Graph Neural Network Flavor Tagging and Measurement of sin2β at Belle II

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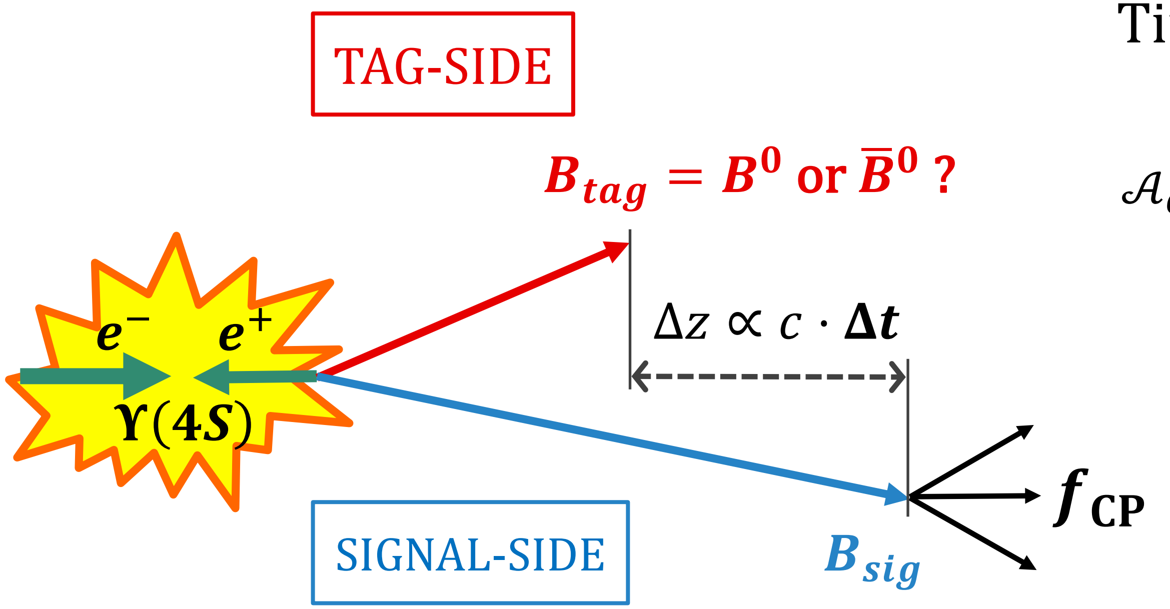
Belle II

Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

cnrs

Université de Strasbourg

Flavor Tagging at Belle II



Time-dependent CP asymmetry:

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

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

Mixing induced CP violation

Direct CP violation

- Flavor Tagging is essential in time-dependent and time-integrated CP asymmetry measurements
- Determine tag-side B flavor $q = \pm 1$ at the time of its decay; either B^0 or $\bar{B}^0$
- Charge of final state particle in tag-side correlates to B_{tag} flavor, i.e. $B^0 \to D^- \mu^+ \nu_\mu$

