Belle II Highlights

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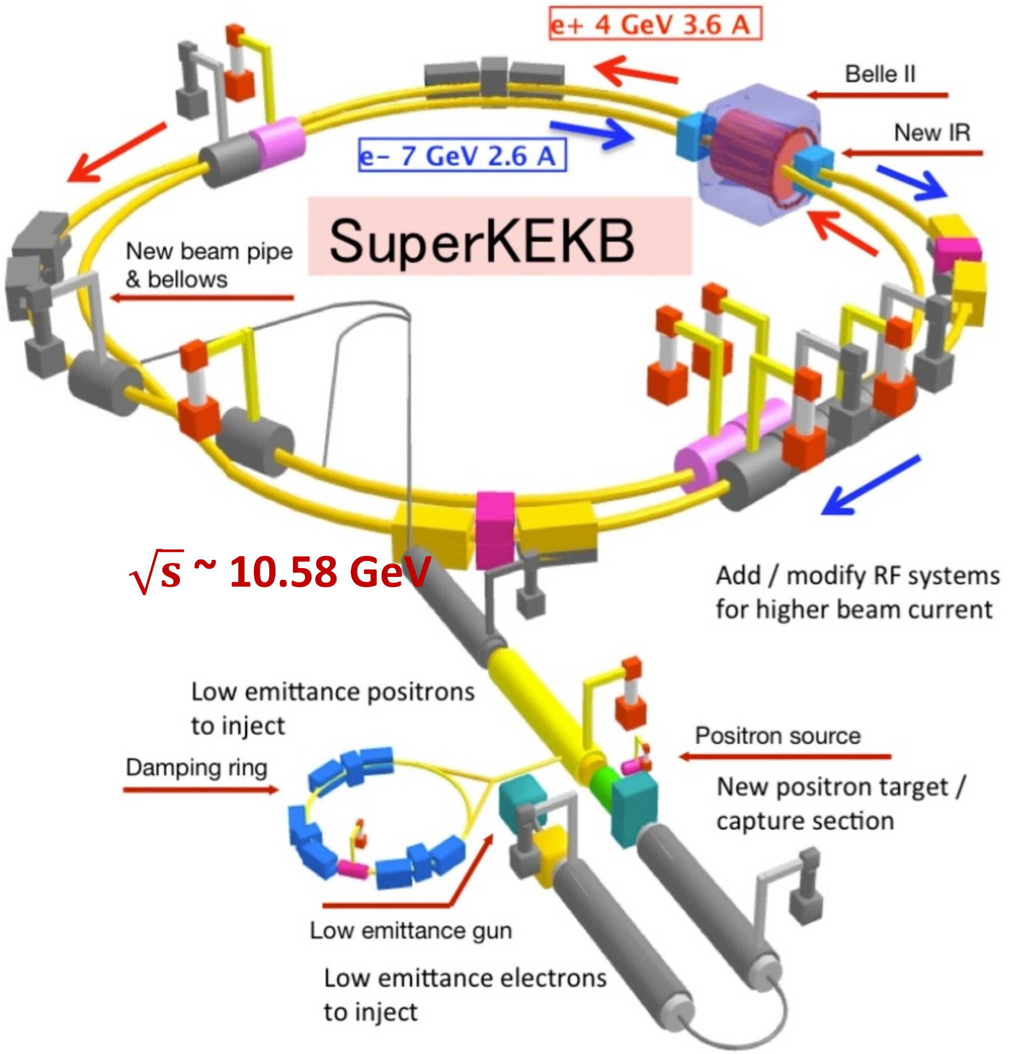
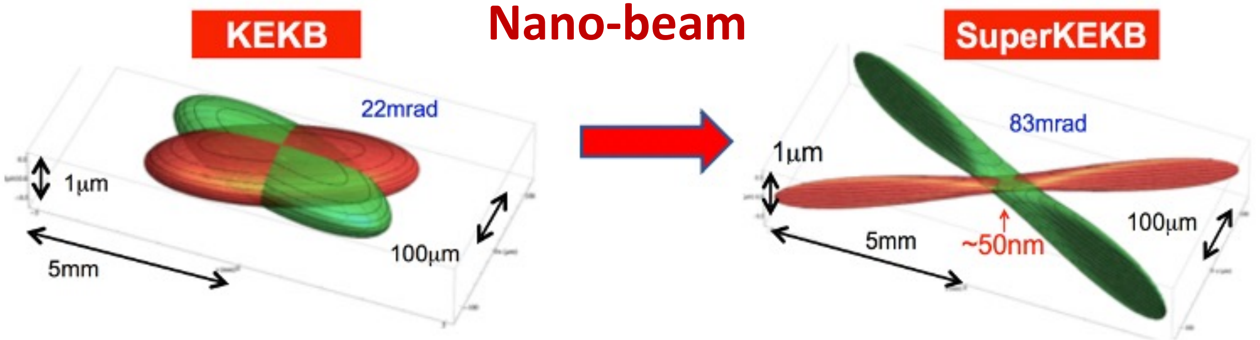
Outline

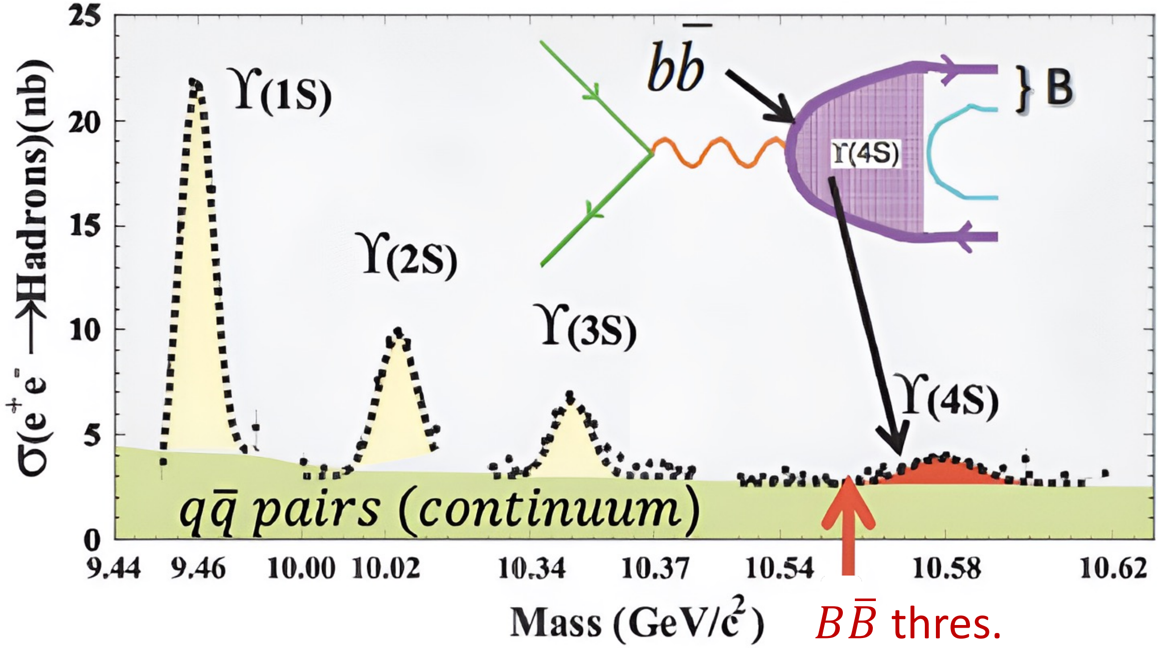
- Luminosity
- Physics highlights (recent results)
  - **B CPV**
  - **charm physics**
  - **B rare decay**
  - quarkonium and exotic
  - tau physics and dark sector
- Summary

SuperKEKB

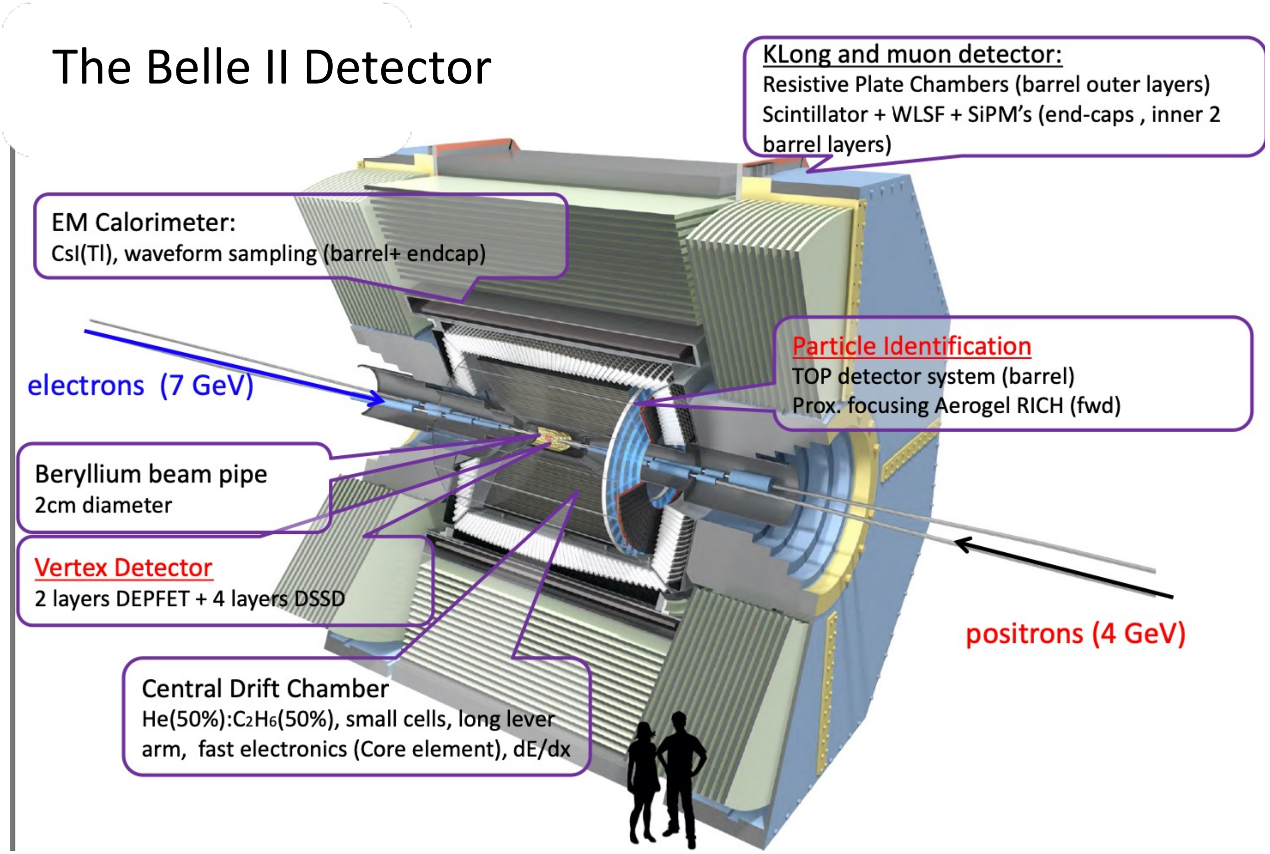


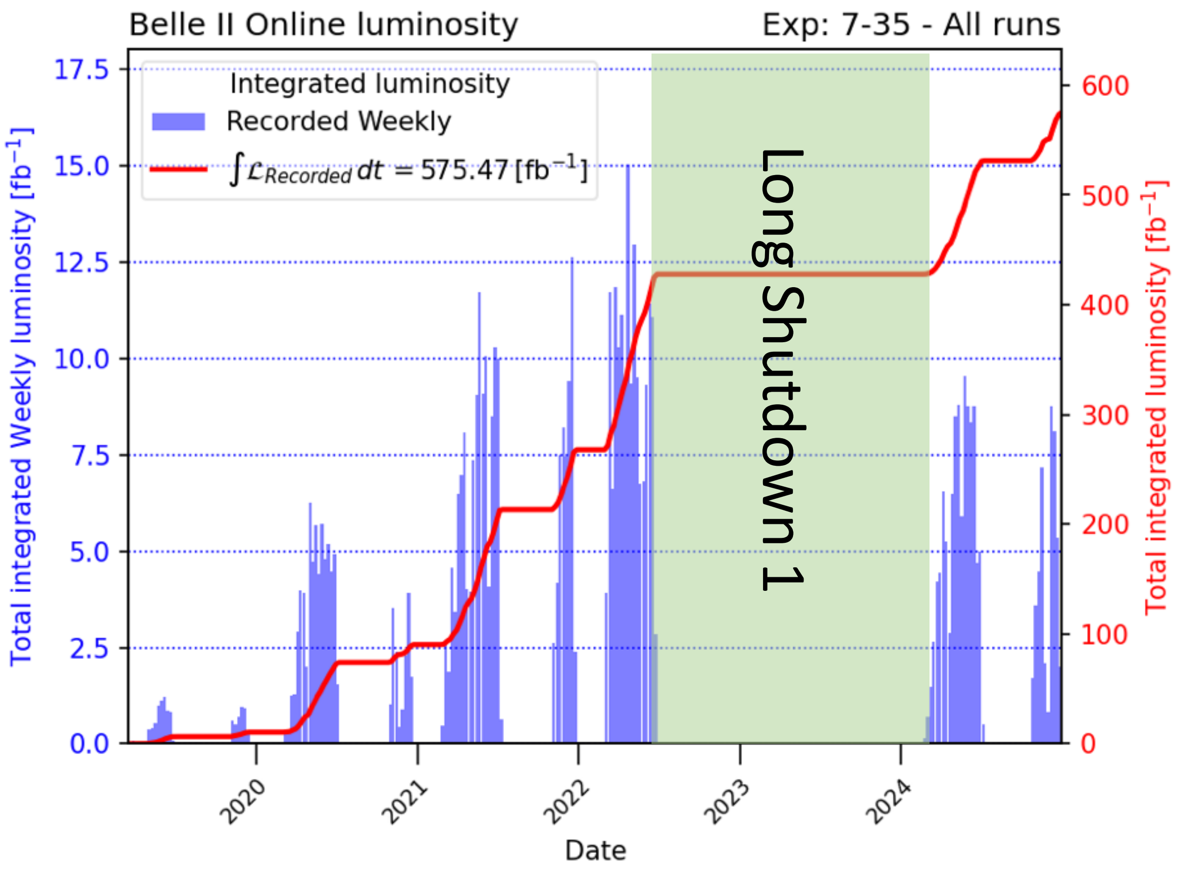


In Dec. 2024, SuperKEKB achieved WR: $\underline{5.1\times10^{34}\ \mathrm{cm^{-2}s^{-1}}}$



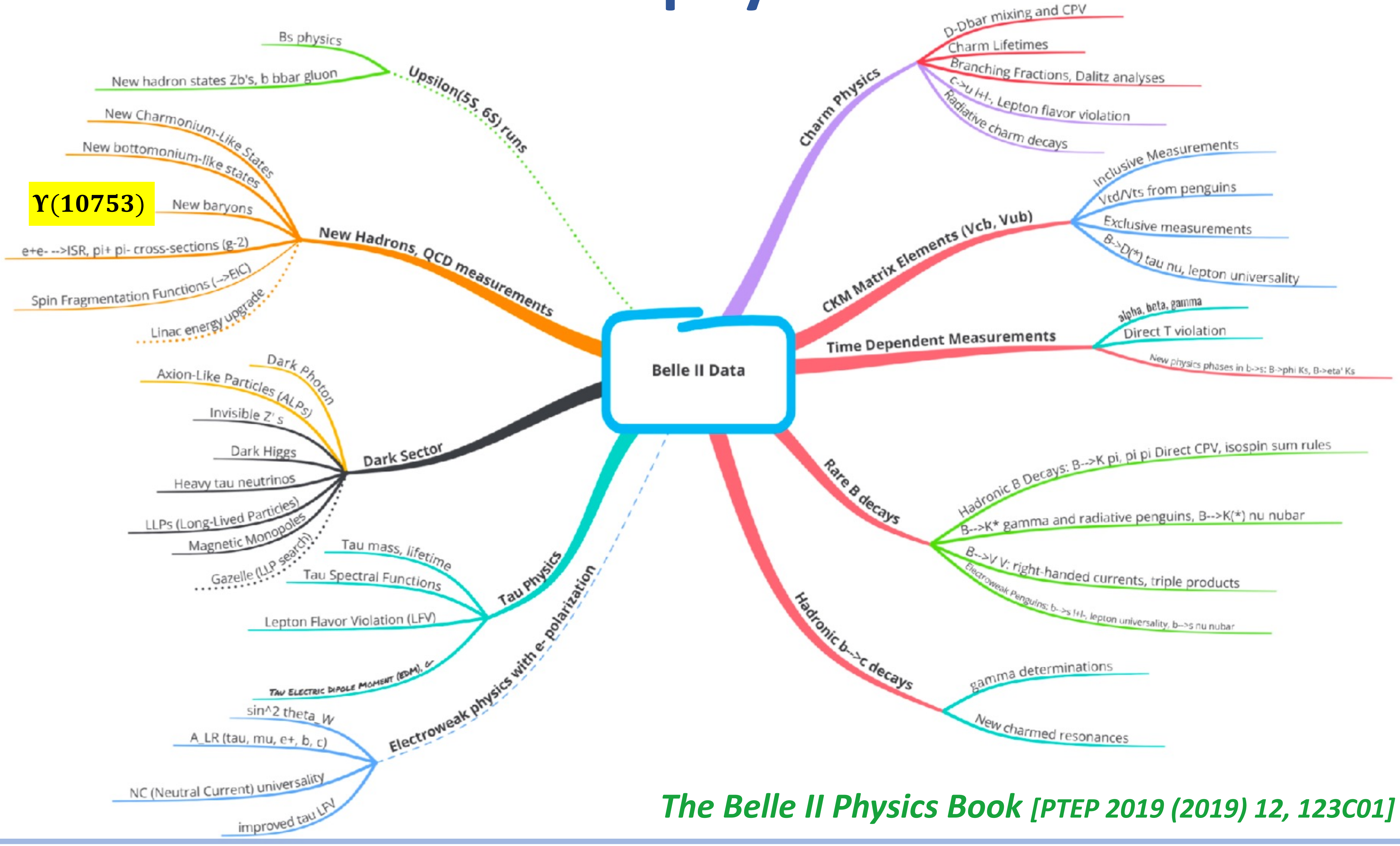
Detector & Luminosity





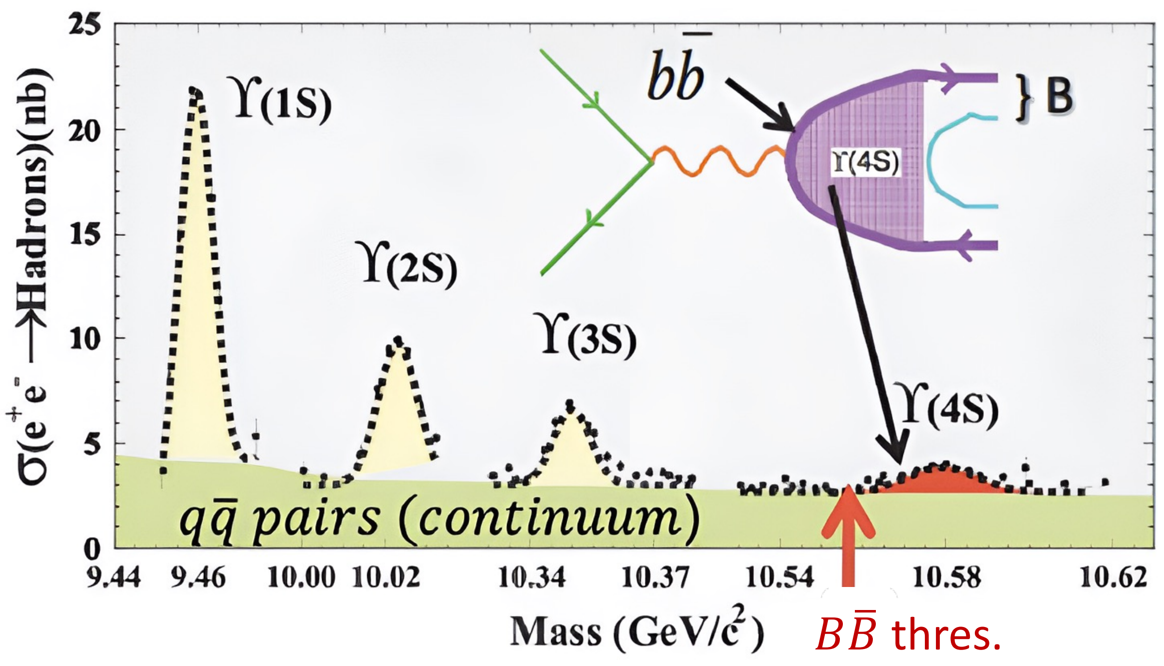
Belle II homepage: "Belle II has been designed to make precise measurements of weak interaction parameters, study exotic hadrons, and search for new phenomena beyond the Standard Model of particle physics."

