Latest results and BSM searches from Belle II

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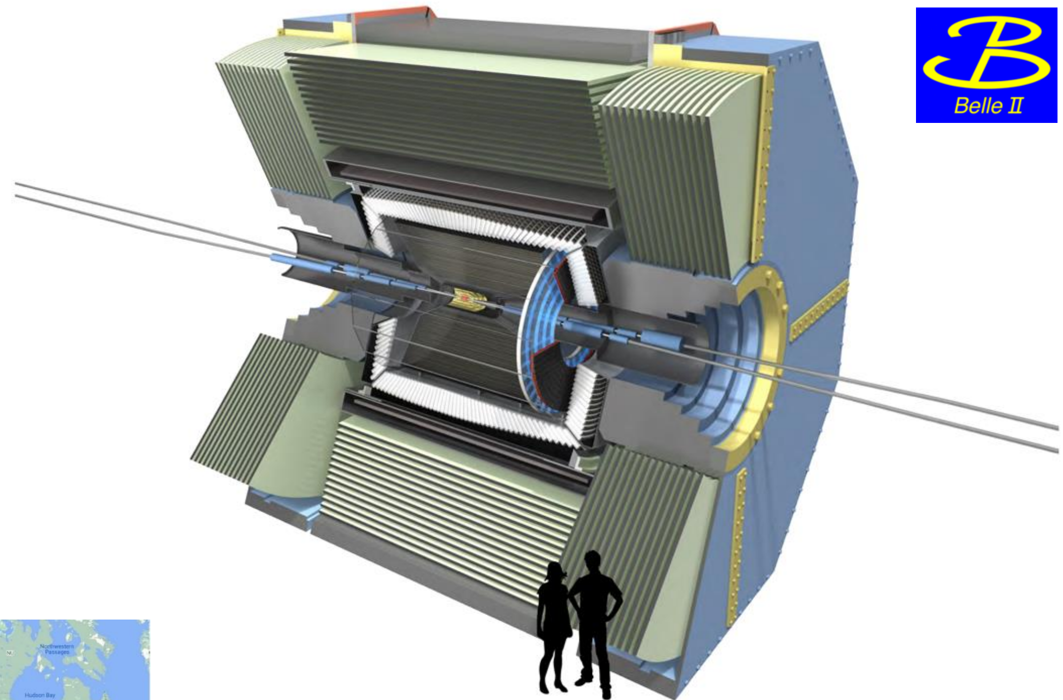
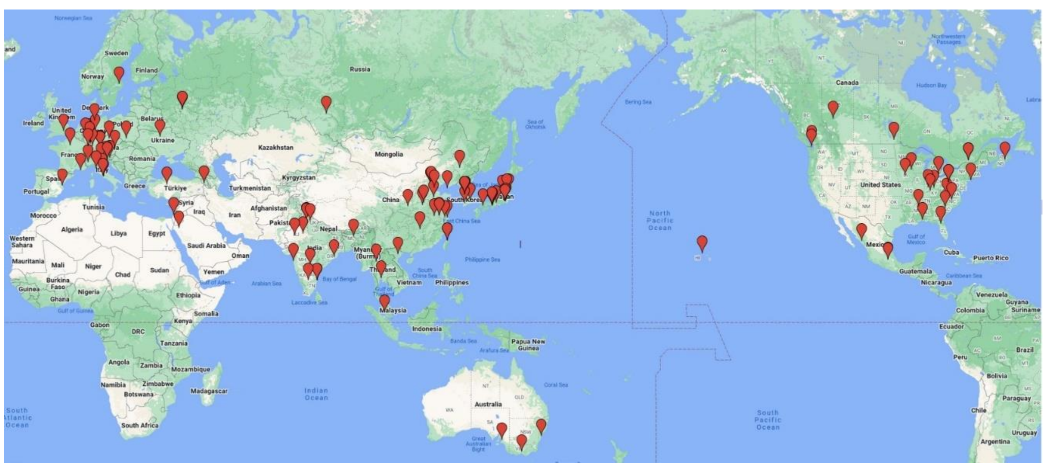
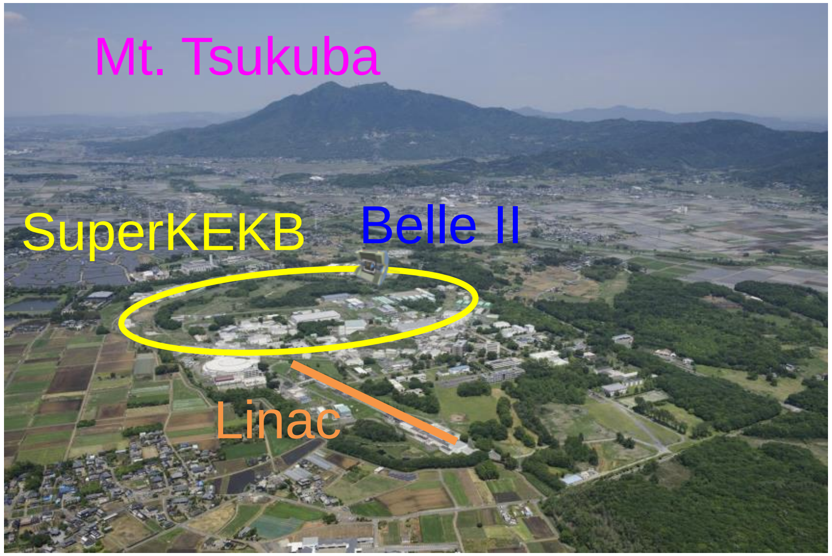


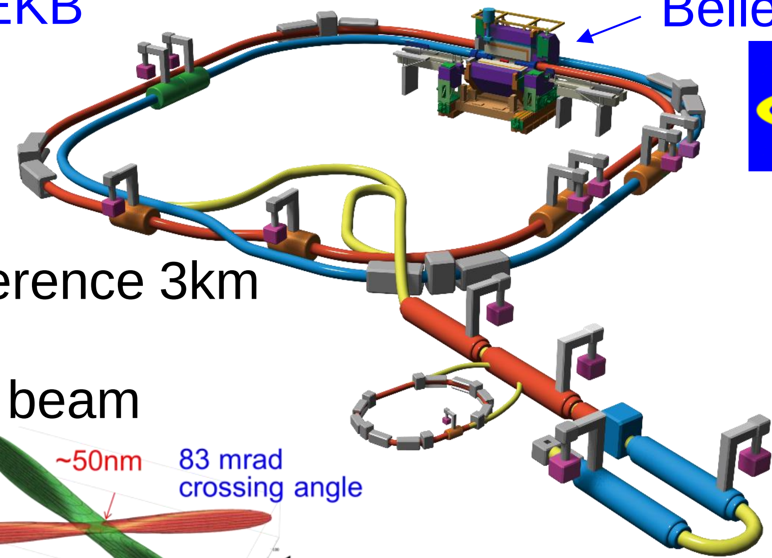
Belle II

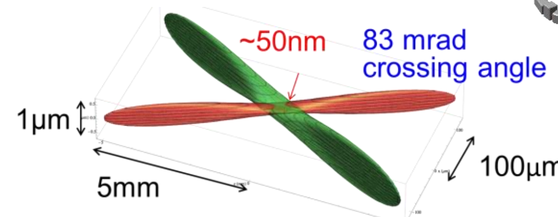


Belle II Collaboration:
- 28 countries
- 125 institutes
- ~1200 researchers

SuperKEK と Belle II







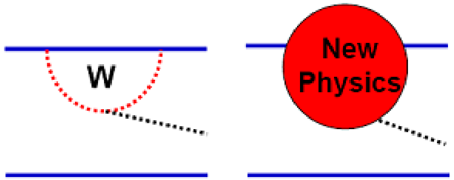
SuperKEKB and Belle II

- Located at KEK, Tsukuba, Japan.
- SuperKEKB: asymmetric e^+e^- collider (4 GeV e^+ + 7 GeV e^-)
  - ✓ Nano-beam scheme to achieve high luminosity.
- Belle II: flavor physics experiment at SuperKEKB.
- Successor of KEKB, Belle in operated in 1999-2010
  - ✓ Verified Kobayashi-Maskawa theory in the study of CP violation in B mesons.

Kibayashi, Maskawa (2008 Nobel Prize)

