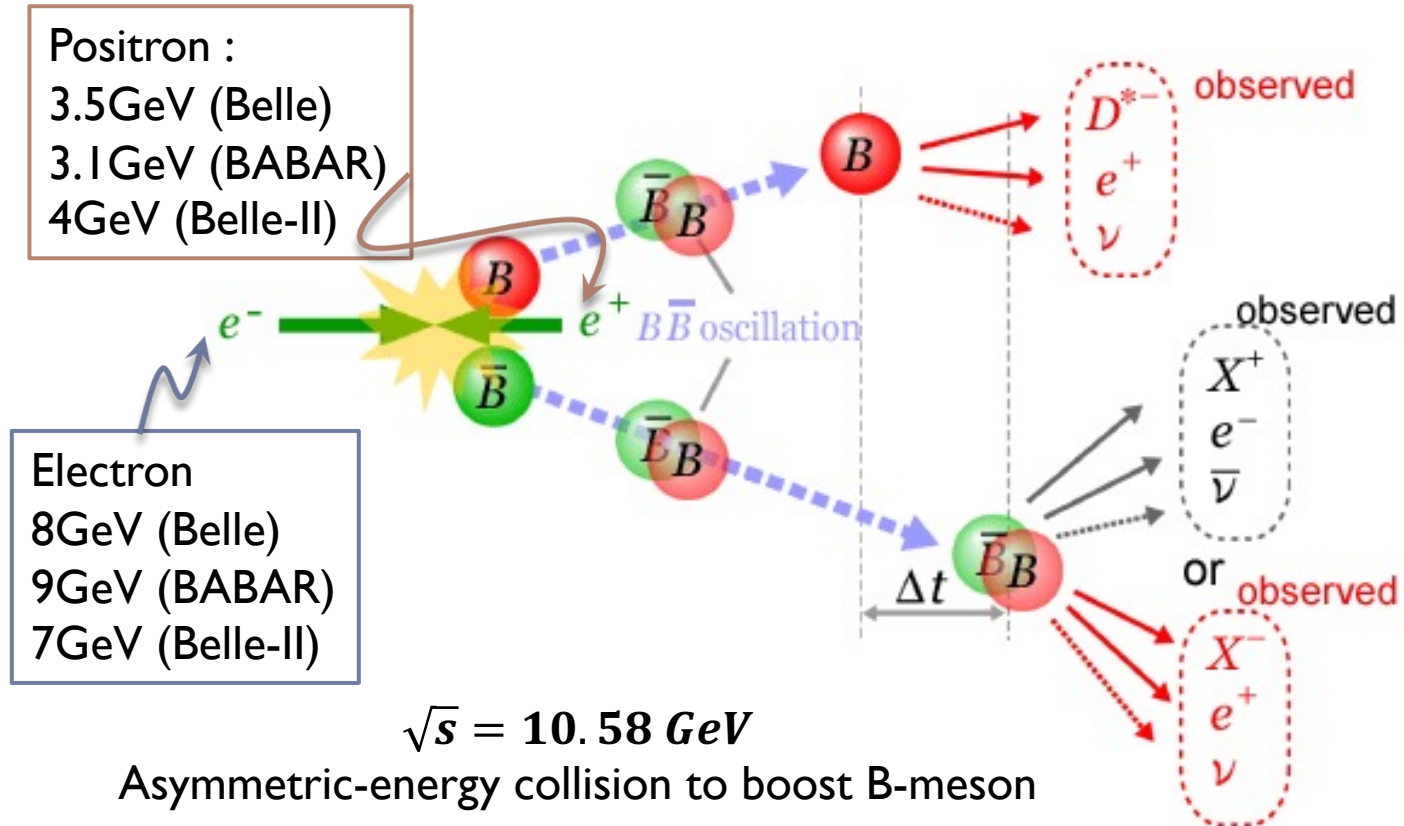


# Belle and Belle II Experiment

MyeongJae Lee (SKKU), Nov 23, 2023, KSHEP

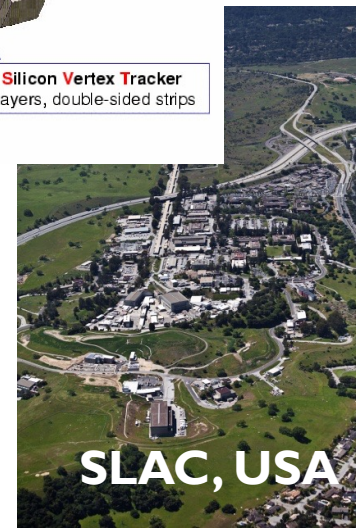
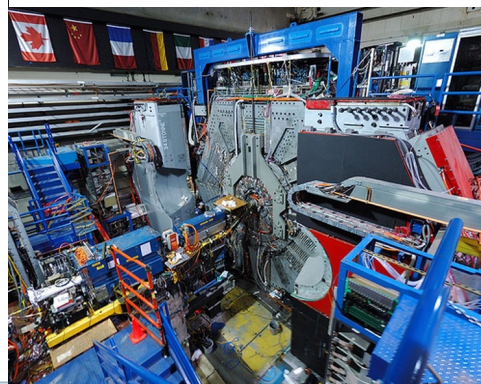
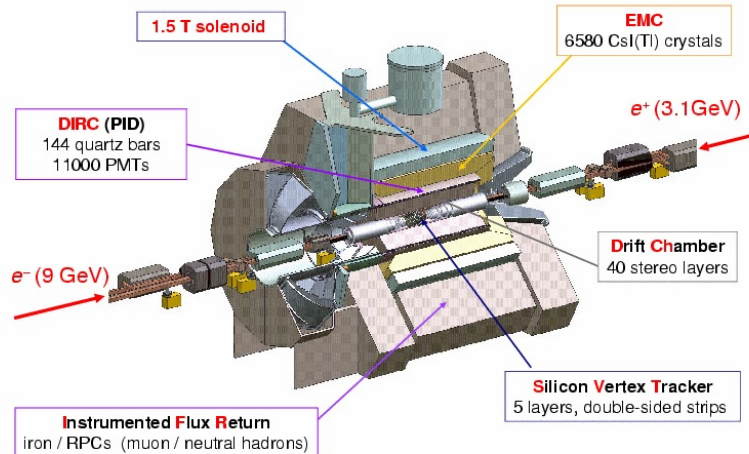
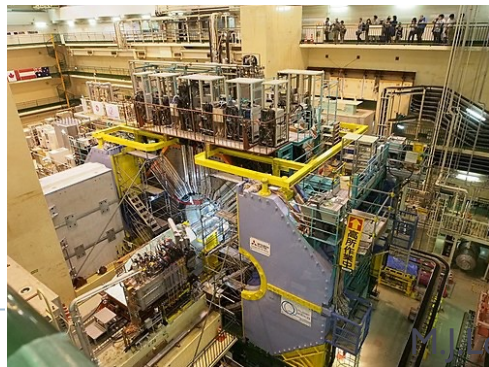
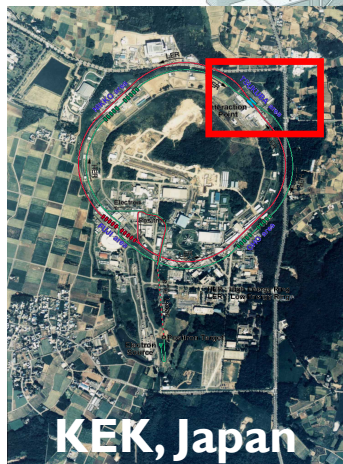
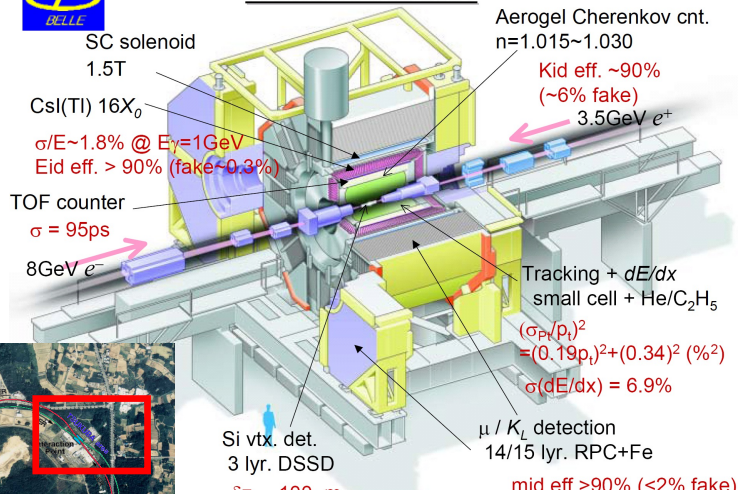
# B-Factory Experiments : Belle / BABAR



# B-Factory Experiments : Belle / BABAR



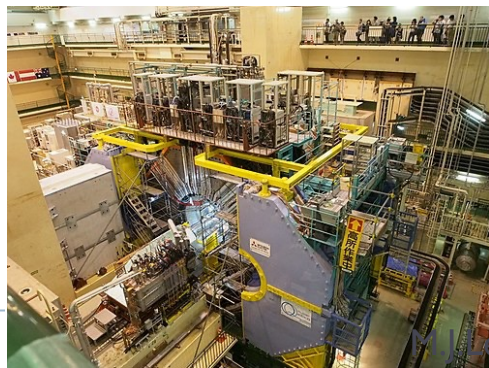
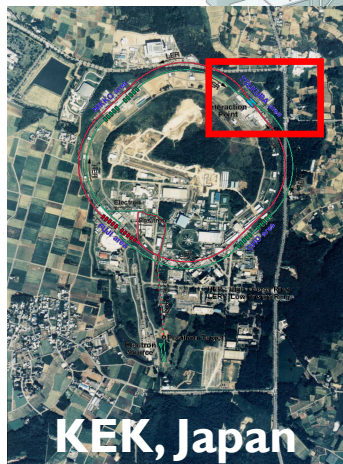
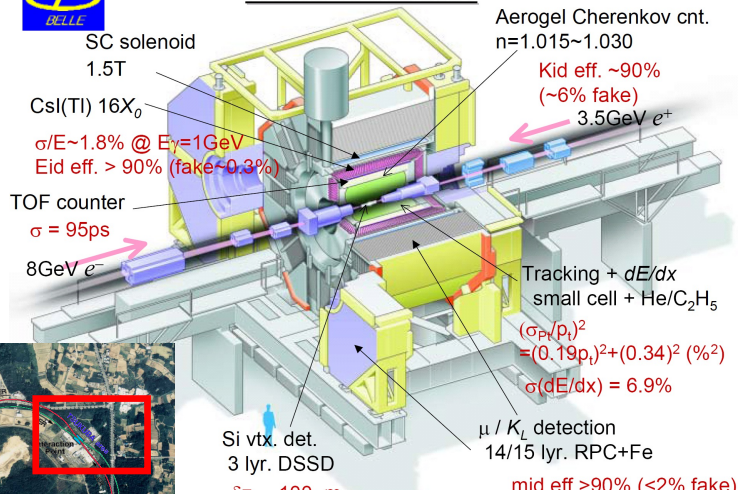
## Belle Detector



