Belle II实验在味物理和CPV领域的进展

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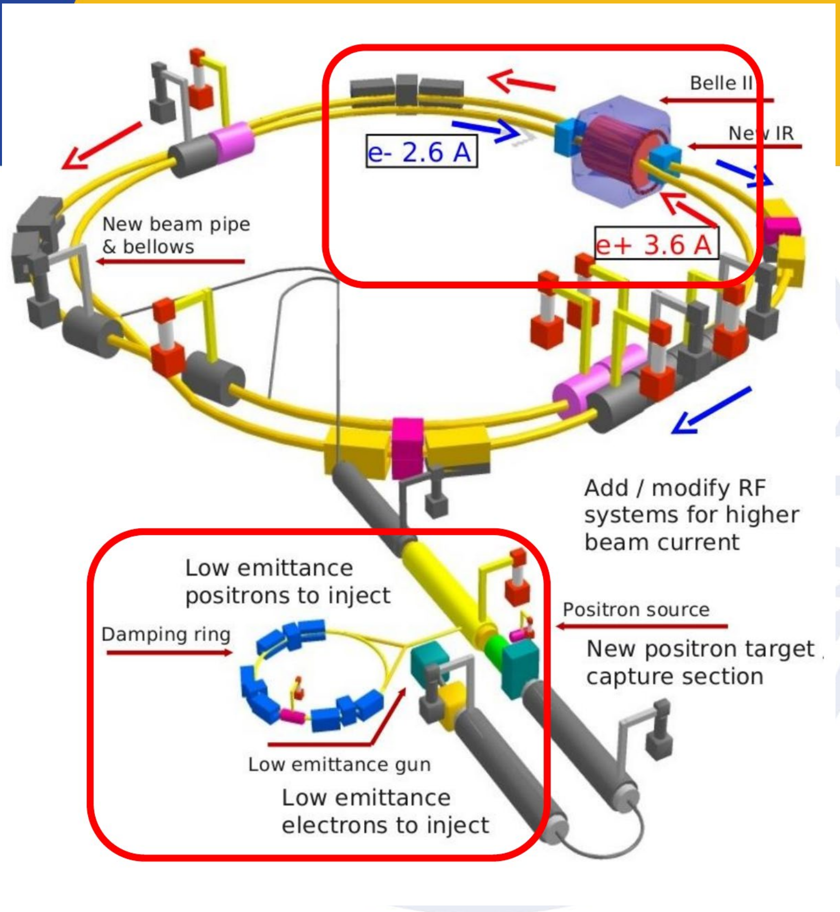
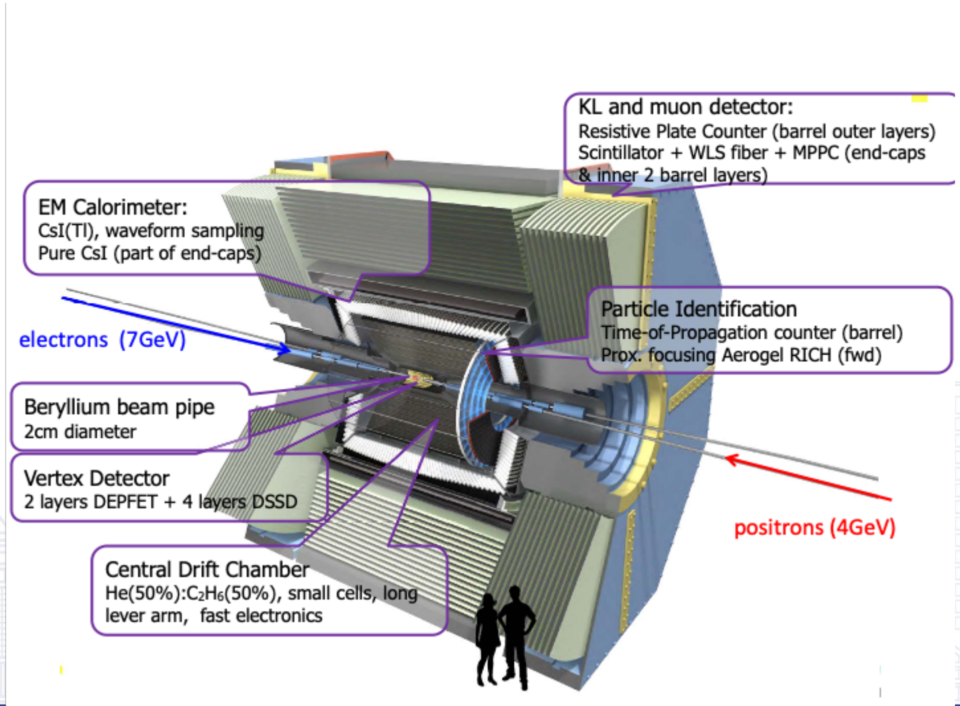
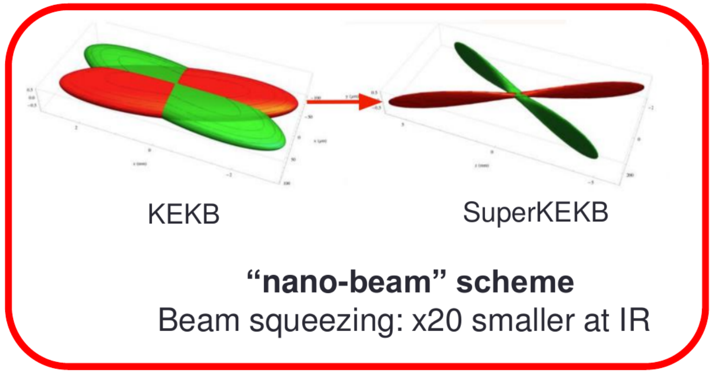
第七届全国重味物理与量子色动力学研讨会
4月19日，南京

SuperKEKB加速器与Belle II实验



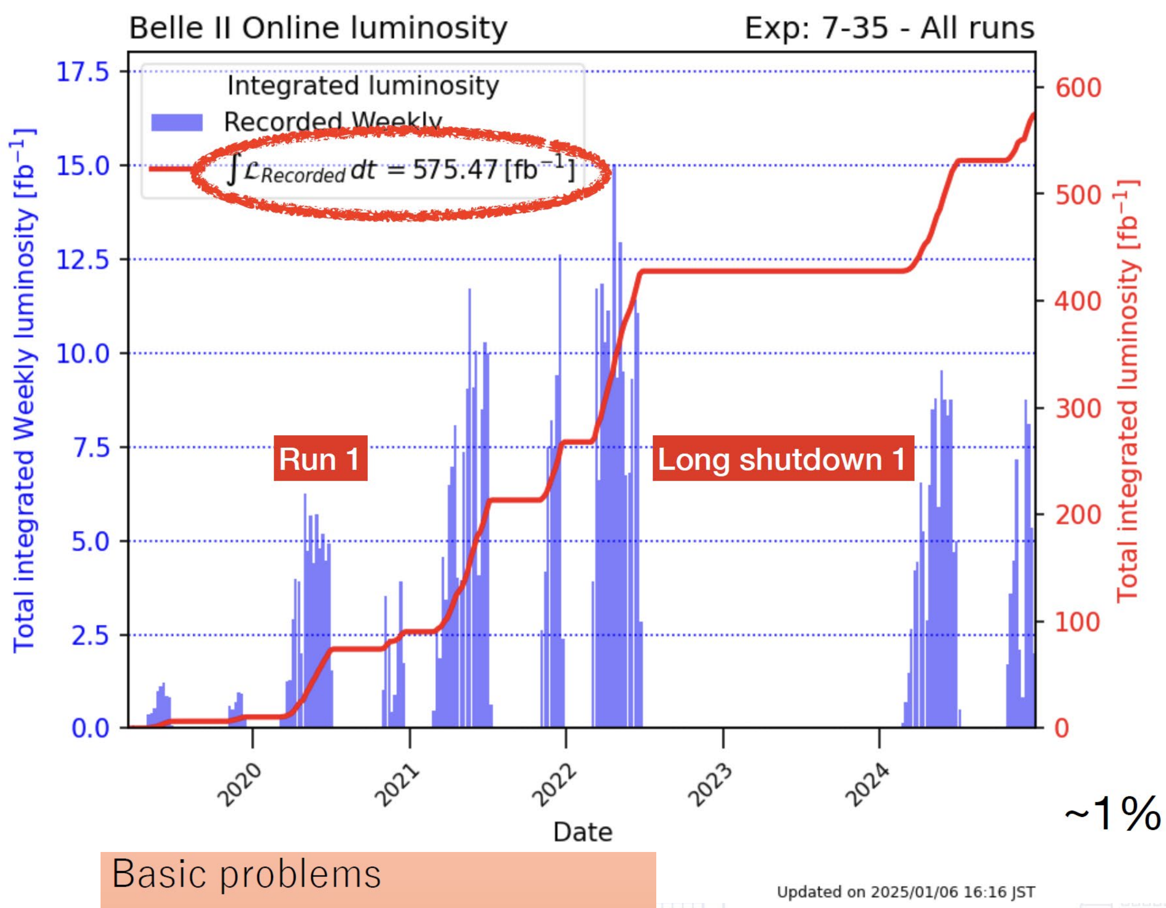
- **高亮度前沿实验：**
  - 运行于$\Upsilon(4S)$能区附近的非对称e^+e^-对撞机实验
  - 采用“纳米束流(nano-beam)”方案，并提高流强
- **设计亮度与积分亮度：**
  - $6.5 \times 10^{35} cm^{-2} s^{-1}, 50\ ab^{-1}$