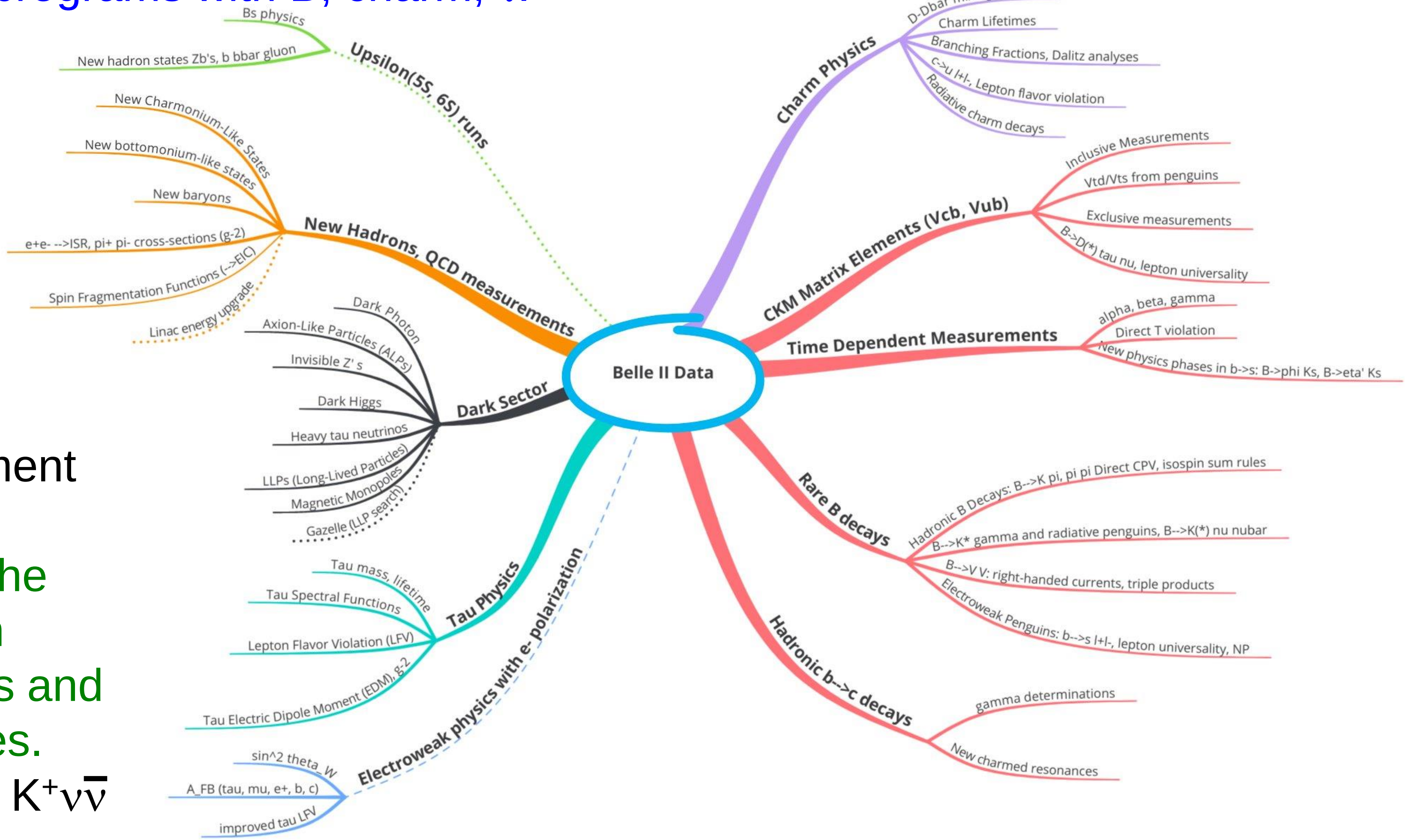
Belle II: flavor physics experiment

- Flavor = species of the quarks and leptons
- Produce large number of B mesons, charm, τ at SuperKEKB.
- Precise measurements of the B, c, τ decays provide information of New Physics (NP) Beyond the Standard Model (BSM)
  - ✓ Loop diagrams: BSM particles can virtually contribute to the decays.
  - ✓ Compare with the prediction of the Standard Model (SM)



- Signature sensitive to BSM.
  - ✓ Lepton Flavor Violation (LFV): inhibited at the SM.
  - ✓ Lepton Flavor Universality (LFU): SM interaction does not depend on the lepton species (e, μ, τ).
  - ✓ CP asymmetry, … : observables with precise SM prediction
  - ✓ Smaller SM contribution: rare decays.

- Intensity frontier experiment: Search for New Physics with precise measurements.
- Rich physics programs with B, charm, τ.



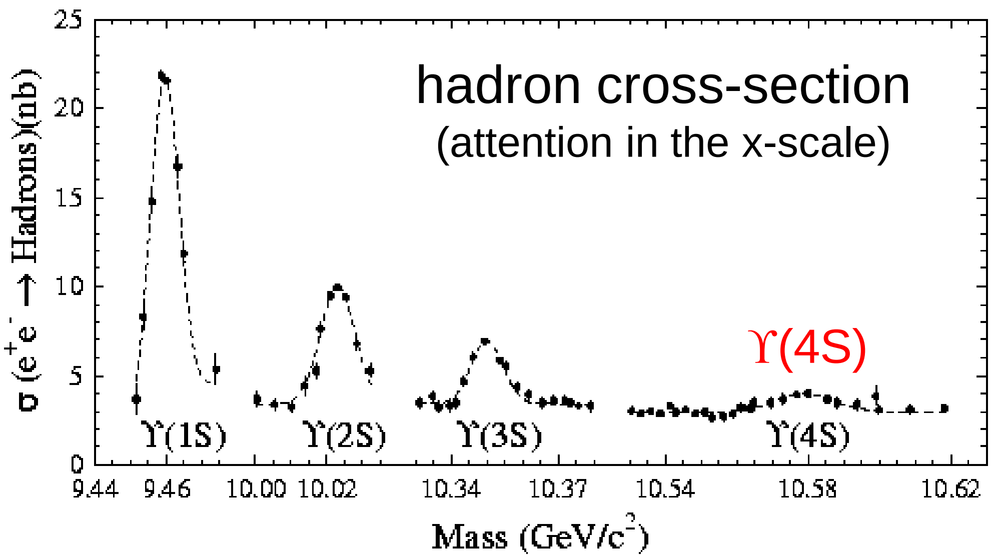
- Clean environment (e^+e^- collider) : advantage for the final states with neutral particles and missing particles.
  - ✓ e.g. $B^+ \to K^+\nu\bar{\nu}$

SuperKEKB and Belle II

- SuperKEKB is mainly operated at ϒ(4S) mass (10.58 GeV)

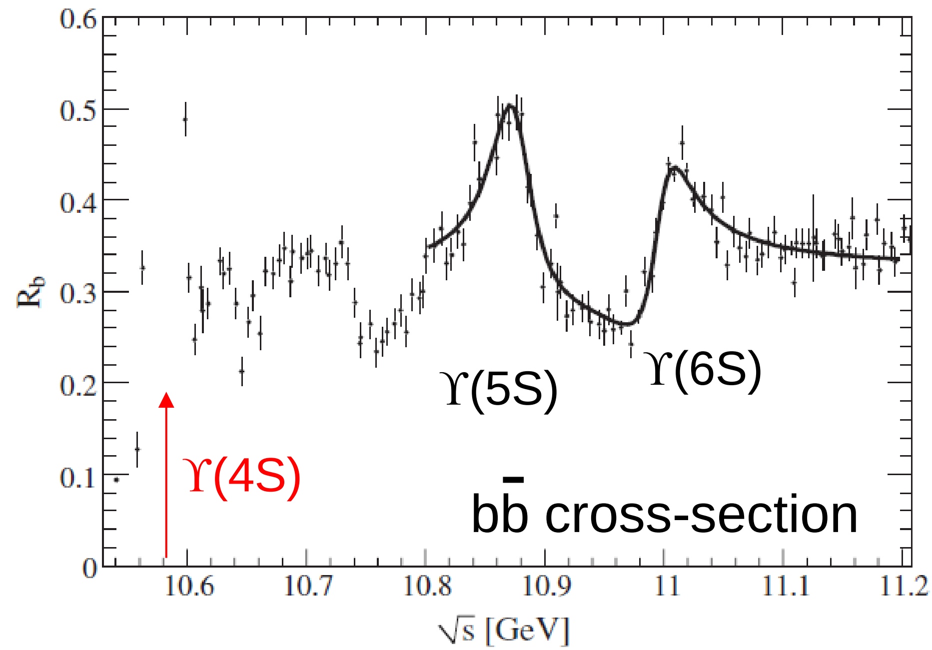
$e^+e^- \to \Upsilon(4S) \to B\bar{B}$	(1.1nb)
$e^+e^- \to q\bar{q}$ (q = u,d,s,c)	(~3nb)
$e^+e^- \to \tau^+\tau^-$	(0.9nb)

Not only B mesons, but also charm and τ are produced



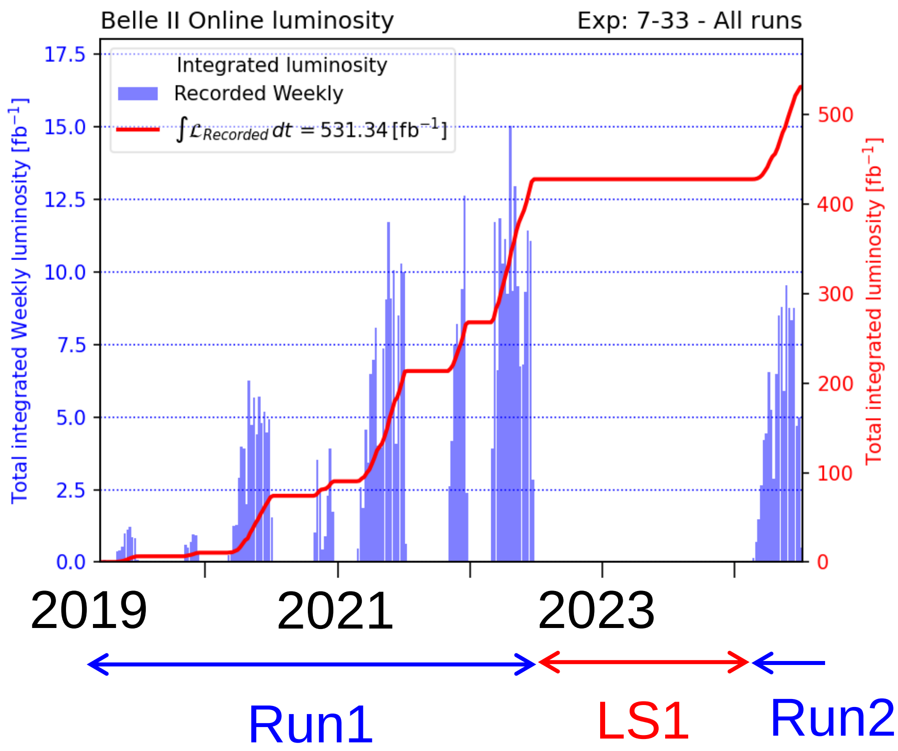
- Some data are taken at off-resonance (60 MeV below ϒ(4S))
- Energy scan data above ϒ(4S) (10.66-10.81 GeV) is taken for bottomonium study at Belle II.
- Belle took data at ϒ(1,2,3,5S), too.