Belle II physics

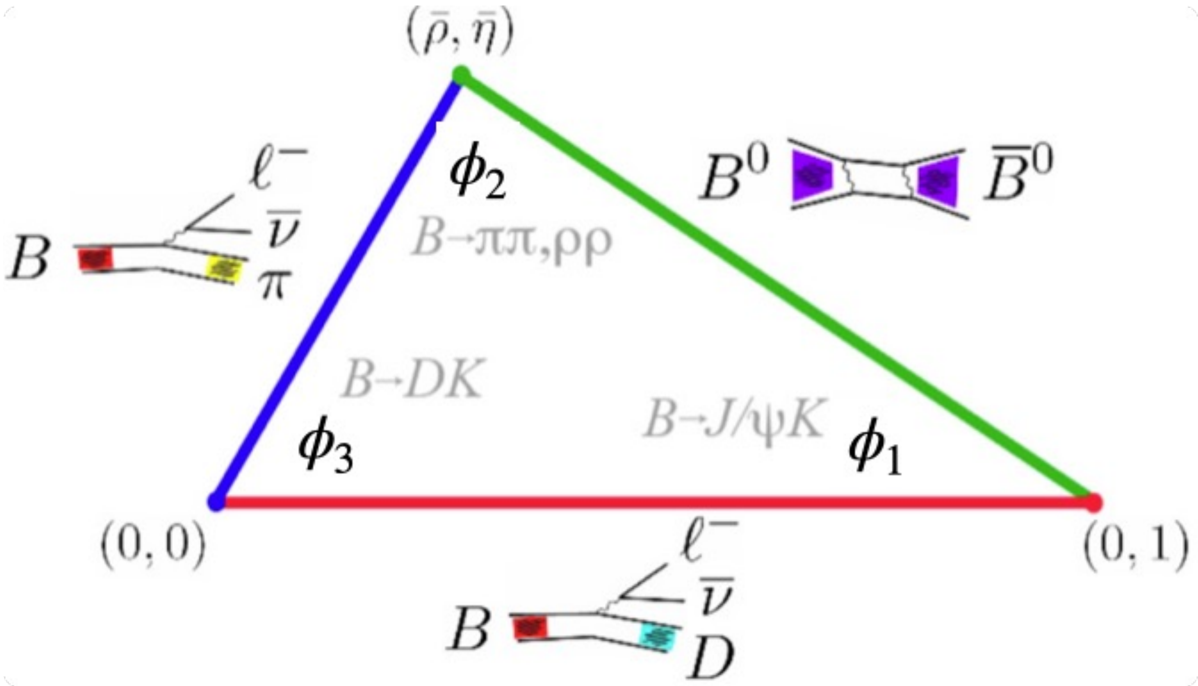


The Belle II Physics Book [PTEP 2019 (2019) 12, 123C01]

B CPV



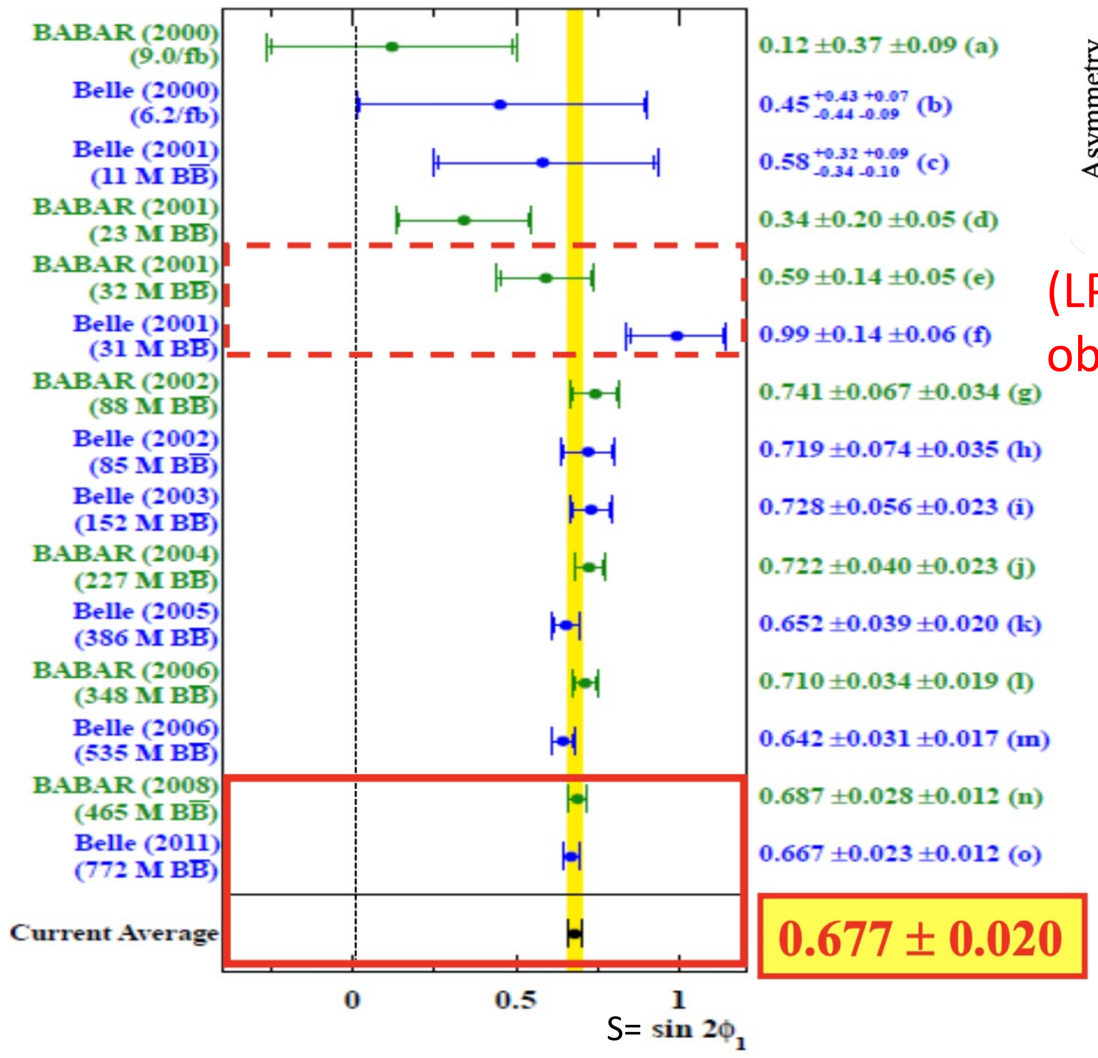
σ(e+e- →Hadrons)(nb)
Mass (GeV/c²)
Υ(1S)
Υ(2S)
Υ(3S)
Υ(4S)
bb̄
}B
$q\bar{q}$ pairs (continuum)
$B\bar{B}$ thres.

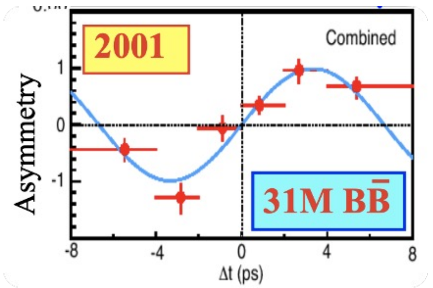


$(\bar{\rho}, \bar{\eta})$
ϕ_2
$B \to \pi\pi, \rho\rho$
B^0
$\overline{B}^0$
$B \to DK$
$B \to J/\psi K$
ϕ_3
ϕ_1
(0, 0)
(0, 1)
B
ℓ^-
$\overline{\nu}$
π
D

$\sin 2\phi_1$ precise measurement

10 years' hard-working





(LP2001)Belle+BABAR: First observed CPV in B >6σ

This discovery provides the exp. support for the Nobel prize of Kobayashi and Maskawa in 2008

as a typical achievement of 1st generation asymmetric B-factories.

Precision measurement

Reference for NP

$\sin 2\phi_1$: $B^0 \to J/\psi\, K_S^0$

(Belle II) PRD 110, 012001 (2024)

Flavor tagging

PhysRevD.110.012001

Category-based FBDT flavor tagger

- Kinematics, charge, PID of charged particles

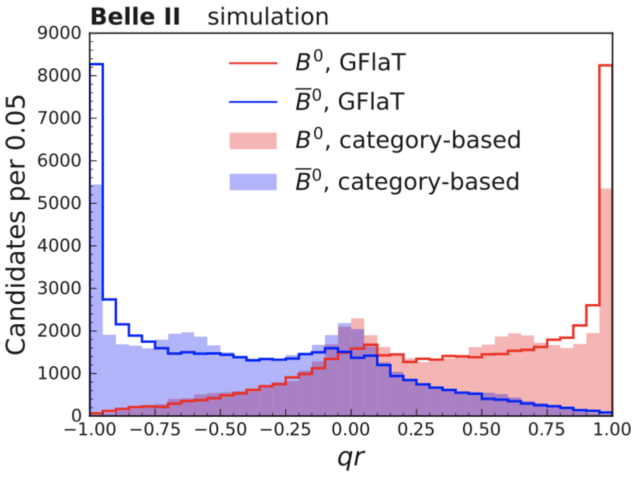
$\epsilon_{\text{eff}} = (31.68 \pm 0.45)\%$

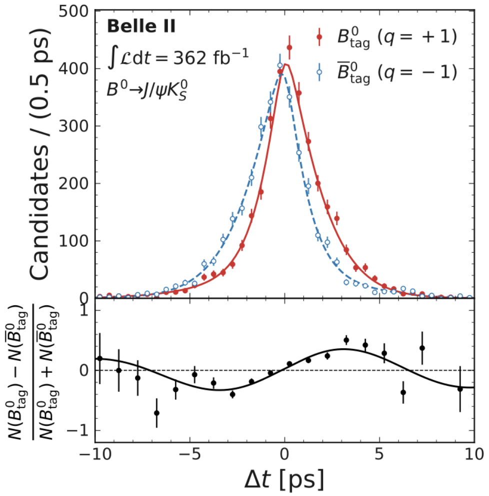
Graph neural network flavor tagging(GFlaT)

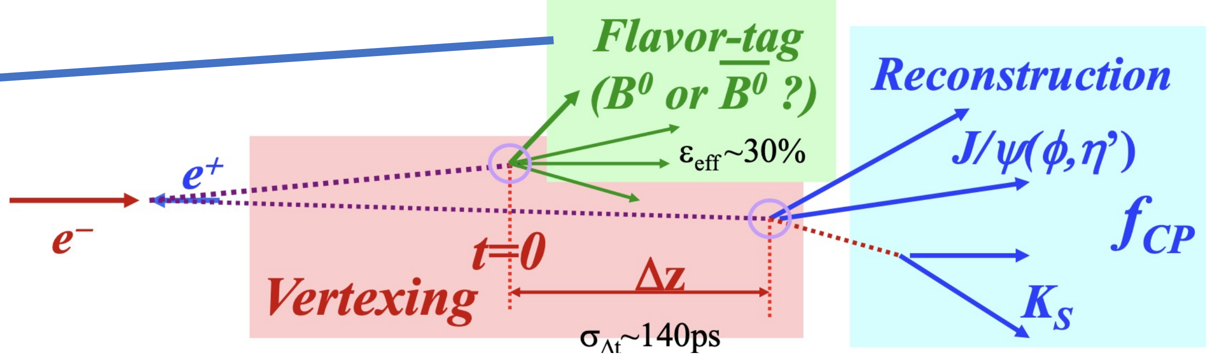
- Improved performance by learning correlations between final-state particles

$\epsilon_{\text{eff}} = (37.40 \pm 0.43 \pm 0.36)\%$

18% improvement!







CPV par.	Belle II (362 fb^{-1}) PRD 119, 012002 (2024)	Belle (711 fb^{-1}) PRL 108, 171802 (2012)
S	$0.724 \pm 0.035 \pm 0.009$	$0.670 \pm 0.029 \pm 0.013$
C	$-0.035 \pm 0.026 \pm 0.029$	$-0.015 \pm 0.021^{+0.045}_{-0.023}$

CPV par.	LHCb (6 fb^{-1}) PRL 132, 021801 (2024)
S	$0.722 \pm 0.014 \pm 0.007$
C	$0.015 \pm 0.013 \pm 0.003$

Large mixing-induced CPV par: its precision is dominated by LHCb.

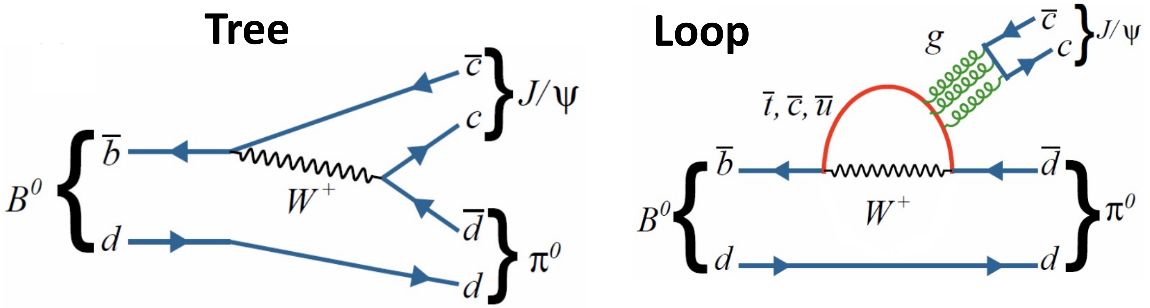
what else can Belle II do?

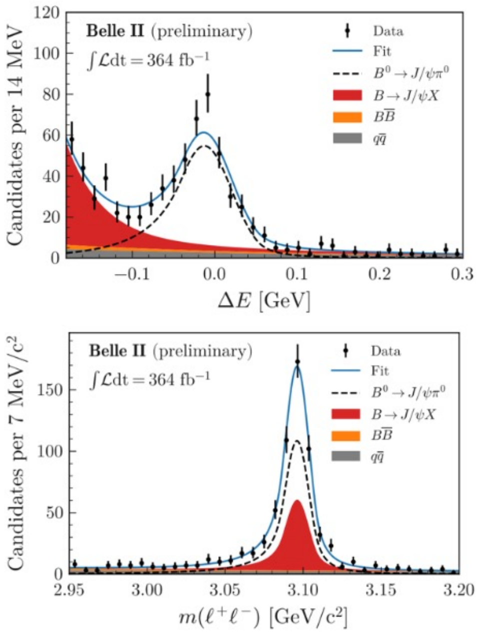
$\sin 2\phi_1$: $B^0 \to J/\psi\,\pi^0$

(Belle II) PRD 111 (2025) 012011

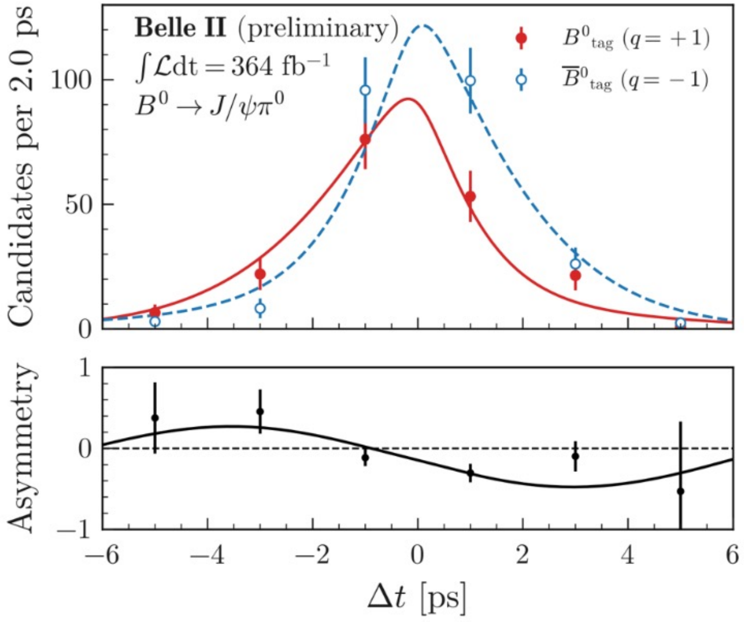
$S = -\sin 2\phi_1$, $C = 0$ if there is only tree amplitude
Tree is color and CKM suppressed
→ can be used to understand the loop contribution in $B^0 \to J/\Psi K_S^0$

- Improved sensitivity by the better π^0 selection and GflaT
- $\Delta E - m(ll)$ fit to extract signal





($\Delta E = E_B - E_{\text{beam}}$)



$$S = -0.88 \pm 0.17 \pm 0.03$$
$$C = 0.13 \pm 0.12 \pm 0.03$$
$$\mathcal{B} = (2.02 \pm 0.12 \pm 0.10) \times 10^{-5}$$

Most precise,

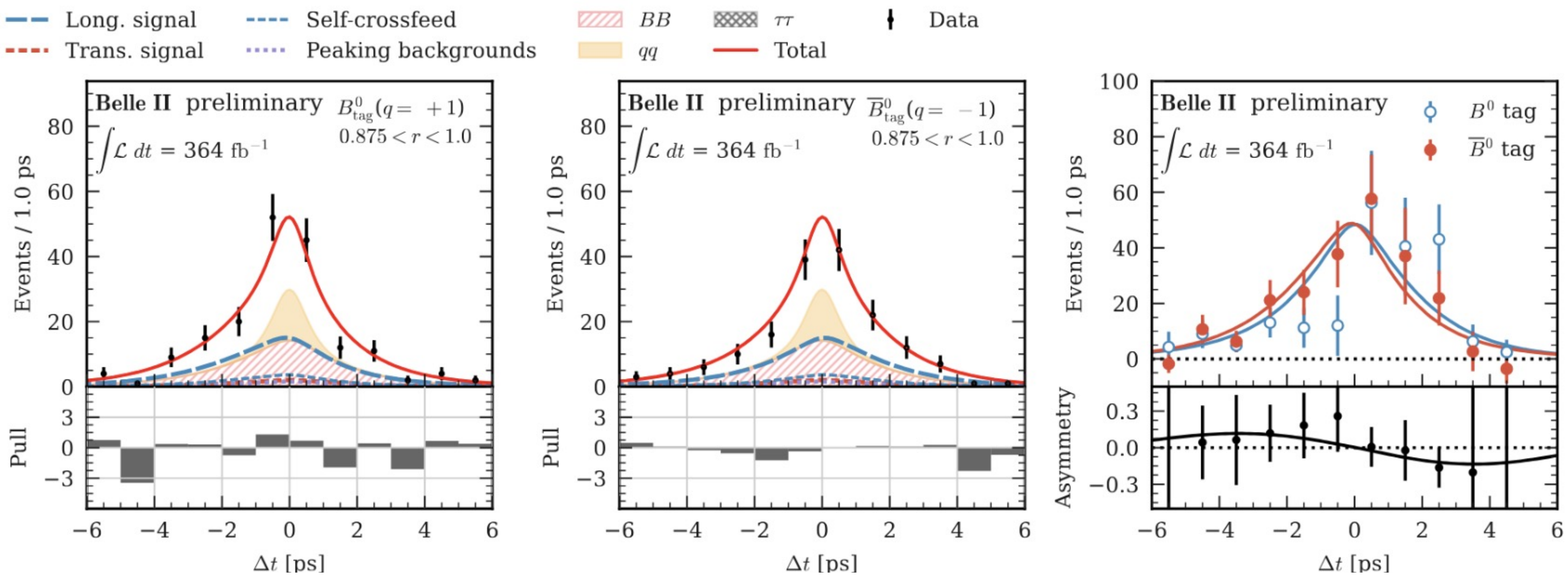
- first observation of non-zero S parameter (mixing-induced CPV) in this mode

ϕ_2: $B^0 \to \rho^+\rho^-$

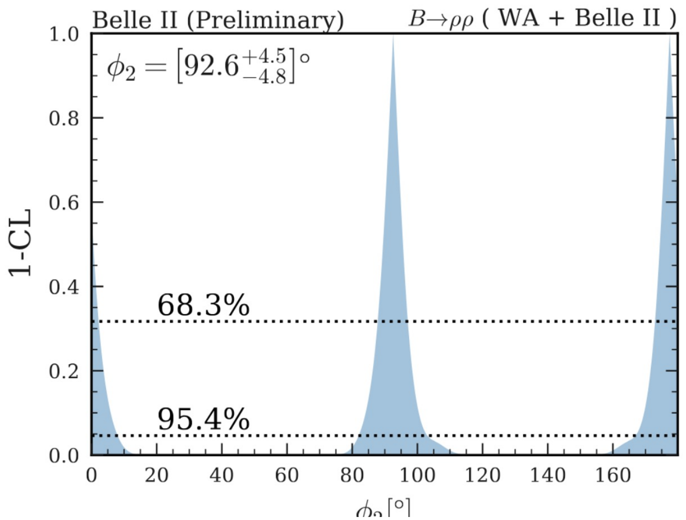
$\phi_2 = \arg(-V_{td}V_{tb}^*/V_{ud}V_{ub}^*)$

(Belle II) arXiv:2412.19624 (accepted)

- $B^0 \to \rho^+\rho^-$: much smaller loop contribution → dominates ϕ_2 precision
- two π^0's reconstruction needed → a channel suitable for Belle II



➢ Extract ϕ_2 using this new result



	$\mathcal{B}(10^{-6})$	f_L	S	C
Belle II	$29.0^{+2.3}_{-2.2}\ ^{+3.1}_{-3.0}$	$0.921^{+0.024}_{-0.025}\ ^{+0.017}_{-0.015}$	$-0.26 \pm 0.19 \pm 0.08$	$-0.02 \pm 0.12^{+0.06}_{-0.05}$
Belle	$28.3 \pm 1.5 \pm 1.5$	$0.988 \pm 0.012 \pm 0.006$	$-0.13 \pm 0.15 \pm 0.05$	$0.00 \pm 0.10 \pm 0.06$
BABAR	$25.5 \pm 2.1\ ^{+3.6}_{-3.9}$	$0.992 \pm 0.024\ ^{+0.026}_{-0.013}$	$-0.17 \pm 0.20^{+0.05}_{-0.06}$	$0.01 \pm 0.15 \pm 0.06$

$B \to \rho\rho$ world average
$\phi_2 = (91.5^{+4.5}_{-5.4})^\circ$

$B \to \rho\rho$ world average
+ Belle II $\rho^+\rho^-$ results
→ $\phi_2 = (92.6^{+4.5}_{-4.8})^\circ$

6%

ϕ_2: $B^0 \to \pi^0\pi^0$

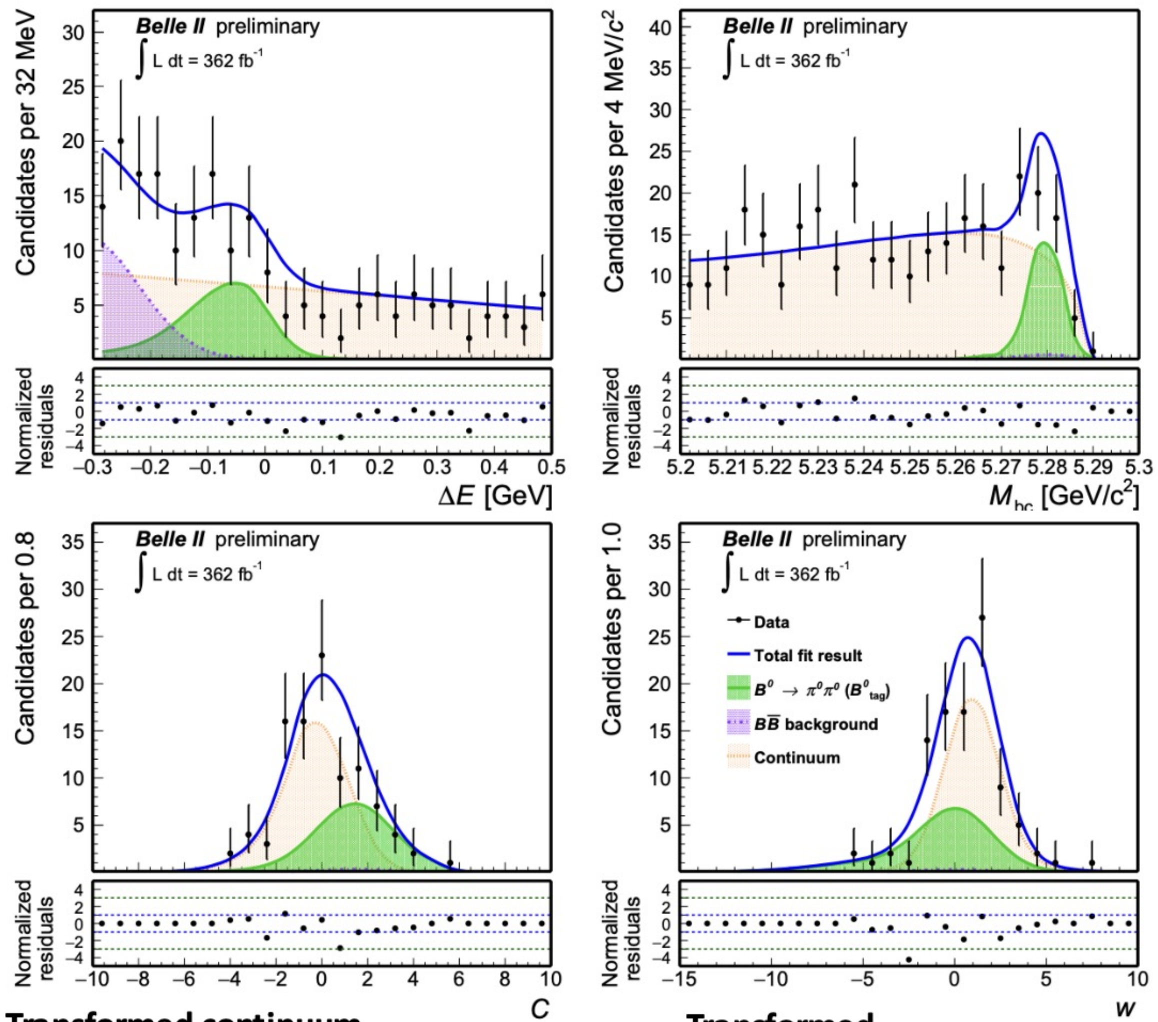
$\phi_2 = \arg(-V_{td}V_{tb}^*/V_{ud}V_{ub}^*)$

(Belle II) PRD 111 (2025) L071102

- Require 4γ reconstruction (Unique to Belle II) from a large background due to hadronic clusters, beam background
  → Developed an MVA for γ selection
- Improved sensitivity by GFlaT.