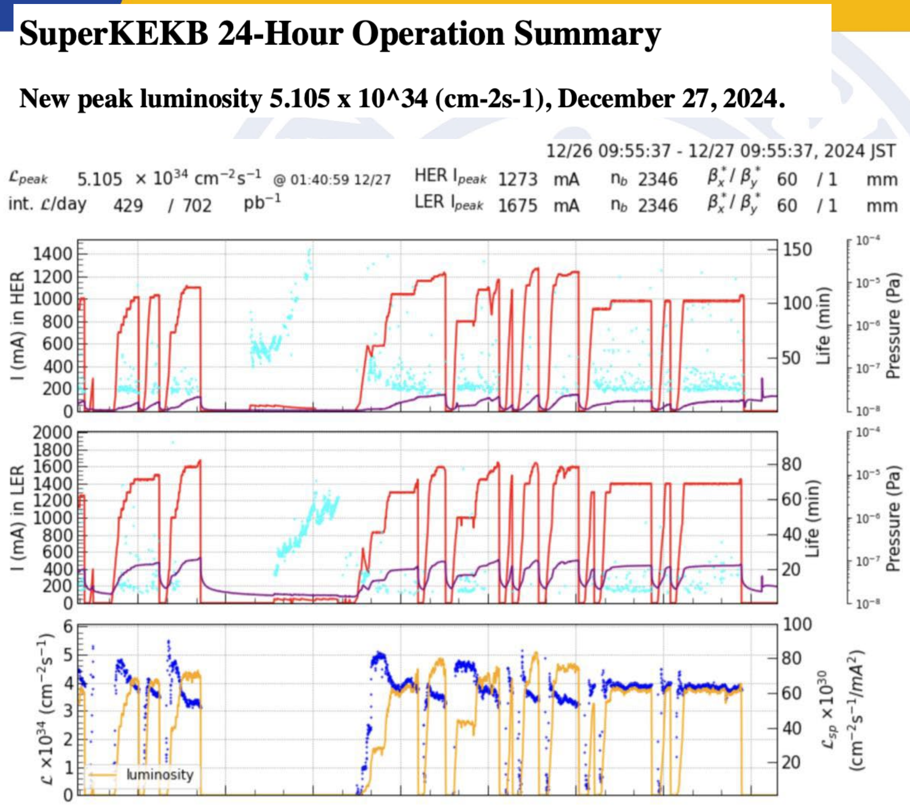




FUDAN UNIVERSITY 1905 復旦大學 FUDAN UNIVERSITY

SuperKEKB加速器状态与 Belle II数据样本





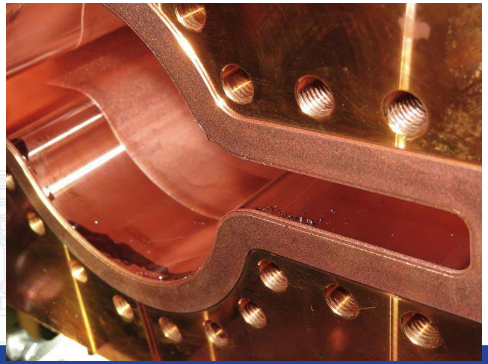
~1% of 50/ab target

Basic problems

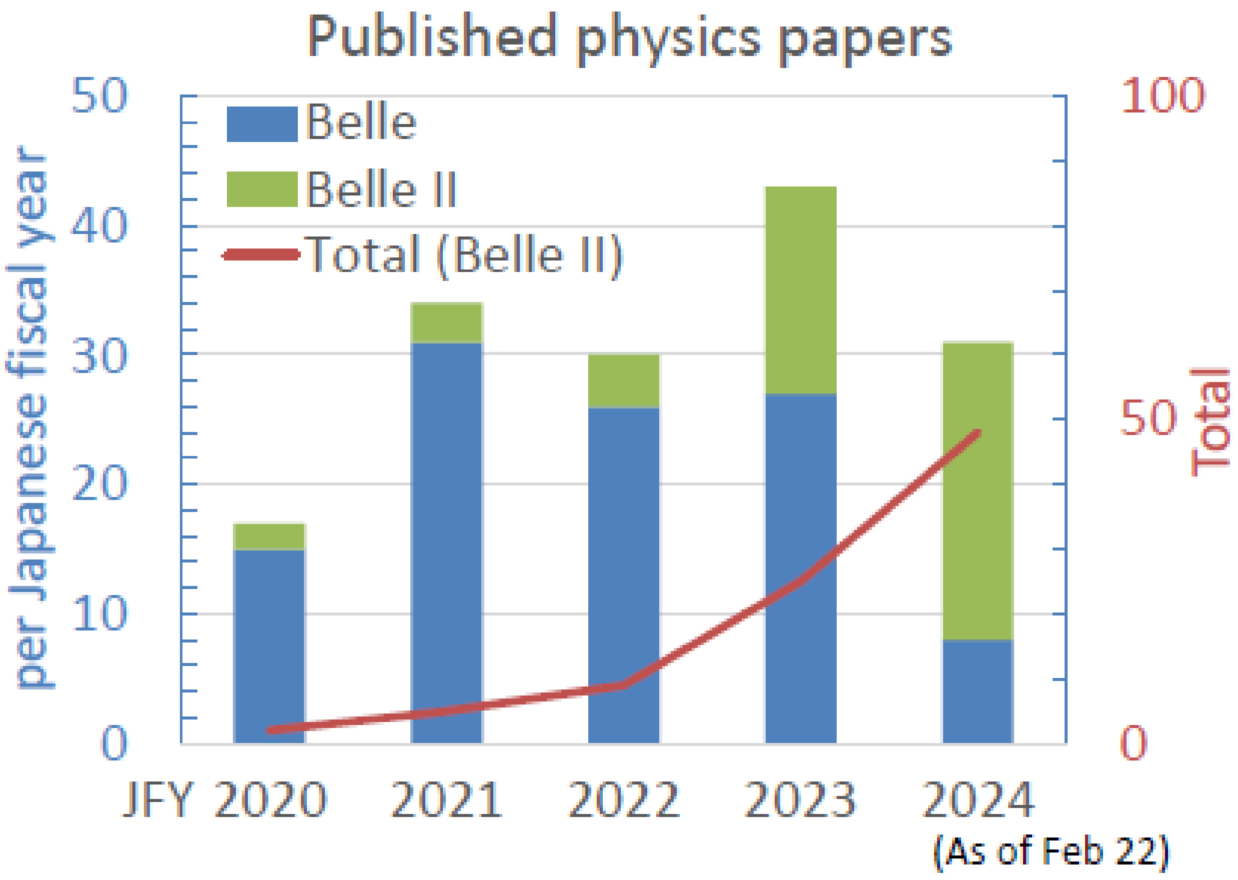
1) Short beam lifetime
2) **Beam instabilities（SBL ）**
3) Low machine stability
4) Low injection efficiency

We can not increase current
1) **SBL**
2) low efficiency injection

“Vac seal” is one cru of SBL



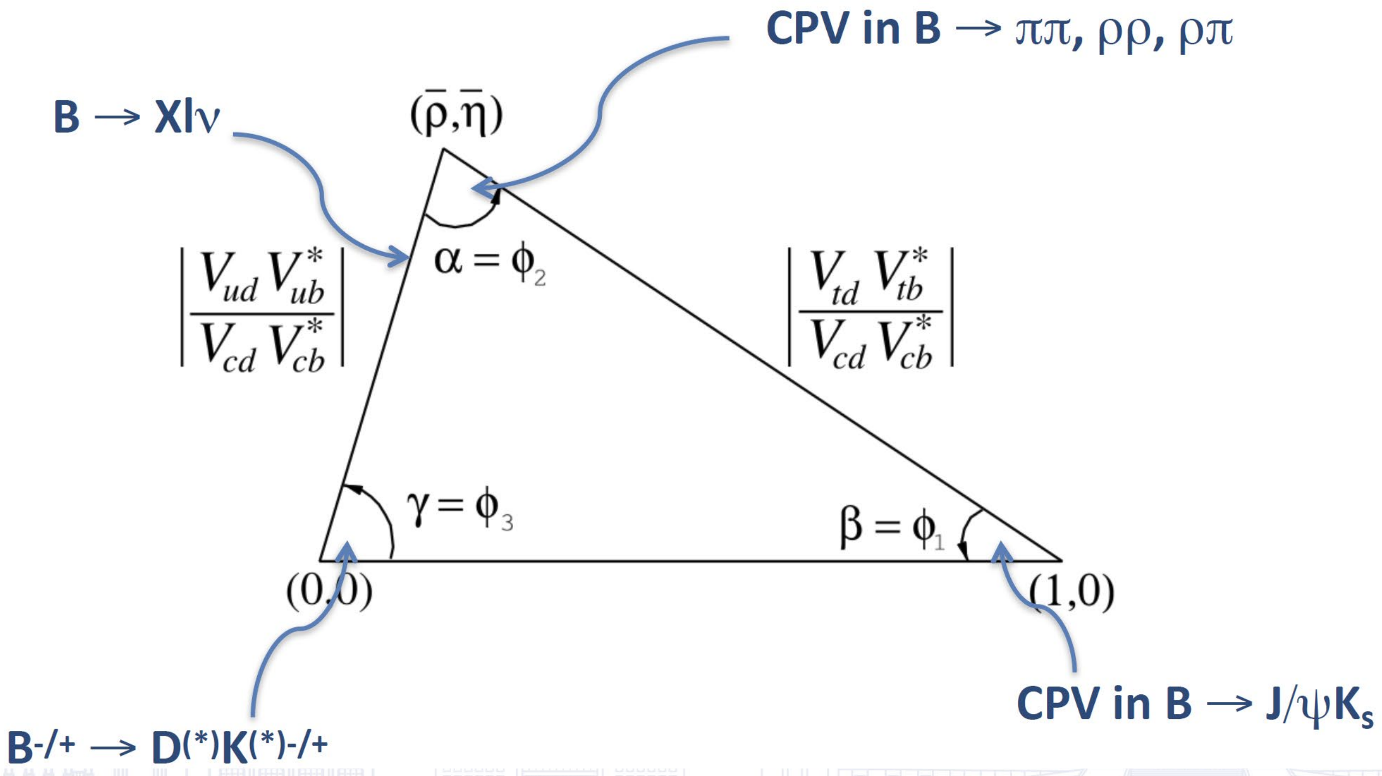
Publication: Belle → Belle II



The CKM unitarity triangle

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

…and how to probe it with B mesons



近期的B物理研究成果

- $|V_{ub}|$ from $B^0 \to \pi^- l^+ \nu$ and $B^+ \to \rho^0 l^+ \nu$
  [arXiv: 2407.17403] submitted to PRD

- Branching fraction of $B^+ \to \tau^+ \nu$
  [arXiv:2502.04885] submitted to PRD

- Branching fraction and CPV in $B^0 \to \pi^0 \pi^0$
  [arXiv:2412.14260] submitted to PRD