[BaBar, PRL102, 012001]



Luminosity

- Luminosity (~intensity) is a key for the experiment.
  - ✓ Luminosity [$cm^{-2} s^{-1}$] = (event rate [s^{-1}]) / (cross-section [cm^{-2}])
  - ✓ Integrated luminosity = Luminosity × (operation time) : collected data size



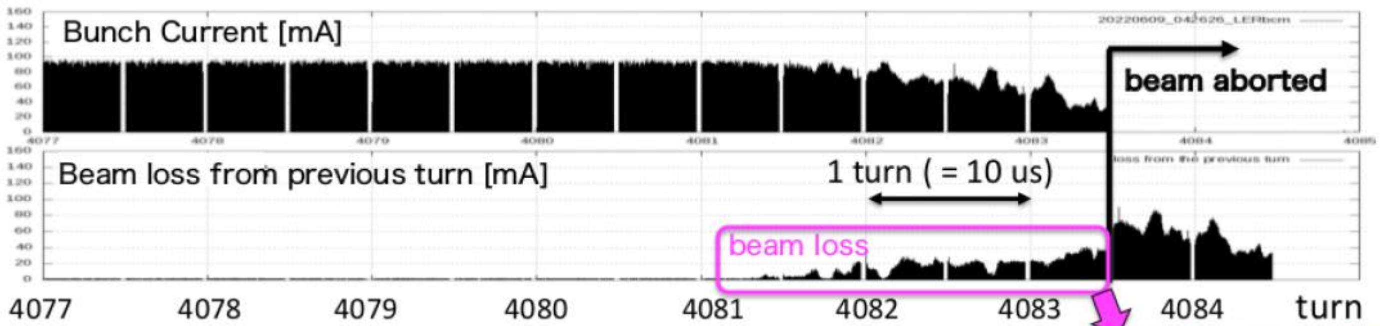
Long shutdown to fully install PXD detector

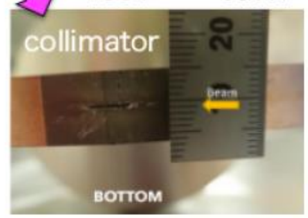
- Luminosity 4.7×10^{34} $cm^{-2} s^{-1}$ achieved (Jun. 2022):
  - ✓ World record (~ ×2 of KEKB)
  - ✓ Aiming one order higher.
- 530 fb^{-1} of data accumulated so far.
  - ✓ Similar to BaBar data set.
  - ✓ Belle: 1 ab^{-1} (=1000 fb^{-1}) in 11 years.
- Belle II target: 50 ab^{-1}
- Run 2 just started.

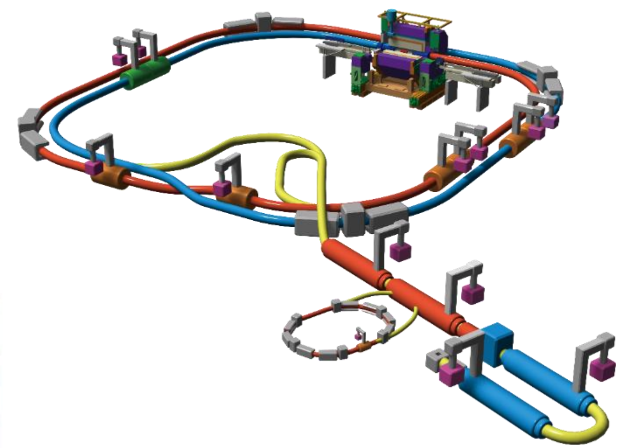
Status of SuperKEKB

Current issue in SuperKEKB: Sudden Beam Loss (SBL)

- All the beam is lost within a few turns.



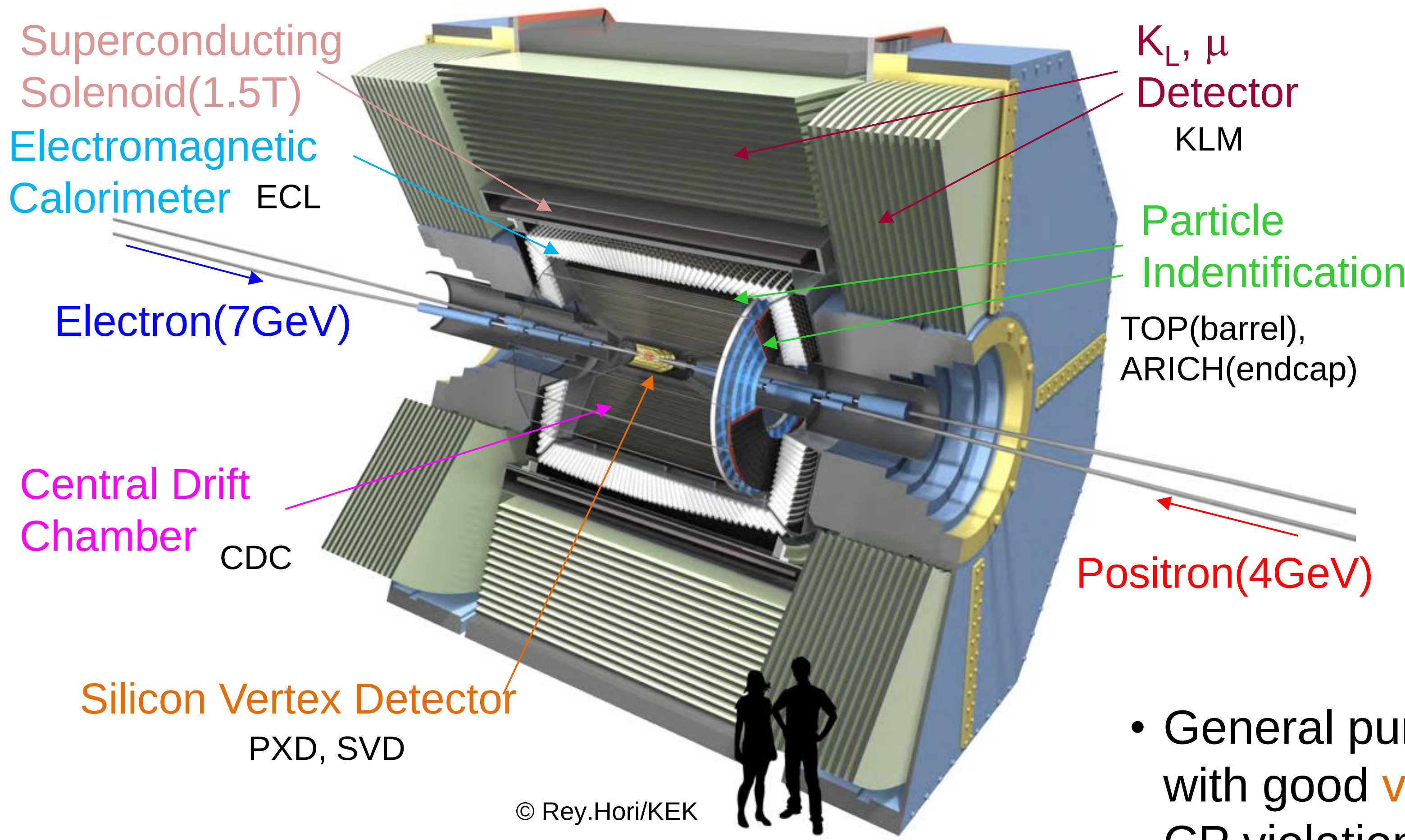


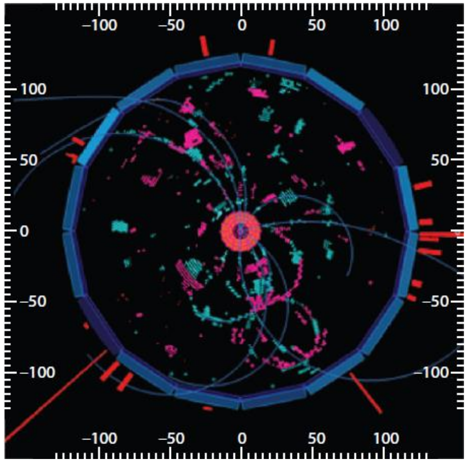


In few cases, damaged Belle II detector and accelerator equipment (QCS quenches)

- The beam current needs to be increased to obtain high luminosity.
  - ✓ Now, LER/HER = 1.4/1.2 A
- Frequent SBL prevents the operation in high beam current.
- From the investigation in 2024, we find some hints of the source of SBL (dust in some section ?). To be solved in the autumn 2024 run.

Belle II





Belle II Detector (8m×8m×8m, 1400t)

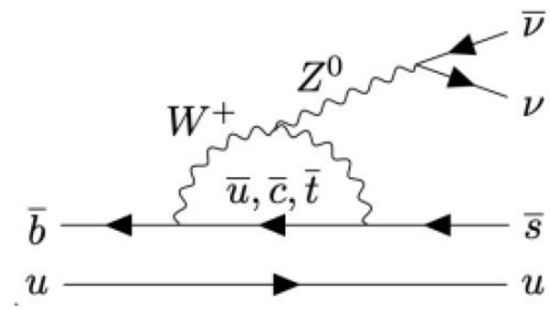
- General purpose 4π detector with good vertexing (for time CP violation) and particle identification.

Recent Belle II Results

$B^+ \to K^+\nu\nu$

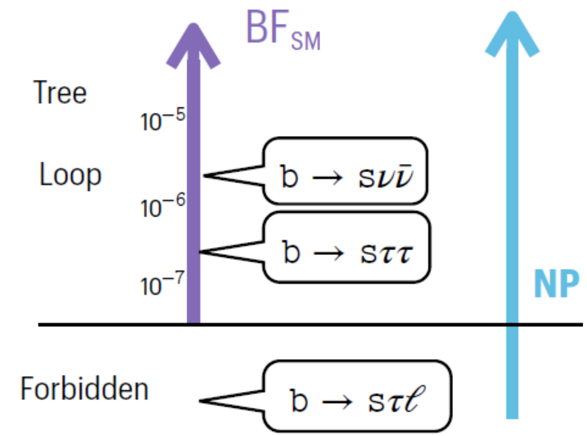
b → s

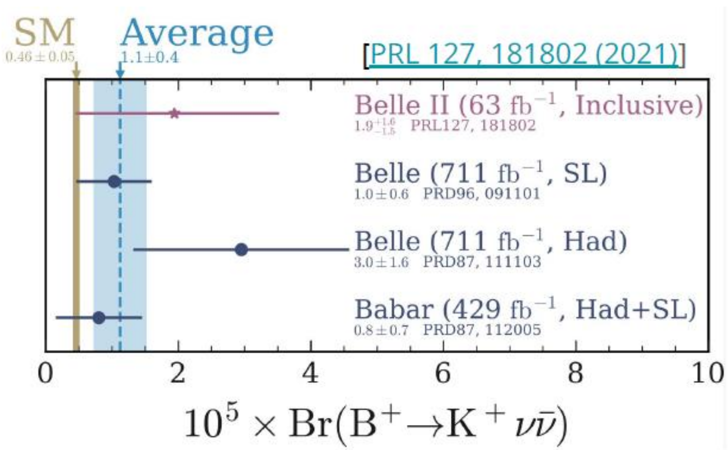
- Flavor Changing Neutral Current (FCNC)
  - ✓ Electroweak penguin, Sensitive to NP
  - ✓ Small branching fraction (BF) in SM ($<10^{-5}$)



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

- Two neutrinos in the final states.
  - ✓ Unique to e^+e^- collider.
- BF precisely predicted in the SM.
  - ✓ Uncertainty dominated by hadronic form factors.





