# Belle II Experiment

Shohei Nishida
KEK, Sokendai

KEKSSP

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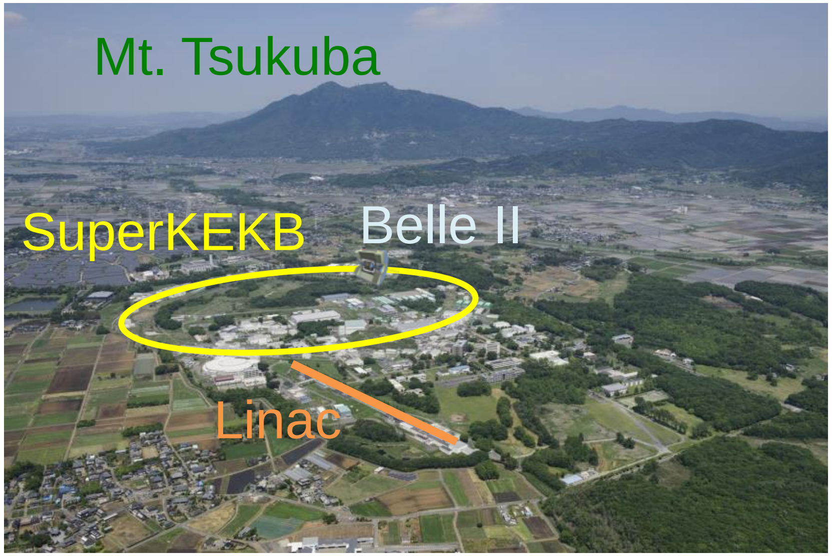
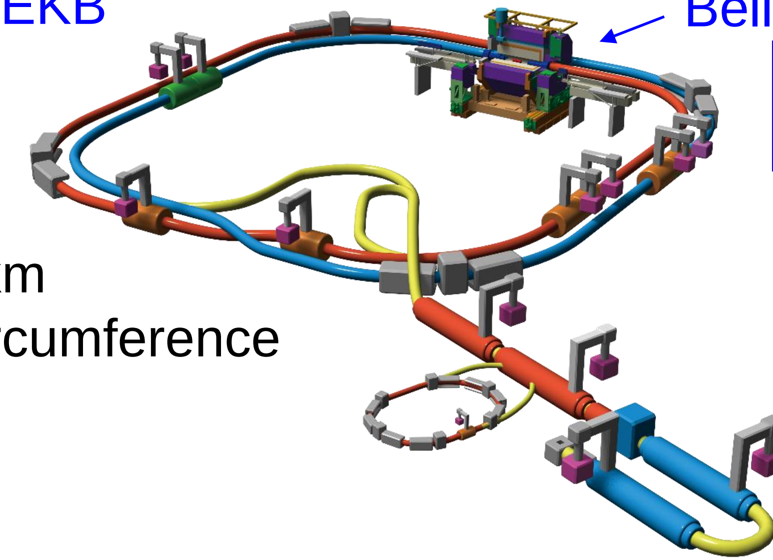
# SuperKEK and Belle II




SuperKEKB accelerator and Belle II experiment

- High energy accelerator research organization (KEK) @ Tsyjyba
- Asymmetric $e^+$-$e^-$ collider SuperKEKB (4 GeV + 7 GeV)
  - ✓ World highest luminosity
- Belle II: flavor physics experiment with Belle II detector
- Successor of KEKB, Belle (1999-2010)
  - ✓ Verification of Kobayashi Maskawa theory with the study of CP violation in B mesons.

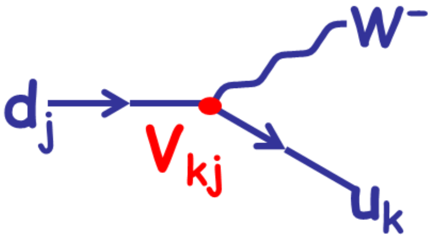
# CP Violation and KM theory

- CP violation: a key for the matter-antimatter asymmetry.
- Kobayashi-Maskawa theory (1973)
  - ✓ CP violation in the Standard Model (SM)
  - ✓ Complex phase in the quark mixing matrix
    → source of CP violation in weak interaction.
  - ✓ requires 3 (or more) generation of quarks

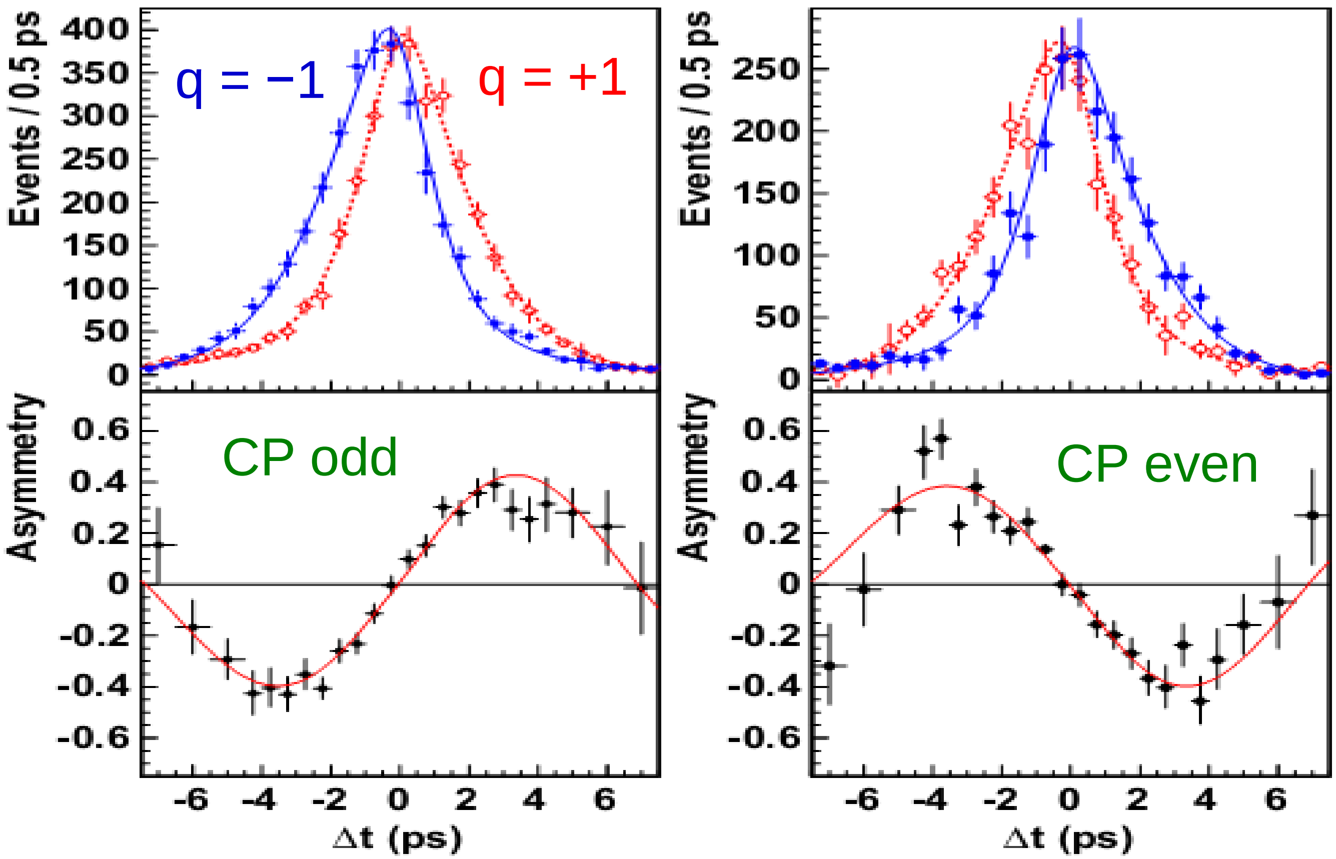
CKM (Cabibbo-Kobayashi-Maskawa) Matrix

$$V=\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- When the theory is proposed, only 3 quarks (u, d, s) were known.



Study of CP violation in B system was the main purpose of Belle experiment




$\sin(2\phi_1) = 0.667 \pm 0.023 \pm 0.012$

$A = 0.006 \pm 0.016 \pm 0.012$

[PRL 108, 171802 (2012)]

Discovery of CP violation in B system (2001)

⇩

Nobel Prize in Physics to Kobayashi and Maskawa (2008)

# CP Violation in B Meson

Mixing-induced CP asymmetry of B mesons

- $B^0$ and $\overline{B}^0$ decay to a common CP eigenstate $f_{CP}$.
- CP violation appears as a decay time difference.

