Recent Belle II results on decay-time-dependent CP violation

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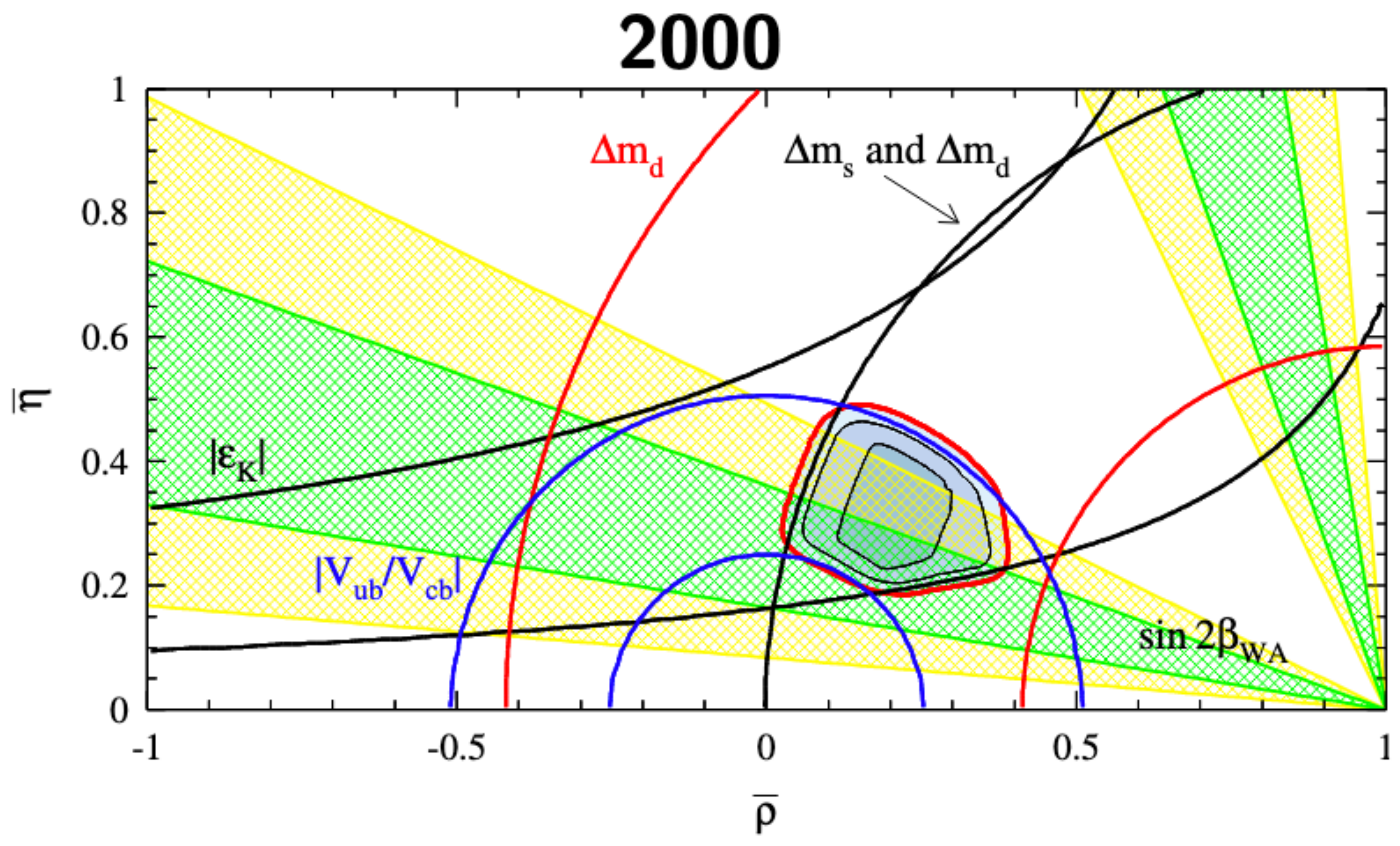
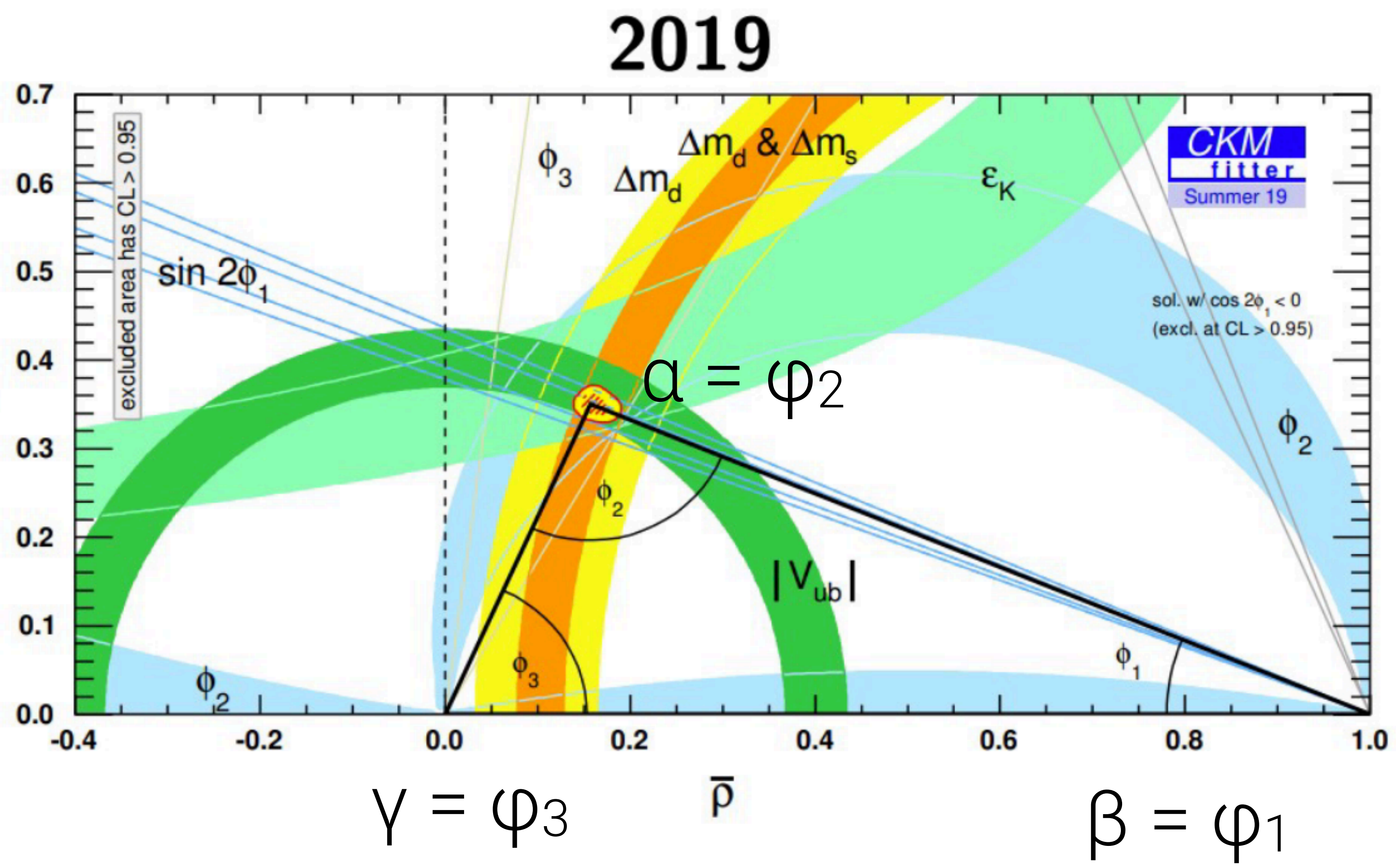
Landscape

Last ~20 years: tremendous progresses in understanding flavor dynamics mainly thanks to Belle and BaBar and LHCb along with lattice and pheno advances

And year by year the constraints on the UT improved….





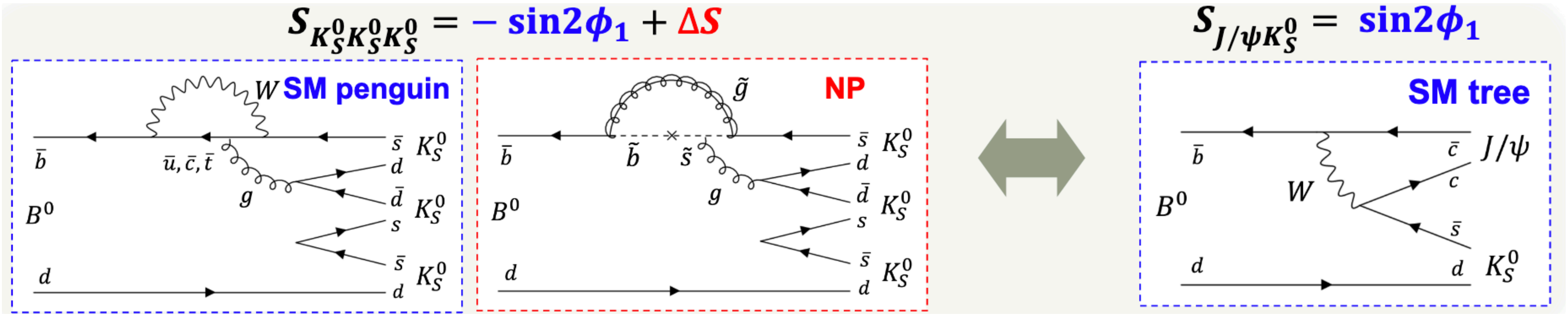
Belle II has the potential to go further. Not only by improving existing knowledge but also by searching for observable signatures of virtual contributions from non-SM particles in processes uniquely accessible to Belle II:

- Large data set (50x Belle data set)
- Constrained kinematics and lower-background environment with respect LHC experiments

Why a sin2ϕ_1 measurement?

