CPV at Belle and Belle II

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KEK, IPNS

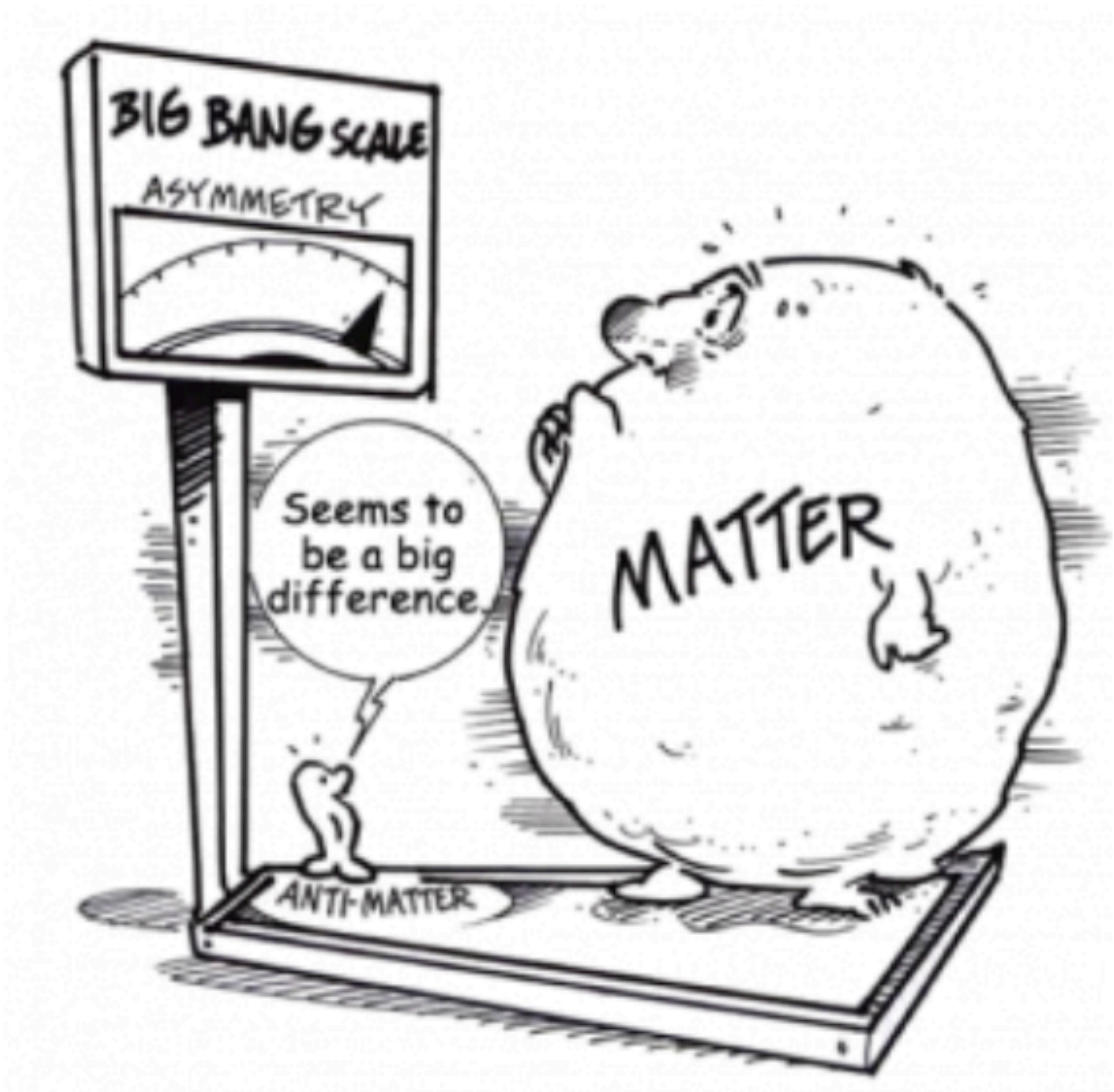
FIND CP violation at electroweak scale and beyond
USTC
2023.08.26-27

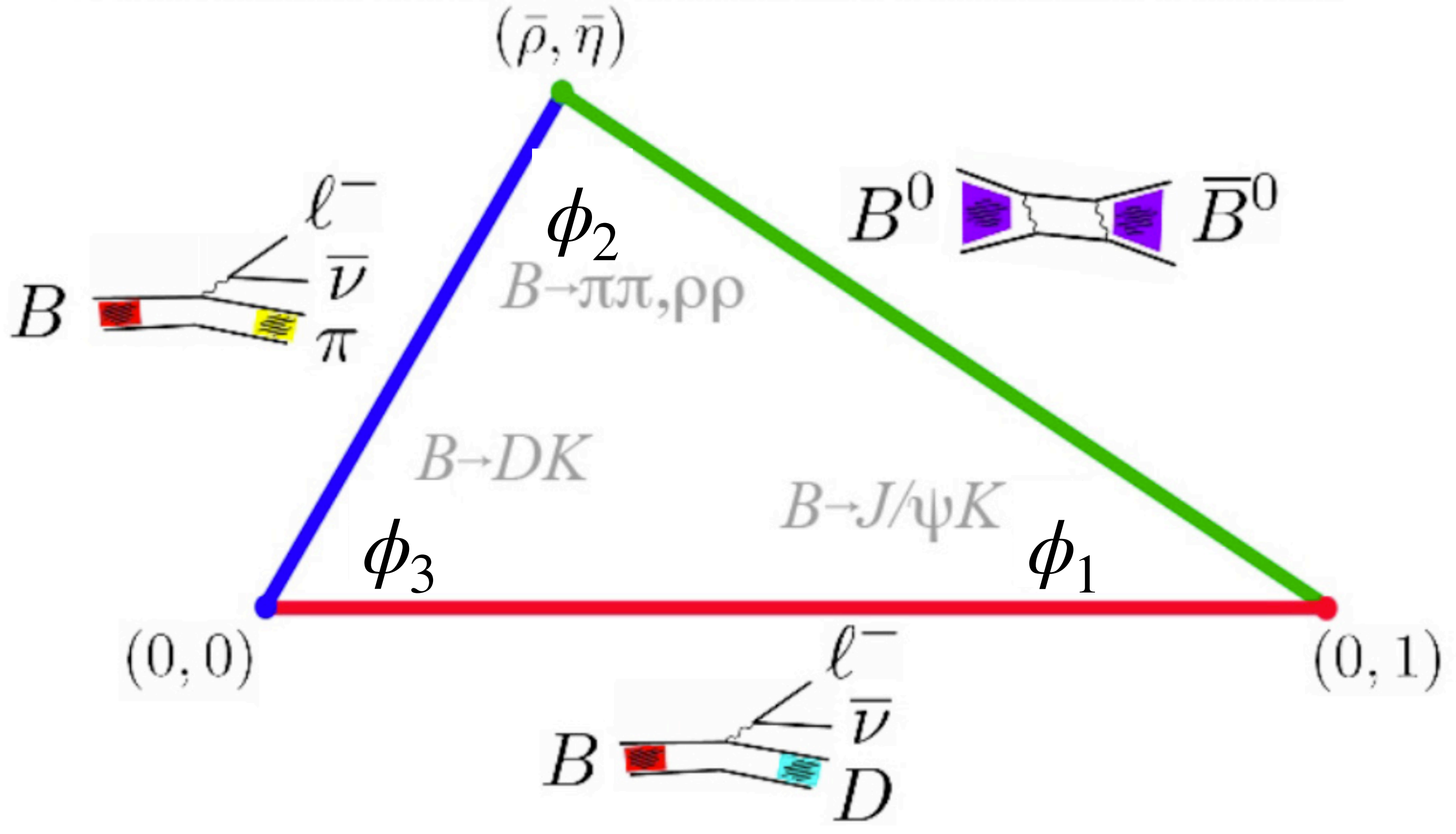
Matter-antimatter asymmetry

- In Big Bang theory, equal antimatter and matter in the initial period of this Universe. But now very large asymmetry between matter and antimatter.
- **CP violation (CPV)** is one of three conditions to explain the matter-antimatter asymmetry.

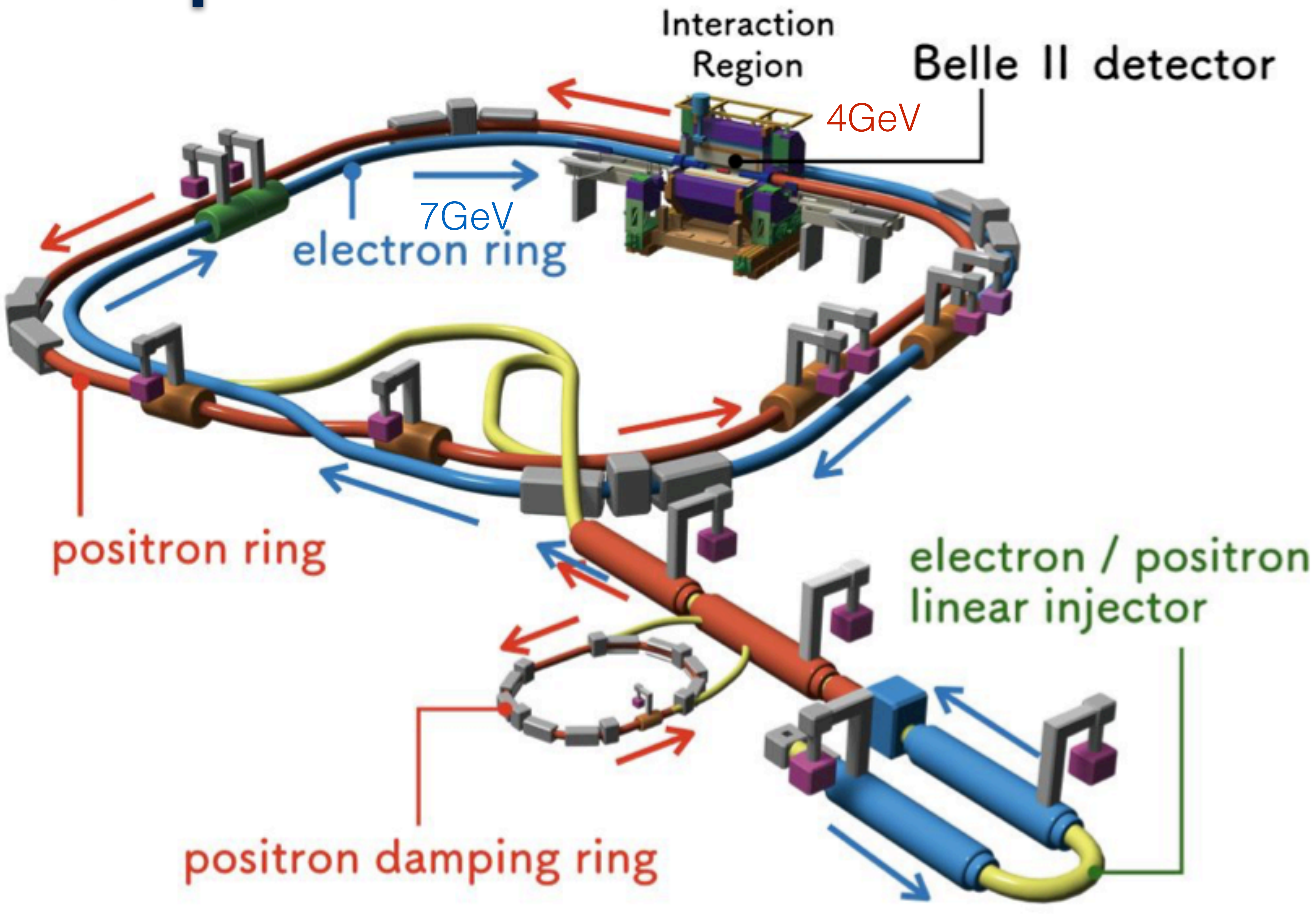
- CPV observed in K, B, D system.
- Standard Model (SM) describes the CPV by a phase in Cabibbo-Kobayashi-Maskawa (CKM) matrix, but it's too small to explain the current large matter-antimatter asymmetry.
- hint of new physics from CPV?

- In my talk: recent Belle (II) results of ϕ_1, ϕ_2, ϕ_3 and CPV in charm.

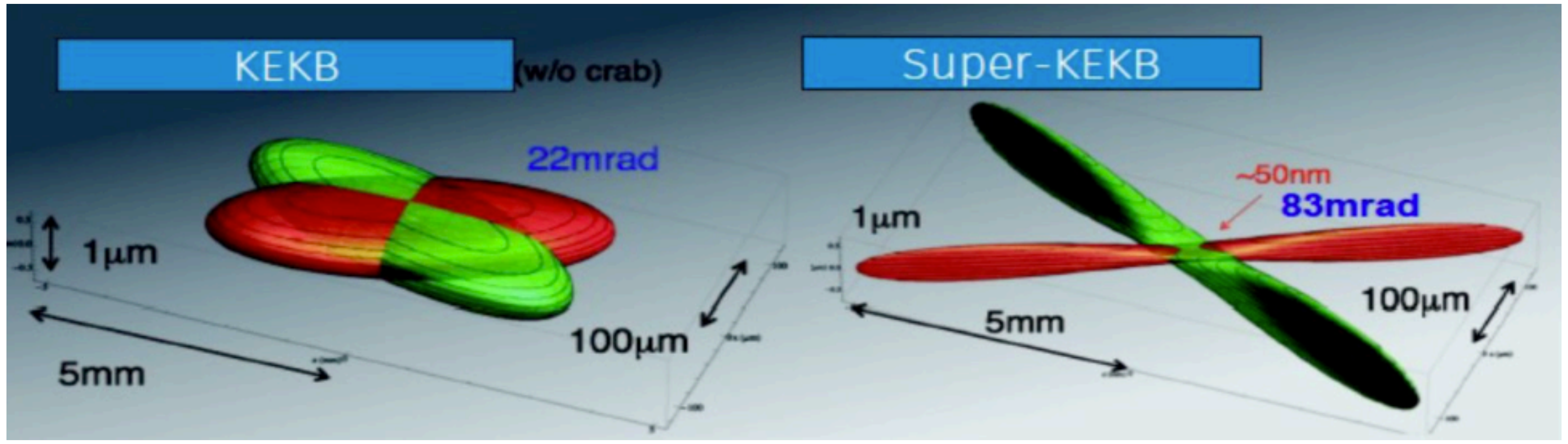




SuperKEKB



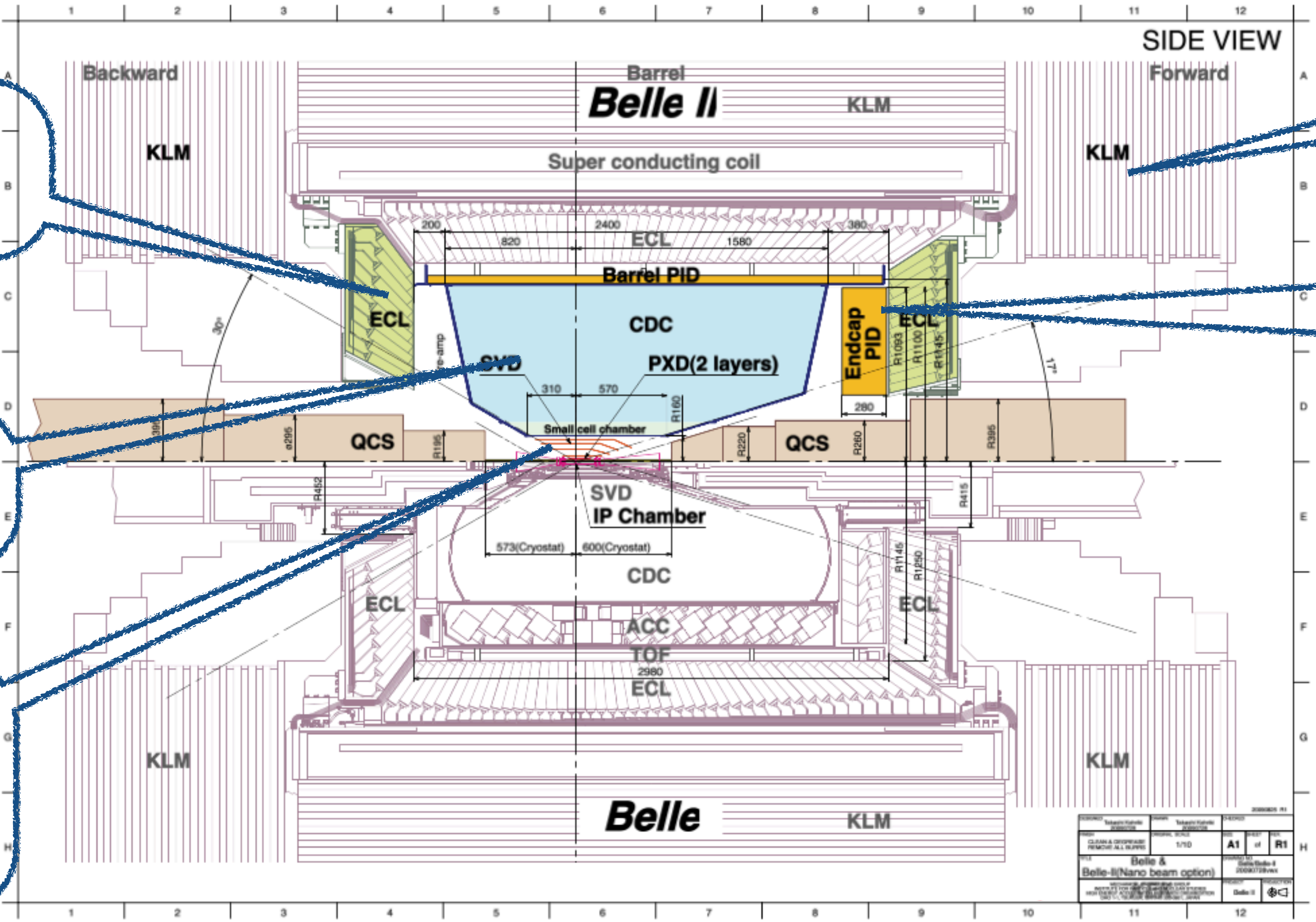
PTEP 2013, 03A011 (2013)



