Decay-time dependent *CP*-violation at Belle II

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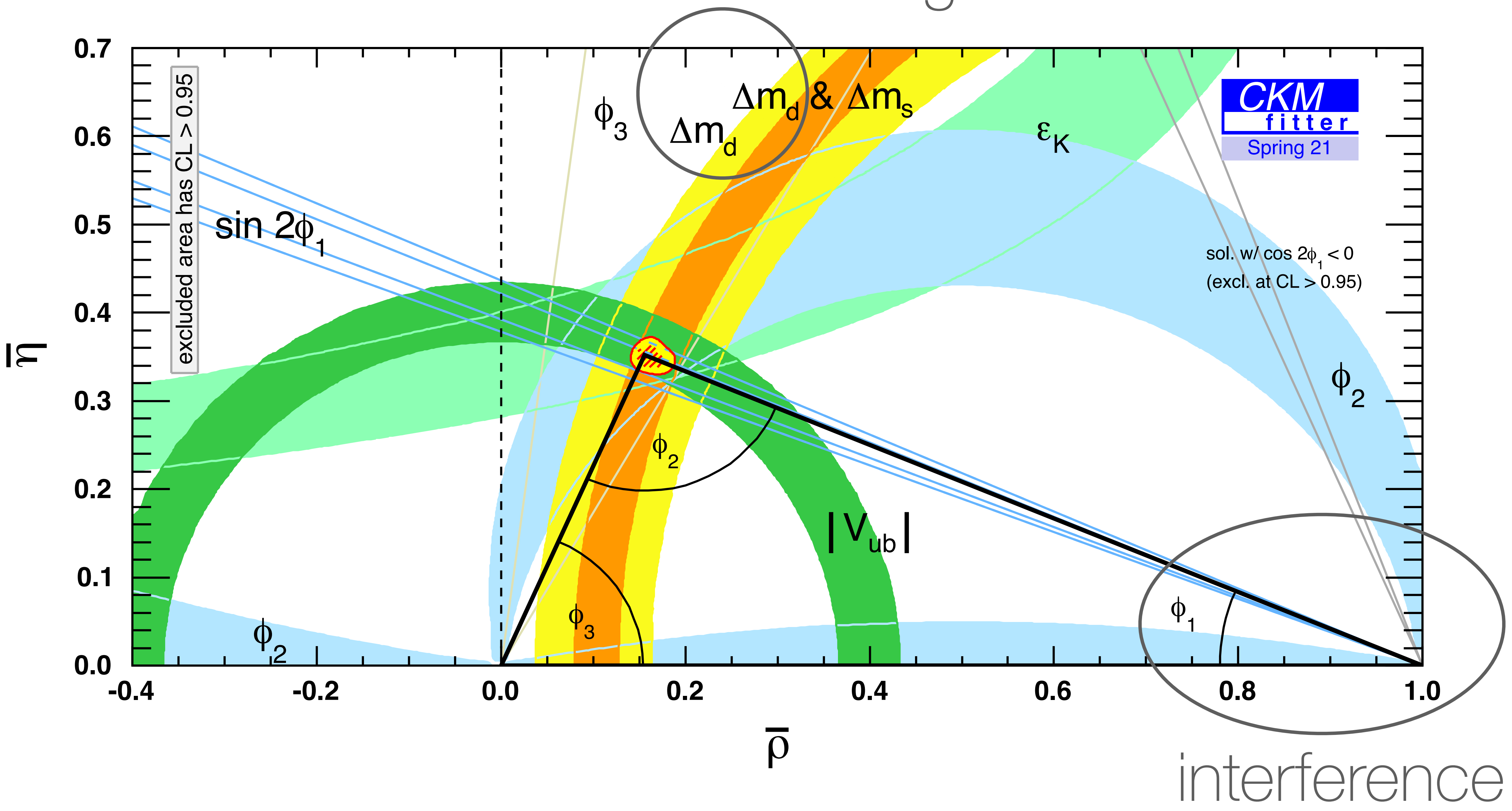
Moriond EW, 18-25 March 2023

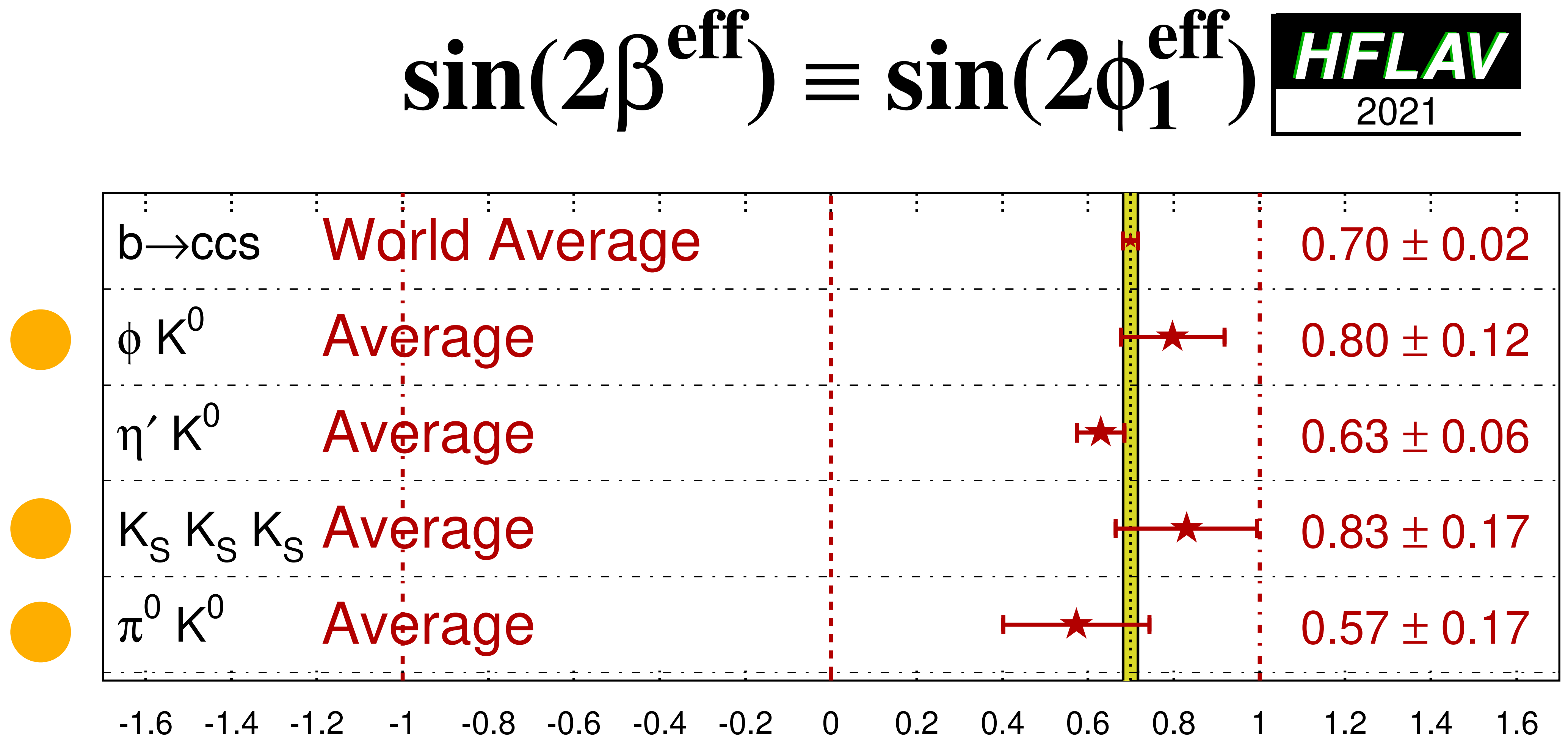
Iowa State University

Belle II

Time-dependent CPV as discovery tool

- Measurements of $\sin 2\phi_1$ in b->qqs transitions as a probe of beyond SM physics
  - Clean theory prediction (~few %)
  - Loop-suppressed, potentially affected by competing BSM amplitudes
- Experimentally challenging, due to
  - Small BF (~10^{-6}) and neutrals in the final state (K_S, π^0)
  - Sophisticated analysis techniques (tagging and Δt resolution)
- Validated with benchmark mixing and CPV analyses (B->D(*)π and B->J/ψK_S)

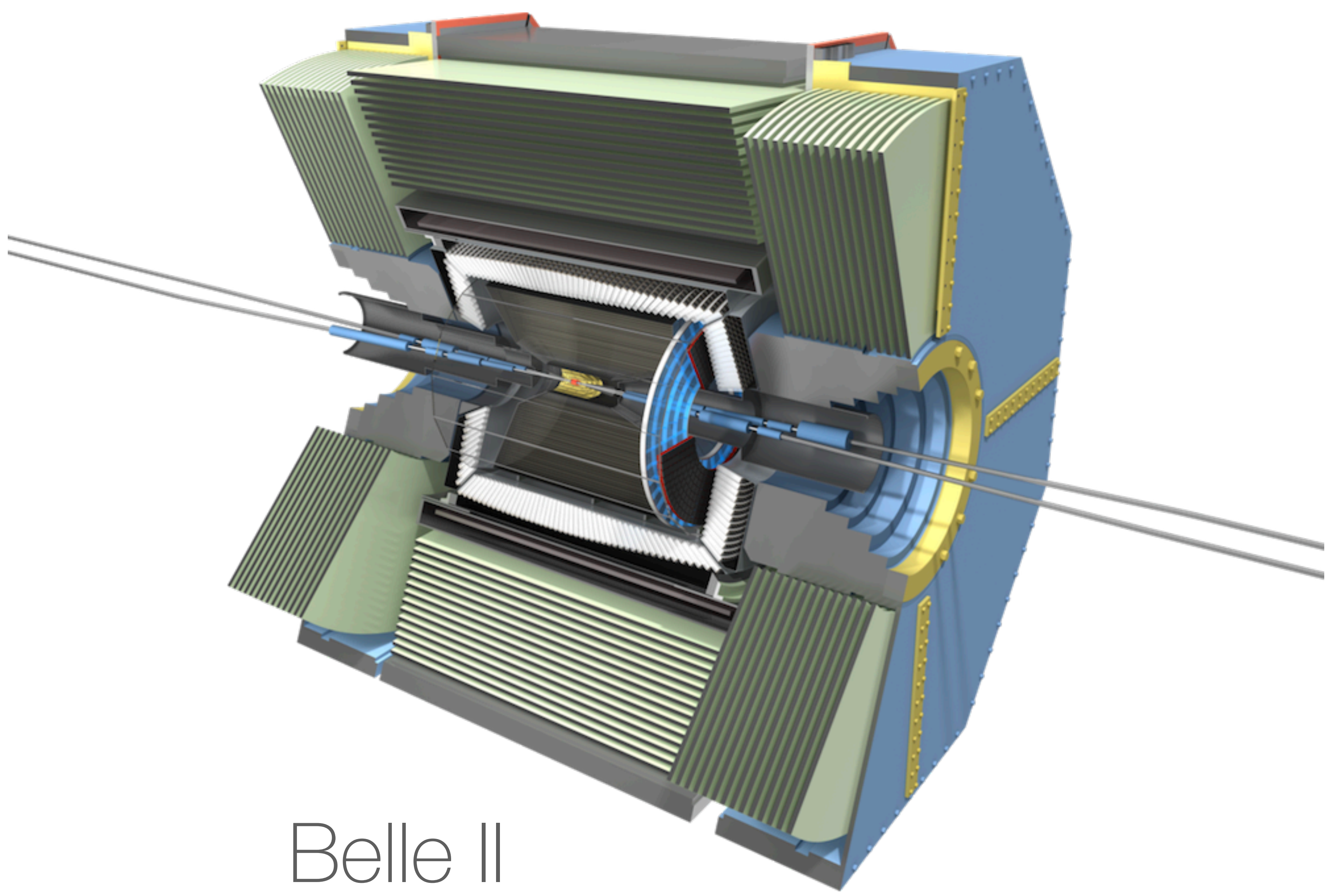




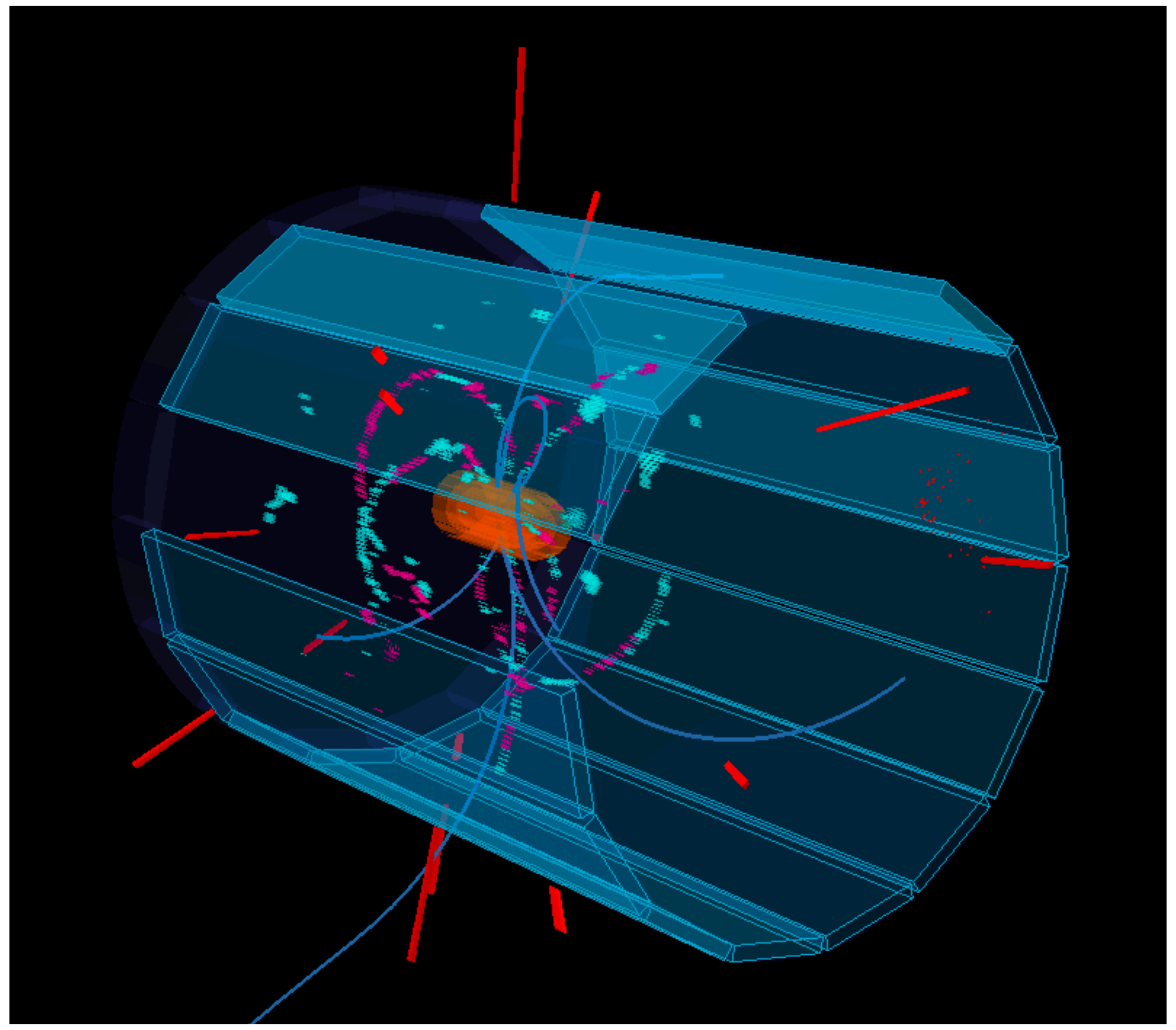
NEW FOR MORIOND

Belle II at SuperKEKB

- Asymmetric e^+e^- collisions at the SuperKEKB accelerator complex in Japan
  - Recorded world's highest instantaneous luminosity (4.7×10^{34} $cm^{-2}s^{-1}$)
  - Collected 362 fb^{-1} dataset at the Y(4s) in 2019-22, corresponding to 387M $B\overline{B}$ pairs
- Brand new detector, especially important for time-dependent measurements
  - Excellent vertex resolution from pixel and silicon vertex detectors
  - Efficient neutrals reconstruction (π^0, K_S) and K/π separation