Category–based Flavor Tagger

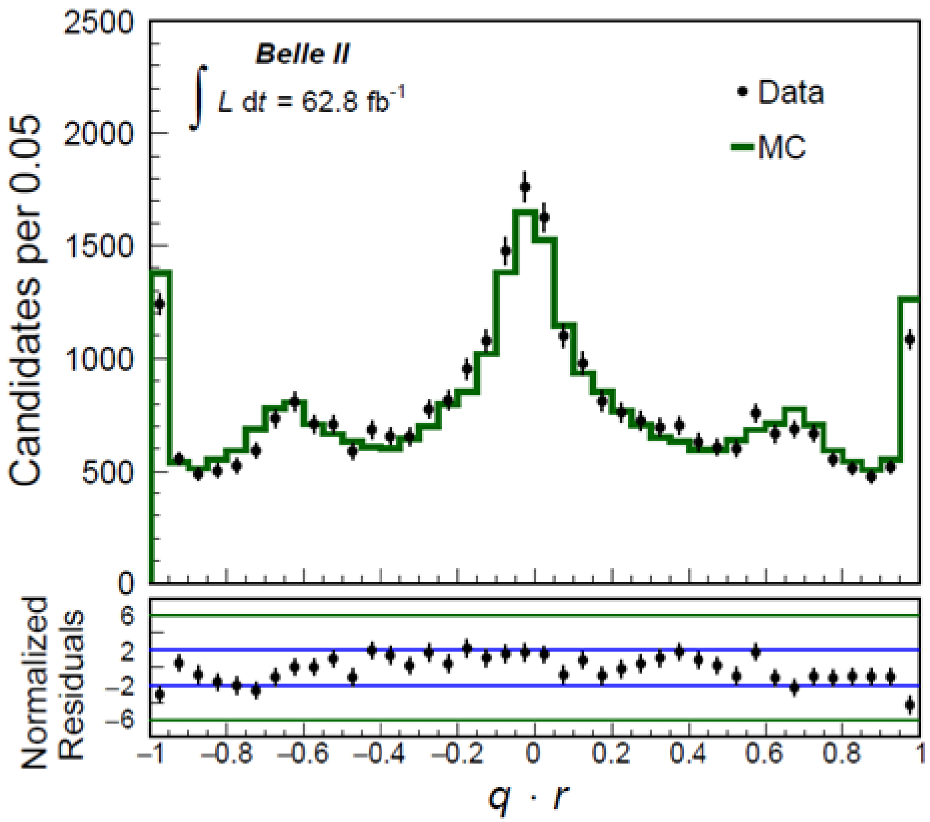
- Kinematic, topology and particle identification information → unique signature of "flavor-specific" B decays
- Flavor Tagger output: $\boldsymbol{q} \cdot \boxed{\boldsymbol{r}}$ → confidence of flavor prediction
- Accounting for inefficiencies in Flavor Tagging:

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

with w the **mis-tag fraction** and Δw the asymmetry in wrongly tagging B^0 and $\bar{B}^0$

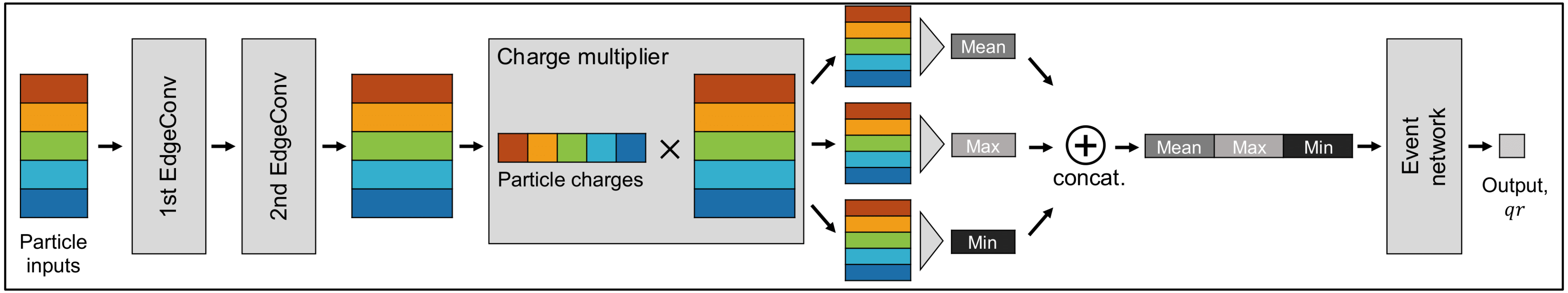
- Flavor Tagger performance metric: **effective tagging power**
- Increase in effective tagging power ⇒ higher statistical precision of time-dependent CP asymmetry measurement

