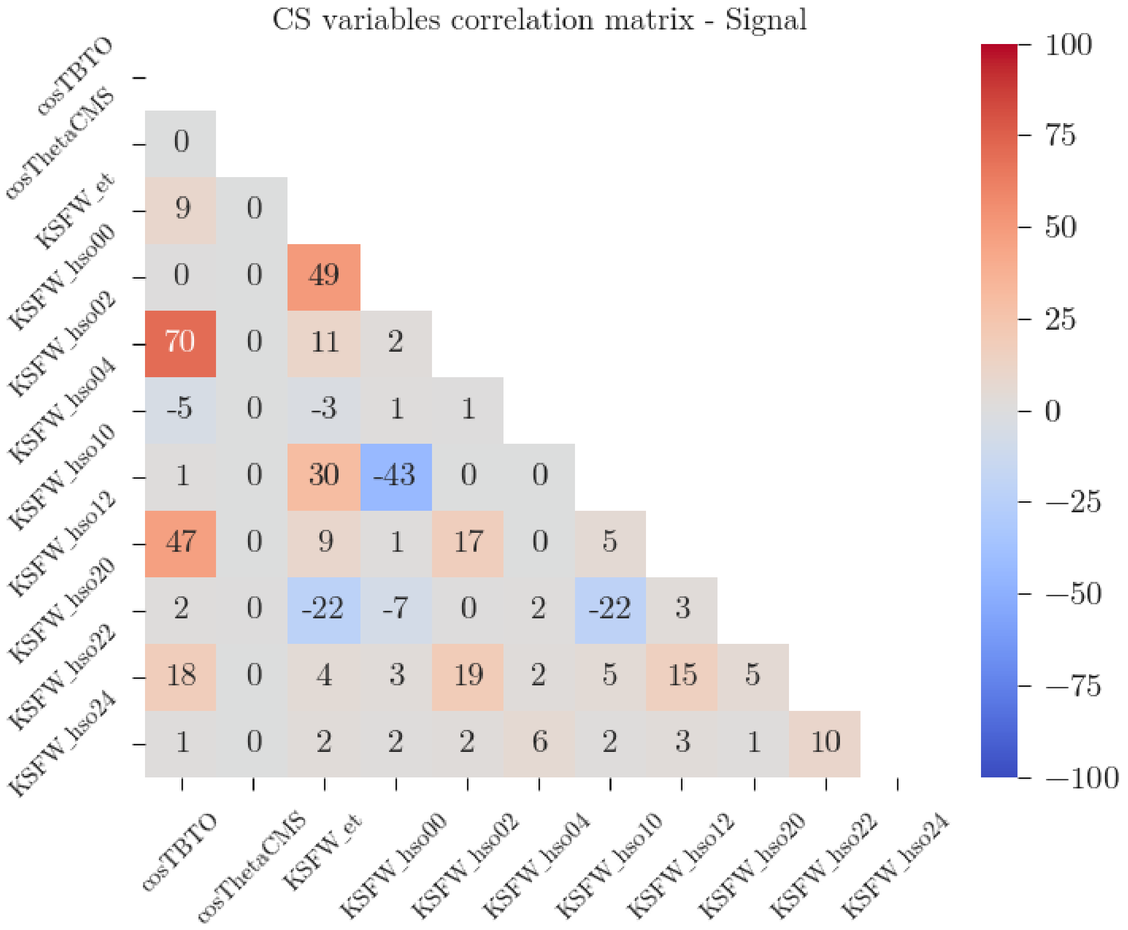


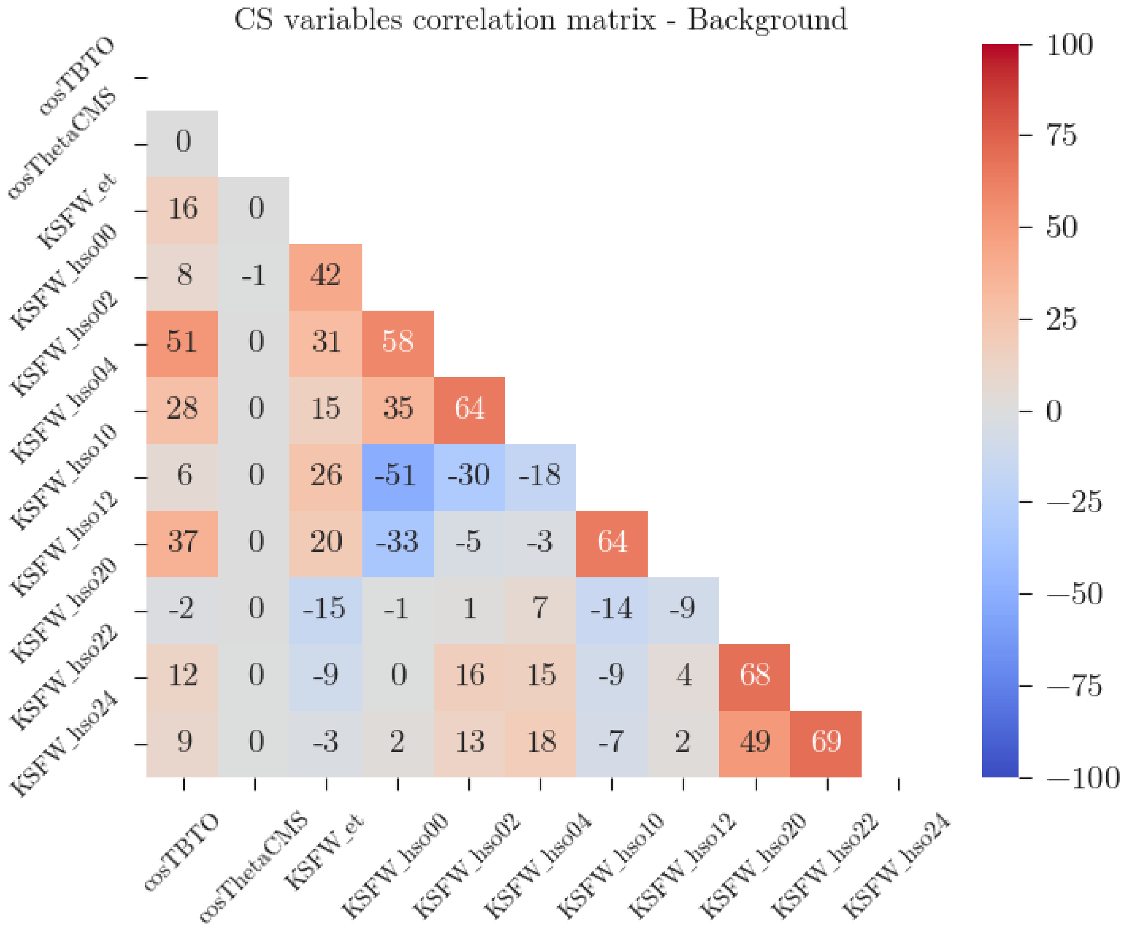




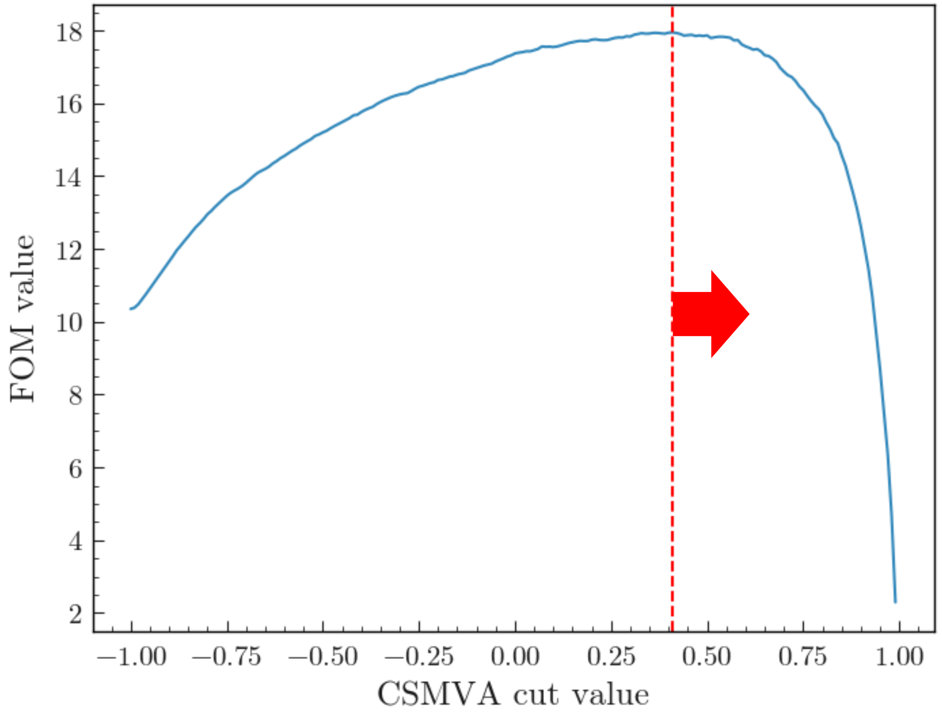


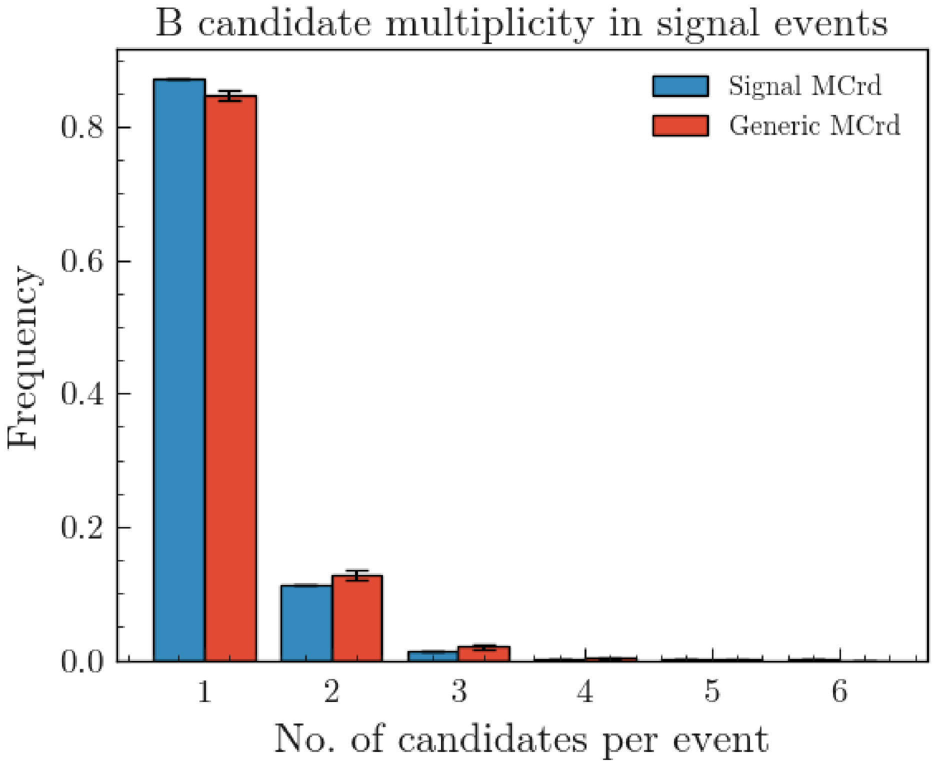
CSMVA input variable correlations





CSMVA cut & Candidate Multiplicity





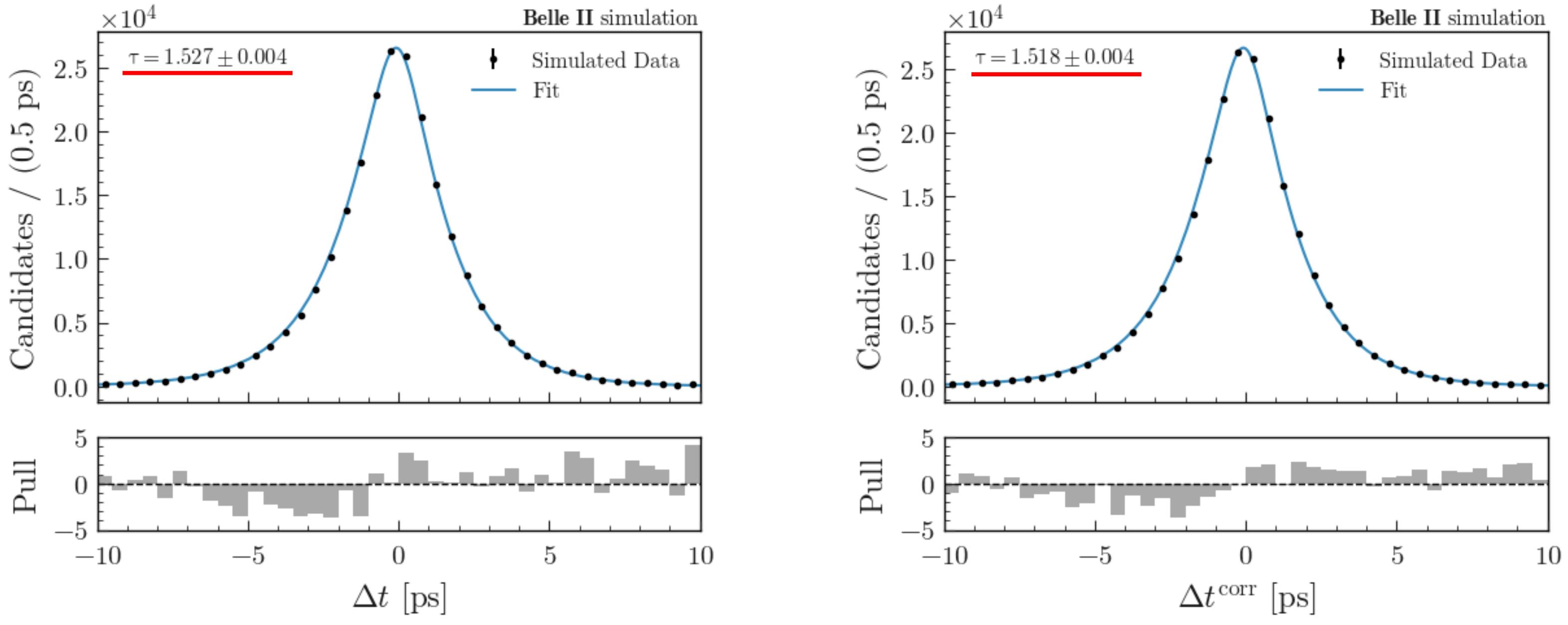
Selection efficiencies

Selection criterion	Signal (%)	Self-crossfeed (%)	$B\overline{B}$ bkg (%)	$q\bar{q}$ bkg (%)
Prompt $\pi^{\pm}$ PID	81.93 (81.93)	76.09 (76.09)	67.72 (67.72)	71.99 (71.99)
π^0 veto	69.61 (84.97)	63.19 (83.05)	31.54 (46.57)	17.05 (23.69)
ρ^0 mass window	35.63 (51.19)	24.76 (39.19)	12.77 (40.49)	6.51 (38.21)
K_S^0 MVA > 0.95	32.97 (92.52)	6.95 (28.05)	1.42 (11.15)	0.62 (9.49)
CSMVA > 0.41	23.03 (69.84)	3.45 (49.71)	0.67 (46.86)	0.05 (8.76)
Single candidate	19.38 (85.93)	2.55 (72.50)	0.57 (85.67)	0.05 (91.16)

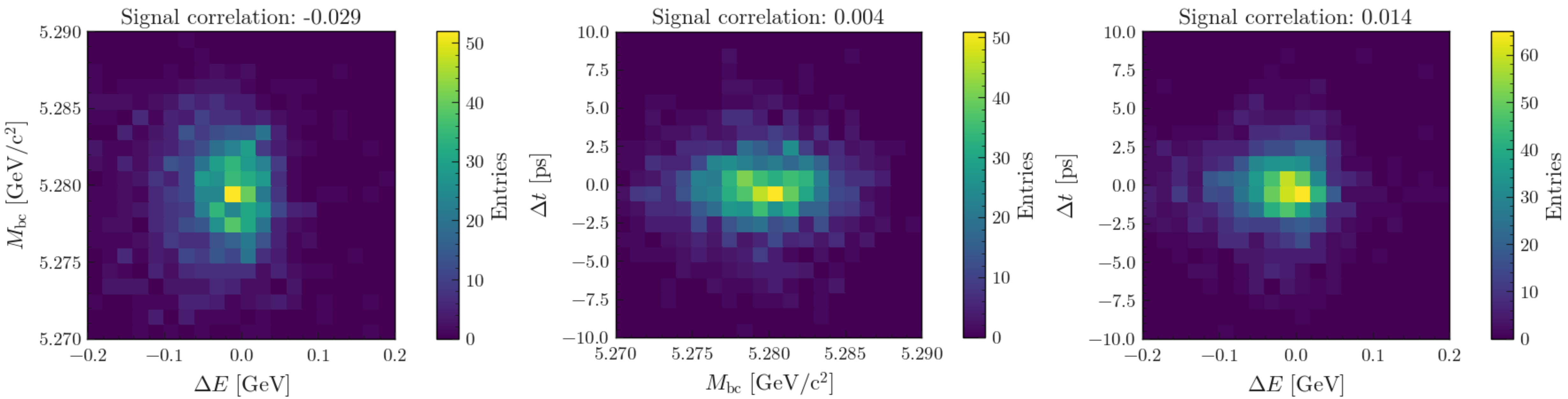
Kinematic approximation

- The small motion of the B mesons in the $\Upsilon(4S)$ rest frame is neglected by the relation $\Delta t \approx \Delta z/\beta\gamma$ (kinematic approximation)
- The following transformation is applied to correct for this effect:

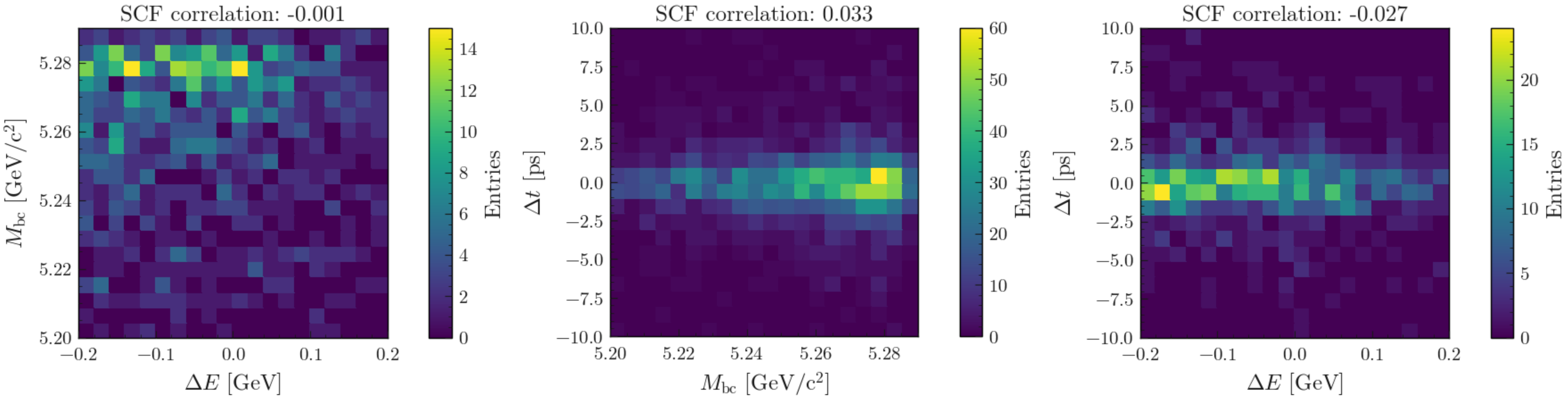
$$\Delta t^{\text{corr}} = \frac{\Delta t - (\alpha/\beta)\, cos\theta \cdot \tau_B}{1 + sign(\Delta z) \cdot (\alpha/\beta)\, cos\theta}$$



2D plots – Signal

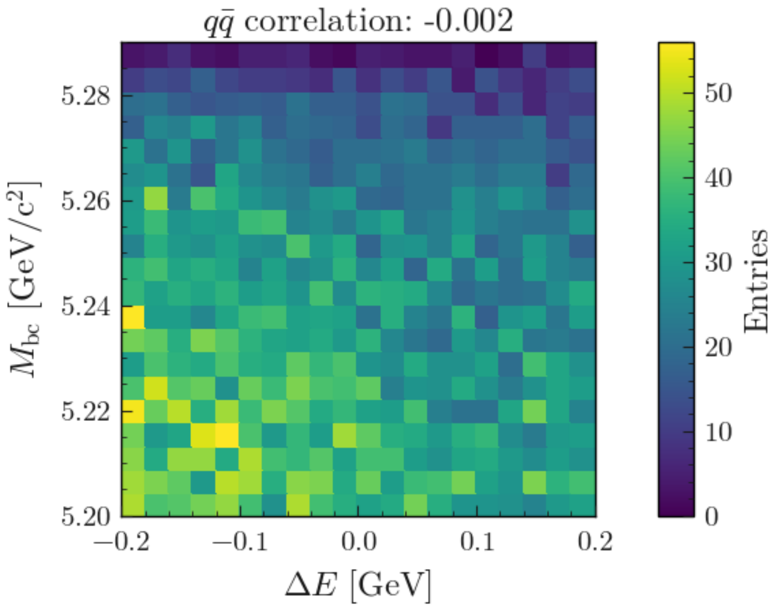


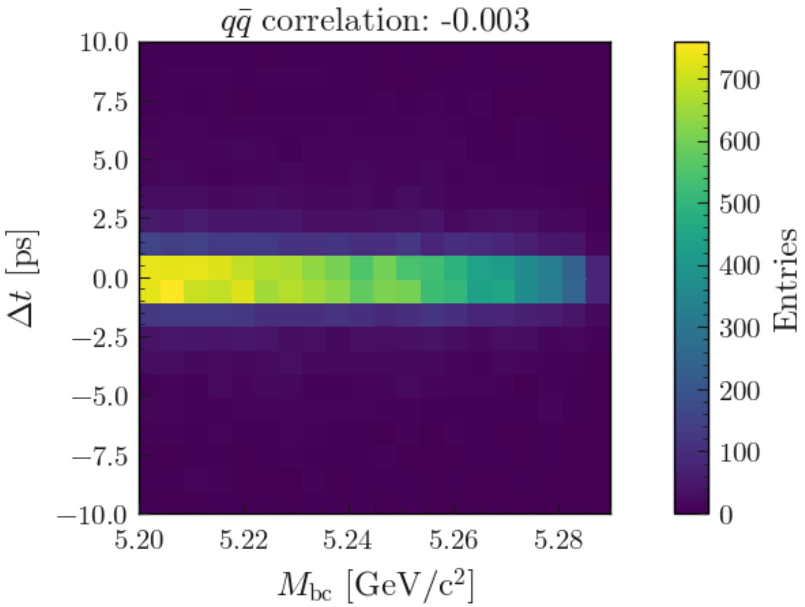
2D plots – SCF

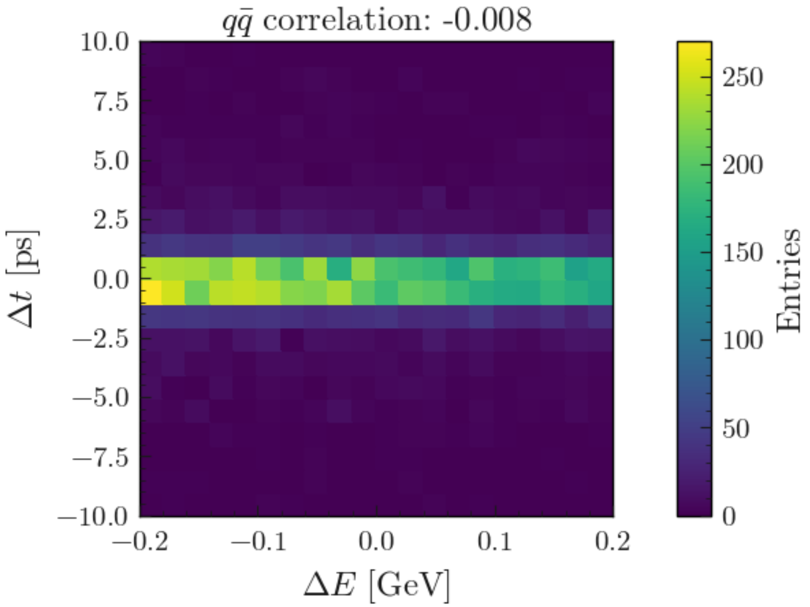


SCF correlation: -0.001
SCF correlation: 0.033
SCF correlation: -0.027
M_{bc} [GeV/c^2]
ΔE [GeV]
Δt [ps]
Entries

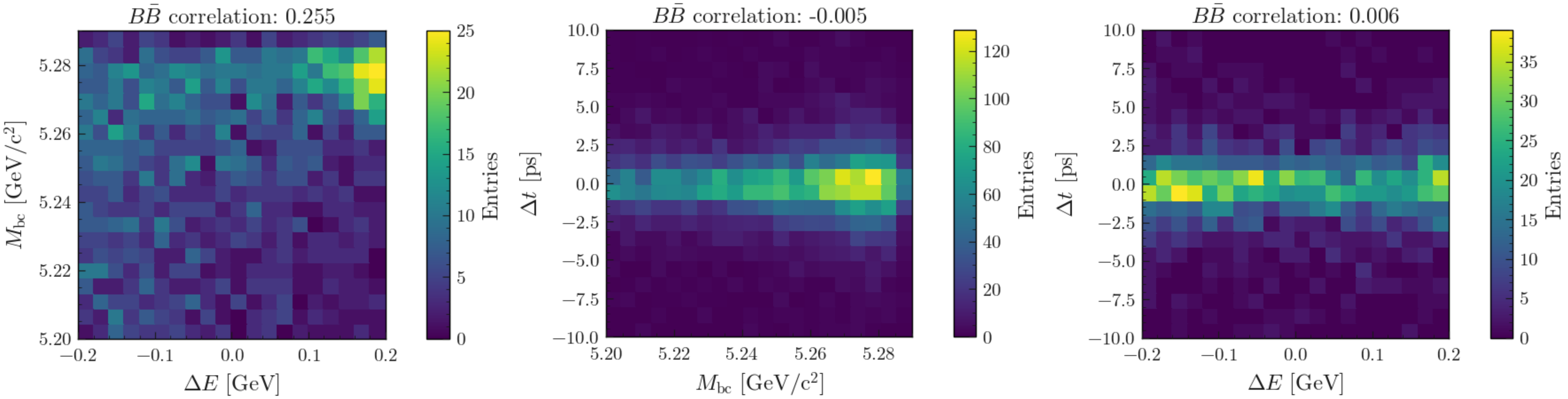
2D plots – Continuum







2D plots – $B\bar{B}$ background

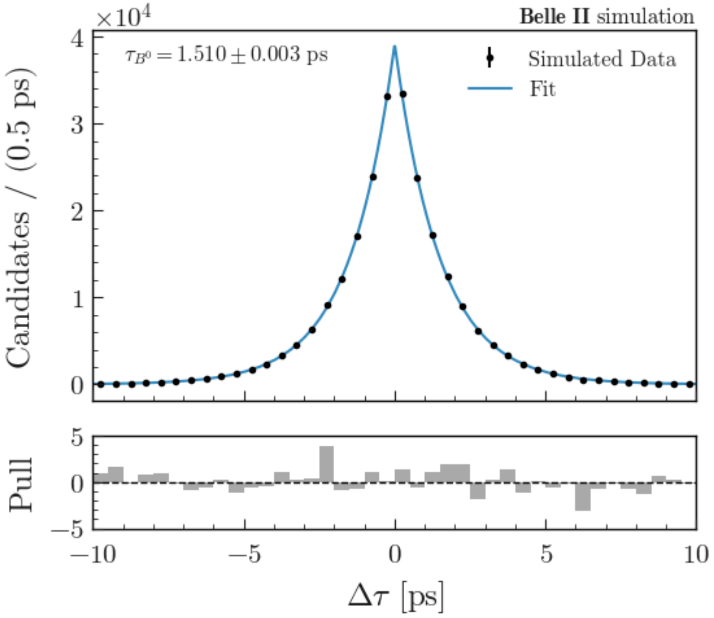


Δt residual: $\Delta t_{\text{reco}} - \Delta t_{\text{true}}$

Signal-only Lifetime Fit

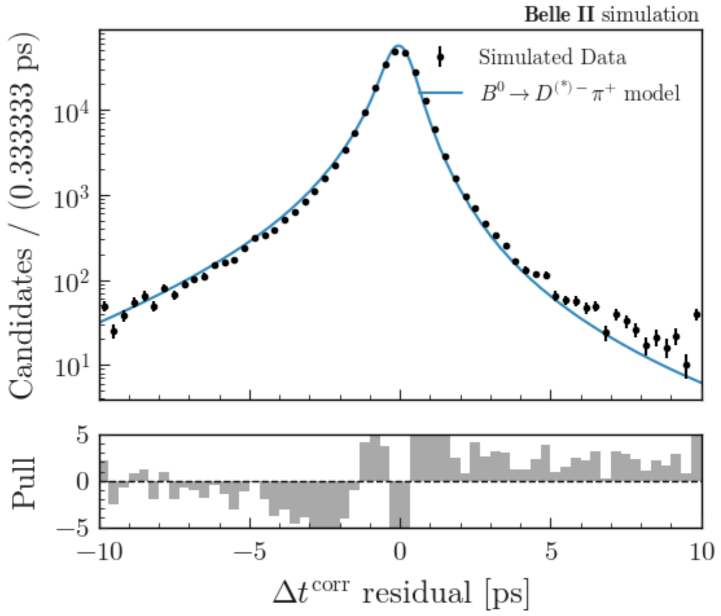
- Fit for $\boldsymbol{B^0}$ **lifetime** in signal-only MC sample as a quick **validity check** for the Δt fit model
- Agreement between calibrated Δt Resolution Function and Δt residual distribution not perfect but good enough for **available statistics**

Generated distribution



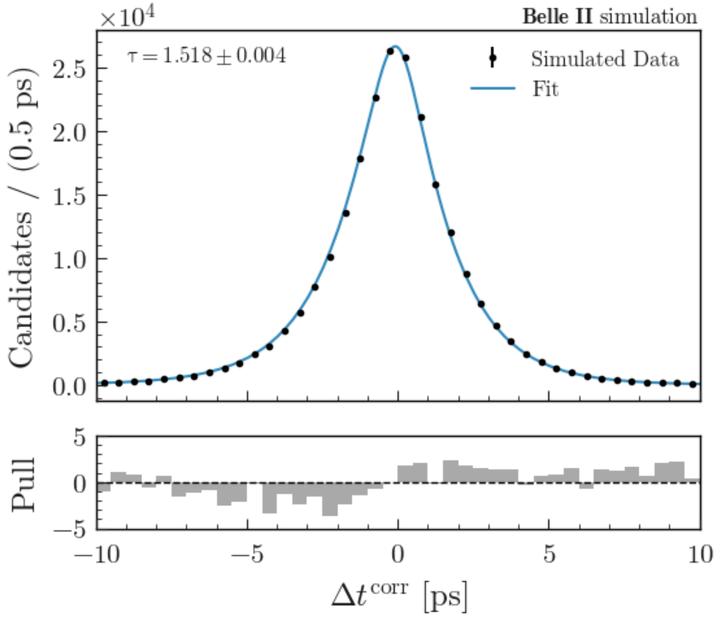
$\otimes$

Detector resolution



$=$

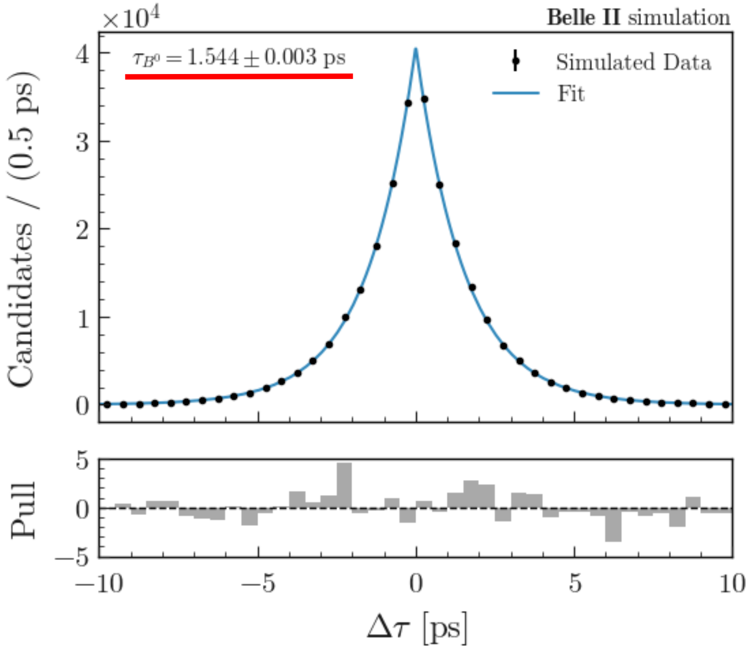
Reconstructed distribution



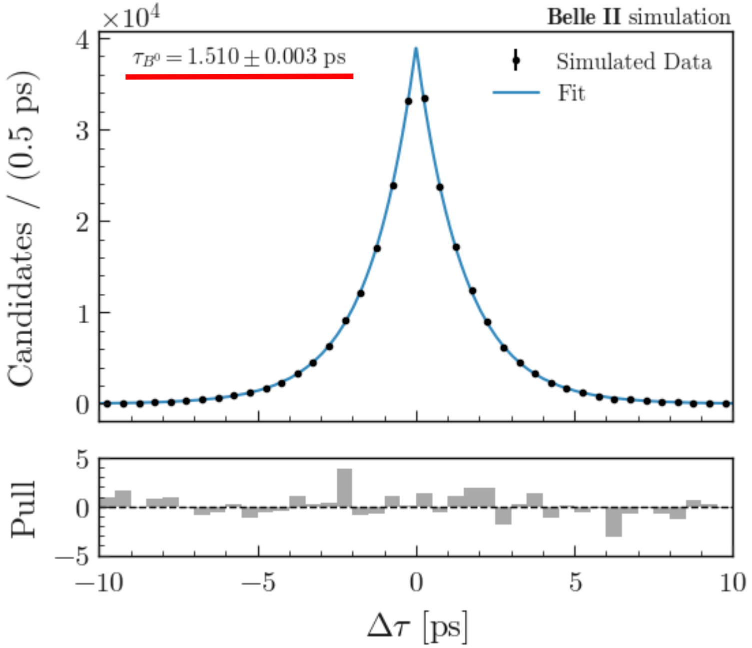
Single Candidate Selection

- Multiple B candidates per event after applying selection criteria ⇒ select one **randomly**
- Selecting single candidate based on χ^2 probability of B_{sig} vertex fit leads to **biased B^0 lifetime**