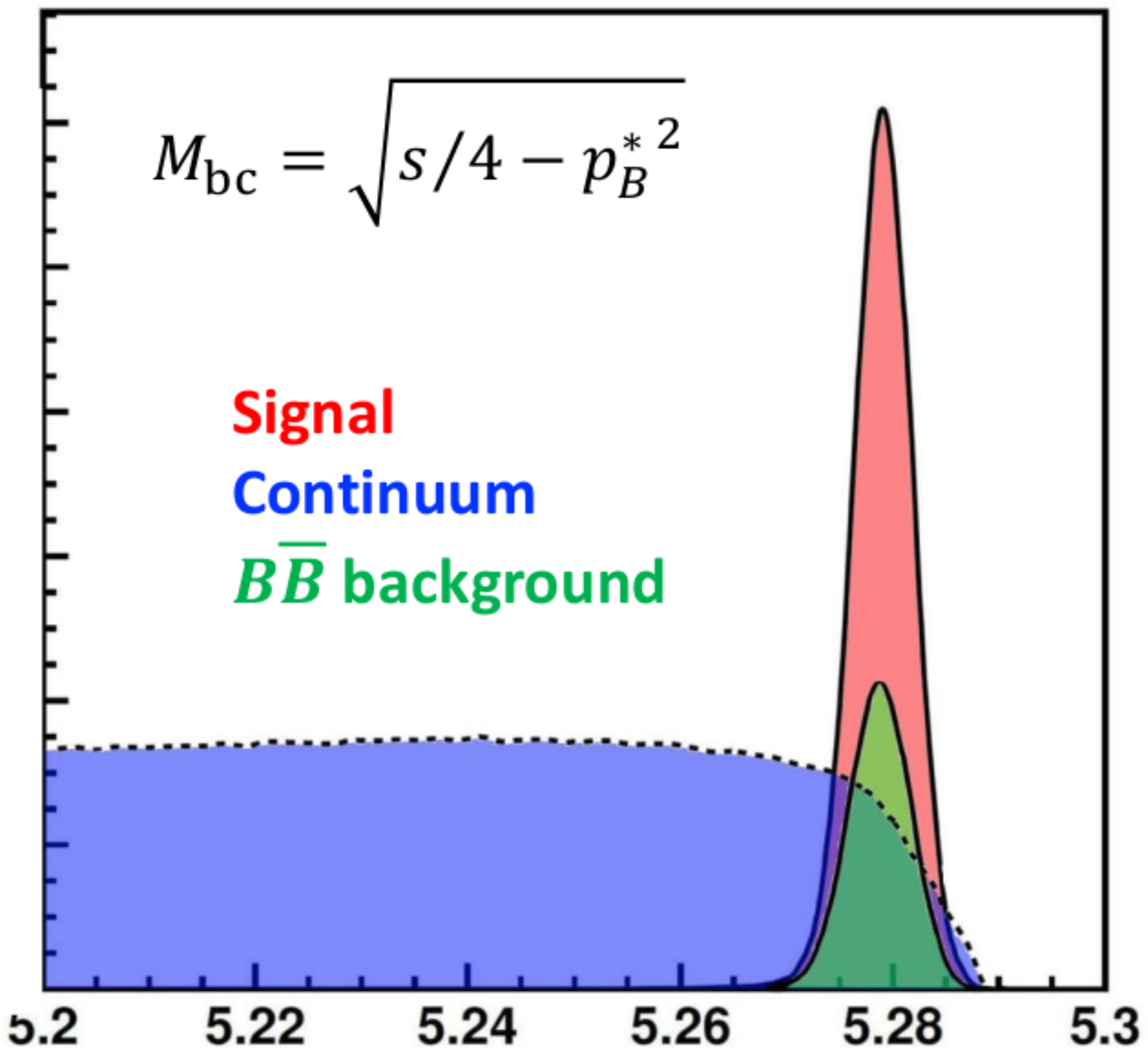


Belle II

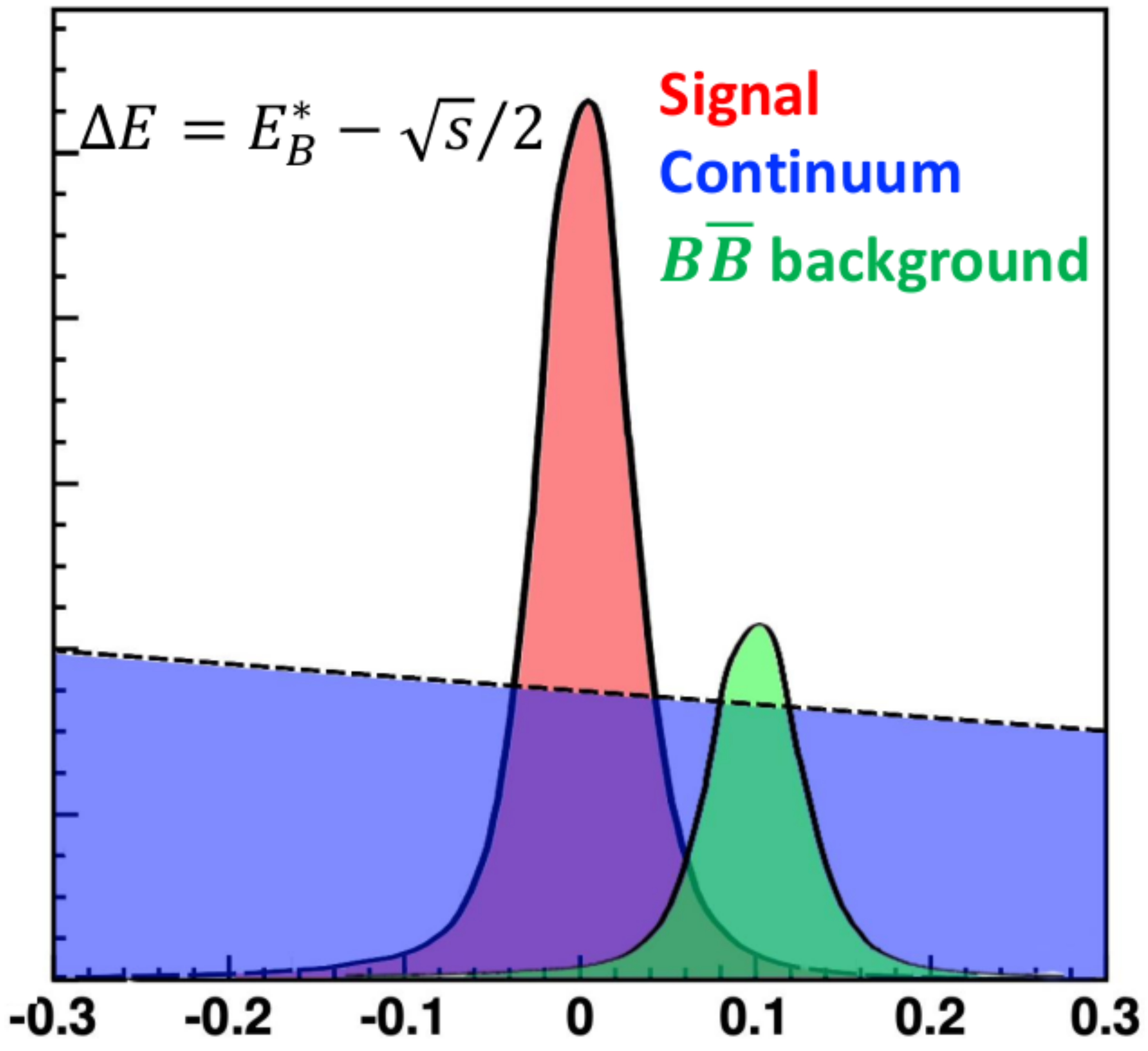


e^+e^- collision

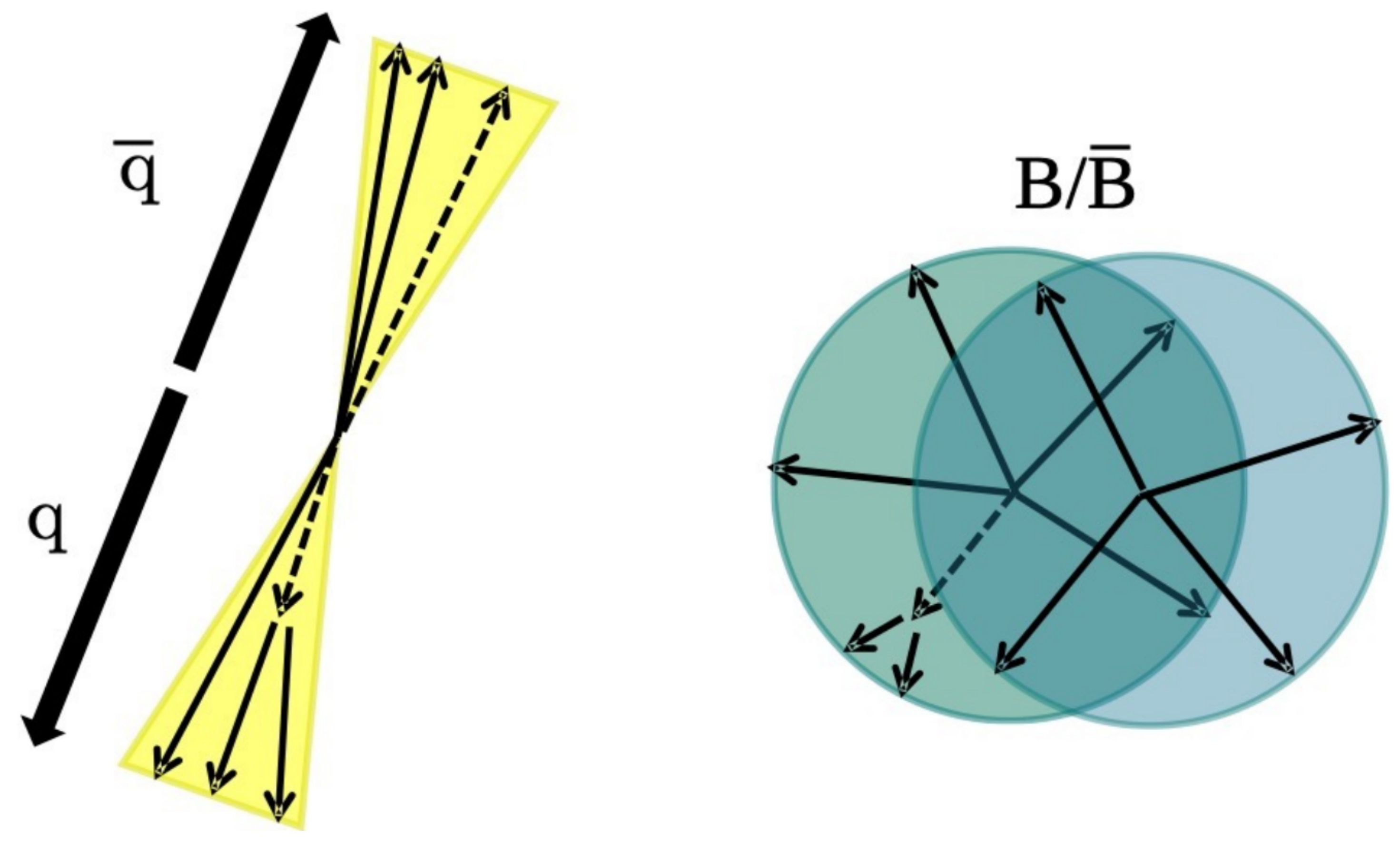
B-factory analysis 101



Beam-constrained mass [GeV/c²]



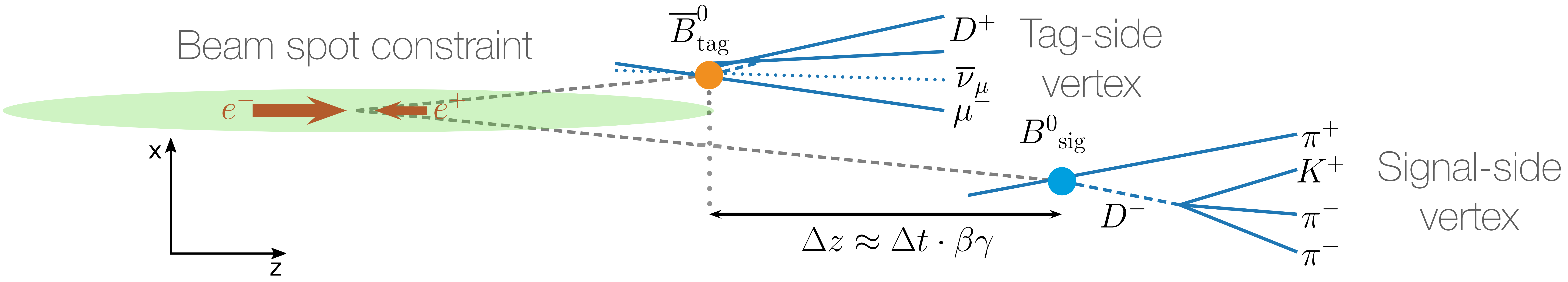
Energy difference [GeV]



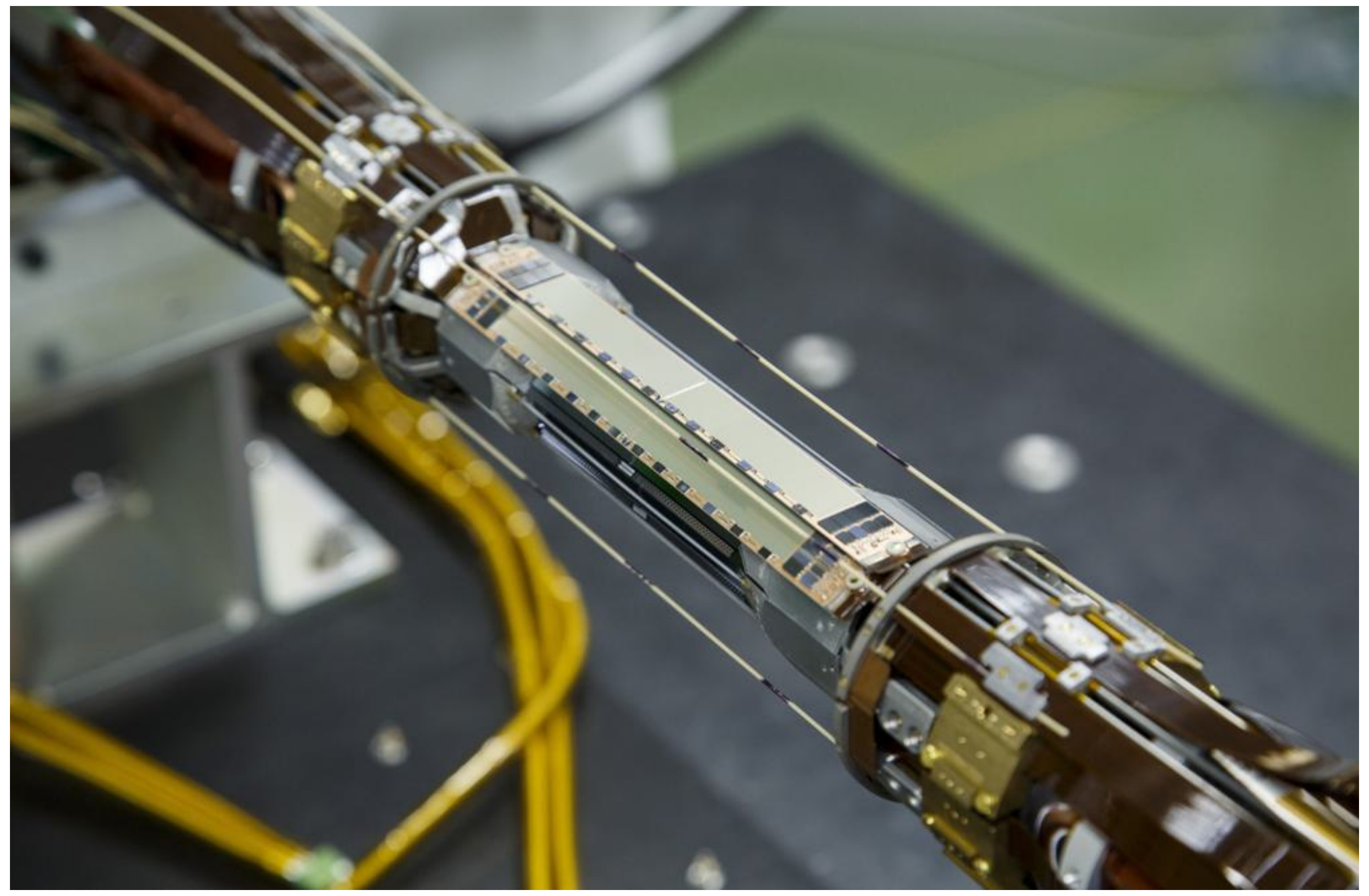
Event shape

- High resolution (~2-10 MeV) high-level analysis variables (M_{bc}, ΔE), separating signal from backgrounds, using to the knowledge of beam energy
- Several event shape variables exploiting the correlations in e^+e^- collision

Time measurement



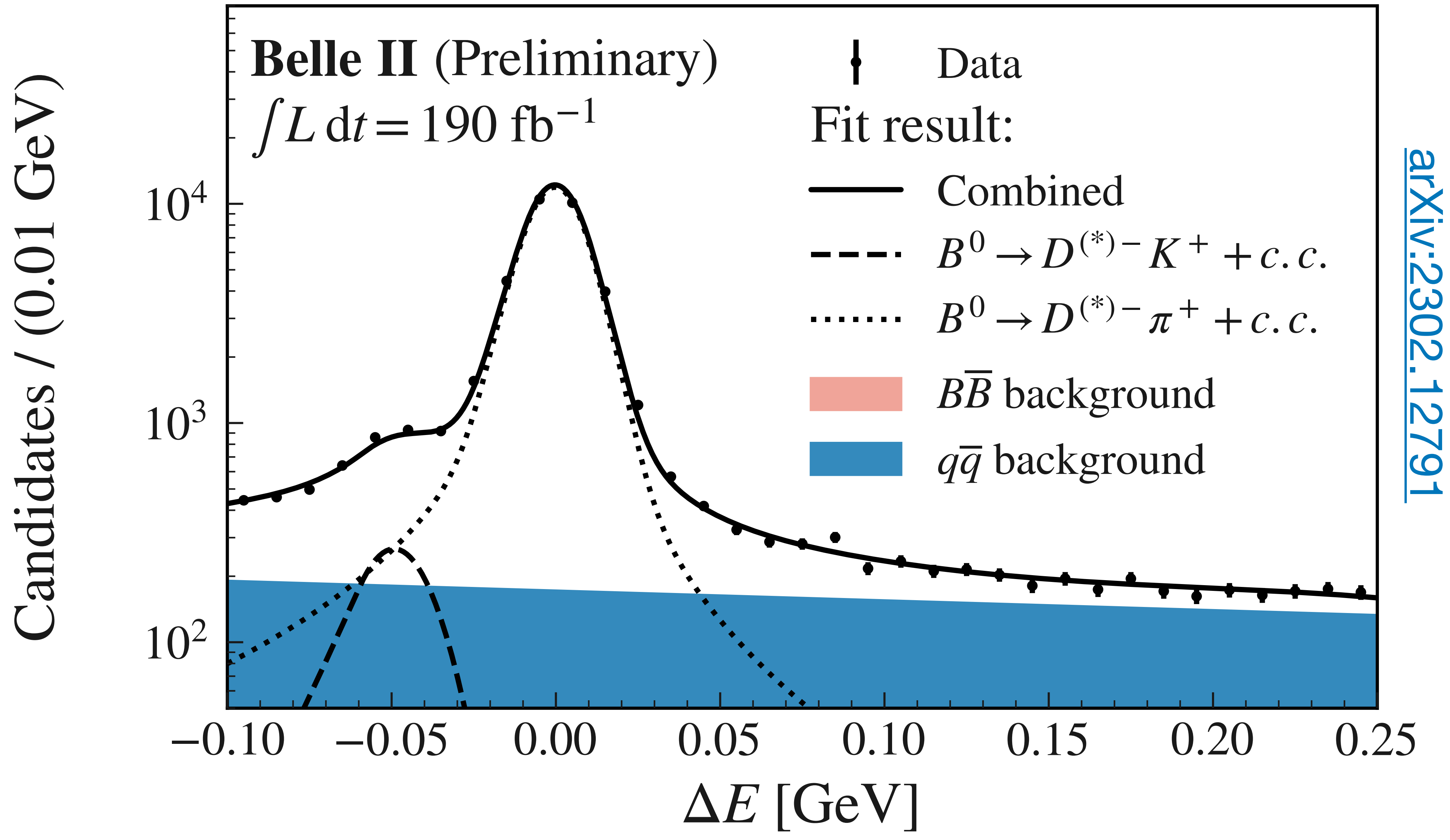
- Measuring the time difference Δt of coherently produced $B\overline{B}$ pairs from the decay of a Υ(4S), boosted along z
- Improved vertex resolution from pixel in spite of lower boost
  - Belle: βγ=0.43, Δz≈200μm —> Belle II: βγ=0.29, Δz≈130μm
- Enhanced Δt resolution from the beam spot profile in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



