

Belle II Experiment

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KEK, Sokendai

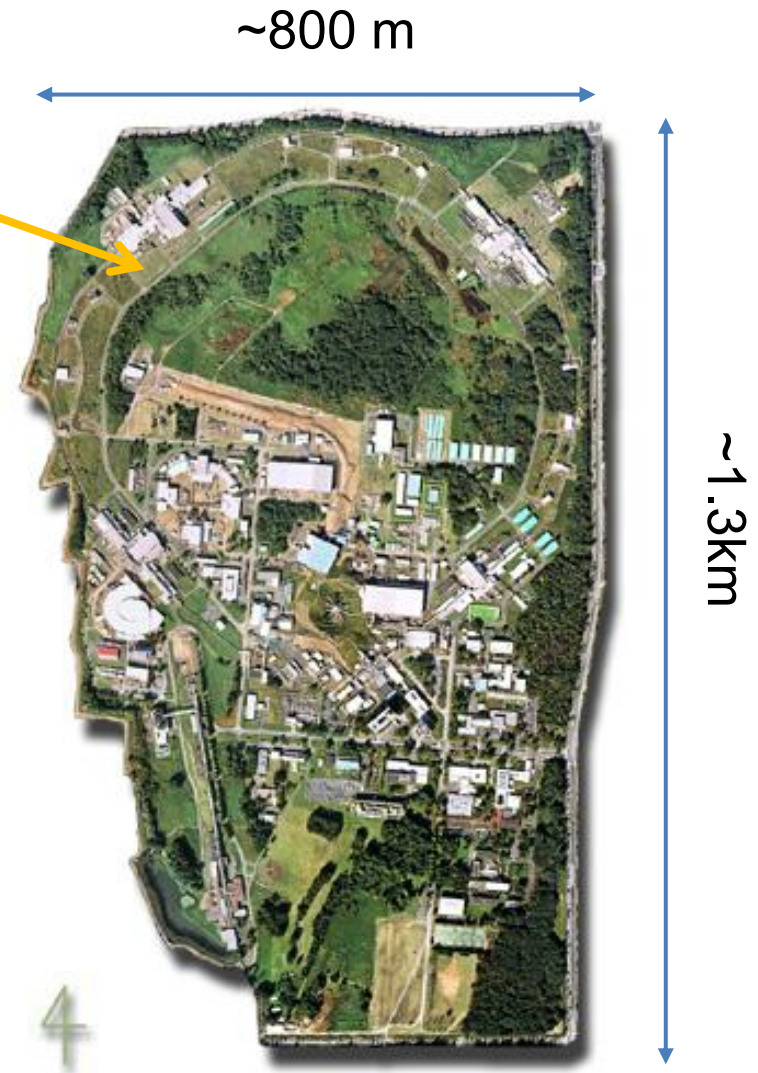
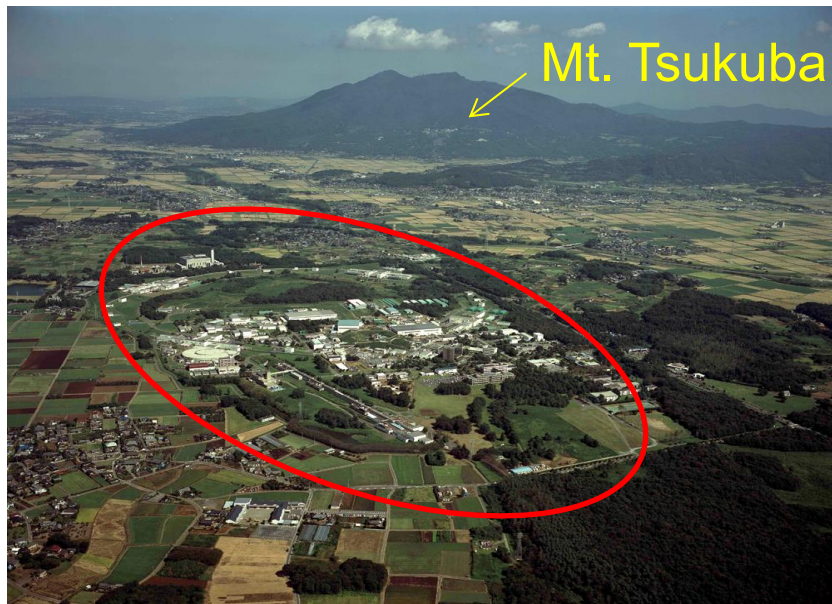
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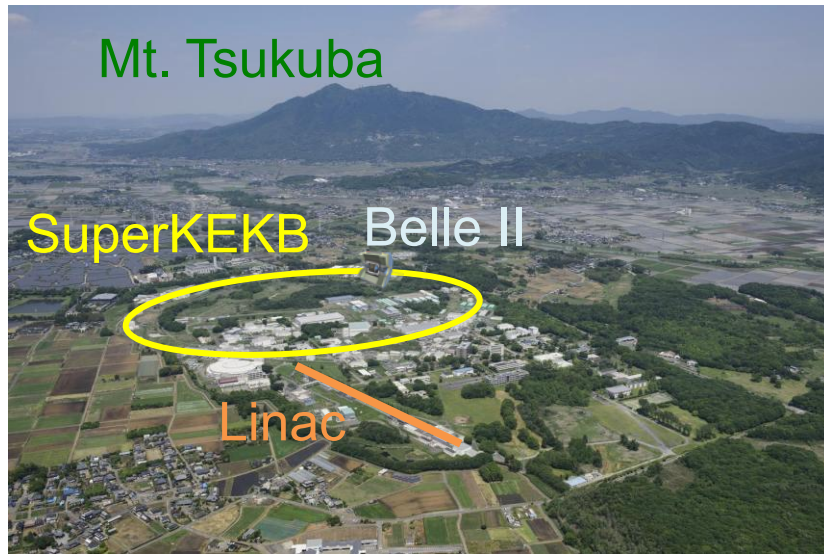
Jul. 22, 2026

KEK Tsukuba Campus

electron positron collider (3km)

- TRISTAN (1986-1995)
 - ✓ Highest energy at that time
- KEKB (1999-2010)
 - ✓ B factory experiment
- SuperKEKB (2018-)

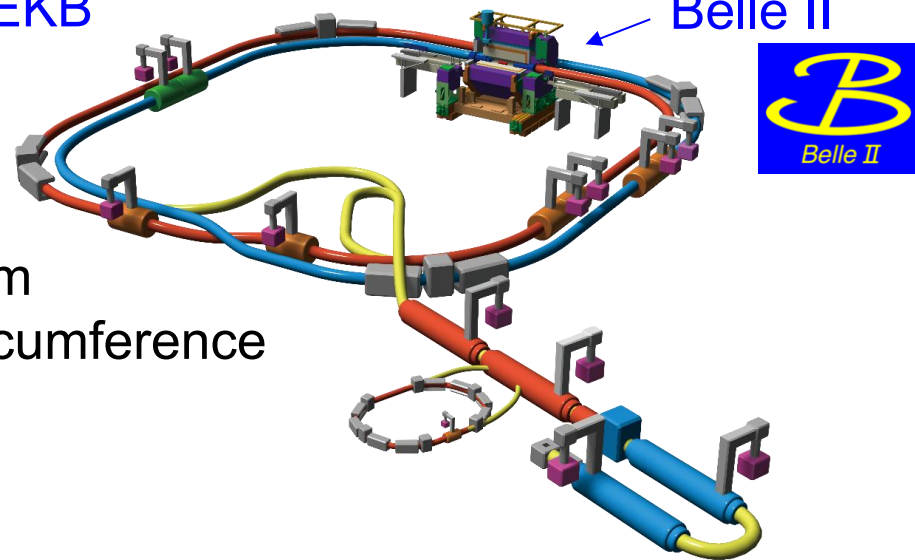




SuperKEKB

Belle II

3km
circumference



SuperKEKB accelerator and Belle II experiment

- High energy accelerator research organization (KEK) @ Tba
- 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.