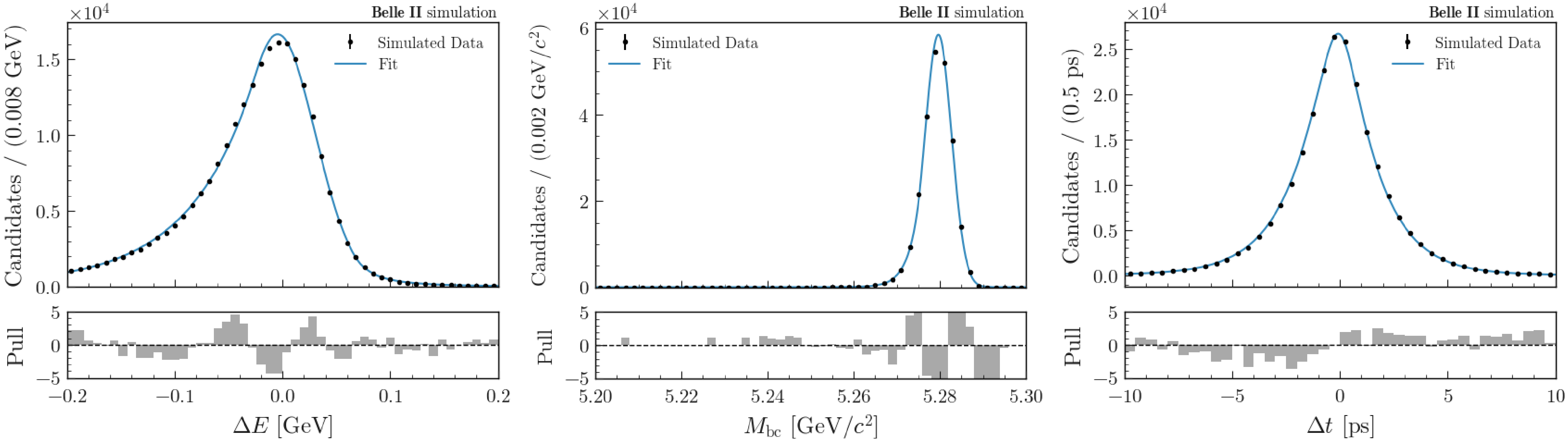
Based on B_{sig} vertex χ^2



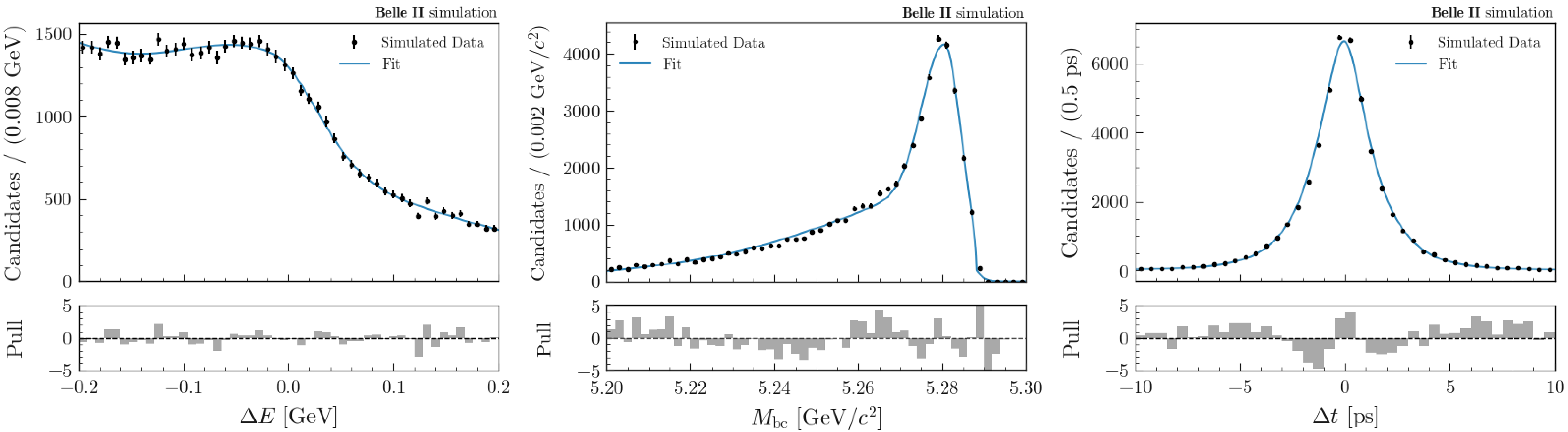
Random



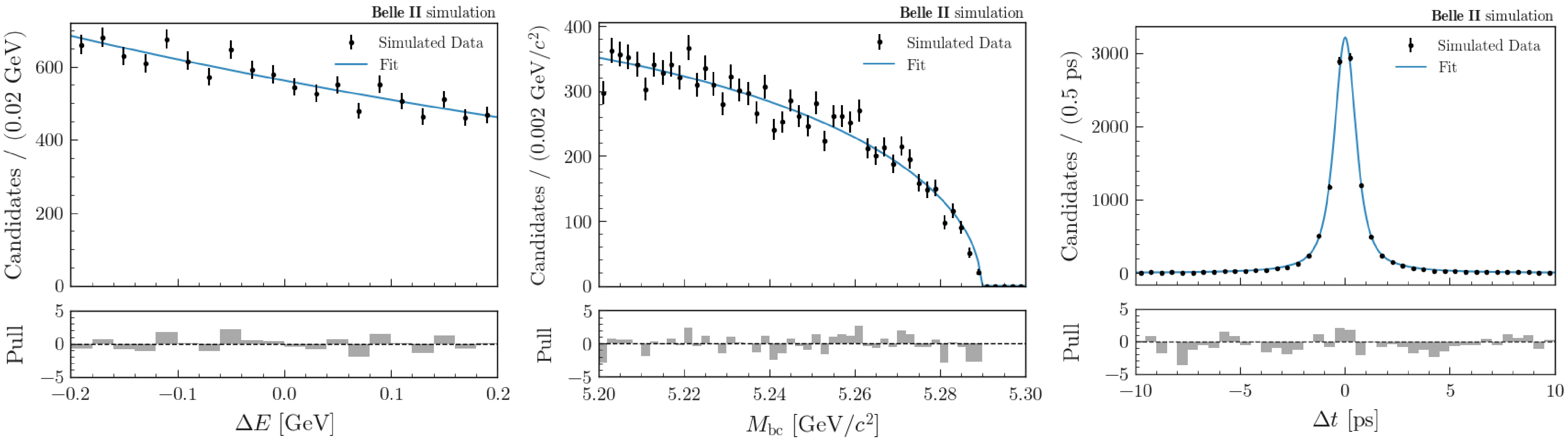
Shape Fits – Signal



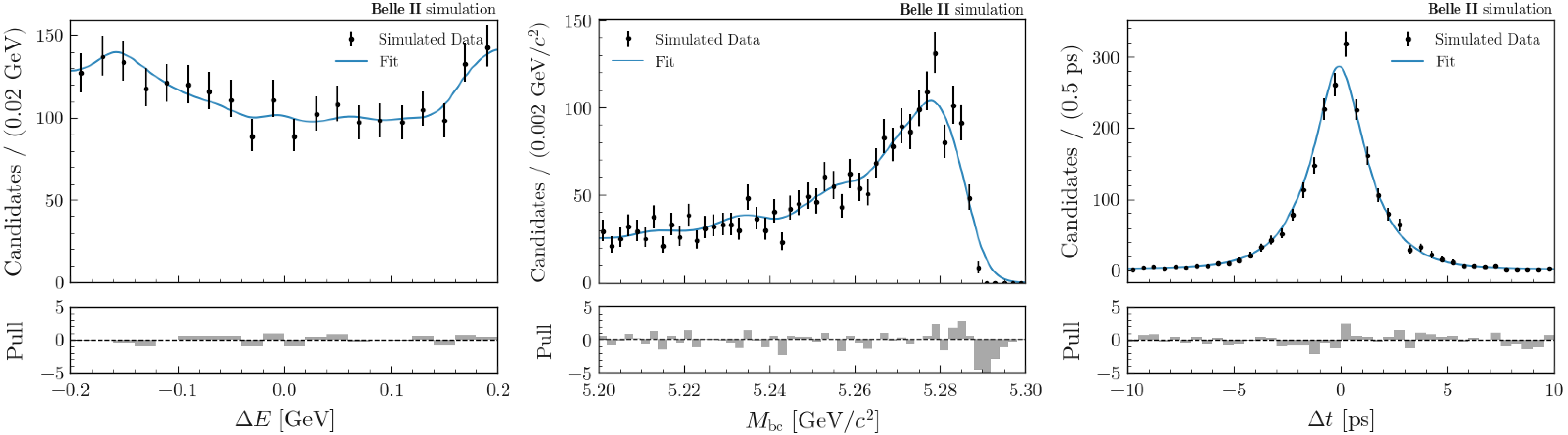
Shape Fits – SCF



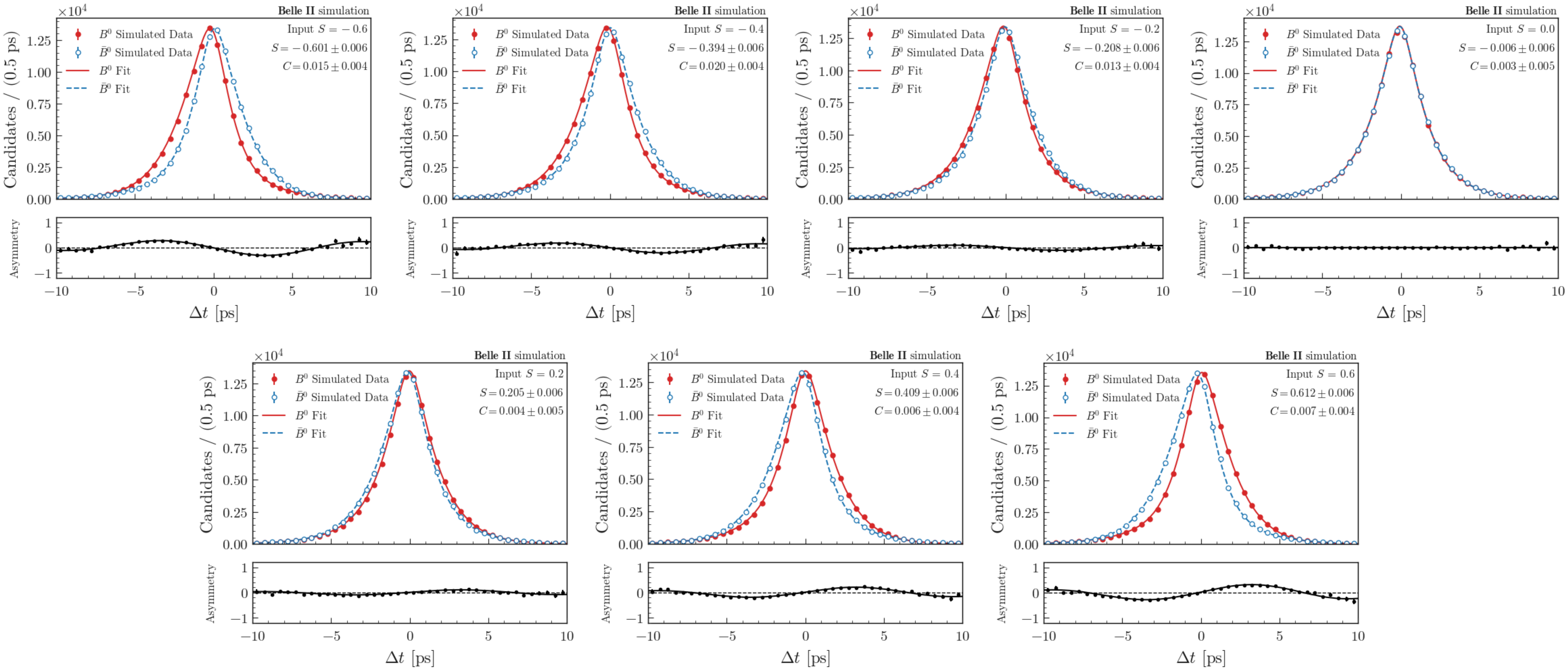
Shape Fits – Continuum



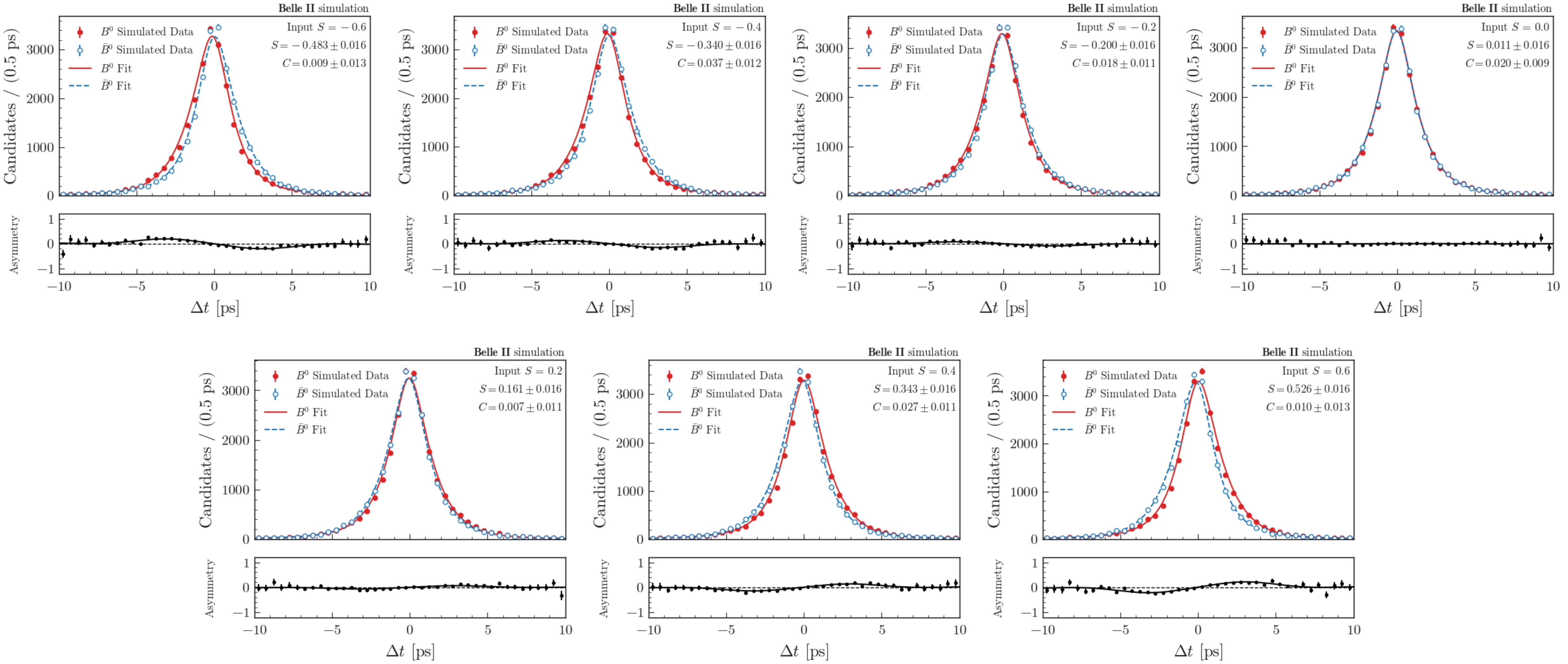
Shape Fits – $B\bar{B}$ background



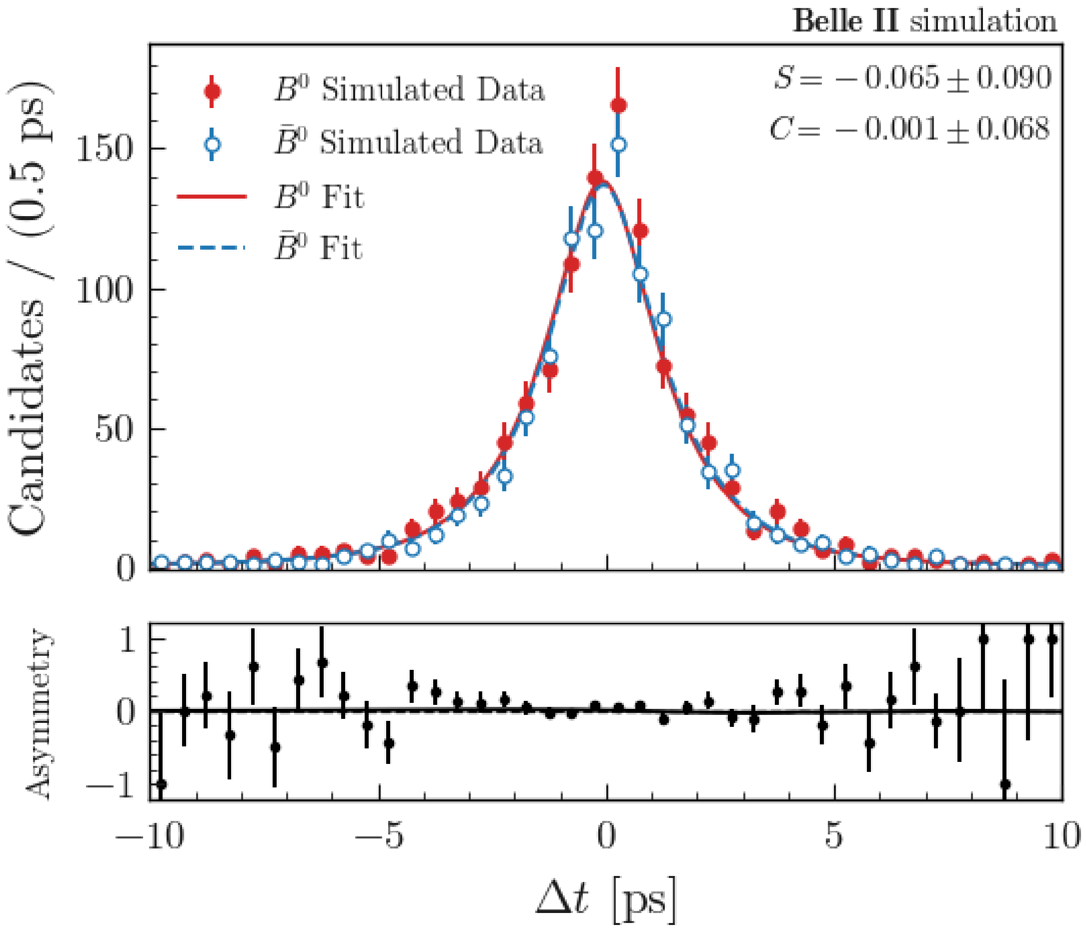
CP fits – Signal



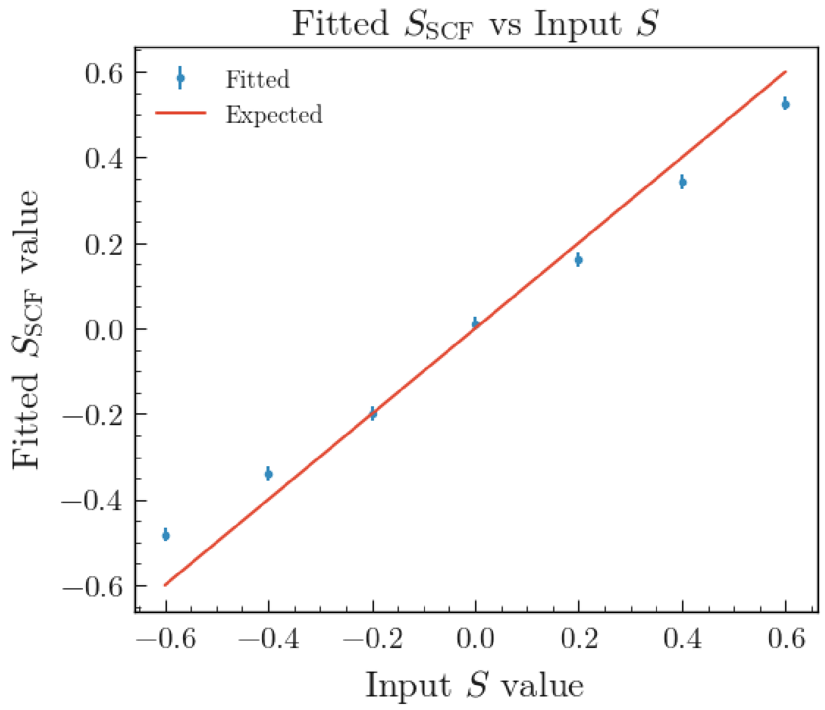
CP fits – SCF


Belle II simulation
B^0 Simulated Data
$\bar{B}^0$ Simulated Data
B^0 Fit
$\bar{B}^0$ Fit
Input $S = -0.6$
$S = -0.483 \pm 0.016$
$C = 0.009 \pm 0.013$
Input $S = -0.4$
$S = -0.340 \pm 0.016$
$C = 0.037 \pm 0.012$
Input $S = -0.2$
$S = -0.200 \pm 0.016$
$C = 0.018 \pm 0.011$
Input $S = 0.0$
$S = 0.011 \pm 0.016$
$C = 0.020 \pm 0.009$
Input $S = 0.2$
$S = 0.161 \pm 0.016$
$C = 0.007 \pm 0.011$
Input $S = 0.4$
$S = 0.343 \pm 0.016$
$C = 0.027 \pm 0.011$
Input $S = 0.6$
$S = 0.526 \pm 0.016$
$C = 0.010 \pm 0.013$
Candidates / (0.5 ps)
Asymmetry
Δt [ps]

CP fit – $B\bar{B}$ background



κ_{SCF} MC study



- $S_{\mathrm{SCF}} = \kappa_{\mathrm{SCF}} \cdot S$ linear law with $\kappa_{\mathrm{SCF}} \simeq 0.8$
- Sensitivity improvement by making S_{SCF} & C_{SCF} proportional to S & C in the fit
- Gaussian constraint on κ_{SCF} with mean 0.8 and width 0.2

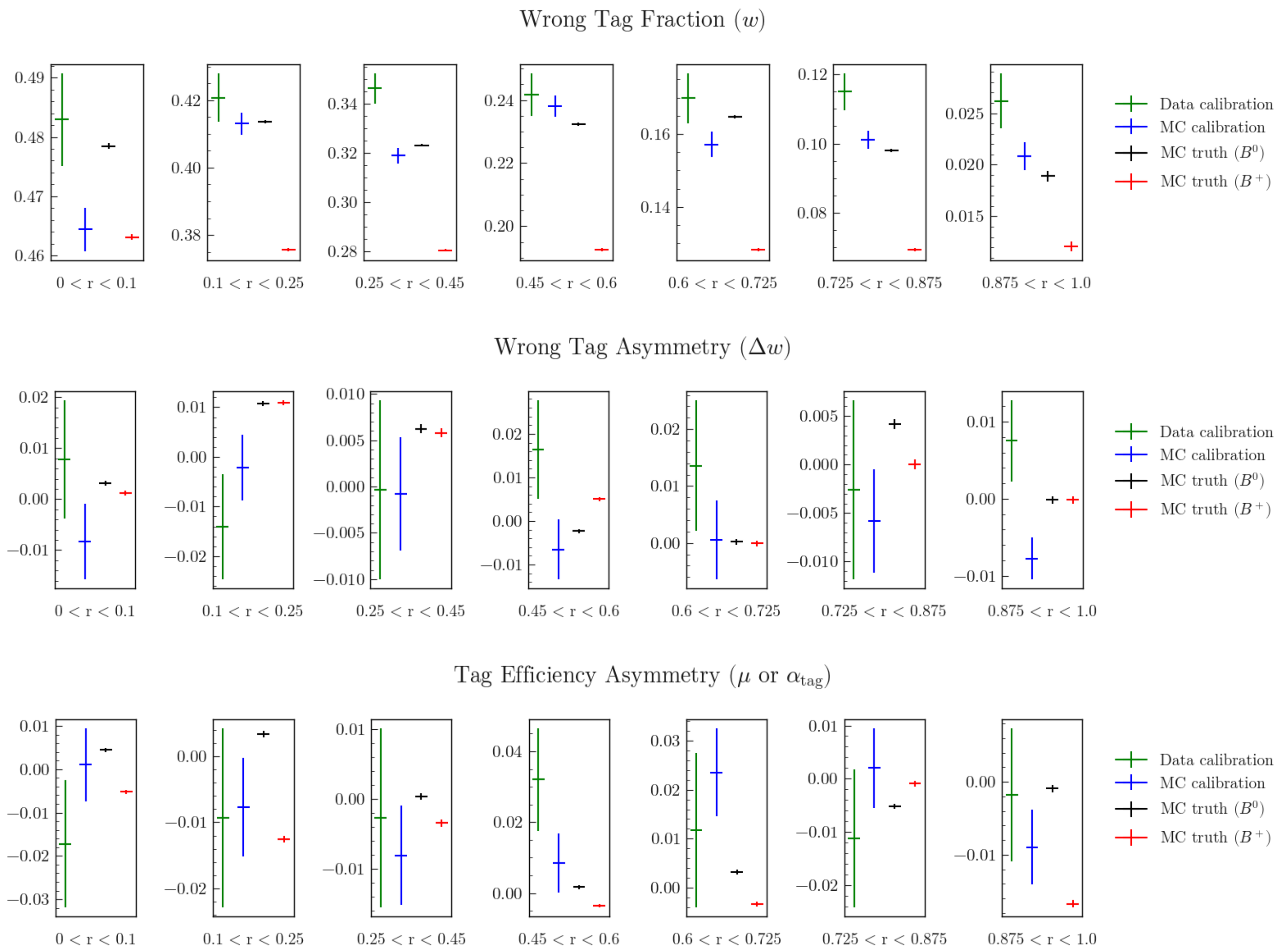
Flavor Tagging parameters

r-bin	r-range	w [%]	Δw [%]	a_{tag} [%]
0	$0.0 - 0.1$	$48.29 \pm 0.78 \pm 0.75$	$0.78 \pm 1.16 \pm 0.71$	$-1.72 \pm 1.47 \pm 1.32$
1	$0.1 - 0.25$	$42.07 \pm 0.72 \pm 0.32$	$-1.41 \pm 1.06 \pm 0.92$	$-0.94 \pm 1.36 \pm 1.45$
2	$0.25 - 0.45$	$34.63 \pm 0.61 \pm 0.61$	$-0.04 \pm 0.97 \pm 1.28$	$-0.28 \pm 1.28 \pm 1.46$
3	$0.45 - 0.6$	$24.17 \pm 0.68 \pm 0.36$	$1.64 \pm 1.13 \pm 0.52$	$3.21 \pm 1.44 \pm 1.50$