Eur. Phys. J. C 82: 283

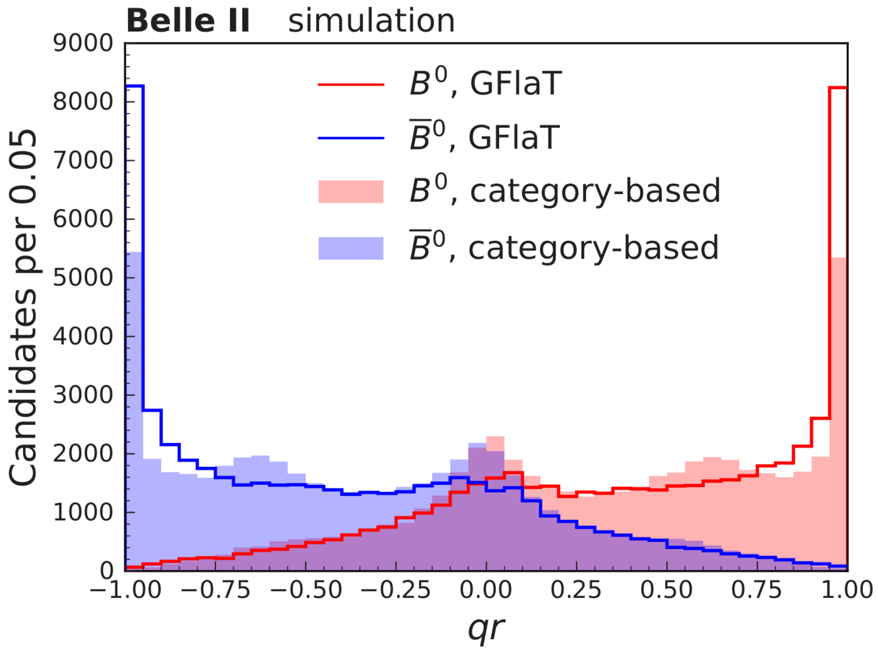


New Flavor Tagger: GFlaT

arXiv:2402.17260



- 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 power from simulation



arXiv:2402.17260

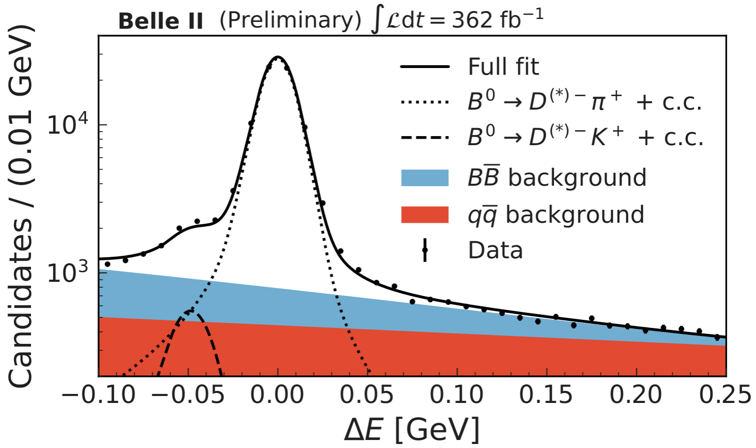
Calibration with data

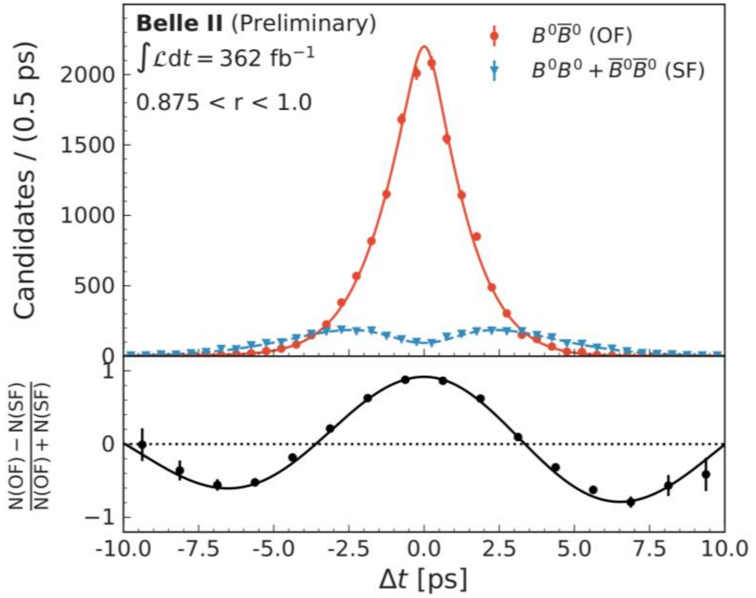
$$\Delta E = E_B^* - \sqrt{s}/2$$

- Calibrate Flavor Tagger and Δt Resolution Function parameters using "self-tagging" 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 ΔE and subtract Δt background from sideband (*sPlot* NIMA 555, 356-369)
- Fit background-free Δt for parameters of interest
- Relative improvement of **18%** in effective tagging power:

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

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





Measurement of sin2β

- GNN-based Flavor Tagger is used to measure sin2β in $B^0 \to J/\psi\ K_S^0$ decays
- Yield extraction fit to ΔE and fit on background-free Δt:

$$S = \quad 0.724 \pm 0.035\ (\text{stat}) \pm 0.014\ (\text{syst})$$

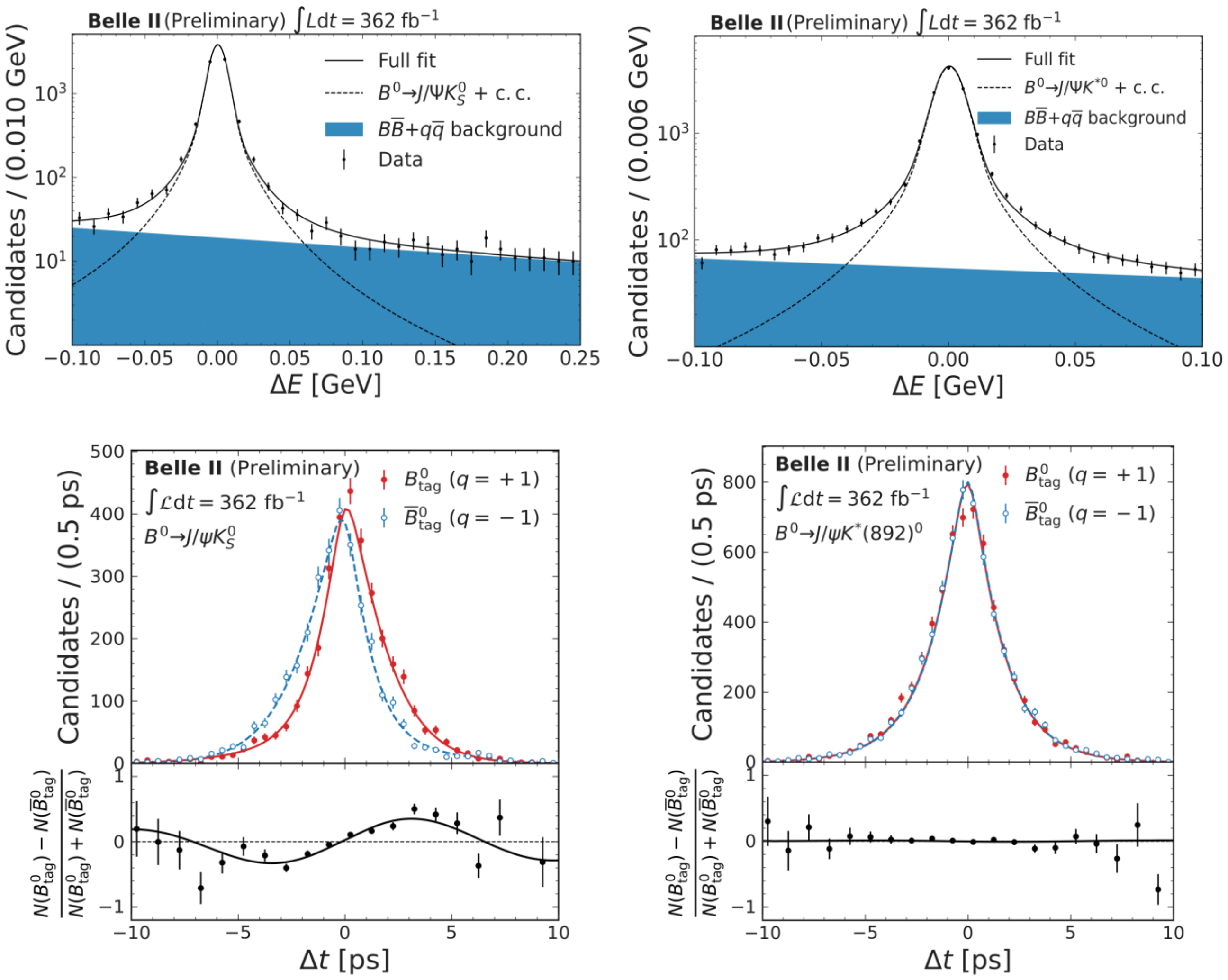
$$C = -0.035 \pm 0.026\ (\text{stat}) \pm 0.013\ (\text{syst})$$

