Recent Belle II results on time-dependent CP violation and charm

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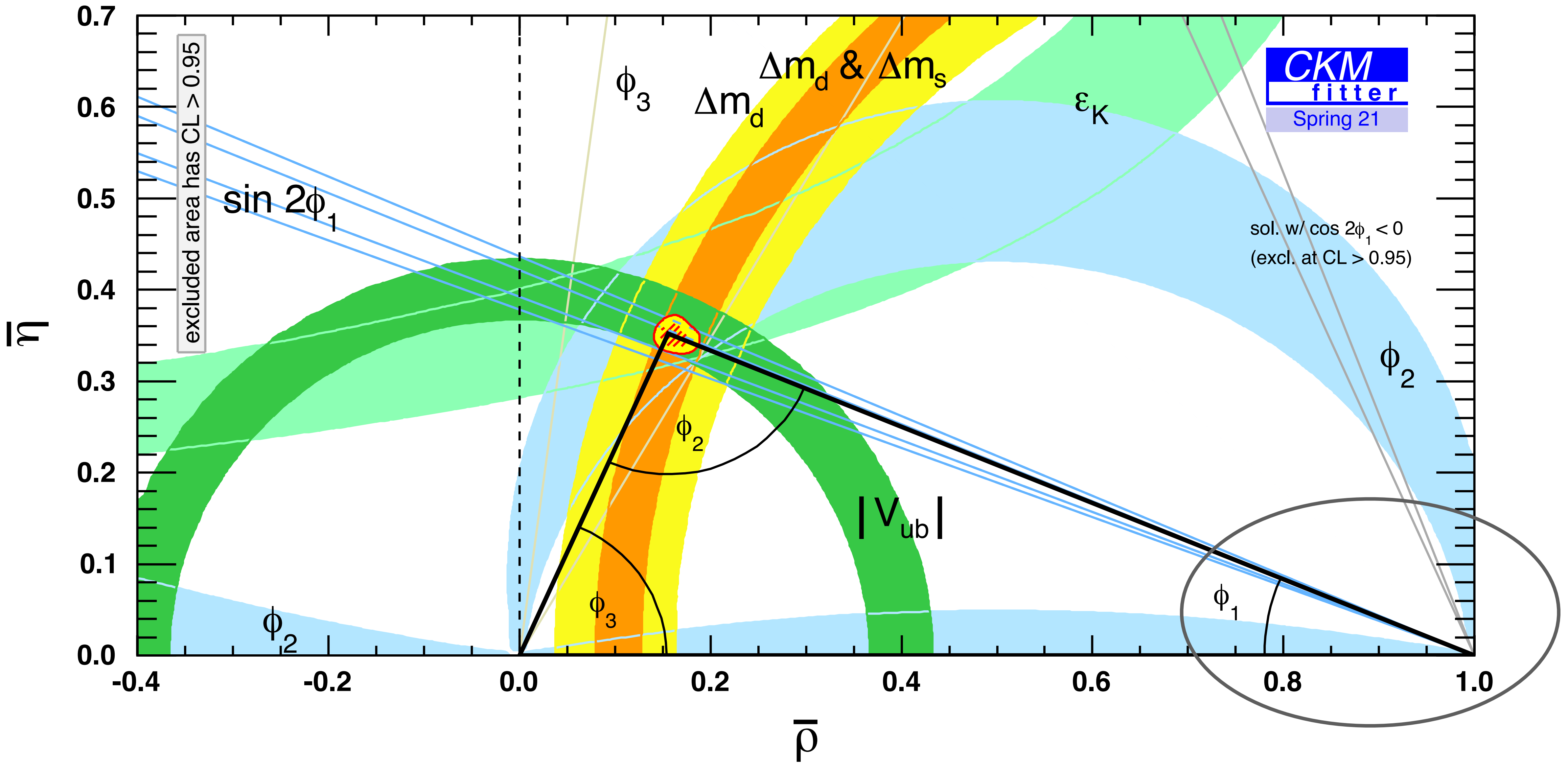
Belle II

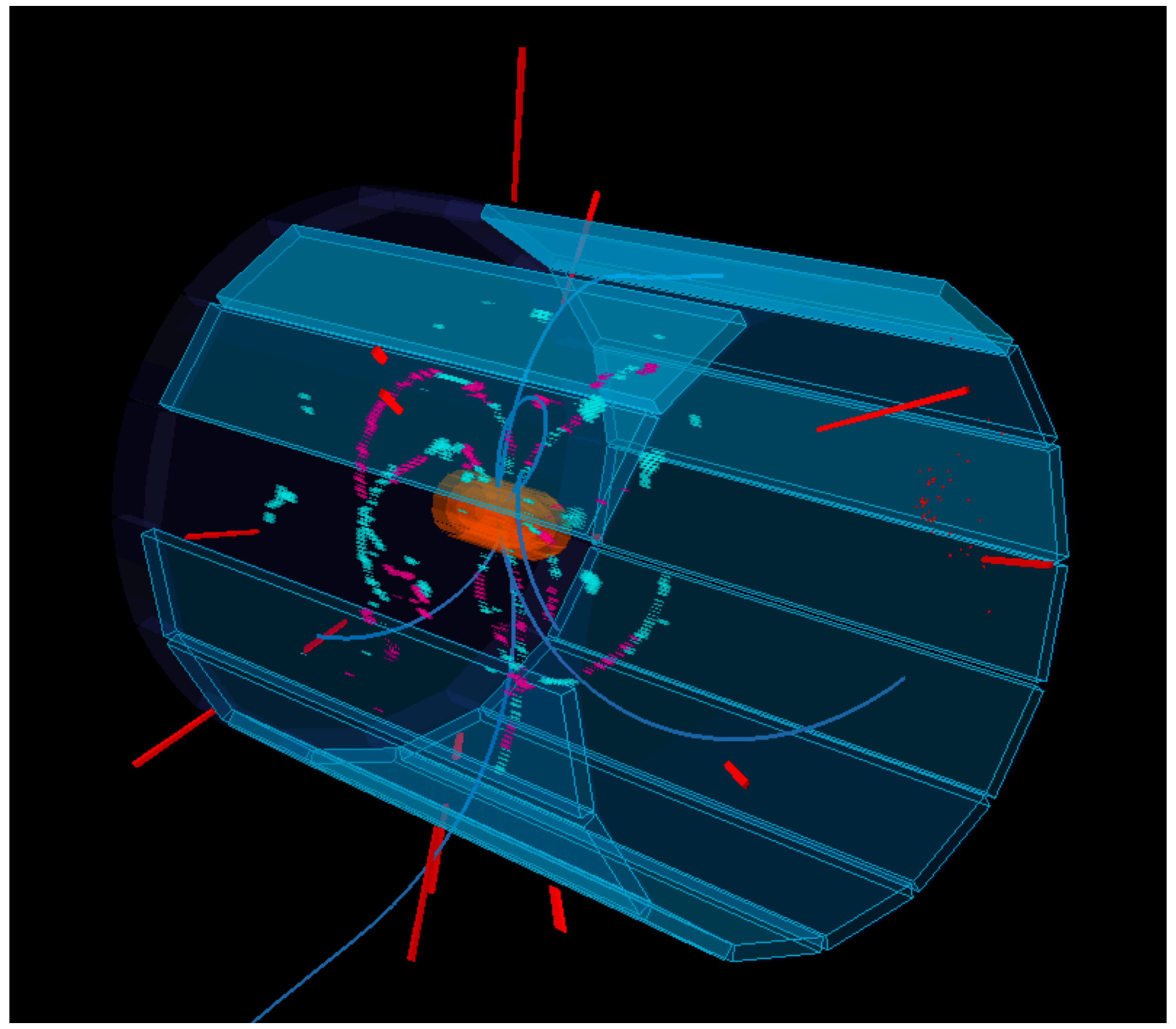
Introduction

- Measurements of sin2ϕ_1 in loop-suppressed $b \to s q\bar{q}$ transitions, probing interference with non-SM amplitudes
  - Clean theory prediction, only few % deviation from tree-level $b \to s c\bar{c}$
  - Many final states with neutrals, ideal at Belle II
- Rich program of charm-hadron lifetime measurements (D^0, D^+, Λ_c^+, Ω_c^0, D_s^+)
  - Test of non-perturbative QCD (e.g. lifetime hierarchy)
  - Probing absolute lifetimes with decay-time independent selection efficiency, unique to e^+e^- collider

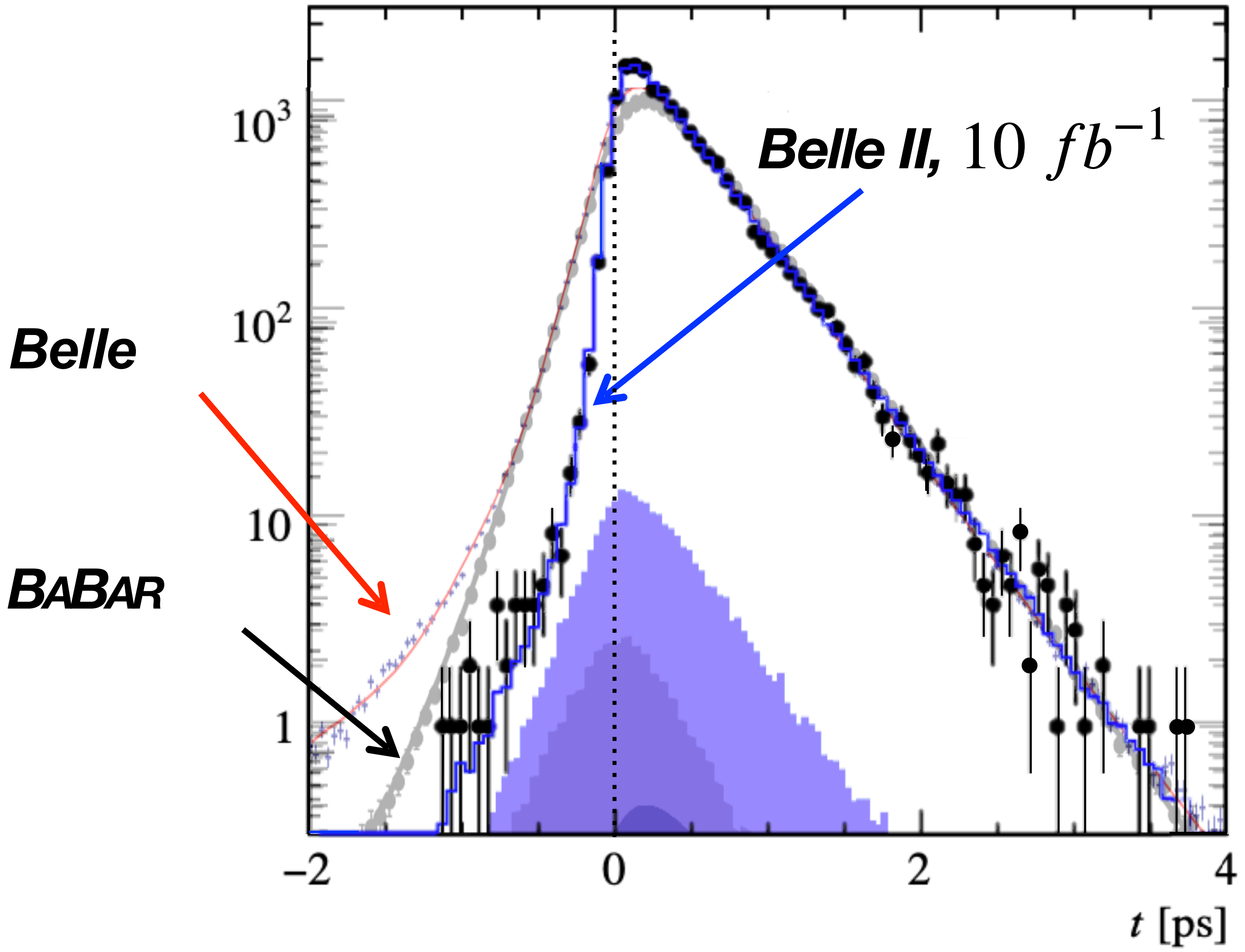


Belle II at SuperKEKB

- Asymmetric e+e- collisions at the SuperKEKB accelerator complex in Japan
  - Achieved world's highest instantaneous luminosity (4.7x10^{34} cm^{-2}s^{-1})
  - Collected 362 fb^{-1} at the Y(4S) in 2019-22, corresponding to 387M B$\overline{B}$ pairs
  - Additional 42.3 fb^{-1} off-resonance
- Almost brand new detector, especially important for time-dependent measurements
  - x2 better impact parameter resolution wrt Belle (radial/longitudinal =10/15 μm), thanks to pixel detector closer to interaction region
  - Efficient neutrals reconstruction (π^0, K_S) and charged K/π separation



e+e- collision

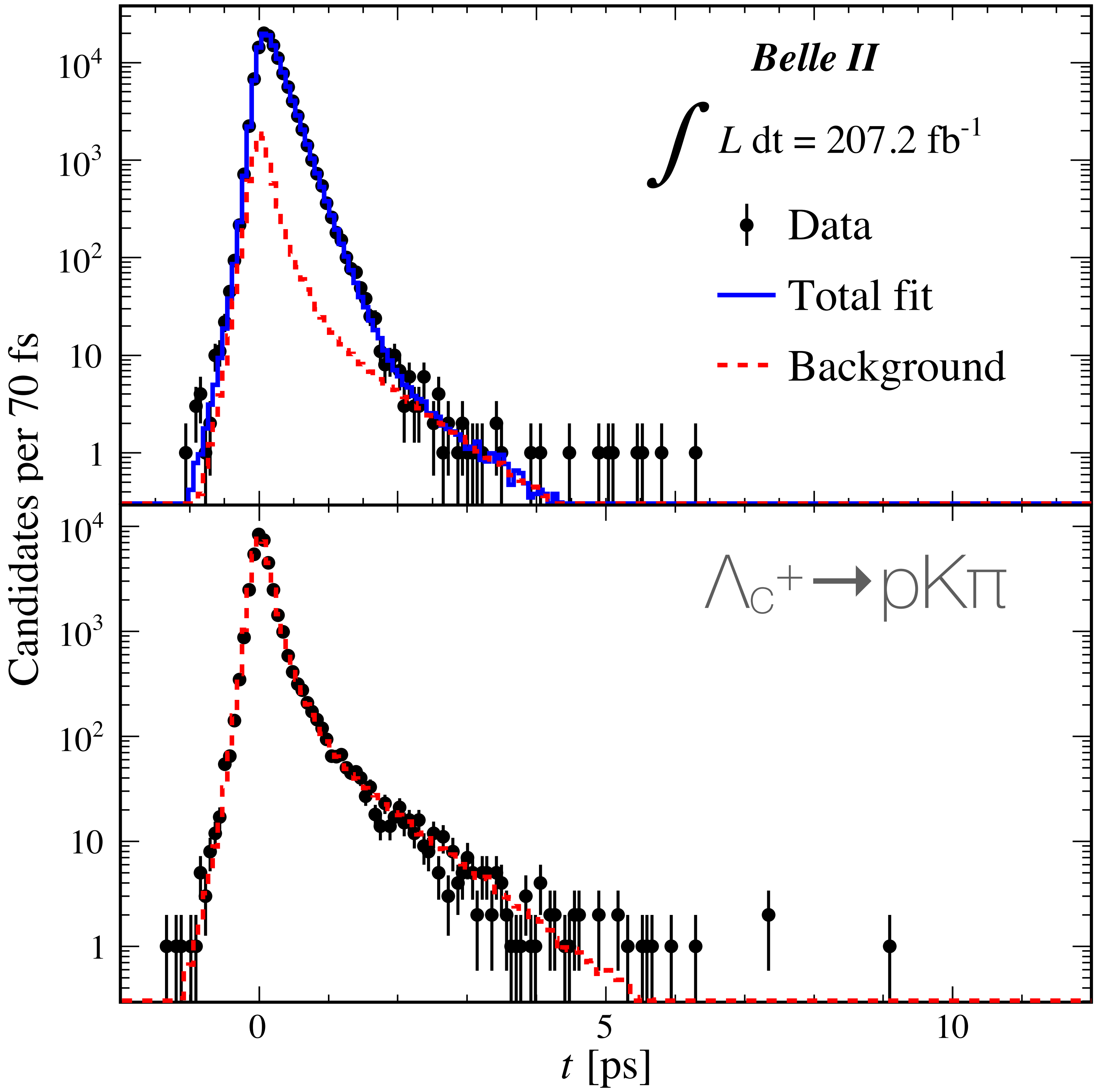


t<0: detector resolution

Charm baryon lifetimes

- Measurement of absolute lifetimes
  - Calibration of the position of the interaction region (~250 μm in z)
  - Distance between e^+e^- interaction point and decay vertex (~100 μm)
- Recent results on charmed baryons
  - Most precise measurement of the Λ_c^+ lifetime (better than WA)
  - Independent Ω_c^0 lifetime measurement, confirmed new lifetime hierarchy observed by LHCb