4	$0.6 - 0.725$	$16.98 \pm 0.68 \pm 0.92$	$1.36 \pm 1.15 \pm 0.72$	$1.17 \pm 1.58 \pm 1.47$
5	$0.725 - 0.875$	$11.50 \pm 0.53 \pm 0.39$	$-0.26 \pm 0.92 \pm 0.71$	$-1.13 \pm 1.30 \pm 1.55$
6	$0.875 - 1.0$	$2.62 \pm 0.27 \pm 0.14$	$0.75 \pm 0.53 \pm 0.60$	$-0.18 \pm 0.91 \pm 1.30$

Δt Resolution Function parameters

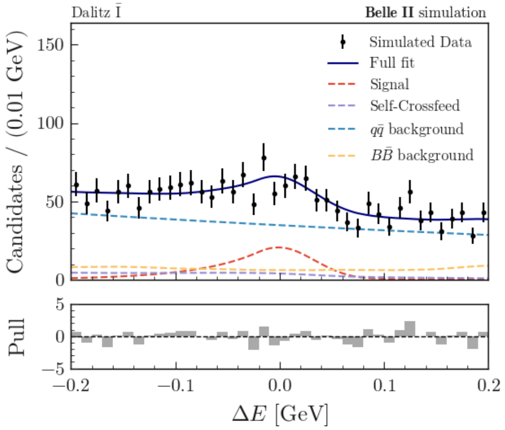
Parameter	Fitted value	Calibrated value (MC)	Calibrated value (data)
m_{core}^{0-5}	-0.1298 ± 0.0042	-0.1668 ± 0.0282	-0.1036 ± 0.0443
m_{core}^{6}	-0.0717 ± 0.0066	-0.0461 ± 0.0469	0.1094 ± 0.0931
s_{core}	1.3129 ± 0.0039	1.1874 ± 0.0329	1.0332 ± 0.0592
m_{tail}^{0-5}	-0.7751 ± 0.0186	-0.8132 ± 0.1035	-0.5346 ± 0.2027
m_{tail}^{6}	-0.5435 ± 0.0284	-0.6176 ± 0.1651	-0.9292 ± 0.3210
s_{tail}	2.3455 ± 0.0165	2.3687 ± 0.1271	2.2015 ± 0.3034
f_R^{0-5}	0.3237 ± 0.0081	0.2637 ± 0.0055	fixed from MC calibration
f_R^{6}	0.2756 ± 0.0081	0.2014 ± 0.0084	fixed from MC calibration
f_{exp}^{0-5}	0.2602 ± 0.0055	0.2048 ± 0.0045	fixed from MC calibration
f_{exp}^{6}	0.2540 ± 0.0084	0.2415 ± 0.0071	fixed from MC calibration
κ^{0-5}	3.7072 ± 0.0523	4.2343 ± 0.0567	fixed from MC calibration
κ^{6}	4.0091 ± 0.0900	4.2718 ± 0.0762	fixed from MC calibration
$f_t^{\max}$	0.5788 ± 0.0132	0.3151 ± 0.0249	0.3159 ± 0.0506
f_t^{μ}	0.0000 ± 0.0119	0.2372 ± 0.0012	fixed from MC calibration
f_t^{σ}	0.1994 ± 0.0434	0.0914 ± 0.0022	fixed from MC calibration
f_{OL}	0.0023 ± 0.0001	0.00013 ± 0.00002	fixed from MC calibration

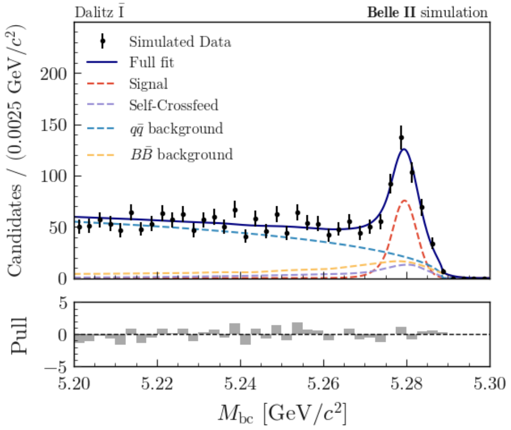
Flavor Tagging parameters for control mode

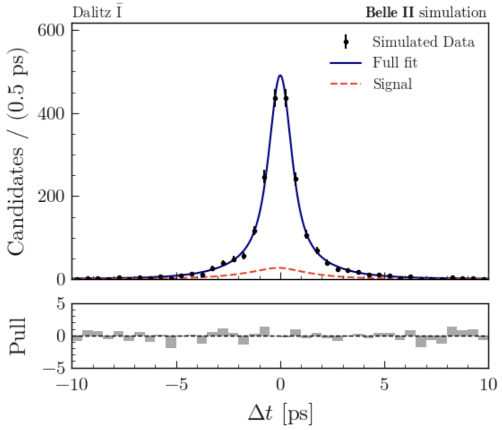


Dalitz-split fit example

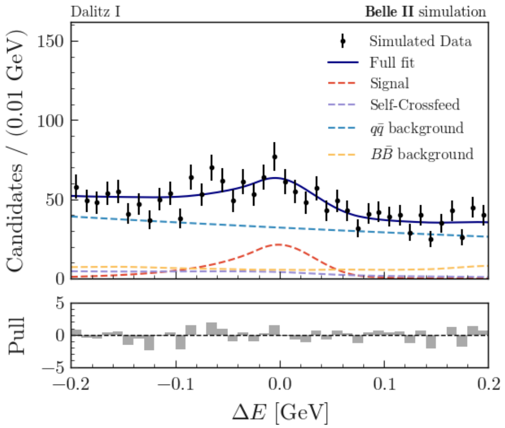
$m^2_{K_S\pi^+} > m^2_{K_S\pi^-}$

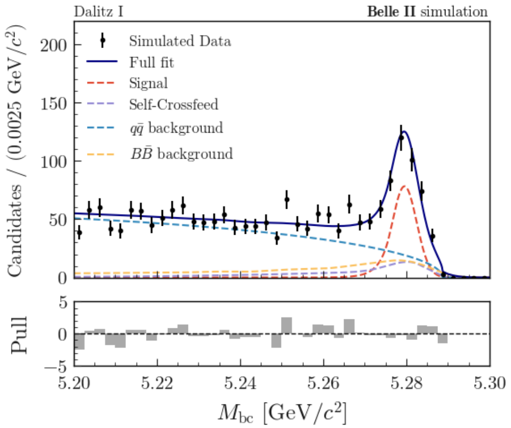


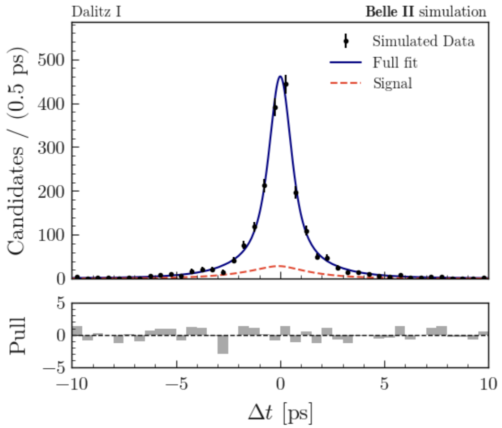




$m^2_{K_S\pi^+} < m^2_{K_S\pi^-}$







Fitted *CP* parameters:

$S^+ = -0.16 \pm 0.28$

$S^- = -0.02 \pm 0.28$

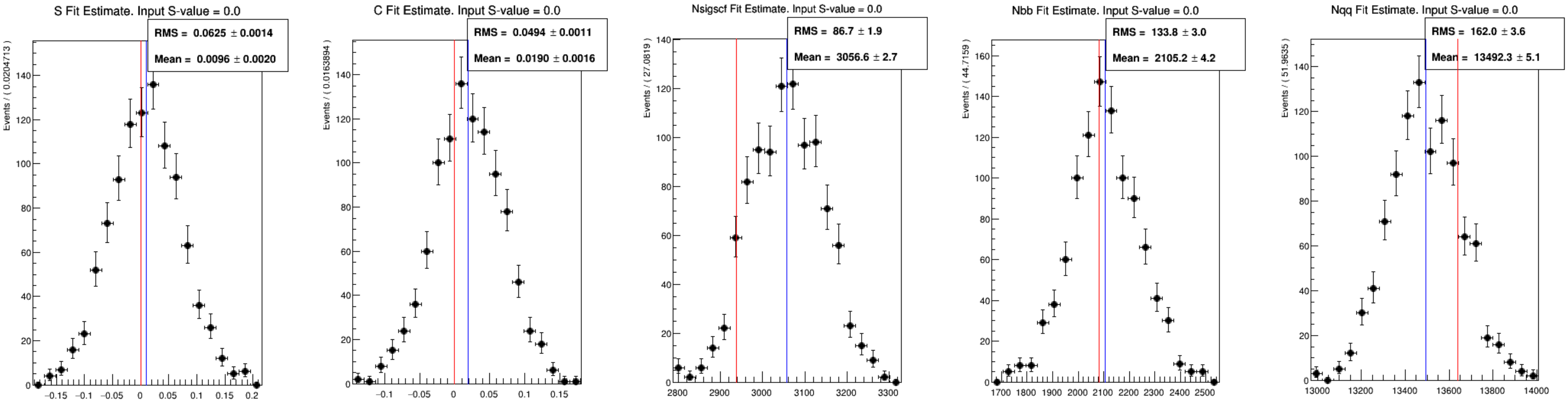
or equivalently:

$S^I = -0.09 \pm 0.20$

$S^{\bar{I}} = -0.07 \pm 0.20$

Bootstrapping: Control mode

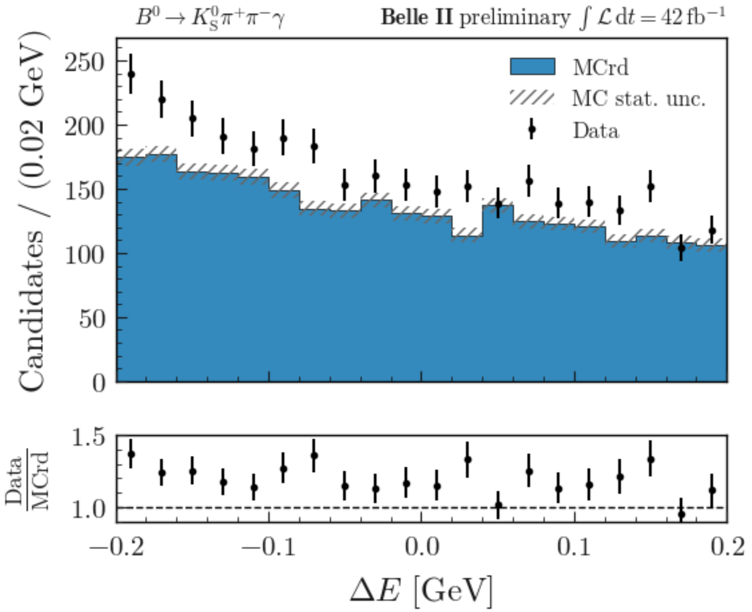
- Test for fit biases by fitting multiple replica datasets sampled from simulation
- Use signal samples with inputs $S = 0$ and $C=0$

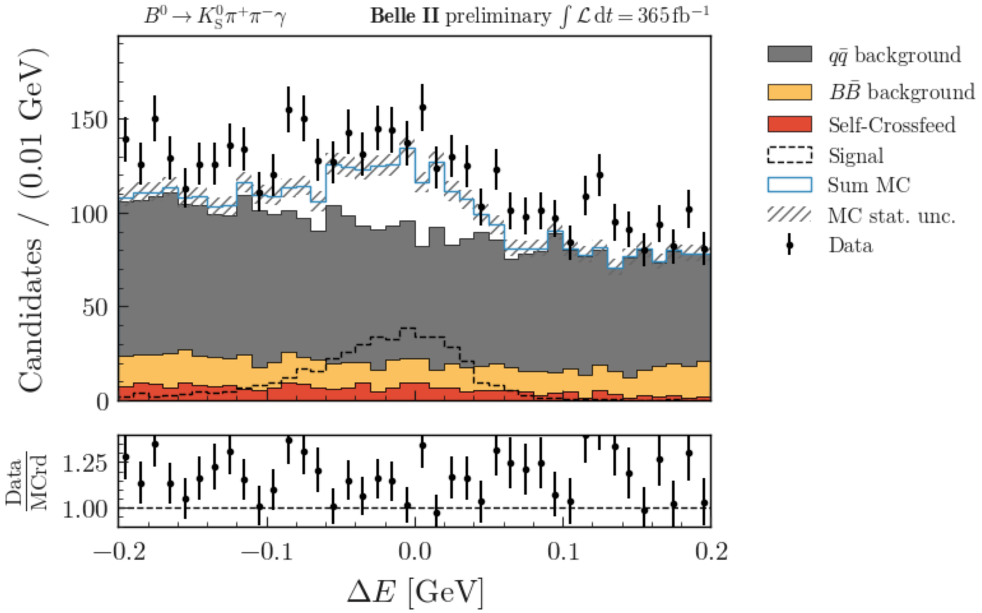


- Small biases in S and C, similar biases in the yields as in signal mode

Validation: Signal mode

- Check data/MC agreement in off-resonance and on-resonance samples

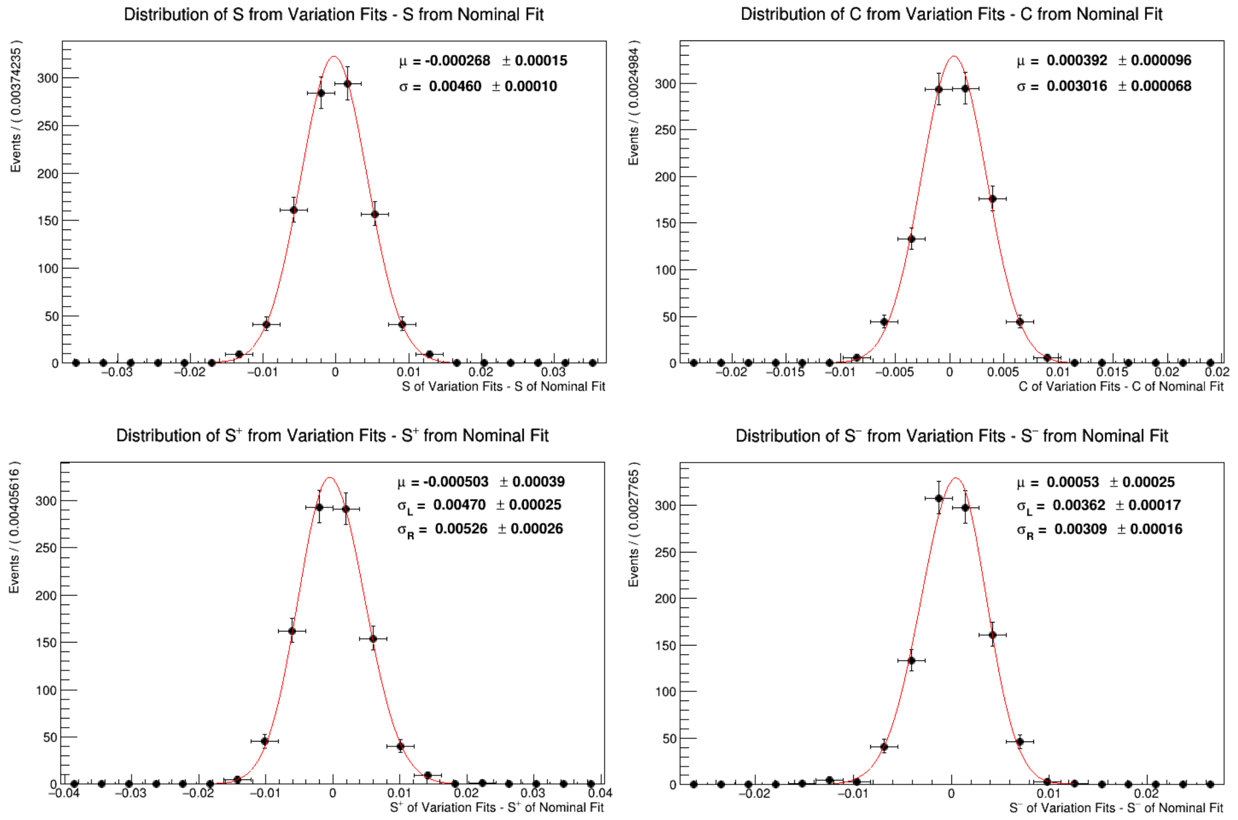




- ~20% more continuum and ~20% less signal in data compared to MC

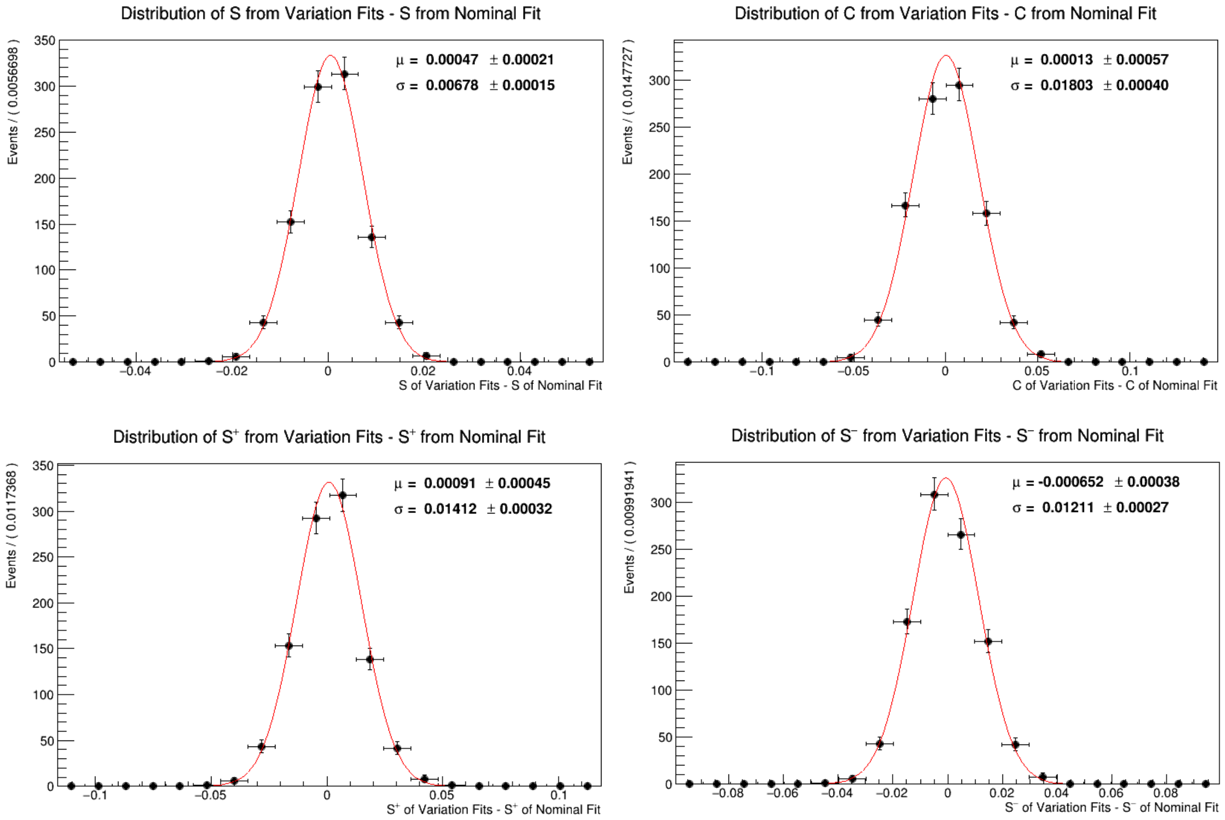
Systematics: Fixed shape parameters

- Estimated systematic due to **fixed $\boldsymbol{\Delta E}$, $\boldsymbol{M_{\mathrm{bc}}}$ & $\boldsymbol{\Delta t}$ shape parameters**
- Fit a single bootstrap toy 1000 times each time varying all fixed parameters within their uncertainties
- Quote standard deviation of resulting distribution as systematic uncertainty for each parameter



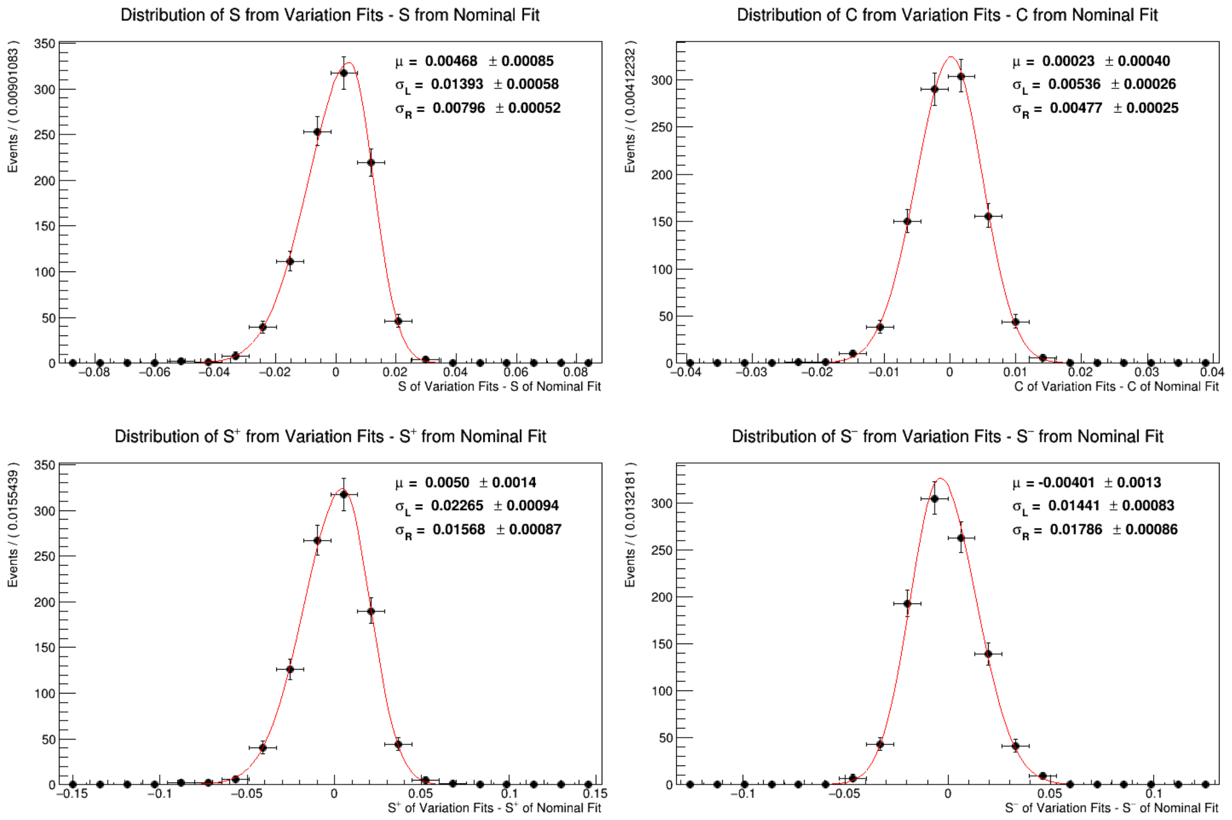
Systematics: Flavor Tagging parameters

- Estimated systematic due to **fixed Flavor Tagging shape parameters**
- Fit a single bootstrap toy 1000 times each time varying all fixed parameters within their uncertainties using the covariance matrix from the calibrations
- Quote standard deviation of resulting distribution as systematic uncertainty for each parameter