SM prediction

$$B(B^+ \to K^+\nu\bar{\nu}) = (0.56 \pm 0.04) \times 10^{-5}$$

[PRD 107, 014511 (2023)]

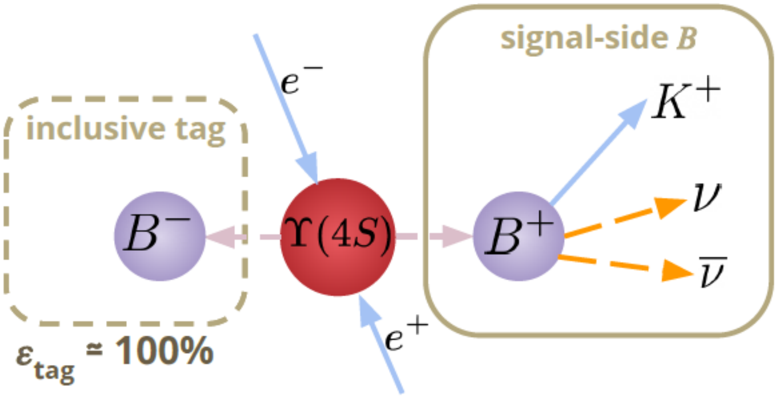
including long-distance effect of $B^+ \to \tau^+ (K^+\bar{\nu})\, \nu$

$B^+ \to K^+\nu\nu$

Belle II Analysis with Run1 data (365 fb^{-1})

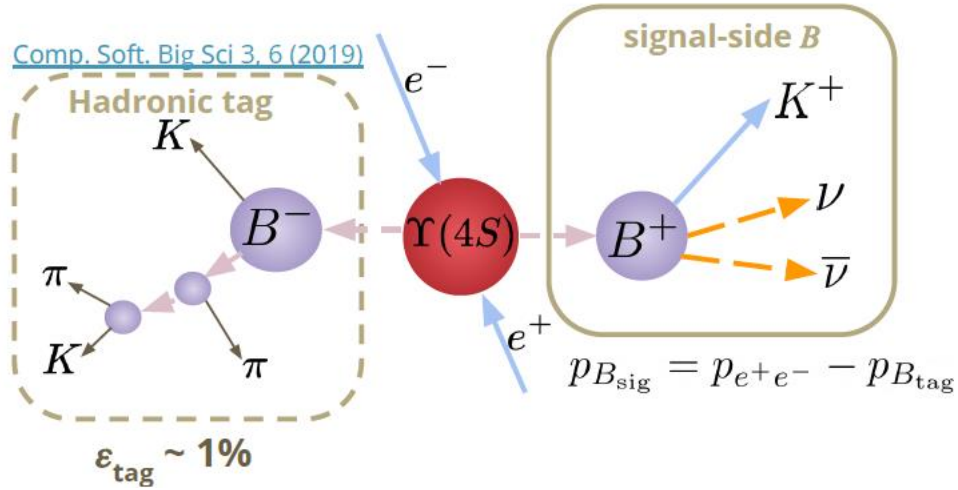
[PRD 109, 112006 (2024)]

Inclusive Tag Analysis (ITA)



- Newly developed at Belle II
  - ✓ Used in the search with 63 fb^{-1}.
- Reconstruct signal B (pick up K$^+$) only, exploit the rest of the event (ROE) to suppress backgrounds.
- More sensitive than HTA.

Hadronic Tag Analysis (HTA)

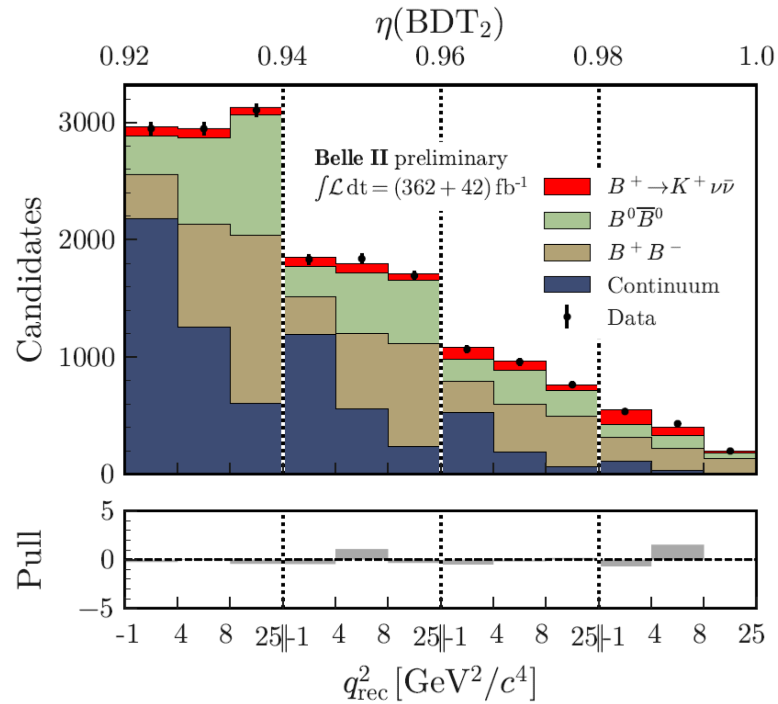


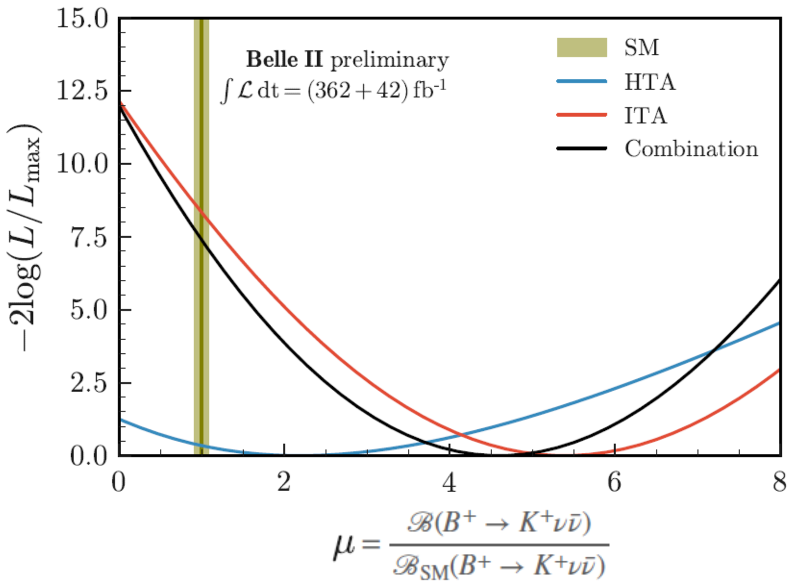
- Conventional method.
- Reconstruct the tag side B with hadronic mode.
- Lower background → validation of ITA.

$B^+ \to K^+\nu\nu$

- Two BDTs to suppress background (ITA).
- Control sample $B^+ \to J/\psi\ K^+$ (removing J/ψ).
- Detailed studies of other B decay modes, especially with K_L in the final states.

- ITA and HTA results are combined.
  - ✓ Common events are removed from ITA (~2%).





$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = [2.4 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})] \times 10^{-5}$$

- First evidence of the signal (3.5σ)
- 2.7σ deviation from the SM prediction.

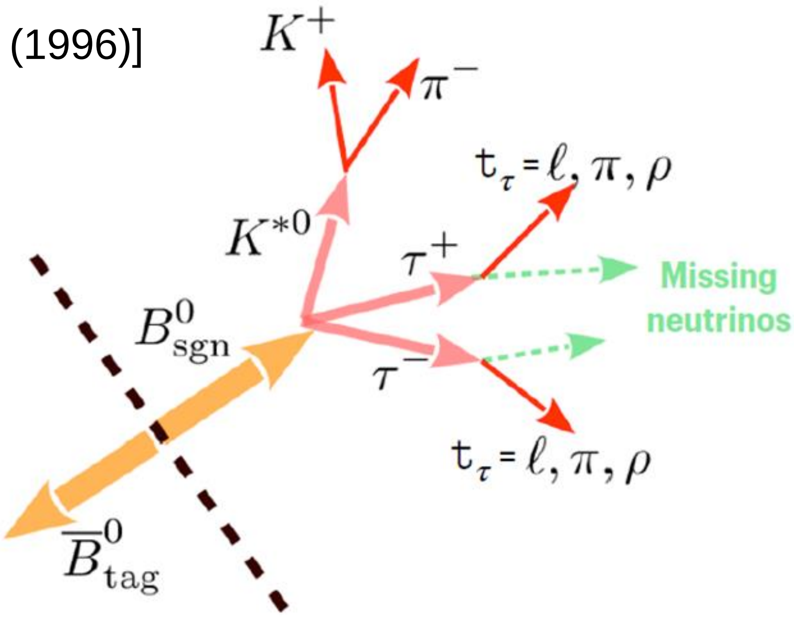
$B^0 \to K^{*0}\tau^+\tau^-$

SM prediction [PRD 53, 4964 (1996)]

New @ ICHEP2024
(paper in preparation)

$B(B^0 \to K^{*0}\tau^+\tau^-) = (0.98 \pm 0.10) \times 10^{-7}$

- If $b \to s\nu\bar{\nu}$ or $b \to c\tau\nu$ is enhanced by the BSM, $b \to s\tau\tau$ may be also enhanced by a few order of magnitude.
- Difficult analysis: two τ, and each τ decays to one or more ν.
- Previous result (Belle, 711 fb^{-1})
  $B(B^0 \to K^{*0}\tau^+\tau^-) < 3.1 \times 10^{-3}$ [PRD 53, 4964 (1996)]