- ϕ_2/α from $B^0 \to \rho^+ \rho^-$
  [arXiv:2412.19624] submitted to PRD

近期的B物理研究成果+五夸克态的寻找

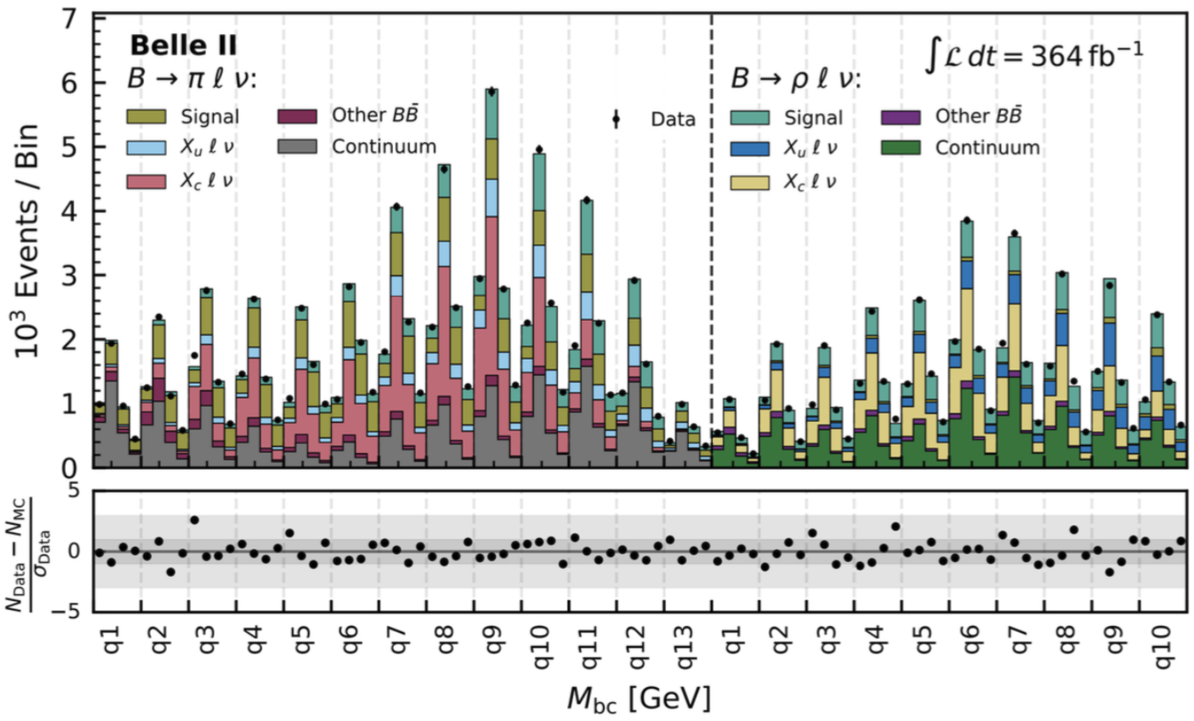
- $|V_{ub}|$ from $B^0 \to \pi^- l^+ \nu$ and $B^+ \to \rho^0 l^+ \nu$
  [arXiv: 2407.17403] submitted to PRD
- Branching fraction of $B^+ \to \tau^+ \nu$
  [arXiv:2502.04885] submitted to PRD
- Branching fraction and CPV in $B^0 \to \pi^0 \pi^0$
  [arXiv:2412.14260] submitted to PRD
- ϕ_2/α from $B^0 \to \rho^+ \rho^-$
  [arXiv:2412.19624] submitted to PRD
- Search for Pc in pJ/ψ final states
  [arXiv:2403.04340]
- Search for Pcs in $\Lambda J/\psi$ final states
  [arXiv:2502.09951]

$|V_{ub}|$ from $B^0 \to \pi^- l^+ \nu$ and $B^+ \to \rho^0 l^+ \nu$

arXiv: 2407.17403

- Run 1 dataset (364/fb), untagged analysis, $\pi^-\ell^+$ and $\rho^0\ell^+$ are reconstructed, neutrino is inferred from the missing energy and momentum in th event
- Background suppression with multivariate methods (BDTs)
- Signal extraction from a simultaneous fit in bins of q^2

$q^2 = (p_B - p_{\pi/\rho})^2$

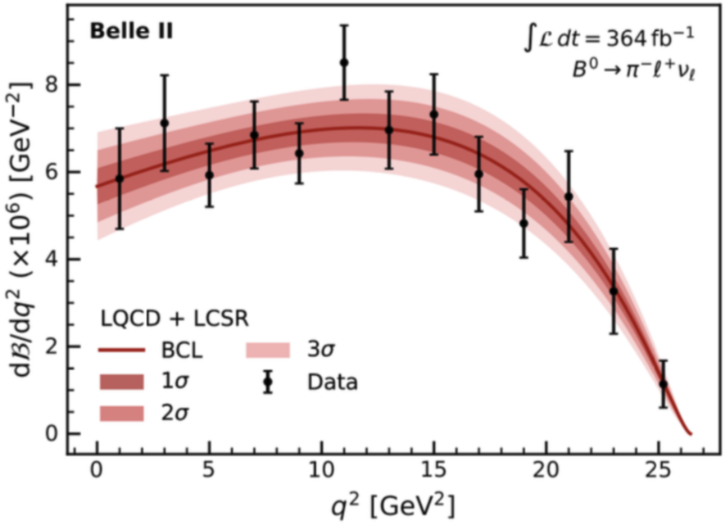


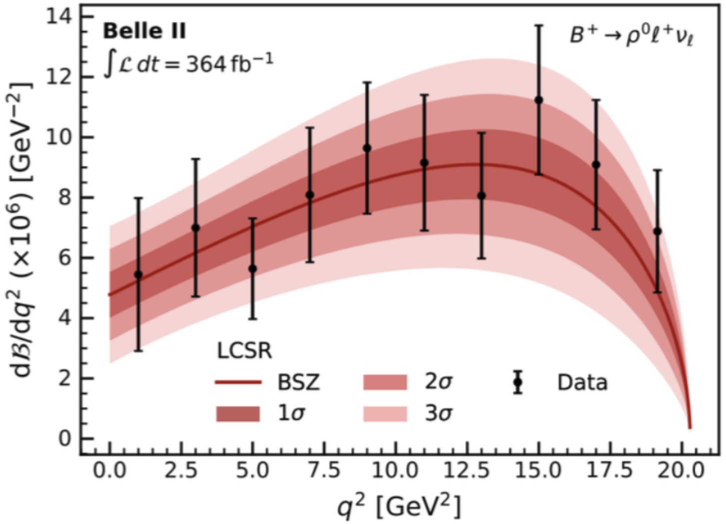
$$\mathcal{B}(B^0 \to \pi^-\ell^+\nu_\ell) = (1.516 \pm 0.042 \pm 0.059) \times 10^{-4}$$
$$\mathcal{B}(B^+ \to \rho^0\ell^+\nu_\ell) = (1.625 \pm 0.079 \pm 0.180) \times 10^{-4}$$

$|V_{ub}|$ from $B^0 \to \pi^- l^+ \nu$ and $B^+ \to \rho^0 l^+ \nu$

arXiv: 2407.17403

- $|V_{ub}|$ is extracted from a combined fit to lattice QCD and light-cone sum rule calculations
  - Lattice QCD (LQCD) [Eur. Phys. J. C 82, 869 (2022)]
  - Light-cone sum rule (LCSR)
    [J. High Energ. Phys. 2021, 36 (2021), J. High Energ. Phys. 2016, 98 (2016)]





$$|V_{ub}|^{\mathrm{LQCD}}_{B\to\pi\ell\nu} = (3.93 \pm 0.09 \pm 0.13 \pm 0.19) \times 10^{-3}$$
(stat.) (syst.) (theo.)

$$|V_{ub}|^{\mathrm{LQCD+LCSR}}_{B\to\pi\ell\nu} = (3.73 \pm 0.07 \pm 0.07 \pm 0.16) \times 10^{-3}$$

$$|V_{ub}|^{\mathrm{LCSR}}_{B\to\rho\ell\nu} = (3.19 \pm 0.12 \pm 0.17 \pm 0.26) \times 10^{-3}$$

HFLAV $|V_{ub}|$ exclusive: $(3.43 \pm 0.12) \times 10^{-3}$

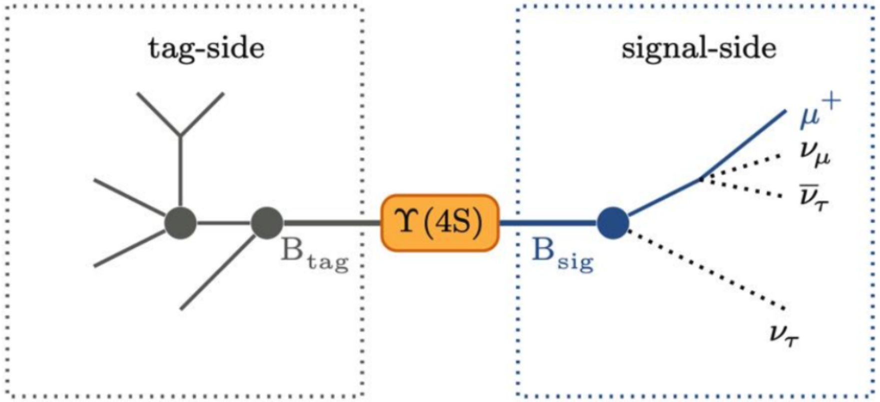
$B^+ \to \tau^+ \nu$

arXiv:2502.04885

- Leptonic B decay with the largest branching fraction that might be affected by New Physics

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

- Tagged analysis using 365/fb, on the signal side e^+, μ^+, π^+ or $\rho^+ \to \pi^+\pi^0$ are reconstructed
- Discriminating variables
  - $E_{\mathrm{ECL}}^{\mathrm{extra}}$ – residual energy in the em. calorimeter
  - M_{miss}^2 – missing mass squared in the event



$B^+ \to \tau^+ \nu$

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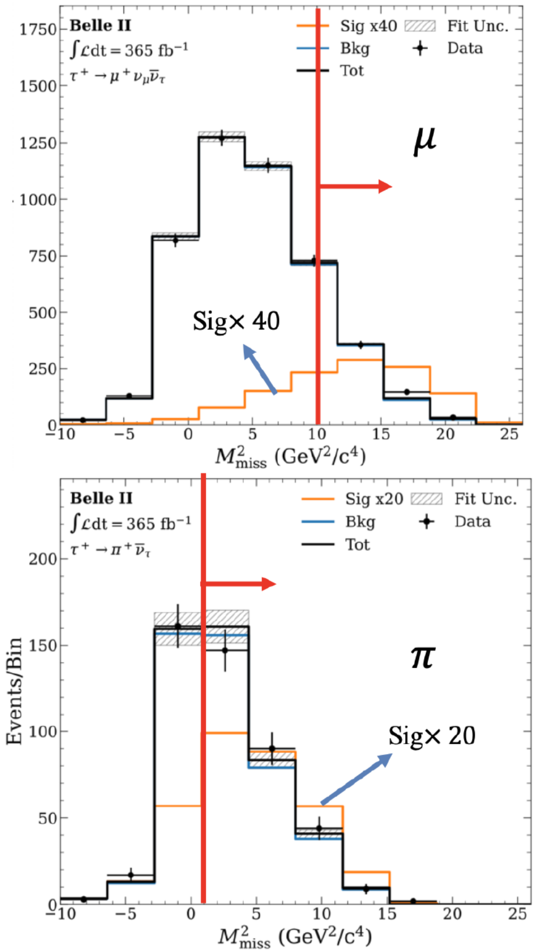