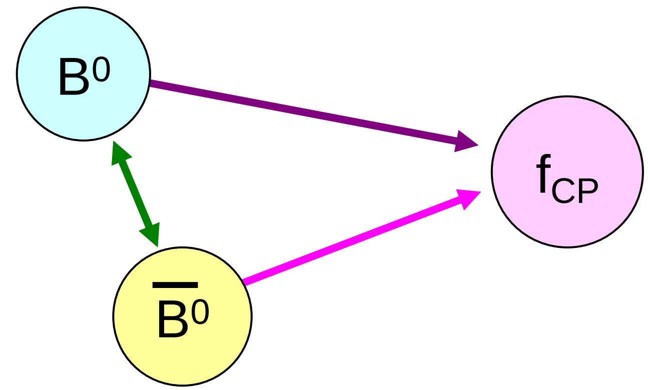
$$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})}$$

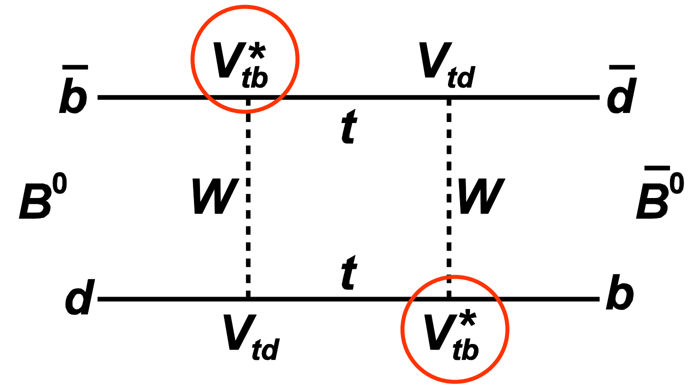
$$= S \sin(\Delta m \Delta t) - C \cos(\Delta m \Delta t)$$

S : mixing induced CPV
C : direct CPV (=−A)

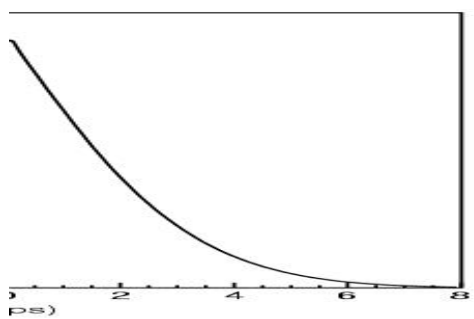
$S = -\xi \sin(2\phi_1)$ for $B \to J/\psi K_S$

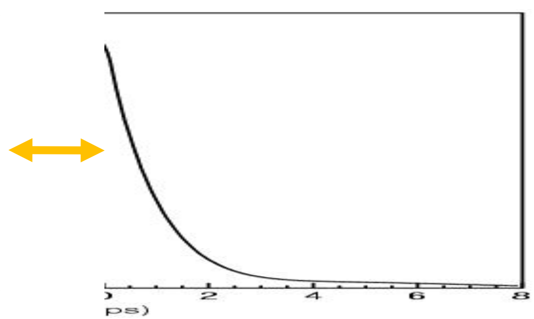
$\phi_1 = \beta$




$$\Gamma(\overline{B}^0(t) \to J/\psi K_S^0) \propto e^{-t/\tau}(1 + \mathcal{S} \sin \Delta m t)$$

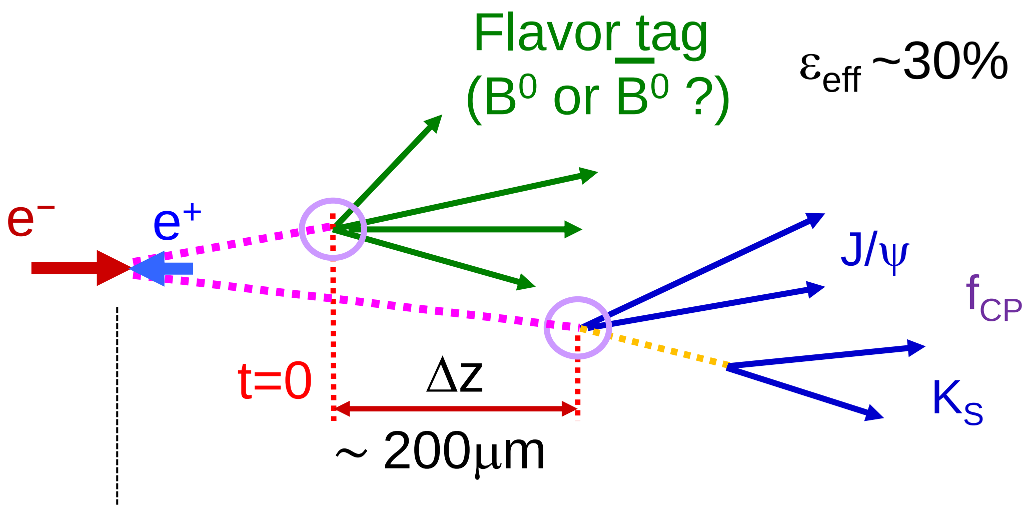



$$\Gamma(B^0(t) \to J/\psi K_S^0) \propto e^{-t/\tau}(1 - \mathcal{S} \sin \Delta m t)$$

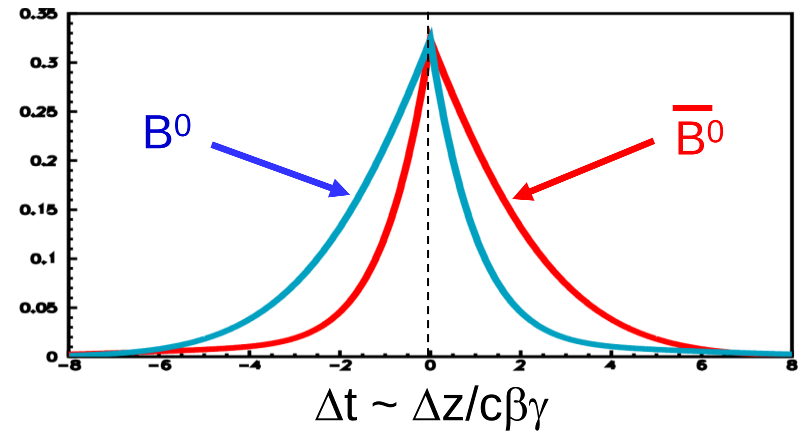
# CP Violation in B Meson

"Lorentz-boost"




$B^0$ / $\bar{B}^0$ Quantum entanglement (uncertain which is $B^0$)

Measure position instead of time




Δt can be negative (one cannot tell which B decays first)

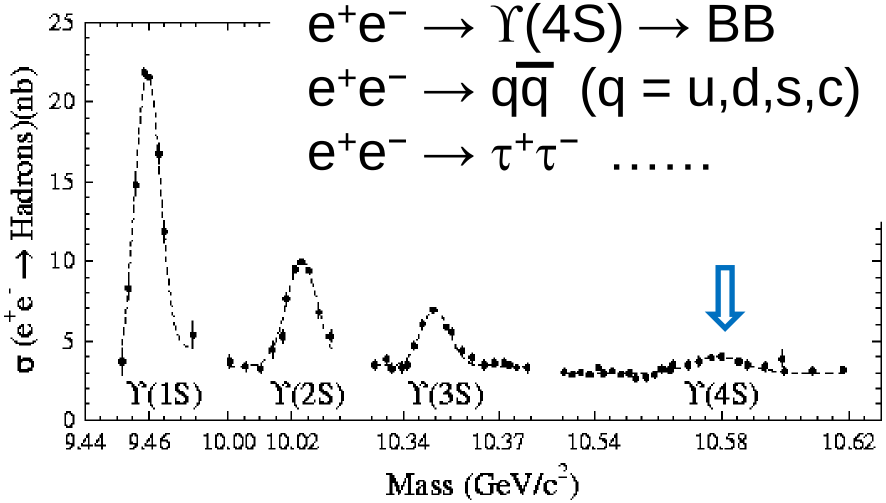
- Asymmetric beam energy

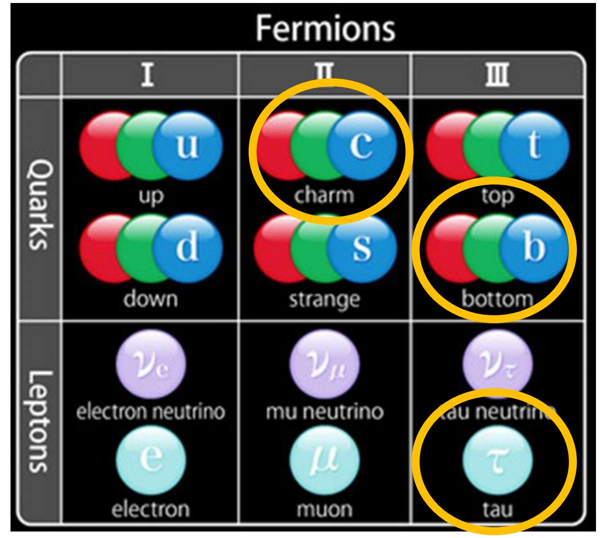
# Belle II Experiment

$e^+e^- \to \Upsilon(4S) \to B\overline{B}$ (1.1nb)

$e^+e^- \to q\overline{q}$ (q = u,d,s,c) (~3nb)

$e^+e^- \to \tau^+\tau^-$ ……




Flavor = species of quarks or leptons

- Belle II: flavor physics experiment
- Heavy Flavor Physics: c, b, τ
  - ✓ Many kinds of decay modes.
- Large number of B mesons, charm (D mesons etc.) and τ leptons are produced at Belle II
  - ✓ Precise study of these decays.
  - ✓ Search for New Physics beyond the Standard Model (SM) by comparing with the SM prediction.