- Asymmetric e^+e^- collider at KEK
- Design instant luminosity: 6.5×10^{35}cm^{-2}s^{-1}
- Nano-beam collision scheme, large crossing angle, crab waist scheme
- Instant luminosity record of 4.7×10^{34}cm^{-2}s^{-1} (x2 of KEKB's peak luminosity)

- First physics run recorded in 2019
- 362/fb at Y(4S); goal: 50/ab.
- Belle has 711/fb at Y(4S)

Belle and Belle II detector



ECL
CsI(Tl)+waveform sampling
Energy resolution: 1.6~4%

CDC
Track efficiency: ~99%
dE/dx resolution: 5%
Pt resolution: 0.4%

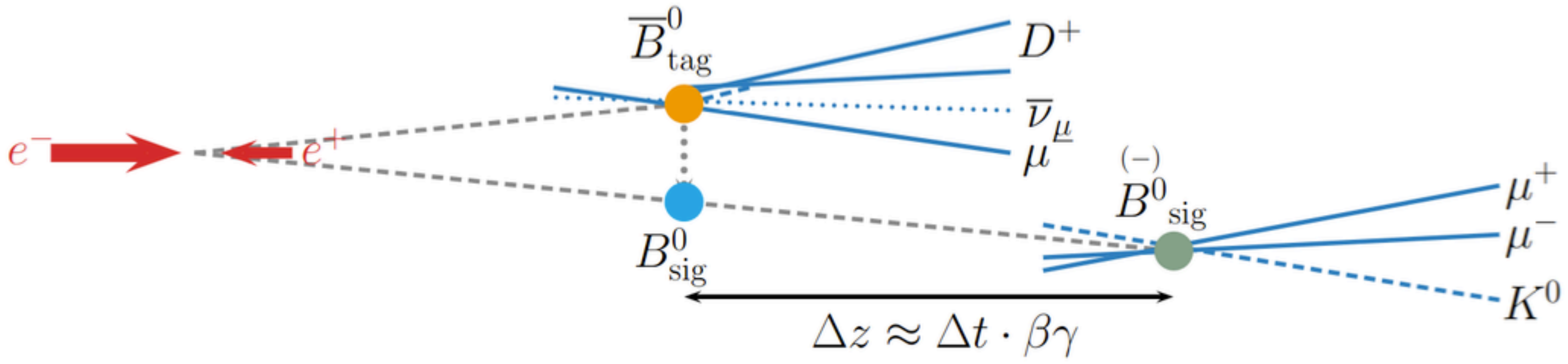
VXD
Inner 2 layers: pixel detector (PXD)
Outer 4 layers: strip sensor (SVD)
Vertex resolution: 15 μm

KLM
Outer barrel: Resistive Plate Counter (RPC)
Endcap/inner barrel: Scintillator

PID
Barrel: Time-Of-Propagation counters(TOP)
Endcap/inner barrel: Scintillator

- Nearly 4π detector
- Belle II re-use magnet, calorimeter crystals.

Time dependent CPV measurement



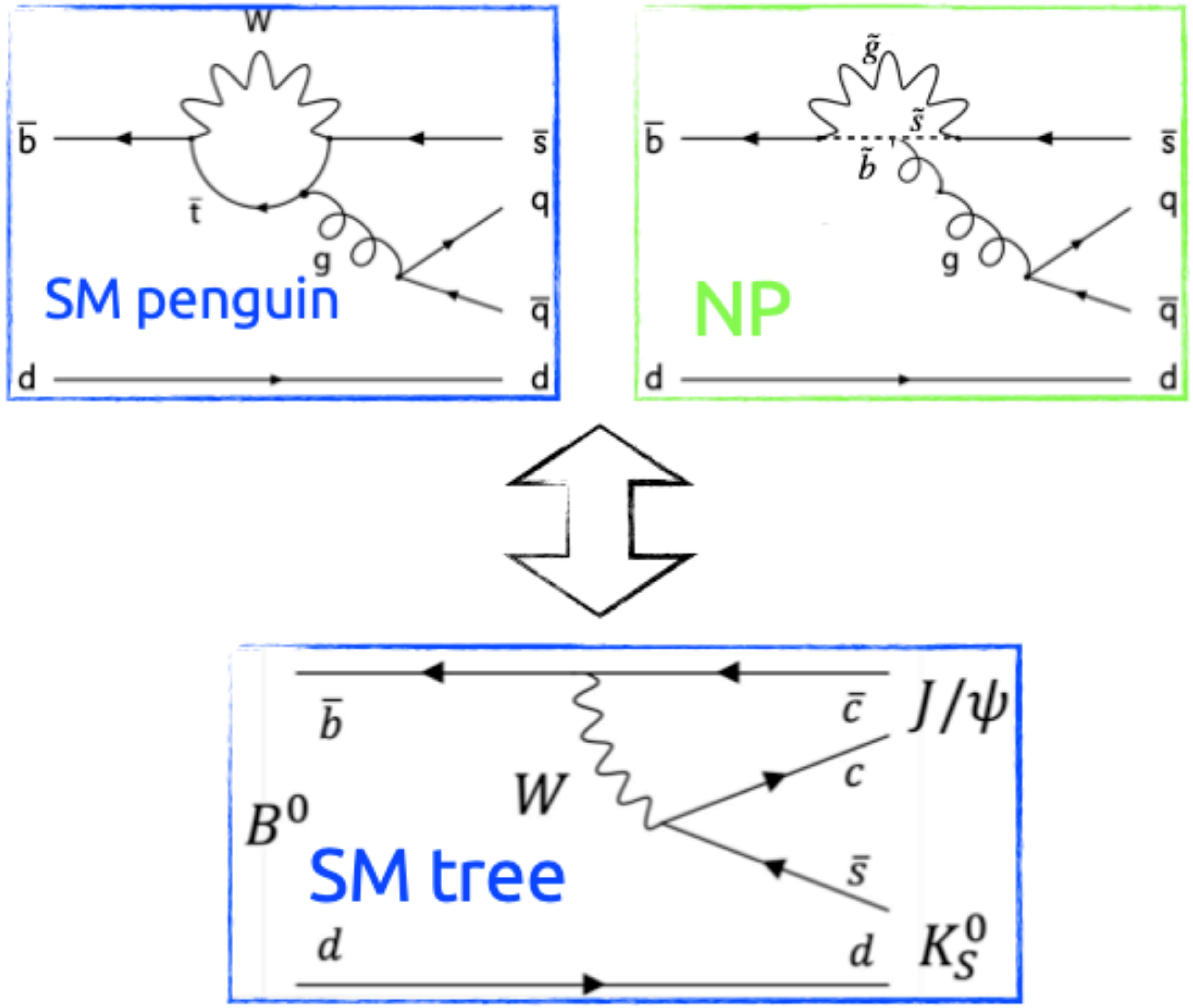
- Asymmetric collision (boost effect): better measurement on displacement. (Belle II: $\Delta z \approx 130\mu m$, Belle: $\Delta z \approx 200\mu m$)
- Good vertex resolution: 15 μm; 2 layers of PXD and 4 layers of SVD.
- Coherent $B\bar{B}$ pairs.
- High tagging efficiency (Belle II: $\epsilon_{tag} = (31.7 \pm 0.4)\,\%$; Belle: $\epsilon_{tag} = (30.1 \pm 0.4)\,\%$)

$b \to s\bar{q}q(q = d, s)$ process

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

Mixing-induced CPV (S)

Direct CPV (C)

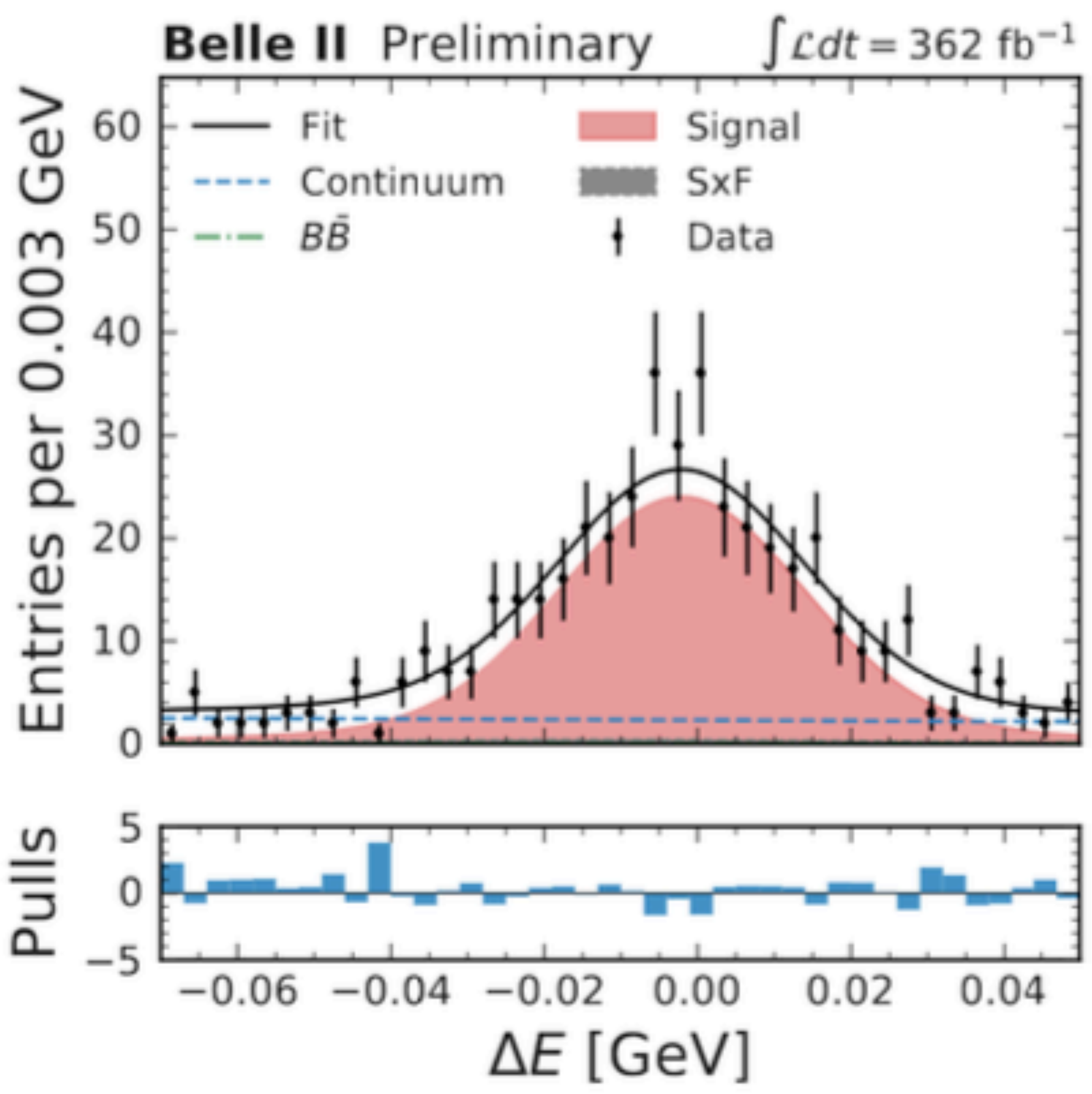


- Gluonic penguin process:
  - Shall be more sensitive to **New physics**.
- $S^{eff} = \sin(2\phi_1) + \Delta S$, ΔS may come from SM or NP.
- Using precise W.A. $\sin(2\phi_1) = 0.699 \pm 0.017$, measure ΔS, compare with SM's ΔS.

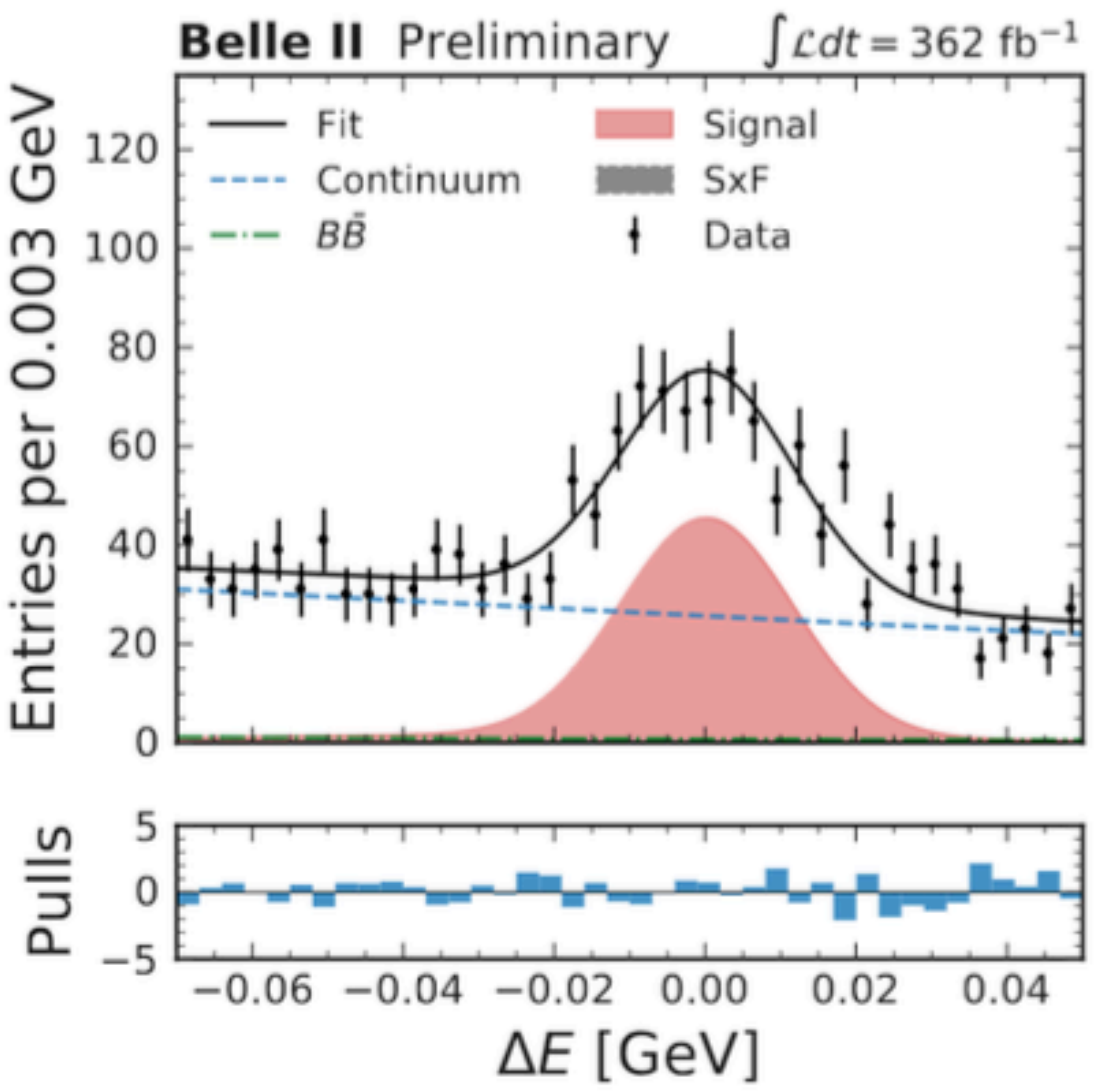
$B^0 \to \eta' K_S^0$

New EPS result this week!