Pixel detector radius ≈ 1.4 cm

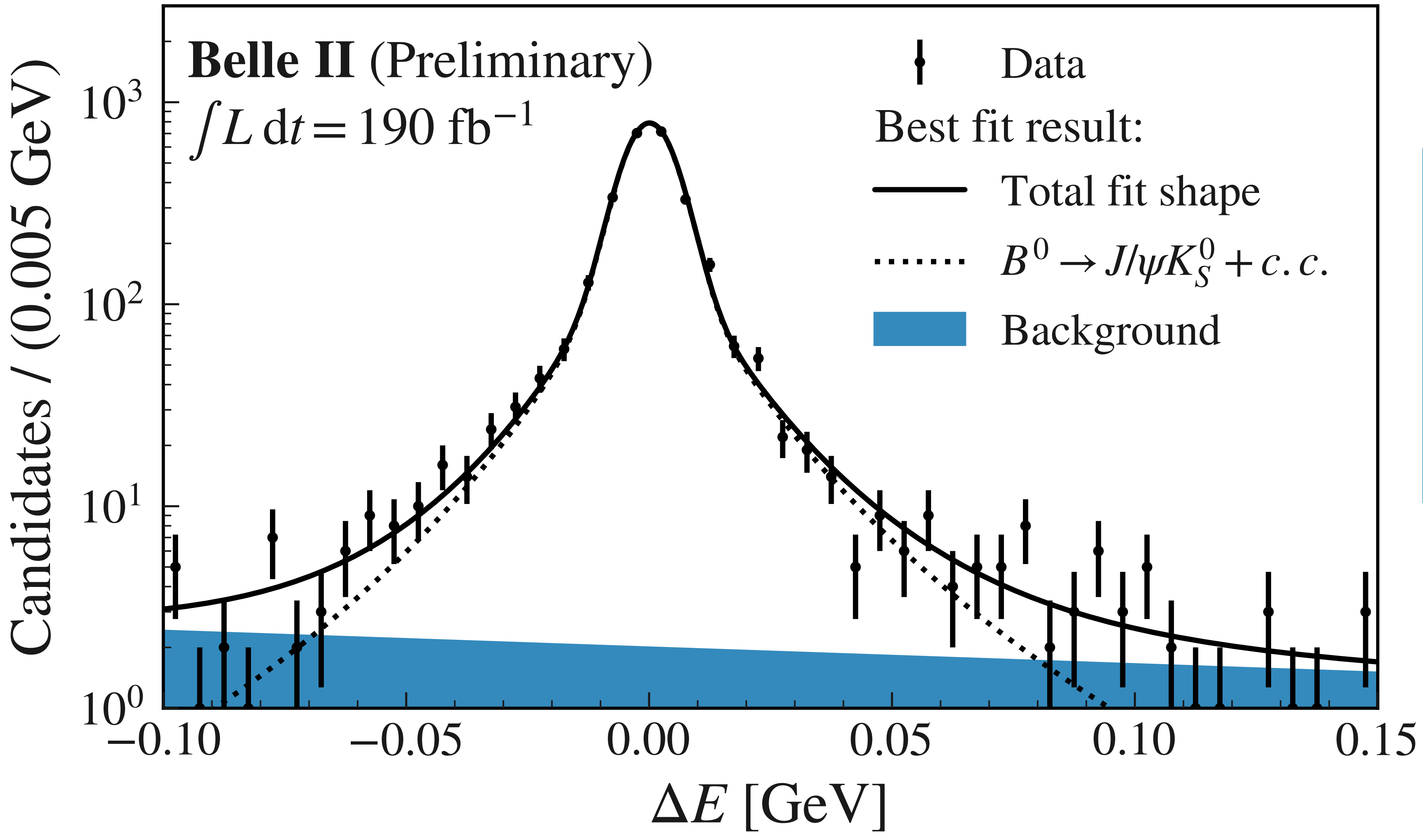
Δm and sin2ϕ_1

Energy difference ~33k B->D(*)π



arXiv:2302.12791

Energy difference ~2.8k B->J/ψK_S

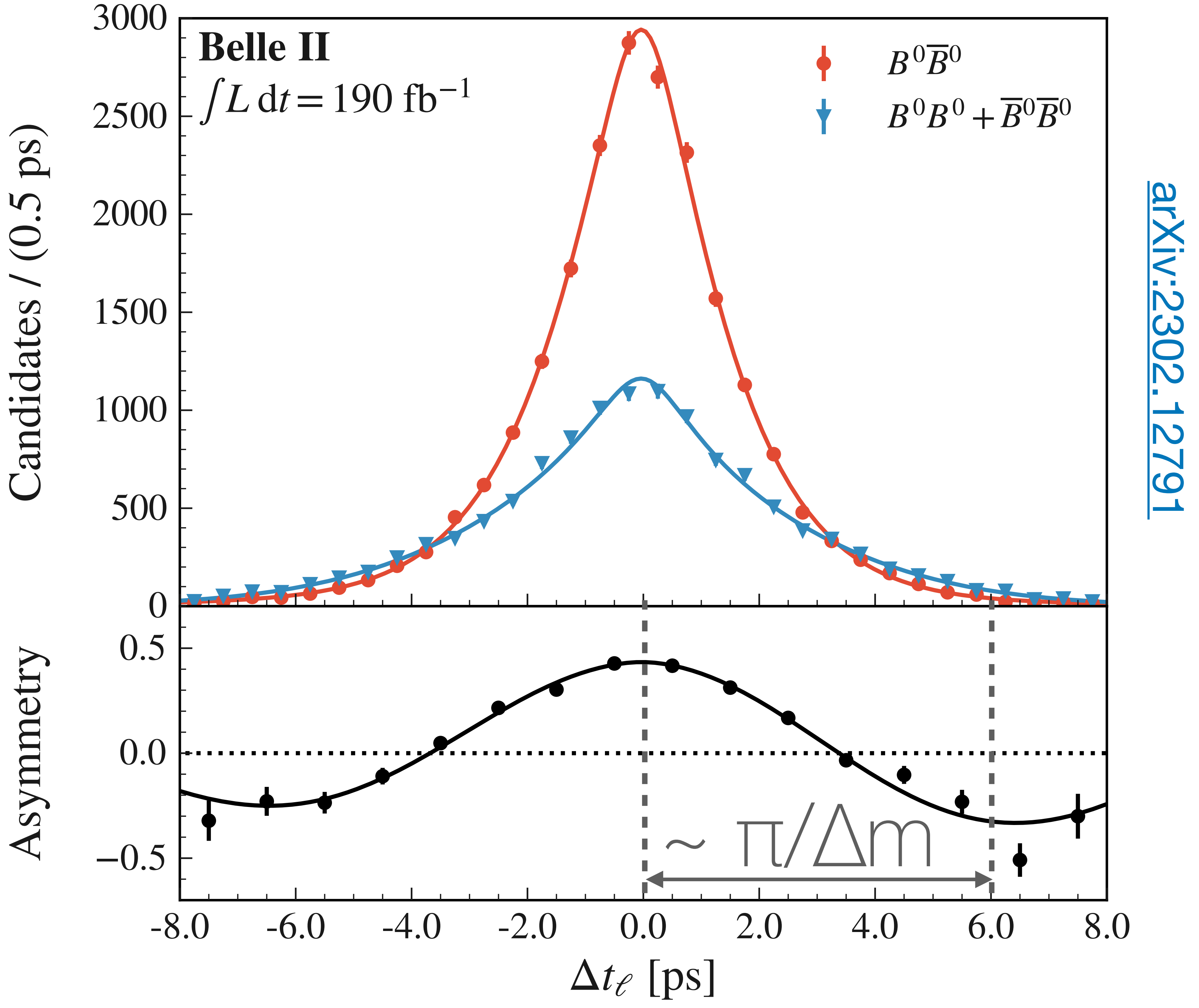


arXiv:2302.12898

- High-yield, low-background modes used for benchmark measurements of time-dependent observables
- Main challenge: accurate understanding of vertex resolution (Δt resolution ~1 ps) and tagging (ε_{tag}~30%)

Δm and sin2ϕ₁

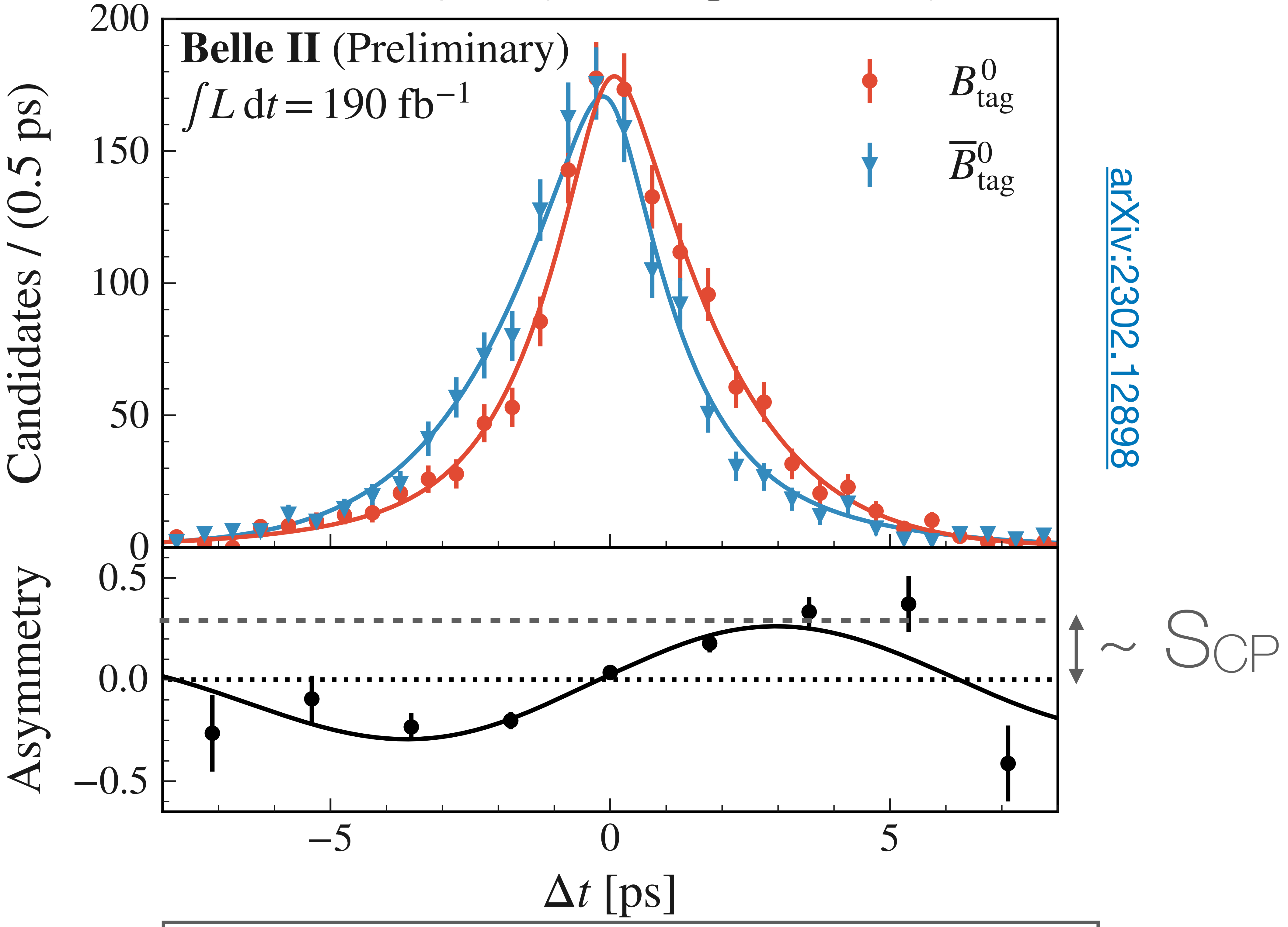
B->D(*)π (flavor specific)



$$\tau_{B^0} = (1.499 \pm 0.013 \pm 0.008)\ \text{ps}$$
$$\Delta m_d = (0.516 \pm 0.008 \pm 0.005)\ \text{ps}^{-1}$$

HFLAV: τ =1.519±0.004 ps,
Δm= 0.5065±0.0019 ps^{-1}

B->J/ψKs (CP eigenstate)



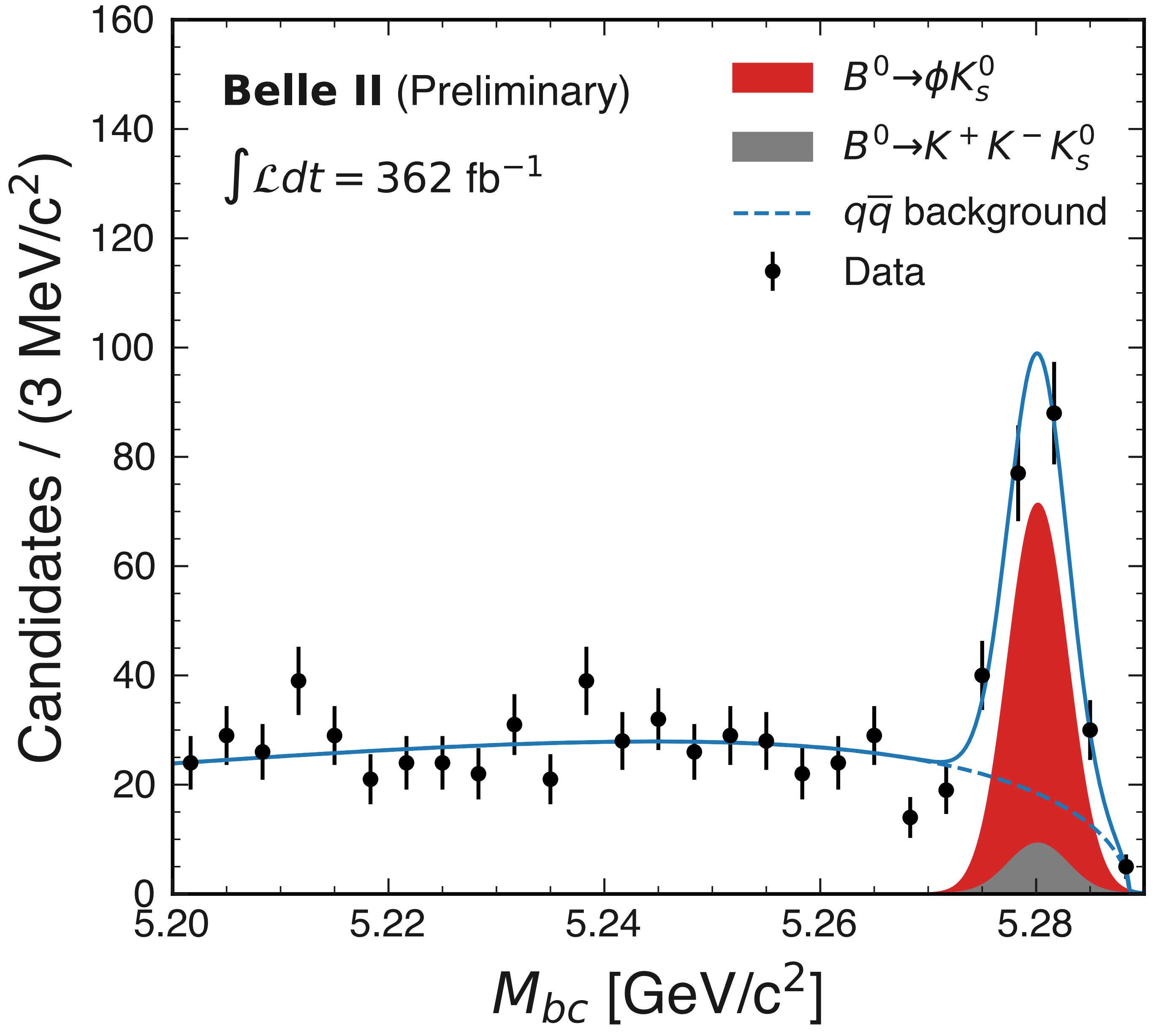
$$S_{CP} = 0.720 \pm 0.062(\text{stat}) \pm 0.016(\text{syst})$$
$$A_{CP} = 0.094 \pm 0.044(\text{stat})^{+0.042}_{-0.017}(\text{syst})$$

HFLAV: S = 0.699±0.017,
A = 0.005±0.015

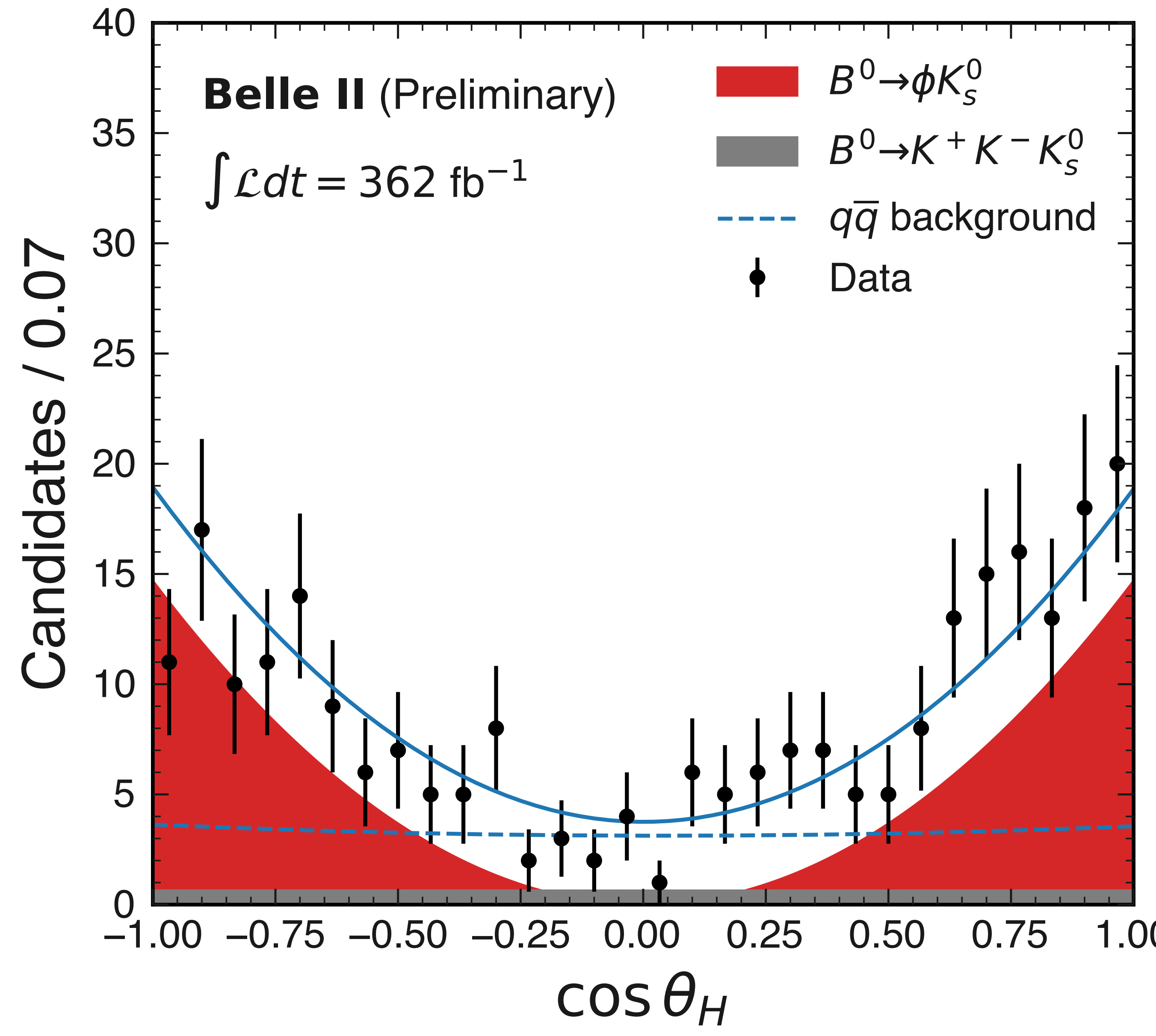
B-> φ K_S NEW FOR MORIOND

- Clean experimental signature with similar Δt resolution as B->J/ψK_S
- Main challenge: dilution from non-resonant decays with opposite CP
- Quasi-two body analysis of resonant B-> φ K_S decays
  - Non-resonant B->$K^+K^-K_S$ component disentangled in cosθ
  - Effect of neglecting interference estimated with inputs from previous Dalitz measurements