# Belle II Detector

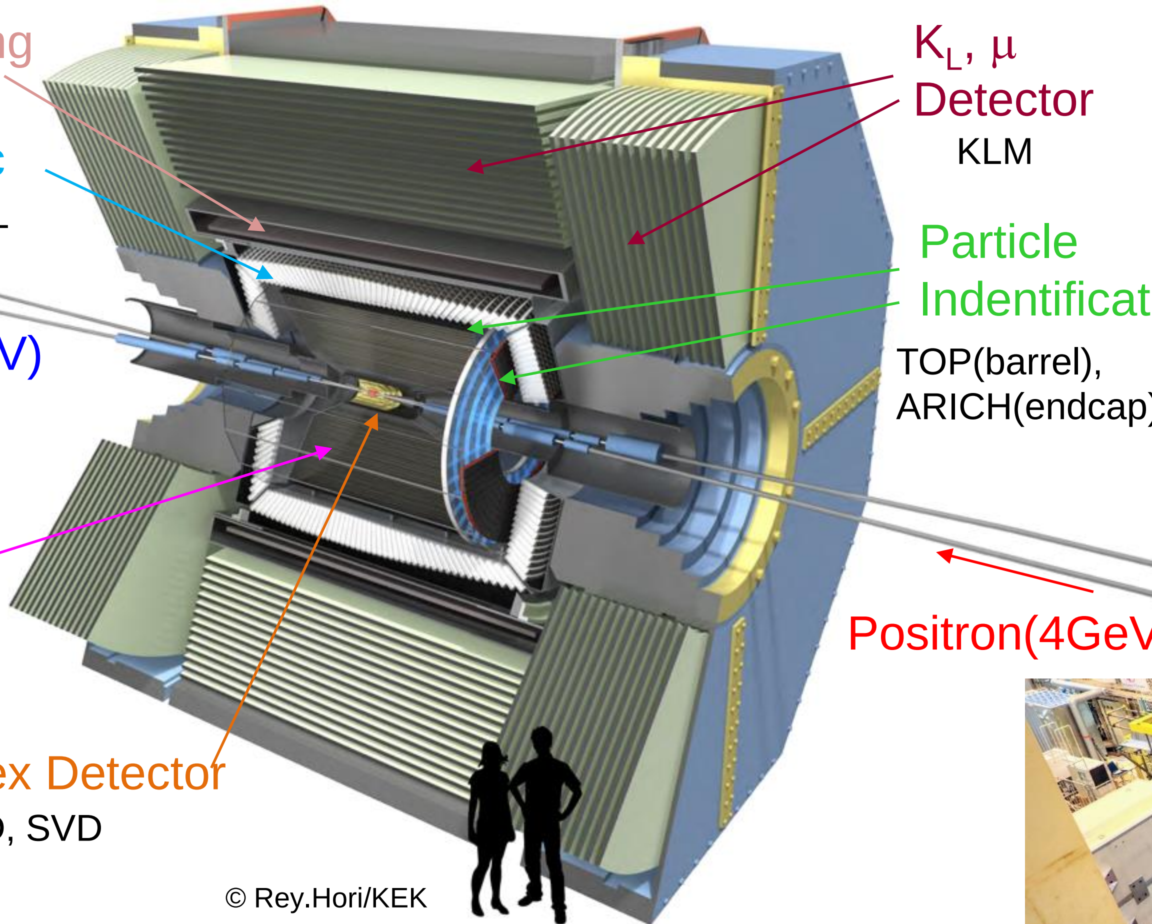
Superconducting Solenoid(1.5T)

Electromagnetic Calorimeter ECL

Electron(7GeV)

Central Drift Chamber CDC

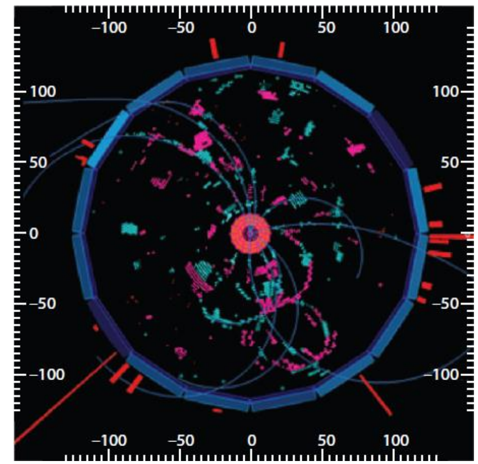
Silicon Vertex Detector PXD, SVD



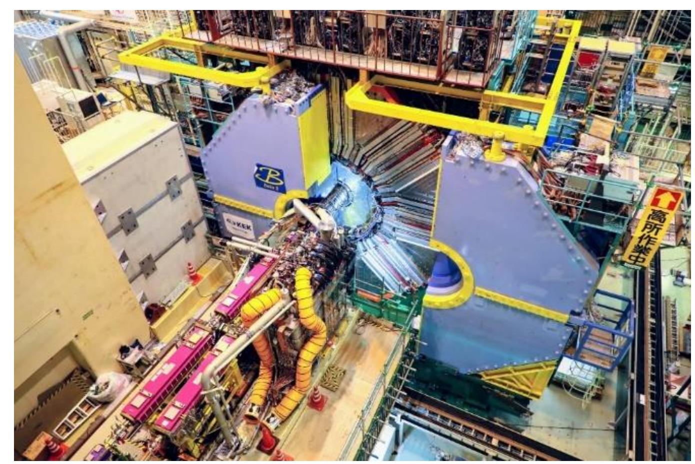

$K_L$, μ Detector KLM

Particle Indentification TOP(barrel), ARICH(endcap)

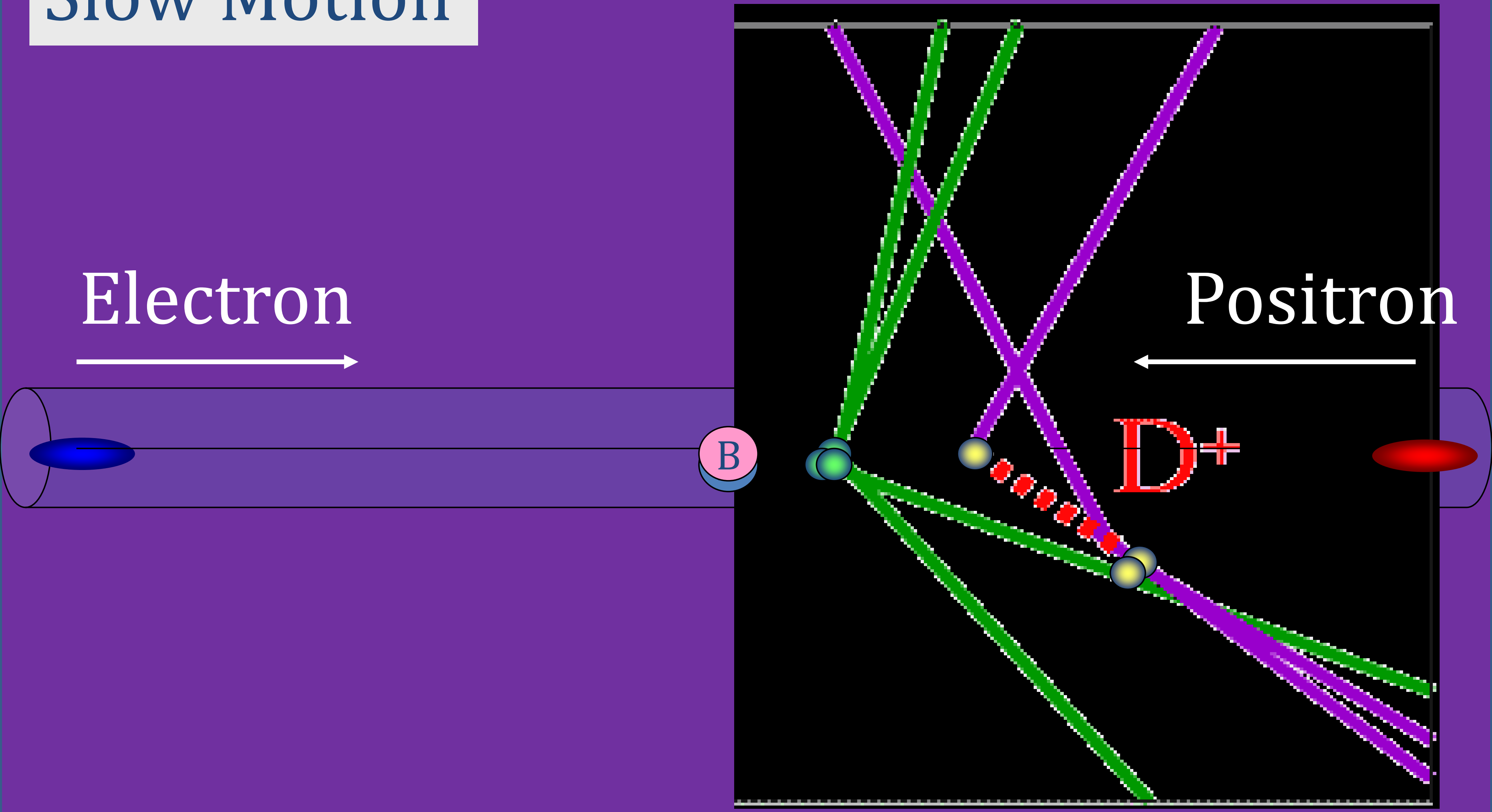
Positron(4GeV)