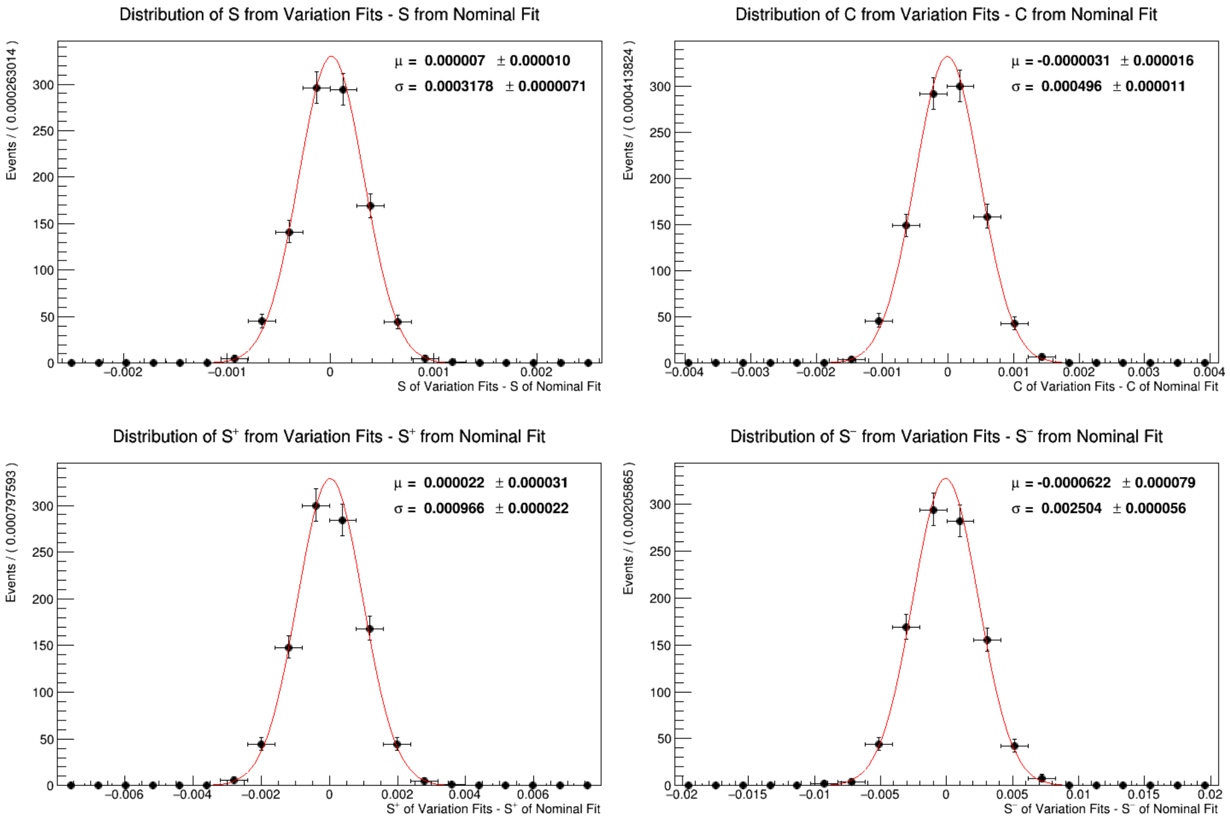
Systematics: Δt resolution parameters

- Estimated systematic due to **fixed Δt resolution model parameters**
- Fit a single bootstrap toy 1000 times each time varying all fixed parameters within their uncertainties
- Quote standard deviation of resulting distribution as systematic uncertainty for each parameter



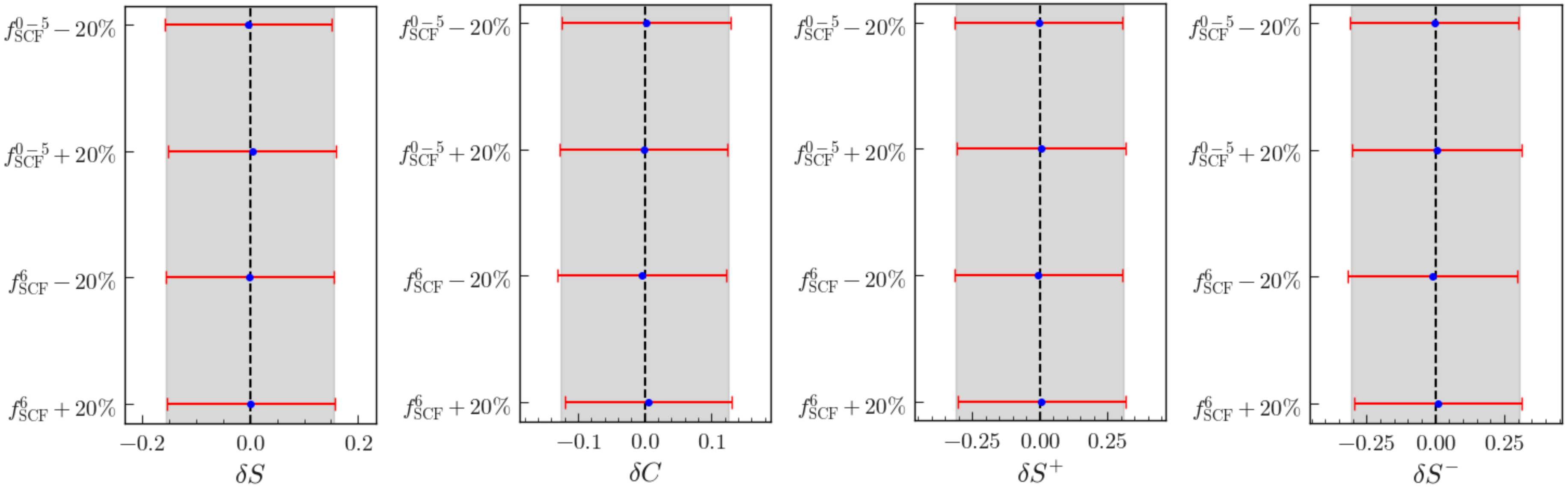
Systematics: τ_B & Δm_d

- Estimated systematic due to **fixed *B* lifetime and mixing parameters**
- Fit a single bootstrap toy 1000 times each time varying both parameters within their PDG uncertainties
- Quote standard deviation of resulting distribution as systematic uncertainty for each parameter



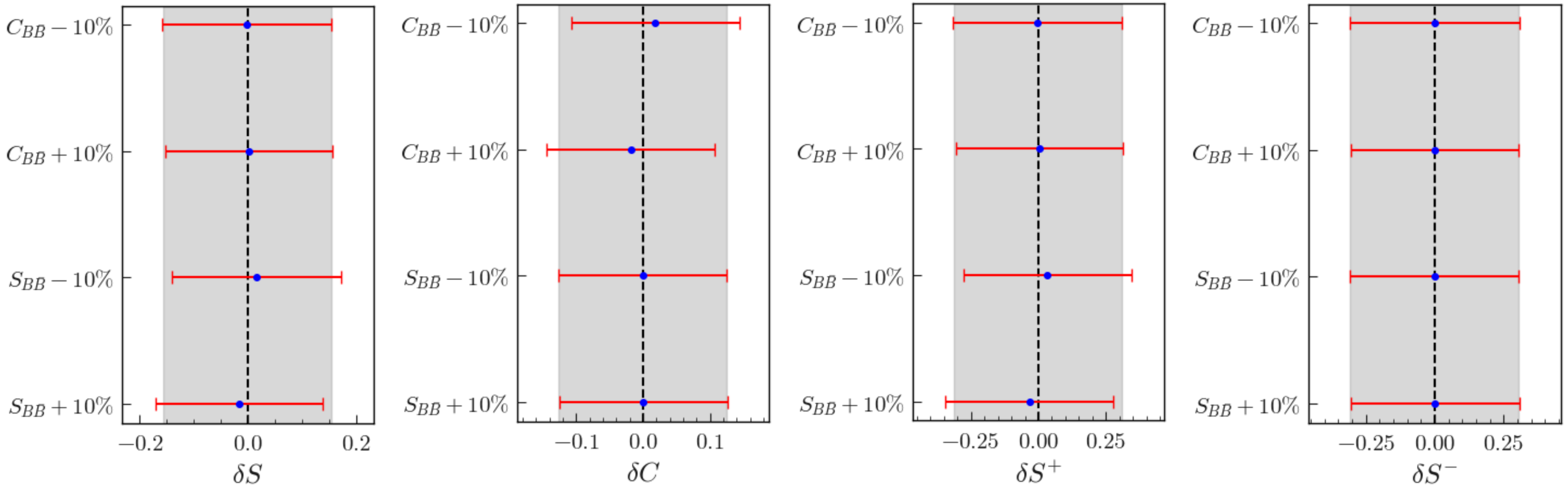
Systematics: Fixed SCF fraction

- Estimated systematic uncertainty due to **fixed background fractions** by varying them by ±20%
- Observed deviation assigned as systematic uncertainty



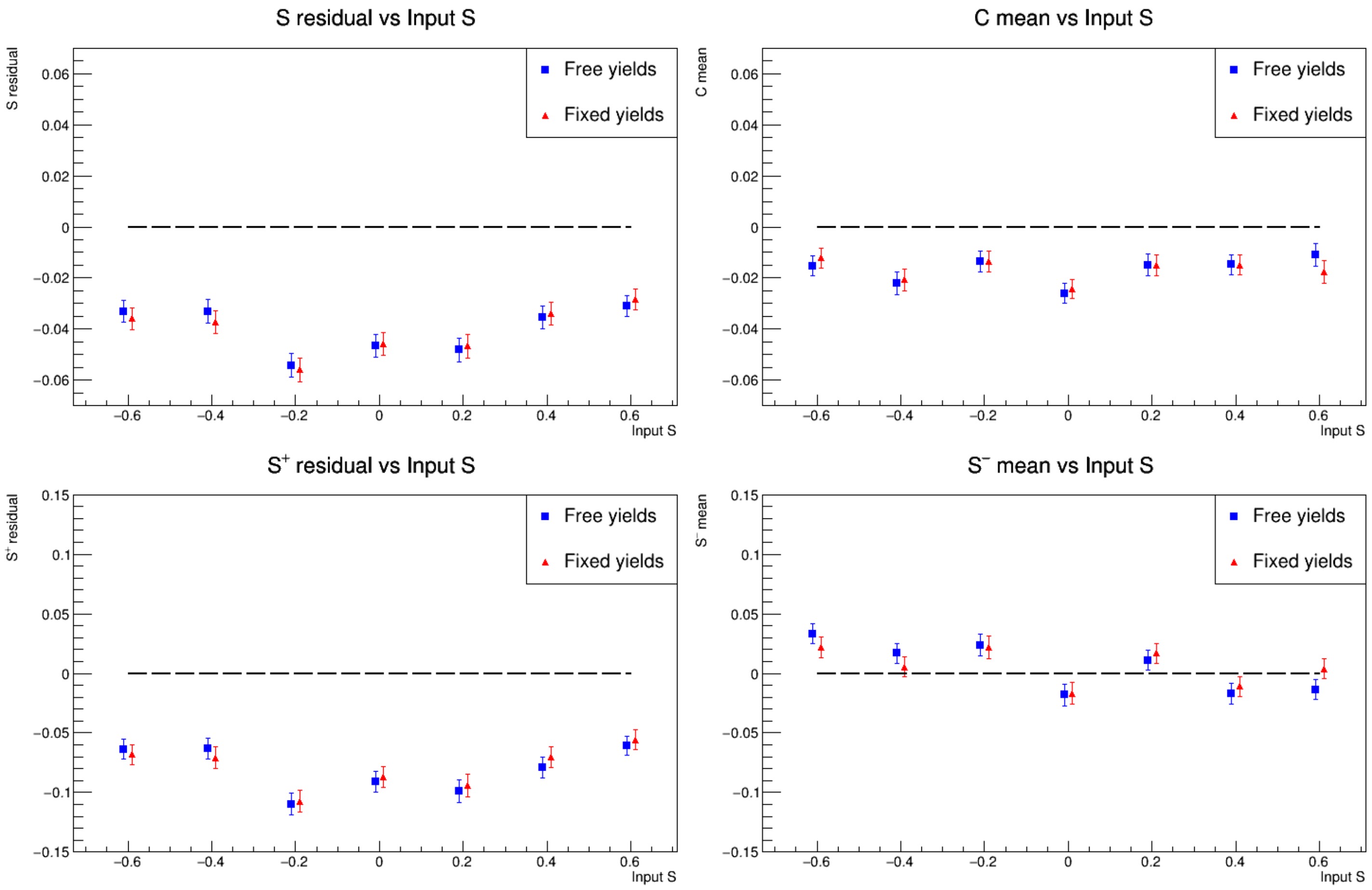
Systematics: CP violation in the $B\bar{B}$ background

- Estimated systematic uncertainty due to **fixing $S_{B\bar{B}}$ and $C_{B\bar{B}}$ to 0** by varying them by $\pm 10\%$
- Observed deviation assigned as systematic uncertainty

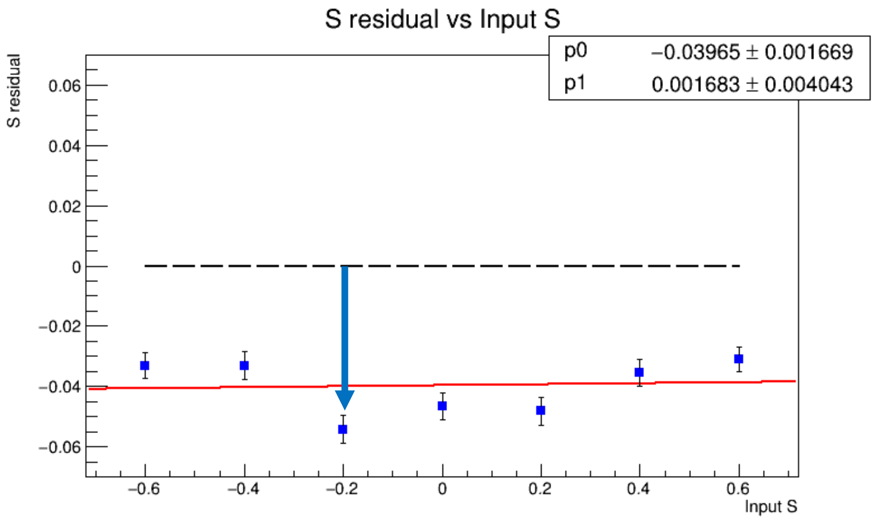


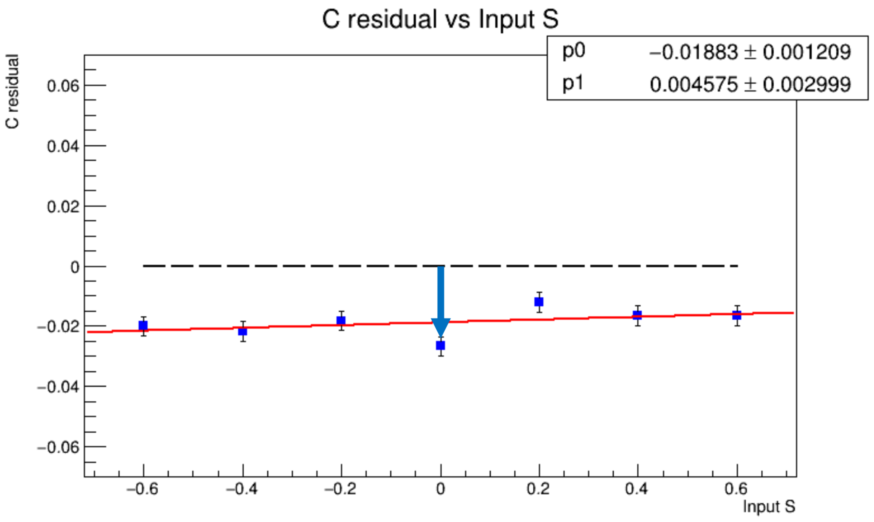
Systematics: Yield bias

- Estimated systematic uncertainty due to **yield bias** by fixing them to their true values and performing ensemble fits
- Observed deviation assigned as systematic uncertainty



Systematics: CP fit validation

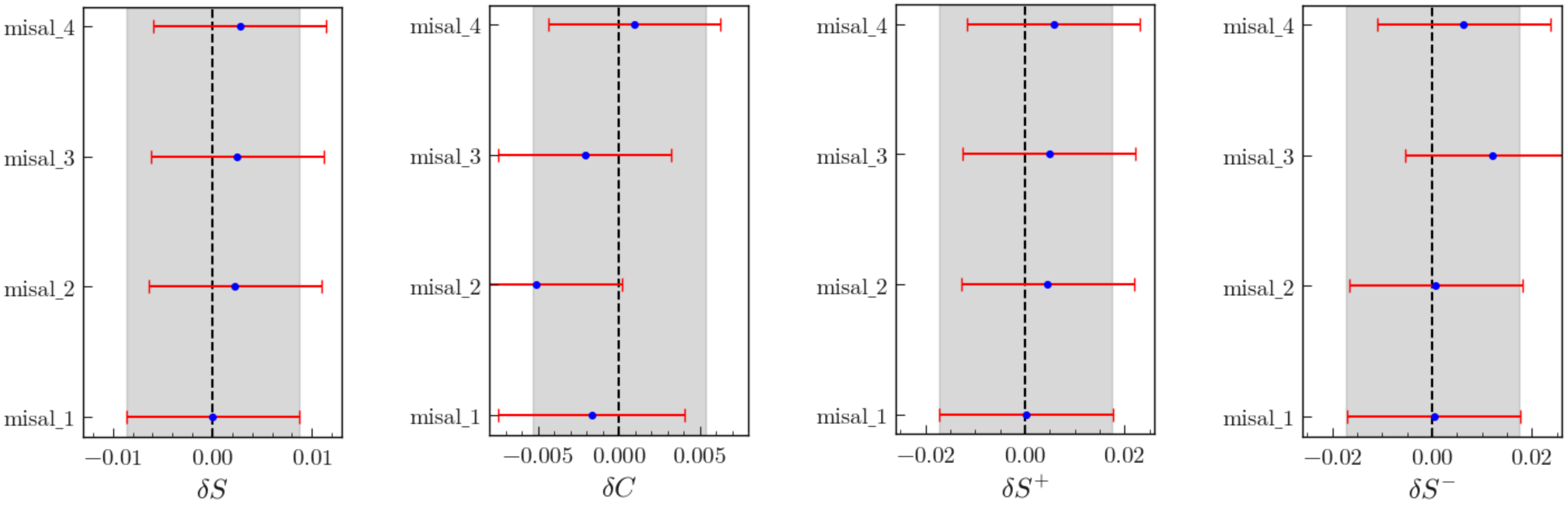




- Taken as the **largest deviation** seen in the ensemble fits to bootstrap samples
- **Dominant** source of systematic uncertainty