- Statistical uncertainties **8%** smaller than with category-based Flavor Tagger
- CKM mixing angle β (or φ_1) calculated from S:

$$\beta = \left(23.2 \pm 1.5\ (\text{stat}) \pm 0.6\ (\text{syst})\right)^\circ$$

- Take-home: New GNN-based Flavor Tagger will lead to higher “effective” integrated luminosity ⇒ more precise measurements at Belle II

Signal mode | Control mode



Thank You!

Questions?

Backup

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

$$\overline{B}^0 \to D^{*+}\ \bar{\nu}_\ell\ \ell^-$$
$$\hookrightarrow D^0\ \pi^+$$
$$\hookrightarrow X\ K^-$$

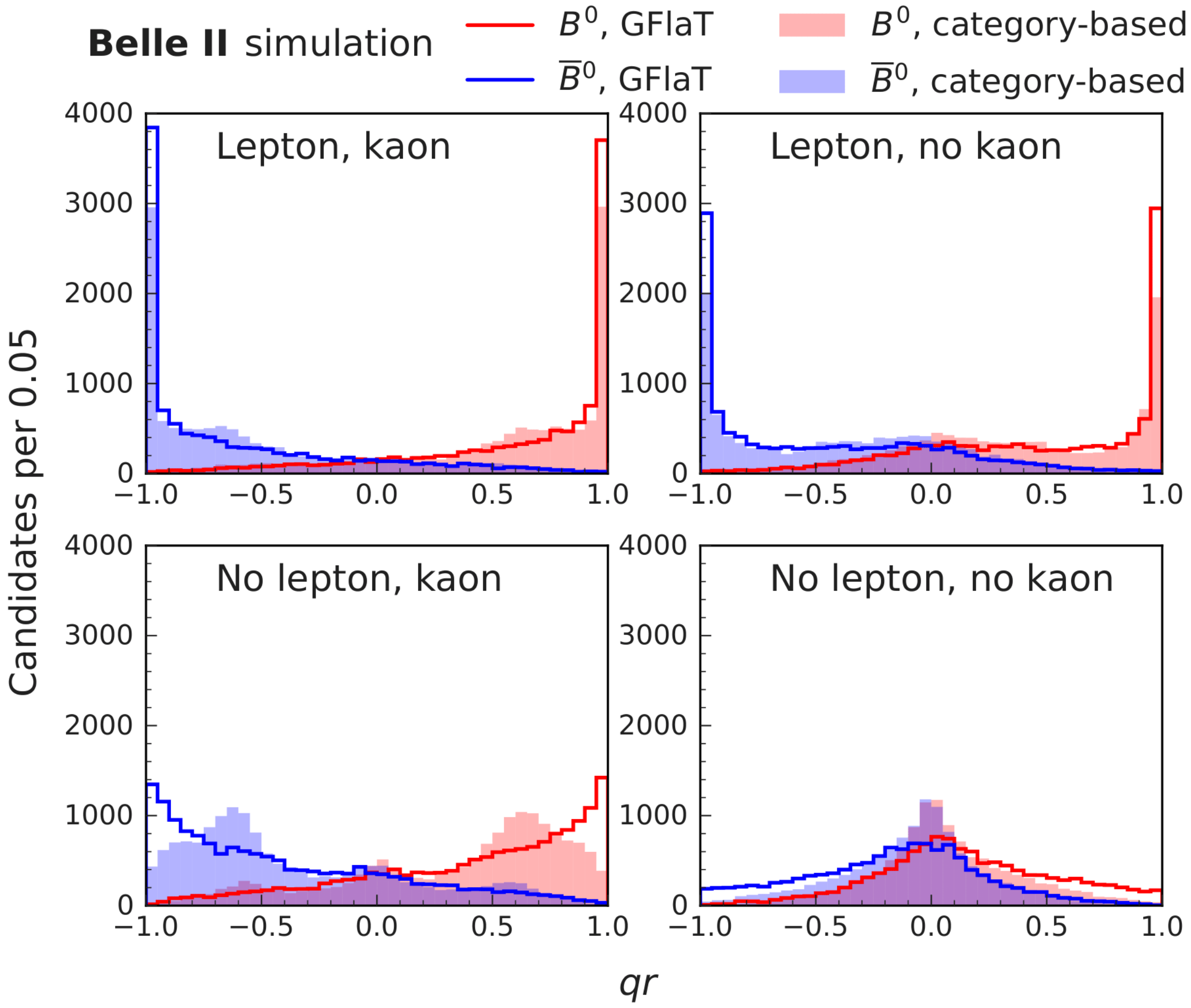
$$\overline{B}^0 \to D^+\ \pi^-\ (K^-)$$
$$\hookrightarrow \overline{K}^0\ \nu_\ell\ \ell^+$$