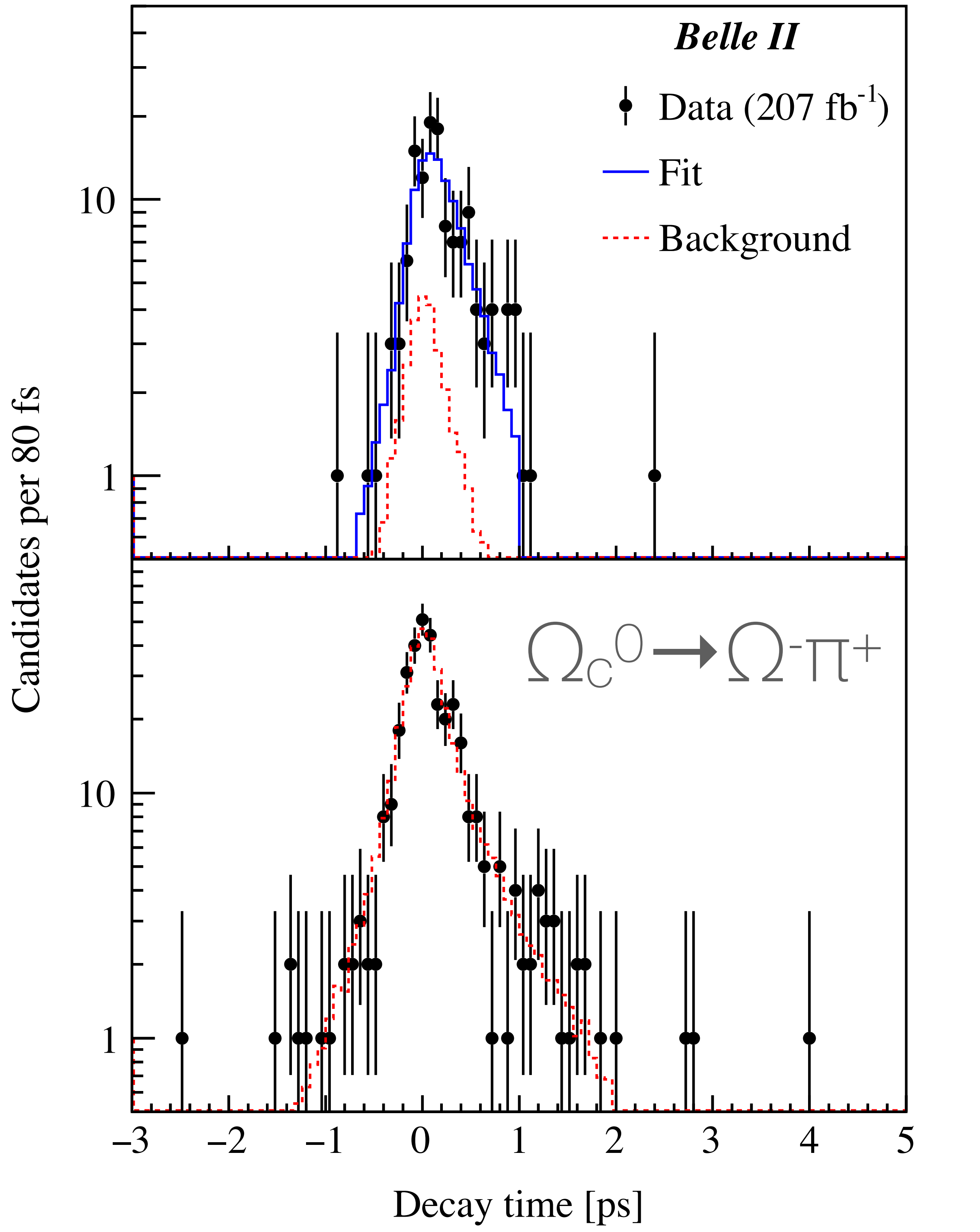
PRL130, 071802 (2023)



$$\tau(\Lambda_c^+) = 203.20 \pm 0.89 \pm 0.77 \text{ fs}$$

PDG: 201.5 ± 2.7 fs

PRD107, L031103 (2023)



$$\tau(\Omega_c^0) = 243 \pm 48 \pm 11 \text{ fs}$$

LHCb: 274.5 ± 12.4 fs

$$\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$$

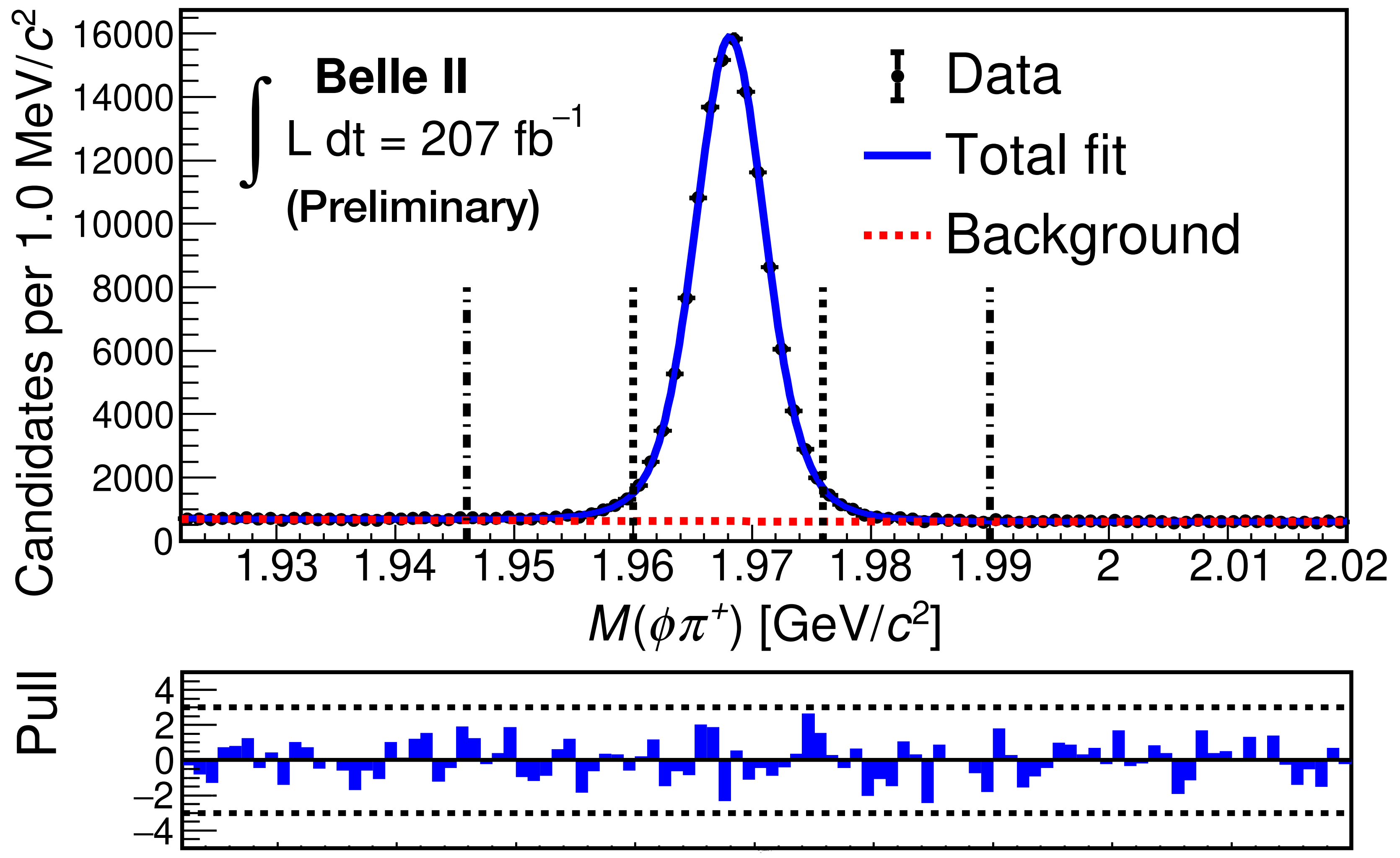
Precise D_s^+ lifetime

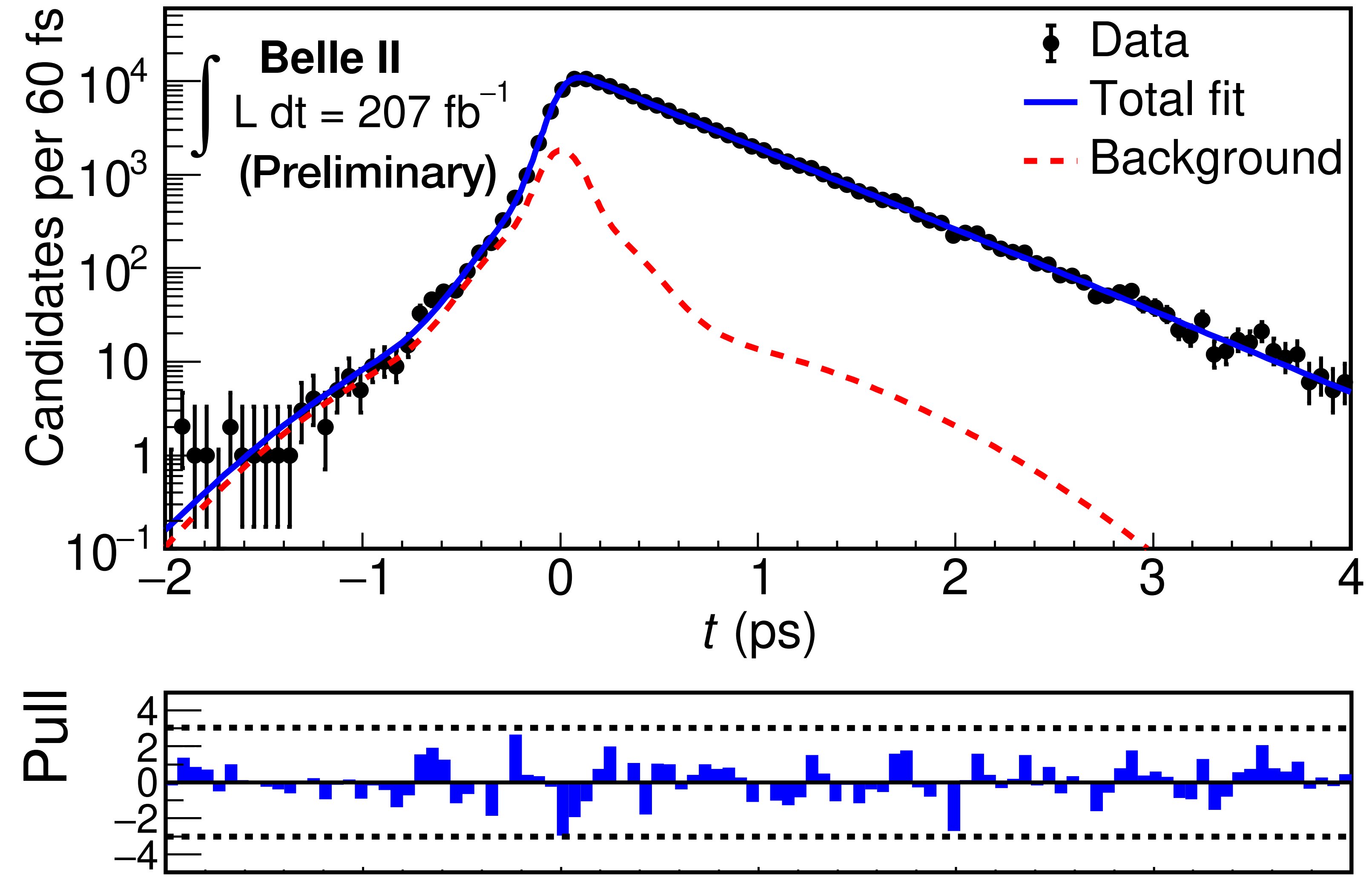
arxiv:2306.00365

- Reconstructing 116k $D_s^+ \rightarrow \phi\pi^+$ decays, using ~half of Belle II dataset
  - Secondary D_s^+ from B decays efficiently rejected with requirement on momentum
  - Background decay-time PDF modeled with events from the upper D_s^+ mass sideband
- Most precise D_s^+ lifetime measurement (~twice as precise as world average)
  - Leading systematic uncertainties from the resolution function and residual misalignment

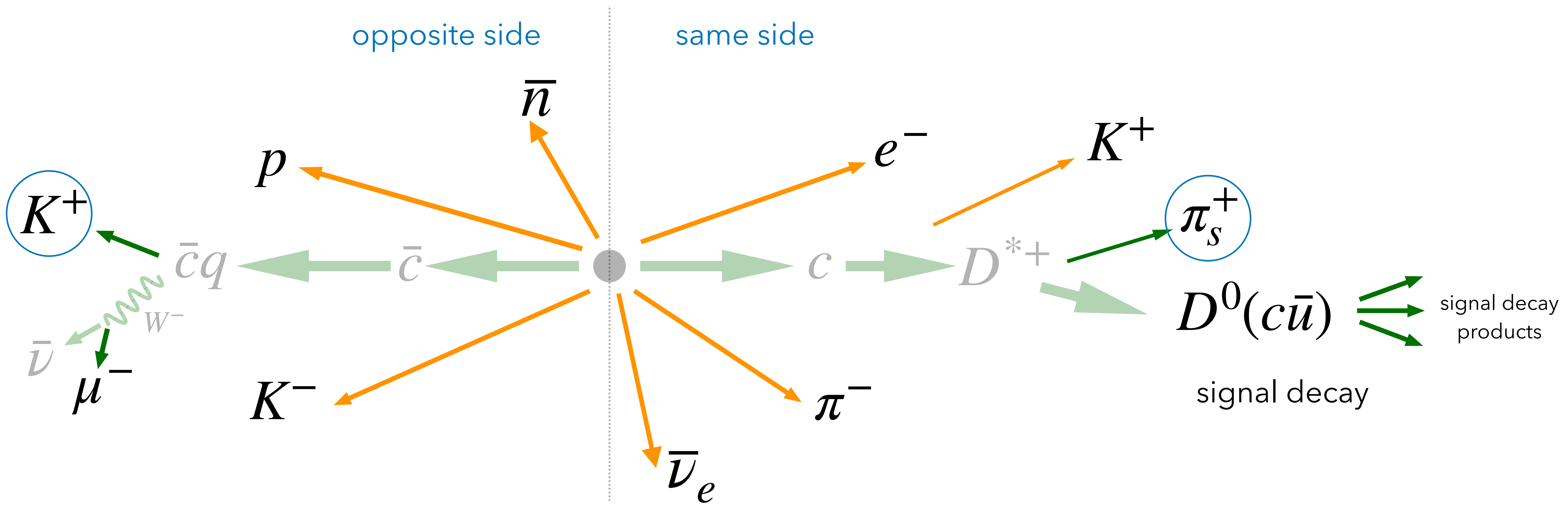
$$\tau_{D_s^+} = (498.7 \pm 1.7^{+1.1}_{-0.8})\mathrm{fs}$$

PDG: τ = 504±4 fs

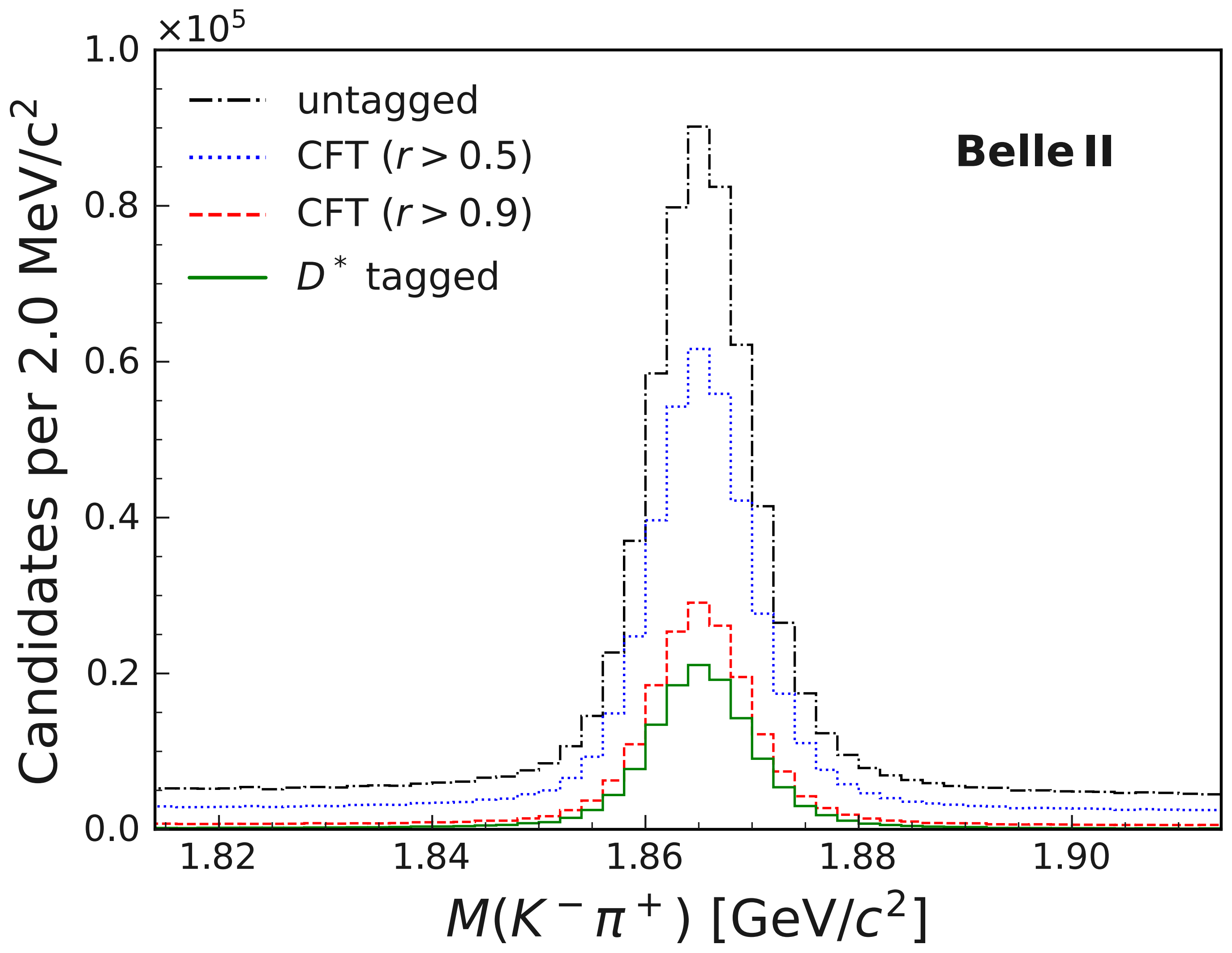




Charm flavor tagger

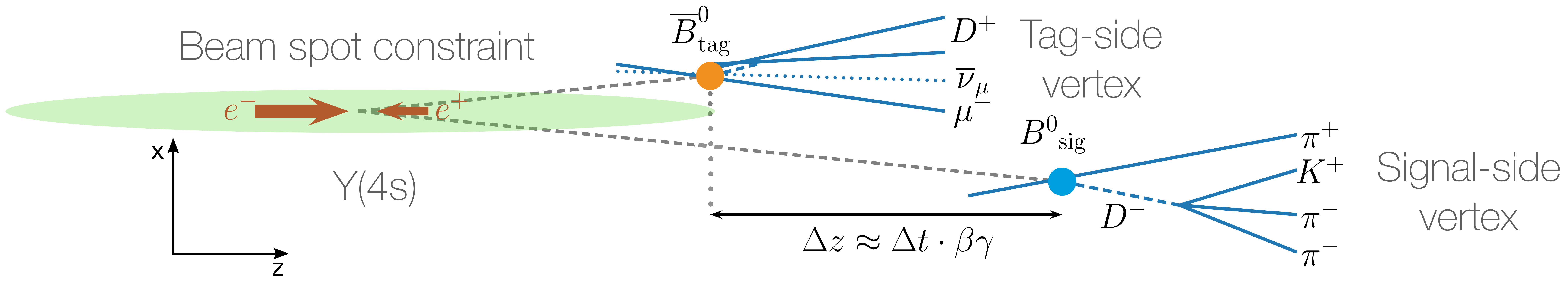


[Phys. Rev. D 107, 112010]