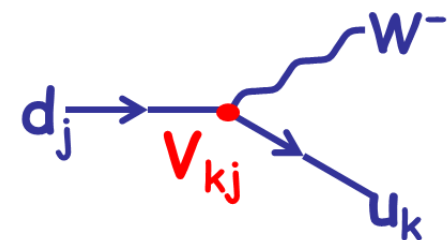
- CP violation: a key for the matter-antimatter asymmetry.
- Kobayashi-Maskawa theory (1973)
 - ✓ CP violation in the Standard Model (SM)
 - ✓ Complex phase in the quark mixing matrix
→ source of CP violation in weak interaction.
 - ✓ requires 3 (or more) generation of quarks



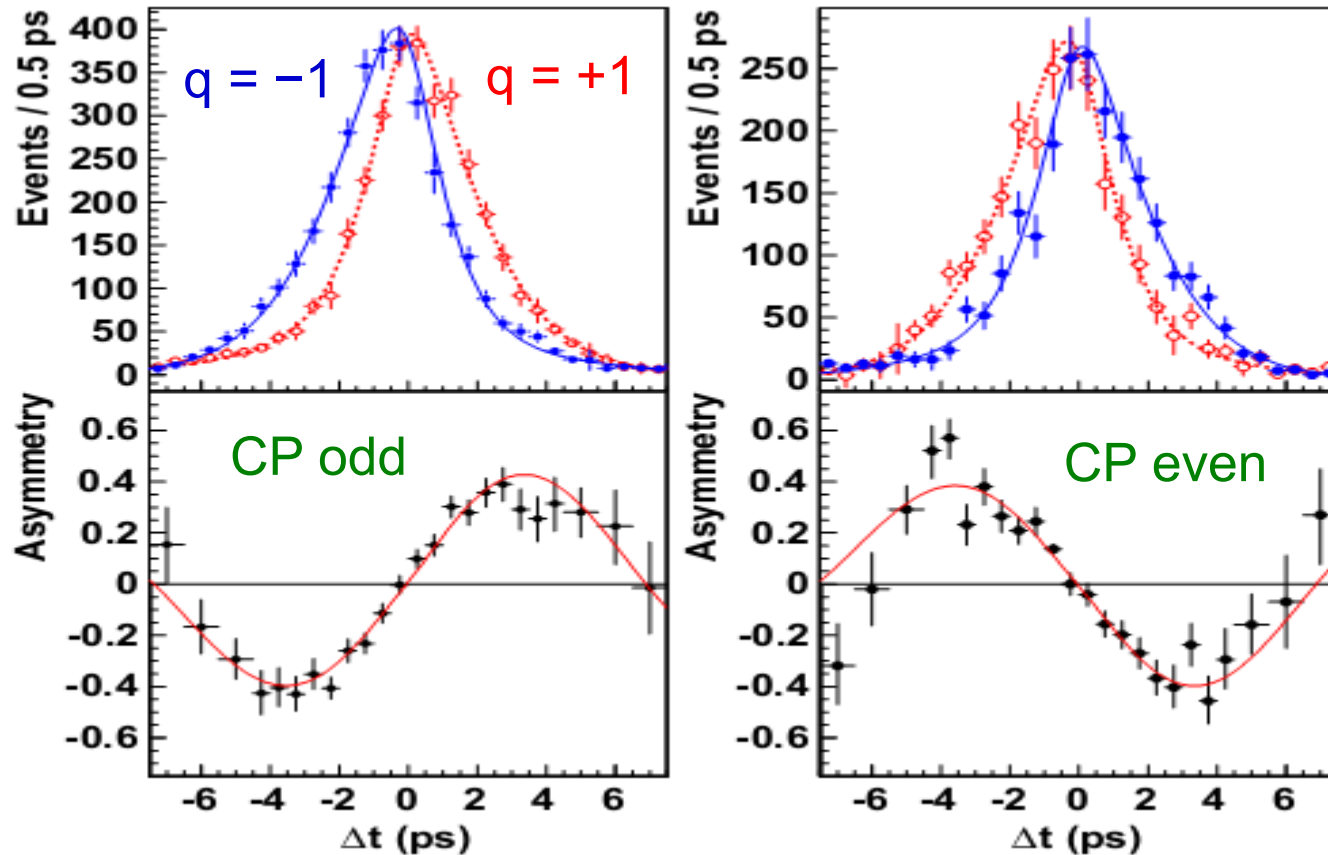
CKM (Cabibbo-Kobayashi-Maskawa) Matrix

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

- 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)



Mixing-induced CP asymmetry of B mesons

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

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

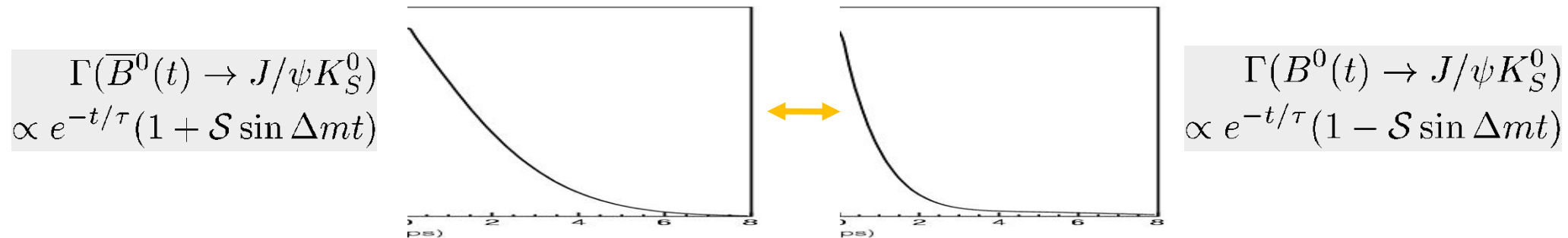
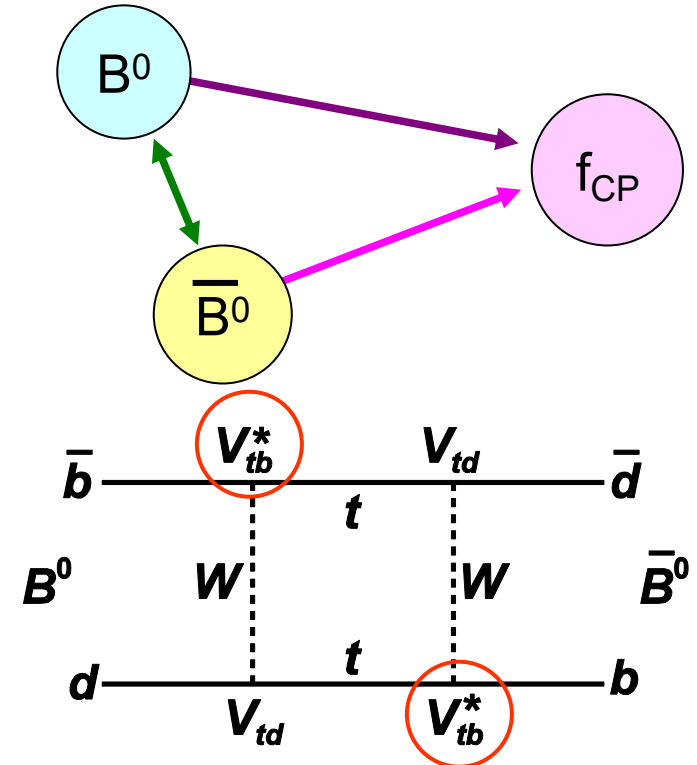
$$= S \sin(\Delta m \Delta t) - C \cos(\Delta m \Delta t)$$