Belle II Detector（8m×8m×8m, 1400t）



# Slow Motion

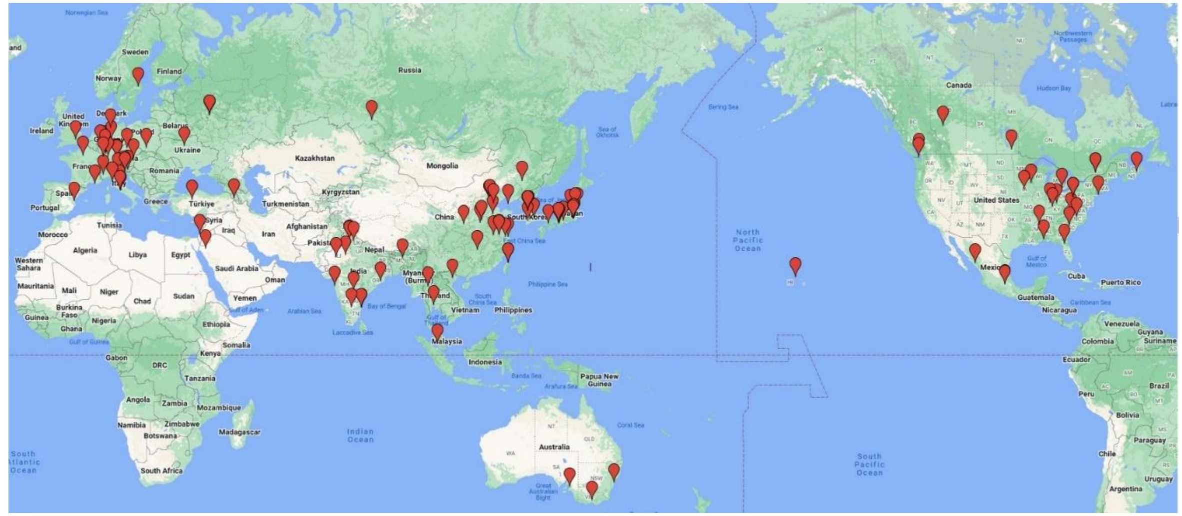


# Belle II

## Belle II Collaboration

- 28 countries and regions
- 125 institutes
- ~1200 researchers

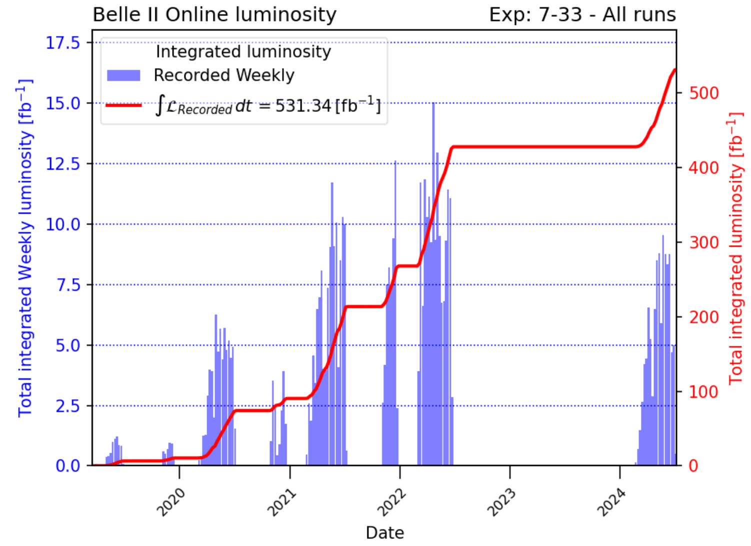
(@Jul. 2024)



International collaboration

# Belle II Operation

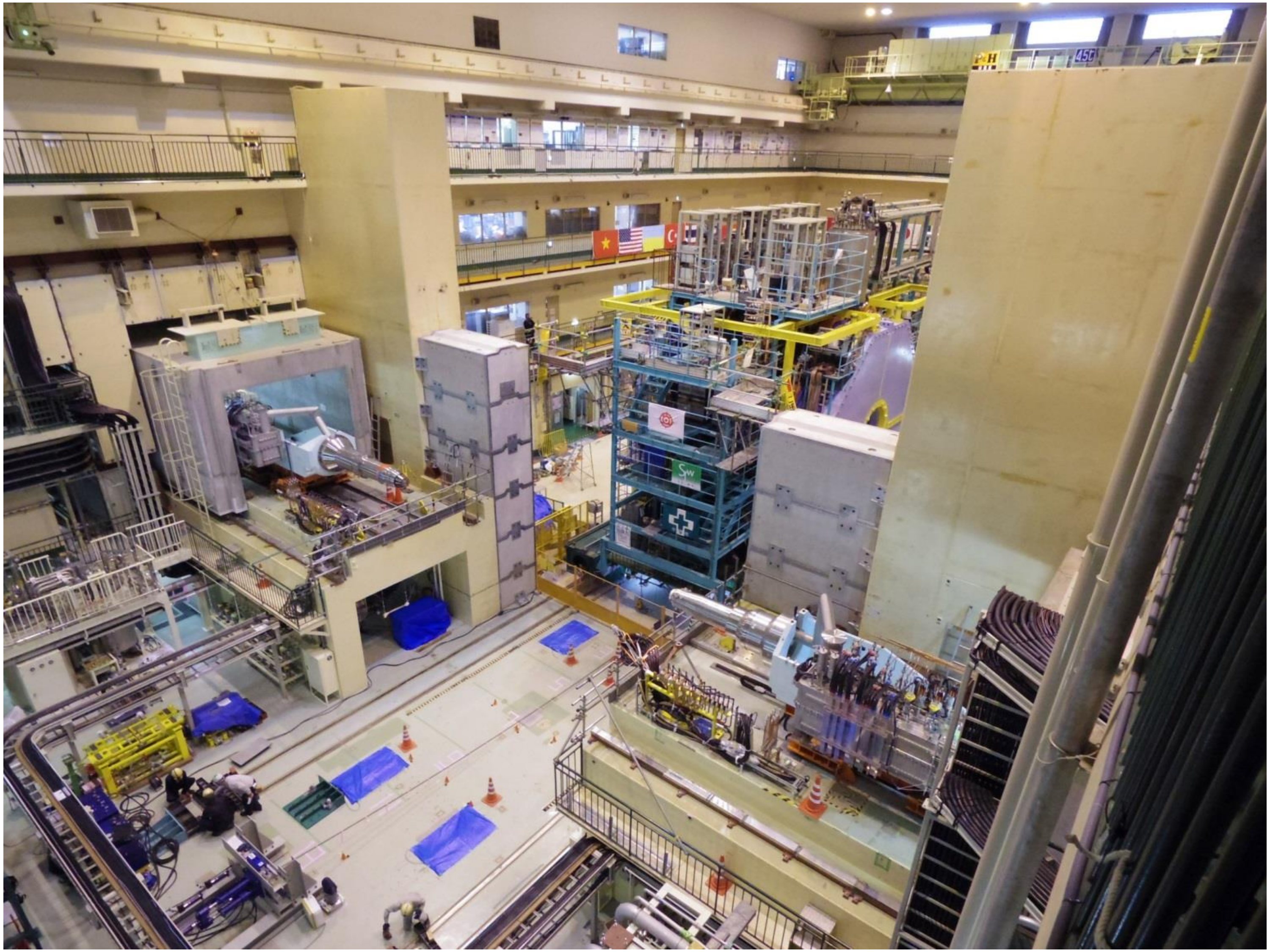
2010/06: End of the operation of Belle
2016/02-06: test operation without Belle II (Phase 1)
2018/02-07: test operation with Belle II (Phase 2)
2019/02-: operation (Phase 3) : Run 1
2022/07-2023/12：LS1 (Long shutdown 1)
2024/01- : Run 2




Work during LS1 (Installation of Pixel Detector)