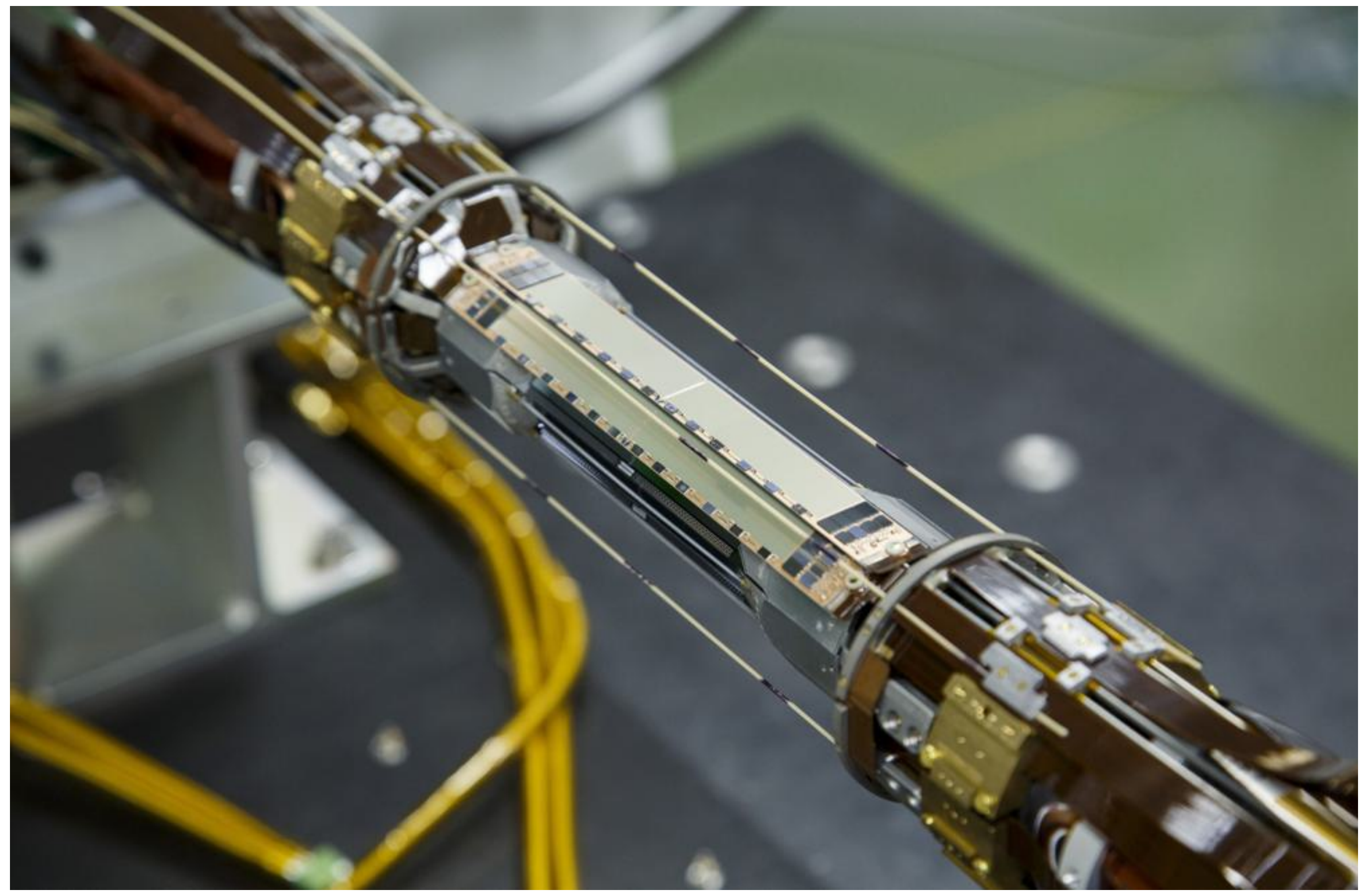
- Novel flavor-tagging algorithm recovering D^0 candidates not tagged by traditional approach of reconstructing the $D^{*+} \rightarrow D^0\pi^+$ decay chain
- Exploiting charm pair production and charge correlation between signal D flavor and the tracks in the rest of the event
- Effective tagging efficiency calibrated in data with flavor-specific decays, roughly doubling the size of tagged D^0 sample: ε_{eff} = 47.91±0.07 (stat) ±0.51 (syst) %

Proper-time difference



$$P(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left\{1 + q\left[S\sin(\Delta m_d \Delta t) + A\cos(\Delta m_d \Delta t)\right]\right\}, \qquad q = +1\,(B^0_{\text{tag}}),\ -1\,(\overline{B}^0_{\text{tag}})$$

- Measuring the time difference Δt of coherently produced B$\overline{\text{B}}$ pairs from the decay of a Y(4S), boosted along z
- Improved Δz resolution from pixel detector, in spite of lower boost
  - Belle: βγ=0.43, Δz≈200μm —> Belle II: βγ=0.29, Δz≈130μm
- Enhanced Δt resolution from the beam spot profile in combination with the new nano-beam scheme



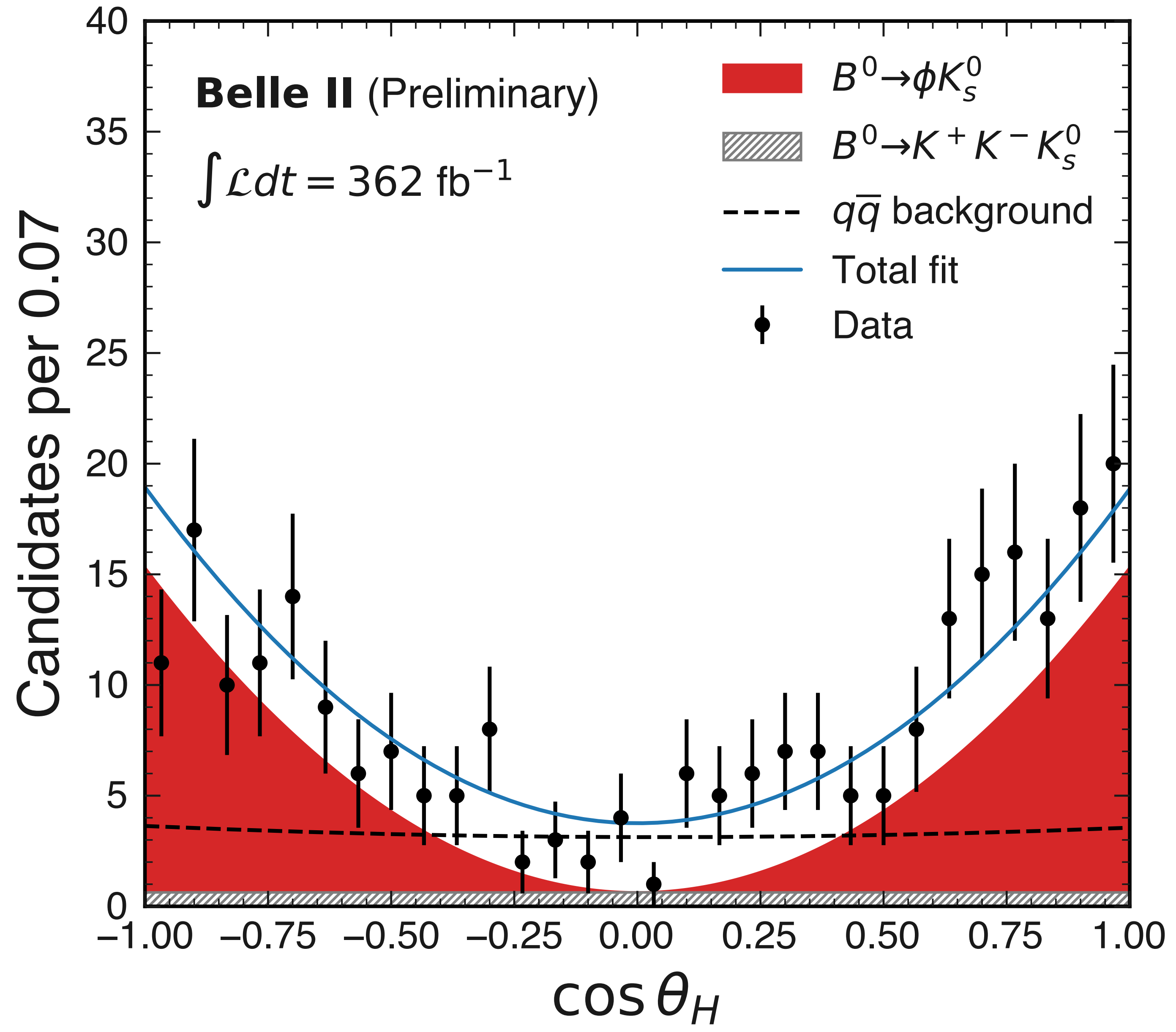
Pixel detector radius ≈ 1.4 cm

B→ϕK$_S$

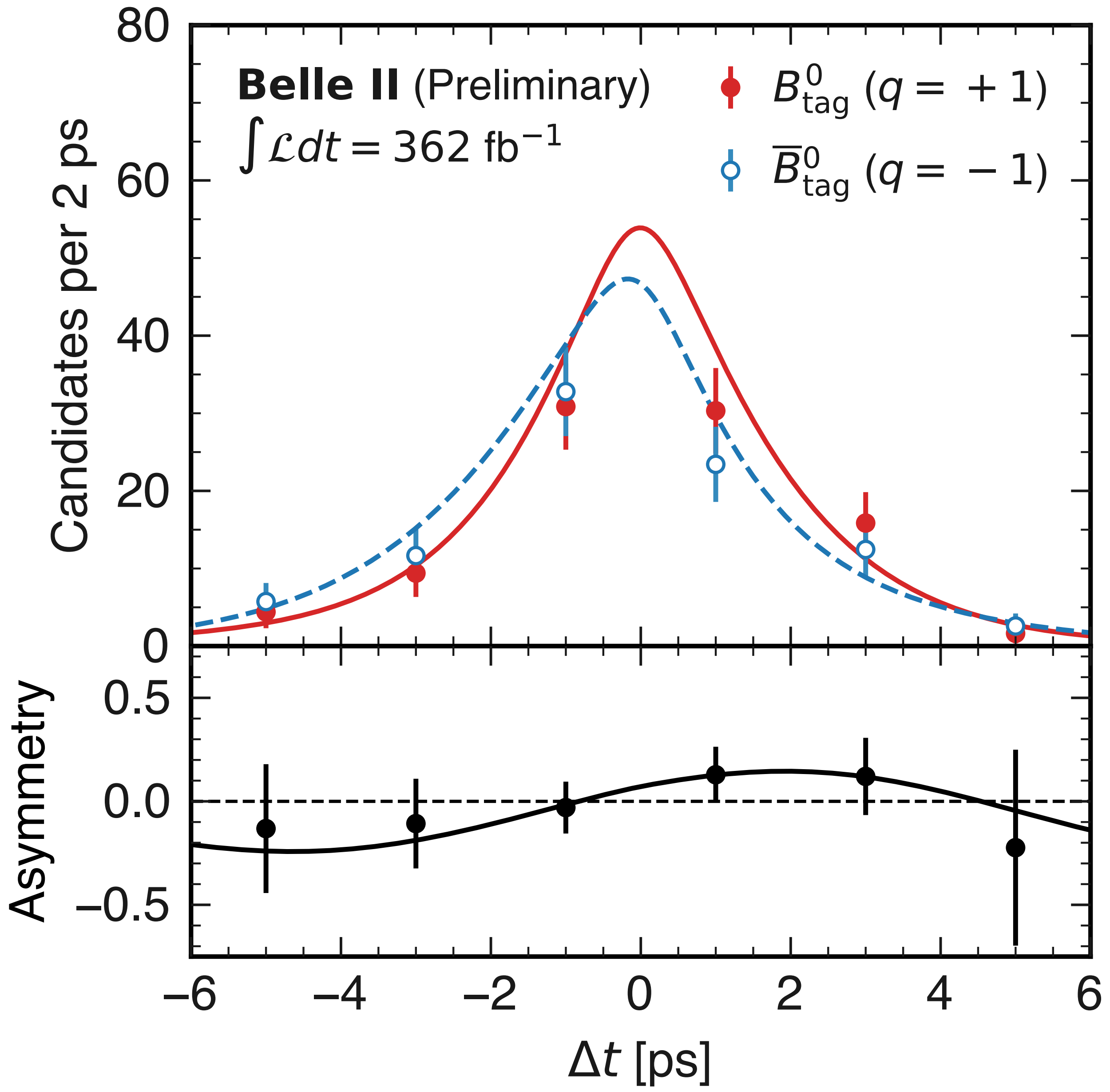
arxiv:2307.02802

- Sensitive to effective value of sin2ϕ$_1$ in b→ss$\bar{s}$ penguin transitions
  - Experimentally clean with good Δt resolution from 2 prompt tracks
  - Main challenge: dilution from non-resonant decays with opposite CP
- Quasi-two body analysis of resonant B→ϕK$_S$ decays
  - Non-resonant B→K$^+$K$^-$K$_S$ disentangled in cosθ$_H$
  - Effect of neglecting interference estimated with inputs from previous Dalitz measurement [PRD 82, 073011]

Cosine of the helicity angle



Proper-time difference



162±17 B→ φ K$_S$ signal events with 387M B$\bar{B}$ pairs

$$A_{CP} = 0.31 \pm 0.20 \pm 0.05$$
$$S_{CP} = 0.54 \pm 0.26^{+0.06}_{-0.08}$$

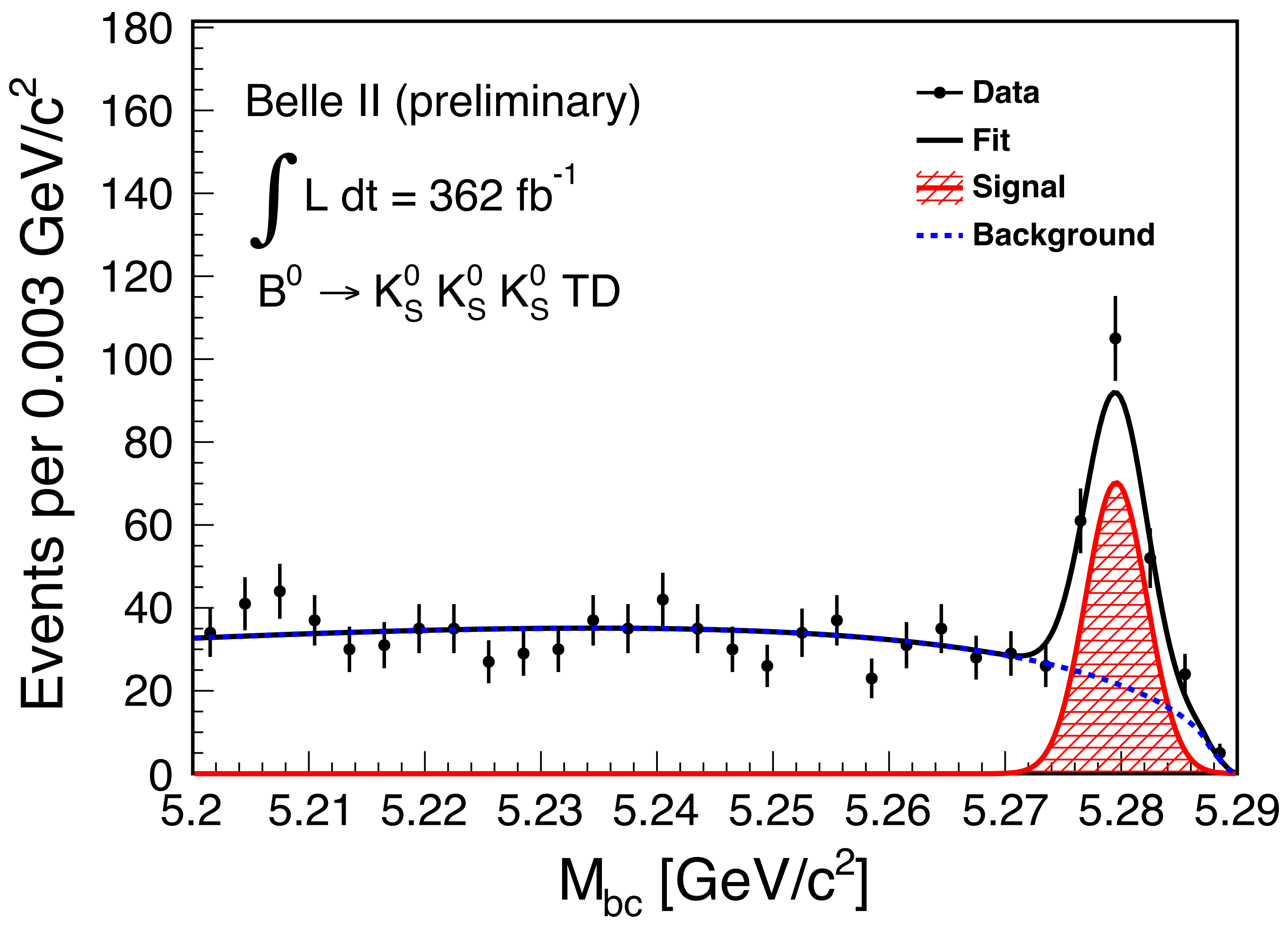
Similar precision on ACP as previous determinations