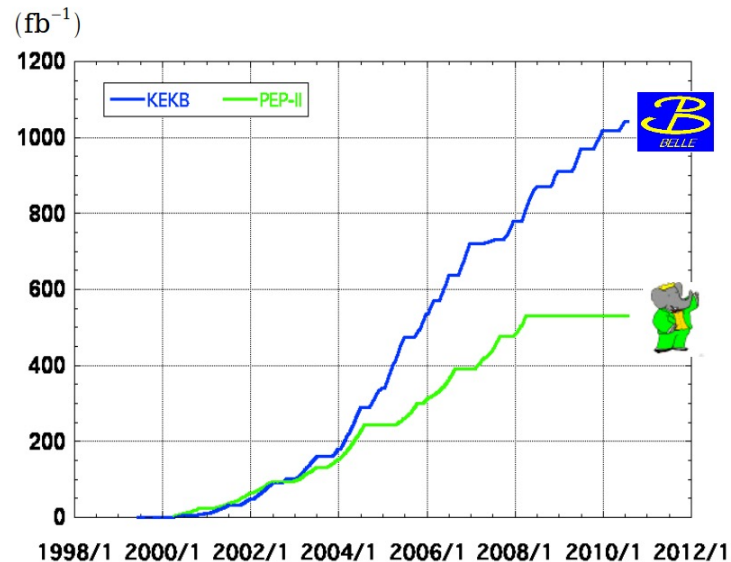
# B-Factory Experiment : Belle



## Belle Detector



## Integrated luminosity of B factories



**$> 1 \text{ ab}^{-1}$**   
**On resonance:**  
 $Y(5S): 121 \text{ fb}^{-1}$   
 $Y(4S): 711 \text{ fb}^{-1}$   
 $Y(3S): 3 \text{ fb}^{-1}$   
 $Y(2S): 25 \text{ fb}^{-1}$   
 $Y(1S): 6 \text{ fb}^{-1}$   
**Off reson./scan:**  
 $\sim 100 \text{ fb}^{-1}$

**$\sim 550 \text{ fb}^{-1}$**   
**On resonance:**  
 $Y(4S): 433 \text{ fb}^{-1}$   
 $Y(3S): 30 \text{ fb}^{-1}$   
 $Y(2S): 14 \text{ fb}^{-1}$   
**Off resonance:**  
 $\sim 54 \text{ fb}^{-1}$

# Achievements of Belle

- ▶ 645 publications from 2001 to now
- ▶ Still very productive : 47 publications (including submission) in 2023
- ▶ Data analysis efforts are now merging into Belle II collaboration



**Belle Journal Publications**  
***The Belle Collaboration***

**- Physics Publications**

645. **Measurement of the Ratio of Partial Branching Fractions of Inclusive  $\bar{B} \rightarrow X_u \bar{\nu}$  to  $\bar{B} \rightarrow X_c \bar{\nu}$  and the Ratio of their Spectra with Hadronic Tagging**  
M. Hohmann, P. Urquijo, et al. (Belle Collaboration), submitted to PRD  
Belle preprint 2023-17, KEK Preprint 2023-30, [arXiv:2311.00458 \[hep-ex\]](#)
644. **Search for the baryon and lepton number violating decays  $D \rightarrow p\bar{\ell}$**   
S. Maity, R. Garg, S. Bahinipati, V. Bhardwaj, et al. (Belle Collaboration), submitted to PRD  
Belle preprint 2023-15, KEK Preprint 2023-20, [arXiv:2310.07412 \[hep-ex\]](#)
643. **Search for charged-lepton flavor violation in  $\Upsilon(2S) \rightarrow \ell^{\mp} \tau^{\pm}$  ( $\ell=e, \mu$ ) decays at Belle**  
R. Dhamija, S. Nishida, A. Giri, et al. (Belle Collaboration), submitted to JHEP  
Belle preprint 2023-14, KEK Preprint 2023-19, [arXiv:2309.02739 \[hep-ex\]](#)
642. **Observation of charmed strange meson pair production in  $\Upsilon(2S)$  decays and in  $e^+e^-$  annihilation at  $\sqrt{s} = 10.52$  GeV**  
B.S. Gao, W.J. Zhu, X.L. Wang, et al. (Belle Collaboration), to appear in PRD  
Belle preprint 2023-12, KEK Preprint 2023-16, [arXiv:2308.08900 \[hep-ex\]](#)
641. **Search for a dark leptophilic scalar produced in association with  $\tau^+\tau^-$  pair in  $e^+e^-$  annihilation at center-of-mass energies near 10.58 GeV**  
D. Biswas, Sw. Banerjee, et al. (Belle Collaboration), submitted to PRL  
Belle preprint 2023-13, KEK Preprint 2023-17, [arXiv:2207.07476 \[hep-ex\]](#)
640. **Evidence of  $B^0 \rightarrow p\bar{\Sigma}^-\pi^+$  at Belle**  
C.-Y. Chang, M.-Z. Wang, et al. (Belle Collaboration), published in [PRD 108, 052011 \(2023 September 22\)](#)  
Belle preprint 2023-10, KEK Preprint 2023-12, [arXiv:2305.18821 \[hep-ex\]](#)
639. **Search for double-charmonium state with  $\eta_c J/\psi$  at Belle**  
J.H. Yin, Y.B. Li, E. Won, et al. (Belle Collaboration), published in [JHEP 2308.121 \(2023 August 18\)](#)  
Belle preprint 2023-11, KEK Preprint 2023-13, [arXiv:2305.17947 \[hep-ex\]](#)

# The most cited paper from Belle (Not on CPV)

VOLUME 91, NUMBER 26

PHYSICAL REVIEW LETTERS

week ending  
31 DECEMBER 2003

## Observation of a Narrow Charmoniumlike State in Exclusive $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ Decays

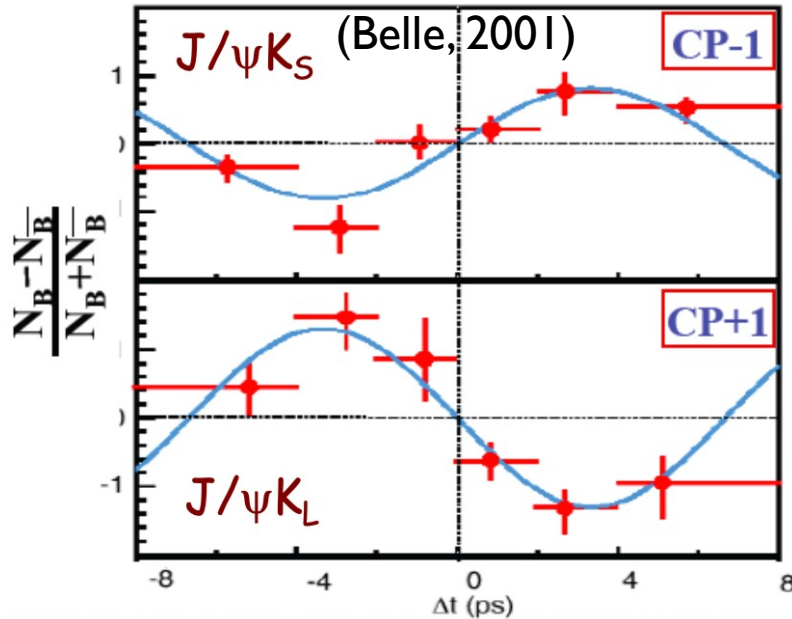
S.-K. Choi,<sup>5</sup> S. L. Olsen,<sup>6</sup> K. Abe,<sup>7</sup> T. Abe,<sup>7</sup> I. Adachi,<sup>7</sup> Byoung Sup Ahn,<sup>14</sup> H. Aihara,<sup>43</sup> K. Akai,<sup>7</sup> M. Akatsu,<sup>20</sup> M. Akemoto,<sup>7</sup> Y. Asano,<sup>48</sup> T. Aso,<sup>47</sup> V. Aulchenko,<sup>1</sup> T. Aushev,<sup>11</sup> A. M. Bakich,<sup>38</sup> Y. Ban,<sup>31</sup> S. Banerjee,<sup>39</sup> A. Bondar,<sup>1</sup> A. Bozek,<sup>25</sup> M. Bračko,<sup>18,12</sup> J. Brodzicka,<sup>25</sup> T. E. Browder,<sup>6</sup> P. Chang,<sup>24</sup> Y. Chao,<sup>24</sup> K.-F. Chen,<sup>24</sup> B. G. Cheon,<sup>37</sup> R. Chistov,<sup>11</sup> Y. Choi,<sup>37</sup> Y. K. Choi,<sup>37</sup> M. Danilov,<sup>11</sup> L. Y. Dong,<sup>9</sup> A. Drutskoy,<sup>11</sup> S. Eidelman,<sup>1</sup> V. Eiges,<sup>11</sup> J. Flanagan,<sup>7</sup> C. Fukunaga,<sup>45</sup> K. Furukawa,<sup>7</sup> N. Gabyshev,<sup>7</sup> T. Gershon,<sup>7</sup> B. Golob,<sup>17,12</sup> H. Guler,<sup>6</sup> R. Guo,<sup>22</sup> C. Hagner,<sup>50</sup> F. Han,<sup>2</sup> T. Hara,<sup>29</sup> N. C. Hastings,<sup>7</sup> H. Hayashii,<sup>21</sup> M. Hazumi,<sup>7</sup> L. Hinz,<sup>16</sup> Y. Hoshi,<sup>41</sup> W.-S. Hou,<sup>24</sup> Y. B. Hsiung,<sup>2</sup> H.-C. Huang,<sup>24</sup> T. Iijima,<sup>20</sup> K. Inami,<sup>20</sup> A. Ishikawa,<sup>20</sup> R. Itoh,<sup>7</sup> M. Iwasaki,<sup>43</sup> Y. Iwasaki,<sup>7</sup> J. H. Kang,<sup>52</sup> S. U. Karim,<sup>2</sup> N. Katayama,<sup>7</sup> H. Kawai,<sup>2</sup> T. Kawasaki,<sup>27</sup> H. Kichimi,<sup>7</sup> E. Kikutani,<sup>7</sup> H. J. Kim,<sup>52</sup> Hyunwoo Kim,<sup>14</sup> J. H. Kim,<sup>20</sup>

2389 citations  
(as of today)

We report the observation of a narrow charmoniumlike state produced in the exclusive decay process  $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ . This state, which decays into  $\pi^+ \pi^- J/\psi$ , has a mass of  $3872.0 \pm 0.6(\text{stat}) \pm 0.5(\text{syst})$  MeV, a value that is very near the  $M_{D^0} + M_{D^{*0}}$  mass threshold. The results are based on an analysis of 152M  $B-\bar{B}$  events collected at the  $\Upsilon(4S)$  resonance in the Belle detector at the KEKB collider. The signal has a statistical significance that is in excess of  $10\sigma$ .