S : mixing induced CPV

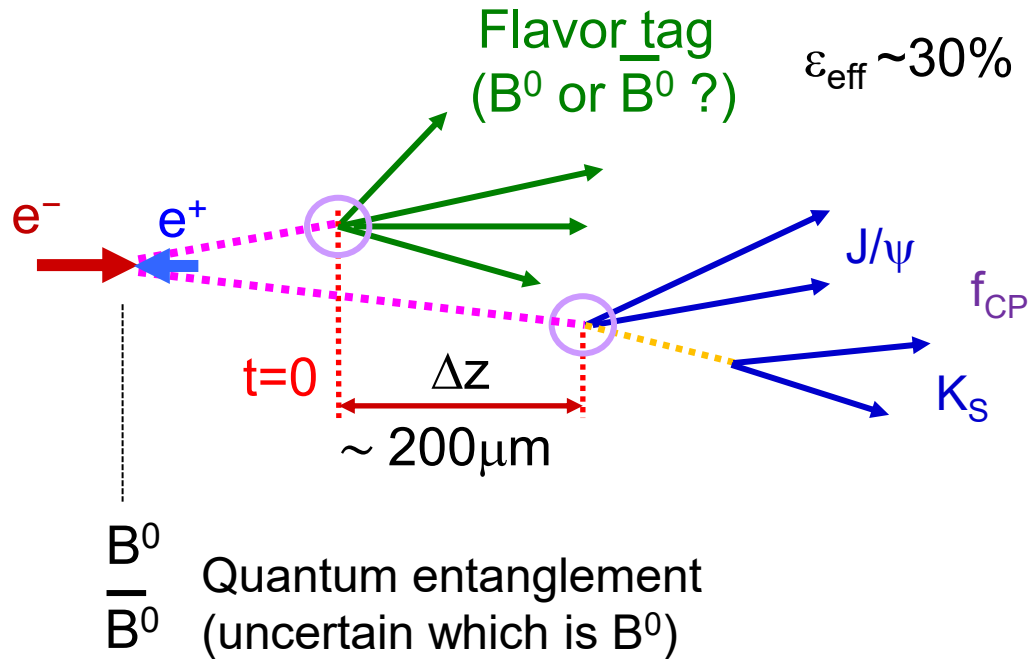
C : direct CPV ($= -A$)

$$S = -\xi \sin(2\phi_1) \text{ for } B \rightarrow J/\psi K_S$$

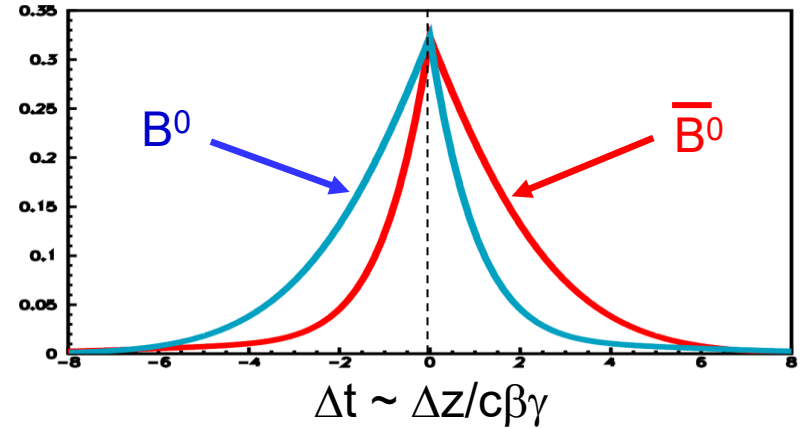
$$\phi_1 = \beta$$



“Lorentz-boost”

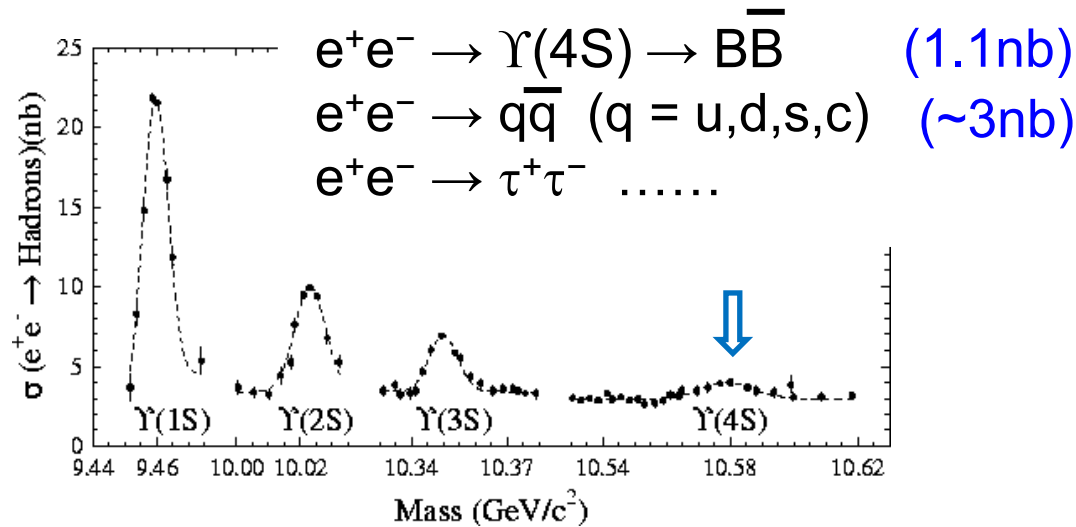


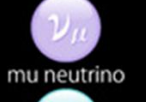
Measure position instead of time



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

- Asymmetric beam energy



Fermions			
	I	II	III
Quarks	 u up	 c charm	 t top
	 d down	 s strange	 b bottom
Leptons	 ν_e electron neutrino	 ν_μ mu neutrino	 ν_τ tau neutrino
	 e electron	 μ muon	 τ 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.

