Recent highlights from the Belle II experiment

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on behalf of the Belle II collaboration

29/03/23

International Conference
on the Physics of the Two Infinities

Belle II

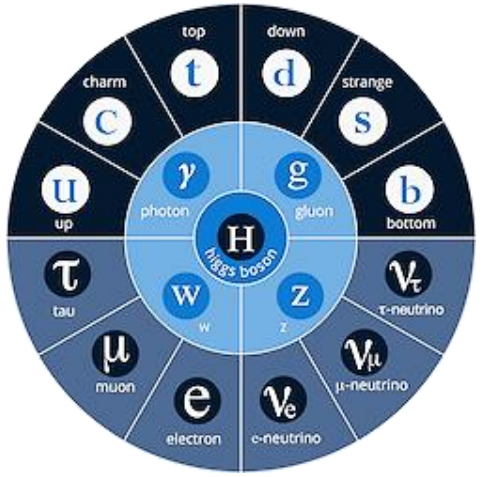
素粒子原子核研究所
Institute of Particle and Nuclear Studies

KEK

Beyond the Standard Model

- One of the most successful theory, impressive predicting power
  - 10 Nobel Prizes so far!

Examples: *Fermi constant 9.10^{-6} precision*
Fine structure constant 3.10^{-9} precision
….

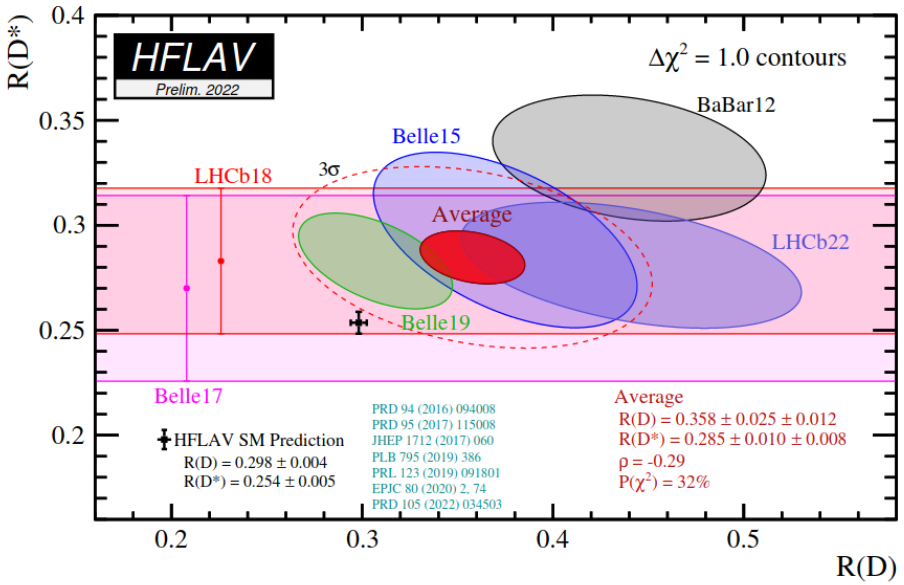


- Not the end of the story

Examples: *Neutrino mass?*
Not enough CP violation to explain matter/antimatter asymmetry?
Dark matter/ energy?

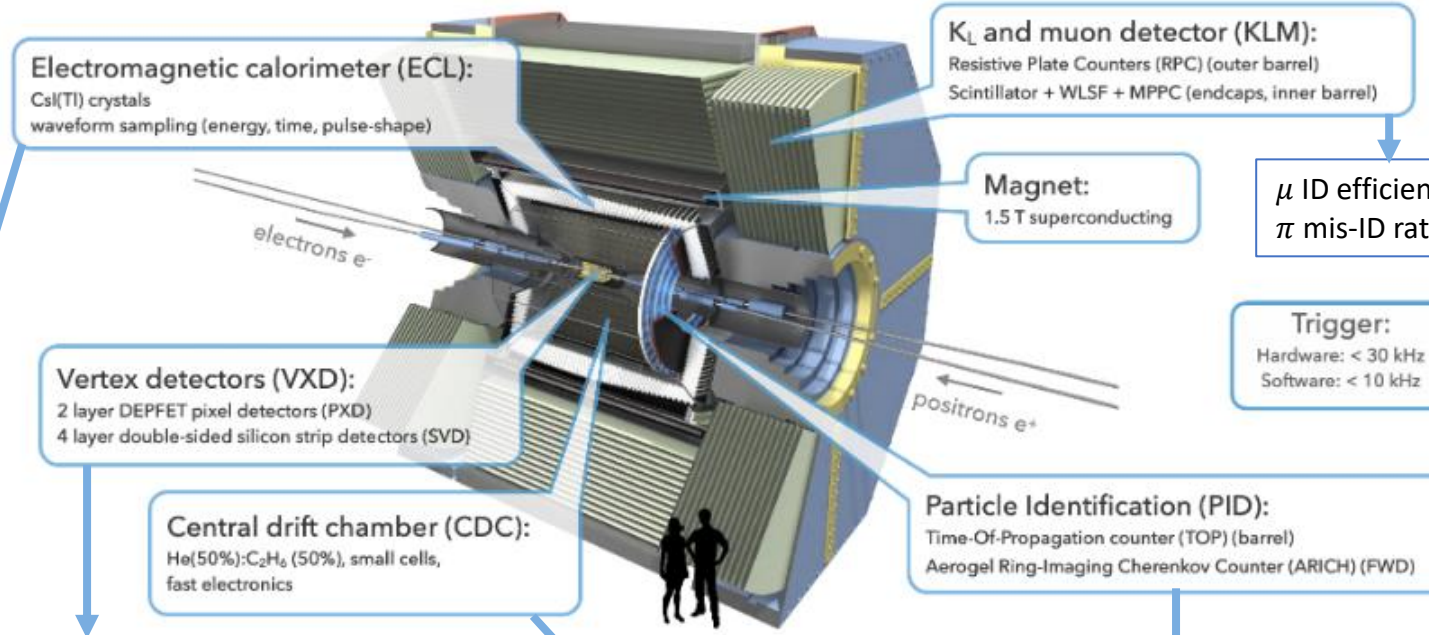
- Tensions with predictions (muon g-2, R(D*)…)

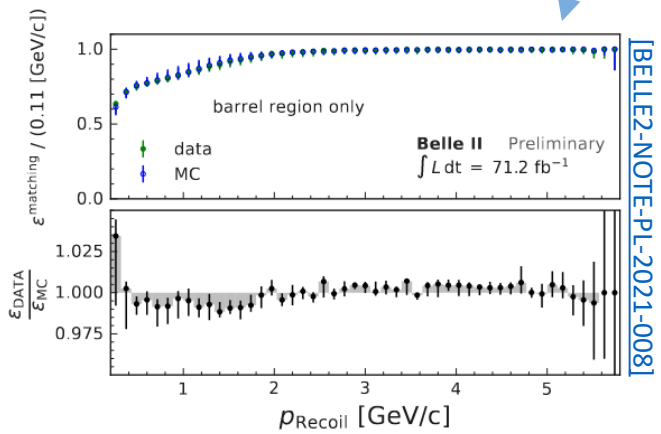
- **Precision** measurements and **high statistics** needed to discover New Physics



Belle II detector

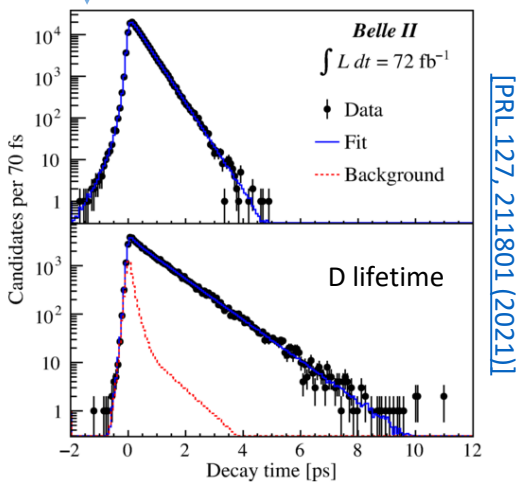
- Designed to give similar or better performance than Belle even with lower boost and higher beam backgrounds
- Low track multiplicity
- Occupancy dominated by machine induced background





[BELLE2-NOTE-PL-2021-008]

High photon reconstruction efficiency $\frac{\sigma(E)}{E} \approx 2\%\sim4\%$

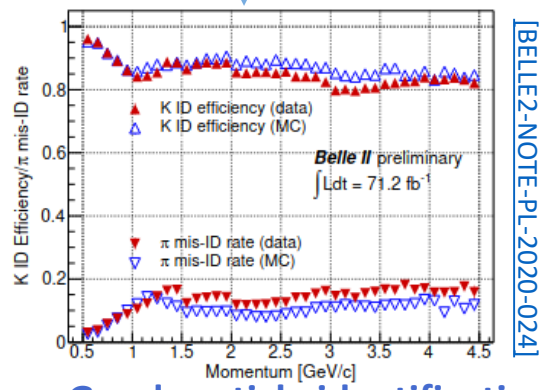


[PRL 127, 211801 (2021)]

Factor 2 improvement in proper time resolution despite lower boost

$\sigma(\text{vertex}) \approx 15\mu\text{m}$

Spatial resolution $\approx 100\mu\text{m}$
dE/dx resolution $\approx 5\%$
$\sigma(p_T)/p_T \approx 0.4\%$



[BELLE2-NOTE-PL-2020-024]

Good particle identification

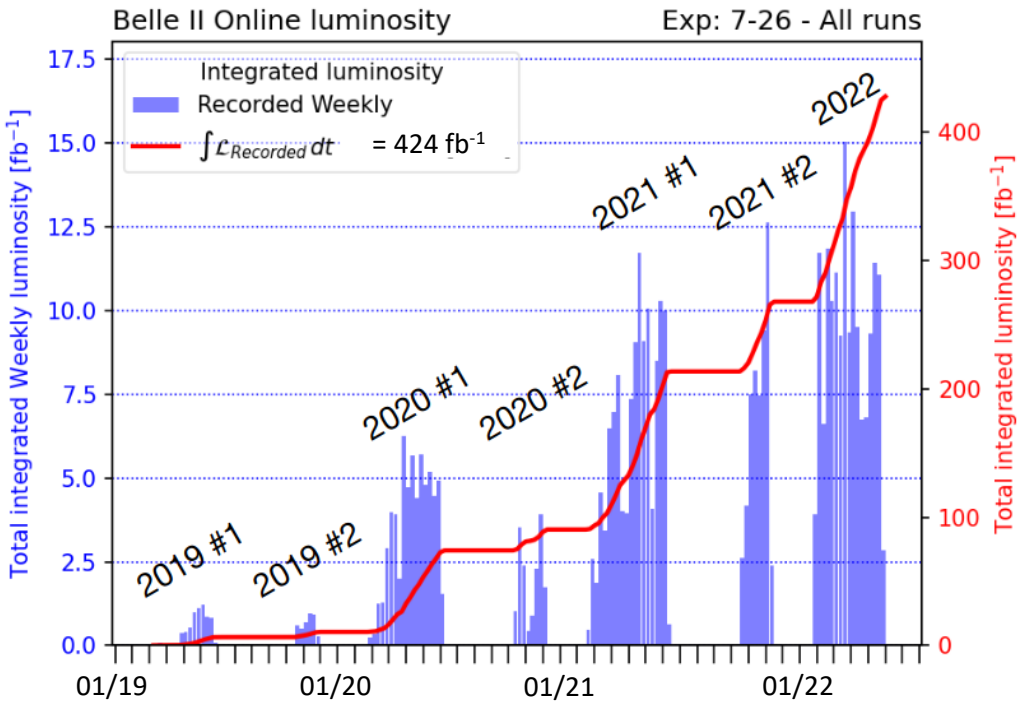
K ID efficiency $\approx 90\%$
π mis-ID rate $\approx 5\%$

Luminosity

Status

- Collected **~ 362 fb^{-1} at Y(4S)** since April 2019
- **Record-breaking instantaneous luminosity:**
  4.7 x 10^{34} cm^{-2}s^{-1} (last: LHC 2.14 x 10^{34} cm^{-2} s^{-1})
- Ramping up toward the target luminosity
- **Highest daily integrated luminosity: 2.5 fb^{-1}**

