Calibration of the Flavor Tagger and Δt Resolution function parameters with MC15

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Physics Motivation

- Time-dependent CP violation analyses depend on the quality of the **Flavor Tagger** to extract CP violation parameters: S_{CP} and A_{CP}
- Usual strategy involves fitting Δt distribution of measured events using:

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}}\{1 + q[S_{CP}\sin(\Delta m_d \Delta t) + A_{CP}\cos(\Delta m_d \Delta t)]\}$$

then extracting S_{CP} and A_{CP} from the fit

- Precise knowledge of the B meson flavor q at time $t = t_0$ is required for carrying out all time-dependent analyses

$$\mathcal{A}_{CP}(\Delta t) = \frac{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})} = S_{CP}\sin(\Delta m_d \Delta t) + A_{CP}\cos(\Delta m_d \Delta t)$$

Δt: Time difference b/w decays of B^0 and $\bar{B}^0$ in the event

Δm_d: Oscillation frequency of $B^0\bar{B}^0$ mixing

τ_{B^0}: Neutral B meson lifetime

Physics Motivation

- Calibration of Flavor Tagger parameters using **self-tagged** decays $B^0 \to D^{(*)-}\pi^+$ (+ charge conjugated)

- Need to fit Δt distribution of such events using:

$$\mathcal{P}_{\text{flav}}(\Delta t, q, q_\pi) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 - q\boldsymbol{\Delta w} + q\boldsymbol{\mu}(1-2\boldsymbol{w}) - q_\pi[q(1-2\boldsymbol{w}) + \boldsymbol{\mu}(1-q\boldsymbol{\Delta w})]\cos(\Delta m_d \Delta t)\}$$

$q, q_\pi = +1(-1)$ for tag-side and signal-side $B^0(\bar{B}^0)$

- Δt resolution *smears* above PDF $\Rightarrow$ result: $\mathcal{P}_{\text{flav}} * \mathcal{R}(\delta t)$, with: $\delta t = \Delta t_{\text{reco}} - \Delta t_{\text{true}}$

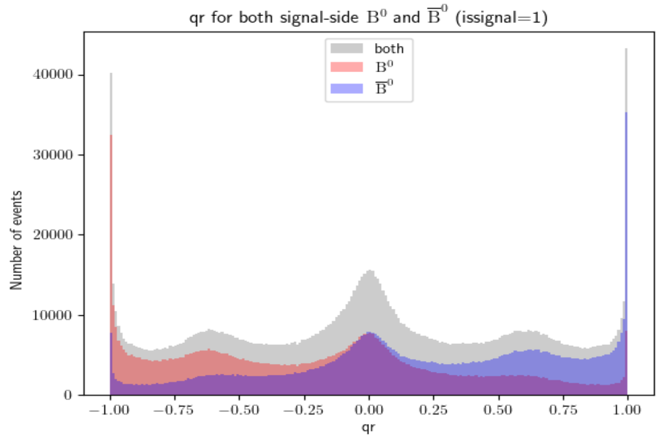
$\boldsymbol{w}$: Fraction of events with wrong assignment of B-tag flavor

$\boldsymbol{\Delta w}$: Asymmetry b/w wrongly tagging B^0 as $\bar{B}^0$ and vice-versa

$\boldsymbol{\mu}$: Tag-side reconstruction efficiency asymmetry (b/w B^0 and $\bar{B}^0$)

} Flavor Tagger parameters

Some technical details…



qr distribution for signal events

- Flavor Tagger outputs 2 values: $\boldsymbol{q_{tag}}$ $(=\pm 1)$ and $\boldsymbol{r} \in (0, 1)$
  - Split r into 7 intervals (**bins**): $(0.0, 0.1, 0.25, 0.45, 0.6, 0.725, 0.875, 1.0)$
- Determine FT parameter values in each bin by performing an unbinned likelihood fit to Δt distribution of events containing $B^0 \rightarrow D^{(*)-}\pi^+$ decays
- Fit contains 28 free parameters in total: 21 flavor tagger parameters and 7 Δt resolution function parameters
- First step: perform the fit on **signal Monte Carlo only** and check for potential biases…

(See BELLE2-CONF-2022-021 for more details…)