$\varphi_1 = \arg[-V^*_{cb} V_{cd}/(V^*_{tb} V_{td})]$ is the B^0 mixing phase

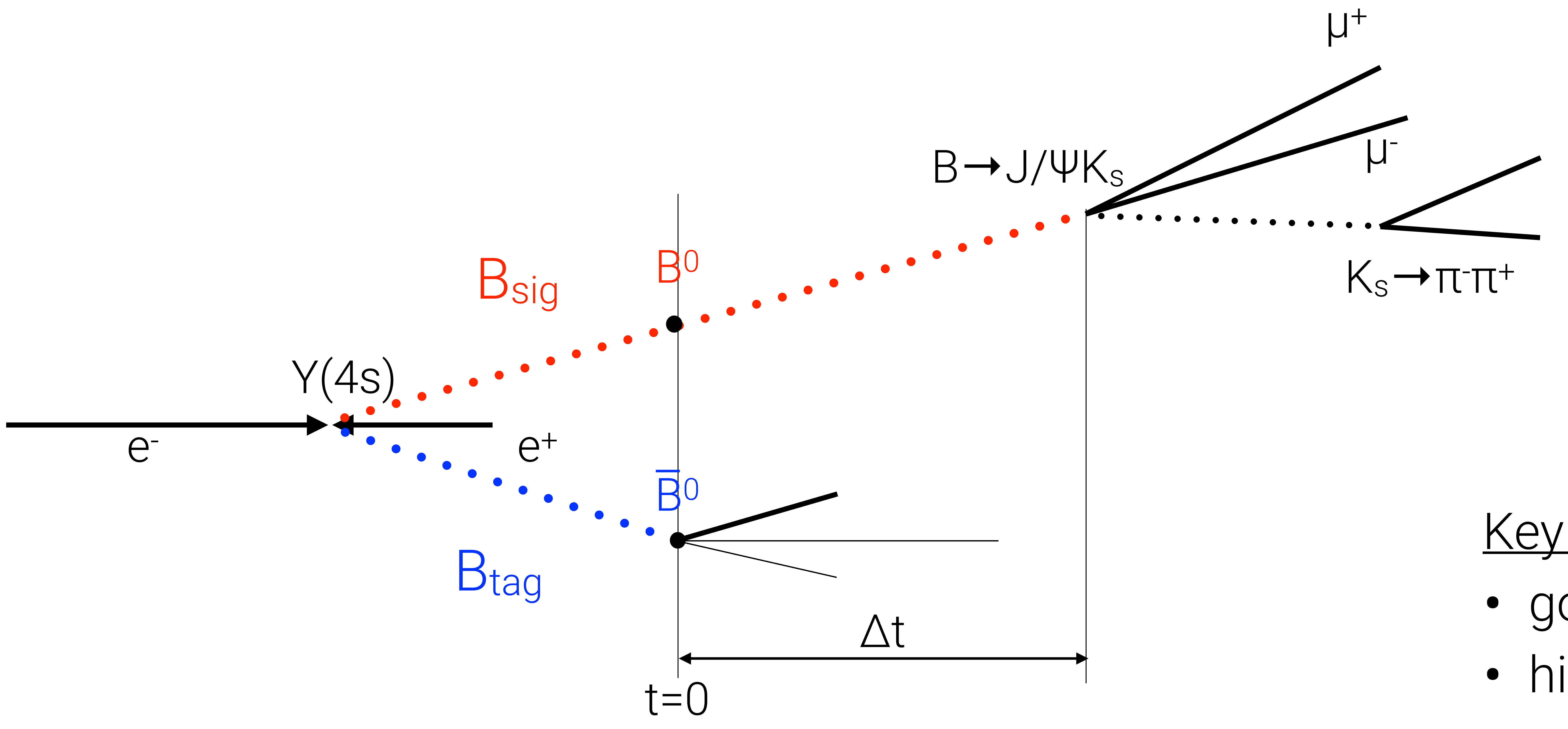
- with "tree" decays ($B^0 \to J/\psi\ K^0$) $\Longrightarrow$ to further constrain possible non-SM physics in B0 mixing (well constrained)
- with "penguin" decays ($B^0 \to K^0 K^0 K^0$) $\Longrightarrow$ to probe non-SM in decay by comparing with tree determinations



- Unique impact of Belle II on several penguin-dominated modes
- Today: sin2ϕ_1 with $B^0 \to J/\psi\ K^0$ $\Longrightarrow$ for precise comparison and to perfect all the tools for these measurements

Decay-time dependent analysis

7-GeV electrons on 4-GeV positrons produce Υ(4S) that decays promptly in a quantum-coherent $B\bar{B}$ pair



B_{sig} => fully reconstructed in a final state f_{CP} common to B^0 and $\bar{B}^0$

B_{tag} ⇒ only flavor information + vertex position

Key aspects:

- good vertex resolution
- high tagging efficiency

CP-asymmetry in interference between a decay without mixing $B^0 \rightarrow f_{CP}$ and a decay with mixing $B^0 \rightarrow \bar{B}^0 \rightarrow f_{CP}$:

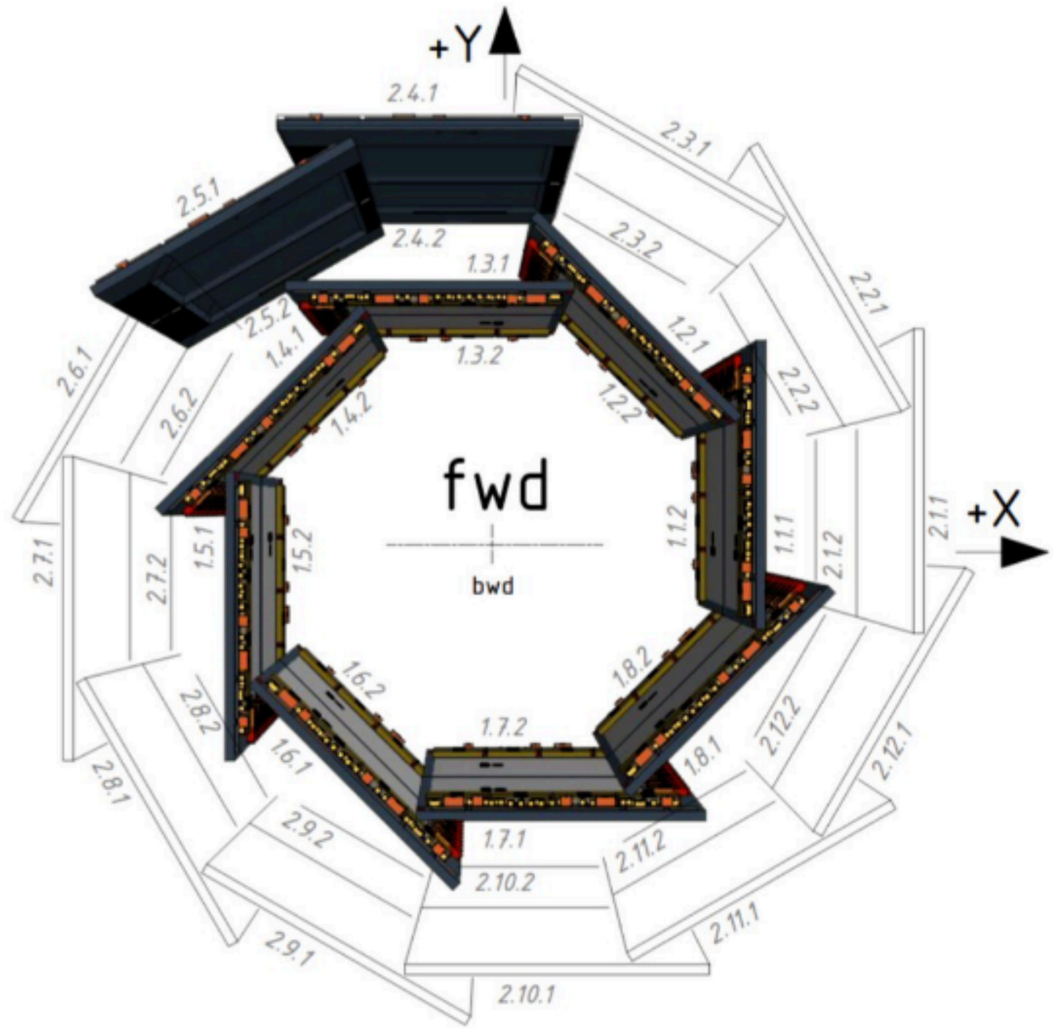
$$\mathcal{A}^{raw}(\Delta t) = \frac{N(\bar{B}^0 \rightarrow f_{CP}) - N(B^0 \rightarrow f_{CP})}{N(\bar{B}^0 \rightarrow f_{CP}) + N(B^0 \rightarrow f_{CP})}(\Delta t) = A_{CP}\cos(\Delta m_d \Delta t) + S_{CP}\sin(\Delta m_d \Delta t)$$