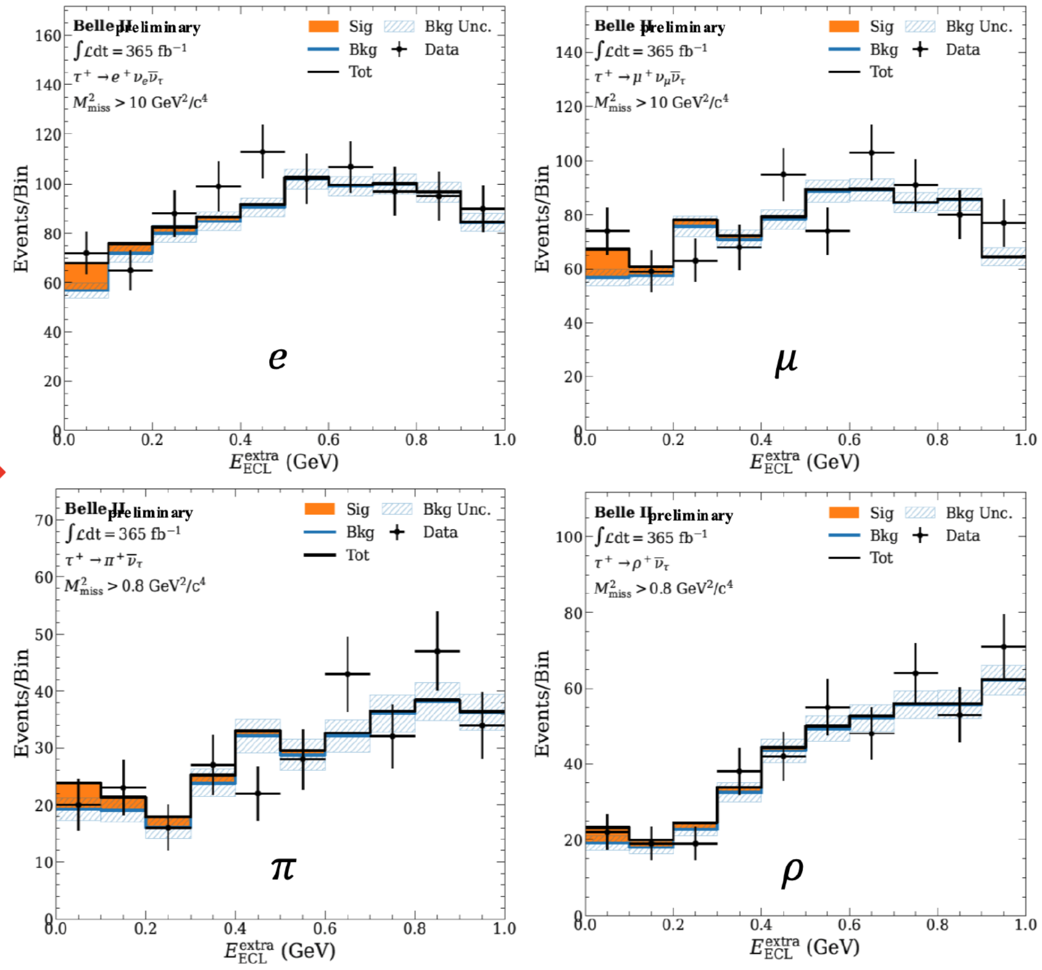

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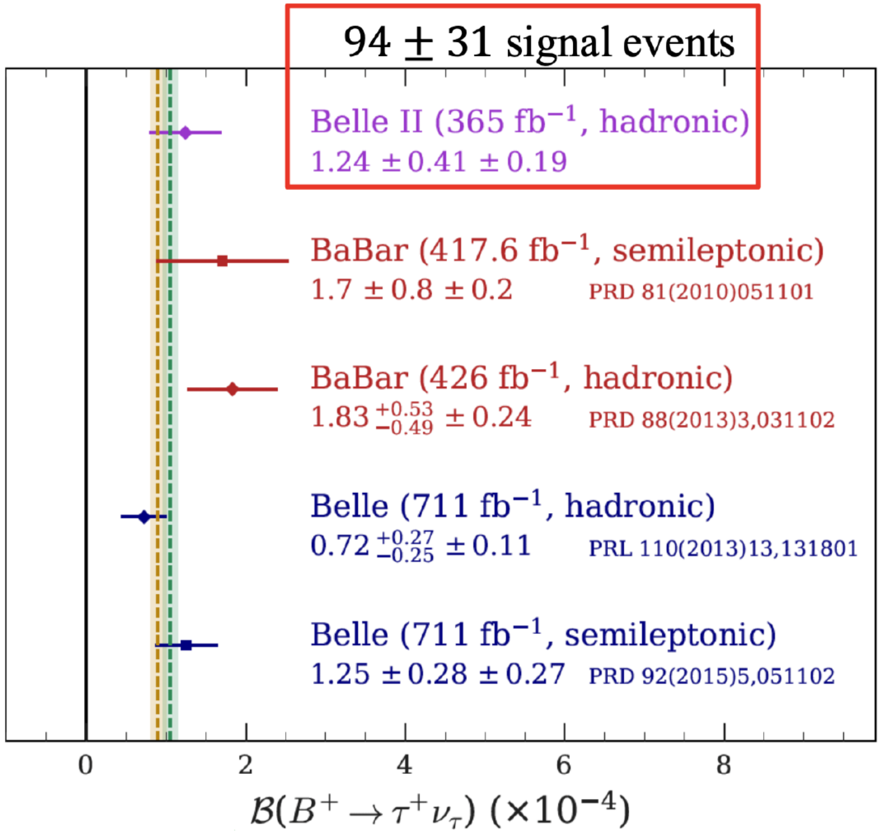


World average BR goes from

$$(1.09 \pm 0.24) \times 10^{-4}$$

to

$$(1.12 \pm 0.21) \times 10^{-4}$$

Leads to:

$$V_{ub}^{\tau\nu} = \left(4.19 \begin{array}{l} +0.38 \\ -0.41 \end{array}\right) \times 10^{-3}$$

Relative uncertainty: $^{+9\%}_{-10\%}$

HFLAV $|V_{ub}|$ exclusive: $(3.43 \pm 0.12) \times 10^{-3}$

Determination of ϕ_2/α

- Probability for $B \to CP$-Eigenstate

C: CP violation (CPV) in decay
S: CPV in mixing-decay interference

$$P(q,\Delta t) \propto 1 \pm S \sin \Delta m \Delta t - C \cos \Delta m \Delta t$$

$$q = \begin{cases} +1 & B_{\mathrm{tag}} = B^0 \\ -1 & B_{\mathrm{tag}} = \bar{B}^0 \end{cases}$$

Δt: $t_{CP} - t_{\mathrm{tag}}$

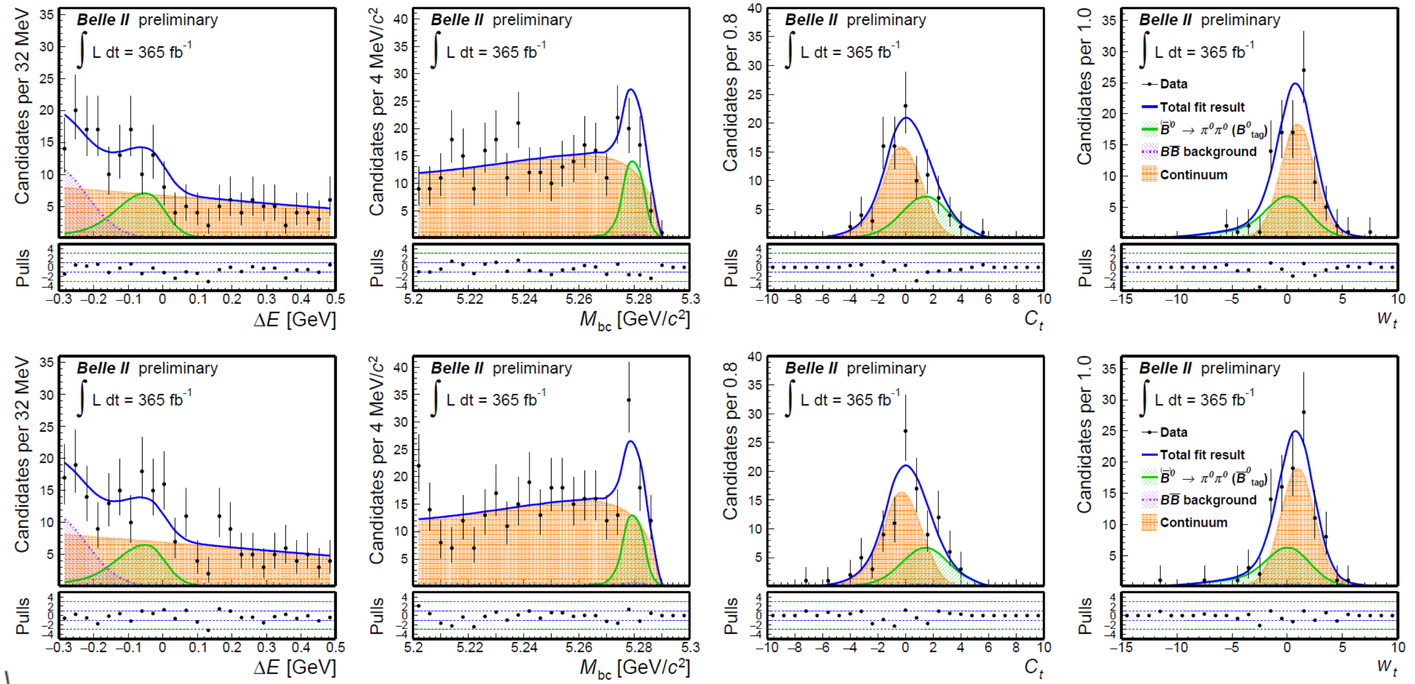
Δm: $M(B_H) - M(B_L)$

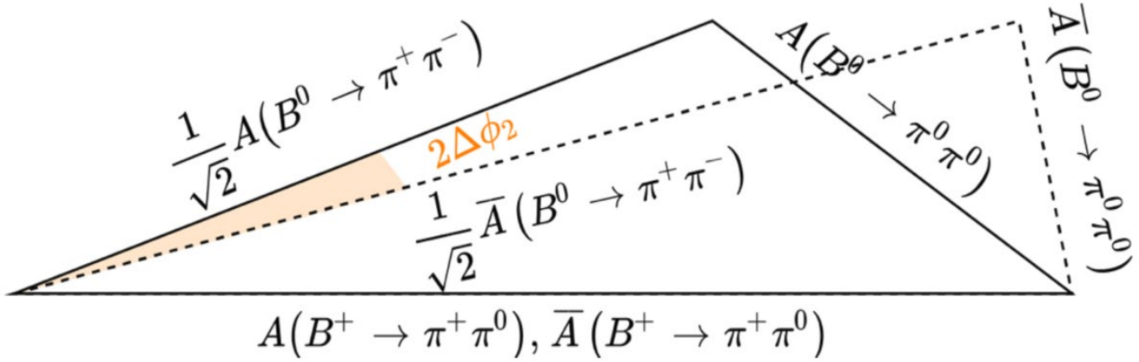
- In tree-level $b \to u\bar{u}d$ transitions to final states $\pi\pi$, $\pi\rho$, $\rho\rho$, πa_1: $S = \sin 2\phi_2$
- But $b \to$ loop contributions change this to $\sqrt{1 - C^2}\sin(2\phi_2 + \Delta\phi_2)$