	$\mathcal{B}(\times 10^{-6})$	C	N_{BB}
Belle II	$1.26 \pm 0.20 \pm 0.12$	$-0.06 \pm 0.30 \pm 0.05$	388×10^6
Belle	$1.31 \pm 0.19 \pm 0.19$	$-0.14 \pm 0.36 \pm 0.10$	772×10^6
BABAR	$1.83 \pm 0.21 \pm 0.13$	$-0.43 \pm 0.26 \pm 0.05$	383.6×10^6

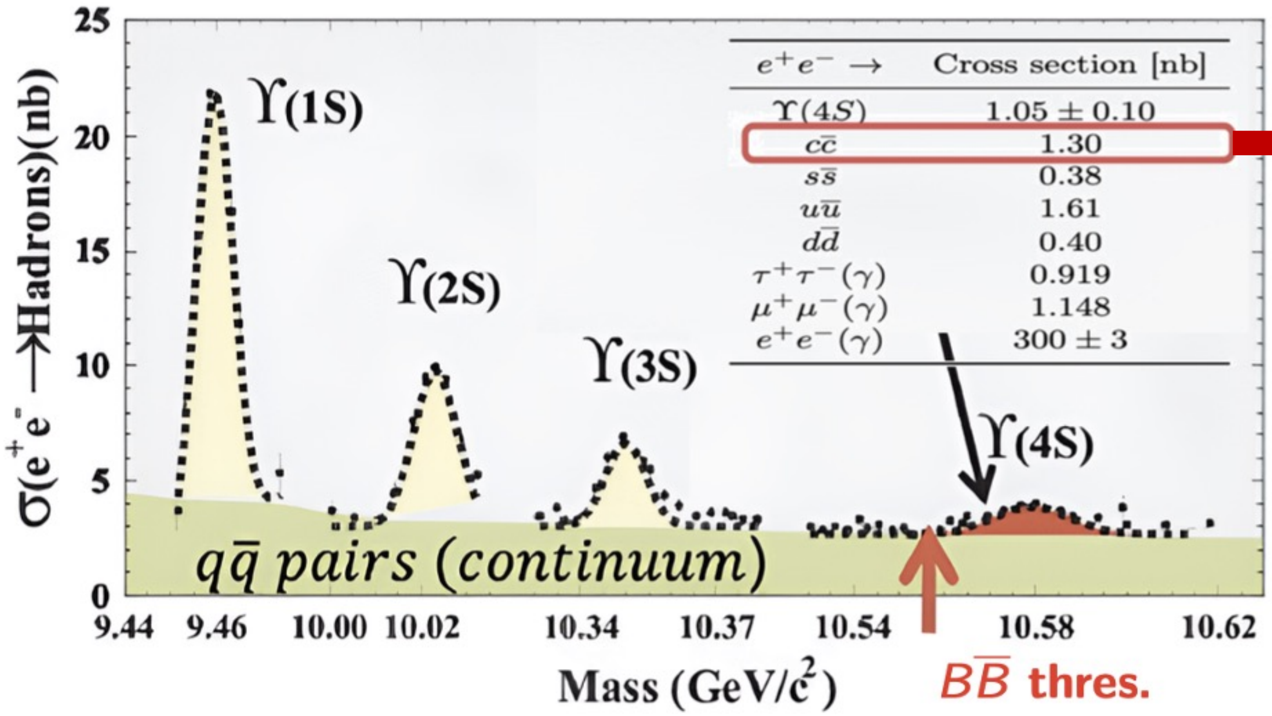
Consistent with previous experiments and Comparable sensitivity with small statistics.



Transformed continuum suppression output

Transformed wrong flavor tag probability

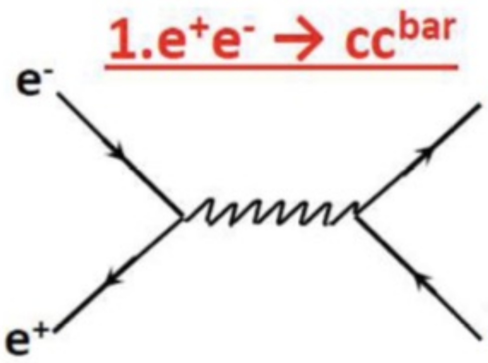
Charm physics

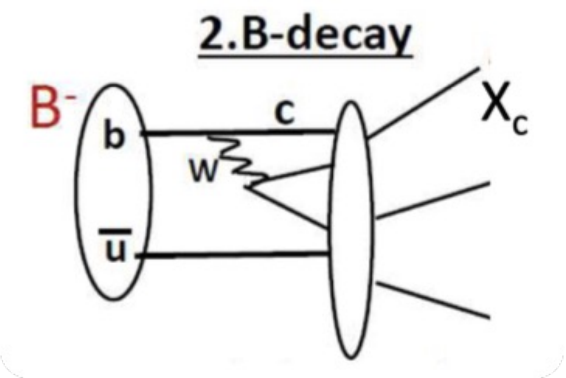


Belle (II): a charm super-factory

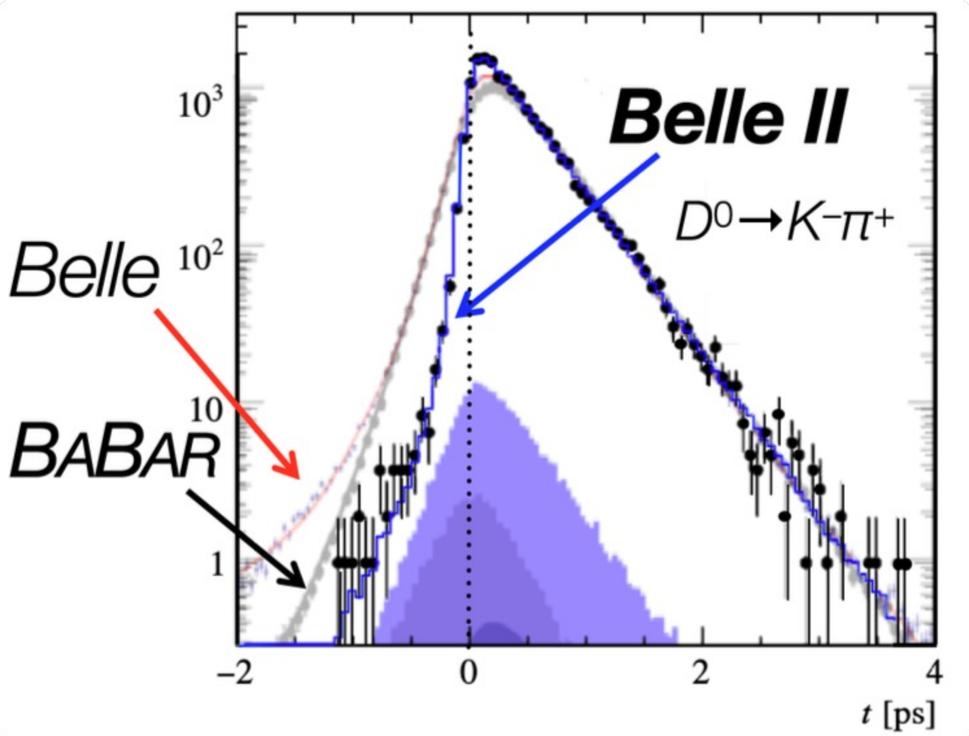
1) $e^+e^- \rightarrow c\bar{c}$ (e.g. CPV searches)

2) B decays involving charmed hadrons (e.g. charm spectrum)





Charm lifetime (first charm wave)

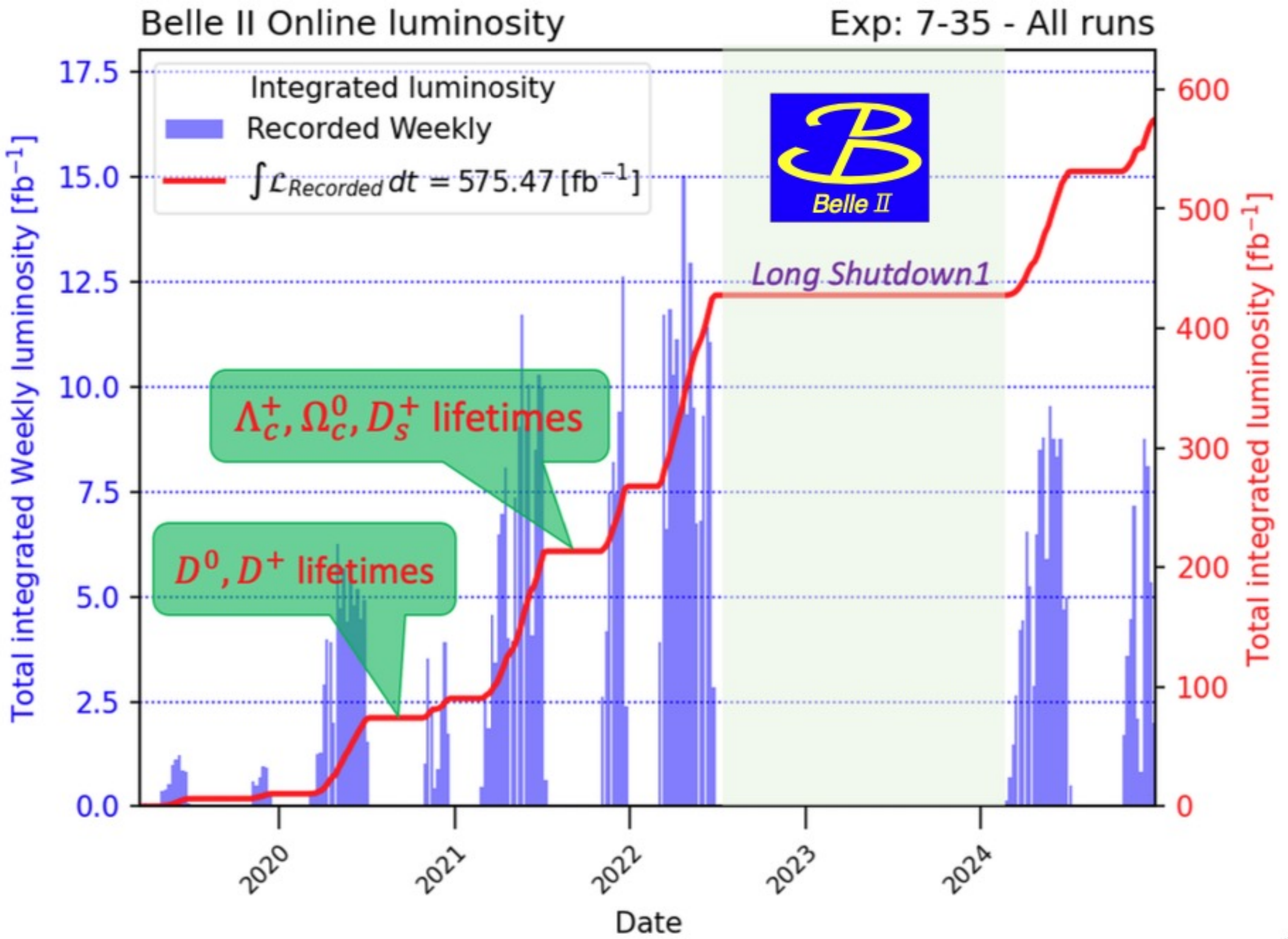


most precise charm lifetimes:

$$\tau(D^0) = 410.5 \pm 1.1 \pm 0.8 \text{ fs},$$
$$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1 \text{ fs},$$
$$\tau(D_s^+) = 499.5 \pm 1.7 \pm 0.9 \text{ fs},$$
$$\tau(\Lambda_c^+) = 203.20 \pm 0.89 \pm 0.77 \text{ fs}$$

第一波粲物理结果：基于早期数据的粲强子寿命的精确测量

PRL 127, 211801 (2021); PRL 131, 171803 (2023);
PRD 107, L031103 (2023); PRL 130, 071802 (2023).



Charm CPV (next charm wave)

- Charm CPV effect is very small (10^{-3} level or smaller); a sensitive probe for New Physics.
- 2019, charm CPV observation by LHCb[1]: $\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-) = (-15.4 \pm 2.9)\times 10^{-4}$ (5.3σ)
  2023, first evidence for direct CPV in a specific D decay[2]: $A_{\pi\pi}^{\mathrm{dir}} = (2.32 \pm 0.61)\times 10^{-3}$.
  ➔ to understand this CPV, more results and more precise measurements are desired.
- CPV before 2025: observed in all open-flavor meson sector, not yet in the baryon sector. Recently, LHCb reported the first observation of baryon CPV in $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decays[3].
  ➔ charmed baryon CPV, the last piece for heavy-flavor hadron CPV, to be observed.
- Recent charm CPV results at Belle II
  - $A_{CP}(D^0 \to K_S^0 K_S^0)$: **PRD 111, 012015 (2025)** + arXiv:2504.15881 (preliminary result)
  - $A_{CP}^X(D^+ \to K_S^0 K^- \pi^+\pi^+)$: **JHEP 04 (2025) 036**
  - $A_{CP}(D^0 \to \pi^0\pi^0)$: preliminary result
  - $A_{CP}(D^+ \to \pi^+\pi^0)$: preliminary result

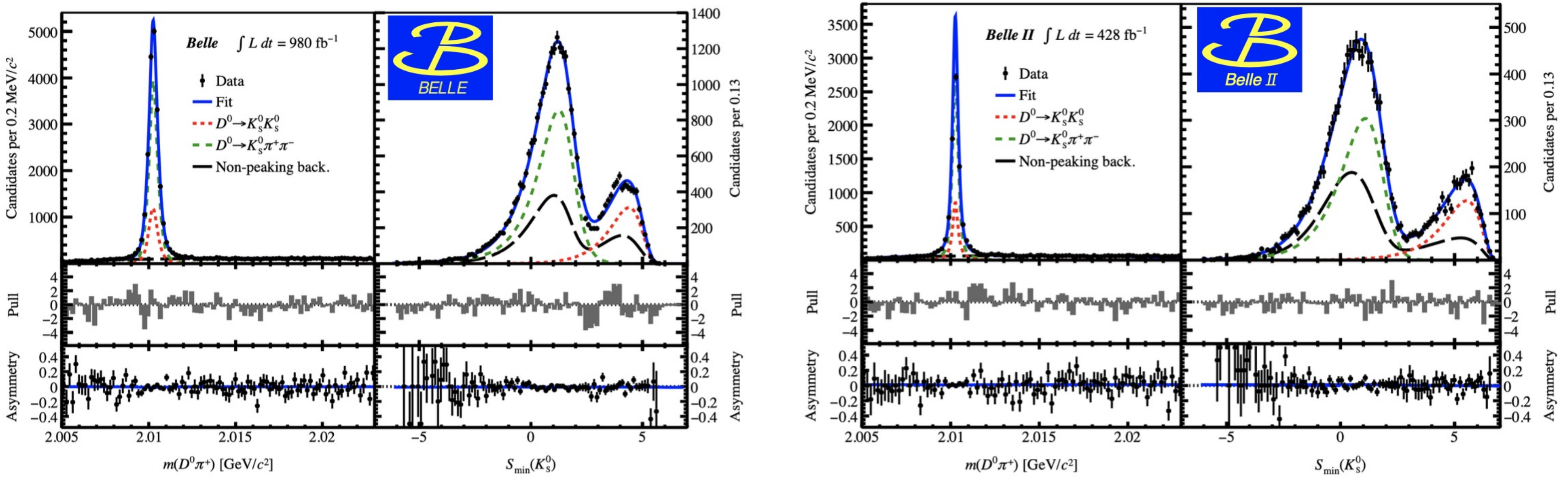
New charm wave.

[1]LHCb, PRL 122, 211803 (2019) [2]LHCb, PRL 131, 091802 (2023) [3]LHCb, arXiv:2503.16954

Charm CPV: $A_{CP}(D^0 \to K_S^0 K_S^0)$

(B+B2) PRD 111, 012015 (2025)

- (one golden channel) $A_{CP}(D^0 \to K_S^0 K_S^0)$ may be enhanced to 1% level with the SM, by the interf. of $c \to us\bar{s}$ and $c \to ds\bar{s}$ amplitudes. [PRD 99, 113001 (2019), PRD 92, 054036 (2015)]



- Belle: $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.1 \pm 1.6 \pm 0.1)\%$ Belle II: $A_{CP}(D^0 \to K_S^0 K_S^0) = (-2.2 \pm 2.3 \pm 0.1)\%$
- Combined $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.4 \pm 1.3 \pm 0.1)\%$: comparable to the world-best result: $(-3.1 \pm 1.3)\%$ PRD 104 (2021) L031102
- Belle(II)+LHCb average: $(-2.3 \pm 0.9)\%$ vs. CMS: $(6.2 \pm 3.1)\%$: 2.6σ diff. $\Rightarrow$ more precise result desired.

EPJC 84 (2024) 1264

Charm CPV: $A_{CP}(D^0 \to K_S^0 K_S^0)$

(B+B2) arXiv:2504.15881

An independent sample: using opposite-side flavor tagging for $e^+e^- \to c\bar{c}$ events

[(B2) PRD 107, 112010 (2023)]

Belle sample (980/fb):
$N_{\text{sig}} = 14\,490 \pm 340$ and $A_{CP} = (+2.5 \pm 2.7 \pm 0.4)\%$

Belle II sample (428/fb):
$N_{\text{sig}} = 5\,180 \pm 120$ and $A_{CP} = (-0.1 \pm 3.0 \pm 0.3)\%$

Combined result based on such new tagging:

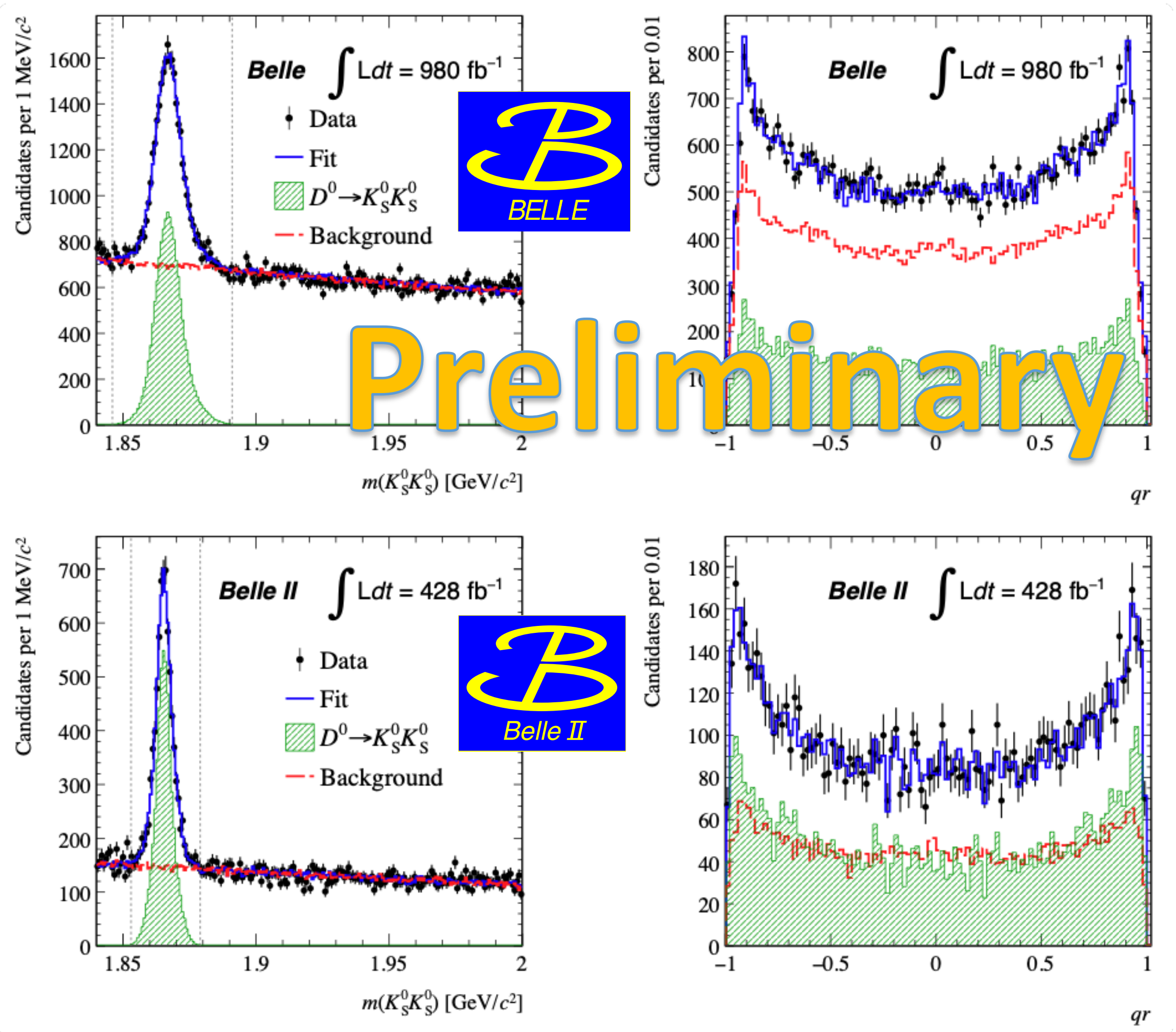
$$A_{CP}(D^0 \to K_S^0 K_S^0) = (+1.3 \pm 2.0 \pm 0.2)\%$$

Then combining it with that from D^{*+}-tagged sample:

$$A_{CP}(D^0 \to K_S^0 K_S^0) = (-0.6 \pm 1.1 \pm 0.1)\%$$

most precise (temporary)

- ➢ B2+LHCb vs. CMS: 2.6σ diff → 2.1σ diff
- ➔ Looking forward to LHCb's updated result (9/fb)



Charm CPV: $A_{CP}(D^0 \to \pi^0\pi^0)$

(B2) Preliminary result

- The following sum-rule for D→ππ decays helps determine the source of CPV:

$$R = \frac{A_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}^{\mathrm{dir}}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}}\left(\frac{\mathcal{B}_{+-}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}^{\mathrm{dir}}(D^+ \to \pi^+\pi^0)}{1 - \frac{3}{2}\frac{\tau_{D^+}}{\mathcal{B}_{+0}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{\mathcal{B}_{+-}}{\tau_{D^0}}\right)}$$

  - if $R \neq 0$, CPV: from ΔI=1/2 amplitude; if R=0 & a $A_{CP}^{\mathrm{dir}} \neq 0$, CPV: from a beyond-SM ΔI=3/2 amplitude.
  - $A_{CP}(D^0 \to \pi^+\pi^-)$ precision: leading by LHCb; first evidence of direct CPV in a specific D decay.