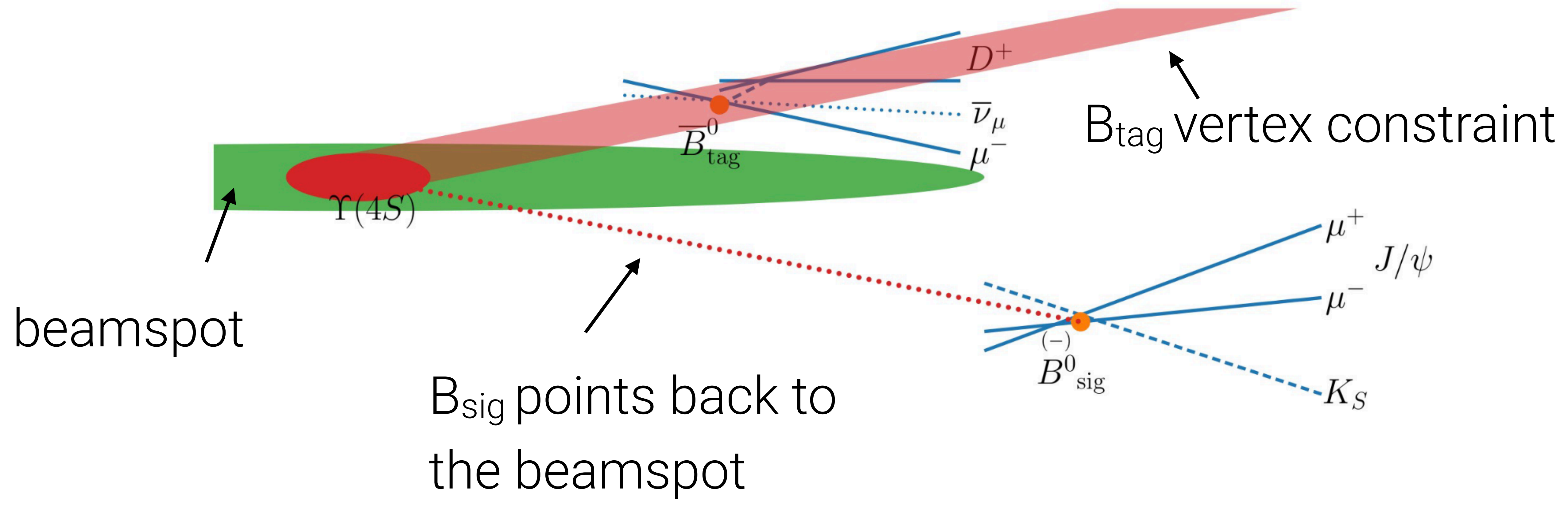
A_{CP}: direct CP asymmetry; S_{CP}: mixing-induced CP asymmetry

Δt reconstruction

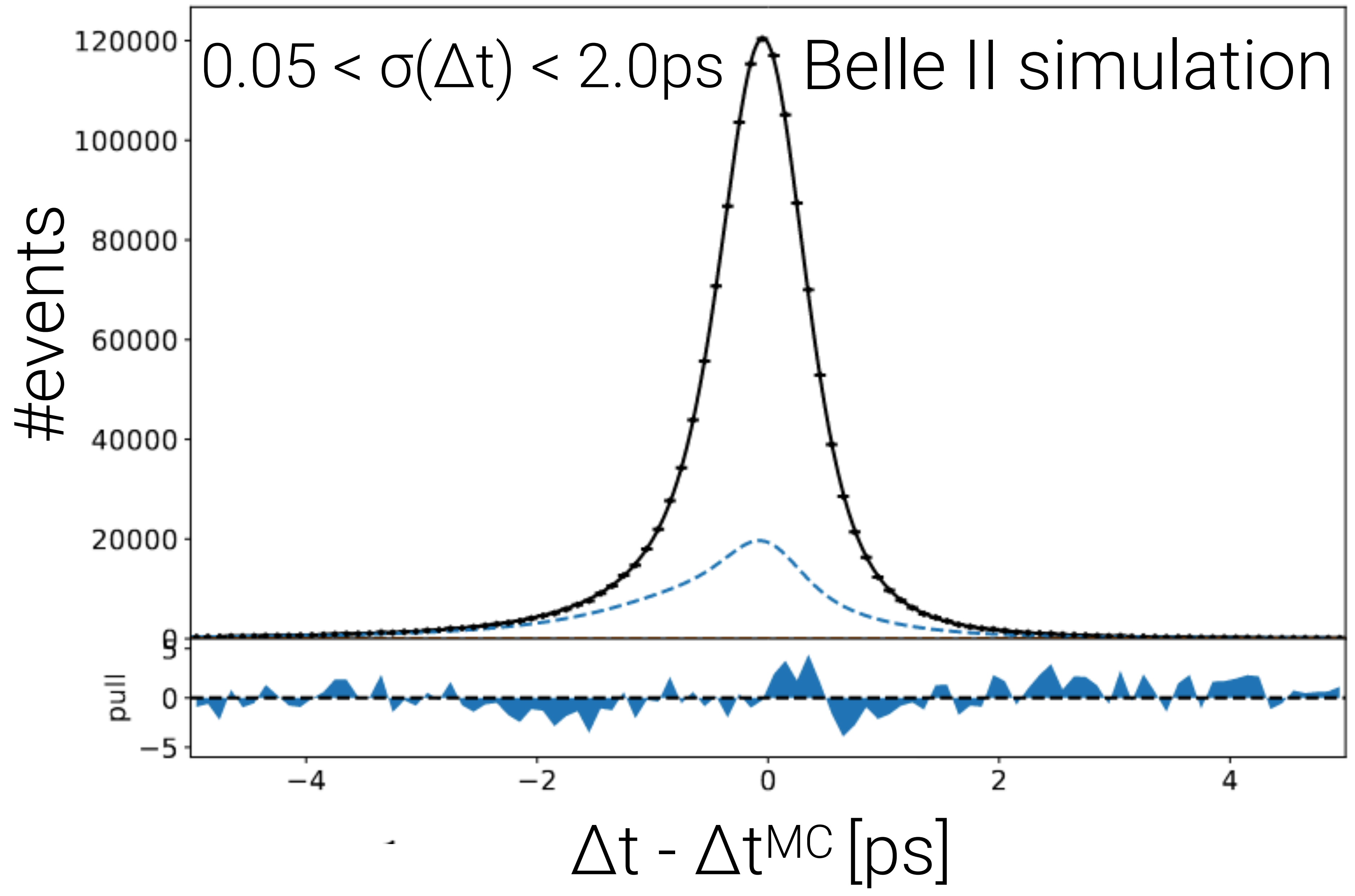
- Δt measured from the distance Δz between B_{sig} and B_{tag} ⇒ $\Delta t \sim \Delta z/\beta\gamma c$
- Υ(4s) is boosted $(\beta\gamma)_{BelleII}=0.28$ ⇒ Δz=130μm

  ⇒ Pixel detector added to improve precision in Δt





- σ_Y=0.2μm and σ_X=10μm beam size improves B_{tag} vertex precision and thus Δt resolution