Isospin relations and $B^0 \to \pi^0\pi^0$

arXiv:2412.14260

- 通过同位旋关系消除圈图影响，从而测量α角。
- 需要测量$\pi^+\pi^-$, $\pi^+\pi^0$和$\pi^0\pi^0$的分支比和CP不对称性。





$$\mathscr{B} = (1.26^{+0.20}_{-0.19} \pm 0.11) \times 10^{-6}$$
$$A_{CP} = 0.06 \pm 0.30 \pm 0.06$$

30% reduction in α uncertainty

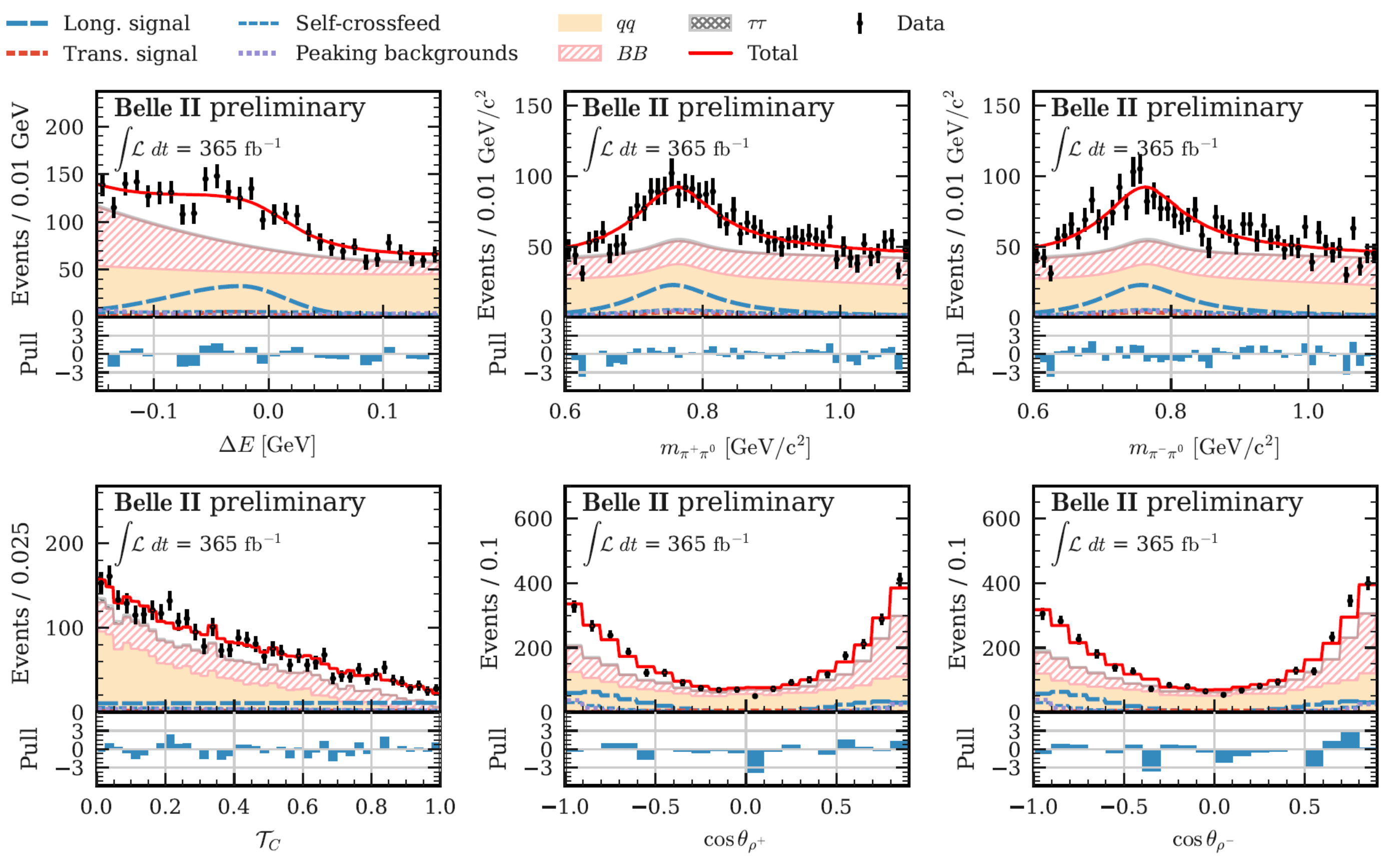
$B^0 \to \rho^+\rho^-$

arXiv:2412.19624

- 同样地，利用同位旋关系测量α角。
- 只有较小的企鹅图污染，因此是测量α角的黄金道。
- 通过6D拟合，测量信号分支比和纵向极化率。

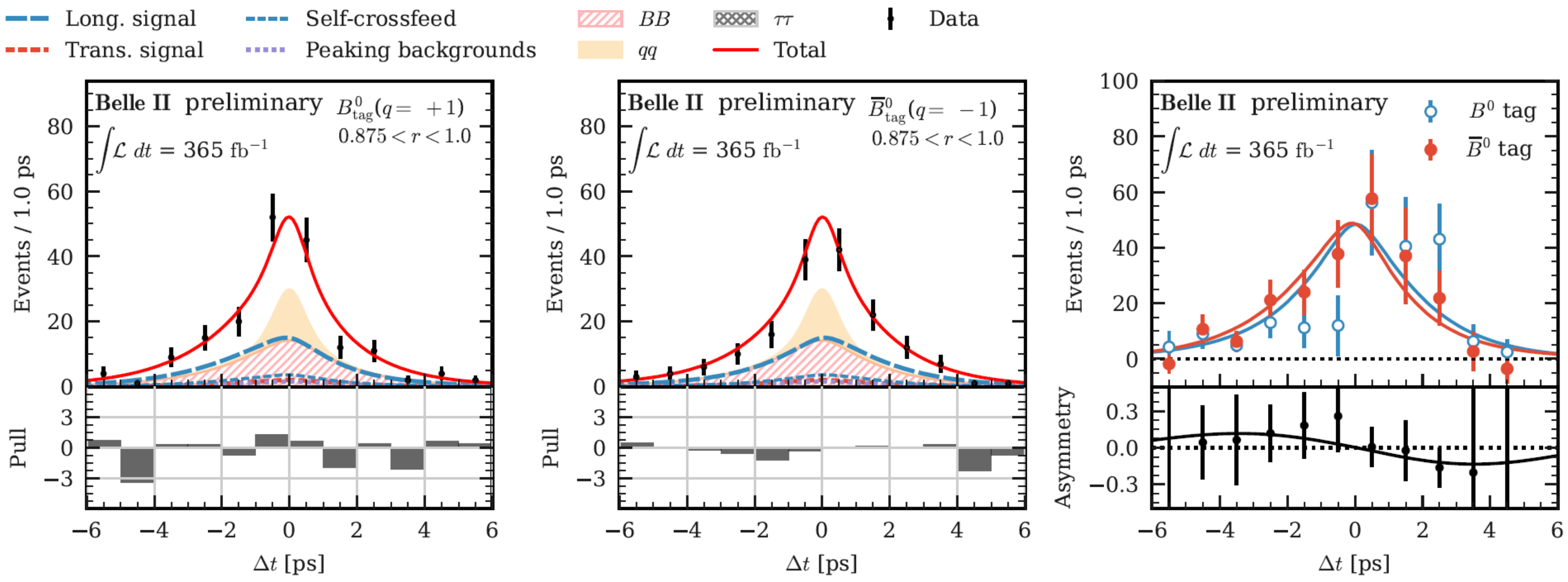
$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (2.88^{+0.23+0.29}_{-0.22-0.27}) \times 10^{-5}$$