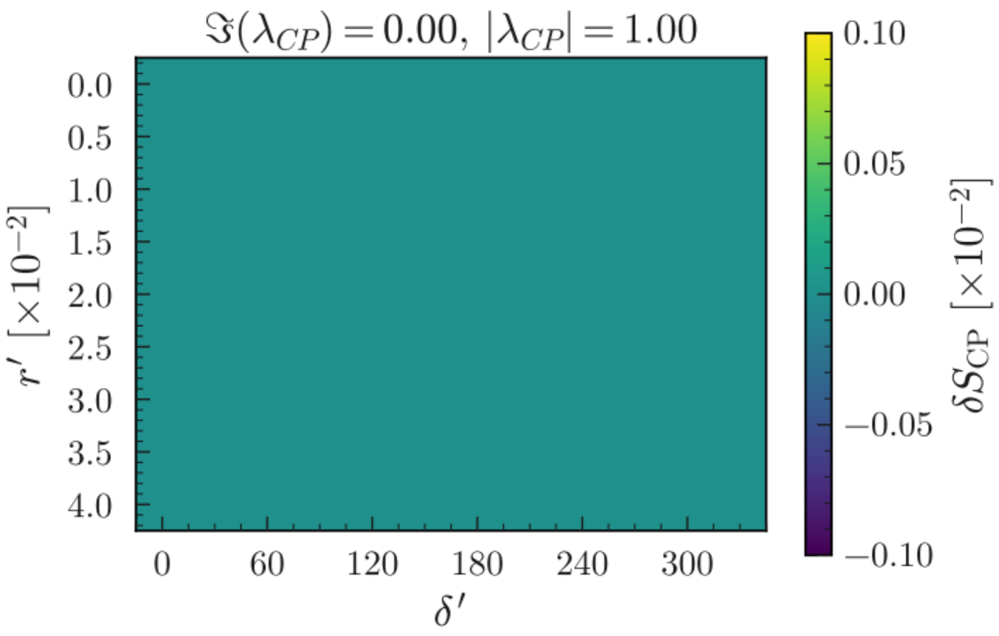
Systematics: Residual misalignment

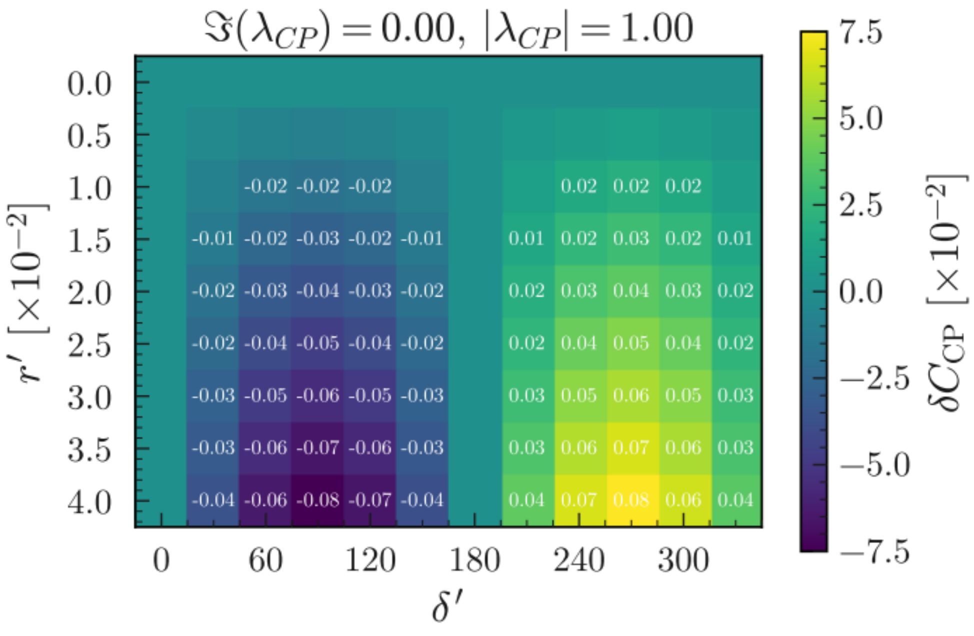
- Estimated using misaligned signal MC samples
- Uncertainties correspond to 100 × signal expected in data



Systematics: Tag-side interference

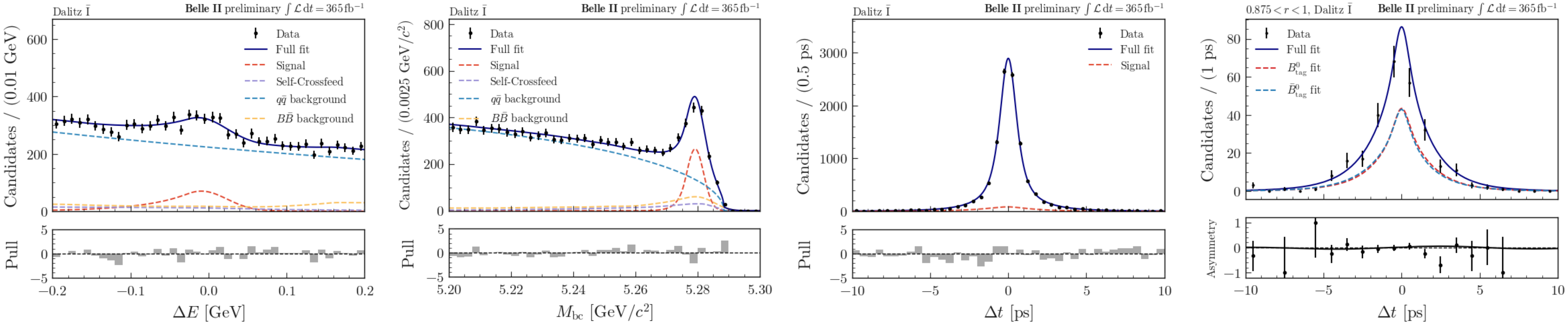
- Estimate effect of CP violation in the B_{tag} decay on fitted S and C values
- Scan values of δ' and quote δS_{CP} and δC_{CP} at $r' = 0.02$



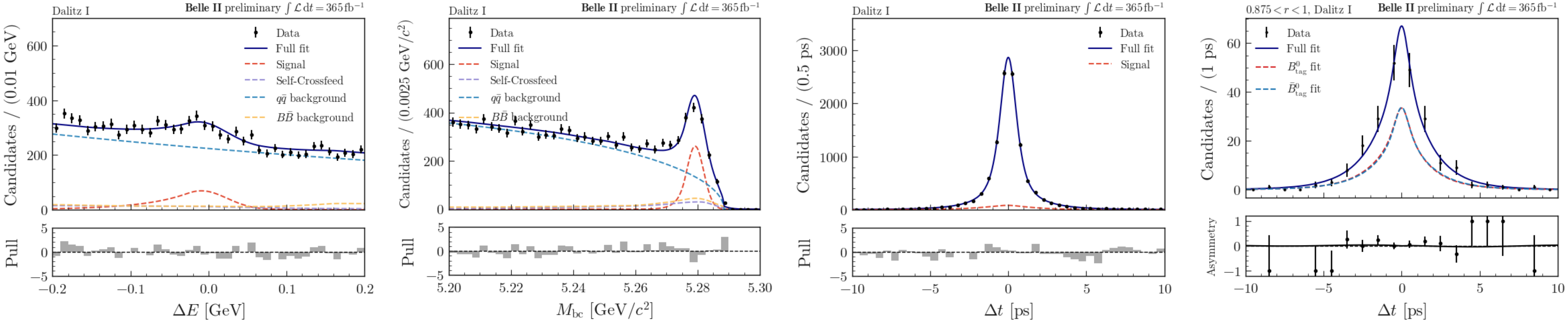


Control mode Dalitz-split fit projections

$m^2_{K_S\pi^+} > m^2_{K_S\pi^-}$

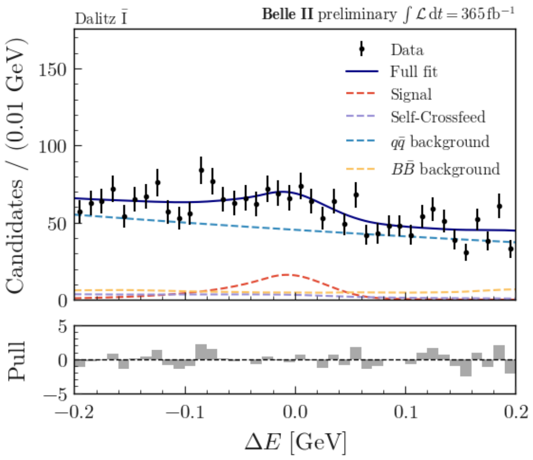


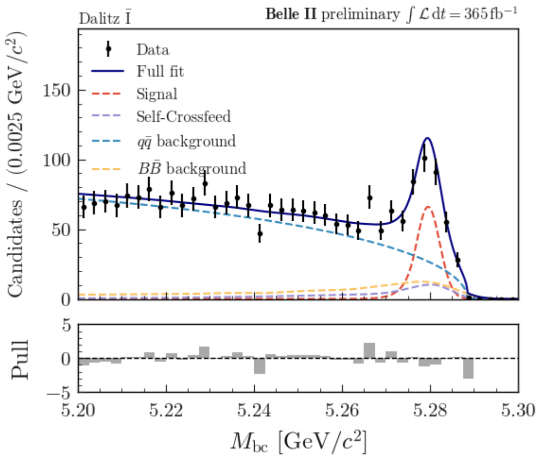
$m^2_{K_S\pi^+} > m^2_{K_S\pi^-}$

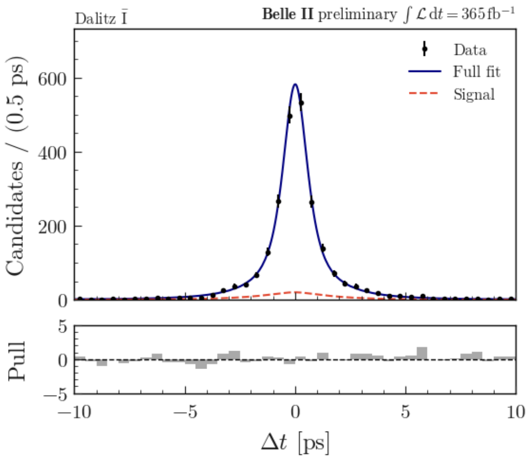


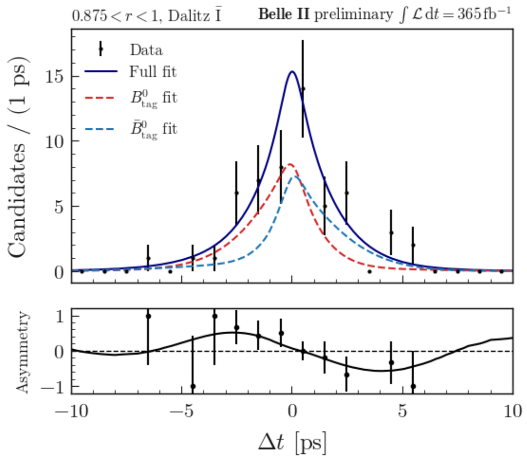
Signal mode Dalitz-split fit projections

$m^2_{K_S\pi^+} > m^2_{K_S\pi^-}$

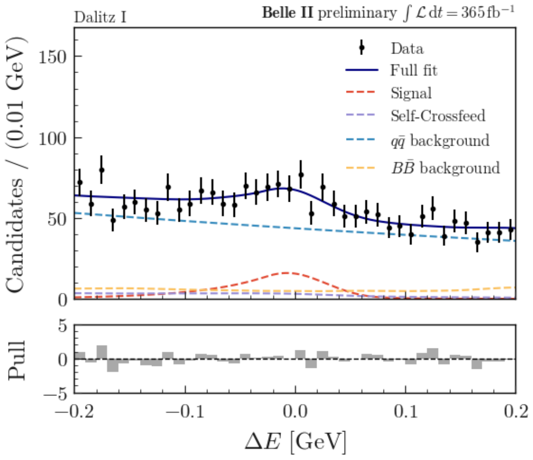


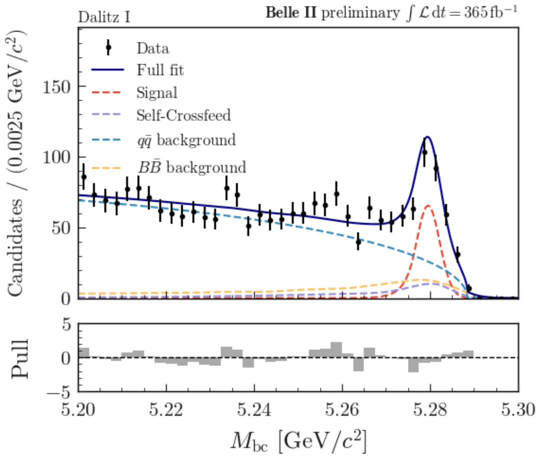


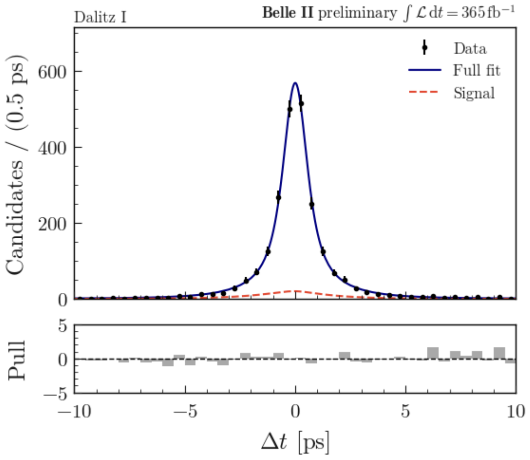


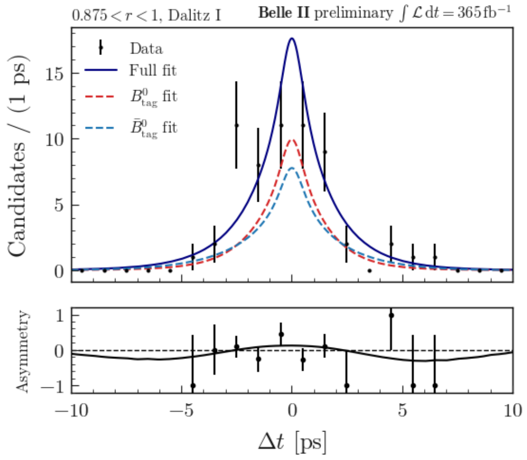


$m^2_{K_S\pi^+} > m^2_{K_S\pi^-}$



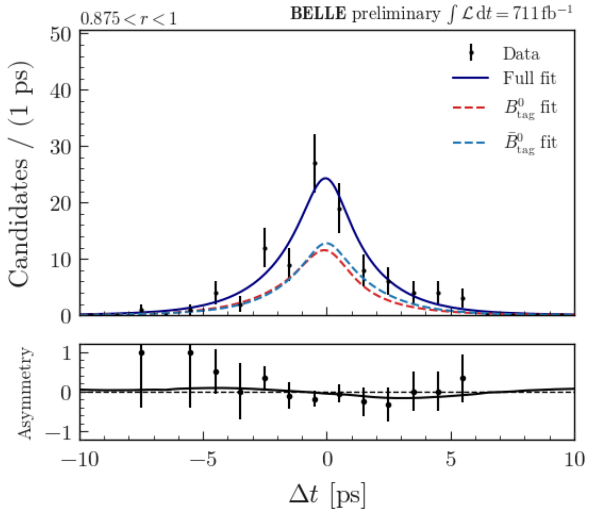






Belle results

- Analysis of the full Belle dataset (711 fb^{-1}) performed in parallel
- Measurement strategies as similar as possible with irreducible differences due to different detectors and software frameworks
- **Similar precision** between Belle and Belle II despite the difference in dataset size due to improved detector and better flavor tagging
- Belle results within 1σ from SM expectation while being mostly in agreement with Belle II results
- Most notable difference is in S^- (3σ); for Belle the observed asymmetry originates from the other Dalitz half-plane w.r.t. Belle II



Belle results:

$C = -0.04 \pm 0.11 \pm 0.07$

$S = -0.18 \pm 0.17 \pm 0.08$

$S^+ = -0.33 \pm 0.34 \pm 0.15$

$S^- = -0.36 \pm 0.38 \pm 0.11$

Belle systematics

Belle

Source of uncertainty	C	S	S^+	S^-
Fixed shape parameters	0.003	0.002	0.004	0.004
Flavor Tagging parameters	0.003	0.002	0.006	0.006
Resolution function parameters	0.009	0.033	0.063	0.027
τ_{B^0} & Δm	0.001	0.001	0.002	0.002
Fixed SCF fraction	0.005	0.006	0.010	< 0.001
Yield bias	0.001	0.008	0.015	0.002
CP fit validation	0.018	0.019	0.035	0.075
Tag-side interference	0.028	< 0.001	< 0.001	< 0.001
CP violation in $B\overline{B}$ background	0.047	0.039	0.060	0.079
Residual misalignment	0.03	0.06	0.12	< 0.001
Total systematic uncertainty	0.066	0.081	0.153	0.112

Belle II

Source of uncertainty	C	S	S^+	S^-
Fixed shape parameters	0.003	0.005	0.005	0.004
Flavor Tagging parameters	0.018	0.007	0.014	0.012
Resolution function parameters	0.005	0.014	0.023	0.018
τ_{B^0} & Δm	< 0.001	0.001	0.001	0.003
Fixed SCF fraction	0.006	0.004	0.008	0.011
Yield bias	0.005	0.004	0.008	0.014
CP fit validation	0.027	0.054	0.117	0.033
Tag-side interference	0.028	< 0.001	< 0.001	< 0.001
CP violation in $B\overline{B}$ background	0.019	0.017	0.034	0.001
Residual misalignment	0.005	0.003	0.006	0.012
Total systematic uncertainty	0.048	0.059	0.126	0.045

Discussion

- Combined results exhibit tension with the SM expectation with significance between $1.3\sigma - 2.4\sigma$
- Extensive validation of the fit strategy did not reveal any major issues
  $\Rightarrow$ statistical fluctuation in the data?
- Some tension with previous measurements by Belle and BaBar
  $\Rightarrow$ Belle results are in agreement with previous Belle measurement
- Precision still limited $\Rightarrow$ more data needed to reach any substantial conclusions

Post-unblinding checks

Central values off by $\sim 2.3\sigma$ w.r.t. the SM prediction (stat. only)

$$S = -0.36 \pm 0.16$$
$$C = -0.29 \pm 0.13$$

a. Is it a problem of the fit?

b. Are we missing CP background(s)?

c. Is it a mismodelling of a $B\bar{B}$ background?