Calibration procedure

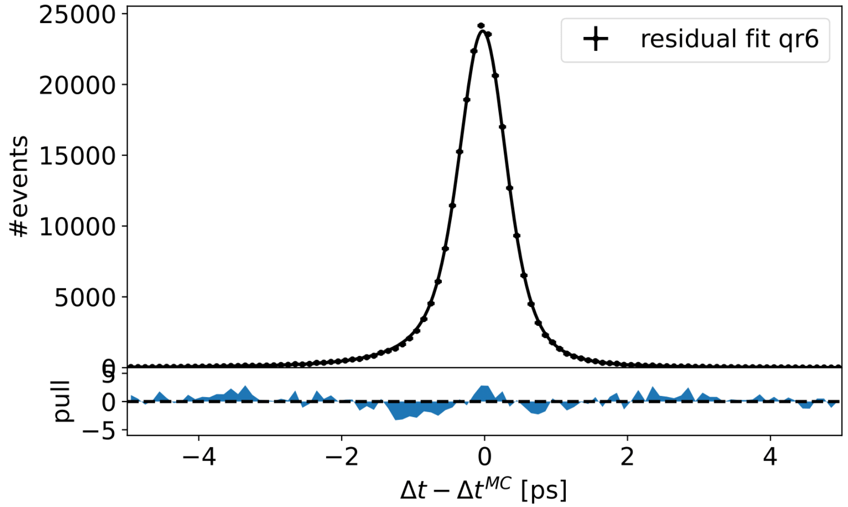
➢ Reconstruction of signal MC15 sample:

- events with at least one $B^0 \to D^{(*)-}\pi^+$ truth-matched decay
- signal- and tag-side vertex fits successful

➢ Fit Δt residual distribution using:

$$\mathcal{R}(\delta t;\sigma_{\Delta t}) = f_{\text{core}}\,\mathcal{G}(\delta t; m_{\text{core}}\sigma_{\Delta t}, s_{\text{core}}\sigma_{\Delta t}) + f_{\text{tail}}\,\mathcal{R}_{\text{tail}}(\delta t; m_{\text{tail}}\sigma_{\Delta t}, s_{\text{tail}}\sigma_{\Delta t}, {}^{c}/_{\sigma_{\Delta t}}, f_{>}, f_{<}) + f_{\text{OL}}\,\mathcal{G}(\delta t; 0, \sigma_{\text{OL}})$$

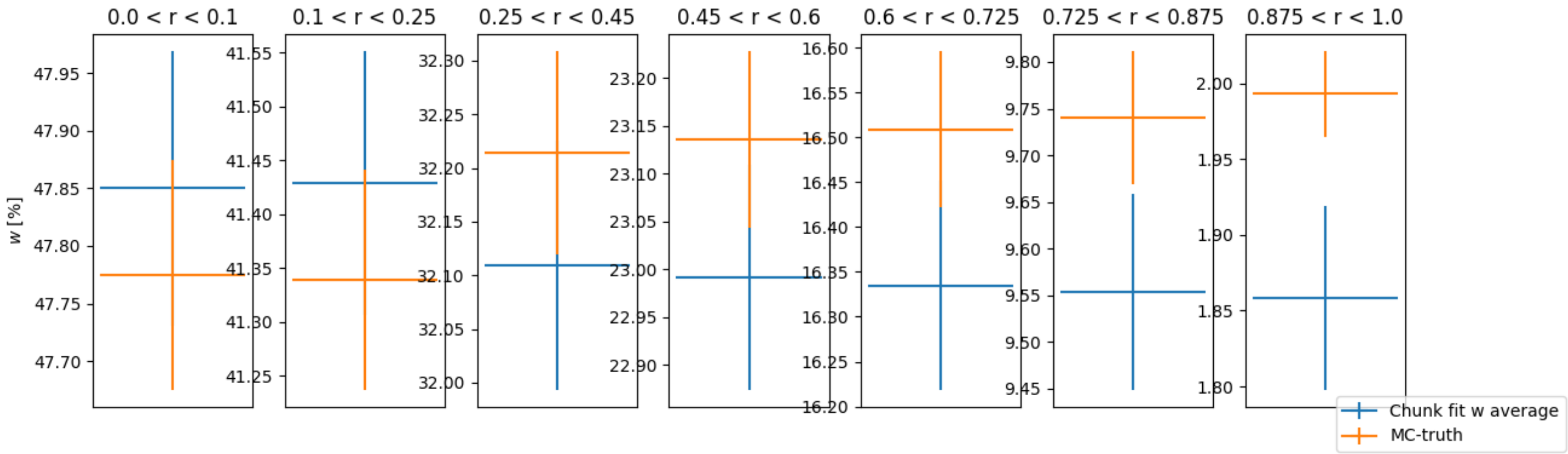
to obtain Δt resolution function parameters