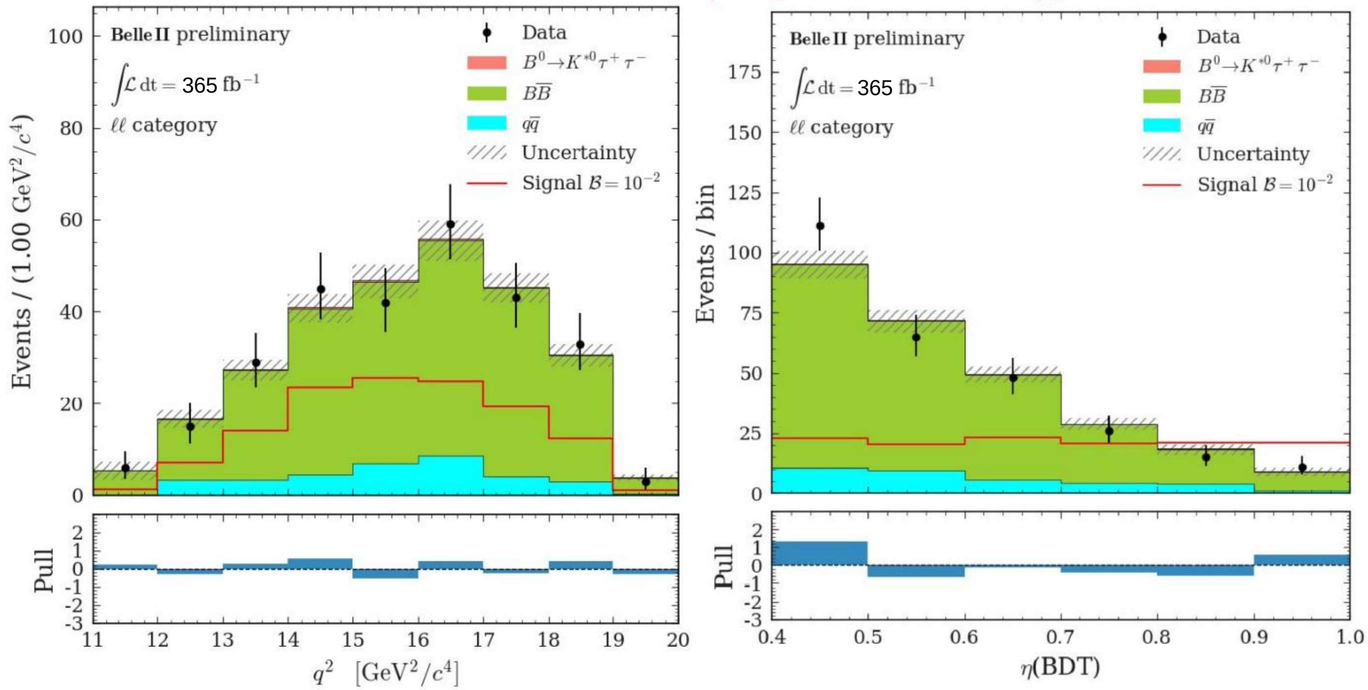
New Belle II analysis (365 fb^{-1})

- Hadronic Tag
- 4 categories of charged particle from τ
  - ✓ $\ell\ell$, $\ell\pi$, $\pi\pi$, ρX (ℓ = e, μ)
- Signal extraction using background-suppression variable η(BDT).

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

$\ell\ell$ as an example [best sensitivity]

New @ ICHEP2024
(paper in preparation)



η(BDT) :
E_{extra}, q^2, $M(K^{*2}, t)$ …

track from τ

$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3}$

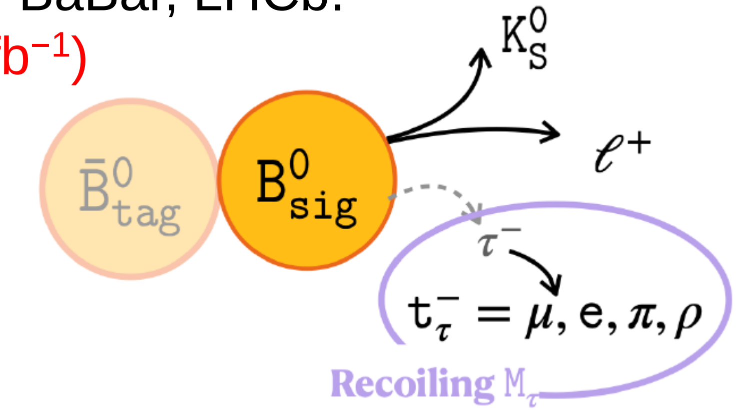
- Twice better sensitivity with only half data compared Belle result.
- The most stringent limit.
- c.f.) SM prediction ~1×10^{-7}.

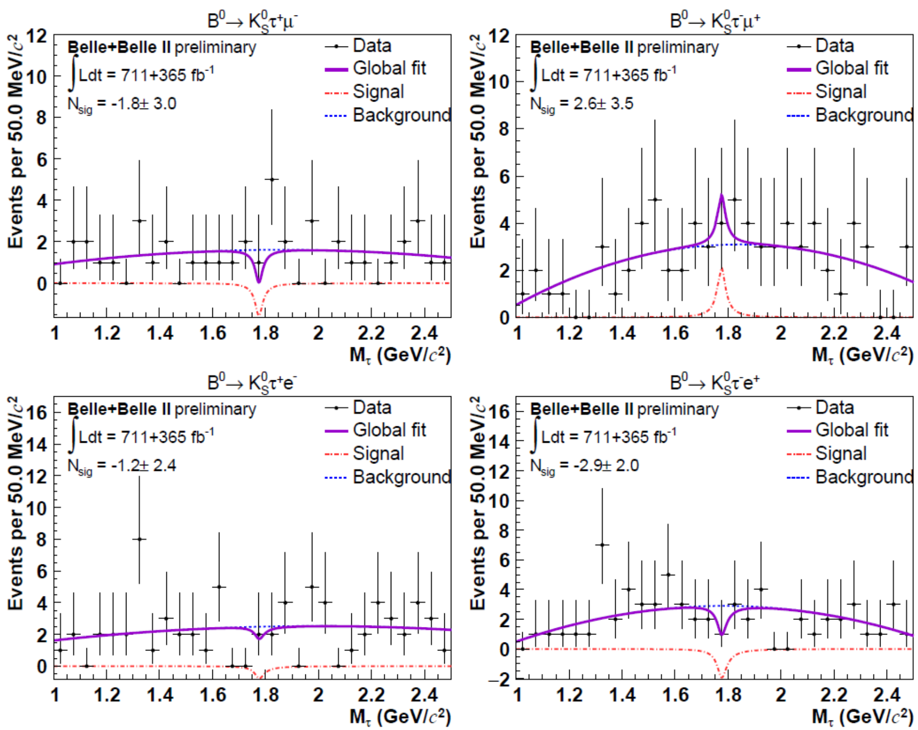
$B^0 \to K_S\tau\ell$

$B^0 \to K_S\tau\ell$ (ℓ = e, μ)

New @ ICHEP2024
(paper in preparation)

- LFV decays in $b \to s\tau\ell$
- Past searches are for $B^+ \to K^+\tau\ell$, $B^0 \to K^{*0}\tau\ell$ in Belle, BaBar, LHCb.
- First search using Belle + Belle II data (711 + 365 fb^{-1})
- Hadronic B tagging and look at recoil mass.





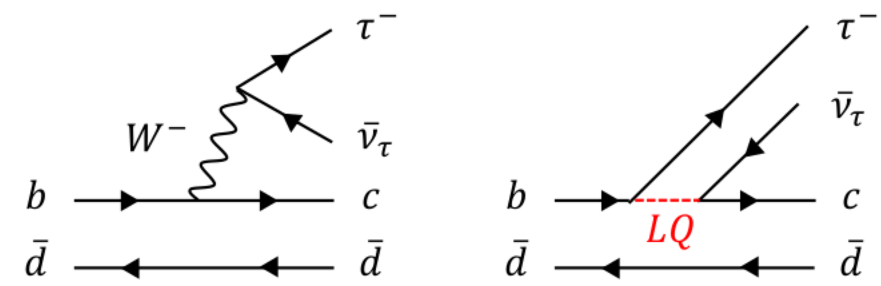
$$\mathcal{B}(B^0 \to K_S^0\tau^+\mu^-) < 1.1 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0\tau^-\mu^+) < 3.6 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0\tau^+e^-) < 1.5 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0\tau^-e^+) < 0.8 \times 10^{-5}$$

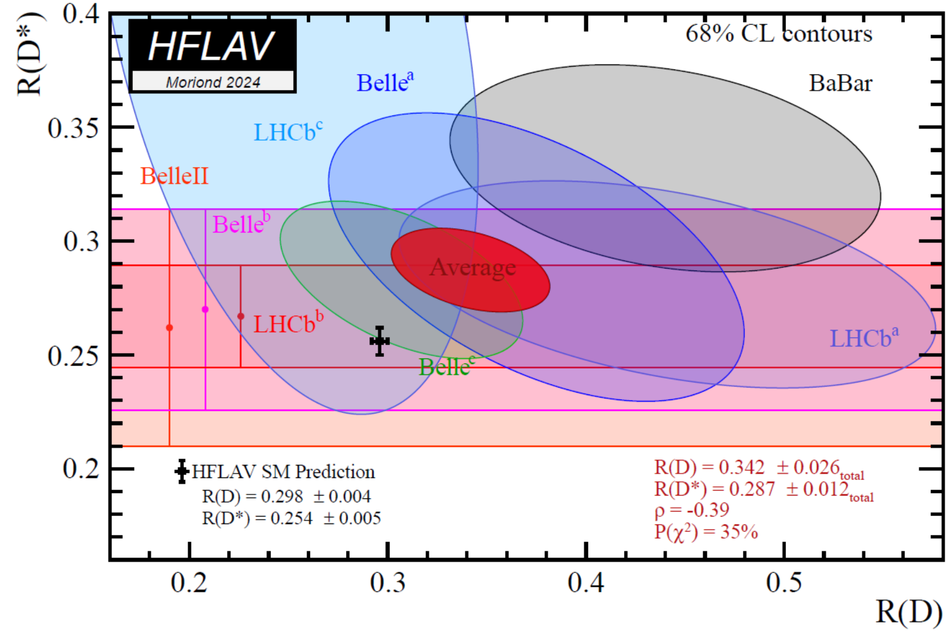
Most stringent limits among $b \to s\tau\ell$

$R(D^{(*)})$: LFU in $B \to D^{(*)}\ell^+\nu$

Lepton Flavor Universality (LFU)

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)} \quad (\ell = e \text{ or } \mu)$$





Now 3.3 σ discrepancy (B anomaly)

- Sensitive to the contributions of New Physics (e.g. leptoquark)
- First result from Belle II was presented in 2023 (189 fb^{-1})
  - ✓ Using hadronic B tag

[arXiv:2401.02840]

$$R(D^*) = 0.262\ ^{+0.041}_{-0.039}(\text{stat})\ ^{+0.035}_{-0.032}(\text{syst}).$$

comparable stat. precision as Belle

dominant by PDF shapes, MC sample size

Analysis of R(D), R(D*) with Run 1 dataset is going on.