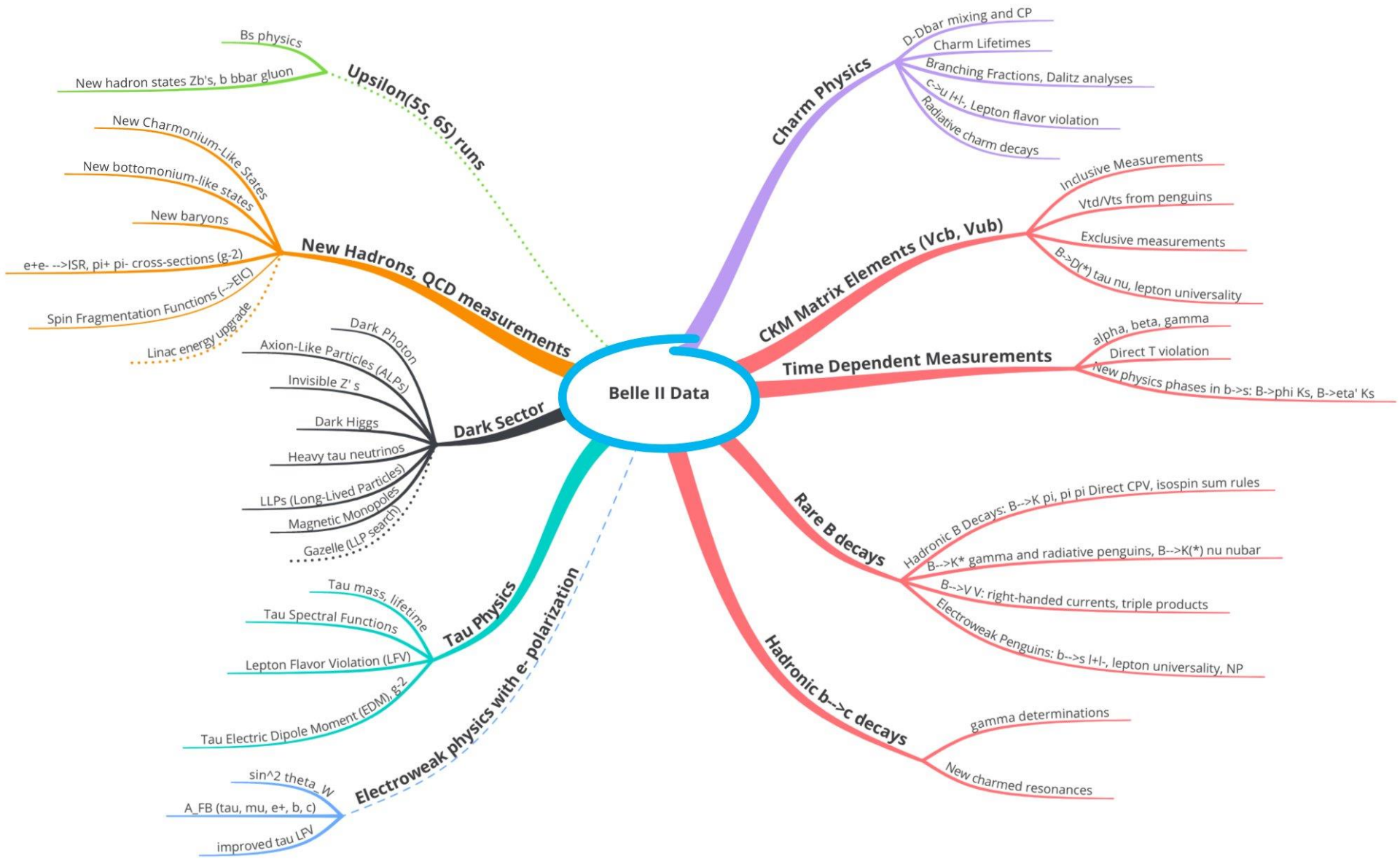
Goal: 50 ab^{-1}



L (fb^{-1})	Belle	*BABAR*	total
Y(5S)	121	-	121
Y(4S)	711	433	1144
Y(3S)	3	30	33
Y(2S)	25	14	39
Y(1S)	6	-	6
off-res	100	54	154

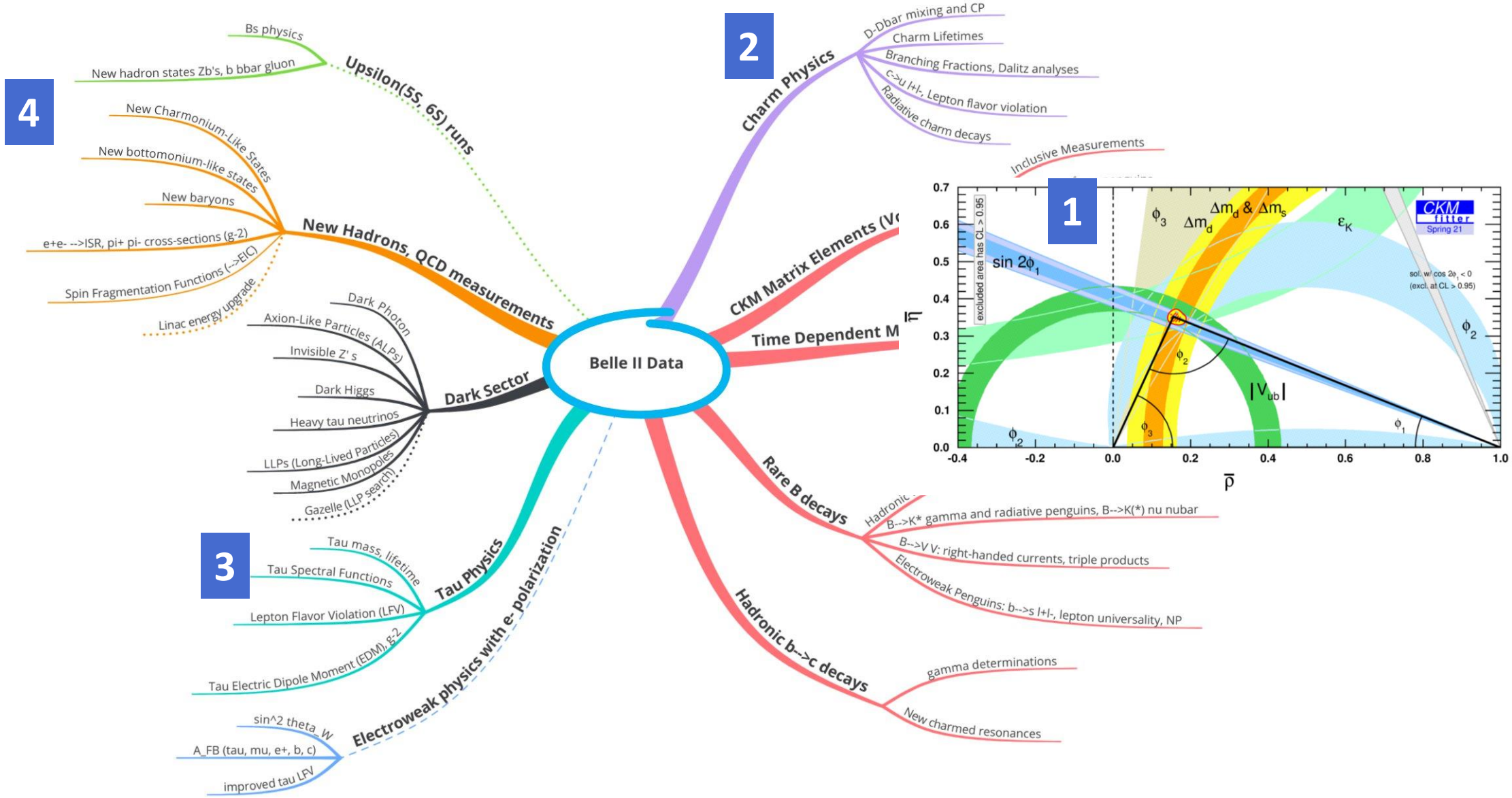
Belle II physics program

[Snowmass White Paper]



Belle II physics program

[Snowmass White Paper]



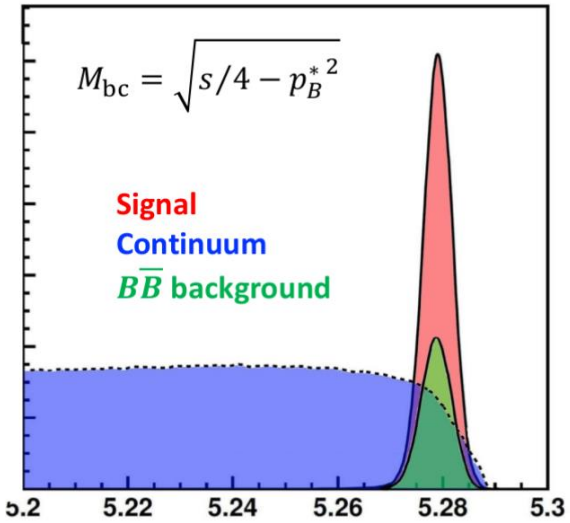
B-factory basics

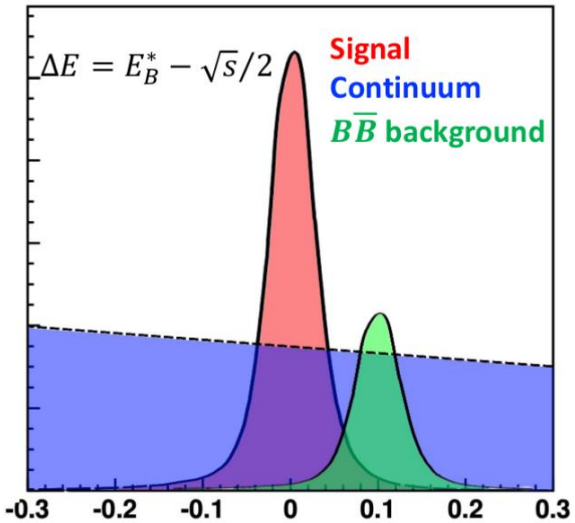
- **e^+e^- collision**
  - Collision energy well defined
  - Kinematic well constrained

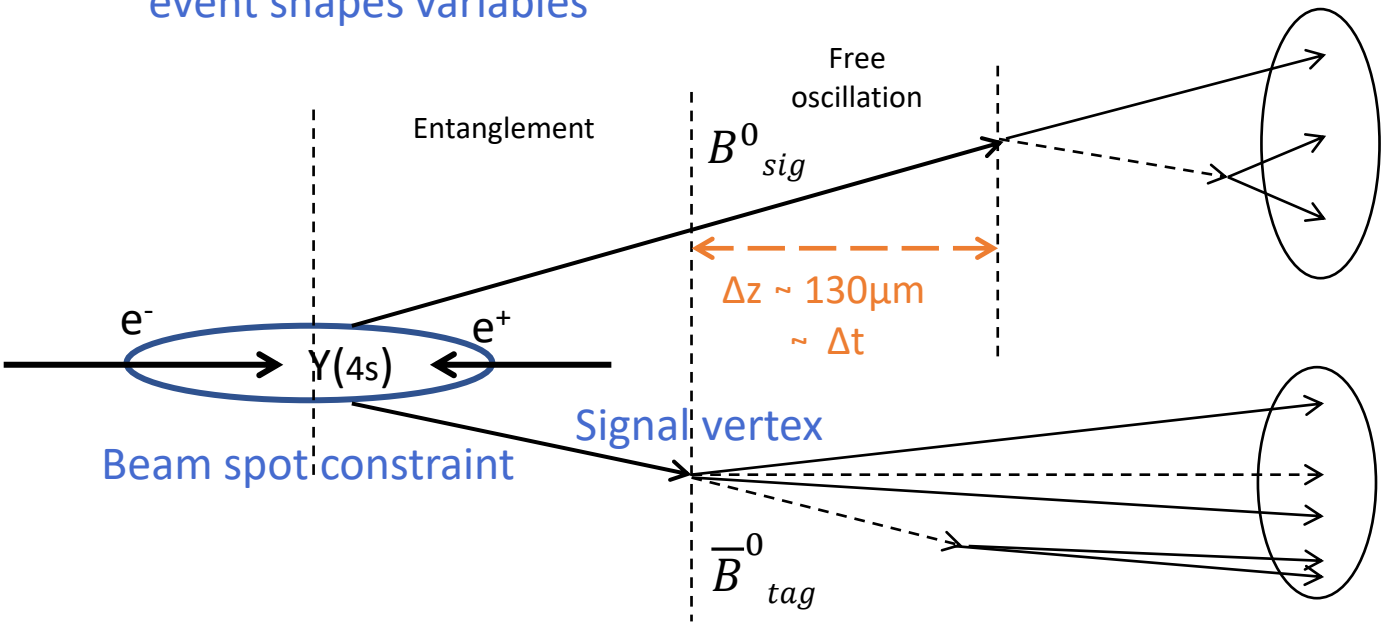
  > Beam-constrained mass (M_{bc}) and energy difference (ΔE)

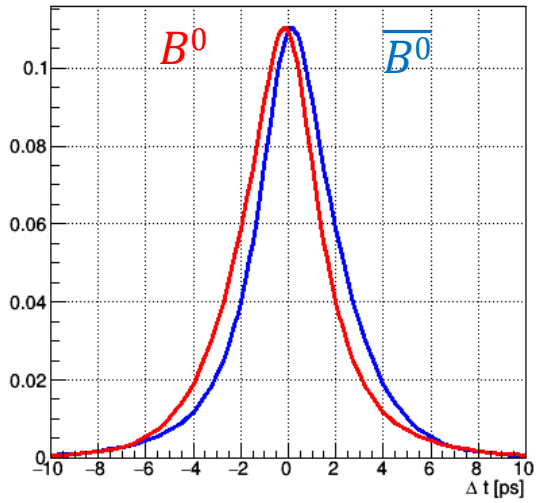
- Time difference Δt measured thanks to the boost along z

- Signal side fully reconstructed
- Vertexing and Flavor tagger on Tag side
- Continuum suppression (CSMVA) variable trained on BDTs using event shapes variables