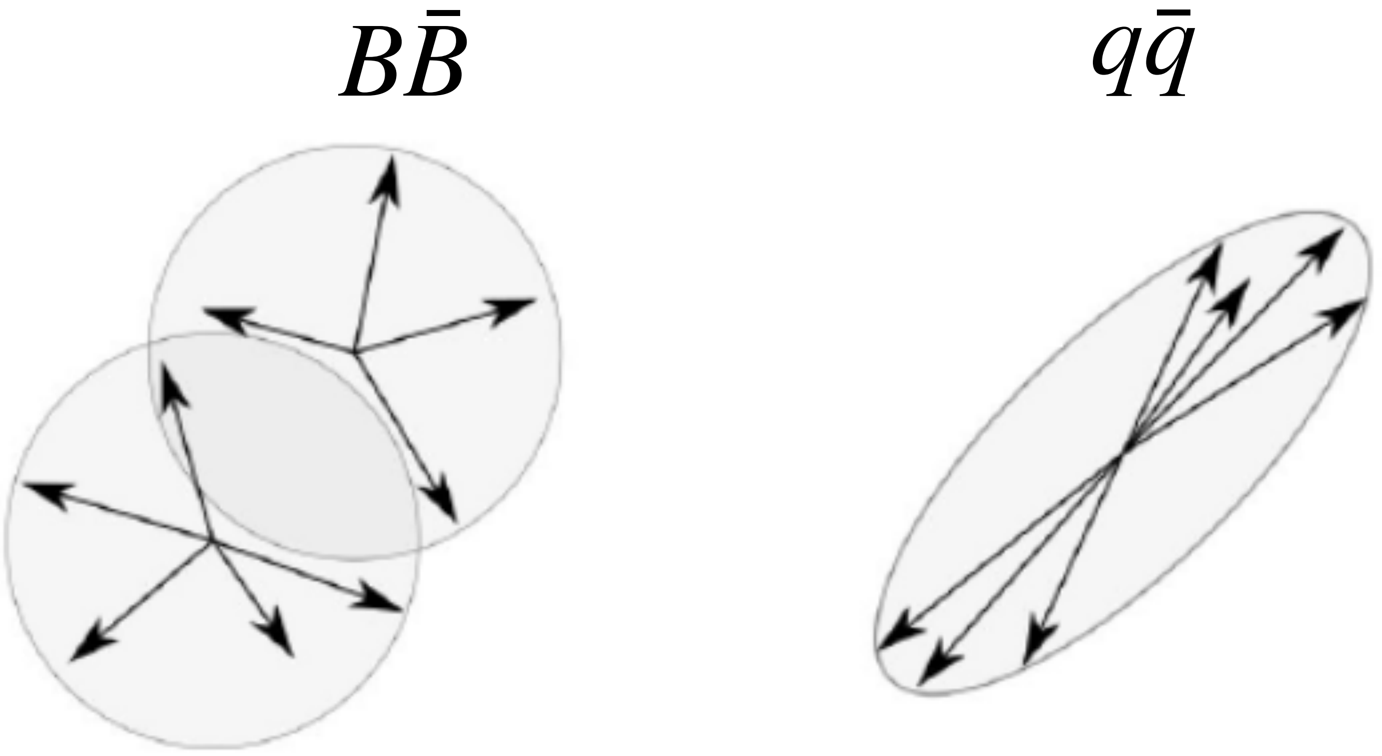
$\eta'[\to \eta\pi^+\pi^-]$



$\eta'[\to \rho\gamma]$



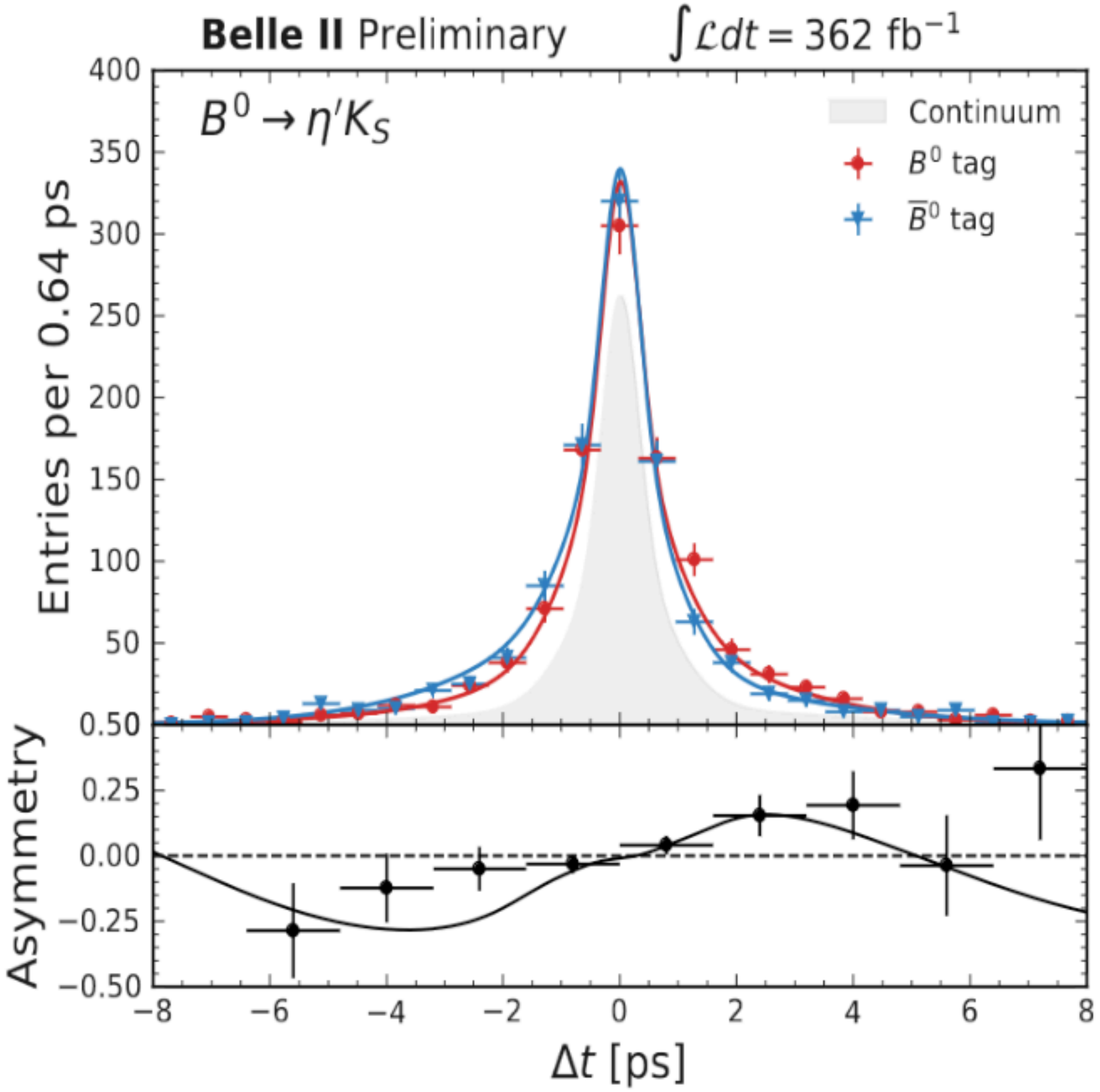
$$\Delta E = E_B^* - E_{\mathrm{beam}}^*$$



- Challenge: high background from $q\bar{q}$
- Train event-shape MVA for $q\bar{q}$ background
- Signal yield: $n_{sig} = 829 \pm 35$

$B^0 \to \eta' K_S^0$

New EPS result this week!



- Get Δt shape of $q\bar{q}$ from sideband region.
- Extract S_{CP} and C_{CP} from the fit in signal region.
- Validate the fit with $B^\pm \to \eta' K^\pm$

$$C_{CP} = 0.19 \pm 0.08 \pm 0.03$$
$$S_{CP} = 0.67 \pm 0.10 \pm 0.04$$

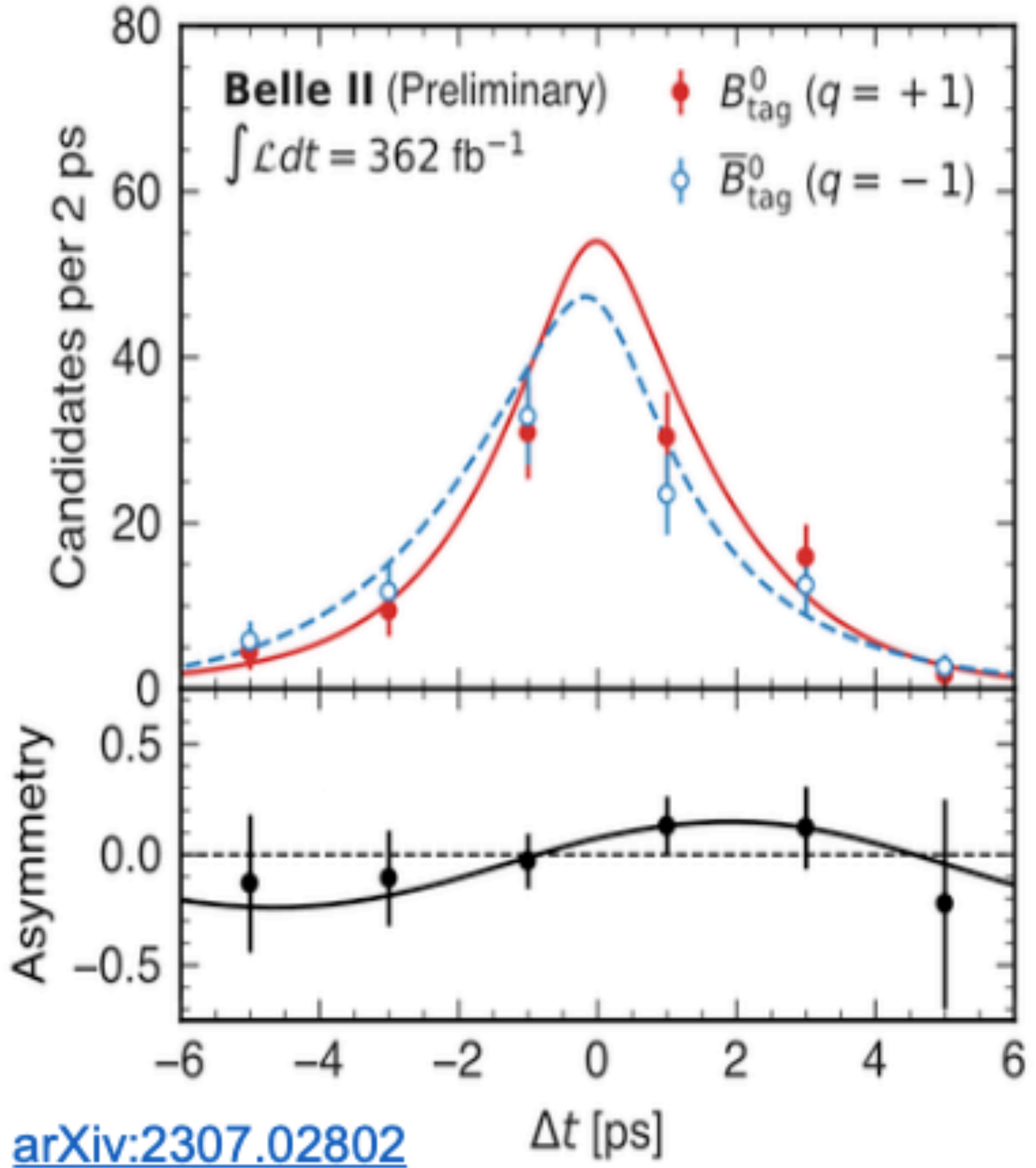
HFLAV: $C_{CP} = -0.05 \pm 0.04$ $S_{CP} = 0.63 \pm 0.06$

- ΔS_{CP}(SM) $= 0.01 \pm 0.01$(arXiv:hep-ph/0505075)