- Raw asymmetry of the tagged $D^0 \to \pi^0\pi^0$ sample:

$$A^{\pi^0\pi^0} = A_{CP}(D^0 \to \pi^0\pi^0) + A_{\mathrm{P}}^{D^{*+}} + A_{\epsilon}^{\pi_s}$$

specificity

  - $A_P^{D^{*+}}$: being an odd function of $\cos\theta^*$ i.e. the cosine of the charmed-meson polar angle in e^+e^- c.m.s
  - $A_\varepsilon^{\pi_s}$: using tagged and untagged $D^0 \to K^-\pi^+$ samples

- Time-integrated CP asymmetry:

$$A_{CP}(D^0 \to \pi^0\pi^0) = A'^{\pi^0\pi^0} - A'^{K\pi} + A'^{K\pi,\mathrm{untag}}$$

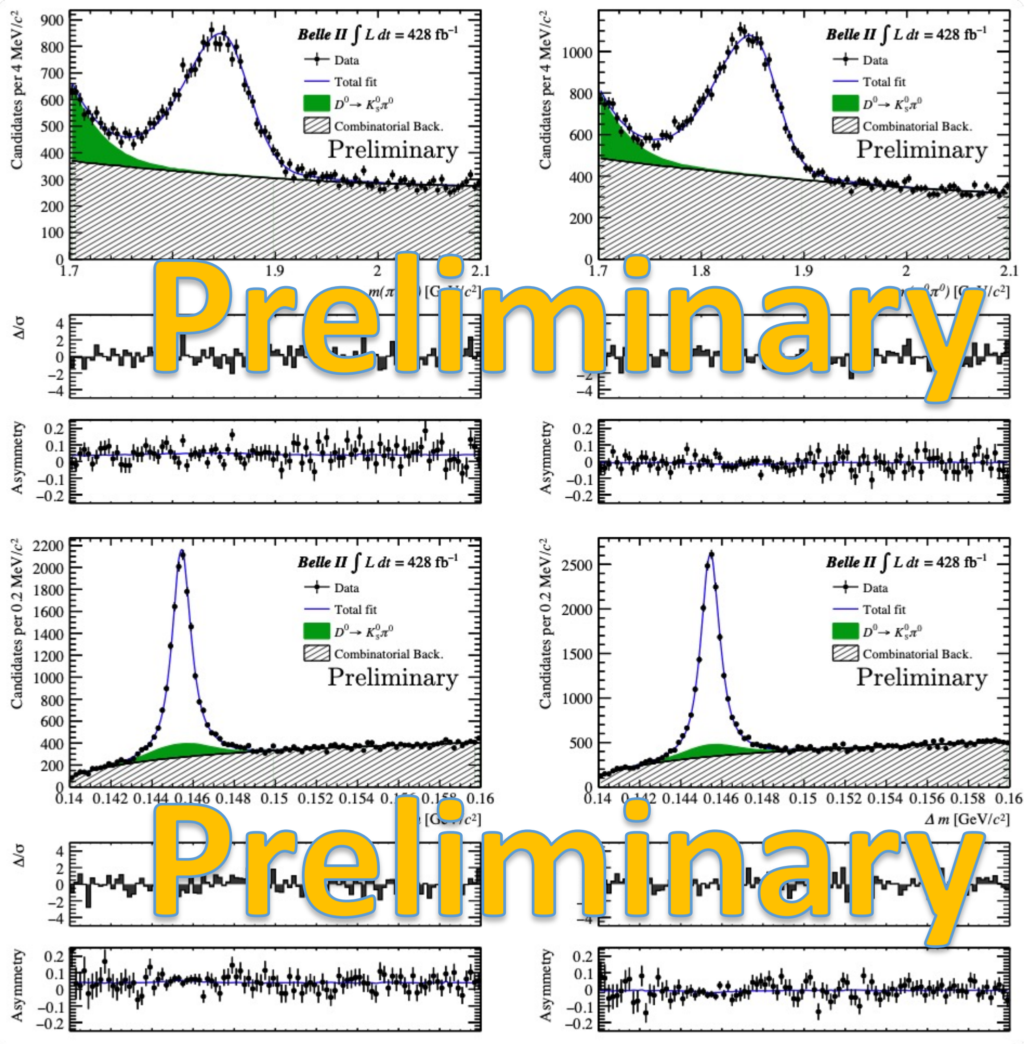
; where $A'^f = \frac{A^f(\cos\theta^* < 0) + A^f(\cos\theta^* > 0)}{2}$

$f = \pi^0\pi^0;\ K\pi;\ K\pi,\ \mathrm{untag.}$

Charm CPV: $A_{CP}(D^0 \to \pi^0\pi^0)$

(B2) Preliminary result

$\cos\theta^*(D^{*+}) > 0$ vs. $\cos\theta^*(D^{*+}) < 0$



- Result at Belle II (428/fb):

$$A_{CP}^{\pi^0\pi^0} = (+0.30 \pm 0.72 \pm 0.20)\%$$

➔ only 15% less precise than Belle's result (σ=0.65%) based on 980/fb data [PRL 112, 211601 (2014)]

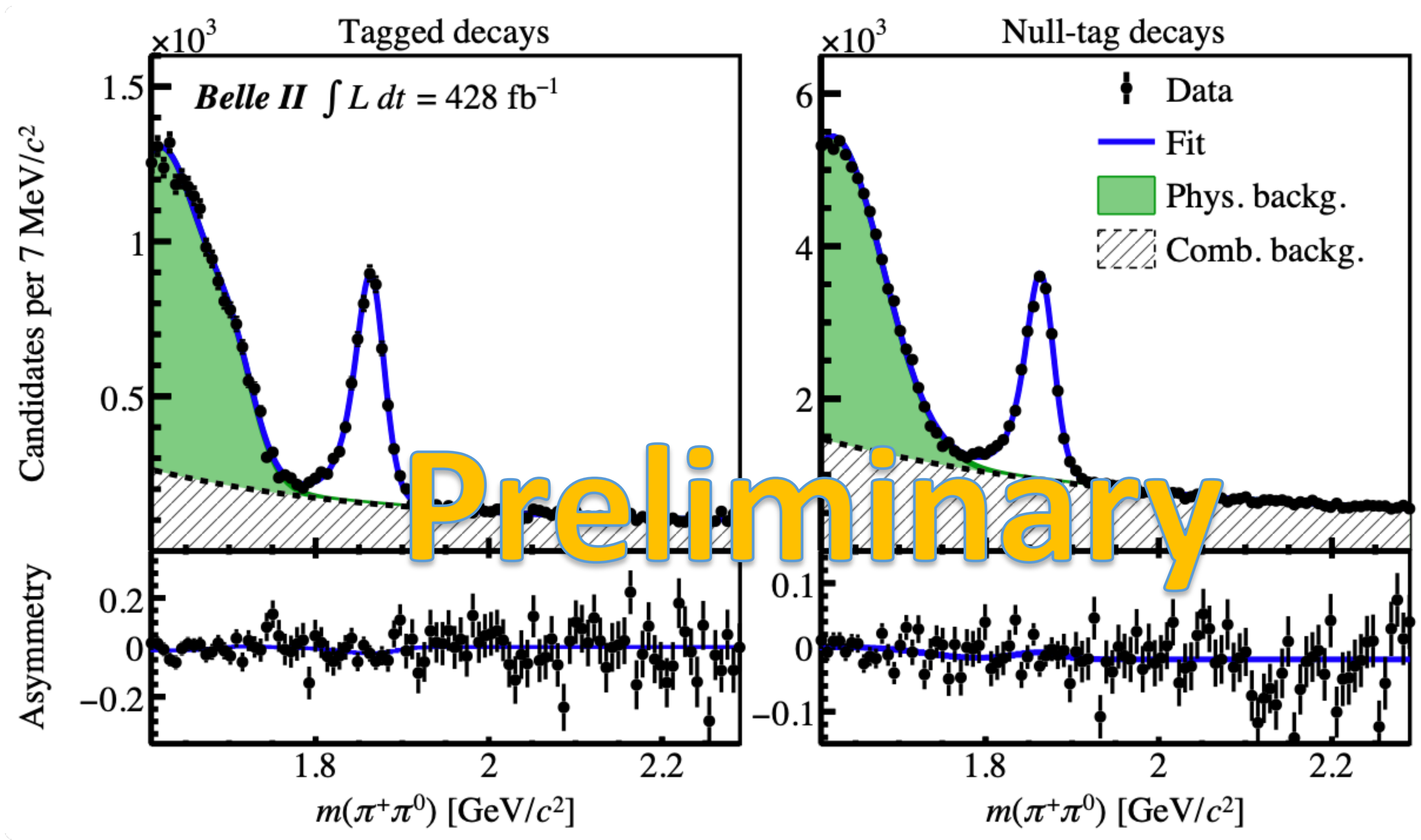
- Using our result, $A_{CP}^{\pi^+\pi^-}$(LHCb), W.A. $A_{CP}^{\pi^+\pi^0}$, ΔY(LHCb), W.A. BR, and D lifetimes,

$$R = (1.5 \pm 2.5)\times 10^{-3}$$

→ 20% improved precision

Charm CPV: $A_{CP}(D^+ \to \pi^+\pi^0)$

(B2) Preliminary result



$N_{\text{sig}} = 5130 \pm 110$
$A_{CP} = (-3.9 \pm 1.8 \pm 0.2)\%$

$N_{\text{sig}} = 18510 \pm 240$
$A_{CP} = (-1.1 \pm 1.0 \pm 0.1)\%$

Using $D^+ \to \pi^+ K_S^0$ (obtain ~1.6M signals) to eliminate two common asymmetry sources: $A_{\text{prod}}^D + A_\varepsilon^{\pi^+}$. Thus, the CP asymmetry of interest is

$$A_{CP} = A_{\text{raw}}^{\pi^+\pi^0} - A_{\text{raw}}^{\pi^+K_S^0} + A^{\bar{K}^0}$$

Combined result at Belle II (428/fb):

$$A_{CP} = (-1.8 \pm 0.9 \pm 0.1)\%$$

➔ most precise; and 30% improved precision compared to Belle's result σ=1.26% (980/fb)

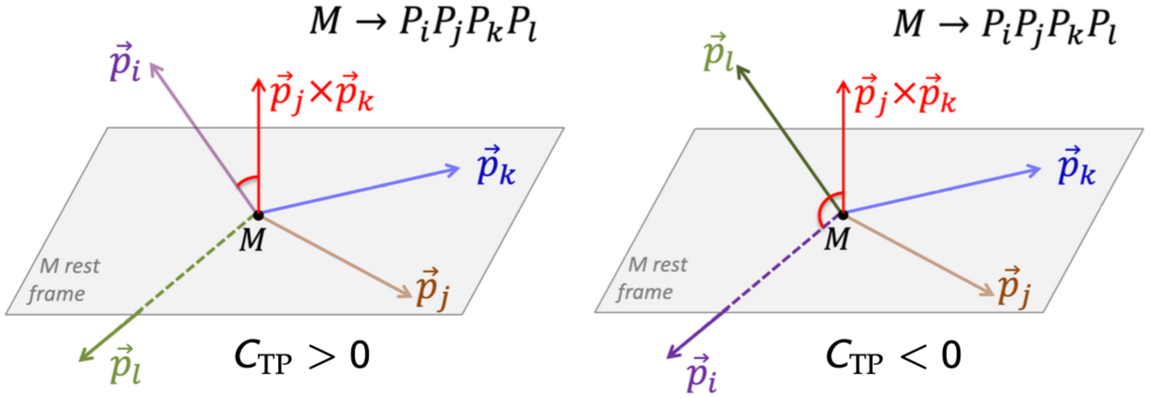
[PRD 97, 011101 (2018)]

Charm CPV: $A_{CP}^{\mathrm{TP}}(D^+ \to K_S^0 K^- \pi^+ \pi^+)$

(B+B2) JHEP 04 (2025) 036

- For four-body decays, TP asymmetry is used for CPV searches.

  triple-product (TP): $C_{\mathrm{TP}} = \vec{p}_i \cdot (\vec{p}_j \times \vec{p}_k)$.



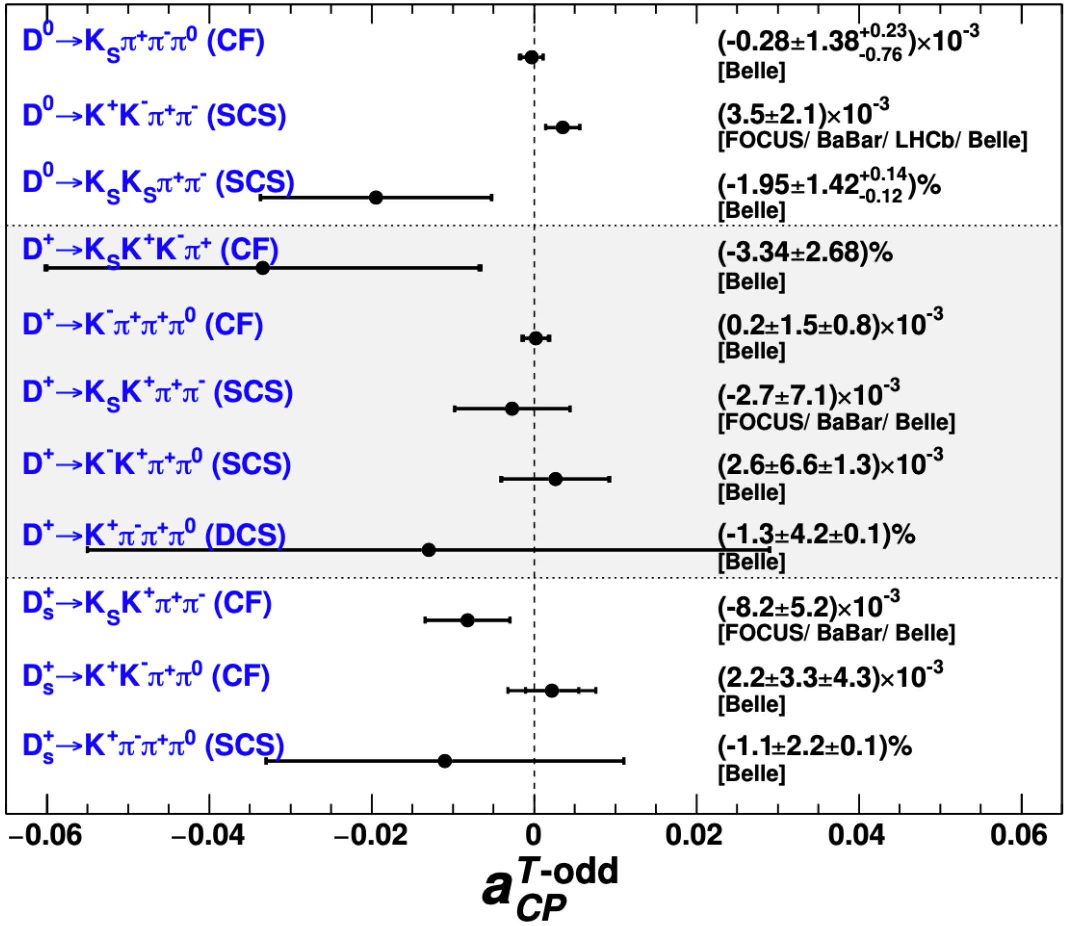
The asymmetry between the cases of $\vec{p}_i$ at the up-side (down-side) of $\vec{p}_j \vec{p}_k$ plane $\Rightarrow$ so-called 'up-down asymmetry'.

$$A_X(D^+) = \frac{N_{D^+}(X>0) - N_{D^+}(X<0)}{N_{D^+}(X>0) + N_{D^+}(X<0)} \qquad X = C_{TP}$$

$$A_{\overline{X}}(D^-) = \frac{N_{D^-}(\overline{X}>0) - N_{D^-}(\overline{X}<0)}{N_{D^-}(\overline{X}>0) + N_{D^-}(\overline{X}<0)} \qquad \overline{X} = \eta_{CP} C_{TP}$$

$$A_{CP}^{X} = \frac{1}{2}\left(A_X(D^+) - A_{\overline{X}}(D^-)\right)$$

Current world averages of all $a_{CP}^{C_{\mathrm{TP}}}$ measurements:



Available large sample of $D^+ \to K_S^0 K^- \pi^+ \pi^+$; but no CPV searches.

Charm CPV: $A_{CP}^{X}(D^+ \to K_S^0 K^- \pi^+ \pi^+)$

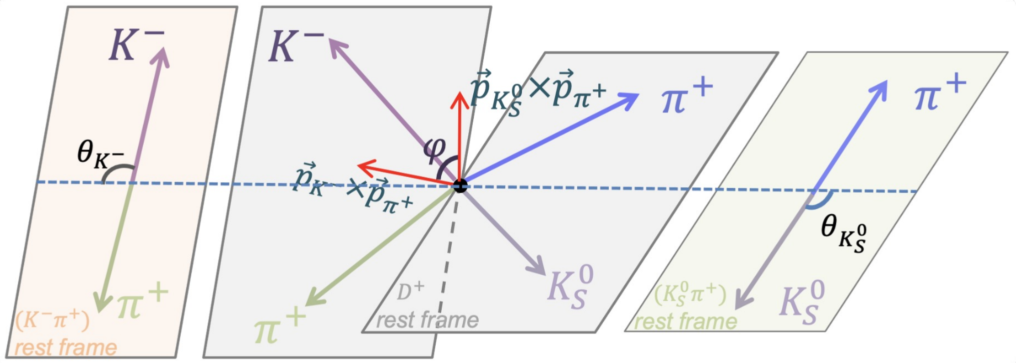
(B+B2) JHEP 04 (2025) 036

- CPV searches using triple-product (TP):

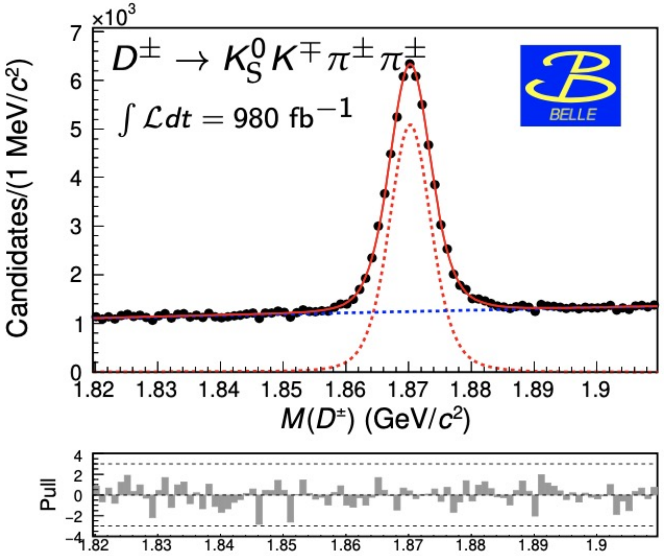
$$C_{\mathrm{TP}} = (\vec{p}_{K^-} \times \vec{p}_{\pi_h^+}) \cdot \vec{p}_{K_S^0}$$

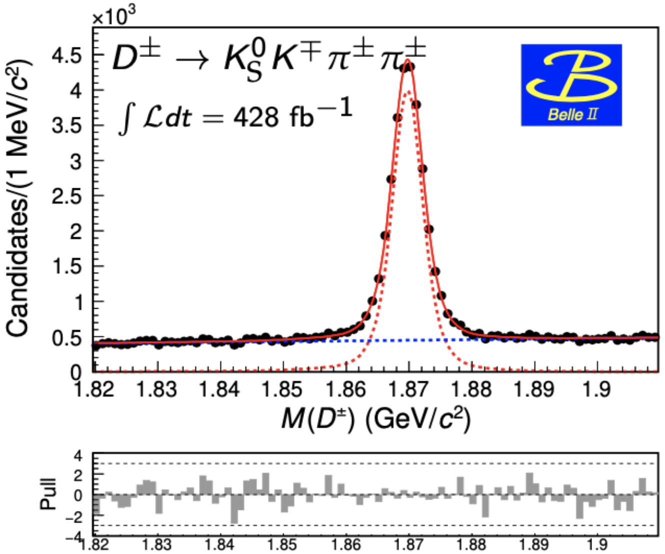
- First CPV search using quadruple-product (QP):

$$C_{\mathrm{QP}} = (\vec{p}_{K^-} \times \vec{p}_{\pi_h^+}) \cdot (\vec{p}_{K_S^0} \times \vec{p}_{\pi_l^+})$$



- Using six X-variables considering angular-related amplitude terms.





X	Combined $\mathcal{A}_{CP}^{X}$ (10^{-3})	
C_{TP}	$-2.3 \pm 4.5 \pm 1.5$	0.5σ
C_{QP}	$-0.7 \pm 4.5 \pm 1.7$	0.2σ
$C_{\mathrm{TP}} C_{\mathrm{QP}}$	$+3.9 \pm 4.5 \pm 1.1$	0.8σ
$\cos\theta_{K_S^0} \cos\theta_{K^-}$	$-2.9 \pm 4.5 \pm 2.1$	0.6σ
$\cos\theta_{K_S^0} \cos\theta_{K^-} C_{\mathrm{TP}}$	$+1.0 \pm 4.5 \pm 1.4$	0.2σ
$\cos\theta_{K_S^0} \cos\theta_{K^-} C_{\mathrm{QP}}$	$+11.6 \pm 4.5 \pm 1.1$	2.5σ

More observables? CPV searches via PWA

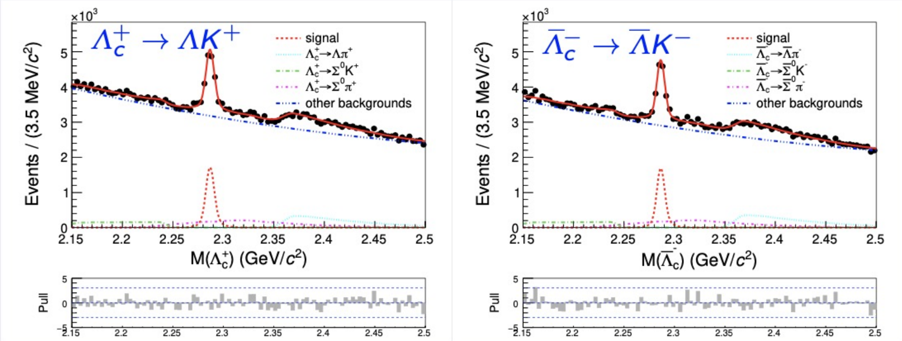
Thank Fu-Sheng Yu and Zhen-Hua Zhang for valuable and helpful discussions.