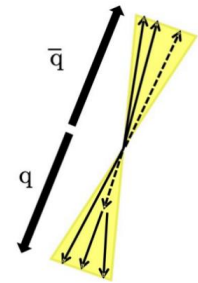


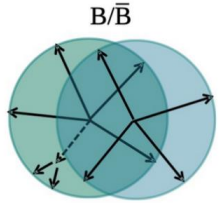






Event shapes

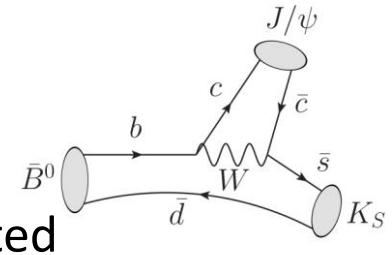


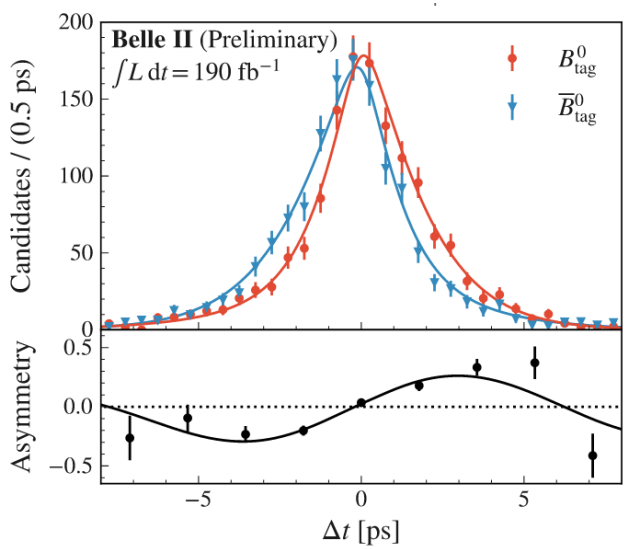


Toward ϕ_1 (β)

$B^0 \to J/\psi\, K^0_S$

- High-yield, low background
- Both $J/\psi \to ee$ and $J/\psi \to \mu\mu$ channels reconstructed
- 2755 events in 200M $B^0\overline{B^0}$ pairs
  - Statistically limited but consistent with expectation





[arXiv:2302.12898]

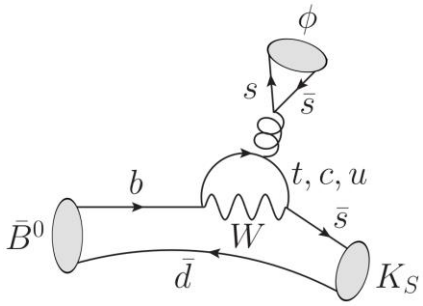
$$S_{CP} = 0.720 \pm 0.062(\text{stat}) \pm 0.016(\text{syst})$$
$$A_{CP} = 0.094 \pm 0.044(\text{stat})\,^{+0.042}_{-0.017}(\text{syst})$$

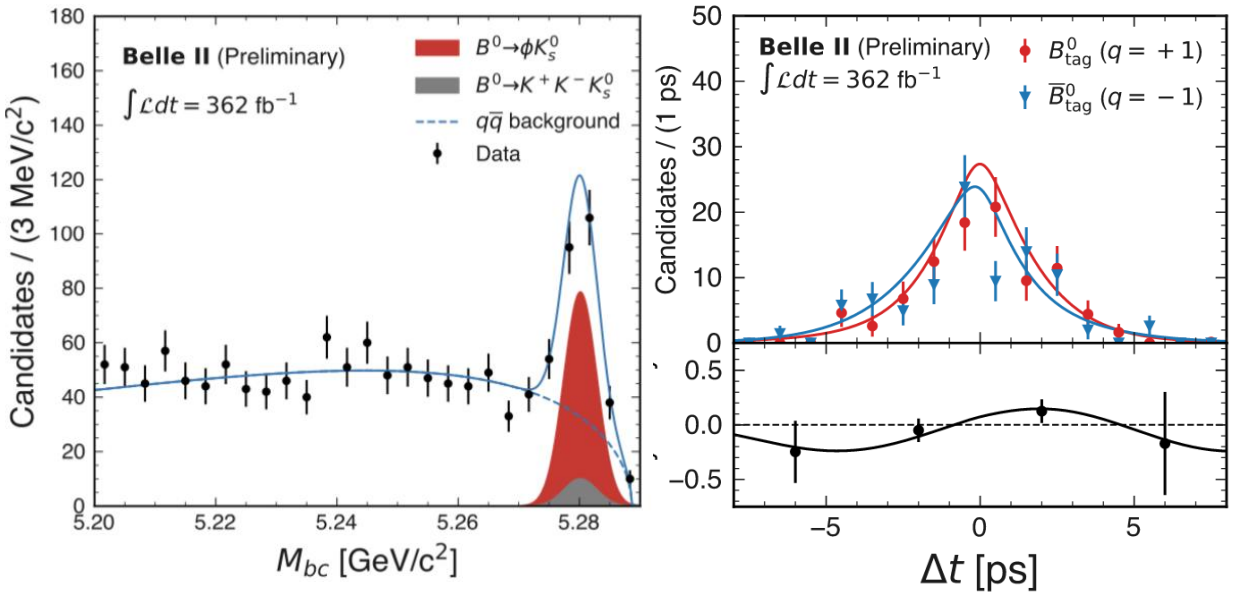
$$\phi_1 = (23.0 \pm 2.6(\text{stat}) \pm 0.7(\text{syst}))^\circ$$

$B^0 \to \phi\, K^0_S$

- Clean experimental signature but non-pure CP eigenstate
- Validated with $B^+ \to \phi\, K^+$
- 163 events in 387M $B^0\overline{B^0}$ pairs

> Compatible and on-par with most precise determination of A_{cp}



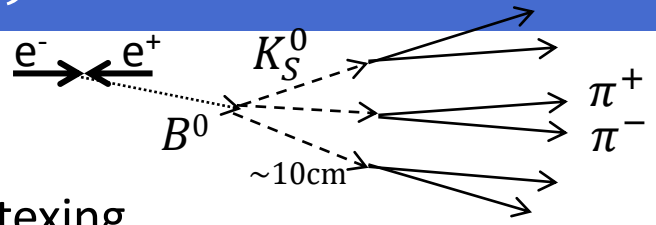


To be submitted to PRD

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

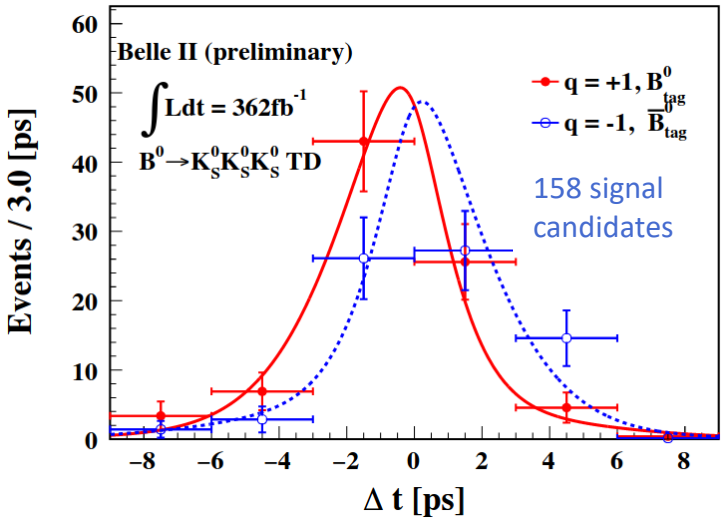
Toward ϕ_1 (β)

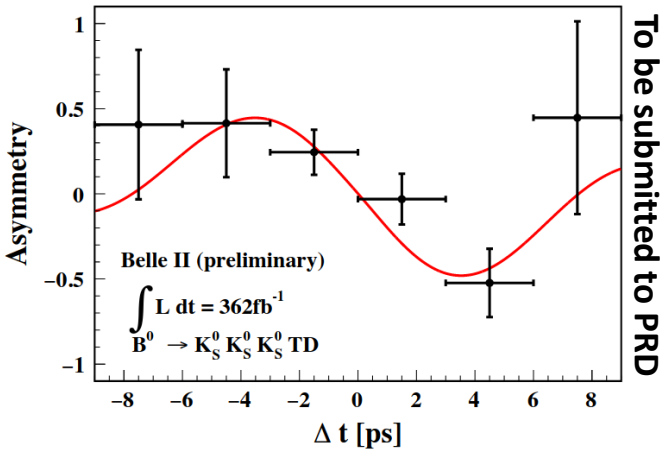
$B^0 \to K^0_S K^0_S K^0_S$



- Complex vertexing
- Reach similar precision as world's best results

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



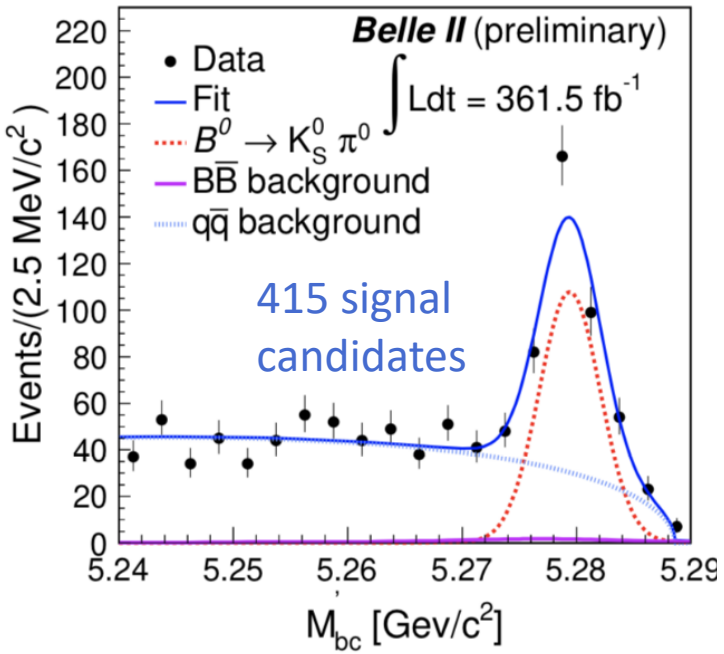


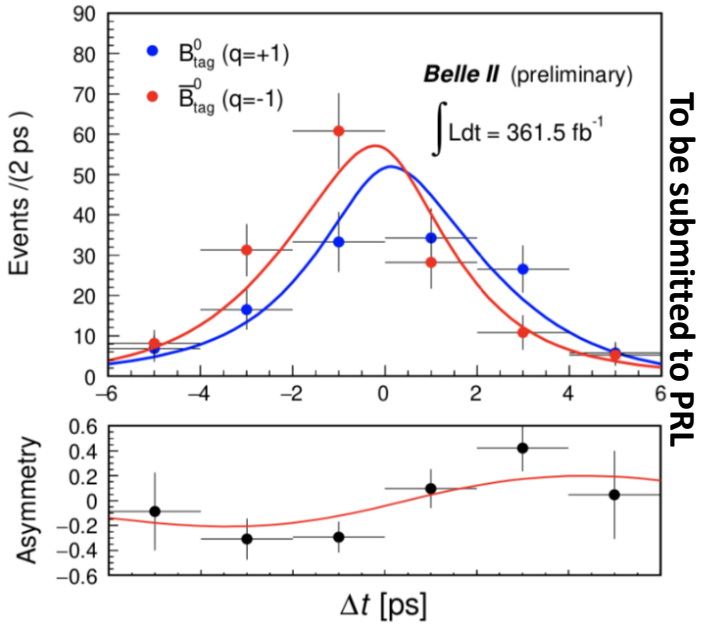
$B^0 \to K^0_S \pi^0$

- Challenging vertex reconstruction
- $B^0 \to J/\psi\, K^0_S$ as control channel
- Better π^0 reconstruction and CSMVA

> Competitive precision with world best results

$$A_{CP} = 0.04^{+0.15}_{-0.14} \pm 0.04$$
$$S_{CP} = 0.74^{+0.20}_{-0.23} \pm 0.04$$



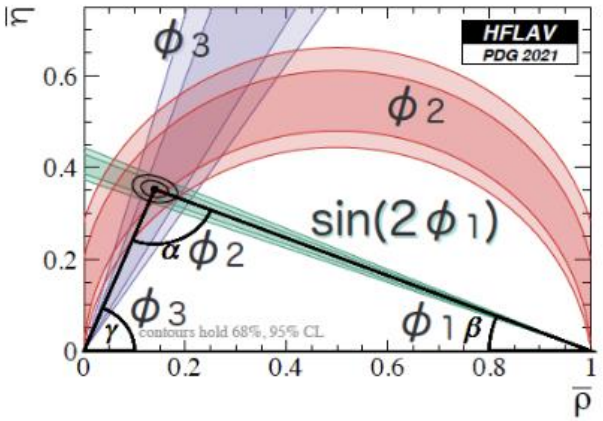


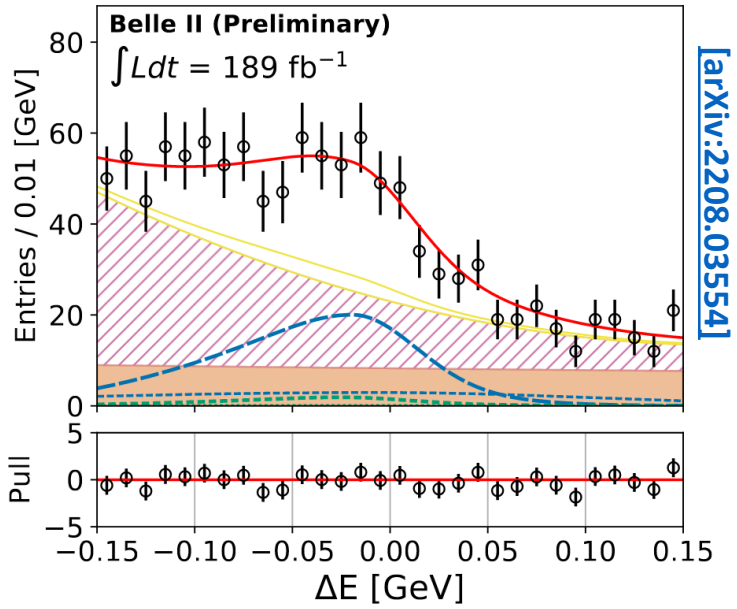
Toward ϕ_2 (α)