Other three $b \to s\bar{q}q(q = d, s)$

Moriond 2023 results

$B^0 \to \varphi K_S$

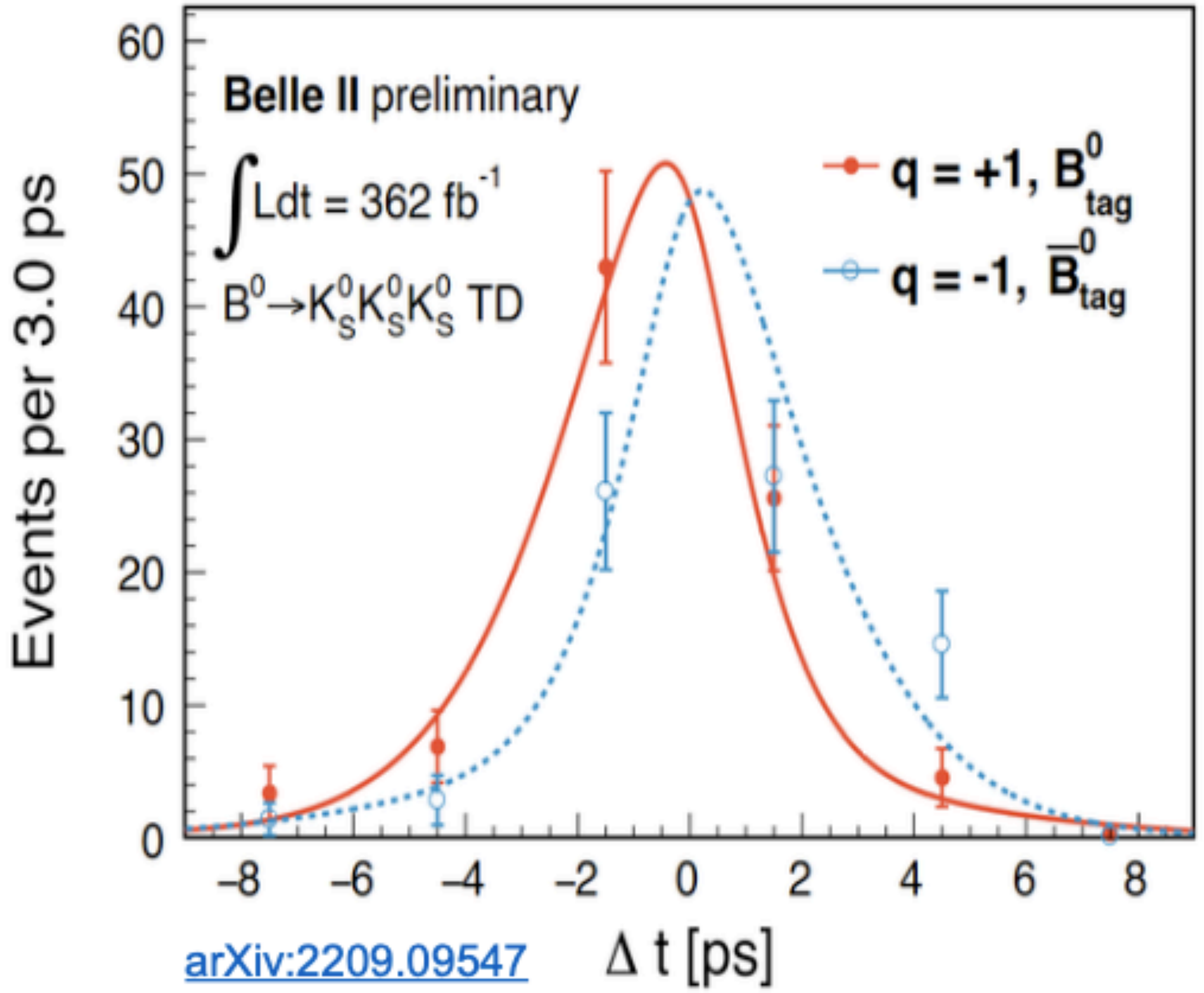


arXiv:2307.02802

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

HFLAV: $C_{CP} = 0.01 \pm 0.14$ $S_{CP} = 0.74^{+0.11}_{-0.13}$

$B^0 \to K_S K_S K_S$

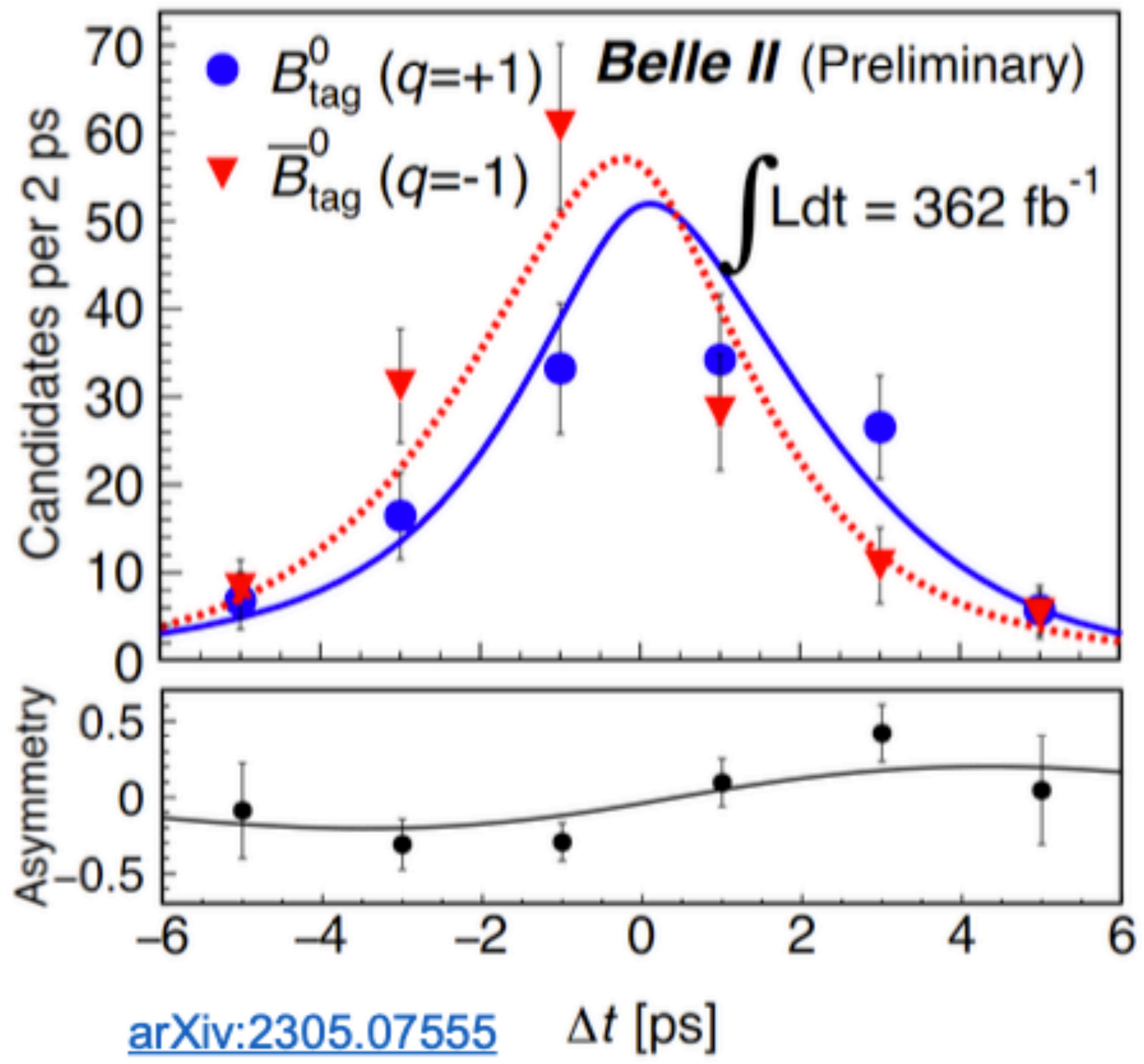


arXiv:2209.09547

$$C_{CP} = -0.07 \pm 0.20 \pm 0.05$$
$$S_{CP} = -1.37^{+0.35}_{-0.45} \pm 0.03$$

HFLAV: $C_{CP} = -0.15 \pm 0.12$ $S_{CP} = -0.83 \pm 0.17$

$B^0 \to K_S \pi^0$



arXiv:2305.07555

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

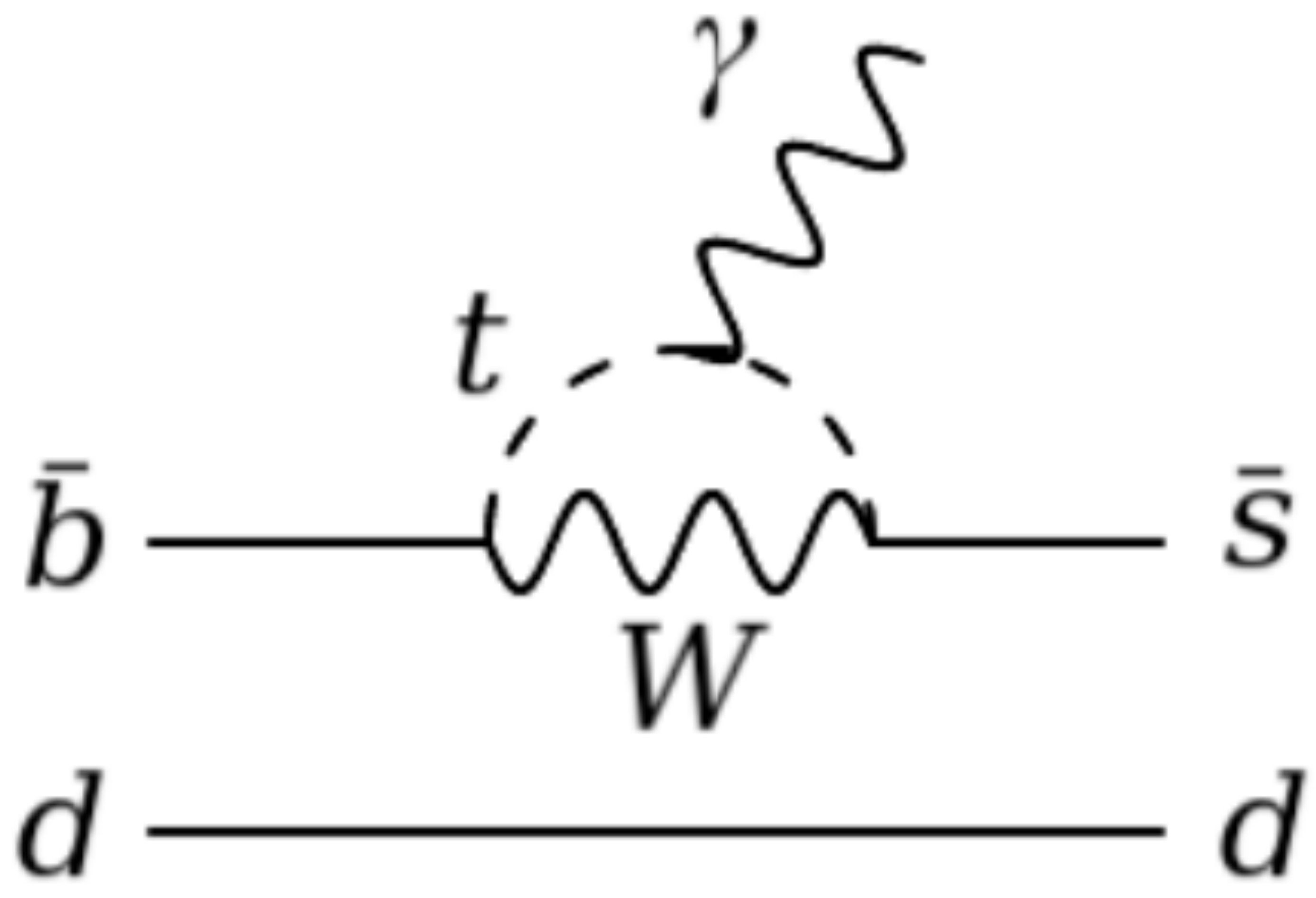
HFLAV: $C_{CP} = 0.01 \pm 0.10$ $S_{CP} = 0.57 \pm 0.17$

arXiv:2307.02802

arXiv:2305.07555

Radiative penguins ($B^0 \to K_S\pi^0\gamma$)

- In SM, the mixing-induced CPV S_{CP} is helicity suppressed. e.g. $S_{CP}(B^0 \to K_S\pi^0\gamma) = -0.035 \pm 0.017$ (arXiv:hep-ph/0406055)
- NP could contribute into S_{CP} significantly.



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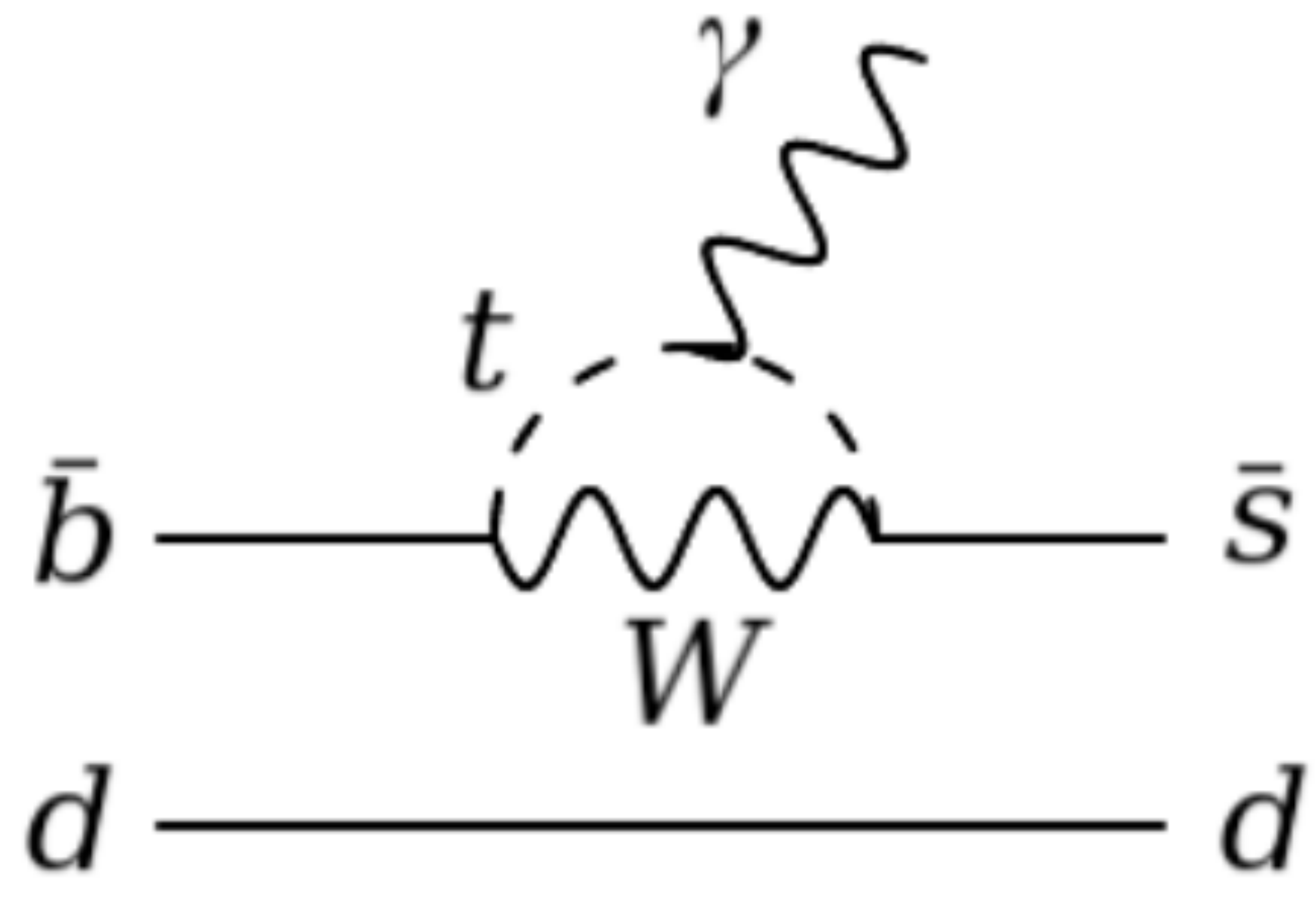


About reconstruction of $B^0 \to K_S \pi^0 \gamma$:

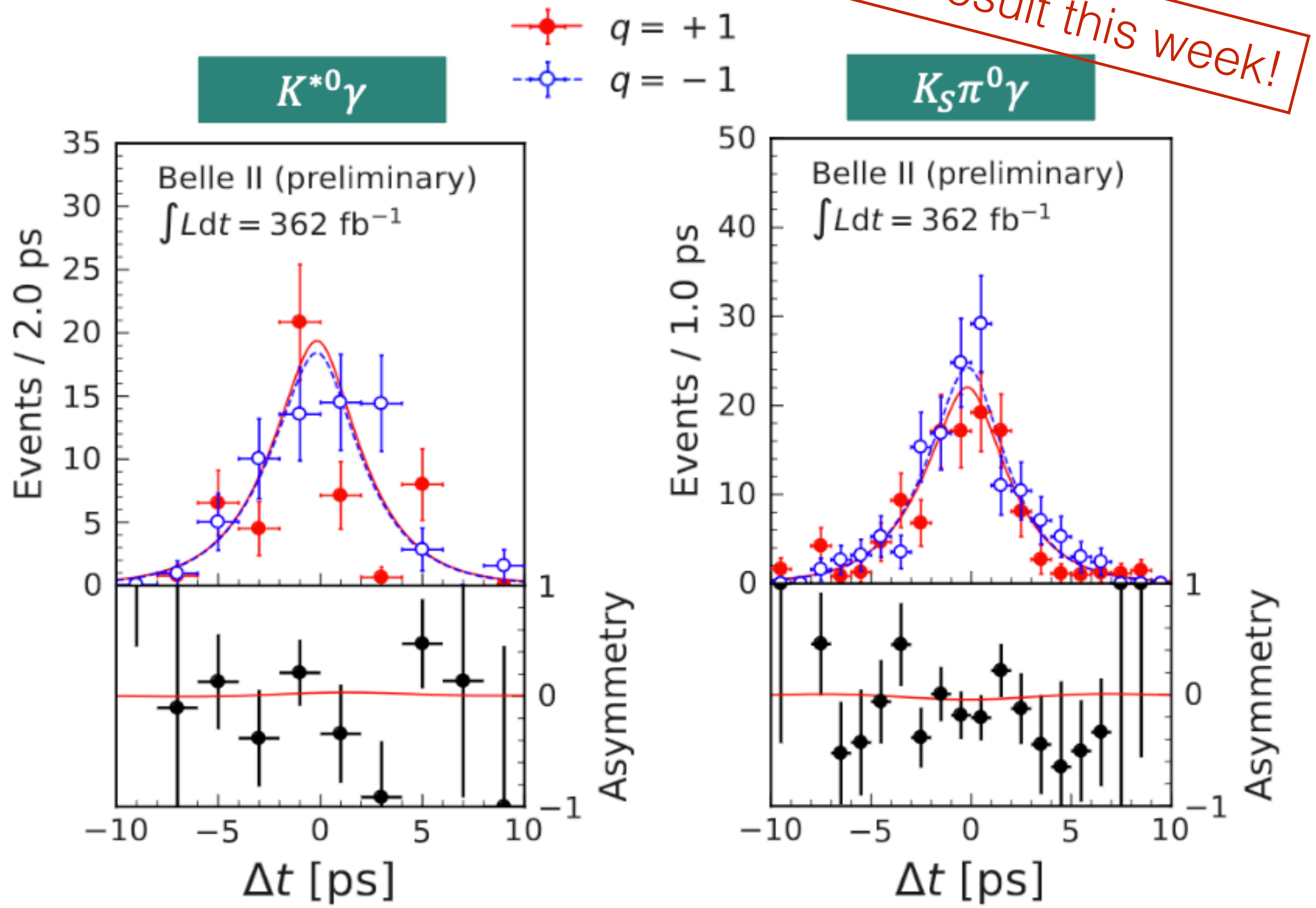
- Challenge: no prompt tracks; reconstruct vertex only from Ks using a beam-spot constraint.
- The candidates with poor vertex reconstruction are only used to measure C_{CP} in a time-integrated way.
- High multiplicity from fake beam background π^0: use MVA methods to select single one.

$B^0 \to K_S\pi^0\gamma$

New EPS result this week!

- Consider exclusive decay $B^0 \to K^{*0}(K_S\pi^0)\gamma$ and inclusive decay separately.

