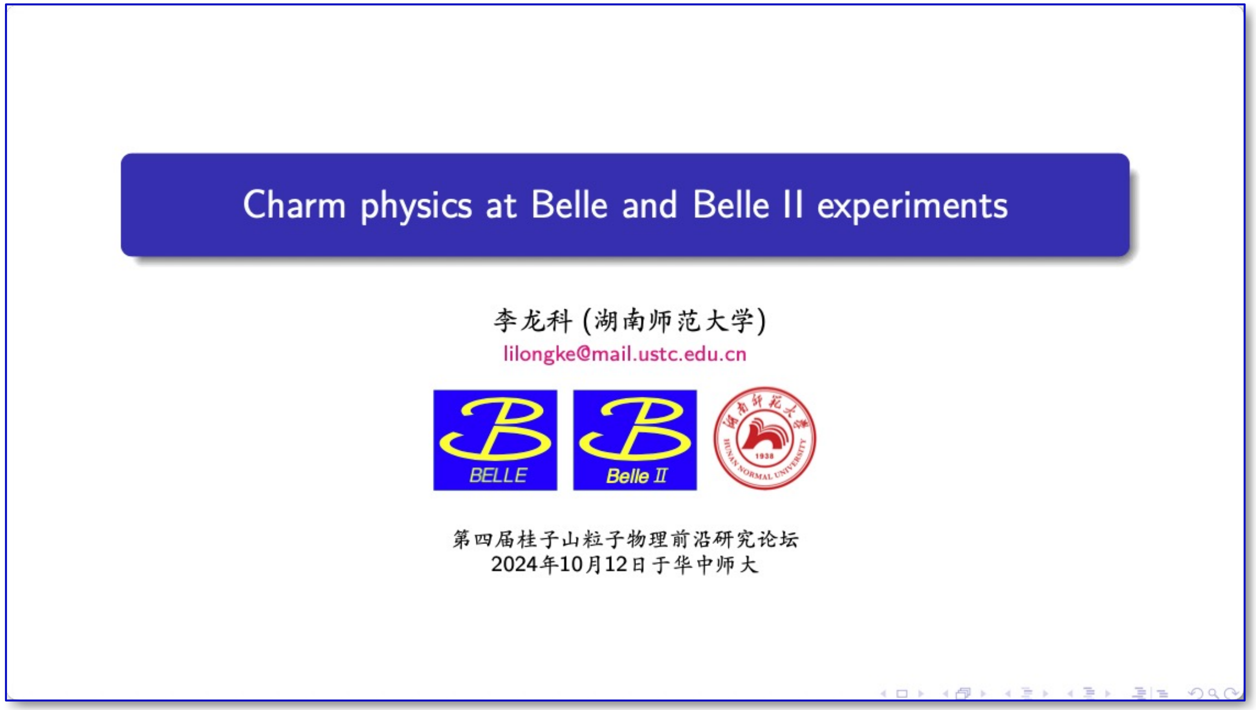
Belle II实验近期成果介绍

李龙科（湖南师范大学）

第二届重味物理前沿论坛研讨会

2025年9月13日于华中师范大学

感谢CCNU的邀请



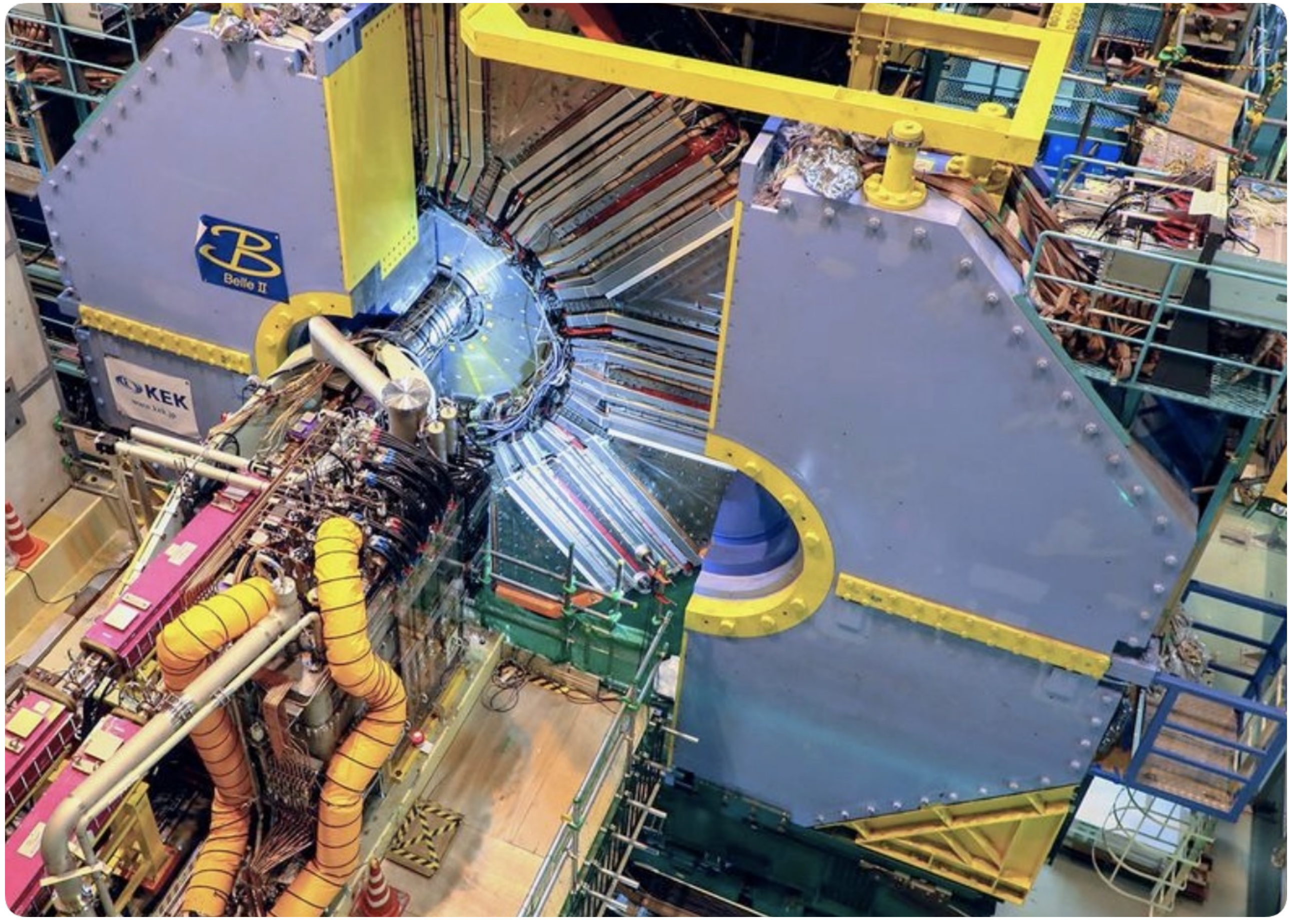
感谢华师持续提供着这么多个学术交流平台.

【内心OS】要不立个Flag：以后每学期来一次CCNU？

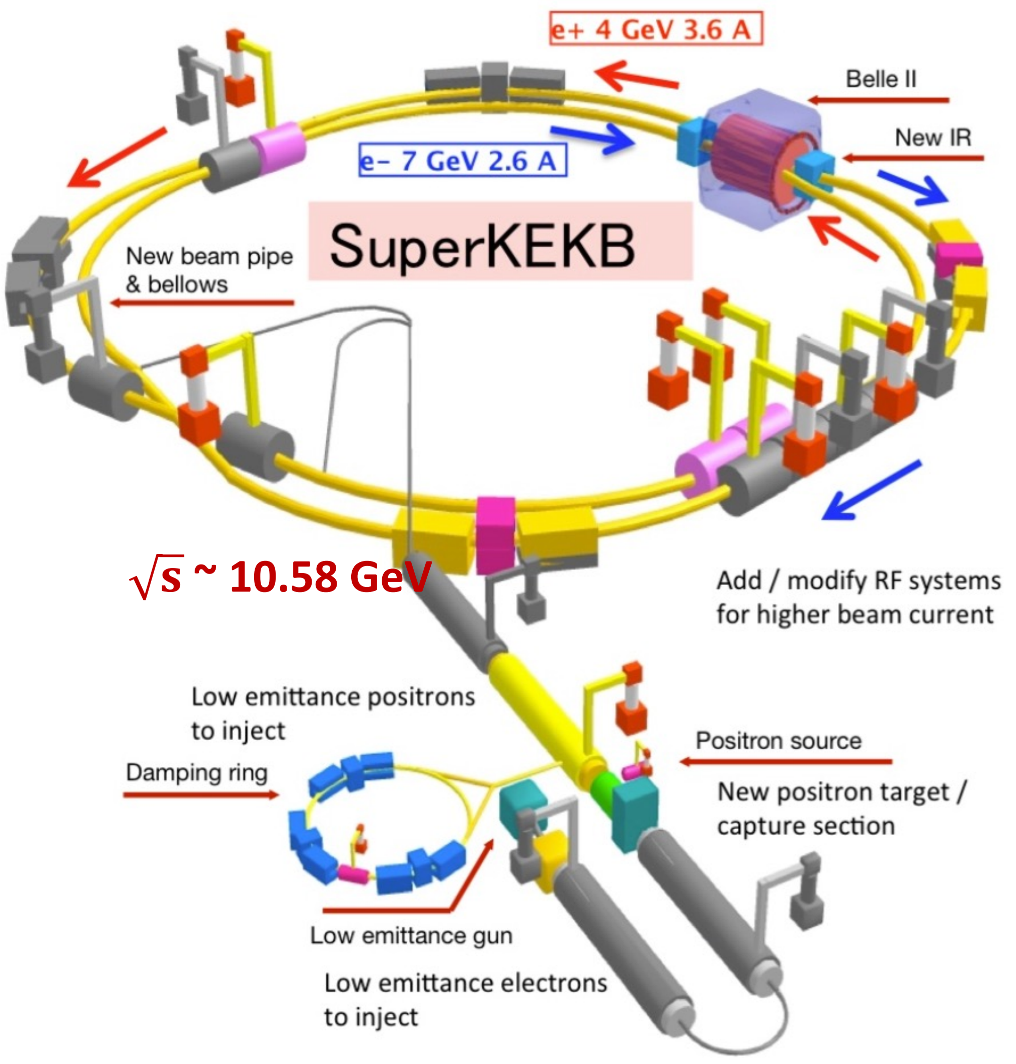
Outline

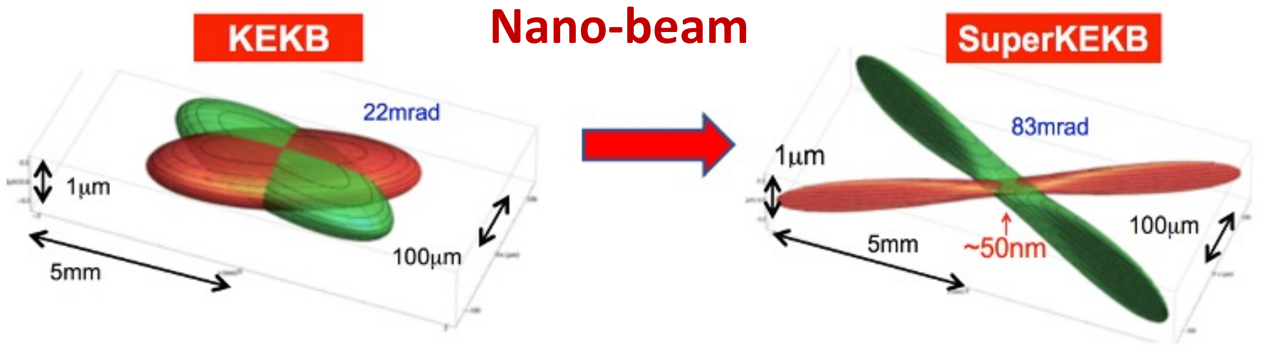
Recent = in 2025

- Luminosity
- Recent B results
- Recent charm results
- Recent $q\bar{q}$ and exotic
- Recent tau and dark sector
- Summary

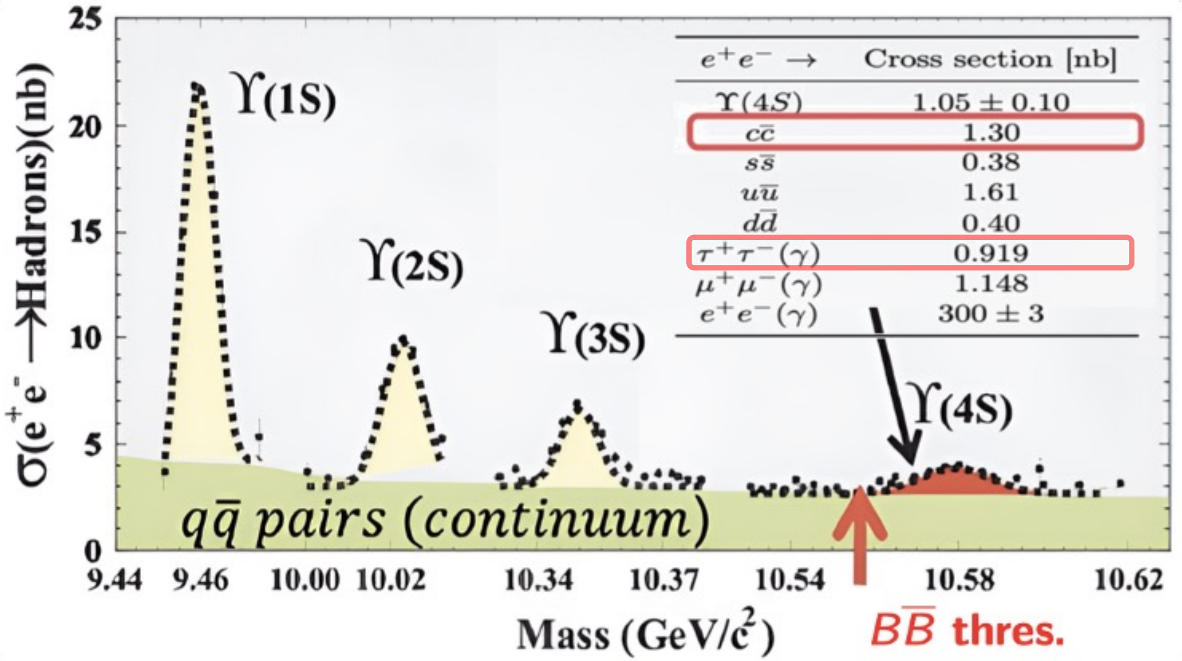


SuperKEKB





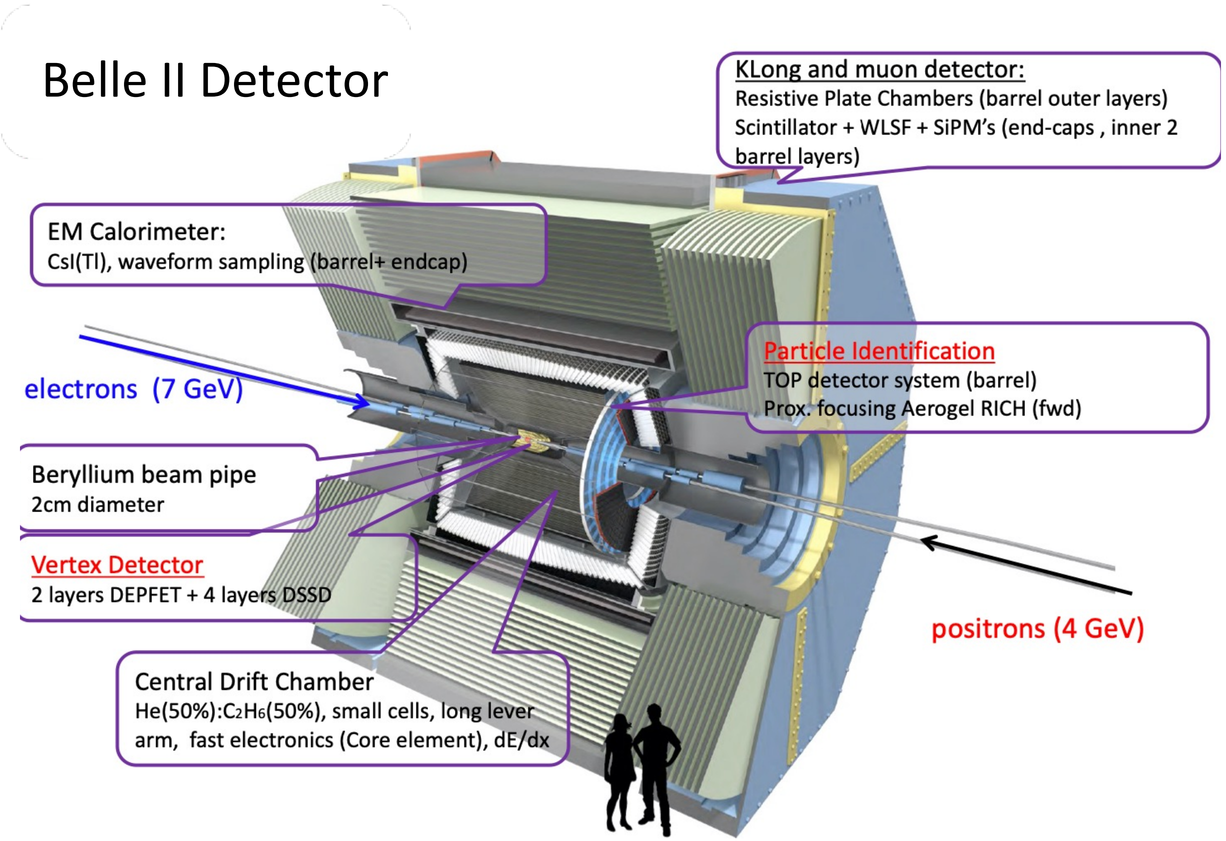
In Dec. 2024, SuperKEKB achieved WR: $\mathbf{5.1{\times}10^{34}\ cm^{-2}s^{-1}}$