- Least known angle of the UT

$B \to \rho\rho$ and $B^0 \to \pi^0\pi^0$

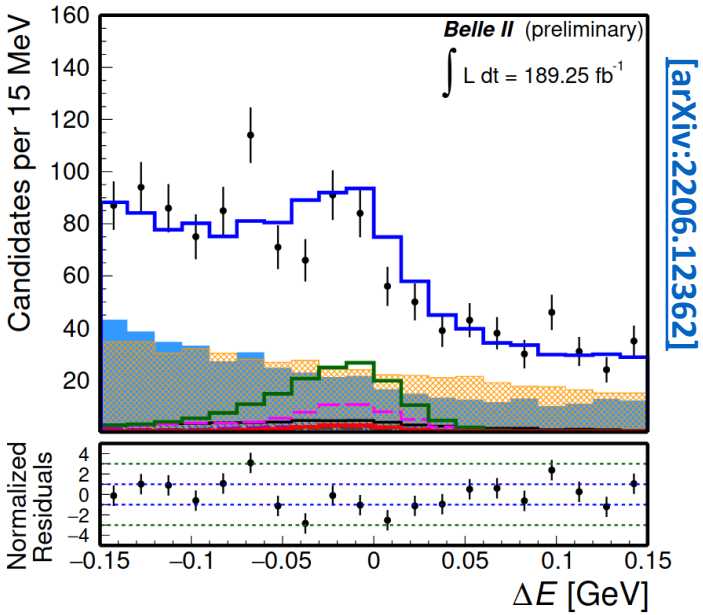
- Measurement of BR and A_{cp} of these 3 channels
  - Combined analyses to suppress hadronic unknowns
  - Belle II provides unique access to all inputs





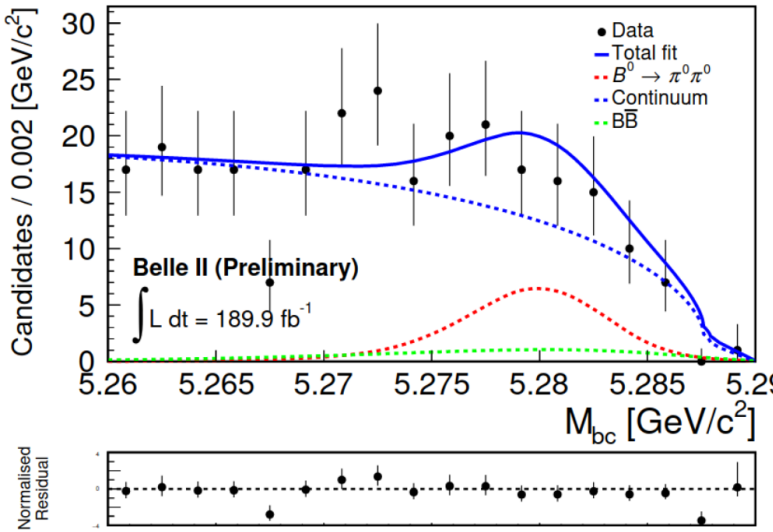
[arXiv:2208.03554]

$$\mathcal{B}(B^0 \to \rho^+\rho^-) = [2.67 \pm 0.28\,(\text{stat}) \pm 0.28\,(\text{syst})] \times 10^{-5},$$
$$f_L = 0.956 \pm 0.035\,(\text{stat}) \pm 0.033\,(\text{syst}),$$



[arXiv:2206.12362]

$$\mathcal{B}(B^+ \to \rho^+\rho^0) = [23.2^{+\ 2.2}_{-\ 2.1}(\text{stat}) \pm 2.7(\text{syst})] \times 10^{-6},$$
$$f_L = 0.943^{+\ 0.035}_{-\ 0.033}(\text{stat}) \pm 0.027(\text{syst}),$$
$$\mathcal{A}_{CP} = -0.069 \pm 0.068(\text{stat}) \pm 0.060(\text{syst}).$$



To be submitted to PRL

$$A_{CP} = 0.14 \pm 0.46 \pm 0.07$$
$$\mathcal{B} = (1.27 \pm 0.25 \pm 0.17) \cdot 10^{-6}$$

Close to Belle precision with only ¼ dataset

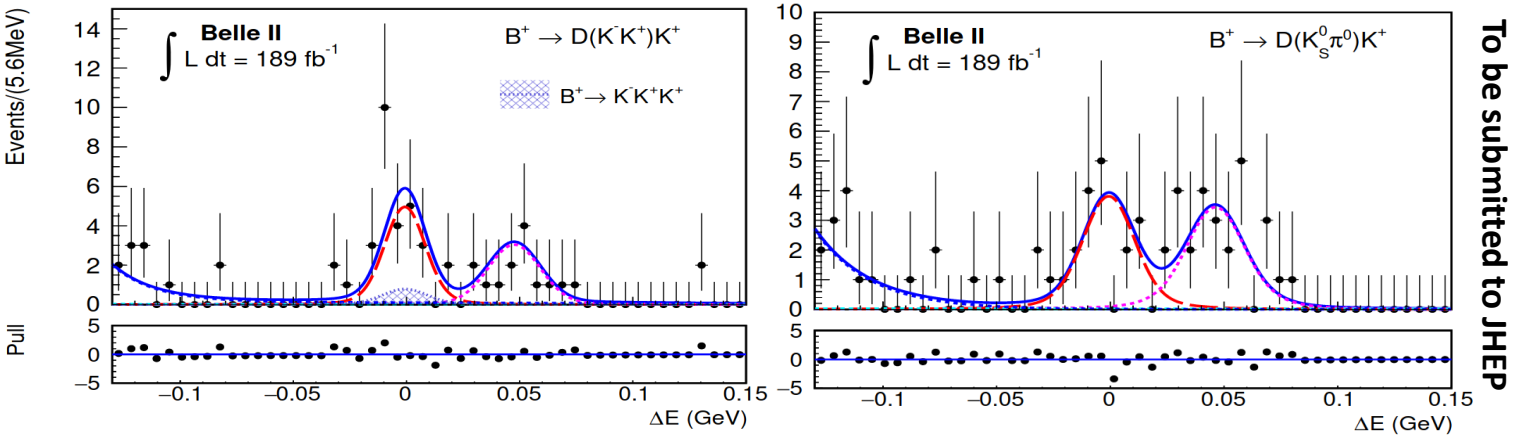
Toward ϕ_3 (γ)

$B^{\pm} \to D_{CP\pm} K^{\pm}$

- CP eigenstates such as K^+K^- (cp even) or $K_S^0\,\pi^0$ (cp odd)
- Belle + Belle II dataset used (711 + 189 fb^{-1})

$$
\begin{aligned}
R_{CP+} &= 1.164 \pm 0.081 \pm 0.036, \\
R_{CP-} &= 1.151 \pm 0.074 \pm 0.019, \\
\mathcal{A}_{CP+} &= +0.125 \pm 0.058 \pm 0.014 \\
\mathcal{A}_{CP-} &= -0.167 \pm 0.057 \pm 0.006.
\end{aligned}
$$

Parameter	68.3% C.L.	95.4% C.L.
γ (°)	[8.7, 20.5] [83.8, 96.1] [163.4, 173.1]	[4.7, 175.8]
r_B	[0.282, 0.489]	[0.069, 0.560]

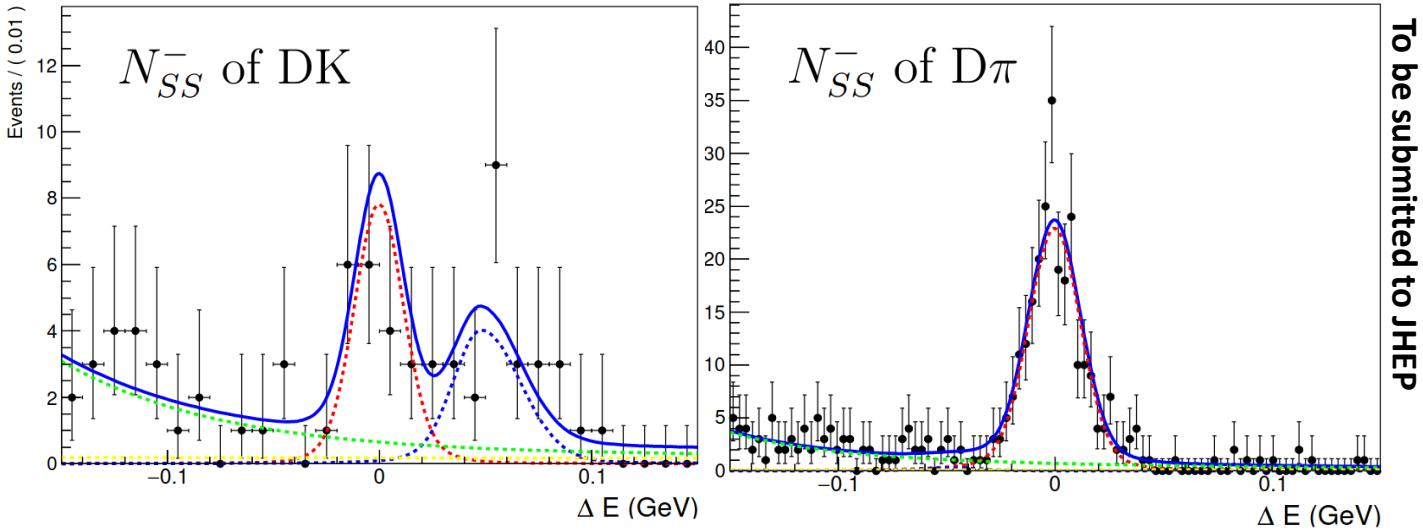


To be submitted to JHEP

$B^{\pm} \to Dh^{\pm}$

- Belle + Belle II dataset used (711 + 363 fb^{-1})
- 7 observables (4 CP asymmetries and 3 BR)

$$
\begin{aligned}
A_{SS}^{DK} &= -0.089 \pm 0.091 \pm 0.011, \\
A_{OS}^{DK} &= 0.109 \pm 0.133 \pm 0.013, \\
A_{SS}^{D\pi} &= 0.018 \pm 0.026 \pm 0.009 \\
A_{OS}^{D\pi} &= -0.028 \pm 0.031 \pm 0.009, \\
R_{SS}^{DK/D\pi} &= 0.122 \pm 0.012 \pm 0.004, \\
R_{OS}^{DK/D\pi} &= 0.093 \pm 0.013 \pm 0.003, \\
R_{SS/OS}^{D\pi} &= 1.428 \pm 0.057 \pm 0.002.
\end{aligned}
$$



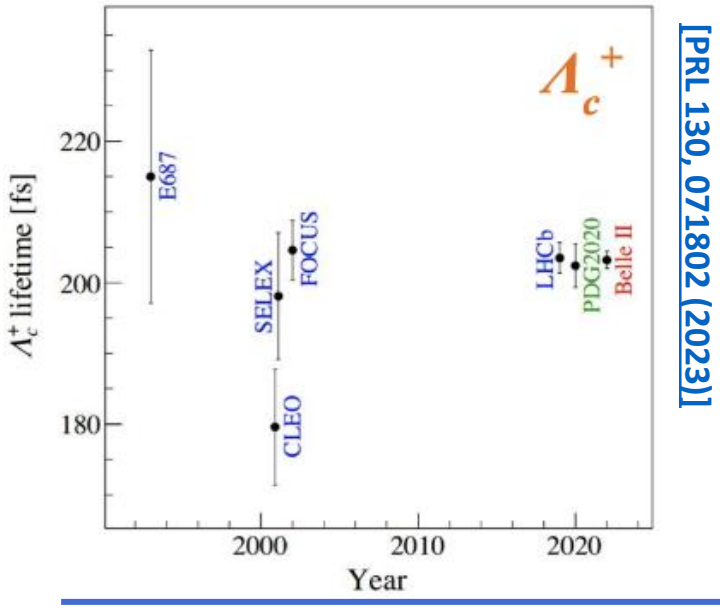
To be submitted to JHEP

Charm physics at Belle II

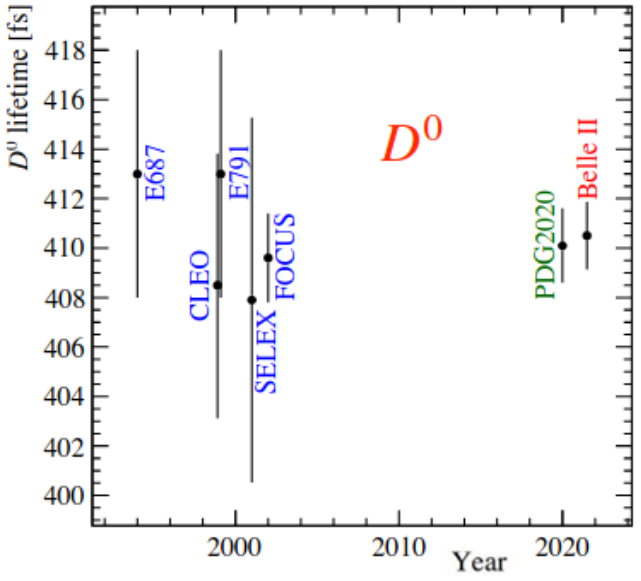
Λ_c^+ and Ω_c^0 lifetimes

- World most precise measurements of the Λ_c^+, D^0 and D^+ lifetimes
- Consistent with world average (Λ_c^+ , D) and LHCb result (Ω_c^0) that challenged earlier determinations and HQE expectations