Charm CPV in charmed baryon decays

(Belle) Science Bulletin 68 (2023) 583

direct CPV in $\Lambda_c^+ \to \Lambda K^+, \Sigma^0 K^+$

- The sources of raw asymmetry of $\Lambda_c^+ \to \Lambda h^+$:
  $A_{\rm raw}(\Lambda_c^+ \to \Lambda K^+) \approx \mathcal{A}_{CP}^{\Lambda_c^+\to\Lambda K^+} + \mathcal{A}_{CP}^{\Lambda\to p\pi^-} + A_\varepsilon^{\Lambda} + A_\varepsilon^{K^+} + A_{\rm FB}^{\Lambda_c^+}$
- Using (CF) $\Lambda_c^+ \to \Lambda\pi^+$, $\Sigma^0\pi^+$ to remove common sources.

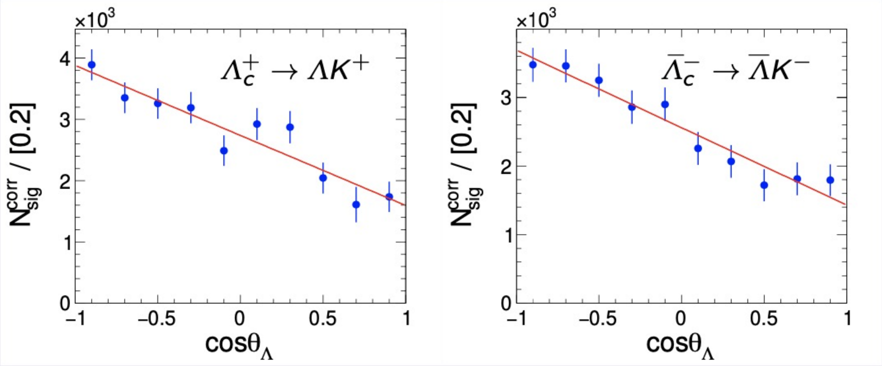


- $\mathcal{A}_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) = (+2.1 \pm 2.6 \pm 0.1)\%$
- $\mathcal{A}_{CP}^{\rm dir}(\Lambda_c^+ \to \Sigma^0 K^+) = (+2.5 \pm 5.4 \pm 0.4)\%$

First $\mathcal{A}_{CP}^{\rm dir}$ for SCS two-body decays of charmed baryons.

α-induced CPV in $\Lambda_c^+ \to \Lambda K^+, \Sigma^0 K^+$

- Measure $\alpha/\bar\alpha$ for the separate $\Lambda_c^+/\bar\Lambda_c^-$ samples.
- Calculate $\mathcal{A}_{CP}^{\alpha} \equiv (\alpha_{\Lambda_c^+} + \alpha_{\bar\Lambda_c^-})/(\alpha_{\Lambda_c^+} - \alpha_{\bar\Lambda_c^-})$.



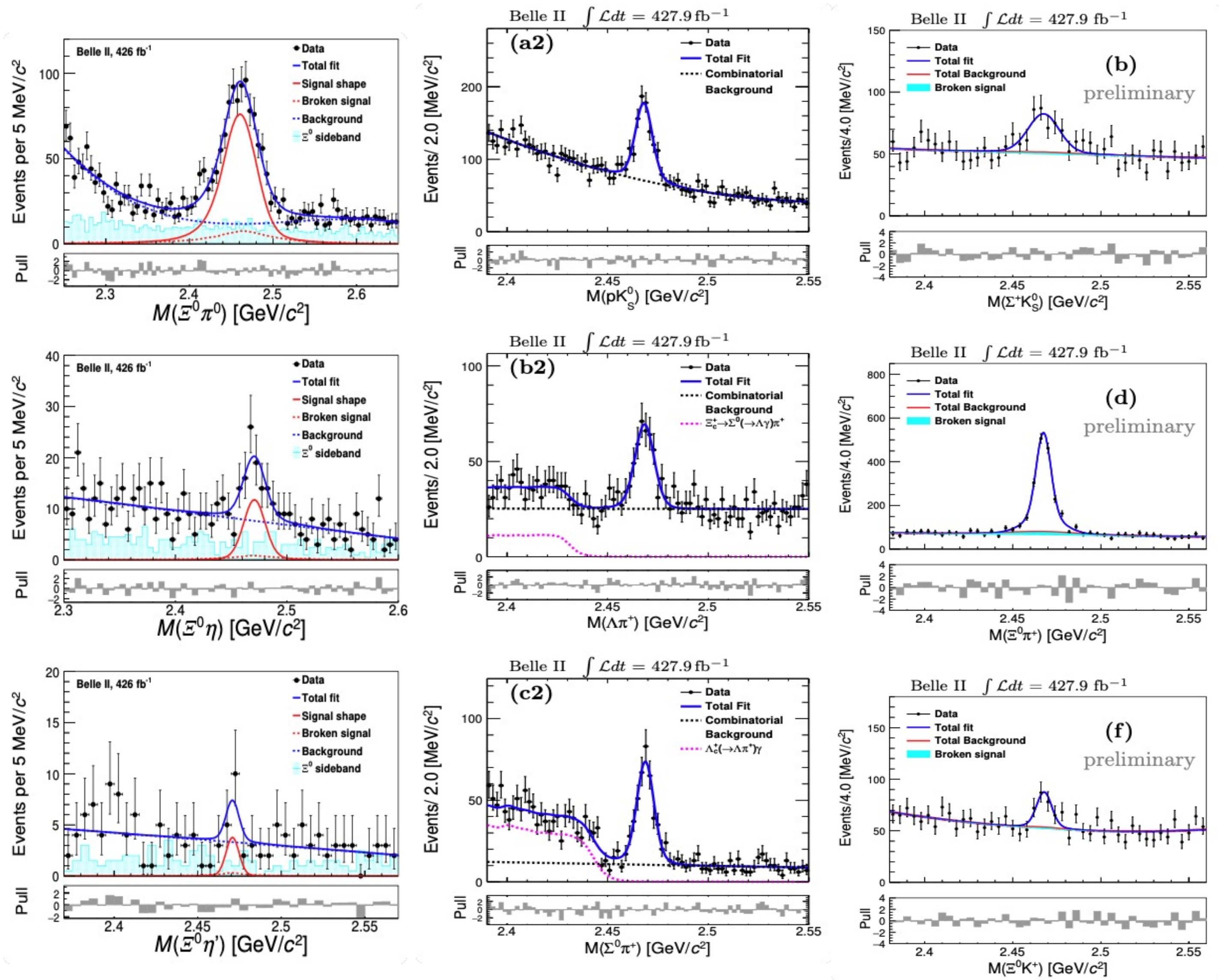
- $\mathcal{A}_{CP}^{\alpha}(\Lambda_c^+ \to \Lambda K^+) = -0.023 \pm 0.086 \pm 0.071$
- $\mathcal{A}_{CP}^{\alpha}(\Lambda_c^+ \to \Sigma^0 K^+) = +0.08 \pm 0.35 \pm 0.14$
  First $\mathcal{A}_{CP}^{\alpha}$ results for SCS decays of charmed baryons.
- No evidence of CPV is found.

No results yet at Belle II…… some results on the road. Please stay tuned.

(e.g. $\Lambda_c^+ \to p h^+ h^-$, $\Lambda_c^+ \to \Lambda K_S^0 h^+$, $\Xi_c^+ \to \Sigma^+ h^+ h^-$, etc.)

Charmed baryons

(B+B2) JHEP 10(2024)045, JHEP 03(2025)061, arXiv:2503.17643



B+B2 combined BR results for 5 CF and 4 SCS decays:

$B(\Xi_c^0 \to \Xi^0\pi^0)/B(\Xi_c^0 \to \Xi^-\pi^+) = 0.48 \pm 0.02 \pm 0.07$

$B(\Xi_c^0 \to \Xi^0\eta)/B(\Xi_c^0 \to \Xi^-\pi^+) = 0.11 \pm 0.01 \pm 0.01$

$B(\Xi_c^0 \to \Xi^0\eta')/B(\Xi_c^0 \to \Xi^-\pi^+) = 0.08 \pm 0.02 \pm 0.01$

$B\left(\Xi_c^+ \to pK_S^0\right)/B(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = (2.47 \pm 0.16 \pm 0.07)\%$

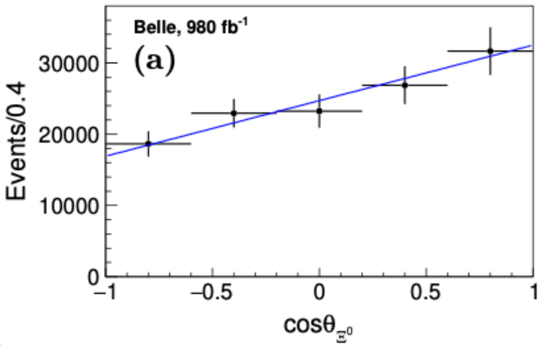
$B(\Xi_c^+ \to \Lambda\pi^+)/B(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = (1.56 \pm 0.14 \pm 0.09)\%$

$B(\Xi_c^+ \to \Sigma^0\pi^+)/B(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = (4.13 \pm 0.26 \pm 0.22)\%$

$B\left(\Xi_c^+ \to \Sigma^+K_S^0\right)/B(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = 0.067 \pm 0.007 \pm 0.003$

$B(\Xi_c^+ \to \Xi^0\pi^+)/B(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = 0.248 \pm 0.005 \pm 0.009$

$B(\Xi_c^+ \to \Xi^0K^+)/B(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = 0.017 \pm 0.003 \pm 0.001$



$$\alpha(\Xi_c^0 \to \Xi^0\pi^0) = -0.90 \pm 0.15(\mathrm{stat}) \pm 0.23(\mathrm{syst})$$

Next step:

- more channels
- absolute BR
- PWA (CF)
- CPV (SCS)

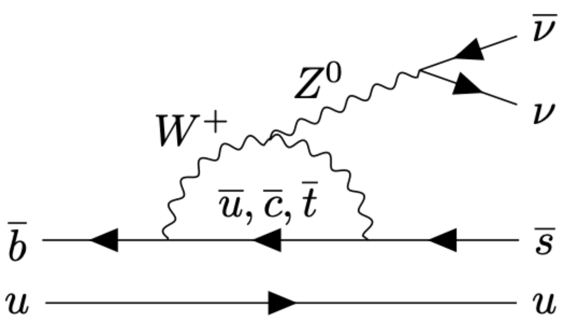
B rare or forbidden decay

Belle II homepage: “Belle II has been designed to make precise measurements of weak interaction parameters, study exotic hadrons, and search for new phenomena beyond the Standard Model of particle physics.”

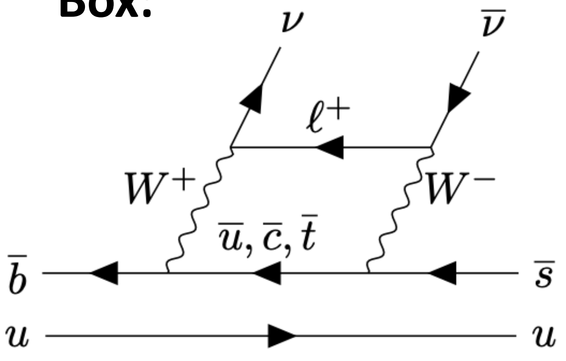
$B \to K\nu\bar{\nu}$: first evidence

(B2) PRD 109 (2024) 112006

Penguin:



Box:



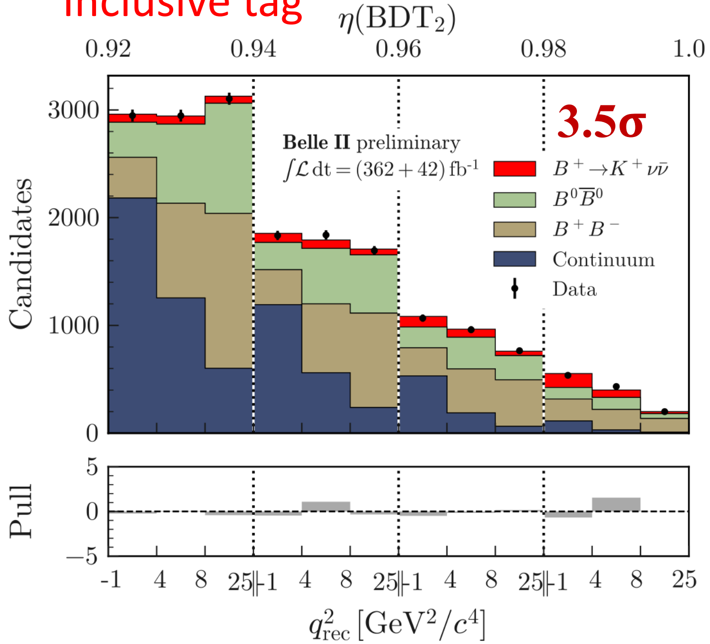
High accuracy in the SM [PRD 107, 014511 (2023)]

$\mathcal{B}(B \to K\nu\bar{\nu}) = (5.6 \pm 0.4) \times 10^{-6}$

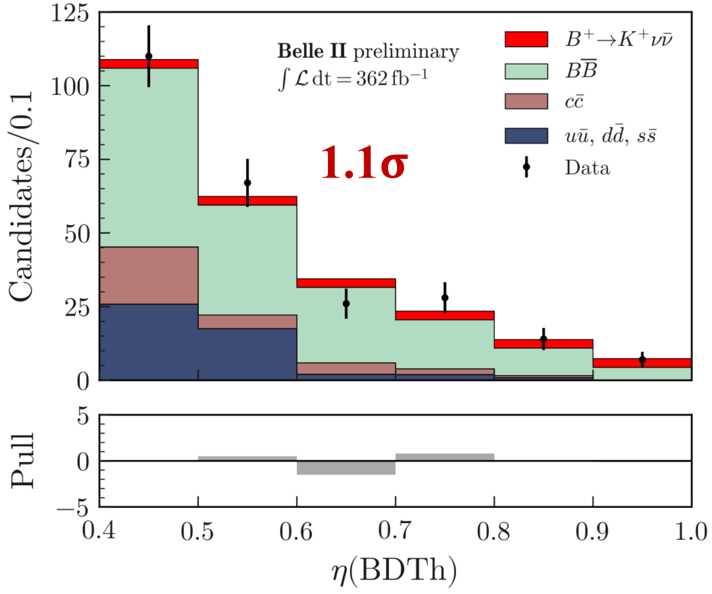
Extensions beyond SM may lead to significant rate increase.

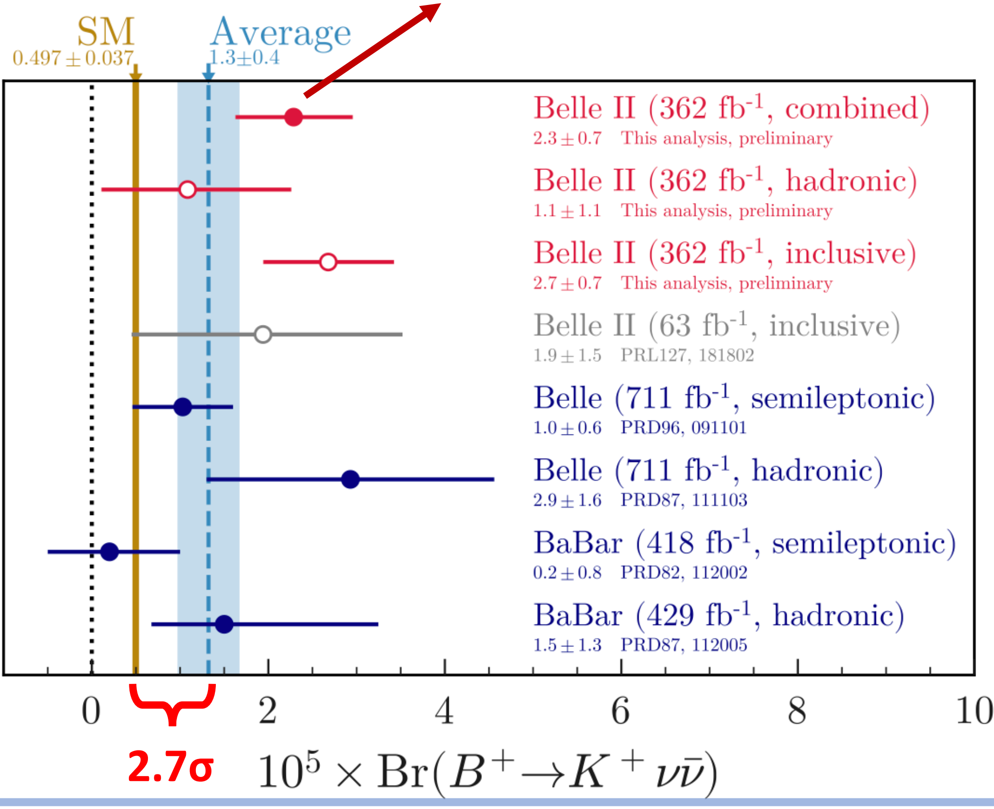
$\mathcal{B}(B \to K\nu\bar{\nu}) = (2.3 \pm 0.7) \times 10^{-5}$ **(3.5σ)**

Inclusive tag



Hadronic tag



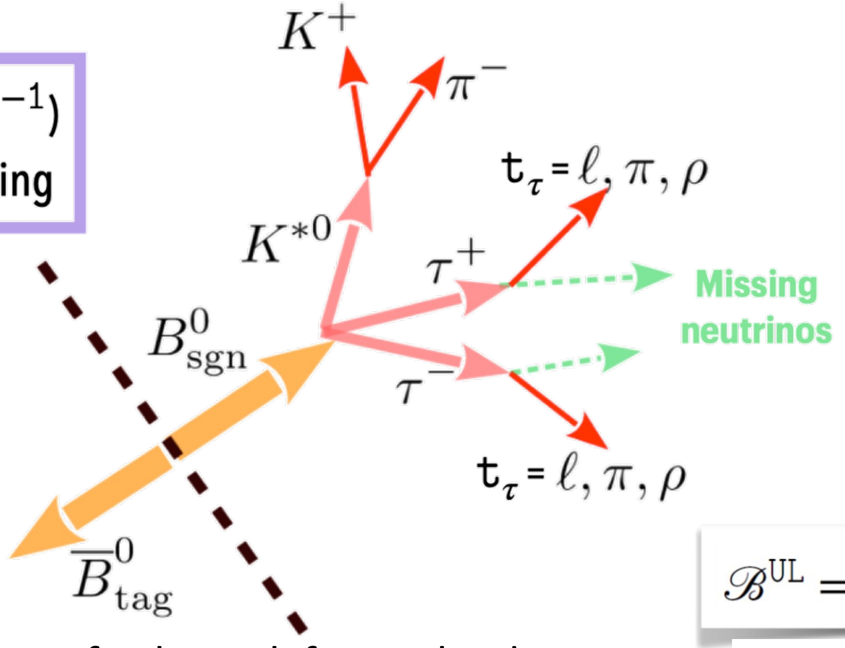


Search for $B^0 \to K^{*0}\tau^+\tau^-$

(B2) arXiv:2504.10042

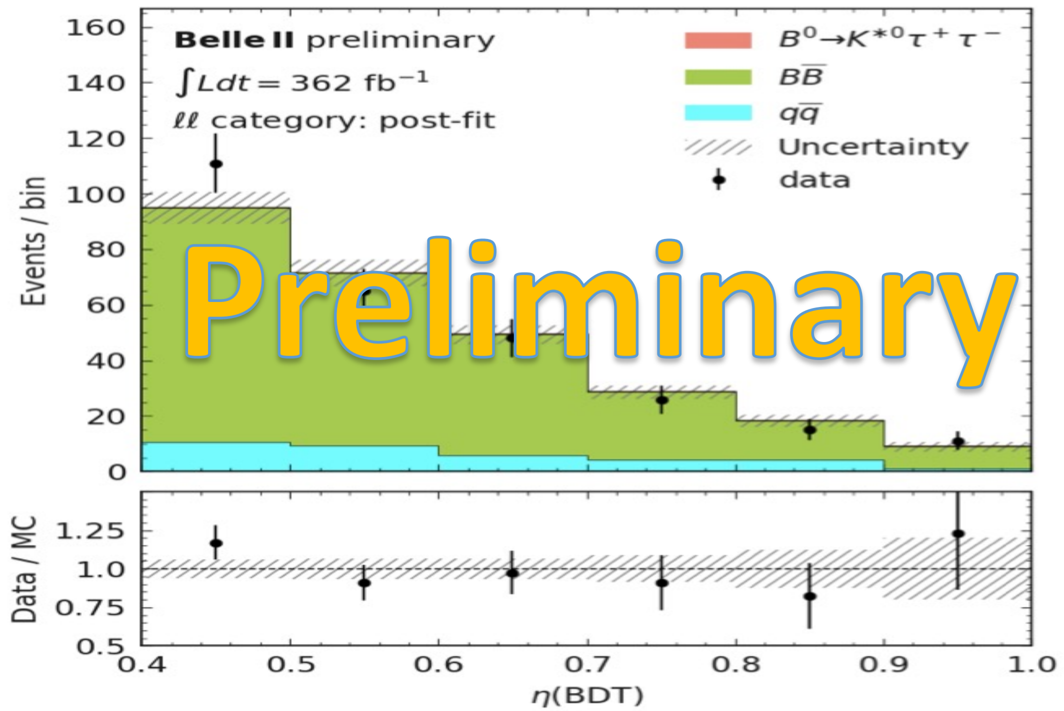
- Non-SM particles, explaining recent anomalies, would enhance BF upto $\mathcal{O}(10^3)$ due to presence of two τs
- Main challenge: no signal peaking kinematic observable due to multiple undetected neutrinos
- Relies on missing energy information and residual calorimeter energy; Belle II is ideally suited

Belle II (364 fb^{-1})
hadronic B-tagging



Combinations of sub-track from τ lead to 4 categories: $\ell\ell, \ell\pi, \pi\pi, \rho X$

BDT is trained using missing energy, extra cluster energy in EM calorimeter, $M(K^{*0}t_\tau)$, q^2,etc



vs Belle: 3.1x10^{-3} [PRD 108 (2023) L011102]

$\mathcal{B}^{\rm UL} = 1.8 \times 10^{-3}$ at 90% confidence level

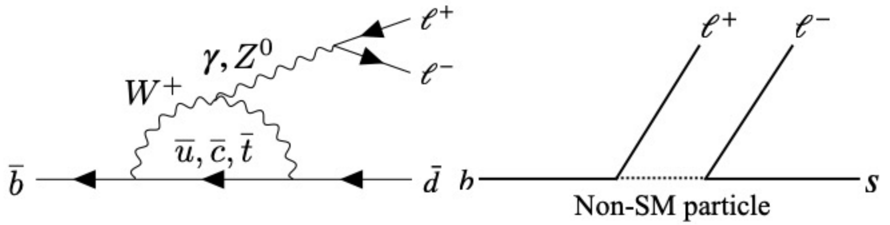
Twice better with only half sample wrt Belle!
Better tagging + more categories + BDT classifer...

