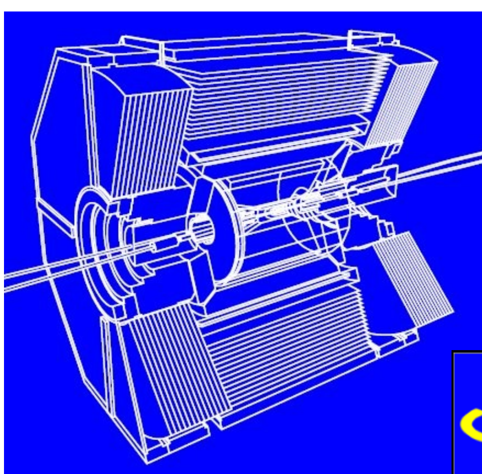
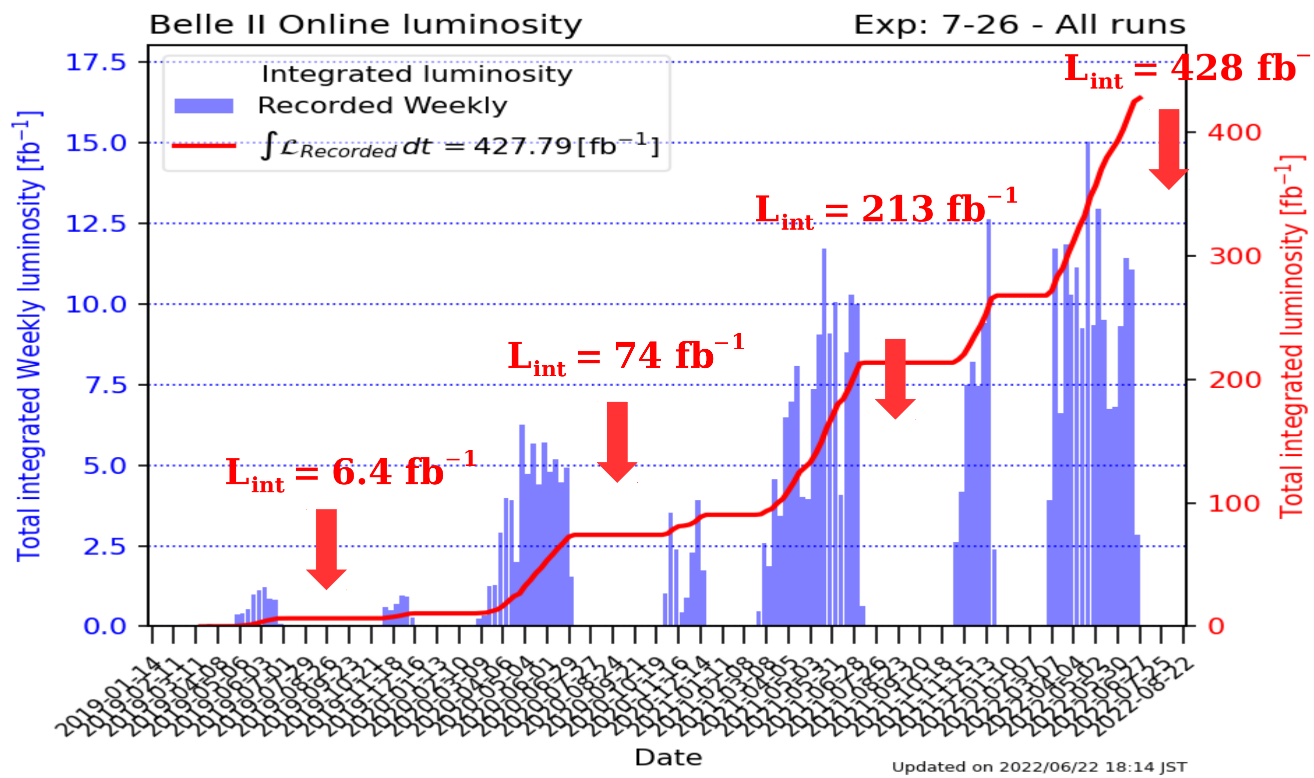
Hadronic B-Meson Decays at Belle II

K. Trabelsi (IJCLab)
karim.trabelsi@in2p3.fr





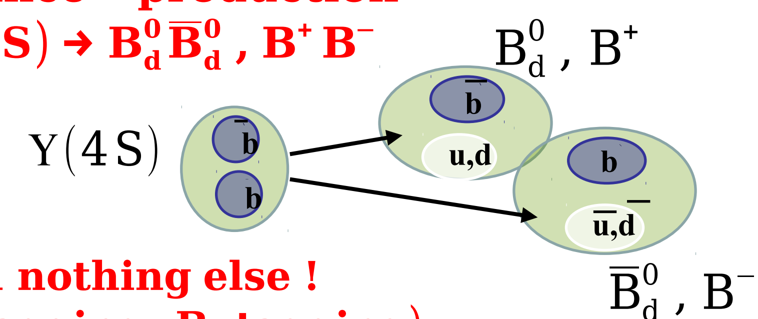
Belle II, a flavour-factory, a rich physics program ...

(Belle ~ 1 ab^{-1})

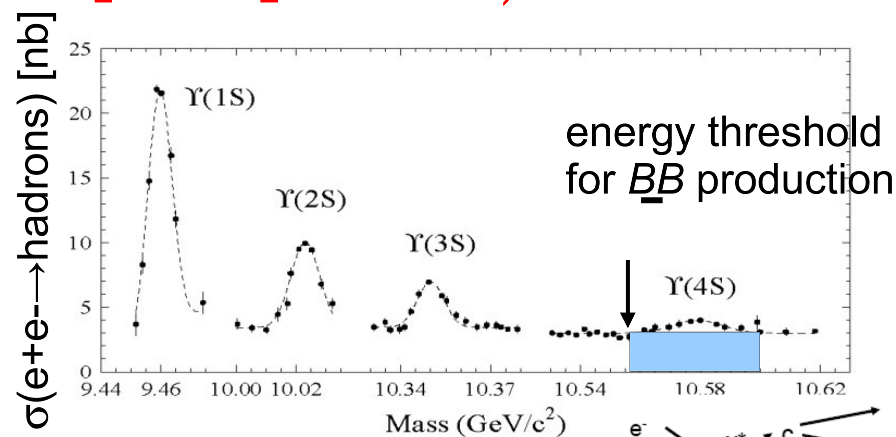
- We plan to ultimately collect many ab^{-1} of e^+e^- collisions at (or close to) the $\Upsilon(4S)$ resonance, so that we have:

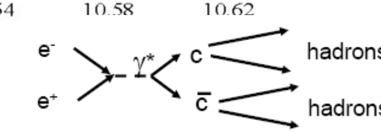
– a (Super) B-factory ($\sim 1.1 \times 10^9$ $B\bar{B}$ pairs per ab^{-1})

''on resonance'' production
$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B_d^0\bar{B}_d^0$, B^+B^-



- **2 B's and nothing else !** **(flavour tagging, B-tagging)**
- 2 B mesons are created simultaneously in a L=1 coherent state





Time-dependent CP Violation Measurements at Belle II: S.Hazra
b->s Penguin results from Belle II (b->sll, b->sgamma): L.Martel
Recent Belle II results related to B anomalies: Y.Fan
Measurements of |Vcb| and |Vub| at Belle and Belle II: L.Cao

Charm Physics at Belle II: T.Higuchi
Quarkonium/QCD results at Belle II: MC Chang

– a (Super) charm factory ($\sim 1.3 \times 10^9$ $c\bar{c}$ pairs per ab^{-1})

(but also charmonium, X, Y, Z, pentaquarks, tetraquarks, bottomonium...)
(scan data are also crucial here)

– a (Super) τ factory ($\sim 0.9 \times 10^9$ $\tau^+\tau^-$ pairs per ab^{-1})

Dark matter and tau results at Belle II: R.Leboucher

– exploit the clean e^+e^- environment to probe the existence of exotic hadrons, dark photons/Higgs, light Dark Matter particles, ALPs, LLPs ...

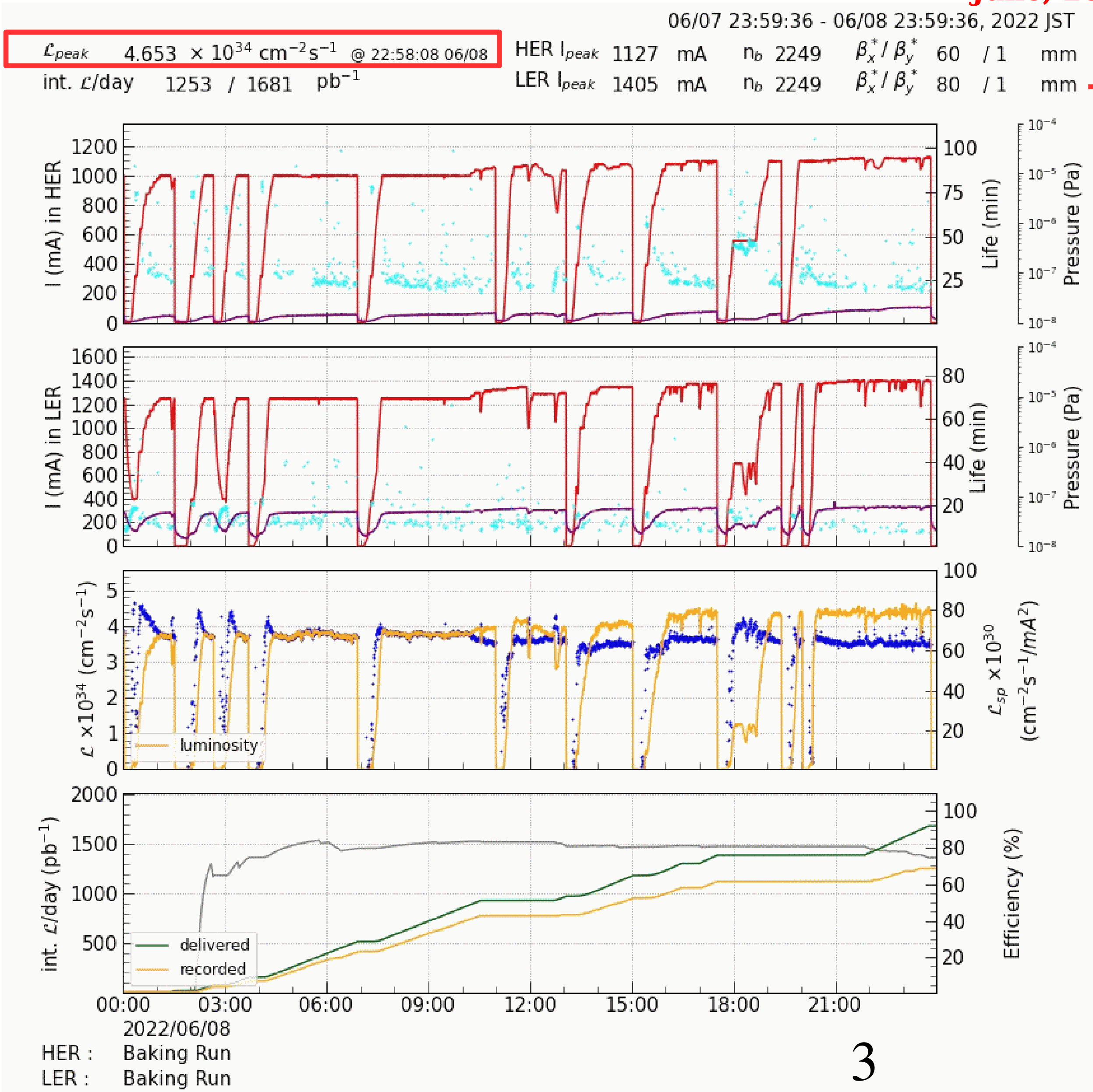
Belle II run I (2019 - 2022)

data taking from March 2019 to June 2022

→ despite difficult conditions since March 2020 (Covid, war in Ukraine, energy cost …)

luminosity : $4.7\times10^{34}/cm^2/s$! > 2 fb^{-1} per day !