HFLAV: S = 0.74$^{+0.11}_{-0.13}$, A = -0.01±0.14

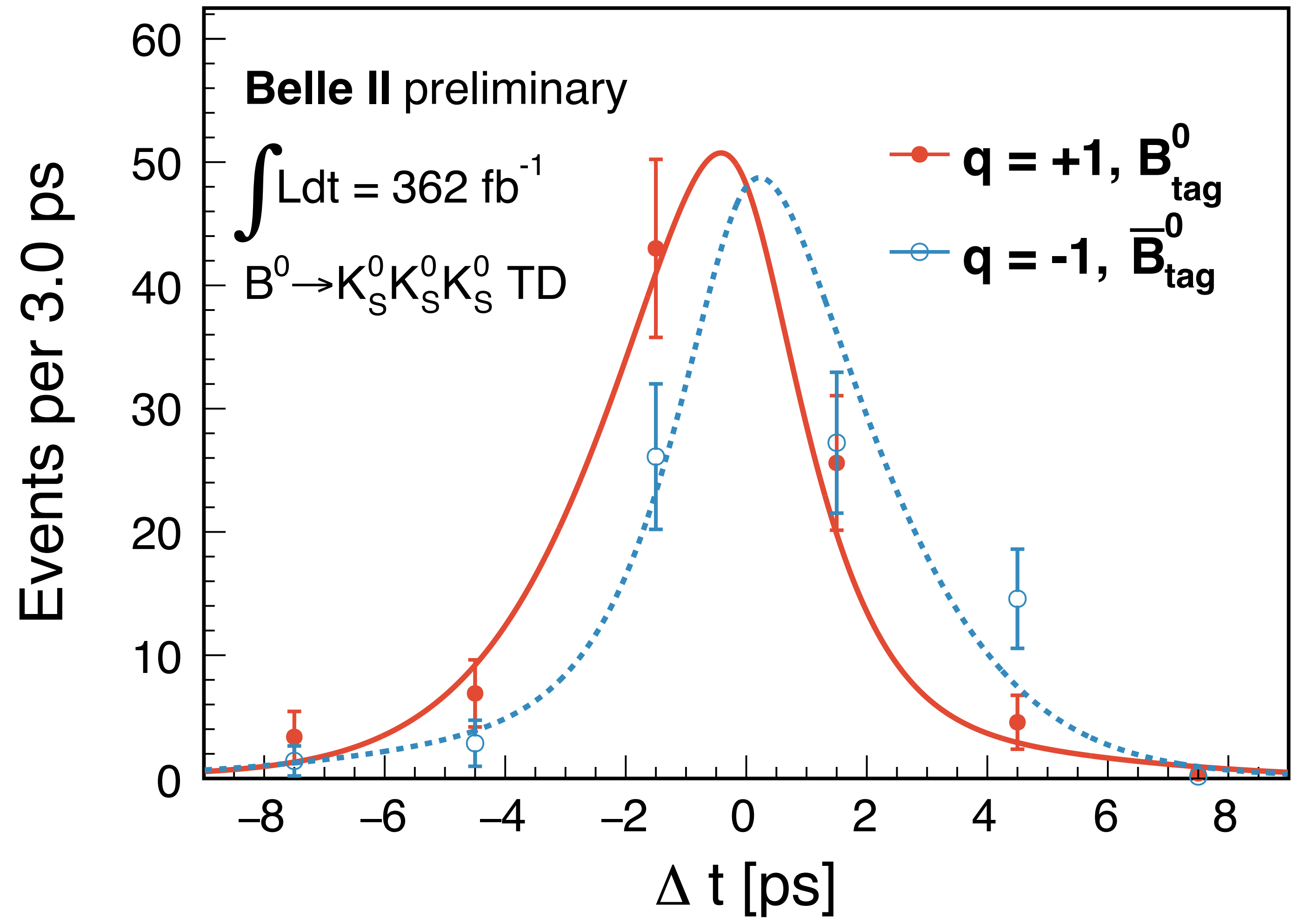
B→$K_S K_S K_S$

- Same underlying quark transition as B→ϕK_S, w/o contributions from opposite-CP backgrounds
- Main challenge: no prompt tracks
  - Vertex reconstruction relies on the K_S trajectories and profile of the interaction point
- Dataset divided into events with (TD) and without (TI) vertex information
  - TD events used in the Δt fit for the determination of A_{CP} and S_{CP}
  - TI events used only to constrain A_{CP}

Beam-constrained mass



Proper-time difference



158^{+14}_{-13} (TD) + 62±9 (TI) B→$K_S K_S K_S$ signal events with 387M $B\bar{B}$ pairs

$$A_{CP} = 0.07^{+0.15}_{-0.20} \pm 0.02$$
$$S_{CP} = -1.37^{+0.35}_{-0.45} \pm 0.03$$

Similar precision on ACP as previous determinations

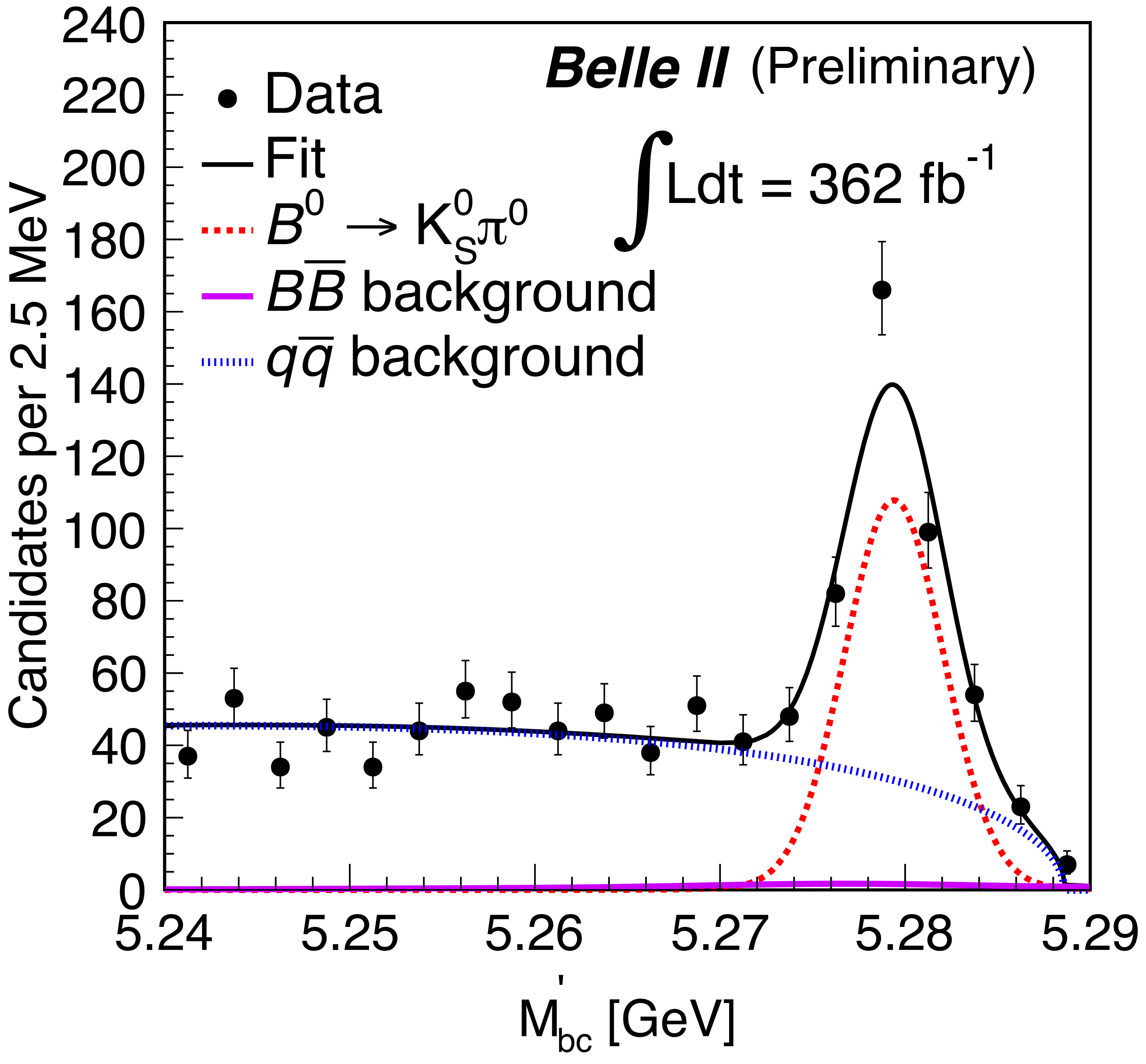
HFLAV: S = -0.83±0.17, A = 0.15±0.12

B→$K_S\pi^0$

arxiv:2305.07555

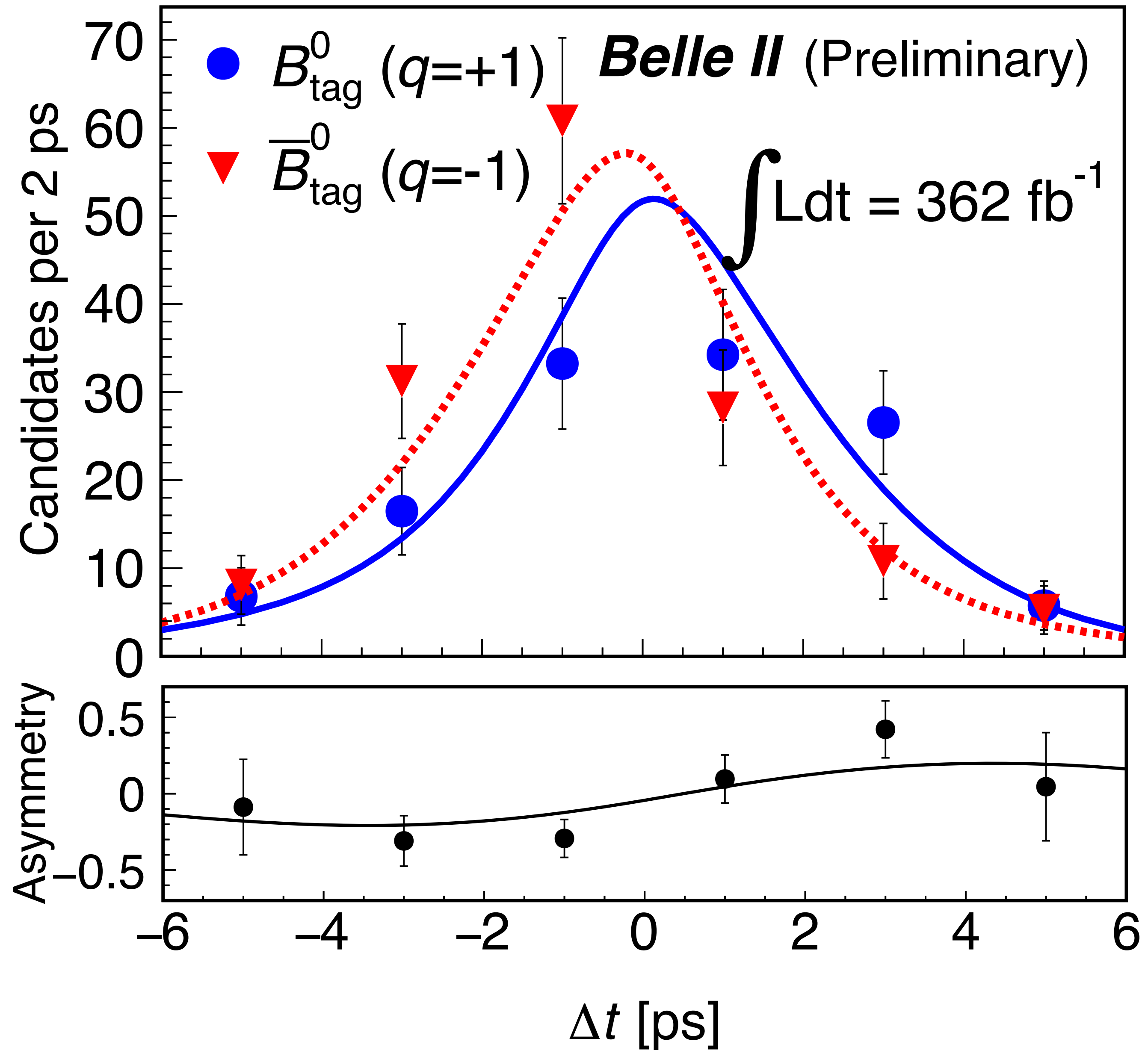
- Sensitive to effective value of sin2ϕ_1 in b→s$d\bar{d}$ and limiting the precision of the isospin sum-rule in B→hh (see Xiaodong's talk)
- Requires excellent capabilities with neutrals, unique to Belle II
  - K_S reconstruction & vertexing
  - High purity & efficient π^0 selection
- Validated on B→J/ψK_S events reconstructed w/o J/ψ vertex
- Competitive with world's best results using much less luminosity