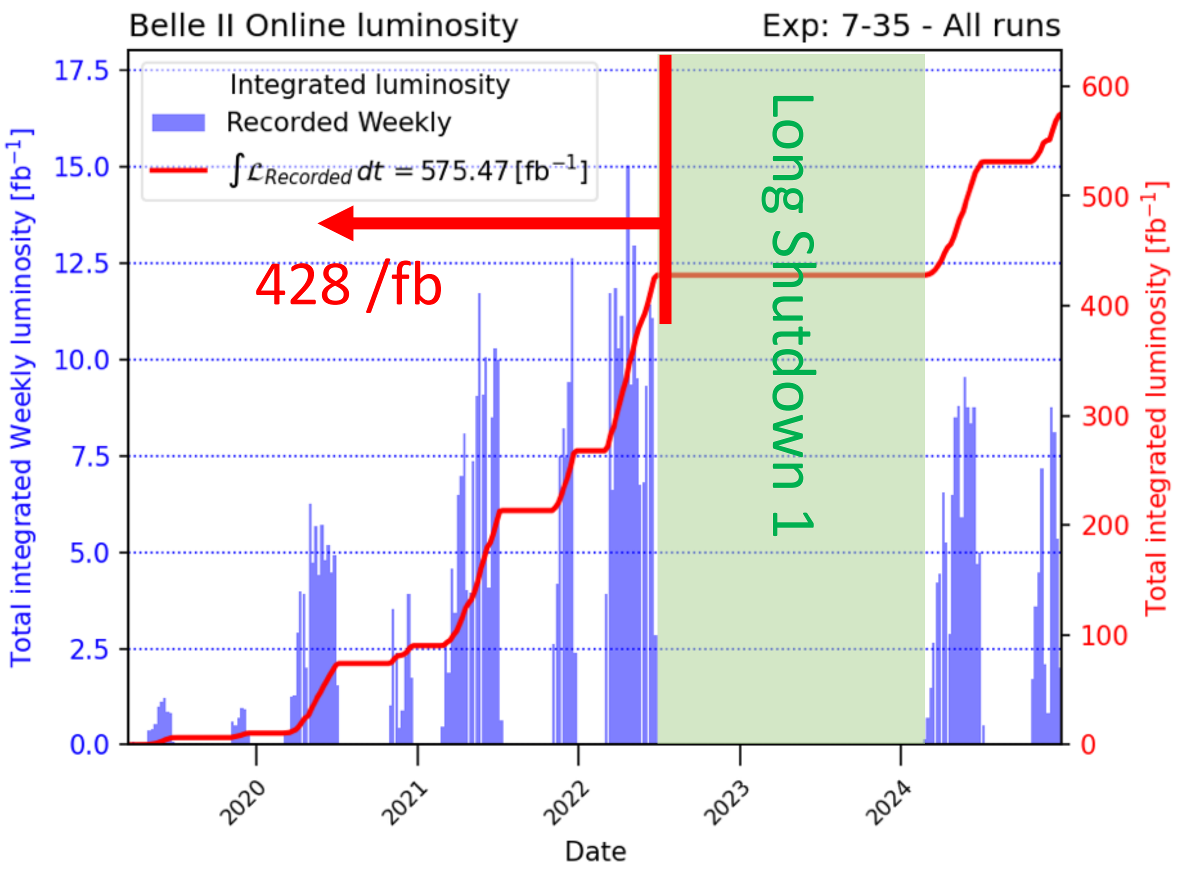


target on some special physics: other energy points

10.75 GeV (19/fb)

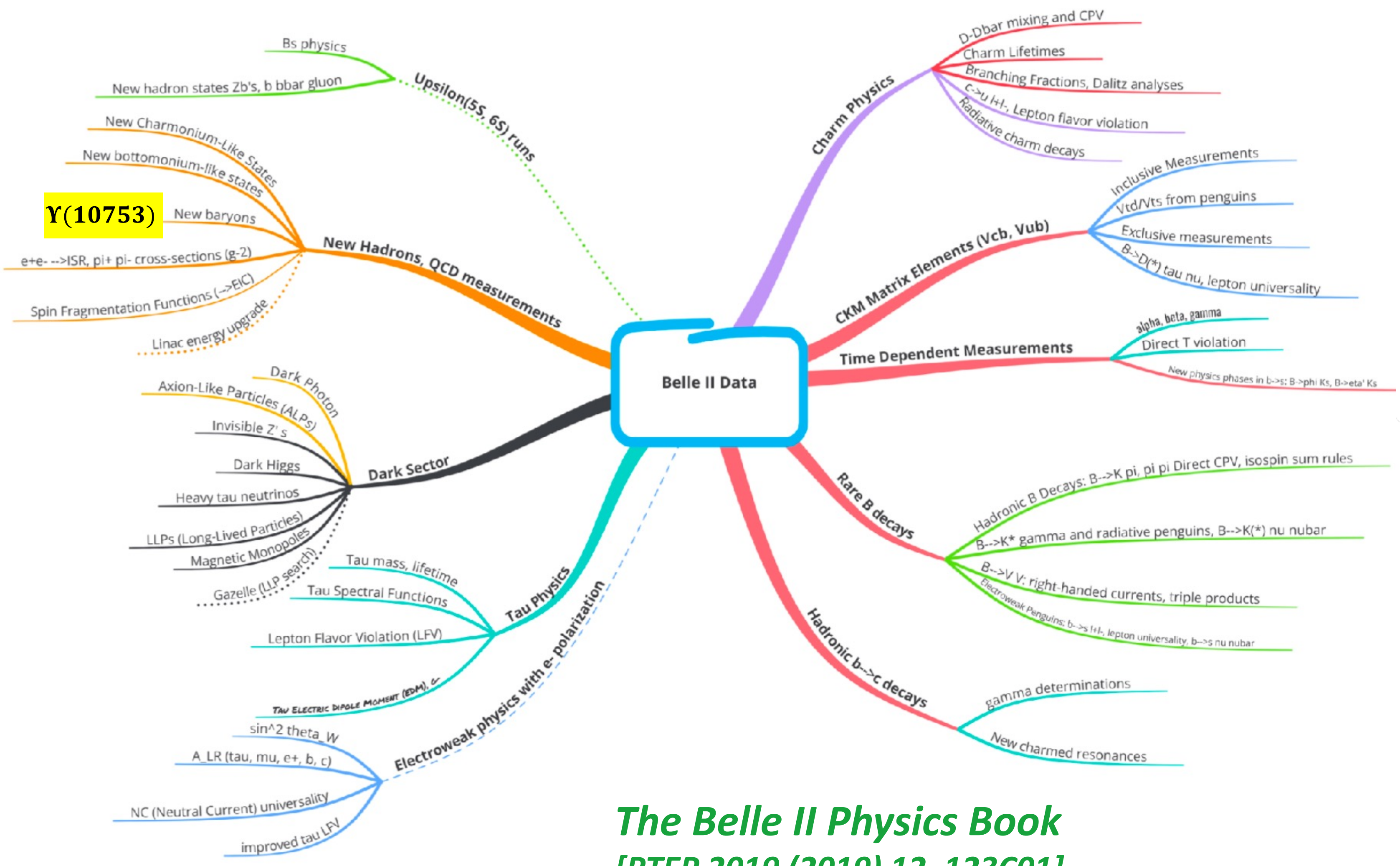
Detector & Luminosity



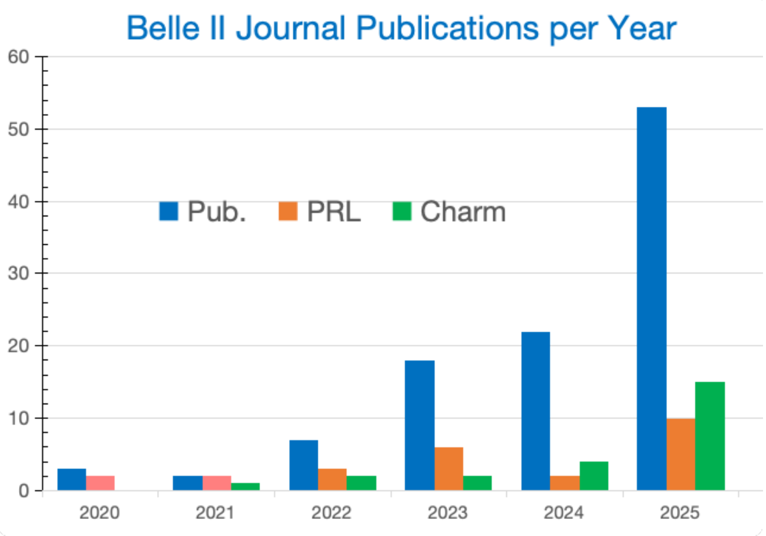


"Belle II has been designed to make precise measurements of weak interaction parameters, study exotic hadrons, and search for new phenomena beyond the Standard Model of particle physics." -- from Belle II website homepage [link].

Belle II Physics & Publications



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

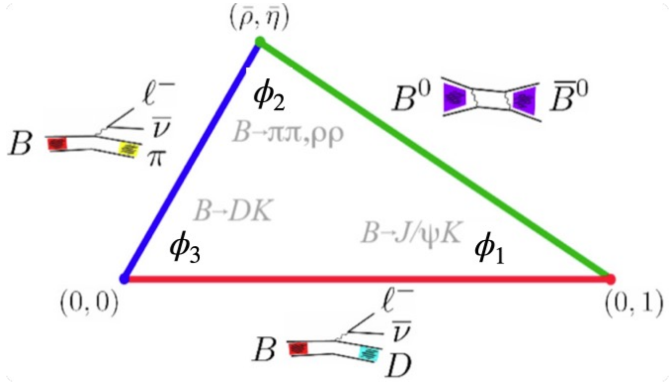


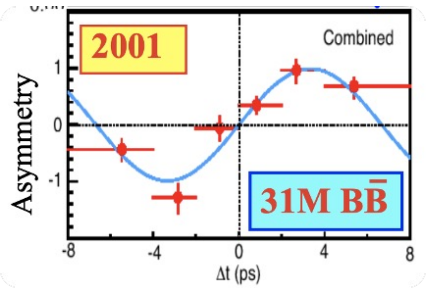
- 目前文章数（含arXiv）：>100
- PRL占比：24% < Belle（33%）

奥利给！

Outline

- Luminosity
- Recent B results
  - B CPV
  - B rare/forbidden
  - B (semi-)leptonic
- Recent charm results
- Recent $q\bar{q}$ and exotic
- Recent tau and dark sector
- Summary





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

Belle+BABAR final result:

$S = \sin 2\phi_1 = 0.677 \pm 0.020$

LHCb (PRL 132, 021801 (2024)):

$S = 0.722 \pm 0.014 \pm 0.007$

its precision is dominated by LHCb.

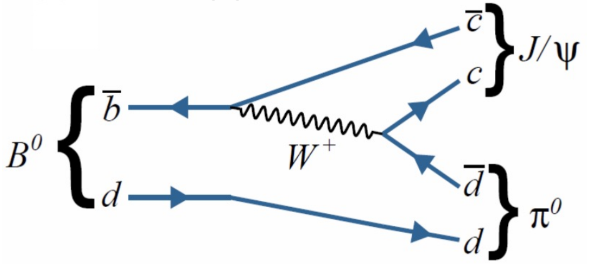
$\sin 2\phi_1$: $B^0 \to J/\psi\, \pi^0$

$\phi_1 = \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$ PRD 111 (2025) 012011

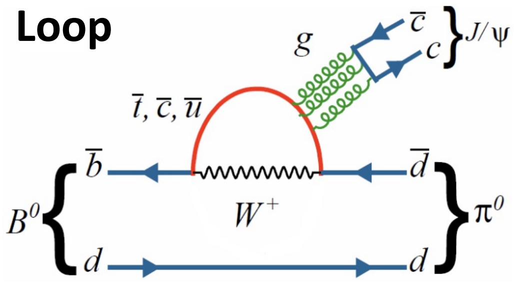
$S = -\sin 2\phi_1$, $C = 0$ if there is only tree amplitude
Tree is color and CKM suppressed
→ can be used to understand the loop contribution in $B^0 \to J/\Psi K_S^0$

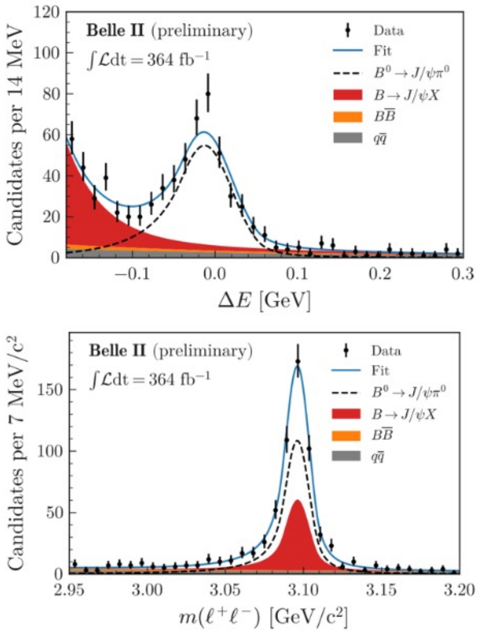
- Improved sensitivity by the better π^0 selection and GflaT
- $\Delta E - m(ll)$ fit to extract signal

Tree

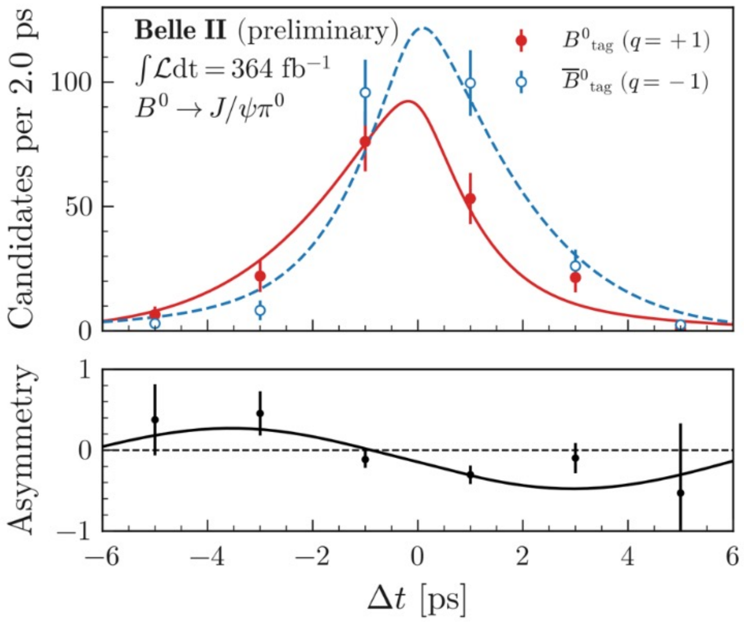


Loop





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



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

Most precise,

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

ϕ_2: $B^0 \to \pi^0\pi^0$

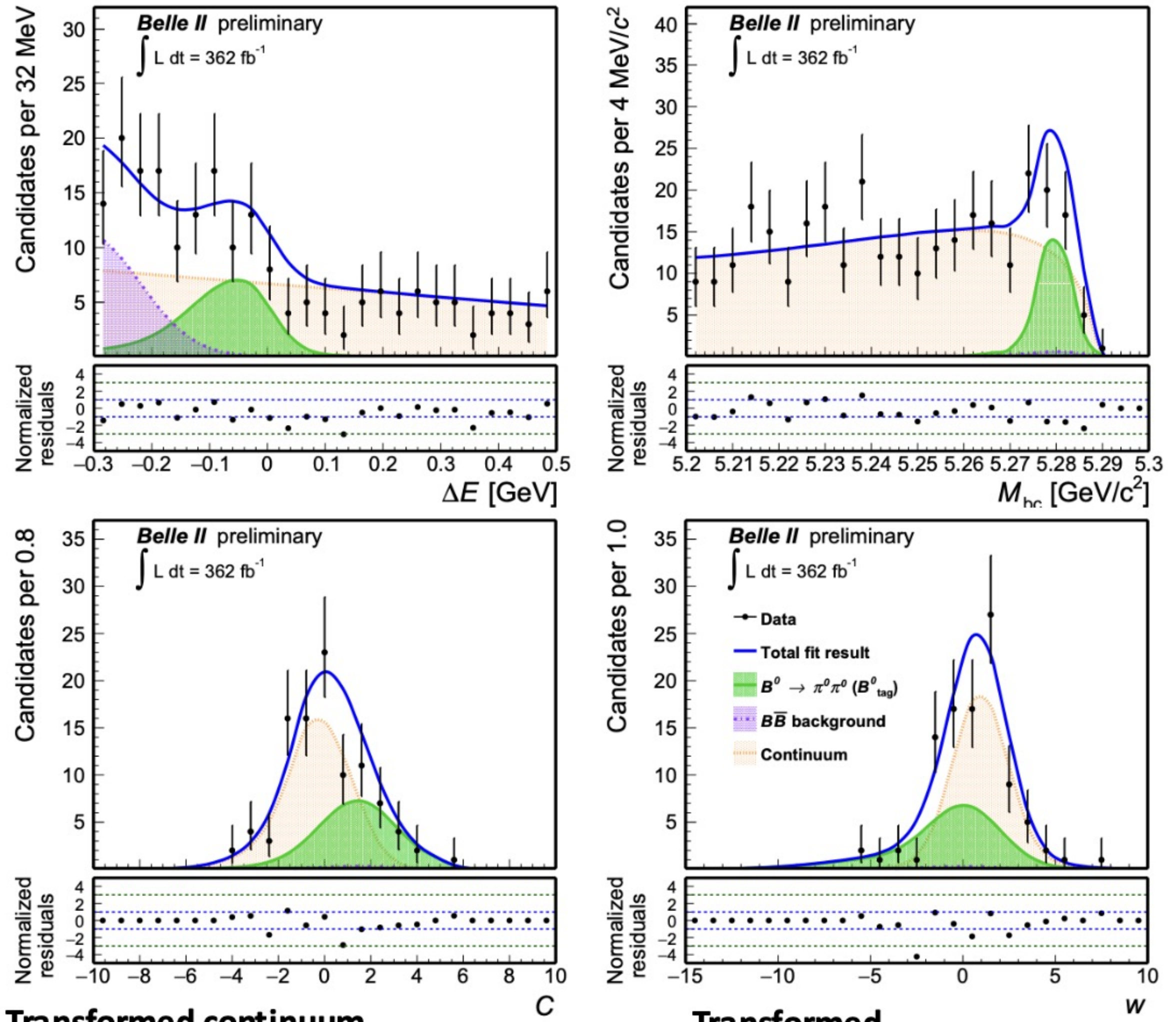
$\phi_2 = \arg(-V_{td}V_{tb}^*/V_{ud}V_{ub}^*)$

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.



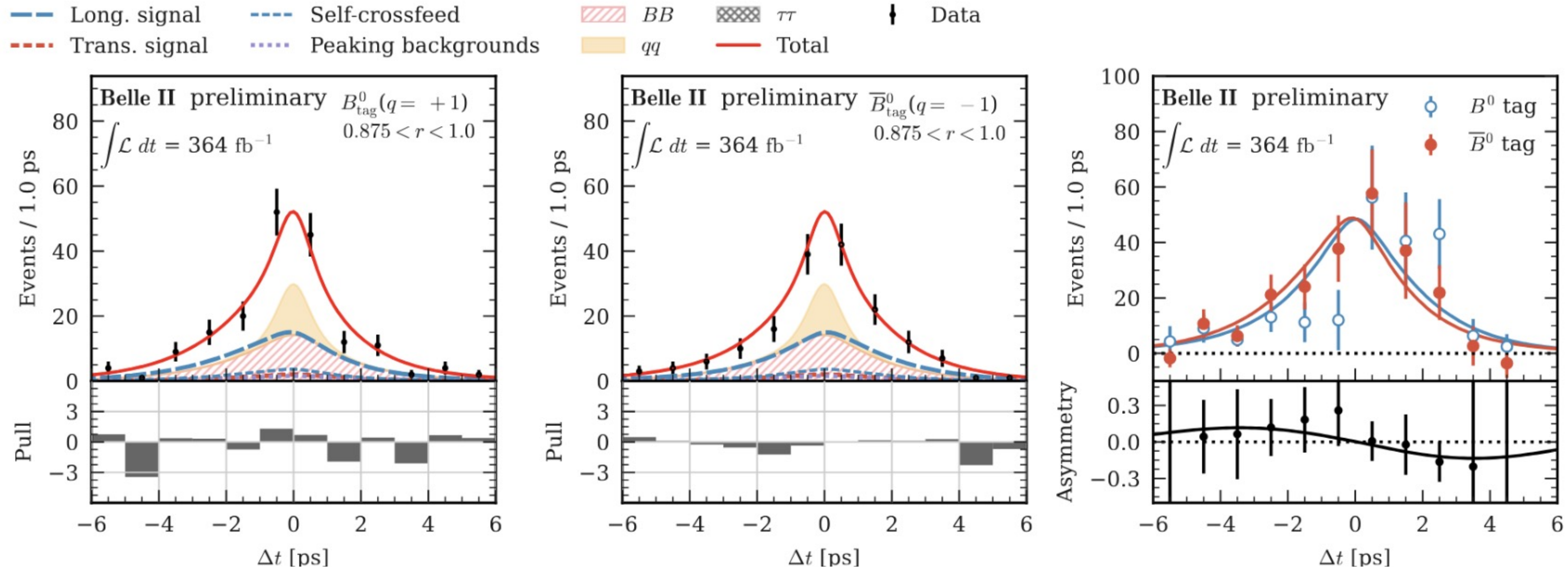
Transformed continuum suppression output

Transformed wrong flavor tag probability

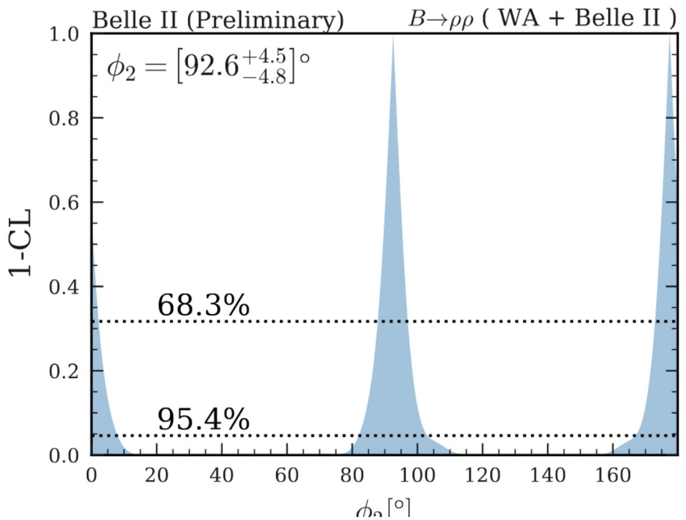
ϕ_2: $B^0 \to \rho^+\rho^-$ $\phi_2 = \arg(-V_{td}V_{tb}^*/V_{ud}V_{ub}^*)$

PRD 111 (2025) 092001

- $B^0 \to \rho^+\rho^-$: 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
$\phi_2 = (91.5^{+4.5}_{-5.4})°$

$B \to \rho\rho$ world average
+ Belle II $\rho^+\rho^-$ results
→ $\phi_2 = (92.6^{+4.5}_{-4.8})°$ 6%⬆

10

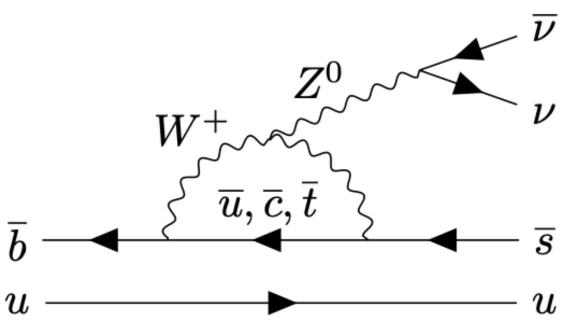
$B \to K\nu\bar{\nu}$

[PRD 109 (2024) 112006](PRD 109 (2024) 112006)

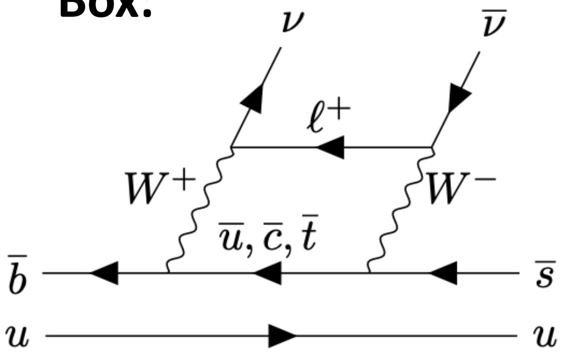
Belle II

FCNC

Penguin:



Box:



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

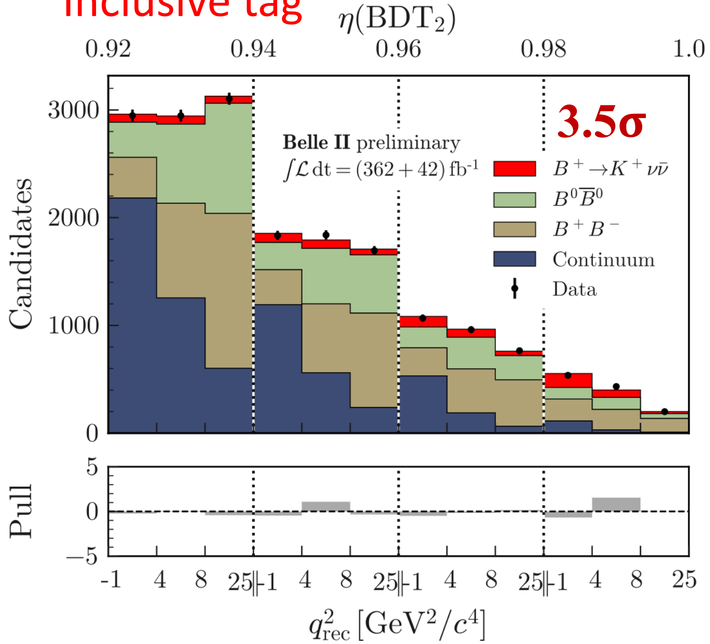
$\mathcal{B}(B \to K\nu\bar{\nu}) = (5.6 \pm 0.4) \times 10^{-6}$

Extensions beyond SM may lead to significant rate increase.