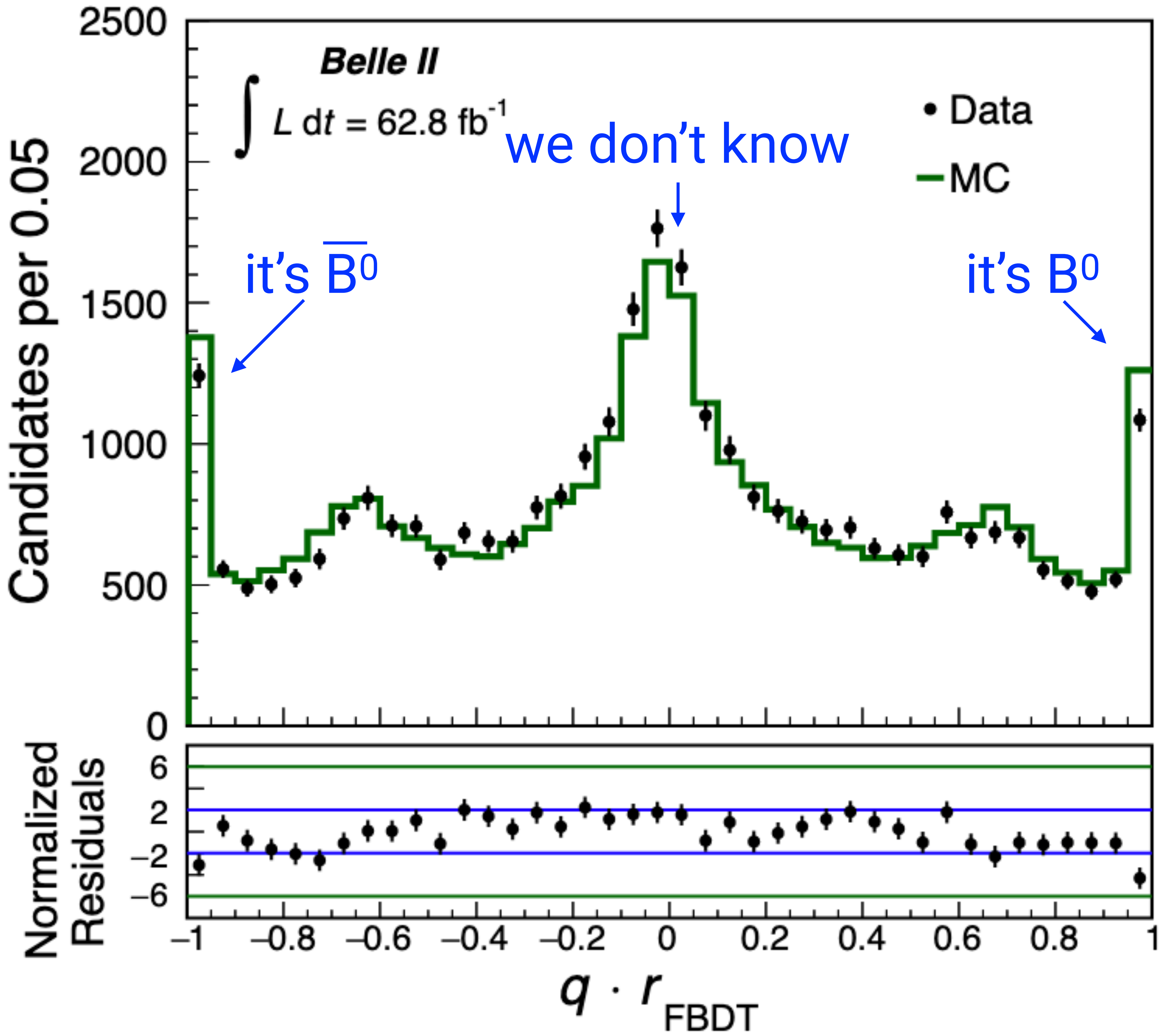


- Effect of Δt resolution function ⇒ $\mathcal{A}(\Delta t) = \mathcal{A}^{raw}(\Delta t) \otimes R(\Delta t)$

Flavor tagging

[Eur. Phys. J. C 82, 283(2022)]

- Crucial to determine the quark-flavor content of B_{tag}
- The flavor tagger applies a complex multivariate algorithm that uses discriminating input variables from the particles on the tag side (kinematic, track-hit, and particle-identification information) by looking for flavor-specific signatures to identify the flavor of the B_{tag}.



Performance:

- wrong tag fraction w
- efficiency = $\varepsilon = N_{tag}/N \Rightarrow$ dilution effect of w =>

effective efficiency $\varepsilon_{eff} = \varepsilon\,(1-2w)^2$

ε_{eff}(Belle II) = (30.0 ± 1.2 ± 0.4)%

$$\Rightarrow \mathcal{A}(\Delta t) = \mathcal{A}^{raw}(\Delta t) \cdot (1-2w) \otimes R(\Delta t)$$

Lifetime and mixing measurement

Important for preparing to sin2ϕ_1 measurement

~30k $B^0 \to D^{(*)-}\pi^+$ decays are used

Mixing measurement from the asymmetry:

$$\mathcal{A}(\Delta t) = \frac{N_{B\bar{B}} - N_{BB,\bar{B}\bar{B}}}{N_{B\bar{B}} + N_{BB,\bar{B}\bar{B}}} = cos(\Delta m_d \Delta t)(1-2w) \otimes R(\Delta t)$$

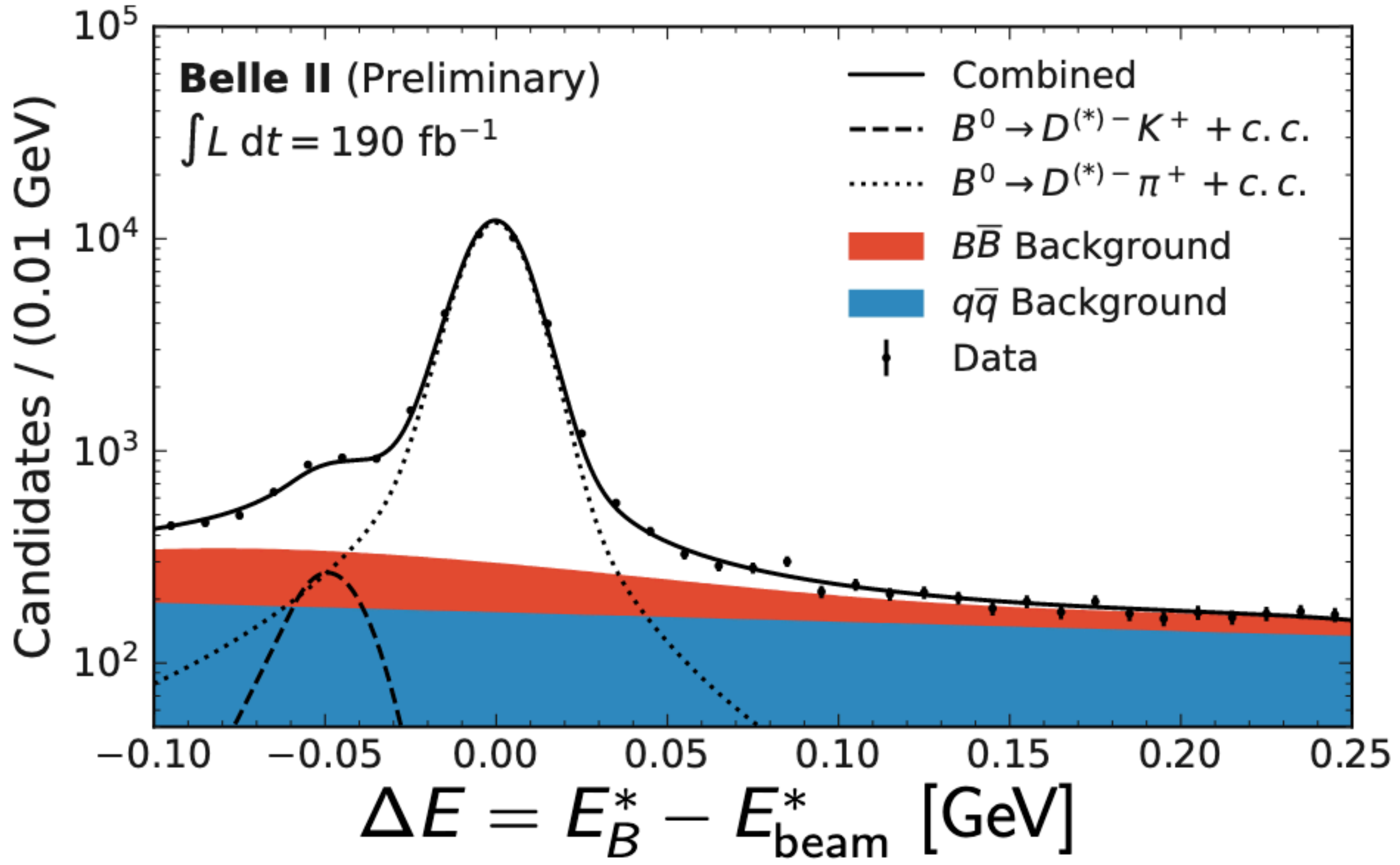
τ_{B^0} = 1.499 ± 0.013 (stat.) ± 0.008 (syst.) ps

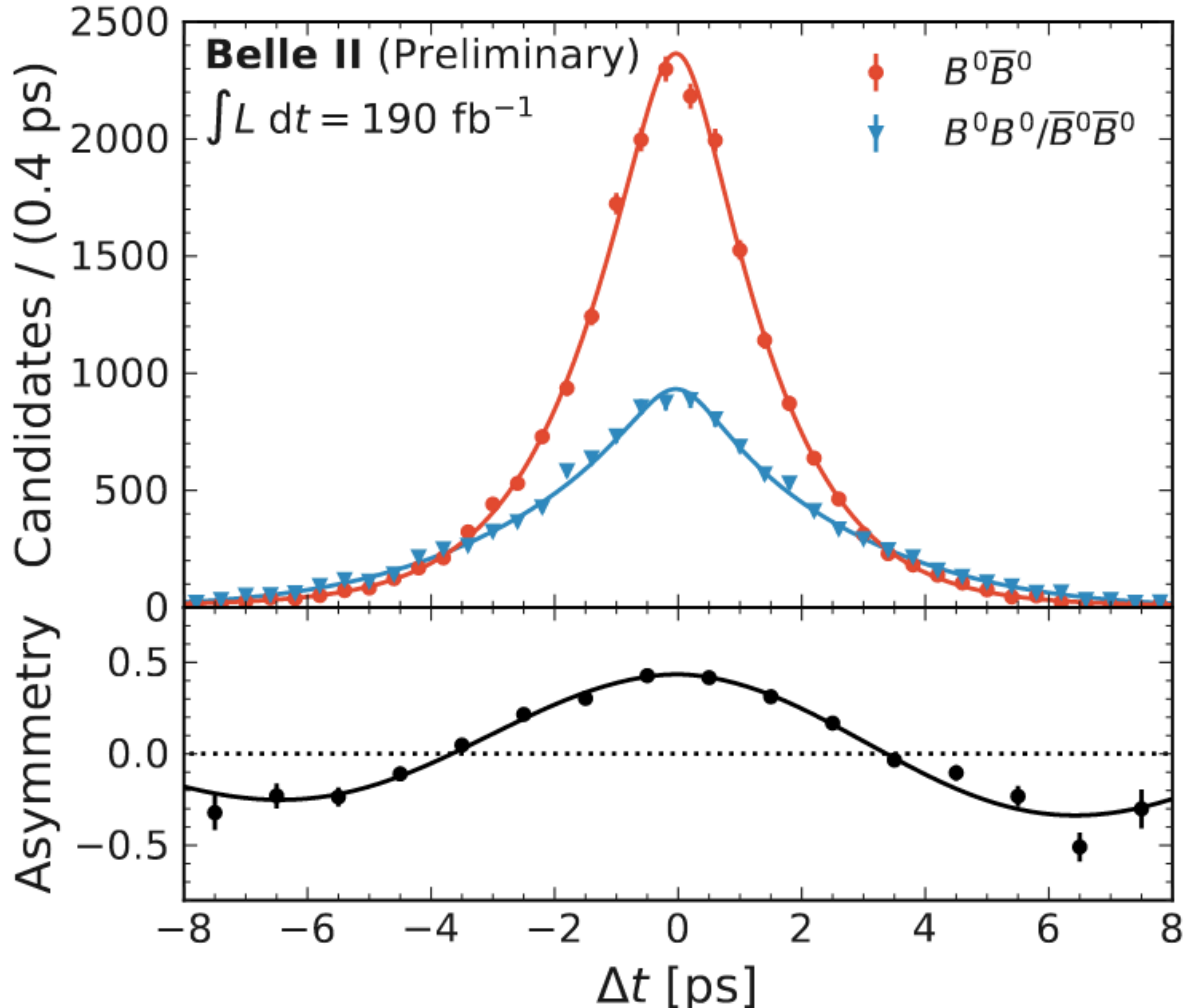
Δm_d = 0.516 ± 0.008 (stat.) ± 0.005 (syst.) ps^{-1}