“X(3872)”

# Achievements of Belle



Much more precise measurements done by Belle, BABAR, and LHCb



Photo: University of Chicago  
Yoichiro Nambu  
Prize share: 1/2



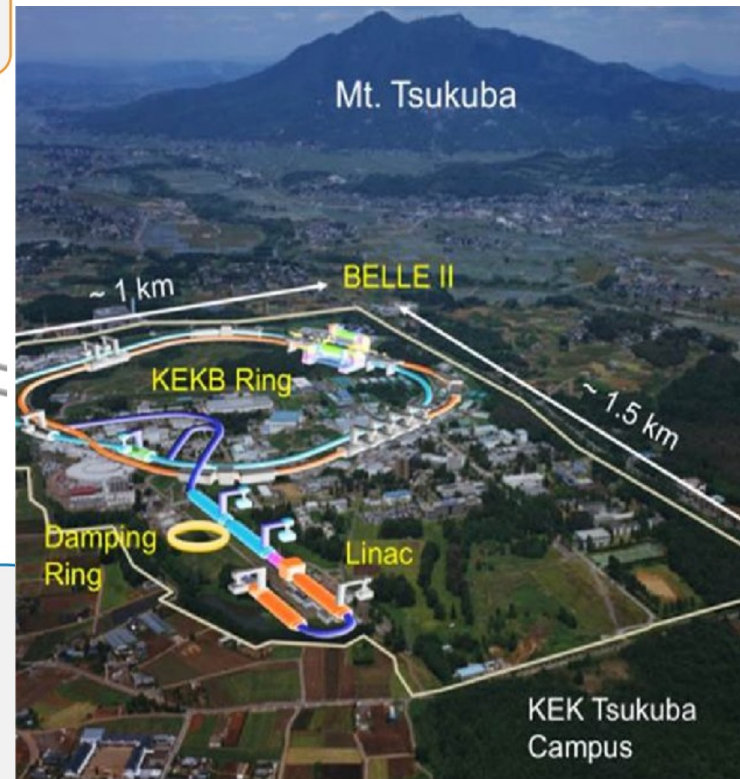
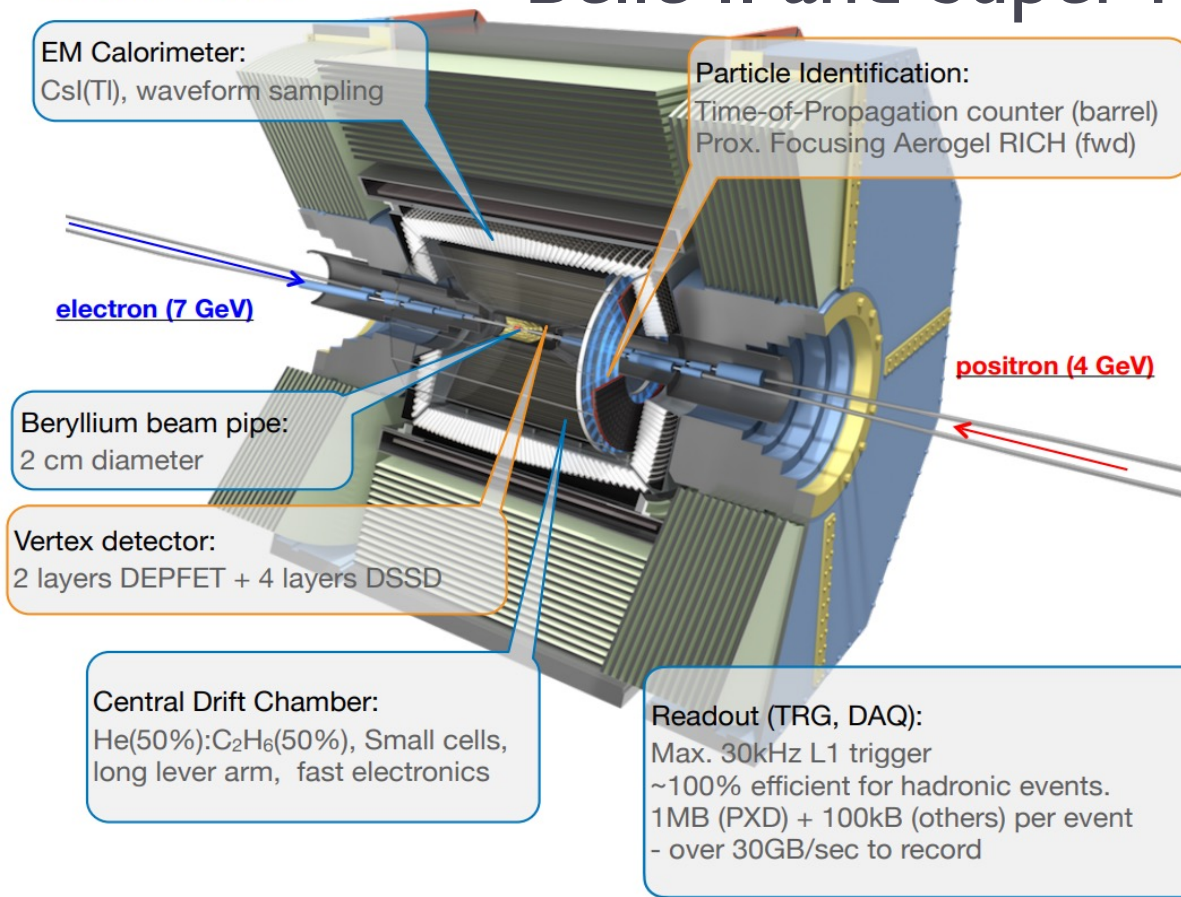
© The Nobel Foundation Photo: U. Montan  
Makoto Kobayashi



© The Nobel Foundation Photo: U. Montan  
Toshihide Maskawa

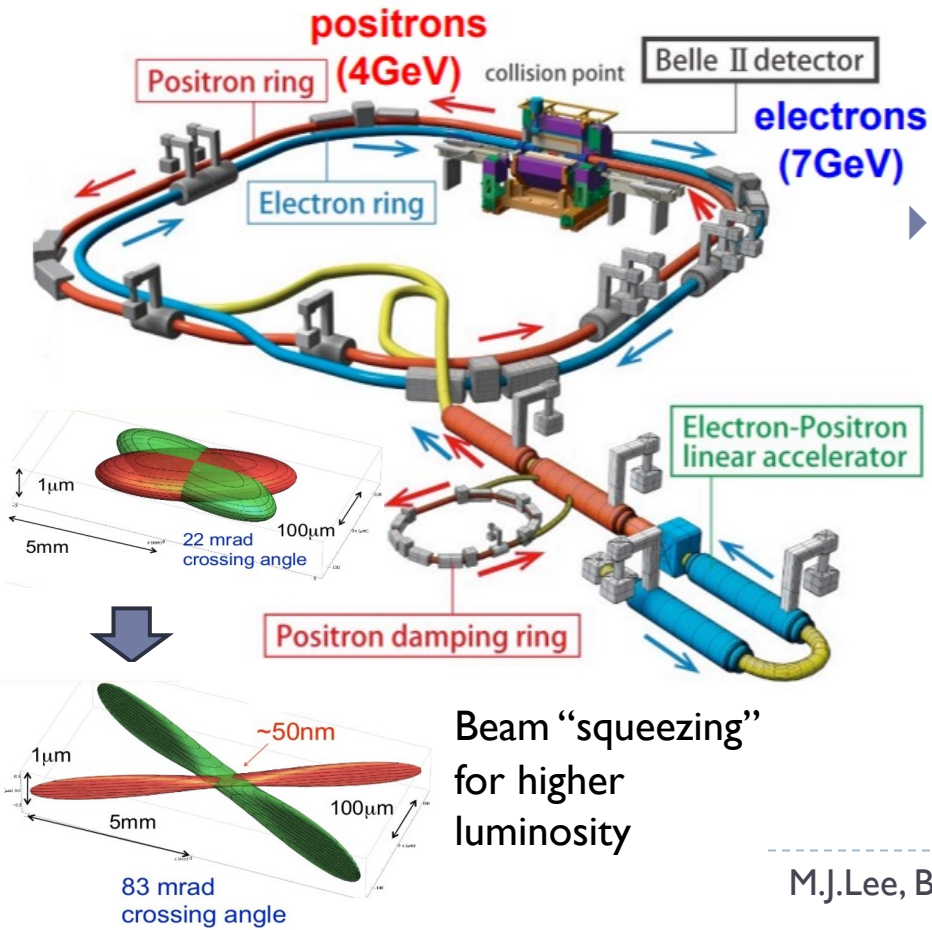
The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu "for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics", the other half jointly to Makoto Kobayashi and Toshihide Maskawa "for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature."

# Belle II and Super-KEKB, for x50 data





# Belle II and Super-KEKB, for x50 data



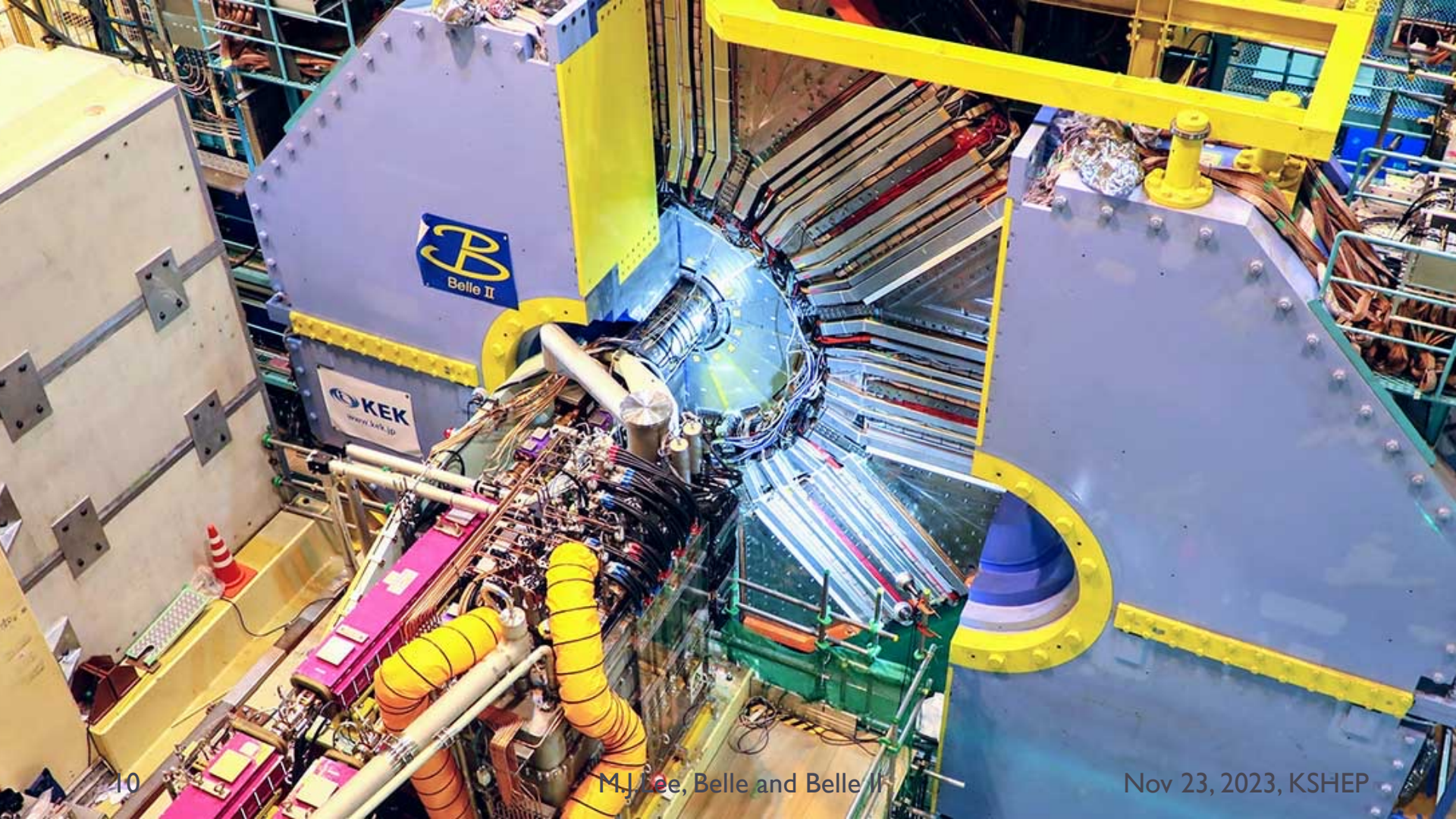
$$L \propto \frac{I_{e^+} I_{e^-}}{\sigma_x \sigma_y}$$