Beam-constrained mass



Cosine of the helicity angle



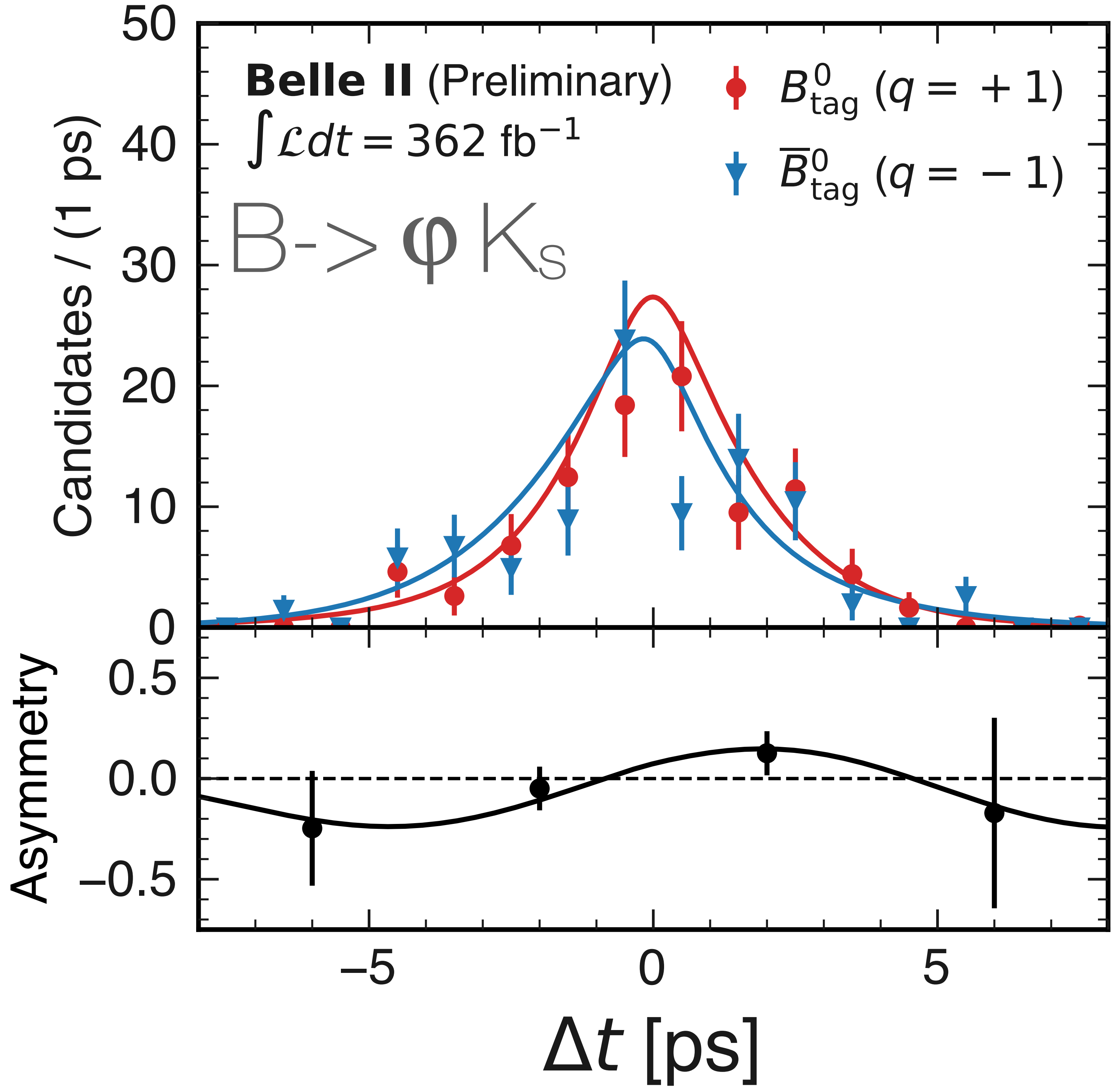
162±17 B-> φ K_S signal events with 387M $B\bar{B}$ pairs

B-> φ K_S NEW FOR MORIOND

(background subtracted)

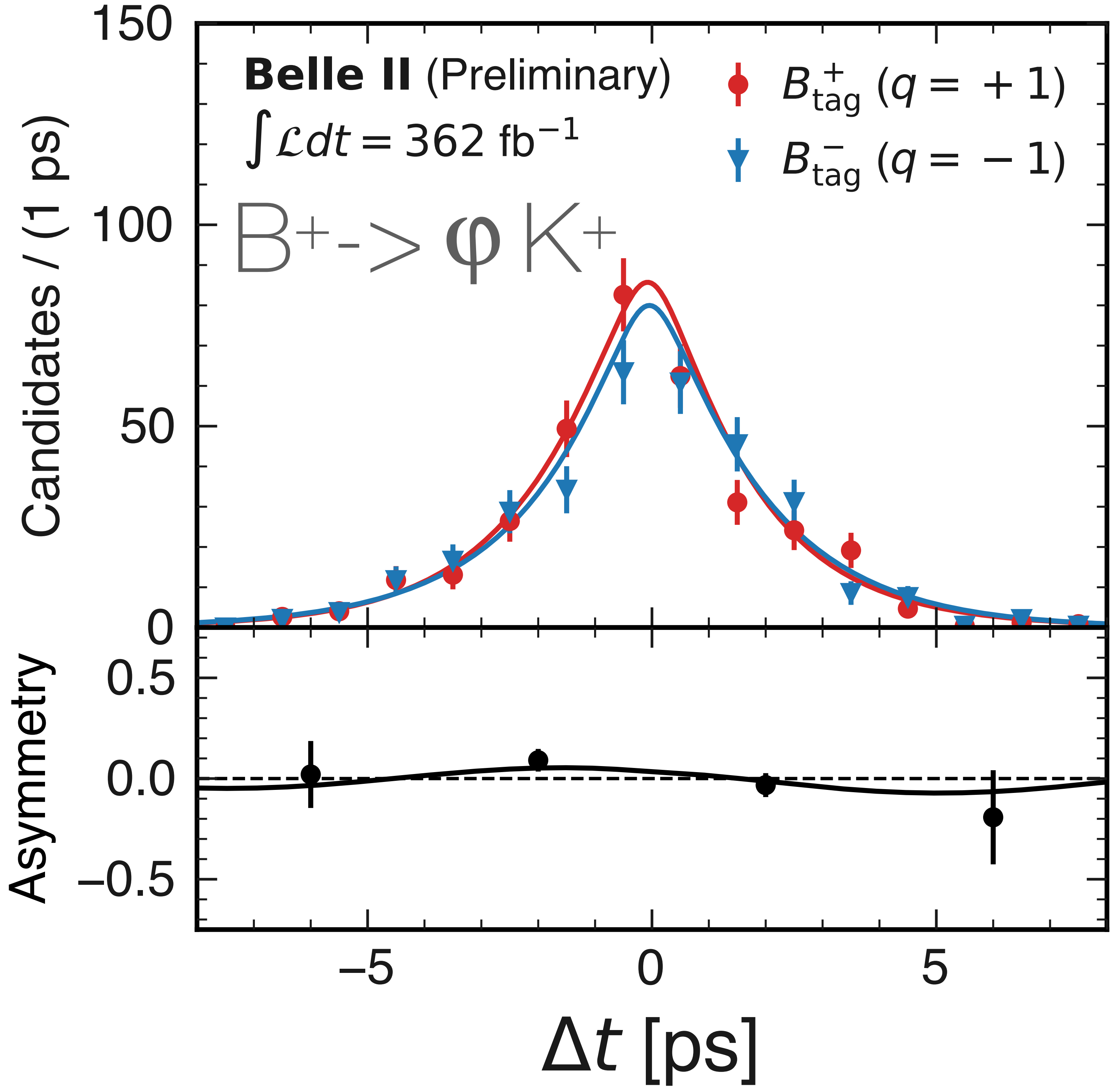
- Simultaneous Δt fit to extract the CP asymmetries
  - B->$K^+K^-K_S$ fixed from HFLAV
  - Validated on the B^+ control sample (null asymmetry)
- Mostly unique to Belle II
  - On par with most precise determinations of A_{CP}
  - 10-20% improvement on S_{CP} for the same signal yield wrt Belle/BaBar determinations

Signal channel



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

Control channel



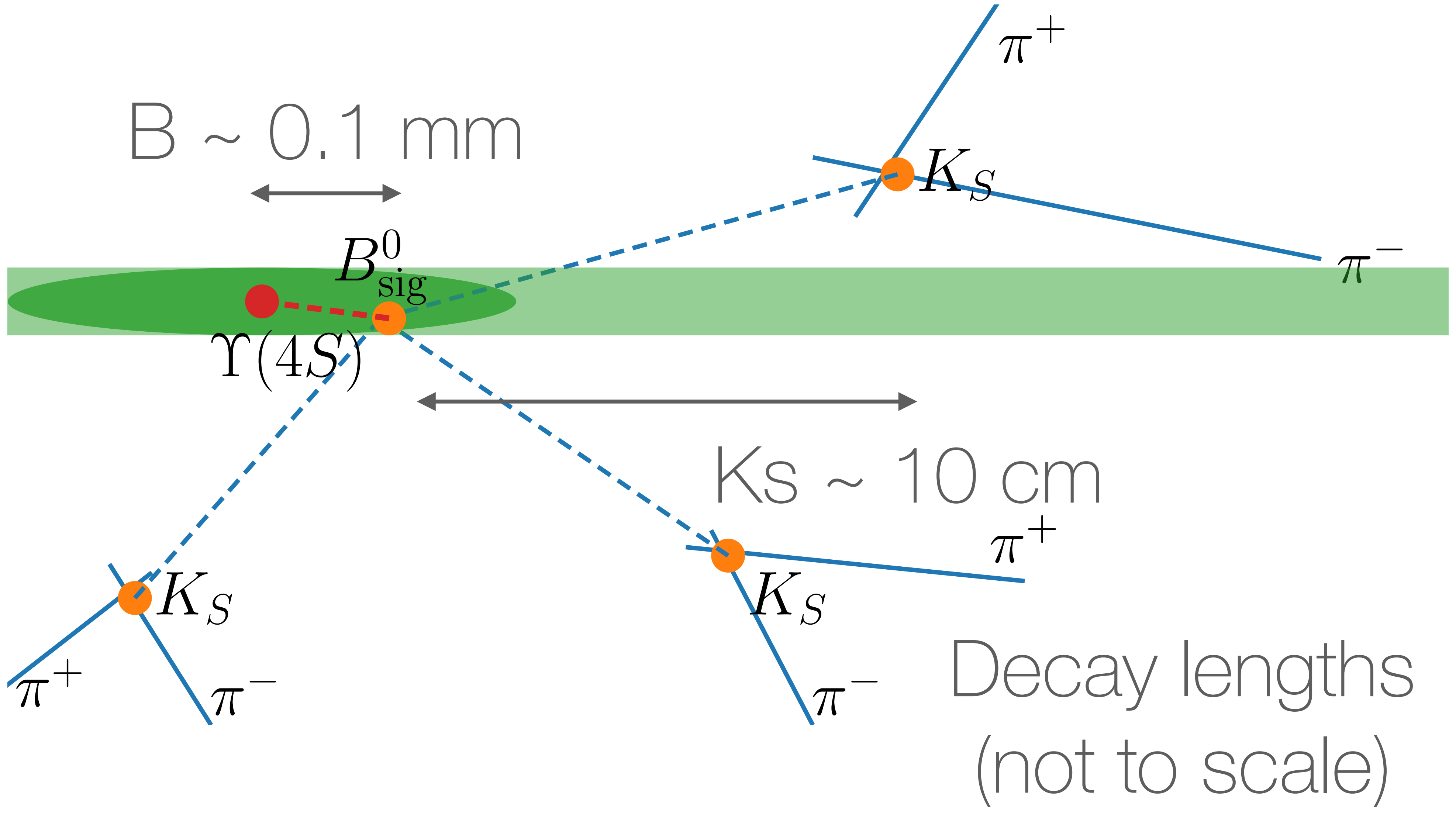
$$A_{CP} = 0.12 \pm 0.10 \text{ (stat.)}$$
$$S_{CP} = -0.09 \pm 0.12 \text{ (stat.)}$$

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

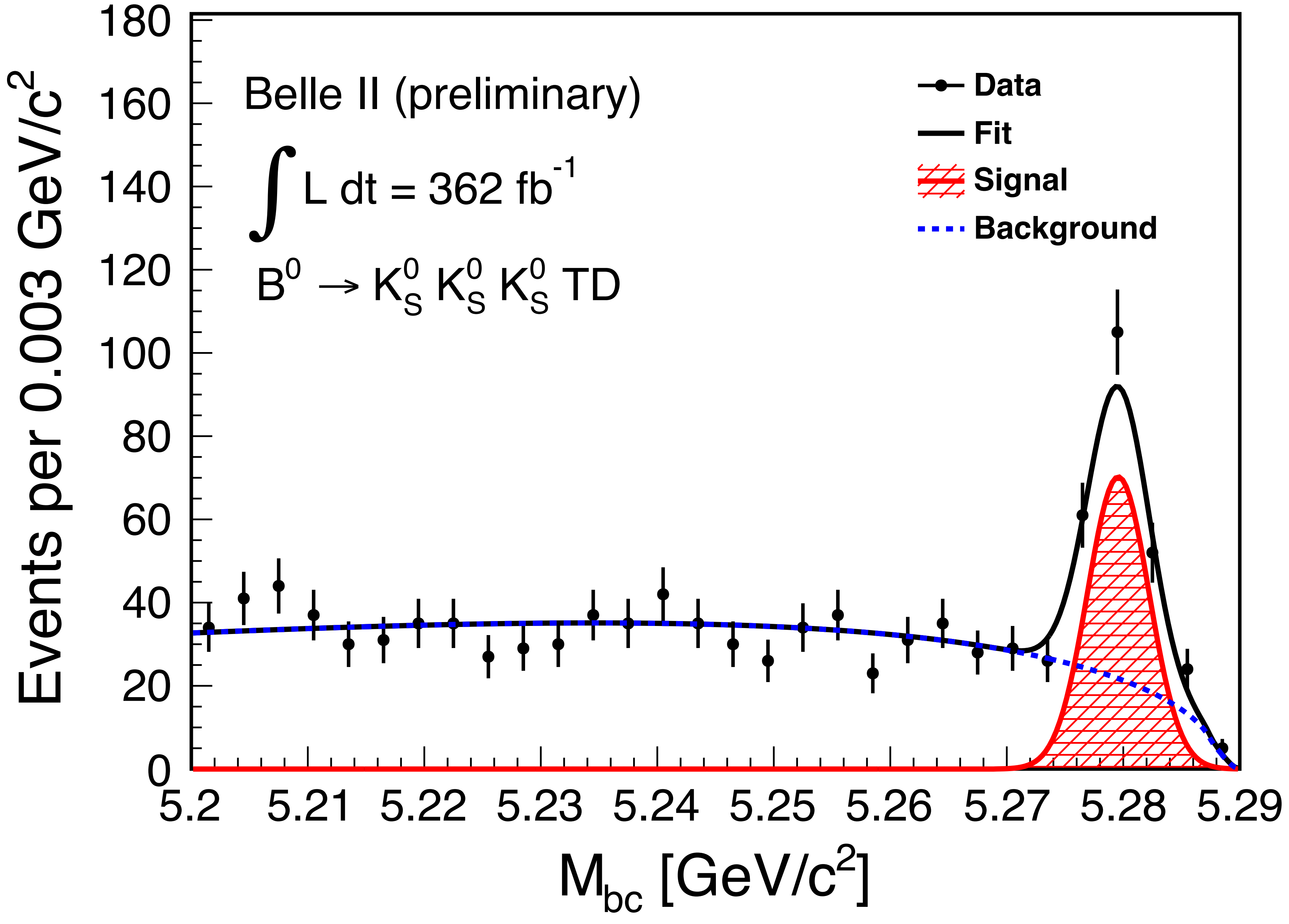
$B \to K_S K_S K_S$ NEW FOR MORIOND

- Same underlying quark transition as $B \to \varphi K_S$, w/o contributions from opposite-CP backgrounds
- Main challenge: no prompt tracks to form a vertex
  - Decay vertex reconstruction relies on the K_S trajectory and profile of the interaction point
  - Dataset divided into events with (TD) and without (TI) information from the vertex detector
- 2 BDTs to suppress fake K_S (kinematic/hits $\pi^\pm$ tracks) and continuum (event shape variables)