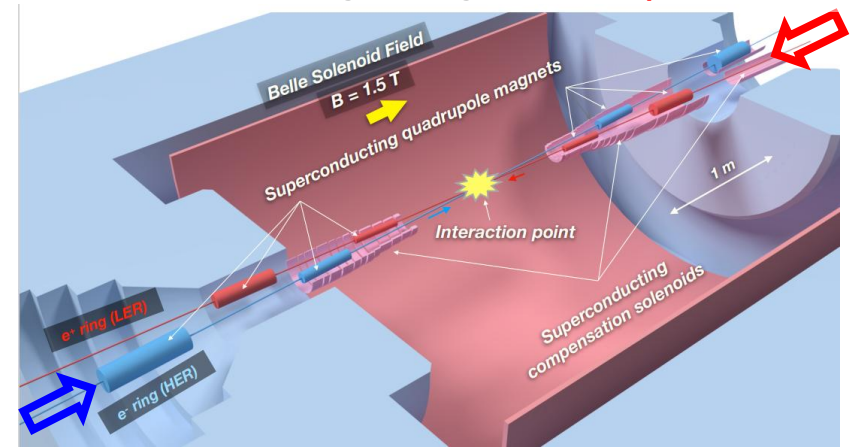
To improve luminosity

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

Beam current

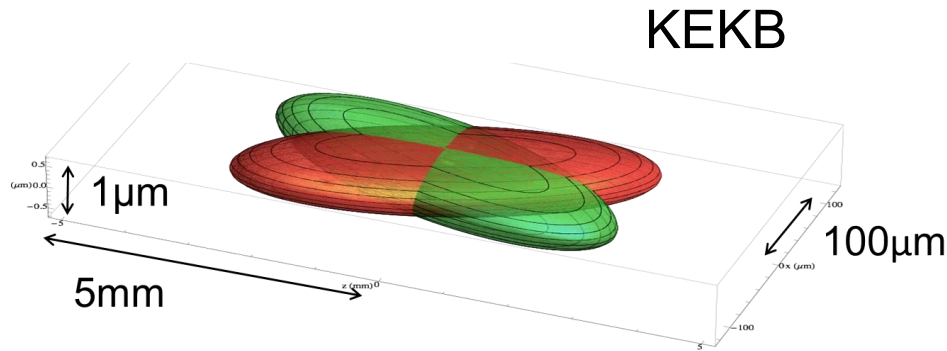
Beam size at the interaction point

Final focusing magnet



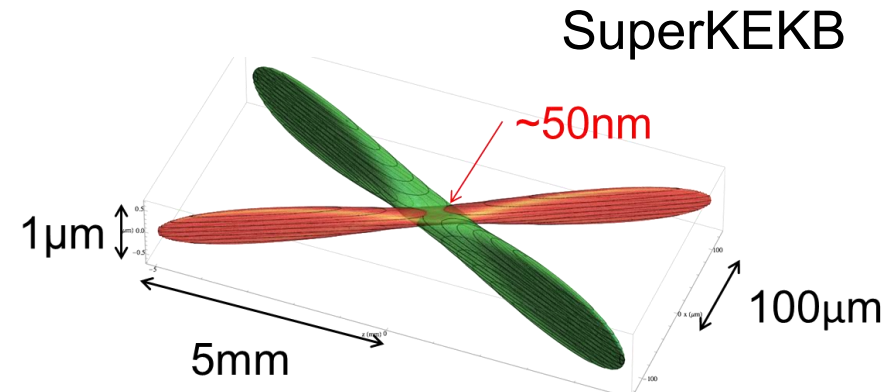
electron beam

Nano beam



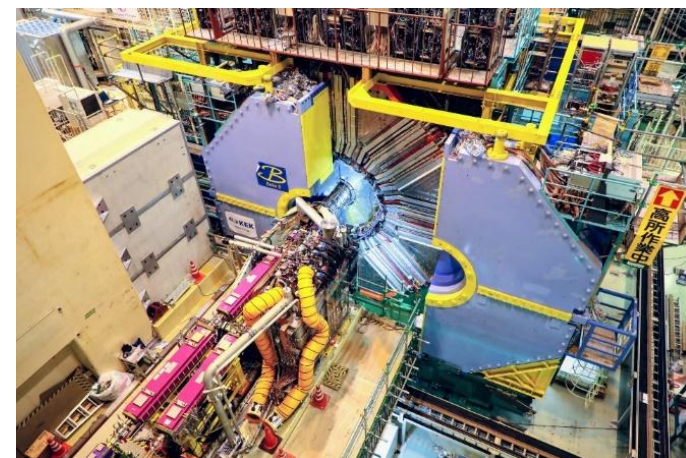
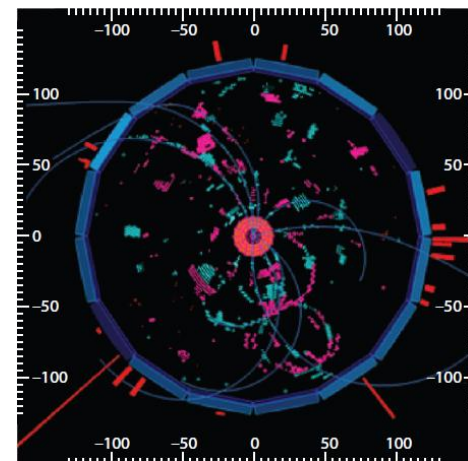
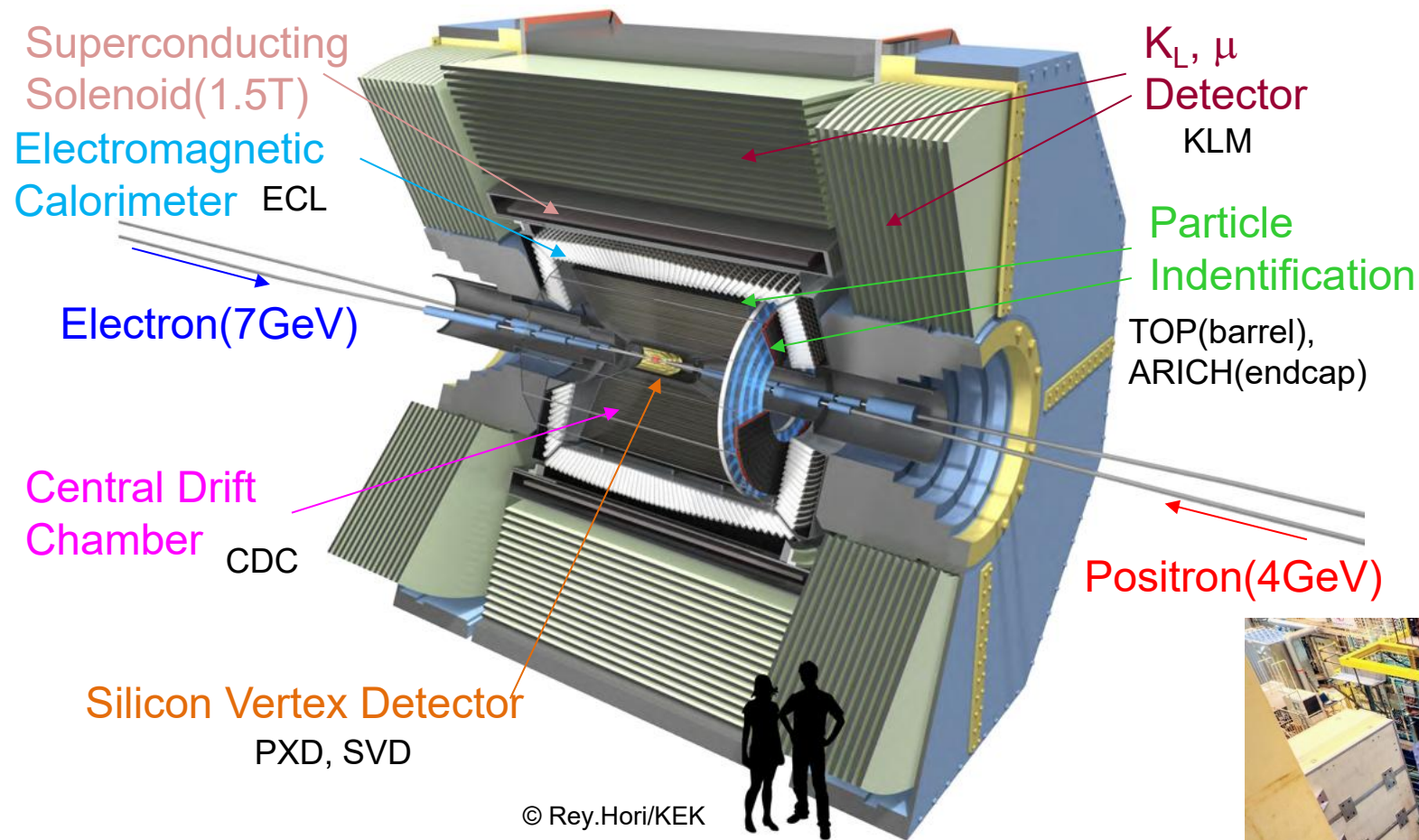
KEKB

Crossing angle 22 mrad



SuperKEKB

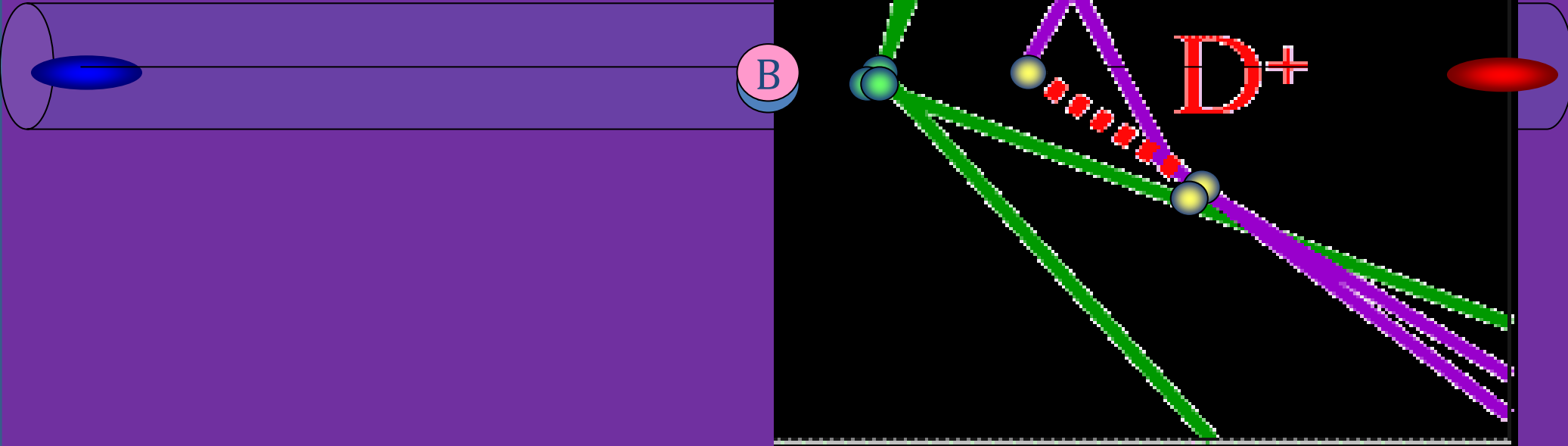
Crossing angle 83 mrad



Belle II Detector (8m×8m×8m, 1400t)