The most stringent limit on the $B^0 \to K^{*0}\tau^+\tau^-$ decay

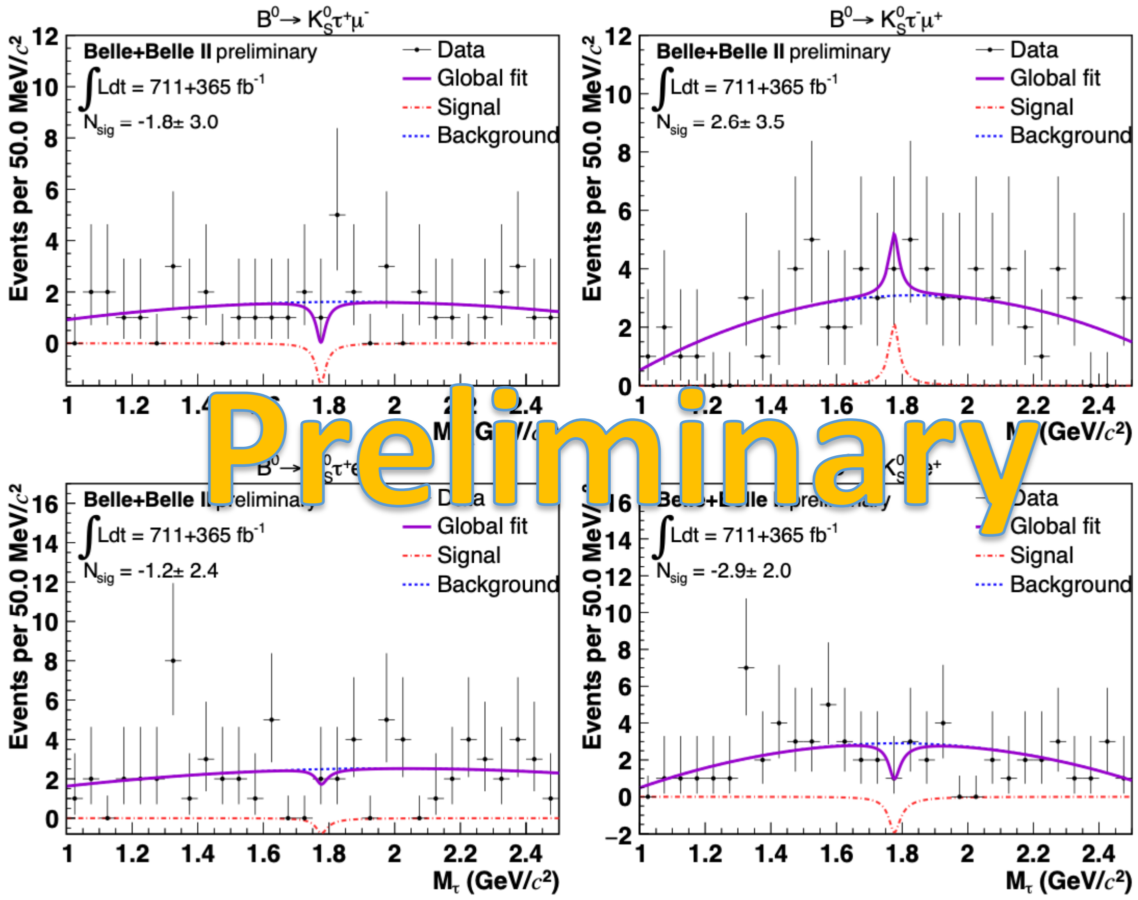
Search for $B^0 \to K_S^0 \tau^\pm \ell^\mp$

(B2) arXiv:2412.16470

- Flavor changing neutral current processes are forbidden in SM at tree level.
- NP that accommodate the b → cτℓ anomalies predict an enhancement of several orders of magnitude with τ.



- High K_S^0 purity (>98%)
- 1-prong τ decays: $\tau^+ \to \ell^+ \nu \bar{\nu}$, $\pi^+ \nu$, $\rho^+ \nu$
- Fit recoil τ mass (M_τ) for signal extraction

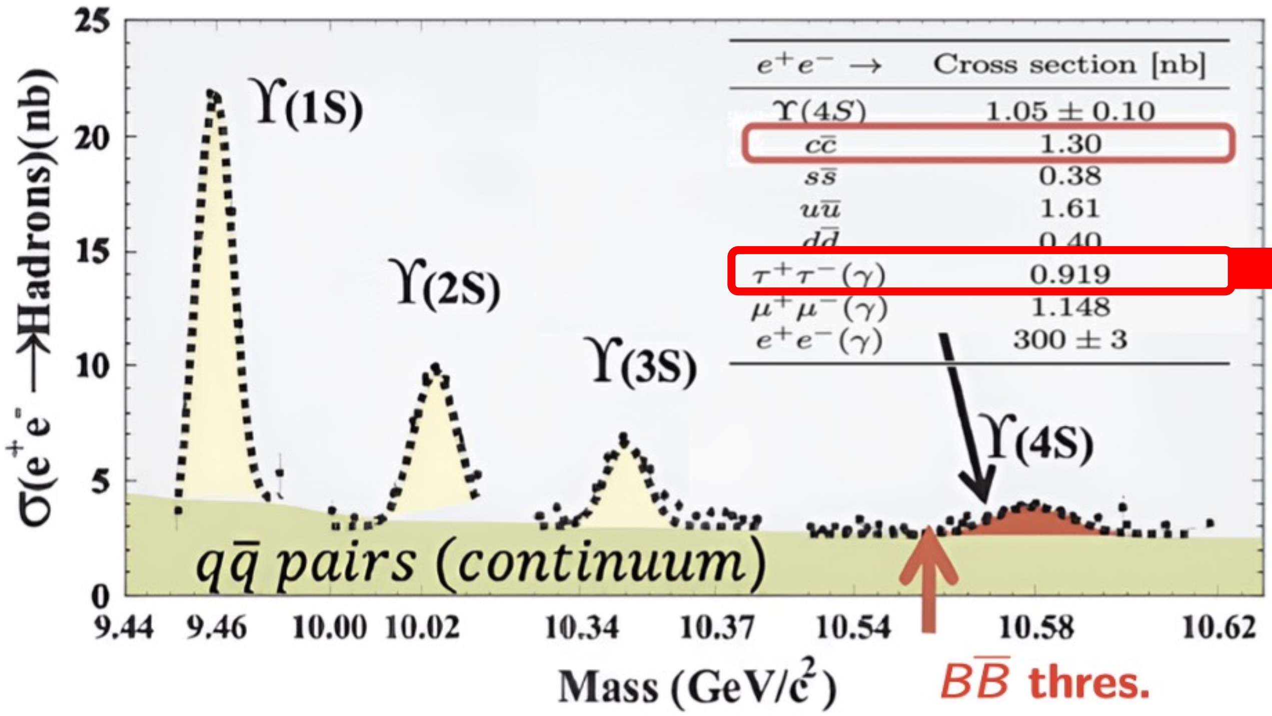


$$\mathcal{B}(B^0 \to K_S^0 \tau^+ \mu^-) < 1.1 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^- \mu^+) < 3.6 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^+ e^-) < 1.5 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^- e^+) < 0.8 \times 10^{-5}$$

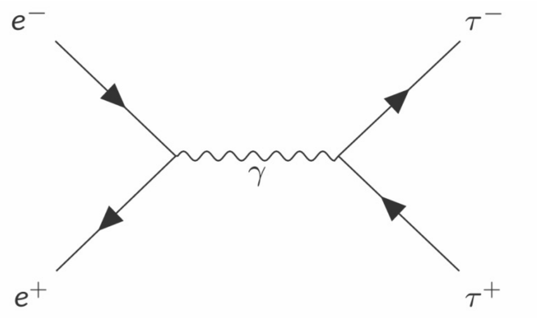
@90% CL

First search for $B^0 \to K_S^0 \tau^\pm \ell^\mp$ decays

tau physics



$e^+e^- \to$	Cross section [nb]
$\Upsilon(4S)$	1.05 ± 0.10
$c\bar{c}$	1.30
$s\bar{s}$	0.38
$u\bar{u}$	1.61
$d\bar{d}$	0.40
$\tau^+\tau^-(\gamma)$	0.919
$\mu^+\mu^-(\gamma)$	1.148
$e^+e^-(\gamma)$	300 ± 3



Belle II: a tau super-factory

Advantages at Belle II:

- ✓ High luminosity
- ✓ Good vertexing and tracking capabilities
- ✓ Sophisticated trigger system and particle ID

tau physics: LFV

(B2) JHEP 09 (2024) 062, PRD 110, 112003 (2024), arXiv:2504.15745

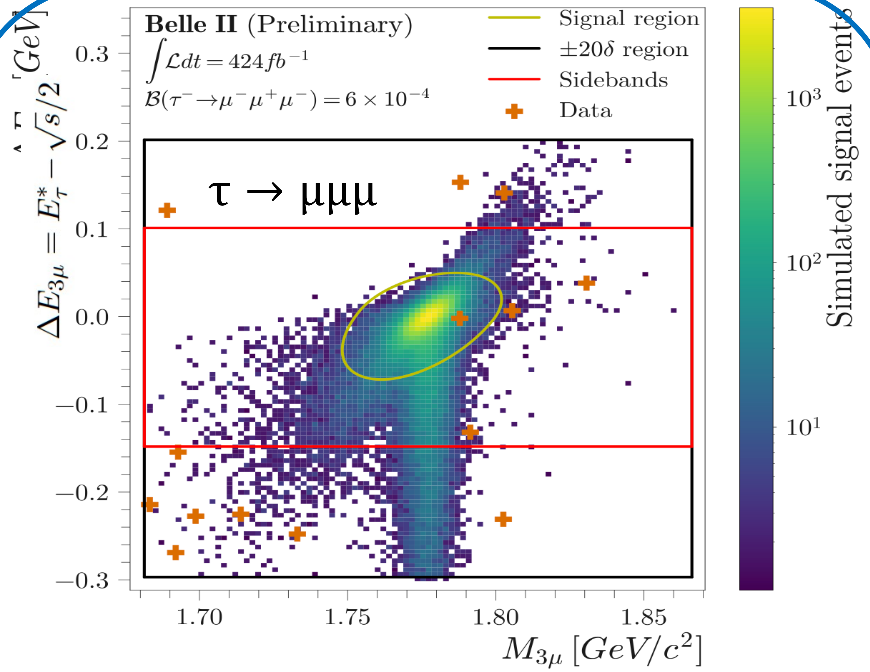
Lepton flavour violation is only allowed by:

- **Neutrino oscillations** $\mathcal{O}(10^{-55})$

far beyond current experimental sensitivities

- **New Physics models** $\mathcal{O}(10^{-8})$

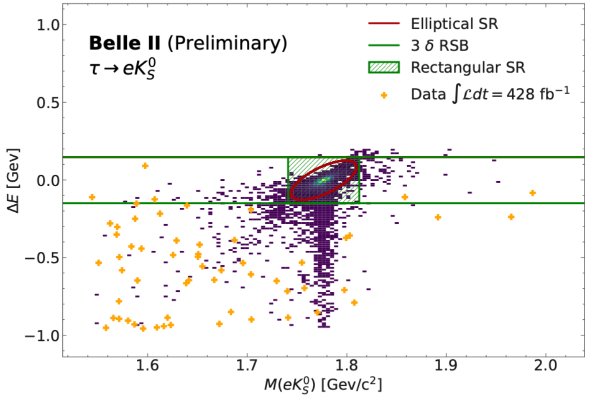
e.g. Leptoquarks for $\tau^- \to \ell^- V^0$ deals with $R(K^{*0})$ anomalies

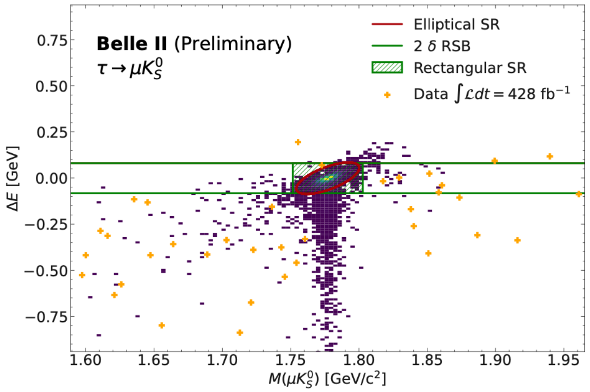


$\mathcal{B}^{\text{UL}}(\boldsymbol{\tau \to \mu\mu\mu}) < 1.9\times10^{-8}$

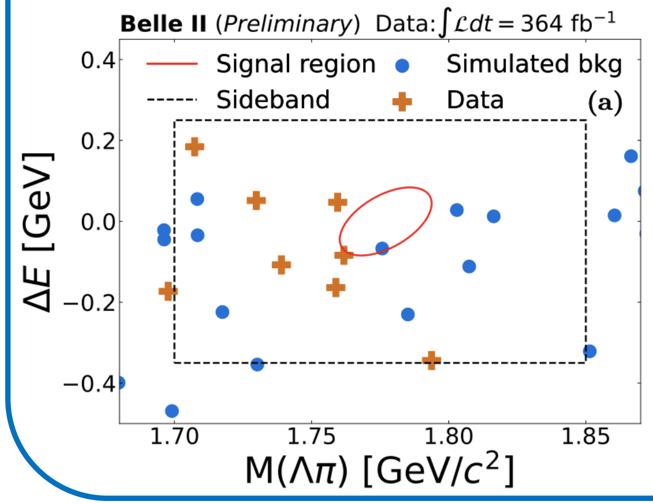
more restrictive than Belle

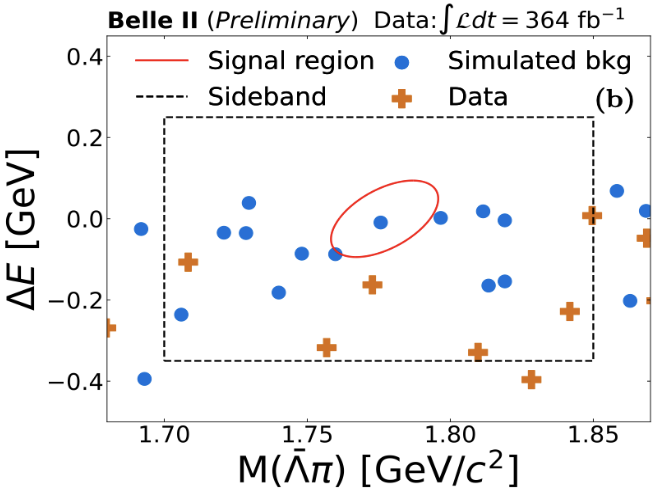
$\mathcal{B}^{\text{UL}}(\boldsymbol{\tau \to e(\mu)K_S^0}) < 0.8(1.2)\times10^{-8}$: **most stringent**





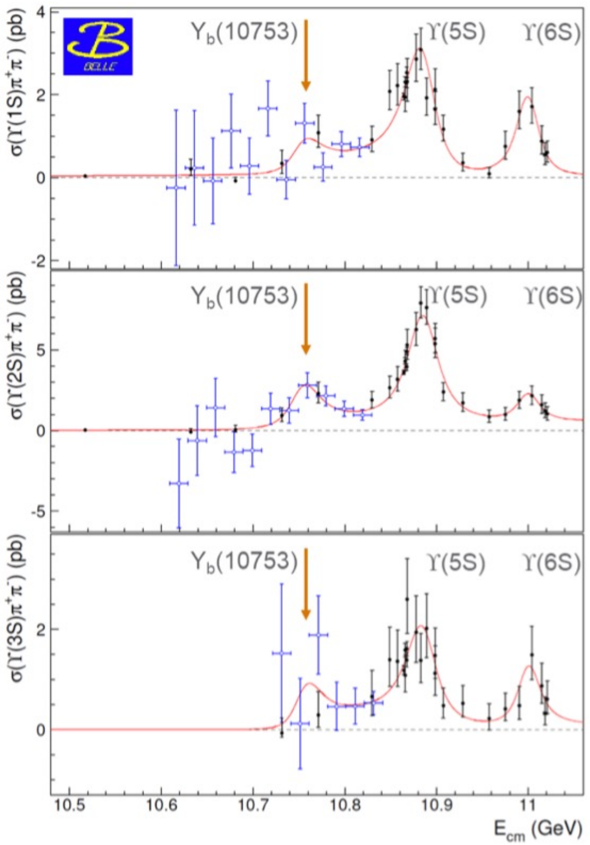
$\mathcal{B}^{\text{UL}}(\boldsymbol{\tau^- \to \Lambda\pi^-(\bar{\Lambda}\pi^-)}) < 4.7(4.3)\times10^{-8}$: most stringent



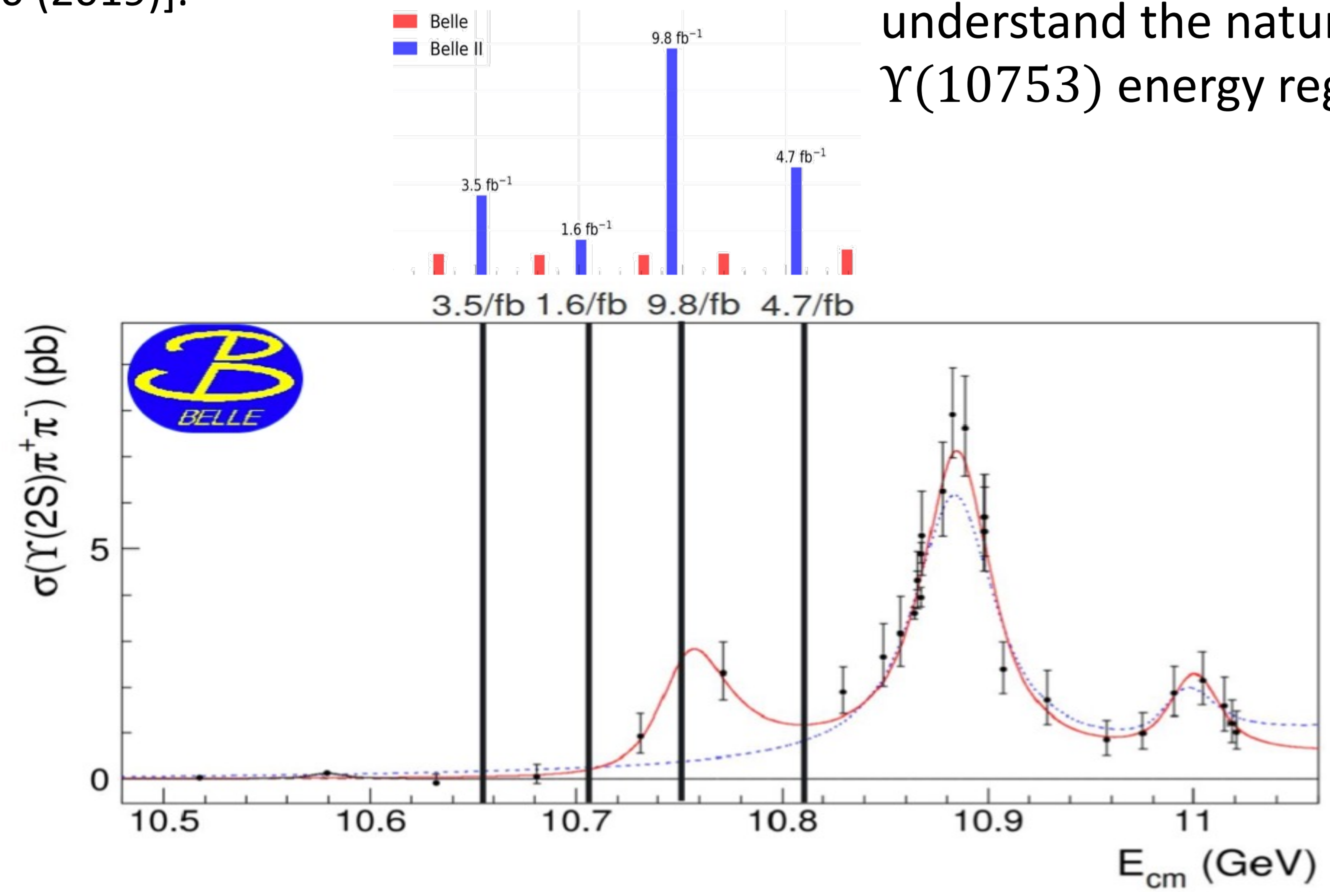


quarkonium (+exotic)

The $\Upsilon(10753)$ was first discovered in $\pi^+\pi^-\Upsilon(nS)$ final states using scan data by Belle [JHEP 10, 220 (2019)].