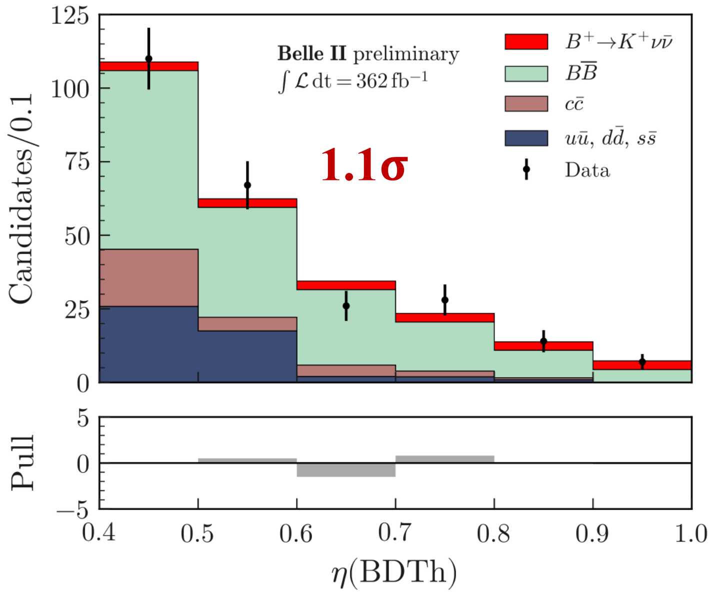
$\mathcal{B}(B \to K\nu\bar{\nu}) = (2.3 \pm 0.7) \times 10^{-5}$ **(3.5σ)**

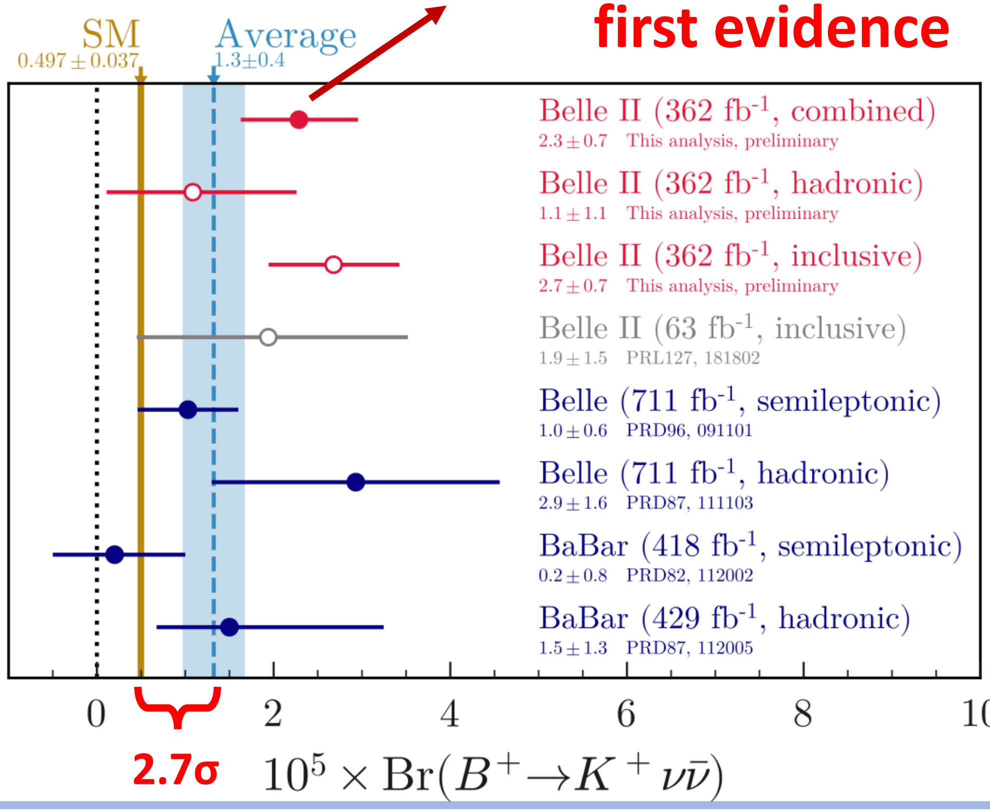
first evidence

Inclusive tag



Hadronic tag

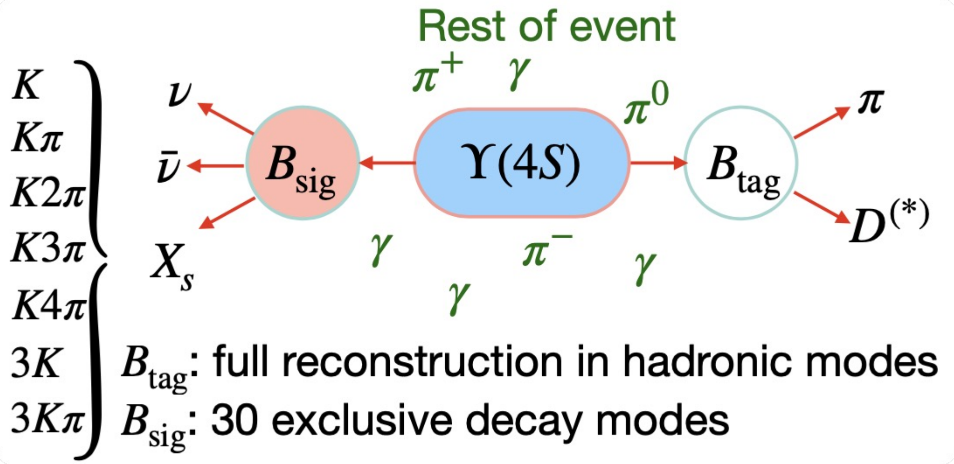




$B \to X_s \nu\bar{\nu}$ Search

Preliminary result

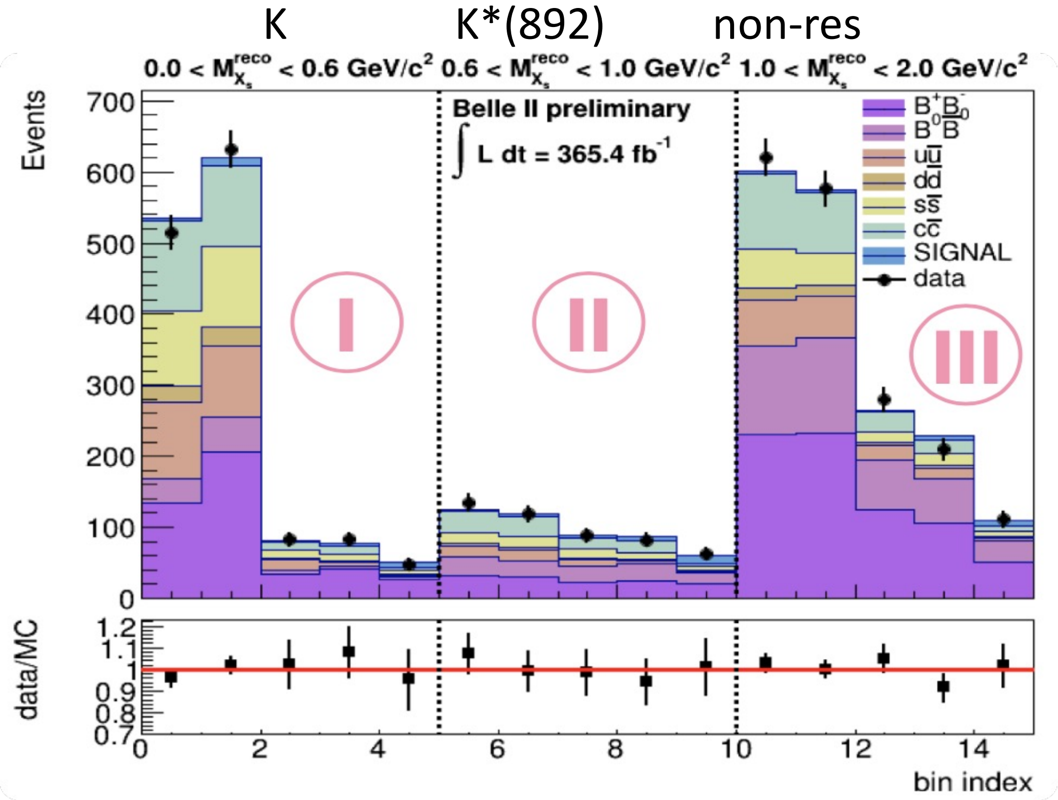
- Complimentary measurement to the exclusive $B \to K(^*)\nu\bar{\nu}$ searches.



M_{X_s} [GeV/c^2]	ϵ	N_{sig}	$\mathcal{B}$ [10^{-5}] Central value	UL_{obs}	UL_{exp}
* [0, 0.6]	0.26%	10^{+18+18}_{-17-16}	$0.5^{+0.9+0.9}_{-0.8-0.8}$	2.5	2.4
[0.6, 1.0]	0.12%	37^{+27+31}_{-25-26}	$3.8^{+2.8+3.2}_{-2.6-2.7}$	10.1	7.3
[1.0, m_B]	0.06%	33^{+44+63}_{-42-53}	$7.3^{+9.6+13.7}_{-9.3-11.5}$	34.4	27.4

*Compatible with the hadronically-tagged Belle II $B^+ \to K^+\nu\bar{\nu}$ result

➢ Main syst. error: MC statistics, background normalization



Full M_{X_s} range result:

$$\mathcal{B}(B \to X_s\nu\bar{\nu}) = [11.6^{+8.9}_{-8.6}(\text{stat})^{+13.5}_{-11.4}(\text{syst})] \times 10^{-5}$$

$$\mathcal{B}(B \to X_s\nu\bar{\nu}) < 3.6 \times 10^{-4}\ (90\ \%\ \text{CL})$$

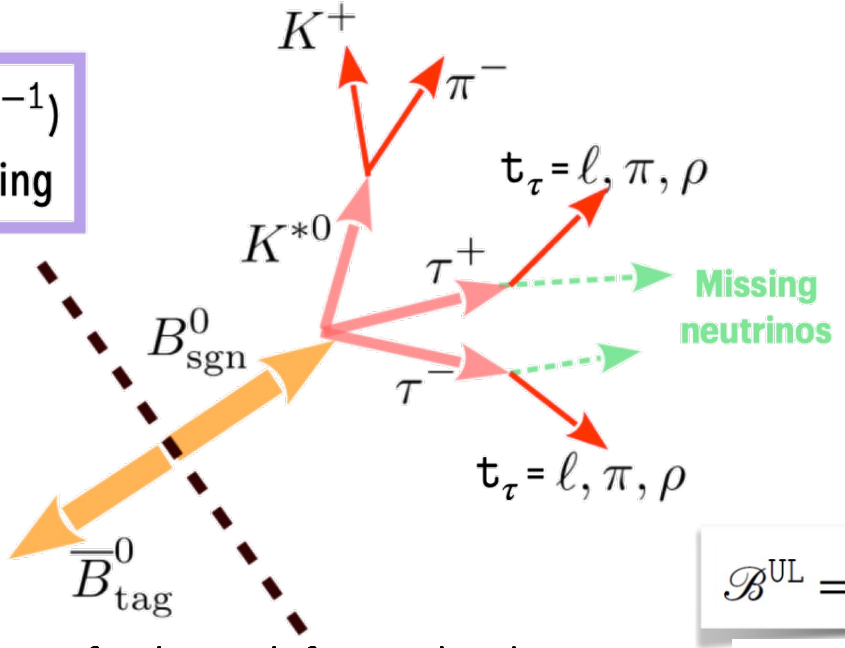
Most stringent upper limit on the inclusive rate

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

arXiv:2504.10042

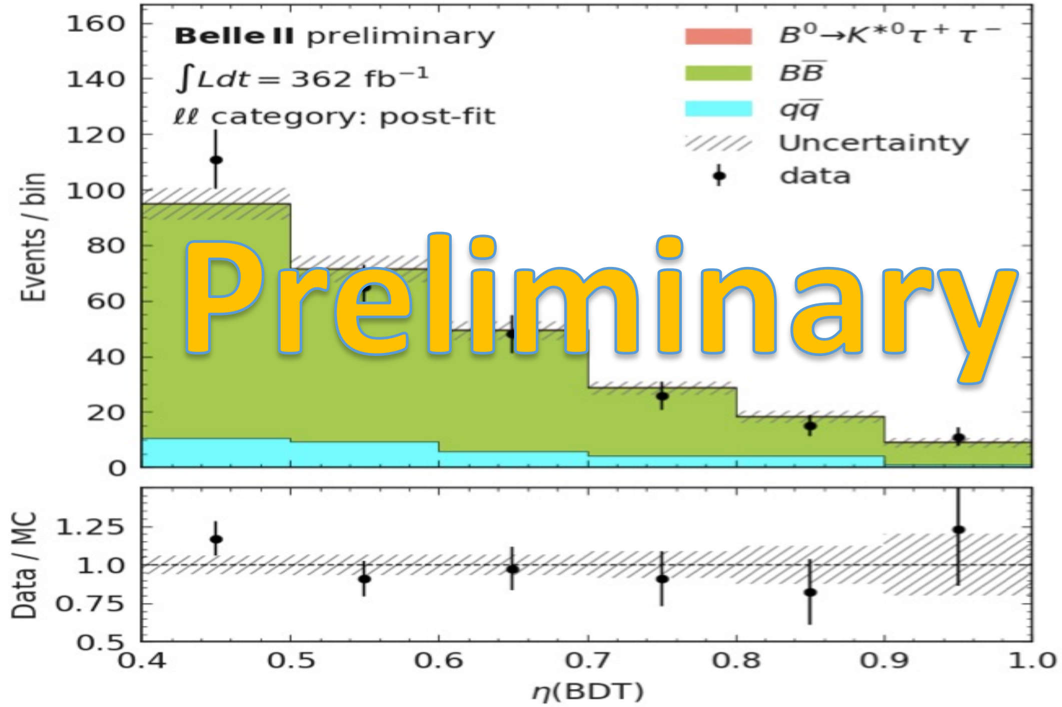
- Non-SM particles, explaining recent anomalies, would enhance BF upto $\mathcal{O}(10^3)$ due to presence of two τs
- Main challenge: no signal peaking kinematic observable due to multiple undetected neutrinos
- Relies on missing energy information and residual calorimeter energy; Belle II is ideally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

$\mathcal{B}^{UL} = 1.8 \times 10^{-3}$ 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

$B^0 \to K_S^0 \tau^\pm \ell^\mp$: first search

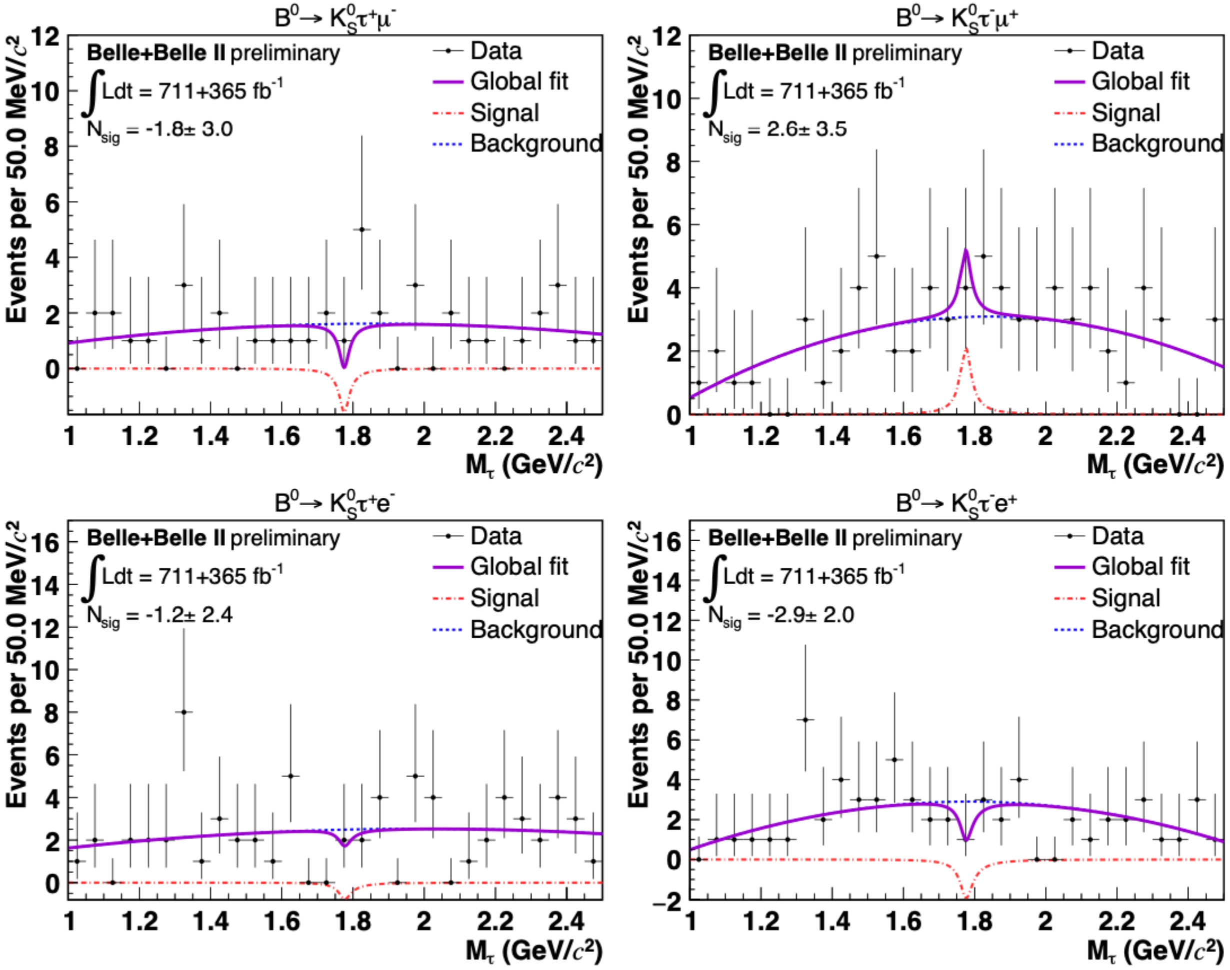
PRL 135 (2025) 041801

- 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% C.L.