## ▶ Luminosity improvement by

- ▶ “Nanobeam scheme,” x20
- ▶ Increasing beam current, x1.5

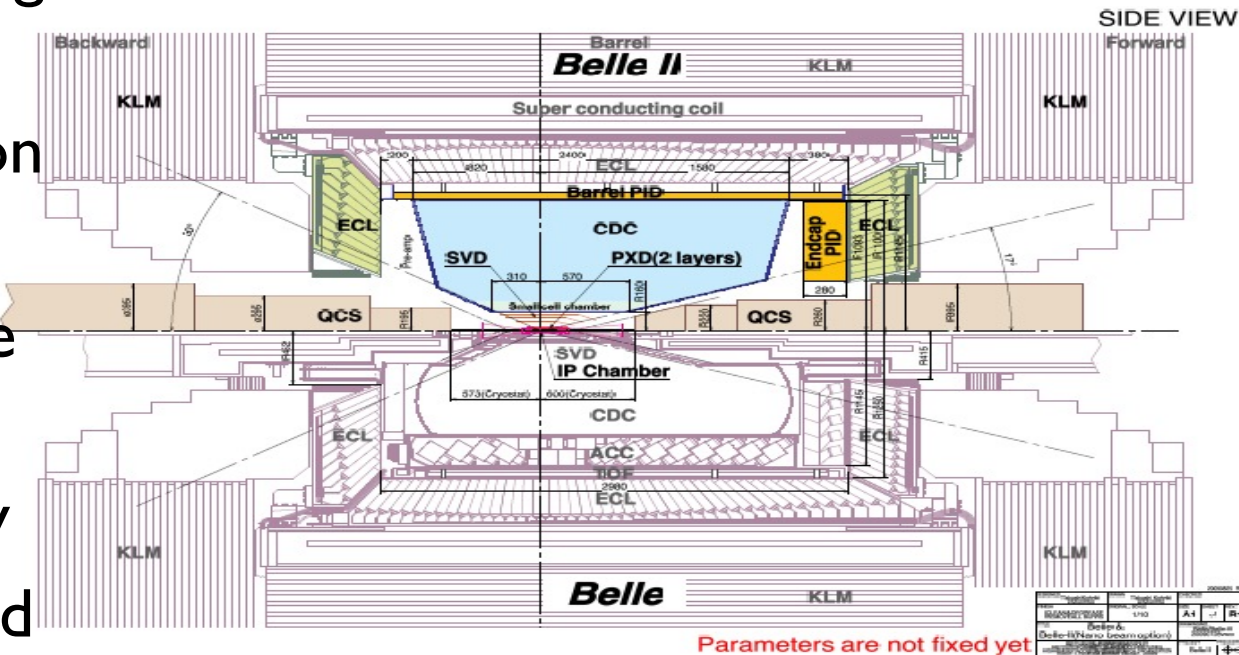
	$I_{e^+}$	$I_{e^-}$	$\sigma_y$
Design	2.8 A	2.0 A	60 nm
Achieved (by 2021)	0.7 A	0.8 A	230 nm

- ▶ Target luminosity :  $6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$



# Belle II Detector

- ▶ Improved vertexing by PXD + SVD
- ▶ Better  $p_t$  resolution (larger chamber)
- ▶ Higher acceptance
- ▶ Lower boost and better hermeticity
- ▶ More sophisticated trigger



# Belle II Collaboration



**28 countries**  
**122 institute**  
**~1170 collaborators**  
Spokesperson : Karim Trabelsi  
IB chair : Doris Kim

# Belle II Detector



10 Institutes, ~40 collaborators

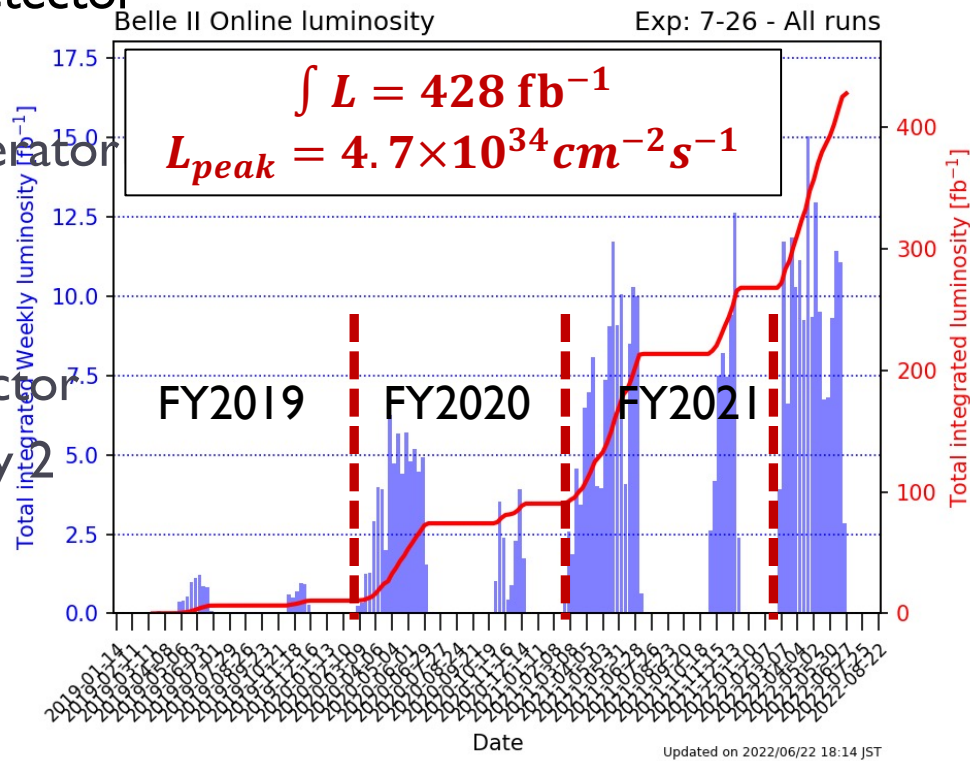
# Korean Belle II

- ▶ Software development and data monitoring
  - ▶ Simulation software improvement
- ▶ Detector development
  - ▶ Calorimeter trigger, Vertex detector
- ▶ Accelerator study
  - ▶ Beam dynamics, beam instability
- ▶ Data analysis on B and D Physics
  - ▶ CPV and rare decays in B and D,  $\Lambda_C^+$ ,  $X(3872)$
- ▶ Data analysis on  $\tau$  Physics
  - ▶  $\tau$  LFV



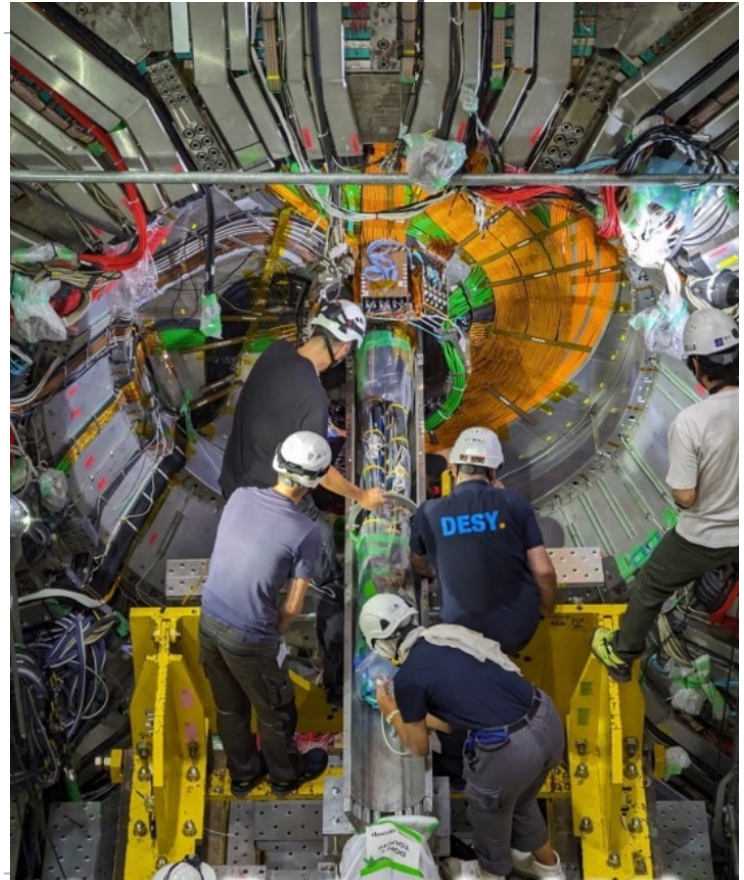
# Operation history / Long shutdown I

- ▶ Phase I (2016): accelerator test w/o detector
- ▶ Phase 2 (2018):
  - ▶ First collisions with complete accelerator
  - ▶ Incomplete detector (no VXD)
- ▶ Phase 3 (2019-)
  - ▶ Luminosity run with complete detector
  - ▶ Pixel Detector (PXD): layer 1 + only 2 ladders in layer 2
  - ▶ Full 4-layers strip detector (SVD)
- ▶ **Long shutdown (2022 – 2023)**
- ▶ **Run2 starts Jan 2024**



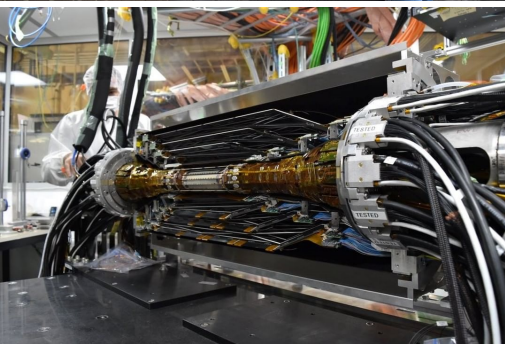
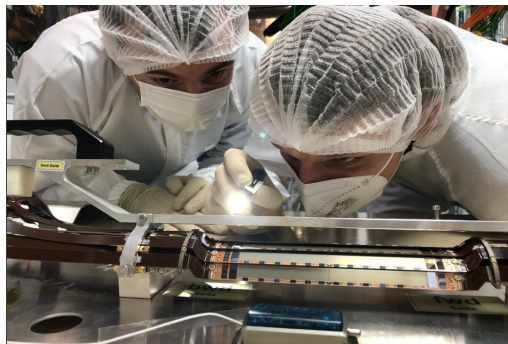
# Long Shutdown I (June 2022 – Dec 2023)

- ▶ TOP : MCP-PMT replacement: most of conventional PMTs were replaced with life-extended PMTs
- ▶ CDC : HV register replacement: mitigate the gain drop due to beam BG increase, Additional H<sub>2</sub>O and O<sub>2</sub> monitors, Additional outlet ports: uniformity of gas flow in CDC
- ▶ **VXD : Installation of new VXD with PXD2** (July 28, 2023)
- ▶ DAQ : Full transition to PCIe40, Direct ROOT storage in STORE
- ▶ BG shield : Additional VXD bellows pipe shields, Additional neutron shields