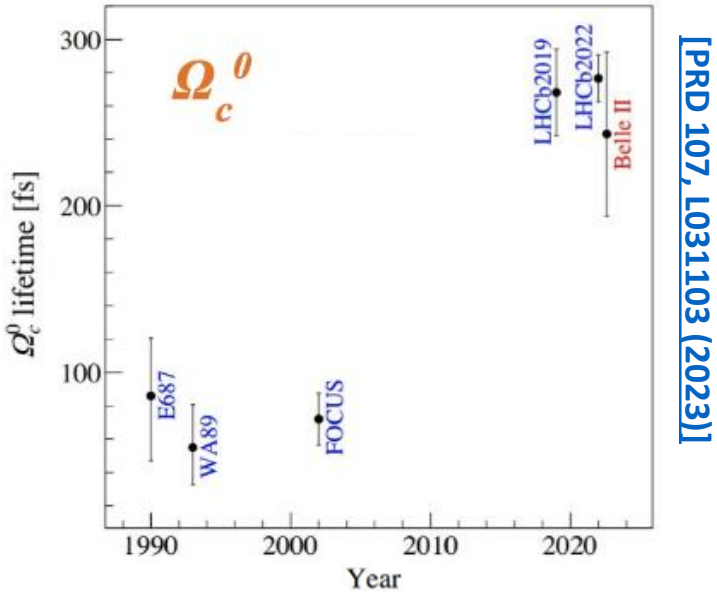
- Few per-mill accuracy establishes the excellent performance of our detector



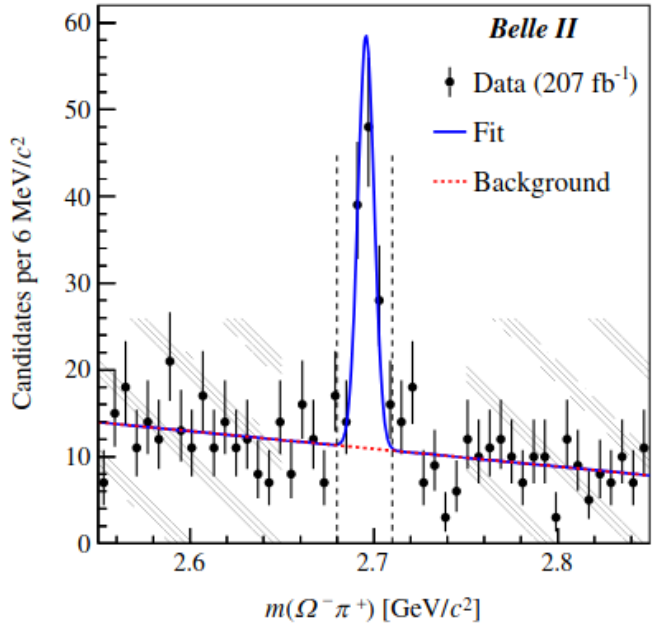
[PRL 130, 071802 (2023)]



[PRL 127, 211801(2021)]



[PRD 107, L031103 (2023)]



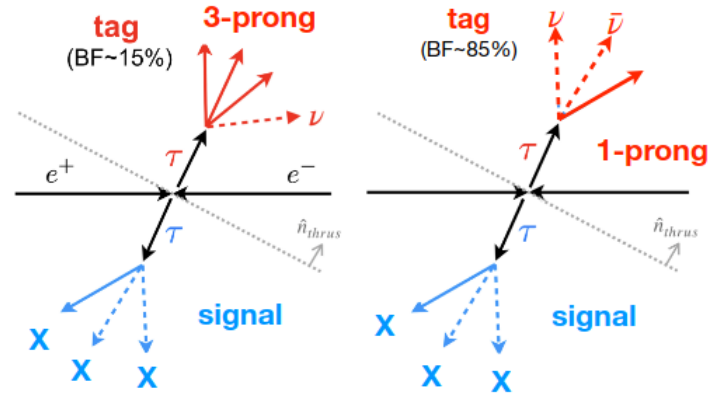
τ Physics at Belle II

- High production allow high-precision measurements

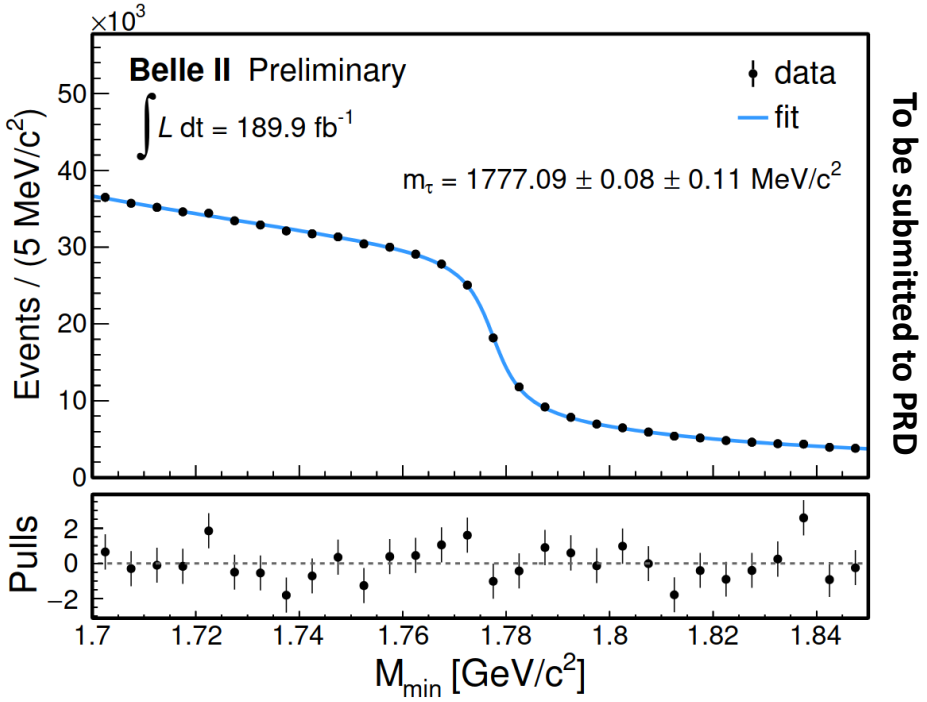
$\boldsymbol{\tau^+ \to \pi^+\pi^-\pi^+\nu}$

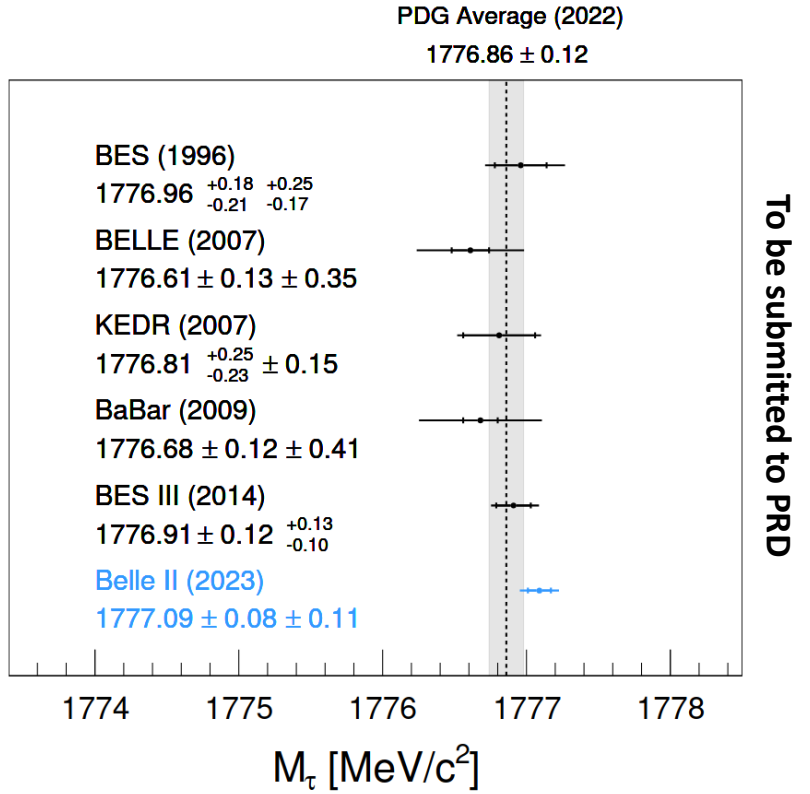
- Using 1-prong and 3-prong events for tag side
  - Crucial knowledge of beam-energy and its resolution (ARGUS method)