$B^+ \to \mu^+ \nu_\mu$

Approved yesterday

Preliminary result

BELLE   Belle II

- SM branching fraction:

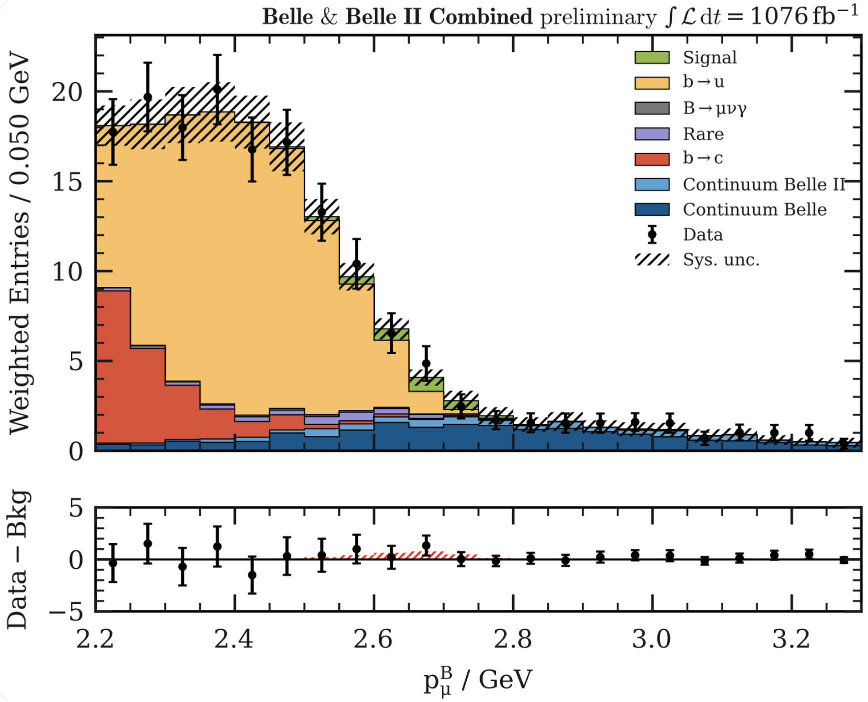
$$\mathcal{B}(B^+ \to \mu^+\nu_\mu) = \frac{G_F^2 m_B m_\mu^2}{8\pi}\left(1 - \frac{m_\mu^2}{m_B^2}\right)^2 f_B^2 \left|V_{ub}\right|^2 \tau_{B^+} \,,$$

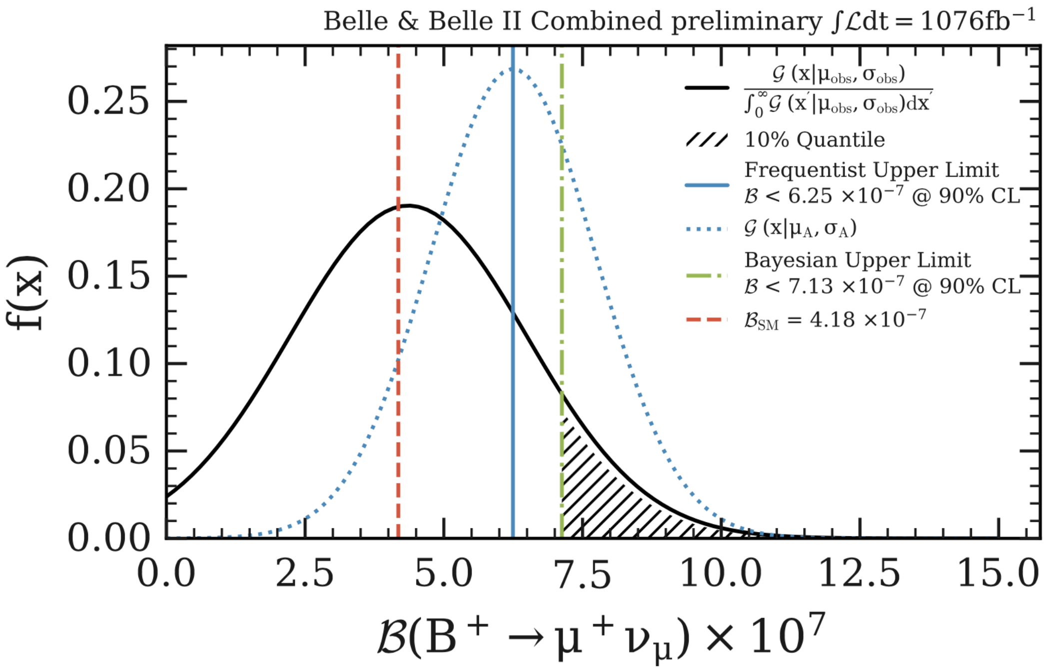
- SM predicted: $B = (4.18 \pm 0.44) \times 10^{-7}$.
- Belle: $B = (5.3 \pm 2.0 \pm 0.9) \times 10^{-7}$ (2.8σ) (PRD 101 (2020) 032007)

- Belle + Belle II (1076/fb):
  - $B(B^+ \to \mu^+\nu_\mu) = (4.36 \pm 1.89 \pm 1.01) \times 10^{-7}$ (2.35σ)

45页的文章！

- Also search for sterile neutrinos, no signals observed.



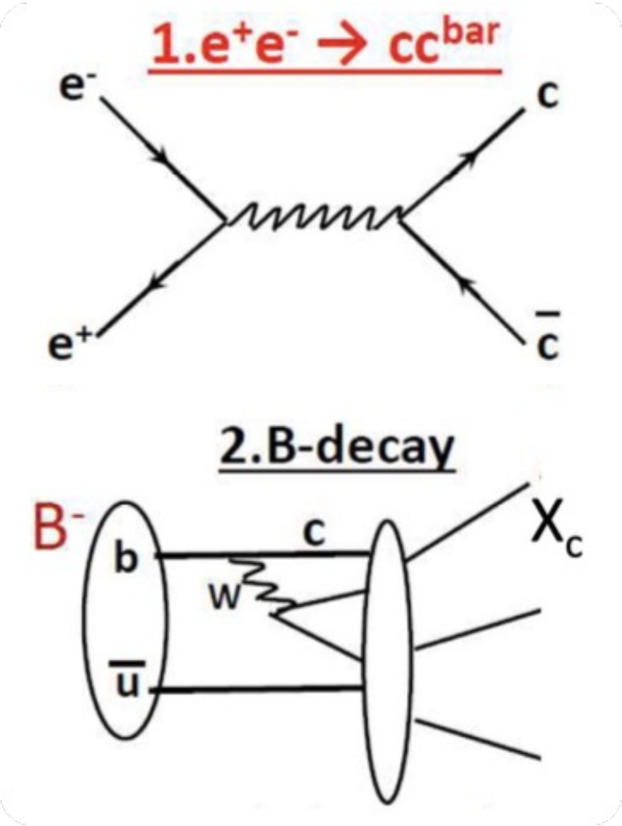


These are the most stringent limits to date.

Outline

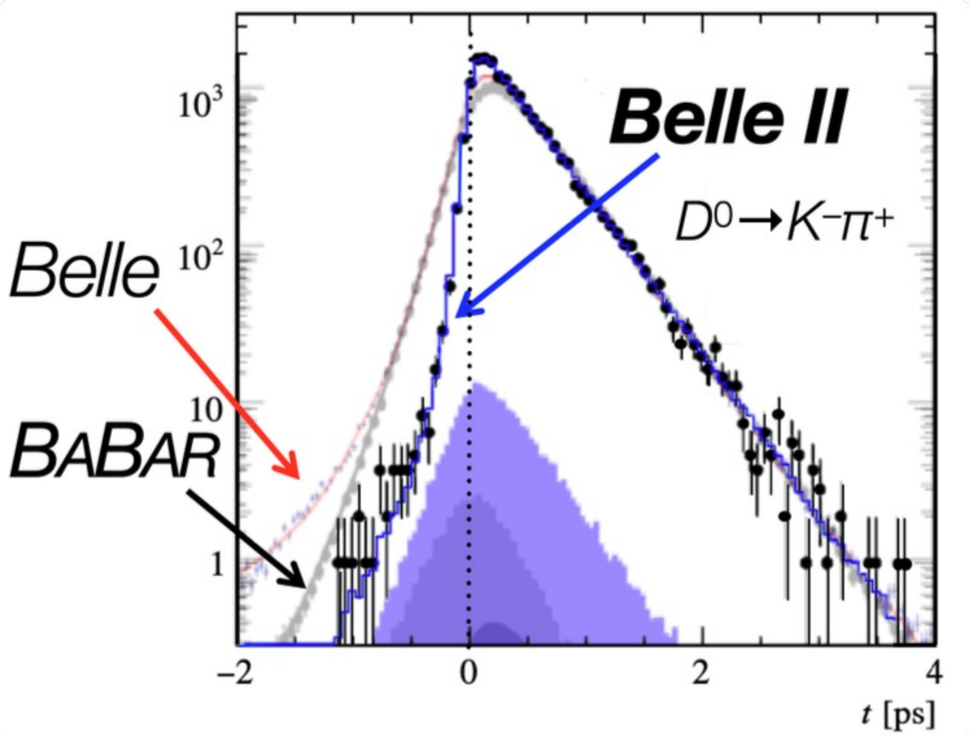
- Luminosity
- Recent B results
- Recent charm results
  - charm CPV
  - charmed baryon
  - charm spectrum
- Recent $q\bar{q}$ and exotic
- Recent tau and dark sector
- Summary

Belle (II): charm super-factory



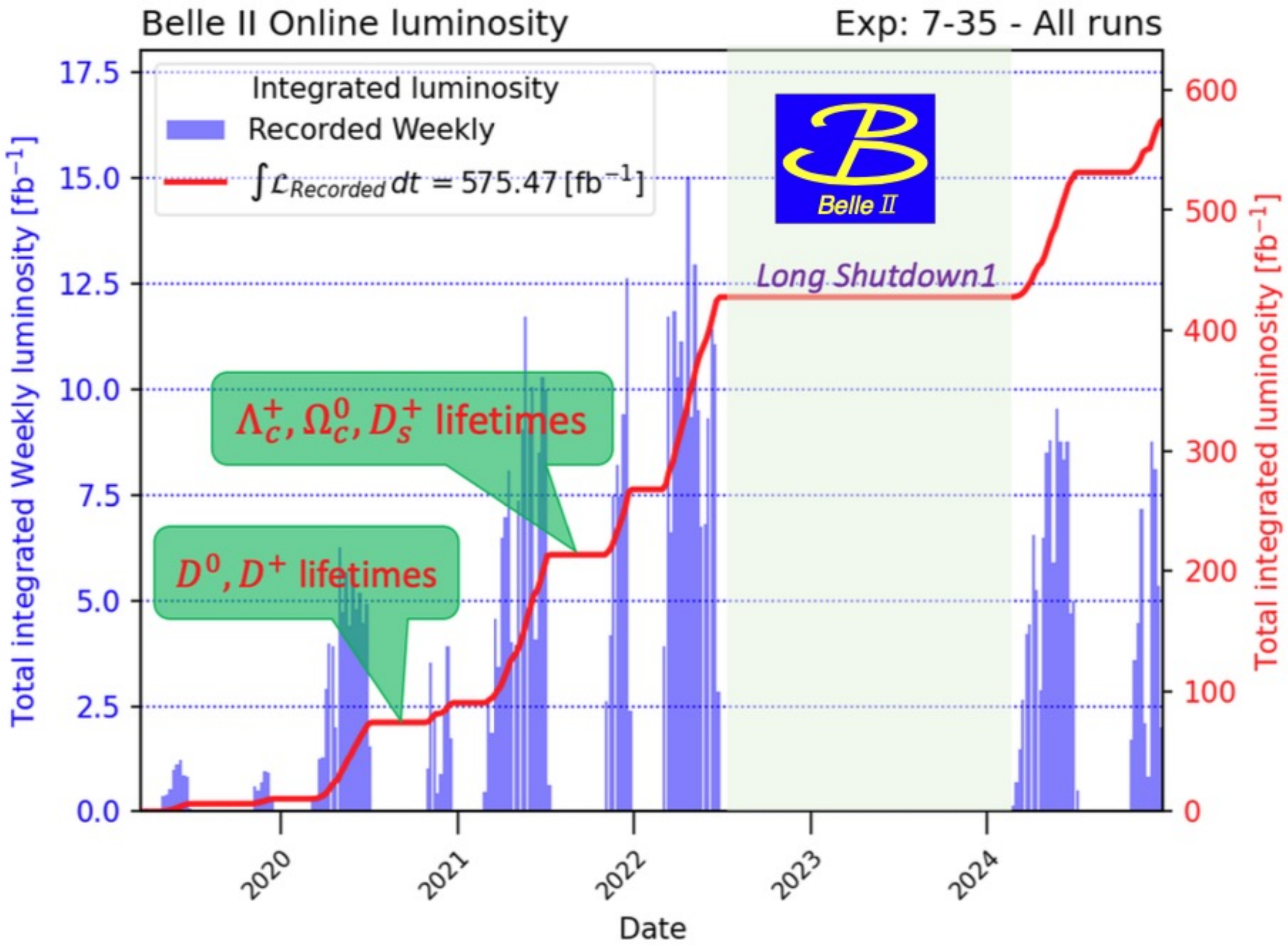
PS: no Λ_b^0 sample

First charm wave: lifetimes



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).



most precise charm lifetimes:

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

New charm wave: Charm CPV

- Charm CPV effect is very small (10^{-3} level or smaller); a sensitive probe for New Physics.
- 2019, LHCb: $\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-) = (-15.4 \pm 2.9)\times 10^{-4}$ (5.3σ)[1];
  2023, LHCb: $A_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-) = (2.32 \pm 0.61)\times 10^{-3}$ (3.8σ)[2].
  ➔ to understand this CPV, more results and more precise measurements are desired.
- CPV <2025: observed in all open-flavor meson sector, not yet in the baryon sector.
  2025, LHCb: $A_{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (2.45 \pm 0.46 \pm 0.10)\%$ (5.2σ)[3].
  ➔ charmed baryon CPV, the last piece for heavy-flavor hadron CPV, yet to be observed.

[1]LHCb, PRL 122, 211803 (2019)
[2]LHCb, PRL 131, 091802 (2023)
[3]LHCb, Nature 643 (2025) 8074

Belle II

New charm wave.

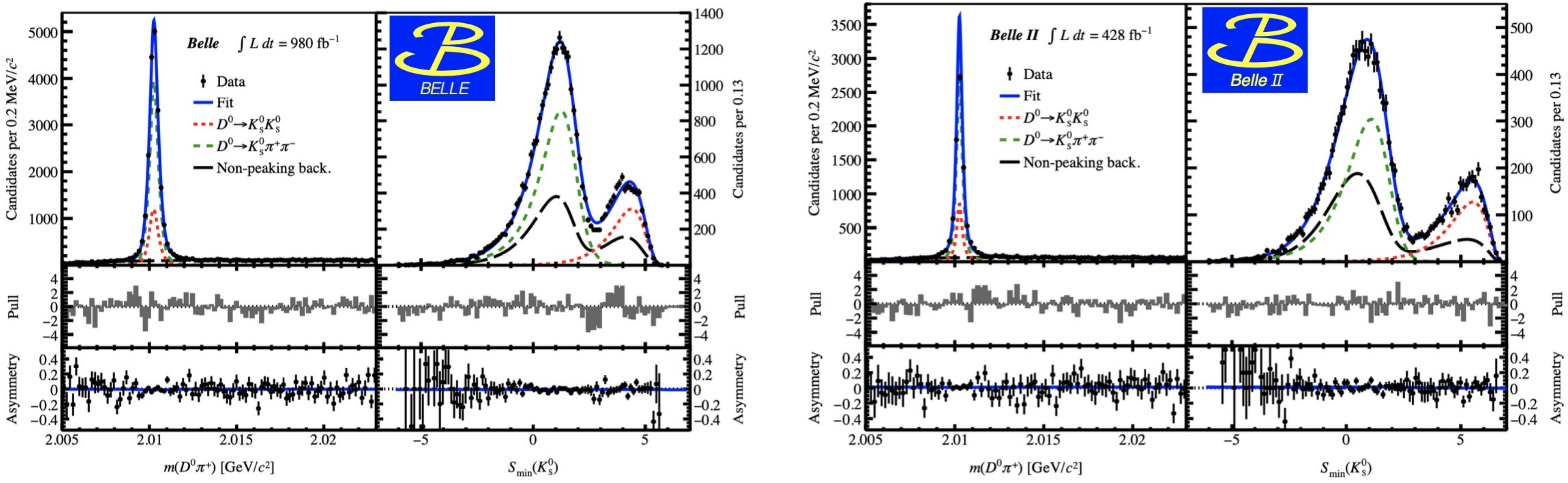
去年桂子山论坛讲过

- $A_{CP}(D^0 \to K_S^0 K_S^0)$: **PRD 111, 012015 (2025)** + PRD 112, 012017 (2025)
- $A_{CP}^X(D^+ \to K_S^0 K^-\pi^+\pi^+)$: **JHEP 04 (2025) 036**
- $A_{CP}(D^0 \to \pi^0\pi^0)$: PRD 112, 012006 (2025)
- $A_{CP}(D^+ \to \pi^+\pi^0)$: PRD 112, L031101 (2025)
- $A_{CP}(D^0 \to \pi^+\pi^-\pi^0)$: preliminary result
- $A_{CP}(\Lambda_c^+ \to ph^+h^-)$, $A_{CP}(\Xi_c^+ \to \Sigma^+h^+h^-)$: preliminary result

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

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

PRD 112, 012017 (2025)

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

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

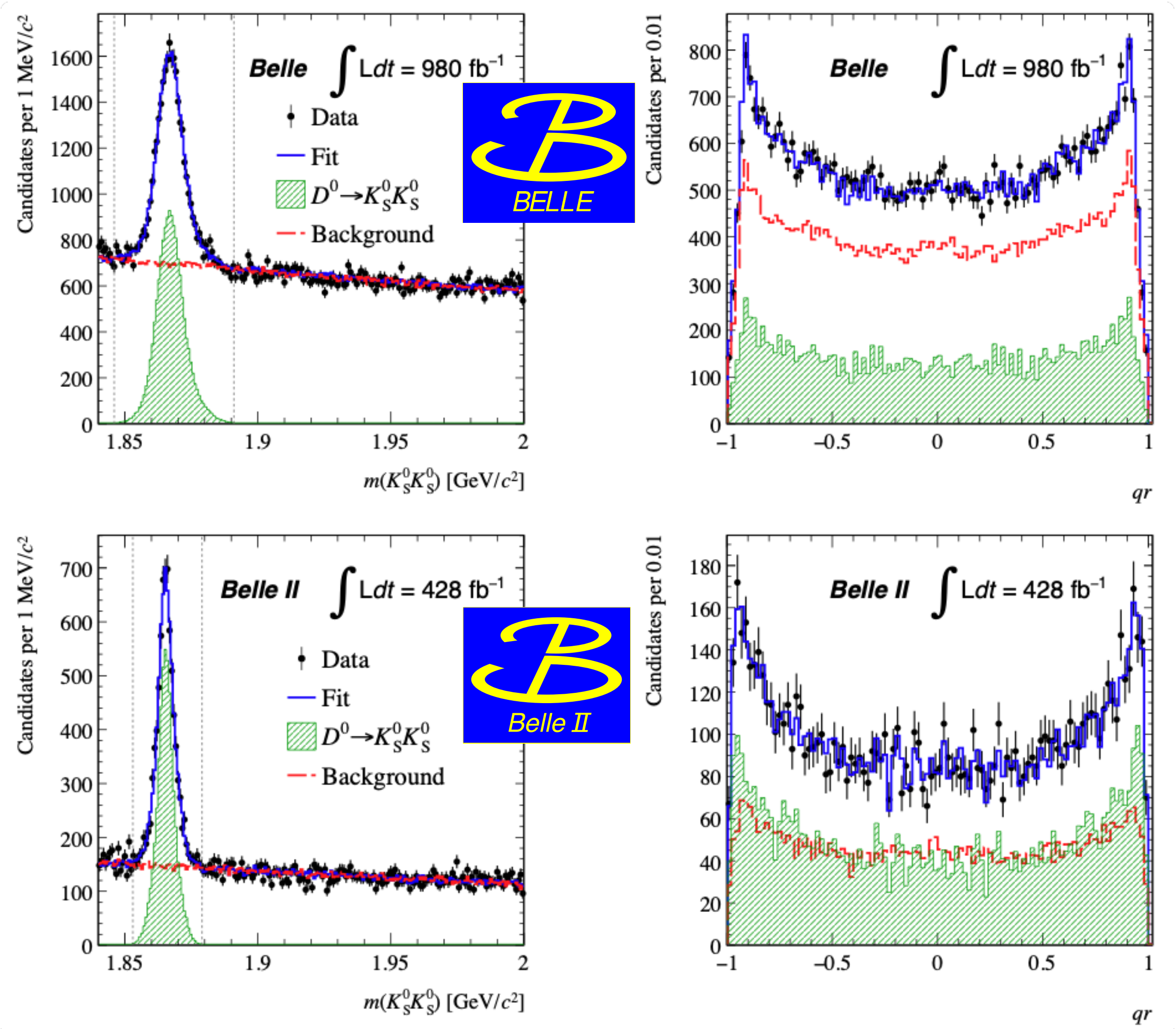
Then combining it with that from D*+-tagged sample:

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

most precise

- B2+LHCb vs. CMS: 2.6σ diff → 2.1σ diff

➔ Looking forward to LHCb's updated result (9/fb)



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

PRD 112, 012006 (2025)

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

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

  - if $R \neq 0$, CPV: from ΔI=1/2 amplitude; if R=0 & a $A_{CP}^{\rm dir} \neq 0$, 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:

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

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:

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

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

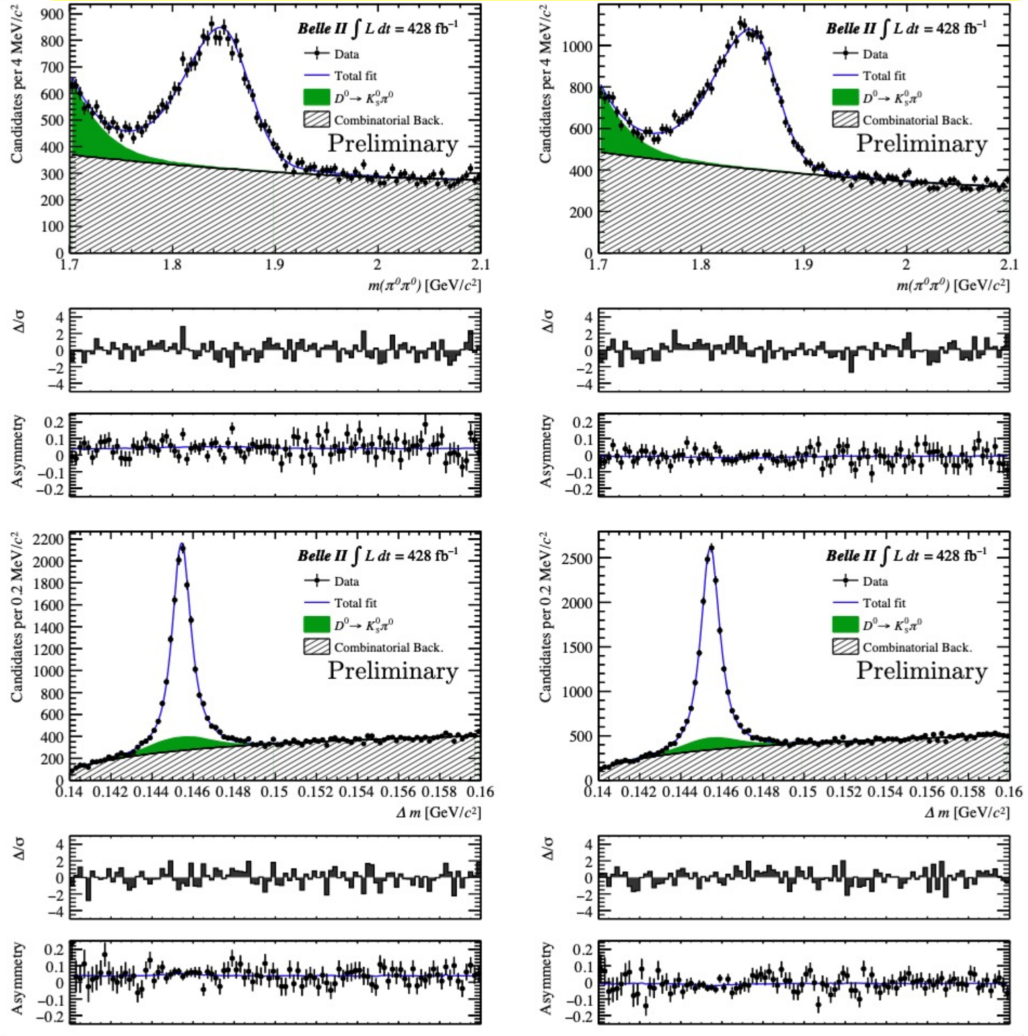
$f = \pi^0\pi^0;\ K\pi;\ K\pi,\ \text{untag}.$

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

[PRD 112, 012006 (2025)]

Belle II

$\cos\theta^*(D^{*+}) > 0$ 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,

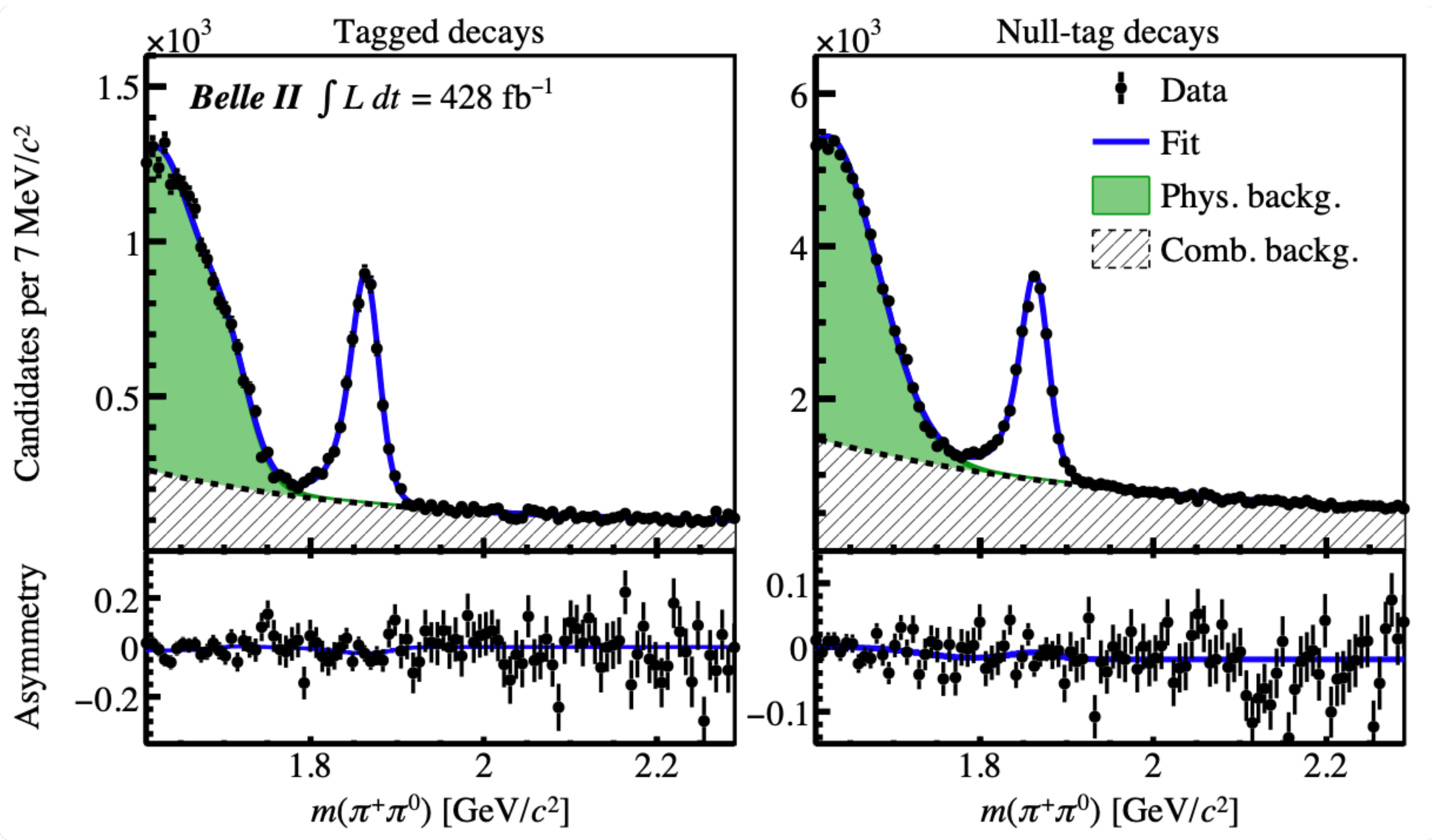
$$R = (1.5 \pm 2.5)\times 10^{-3}$$

→ 20% improved precision

22

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

PRD 112, L031101 (2025)



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

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

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

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

Belle II (428/fb) result:

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

➔ most precise; and 30% improved precision compared to Belle's result σ=1.26% (980/fb) [PRD 97, 011101 (2018)]

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

Preliminary result

$$\mathcal{A}_{\rm raw}^{\pi\pi\pi^0} = \frac{N(D^0 \to \pi^+\pi^-\pi^0) - N(\bar{D}^0 \to \pi^+\pi^-\pi^0)}{N(D^0 \to \pi^+\pi^-\pi^0) + N(\bar{D}^0 \to \pi^+\pi^-\pi^0)}$$

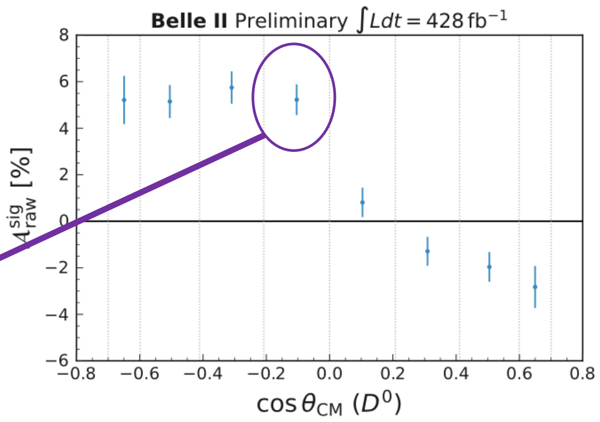
$$\mathcal{A}_{\rm raw}^{\pi\pi\pi^0} \simeq \mathcal{A}_{CP} + \mathcal{A}_{\rm prod} + \mathcal{A}_{\varepsilon}^{\pi\pi\pi^0} + \mathcal{A}_{\varepsilon}^{\pi_{\rm tag}}.$$

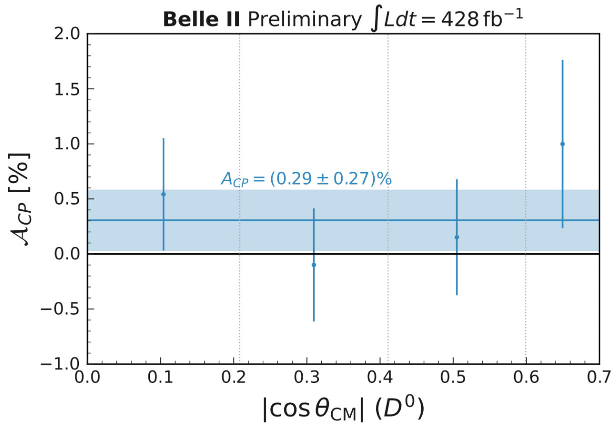
$$\mathcal{A}_{\varepsilon}^{\pi_{\rm tag}} = \mathcal{A}_{\rm raw}^{\rm tagged} - \mathcal{A}_{\rm raw}^{\rm untagged}$$

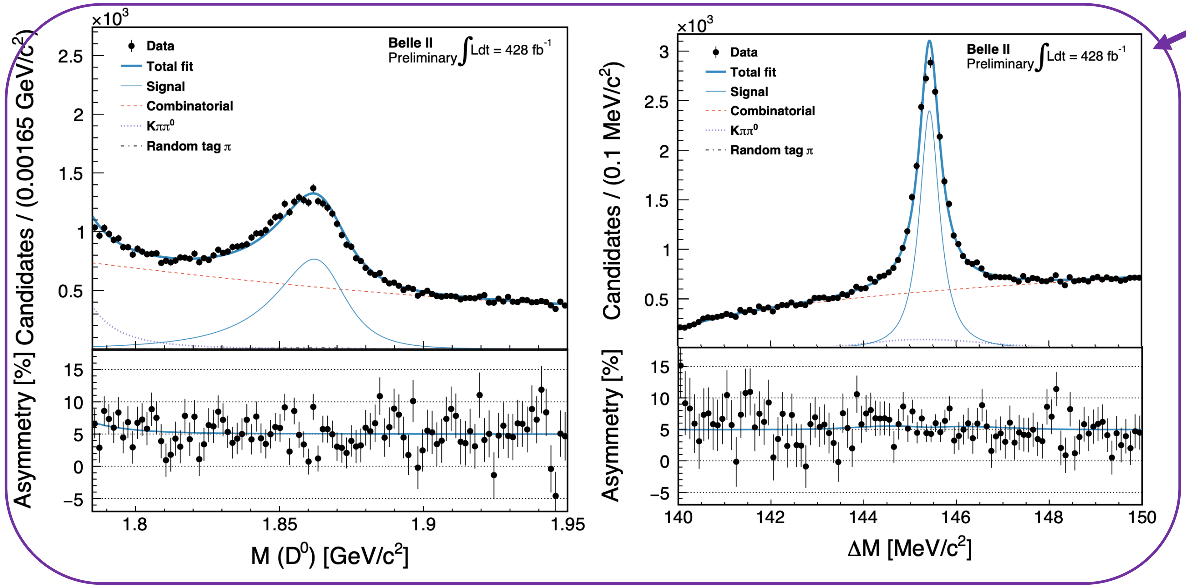
$$\mathcal{A}_{\rm raw}^{\rm tagged} \simeq \mathcal{A}_{\rm prod} + \mathcal{A}_{\varepsilon}^{K\pi} + \mathcal{A}_{\varepsilon}^{\pi_{\rm tag}}$$

$$\mathcal{A}_{\rm raw}^{\rm untagged} \simeq \mathcal{A}_{\rm prod} + \mathcal{A}_{\varepsilon}^{K\pi},$$

$$\mathcal{A}_{\pm i} = \mathcal{A}_{{\rm raw},\pm i}^{\pi\pi\pi^0} - \mathcal{A}_{{\rm raw},\pm i}^{\rm tagged} + \mathcal{A}_{{\rm raw},\pm i}^{\rm untagged} \qquad \mathcal{A}_{CP}^{i} = \frac{\mathcal{A}_{+i} + \mathcal{A}_{-i}}{2}$$







Time-integrated CP asymmetry using 428/fb@Belle II:

$$A_{CP}(D^0 \to \pi^+\pi^-\pi^0) = (0.29 \pm 0.27 \pm 0.13)\%$$

- consistent with CP symmetry
- 34% more precise than the world's best result from BaBar, despite an increase of only ~10%*Lumin.

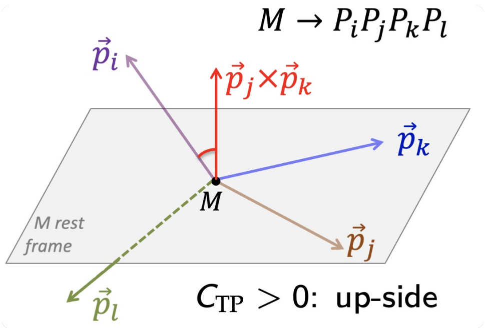
Next: Dalitz-plot- or time-dependent searches for CPV

Charm CPV: $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$

JHEP 04 (2025) 036

三重积变量:

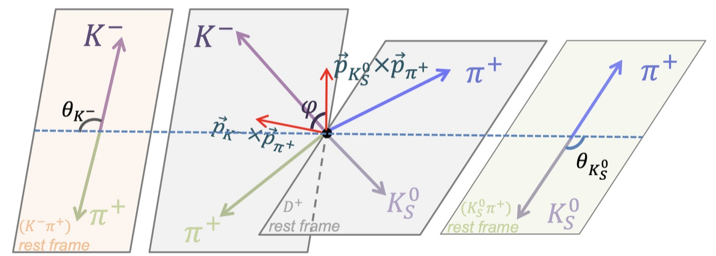
$$C_{\rm TP} = \vec{p}_i \cdot (\vec{p}_j \times \vec{p}_k)$$



四重积变量:

$$C_{\rm QP} = (\vec{p}_{K^-} \times \vec{p}_{\pi^+_h}) \cdot (\vec{p}_{K^0_S} \times \vec{p}_{\pi^+_l})$$

$C_{\rm QP} > 0$: $\vec{p}_{K^-}$ at left-side of $\vec{p}_{K^0_S\pi^+}(\vec{p}_{K^0_S} \times \vec{p}_{\pi^+})$ plane



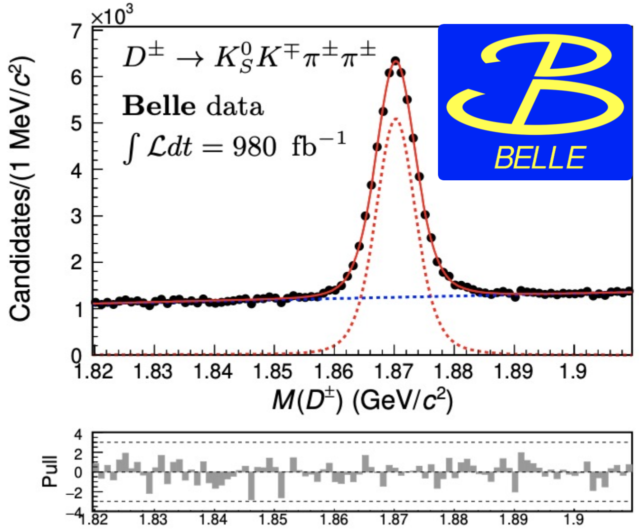
$$A_X(D^+_{(s)}) = \frac{N_+(X>0) - N_+(X<0)}{N_+(X>0) + N_+(X<0)}$$

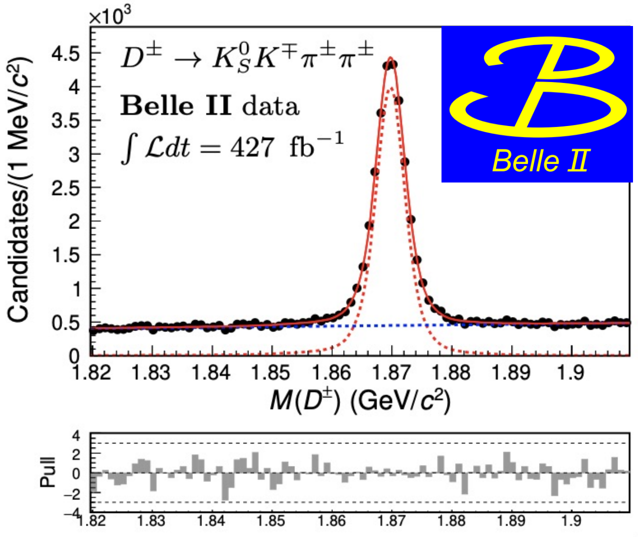
$$A_{\overline{X}}(D^-_{(s)}) = \frac{N_-(\overline{X}>0) - N_-(\overline{X}<0)}{N_-(\overline{X}>0) + N_-(\overline{X}<0)}$$

$$\mathcal{A}^X_{CP} = \frac{1}{2}(A_X(D^+_{(s)}) - A_{\overline{X}}(D^-_{(s)}))$$

X	Combined $\mathcal{A}^X_{CP}$ (10^{-3})
$C_{\rm TP}$	$-2.3 \pm 4.5 \pm 1.5$
$C_{\rm QP}$	$-0.7 \pm 4.5 \pm 1.7$
$C_{\rm TP}\, C_{\rm QP}$	$+3.9 \pm 4.5 \pm 1.1$
$\cos\theta_{K^0_S} \cos\theta_{K^-}$	$-2.9 \pm 4.5 \pm 2.1$
$C_{\rm TP} \cos\theta_{K^0_S} \cos\theta_{K^-}$	$+1.0 \pm 4.5 \pm 1.4$
$C_{\rm QP} \cos\theta_{K^0_S} \cos\theta_{K^-}$	$+11.6 \pm 4.5 \pm 1.1$

Belle 980/fb: 0.59%; Belle II 424/fb: 0.70%





Belle II首批粲CPV结果

精度4.5‰接近$A^{dir}_{CP}(D^0 \to \pi^+\pi^-) = 2.3$‰

李龙科（湖南师大）为主导

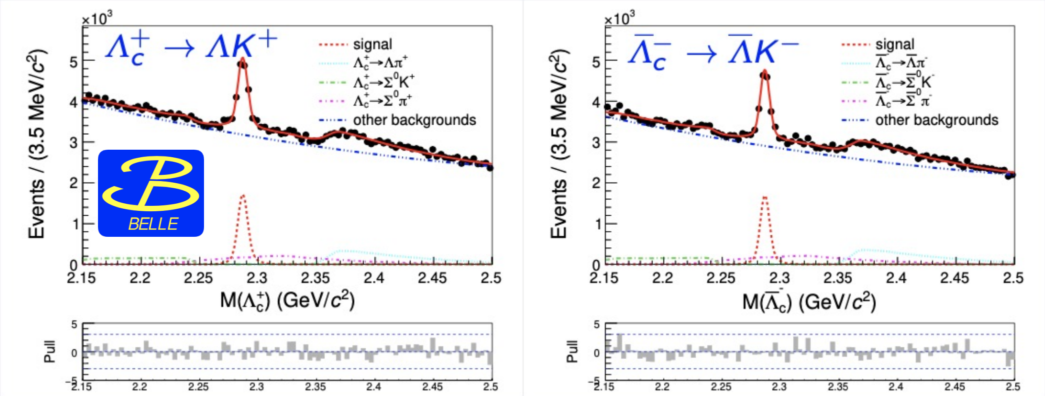
Charm CPV: Charmed baryons

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.