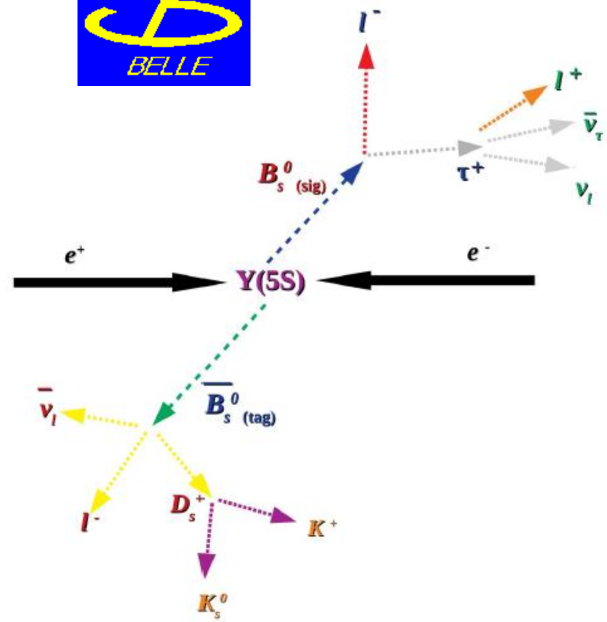
$B_s \to \tau\ell$ at Belle

$B_s \to \tau\ell$ (ℓ = e, μ)

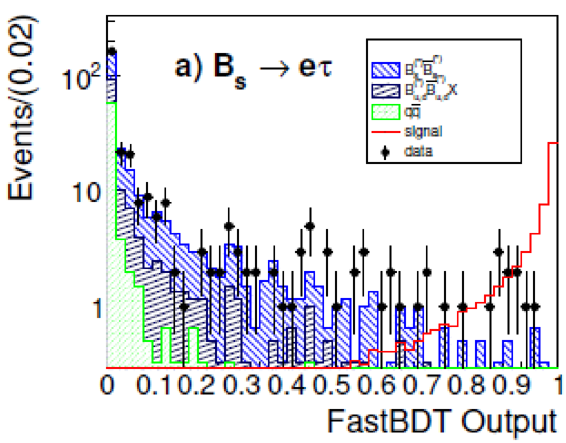
- $e^+e^- \to \Upsilon(5S) \to B_s^{(*)}B_s^{(*)}$
- Belle data of 121 fb^{-1} at $\Upsilon(5S)$: 16 M B_sB_s
- Tag B_s with $B_s \to D_sX\ell\nu$: new method at $\Upsilon(5S)$

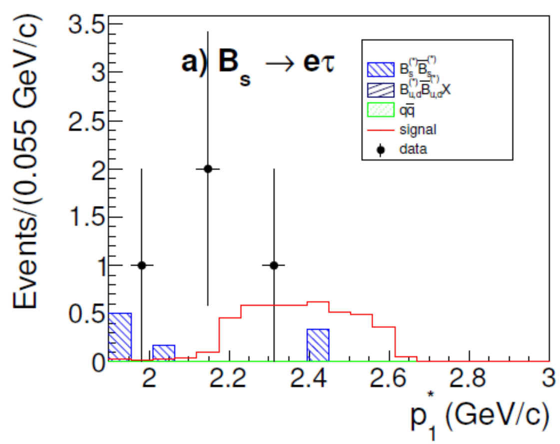
$$B_s \to \ell_1^- \tau^+ \; (\to \ell_2^+ \overline{\nu}_\tau \nu_{\ell_2})$$
$$\overline{B}_s^0 \to D_s^+ \ell_3^- (X) \overline{\nu}_{\ell_3}$$

[JHEP08(2023)178]



- Require same charge for ℓ_1 and ℓ_2 (though opposite change can occur due to B_s mixing)
- FastBDT to remove huge background.





$\mathcal{B}(B_s \to e\tau) < 14\times10^{-4}$
$\mathcal{B}(B_s \to \mu\tau) < 7.3\times10^{-4}$
(90% C.L.)

- First measurement of $B_s \to e\tau$
- $\mathcal{B}(B_s \to \mu\tau) < 3.4\times10^{-5}$ @LHCb [PRL 123, 211801(2019)]

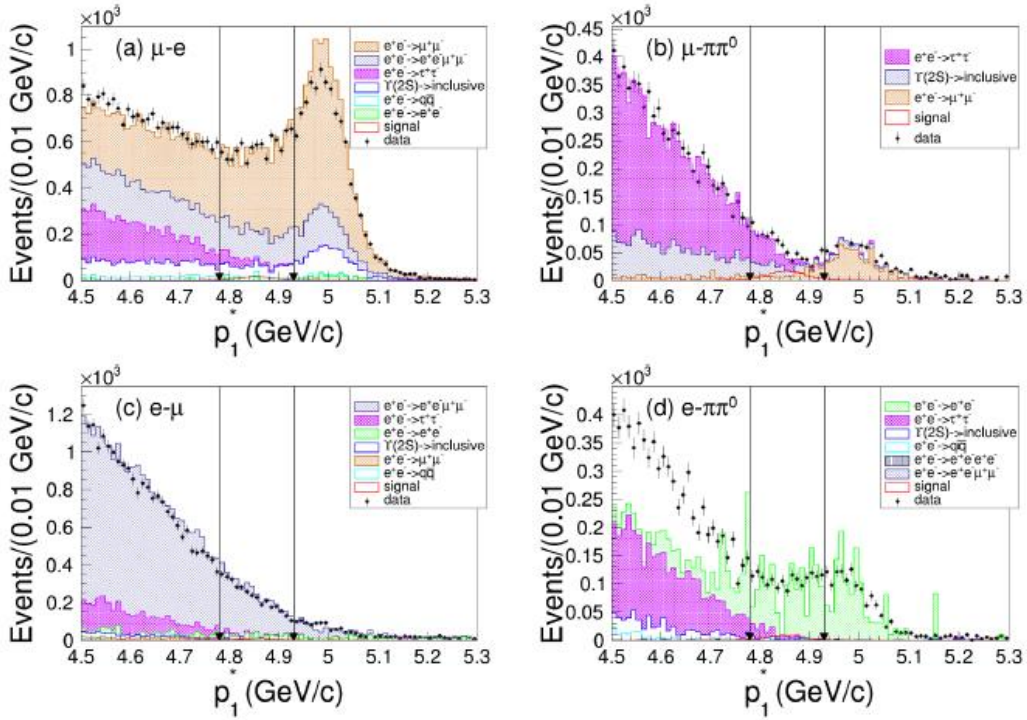
$\Upsilon(2S) \to \ell\tau$ at Belle

[JHEP02(2024)187]

$\Upsilon(2S) \to \ell\tau$ (ℓ = e, μ)

- $e^+e^- \to \Upsilon(2S)$
- Belle data of 25 fb^{-1} at $\Upsilon(2S)$: 158 M $\Upsilon(2S)$
- $\Upsilon(2S) \to \ell_1^+\tau^-$ with $\tau^- \to \ell_2^-\nu\nu$, $\pi^-\pi^0\nu$, where $\ell_1 \neq \ell_2$ to suppress $e^+e^- \to e^+e^-$, $\mu^+\mu^-$.
- Signature: high momentum lepton ℓ_1 (4.85 GeV in the CM frame).
- FastBDT to suppress background.
  - ✓ Visible energy, missing mass, angle between leptons etc.
- Trigger efficiency (~98% for $\mu\tau$, ~88% for $e\tau$) gives large systematic uncertainty.

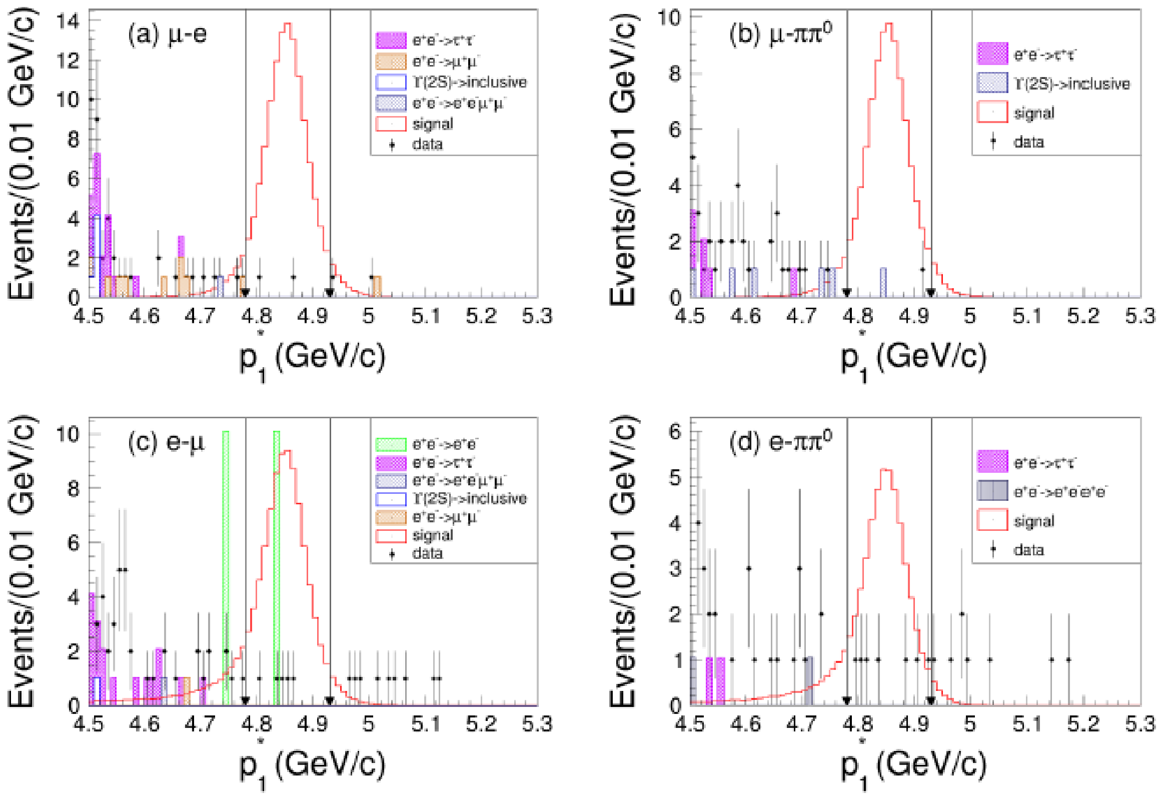
Before background suppression



$\Upsilon(2S) \to l\tau$ at Belle

$\Upsilon(2S) \to \ell\tau$ result

[JHEP02(2024)187]



(signal distribution assumes B.F. of 10^{-5})

Modes	ϵ_{sig} (%)	N^{bkg}_{exp}	N_{obs}
$\Upsilon(2S) \to \mu^{\mp}\tau^{\pm}$	12.3 ± 0.8	3.9 ± 1.8	3
$\Upsilon(2S) \to e^{\mp}\tau^{\pm}$	8.1 ± 1.1	5.9 ± 2.6	12

$B(\Upsilon(2S) \to e\tau) < 0.23\times10^{-4}$
$B(\Upsilon(2S) \to \mu\tau) < 1.12\times10^{-4}$
(90% C.L.)