$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)} \leq M_\tau$$



World best τ mass measurement

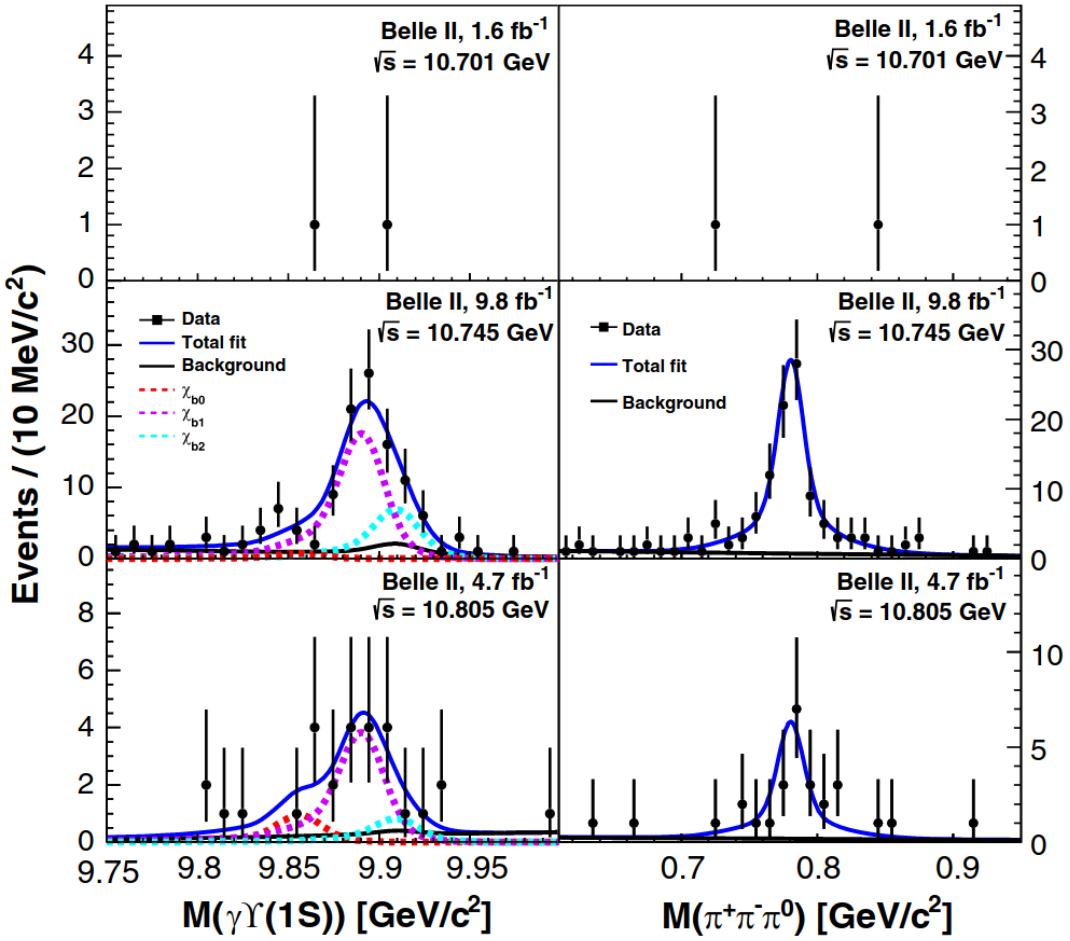


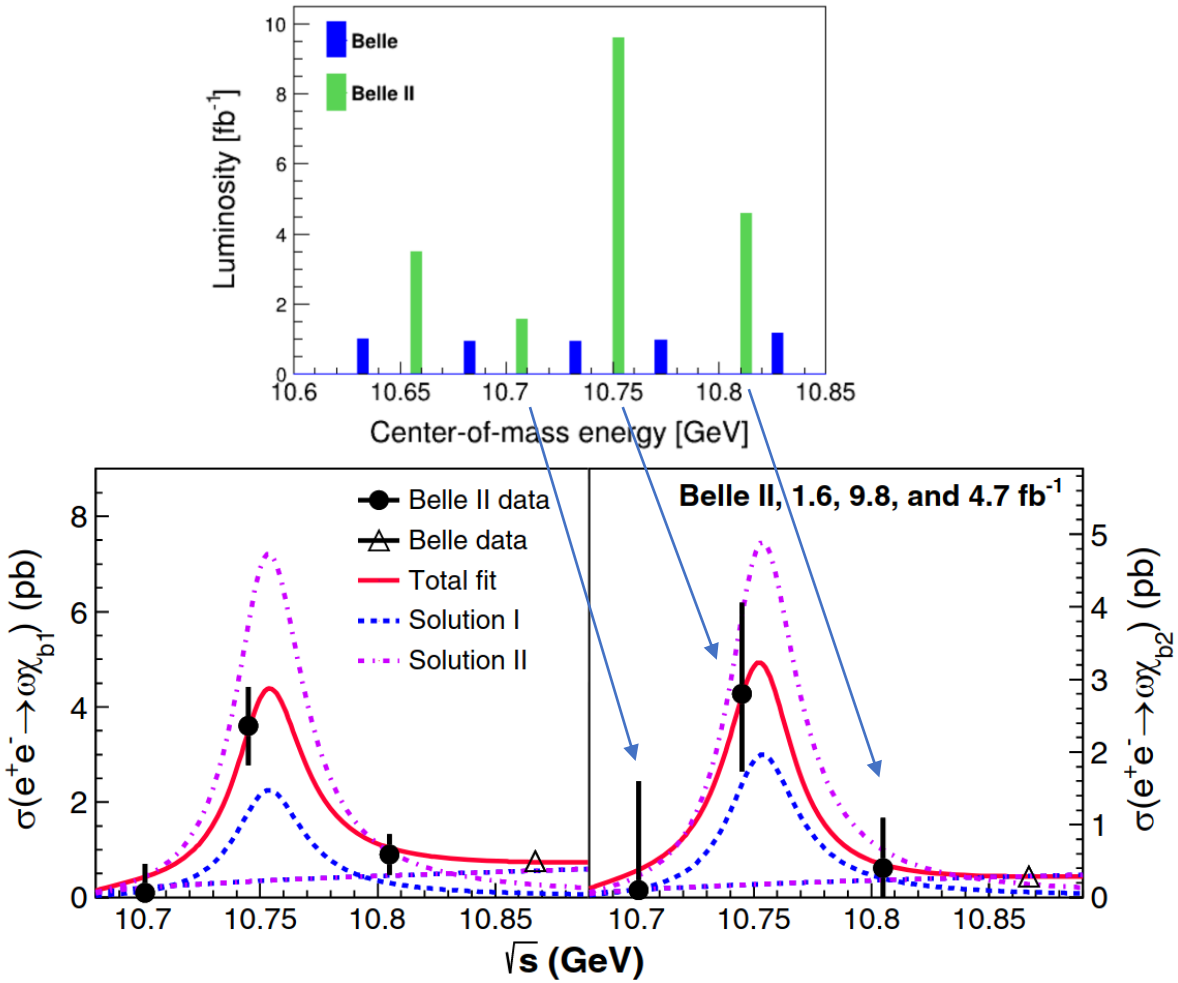


Quarkonium at Belle II

[PRL 130, 091902 (2023)]

- $e^+e^- \to \omega\chi_{b1,b2}(1P)$
  - In 2021, SuperKEKB ran above $\Upsilon(4S)$ resonances

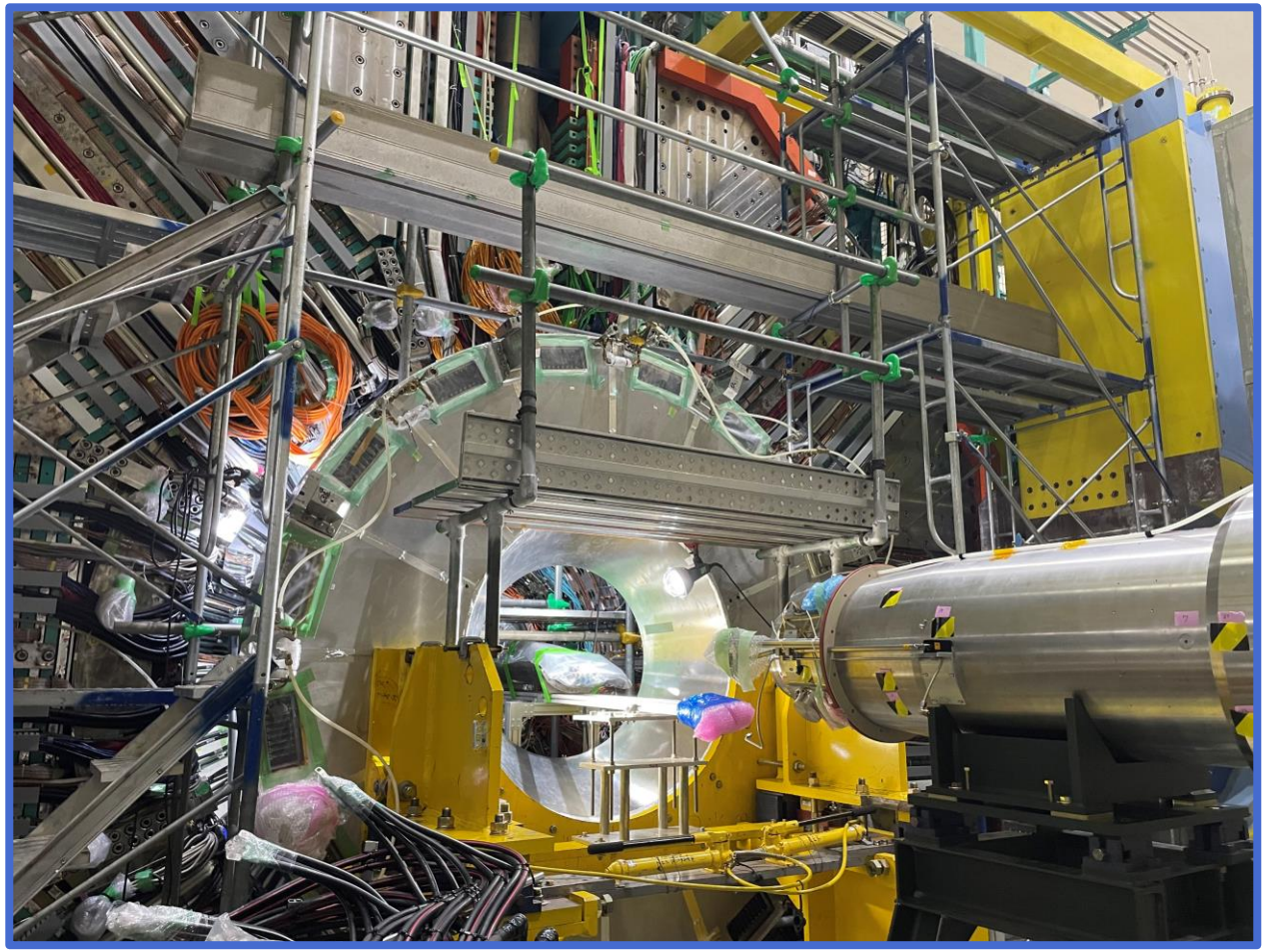


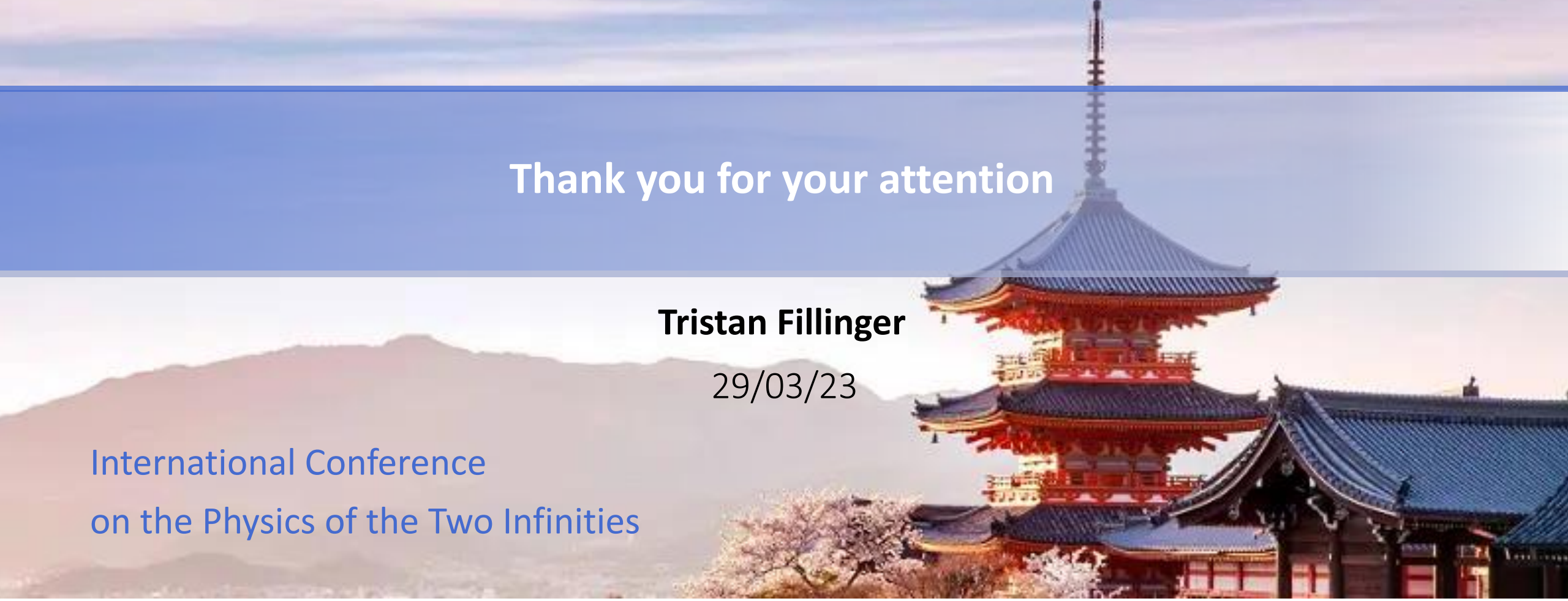


- Measurement of cross-section peak, consistent with $\Upsilon(10753)$ state
- First observation of $\omega\chi_{bJ}(1P)$ signal at $\sqrt{s} = 10.745$ GeV

Summary

- Belle II experiment has collected a sample that matches the size of BaBar's and is half the size of Belle's.
- With the help of an improved detector and refined analysis, we have already achieved results that compete with previous measurements and some results that are exclusive to us.
- Only a selection of the ongoing analyses were presented today
- We plan to resume data collection next winter after preparing the detector and machine to operate at maximum capacity.





Thank you for your attention

Tristan Fillinger

29/03/23

International Conference
on the Physics of the Two Infinities

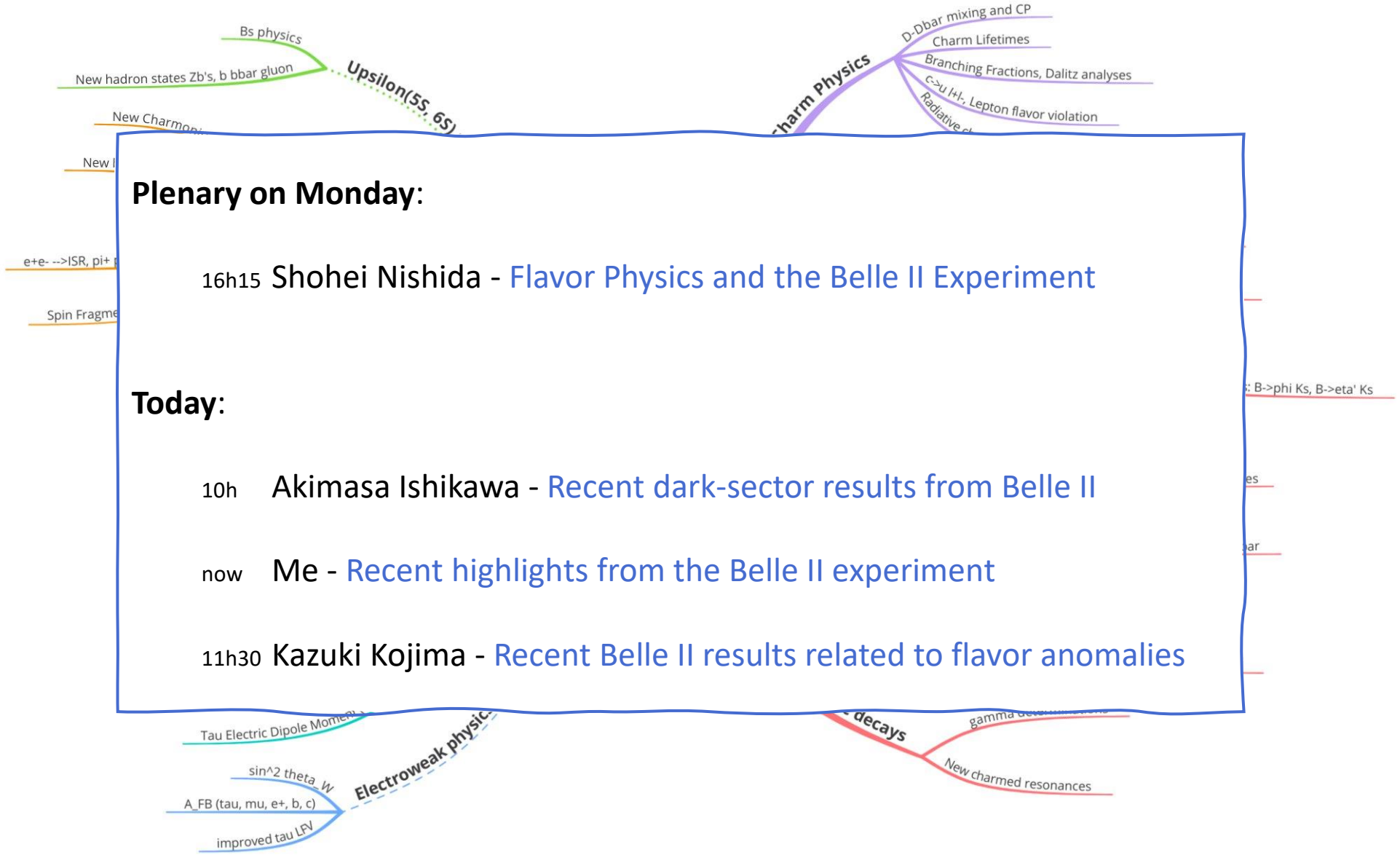
Belle II

iFJNS
素粒子原子核研究所
Institute of Particle and Nuclear Studies

KEK

Belle II physics program

[Snowmass White Paper]