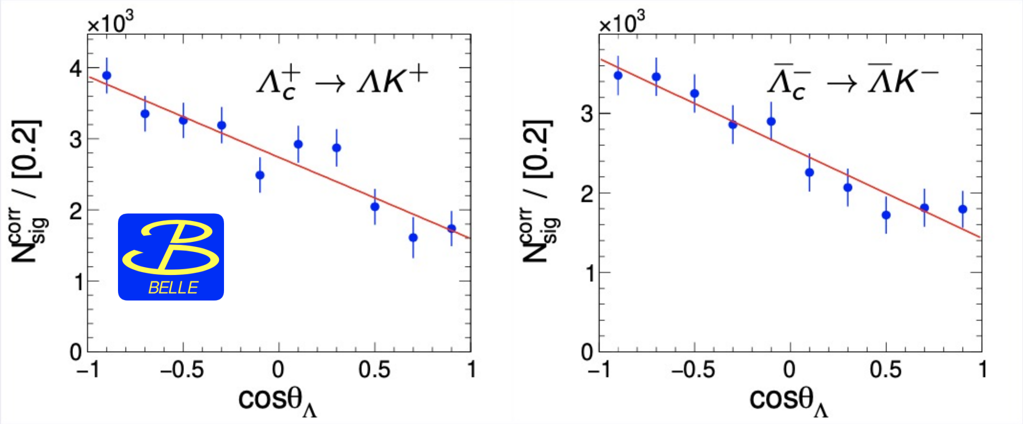


- $\mathcal{A}_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) = (+2.1 \pm 2.6 \pm 0.1)\%$
- $\mathcal{A}_{CP}^{\rm dir}(\Lambda_c^+ \to \Sigma^0 K^+) = (+2.5 \pm 5.4 \pm 0.4)\%$

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.

李龙科（湖南师大）为主导

Belle II粲重子CPV的第一个结果：翘首以盼，终于出来了。

$A_{CP}(\Lambda_c^+ \to p h^+ h^-, \Xi_c^+ \to \Sigma^+ h^+ h^-)$

Preliminary result

- Assuming U-spin symmetry

$$A_{CP}^{dir}(\Lambda_c^+ \to pK^+K^-) + A_{CP}^{dir}(\Xi_c^+ \to \Sigma^+\pi^+\pi^-) = 0$$
$$A_{CP}^{dir}(\Lambda_c^+ \to p\pi^+\pi^-) + A_{CP}^{dir}(\Xi_c^+ \to \Sigma^+K^+K^-) = 0$$

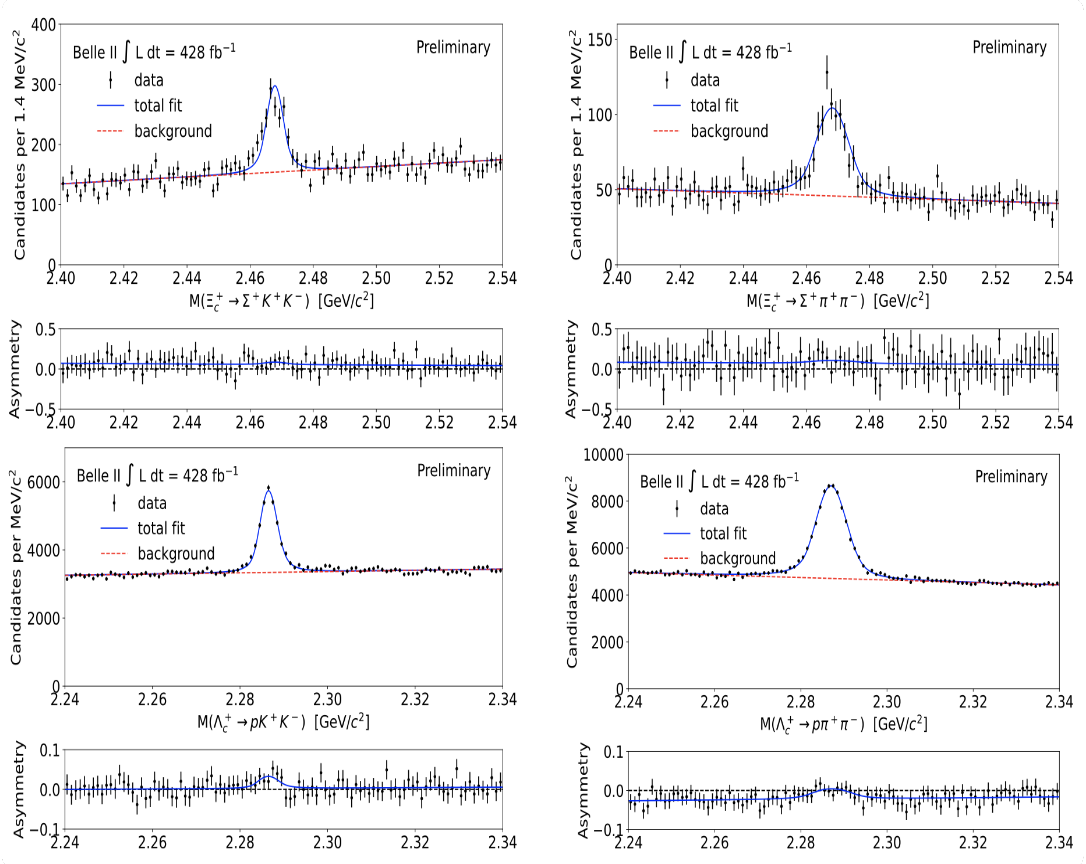
- LHCb: $\Delta A_{CP}^{wgt} = A_{CP}(\Lambda_c^+ \to pK^+K^-) - A_{Cp}^{wgt}(\Lambda_c^+ \to p\pi^+\pi^-) = (0.30 \pm 0.91 \pm 0.61)\%$ [JHEP 03(2018)182]
- Control sample:

$$A_{CP}(\Xi_c^+ \to \Sigma^+h^+h^-) = A_N'(\Xi_c^+ \to \Sigma^+h^+h^-) - A_N'(\Lambda_c^+ \to \Sigma^+h^+h^-),$$
$$A_{CP}(\Lambda_c^+ \to ph^+h^-) = A_N'(\Lambda_c^+ \to ph^+h^-) - A_N'(\Lambda_c^+ \to p\pi^+K^-) + A_N'(D^0 \to \pi^+K^-\pi^+\pi^-)$$

- Belle II (428/fb) gives CP asymmetries:

$$A_{CP}(\Xi_c^+ \to \Sigma^+K^+K^-) = (3.7 \pm 6.6 \pm 0.6)\%,$$
$$A_{CP}(\Xi_c^+ \to \Sigma^+\pi^+\pi^-) = (9.5 \pm 6.8 \pm 0.5)\%,$$
$$A_{CP}(\Lambda_c^+ \to pK^+K^-) = (3.9 \pm 1.7 \pm 0.7)\%,$$
$$A_{CP}(\Lambda_c^+ \to p\pi^+\pi^-) = (0.3 \pm 1.0 \pm 0.2)\%,$$

world's first A_{CP} for 3-body SCS charmed baryon decays



- testing U-spin sum rules:

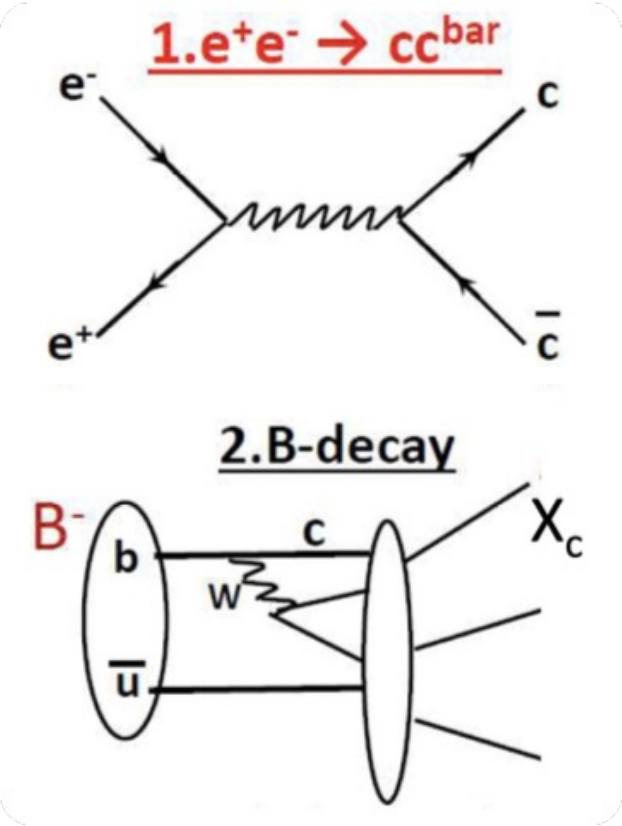
$$A_{CP}(\Xi_c^+ \to \Sigma^+\pi^+\pi^-) + A_{CP}(\Lambda_c^+ \to pK^+K^-) = (13.4 \pm 7.0 \pm 0.9)\%,$$
$$A_{CP}(\Xi_c^+ \to \Sigma^+K^+K^-) + A_{CP}(\Lambda_c^+ \to p\pi^+\pi^-) = (\ 4.0 \pm 6.6 \pm 0.7)\%,$$

More data for precisely searching for CPV and testing U-spin sum rules.

Outline

- Luminosity
- Recent B results
- Recent charm results
  - charm CPV
  - charm spectrum
  - charmed baryon
- Recent $q\bar{q}$ and exotic
- Recent tau and dark sector
- Summary

Belle (II): charm super-factory



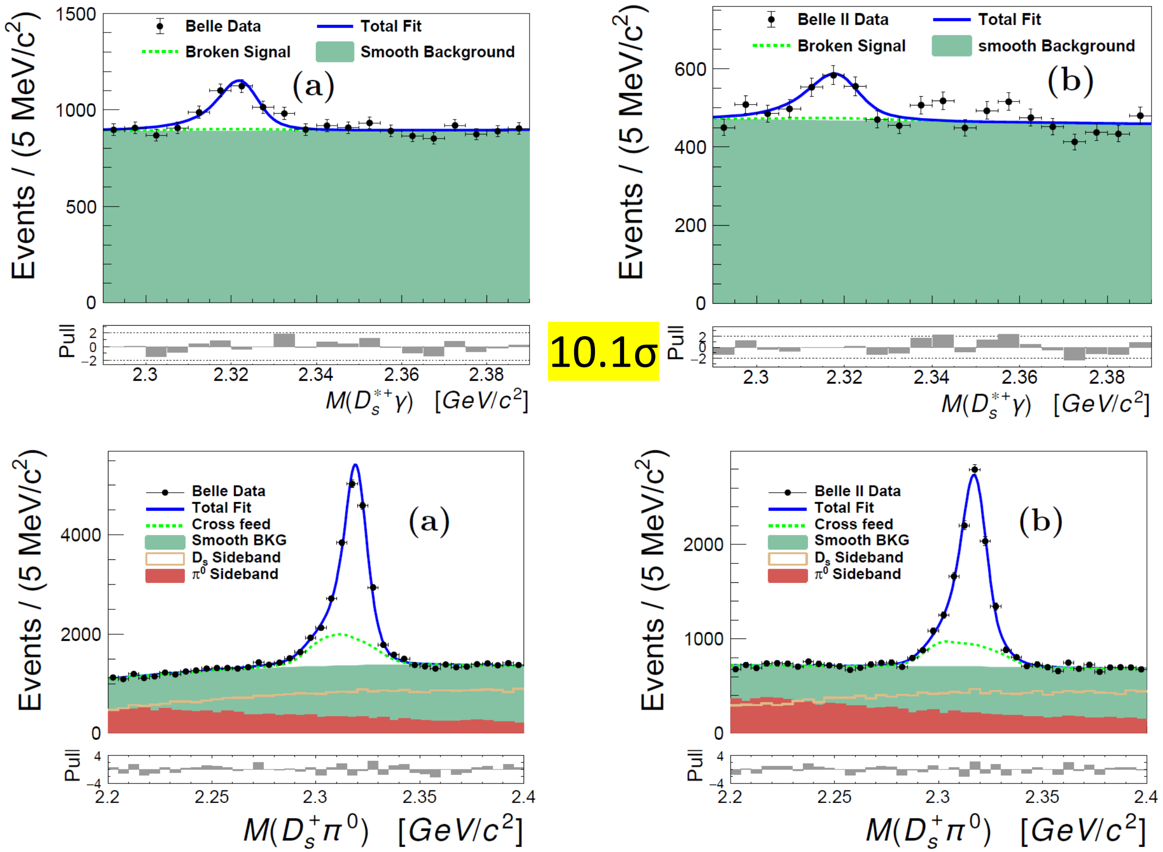
PS: no Λ_b^0 sample

$D_{s0}(2317)^+ \to D_s^{*+}\gamma$

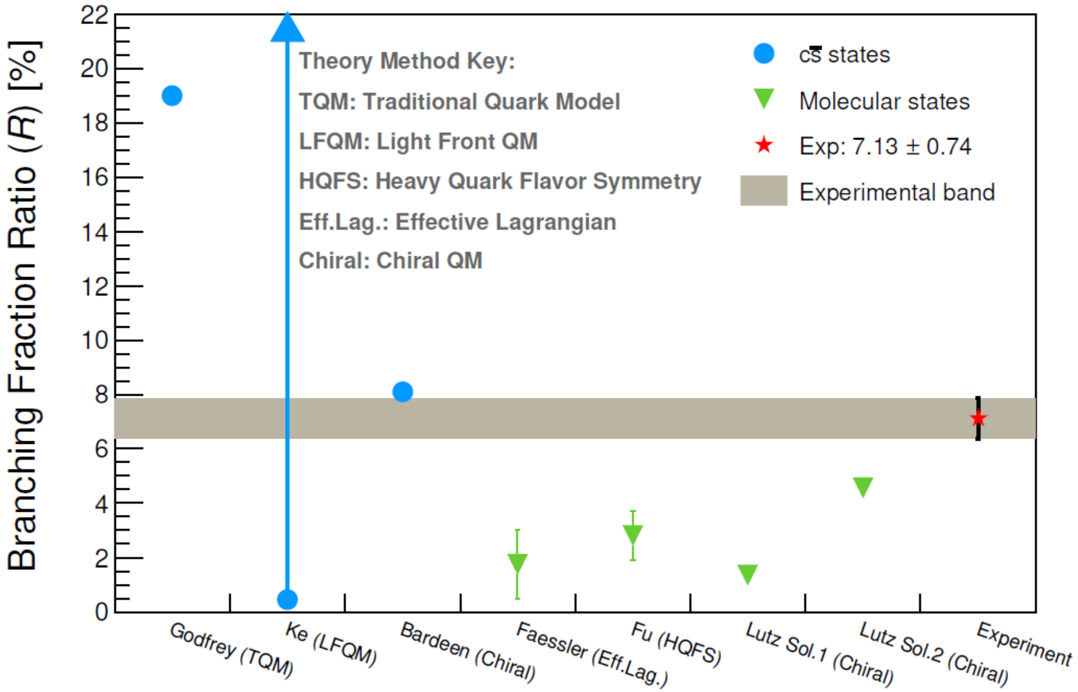
Approved yesterday

Preliminary result

- Precise nature of $D_{s0}^*(2317)^+$ remains unresolved, underscoring the need for new and improved experimental data.
- The width of $D_s(2317)^+$ is unknown: $\Gamma(D_s(2317)^+) < 3.8$ MeV @95% CL.



$$R = \frac{\mathcal{B}(D_s(2317)^+ \to D_s^{*+}\gamma)}{\mathcal{B}(D_s(2317)^+ \to D_s^+\pi^0)} = [7.14 \pm 0.70 \pm 0.23]\%$$



李郁博（西交）+沈成平（复旦）为主导

Charmed baryon decay

JHEP 10(2024)045, JHEP 03(2025)061, JHEP 08(2025)195, Preliminary result

BR results of 5 CF and 7 SCS decays of $\Xi_c^{0,+}$:

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

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

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

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

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

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

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

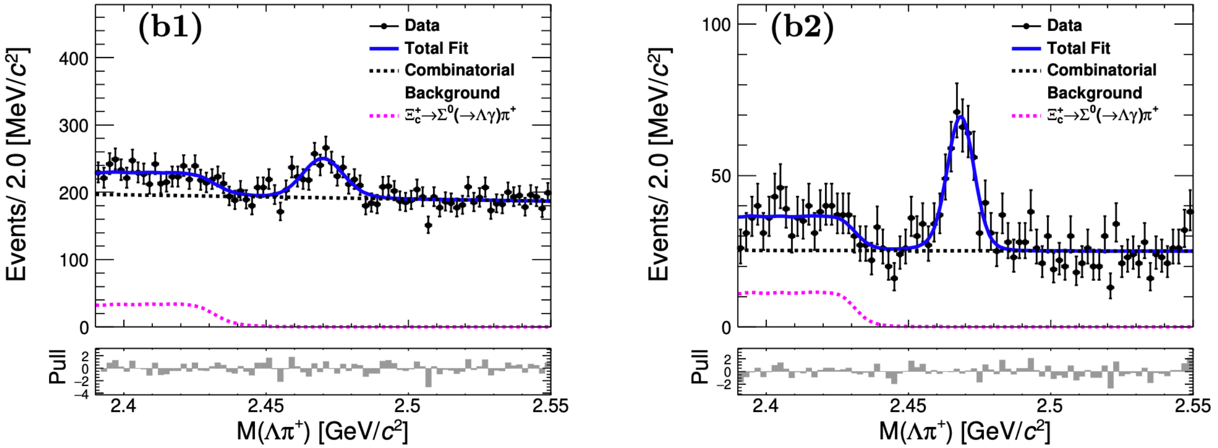
$B(\Xi_c^+ \to \Xi^0\pi^+)/B(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = 0.248 \pm 0.005 \pm 0.009$

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

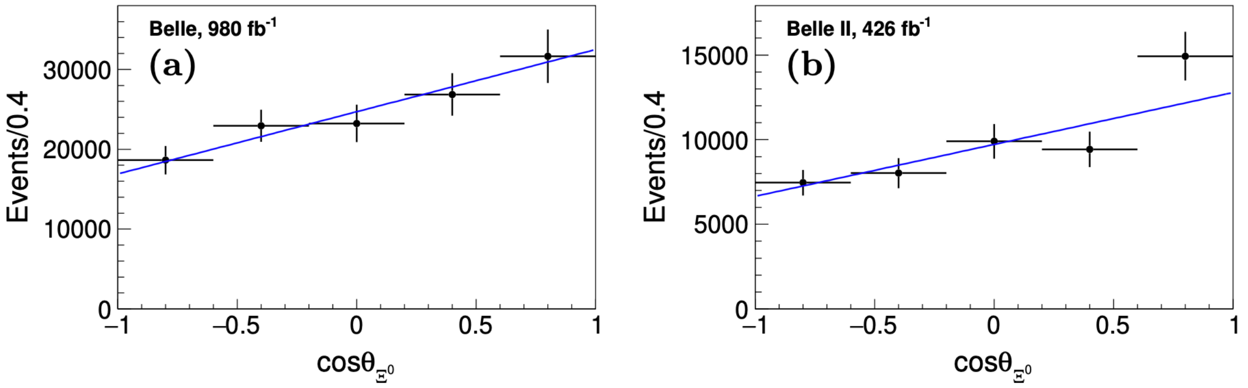
$B(\Xi_c^0 \to \Lambda\pi^0)/B(\Xi_c^0 \to \Xi^-\pi^+) < \mathrm{xx}\%$ $@90\%\ C.L.$