$$f_L = 0.921^{+0.024+0.017}_{-0.025-0.015}$$



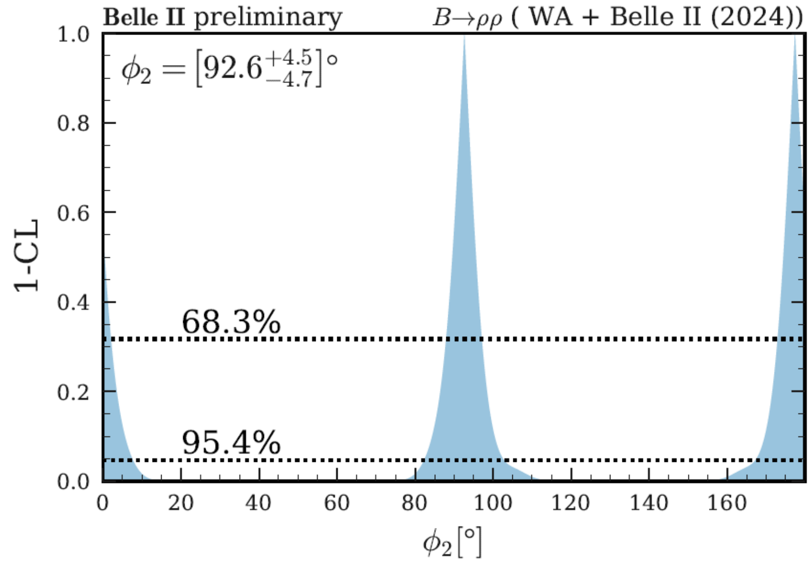
$B^0 \to \rho^+\rho^-$过程CPV的测量

- 对末态进行味道标定以后，对Δt分布进行拟合。
- 根据味道标定和顶点测量，区分$B^0 - \bar{B}^0$



Tag B^0 Tag $\bar{B}^0$ Asymmetry

arXiv:2412.19624

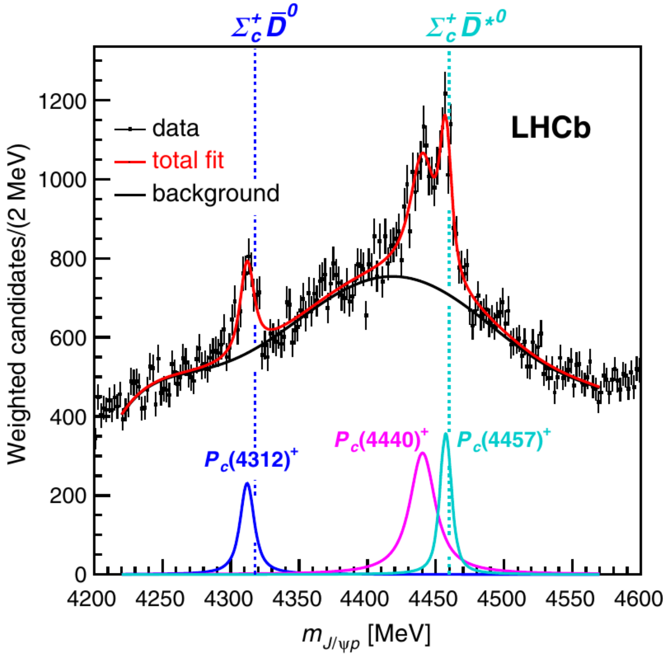


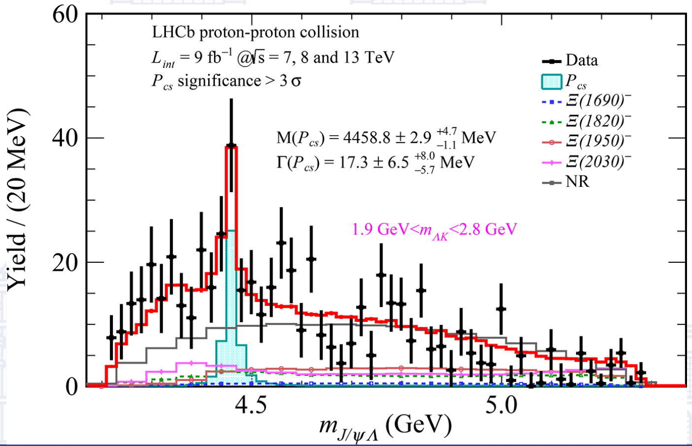
$$S = -0.26 \pm 0.19 \pm 0.08,$$

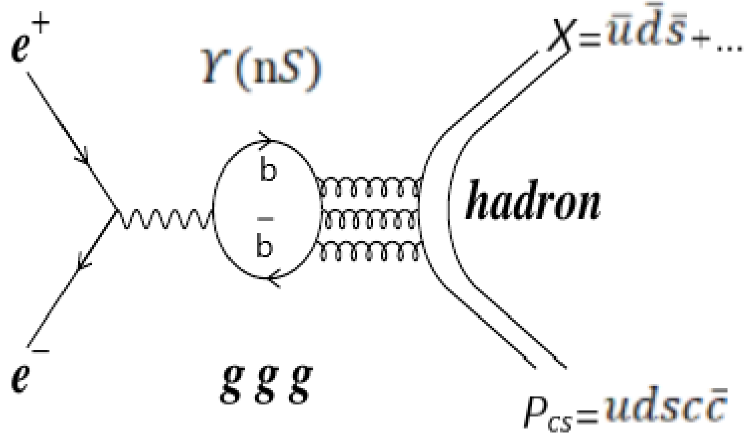
$$C = -0.02 \pm 0.12^{+0.06}_{-0.05},$$

Previous WA: $\phi_2(\rho\rho) = \left(91.5\,^{+4.8}_{-5.2}\right)^{\circ}$

在Belle/Belle II实验上如何寻找Pc/Pcs？！







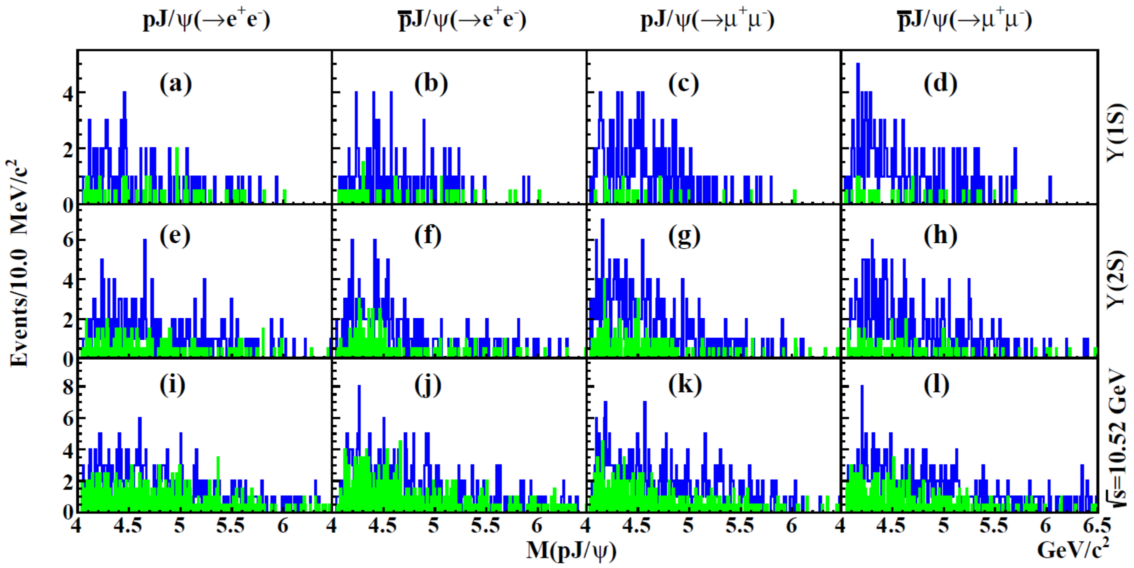
$\boldsymbol{\Upsilon(1,2S)}$单举衰变!

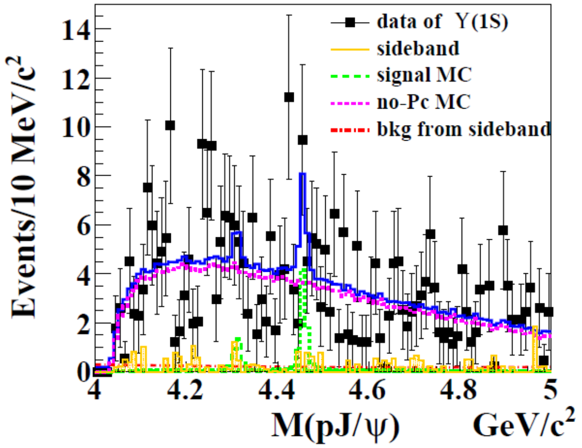
102 M $\Upsilon(1S)$ + 158 M $\Upsilon(2S)$

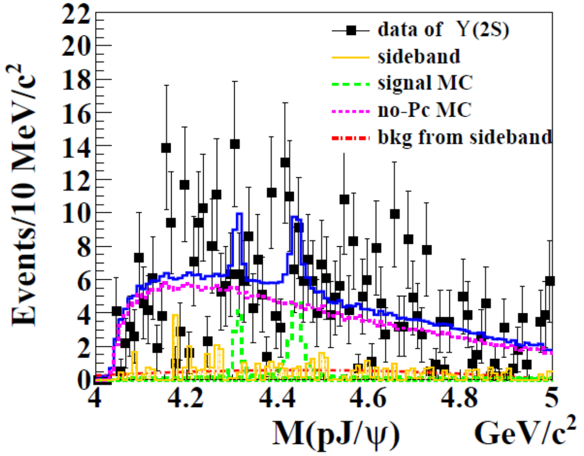
Sci. Bulletin **66**, 1278 (2021)