$$\overline{B}^0 \to \Lambda_c^+\ X^-$$
$$\hookrightarrow \Lambda\ \pi^+$$
$$\hookrightarrow p\ \pi^-$$

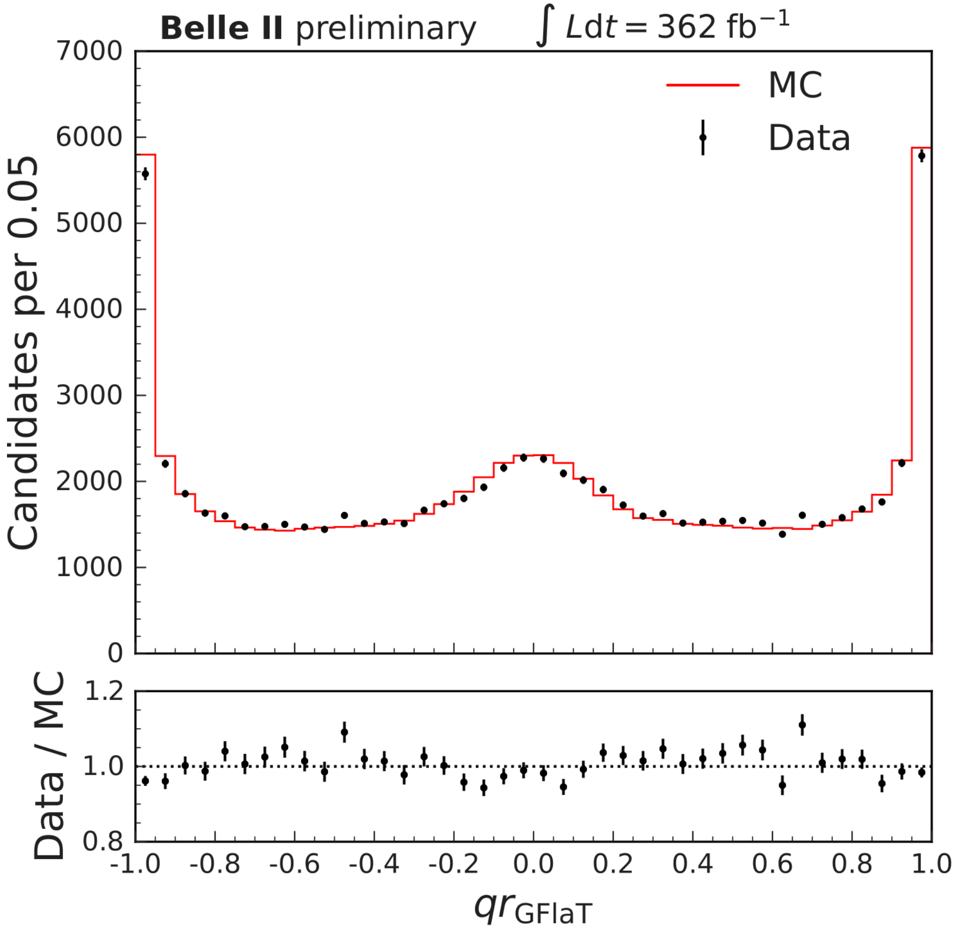
Input variables

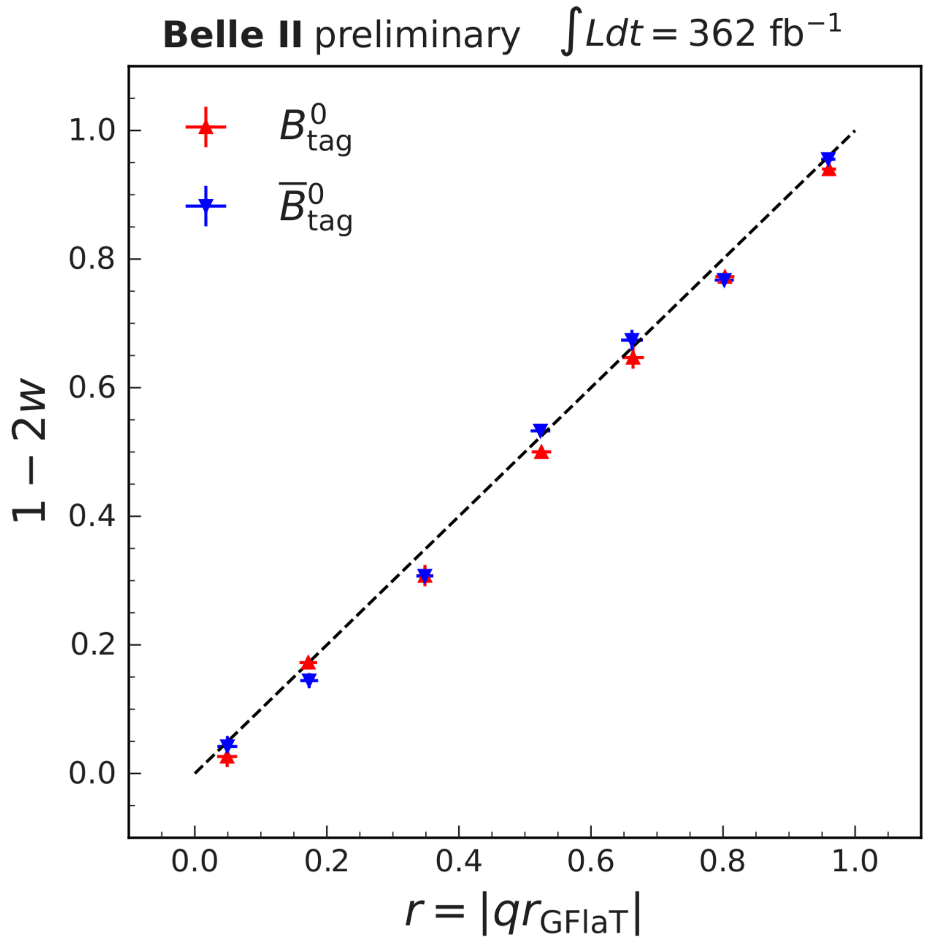
Variables	Usage	Descriptions
QpTrack(categoryName) * charge	Input features	multiplication of the charge of each particle by the category-baed Flavor Tagger output for each of the 13 categories;
p_x, p_y, p_z (px, py, pz)		momentum of a charged particle
electronID_noSVD_noTOP, muonID, pionID, kaonID, 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