Δt resolution model and flavor tagger are working well

⇒ our tools are ready

Signal yield: 33317 ± 203





$\sin 2\phi_1$ validation

NEW

Exercise and validate procedure on $B^+ \to J/\psi K^+$ decays

1- $B^+ \to D^0 \pi^+$ events from lifetime and mixing measurement used as calibration

2- ΔE distribution of signal events fitted and background subtracted

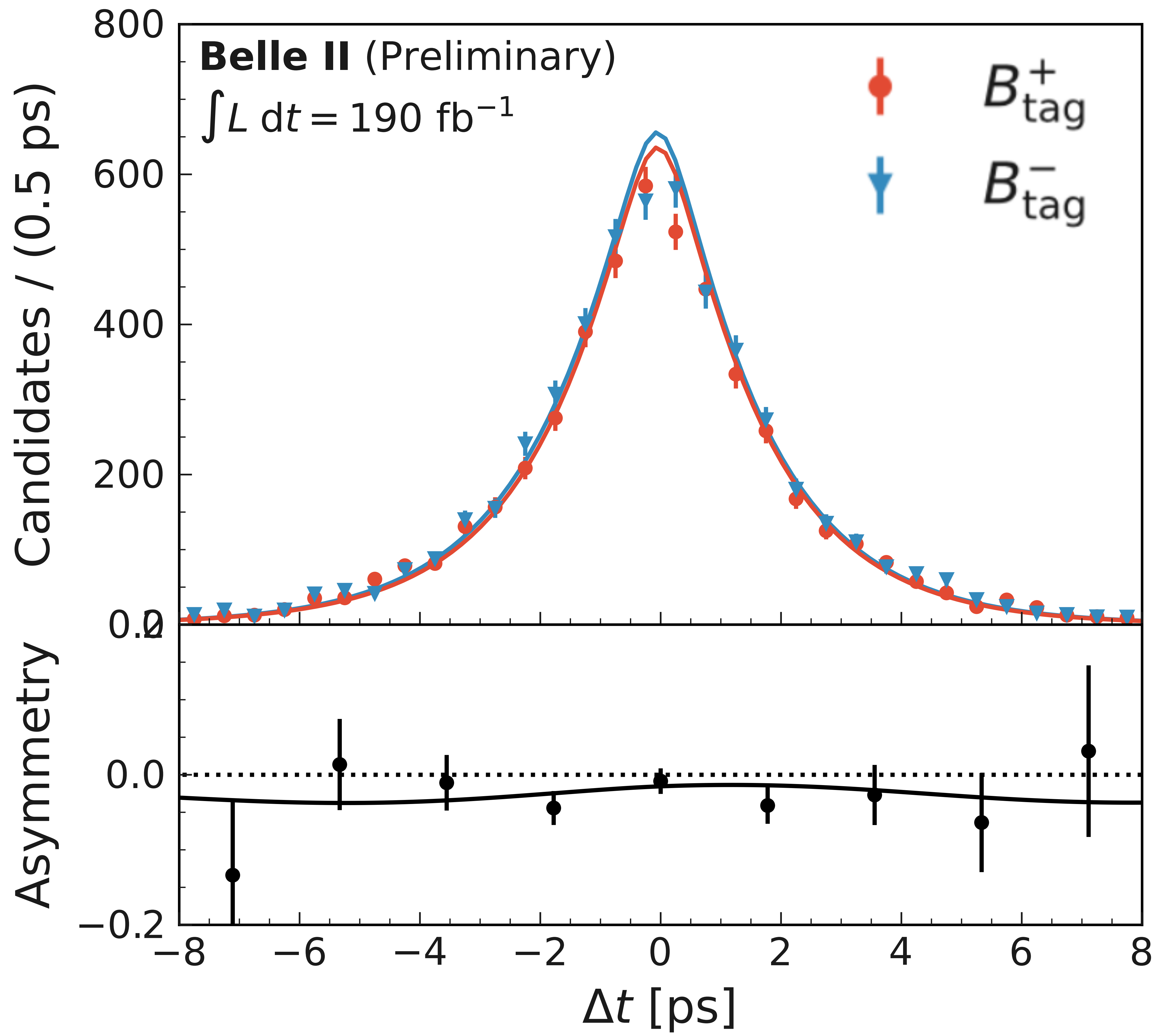
3- time-dependent fit on signal events performed with all flavor tagger and resolution function parameters fixed from step 1

Cross-checks with $B^+ \to J/\psi K^+$. Calibration done with $B^+ \to D^0 \pi^+$:

$S^{B+}_{CP} = 0.016 \pm 0.029$
$A^{B+}_{CP} = 0.021 \pm 0.021$

Null asymmetries as expected - the analysis is ready

Signal yield: 10028 ± 105



$B^0 \to J/\psi\ K_s^0$ reconstruction

NEW

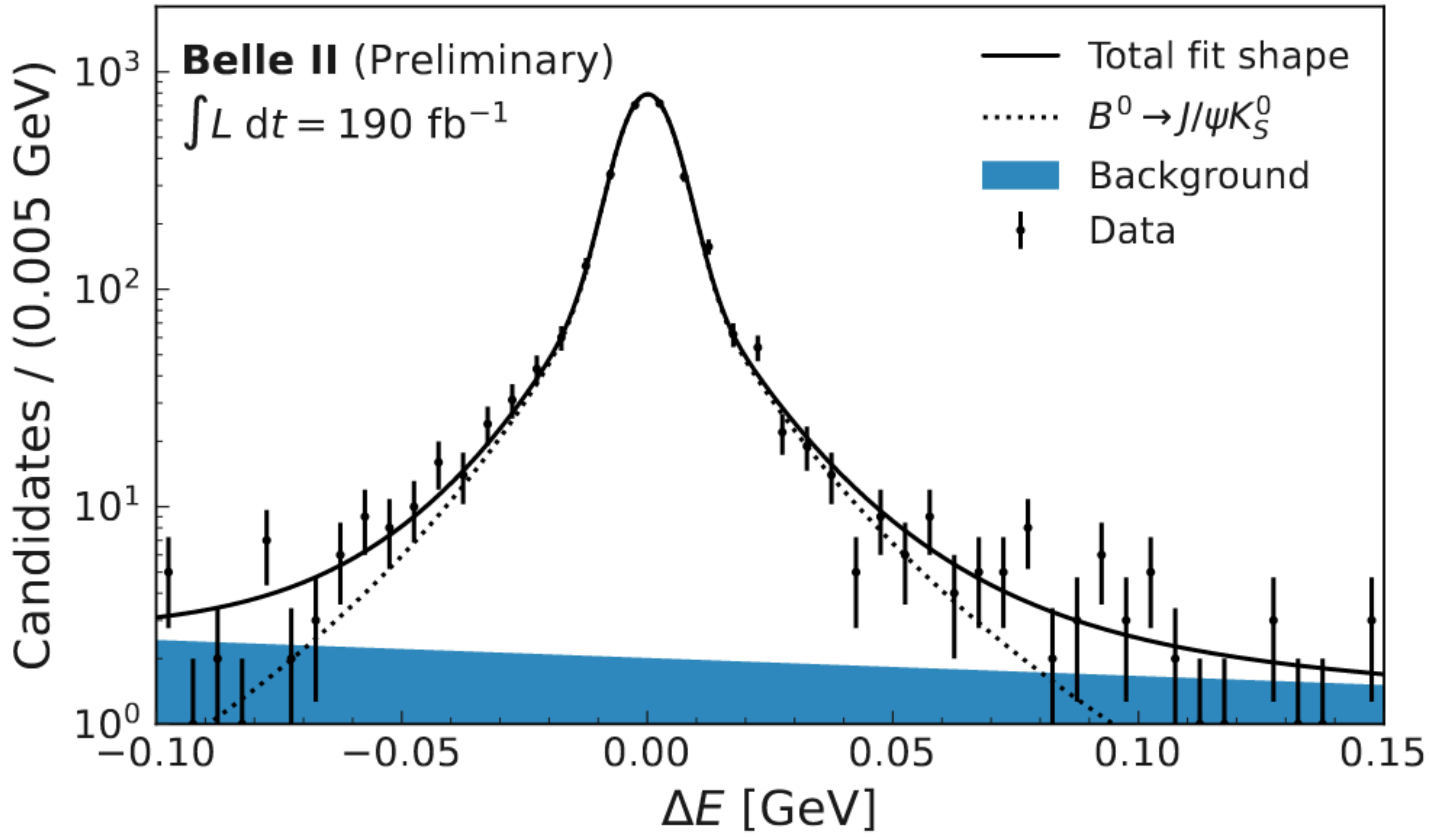
Apply analysis to $B^0 \to J/\psi\ K_S^0$ sample