Channel	$K^{*0}\gamma$	$K_S\pi^0\gamma$
$M_{K_S\pi^0}$-region $[\frac{GeV}{c^2}]$	$]0.8, 1.0[$	$[0.6, 0.8]$or $[0.8, 1.8]$
Signal yield	385 ± 24	171 ± 23



$C_{CP} = 0.10 \pm 0.13 \pm 0.03$
$S_{CP} = 0.00^{+0.27+0.03}_{-0.26-0.04}$

$C_{CP} = -0.06 \pm 0.25 \pm 0.07$
$S_{CP} = 0.04^{+0.45}_{-0.44} \pm 0.10$

HFLAV:

$K^{*0}\gamma$: $C_{CP} = -0.04 \pm 0.14$ $S_{CP} = -0.16 \pm 0.22$

$K_S\pi^0\gamma$: $C_{CP} = -0.07 \pm 0.12$ $S_{CP} = -0.15 \pm 0.20$

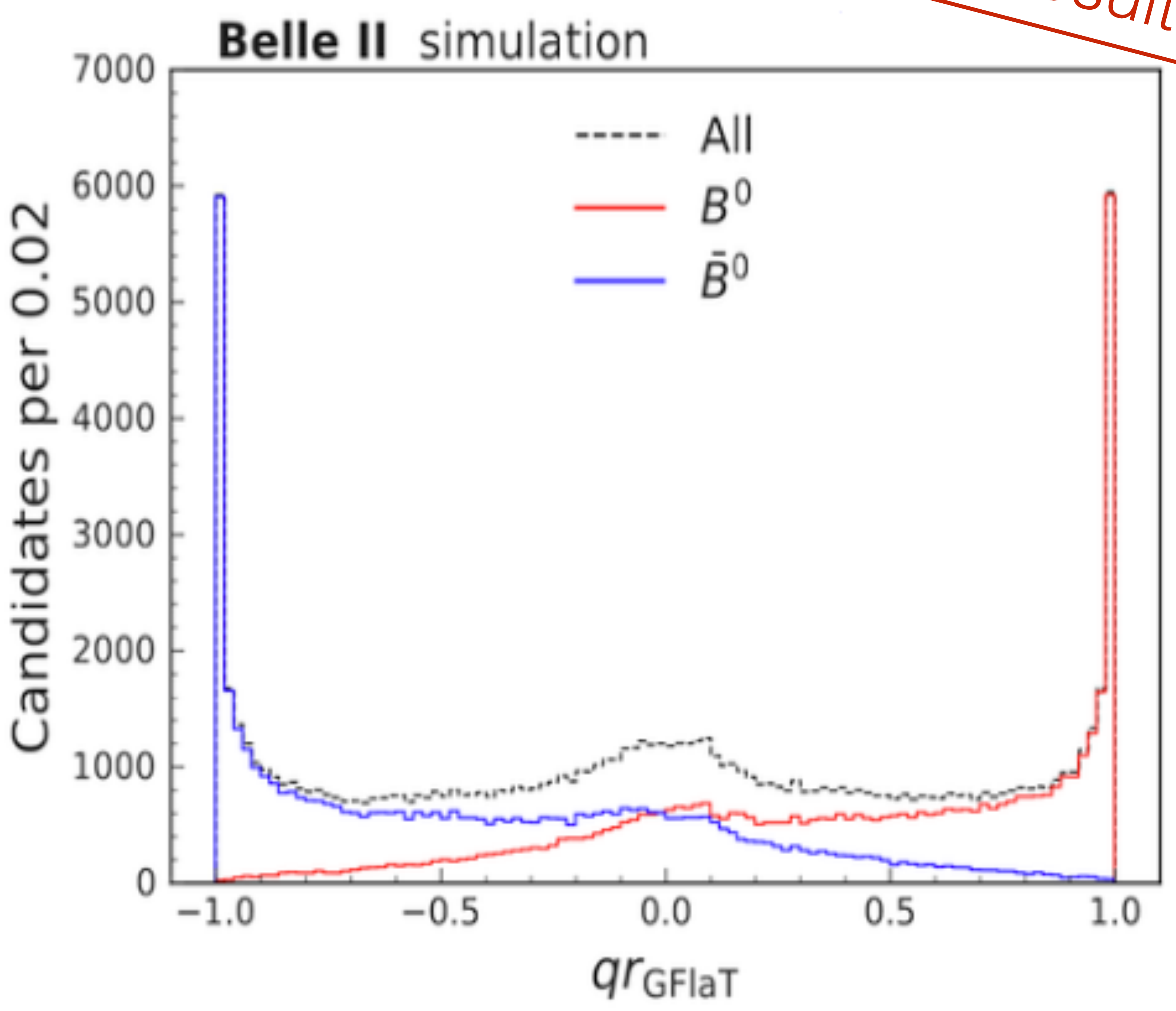
*The HFLAV $K_S\pi^0\gamma$ values include $K^{*0}\gamma$

GNN Flavor Tagger (GFlaT)

New EPS result this week!

- New flavor tagger (GFlaT) based on graph neural network (GNN).
- Use interrelation between particles.
- Gain **18%** relative tagging efficiency compared to category-based flavor tagger (CB FT).

CB FT:	$\epsilon_{tag} = (31.68 \pm 0.45 \pm 0.41)\%$
GFlaT:	$\epsilon_{tag} = (37.40 \pm 0.43 \pm 0.34)\%$



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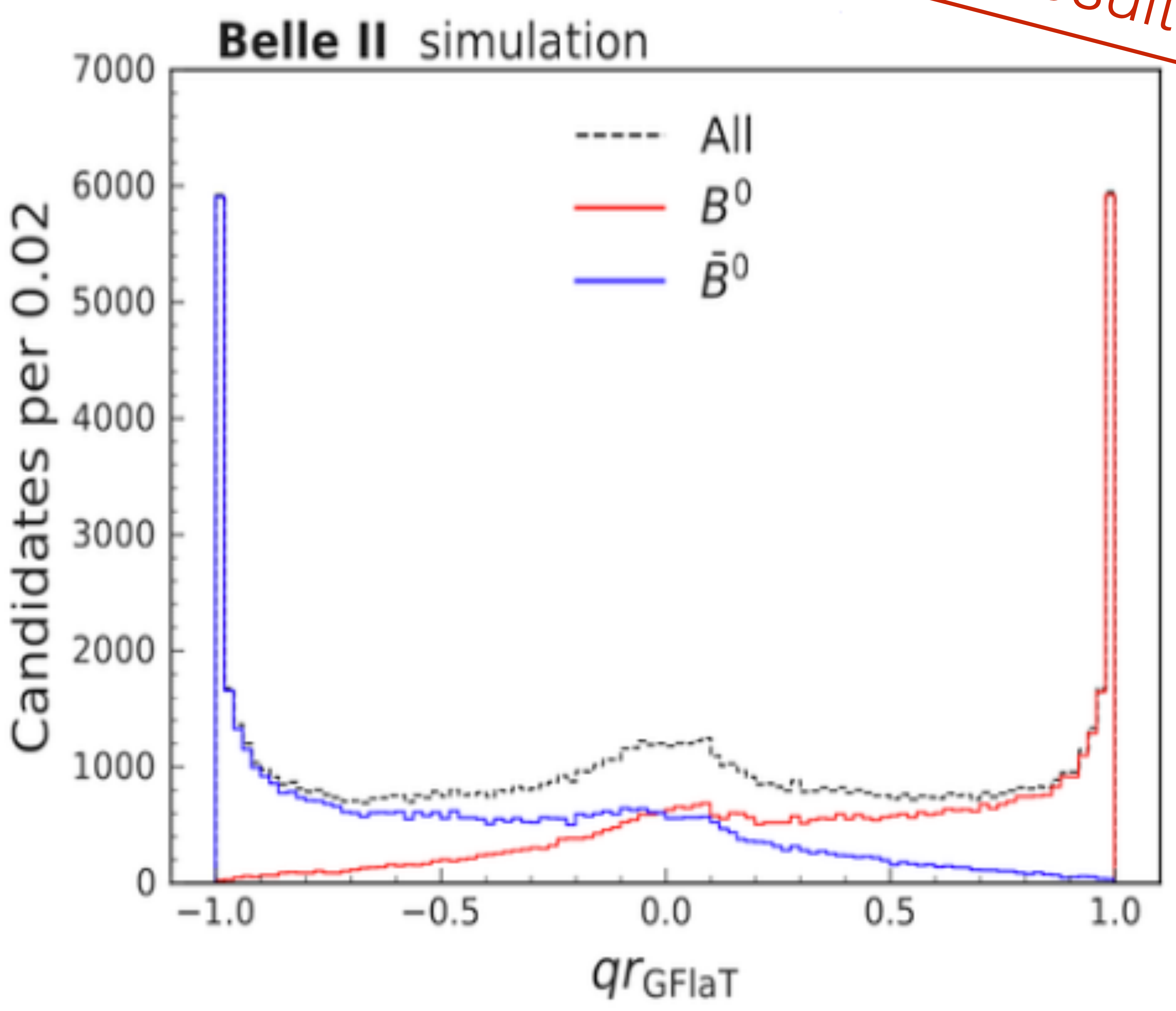

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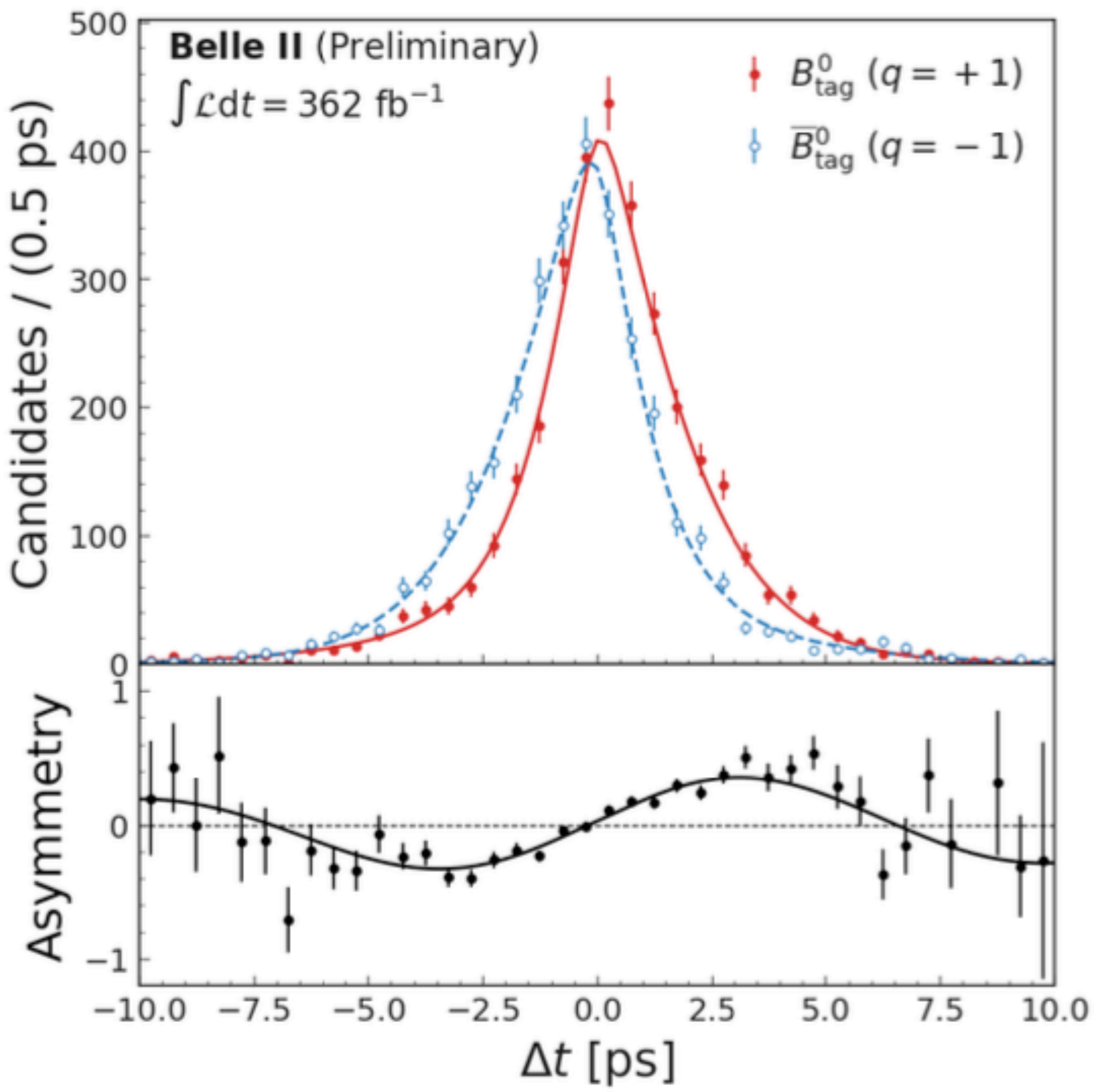
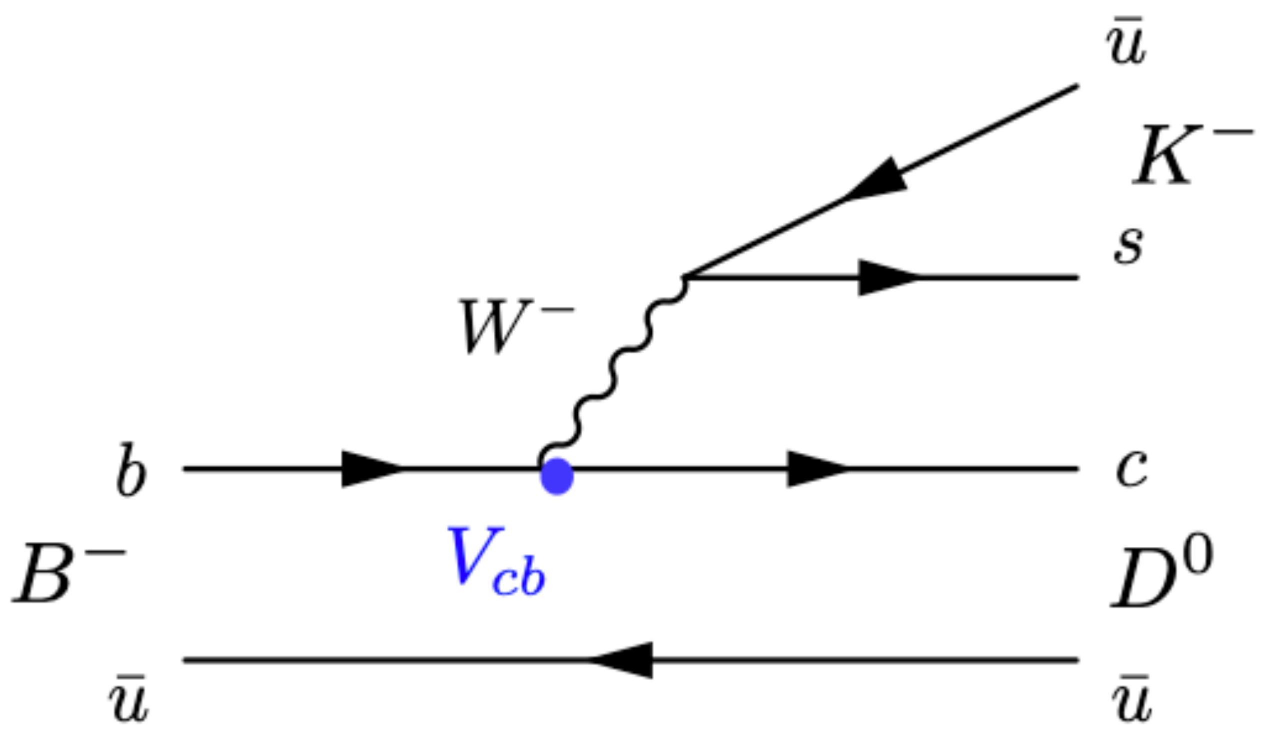


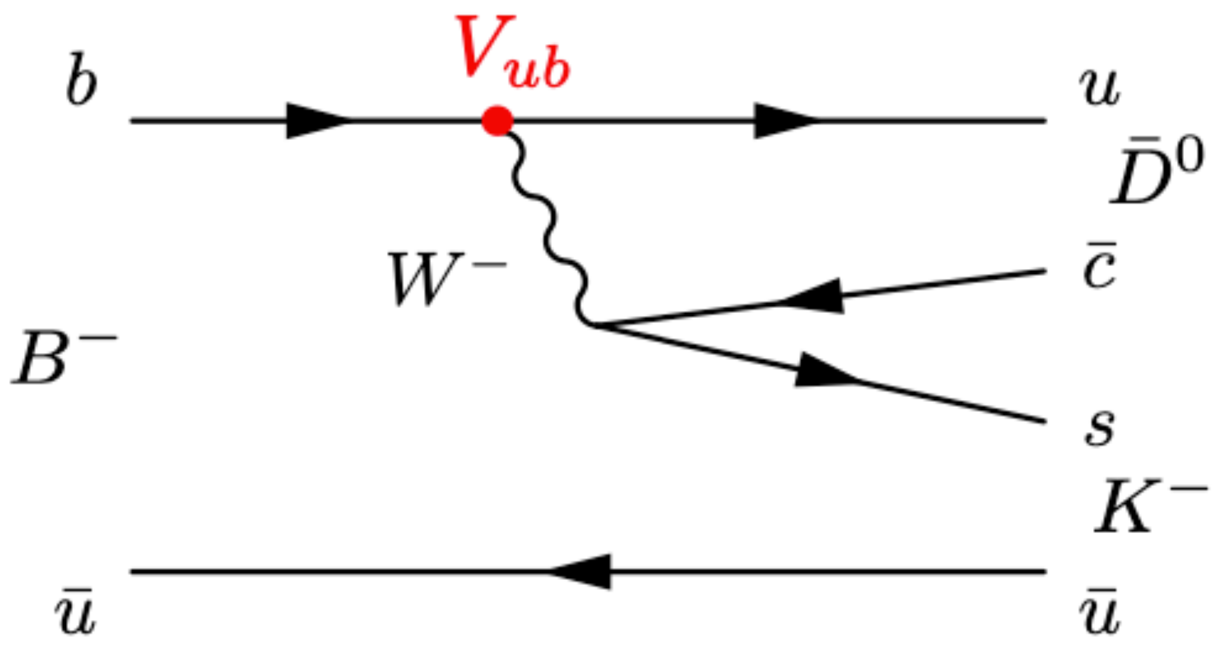
- Validated by the $B^0 \to J/\psi K_S$
- ~8% reduction in statistical uncertainty.

$$C_{CP} = -0.035 \pm 0.026 \pm 0.012$$
$$S_{CP} = 0.724 \pm 0.035 \pm 0.014$$

HFLAV: $C_{CP} = 0.000 \pm 0.020$ $S_{CP} = 0.695 \pm 0.019$

For ϕ_3: GLW & GLS





- CPV in the interference $b \to c\bar{u}s$ and $b \to u\bar{c}s$
  $$\frac{A_{\text{sup}}(B^- \to \bar{D}^0 K^-)}{A_{\text{fav}}(B^- \to D^0 K^-)} = r_B e^{i(\delta_B - \phi_3)}$$
- Irreducible error in SM calculation ~10^{-7} [arXiv:1308.5663]
- W.A. $\phi_3 = (65.9^{+3.3}_{-3.5})^\circ$
- With the coming B data from LHCb and Belle II, the experimental precision is ~ 1.5° (50 ab^{-1} Belle II) ~0.4° (300 fb^{-1} LHCb)

—> ϕ_3 can be a "candle" of SM.