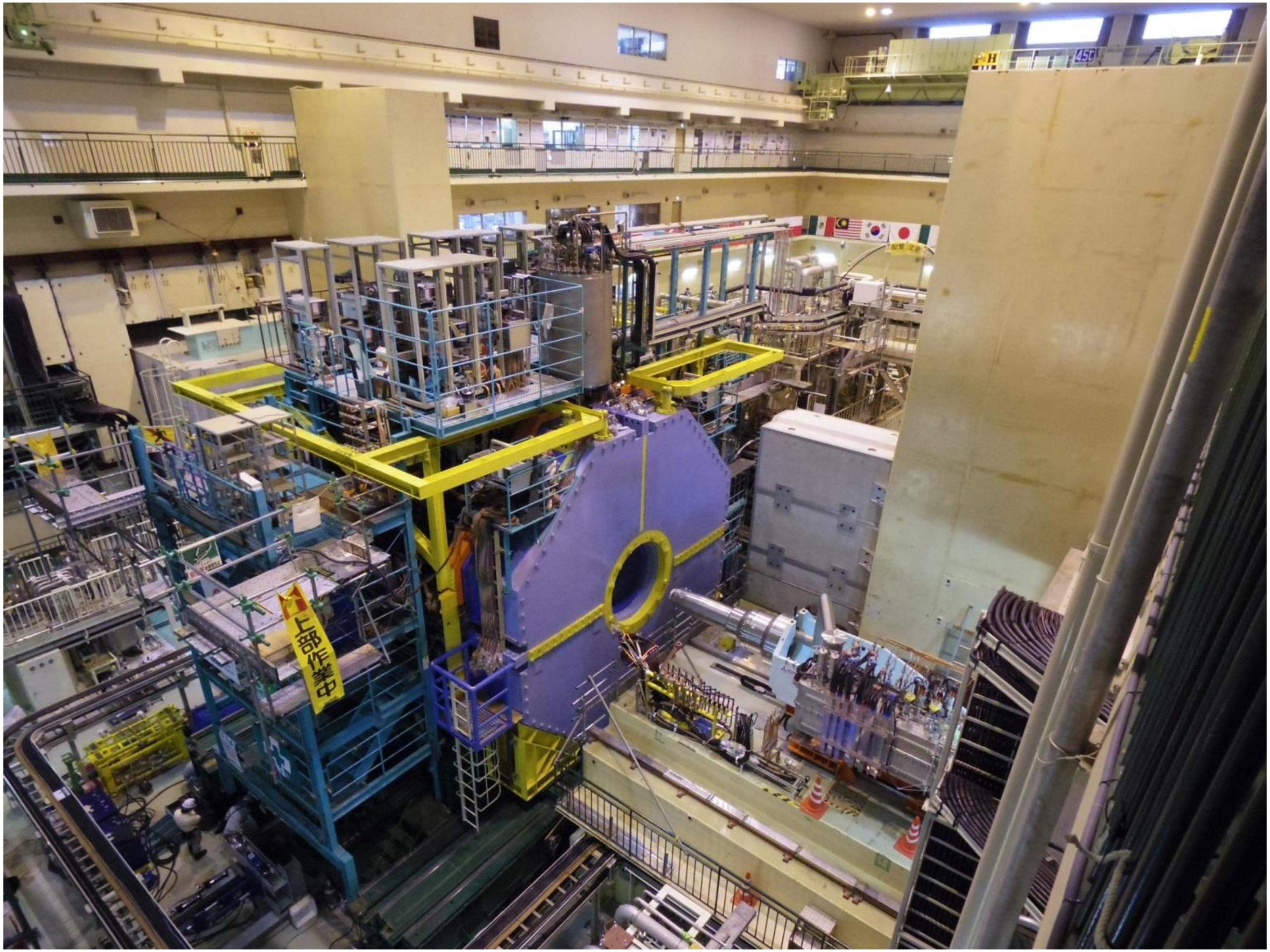

- Luminosity $4.7 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ achieved (Jun. 2022):
  - ✓ World record (~ ×2 of KEKB)
  - ✓ Aiming one order higher.
- 531 fb$^{-1}$ of data accumulated so far.
  - ✓ Larger than BaBar data set.
  - ✓ Belle: 1 ab$^{-1}$ in 11 years.
  - ✓ Belle II target: 50 ab$^{-1}$ .

# Belle II Installation



April 11, 2017

# Belle II Installation

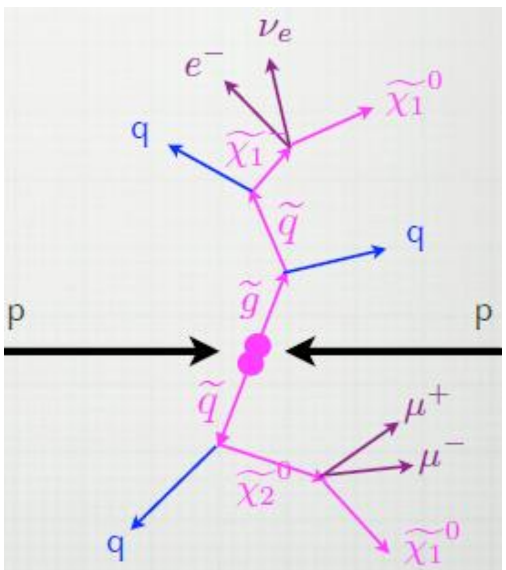



April 11, 2017

# New Physics Search

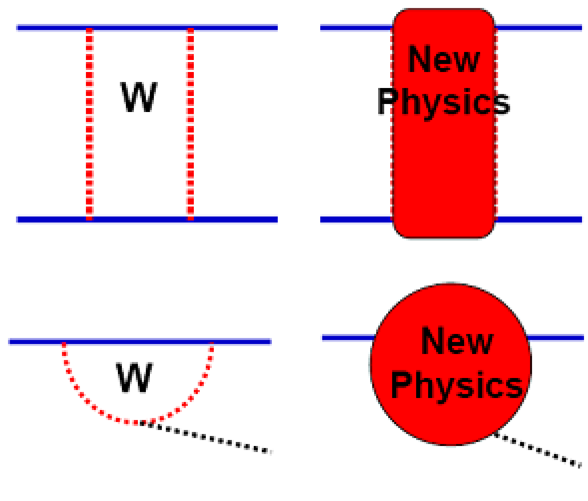
## Direct Search

- Generate New Physics particles with high energy accelerator (e.g. LHC)
- Condition $E_{CM} > M_{NP}$ (at least).




## Indirect Search

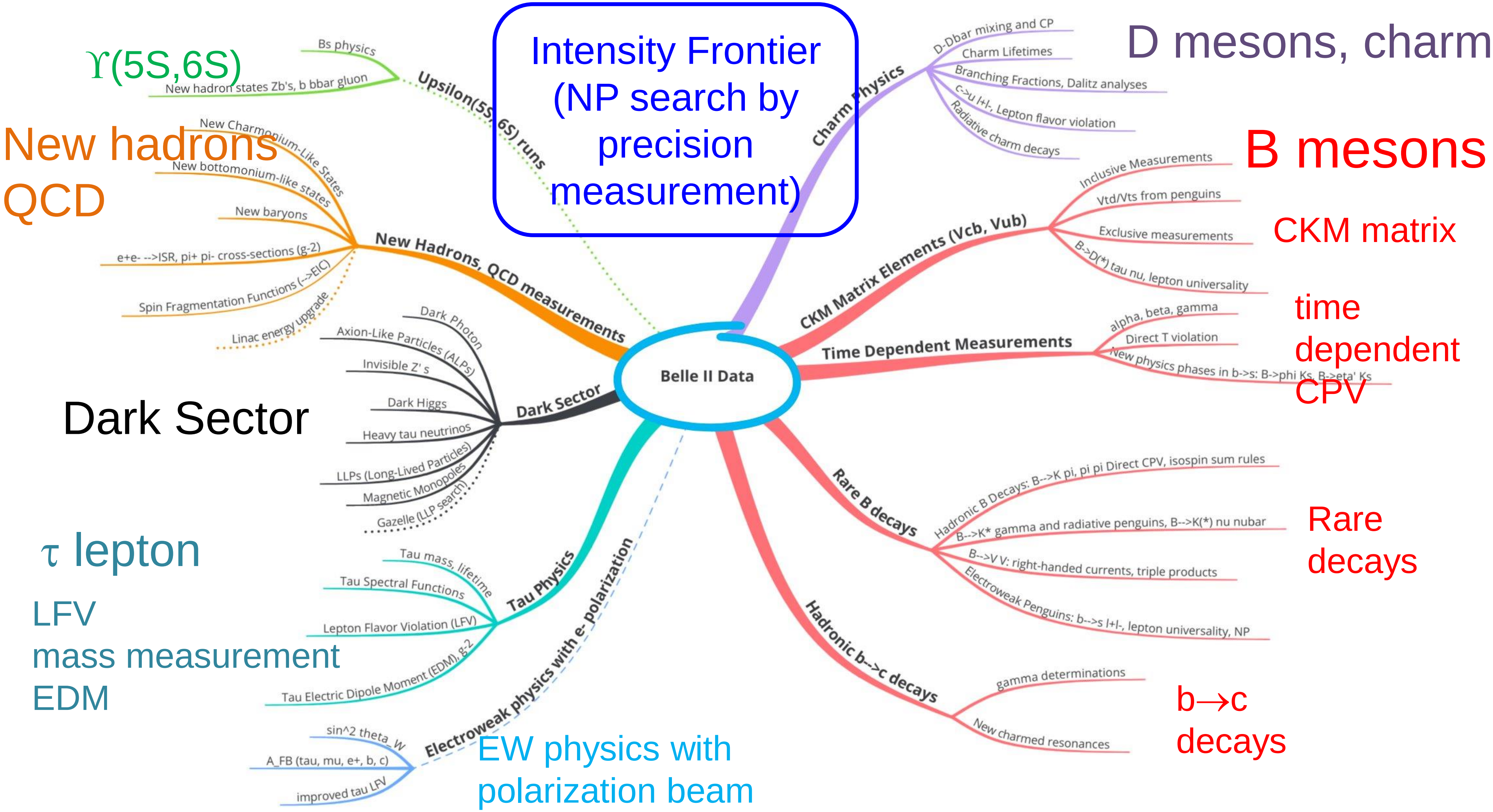
- Study decays of the SM particles.
- Decay through loop diagrams : New Physics particles can virtually contribute to the decays.
- Branching fraction, CP asymmetry can be changed from the SM expectation.
- OK with $E_{CM} < M_{NP}$ . But require huge amount of SM particle decays.