1- $B^0 \to D^{(*)-}\ \pi^+$ events from lifetime and mixing measurement used as calibration

2- ΔE distribution of signal events fitted and background subtracted

3- time-dependent fit on signal events performed with all flavor tagger and resolution function parameters fixed from step 1

Signal yield: 2774 ± 55



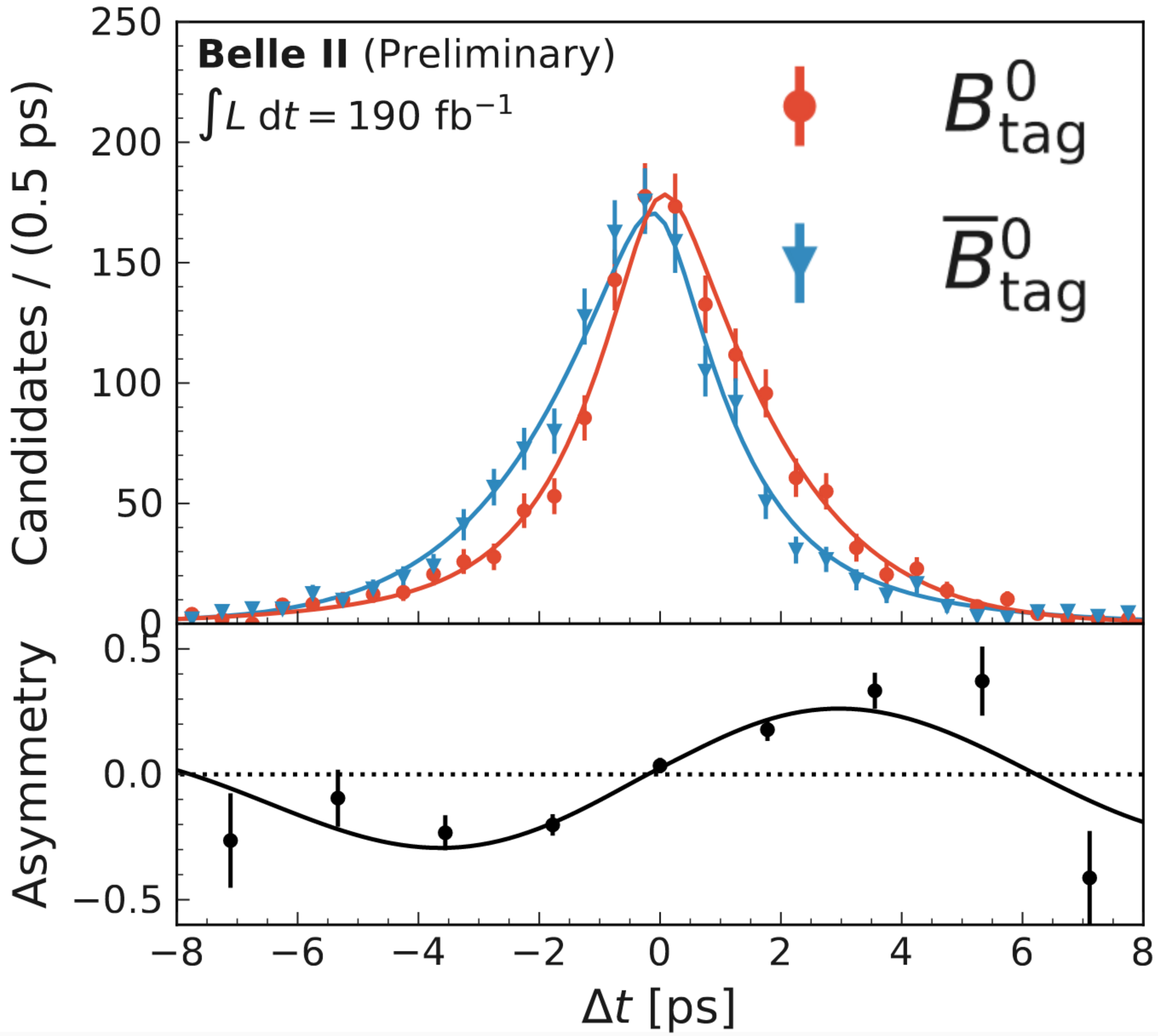
NEW

$\sin 2\phi_1$ results

Apply analysis to $B^0 \to J/\psi K_s^0$ sample

Source	$\sigma(S_{CP})$	$\sigma(A_{CP})$
Statistical	0.0622	0.0439
$B^0 \to D^{(*)-}\pi^+$ sample size	0.0111	0.0093
Analysis bias	0.0080	0.0020
Signal charge asymmetry	0.0027	0.0126
$w_6^+ = 0$ limit	0.0014	0.0001
Resolution function parametrization	0.0039	0.0008
τ_{B^0}, Δm_d	0.0007	0.0002
Alignment	0.0020	0.0042
Beam spot	0.0024	0.0020
Momentum scale	0.0005	0.0013
$\sigma_{\Delta t}$ binning	0.0050	0.0051
Multiple candidates	0.0005	0.0008
Tag-side interference	0.0020	$^{+0.0380}_{-0.000}$
Total systematic	0.0159	$^{+0.0418}_{-0.0173}$

Signal yield: 2774 ± 55



$S_{CP} = 0.720 \pm 0.062\ \text{(stat.)} \pm 0.016\ \text{(syst.)}$

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

Milestone: tools are ready for an impactful $\sin 2\phi_1$ measurement

NEW

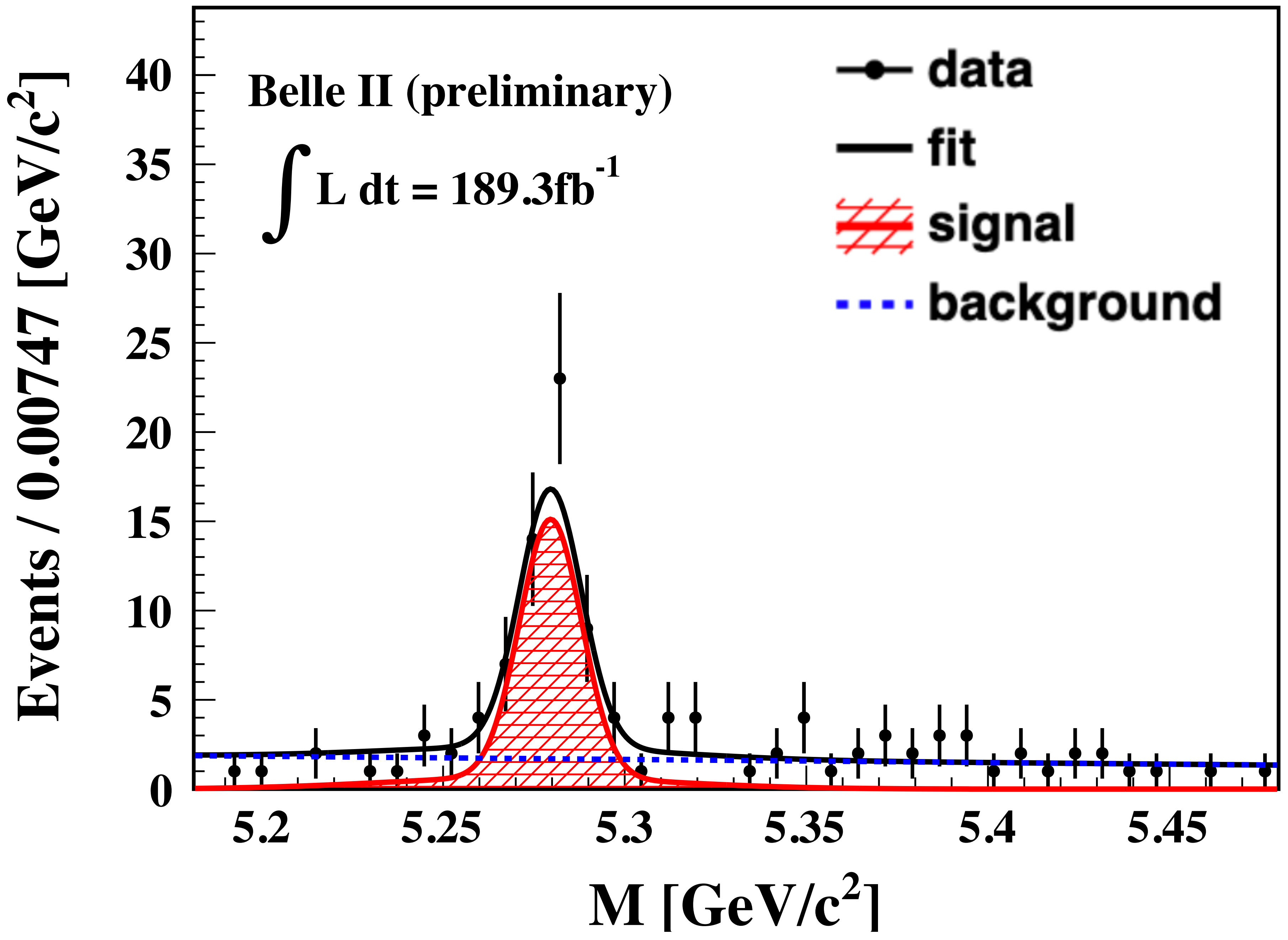
CP violation in $B^0 \to K^0_S K^0_S K^0_S$