Fitted Δt residual distribution for events belonging to 7^{th} r bin

➢ Then perform full fit on "chunks" of signal MC reflecting the size of the real data ($365\ \text{fb}^{-1}$) and check whether FT parameters are biased w.r.t. their MC truth values

Findings



Average of fit w across all chunks compared to MC truth value in each ***r*** *bin*

- In this case tag-side vertex was fitted using the **KFit** algorithm (no bias found when using **Rave**)
- Wrong tag fraction w shows significant bias (~30% of stat. uncertainty in last bin)
- While leaving $\tau_B, \Delta m_\mathrm{d}$ to float in the fit: $\tau_B = 1.5109 \pm 0.0015$ ps (truth value: $\tau_B = 1.519$ ps) & $\Delta m_\mathrm{d} = 0.5136 \pm 0.0013\ \mathrm{ps}^{-1}$ (truth value: $\Delta m_d = 0.507\ \mathrm{ps}^{-1}$)
- Potential origin of bias: quality of Δt residual fit yielded by KFit is poorer, especially in some $|qr|$ bins

Conclusions, Challenges & Outlook

- Found significantly biased Flavor Tagger parameters when fitting Δt distribution of signal MC samples only when using KFit to fit tag-side vertices
- Resolution function could be improved to fit the residuals better, but faster to switch back to Rave for calibration process

Challenges:

- How to judge quality of residual fit? Both KFit and Rave seem OK but lead to different biases?
- How to determine systematically which resolution function parameters to float in the fit and which to fix?

Up next:

- Background study using generic MC sample before performing the fit on real data

Thank You!

Questions?

Backup

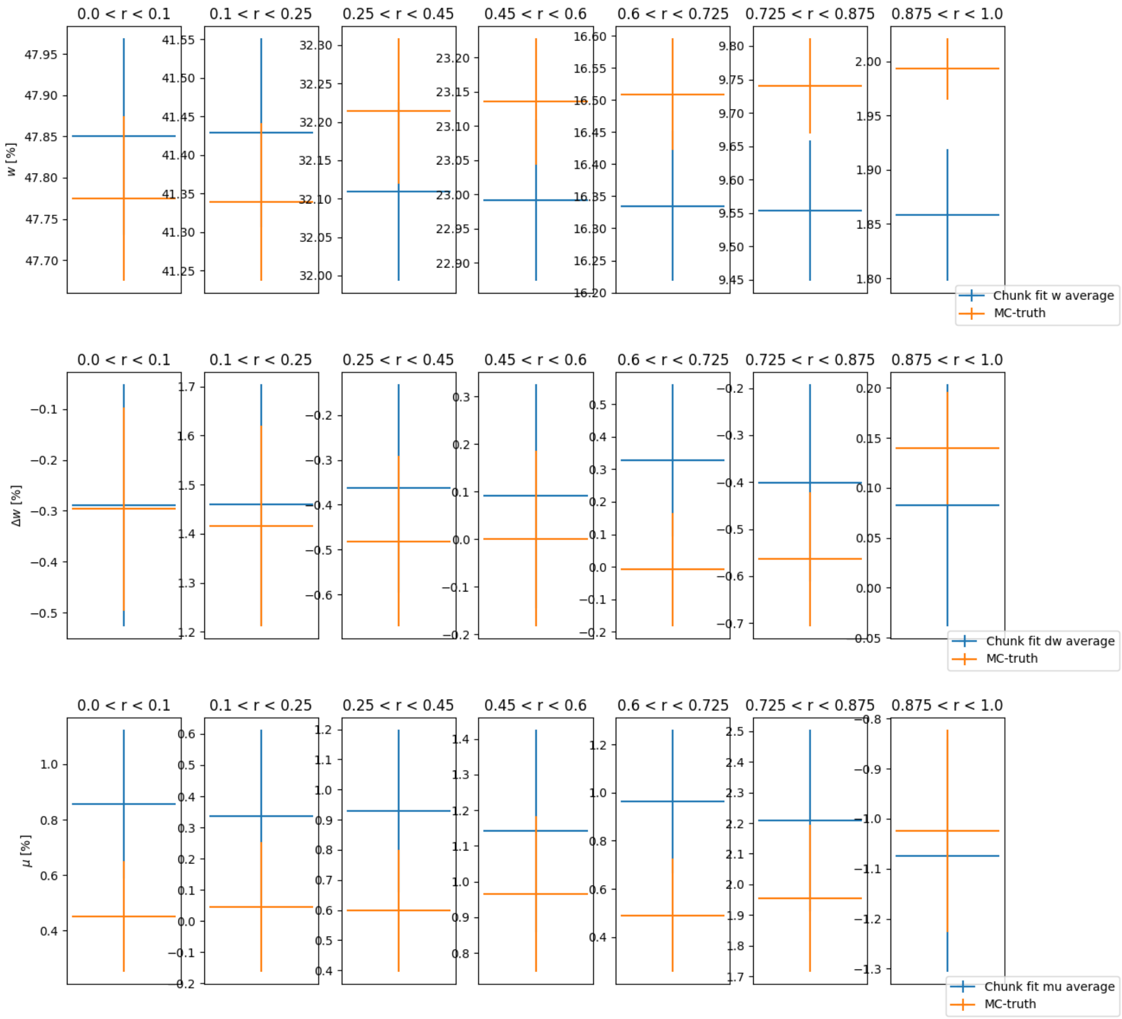
Selection criteria:

- $0.05 < \sigma_{\Delta t} < 2.0$ ps
- Signal-side vertex fit $\chi^2 > 0$
- Tag-side vertex fit $\chi^2 > 0$ & $ndf > 0.5$
- $M_{bc} > 5.27\ GeV/c^2$
- $-0.1 < \Delta E < 0.25$ GeV

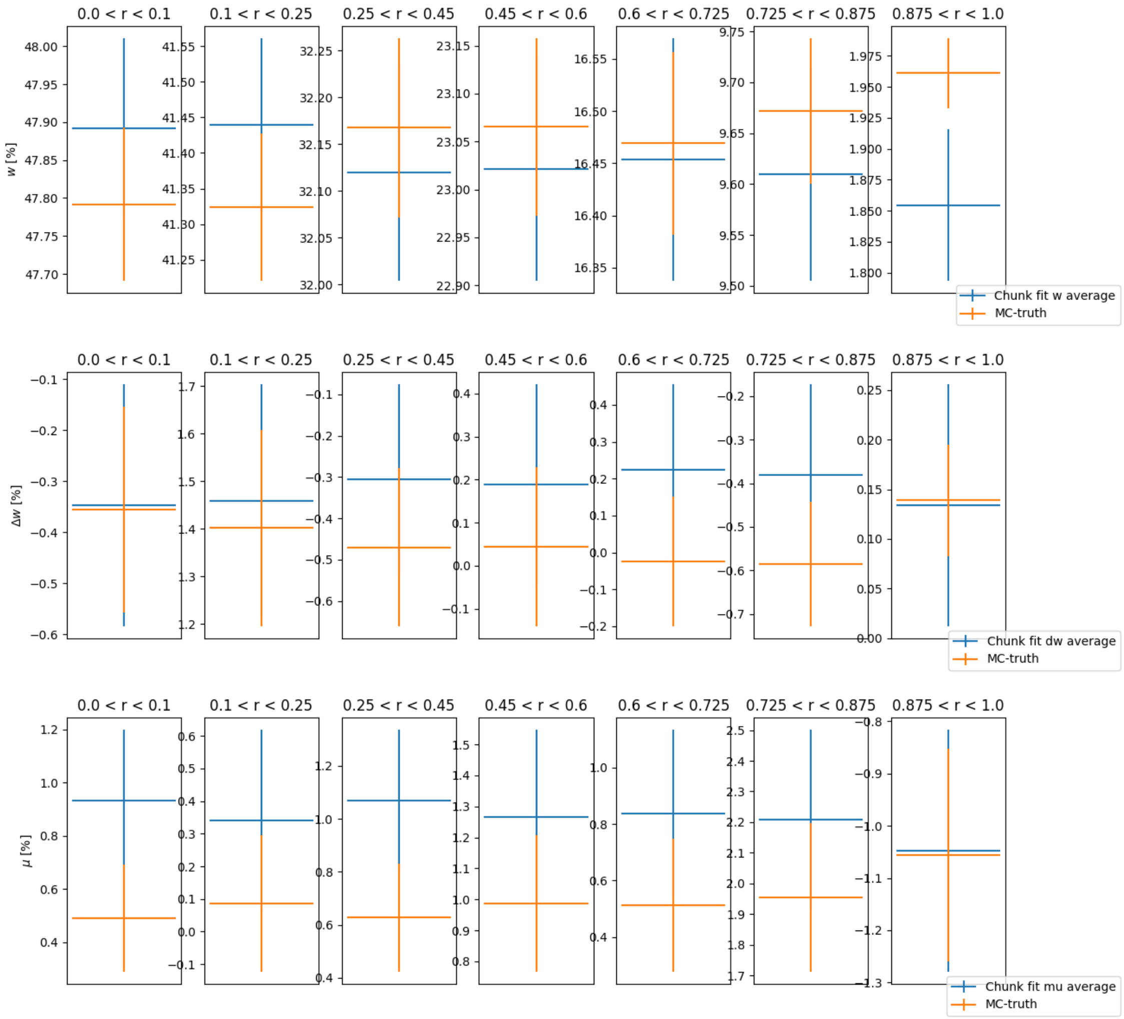
Resolution function parameters:

- Mean and sigma of core Gaussian
- Fraction, mean and sigma of tail Gaussian
- Fraction and slope of exponential tail

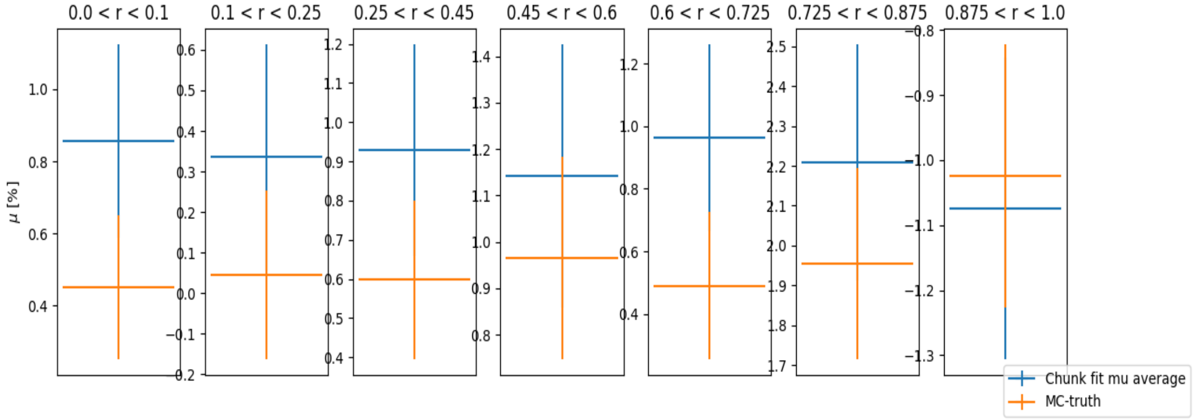
KFit


0.0 < r < 0.1
0.1 < r < 0.25
0.25 < r < 0.45
0.45 < r < 0.6
0.6 < r < 0.725
0.725 < r < 0.875
0.875 < r < 1.0
w [%]
Chunk fit w average
MC-truth
Δw [%]
Chunk fit dw average
MC-truth
μ [%]
Chunk fit mu average
MC-truth