14 (3) times more stringent than the previous result by BaBar
[PRL 104 (2010) 151802]

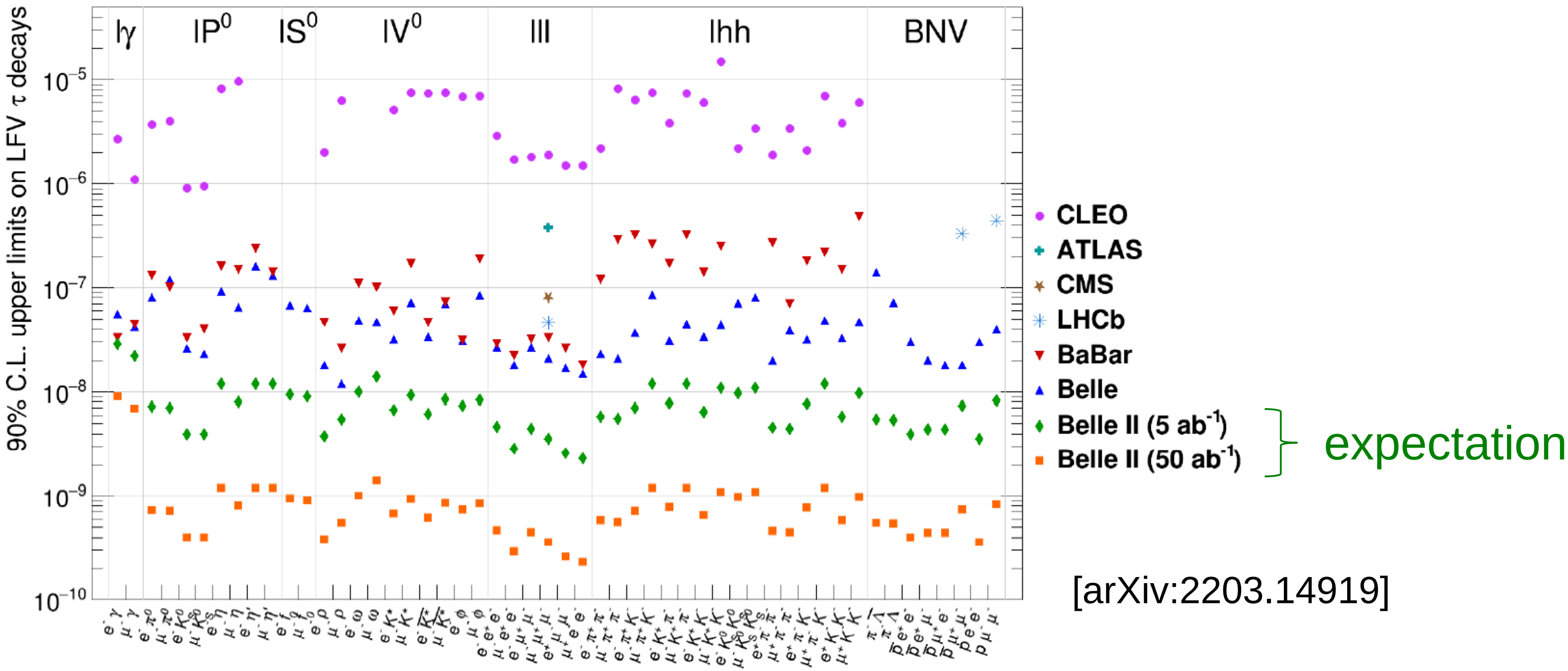
- Belle II can also take at non-Υ(4S) in future, which enlarges its physics potential.

LFV τ Decays

- Belle II : τ factory
- Charged LFV : clear signature of NP
  - ✓ Complementary to LFV μ .
- Current upper limits are set by Belle in most τ LFV modes (~10^{-7}) → Belle II aims 10^{-8} - 10^{-9}

Cross sections

$\sigma(e^+e^- \to b\bar{b}) \simeq 1.1$ nb
$\sigma(e^+e^- \to c\bar{c}) \simeq 1.3$ nb
$\sigma(e^+e^- \to \tau^+\tau^-) \simeq 0.9$ nb



[arXiv:2203.14919]

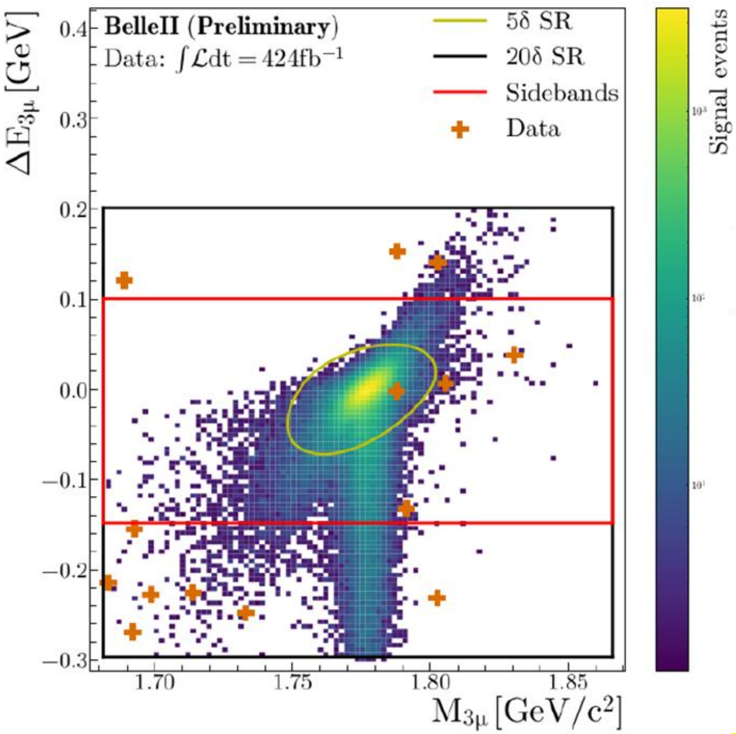
LFV τ Decays

$\tau \to \mu\mu\mu$ from Belle II (424 fb^{-1})

[JHEP09(2024)062]

Inclusive approach

- Allow at most 3 tracks in the tag side.
- High efficiency (~20%, ×3 of Belle).
- Suppress background with BDT.



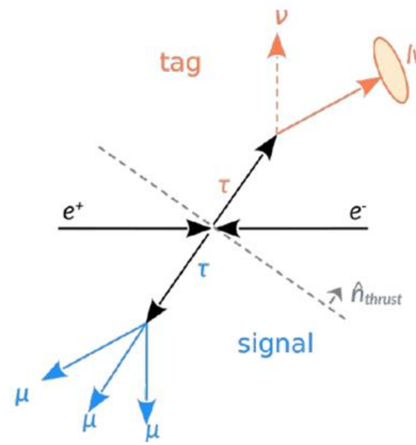
$$N^{\mathrm{Obs}}_{data} = 1$$

$$N^{\mathrm{Exp}}_{\mathrm{bkg}} = 0.50^{+1.4}_{-0.5}$$

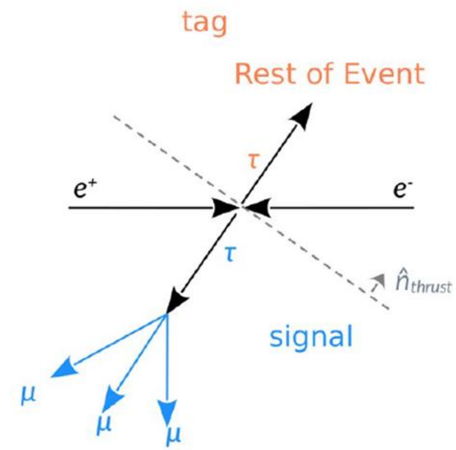
UL 1.9 ×10^{-8} is set

most stringent limit with ~half of Belle data set.

Conventional



New (Belle II)

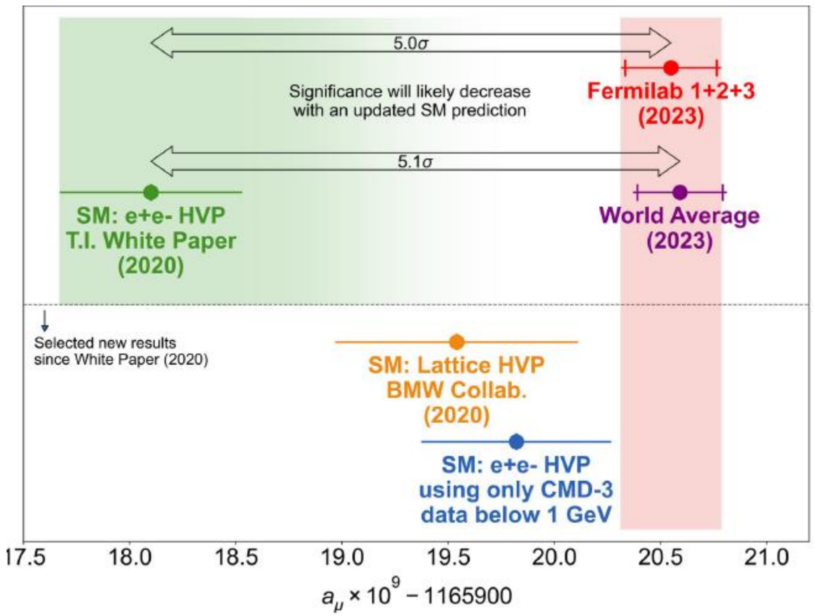


	UL at 90% CL on $B(\tau \to 3\mu)$	
Belle	2.1×10^{-8} ($\mathcal{L}_{int} = 782\mathrm{fb}^{-1}$)	[1]
BaBar	3.3×10^{-8} ($\mathcal{L}_{int} = 468\mathrm{fb}^{-1}$)	[2]
CMS	2.9×10^{-8} ($\mathcal{L}_{int} = 131\mathrm{fb}^{-1}$)	[3]
LHCb	4.6×10^{-8} ($\mathcal{L}_{int} = 2.0\mathrm{fb}^{-1}$)	[4]
Belle II	1.9×10^{-8} ($\mathcal{L}_{int} = 424\mathrm{fb}^{-1}$)	

[1] K. Hayasaka et al., Phys. Lett. B 687 (2010) 139
[2] J. P. Lees et al., Phys. Rev. D 81 (2010) 111101
[3] A. M. Sirunyan et al., JHEP 01 (2021) 163
[4] R. Aaij et al., JHEP 02 (2015) 121

$e^+e^- \to \pi^+\pi^-\pi^0$

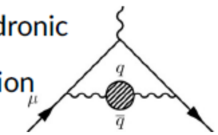
Muon g-2 anomaly



- Major theoretical uncertainty comes from Hadronic Vacuum Polarization (HVP) term.