$B(\Xi_c^0 \to \Lambda\eta)/B(\Xi_c^0 \to \Xi^-\pi^+) = (xxx \pm 0.91 \pm 0.16)\%$

$B(\Xi_c^0 \to \Lambda\eta')/B(\Xi_c^0 \to \Xi^-\pi^+) = (xxx \pm 0.82 \pm 0.16)\%$



$$\frac{dN}{d\cos\theta_{\Xi^0}} \propto 1 + \alpha(\Xi_c^0 \to \Xi^0 h^0)\alpha(\Xi^0 \to \Lambda\pi^0)\cos\theta_{\Xi^0},$$



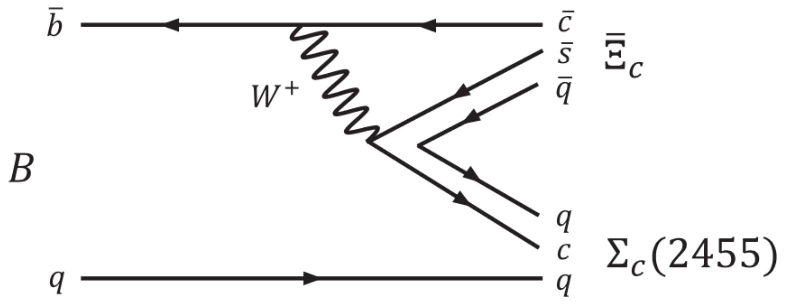
$$\alpha(\Xi_c^0 \to \Xi^0\pi^0) = -0.90 \pm 0.15(\mathrm{stat}) \pm 0.23(\mathrm{syst})$$

“Belle II劳模”沈成平（复旦）课题组为主导

$B^{+,0} \to \Sigma_c(2455)^{++,0}\Xi_c^{-,0}$

PRD 112 (2025) L051101

- These two decays proceed through a purely internal W-emission:



- First searches for these decays:

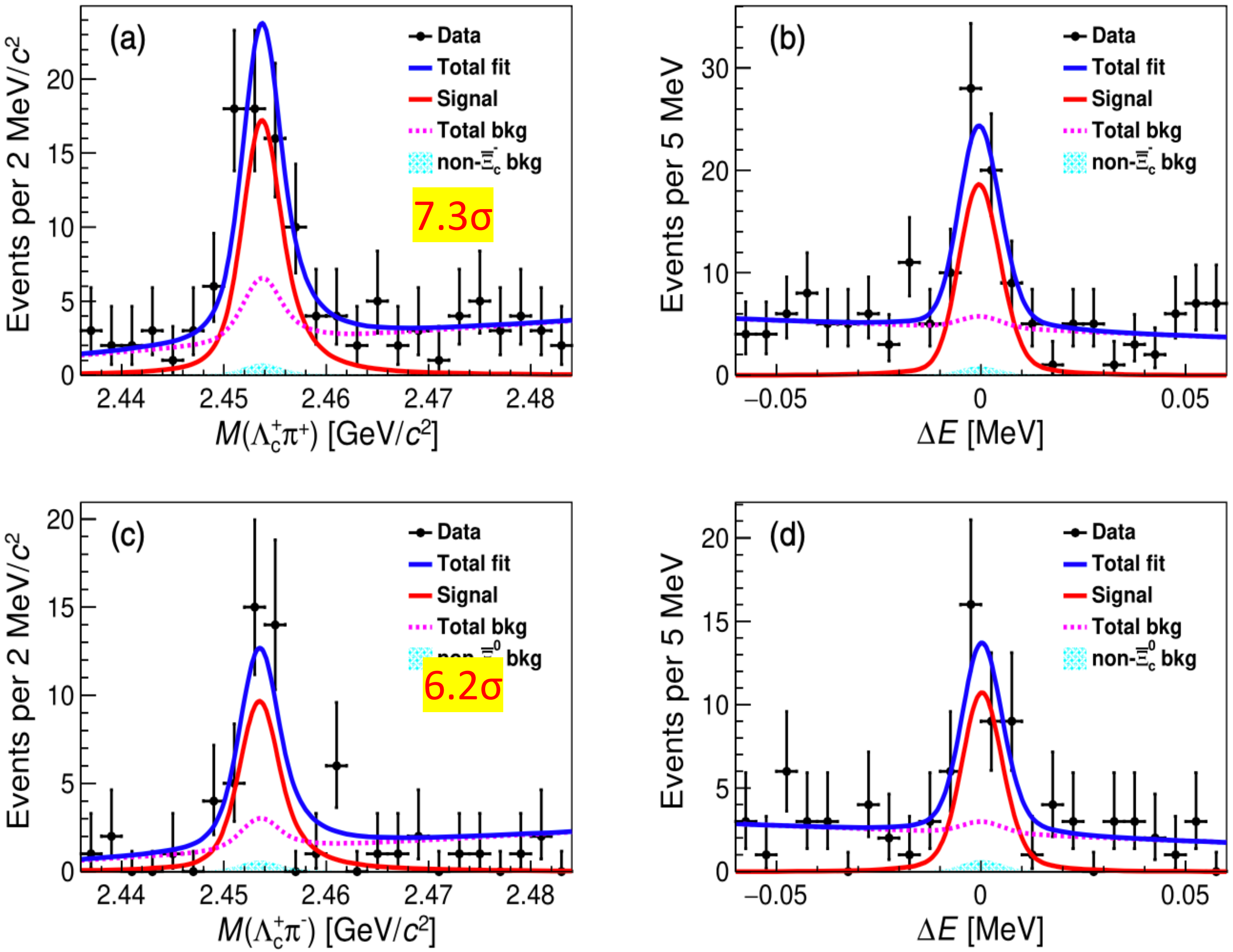
$\mathcal{B}(B^+ \to \Sigma_c^{++}\Xi_c^-) = (5.74 \pm 1.11 \pm 0.42^{+2.47}_{-1.53})\times 10^{-4}$

$\mathcal{B}(B^0 \to \Sigma_c^0\Xi_c^0) = (4.83 \pm 1.12 \pm 0.37^{+0.72}_{-0.60})\times 10^{-4}$

Vs. theoretical prediction by

- the QCD sum rule [1]: 4×10^{-3};
- diquark model [2]: $O(10^{-4})$

[1]Nucl. Phys. B345, 137 (1990). [2]Z. Phys. C 51, 445 (1991)

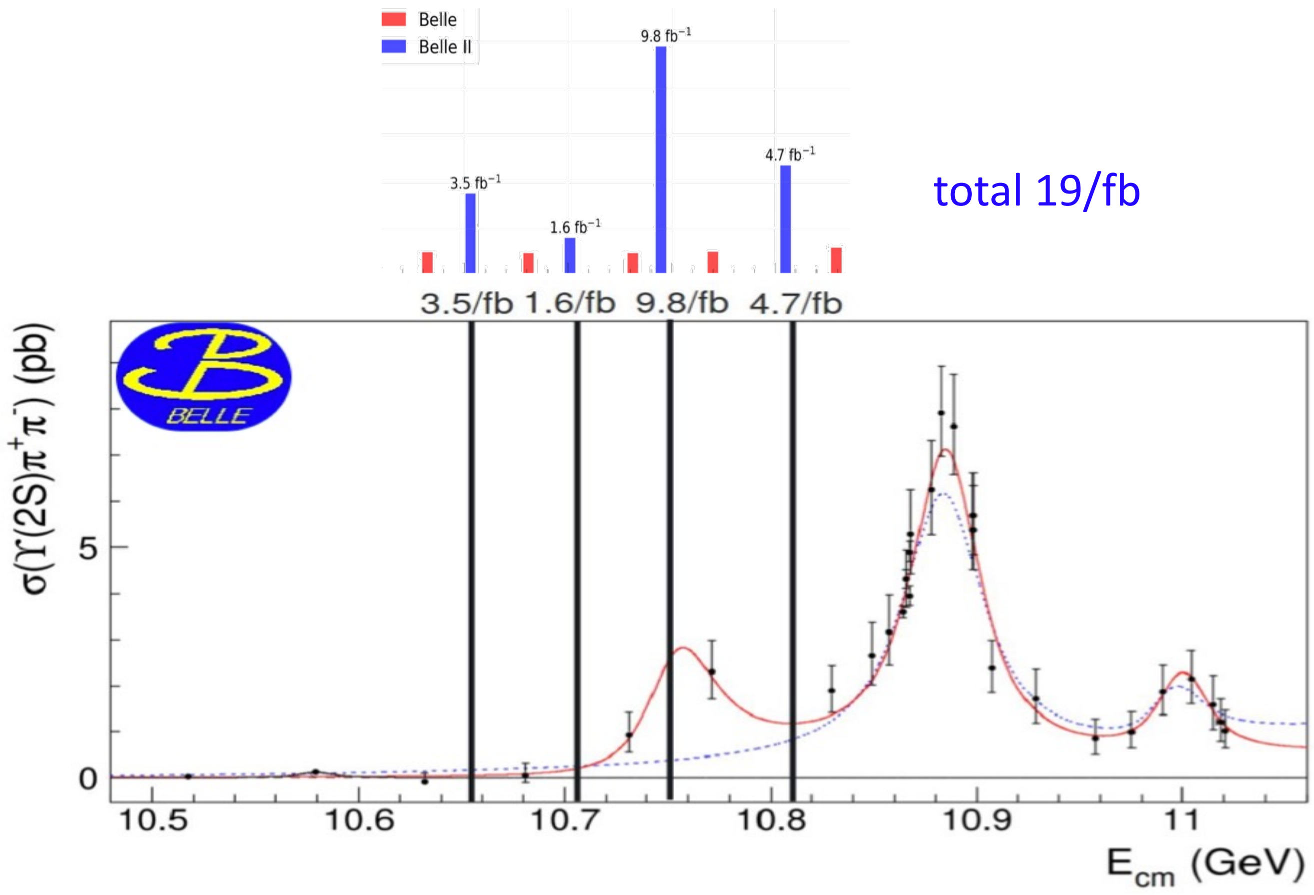


沈成平（复旦）课题组为主导

Outline

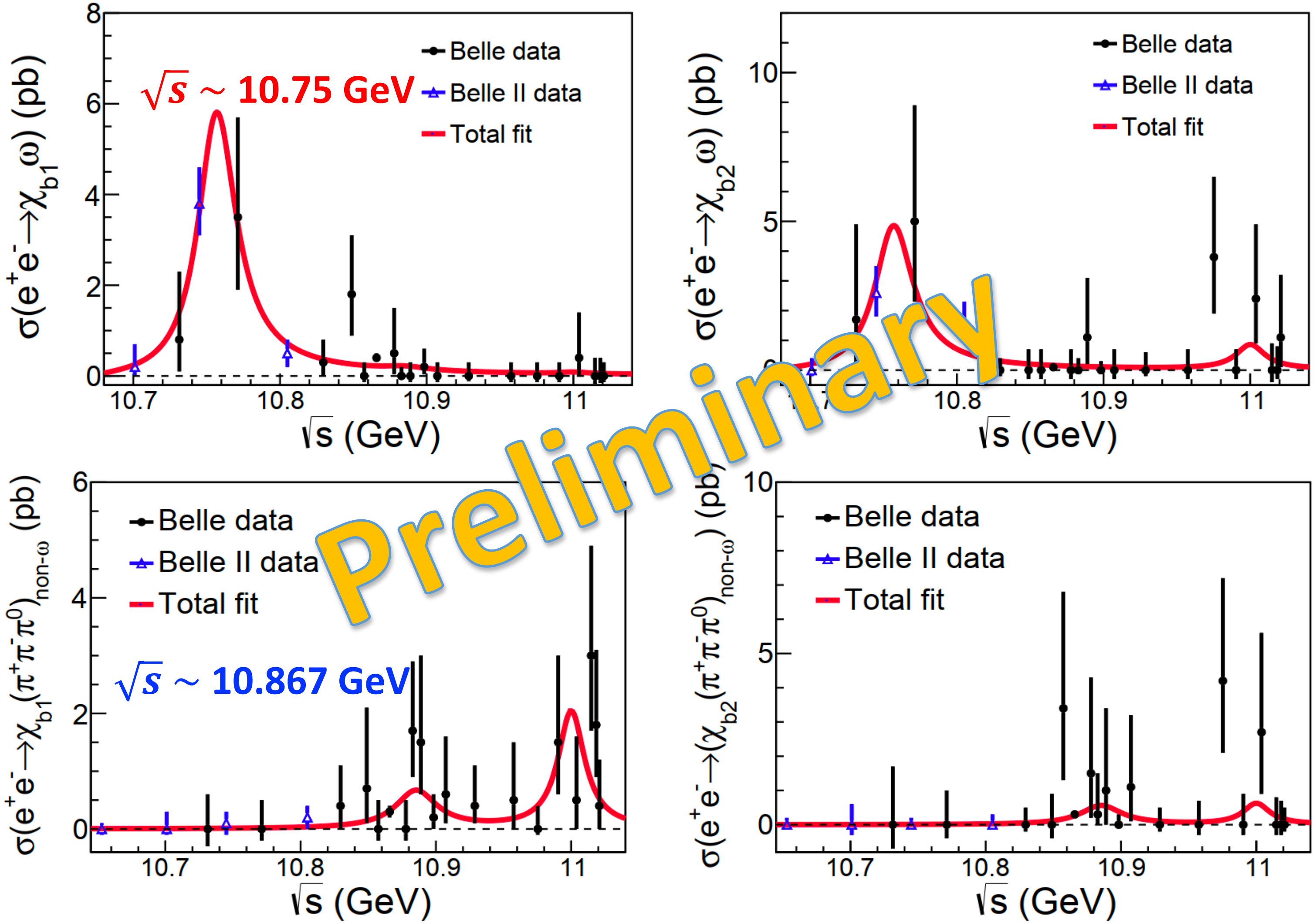
- Luminosity
- Recent B results
- Recent charm results
- Recent $q\bar{q}$ and exotic
- Recent tau and dark sector
- Summary

Physics goal: understand the nature of $\Upsilon(10753)$ observed at Belle [JHEP 10, 220 (2019)].



total 19/fb

$e^+e^- \to \omega\chi_{bJ}$ 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

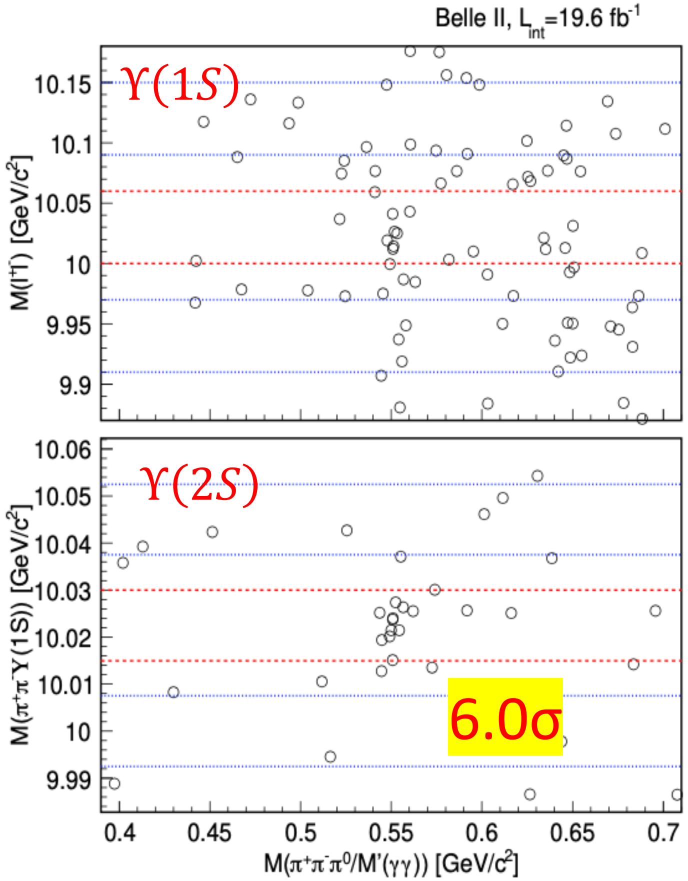
This may indicate the difference in internal structures of $\Upsilon(10753)$ and $\Upsilon(10860)$.

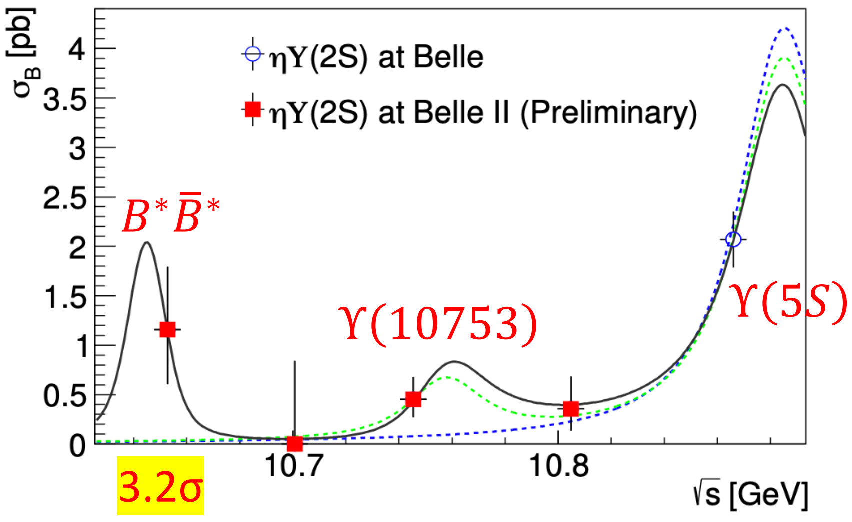
贾森（东南）+沈成平（复旦）为主导

$e^+e^- \to \eta\Upsilon(1,2S), \gamma\chi_{bJ}$ near 10.75 GeV

arXiv:2509.01917 [hep-ex]
arXiv:2508.16036 [hep-ex]

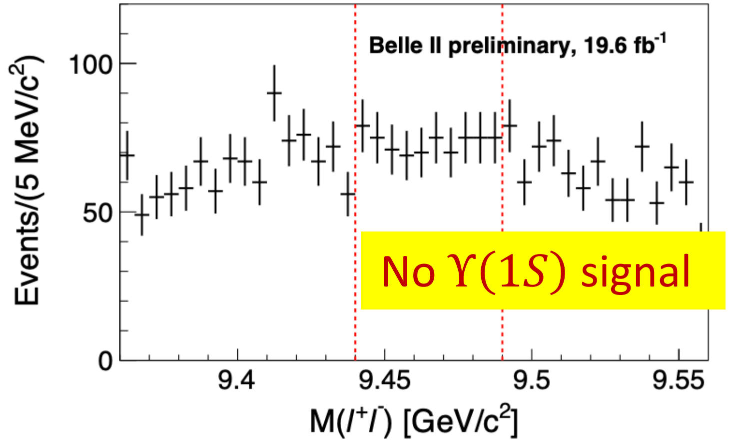
- $e^+e^- \to \eta\Upsilon(1,2S)$

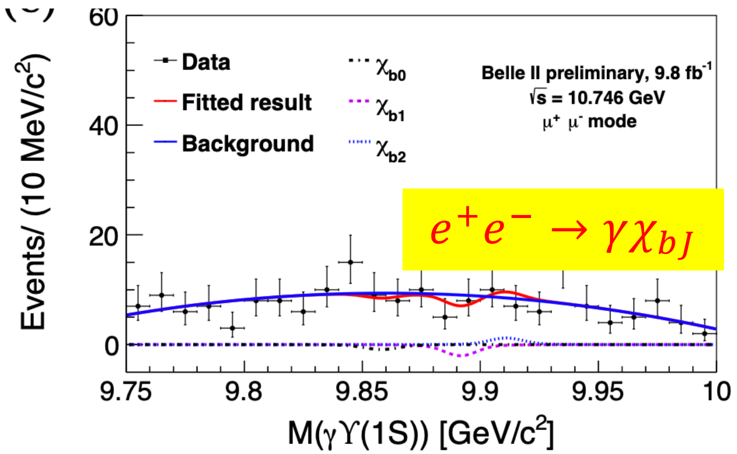




Also search for $e^+e^- \to \gamma X_b$, where X_b is the bottomonium-sector partner of X(3872). No evidence is found.