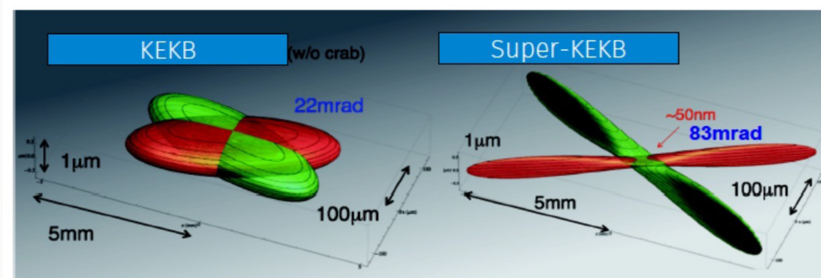
June, 2022



→ **$\beta_y^* = 1\,mm$, $I_{LER/HER} = 1.4/1.1$ A**

record of KEKB/Belle
$2\times10^{34}/cm^2/s$ currents > 1 A

record of PEPII/BaBar
$1\times10^{34}/cm^2/s$ currents > 2 A

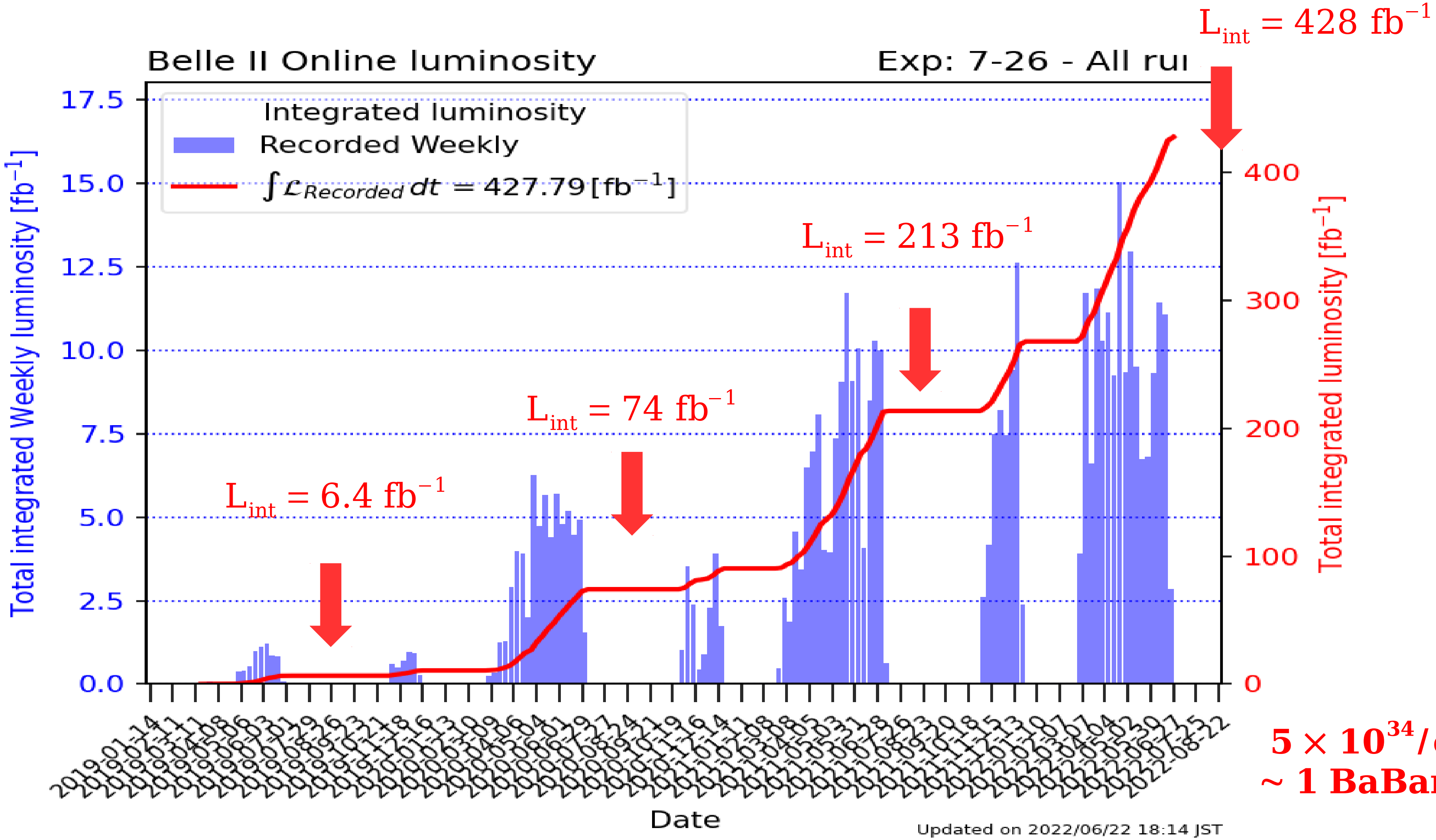


	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

factor 20 factor 2-3

squeezing further β_y^* (→ 0.6 mm)
doubling (or more) the currents
⇒ L > $10^{35}/cm^2/s$ after LS 1

Belle II run I (2019 - 2022)



$5 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$
~ 1 BaBar/year

⇒ 362 fb^{-1} at the $\Upsilon(4S)$ resonance (rest off resonance, and scan)

⇒ Belle II results presented here with either 189 fb^{-1} or 362 fb^{-1}, sometimes adding Belle data sample

Topics covered

- $B \to D^{(*)} K^{-} K_S$
- $B \to DK$ and γ
- $B \to \pi\pi, \rho\rho$ and α
- $B \to K\pi$

⇒ 362 fb^{-1} at the $\Upsilon(4S)$ resonance (rest off resonance, and scan)
⇒ Belle II results presented here with either 189 fb^{-1} or 362 fb^{-1}, sometimes adding Belle data sample

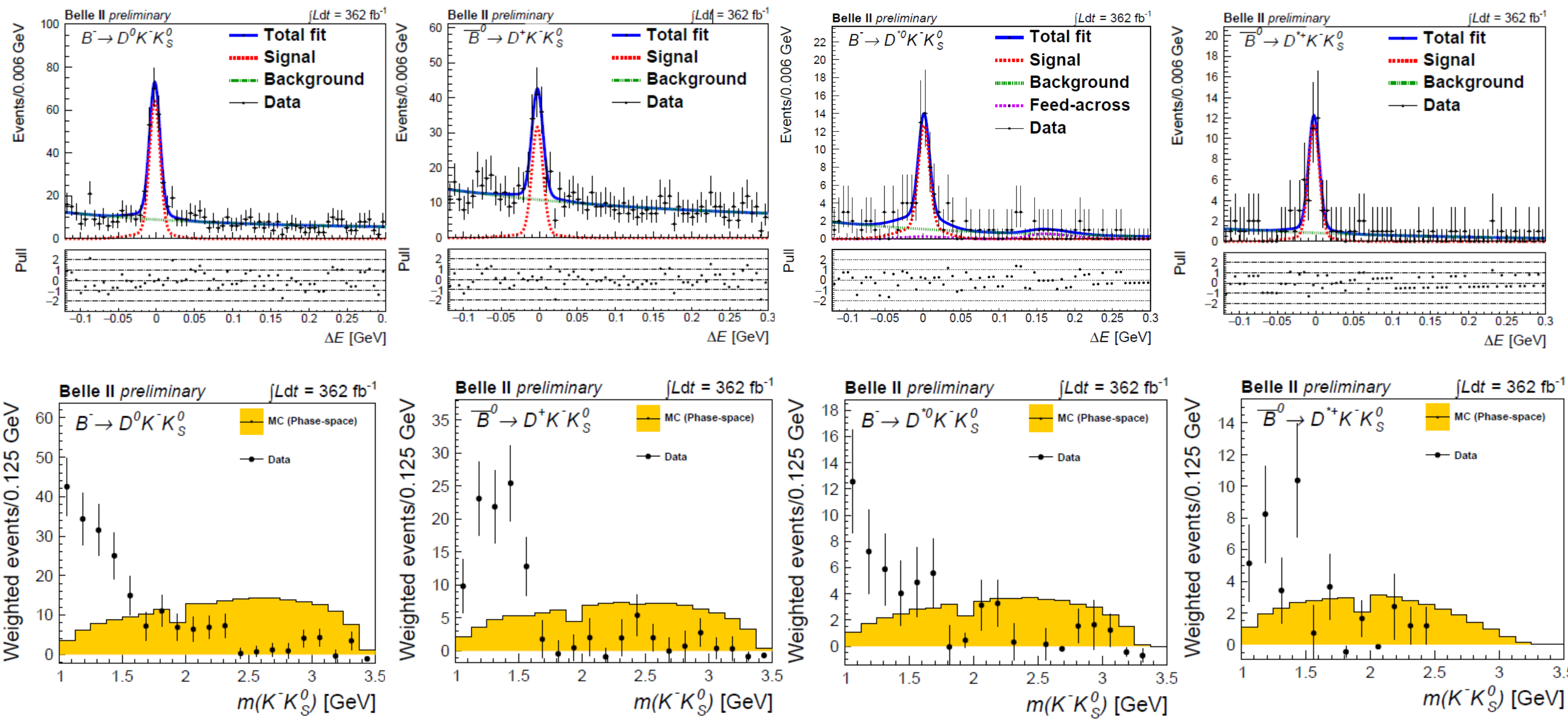
$\mathbf{B \to D^{(*)} K^- K^0_S}$

Belle II with 362 fb^{-1}, previous measurement Belle with 29 fb^{-1}
[arXiv:2305.01321]