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



Beam-constrained mass



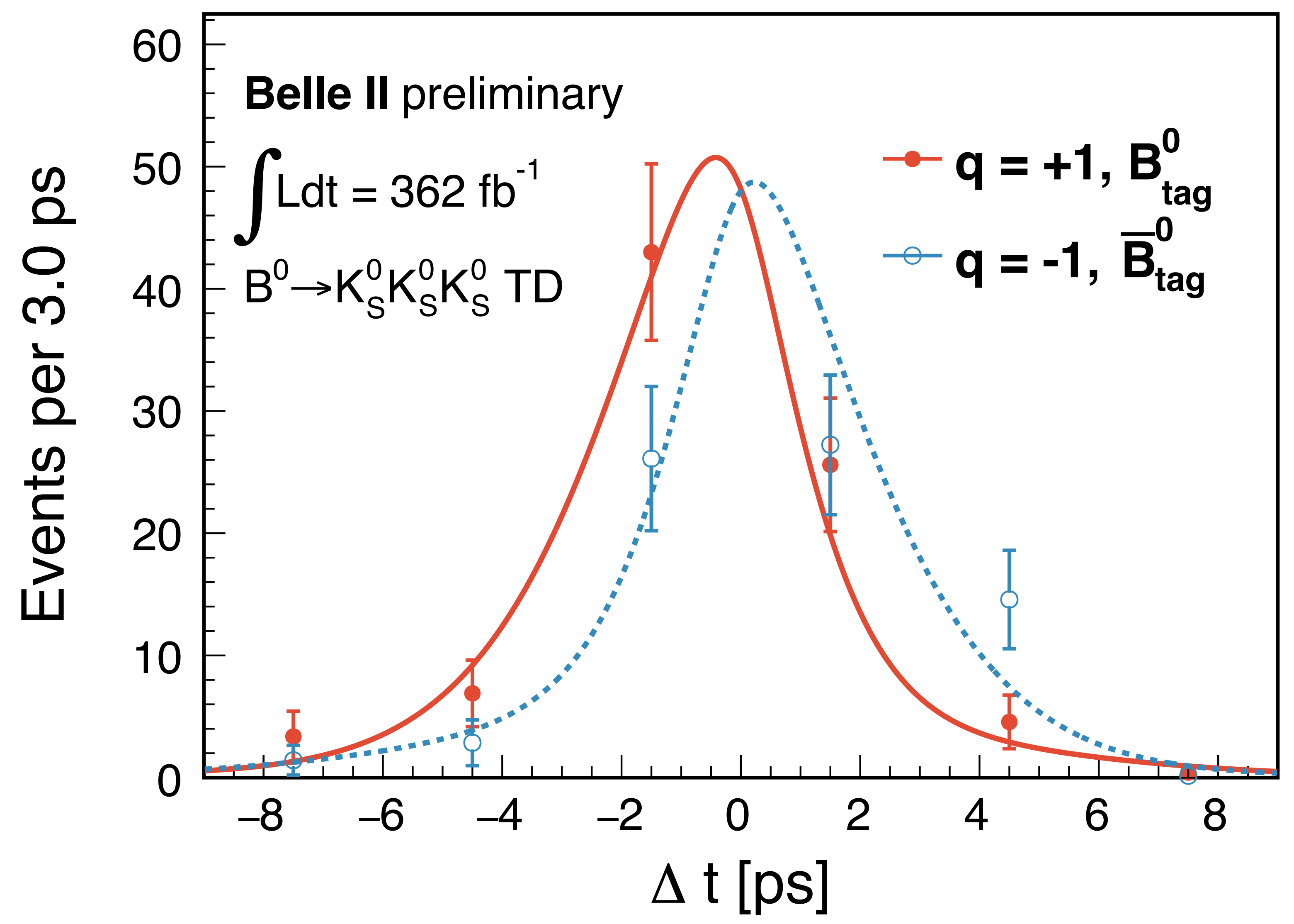
B->$K_S K_S K_S$ NEW FOR MORIOND

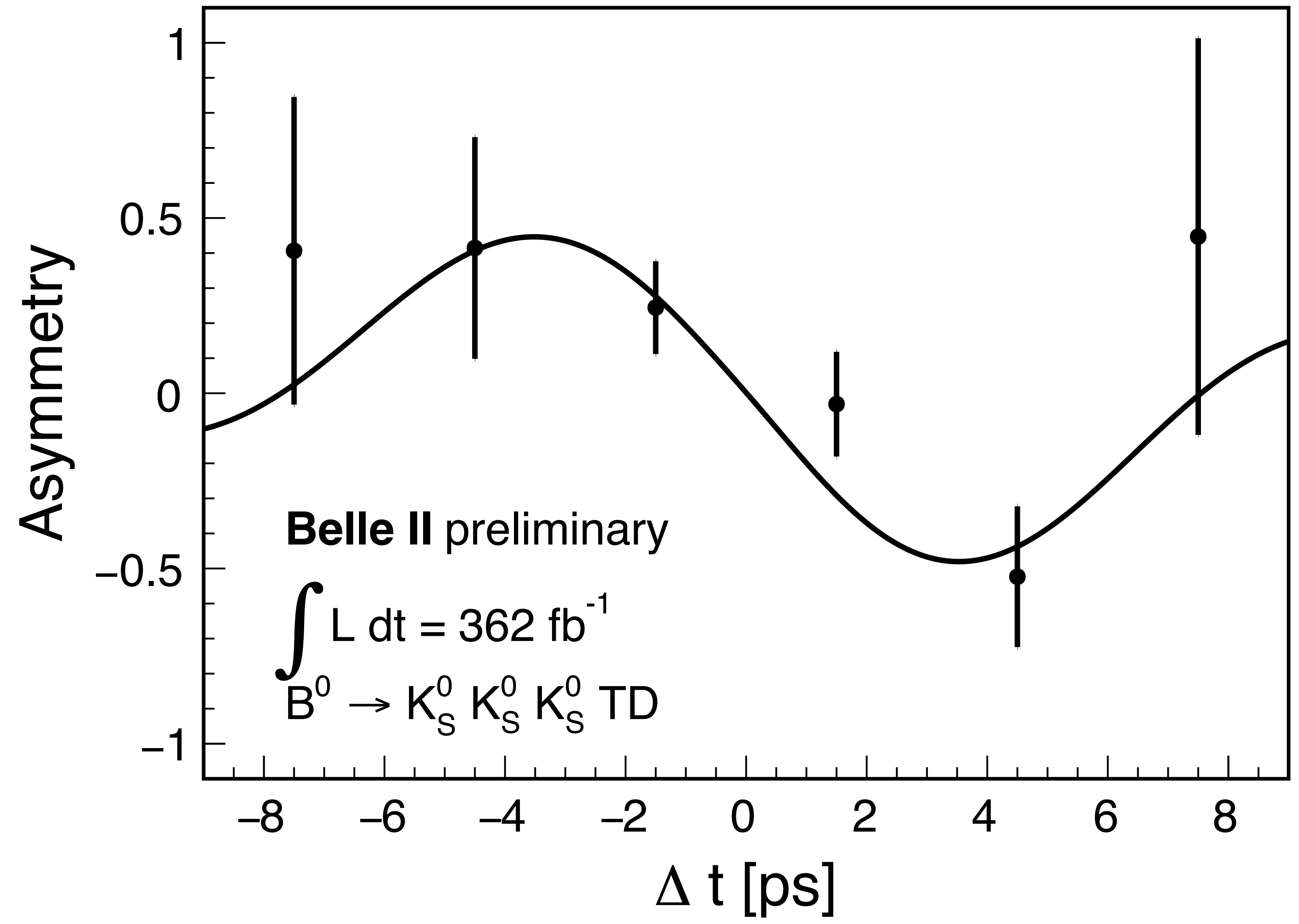
- Simultaneous fit to TI, TD events and B^+->$K_S K_S K^+$
  - TD events used in the Δt fit for the determination of A_{CP} and S_{CP}
  - TI events used only to constrain the time-integrated asymmetry A_{CP}
  - B^+->$K_S K_S K^+$ control sample to constrain background shapes and Δt resolution function
- On par with most precise determination of A_{CP} and unique to Belle II

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

HFLAV: S = -0.83±0.17, A = 0.15±0.12

(background subtracted)

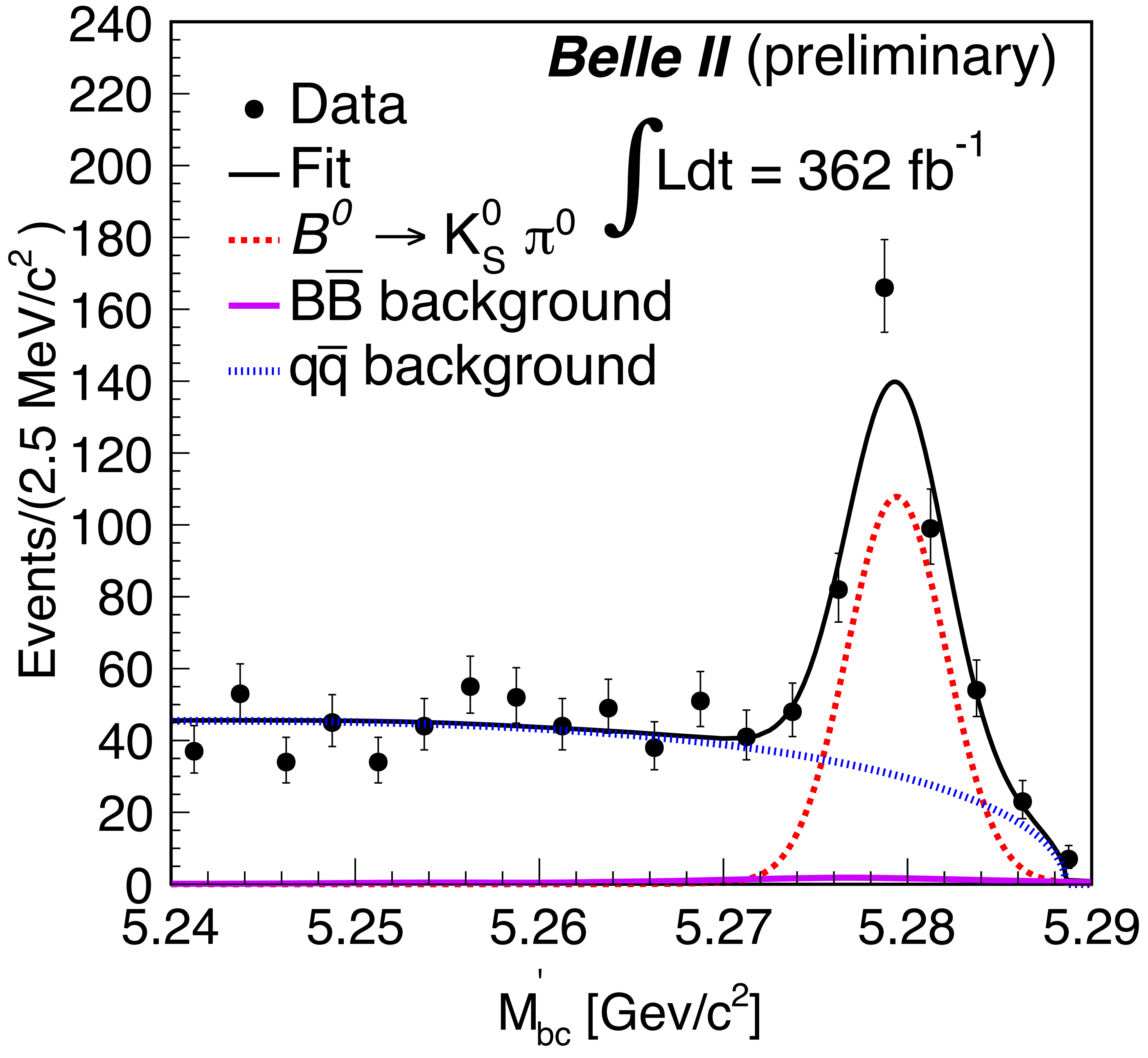




$B \to K_S\pi^0$ NEW FOR MORIOND

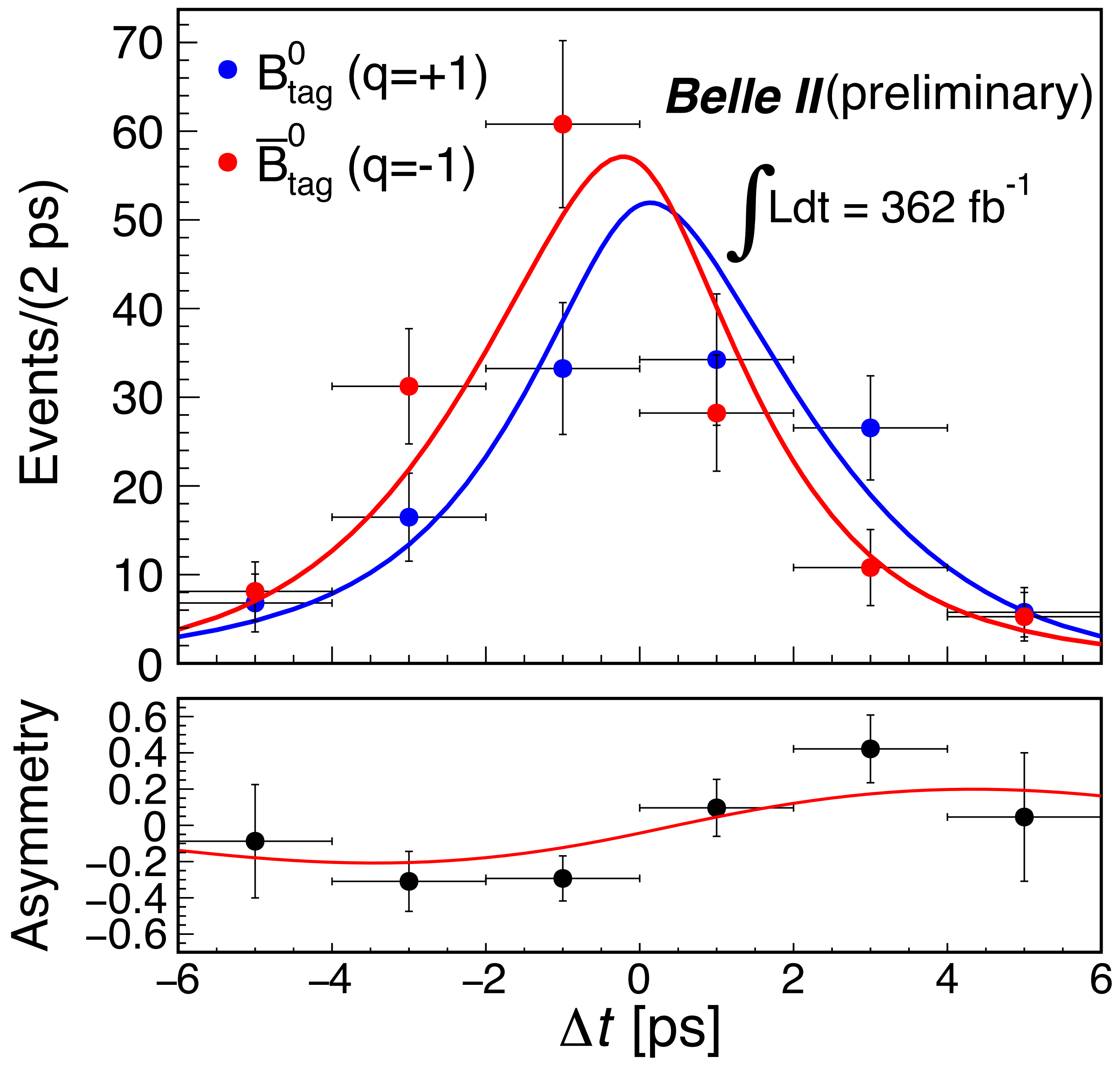
- Sensitive to effective value of $\sin2\phi_1$ and providing inputs to isospin sum-rule
  - See Sagar's talk this afternoon
- Needs excellent capabilities with neutrals, unique to Belle II
  - Validated on $B \to J/\psi K_S$ events reconstructed w/o J/ψ vertex
  - Simultaneous TI/TD fit to maximize the sensitivity on A_{CP}
- Competitive with world's best results with much less luminosity

Beam-constrained mass



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

(background subtracted)

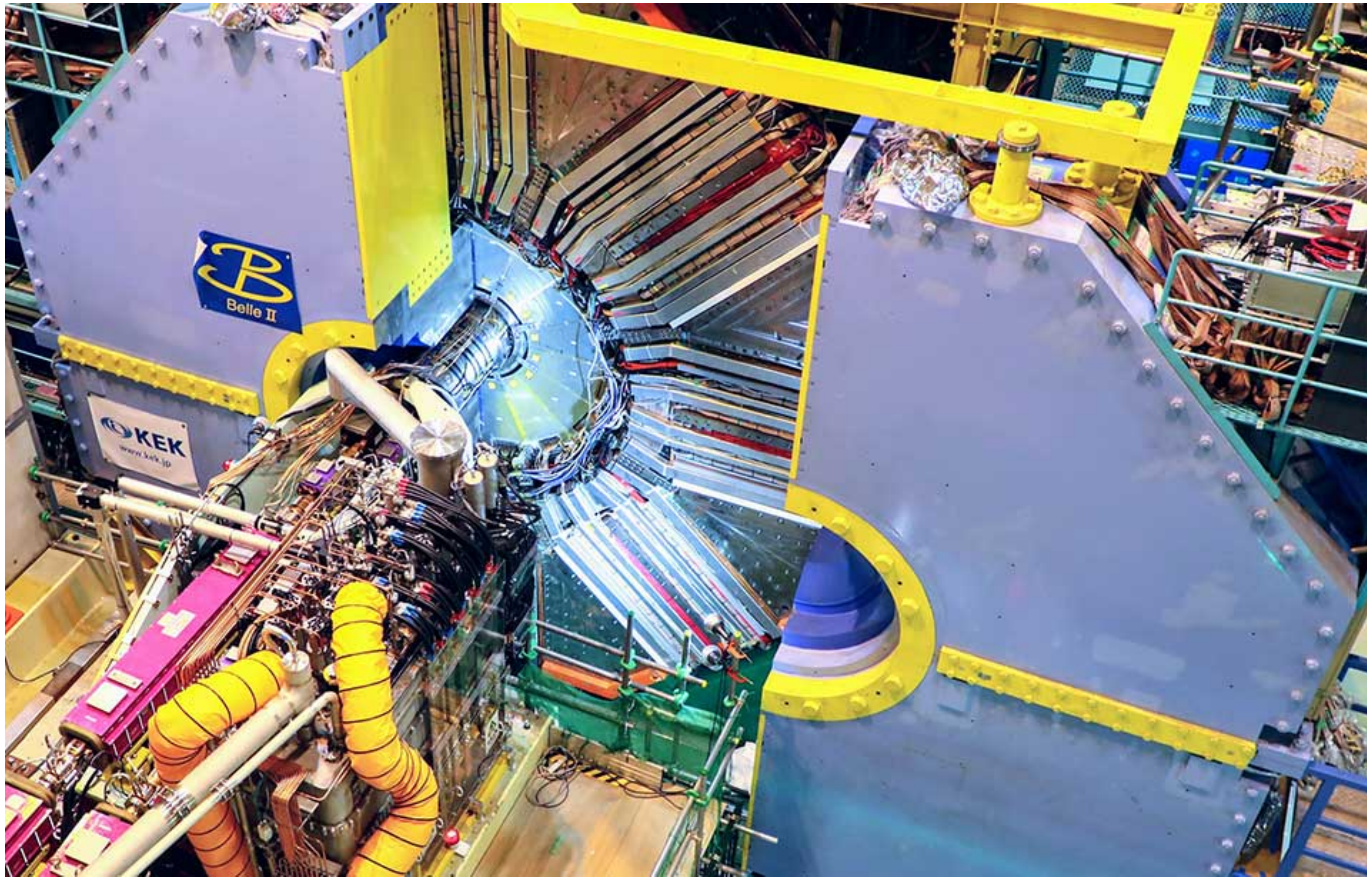


$$A_{CP} = 0.04 \pm 0.15 \pm 0.05$$
$$S_{CP} = 0.75^{+0.20}_{-0.23} \pm 0.04$$

HFLAV: S = 0.57±0.17, A = -0.01±0.10

Summary

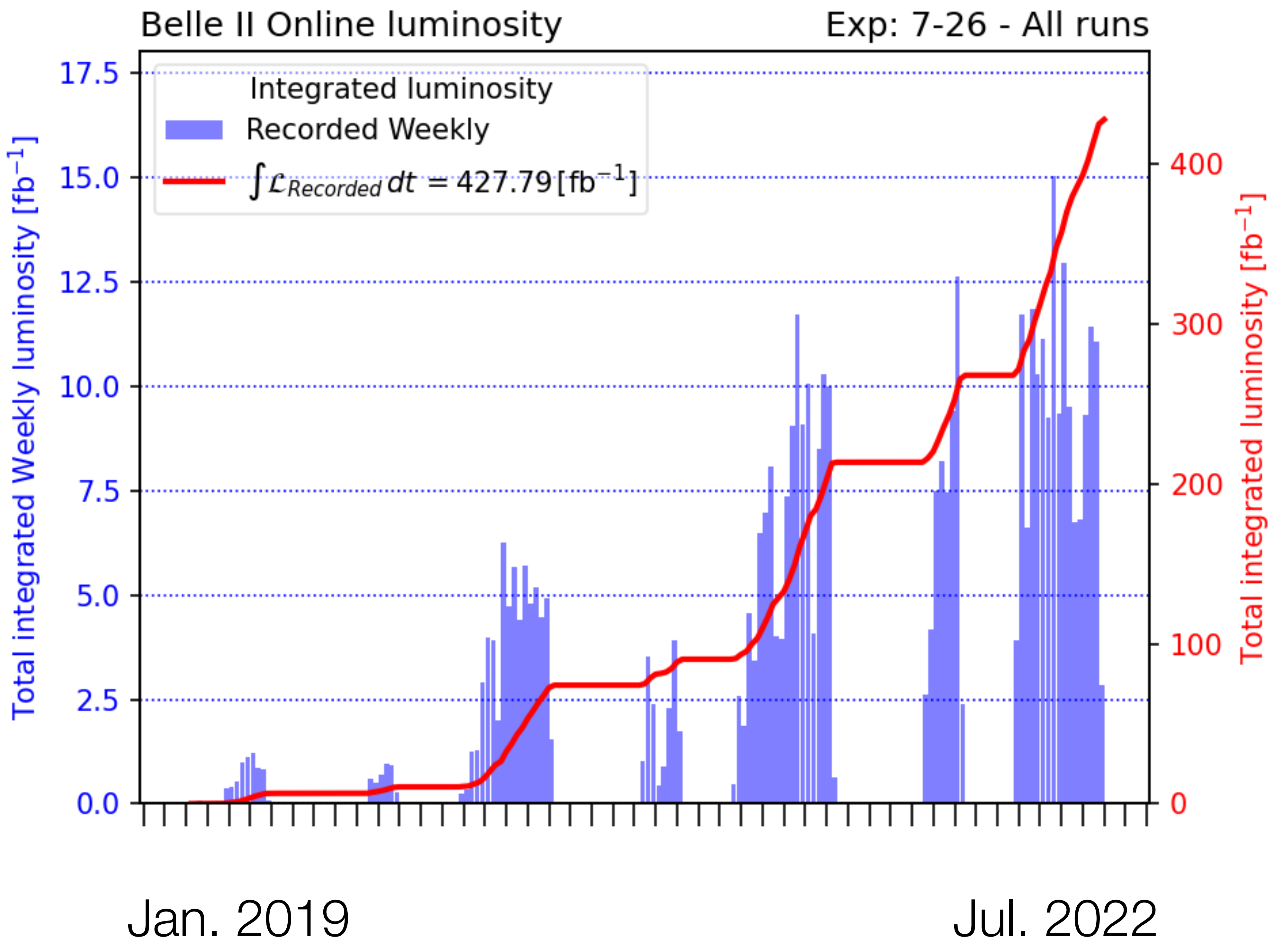
- **3 new results** on time-dependent CP observables with penguins for Moriond
  - Precision on par with world's best determinations in spite of much less luminosity
- These measurements are essential to probe generic BSM physics in loops
  - Belle II is in a unique position to improve our current experimental knowledge on these modes