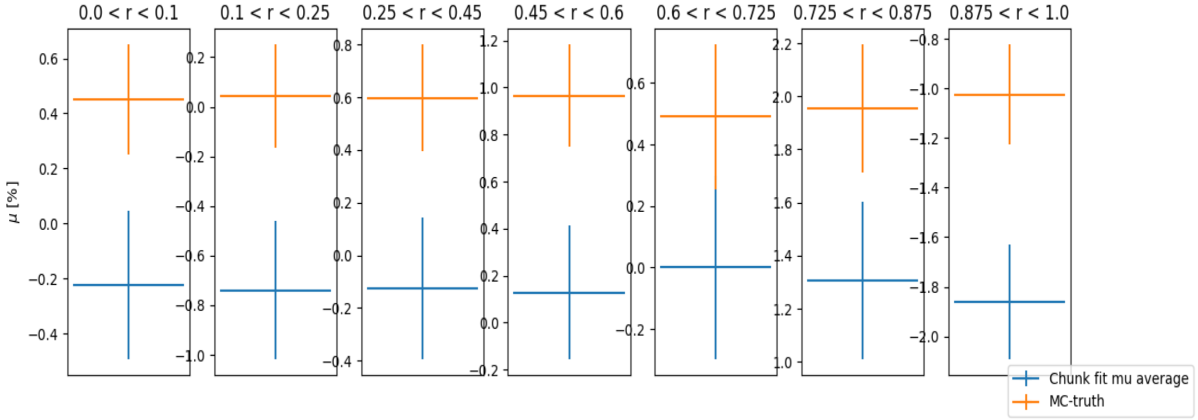
Rave


0.0 < r < 0.1
0.1 < r < 0.25
0.25 < r < 0.45
0.45 < r < 0.6
0.6 < r < 0.725
0.725 < r < 0.875
0.875 < r < 1.0
w [%]
Chunk fit w average
MC-truth
Δw [%]
Chunk fit dw average
MC-truth
μ [%]
Chunk fit mu average
MC-truth