$B \to D^{(*)} K K^{(*)}$ quite unexplored sector: few % of the total B BR, only 0.3% measured

– part of an on-going effort to improve simulation and hadronic B-tagging (famous efficiency < 1%)
– can study the structures observed
– use the $B \to D^{(*)} D_s$ modes as control samples

First observation for 3 modes



◦ Resonances $\rho(1450)^+$ and $\rho(1700)^+$ in $B \to DKK$ decays ? (see for example arXiv:2201.06881)

$B \to D^{(*)} K^- K_S^0$

Belle II with 362 fb^{-1}, previous measurement Belle with 29 fb^{-1}
[arXiv:2305.01321]

$B \to D^{(*)} K K^{(*)}$ quite unexplored sector: few % of the total B BR, only 0.3% measured

- part of an on-going effort to improve simulation and B-tagging techniques
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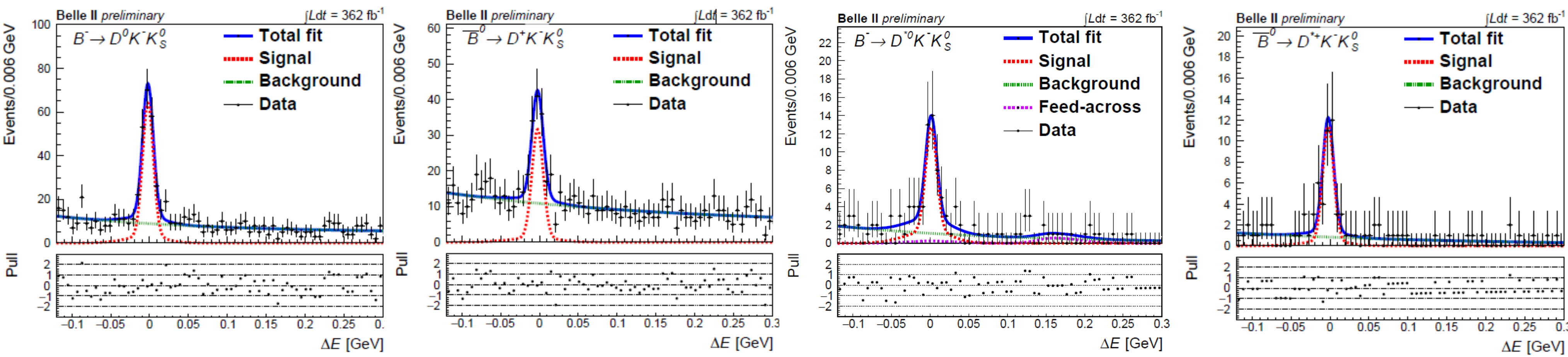
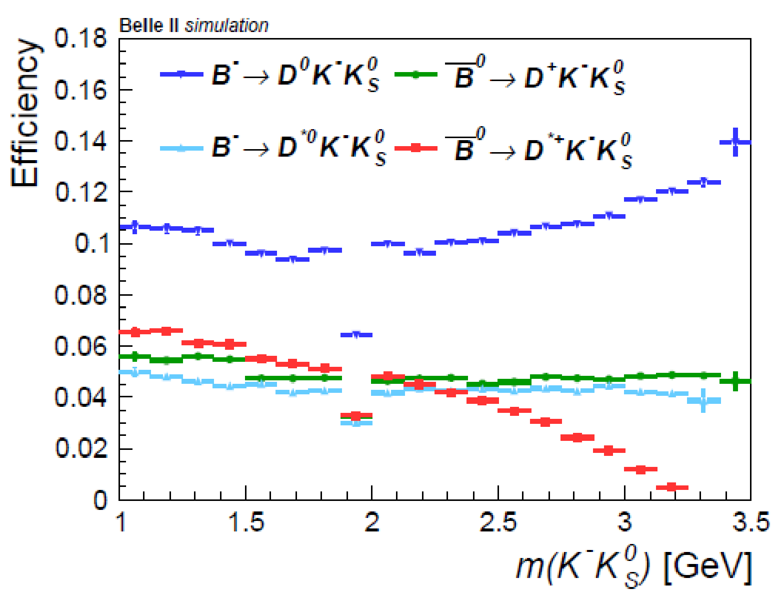
First observation for 3 modes





$$\mathcal{B}(B^- \to D^0 K^- K_S^0) = (1.89 \pm 0.16 \pm 0.10) \times 10^{-4},$$

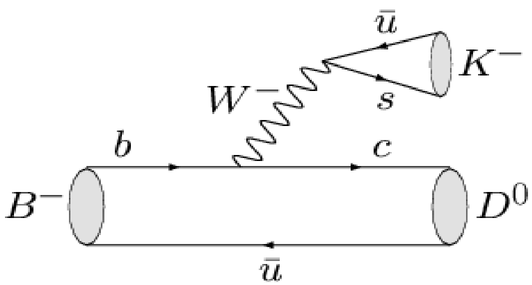
$$\mathcal{B}(\overline{B}^0 \to D^+ K^- K_S^0) = (0.85 \pm 0.11 \pm 0.05) \times 10^{-4},$$

$$\mathcal{B}(B^- \to D^{*0} K^- K_S^0) = (1.57 \pm 0.27 \pm 0.12) \times 10^{-4},$$

$$\mathcal{B}(\overline{B}^0 \to D^{*+} K^- K_S^0) = (0.96 \pm 0.18 \pm 0.06) \times 10^{-4},$$

γ measurements from $B^{\pm} \to DK^{\pm}$

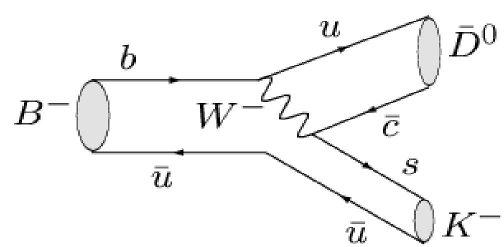
- Theoretically pristine B→DK approach
- Access γ via interference between $B^- \to D^0 K^-$ and $B^- \to \overline{D}^0 K^-$



color allowed

$B^- \to D^0 K^- \sim V_{cb} V^*_{us}$

$\sim A\lambda^3$



color suppressed

$B^- \to \overline{D}^0 K^- \sim V_{ub} V^*_{cs}$

$\sim A\lambda^3(\rho + i\eta)$

relative weak phase is γ

relative strong phase is δ_B

$$r_B = \frac{|A_{suppressed}|}{|A_{favoured}|} \sim \frac{|V_{ub} V^*_{cs}|}{|V_{cb} V^*_{us}|} \times [\text{color supp}] = 0.1 - 0.2$$

$B^{\pm} \to D K^{\pm}$

$B^{\pm} \to D^* K^{\pm},\ D^* \to D \pi^0$

$B^{\pm} \to D^* K^{\pm},\ D^* \to D \gamma$

$B^{\pm} \to D K^{*\pm}$

$B^0 \to D K^{*0}$

$B^{\pm} \to D K \pi\pi$

$B \to \ldots$

$D \to K^+ K^-,\ \pi^+ \pi^- \ldots$

$D \to K_S \pi^0,\ K_S \eta \ldots$

$D \to K K \pi^0,\ \pi\pi\pi^0 \ldots$

$D \to K_S \pi\pi, K_S K K$

$D \to K_S \pi\pi\pi^0$

$D \to \ldots$

BPGGSZ study $B \to D(K_S^0 h^+ h^-) h^-$

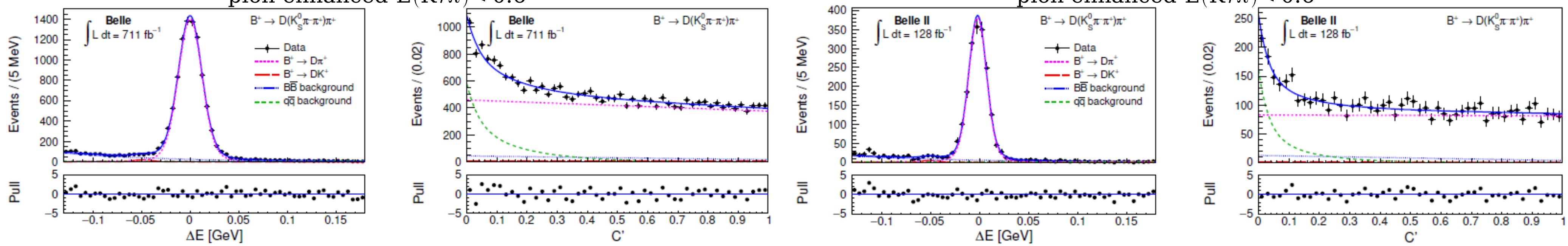
$h = \pi, K$

- Analysis with 711 fb^{-1} Belle data and 128 fb^{-1} Belle II data

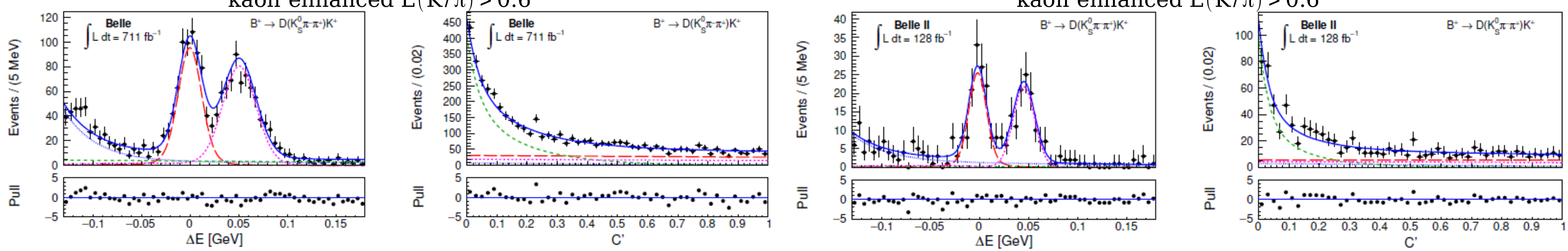
(Belle/Belle II collaboration)
[arXiv:2110.12125, JHEP (2022) 63]