Backup

Collected luminosity

- Collected 424 fb^{-1} in 2019-2022
  - 362 fb^{-1} at 4S (387×10^6 $B\bar{B}$ pairs)
  - 42.3 fb^{-1} at 4S off-resonance
  - 78 pb^{-1} at 4S scan
  - 19.7 fb^{-1} at energy scan



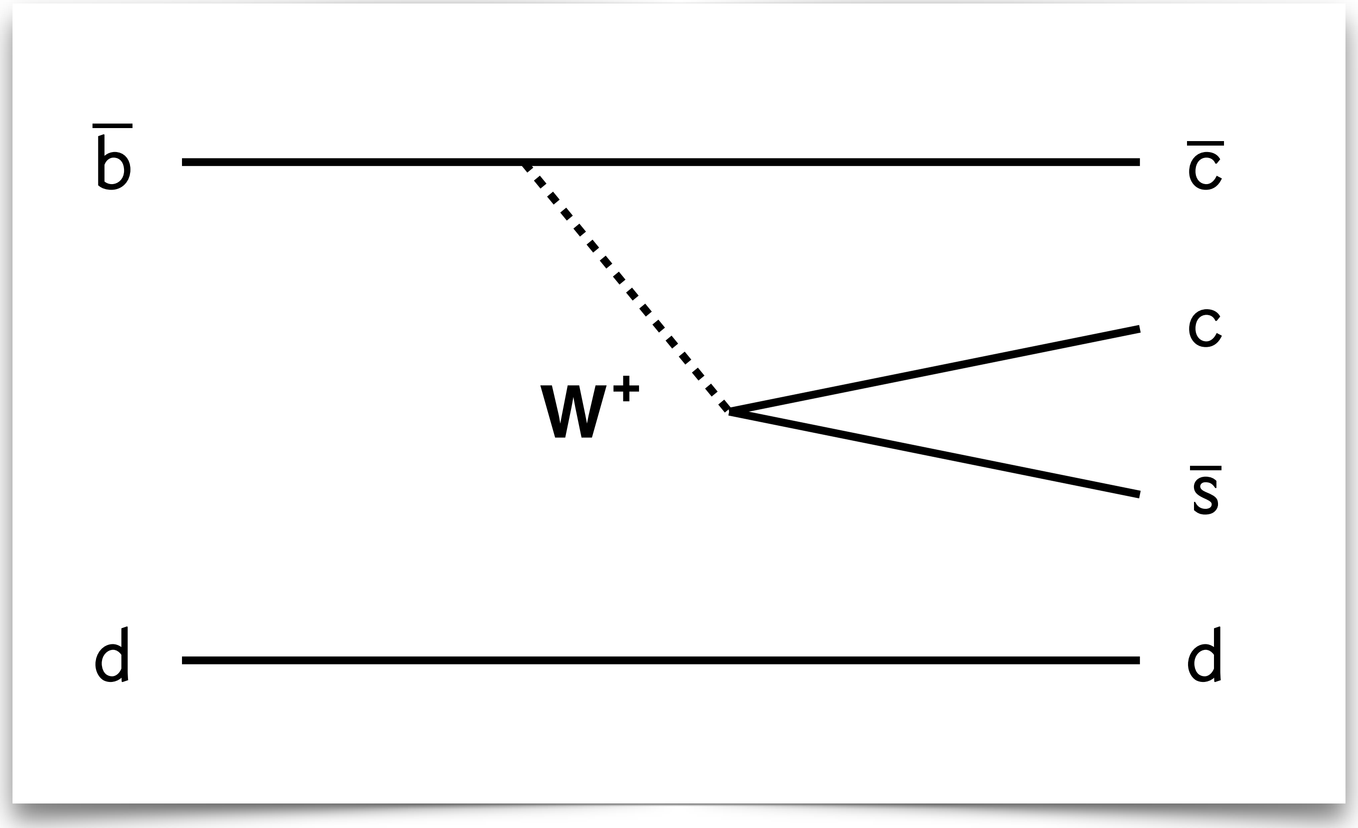
Long-shutdown activity and plans

Belle II stopped taking data in Summer 2022 for a long shutdown for

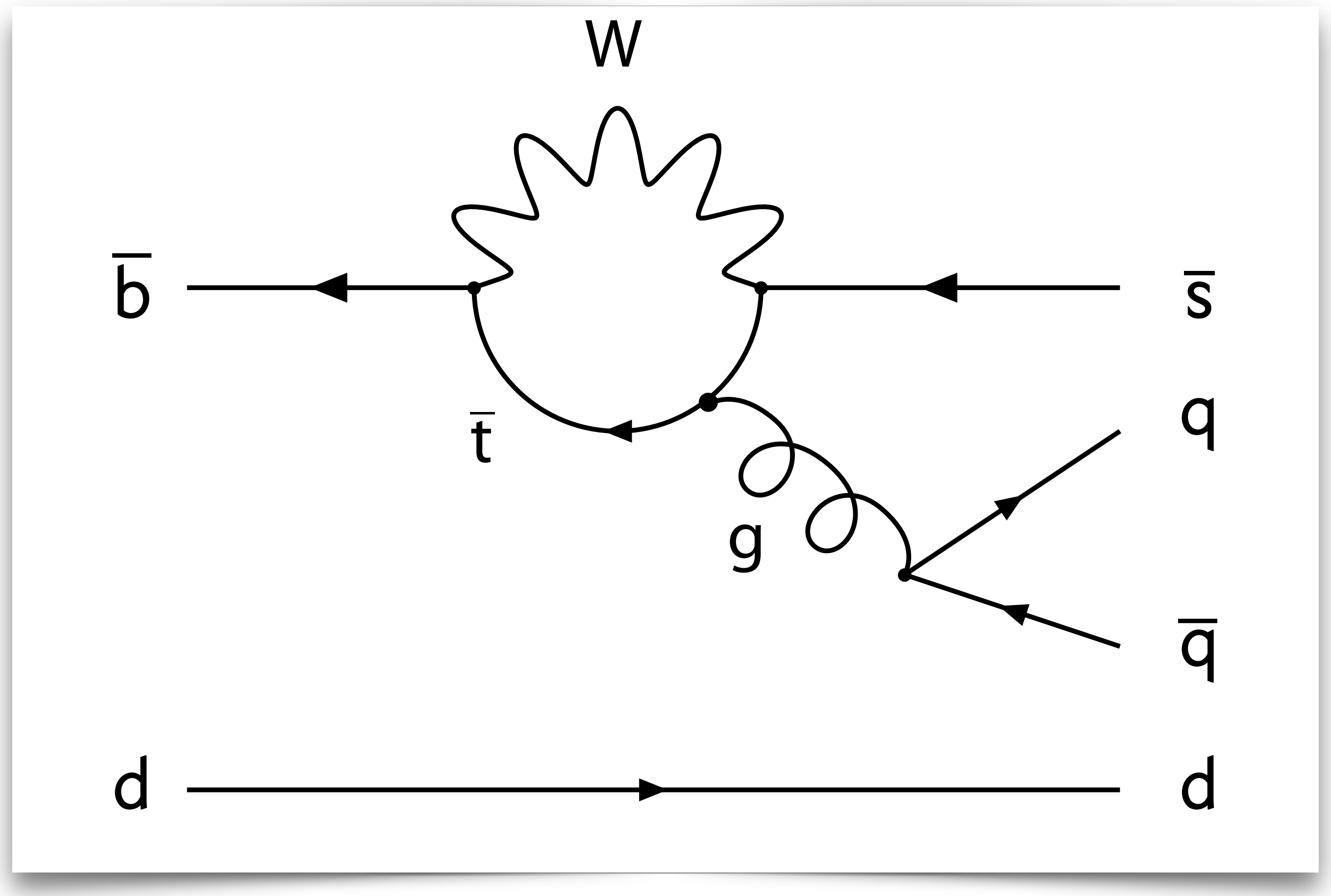
- replacement of beam-pipe
- replacement of photomultipliers of the central PID detector (TOP)
- installation of 2-layered pixel vertex detector
- improved data-quality monitoring and alarm system
- complete transition to new DAQ boards (PCIe40)
- replacing of ageing components
- additional shielding and increased resilience against beam background

Currently working on pixel detector installation:
- shipping to KEK in mid March
- final test in KEK scheduled in April

On track to resume data taking next Winter with new pixel detector.



“Tree” $b \to c\bar{c}s$
e.g. B->J/ψK_S



“Penguin” $b \to q\bar{q}s$
e.g. B-> φ K_S, B->$K_S\pi^0$,
B->$K_SK_SK_S$

$b \to c\bar{c}s$

Experiment		Sample size	$-\eta S_{b\to c\bar{c}s}$	$C_{b\to c\bar{c}s}$
		Most precise		
BABAR $b \to c\bar{c}s$	[324]	$N(B\overline{B}) = 465\text{M}$	$0.687 \pm 0.028 \pm 0.012$	$0.024 \pm 0.020 \pm 0.016$
Belle $b \to c\bar{c}s$	[325]	$N(B\overline{B}) = 772\text{M}$	$0.667 \pm 0.023 \pm 0.012$	$-0.006 \pm 0.016 \pm 0.012$
LHCb $J/\psi K^0_S$	[326, 327]	$\int \mathcal{L}\, dt = 3\ \text{fb}^{-1}$	0.75 ± 0.04	-0.014 ± 0.030
LHCb $\psi(2S)K^0_S$	[327]	$\int \mathcal{L}\, dt = 3\ \text{fb}^{-1}$	$0.84 \pm 0.10 \pm 0.01$	$-0.05 \pm 0.10 \pm 0.01$
Belle II (200M BB pairs) [arXiv:2302.12898]			$0.720 \pm 0.062 \pm 0.016$	$-0.094 \pm 0.044^{+0.042}_{-0.017}$

$b \to q\bar{q}s$

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)			$0.54 \pm 0.26^{+0.06}_{-0.08}$	$-0.31 \pm 0.20^{+0.05}_{-0.06}$
			$K^0_S K^0_S K^0_S$	
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)			$0.74^{+0.20}_{-0.23} \pm 0.04$	$-0.04 \pm 0.15 \pm 0.05$

Systematic uncertainties (1)

B->D(*)π

TABLE I. Systematic uncertainties.

Source	τ_{B^0} [ps]	Δm_d [ps^{-1}]
Fixed response-function parameters	0.006	0.003
Analysis bias	0.004	0.001
Detector alignment	0.003	0.002
Interaction-region precision	0.002	0.001
C-Distribution modeling	0.000	0.001
$\sigma_{\Delta t_\ell}$-Distribution modeling	0.001	0.001
Correlations of ΔE or C and Δt_ℓ	0.001	0.000
Total systematic uncertainty	0.008	0.005
Statistical uncertainty	0.013	0.008

B->J/ψKS

TABLE II. Summary of the individual sources of uncertainties.

Source	$\sigma(S_{CP})$	$\sigma(A_{CP})$
Statistical	0.0622	0.0439
Calibration with $B^0 \to D^{(*)-}\pi^+$decays		
$B^0 \to D^{(*)-}\pi^+$sample size	0.0111	0.0093
Signal charge-asymmetry	0.0027	0.0126
$w_6^+ = 0$ limit	0.0014	0.0001
Fit model		
Analysis bias	0.0080	0.0020
Fixed resolution parameters	0.0039	0.0008
$\sigma_{\Delta t}$ binning	0.0050	0.0051
τ_{B^0}, Δm_d	0.0007	0.0002
Δt measurement		
Alignment	0.0020	0.0042
Beam spot	0.0024	0.0020
Momentum scale	0.0005	0.0013
$B^0 \to J/\psi K_S^0$ ΔE background shape	0.0037	0.0015
Multiple candidates	0.0005	0.0008
CP violation in $B^0_{\rm tag}$ decays	0.0020	${}^{+0.0380}_{-0.0000}$
Total systematic	0.0163	${}^{+0.0418}_{-0.0174}$

Systematic uncertainties (2)

$B \to K_S \pi^0$

Source	δA_{CP}	δS_{CP}
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 modelling	0.004	0.003
Background modelling	0.006	0.018
Possible fit bias	0.005	0.011
External inputs	< 0.001	< 0.001
Tag-side interference	0.008	0.010
VXD misalignment	0.004	0.005
Total	0.045	0.039

$B \to K_S K_S K_S$

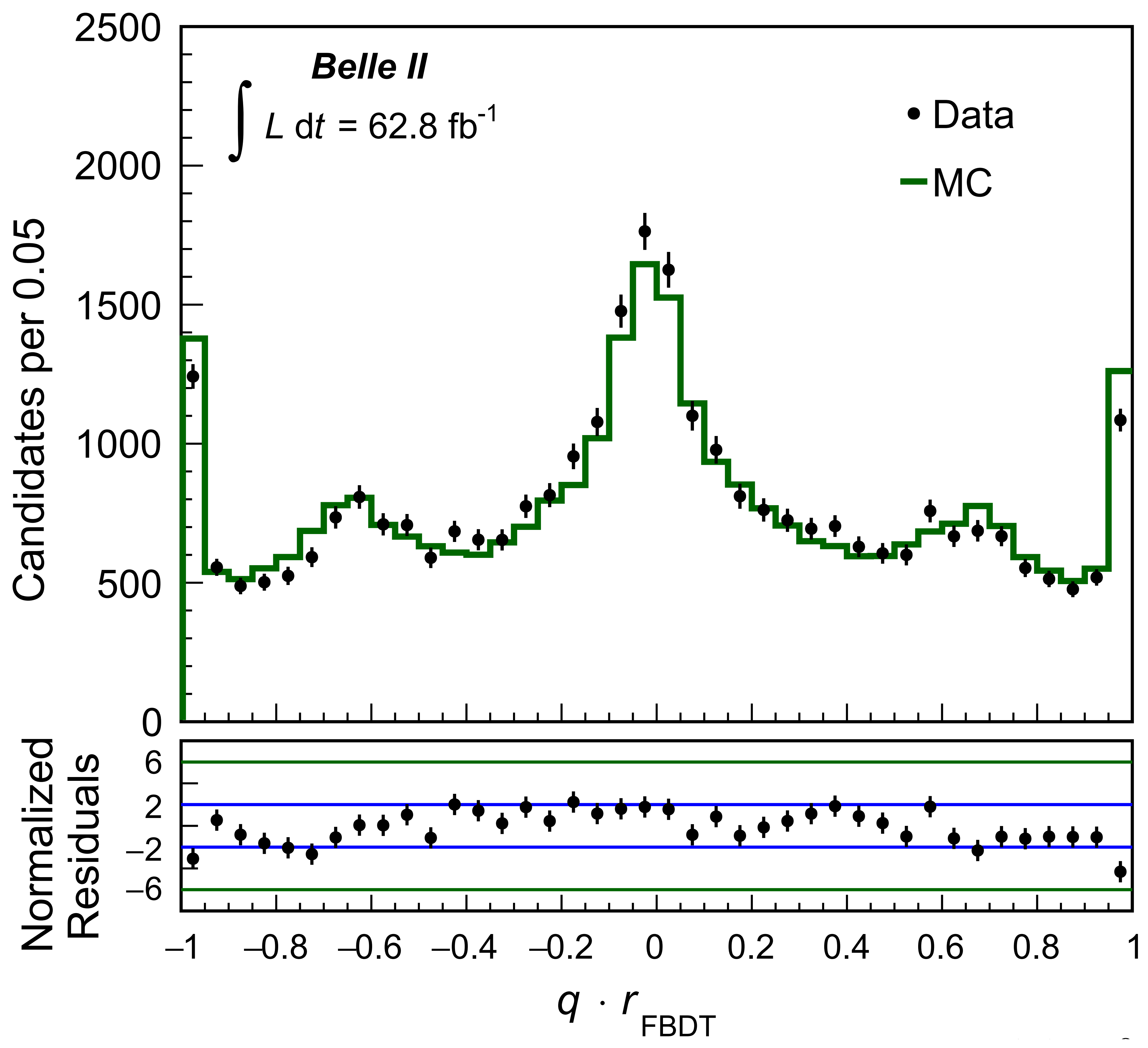
Source	$\delta \mathcal{S}$	$\delta \mathcal{A}$
Signal probability	0.014	0.008
Fit bias	0.014	0.004
Flavor tagging	0.013	0.012
Resolution function	0.013	0.008
Tag-side interference	0.011	0.006
Vertex reconstruction	0.011	0.004
Physics parameters	0.009	0.000
Detector misalignment	0.008	0.007
Background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