Before correction

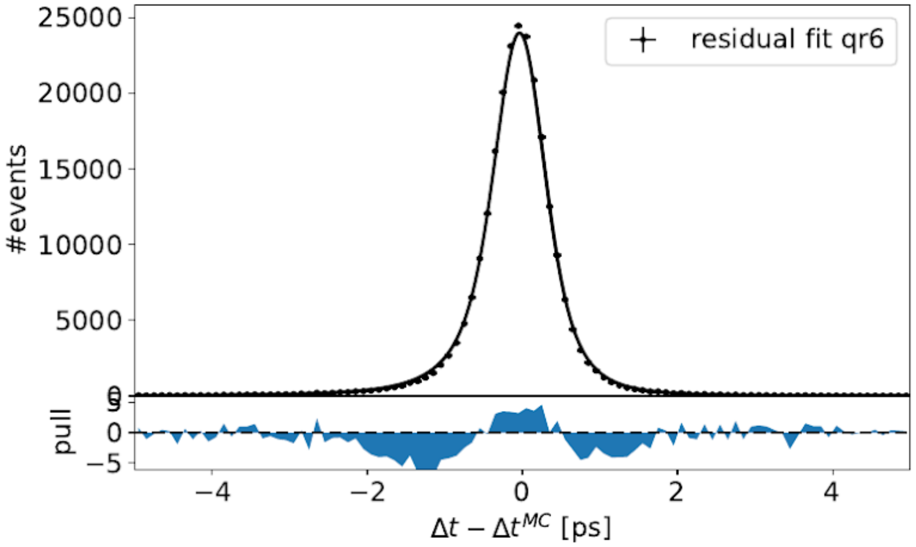


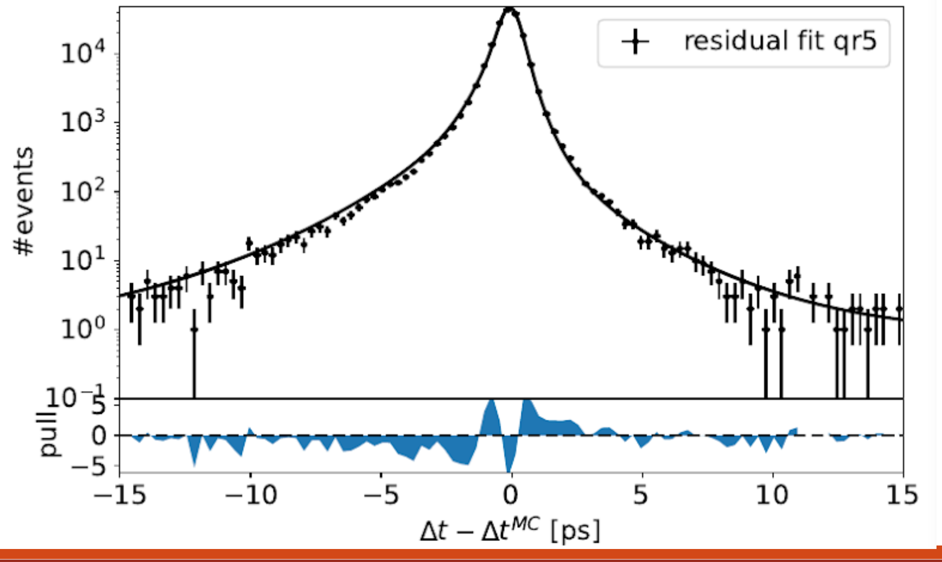
After correction



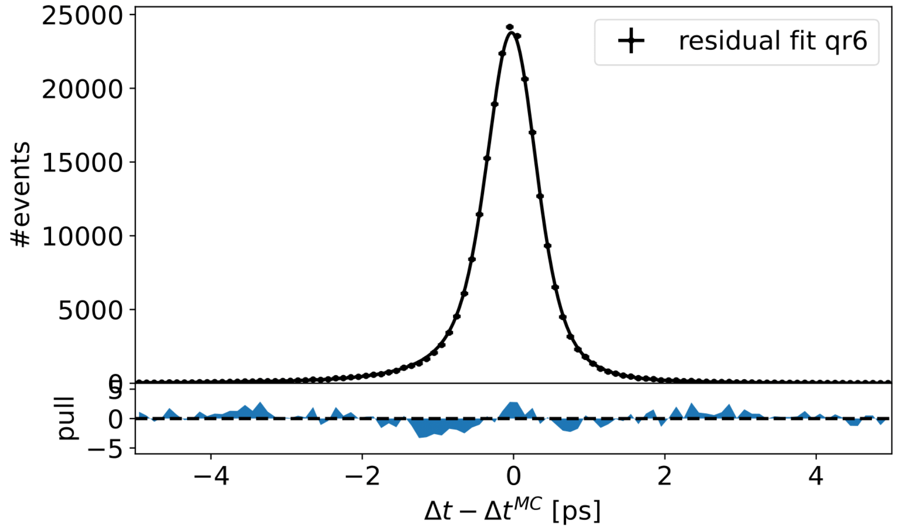
- Implementing a correction to account for signal-side reconstruction efficiency asymmetry led to larger bias for μ ...