Beam-constrained mass



415^{+26}_{-25} B→$K_S\pi^0$ signal events with 387M $B\bar{B}$ pairs

Proper-time difference

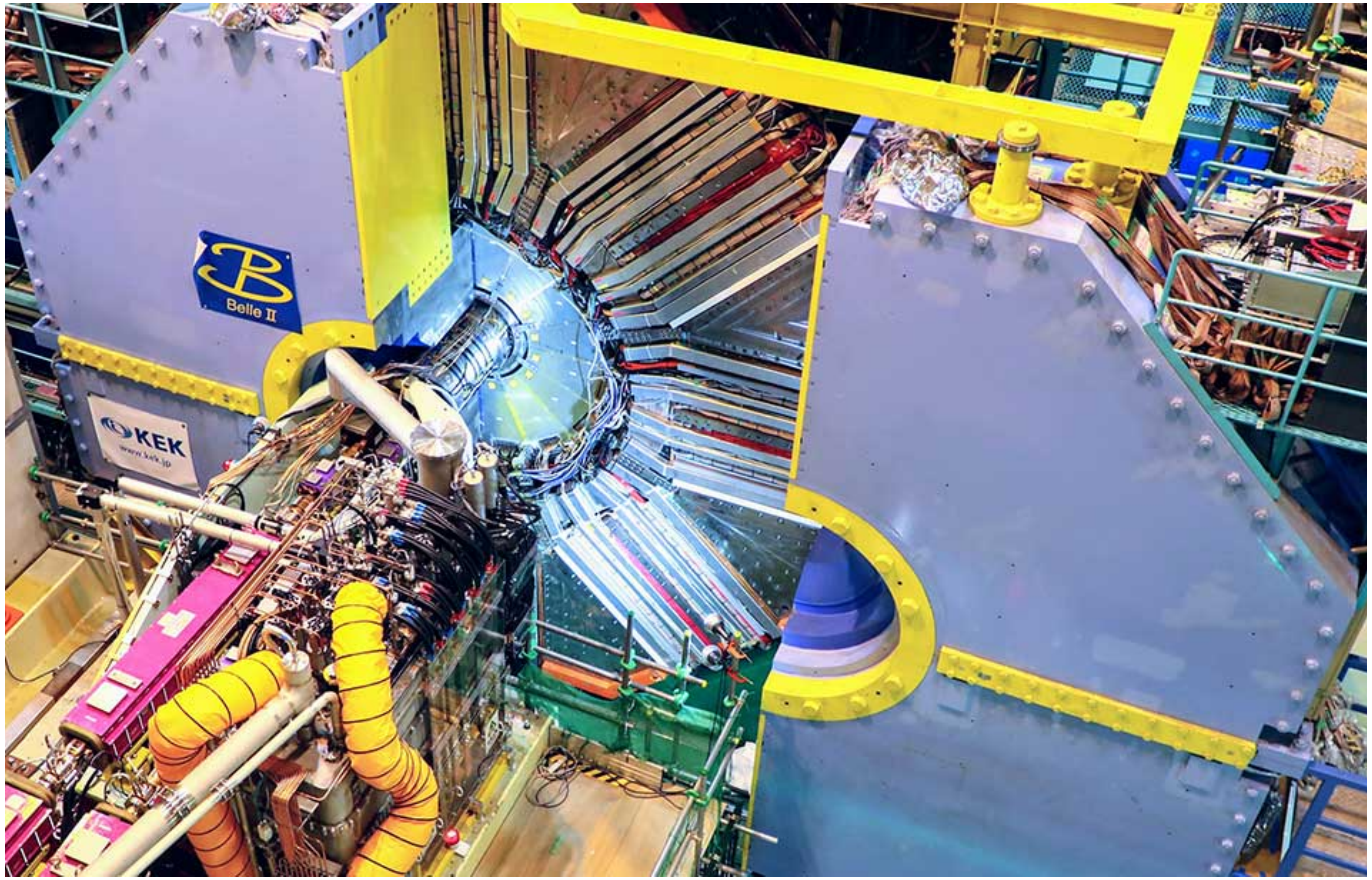


$$A_{CP} = 0.04 \pm 0.15 \pm 0.05$$
$$S_{CP} = 0.75^{+0.20}_{-0.23} \pm 0.04$$

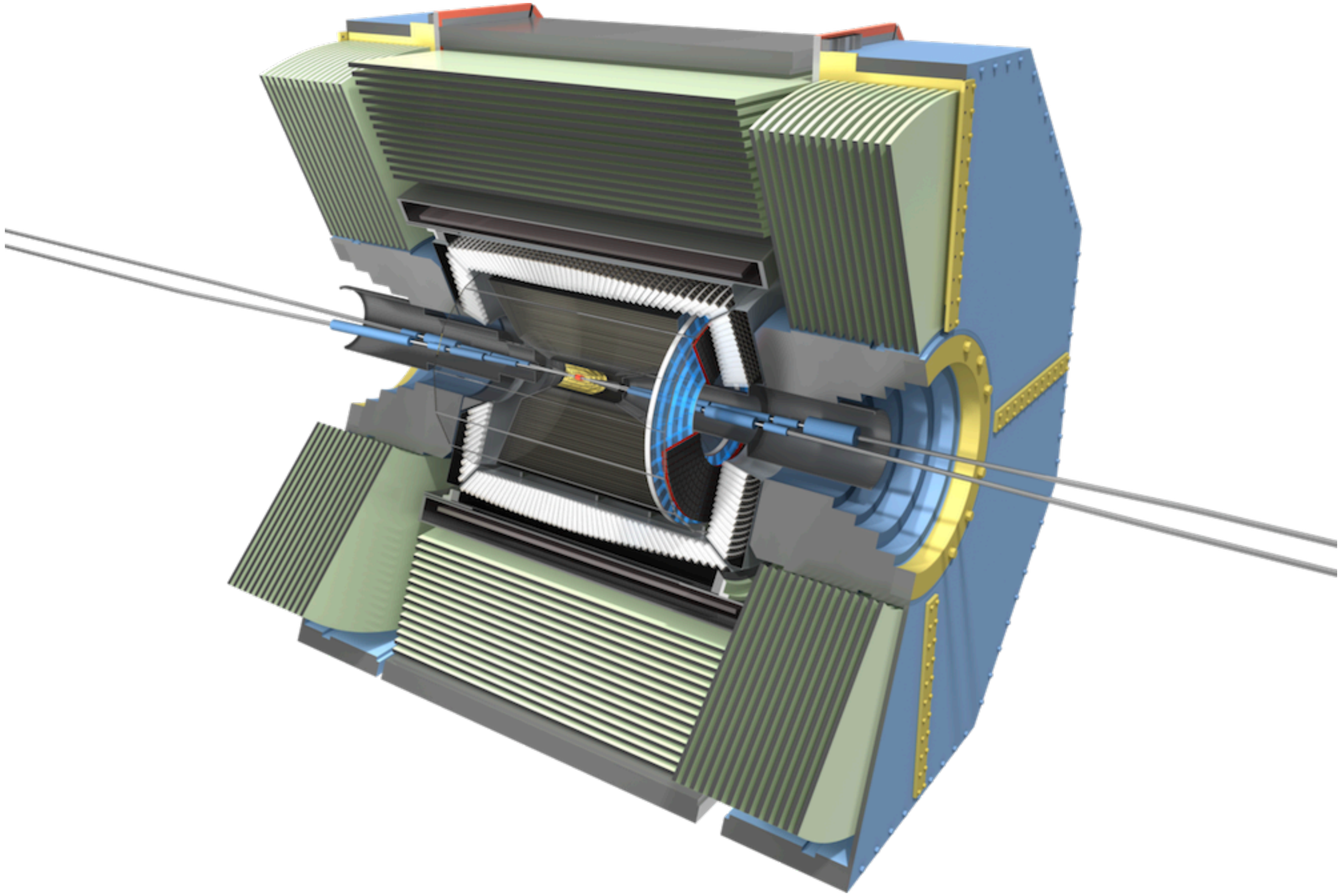
HFLAV: S = 0.57±0.17, A = -0.01±0.10

Summary

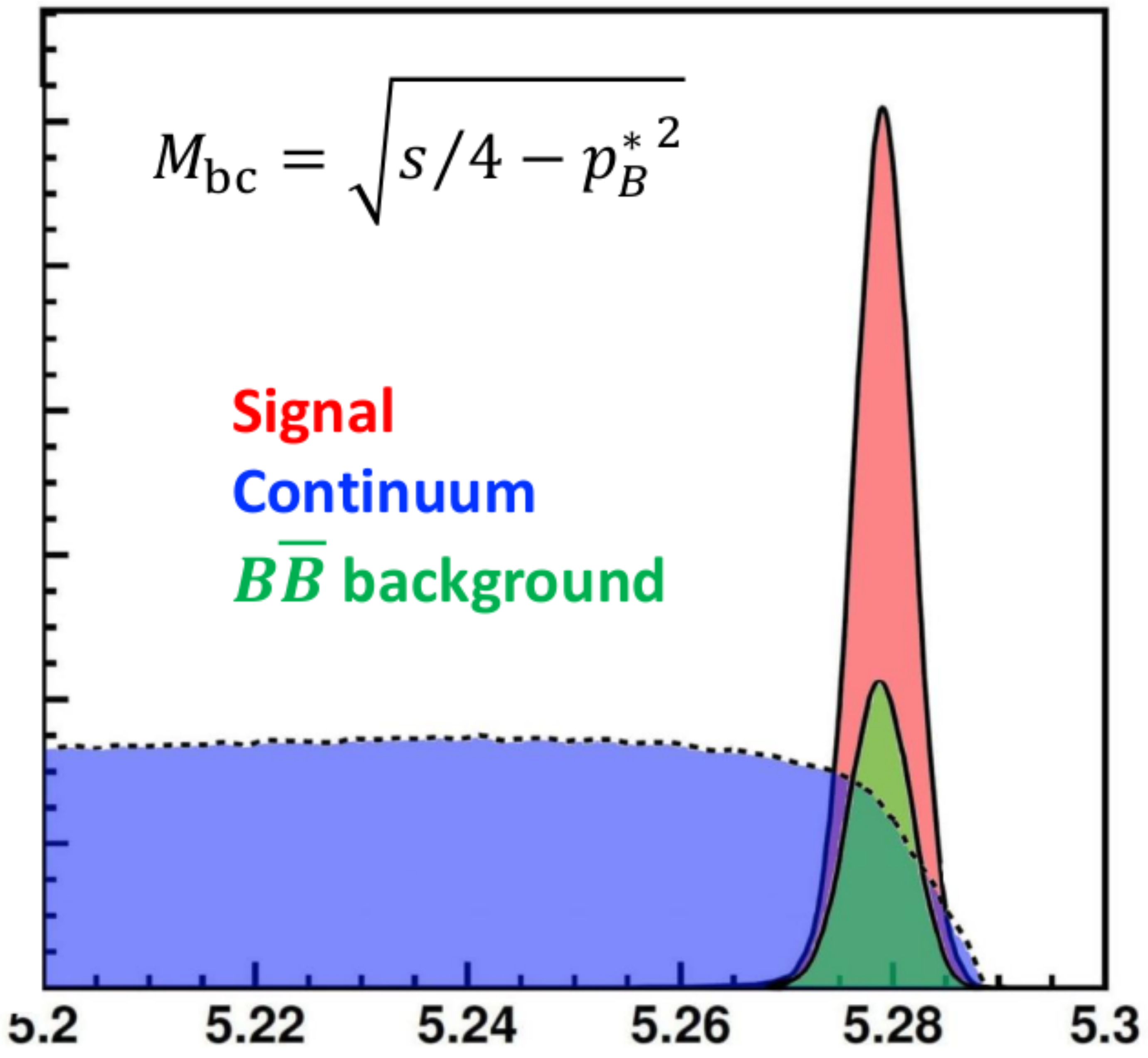
- Continuing effort in charm physics
  - World's leading measurements of charm-hadron lifetimes
  - Expanding effective dataset size with novel tagging algorithms
- Several new results on time-dependent CP violation with penguins
  - Essential to probe generic BSM physics in loops
  - Precision on several observables already on par with world's best and mostly unique to Belle II



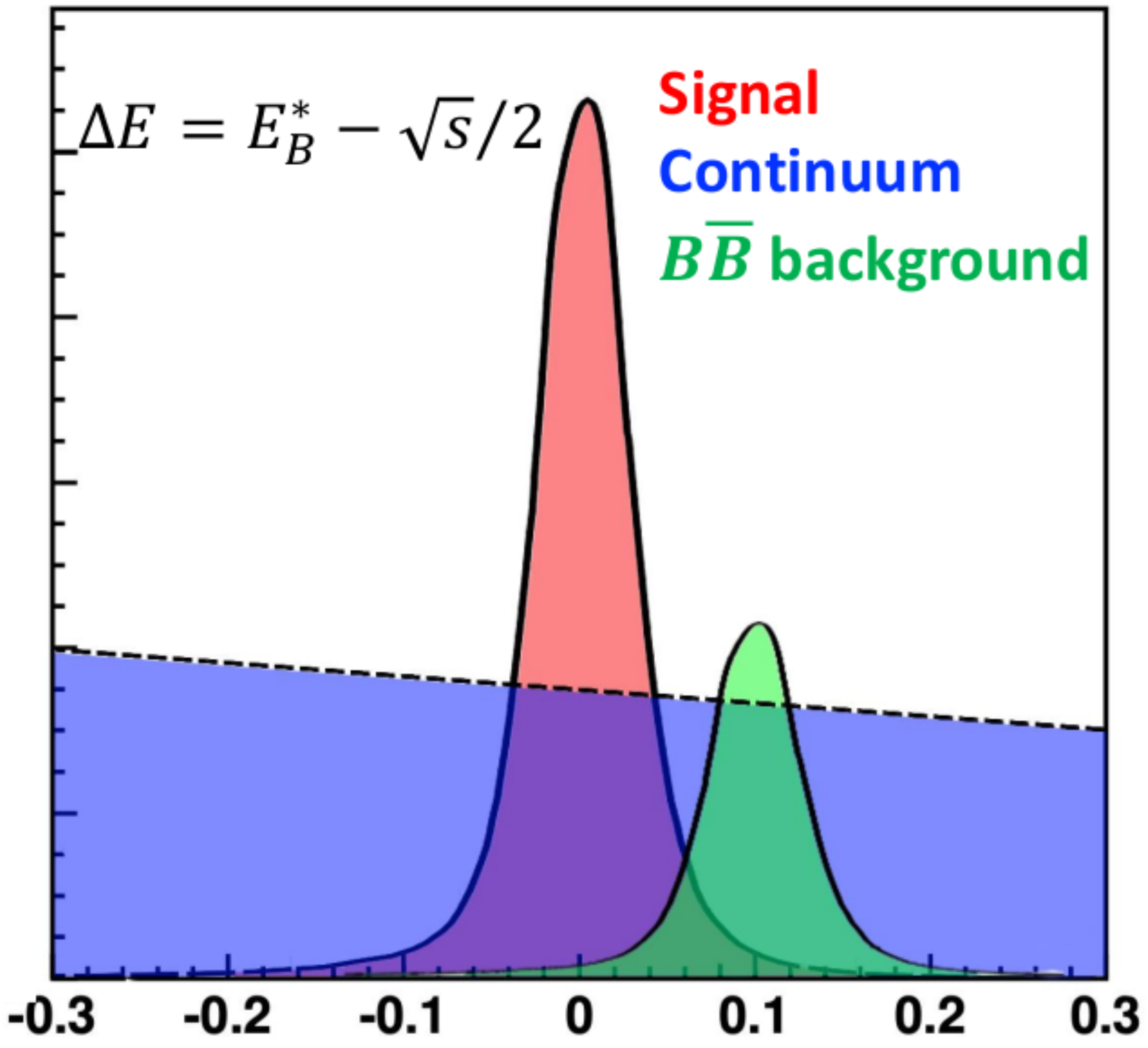
Backup



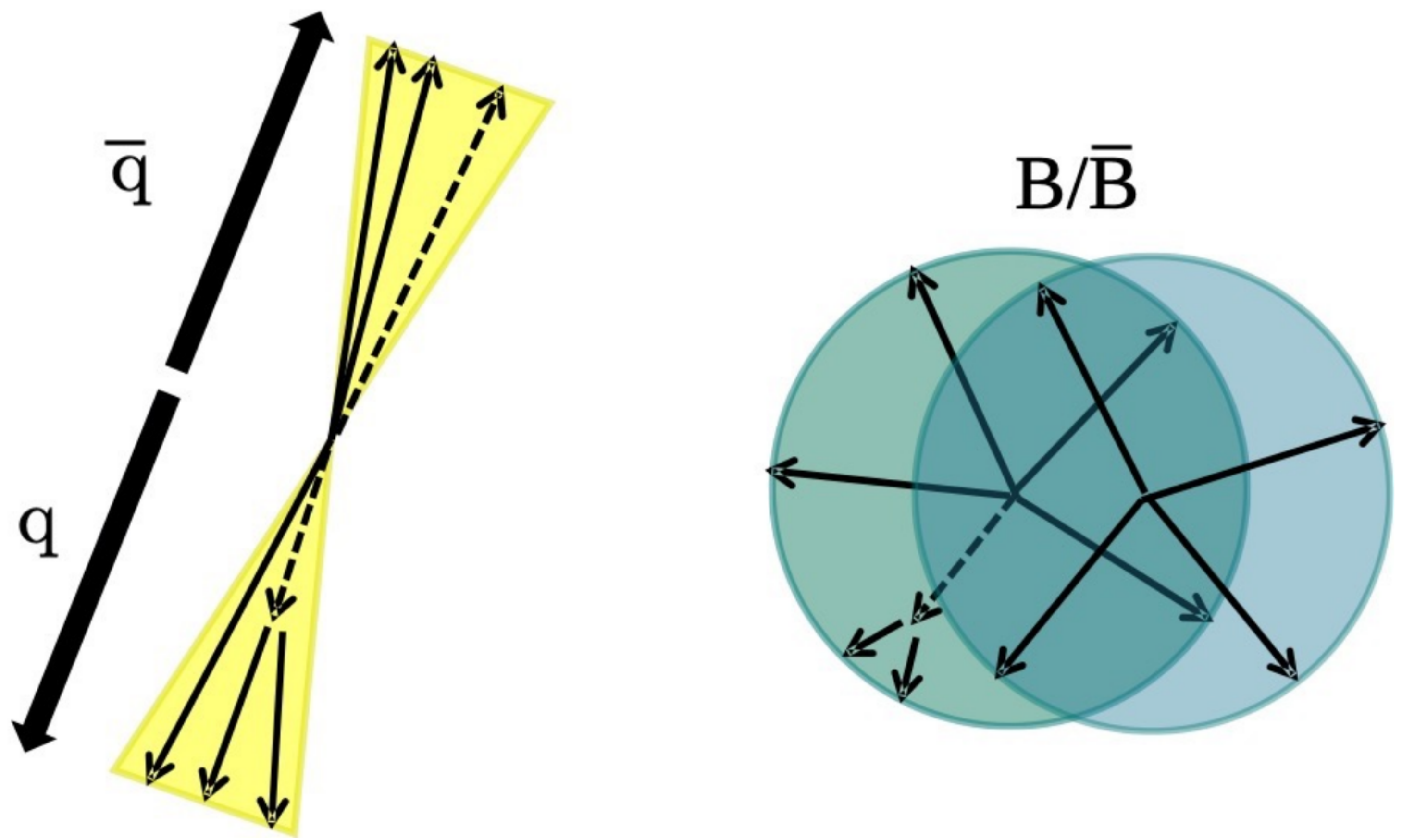
B-factory 101



Beam-constrained mass [GeV/c^2]