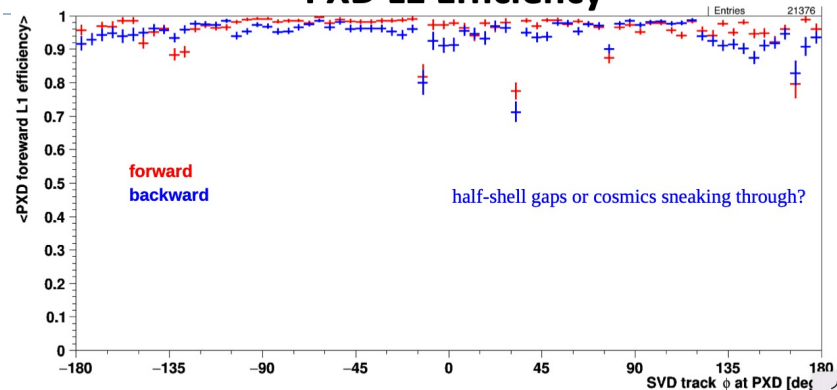




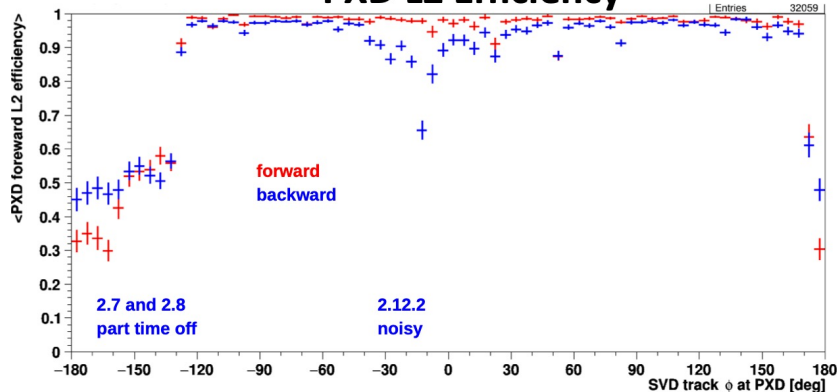
# VXD Upgrade



## PXD L1 Efficiency



## PXD L2 Efficiency



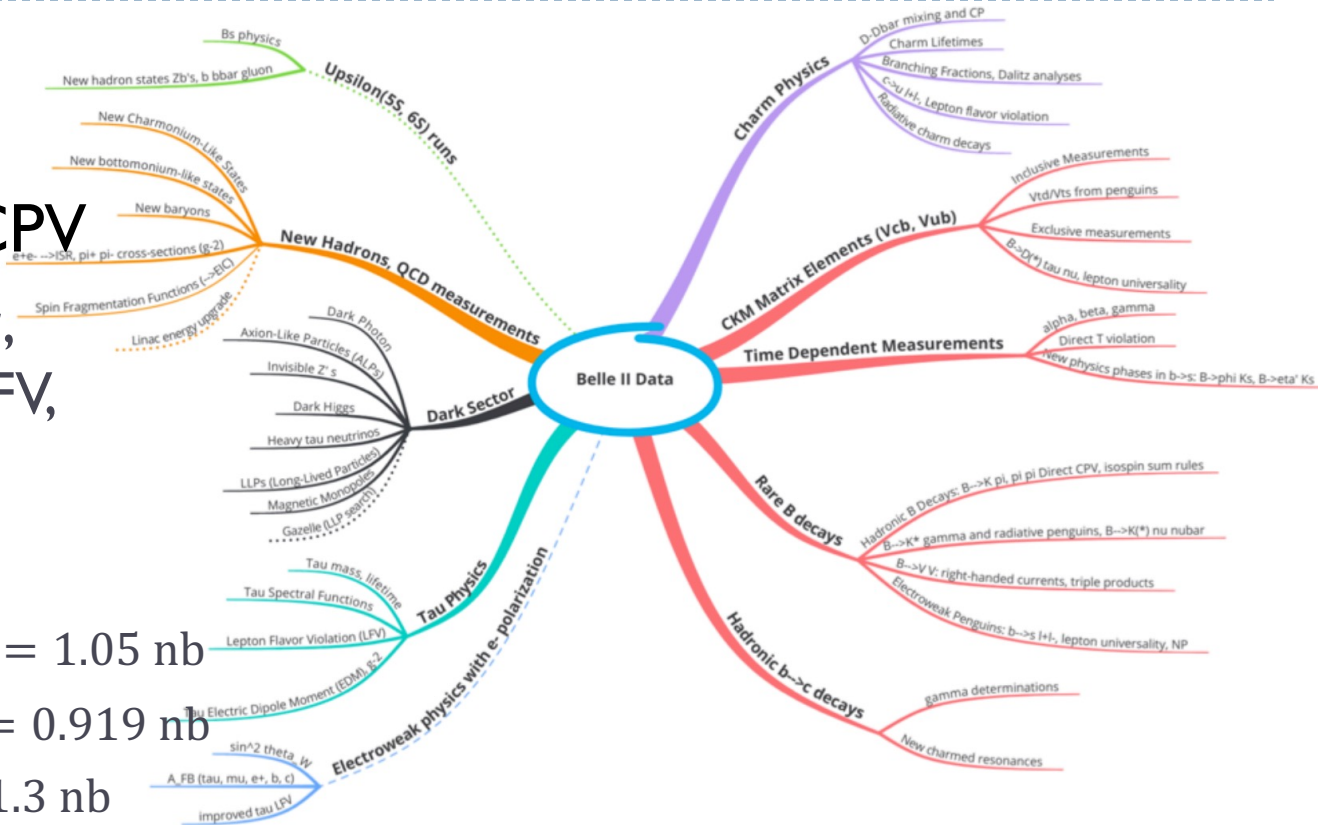
# Physics of Belle II

- ▶ Physics reach is not limited to B-Physics and CPV

- ▶ CKM, Charm,  $\tau$ , rare process, LFV, ALP ...

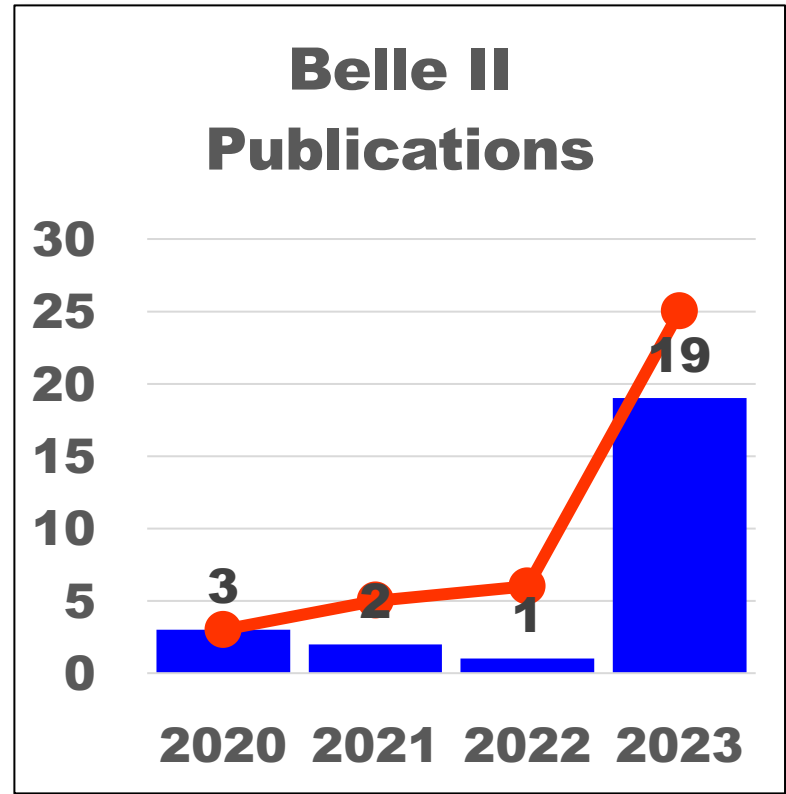
- ▶ Note :

- ▶  $\sigma(e^+e^- \rightarrow \Upsilon(4S)) = 1.05 \text{ nb}$
- ▶  $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.919 \text{ nb}$
- ▶  $\sigma(e^+e^- \rightarrow c\bar{c}) = 1.3 \text{ nb}$



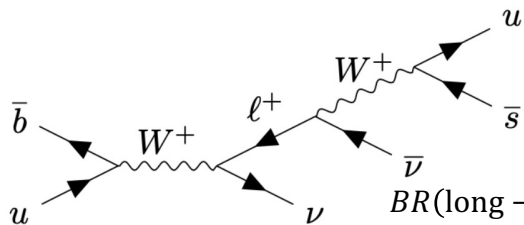
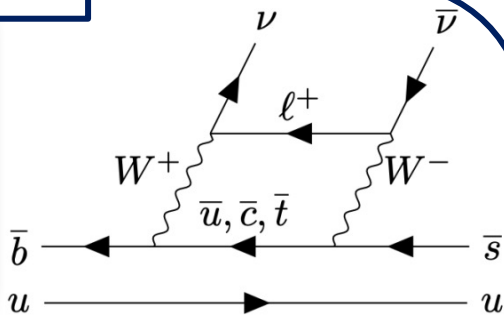
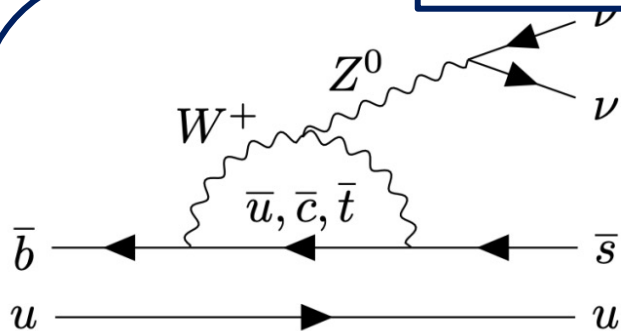
# Physics Results in 2023

$B \rightarrow X_C \ell^+ \bar{\nu}_\ell$	PRD 107, 072002
Dark photon $\rightarrow \mu^+ \mu^- + E_{miss}$	PRL 130, 071804
$\Gamma(\Lambda_C^+)$	PRL 130, 071802
LFV $\tau \rightarrow \ell \alpha$	PRL 130, 181803
$Z' \rightarrow \mu\mu + E_{miss}$	PRL 130, 231801
$\Gamma(\Omega_C^0)$	PRD 107, L031103
CPV $B^0 \rightarrow \pi^0 \pi^0$	PRD 107, 112009
$e^+ e^- \rightarrow \omega \chi_{bJ}, X_b \rightarrow \omega Y(1S)$	PRL 130, 091902
$e^+ e^- \rightarrow \mu^+ \mu^- \tau^+ \tau^-$	PRL 131, 121802
$\Gamma(B^0)$	PRD 107, L091102
LU $B(B \rightarrow X e \nu)/B(B \rightarrow X \mu \nu)$	PRL 131, 051804
$D^0$ identification method	PRD 107, 112010
CPV $B^0 \rightarrow \phi K_S^0$	PRD 108, 072012
CPV $B^0 \rightarrow K_S^0 \pi^0$	PRL 131, 111803
$ V_{cb} $ from $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell$	Accepted PRD
$M(\tau)$	PRD 108, 032006
CPV $B^\pm \rightarrow DK^\pm, B^\pm \rightarrow D\pi^\pm$	JHEP 09 2023, 146
LU $B^0 \rightarrow D^{*-} \ell^+ \nu$	PRL 131, 181801
$\Gamma(D_S^+)$	PRL 131, 171803
<b>19 published in 2023</b>	