Plenary on Monday:

16h15 Shohei Nishida - Flavor Physics and the Belle II Experiment

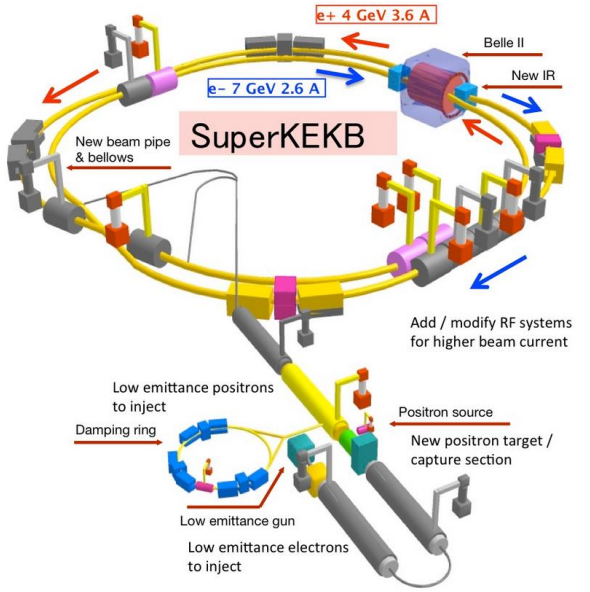
Today:

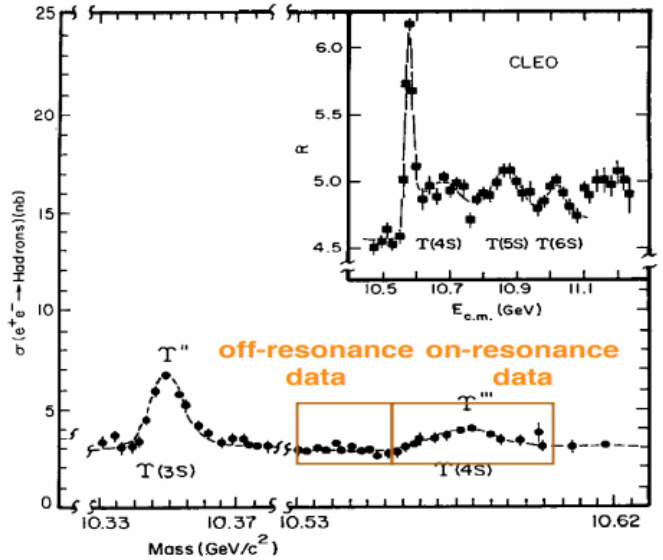
10h Akimasa Ishikawa - Recent dark-sector results from Belle II

now Me - Recent highlights from the Belle II experiment

11h30 Kazuki Kojima - Recent Belle II results related to flavor anomalies

SuperKEKB collider and Belle II





- Electron (7 GeV) - Positron (4 GeV) collider

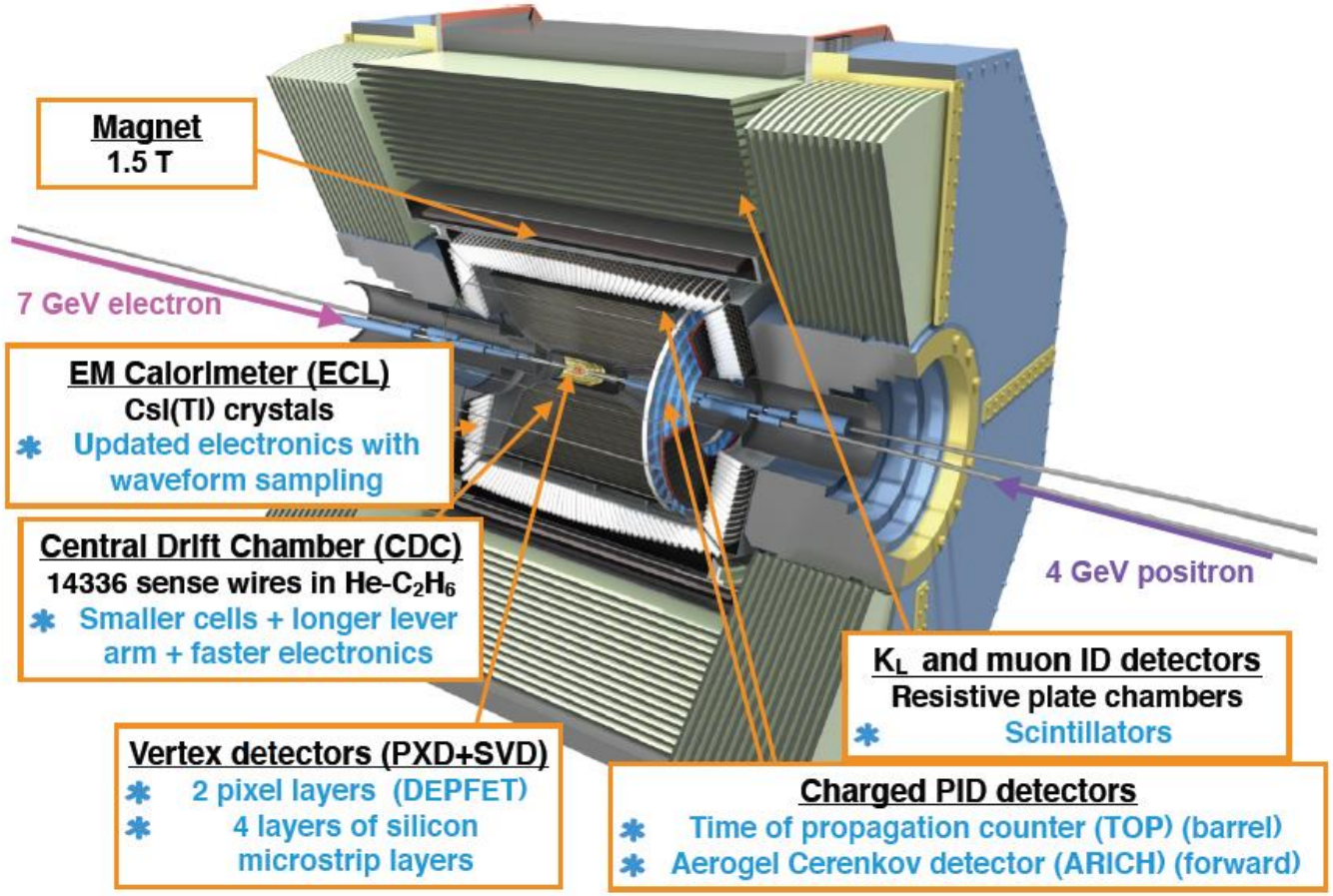
- **KEKB upgrade:**
  - x 1.5 currents
  - x 1/20 vertical beam size (**Nanobeam scheme**)
    → Target up to 30 x higher $\mathcal{L}_{inst}$
  - Higher beam backgrounds

- Build to run on high Υ masses (from Υ(3S) to Υ(6S))

- On-resonance data:
  - Around $\sqrt{s} = 10.58$ GeV
    → Υ(4S) resonance → $B\overline{B}$
    → Clean B sample

- Off-resonance data:
  - 60 MeV below Υ(4S) resonance
  - $e^+e^- \rightarrow q\overline{q}$, $\tau^+\tau^-$, e^+e^- where q = (u, d, s, c)
    → Control sample for continuum background

Belle II detector

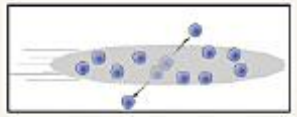


- Designed to give similar or better performance than Belle even under higher backgrounds
- DAQ and trigger systems upgraded

Background types

Machine background

Touschek scattering: single Coulomb scattering event between two particles of the same bunch, that are lost.

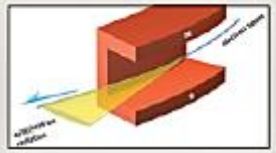


$$R_{Tou} \propto \frac{1}{\sigma E^3 n_b} I_{beam}^2$$

Beam-gas scattering: Coulomb elastic scattering or bremsstrahlung with residual gas atoms.

$$R_{bg} \propto IP$$

Synchrotron Radiation (SR): photon emission from beam particles when subject to acceleration.



$$W_{SR} \propto \frac{E^4}{\rho^2}$$

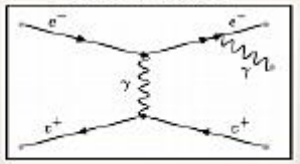
Injection background: injected bunch performing betatron oscillation around the stored bunch, resulting in particle losses especially in the interaction region.

$$R_I \propto R_{inj}$$

Luminosity background

Radiative Bhabha: neutron production from emitted photons (shields used for mitigation); off-energy primary particles lost in final focus magnets.

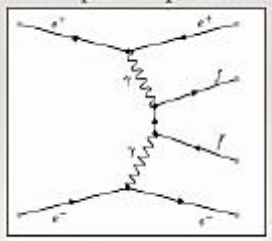
Radiative Bhabha



$$R_{RB} \propto L$$

Two photons process: low momentum electron-positron pairs that can generate multiple hit in the VerteX Detector.