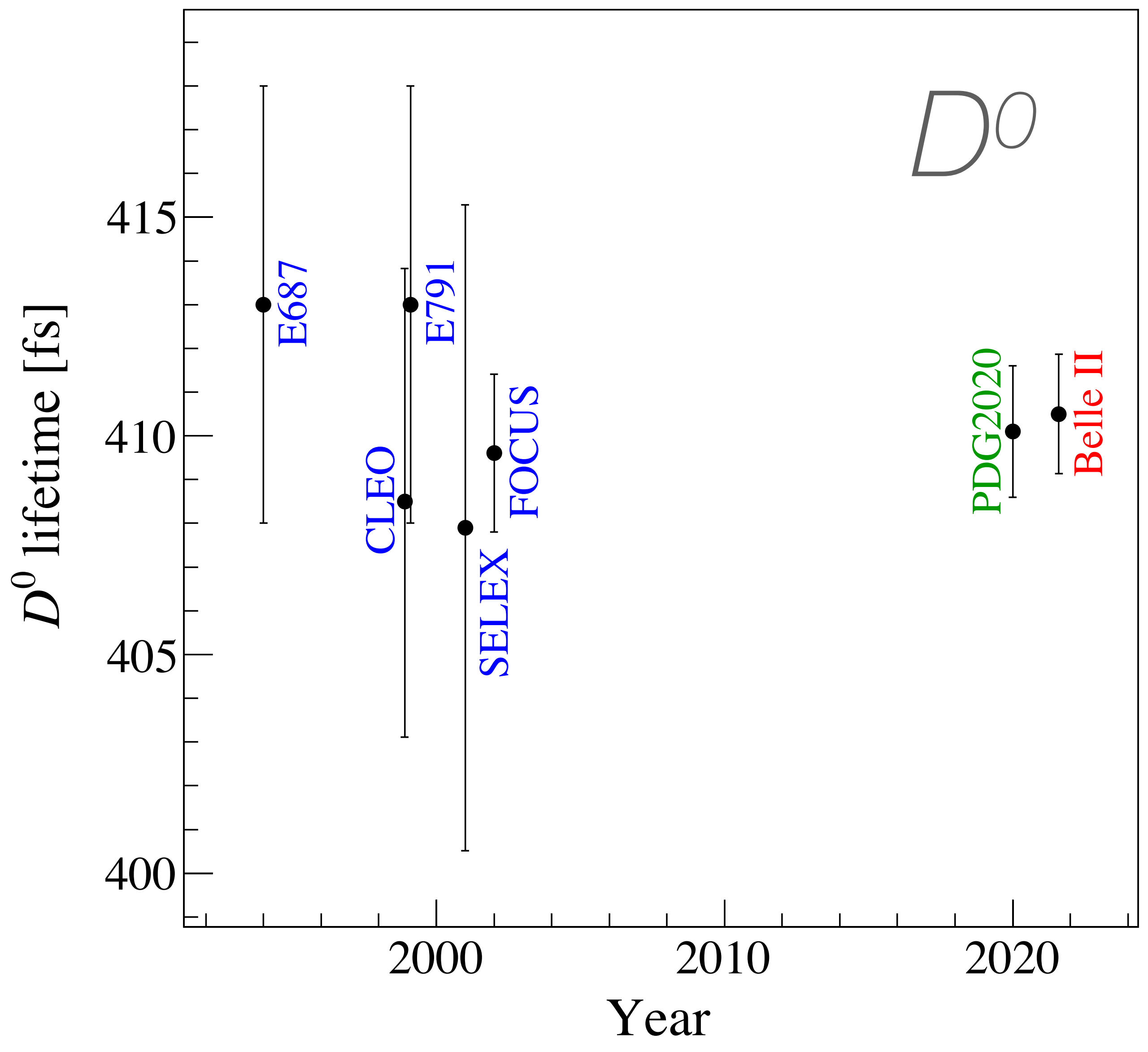


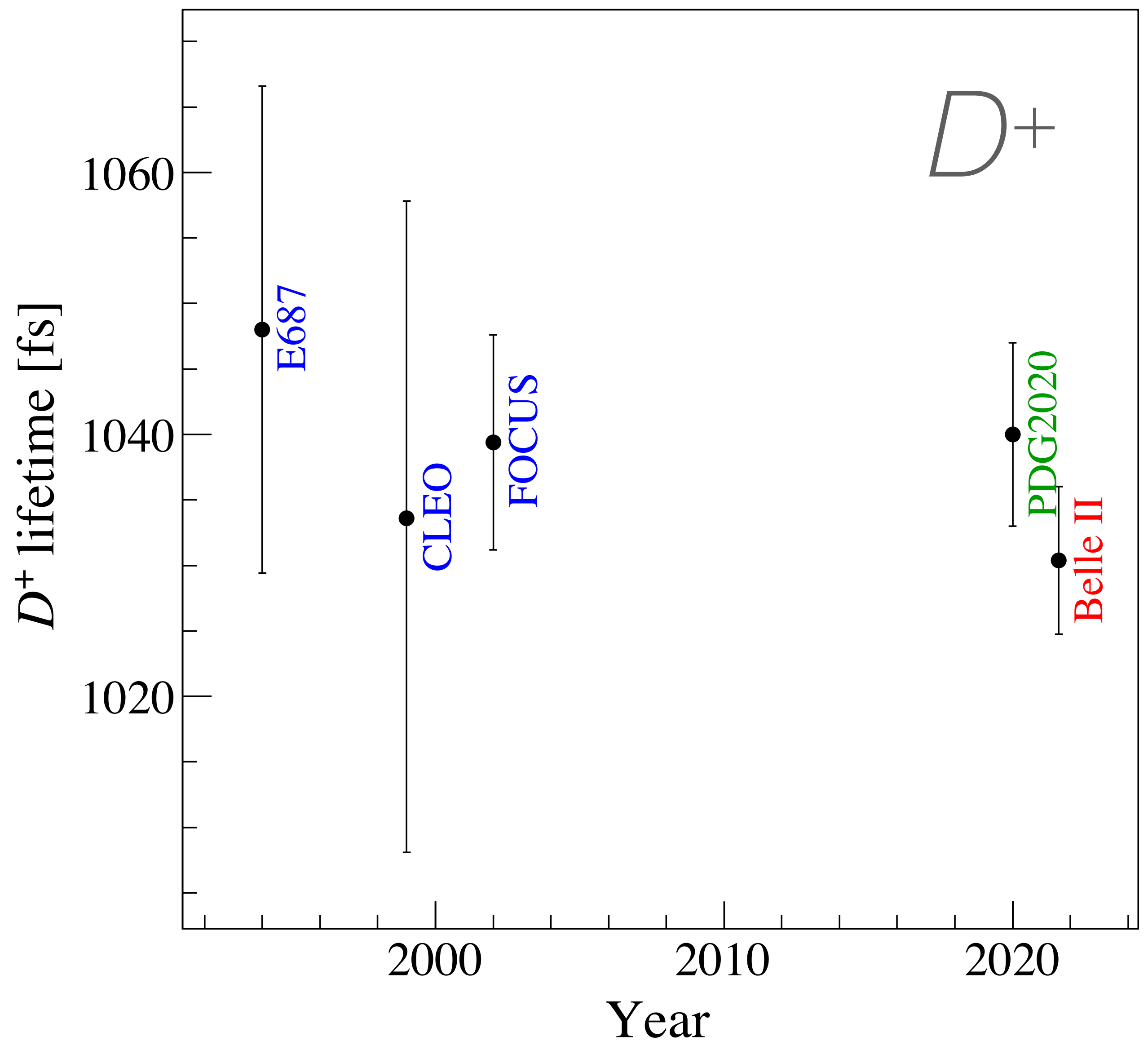
Energy difference [GeV]



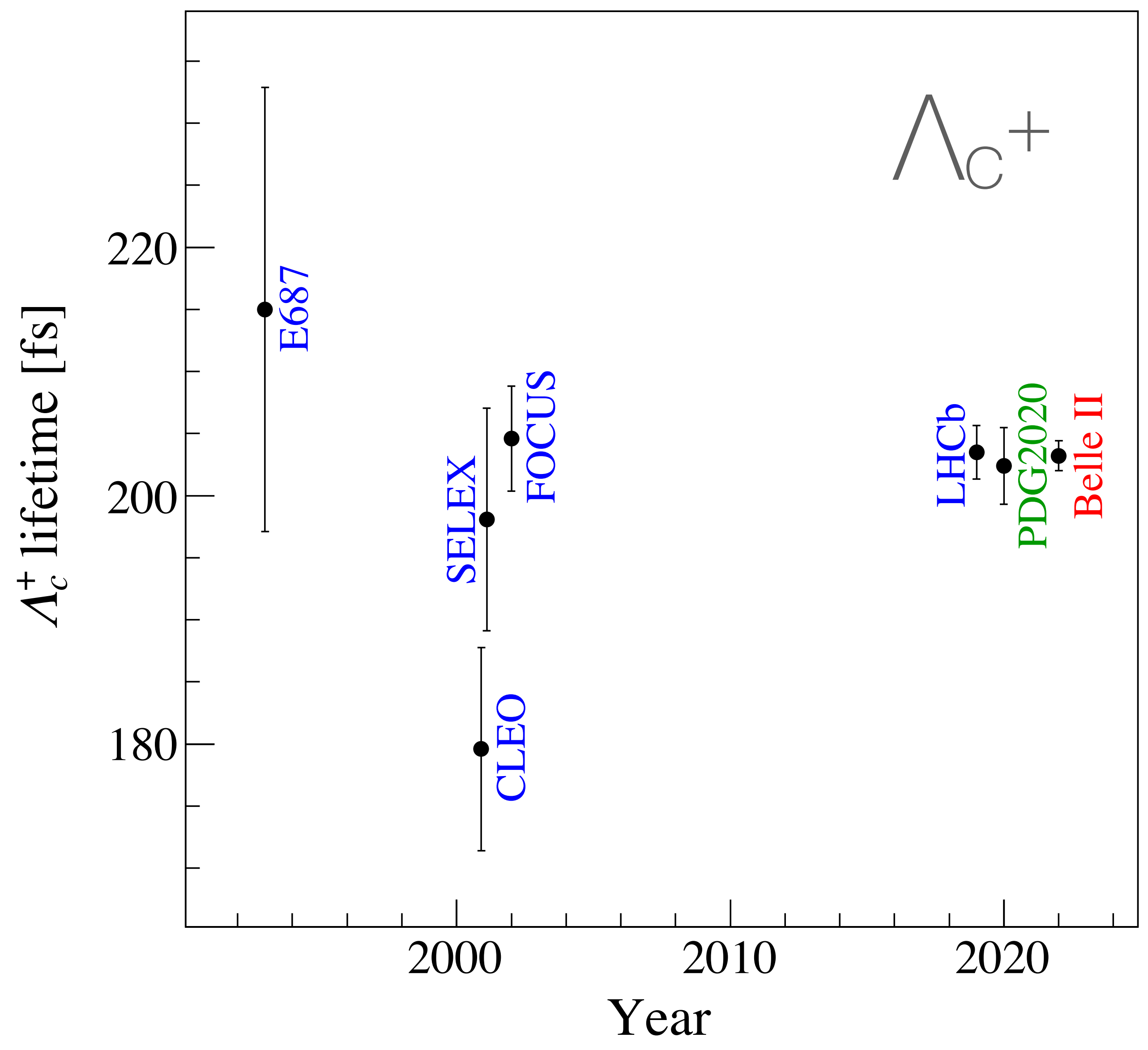
Event shape

PRL127, 211801 (2021)

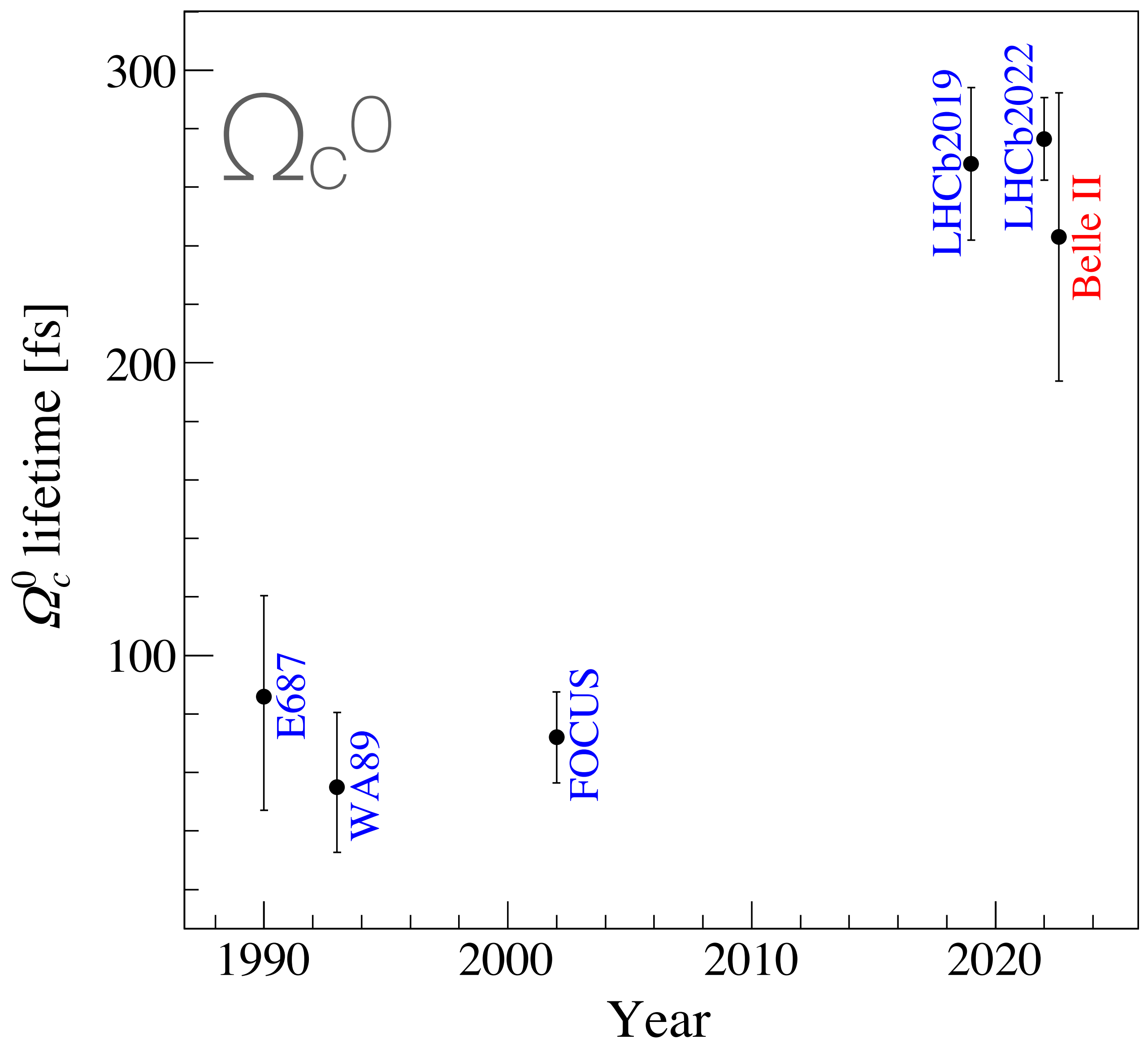




PRL130, 071802 (2023)



PRD107, L031103 (2023)



$\Lambda_c^+ \to pK\pi$

TABLE I. Systematic uncertainties on the Λ_c^+ lifetime.

Source	Uncertainty (fs)
Ξ_c contamination	0.34
Resolution model	0.46
Non-Ξ_c backgrounds	0.20
Detector alignment	0.46
Momentum scale	0.09
Total	0.77

$\Omega_c^0 \to \Omega^- \pi^+$

TABLE I. Systematic uncertainties.

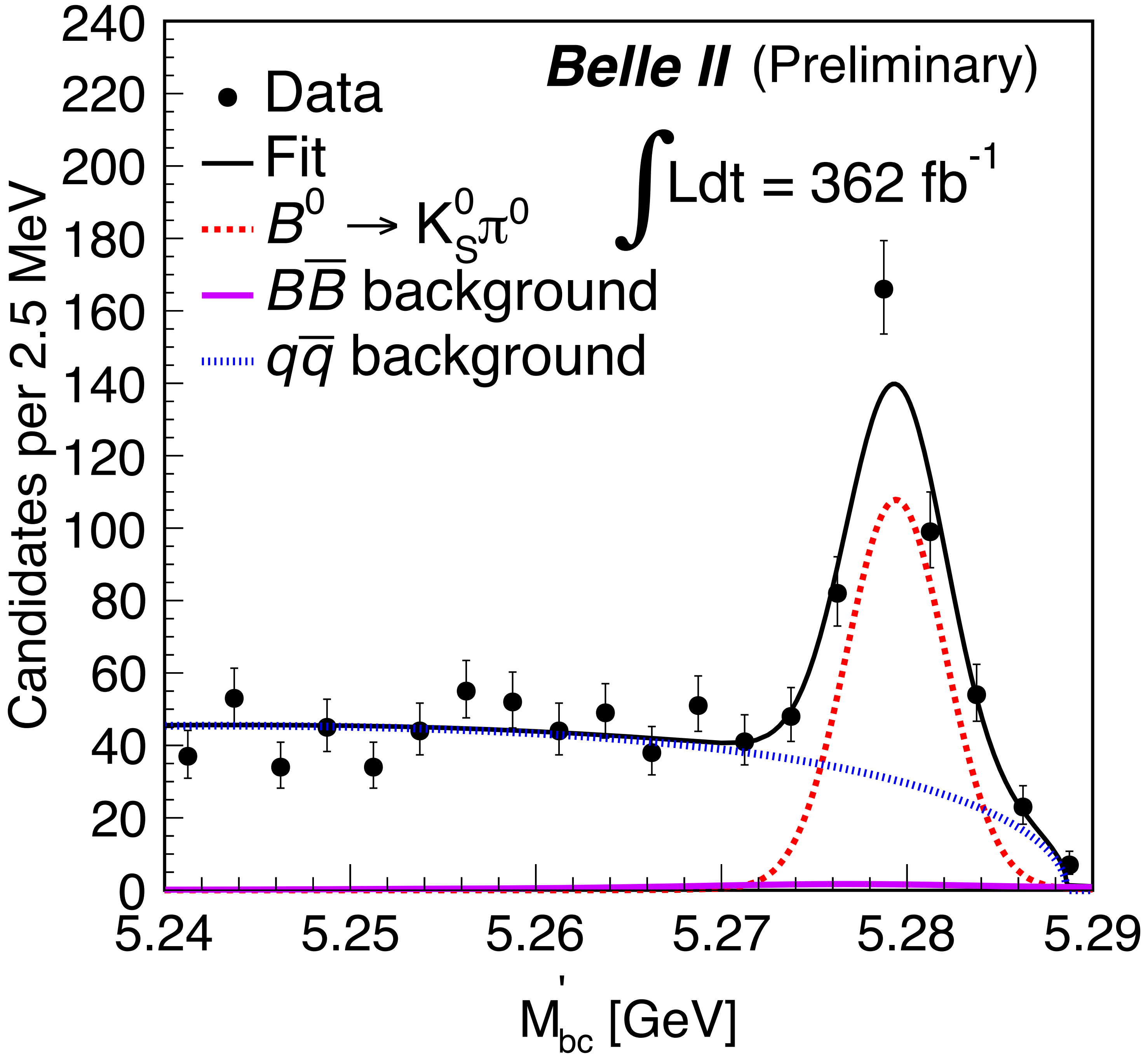
Source	Uncertainty (fs)
Fit bias	3.4
Resolution model	6.2
Background model	8.3
Detector alignment	1.6
Momentum scale	0.2
Input Ω_c^0 mass	0.2
Total	11.0