# $B^+ \rightarrow K^+ \nu \bar{\nu}$ in SM / BSM

## Standard Model

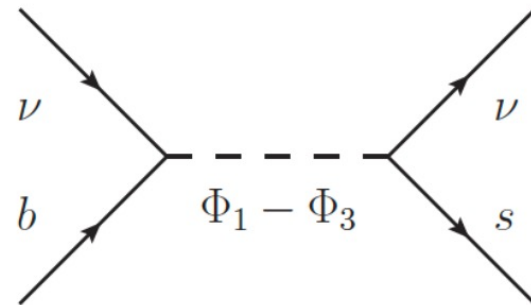


$$BR(\text{long-range}) = (0.61 \pm 0.06) \times 10^{-6}$$

FCNC, GIM suppressed, no hadronic uncertainties

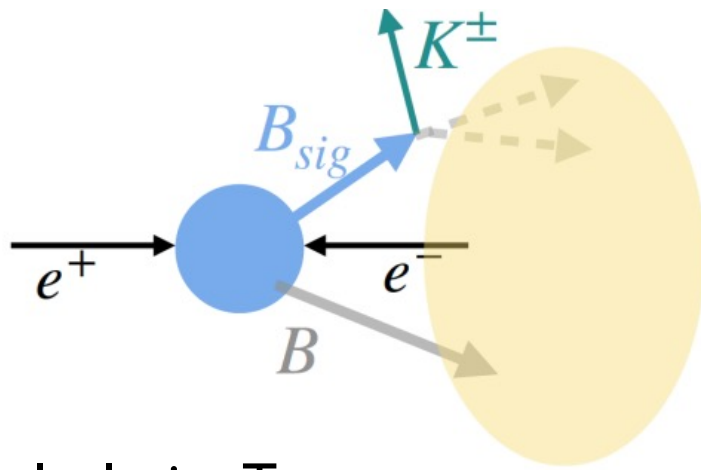
$$BR(B^+ \rightarrow K^+ \nu \bar{\nu}; \text{SM}) = (5.58 \pm 0.37) \times 10^{-6}$$

## BSM

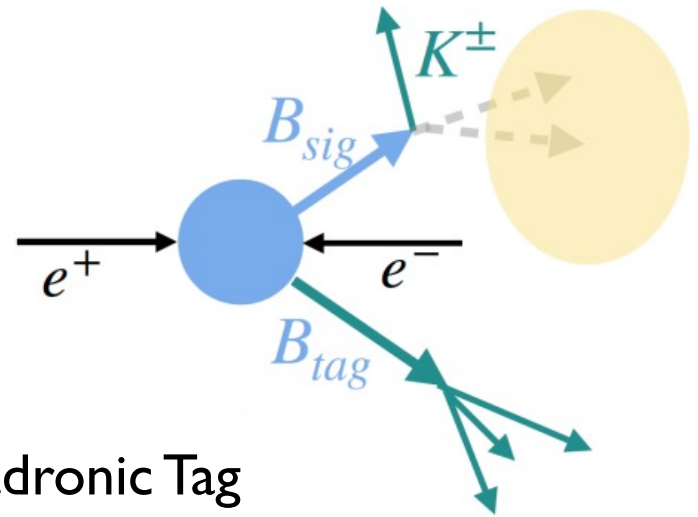


Ex. Leptoquark model  
or  $B^+ \rightarrow K^+ X_{inv}$

# Inclusive Tag Analysis / Hadronic Tag Analysis



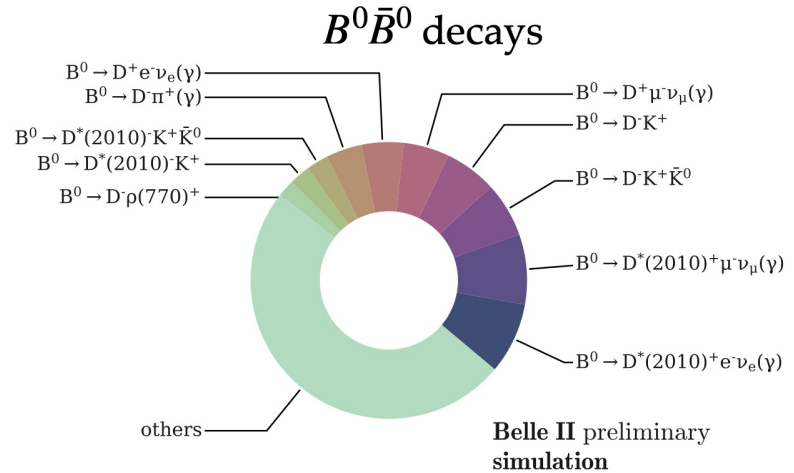
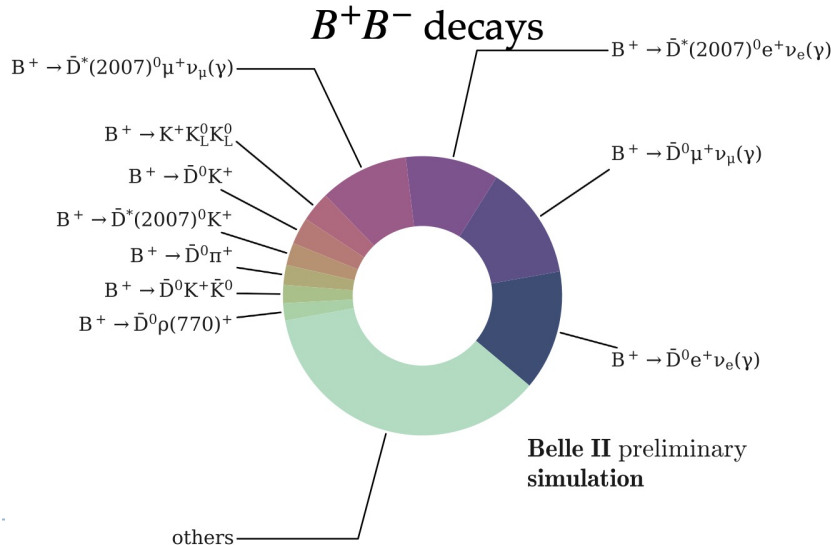
- ▶ Inclusive Tag
  - ▶ Identify objects belonging to “Rest of Event”
  - ▶ Less precise but higher efficiency ( $\epsilon \sim 8\%$ )



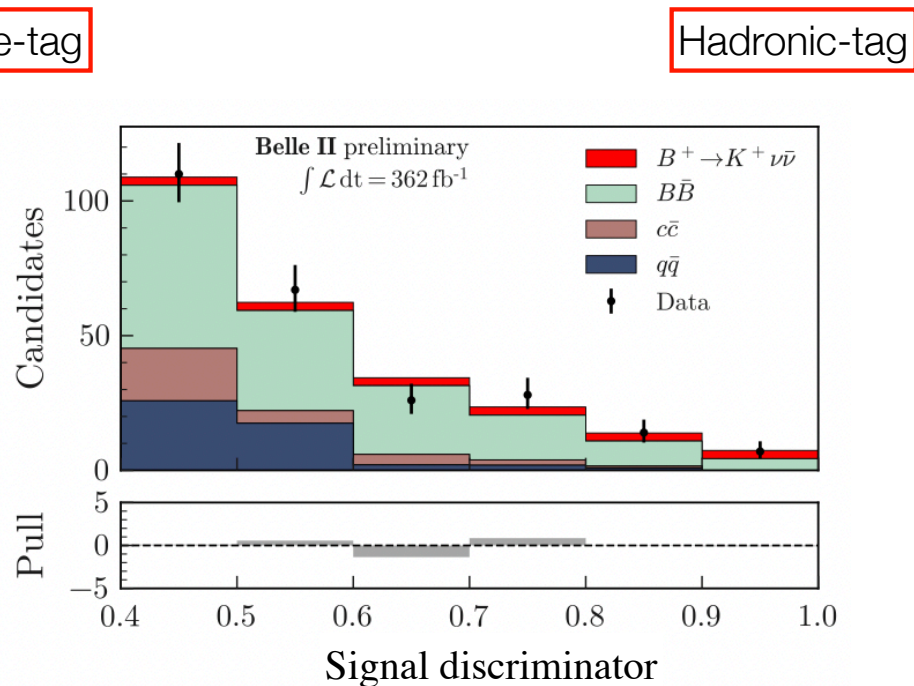
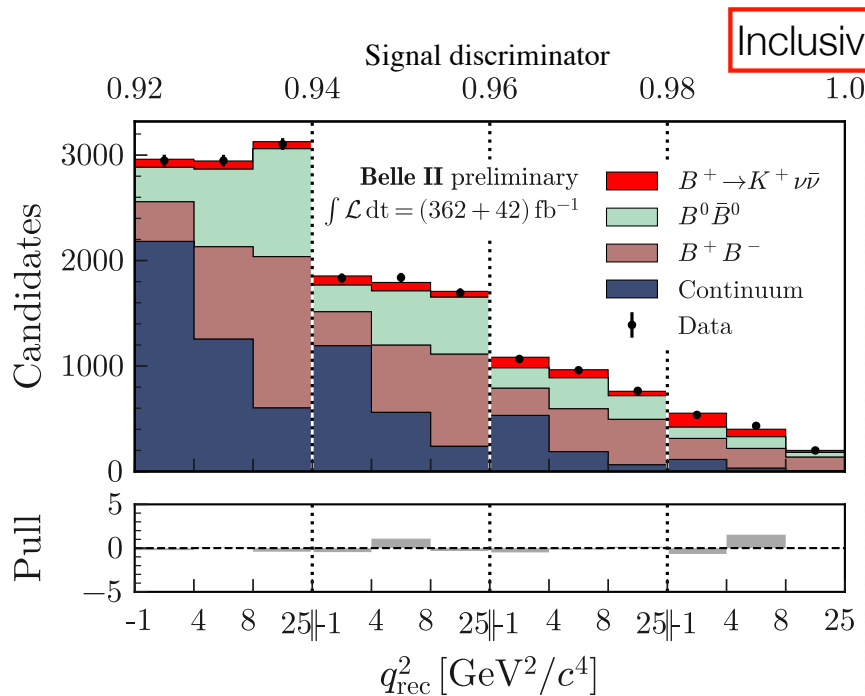
- ▶ Hadronic Tag
  - ▶ Reconstruct  $B_{tag}$  in one of the 35 hadronic final states
  - ▶  $\epsilon \sim 0.4\%$

# Backgrounds Summary

- ▶ 40% from  $q\bar{q}$ , 28% from  $B \rightarrow D(\rightarrow KX)\ell\nu$
- ▶ Hadronic decay  $B^0 \rightarrow K^+ D^{*-}$ ,  $B^+ \rightarrow K^+ D^{*0}$  with  $D$  decay to  $K_L^0$  is most critical



# Fitting Results :



Inclusive : Fit on  $q_{rec}^2$  (mass squared of the  $\nu$  pair) and BDT output / Hadronic : Fit on BDT output

# First Evidence for $B^+ \rightarrow K^+ \nu \bar{\nu}$

$$BR(B^+ \rightarrow K^+ \nu \bar{\nu}) = [2.4 \pm 0.5 (stat)_{-0.4}^{+0.5} (sys)] \times 10^{-5}$$