Two photons process

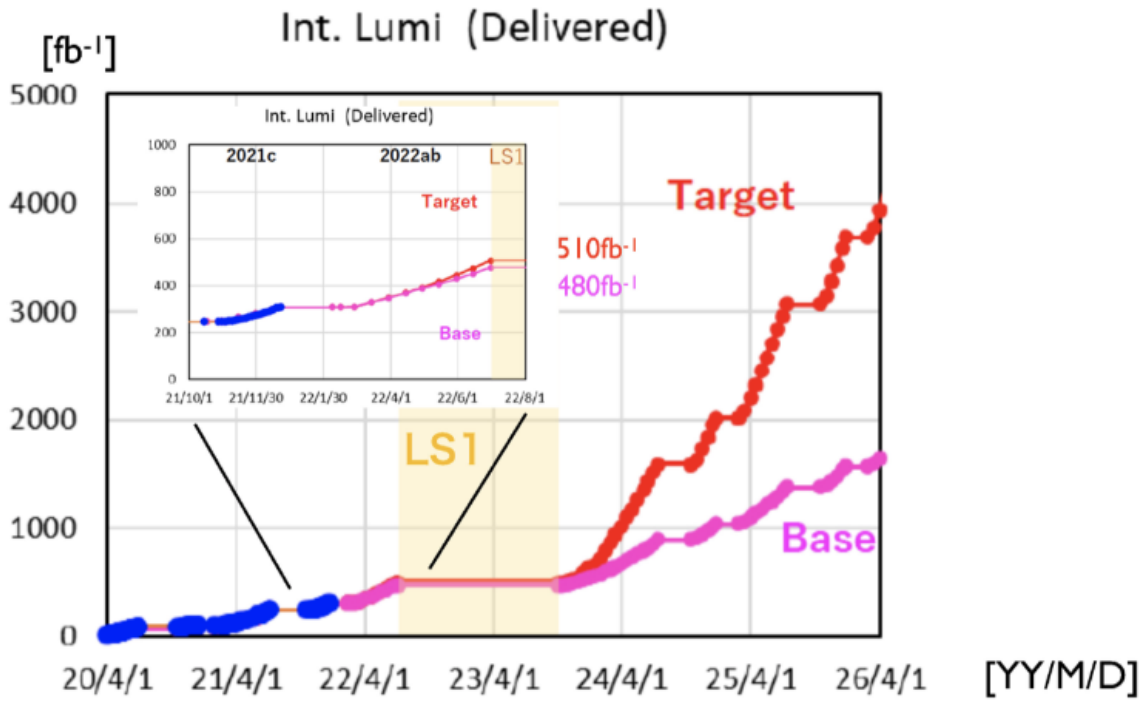


$$R_{RB} \propto L$$

Projection of integrated luminosity delivered by SuperKEKB to Belle II

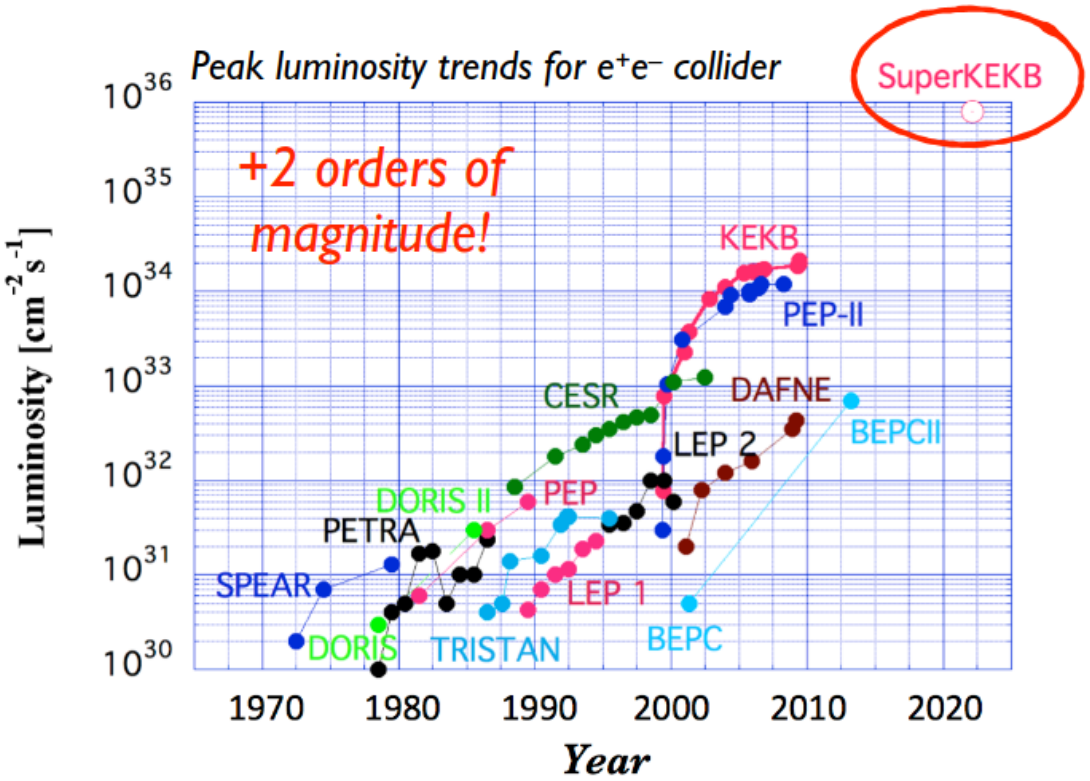
Target scenario: extrapolation from 2021 run including expected improvements.

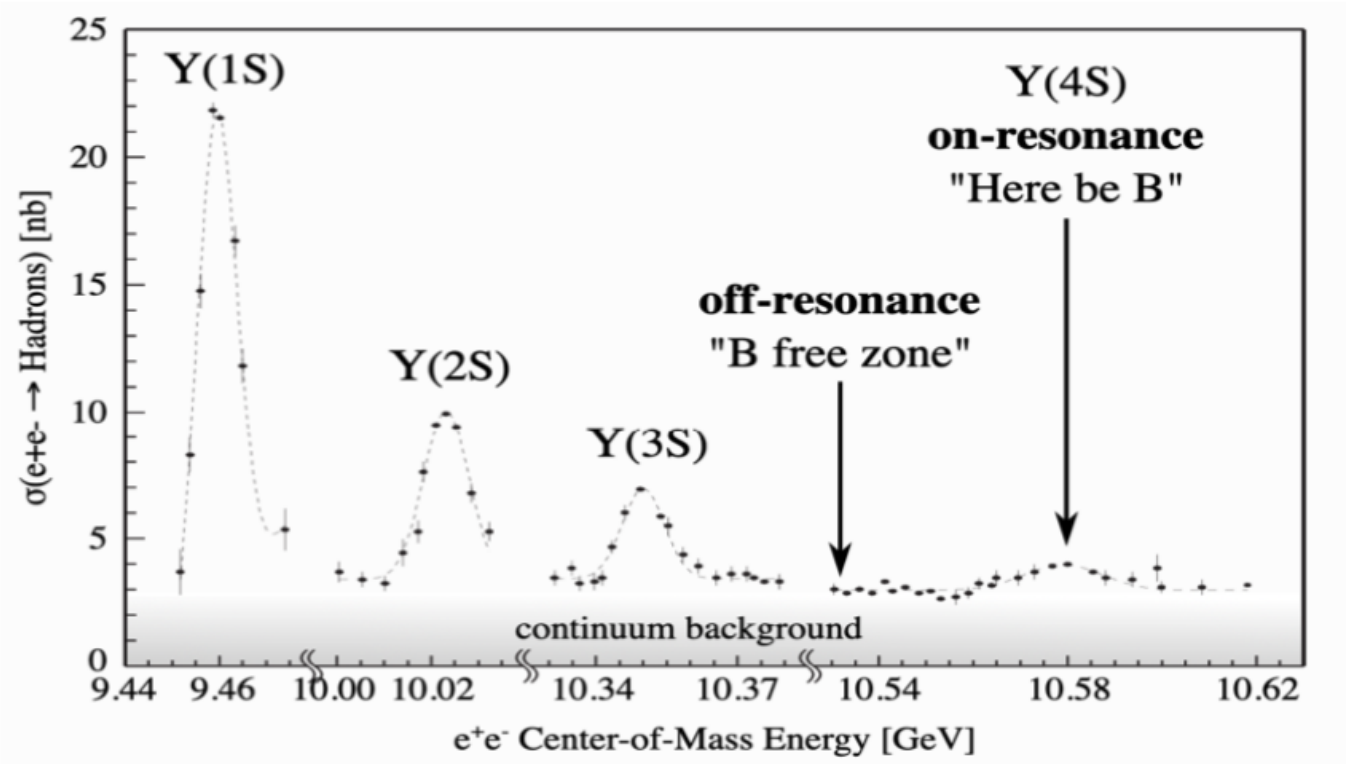
Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run



- We start long shutdown 1 (LS1) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement works of machine and detector.
- We resume physics running from Fall 2023.
- A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.
- An LS2 for machine improvements could happen on the time frame of 2026-2027

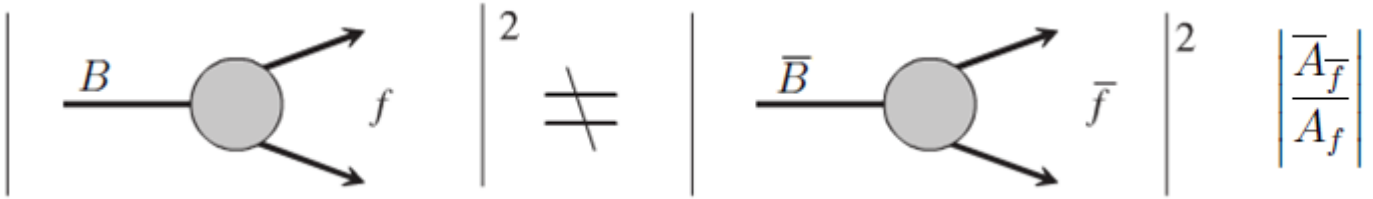
SuperKEKB Highlights



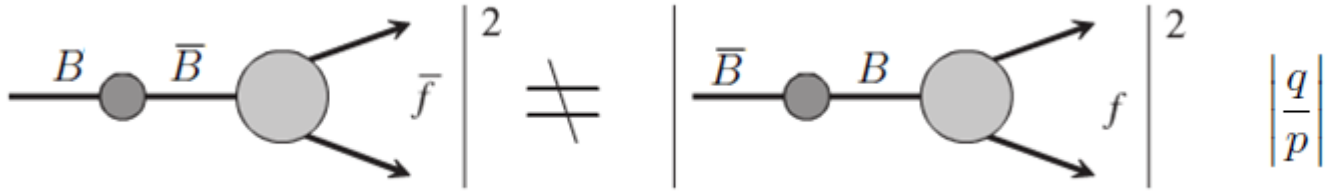


CP violation type

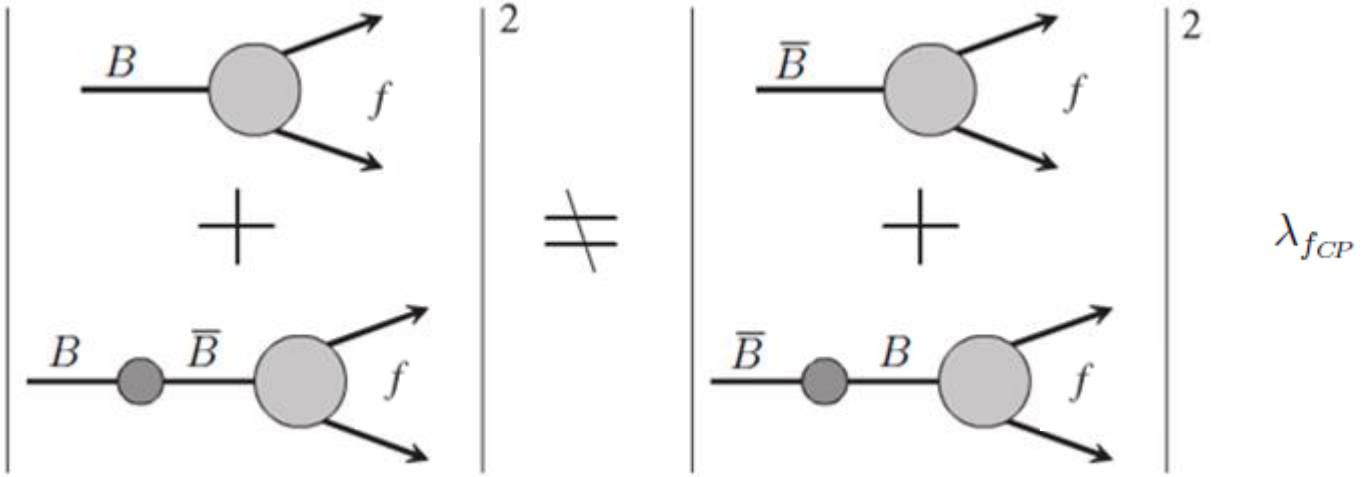
Direct



Indirect



Interference



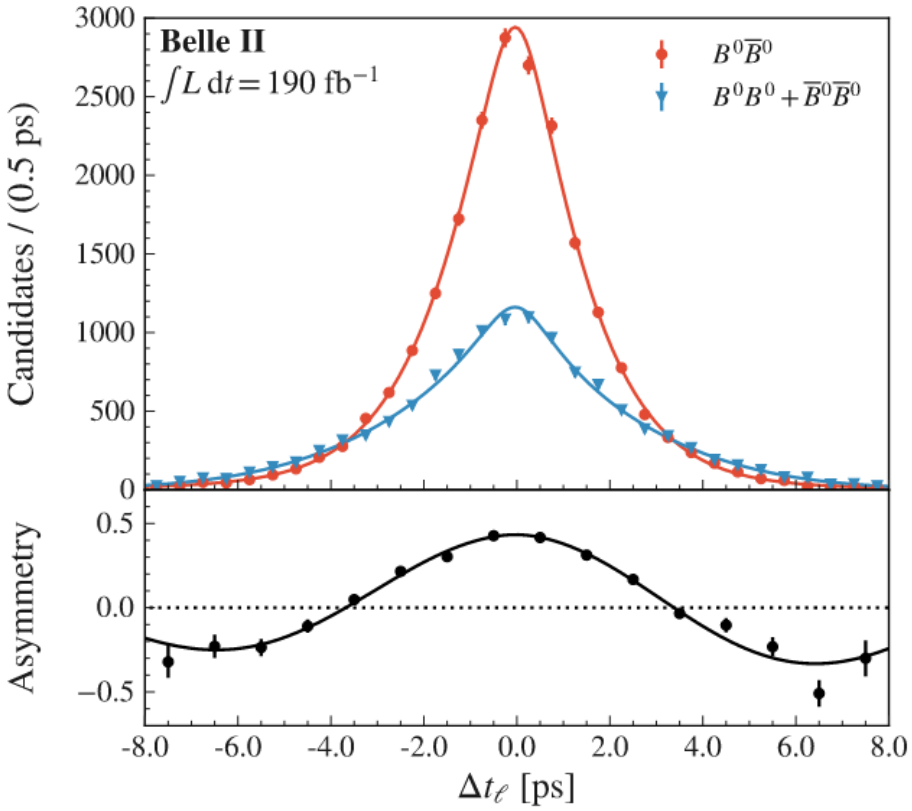
$B^0\overline{B^0}$ mixing benchmark

[arXiv:2302.12791v2]

$\boldsymbol{B \to D^{(*)}\pi}$

- Decay with high-yield and low background benchmark
  - Using half of Belle II dataset (200M $B^0\overline{B^0}$)
  - Statistically limited

- Fundamental inputs for CP asymmetry measurements
  - Δt resolution (around 0.7 ps)
  - Flavor tagging (efficiency around 30%), on-par with best Belle performance



$$\tau_{B^0} = (1.499 \pm 0.013 \pm 0.008)\ \text{ps}$$

$$\Delta m_d = (0.516 \pm 0.008 \pm 0.005)\ \text{ps}^{-1}$$