Slow Motion

Electron

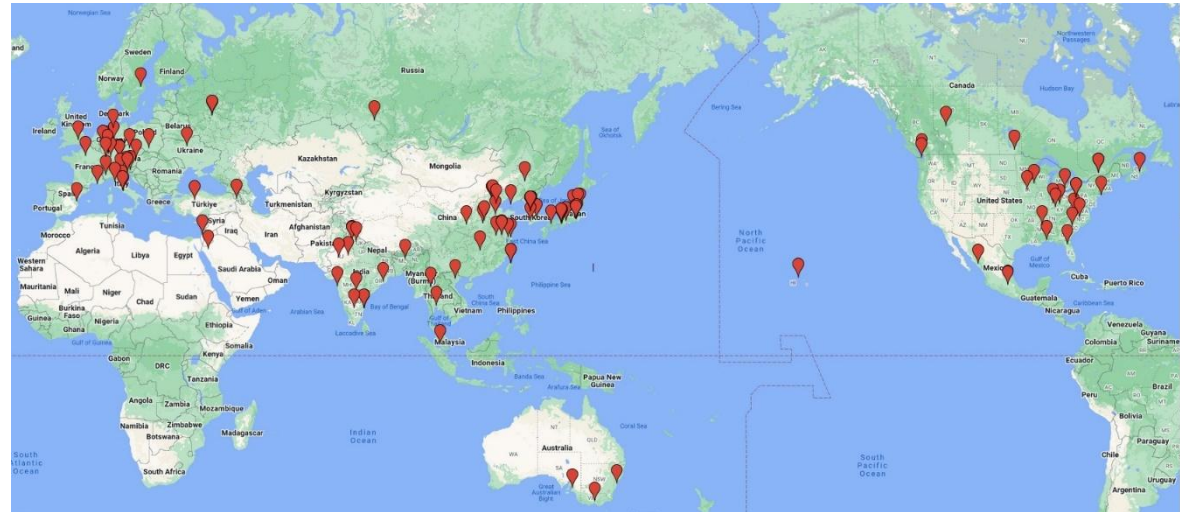


Belle II Collaboration

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

(@Jul. 2026)

International collaboration



Luminosity [$\text{cm}^{-2} \text{s}^{-1}$]

Number of collision event $N [\text{s}^{-1}]$

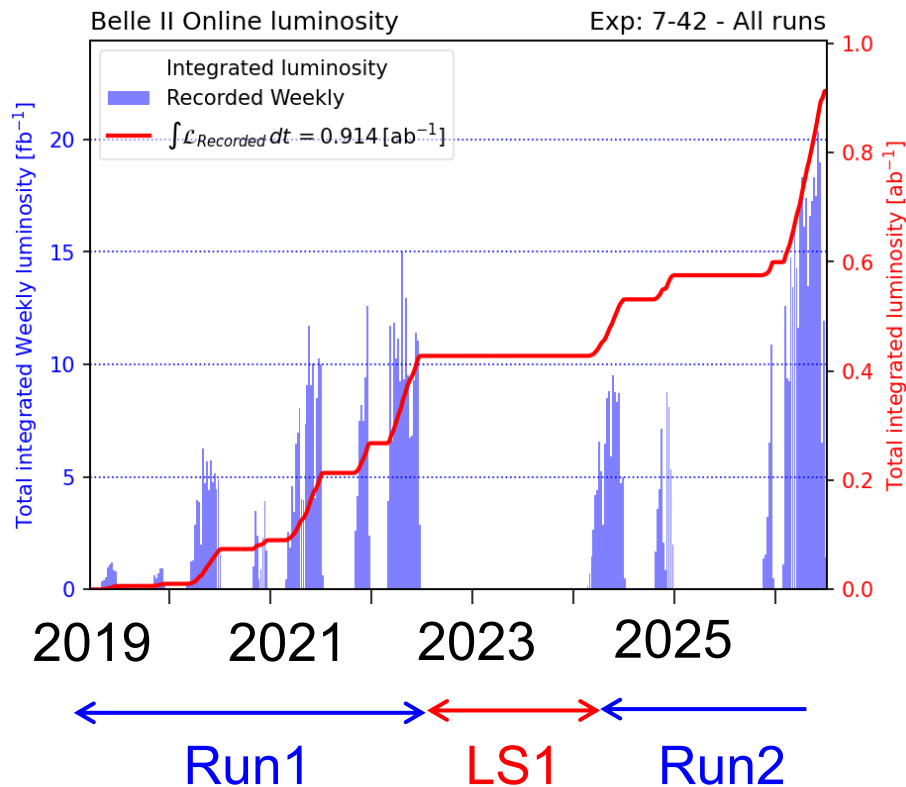
Cross section $\sigma [\text{cm}^2]$

$$N = L \sigma \quad (L: \text{luminosity})$$



$$1 \text{ ab}^{-1} = 1000 \text{ fb}^{-1}$$

- SuperKEKB: highest luminosity
 - ✓ $5.3 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ @2026/5/30
 - ✓ Target: 10 times larger
- Accumulated $\sim 914 \text{ fb}^{-1}$ of data
 - ✓ Belle $\sim 1000 \text{ fb}^{-1} = 1 \text{ ab}^{-1}$ in 11 years
 - ✓ Belle II now have largest $\Upsilon(4S)$ dataset.
 - ✓ Belle II target: 50 ab^{-1}