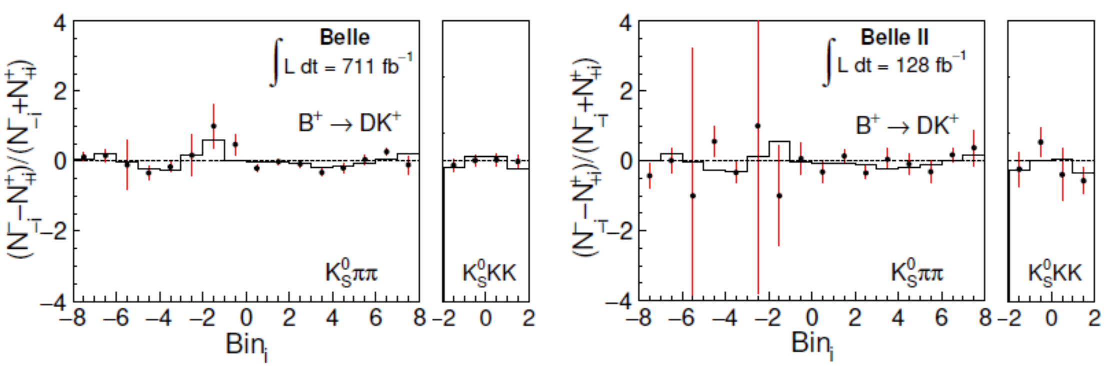
- Unbinned 2D simultaneous fit of ΔE versus C'

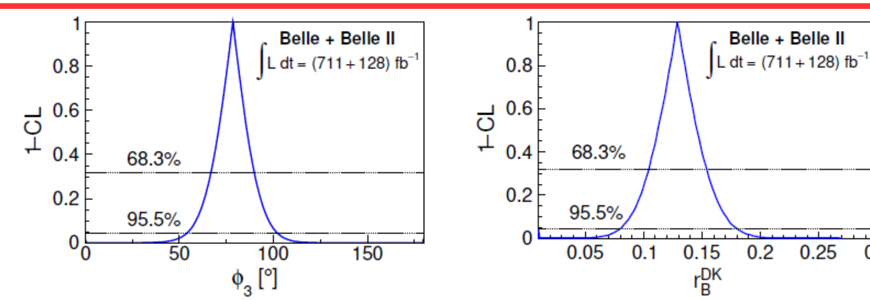
pion enhanced $L(K/\pi) < 0.6$ — pion enhanced $L(K/\pi) < 0.6$



kaon enhanced $L(K/\pi) > 0.6$ — kaon enhanced $L(K/\pi) > 0.6$







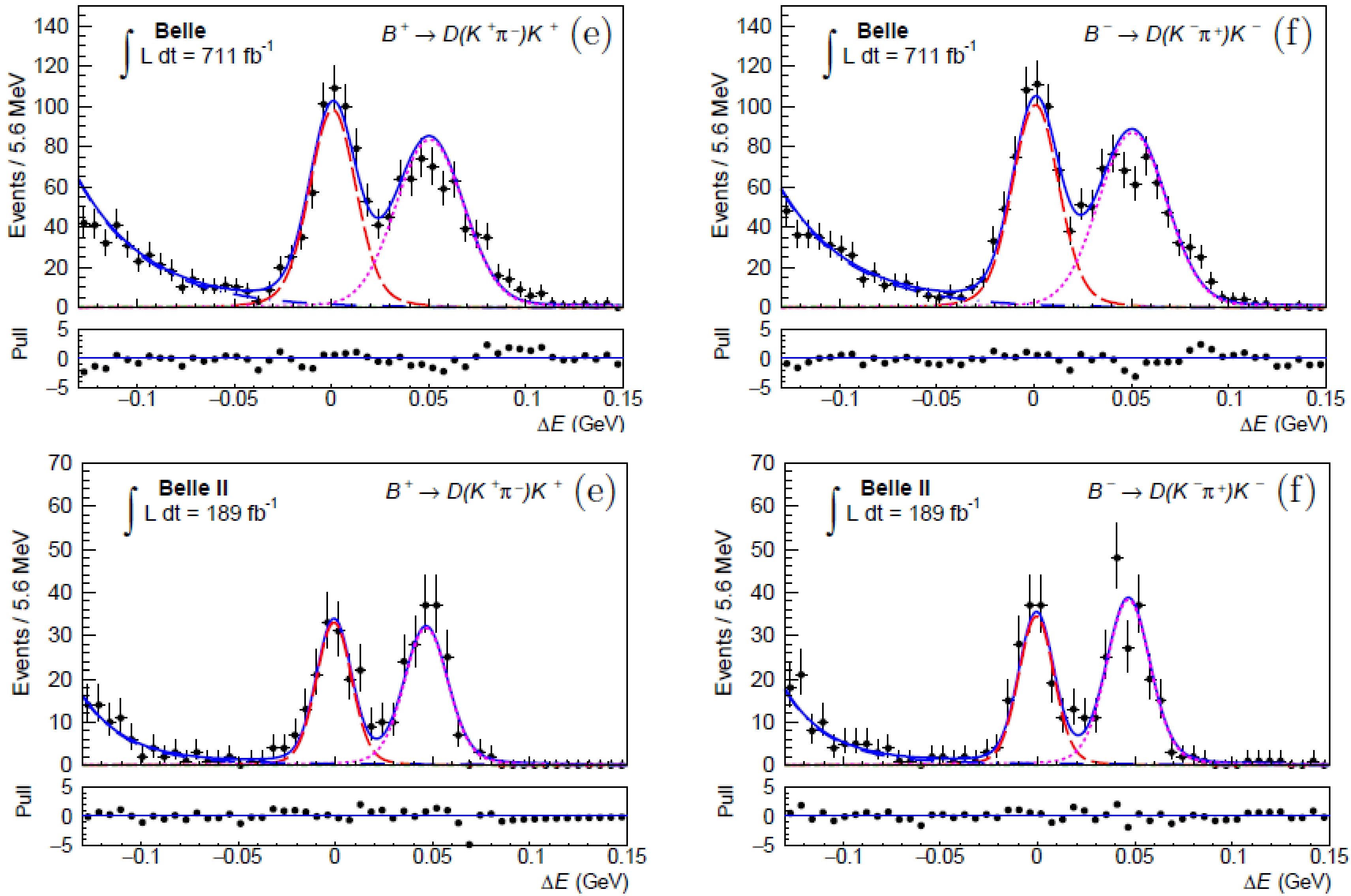
$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ,$$
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002,$$
$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ,$$
$$r_B^{D\pi} = 0.017 \pm 0.006 \pm 0.001 \pm 0.001,$$
$$\delta_B^{D\pi} = (341.0 \pm 17.0 \pm 1.2 \pm 2.6)^\circ.$$

$\sigma_{\phi_3} = 14^\circ$ from earlier Belle measurement

GLW study for B➔D(KK)K and D($K^0_S\pi^0$)K

Using Belle (711 fb^{-1}) and Belle II (189 fb^{-1}), (previous measurement with Belle only 250 fb^{-1})

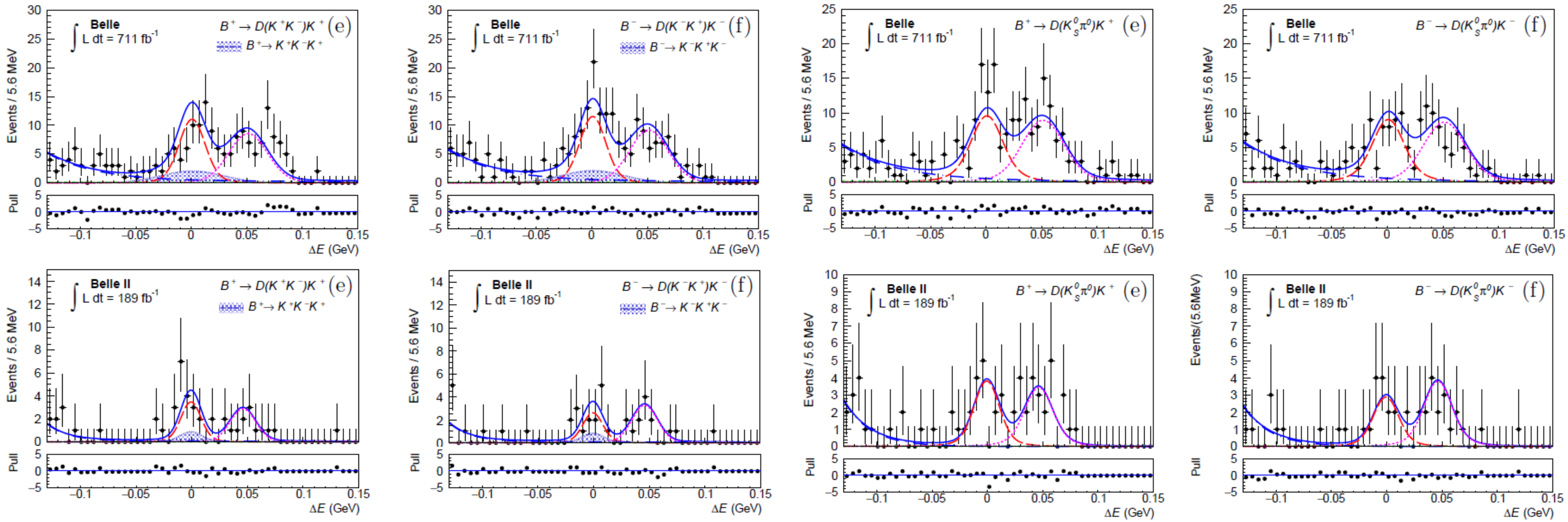
Fitting simultaneously the B➔Dπ and DK samples, D➔Kπ and…



with asymmetry ~ 0 for B➔D(Kπ)K modes

GLW study for B→D(KK)K and $D(K_S^0\pi^0)K$

Fitting simultaneously the B→Dπ and DK samples, D→Kπ and…D→KK and $K_S^0\pi^0$

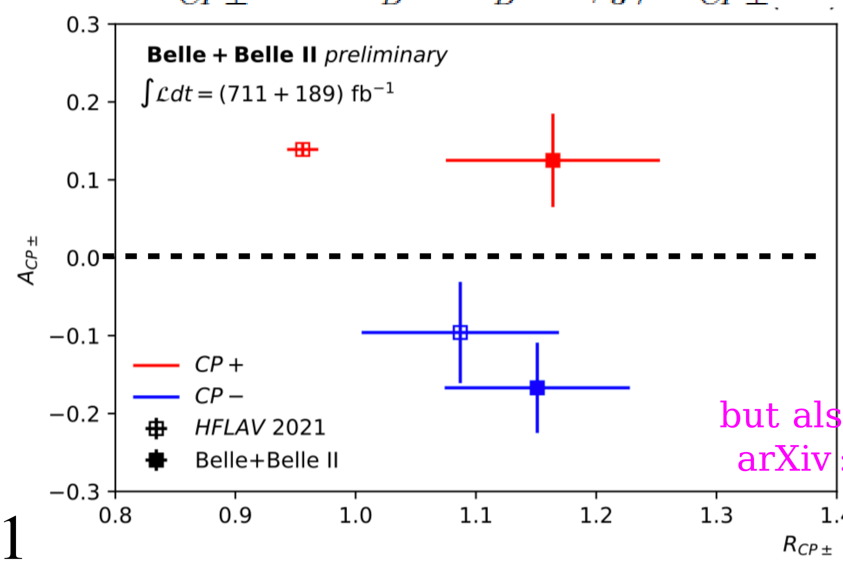


$$\mathcal{R}_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\phi_3,$$

$$\mathcal{A}_{CP\pm} = \pm 2r_B \sin\delta_B \sin\phi_3 \,/\, \mathcal{R}_{CP\pm};$$