$B \to \phi K_S$

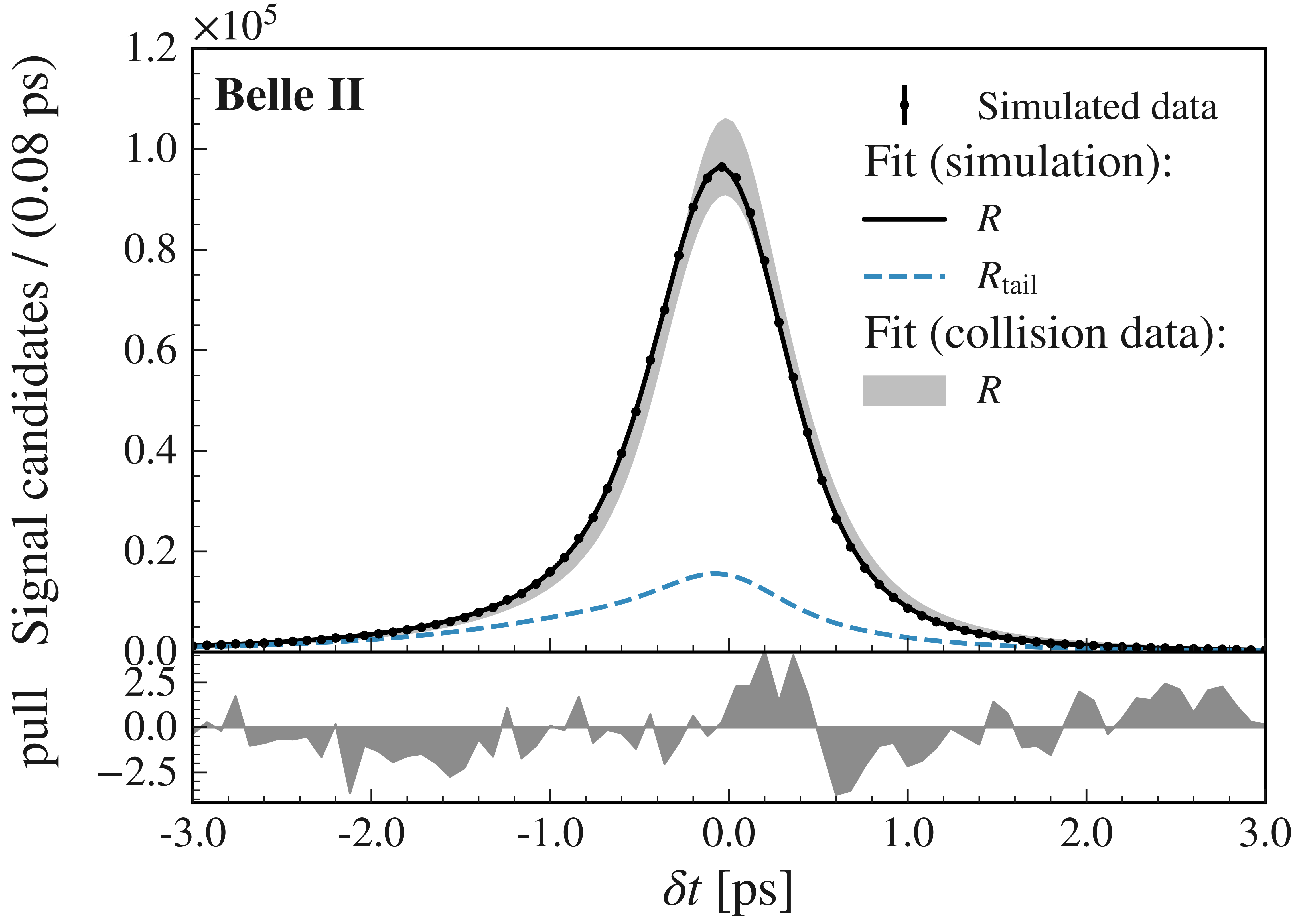
Source	$\sigma(A_{CP})$	$\sigma(S_{CP})$
Calibration with $B^0 \to D^{(*)-}\pi^+$ decays		
Calibration sample size	0.010	0.009
Calibration sample systematic	0.010	0.012
Portability to $B^0 \to \phi K_S^0$	$^{+0.000}_{-0.005}$	$^{+0.021}_{-0.000}$
Analysis model		
Fit bias	$^{+0.017}_{-0.028}$	$^{+0.033}_{-0.062}$
Correlations between observables	$^{+0.000}_{-0.030}$	$^{+0.002}_{-0.000}$
$B^0 \to K^+K^-K_S^0$ backgrounds	$^{+0.000}_{-0.020}$	$^{+0.000}_{-0.011}$
Fixed fit shapes	0.009	0.022
τ_d and Δm_d	0.006	0.022
$A_{CP}^{K^+K^-K}$ and $S_{CP}^{K^+K^-K}$	0.014	0.013
$B\overline{B}$ backgrounds	$^{+0.030}_{-0.019}$	$^{+0.017}_{-0.031}$
Tag-side interference	$^{+0.000}_{-0.000}$	$^{+0.012}_{-0.000}$
Multiple candidates	$^{+0.032}_{-0.000}$	$^{+0.000}_{-0.003}$
Δt measurement		
Detector misalignment	$^{+0.002}_{-0.000}$	$^{+0.000}_{-0.002}$
Momentum scale	0.001	0.001
Beam spot	0.002	0.002
Δt approximation	$^{+0.000}_{-0.000}$	$^{+0.000}_{-0.018}$
Total systematic	$\mathbf{^{+0.052}_{-0.055}}$	$\mathbf{^{+0.058}_{-0.082}}$
Statistical	**0.201**	**0.256**

Flavor tagging and resolution

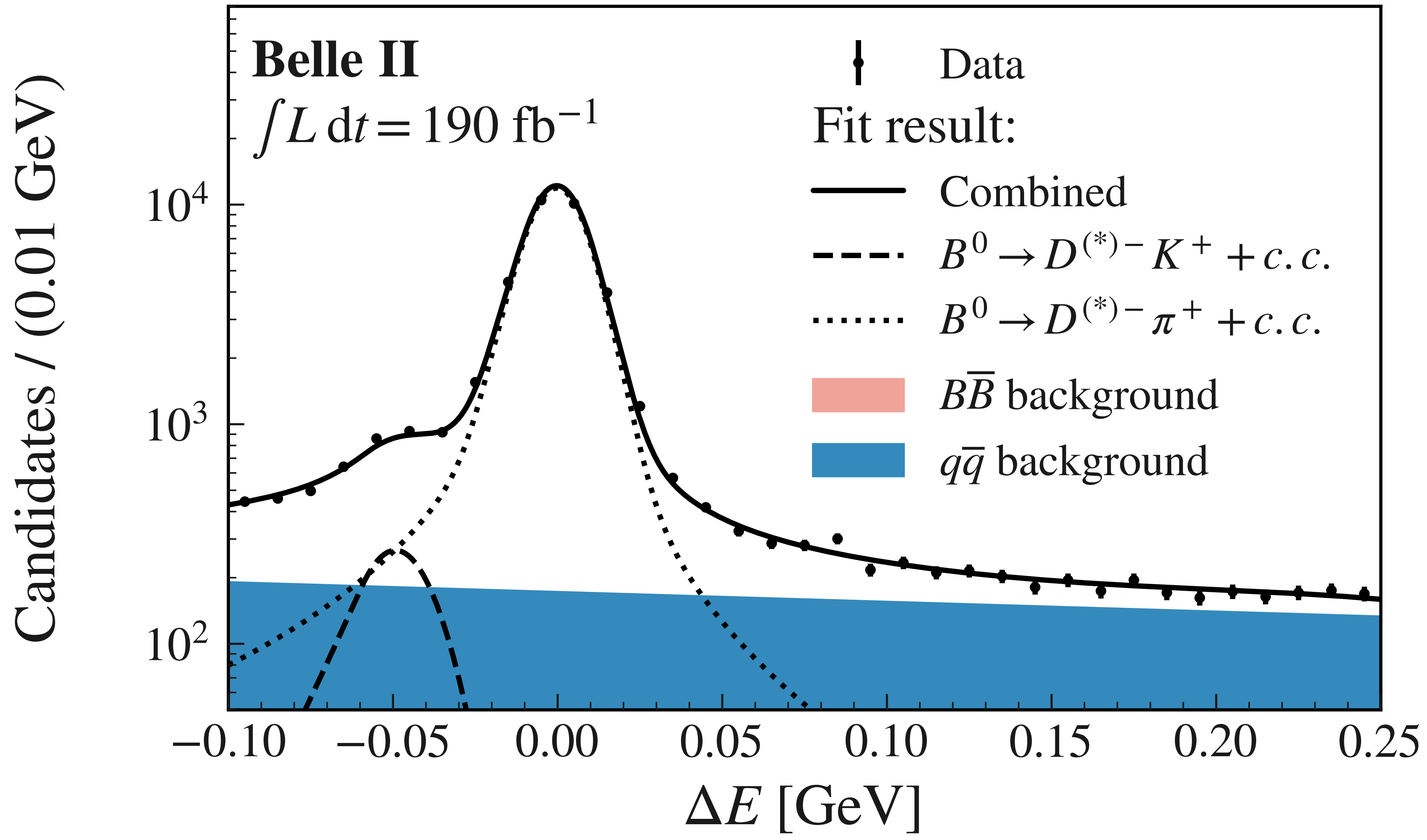
EPJC 82, 283 (2022)

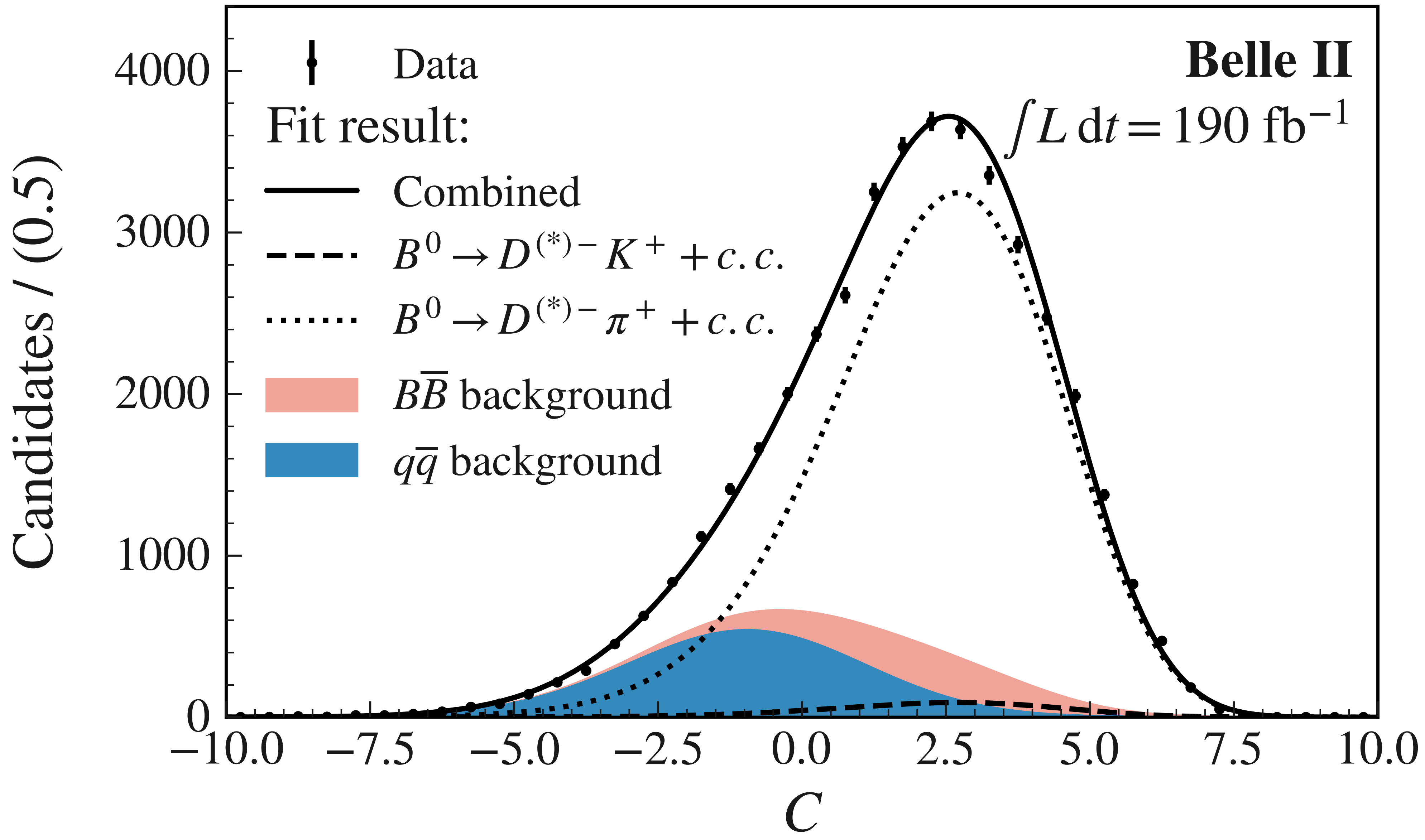


arXiv:2302.12791

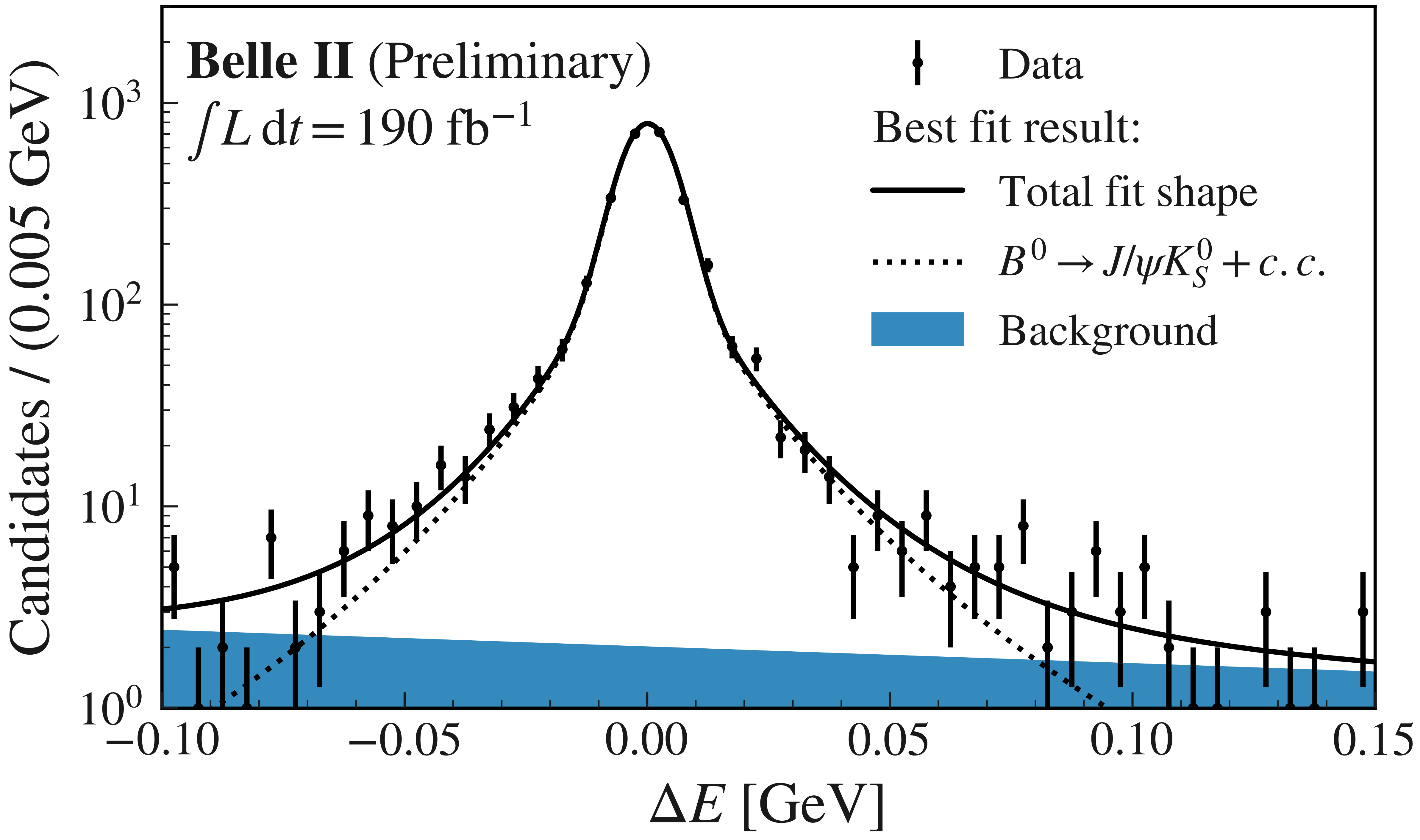


B->D(*)π


Belle II
$\int L\,dt = 190\ fb^{-1}$
Data
Fit result:
Combined
$B^0 \to D^{(*)-} K^+ + c.c.$
$B^0 \to D^{(*)-} \pi^+ + c.c.$
$B\overline{B}$ background
$q\overline{q}$ background
Candidates / (0.01 GeV)
ΔE [GeV]
10^2
10^3
10^4
−0.10
−0.05
0.00
0.05
0.10
0.15
0.20
0.25


Belle II
$\int L\,dt = 190\ fb^{-1}$
Data
Fit result:
Combined
$B^0 \to D^{(*)-} K^+ + c.c.$
$B^0 \to D^{(*)-} \pi^+ + c.c.$
$B\overline{B}$ background
$q\overline{q}$ background
Candidates / (0.5)
C
0
1000
2000
3000
4000
−10.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0

B->J/ψKs

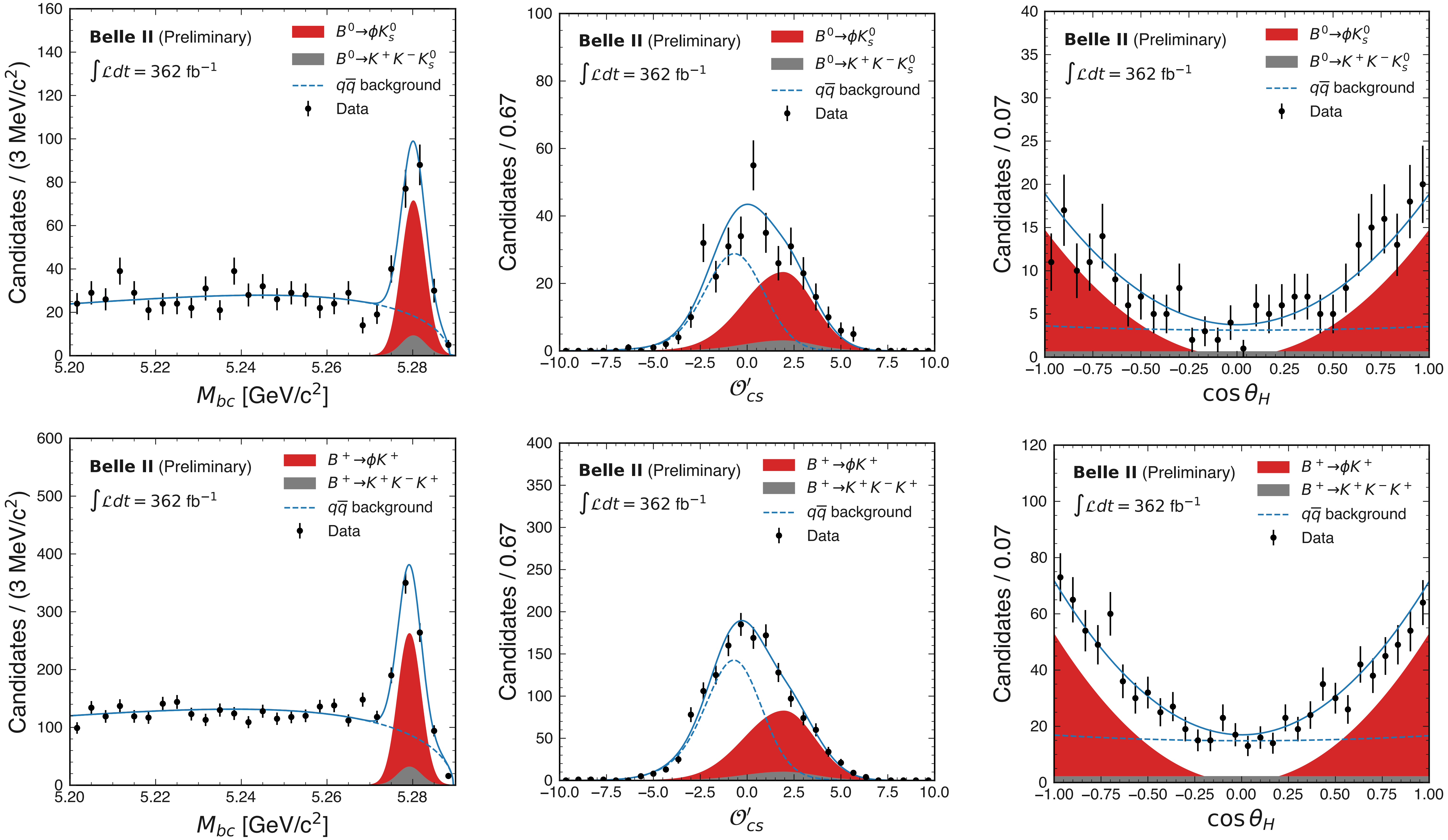


Belle II (Preliminary)
∫L dt = 190 fb⁻¹
Data
Best fit result:
Total fit shape
B⁰ → J/ψK⁰S + c. c.
Background
Candidates / (0.005 GeV)
ΔE [GeV]
10⁰
10¹
10²
10³
−0.10
−0.05
0.00
0.05
0.10
0.15