box diagram

penguin diagram

# Belle II Physics



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

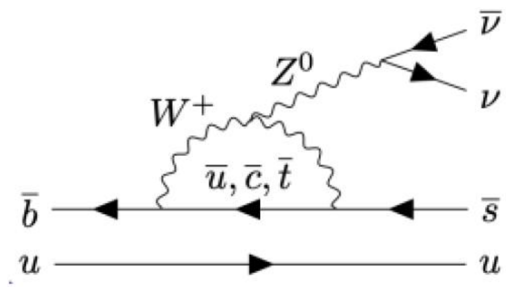


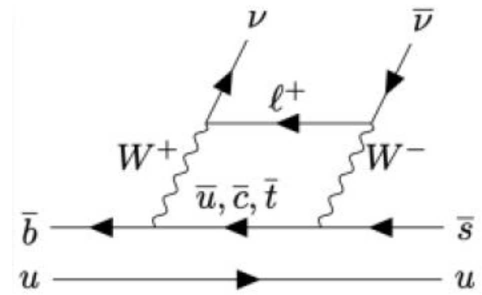
$B^+ \to K^+\nu\bar{\nu}$

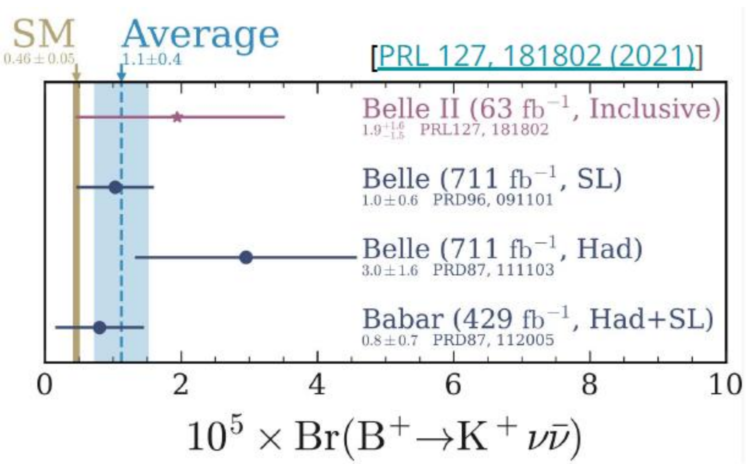
- Two neutrinos in the final states.
  - ✓ Unique to $e^+e^-$ collider.
- FCNC process: EW penguin, sensitive to the New Physics.
- B.F. precisely predicted in the SM.
  - ✓ Uncertainty dominated by hadronic form factors.

$B(B^+ \to K^+\nu\bar{\nu}) = (0.56 \pm 0.04) \times 10^{-5}$ [PRD 107, 014511 (2023)]

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



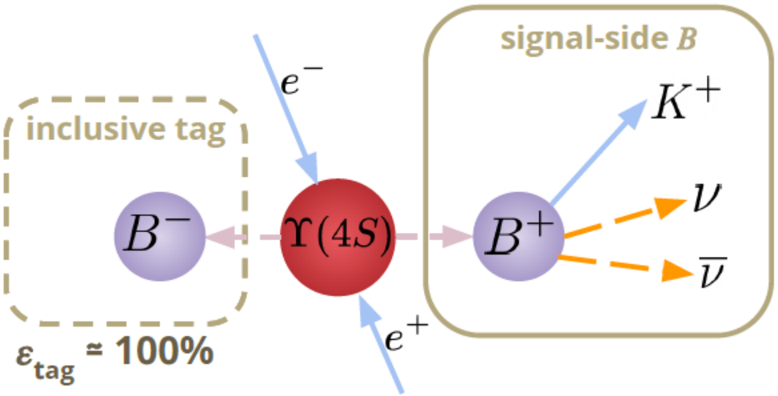



# $B^+ \to K^+\nu\nu$

New analysis by Belle II with Run1 data (362 $fb^{-1}$)

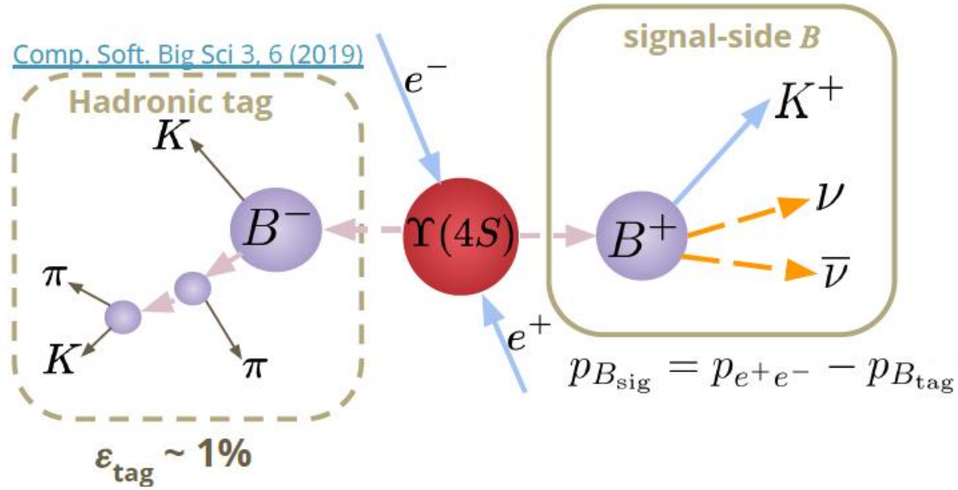
[PRD 109, 112006 (2024)]

## 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.

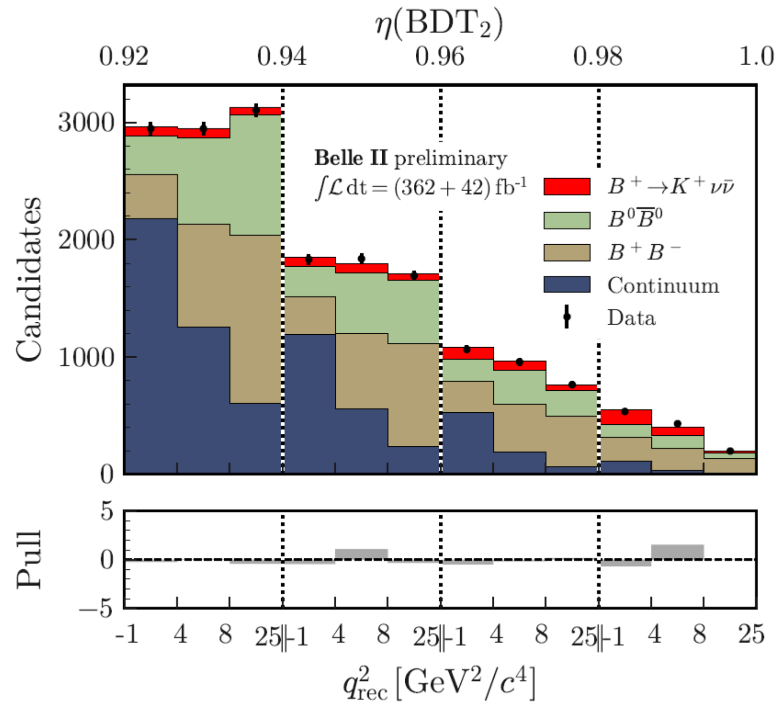
## Hadronic Tag Analysis (HTA)



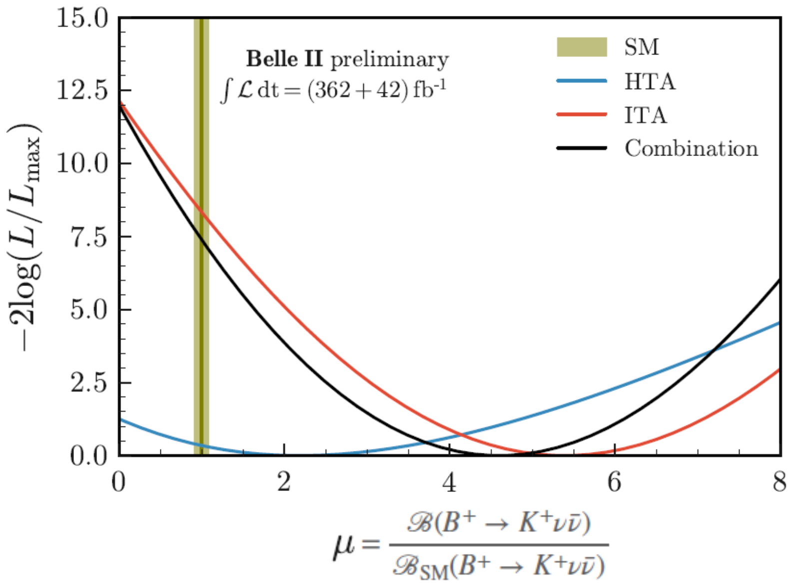

- Conventional method.
- Reconstruct the tag side B with hadronic mode.
- Lower b.g. → validation of ITA.