In GLW, CP−odd state accessible only to B-factories

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



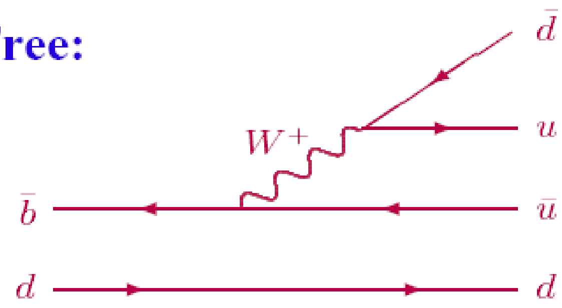
Direct evidence of opposite A_{CP} for even and odd states

but also GLS results arXiv:2306.02940

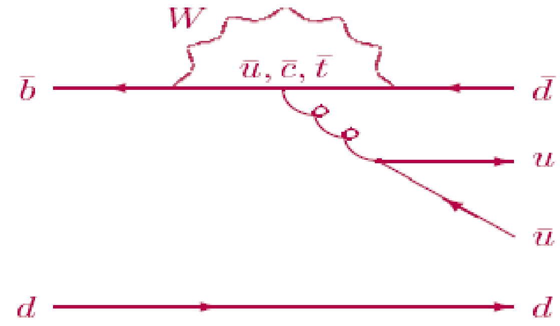
α determination

ϕ_2/α is by now the less know UT angle with 4°-5° precision

Tree:



Penguin:



$$A(B^0 \to \pi^+\pi^-) = T\, e^{i\gamma} + P\, e^{i\delta},\ r = |P|/|T|$$

$$A(t) = S_{\pi^+\pi^-} \sin(\Delta m t) - C_{\pi^+\pi^-} \cos(\Delta m t)$$

$$= \sqrt{1 - C^2_{\pi^+\pi^-}}\, \sin 2\alpha_{eff} \sin(\Delta m t) - C_{\pi^+\pi^-} \cos(\Delta m t)$$

from time dependent CP, we can measure α_{eff}, but we want α !

expanding in r: $\mathbf{S_{\pi^+\pi^-} = \sin 2\alpha} + 2 r \cos\delta \sin(\beta + \alpha) \cos 2\alpha + O(r^2)$

time dependent decay width:

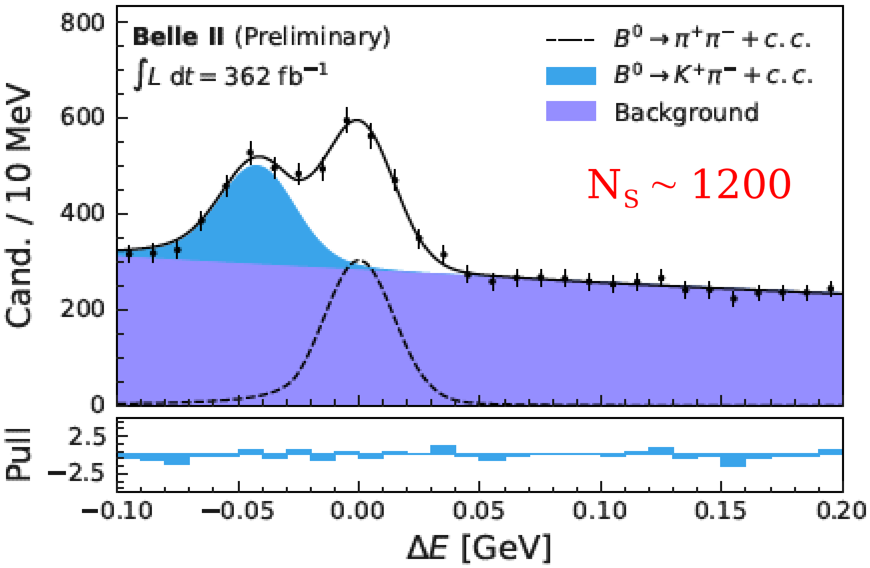
$$\Gamma(B^0(t)) \propto \Gamma_{\pi^+\pi^-} [1 + C_{\pi^+\pi^-} \cos\Delta m t - S_{\pi^+\pi^-} \sin\Delta m t]$$

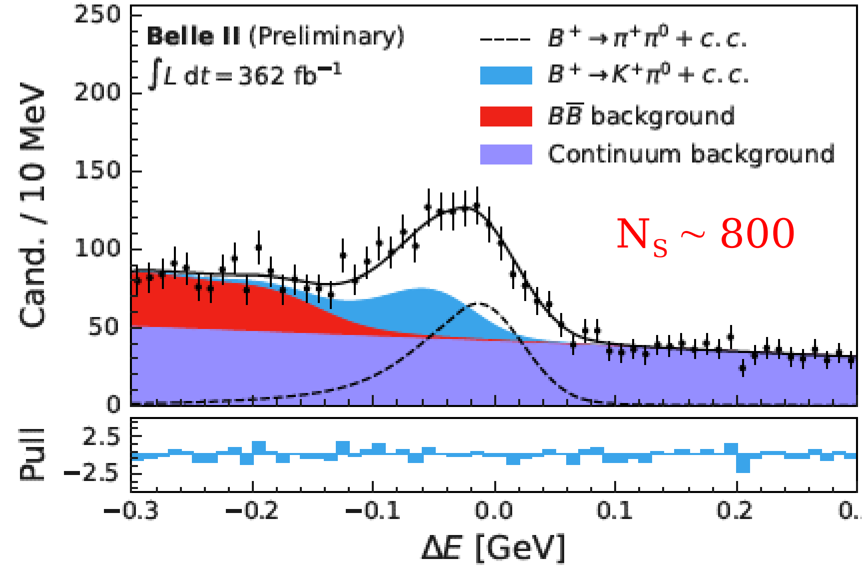
3 measurables vs. 4 unknowns: T, r, δ, γ

→ **additional inputs required to determine the penguin pollution to fix r**

isospin analysis: combining with the information from other $\pi\pi$ modes

α (inputs from $B \to \pi\pi$)



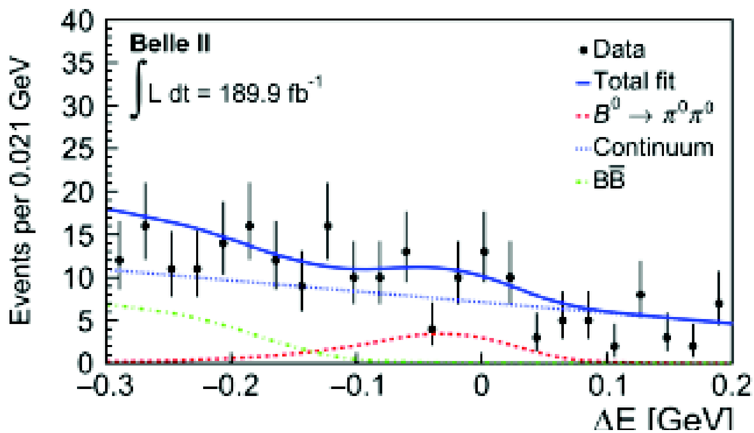


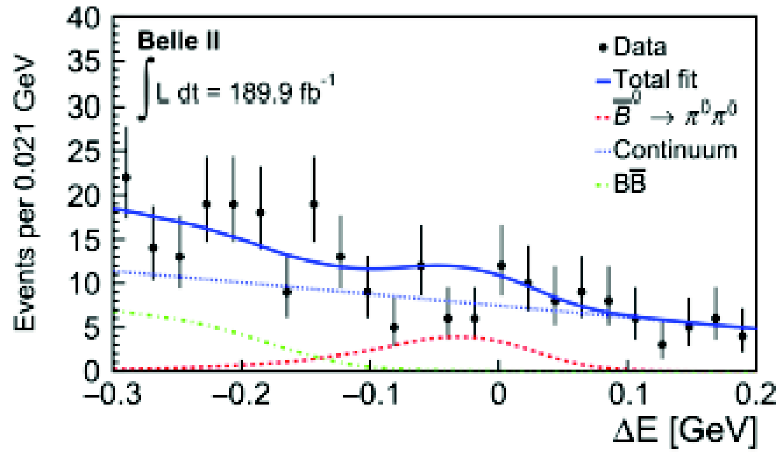
$$\mathcal{B}(B \to \pi^+ \pi^-) = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$$

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

$$A_{CP} = (-0.081 \pm 0.054 \pm 0.008)$$

$\pi^0 \pi^0$: most challenging charmless decay. Only photons in the final state, completely swamped by continuum from real π^0 [arXiv:2303.08354]