► **Inclusive :**

$$BR = [2.8 \pm 0.5 \pm 0.5] \times 10^{-5}$$

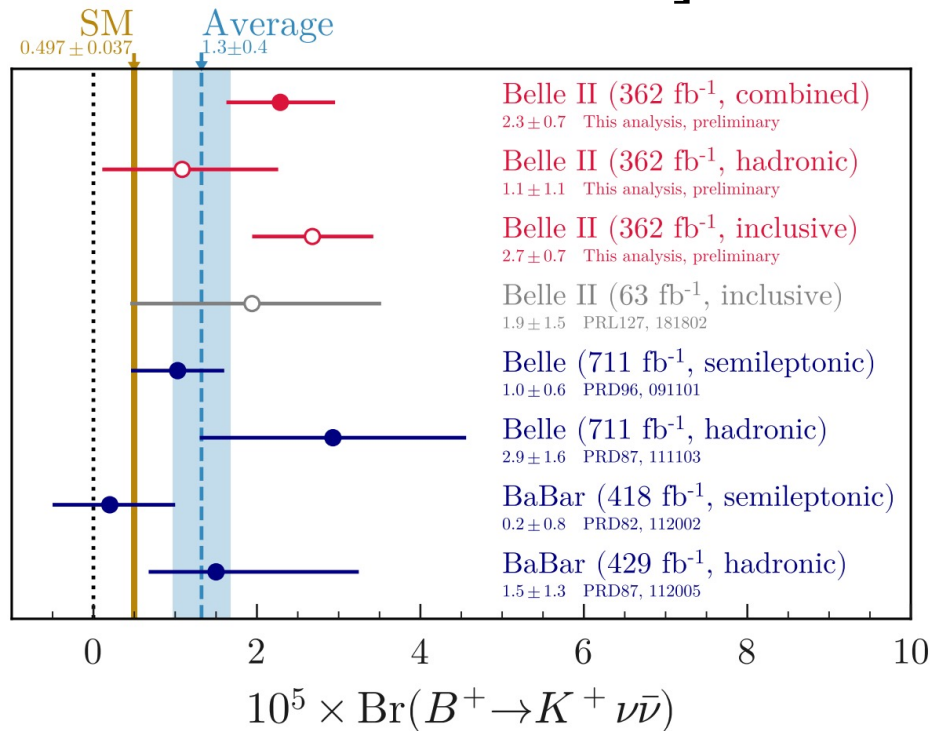
► **Hadronic :**

$$BR = [1.1_{-0.8-0.5}^{+0.9+0.8}] \times 10^{-5}$$

► **Significance:**

► w.r.t null :  $1.1\sigma$

► w.r.t SM :  $2.8\sigma$







# The most precise measurement on $\tau$ mass

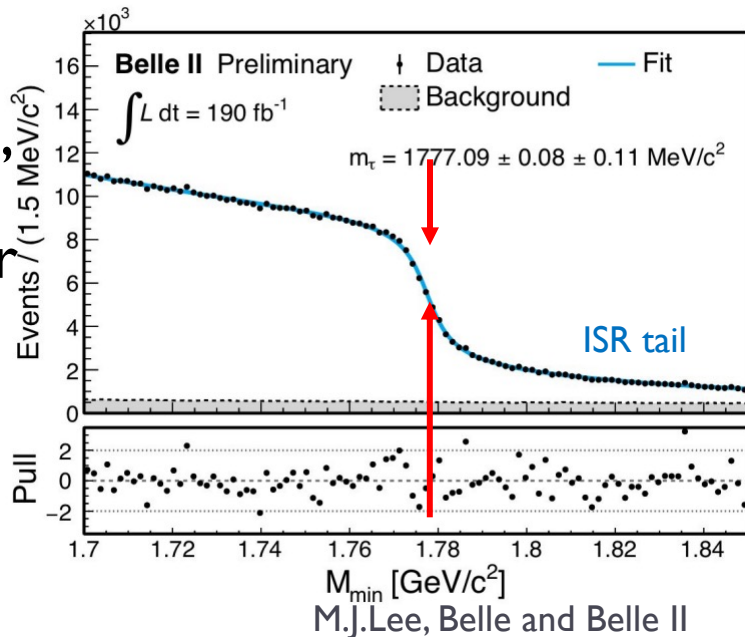
▶ Measurement limited  $p_{\text{track}}$  scale &  $E_{\text{beam}}$  scale

▶ Pseudo-endpoint method :

$$M_{\text{min}} = [M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)]^{1/2} \leq M_{\tau}$$

▶ Less Data,  
Better sys err.,  
Better stat. err.,  
owing to  
Better detector

▶ Improved  
measurement  
of endpoint  
slope



PDG Average (2022)

$$1776.86 \pm 0.12$$

BES (1996)  
 $1776.96^{+0.18}_{-0.21} \pm 0.25_{-0.17}$

BELLE (2007)  
 $1776.61 \pm 0.13 \pm 0.35$

KEDR (2007)  
 $1776.81^{+0.25}_{-0.23} \pm 0.15$

BaBar (2009)  
 $1776.68 \pm 0.12 \pm 0.41$

BES III (2014)  
 $1776.91 \pm 0.12^{+0.10}_{-0.13}$

Belle II (2023)(Preliminary)  
 $1777.09 \pm 0.08 \pm 0.11$

(414 fb<sup>-1</sup>)

Less data

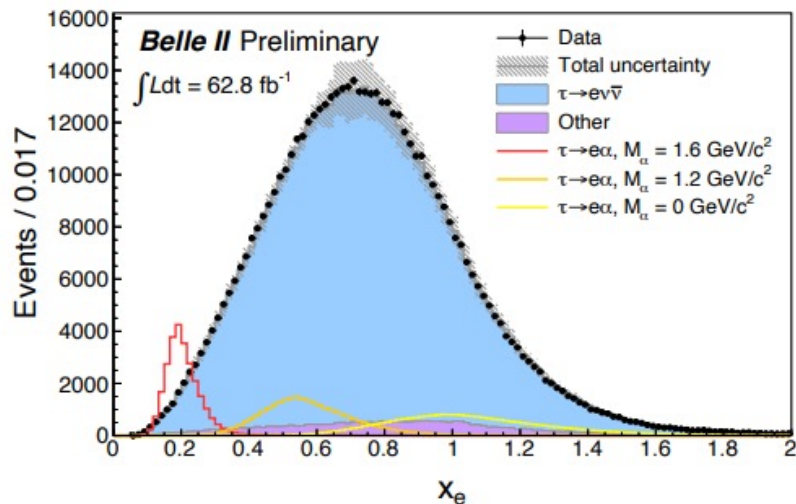
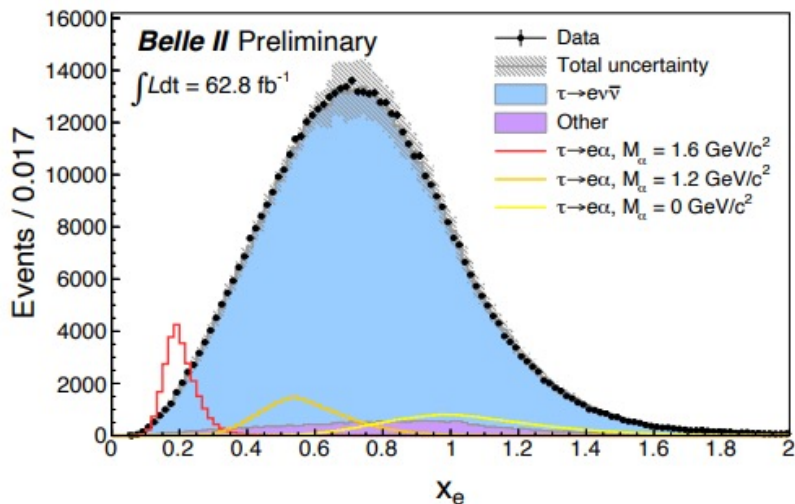
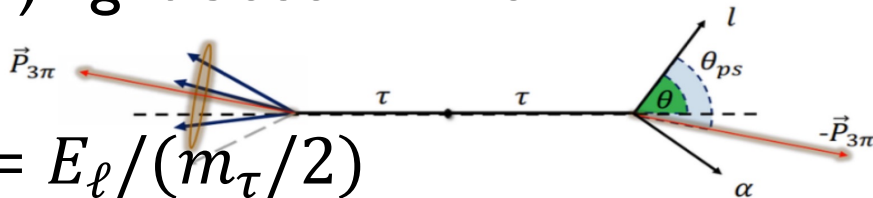
(190 fb<sup>-1</sup>)

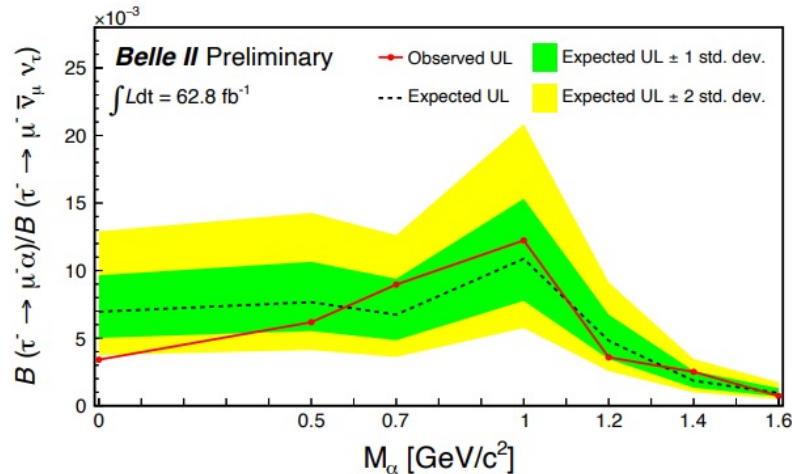
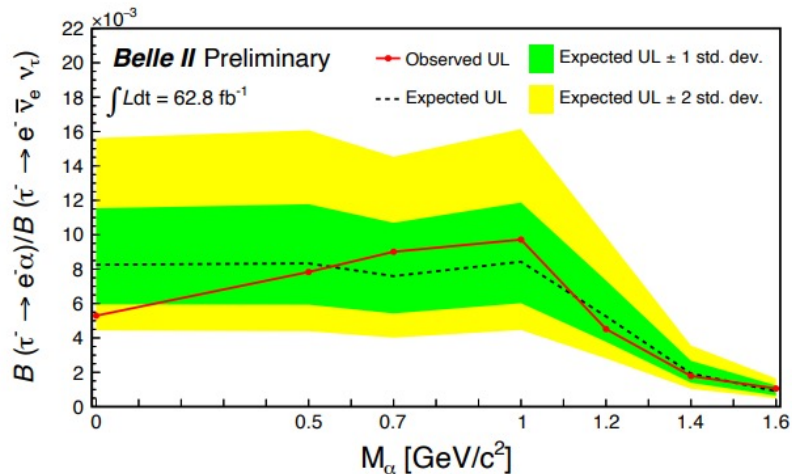
$M_{\tau}$  [MeV/c<sup>2</sup>]

Nov 23, 2023, KSHEP

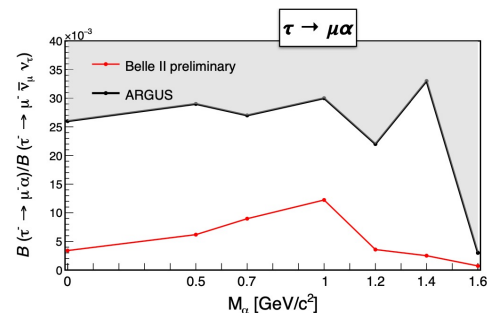
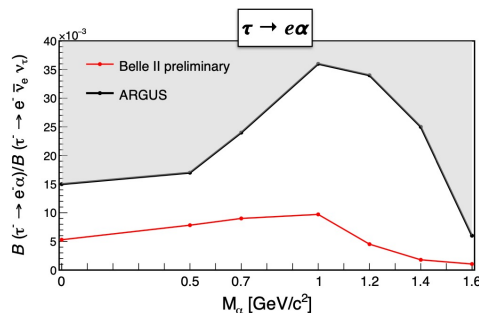
# Recent results: BSM boson search of $\tau \rightarrow \ell \alpha$

- ▶  $\alpha$  is an invisible (pseudo scalar) light boson in BSM (possible similar with axion)
- ▶ Template fit with pdfs on  $x_\ell = E_\ell / (m_\tau / 2)$