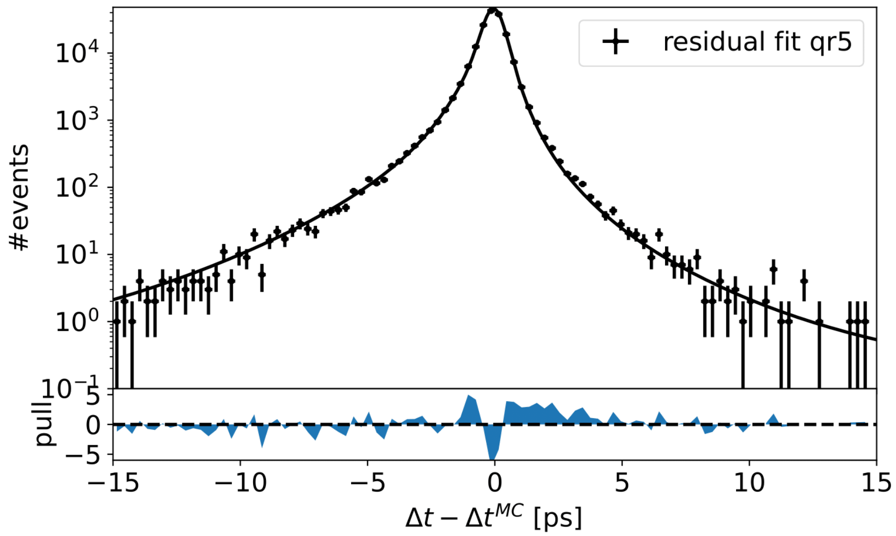
KFit

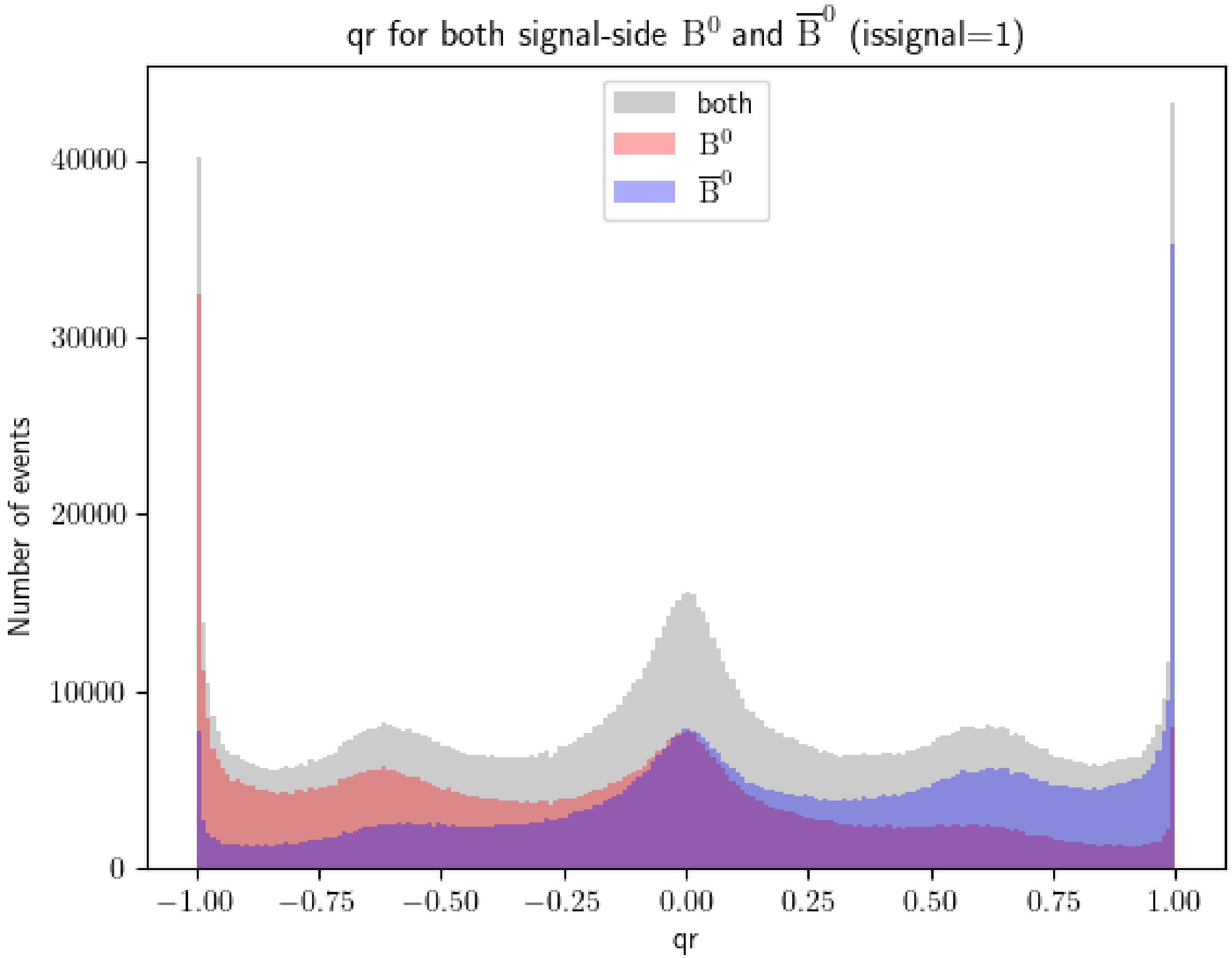

residual fit qr6
#events
pull
Δt − Δt^MC [ps]


residual fit qr5
#events
pull
Δt − Δt^MC [ps]

Rave


residual fit qr6
#events
pull
Δt − Δt^MC [ps]


residual fit qr5
#events
pull
Δt − Δt^MC [ps]


qr for both signal-side B^0 and $\overline{B}^0$ (issignal=1)
both
B^0
$\overline{B}^0$
Number of events
40000
30000
20000
10000
0
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
qr

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta \mathrm{t}|/\tau_{B^0}}}{2\tau_{B^0}}\{1 + q[S_{CP}\sin(\Delta m_d \Delta t) + A_{CP}\cos(\Delta m_d \Delta t)]\}$$

$$\mathcal{P}_{CP}(\Delta t, q) = \frac{e^{-|\Delta \mathrm{t}|/\tau_{B^0}}}{2\tau_{B^0}}\{1 - q\Delta w + q\mu(1 - 2w) + [q(1 - 2w) + \mu(1 - q\Delta w)][S_{CP}\sin(\Delta m_d \Delta t) + A_{CP}\cos(\Delta m_d \Delta t)]\}$$

$$\mathcal{P}_{\mathrm{flav}}(\Delta t, q, q_\pi) = \frac{e^{-|\Delta \mathrm{t}|/\tau_{B^0}}}{4\tau_{B^0}}\{1 - q\Delta w + q\mu(1 - 2w) - q_\pi[q(1 - 2w) + \mu(1 - q\Delta w)]\cos(\Delta m_d \Delta t)\}$$