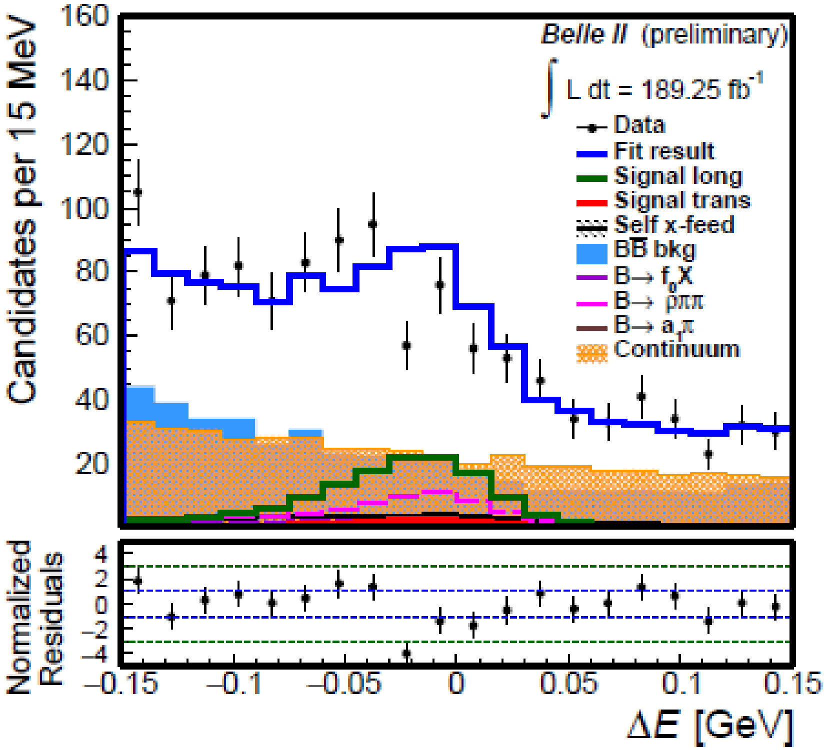


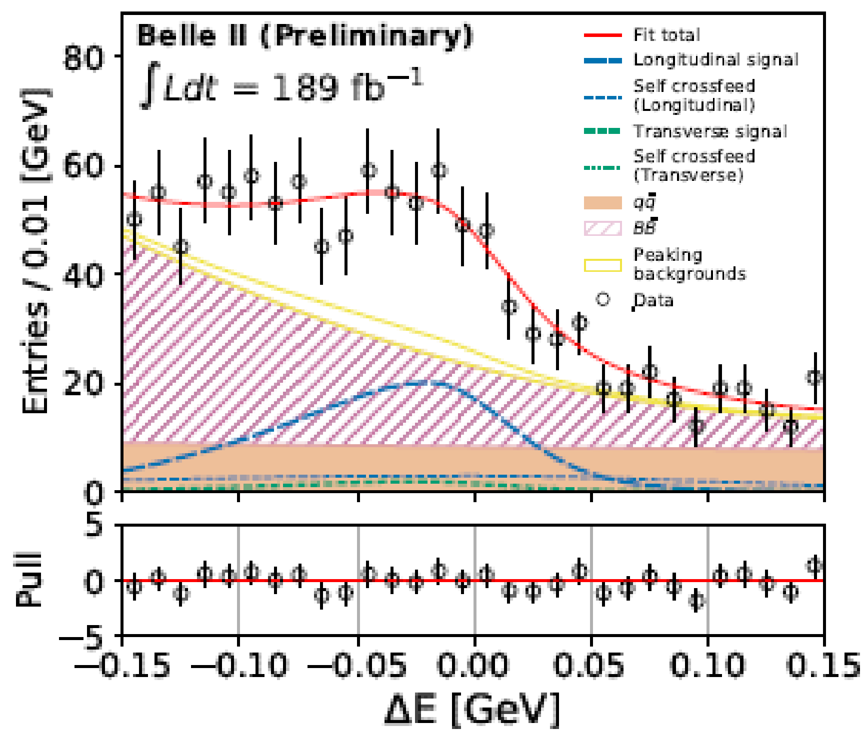
$$\mathcal{B}(B^0 \to \pi^0 \pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6},$$

$$\mathcal{A}_{CP}(B^0 \to \pi^0 \pi^0) = 0.14 \pm 0.46 \pm 0.07.$$

α (inputs from B→ρρ)

Preliminary results reported last year for $B^+ \to \rho^0 \rho^+$ and $B^0 \to \rho^+ \rho^-$ with 189 fb^{-1}
[arXiv:2206.12362], [arXiv:2208.03554]





$B^+ \to \rho^+ \rho^0$ [arXiv:2206.12362]

$$\mathscr{B} = (23.2^{+2.2}_{-2.1} \pm 2.7) \times 10^{-6}$$

$$f_L = 0.943^{+0.035}_{-0.033} \pm 0.027$$

$$A_{CP} = -0.069 \pm 0.069 \pm 0.060$$

$B^0 \to \rho^+ \rho^-$ [arXiv:2208.03554]

$$\mathscr{B} = (26.7 \pm 2.8 \pm 2.8) \times 10^{-6}$$

$$f_L = 0.956 \pm 0.035 \pm 0.033$$

⇒ updates to full Run I sample ongoing ...

Isospin sum-rule and $K_S^0\pi^0$

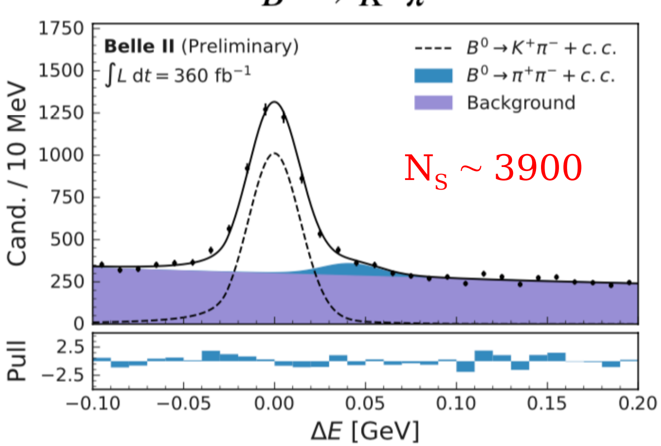
Isospin symmetry can be exploited to construct sum rules: linear combinations of branching fractions and CP asymmetries, and with the set of B→Kπ decays:

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

- Predicted to be zero with 1% in the SM (null test)
- Experimentally consistent with zero ($I_{K\pi} = (-13 \pm 11)\%$)

⇒ with 10% precision limited by the $K_S^0\pi^0$ observables

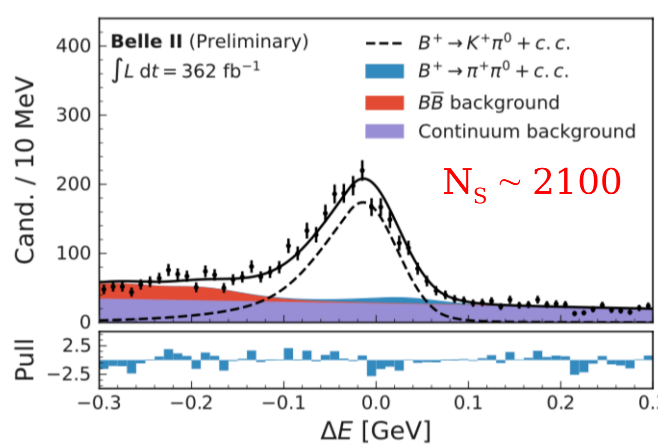
$B^0 \to K^+\pi^-$



$\mathcal{B} = (20.67 \pm 0.37 \pm 0.62) \times 10^{-6}$

$A_{CP} = (-7.2 \pm 1.9 \pm 0.7)\,\%$

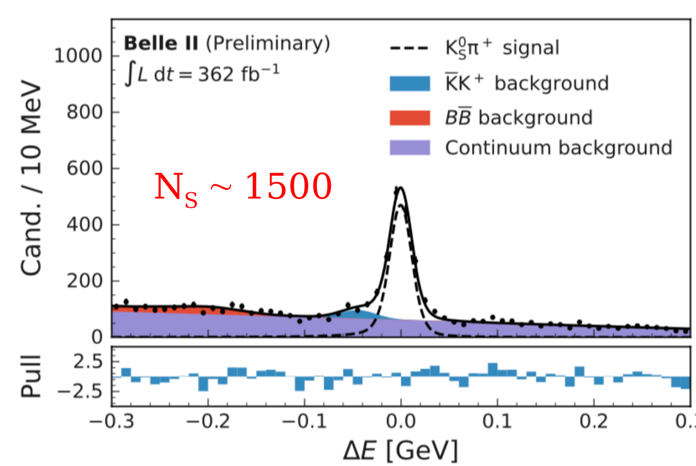
$B^+ \to K^+\pi^0$



$\mathcal{B} = (14.21 \pm 0.38 \pm 0.85) \times 10^{-6}$

$A_{CP} = (1.3 \pm 2.7 \pm 0.5)\,\%$

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



$\mathcal{B} = (24.40 \pm 0.71 \pm 0.86) \times 10^{-6}$

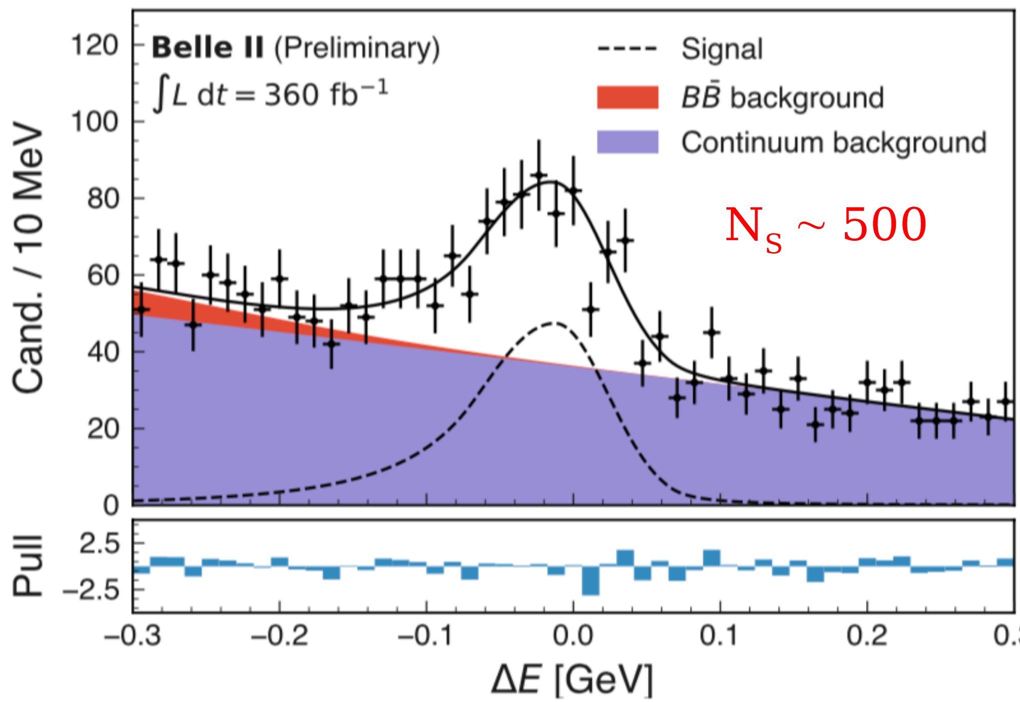
$A_{CP} = (4.6 \pm 2.9 \pm 0.7)\,\%$

Pushing the limit to understand K_S and π^0 systematics at 2% and 5%

Isospin sum-rule and $K_S^0\pi^0$

Two analyses for $B^0 \to K_S^0\pi^0$,
one decay-time integrated and
the other decay-time dependent
[arXiv:2305.07555],
Time-dependent CP Violation Measurements at Belle II: S.Hazra
combined to enhance sensitivity:

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



$$\mathcal{B} = (10.50 \pm 0.62 \pm 0.67) \times 10^{-6}$$

$$A_{CP} = -0.01 \pm 0.12 \pm 0.05$$

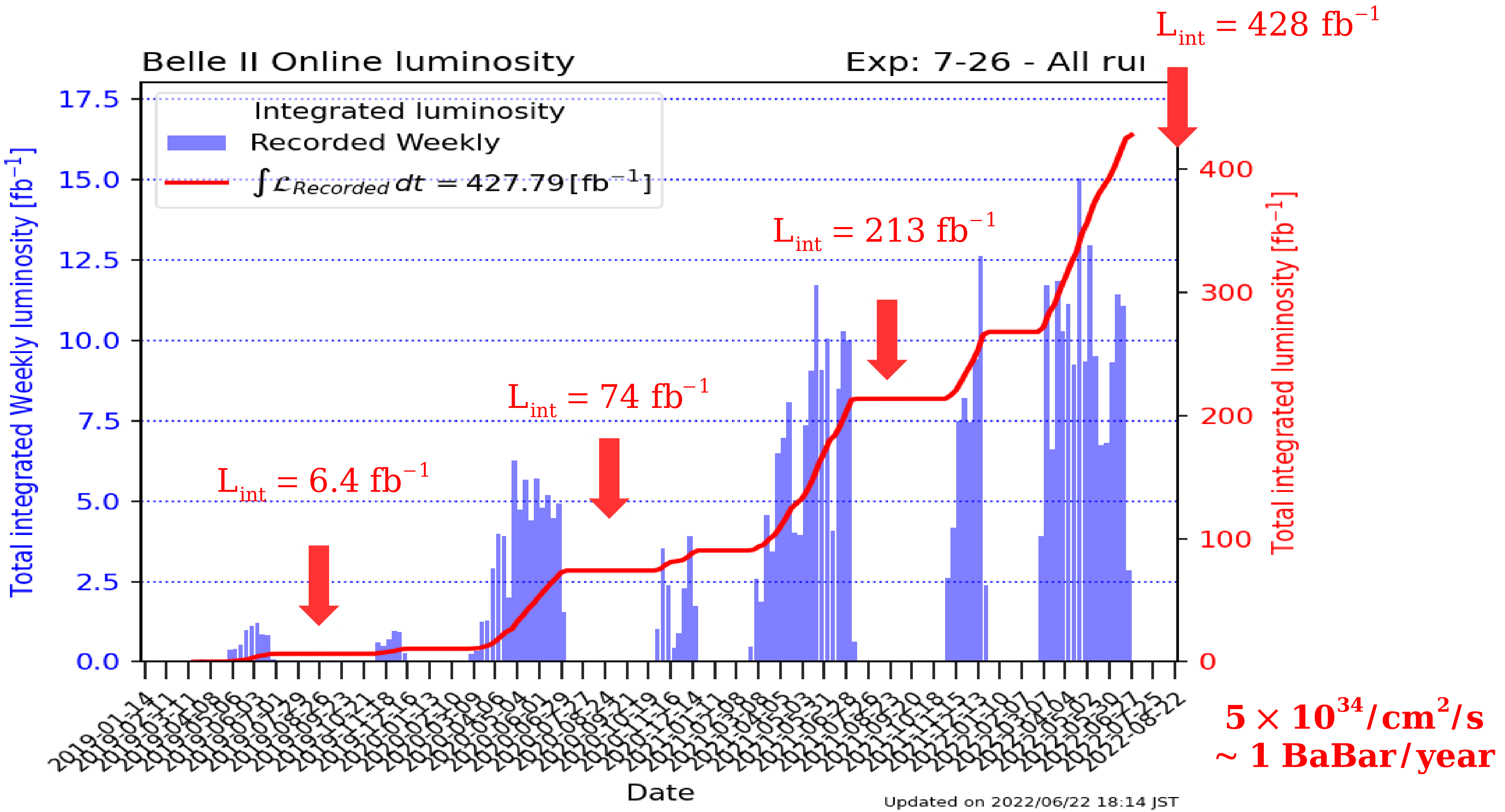
$$S_{CP} = 0.75^{+0.20}_{-0.23} \pm 0.04$$

Putting all $K\pi$ results together, the Belle II isospin sum-rule gives:

$$I_{K\pi} = (-3 \pm 13 \pm 5)\%$$

Agrees with SM. Competitive with world average of $(-13 \pm 11)\%$

Belle II run I (2019 - 2022)



⇒ what about run II ?

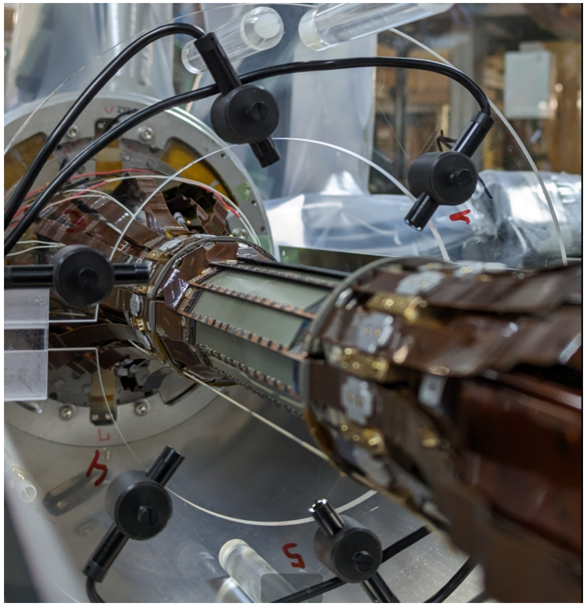
Long-shutdown (LS1) activity and plans

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

- accelerator improvements: injection, non-linear collimators, monitoring...
- additional shielding and increased resilience against beam bckg

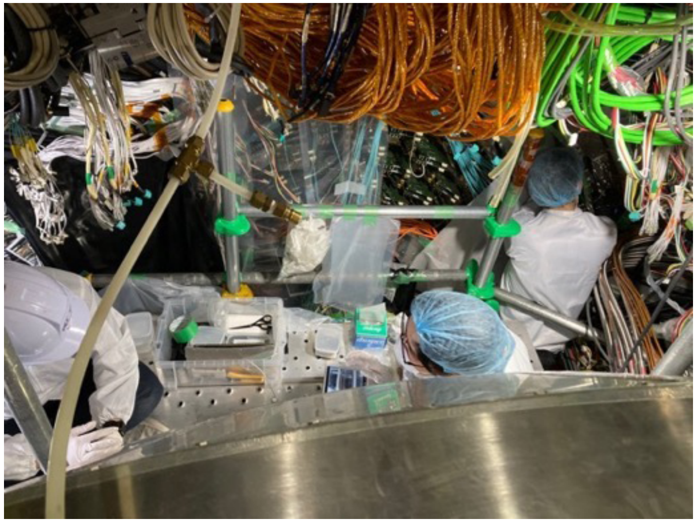
- replacement of beam-pipe
- installation of 2-layered pixel vertex detector
- replacement of photomultipliers of the central PID detector (TOP)
- completed transition to new DAQ boards (PCIe40)
- work on other detectors as CDC, KLM...
- improved data-quality monitoring and alarm system