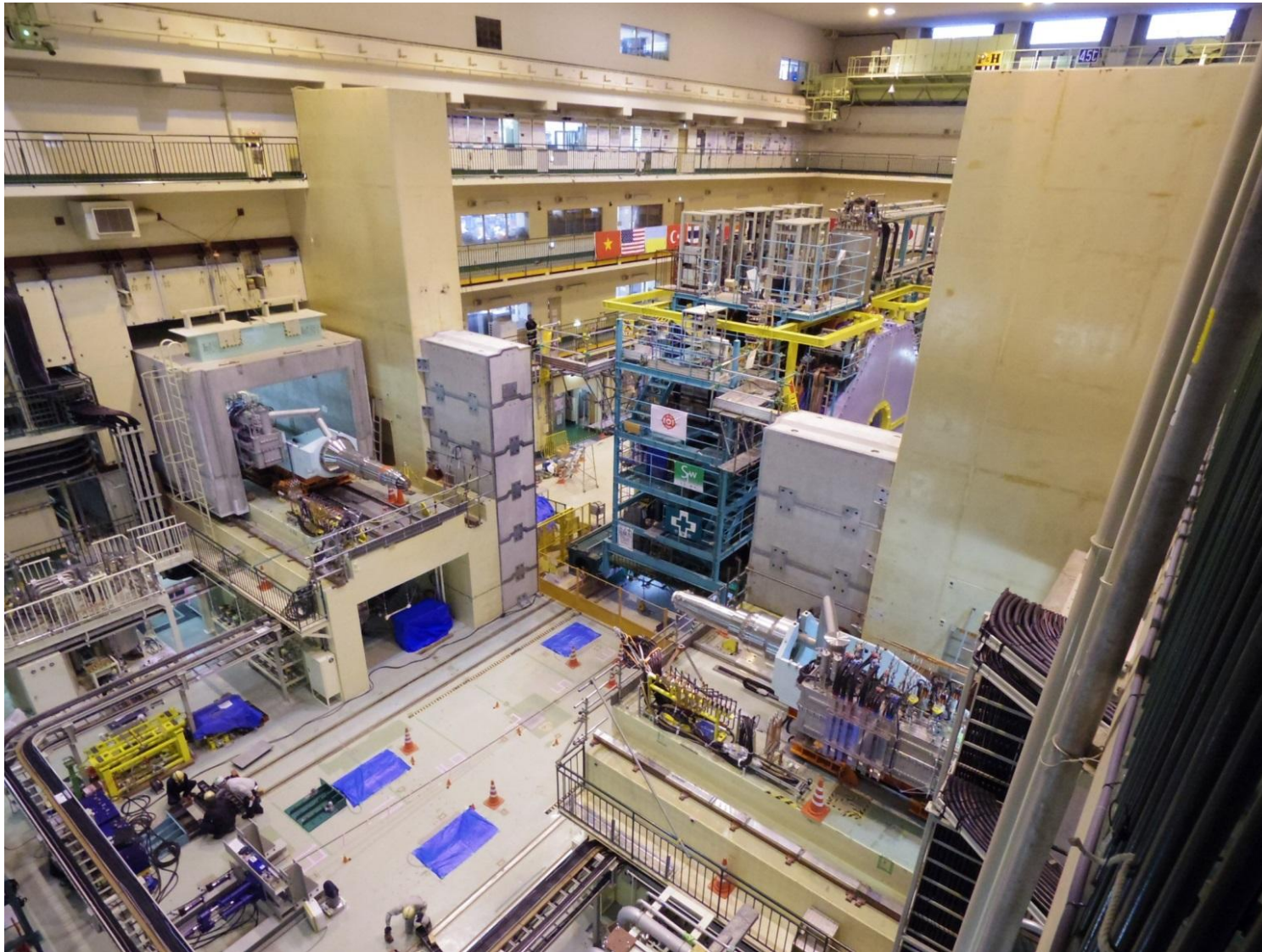


2019/02-2022/06: Run 1

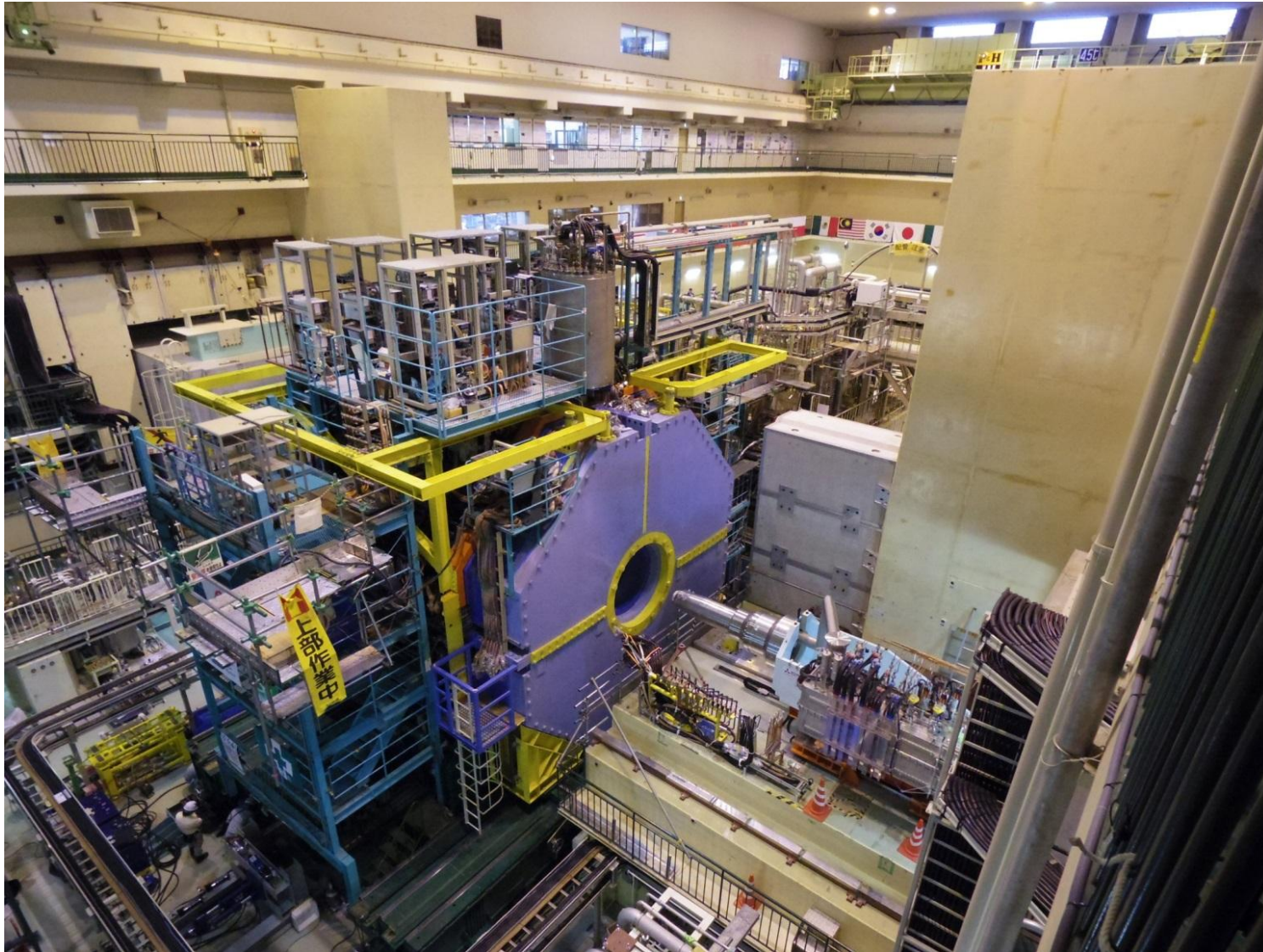
2022/07-2023/12: Long Shutdown 1

2024/01-: Run 2

- 2026 run just finished.
- Next run: 2027 Jan.-



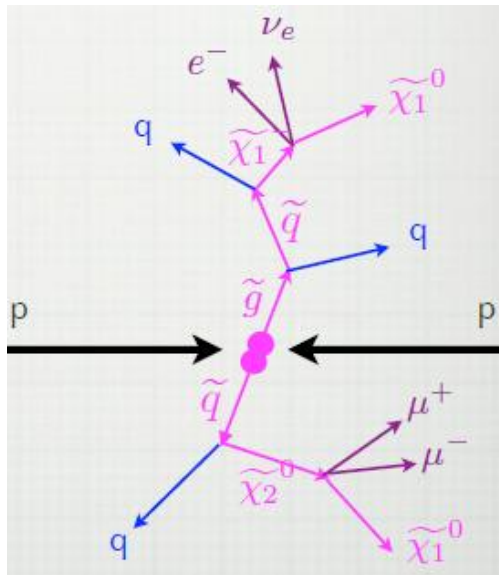
April 11,
2017



April 11,
2017

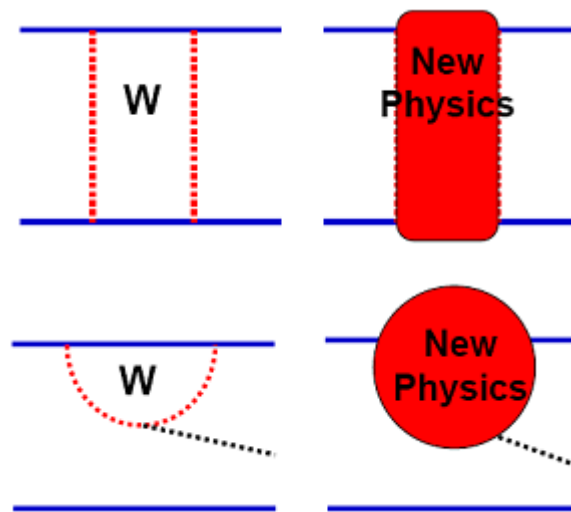
Direct Search

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



Indirect Search

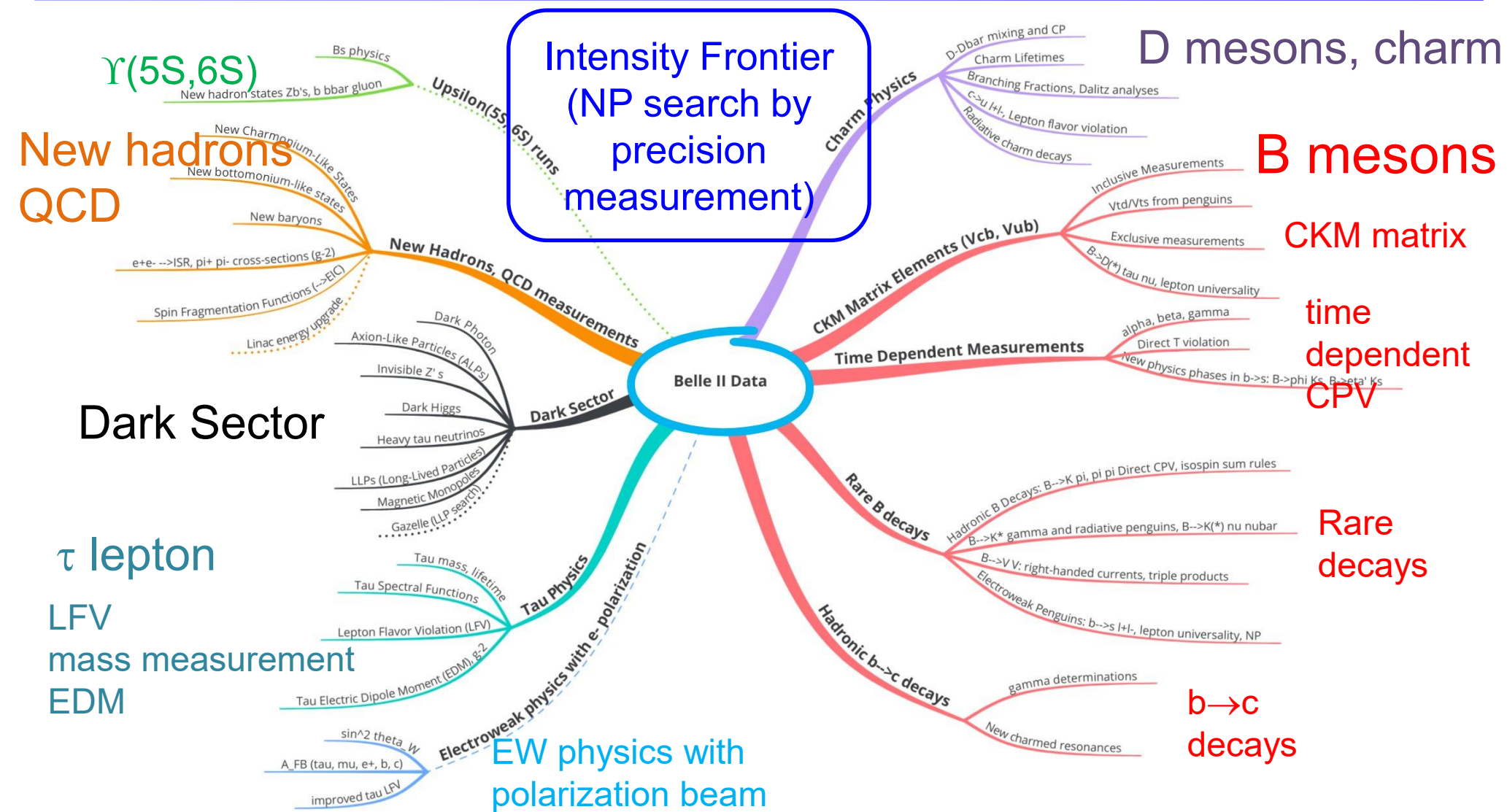
- Study decays of the SM particles.
- Decay through loop diagrams : New Physics particles can virtually contribute to the decays.