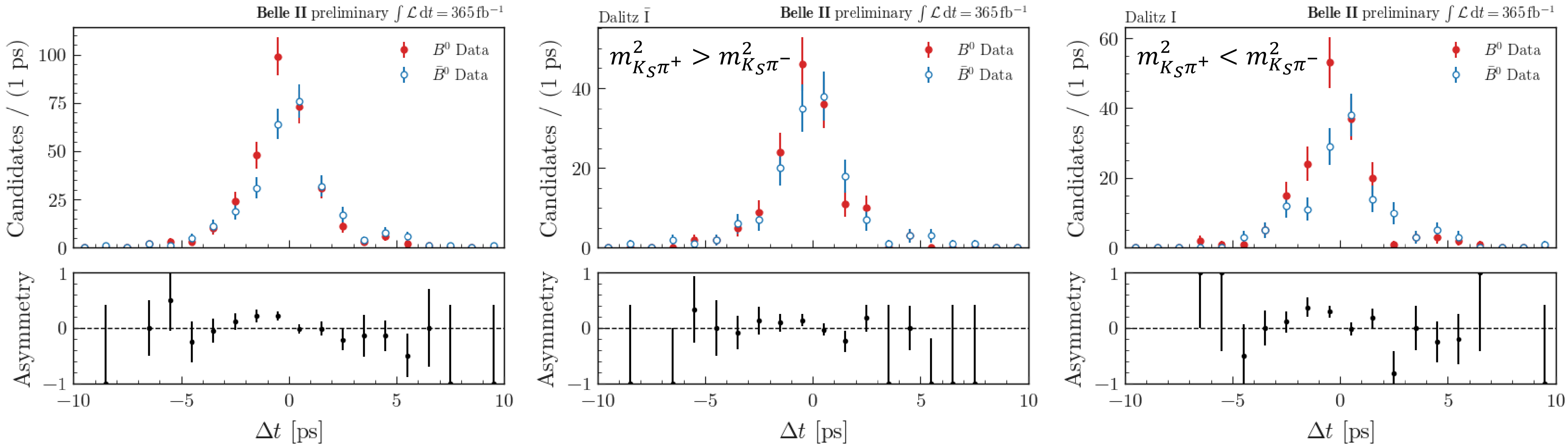
Post-unblinding checks

<u>Signal-enhanced region:</u>

$|\Delta E| < 0.1$ GeV &
$M_{\text{bc}} > 5.27$ GeV$/c^2$

a. Is it a problem of the fit?

- ➢ Looking at the raw Δt distributions in a signal-enhanced region
  $\Rightarrow$ we see a non-zero CP asymmetry



- ➢ We conclude that it is not an issue of the fit

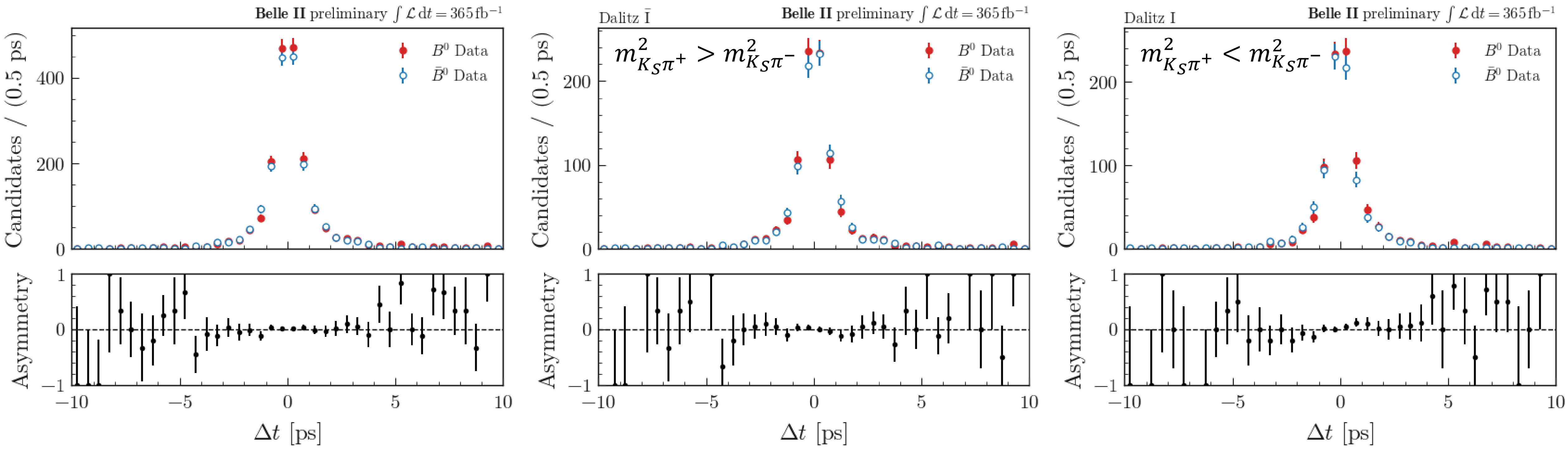
Post-unblinding checks

<u>Sideband region:</u>

$M_{\mathrm{bc}} < 5.27\ \mathrm{GeV}/c^2$

b. Are we missing CP background(s)?

➢ Looking in the sideband region we do not see a significant non-zero CP asymmetry

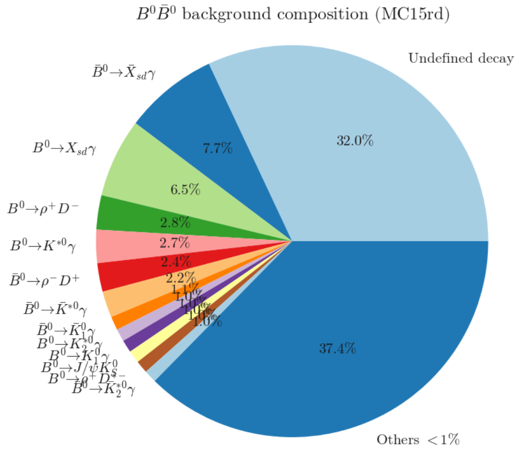


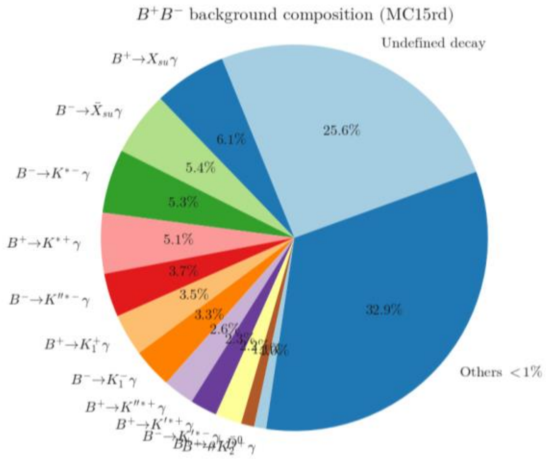
➢ Continuum dominated region, then it might be a peaking $B\bar{B}$ background

Post-unblinding checks

b. Are we missing CP background(s)?

- Maybe we are missing something in the **simulated** $B\bar{B}$ background?





$B^0\bar{B}^0 \sim 24\%$

$B^+B^- \sim 76\%$

- Charged B decays (75%) → no TDCP asymmetry expected
- Mis-reconstructed radiative decays (50%) → no TDCP asymmetry expected
- Test by performing CP fits to different components of $B\bar{B}$ background → no significant CP asymmetry found

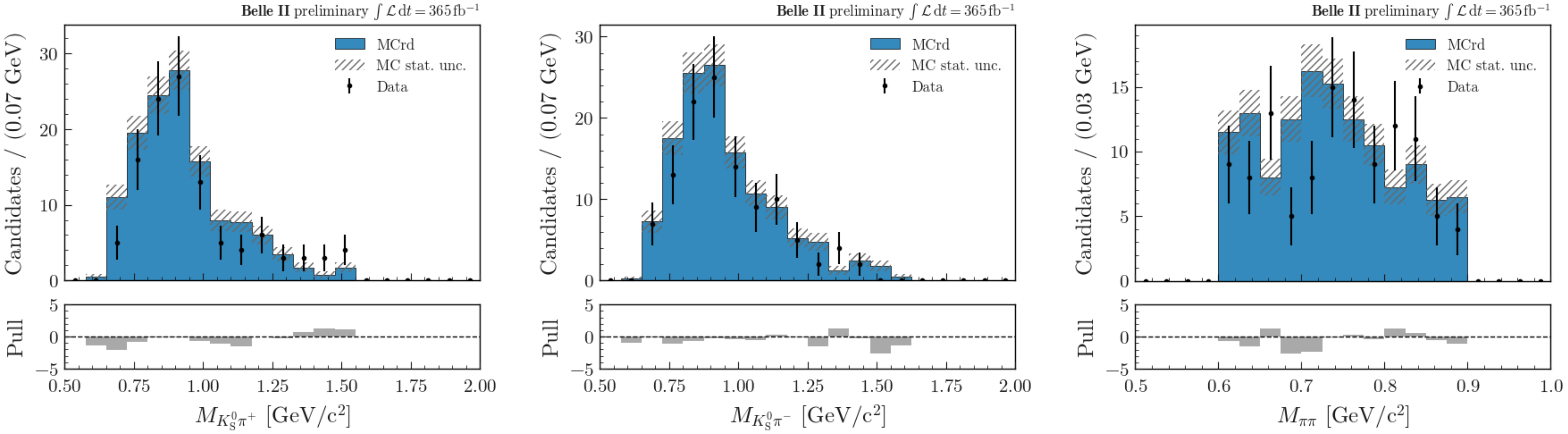
Post-unblinding checks

Signal-enhanced region:

$|\Delta E| < 0.1$ GeV &
$M_{\mathrm{bc}} > 5.27$ GeV/c^2 &
$r > 0.875$ (best r-bin)

b. Are we missing CP background(s)?

- Check for any background structures **in data** in a signal-enhanced region

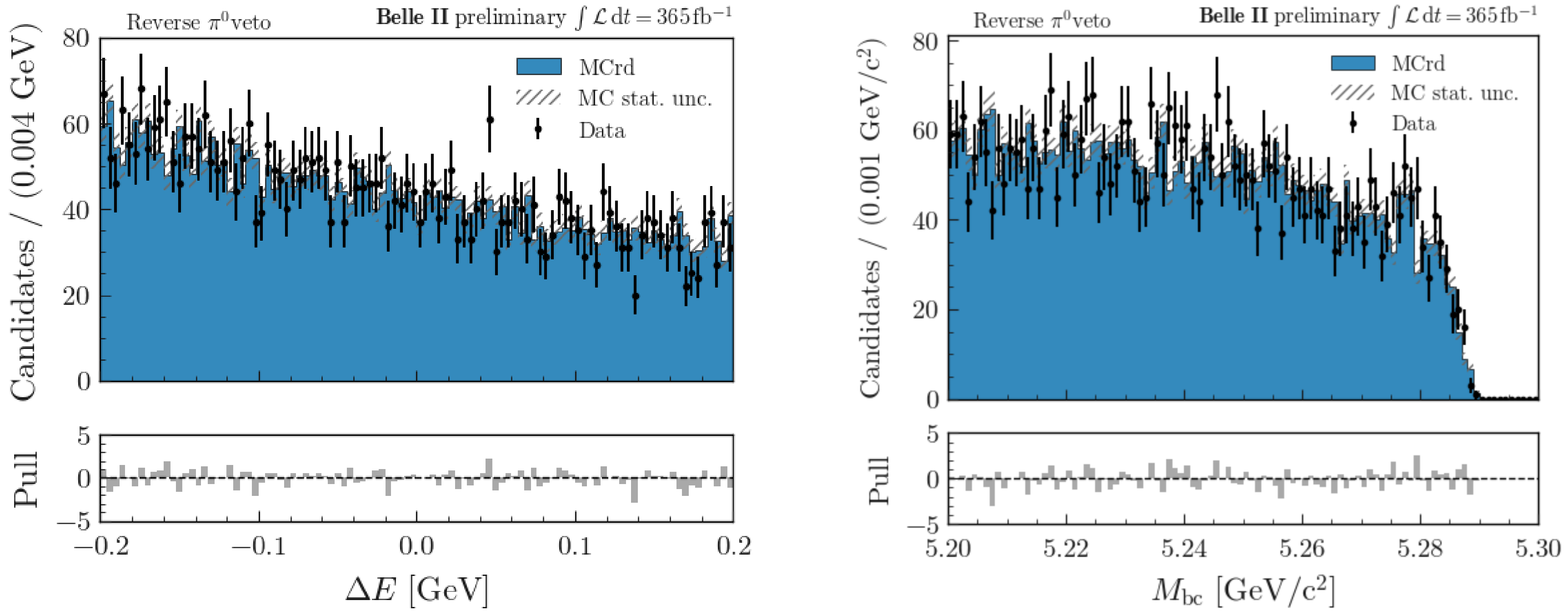


- Good agreement between data & MC in signal-enhanced region

Post-unblinding checks

c. Is it a mismodeling of a $B\bar{B}$ background?

- Inverted π^0 veto selection criterion to check for excess of $B^0 \to K_S^0\pi^+\pi^-\pi^0$ events in the data vs. MC

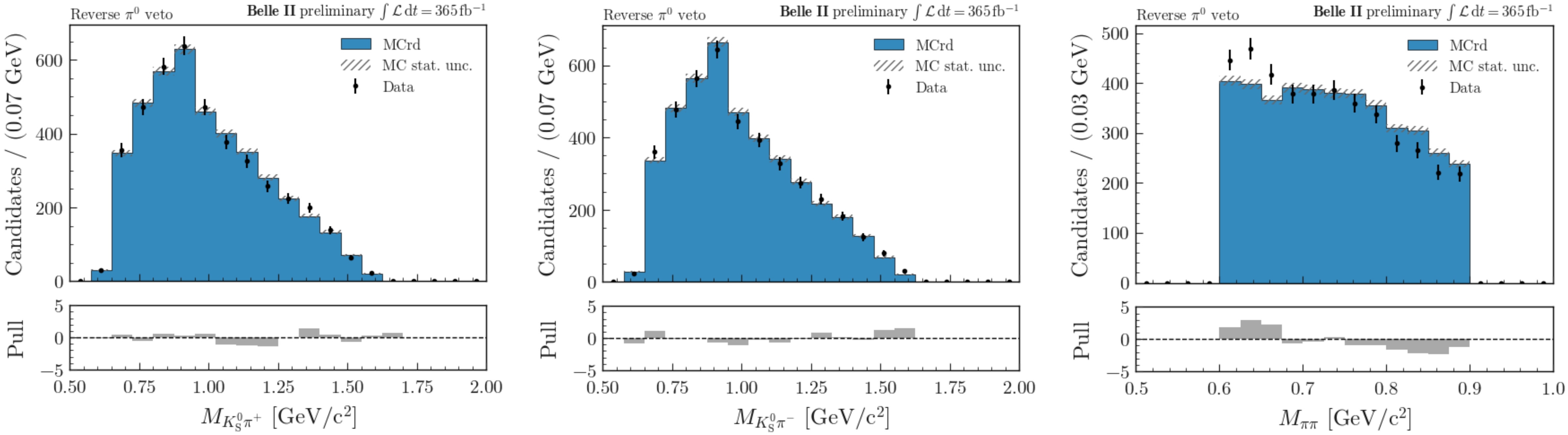


- Good agreement between data & MC in this sideband region

Post-unblinding checks

c. Is it a mismodeling of a $B\bar{B}$ background?

➢ Inverted π^0 veto selection criterion to check for excess of $B^0 \to K_S^0\pi^+\pi^-\pi^0$ events in the data vs. MC



➢ Good agreement between data & MC in this sideband region

Post-unblinding checks

Revisited significance estimation

- Initially estimated significance using **Wilks' theorem**:
  - Belle: 0.13σ
  - Belle II: 2.67σ
- Alternative estimation using **Mahalanobis distance** of the likelihoods:
  - Nominal fit (S & C): 2.23σ
  - Dalitz-split fit (S^+ & S^-): 2.37σ
- Situation does not change significantly

  (the above does not include systematic uncertainties)