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

- Two BDTs to suppress background (ITA).
- Control sample $B^+ \to J/\psi\ K^+$ (removing $J/\psi$).
- 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%).



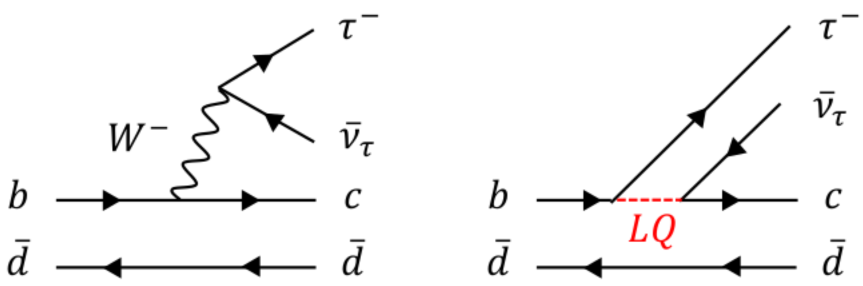

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = [2.4 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})] \times 10^{-5}$$

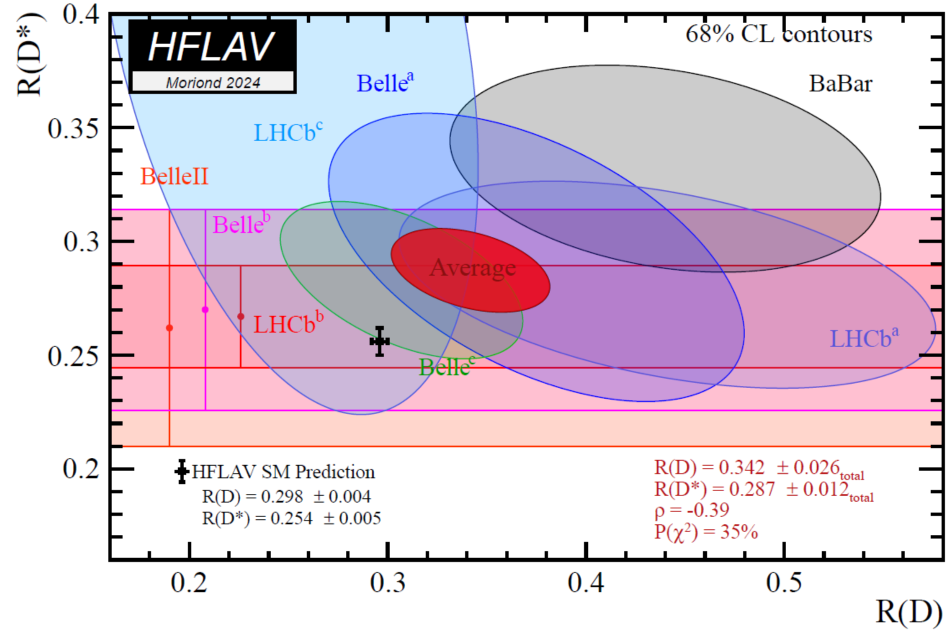
- First evidence of the signal ($3.5\sigma$)
- $2.7\sigma$ deviation from the SM prediction.

# B → D$^{(*)}$l$^{+}$ν での LFU

## Lepton Flavor Universality (LFU)

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




- Lepton Flavor Universality: SM interaction does not depend on lepton species.
  - ✓ SM prediction taking into account the effect of mass difference
- Experimental result is now 3.3σ away from SM prediction!
- Effect of NP particles (leptoquark, charged Higgs)?
- Measurements by Belle II are awaited
  - ✓ First R(D*) result with semileptonic tag in 2023 using 189 fb$^{-1}$ data.

[arXiv:2401.02840]

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

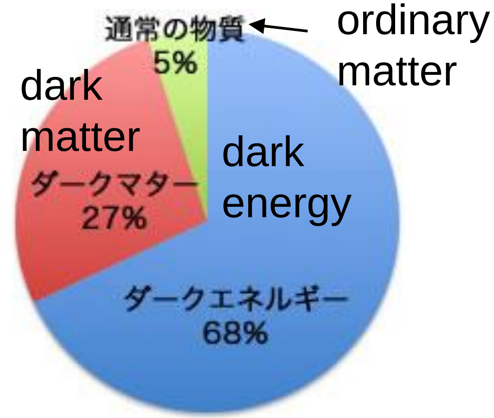
comparable stat. precision as Belle

dominant by PDF shapes, MC sample size

# Dark Matter

Dark matter cannot be explained in the SM.

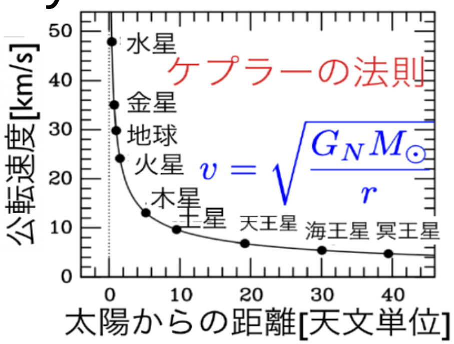
- Dark matter is an unknown matter that exists in the Universe.
- 5 times more than the ordinary matter.
- It's not an SM particle, but its nature is unknown.

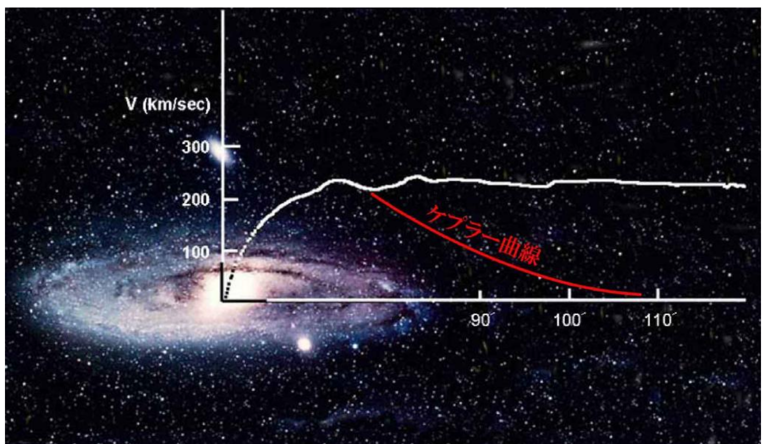



Rotational curve of spiral galaxies

- Outer stars rotate faster than the expectation of Kepler's law

Planet in solar system



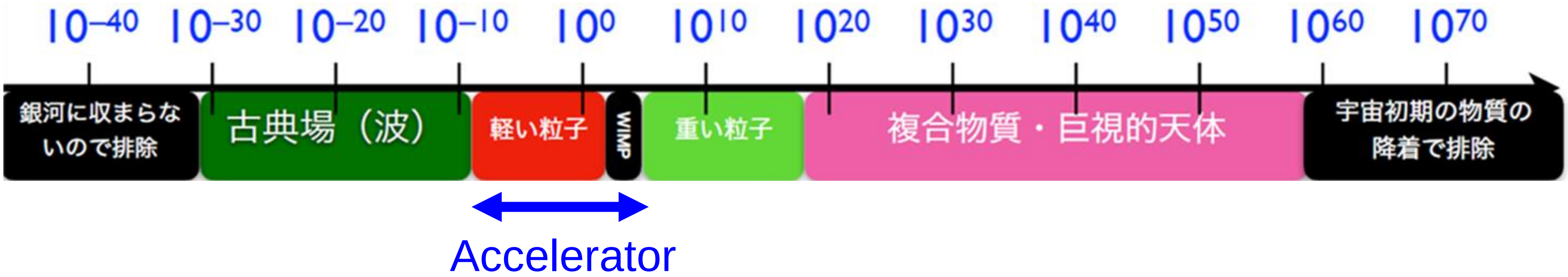

M31（アンドロメダ星雲）の写真に回転速度曲線を重複 (M.Roberts)

Collision of cluster of galaxies.

- Red: ordinary matter (stopping due to the friction)
- Blue: dark matter

# Dark Matter

Dark Matter Mass (GeV)

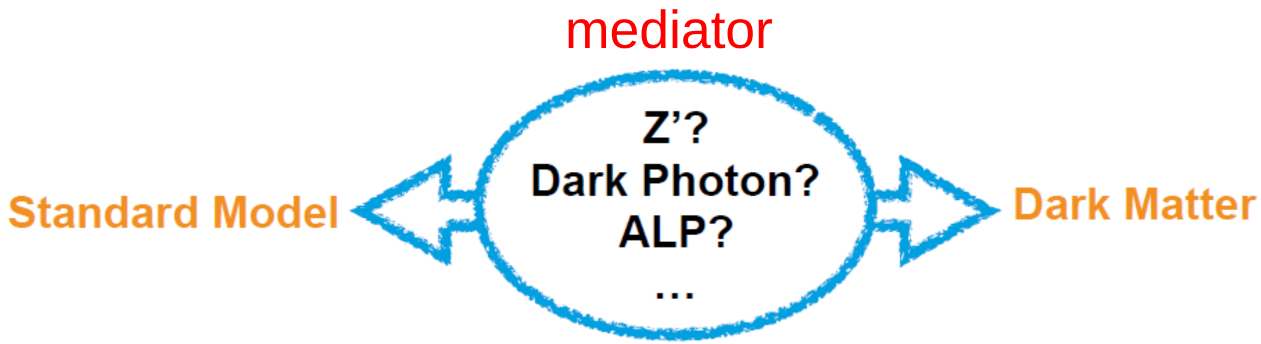



- WIMP (Weak Interacting Massive Particle) was considered to be promising.
  - ✓ Massive particle (~ O(10-1000) GeV) interacting with a force with similar strength as “Weak Force” in the SM.
  - ✓ New Physics (NP) is expected around this mass scale in relation with hierarchy problem.
  - ✓ LHC or other detection experiments find no signal so far.
- Recently, various searches have been performed by various experiments.