- Branching fraction, CP asymmetry can be changed from the SM expectation.
- OK with $E_{\text{CM}} < M_{\text{NP}}$. But require huge amount of SM particle decays.



box diagram

penguin diagram



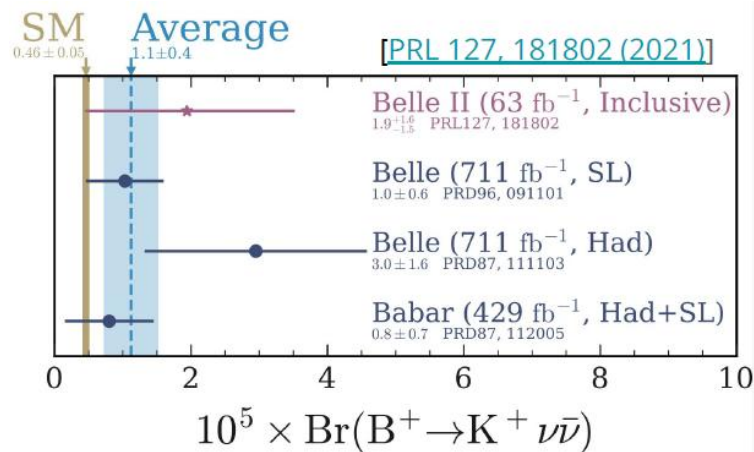
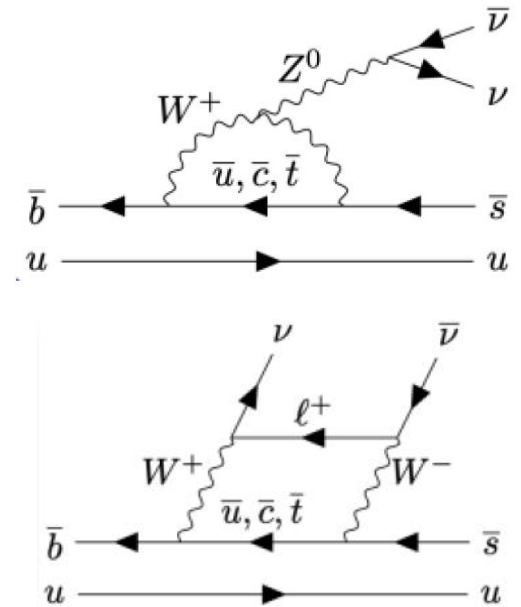


$$B^+ \rightarrow K^+ \nu \bar{\nu}$$

- 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.

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

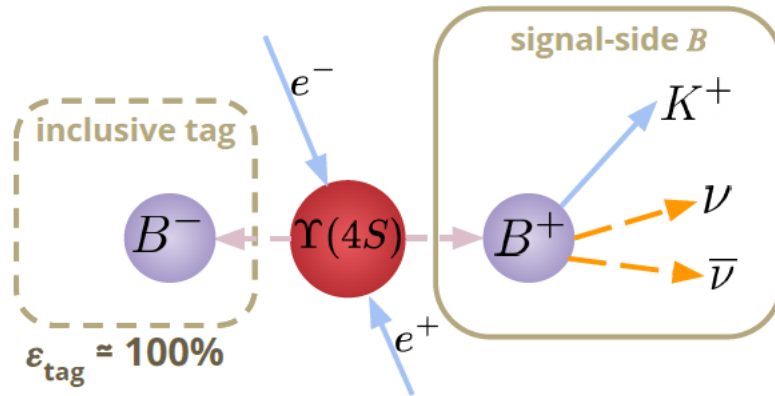
including long-distance effect of $B^+ \rightarrow \tau^+ (K^+ \bar{\nu}) \nu$