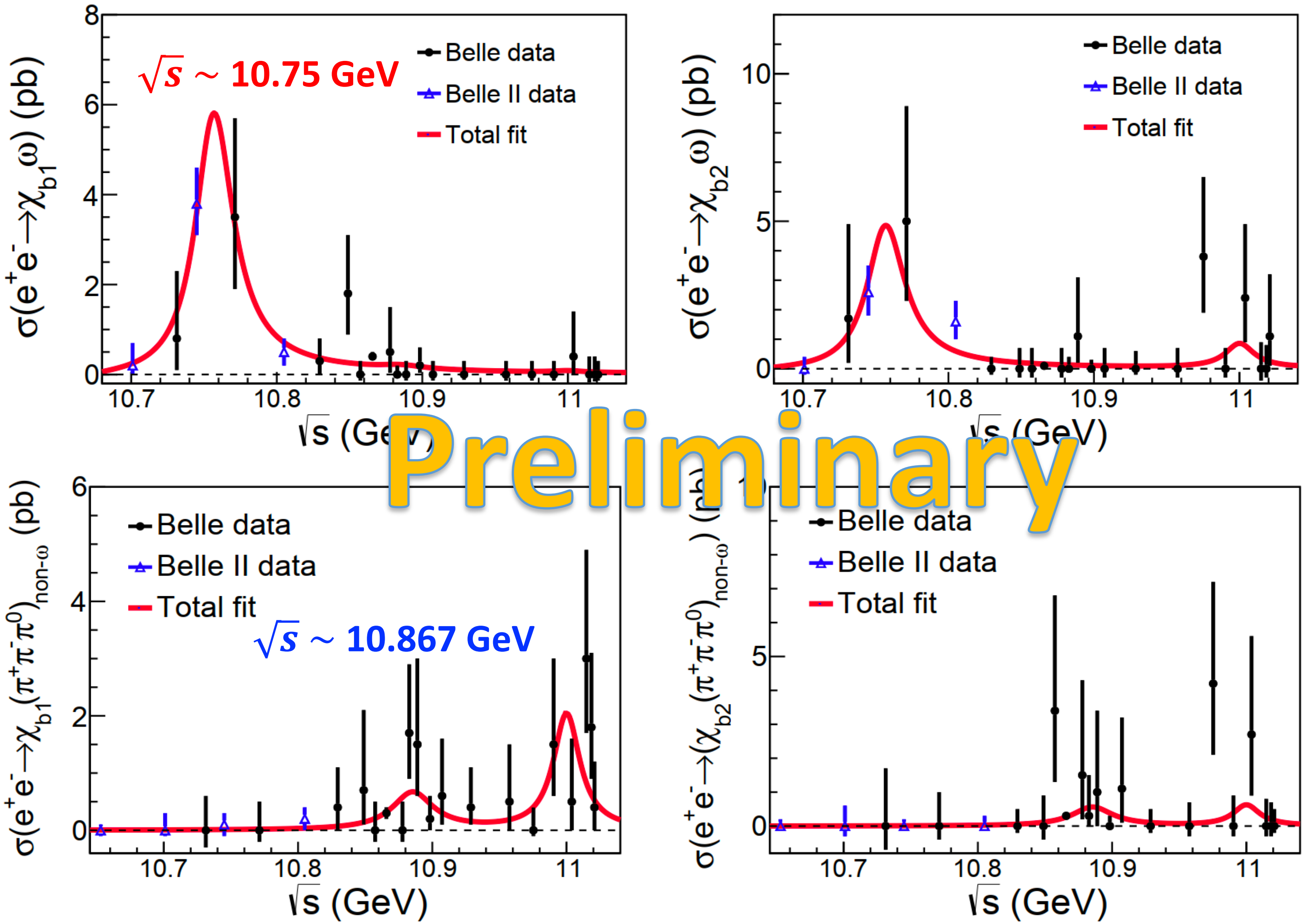
total 19/fb



Physics goal:
understand the nature of $\Upsilon(10753)$ energy region.

$e^+e^- \to \omega\chi_{bJ}$ and $e^+e^- \to (\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}$

Preliminary result



$\Upsilon(10753)$ mass	(10756.1 ± 4.3) MeV/c^2
$\Upsilon(10753)$ width	(32.2 ± 18.7) MeV

Both are consistent with results from $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ [JHEP 07, 116 (2024)]

$$\frac{\sigma(e^+e^-\to\chi_{bJ}(1P)\omega)}{\sigma(e^+e^-\to\Upsilon(nS)\pi^+\pi^-)}$$

1.5 at $\sqrt{s}\sim 10.75$ GeV

0.15 at $\sqrt{s}\sim 10.867$ GeV

This may indicate the difference in internal structures of $\Upsilon(10753)$ and $\Upsilon(10860)$.

More studies on $\Upsilon(10750)$:

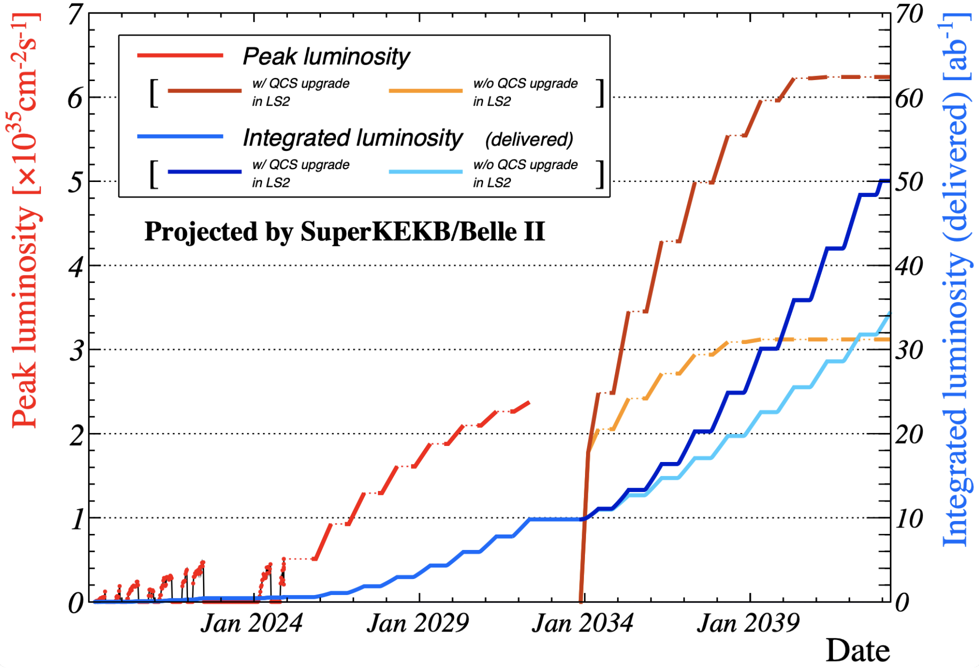
- $\Upsilon(10750) \to \pi^+\pi^-\Upsilon(nS)$ JHEP 07 (2024) 116
- $e^+e^- \to B^{(*)}\bar{B}^{(*)}$ JHEP 10 (2024) 114
- $e^+e^- \to \omega\eta_b(1S), \omega\chi_{b0}(1P)$ PRD 109 (2024) 072013
- $e^+e^- \to \eta\Upsilon(1S,2S)$ preliminary

Summary and prospects

- Belle, as 1st generation of asymmetric B-factory, did emerge as the times require (应运而生)
  → make significant and far-reaching impacts, e.g. observation of CPV in B decays.

- Belle II, as new generation of B-factory, follow the past and herald the future (继往开来).
  - B CPV: $B^0 \to J/\psi K_S^0, J/\psi \pi^0, \rho^+\rho^-, \pi^0\pi^0$ (improved flavor-tagging)
  - Charm: CPV in $D \to K_S^0 K_S^0, \pi^0\pi^0, \pi^+\pi^0, K_S^0 K\pi\pi$; and study of 9 Ξ_c decays (5 CF + 4 SCS).
  - B rare decays: $\mathrm{B} \to \mathrm{K}\nu\bar{\nu} / \mathrm{B}^0 \to \mathrm{K}_S^0 \tau^\pm \ell^\mp / \mathrm{B}^0 \to \mathrm{K}^{*0}\tau^+\tau^-$
  - B (semi-)leptonic and hadronic decay: $B \to D\ell\nu_\ell$,
    $B^+ \to \tau^+\nu_\tau$, $B^0 \to J/\psi\,\omega, D^-\pi^+\pi^0, D^-\rho^+, J/\psi\, X$; etc.
  - τ physics: precise study; search for NP
  - $q\bar{q}$ and exotic: $\Upsilon(10753)$ data (unique in Belle II),
    $\gamma\gamma$ physics, ISR physics, etc.

- Only 1% of targeted luminosity has been collected so far.
  Belle II: improvements as expected (未来“可期”)
  + unexpected excitements (未来可期)



广告：第三届BESIII-Belle II-LHCb粲强子物理联合研讨会

https://indico.ihep.ac.cn/event/24764/

- 会议信息
- 会议日程
- 会议摘要提交
- 会议注册
- 注册人员名单
- 住宿与交通
- 长沙美景美食
- 往届联合研讨会信息
- 湖南师大
- 湖南大学
- 中南大学
- 中国高等科学技术中心

BESIII Belle II LHCb

粲强子物理研究在验证标准模型和探索强相互作用机制方面具有关键作用。通过研究含粲夸克的粒子（如粲介子和粲重子），可揭示量子色动力学在低能区的非微扰特性，可探针电荷共轭-宇称联合对称性破坏（CP破坏）效应，为理解宇宙正反物质不对称性提供了独特平台。粲强子物理的研究也是寻找新物理的敏感探针。

在实验数据方面，BESIII实验于2024年圆满完成了20 /fb的psi(3770) 数据的积累；Belle II实验在10.6 GeV附近已累计采集了近600 /fb的数据；LHCb实验在TeV能区已累计采集了18 /fb的数据。这些数据提供了海量的粲强子样本，能开展丰富的粲物理研究。在此之际，召开BESIII-Belle II-LHCb粲强子物理联合研讨会是很有必要的，交流三个合作组在粲强子等方面研究的重要进展、以及粲强子物理领域理论与实验研究的热点和重点问题，探讨未来几年粲强子物理实验研究可能面临和需要重点解决的物理问题。并以此为契机，希望建立在某些互补性课题方面的合作机制，以期取得更多更有意义的物理成果。

此联合研讨会已成功举办两届：2017年南开大学举办首届，2019年山西师范大学举办第二届。本届联合研讨会由湖南师范大学、湖南大学、中南大学携手联合举办。会议得到了中国高等科学技术中心的资助和湖南省量子科学技术学会的协助。会议以口头报告和自由讨论相结合的形式举办，以促进参会专家、青年学者和研究生之间的讨论交流与合作。诚挚邀请各位专家学者莅临长沙参加此次会议。

会议网站：https://indico.ihep.ac.cn/event/24764/

会议时间：2025年6月27日--30日（27日下午注册）

会议地点：长沙市圣爵菲斯大酒店（百度地图）

会务费：教师/博士后1500元/人；学生1000元/人；家属不收注册费。会议统一安排食宿，费用自理。会务费可现场通过POS刷卡、支付宝、微信缴费。由湖南省量子科技学会统一代收并开具发票，会务费发票将在会议结束后以电子邮件形式提供给会议注册者。
会议注册截止日期：2025年6月13日。

会议联系人：李龙科（湖南师大），15956934447，lilongke@hunnu.edu.cn；
卢　宇（中南大学），18810459153，222027@csu.edu.cn；
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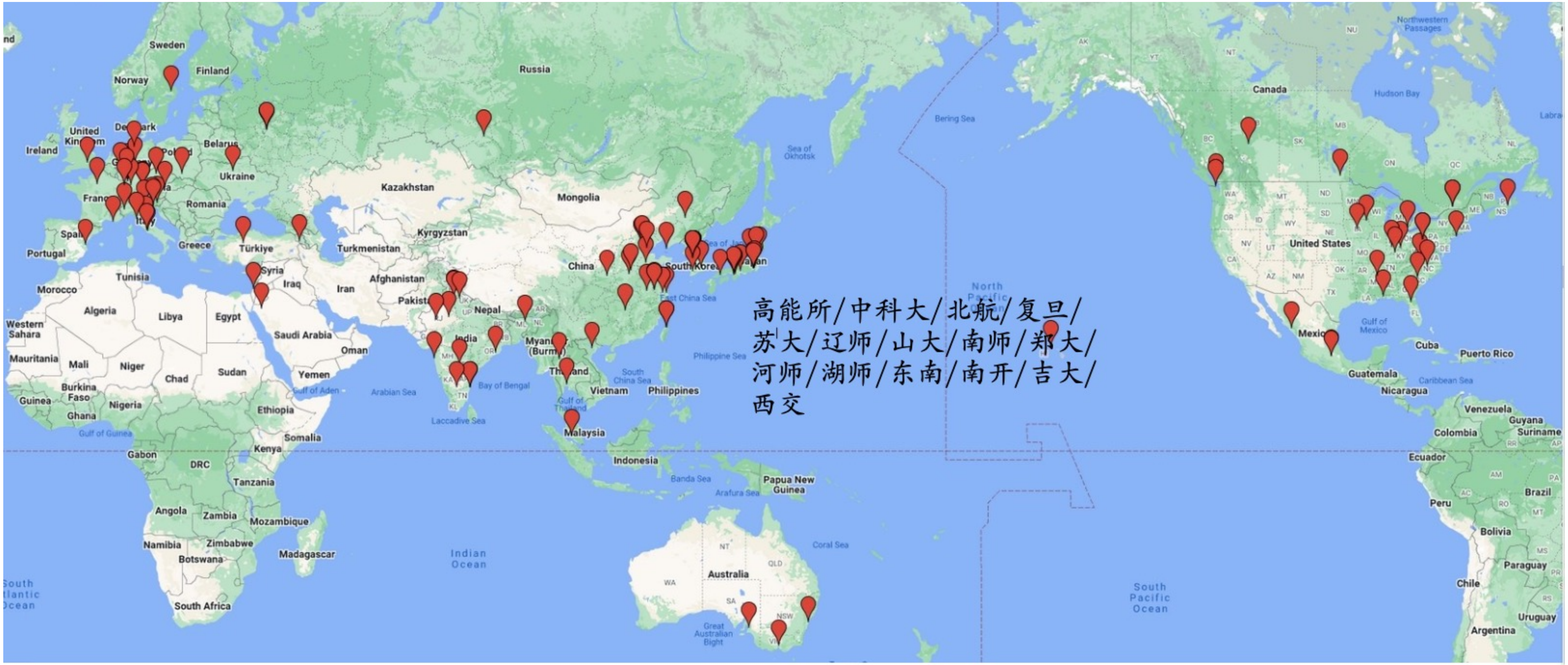
盛暑将至
长沙F5欢迎您

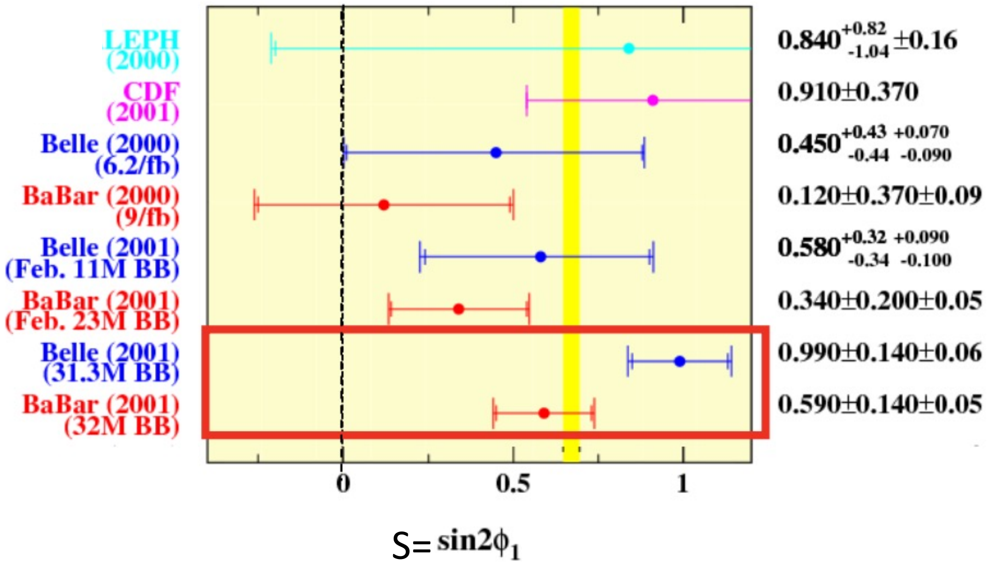
Belle II big family



► Belle II 合作组（中国大陆）：1207 个成员（134：11%，第三位），124（15）个单位，28个国家/地区。

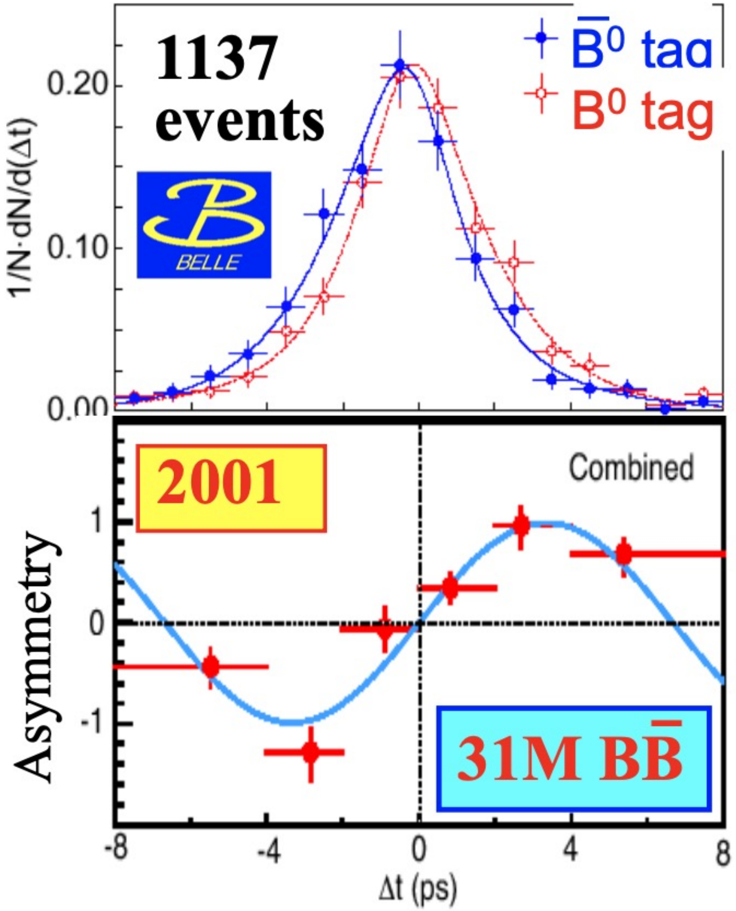
B CPV observation: $\sin 2\phi_1$ measurement

$B^0 \to J/\psi\, K_S^0$



S= $\sin2\phi_1$

2001 Lepton-Photon Rome



开局即巅峰的感觉

小林诚 & 益川敏英

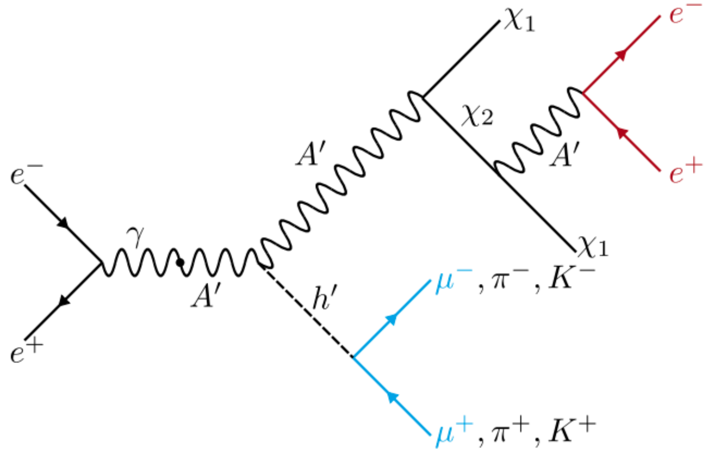
Belle+
BaBar:

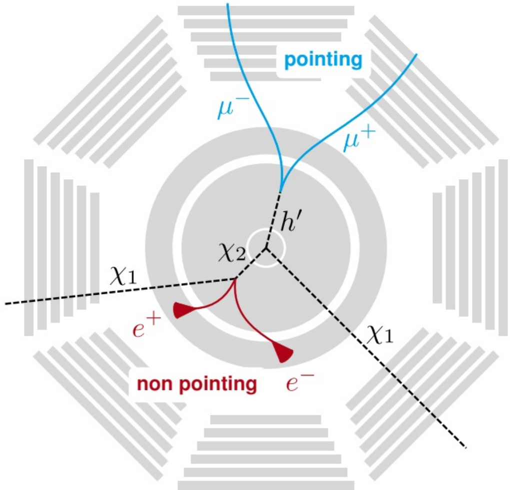
First observed CPV in B (2001) >6σ

This discovery provides the exp. support for the Nobel prize of Kobayashi and Maskawa in 2008

A dark Higgs boson in association with inelastic dark matter

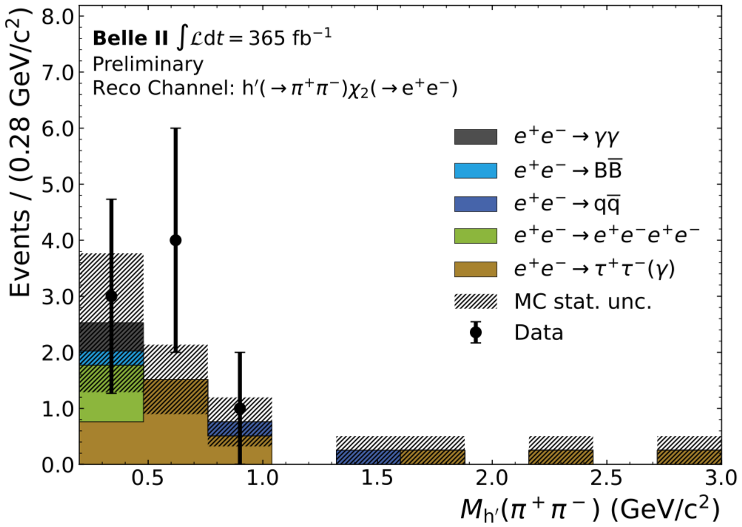
Dark photon A′, dark Higgs h′, and two dark matter states χ_1, χ_2



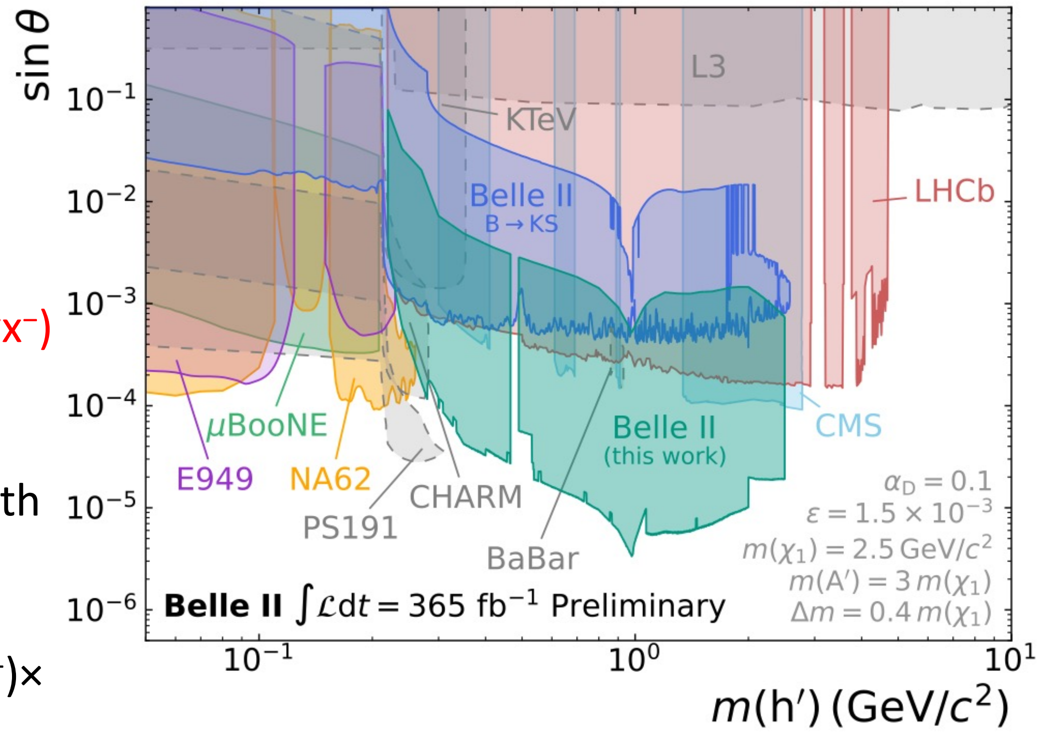


Looking for simultaneous production of A′ and h′

- 4 tracks in the final state
- 2 forming a pointing dispaced vertex
- mising energy