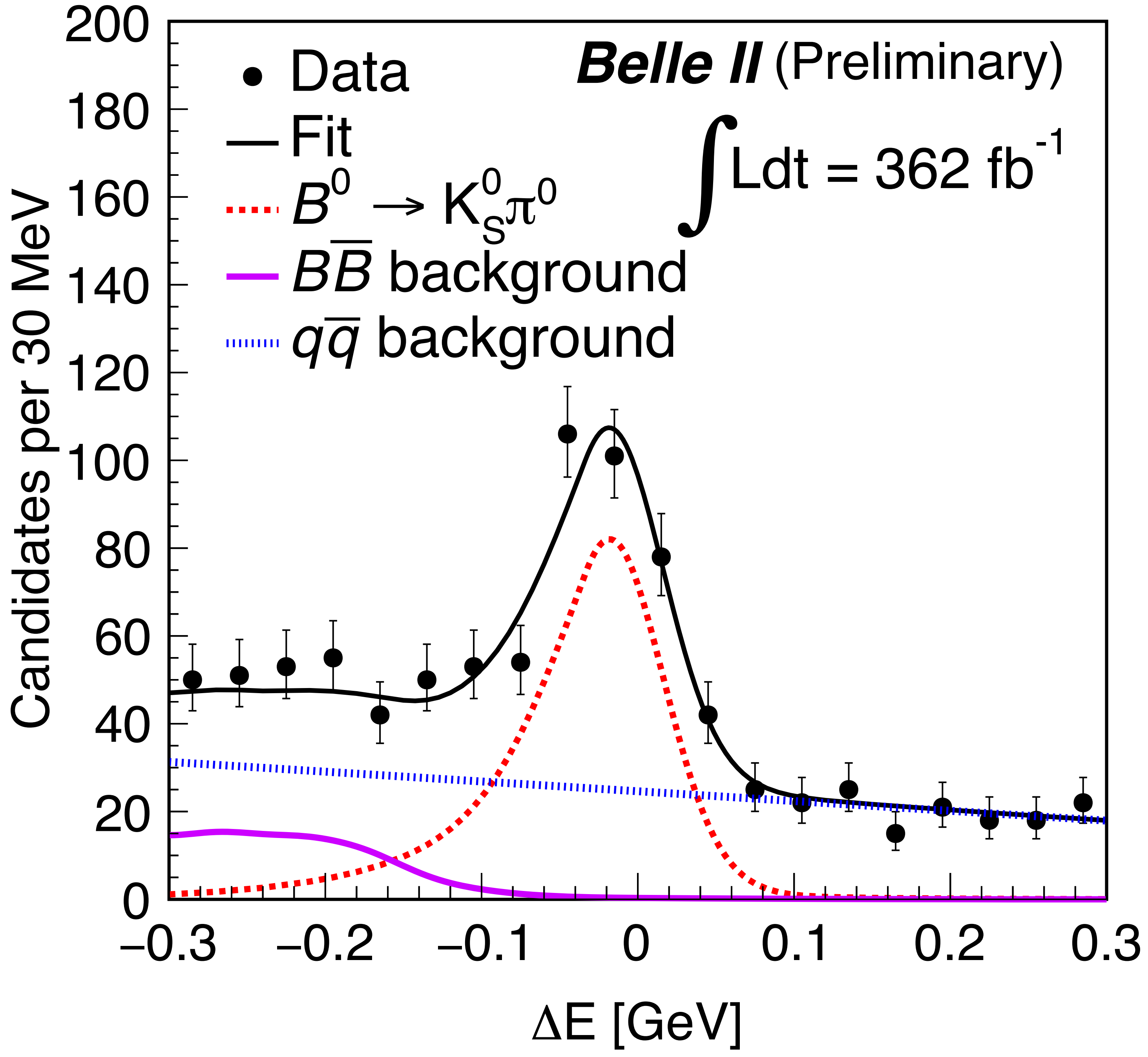
$D_s^+ \to \phi\pi^+$

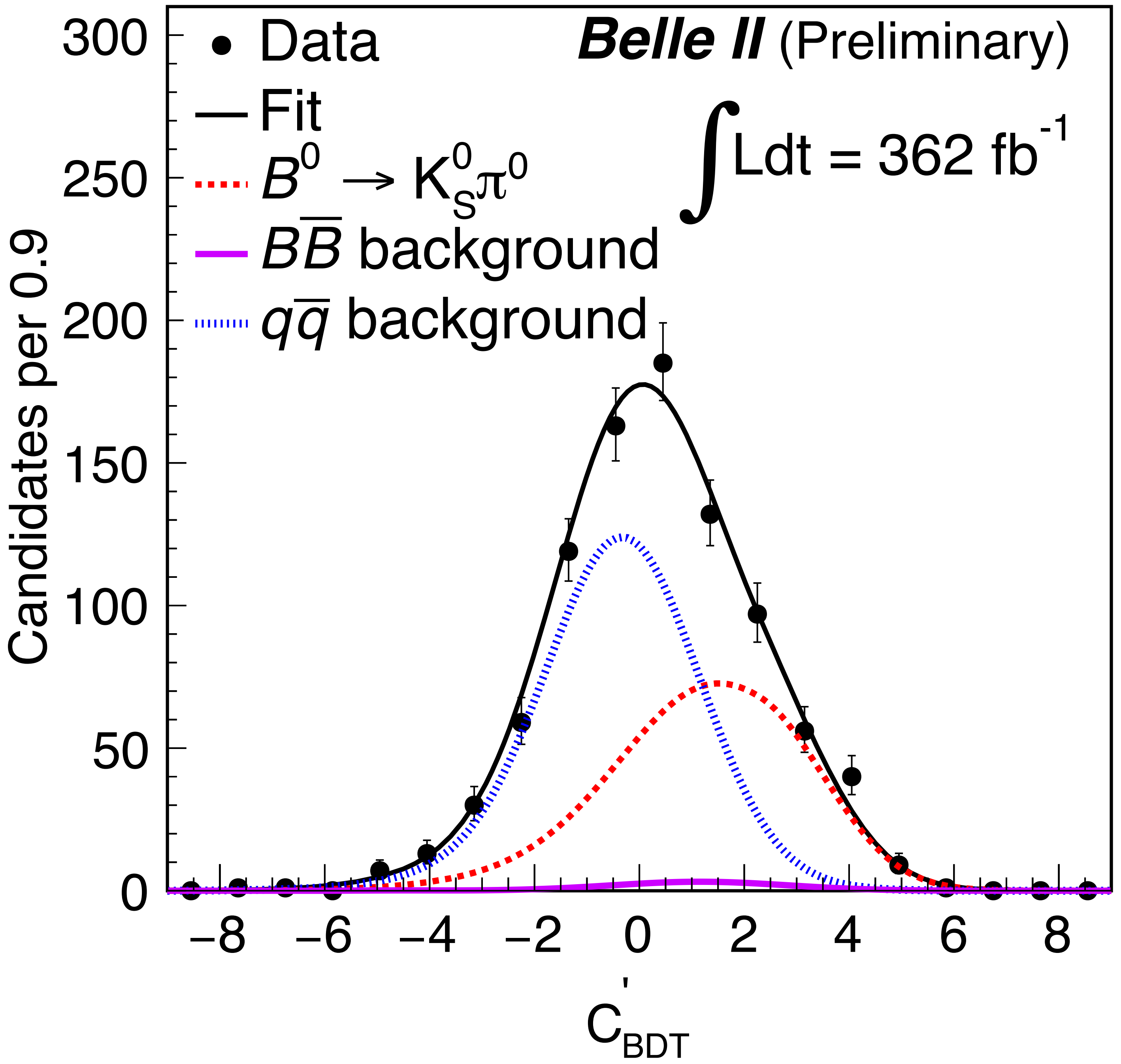
Source	Uncertainty (fs)
Resolution function	+0.85
Background (t, σ_t) distribution	±0.40
Binning of σ_t histogram PDF	±0.10
Imperfect detector alignment	±0.56
Sample purity	±0.09
Momentum scale factor	±0.28
D_s^+ mass	±0.02
Total	$^{+1.14}_{-0.76}$

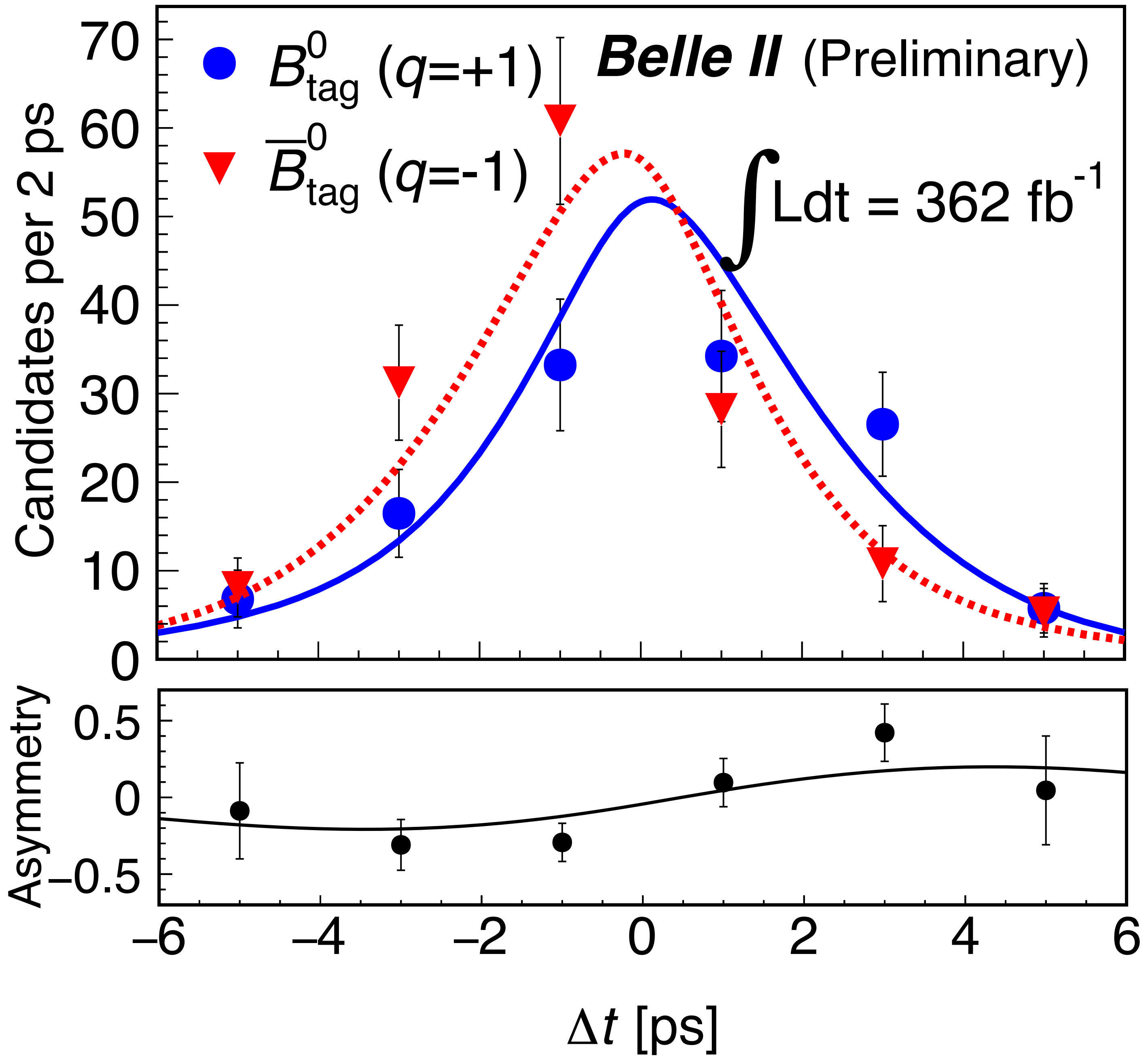
TABLE I. Summary of systematic uncertainties.

Experiment		$N(B\overline{B})$	$-\eta S_{b\to q\bar{q}s}$	$C_{b\to q\bar{q}s}$
			ϕK^0	
BABAR	[262]	470M	$0.66 \pm 0.17 \pm 0.07$	$0.05 \pm 0.18 \pm 0.05$
Belle	[261]	657M	$0.90\,^{+0.09}_{-0.19}$	$-0.04 \pm 0.20 \pm 0.10 \pm 0.02$
Belle II (362M BB pairs)			$0.54 \pm 0.26^{+0.06}_{-0.08}$	$-0.31 \pm 0.20 \pm 0.05$
			$K^0_S K^0_S K^0_S$	
BABAR	[383]	468M	$0.94\,^{+0.21}_{-0.24} \pm 0.06$	$-0.17 \pm 0.18 \pm 0.04$
Belle	[384]	722M	$0.71 \pm 0.23 \pm 0.05$	$-0.12 \pm 0.16 \pm 0.05$
Belle II (362M BB pairs)			$-1.37^{+0.35}_{-0.45} \pm 0.03$	$-0.07^{+0.15}_{-0.20} \pm 0.02$
			$\pi^0 K^0$	
BABAR	[381]	467M	$0.55 \pm 0.20 \pm 0.03$	$0.13 \pm 0.13 \pm 0.03$
Belle	[378]	657M	$0.67 \pm 0.31 \pm 0.08$	$-0.14 \pm 0.13 \pm 0.06$
Belle II (362M BB pairs)			$0.74^{+0.20}_{-0.23} \pm 0.04$	$-0.04^{+0.15}_{-0.14} \pm 0.05$