Unique sensitivity. Vertexing challenging

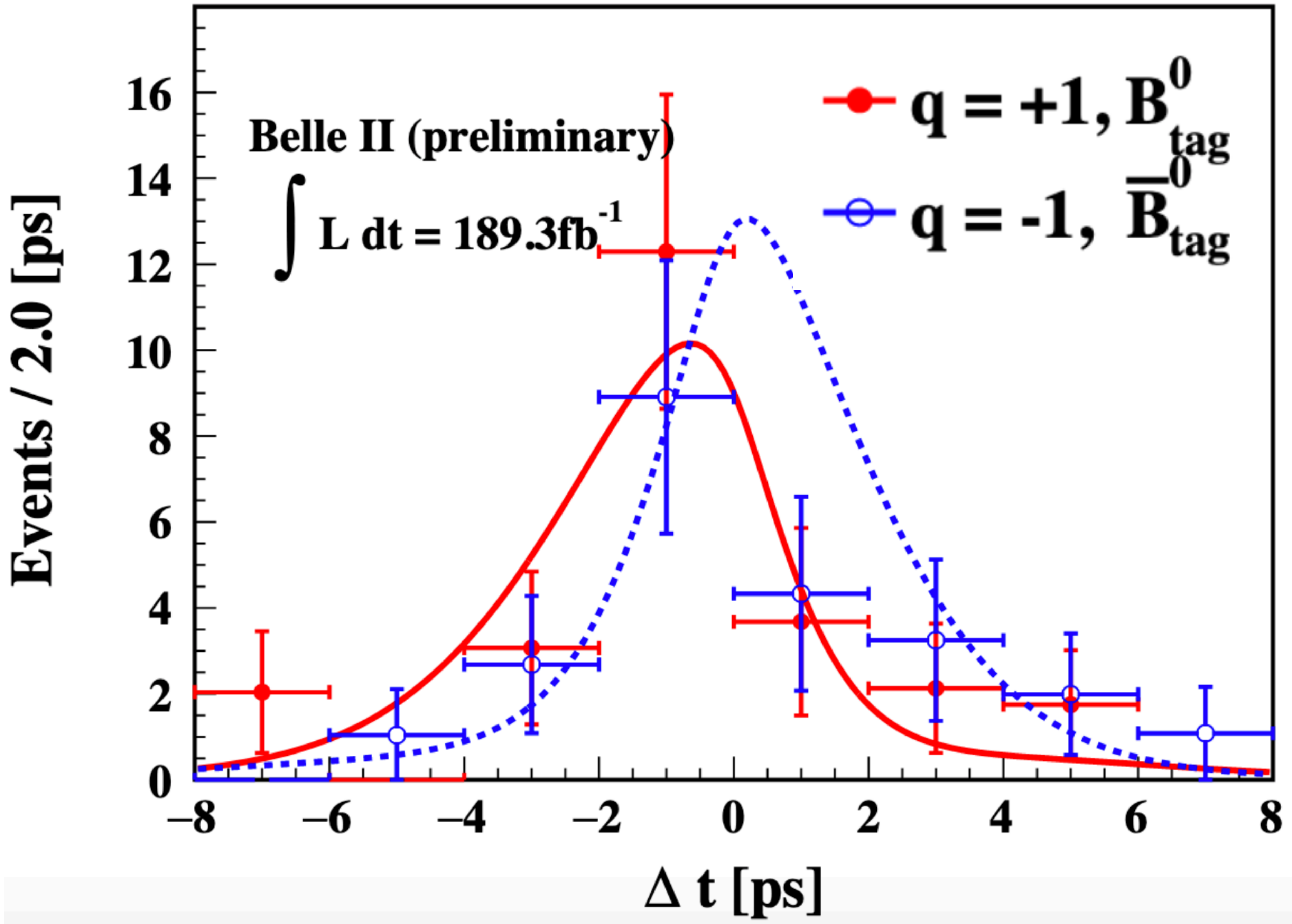
- Signal extraction fit with 3 variables (M_{bc}, invariant mass M, CS classifier)
- $\chi_{c0} K_S$ is rejected
- Main background comes from random combinations of tracks from $e^+e^- \to \bar{u}u, \bar{d}d, \bar{s}s, \bar{c}c$ events suppressed with a multivariate technique
- Analysis validated using $B^+ \to K^+ K^0_S K^0_S$

$S_{CP} = -1.86\ ^{+0.91}_{-0.46}\ \text{(stat.)} \pm 0.09\ \text{(syst.)}$

$A_{CP} = -0.22\ ^{+0.30}_{-0.27}\ \text{(stat.)} \pm 0.04\ \text{(syst.)}$



Signal yield: 53 ± 8



[arXiv:2206.07453]

CP violation in $B^0 \to K_S\pi^0$

$$\mathcal{A}_{CP}(K^+\pi^-) + \mathcal{A}_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{CP}(K^+\pi^0)\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{CP}(K^0\pi^0)\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} = 0,$$