- Depends on the D decay final states, different methods:
  - BPGGSZ: self conjugated multi-body decays, e.g. $K_S^0\pi^+\pi^-$ [JHEP 02 2022, 063 (2022)]
  - **GLW**: CP eigenstates, e.g. $K_S^0\pi^0, K^+K^-$
  - **GLS**: SCS decays, e.g. $K_S^0K^\mp\pi^\pm$
  - …(ADS, TD)

GLW result (Belle+BelleII!)

- $B^\pm \to DK^\pm$ with $D \to K_S^0\pi^0$ (CP-odd) or $D \to K^+K^-$ (CP-even)

Moriond 2023 results

$$R_{CP\pm} = \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D^0K^-) + \mathcal{B}(B^+ \to \bar{D}^0K^+)},$$
$$= 1 + r_B^2 + 2\eta_{CP}r_B\cos(\delta_B)\cos(\phi_3),$$
$$A_{CP\pm} = \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) - \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)},$$
$$= 2\eta_{CP}r_B\sin(\delta_B)\sin(\phi_3)/R_{CP\pm}.$$

- 2D Fit $(\Delta E, C')$ of 6 categories $(DK, D\pi)$x$(K_S^0\pi^0, K^+K^-, K^-\pi^+)$

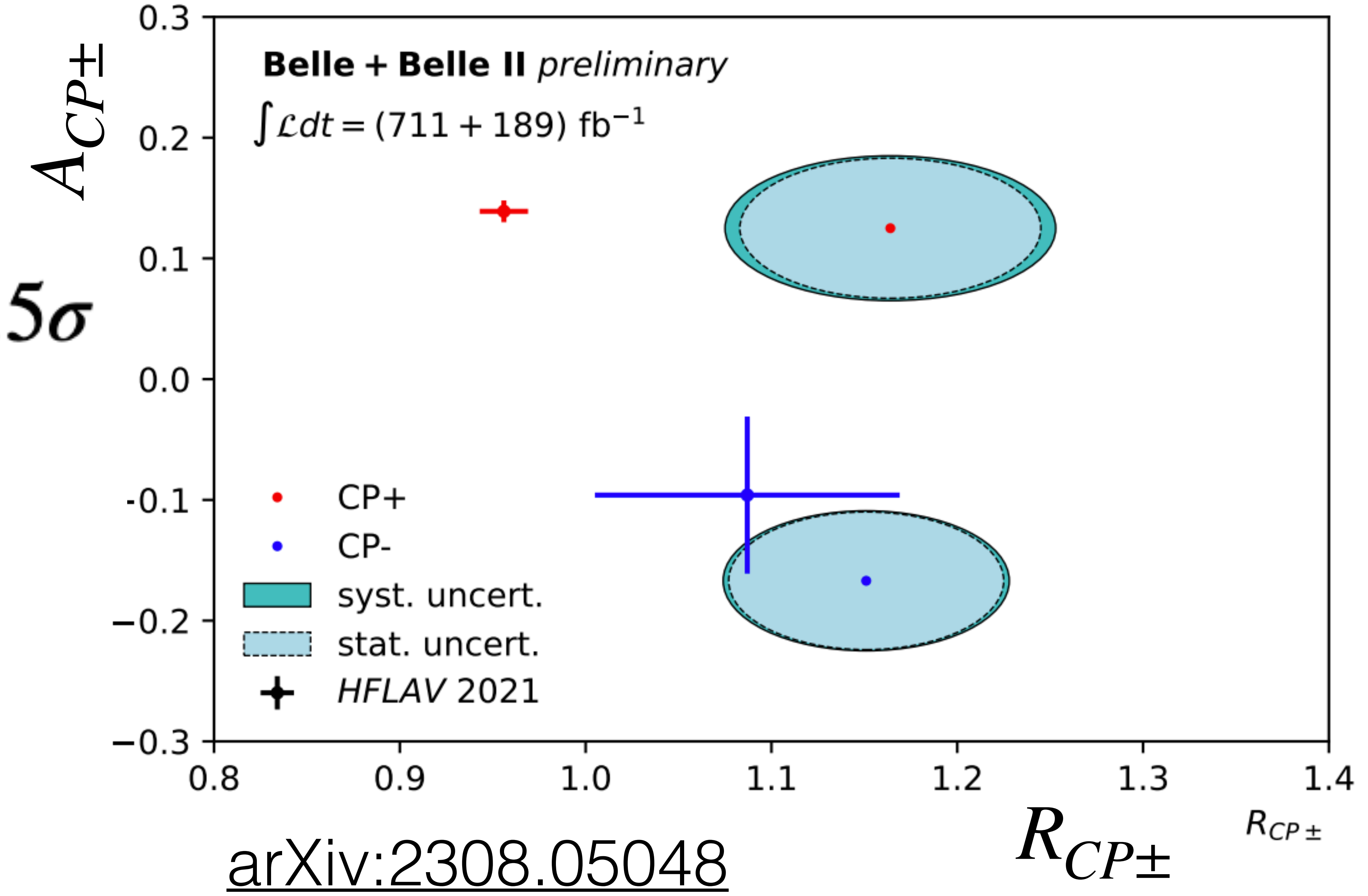
	68.3% CL	95.4% CL
ϕ_3 (°)	[8.5, 16.5]	[5.0, 22.0]
	[84.5, 95.5]	[80.0, 100.0]
	[163.3, 171.5]	[157.5, 175.0]
r_B	[0.321, 0.465]	[0.241, 0.522]

$$\mathcal{R}_{CP+} = 1.164 \pm 0.081 \pm 0.036,$$
$$\mathcal{R}_{CP-} = 1.151 \pm 0.074 \pm 0.019,$$
$$\mathcal{A}_{CP+} = (+12.5 \pm 5.8 \pm 1.4)\%,$$
$$\mathcal{A}_{CP-} = (-16.7 \pm 5.7 \pm 0.6)\%.$$

3.5σ

world average: $\phi_3\,(\circ) = 66.2^{+3.4}_{-3.6}$ $r_B = 0.0996 \pm 0.0026$

Large Rcp+ than W.A.
Competitive Rcp- and Acp- with W.A.



arXiv:2308.05048

GLS result (Belle+BelleII!)

- $B^{\pm} \to DK^{\pm}$ with $D \to K_S^0 K^+ \pi^-$ (SS) or $D \to K_S^0 K^- \pi^+$ (OS)
- Measure 4 Acp and 3 BR ratios.
- Get results in full D phase space and in the K*K region (large δ_D, κ_D).

Moriond 2023 results

In K*K region:

$$
\begin{aligned}
A_{\rm SS}^{DK} &= 0.055 \pm 0.119 \pm 0.020, \\
A_{\rm OS}^{DK} &= 0.231 \pm 0.184 \pm 0.014, \\
A_{\rm SS}^{D\pi} &= 0.046 \pm 0.029 \pm 0.016, \\
A_{\rm OS}^{D\pi} &= 0.009 \pm 0.046 \pm 0.009, \\
R_{\rm SS}^{DK/D\pi} &= 0.093 \pm 0.012 \pm 0.005, \\
R_{\rm OS}^{DK/D\pi} &= 0.103 \pm 0.020 \pm 0.006, \\
R_{\rm SS/OS}^{D\pi} &= 2.412 \pm 0.132 \pm 0.019,
\end{aligned}
$$

arXiv:2306.02940

- First Belle/Belle II result from this channel.
- The precision is worse than LCHb's[arXiv:2002.08858], but consistent.
- With the D information from CLEO-c, will contributed in a combined ϕ_3 from Belle/BelleII.

For ϕ_2: $B^0 \to \pi\pi$

Moriond 2023 results

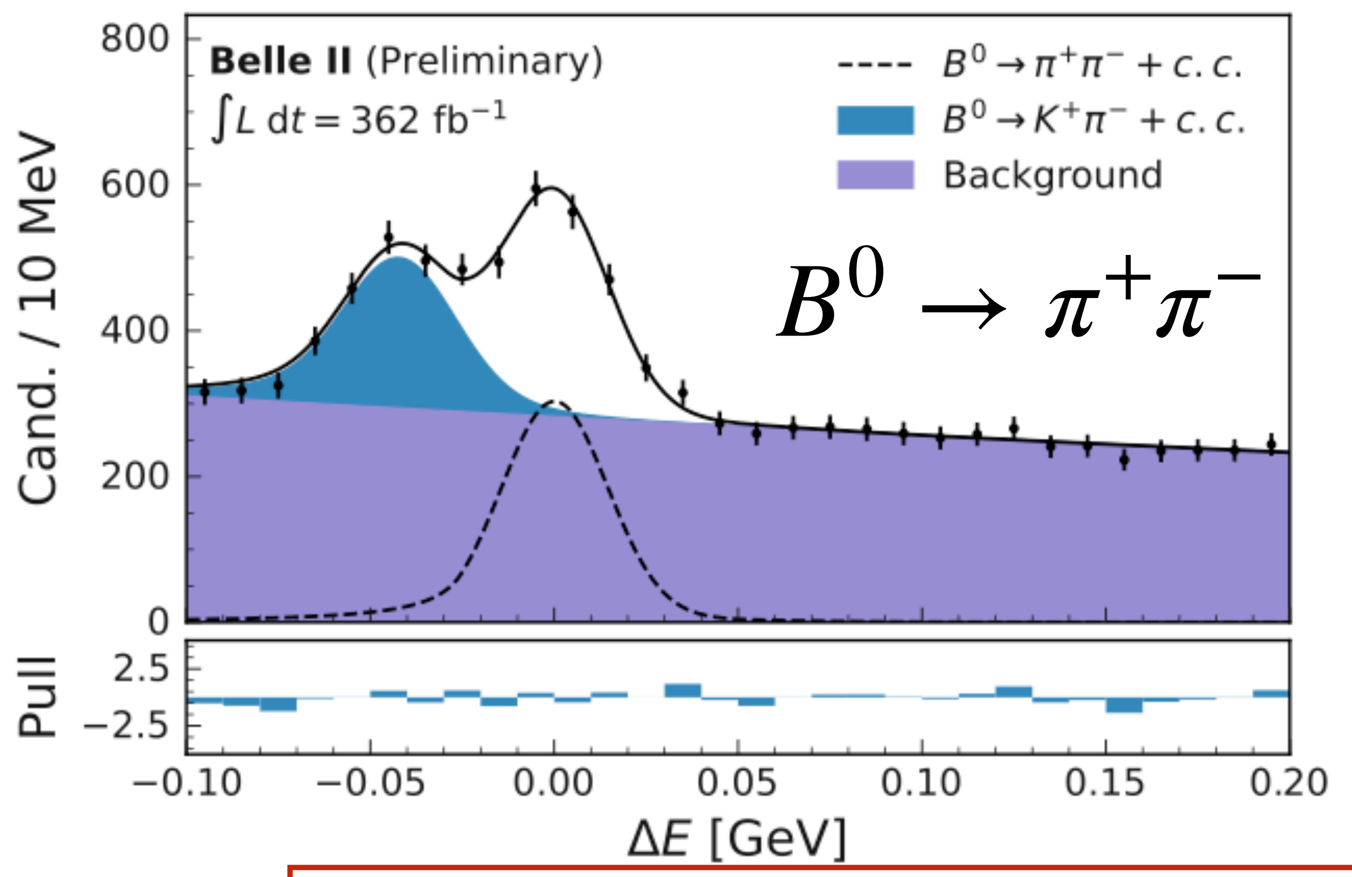
- The CKM angle with most poor precision at the moment: W.A. $\phi_2 = (85.2^{+4.8}_{-4.3})^\circ$ [HFLAV].
- Determined using $B \to \rho\rho$, $B \to \pi\pi$ isospin analysis: using the Br and A_{CP} to reduce hadronic uncertainties.

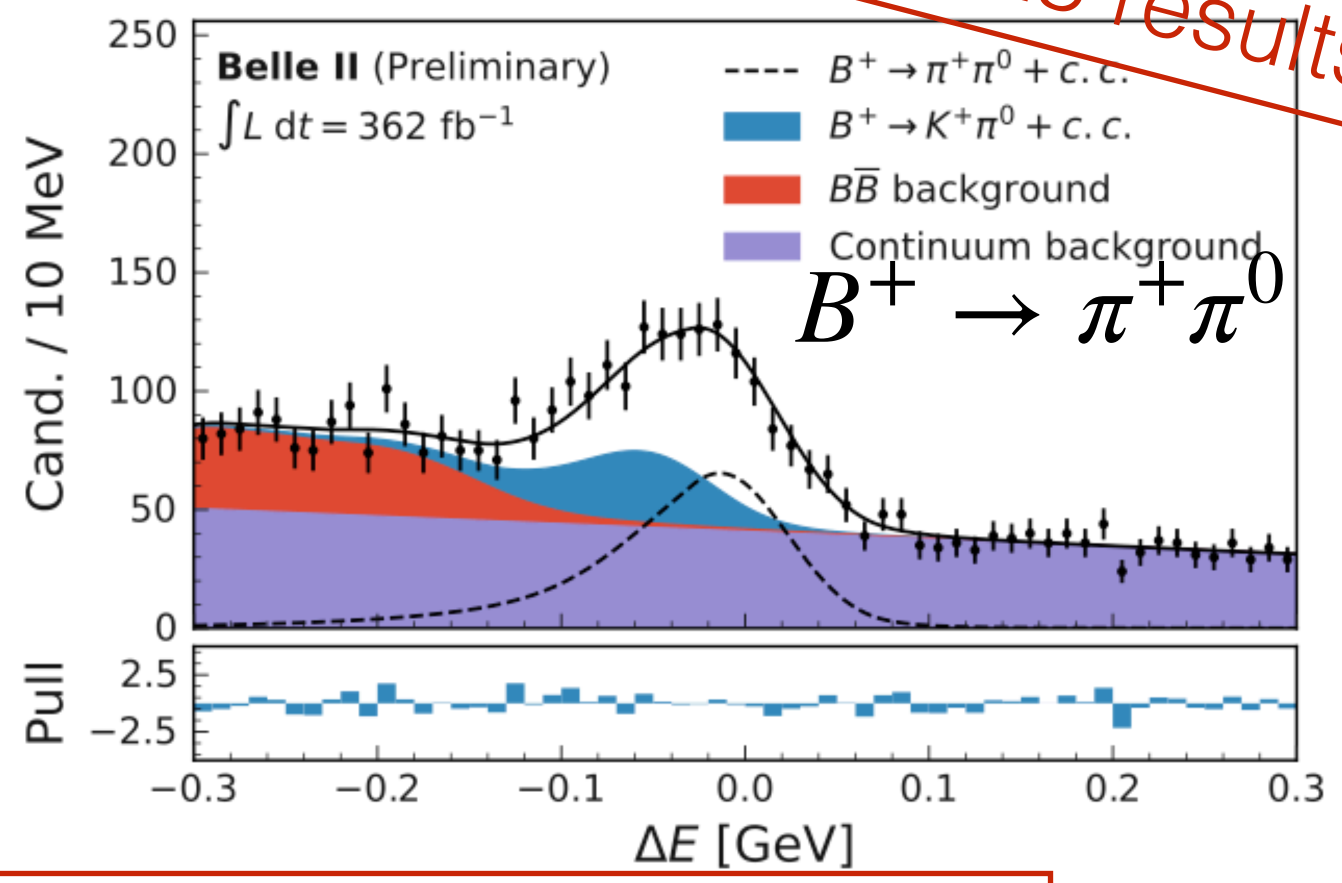
Unique Belle II capability to study all channels.

Last year: $\rho^+\rho^0, \rho^+\rho^-$[arXiv:2206.12362, 2208.03554]

We have $\pi\pi$ results now.