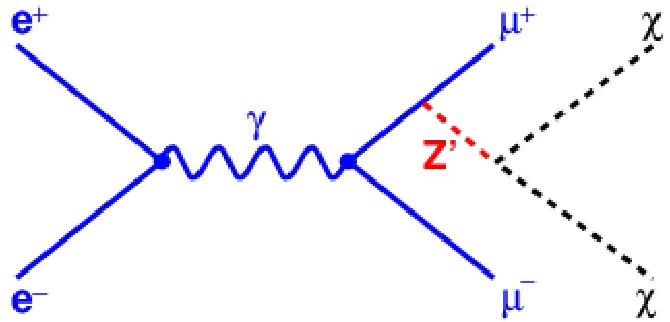
# Dark Matter at Belle II

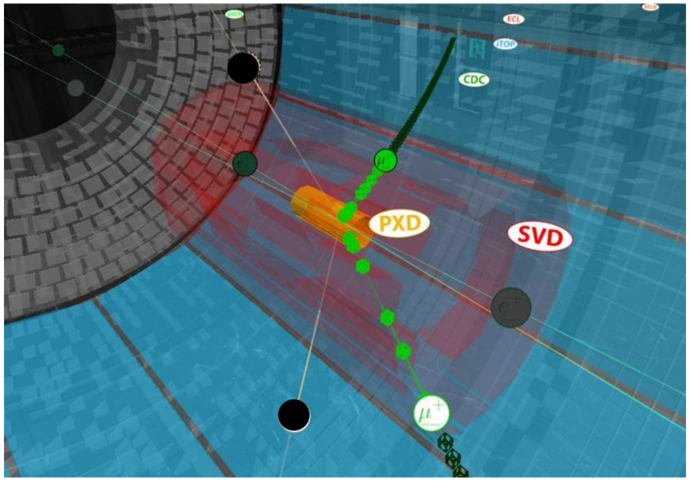


- Search for Dark Matter (DM) at Belle, Belle II.
  - ✓ CM energy is ~10 GeV → mass region up to O(1) GeV ("light DM")




- Typical process
  - ✓ $e^+ + e^- \to$ SM-particles + Mediator
  - ✓ B (or other hadron) → SM-particles + Mediator

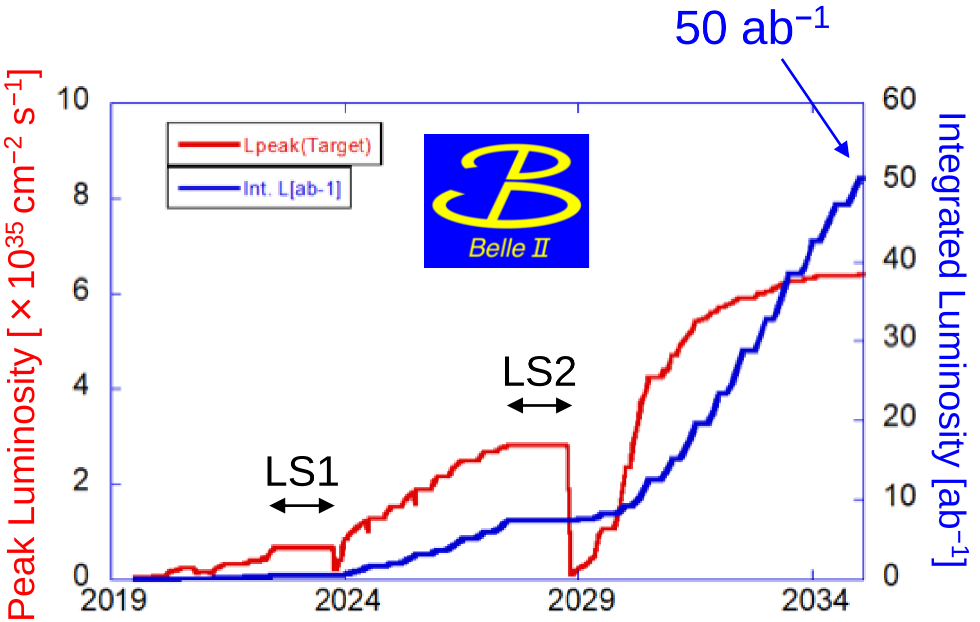


# Belle II Plan

## Near term (physics)

- More results with Run1 data in 2024; with Run1+Run2 data in 2025
  - ✓ R(D), R(D*)
  - ✓ $B \to \mu\nu$
  - ✓ $B \to K\nu\nu$
  - ✓ …
- World leading results even with smaller or similar data set compared to Belle.

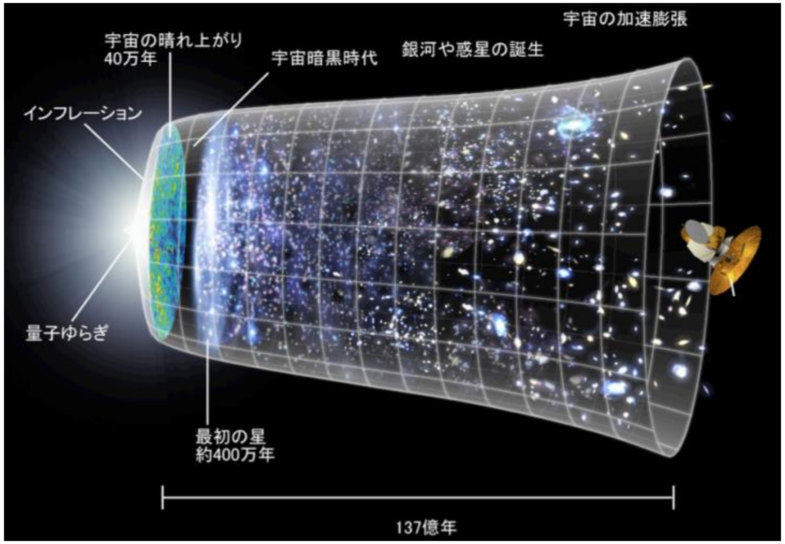



## Toward long term

- Increase the luminosity and accumulate the data.
  - ✓ Exceed Belle dataset.
- Plan for upgrade (LS2) to be decided.
- WIth 50 ab$^{-1}$, sensitivity is expected to be $\Delta R(D^*) \sim 0.5\%$, $\Delta B(K^*\nu\nu) \sim 9\%$, $B(\tau \to \mu\mu\mu) < 0.36 \times 10^{-9}$

# Backup

# CP Violation




- When the Universe was created by the Big Bang, the number of matters and anti-matters are the same.
- However, only matters exist in the present Universe.

There exist some difference between matters and anti-matters (CP violation)

CP violation ~ difference between matters and anti-matters

C : Charge conjugation
P : Parity
T : Time

C,P,T are basic symmetry

- Discovery of parity violation (1957; C.S.Wu)
- CP remained considered to be conserved …
- Discovery of CP violation in K mesons (1964; Cronin, Fitch)

# CP Violation and KM theory

- CP violation: a key for the matter-antimatter asymmetry.
- Kobayashi-Maskawa theory (1973)
  - ✓ CP violation in the Standard Model (SM)
  - ✓ Complex phase in the quark mixing matrix

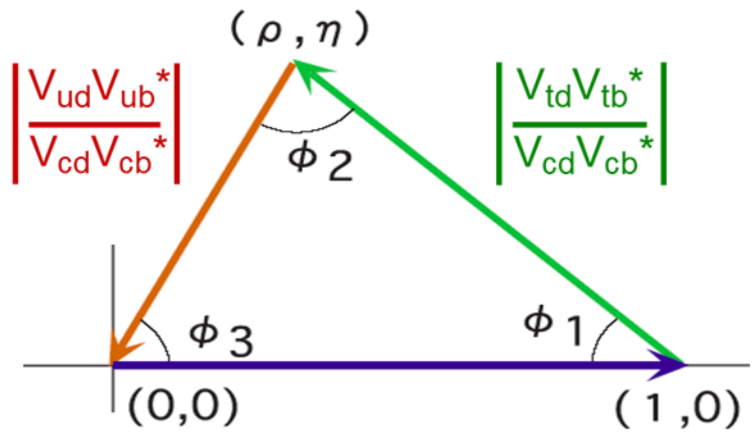
CKM (Cabibbo-Kobayashi-Maskawa) Matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

From the unitarity of the matrix:

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

- Triangles in the complex plane.
- Other triangles exist.




$\phi_1 = \beta$
$\phi_2 = \alpha$
$\phi_3 = \gamma$