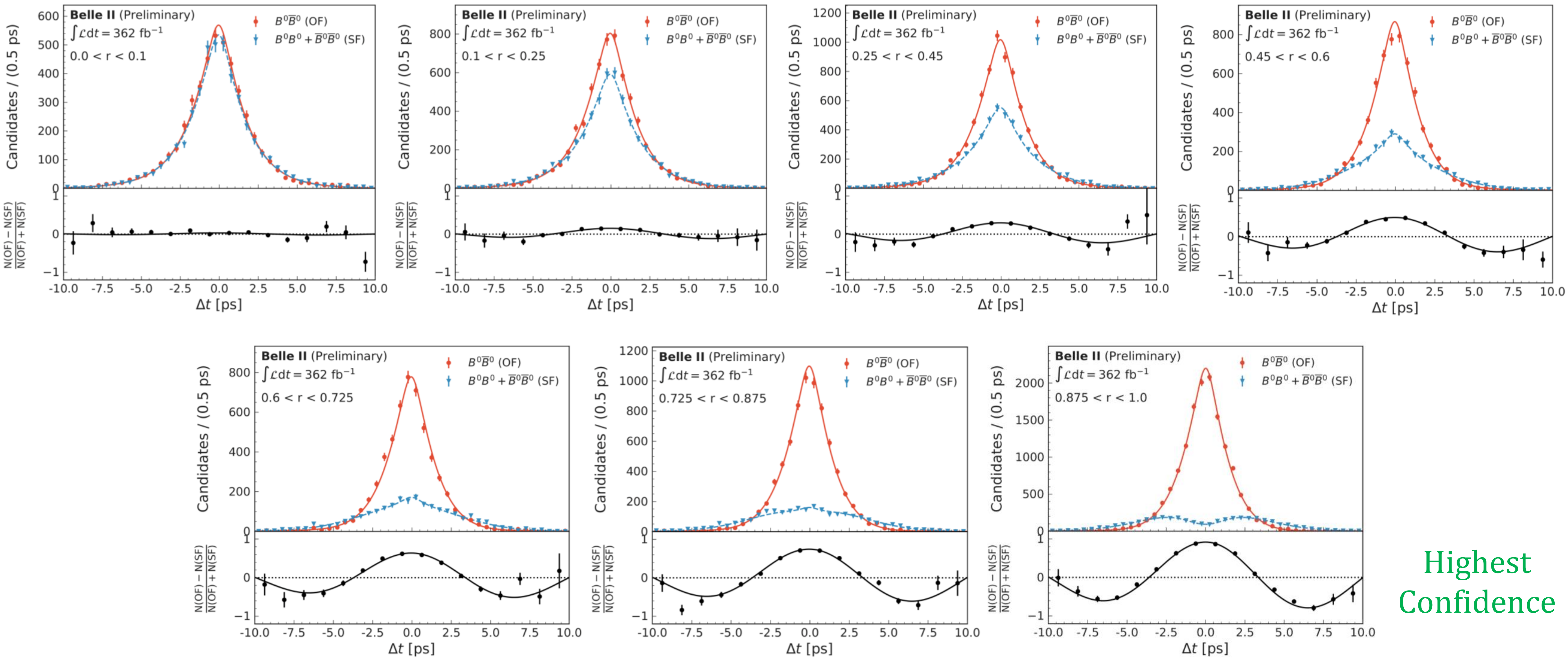
Data/MC & Linearity





Calibration – Δt CP mixing fits

Lowest Confidence



Highest Confidence

Flavor Tagger & Δt Resolution Function Parameters

Parameter name	Value from fit on data [%]	Statistical uncertainty [%]	Systematic uncertainty [%]
w_0	48.2916	0.7802	0.7475
w_1	42.0736	0.7208	0.3234
w_2	34.6287	0.6123	0.6059
w_3	24.1667	0.6774	0.3635
w_4	16.9810	0.6841	0.9186
w_5	11.4997	0.5284	0.3912
w_6	2.6191	0.2665	0.1414
Δw_0	0.7793	1.1631	0.7064
Δw_1	−1.4107	1.0612	0.9201
Δw_2	−0.0350	0.9690	1.1276
Δw_3	1.6422	1.1340	0.5190
Δw_4	1.3587	1.1523	0.7197
Δw_5	−0.2605	0.9248	0.7084
Δw_6	0.7549	0.5266	0.6042
μ_0	−1.7201	1.4723	1.3175
μ_1	−0.9356	1.3556	1.4511
μ_2	−0.2751	1.2807	1.4629
μ_3	3.2054	1.4414	1.4998
μ_4	1.1738	1.5770	1.4744
μ_5	−1.1284	1.2967	1.5478
μ_6	−0.1784	0.9088	1.3012

r bins: $[0, 0.1, 0.25, 0.45, 0.6, 0.725, 0.875, 1]$

Parameter name	Value from fit on data	Statistical uncertainty [%]	Systematic uncertainty [%]
s_{main}	1.03324	0.05921	0.07897
s_{tail}	2.20154	0.30338	0.29226
f_{max}	0.31591	0.05065	0.07122
μ_{main}	−0.10357	0.04430	0.04305
μ_{tail}	−0.53457	0.20269	0.21332
μ^6_{main}	0.10940	0.09314	0.10161
μ^6_{tail}	−0.92925	0.32101	0.48775