For $\pi^0\pi^0$, achieve Belle Br precision using only 1/3 of data.

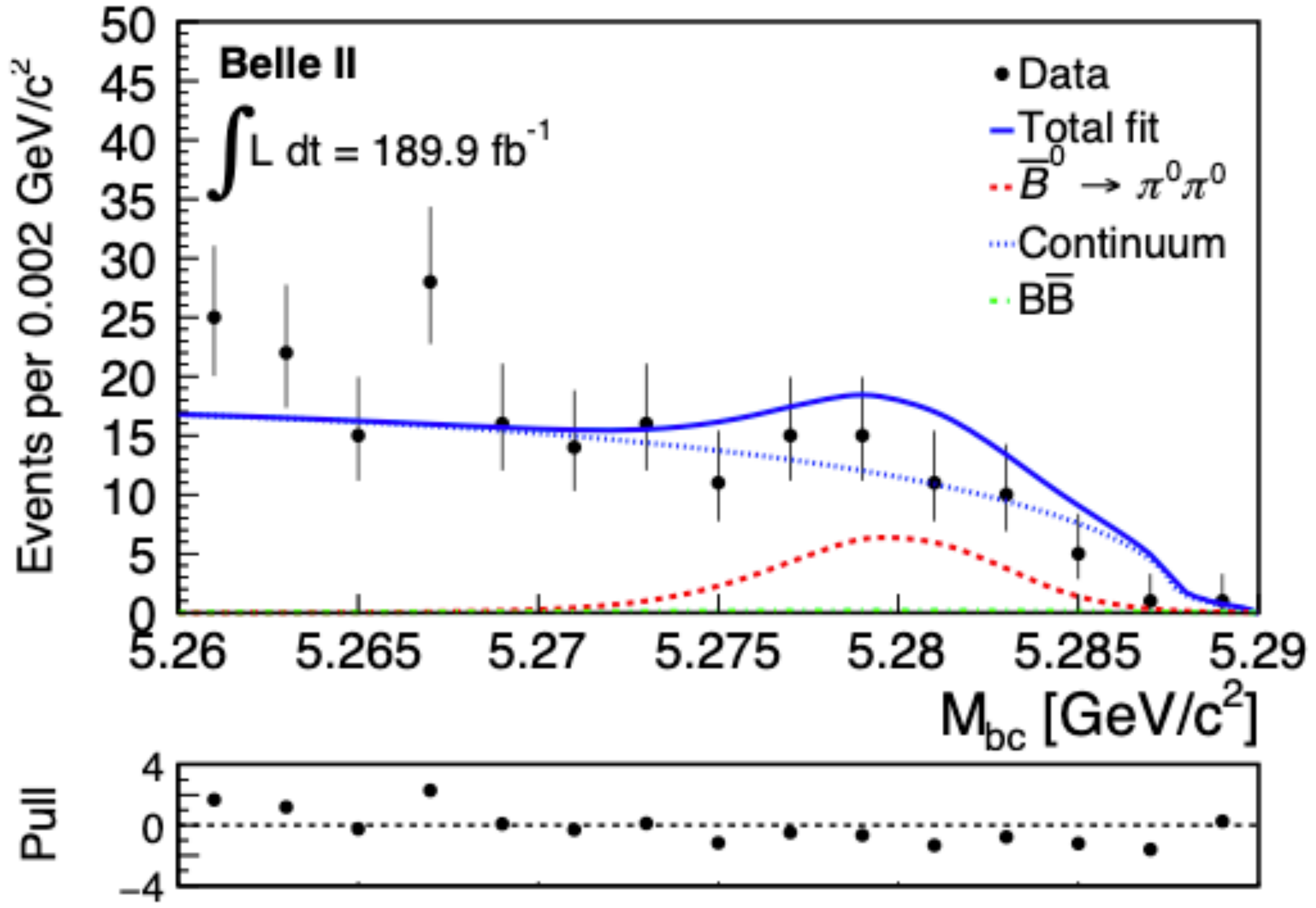


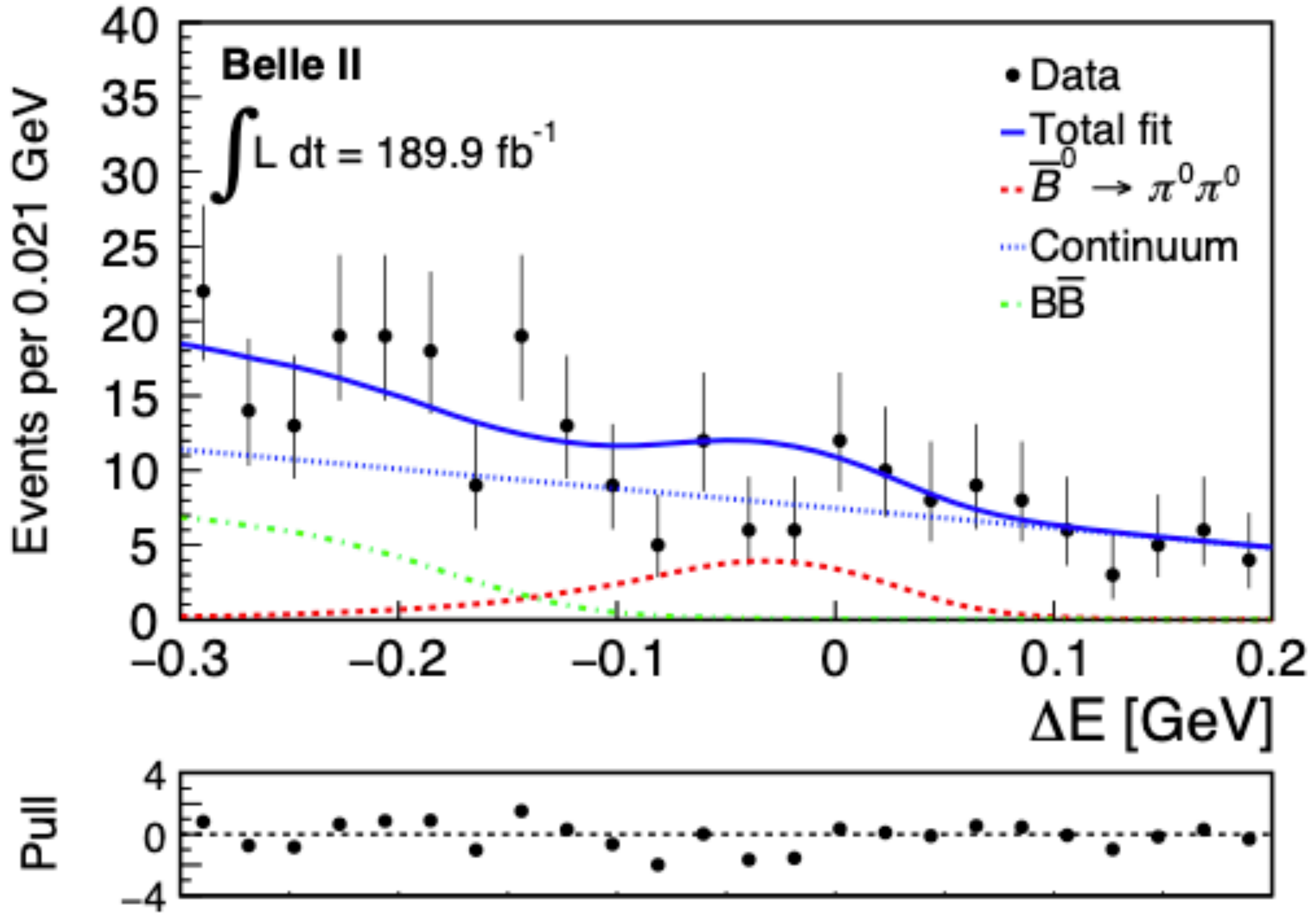


$\text{Br}(B^0 \to \pi^+\pi^-) = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$

$\text{Br}(B^+ \to \pi^+\pi^0) = (5.10 \pm 0.29 \pm 0.32) \times 10^{-6}$

$A_{CP}(B^+ \to \pi^+\pi^0) = -0.081 \pm 0.54 \pm 0.008$





$\text{Br}(B^0 \to \pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$

$A_{CP}(B^0 \to \pi^0\pi^0) = 0.14 \pm 0.46 \pm 0.07$

Phys. Rev. D 107, 112009 (2023)

CPV in $D_{(s)}$

- Belle (II) is also a charm factory $\sigma(e^+e^- \to c\bar{c}) = 1.3nb$

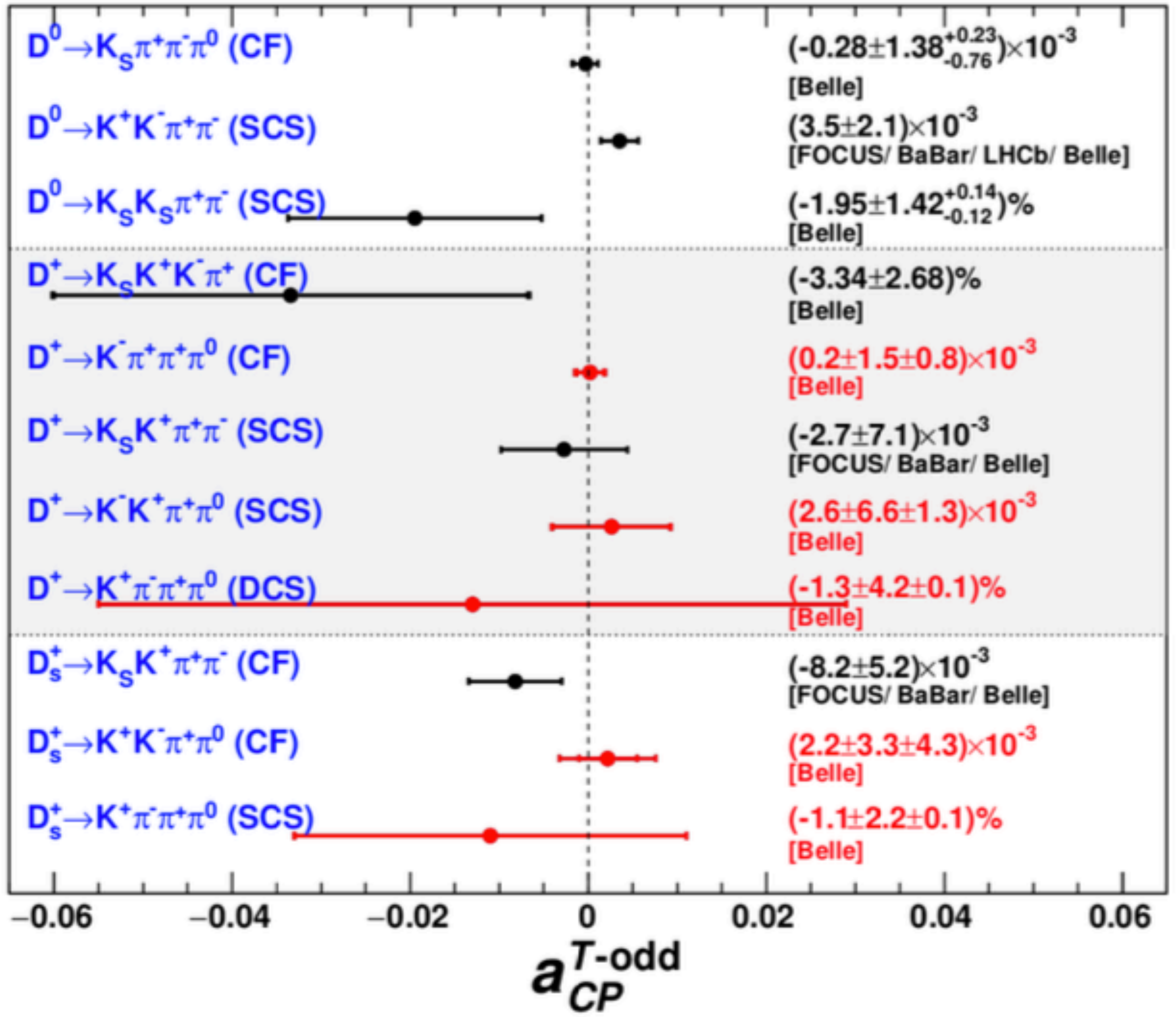
- T-odd CPV: indirectly search for CPV under CPT symmetry conservation.

C_T observable defined by a triple mixed product $C_T = (\vec{p}_1 \times \vec{p}_2) \cdot \vec{p}_3$, satisfying CP($C_T$)=-C($C_T$)=- $\bar{C}_T$

$$A_T = \frac{\Gamma_+(C_T > 0) - \Gamma_+(C_T < 0)}{\Gamma_+(C_T > 0) + \Gamma_+(C_T < 0)} \qquad \bar{A}_T = \frac{\Gamma_-(-\overline{C}_T > 0) - \Gamma_-(-\overline{C}_T < 0)}{\Gamma_-(-\overline{C}_T > 0) + \Gamma_-(-\overline{C}_T < 0)}$$

- T-odd CPV: defined as $a_{CP}^{T-odd} \equiv \frac{1}{2}(A_T - \bar{A}_T)$.

- $D^0 \to K_S^0 K_S^0 \pi^+ \pi^-$ PRD 107, 052001(2023)
- $D^+_{(s)} \to K^+ K_S^0 h^+ h^-$ arXiv:2305.11405



- All results consistent with zero CP Violation.

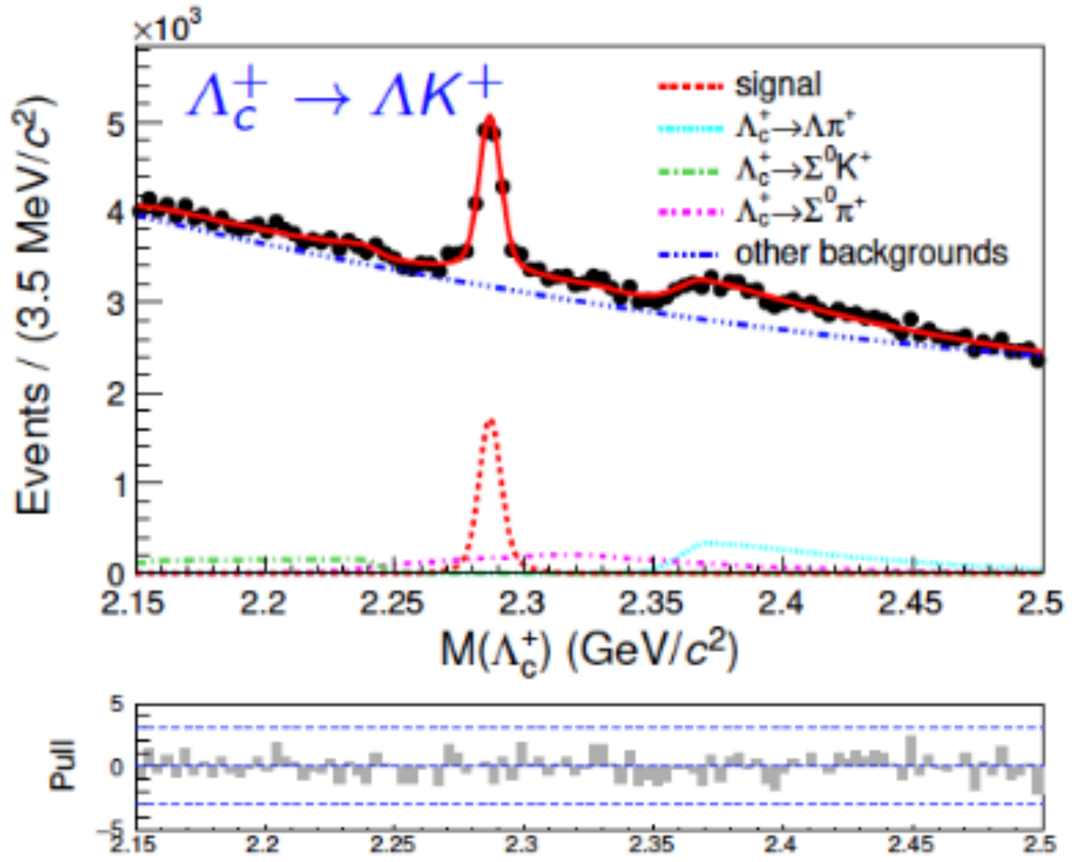
CPV in $\Lambda_c^+ \to \Lambda h^+$ and $\Sigma^0 h^+$