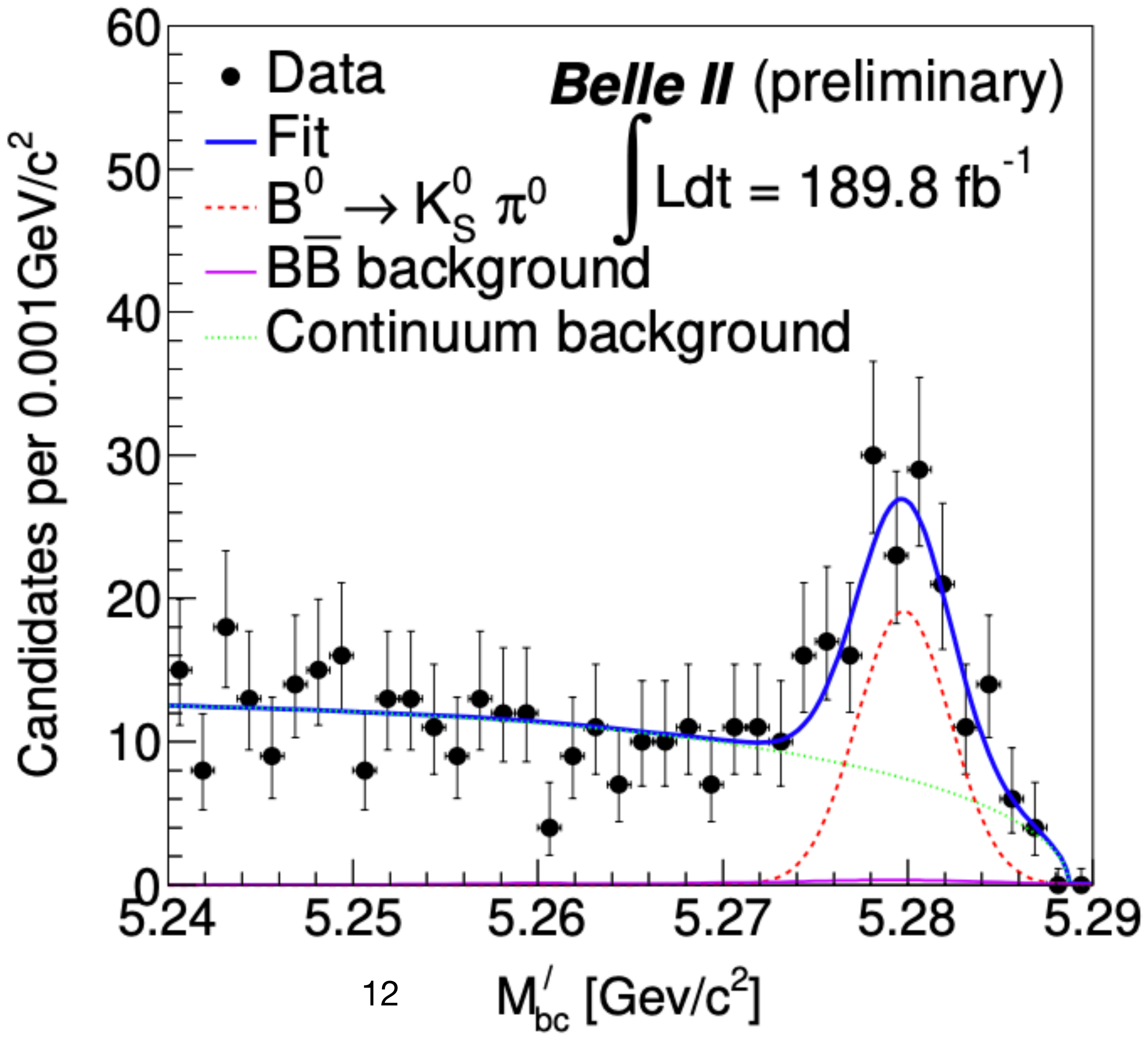
within 1% in SM

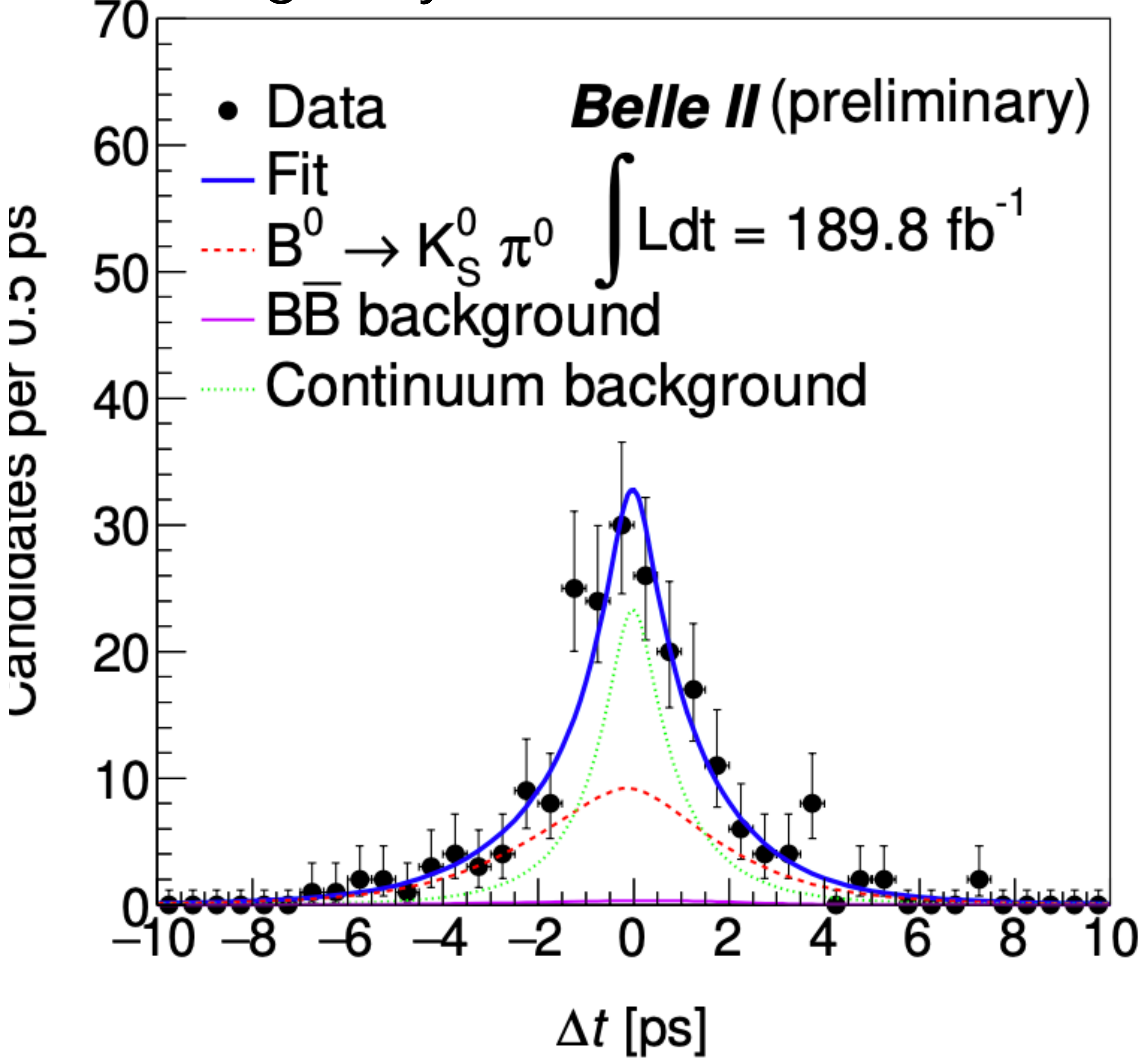
- 10% experimental uncertainty dominated by $A_{CP}(K^0\pi^0)$. This measurement is only feasible at Belle II
- The key challenge is the reconstruction of $B^0 \to K_S\pi^0$ decay vertex
- Signal yield and direct CP asymmetry $A_{CP}(K^0\pi^0)$ from a 4 dimensional fit (M_{bc}, ΔE, Δt, BDT output distribution used to suppress the $e^+e^- \to q\bar{q}$ background)

$A_{CP} = -0.41\ ^{+0.30}_{+0.32}$ (stat.) $\pm$ 0.09 (syst.)

B = (11.0 ± 1.2 (stat.) ± 1.0 (syst.)) x 10^{-6}

Signal yield: $135\ ^{+16}_{-15}$





Summary

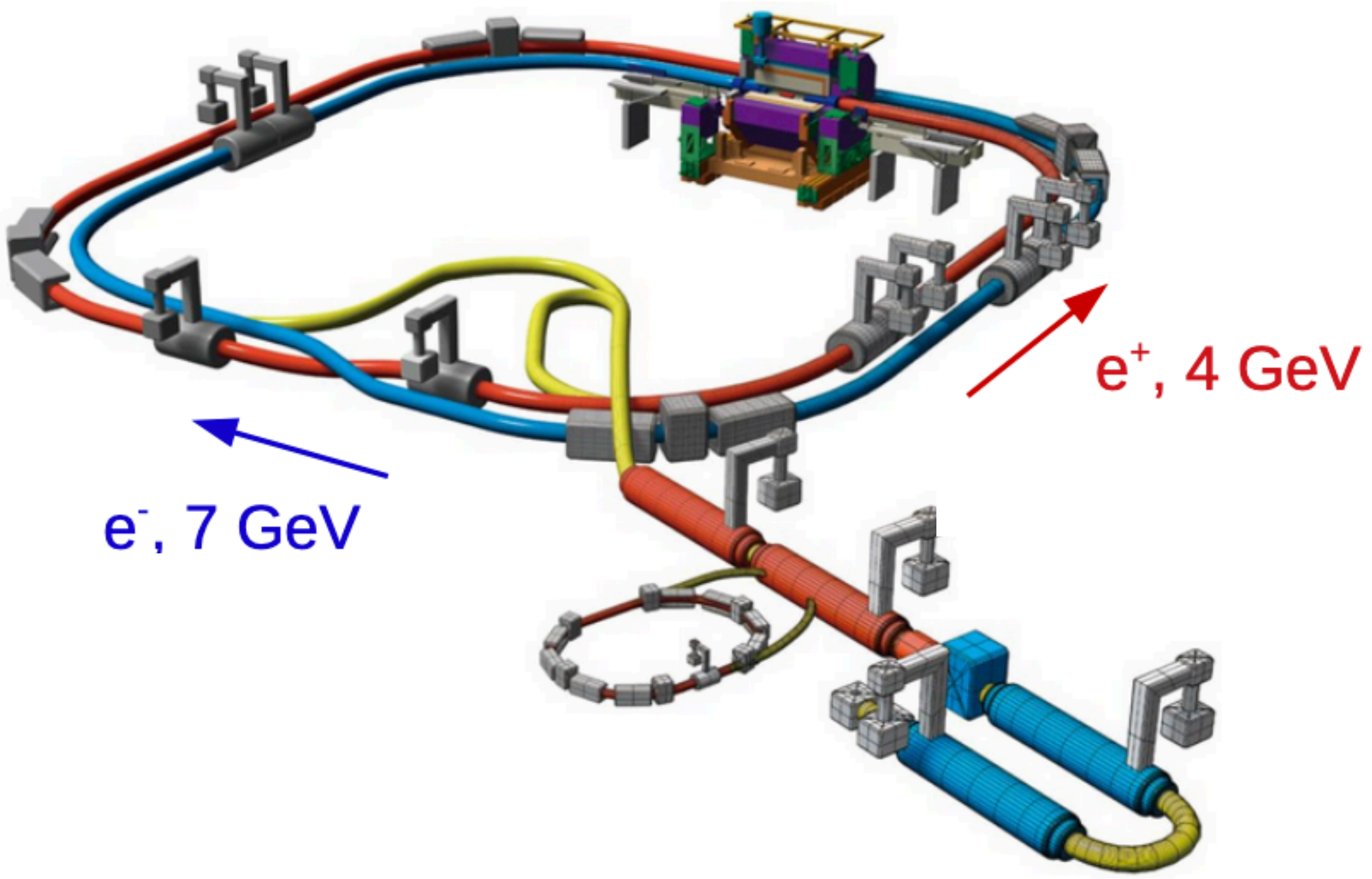
- Belle II accesses unique probes of non-SM physics through decay-time-dependent CP violation in penguin
- Sophisticated analyses that require command of many low- and high-level capabilities (tracking, neutral and Ks/K reconstruction, vertex resolution, flavor tagging etc)

- Systematic preparation is ongoing and yielding first results:
  - Lifetime and B^0 mixing measurement
  - Measurement of $\sin 2\phi_1$ with $B^0 \to J/\psi K_S^0$ NEW at ICHEP
  - First decay-time-dependent CP violation measurements extended to rarer $B^0 \to K^0_S K^0_S K^0_S$ decays NEW at ICHEP

All is ready to open new and unique windows on non-SM physics

Backup

SuperKEKB and Belle II detector



Improvements over KEKB:

- Increase current: x1.5
- Reduced beam spot size (nano beam scheme): x20

Target: $L_{peak} = 6.5 \times 10^{35}\ cm^{-2}\ s^{-1}$
$L_{Int} = 50\ ab^{-1}$ (50 x KEKB)

Achieved: $L_{peak} = 4.7 \times 10^{34}\ cm^{-2}\ s^{-1}$
$L_{Int} \sim 430\ fb^{-1}$ (~0.5 Belle dataset)

Consequences:

- Deal with more severe background conditions
- Boost factor is reduced ($\beta\gamma = 0.43 \rightarrow 0.28$)

=> Many upgrades for Belle II detector to increase the performance and cope with much more severe background conditions