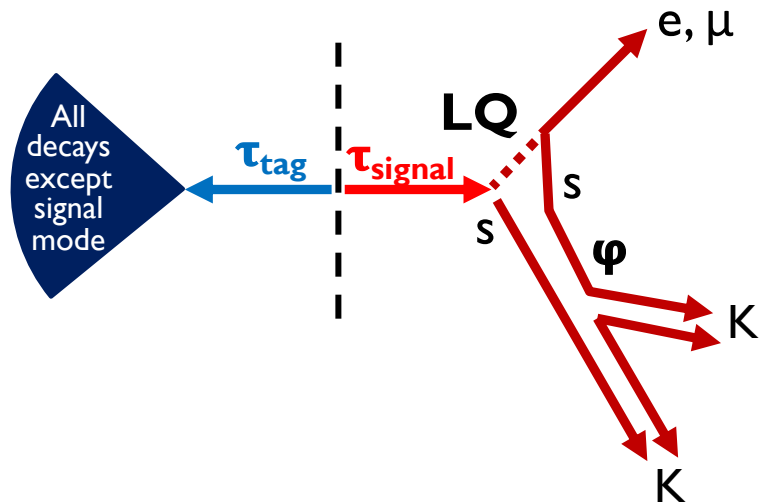
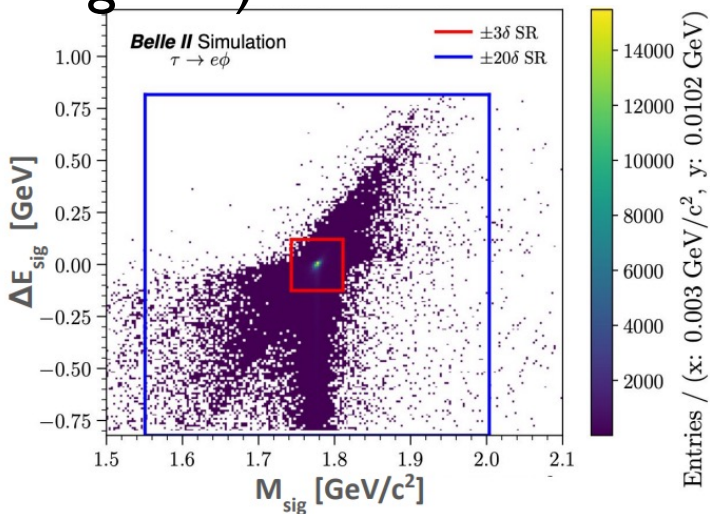


- Using the most early data ( $62.8 \text{ fb}^{-1}$ ), the most stringent limit, 3 – 7 times better than ARGUS measurement (1995,  $476 \text{ pb}^{-1}$ ) was achieved. (arXiv: 2212.03634)

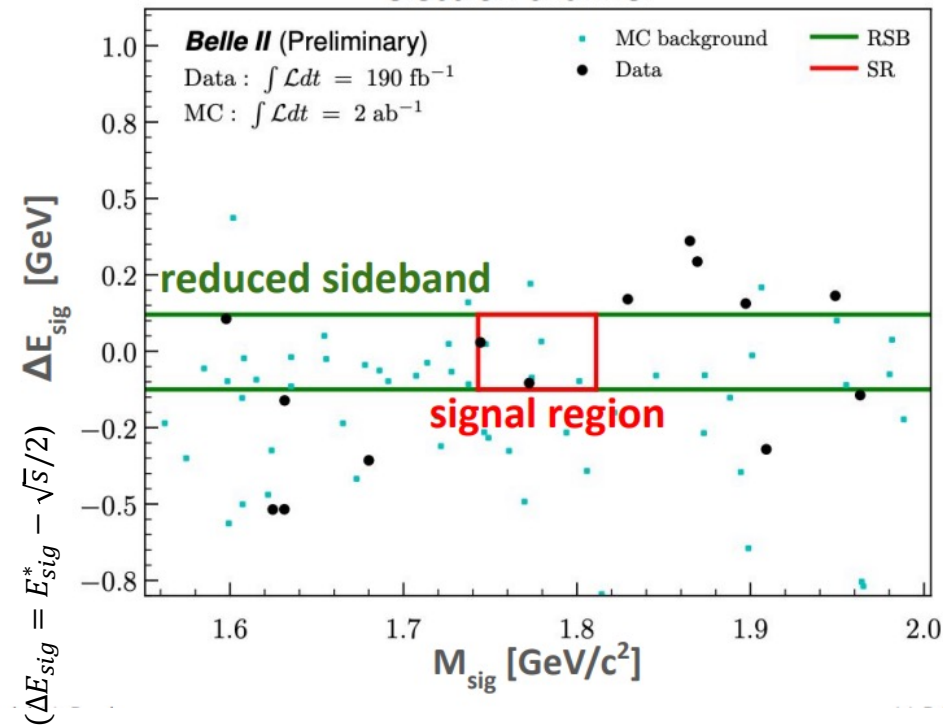


# Recent results: LFV decay of $\tau \rightarrow \ell\phi$

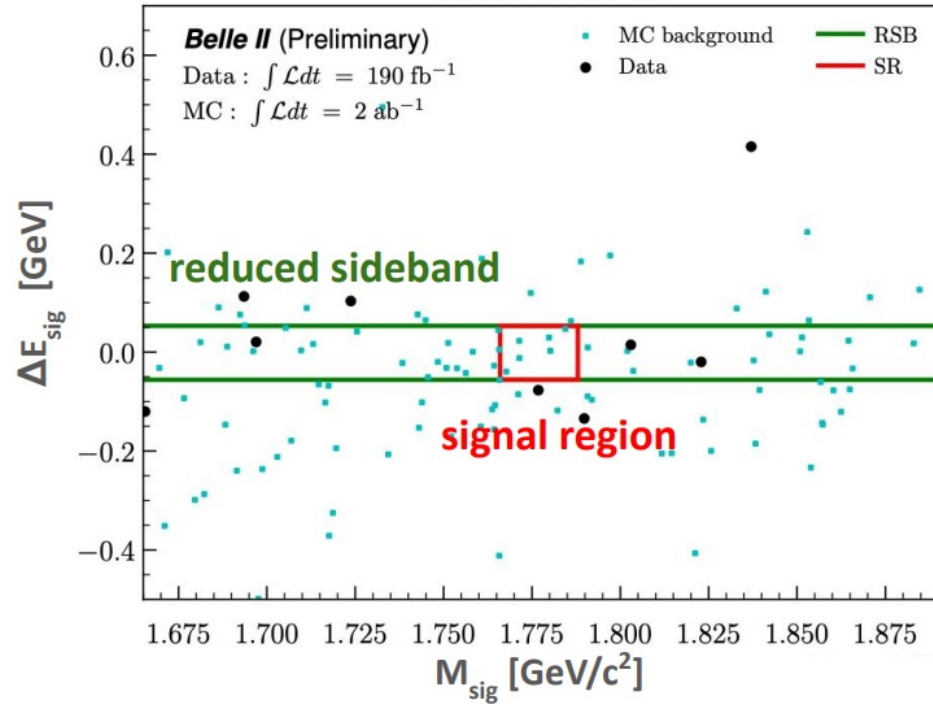
- ▶ Highly suppressed in SM ( $\sim 10^{-50}$ ) but much higher in Leptoquark model ( $\sim 10^{-8} - 10^{-10}$ )
- ▶ Improved efficiency (6.5%, 2xBelle) due to “Rest of Everything” (on tag side) method + BDT



electron channel



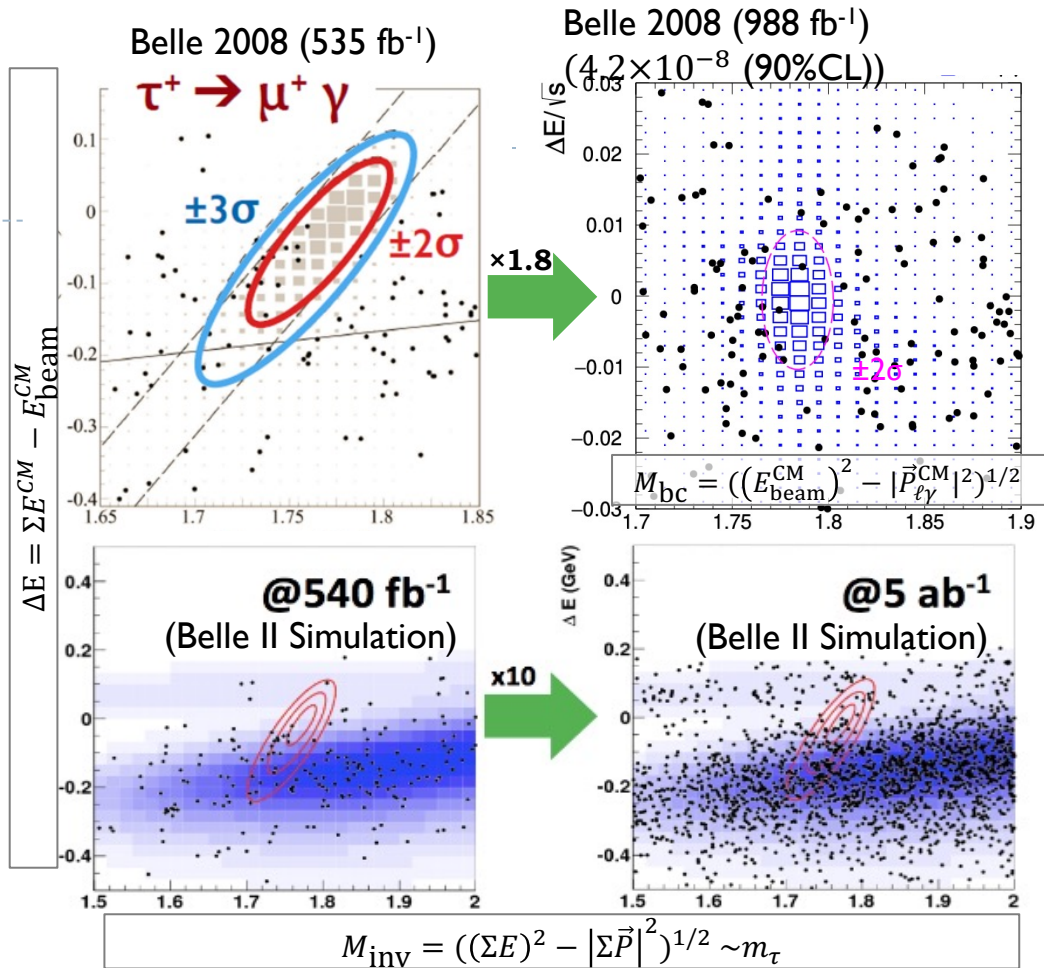
muon channel



- ▶  $\text{BF}(\tau \rightarrow e\phi, 90\% \text{CL}) = 2.3 \times 10^{-7}$ ,  $\text{BF}(\tau \rightarrow \mu\phi, 90\% \text{CL}) = 9.7 \times 10^{-8}$
- ▶ Statistically limited ( $\sim 1/5 \times \text{Belle}$ ), but inclusive tagging successfully applied.

# Prospect: $\tau \rightarrow \ell \gamma$ at Belle II

- ▶  $50 \text{ ab}^{-1} = 5 \times 10^{10} \tau$  pairs  
 $\Rightarrow \text{UL} \sim 10^{-8 \sim -9}$
- ▶ Sensitivity depends on background level
  - ▶ New BG rejection method using kinematic relation enabled fewer BG with increased dataset



# Summary / Prospects

- ▶ Belle is still productive in data analysis
- ▶ Belle II started DAQ in 2019, collected  $\sim 420 \text{ fb}^{-1}$  before Long Shutdown I. DAQ resume in this winter
- ▶ Targeting  $50 \text{ ab}^{-1}$  by middle of 2030s
  - ▶ This requires  $10^{35}$  beam!
- ▶ We just started to (massively) produce physics results with  $\frac{1}{4} \sim \frac{1}{2} \times$  (Belle) data