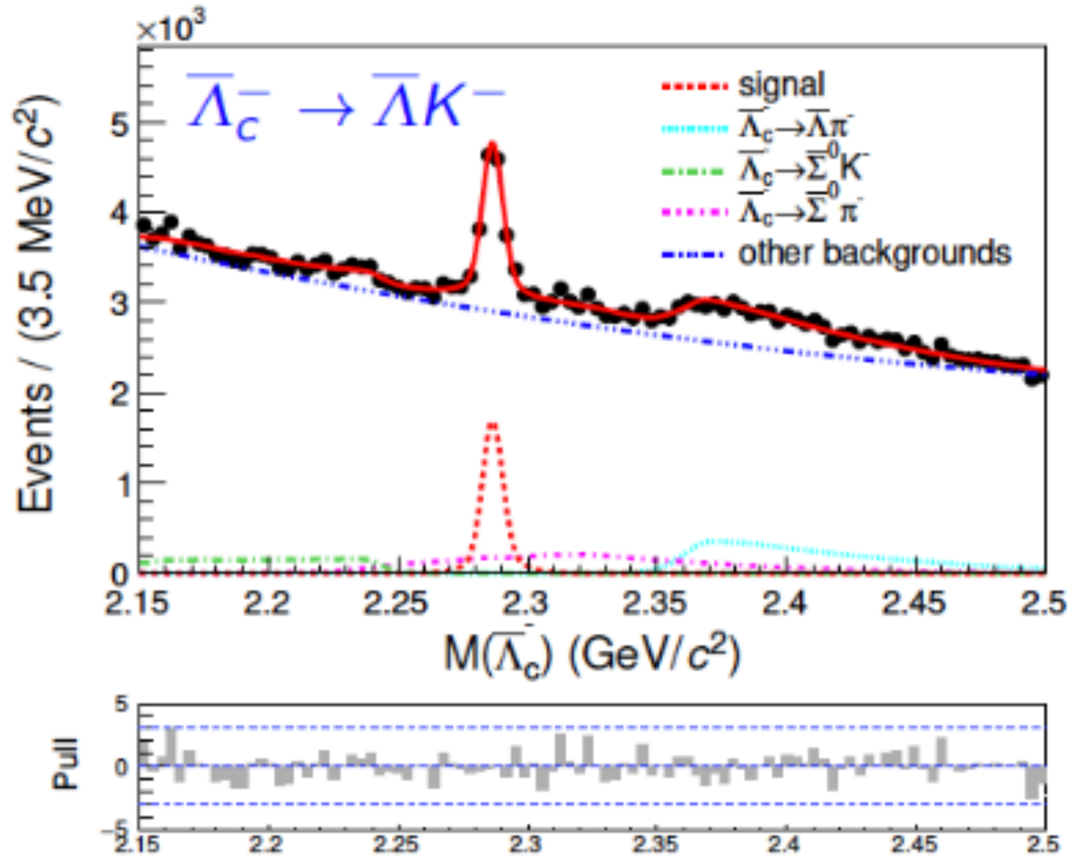
- To date, no CPV observation in baryon sector. Only first evidence in beauty baryon (Nature Physics 13, 391 (2017))

$$A_{\rm raw}(\Lambda_c^+ \to \Lambda K^+) \approx A_{CP}^{\Lambda_c^+\to\Lambda K^+} + A_{CP}^{\Lambda\to p\pi^-} + A_\varepsilon^{\Lambda} + A_\varepsilon^{K^+} + A_{\rm FB}^{\Lambda_c^+}$$

$$A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda K^+) - A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda \pi^+) = A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) - A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda \pi^+).$$

- $A_{CP}^{dir}(\Lambda_c^+ \to \Lambda K^+) = (2.1 \pm 2.6 \pm 0.1)\,\%$
- $A_{CP}^{dir}(\Lambda_c^+ \to \Sigma^0 K^+) = (2.5 \pm 5.4 \pm 0.4)\,\%$





- Also measure α-induced CPV (α is the decay asymmetry parameter)

Channel	$k = \alpha_{\Lambda_c^+}\alpha_-$	$\bar{k} = \alpha_{\bar{\Lambda}_c^-}\alpha_+$	$\alpha_{\Lambda_c^+}$	$\alpha_{\bar{\Lambda}_c^-}$	A_{CP}^{α}	W.A. A_{CP}^{α}	our $A_{CP}^{\alpha}(\Lambda \to p\pi^-)$
$\Lambda_c^+ \to \Lambda K^+$	-0.418 ± 0.053	-0.442 ± 0.053	$-0.566 \pm 0.071 \pm 0.028$	$0.592 \pm 0.070 \pm 0.079$	$-0.023 \pm 0.086 \pm 0.071$	–	–
$\Lambda_c^+ \to \Lambda \pi^+$	-0.582 ± 0.006	-0.565 ± 0.006	$-0.784 \pm 0.008 \pm 0.006$	$0.754 \pm 0.008 \pm 0.018$	$+0.020 \pm 0.007 \pm 0.013$	-0.07 ± 0.22	$+0.017 \pm 0.007 \pm 0.012$
$\Lambda_c^+ \to \Sigma^0 K^+$	-0.43 ± 0.18	-0.37 ± 0.21	$-0.58 \pm 0.24 \pm 0.09$	$0.49 \pm 0.28 \pm 0.14$	$+0.08 \pm 0.35 \pm 0.14$	–	–
$\Lambda_c^+ \to \Sigma^0 \pi^+$	-0.340 ± 0.016	-0.358 ± 0.017	$-0.452 \pm 0.022 \pm 0.023$	$0.473 \pm 0.023 \pm 0.035$	$-0.023 \pm 0.034 \pm 0.030$	–	$-0.026 \pm 0.034 \pm 0.030$
						combined:	$+0.013 \pm 0.007 \pm 0.011$

- No evidence of CPV is found.

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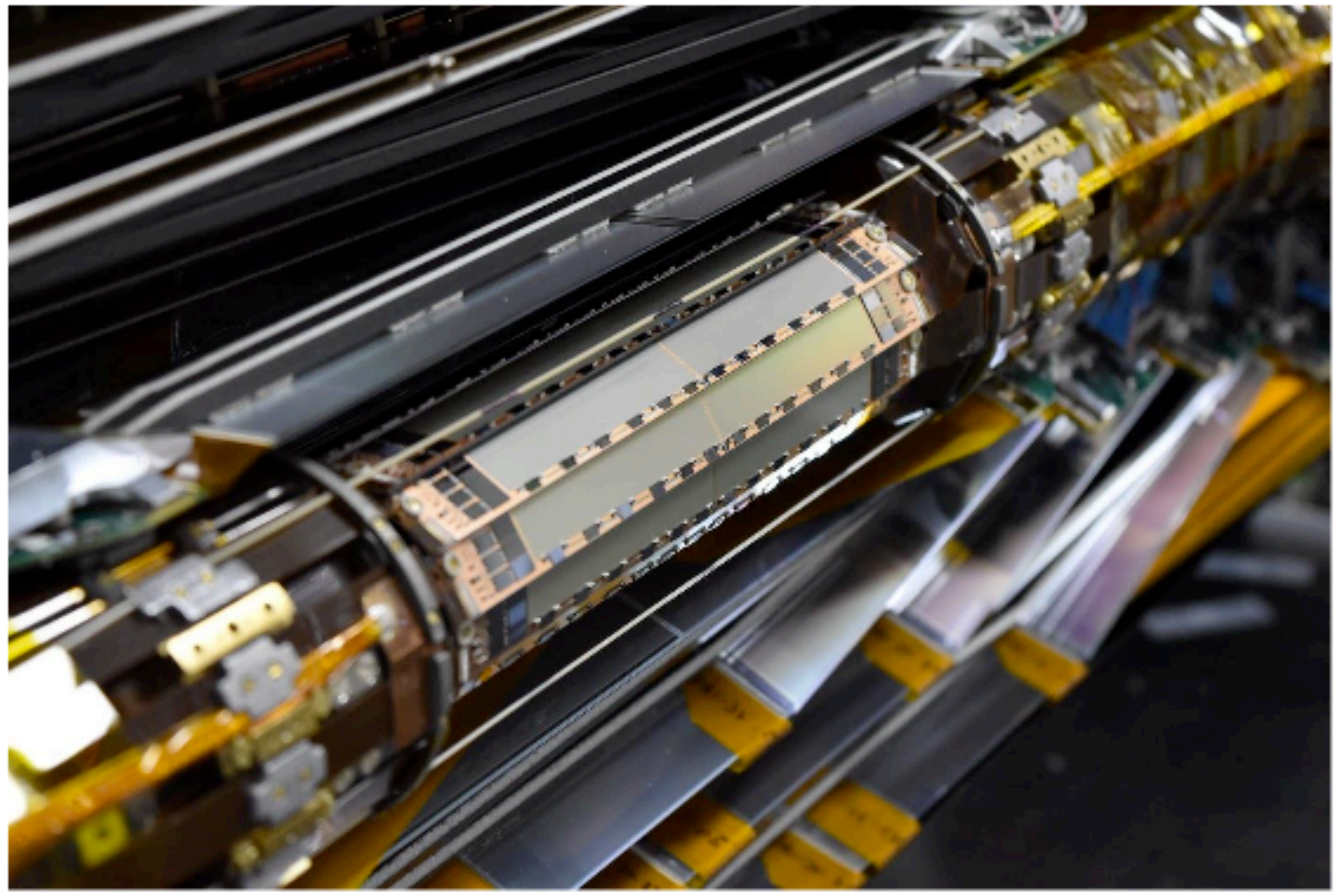
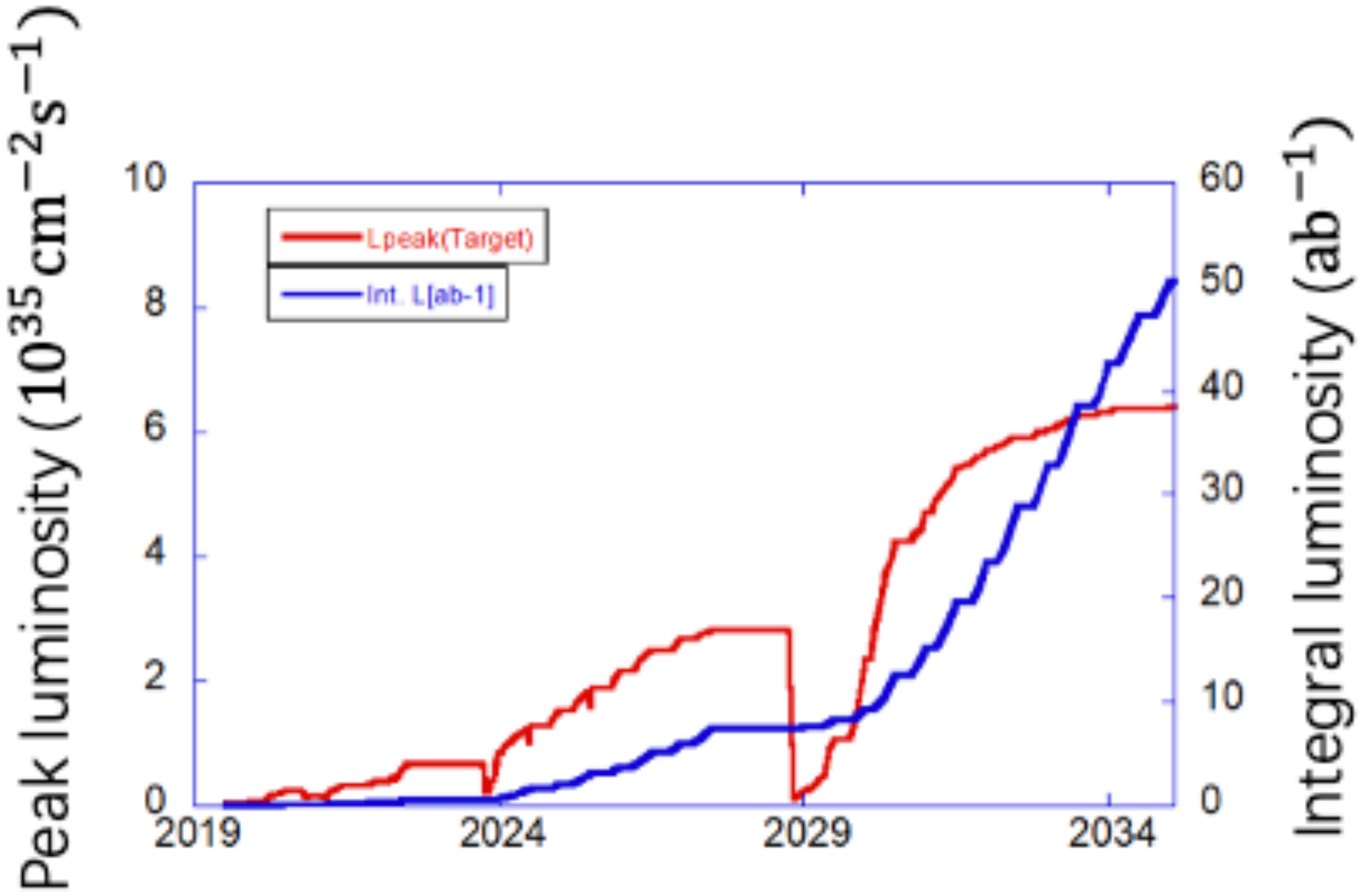
Summary

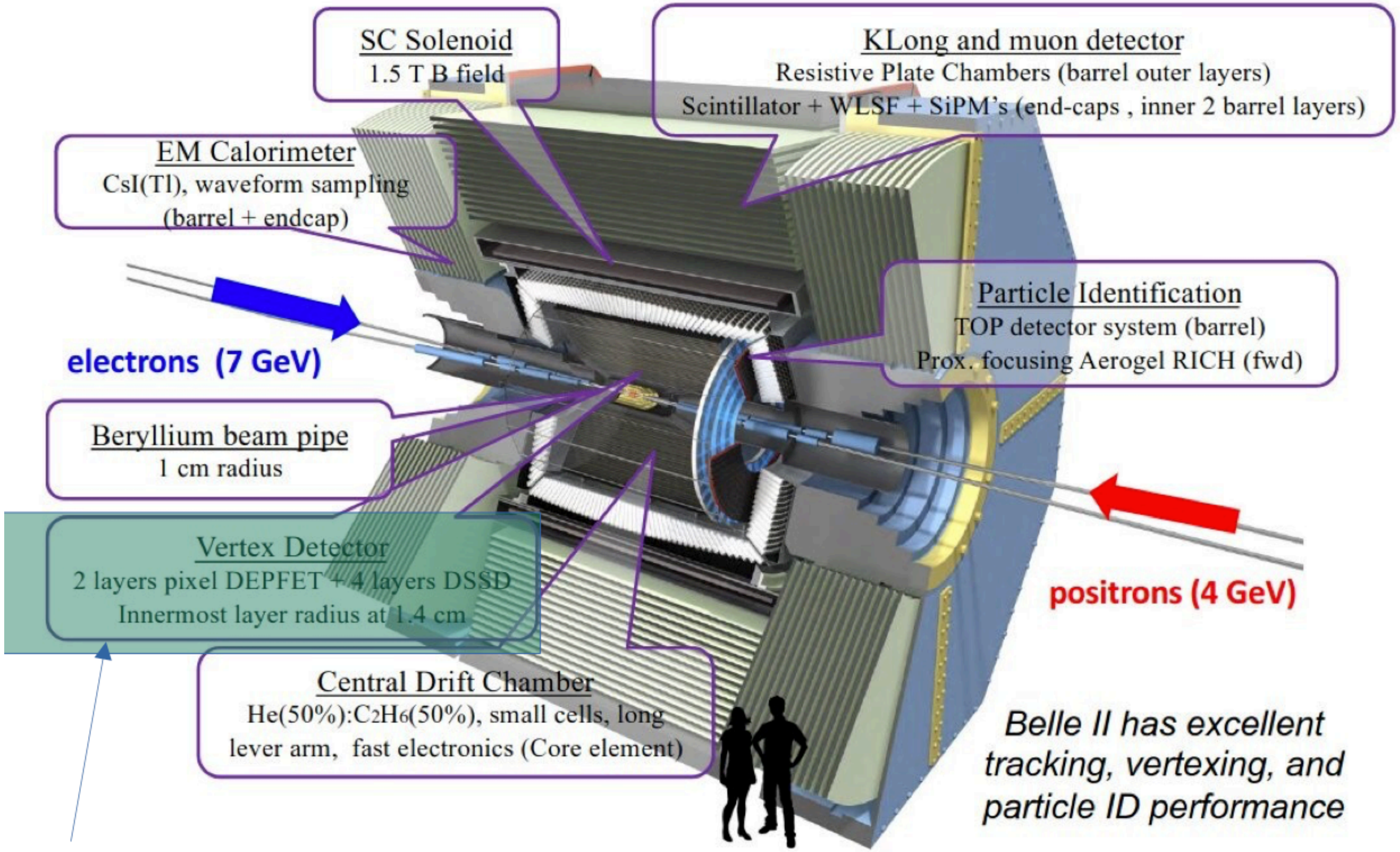
- Many new CPV results from Belle (II) this year (this week)!

- Improved flavor tagger (GFlaT) and full PXD are ready for new run!
- Will re-start data taking from the end of 2023!
- Extra news: new result on EPS of $B^+ \to K^+ \nu\bar{\nu}$: BR 3.6 σ, 2.8 σ vs standard model.





Back-Up



Fully instrumented after LS1