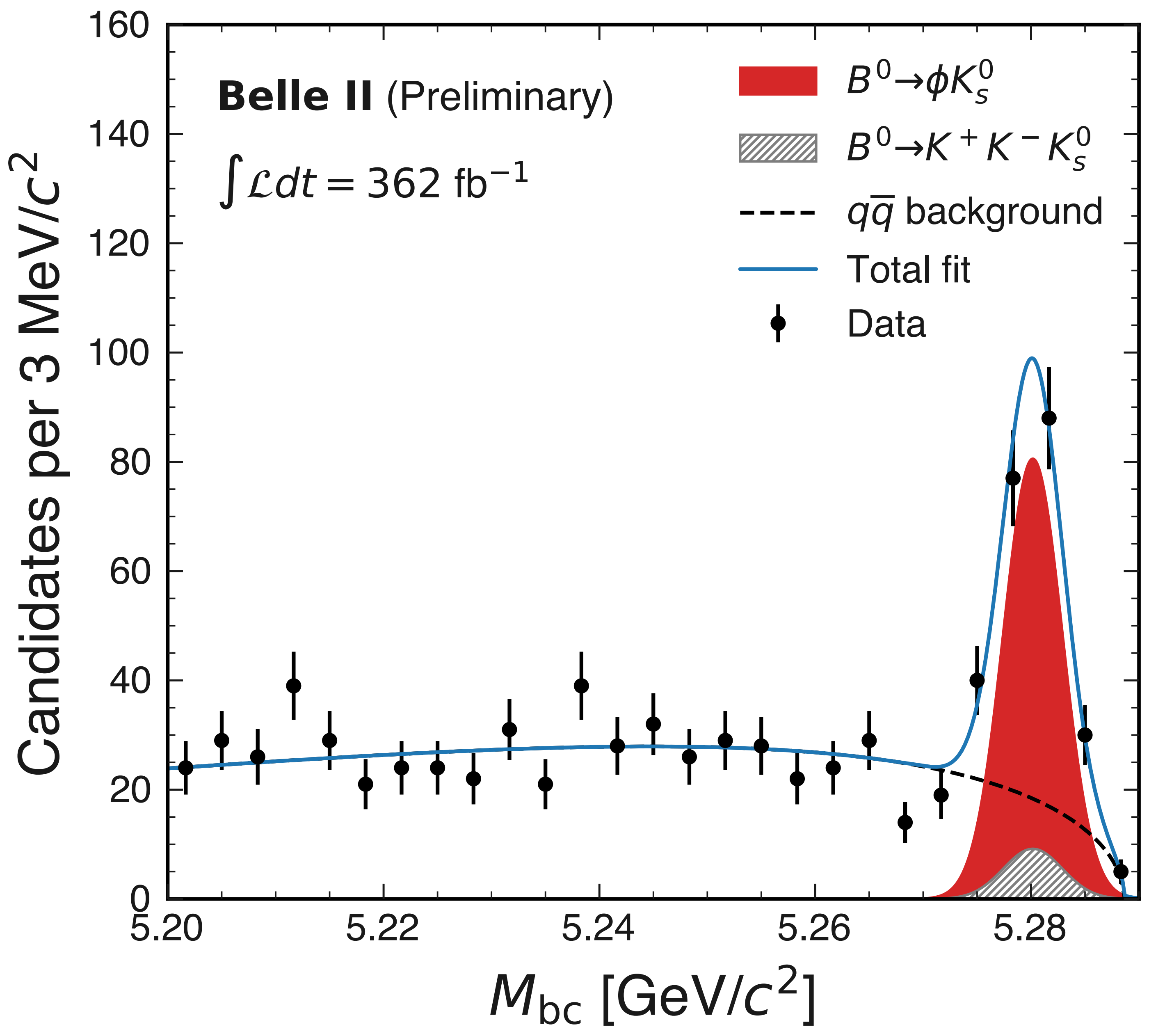


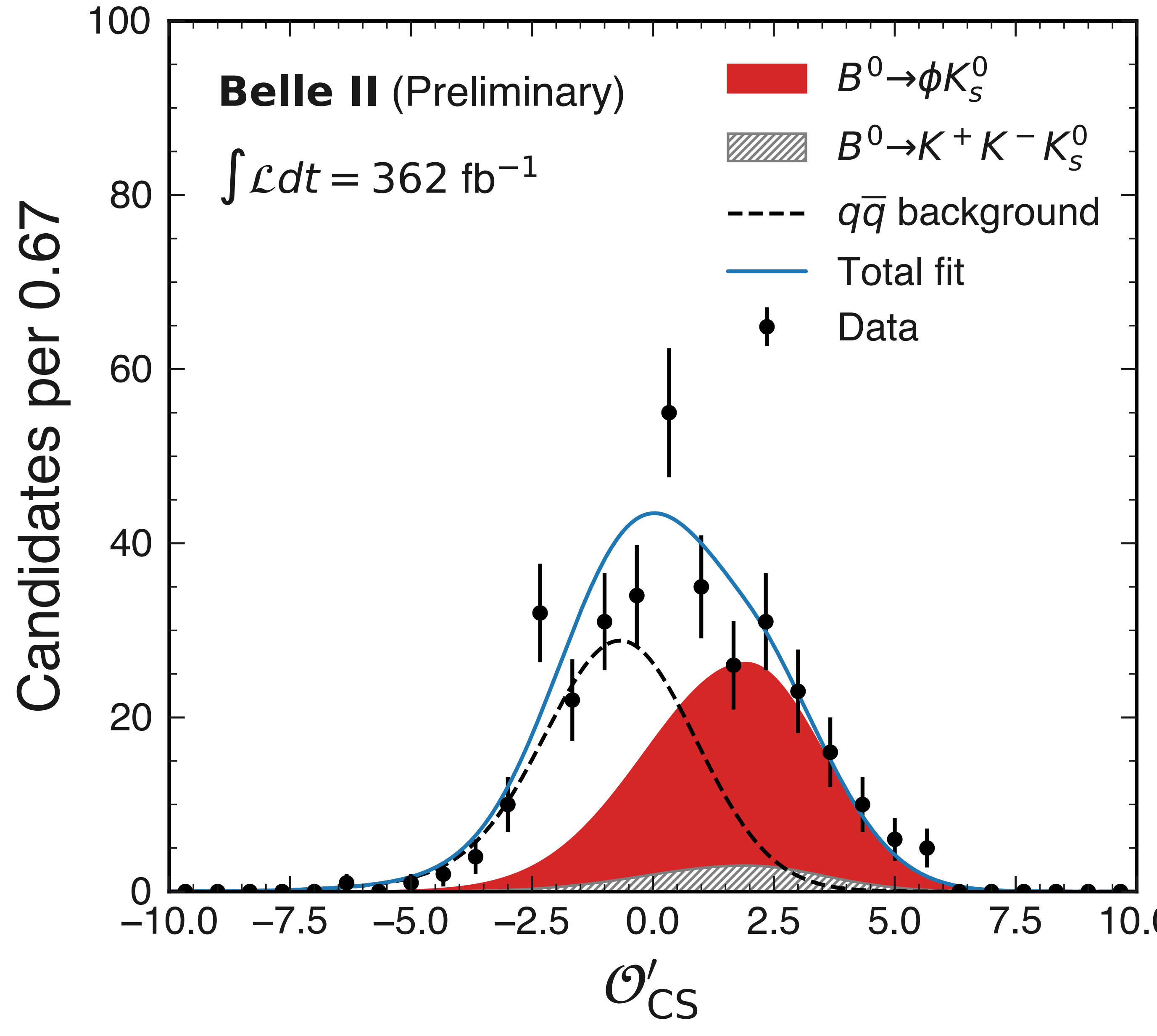


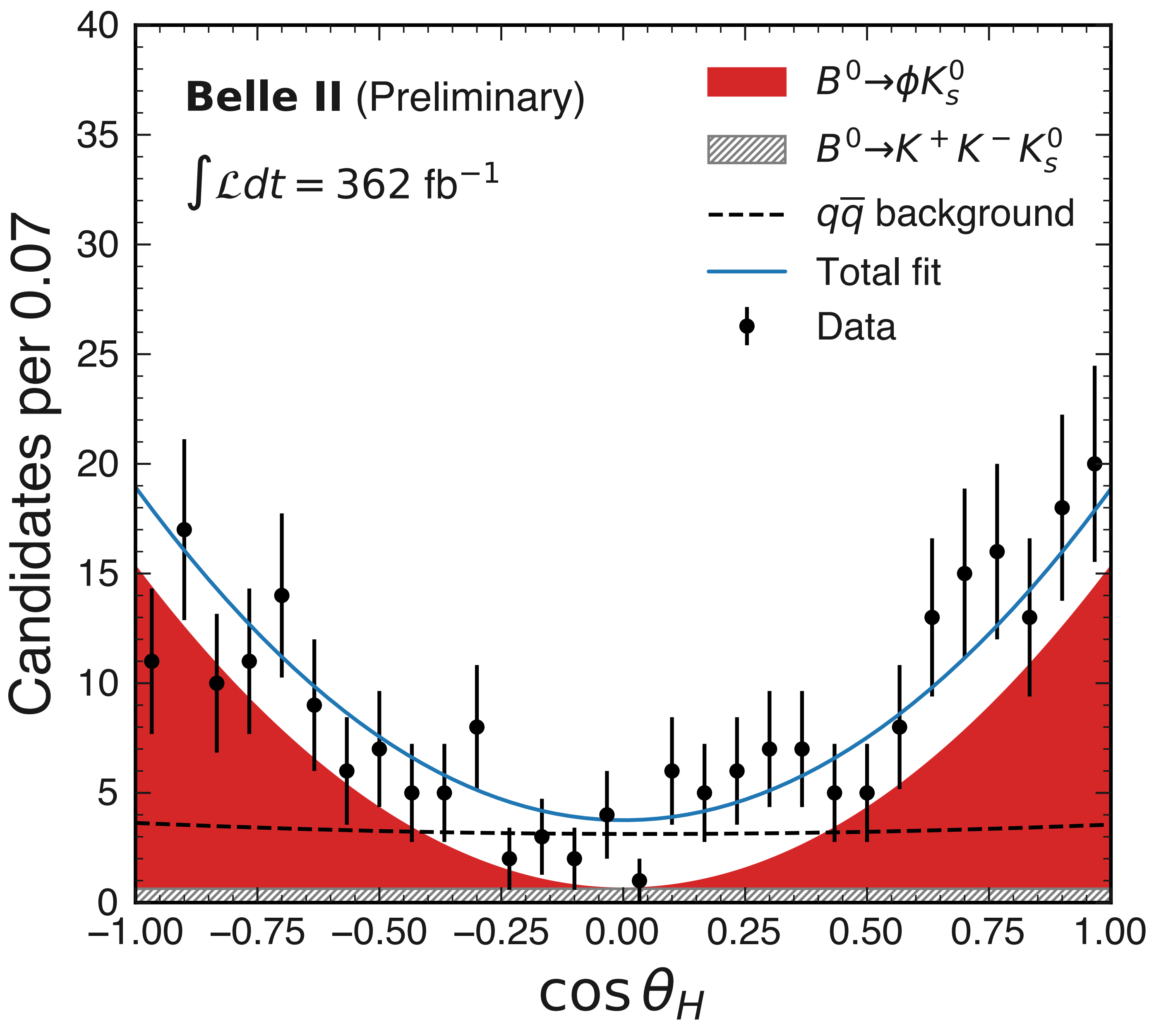
B→Ksπ0

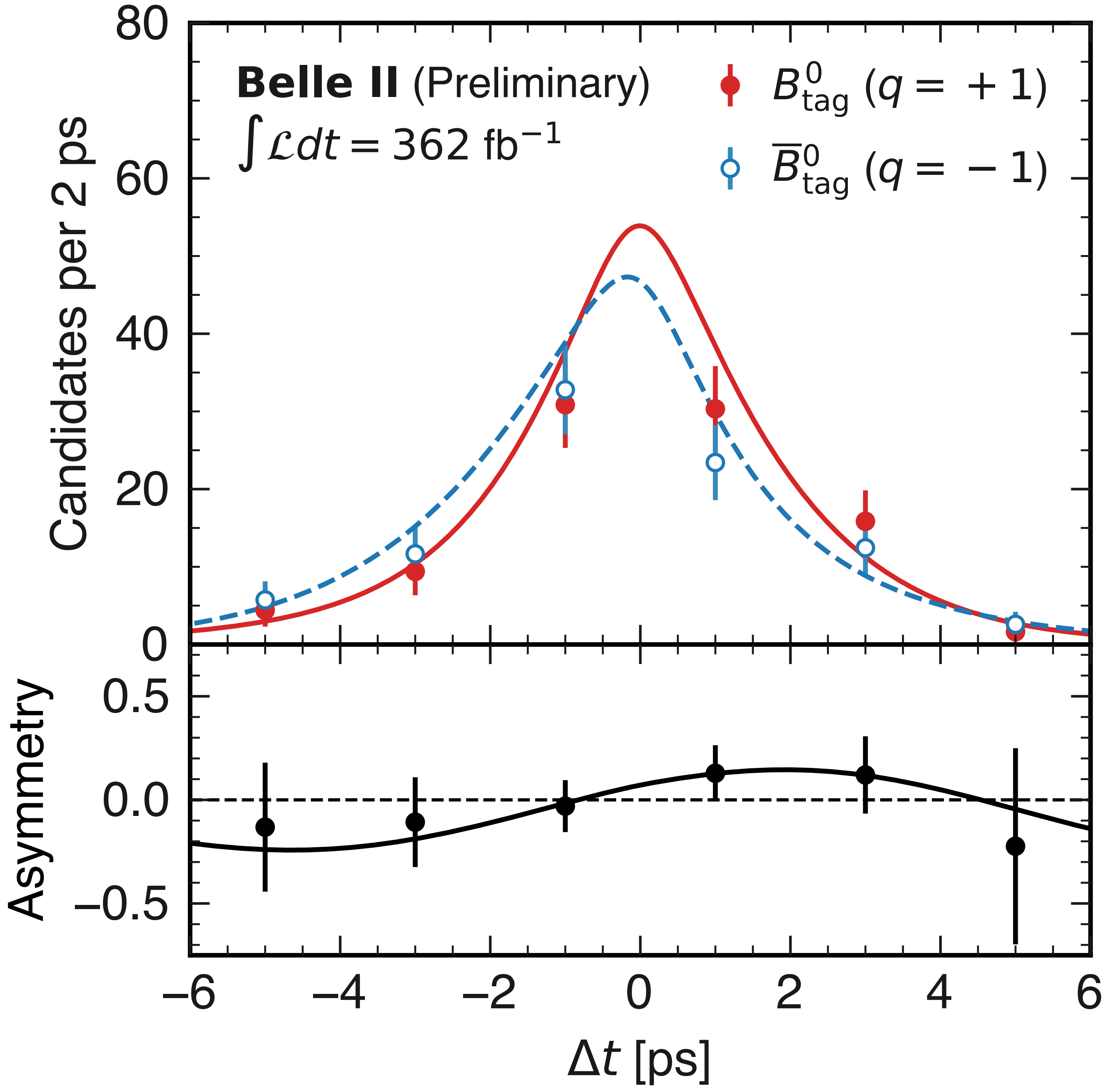
Source	δA	δS
Flavor tagging	0.013	0.011
Resolution function	0.014	0.022
$B\bar{B}$ background asymmetry	0.030	0.018
$q\bar{q}$ background asymmetry	0.028	< 0.001
Signal modeling	0.004	0.003
Background modeling	0.006	0.018
Fit bias	0.005	0.011
Best candidate selection	0.005	0.010
τ_{B^0} and Δm_d	< 0.001	< 0.001
Tag-side interference	0.006	0.011
VXD misalignment	0.004	0.005
Total	0.047	0.040

arxiv:2305.07555







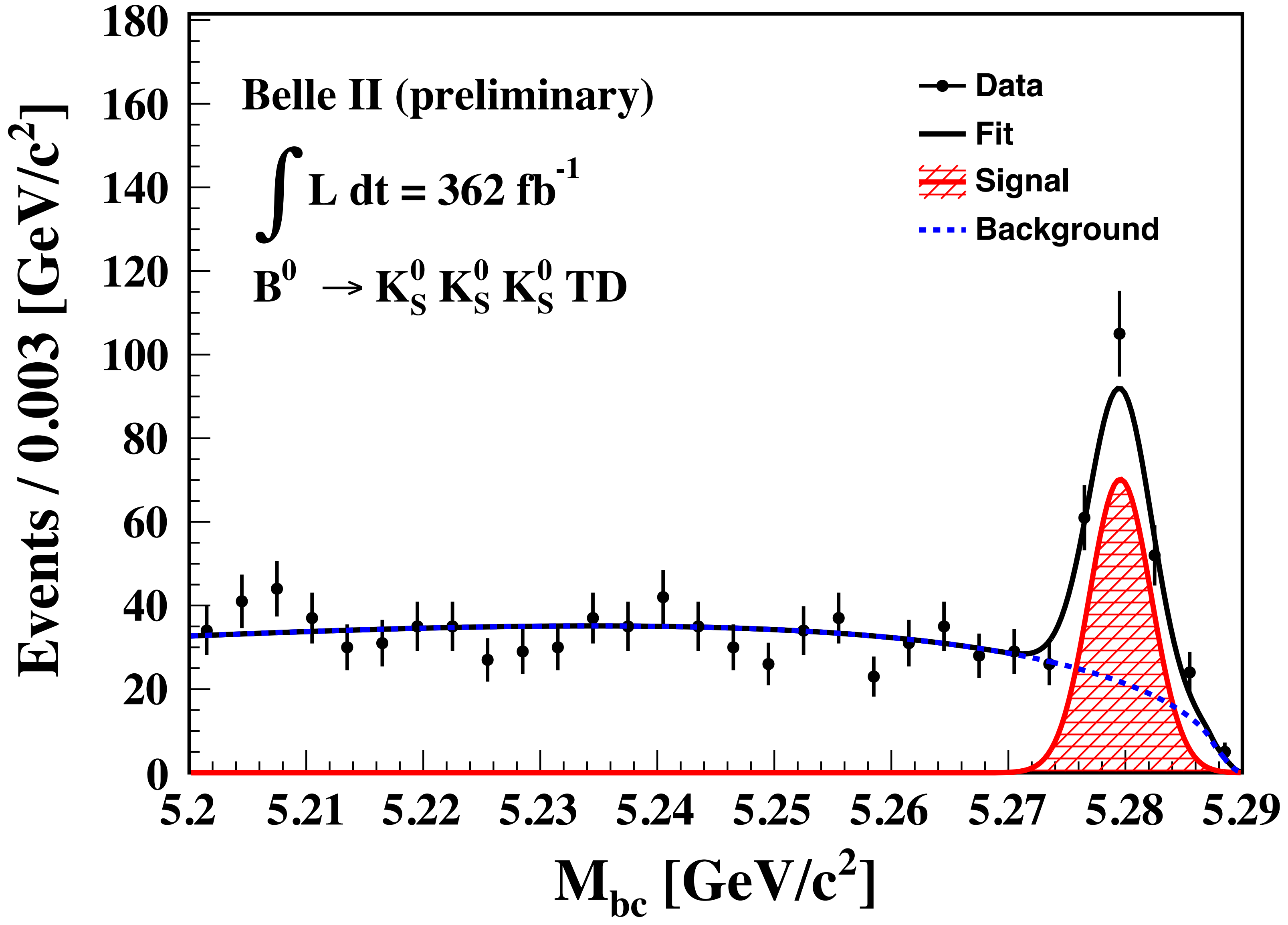


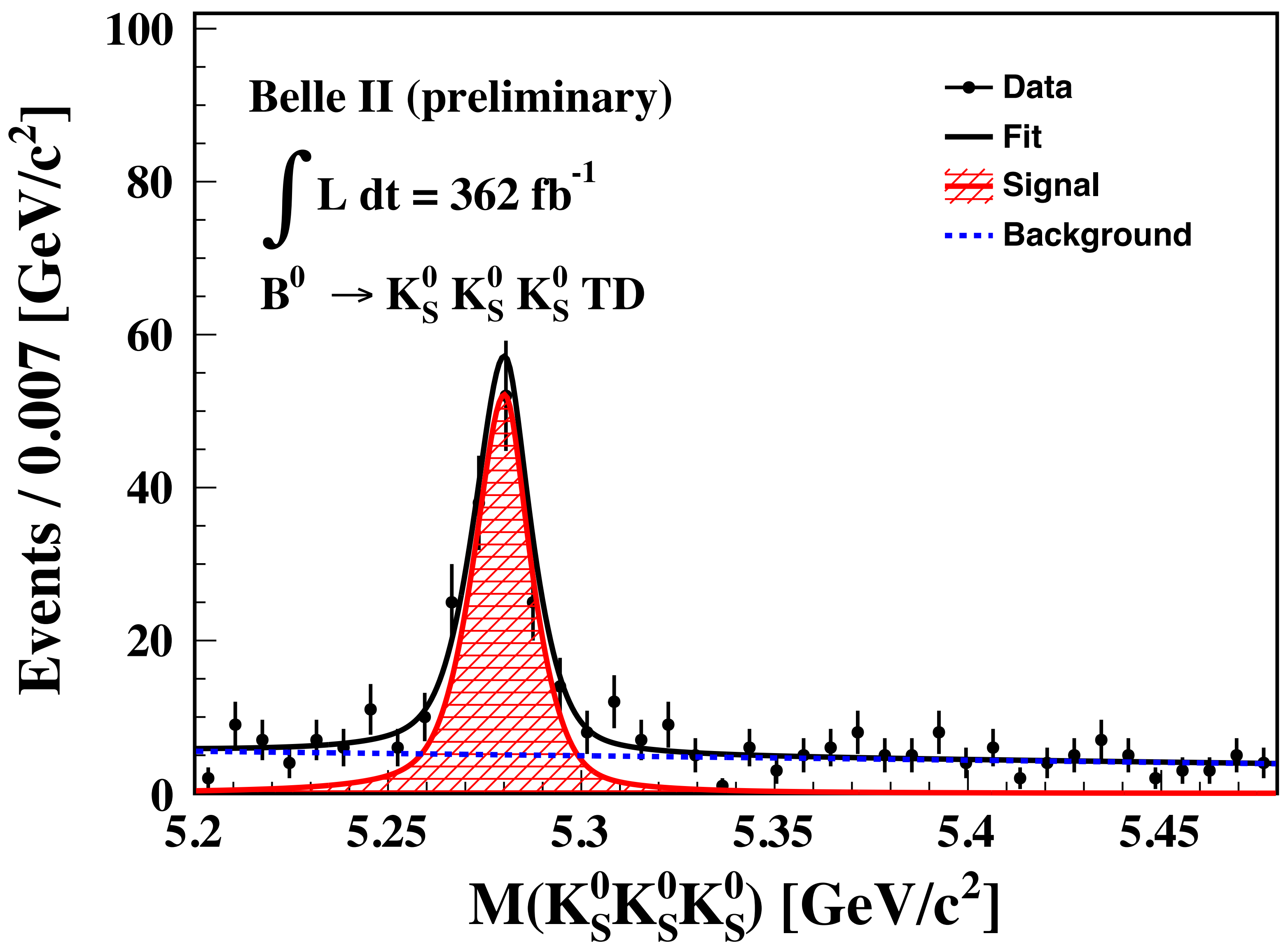
B→φKs

Table II: Summary of systematic uncertainties.

Source	$\sigma(A)$	$\sigma(S)$
Calibration with $B^0 \to D^{(*)-}\pi^+$ decays		
Calibration sample size	±0.010	±0.009
Calibration sample systematic	±0.010	±0.012
Sample dependence	-0.005	$+0.021$
Fit model		
Fit bias	$^{+0.017}_{-0.028}$	$^{+0.033}_{-0.062}$
$B^0 \to K^+K^-K^0_S$ backgrounds	-0.020	-0.011
Fixed fit shapes	±0.009	±0.022
τ_{B^0} and Δm_d uncertainties	±0.006	±0.022
$A_{K^+K^-K^0_S}$ and $S_{K^+K^-K^0_S}$	±0.014	±0.013
$B\overline{B}$ backgrounds	$^{+0.030}_{-0.019}$	$^{+0.017}_{-0.031}$
Tag-side interference	< 0.001	$+0.012$
Multiple candidates	$+0.032$	-0.002
Δt measurement		
Detector misalignment	$+0.002$	-0.002
Momentum scale	±0.001	±0.001
Beam spot	±0.002	±0.002
Δt approximation	< 0.001	-0.018
Total systematic	$^{+0.052}_{-0.046}$	$^{+0.058}_{-0.082}$
Statistical	±0.201	±0.256

arxiv:2307.02802





B->$K_SK_SK_S$

Source	$\delta\mathcal{S}$	$\delta\mathcal{A}$
Signal probability	0.014	0.008
Fit bias	0.014	0.004
Flavor tagging	0.013	0.012
Resolution function	0.013	0.008
Tag-side interference	0.011	0.006
Vertex reconstruction	0.011	0.004
Physics parameters	0.009	0.000
Detector misalignment	0.008	0.007
Background Δt shape	0.004	0.002
Total	0.032	0.020