$\Upsilon(1,2S)$单举衰变中pJ/ψ末态的测量

arXiv:2403.04340



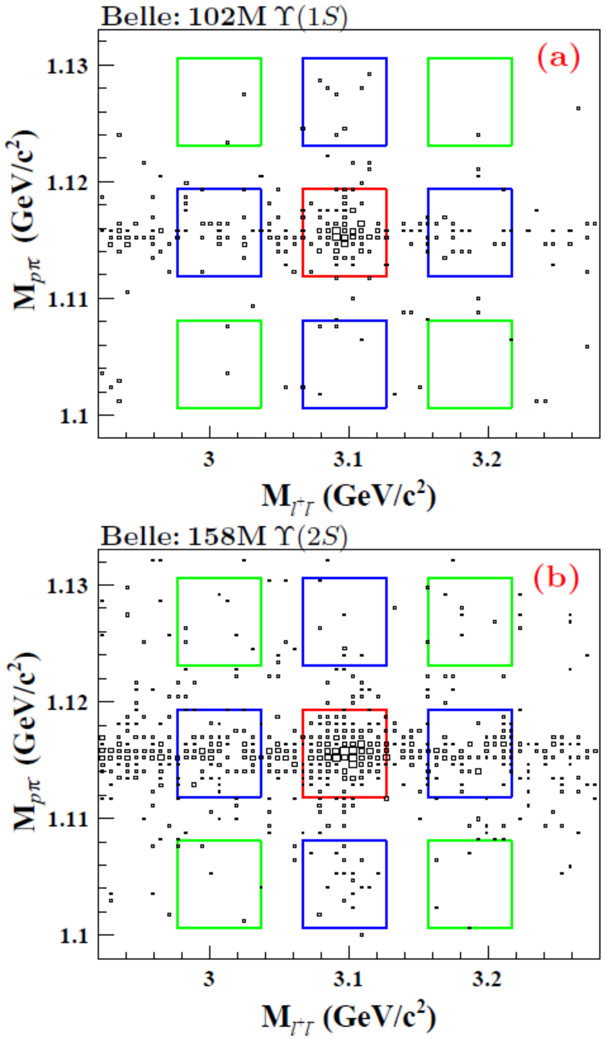


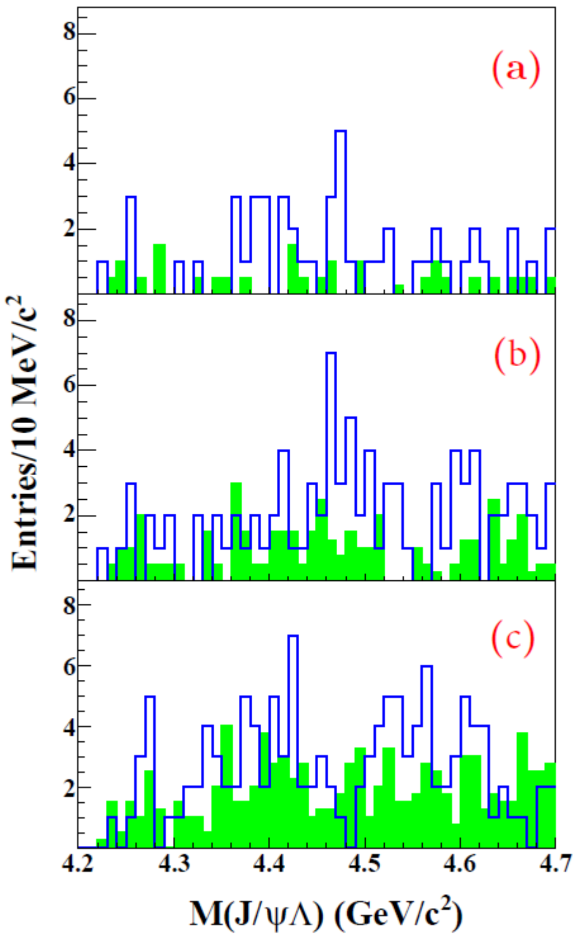


	$\Upsilon(1S)$ decays			$\Upsilon(2S)$ decays		
—	$P_c(4312)^+$	$P_c(4440)^+$	$P_c(4457)^+$	$P_c(4312)^+$	$P_c(4440)^+$	$P_c(4457)^+$
$N^{\rm A}_{\rm fit}$	6 ± 8	10 ± 11	13 ± 10	23 ± 9	30 ± 13	2 ± 15
$N^{\rm A,UL}_{\rm fit}$	20	27	30	40	54	13
$N^{\rm B}_{\rm fit}$	8 ± 9	10 ± 11	10 ± 9	24 ± 9	29 ± 11	3 ± 12
$N^{\rm B,UL}_{\rm fit}$	24	28	31	42	53	15
$N^{\rm UL}_{\rm sig}$	27	43	38	50	77	28
$\mathcal{B}^{\rm UL}$ $(\times10^{-6})$	3.9	6.2	5.5	4.7	7.2	2.6

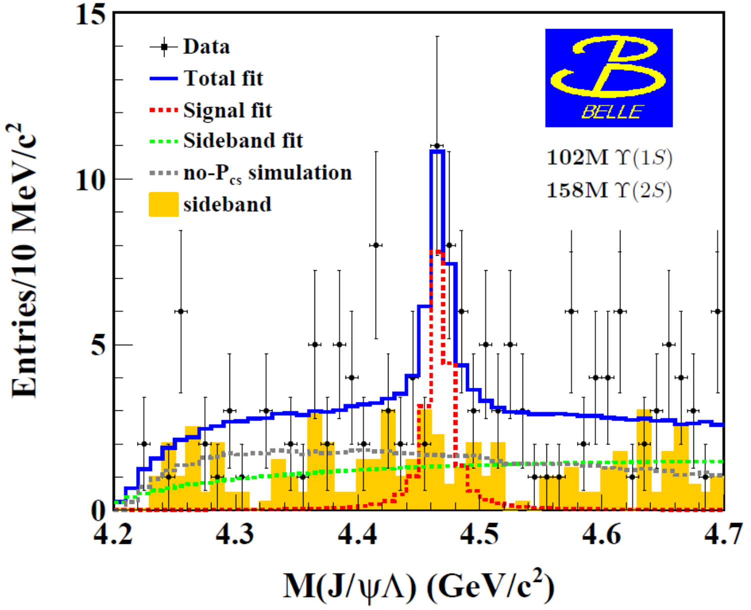
- No significant P_c state is obtained.
- We set upper limits on P_c productions from $\Upsilon(1S,2S)$ inclusive decay.
- We measure the branching fractions of pJ/ψ productions
  - $Br[\Upsilon(1S)\to pJ/\psi + anything] = (4.27\pm0.16\pm0.20)\times10^{-5}$
  - $Br[\Upsilon(2S)\to pJ/\psi + anything] = (3.59\pm0.14\pm0.16)\times10^{-5}$

Evidence for $P_{cs}(4459)$





arXiv:2502.09951



- 限制在LHCb的测量结果，通过ToyMC的检验获得3.3σ显著性。
- 自由拟合获得$P_{cs}(4459)$参数：
  - $\mathbf{M = 4471.7 \pm 4.8 \pm 0.6\ MeV/c^2}$
  - $\mathbf{\Gamma = 21.9 \pm 13.1 \pm 2.7\ MeV}$

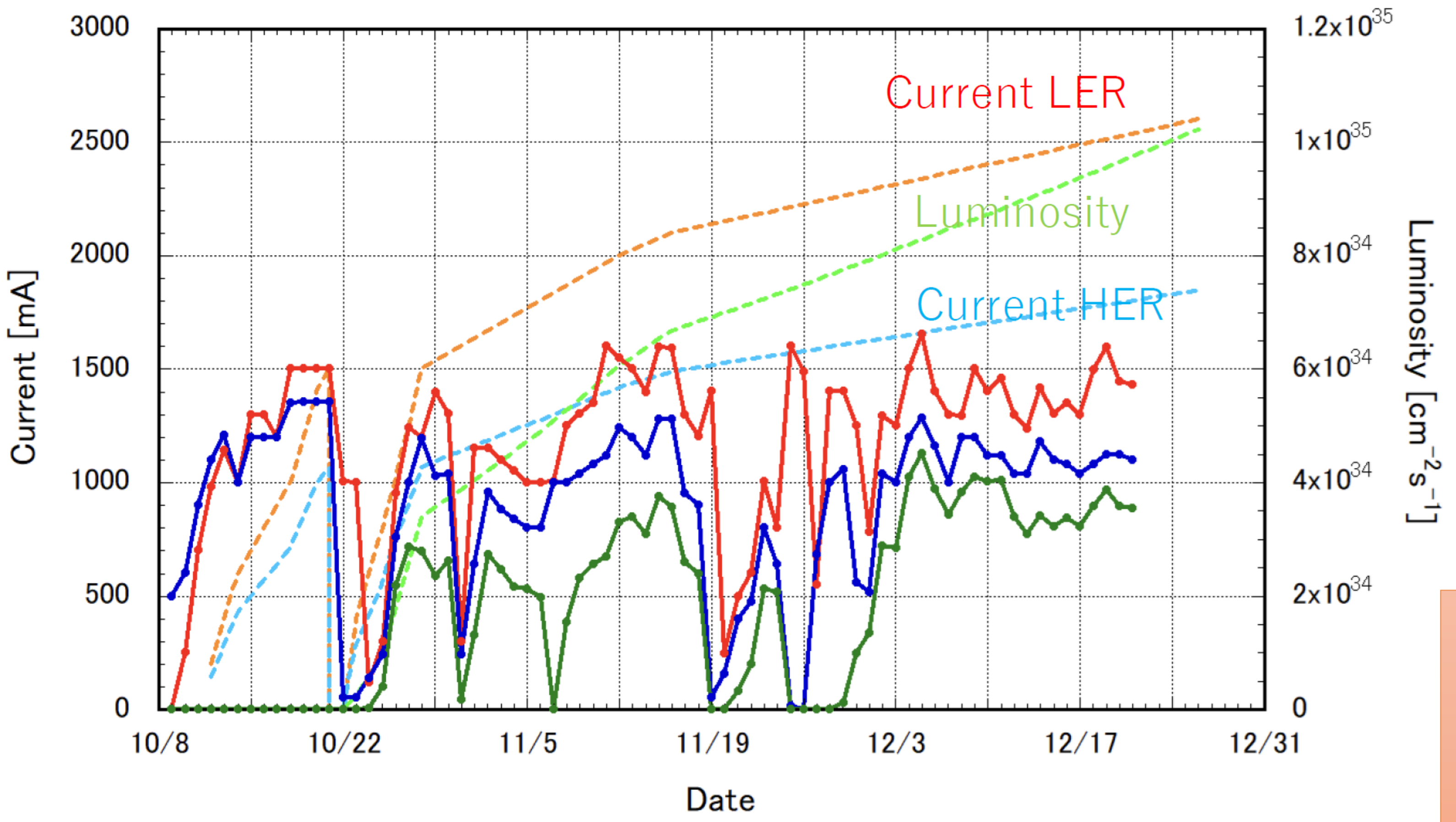
总结

- Belle II实验是当前味物理与CPV领域的两大高亮度前沿实验之一，目前已经采集了$> 500\ fb^{-1}$的$\Upsilon(4S)$数据。
- Belle II实验在B物理方面的进展：
  - $|V_{ub}|$ from $B^0 \to \pi^- l^+ \nu$ and $B^+ \to \rho^0 l^+ \nu$
  - Branching fraction of $B^+ \to \tau^+ \nu$
  - Branching fraction and CPV in $B^0 \to \pi^0 \pi^0$
  - ϕ_2/α from $B^0 \to \rho^+ \rho^-$
- 首次在$\Upsilon(1,2S)$的单举衰变中寻找五夸克态候选者
  - 在pJ/ψ末态中未发现显著的P_c^+的信号，产额上限在10^{-6}量级
  - 在$\Lambda J/\psi$末态中获得$P_{cs}(4459)^0$的证据，3.3σ

谢谢！

But we have still many problems to be fixed.