- $e^+e^- \to \gamma\chi_{bJ}$





殷俊昊（南开）课题组为主导

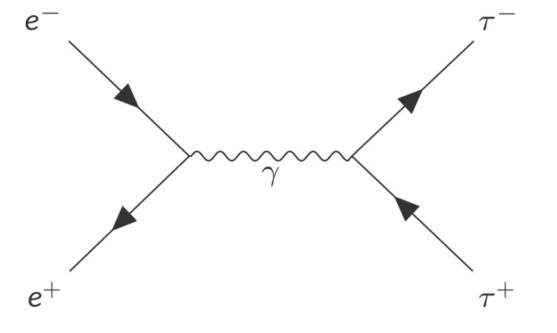
贾森（东南）课题组为主导

Outline

- Luminosity
- Recent B results
- Recent charm results
- Recent $q\bar{q}$ and exotic
- Recent tau results
- Summary

Belle II: a tau super-factory

$$\sigma\left(e^+e^- \to \tau^+\tau^-(\gamma)\right) = 0.919\,nb$$



Advantages at Belle II:

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

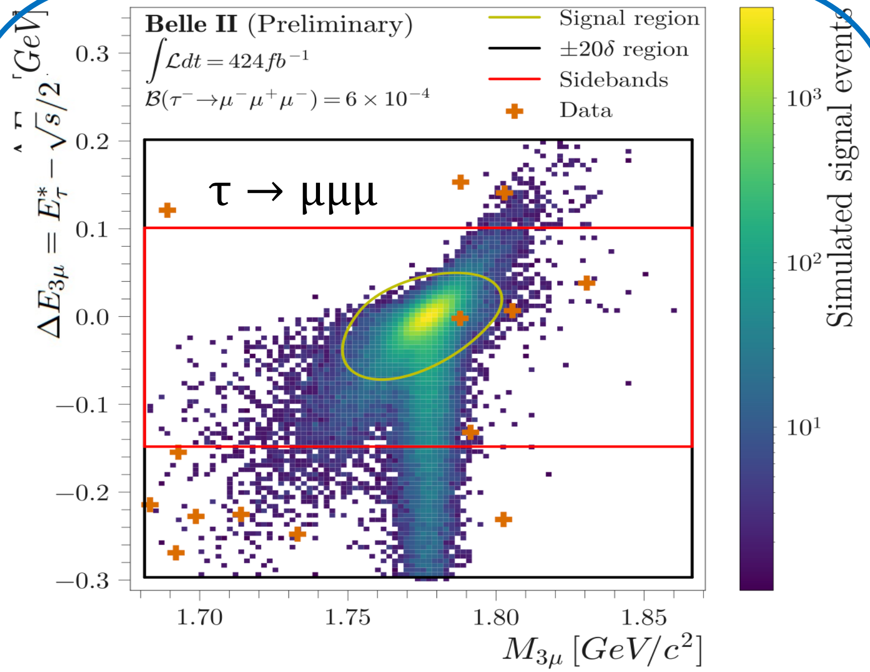
tau LFV decays

JHEP 09 (2024) 062, PRD 110 (2024) 112003, JHEP 08 (2025) 092

Lepton flavour violation is only allowed by:
- **Neutrino oscillations** $\mathcal{O}(10^{-55})$

far beyond current experimental sensitivities
- **New Physics models** $\mathcal{O}(10^{-8})$

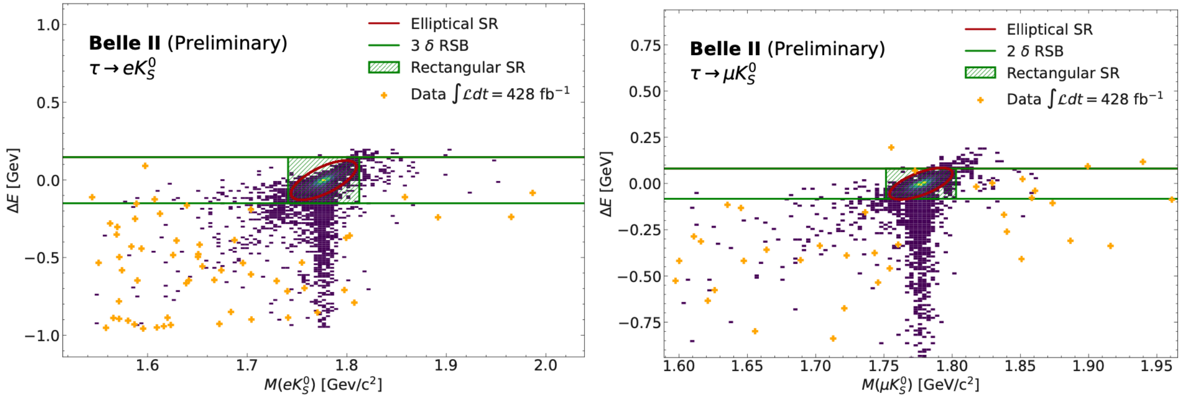
e.g. Leptoquarks for $\tau^- \to \ell^- V^0$ deals with $R(K^{*0})$ anomalies



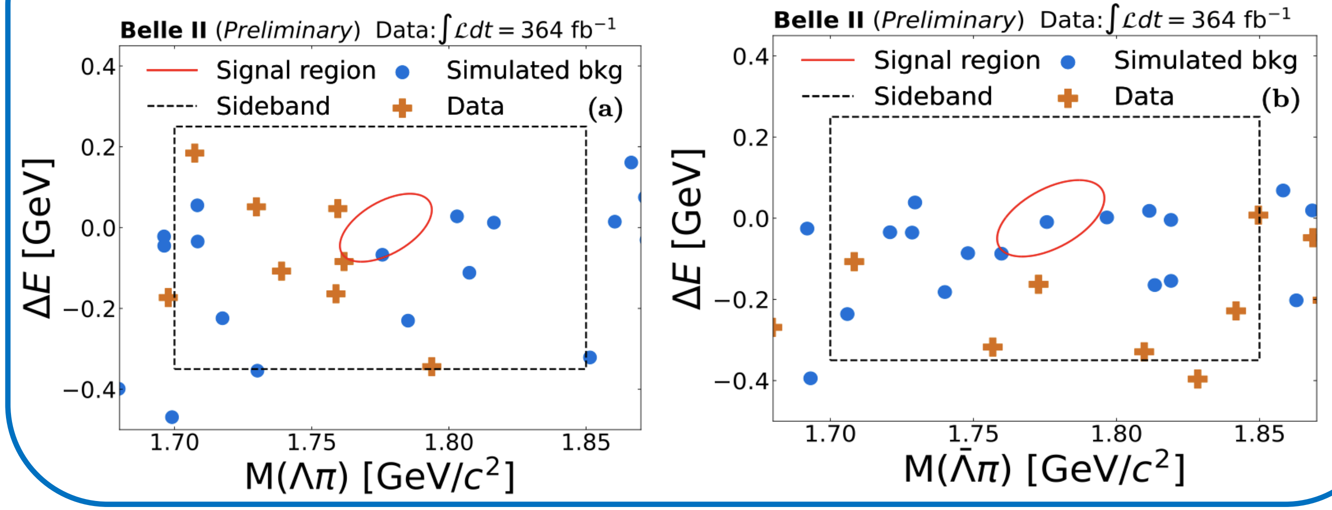
$\mathcal{B}^{UL}(\tau \to \mu\mu\mu) < 1.9\times10^{-8}$

more restrictive than Belle

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



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



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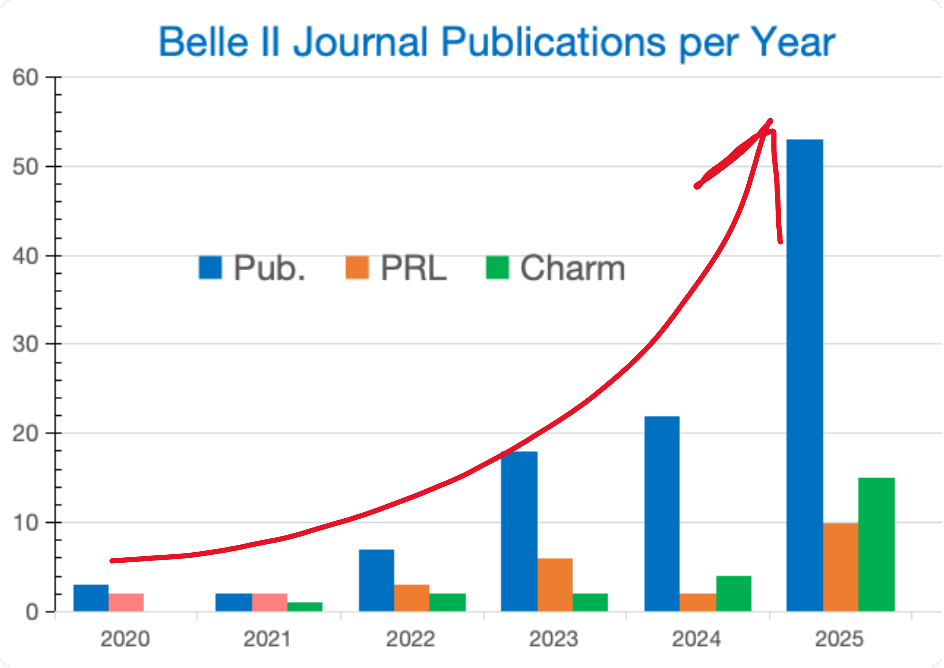
Summary

- Belle II recently achieved fruitful results based on 428/fb data set (before 2023), including some world-leading results, analyses more data and develops new tools.
  - B CPV/rare/hadronic, charm CPV/BF/α/spectrum (radiative), $q\bar{q}$ and exotic, τ physics, dark sector, etc.
- Now Belle II has collected 575/fb data set, only 1% of targeted luminosity (50/ab) has been collected so far.
- More data, more results + more ideas (from u)
- Belle II: improvements as expected (未来“可期”)

  \+ unexpected excitements (未来可期)



高能物理团队@湖南师大

❖固定教职工10人：

❖粒子物理与核物理**理论**：8人

研究强子谱/CP破坏/格点QCD/核物理理论等

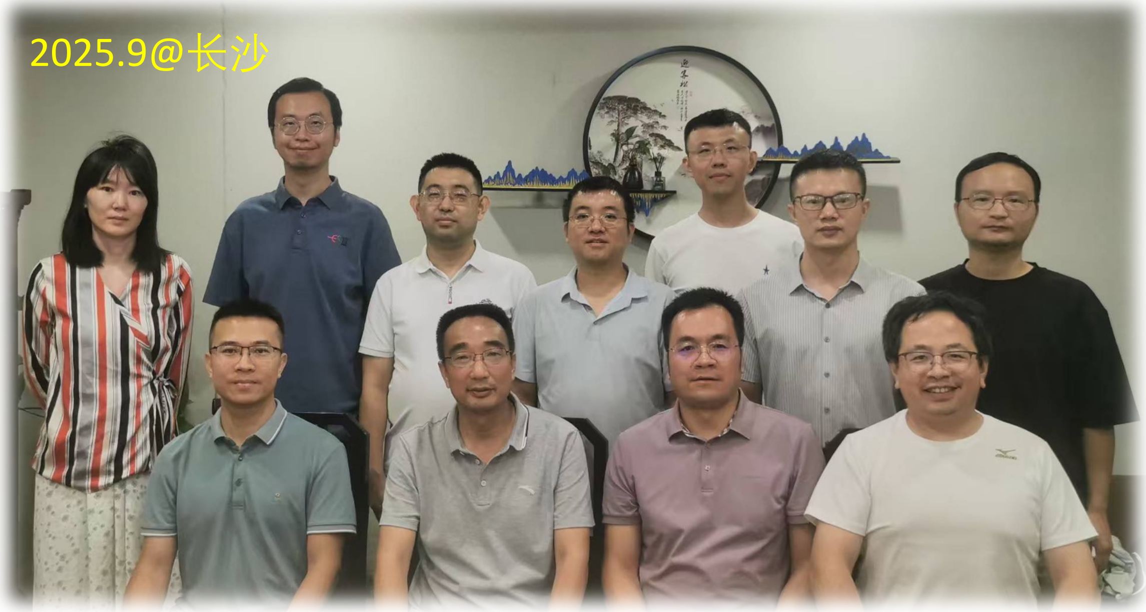
❖粒子物理**实验**：2人

参加BESIII和Belle II实验

研究粲强子/CP破坏/(类)粲偶素等

❖博士后1名；在读研究生~22人

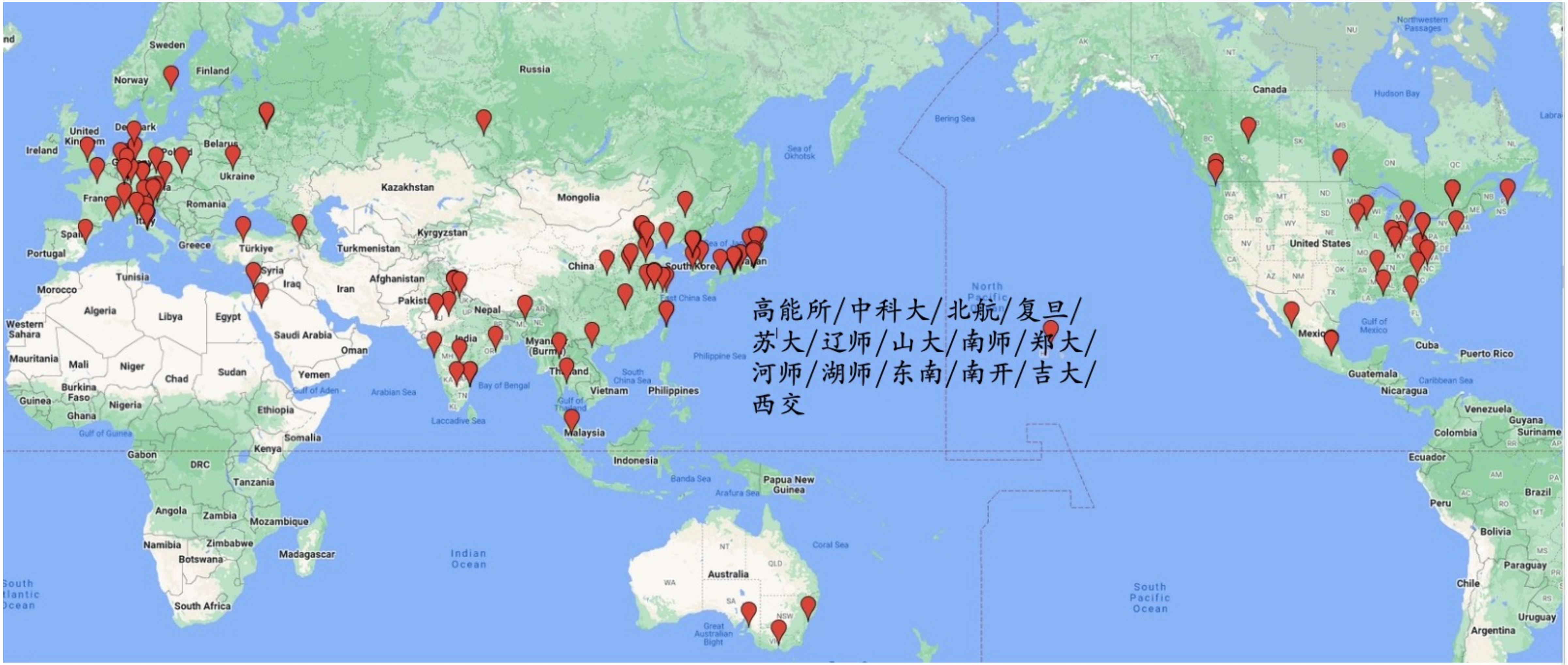
（不完全统计有博士生3人+硕士生19人）



诚邀专家学者莅临指导！

Back up

Belle II big family

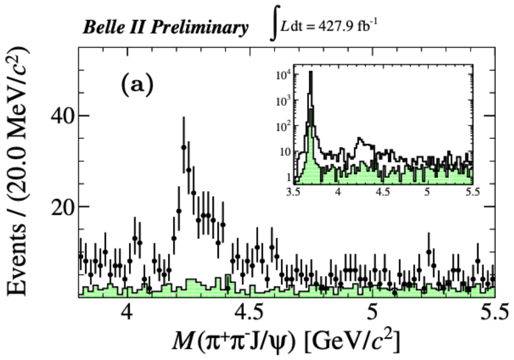


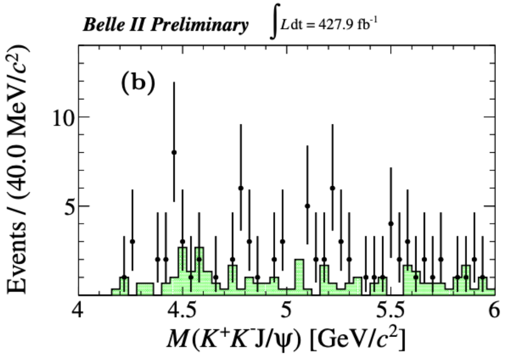
► Belle II 合作组（中国大陆）：1207 个成员（134：11%，第三位），124（15）个单位，28个国家/地区。

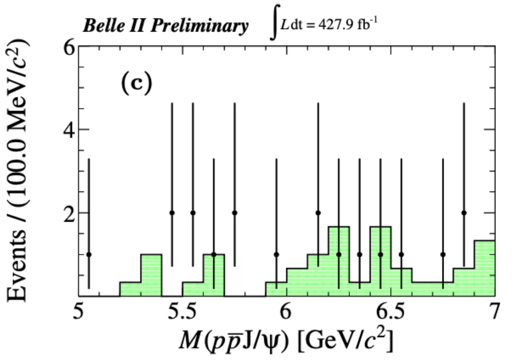
成员人数排序（>80）：德国，日本，中国，美国，意大利

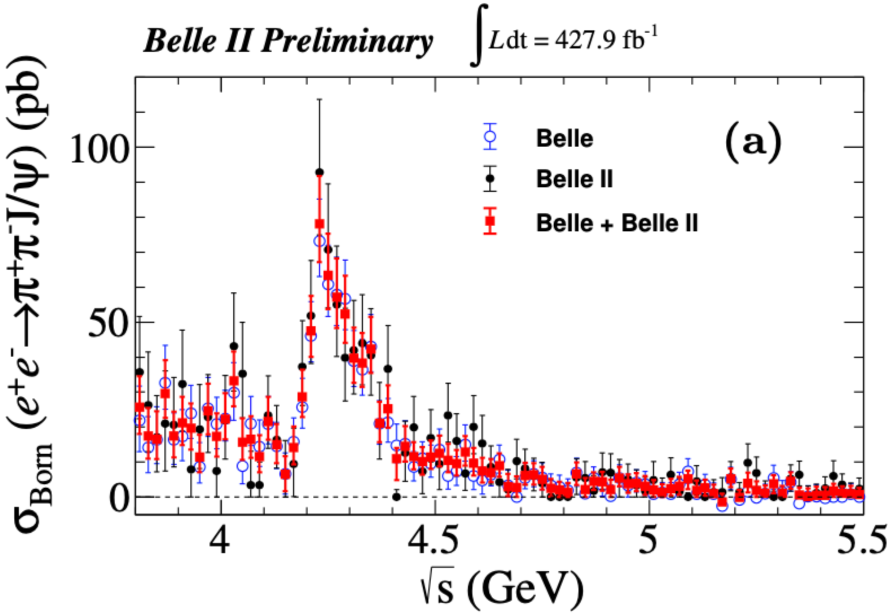
$e^+e^- \to h^+h^- J/\psi$ ($h = \pi, K, p$) via ISR

Preliminary result

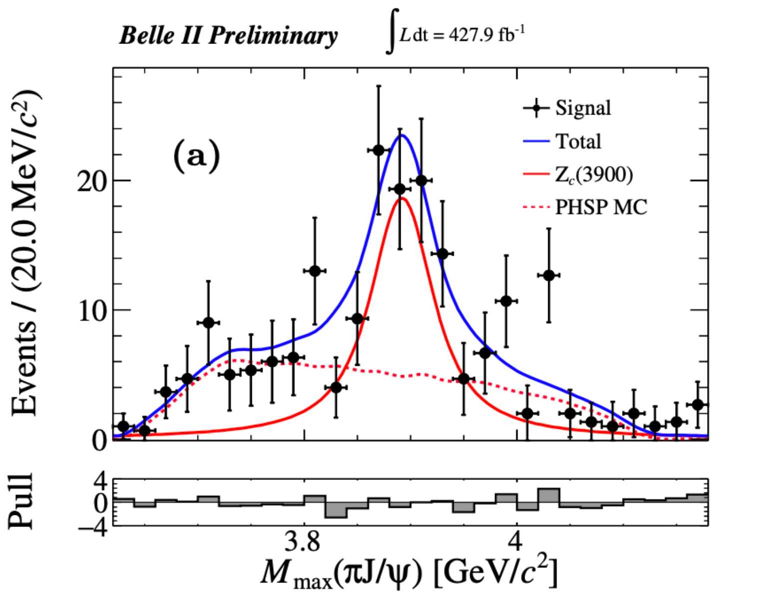








- indicative of the Y(4230/4320) state
- an excess near 4.1 GeV



- Evidence for $Z_c(3900)^{\pm}$ (3.3σ)
- consistent with Belle/BESIII result

The precisions of cross section based on Belle II (428/fb):

- comparable to those from BaBar/Belle using ISR.
- less precise (5% and 10%) than those from BESIII via energy scans

Belle II: Looking forward to more luminosity.