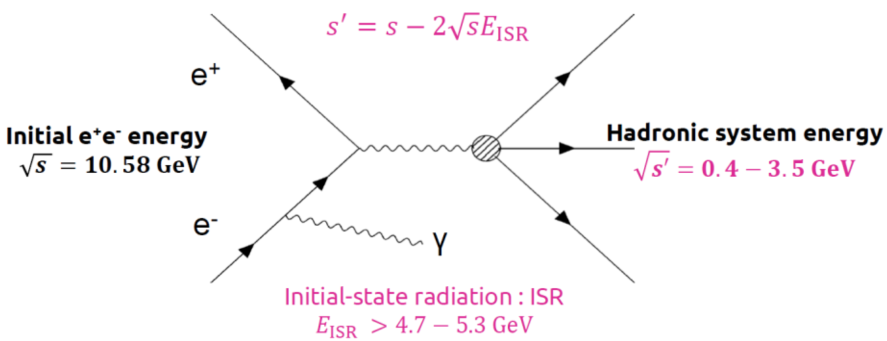
$$a_\mu^{HVP,LO} = \frac{\alpha^2}{3\pi^2}\int_{m_\pi^2}^{\infty}\frac{ds}{s}R(s)K(s)$$

HVP: hadronic vacuum polarization



$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$ Hadronic R-ratio

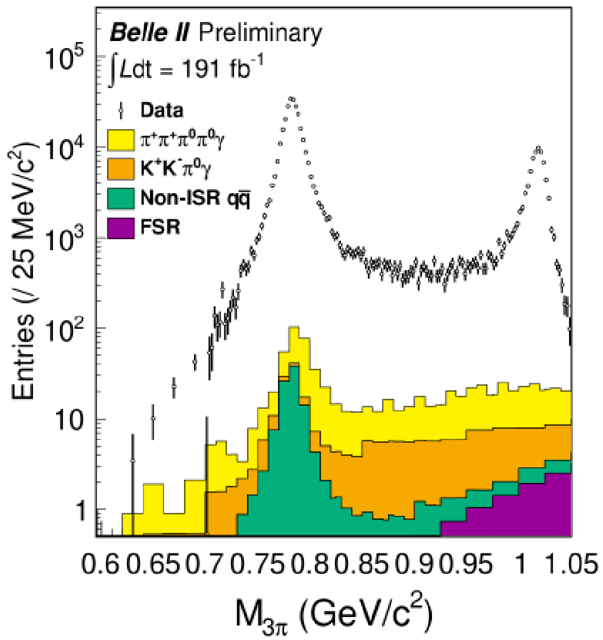
- The largest contribution is from $e^+e^- \to \pi^+\pi^-$.
- Belle II first measures $e^+e^- \to \pi^+\pi^-\pi^0$ with 191 fb^{-1} using radiative return method.
  - ✓ Signal $e^+e^- \to \pi^+\pi^-\pi^0\gamma$
  - ✓ Bkg $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma$, $K^+K^-\pi^0\gamma$
  - ✓ Precise efficiency corrections necessary.
    - ➢ trigger, tracking, ISR γ, π^0
  - ✓ Unfolding (effect of detector resolution)



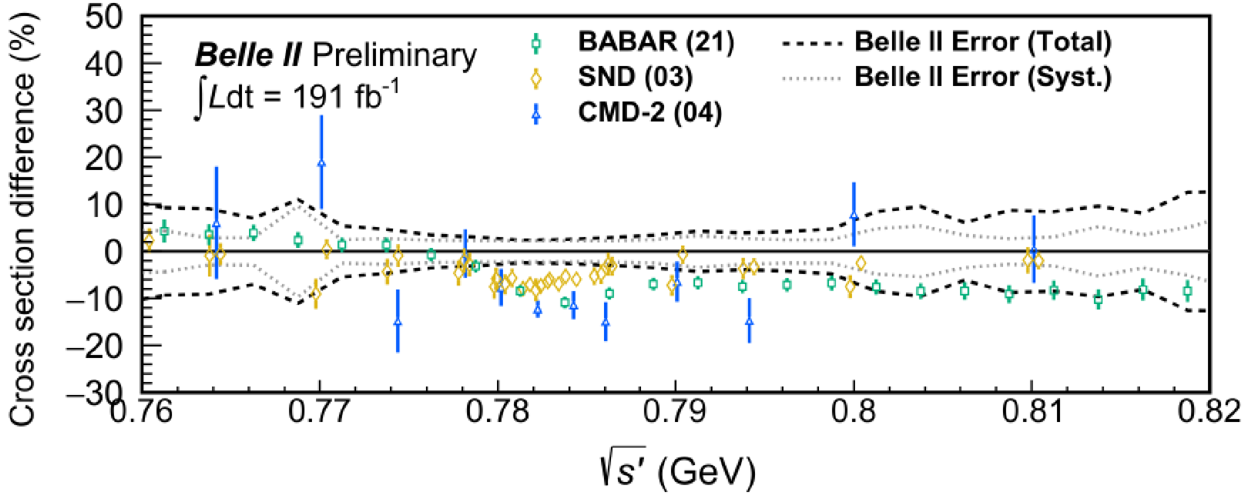
$e^+e^- \to \pi^+\pi^-\pi^0$

[arXiv:2404.04915, accepted at PRD]

3π Mass spectrum



Differences of the measured cross section around the ω resonance



Focus on the mass region around the **ω resonance**
→ most important for the HVP

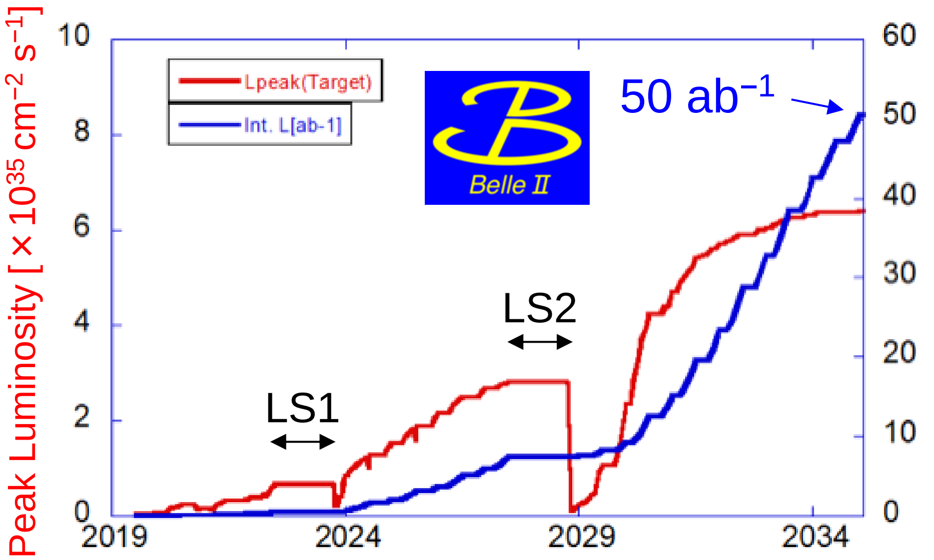
$$a_\mu^{\mathrm{LO,HVP},3\pi}(0.62\text{-}1.8\ \mathrm{GeV}) = \left(48.91 \pm 0.25_{\mathrm{stat}} \pm 1.07_{\mathrm{syst}}\right) \times 10^{-10}$$

- 6.5% higher than the global fit result with 2.5σ significance
- This difference 3×10^{-10} corresponds 10% of $\Delta a_\mu = a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = 25\times10^{-10}$

Next step: $e^+e^- \to \pi^+\pi^-$ (with 0.5% precision)

Summary and Plan

- Belle II @ SuperKEKB
  - ✓ Flavor physics experiment: search for BSM with precise measurements.
  - ✓ Resuming operation after LS1. SuperKEKB is trying to increase the luminosity.
- Recent results from Belle II (and Belle)
  - ✓ Evidence of $B^+ \to K^+ \nu\bar{\nu}$. Larger branching fraction than SM.
  - ✓ Upper limit of $B^0 \to K^{*0}\tau^+\tau^-$, $K_S\tau\ell$, $\tau \to 3\mu$ (better result with smaller data)
  - ✓ $B_s \to \tau\ell$, $\Upsilon(2S) \to \tau\ell$ at Belle.
  - ✓ $e^+e^- \to \pi^+\pi^-\pi^0\gamma$ (input to g−2)
- Belle II Plan
  - ✓ More analyses will come with Belle II (+ Belle) data.
  - ✓ Increase the luminosity and collect more data.
  - ✓ Upgrade studies are going on.



Backup

Abstract

Latest results and BSM searches from Belle II (25+5)

Belle II is a flavor physics experiment at the asymmetric electron-positron collider SuperKEKB at KEK in Japan. Belle II aims to record an order of magnitude more data than the previous Belle experiment. Belle II started operation in 2019 and has accumulated 530 fb^{-1} of data to date. I will present recent results from Belle II with a focus on BSM searches, including the first evidence for the $B^+ ¥to K^+¥nu¥bar{¥nu}$ decay, search for a lepton-flavor violating tau and B decays and tests of lepton flavor universality.