DG's talk



2024 target Luminosity was $> 1 \times 10^{35}$ cm^{-2}s^{-1}
Not yet (half of target)

Final target Luminosity after LS1 : $\sim 2.4 \times 10^{35}$ cm^{-2}s^{-1}

1) Increasing total beam currents
2) Increasing bunch current (beam current)
3) Squeezing βy

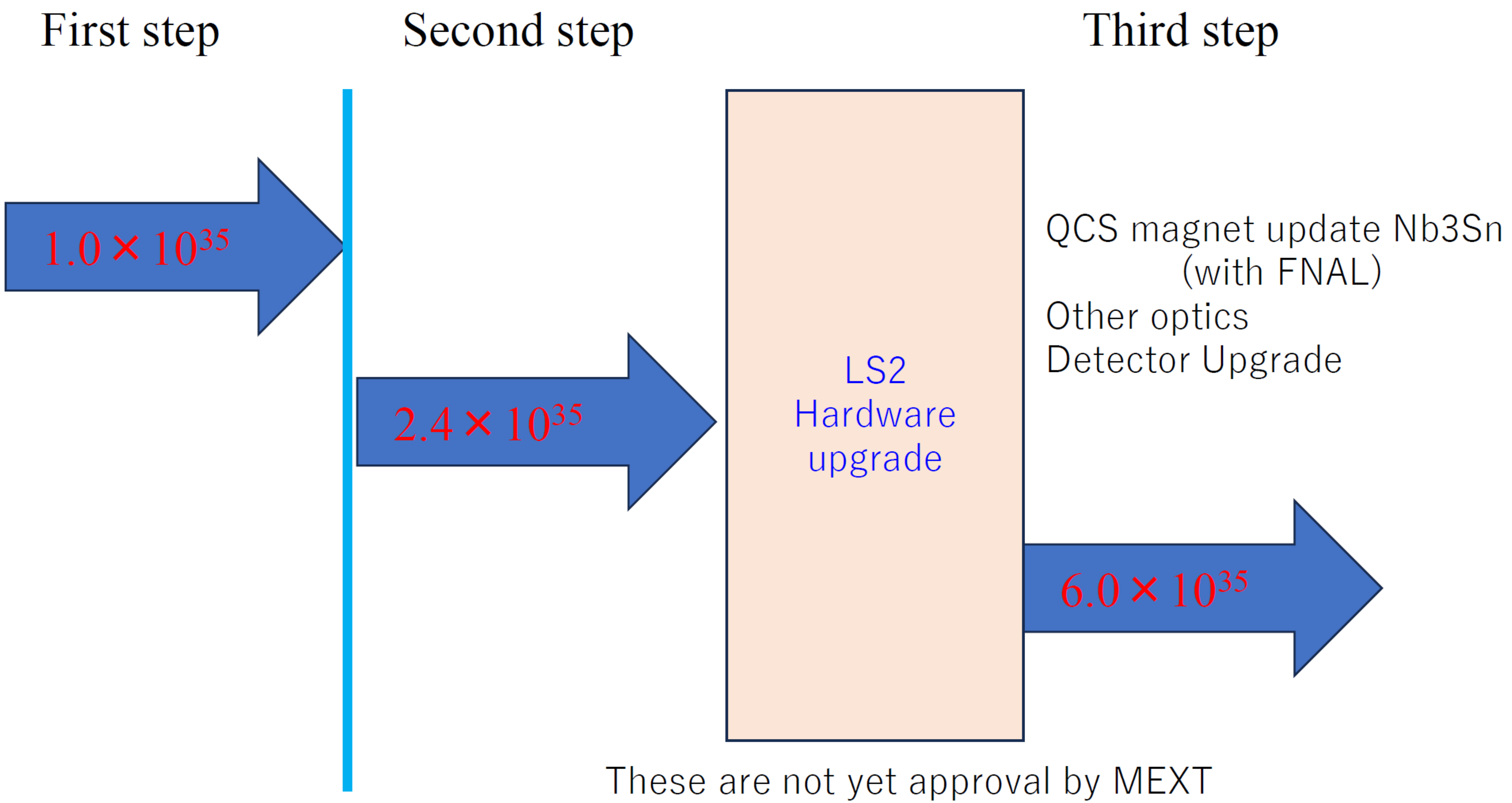
We can not increase current
1) **SBL**
2) low efficiency injection

Overcome SBL is top priority

Basic problems

1) Short beam lifetime
2) **Beam instabilities (SBL)**
3) Low machine stability
4) Low injection efficiency

Three steps

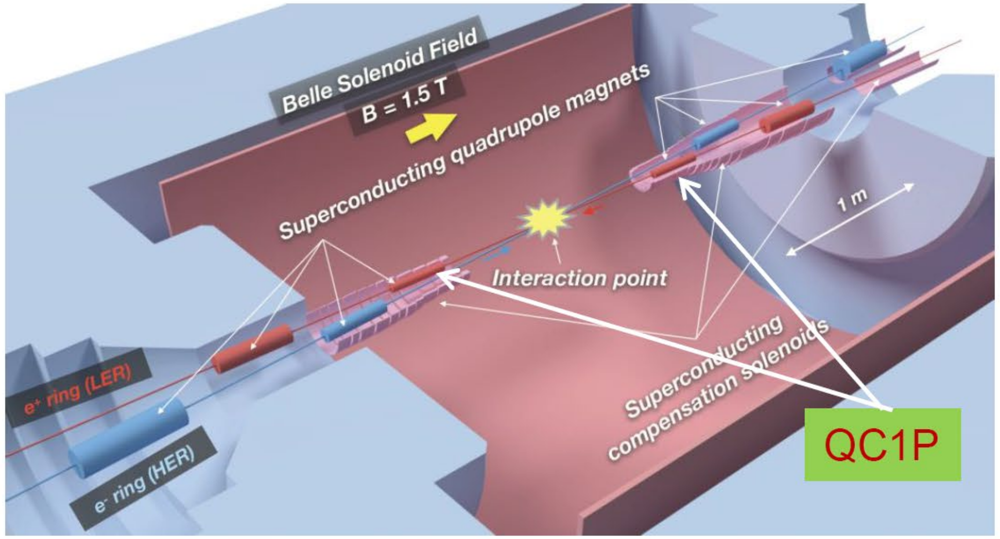


These are not yet approval by MEXT

Development of the SuperKEKB IR Nb_3Sn Quadrupole (QC1P) magnet

Last week
I visited FNAL

US-JAPAN collaboration

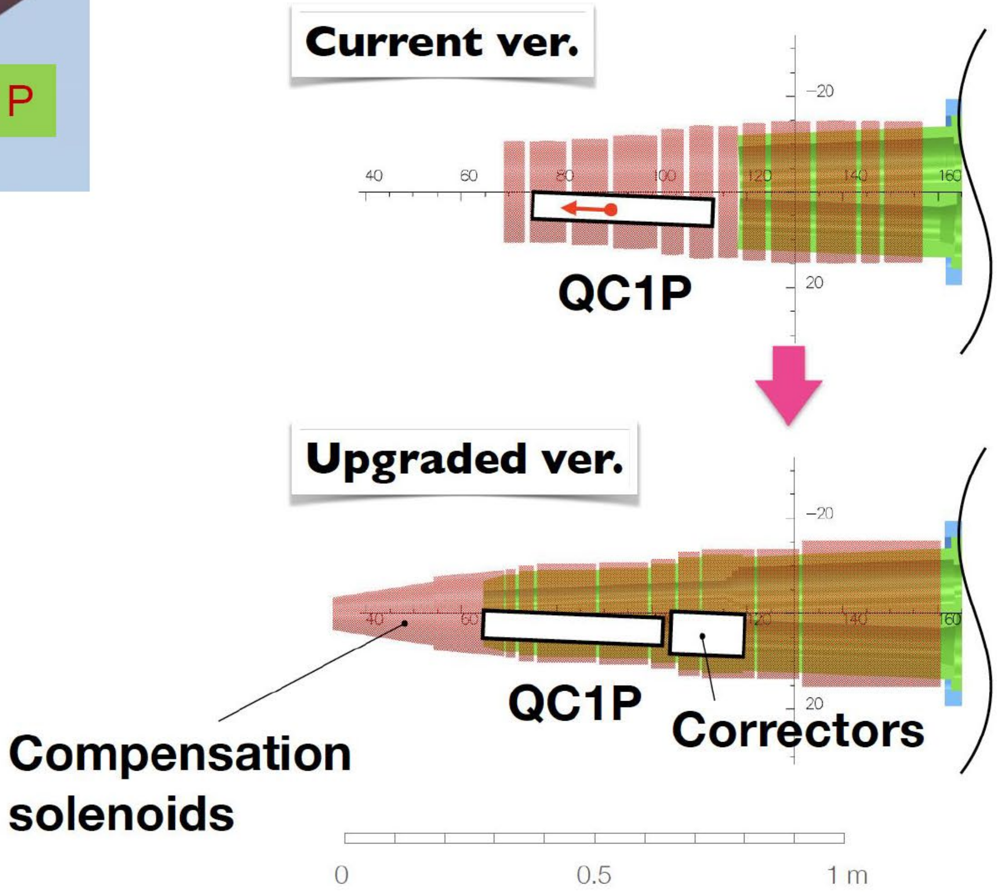


Proposed QCS modification for higher luminosity

QC1P 100 mm closer to IP
- Enlarge dynamic aperture of LER
- Extend the beam lifetime

Change conductor of QC1P from NbTi to Nb3Sn
- Decrease risk of beam-induced quench

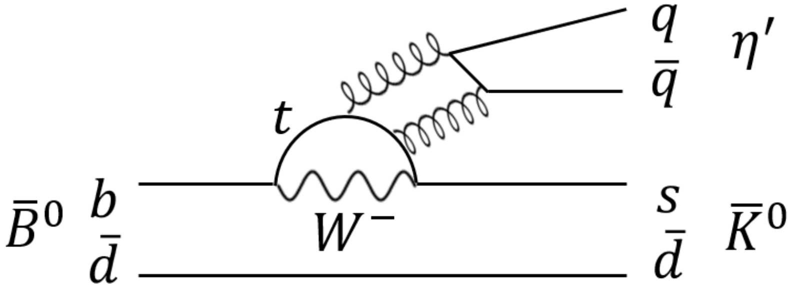
Install a compensation solenoid between the IP and QC1P - Simplify IR optics
- Reduce chromatic xy coupling
- Reduce emittance growth at IR



Insight through Accelerators.
KEK

Phys. Rev. D 110, 112002 (2024)

Time-dependent *CP* violation - $\boldsymbol{B^0 \to \eta' K_S^0}$



- Decay may also have a BSM phase as it is a gluonic penguin
  - alter the value of φ_1 from that measured in $b \to c\bar{c}s$ transitions such as $B^0 \to J/\psi K_S^0$
- Reconstructing $\eta' \to \eta(\gamma\gamma)\pi^+\pi^-$ and $\eta' \to \rho(\pi^+\pi^-)\gamma$ we select 829 ± 35 events in 362 fb^{-1} sample
  - 3D fit to ΔE, m_{BC} and continuum suppression output
- **sin 2φ_1 = 0.67±0.10±0.04**
- Consistent with current HFLAV average and that from $b \to c\bar{c}s$ result