B-> φ Ks

B-> φ Ks

B+-> φ K+

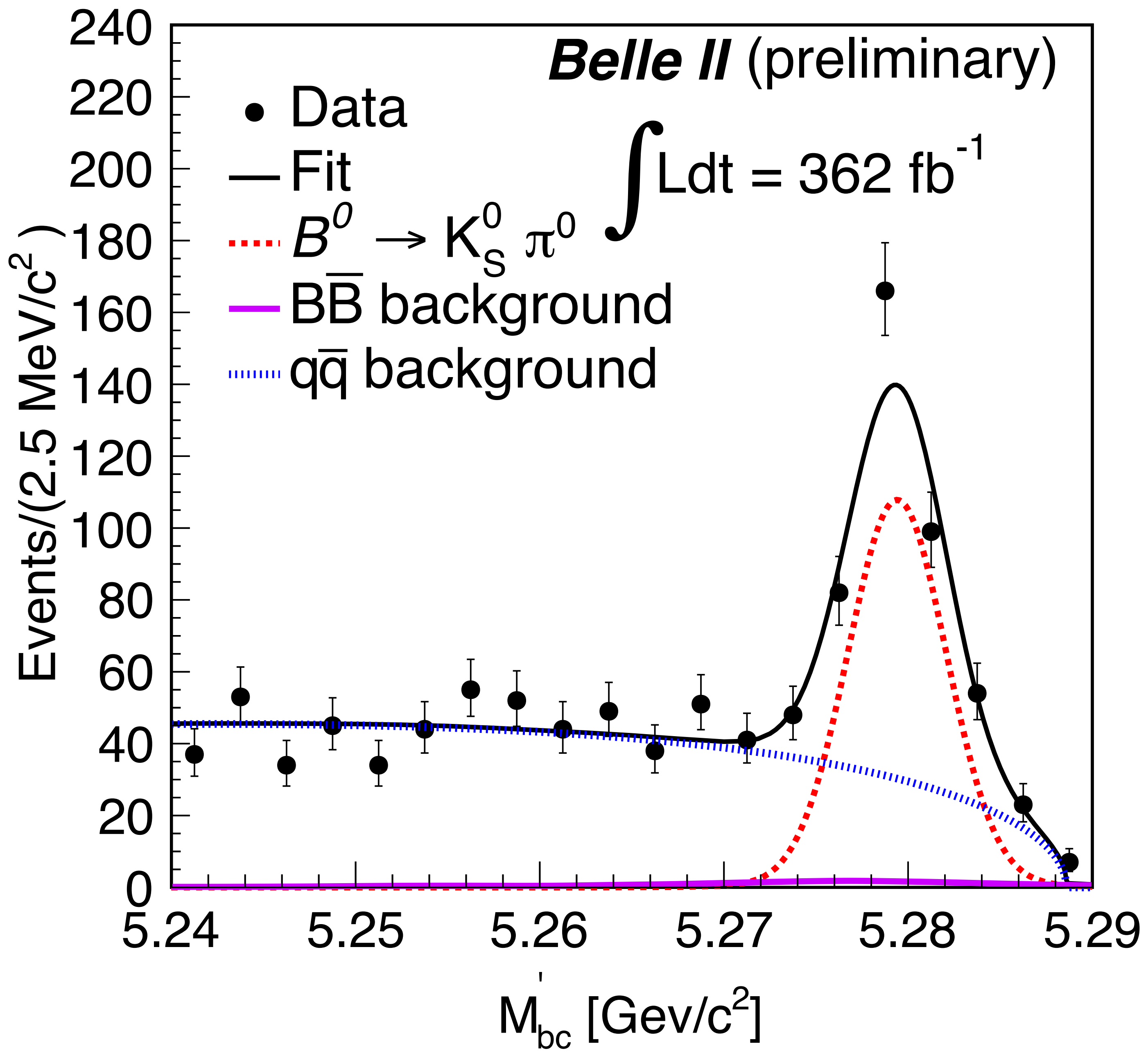


Beam-constrained mass

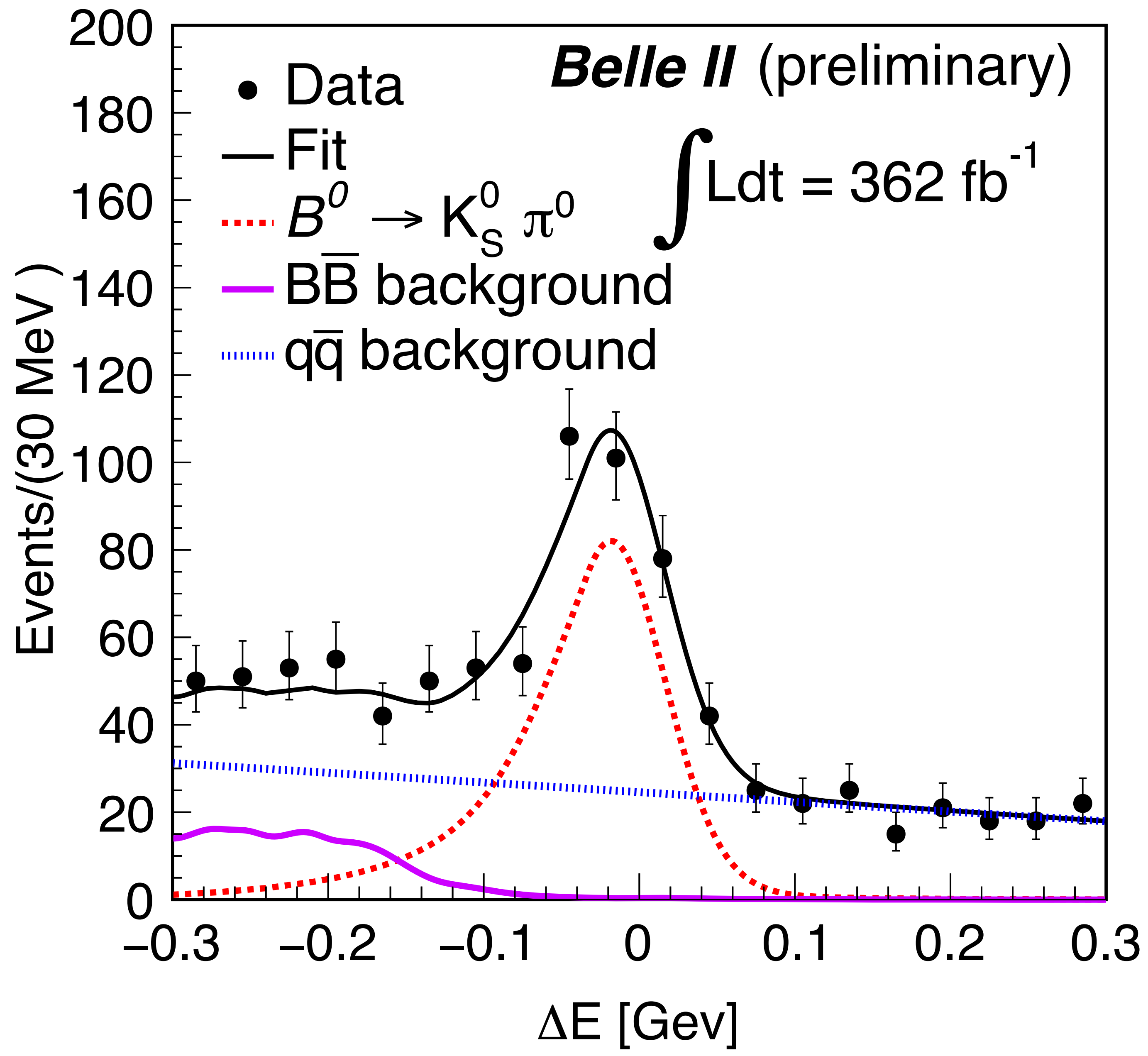
BDT output

Cosine of the helicity angle

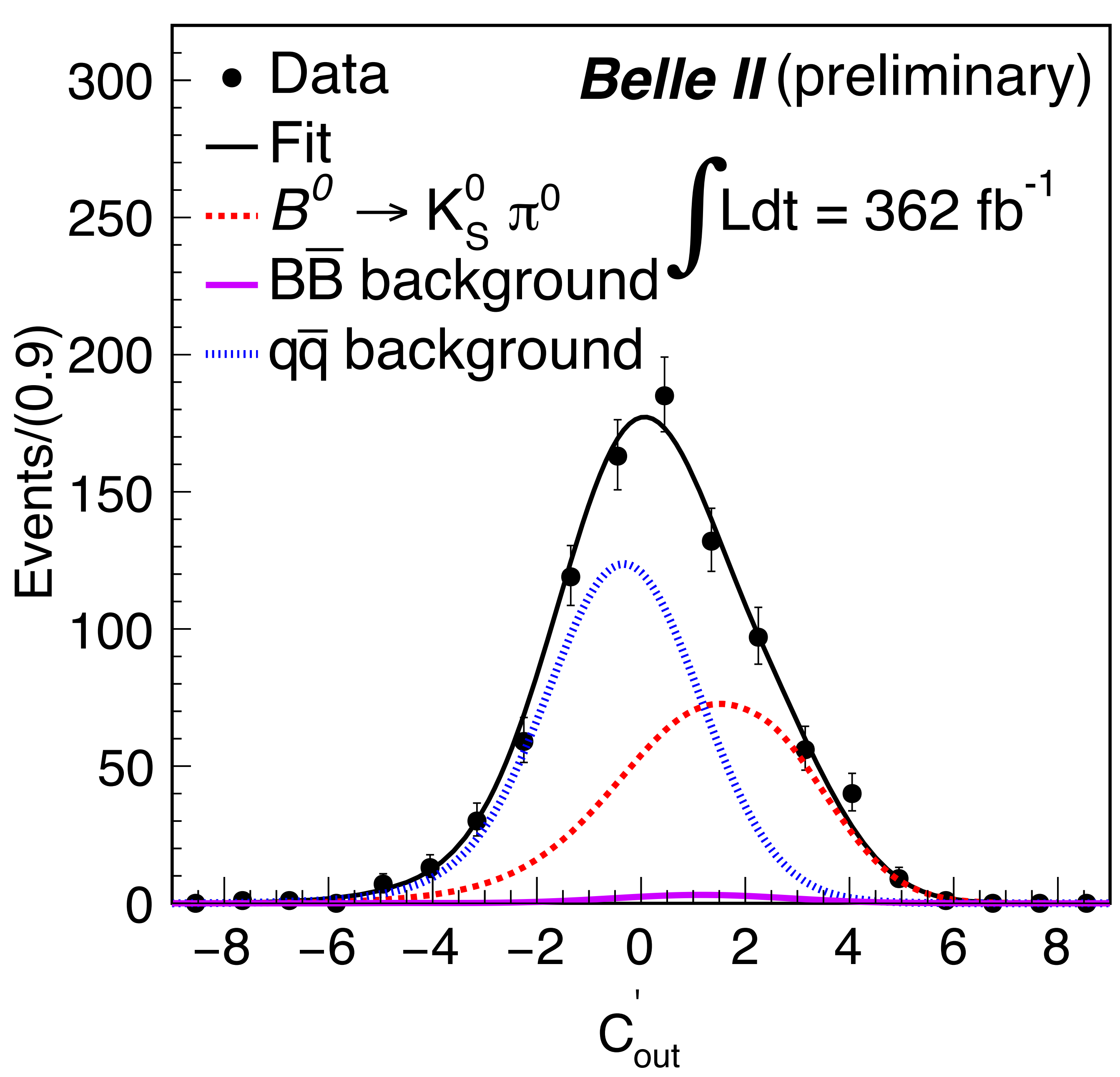
B->$K_S\pi^0$



Beam-constrained mass

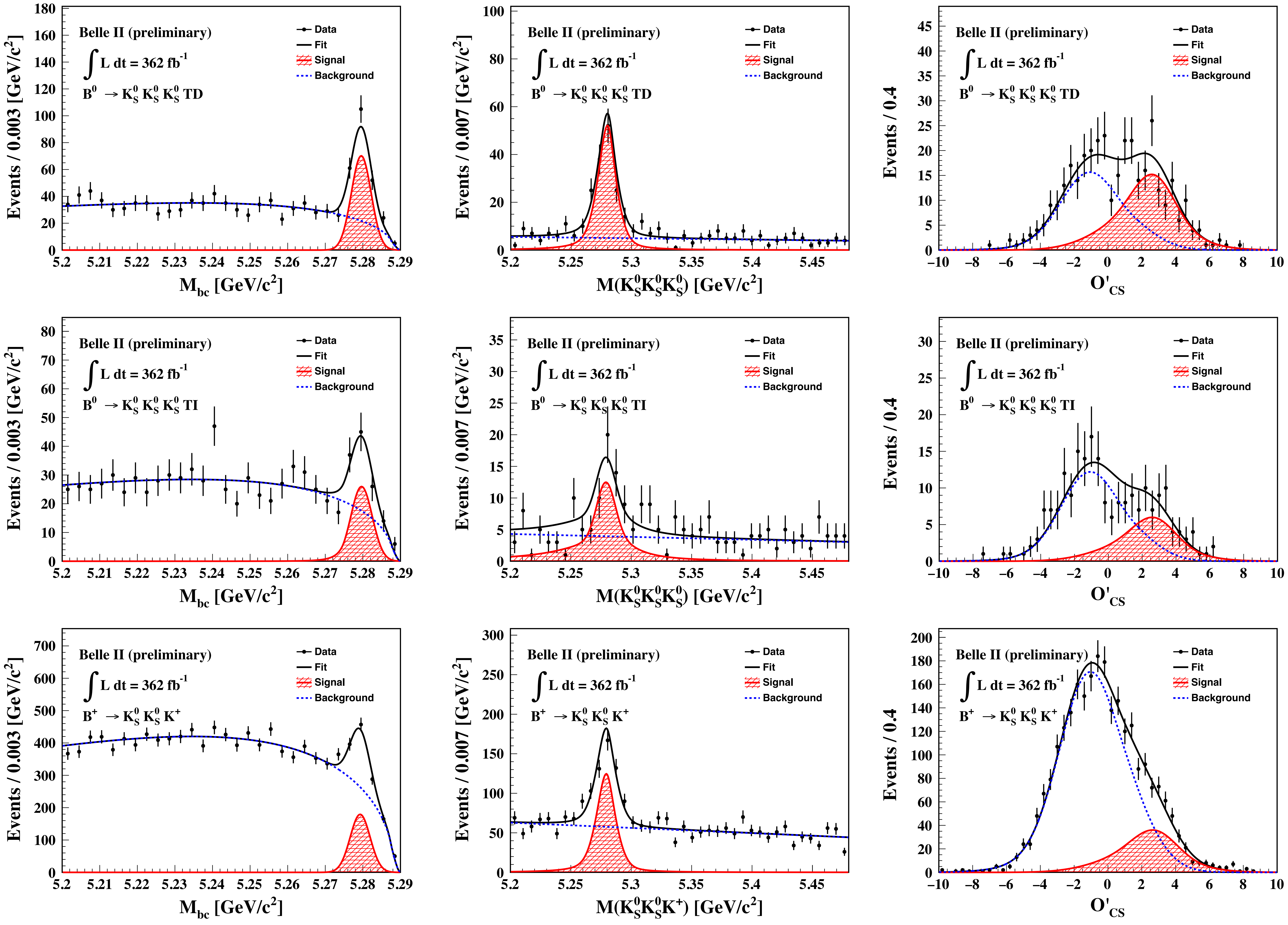


Energy difference



BDT output

B->$K_S K_S K_S$



TD

TI

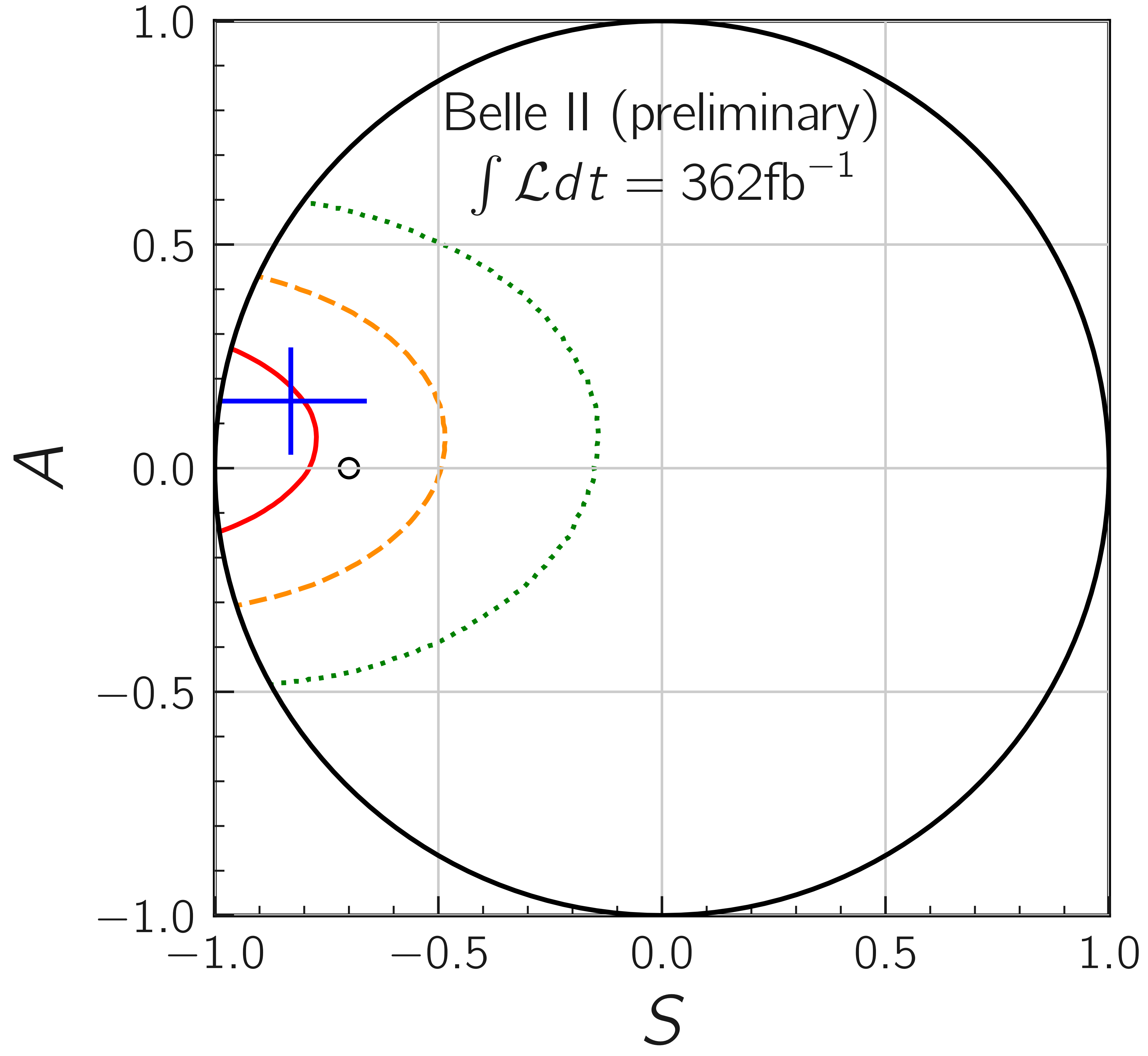
B+

Beam-constrained mass

Invariant mass

BDT output

B->$K_SK_SK_S$


Belle II (preliminary)
$\int \mathcal{L}dt = 362\text{fb}^{-1}$
1.0
0.5
0.0
−0.5
−1.0
A
−1.0
−0.5
0.0
0.5
1.0
S