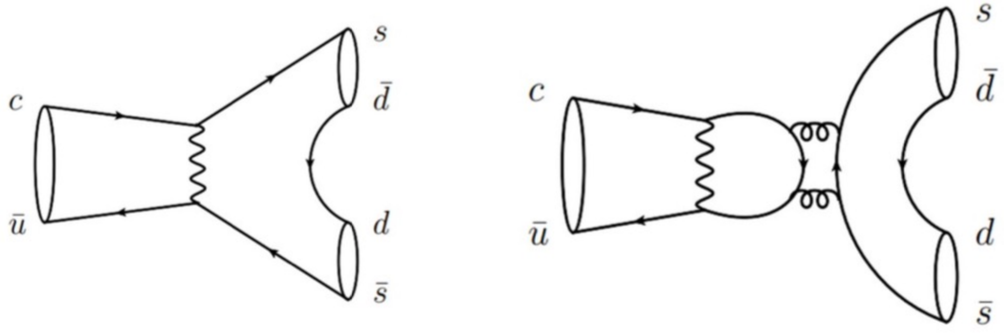
- cut-and-count strategy in $M_{h'}(x^+x^-)$ distributions
- No signicant excess found
- 8 events observed consistent with expected background
- Convert UL at 90% C.L. of $\sigma(e^+e^- \to \chi_1\chi_2 h')\times\mathcal{B}(\chi_2 \to \chi_1 e^+e^-)\times\mathcal{B}(h' \to x^+x^-)$ to mixing angle θ



Back-up

Measurement of $A_{CP}(D^0 \to K_S^0 K_S^0)$

- The time-integrated *CP* asymmetry $\mathcal{A}_{CP}(D^0 \to K_S^0 K_S^0) = \dfrac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\overline{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\overline{D}^0 \to K_S^0 K_S^0)}$.
- It may be enhanced to be an observable level (the 1% level) within the Standard Model, due to the interference of $c \to us\bar{s}$ and $c \to ud\bar{d}$ amplitudes. [PRD 99, 113001 (2019), PRD 86, 014023 (2012), PRD 92, 054036 (2015)]



- World average: $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.9 \pm 1.0)\%$ is dominated by
  - Belle (921 fb^{-1}): $\mathcal{A}_{CP}^{K_S^0 K_S^0} = (-0.02 \pm 1.53 \pm 0.02 \pm 0.17)\%$ using $D^0 \to K_S^0 \pi^0$ as control mode [PRL 119, 171801 (2017)]
  - LHCb (6 fb^{-1}): $\mathcal{A}_{CP}^{K_S^0 K_S^0} = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$ using $D^0 \to K^+ K^-$ as control mode [PRD 104, L031102 (2021)]
- $\mathcal{A}_{CP}(D^0 \to K^+ K^-)$: recently improved by LHCb, uncertainty $< 0.1\%$ [PRL 131, 091802 (2023)]
- Recently, CMS (42 fb^{-1}) reported $\mathcal{A}_{CP}^{K_S^0 K_S^0} = (6.2 \pm 3.0 \pm 0.2 \pm 0.8)\%$ [arXiv:2405.11606]

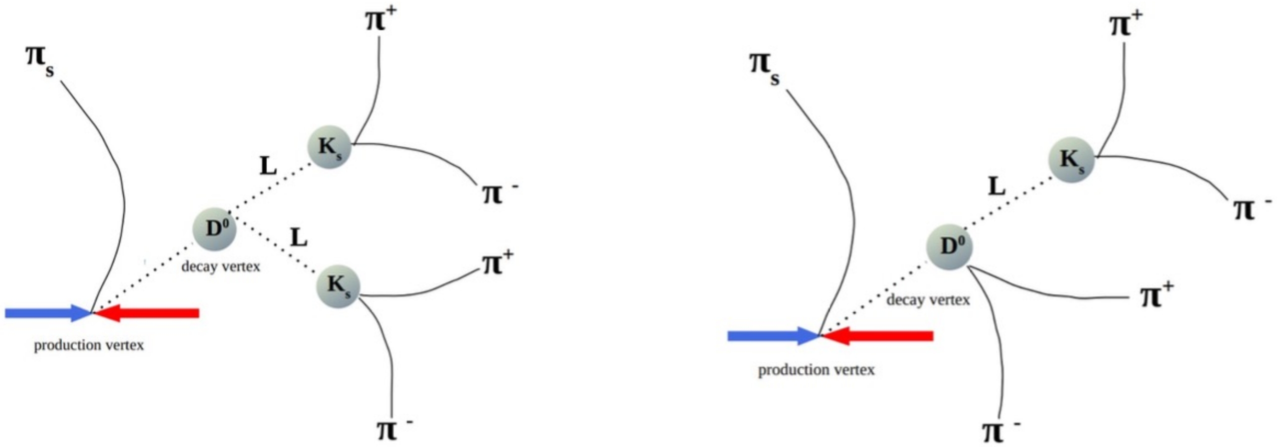
Back-up

Measurement of $A_{CP}(D^0 \to K_S^0 K_S^0)$

- Measure $\mathcal{A}_{CP}(D^0 \to K_S^0 K_S^0)$, using $D^0 \to K^+K^-$ as control mode, with $D^{*+} \to D^0\pi_s^+$ sample at B+B2 (1.4 ab^{-1}).

$$A_{\mathrm{raw}}(D^0 \to f) = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)} = A_{\mathrm{FB}}^{D^{*+}} + A_{CP}^{D^0 \to f} + A_{\varepsilon}^{\pi_s}$$

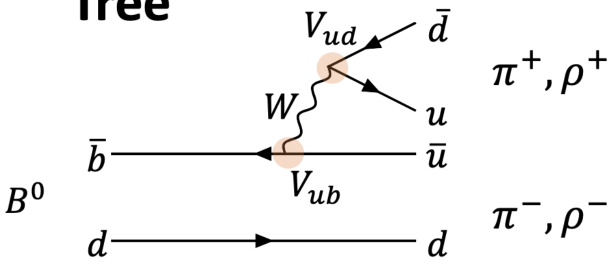
- $\mathcal{A}_{CP}^{K_S^0 K_S^0} = (A_{\mathrm{raw}}^{K_S^0 K_S^0} - A_{\mathrm{raw}}^{K^+K^-}) + \mathcal{A}_{CP}^{K^+K^-}$ assuming that the nuisance asymmetries are identical between two decays, or that they can be made so by weighting the control sample.
- $A_{CP}^{D^0 \to K^+K^-} = A_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-) + \Delta Y = (6.7 \pm 5.4) \times 10^{-4}$ [PRL 131, 091802 (2023), PRD 104, 072010 (2021)]
  - $A_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-) = (7.7 \pm 5.7) \times 10^{-4}$: direct CP asymmetry [PRL 131, 091802 (2023)]
  - $\Delta Y = (-1.0 \pm 1.1) \times 10^{-4}$: CPV in mixing and in the interference between mixing and decay [PRD 104, 072010 (2021)]
- Unbinned fit to $(m(D^0\pi_s), S_{\mathrm{min}})$ of D^0 and $\bar{D}^0$ candidates for $D^0 \to K_S^0 K_S^0$ decays.
  - Flight significance variable $S_{\mathrm{min}} = \log(\min(L_i/\sigma_i))$: separate the peaking background $D^0 \to K_S^0\pi^+\pi^-$.



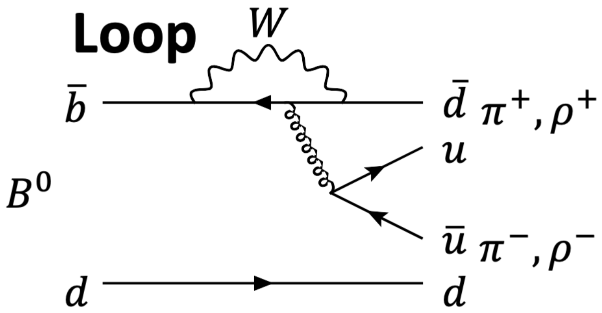
ϕ_2: $B \to \pi\pi, \rho\rho$

$\boxed{\phi_2 = \arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]}$

Tree



Loop



Isospin relations

	Tree	Loop
$\pi^+\pi^-$	○	○
$\pi^+\pi^0$	○	×
$\pi^0\pi^0$	△ (color suppressed)	○

○: Large contribution
×: No contribution
△: Smaller contribution

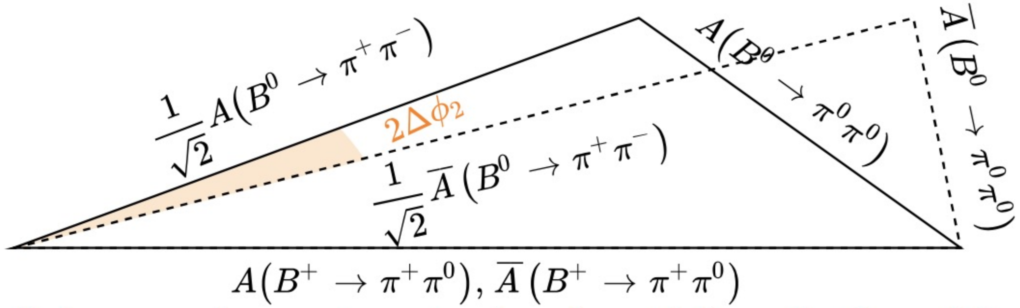
EM loop?
X.-G. He's paper?

$$\frac{\Gamma(\bar{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to f) + \Gamma(B^0 \to f)} = -C \cdot \cos\Delta m_d \Delta t + S \cdot \sin\Delta m_d \Delta t$$

- Using $b \to u$ tree decays (e.g $B^0 \to \pi^+\pi^-, \rho^+\rho^-$), $S = \sin 2\phi_2$ and $C = 0$.
- Due to the interference between tree and loop ($b \to d$), $S = \sin 2\phi_2 + 2\Delta\phi_2$ and $C \neq 0$.

Granou-London isospin relations

$$\frac{1}{\sqrt{2}}A(B^0 \to \pi^+\pi^-) - A(B^0 \to \pi^0\pi^0) = A(B^+ \to \pi^+\pi^0)$$
$$\frac{1}{\sqrt{2}}\bar{A}(B^0 \to \pi^+\pi^-) - \bar{A}(B^0 \to \pi^0\pi^0) = \bar{A}(B^+ \to \pi^+\pi^0)$$



$\Delta\phi_2$ can be extracted using this relationship

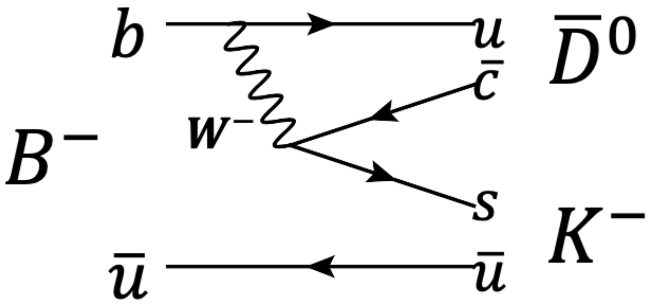
ϕ_3: $B^+ \to D^{(*)} h^+$

(B+B2) JHEP 10 (2024) 143

$\boxed{\phi_3 = \arg(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb})}$

appears in CPV parameter of $b \to u\bar{c}s$ and $b \to c\bar{u}s$ tree decay interference.

Suppressed

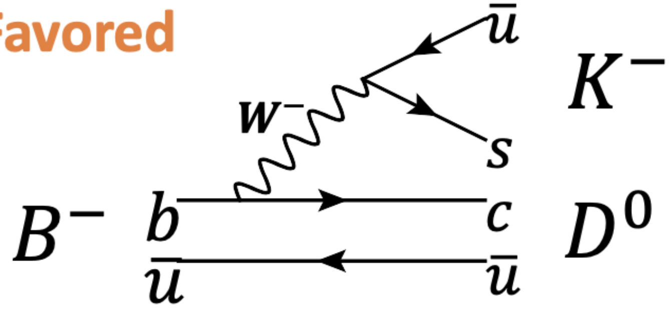


$$\frac{\mathcal{A}(\bar{D}^0K^-)}{\mathcal{A}(D^0K^-)} = r_B \exp(i(\delta_B - \phi_3))$$

$r_B = |\mathcal{A}(\bar{D}^0K^-)|/|\mathcal{A}(D^0K^-)| \simeq c_f|V_{cs}V^*_{ub}/V_{us}V^*_{cb}| \simeq 0.1$ (c_f : Color suppression factor)

δ_B: Strong phase difference between 2 modes

Favored



Methods to measure ϕ_3 using different D^0 decays

- GLW method: $D^0 \to K^+K^-, K^0_S\pi^0$ (CP eigenstates)
- BPGGSZ method: self conjugate multibody decay, ex.) $D^0 \to K^0_S h^+h^-$
- GLS method: $D^0 \to K^0_S K^\pm\pi^\mp$ (singly Cabibbo-suppressed decays)
- ADS method: $D^0 \to K^\pm\pi^\mp$

$\boldsymbol{\phi_3}$: $\boldsymbol{B^+ \to D^{(*)} h^+}$

$\phi_3 = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$

First Belle + Belle II combined ϕ_3 analysis

Combined analysis using 4 methods

Fit results

Parameters	$\phi_3(°)$	r_B^{DK}	$\delta_B^{DK}(°)$	$r_B^{D\pi}$	$\delta_B^{D\pi}(°)$	$r_B^{D^*K}$	$\delta_B^{D^*K}(°)$
Best-fit value	75.2	0.115	137.8	0.0165	347.0	0.229	342
68.3% interval	[67.7, 82.3]	[0.102, 0.127]	[128.0, 146.3]	[0.0113, 0.0220]	[337.4, 355.7]	[0.162, 0.297]	[326,356]
95.4% interval	[59, 89]	[0.089, 0.138]	[116, 154]	[0.006, 0.027]	[322, 366]	[0.10, 0.37]	[306, 371]

Inputs for ϕ_3 measurement

B decay	D decay	Method	Data set (Belle + Belle II)[fb^{-1}]
$B^+ \to Dh^+$	$D \to K_S^0\pi^0, K^-K^+$	GLW	711 + 189 **Belle II**
$B^+ \to Dh^+$	$D \to K^+\pi^-, K^+\pi^-\pi^0$	ADS	711 + 0
$B^+ \to Dh^+$	$D \to K_S^0K^-\pi^+$	GLS	711 + 362 **Belle II**
$B^+ \to Dh^+$	$D \to K_S^0h^-h^+$	BPGGSZ (m.i.)	711 + 128 **Belle II**
$B^+ \to Dh^+$	$D \to K_S^0\pi^-\pi^+\pi^0$	BPGGSZ (m.i.)	711 + 0
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D \to K_S^0\pi^0, K_S^0\phi, K_S^0\omega, K^-K^+, \pi^-\pi^+$	GLW	210+0
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D\gamma, D \to K_S^0\pi^-\pi^+$	BPGGSZ (m.d.)	605 + 0

Belle + Belle II :
$\boldsymbol{\phi_3} = (75.2 \pm 7.6)°$

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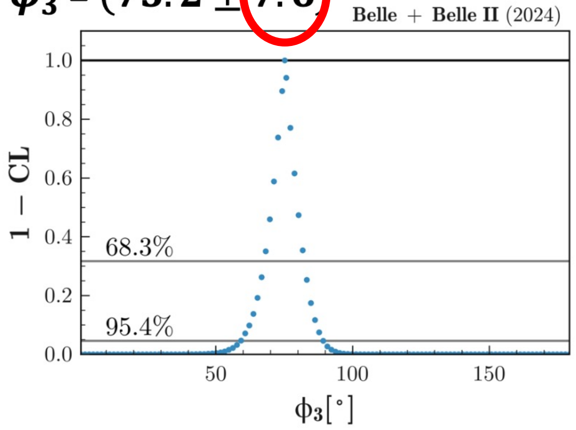
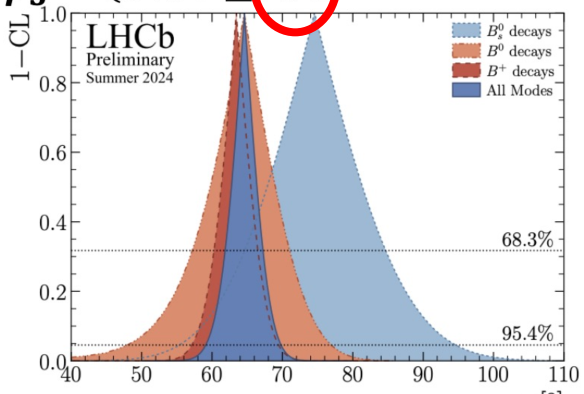


LHCb:
$\boldsymbol{\phi_3} = (64.6 \pm 2.8)°$

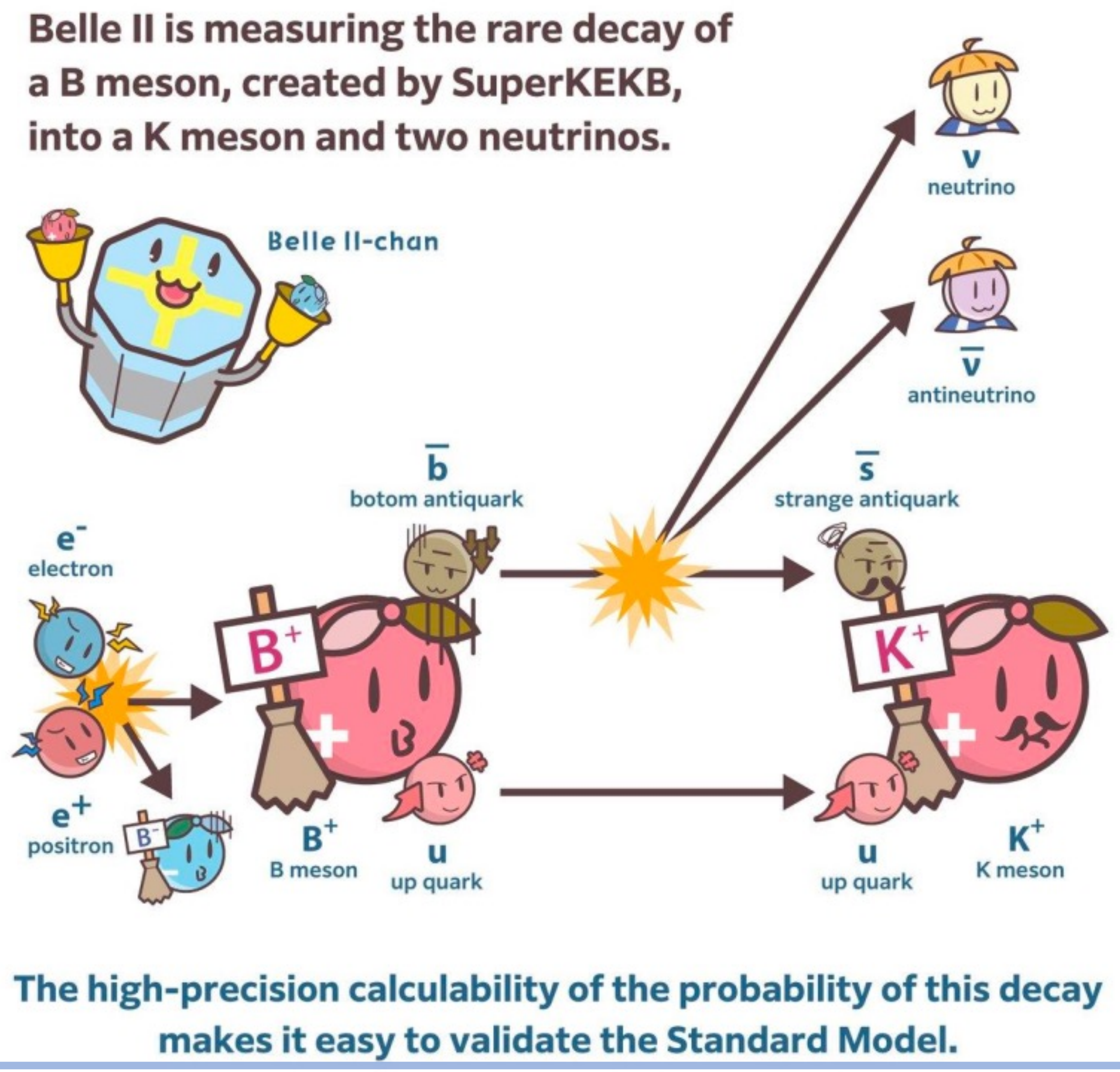
LHCb-CONF-2024-004



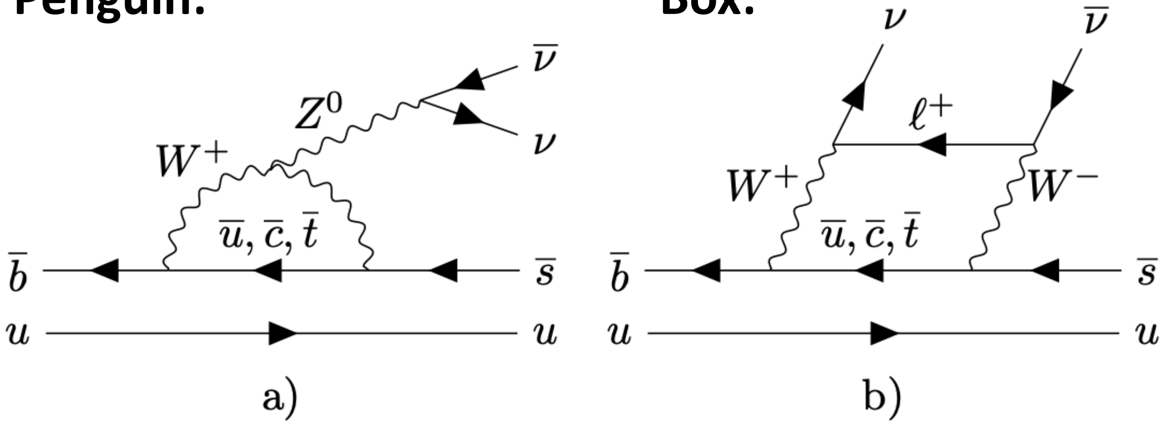
Dominated by LHCb, while Belle II does improve the precision.

$B \to K\nu\bar{\nu}$

(B2) PRD 109 (2024) 112006



Penguin: **Box:**



- **high accuracy in the SM** [PRD 107, 014511 (2023)]
  $\mathcal{B}(\mathrm{B} \to \mathrm{K}\nu\bar{\nu})$ = $(5.6 \pm 0.4) \times 10^{-6}$
- **Extensions beyond SM may lead to significant rate increase.**
- **Very challenging experimentally, not yet observed**