PXD2 at KEK since March



VXD extraction in May

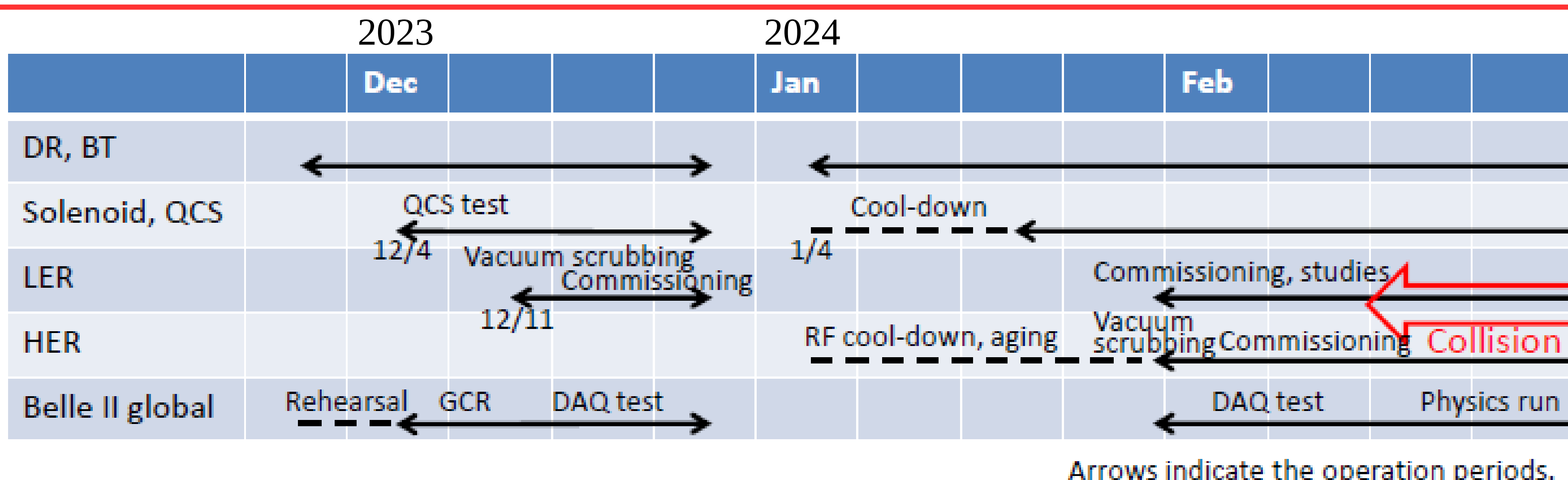
TOP MCP-PMT replacement work



CDC FE reinstallation work

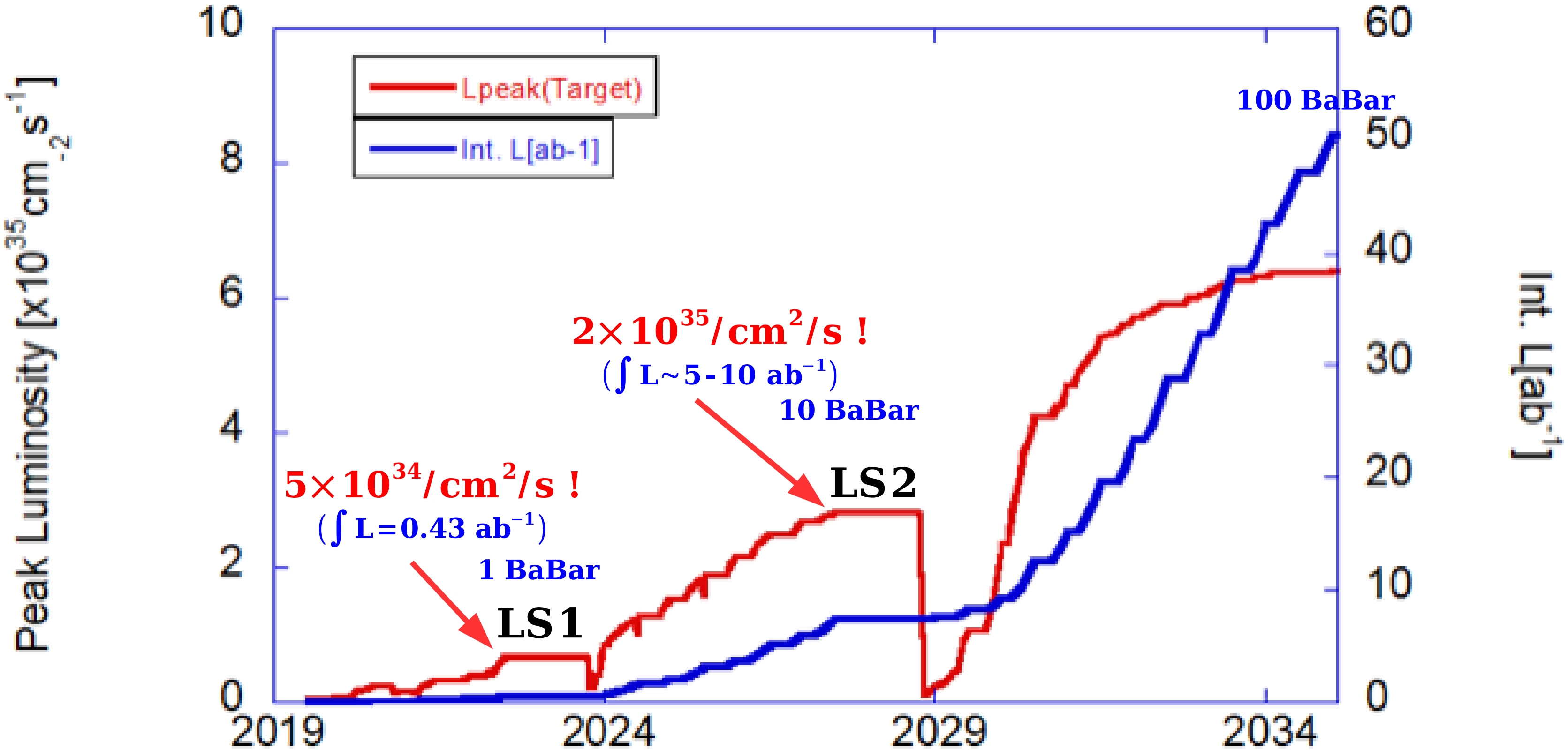
Summary

- Belle II has now on tape a sample equivalent to that of BaBar, half of Belle
- Allow to refine our tools, improve our analyses, understanding our detector
- Some first competitive results: a selection of hadronic B decays shown today
- Currently preparing the detector and the machine to ramp-up at full speed.
- Will resume data-taking next Winter, on our way to the $10^{35}\,cm^{-2}s^{-1}$ world



- Target first day of MR beam operation: Dec 11 (driven by Belle II)

Belle II calendar



run 1 (→ June 2022): integrated luminosity ~0.43 ab^{-1}, 4-5×10^{34}/cm^2/s
PXD complete (2 layers) to be installed during **LS1** (2022-2023)
(+beampipe + TOP PMTs)

run 2 (→ 2027): integrated luminosity 5-10 ab^{-1}, 2×10^{35}/cm^2/s

2027: collider upgrade (QCS+RF) → installation upgraded detector

run 3 (→ 2035): 50 ab^{-1}

SuperKEKB, the first new collider in particle physics since the LHC in 2008 (electron-positron (e^+e^-) rather than proton-proton (p-p))

Phase 1

Background, Optics commissioning

Feb - June **2016**

Brand new 3 km positron ring

Phase 2: Pilot run

Superconducting Final Focus

add positron damping ring

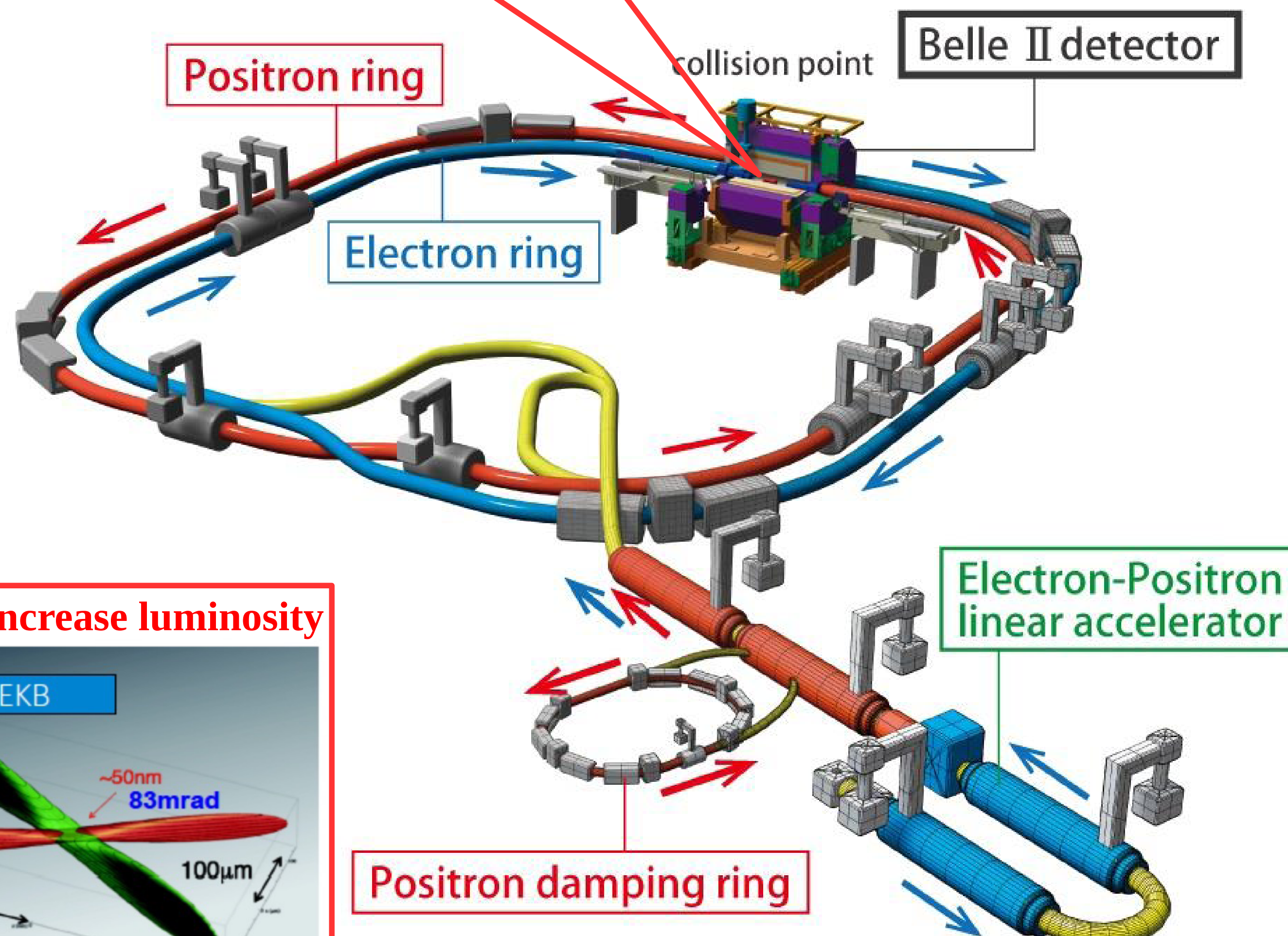
First Collisions ($0.5\ fb^{-1}$)

April 27 - July 17, **2018**

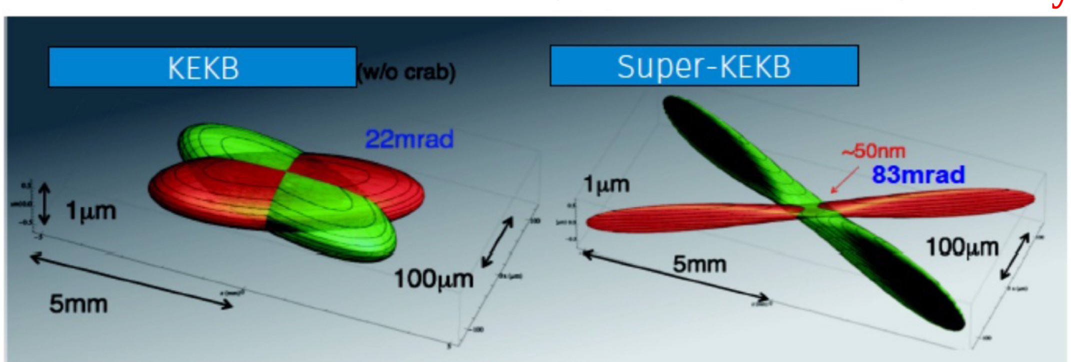
Phase 3: Physics run

Since April, **2019**

Squeeze strongly at IP



Nano-beams and more beam current to increase luminosity



	E (GeV) LER/HER	β*y (mm) LER/HER	β*x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm⁻²s⁻¹)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

factor 20 — factor 2-3

⇒ to reach $\sim 6 \times 10^{35}\ cm^{-2}s^{-1}$

⇒ cumulate $50\ ab^{-1}$ by ~2035