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

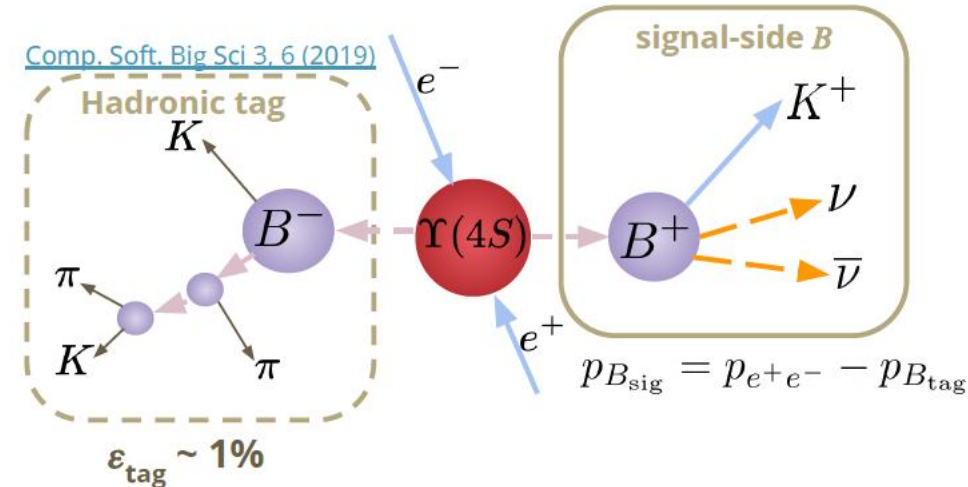
[PRD 109, 112006 (2024)]

Inclusive Tag Analysis (ITA)



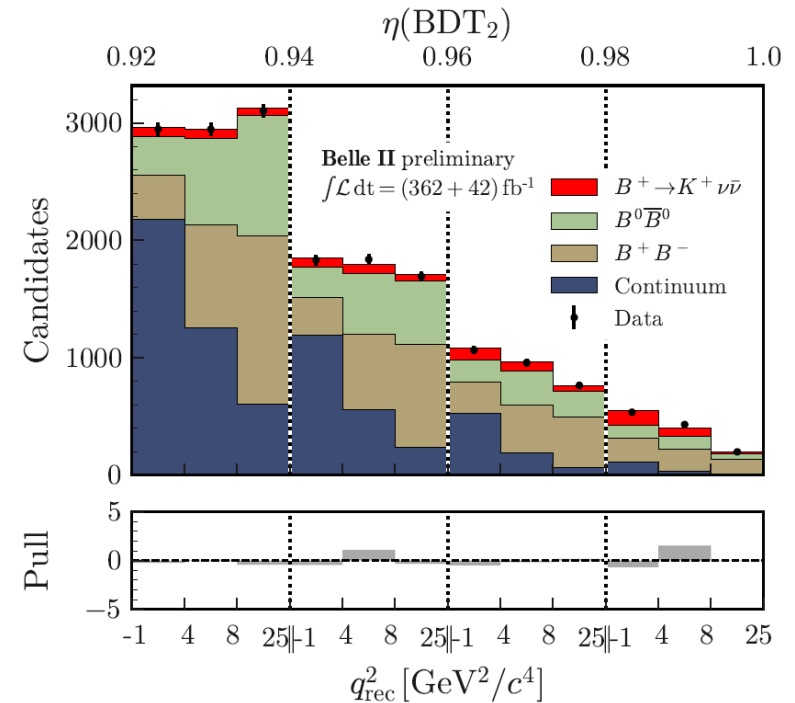
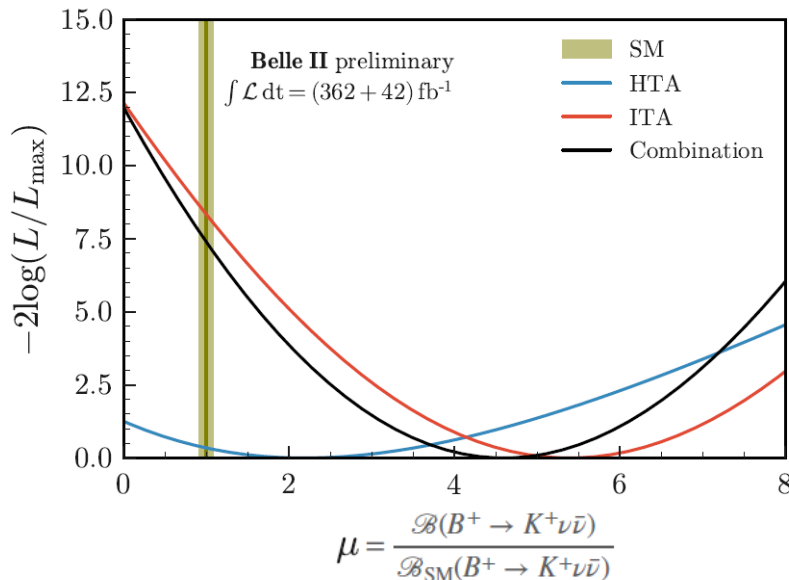
- Newly developed at Belle II
 - ✓ Used in the search with 63 fb^{-1} .
- Reconstruct signal B (pick up K^+) only, exploit the rest of the event (ROE) to suppress backgrounds.
- More sensitive than HTA.

Hadronic Tag Analysis (HTA)



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

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



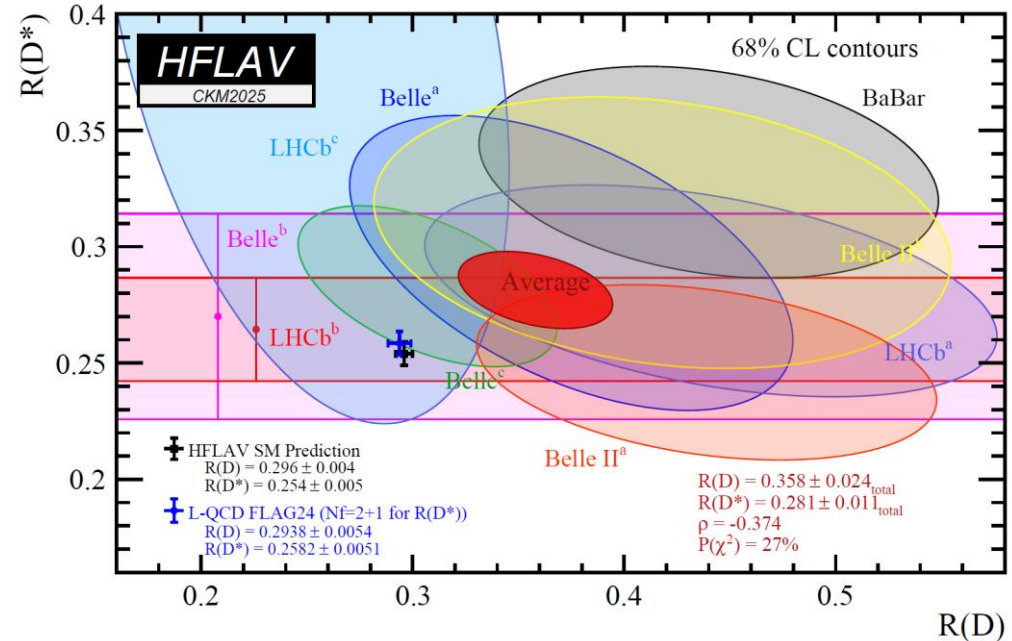
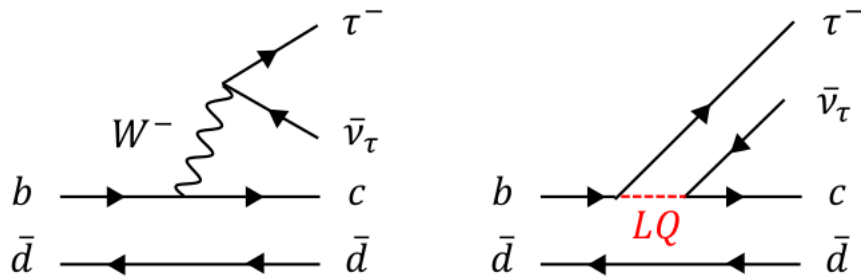
$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) = [2.4 \pm 0.5(\text{stat})_{-0.4}^{+0.5}(\text{syst})] \times 10^{-5}$$

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

Lepton Flavor Universality (LFU)

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)}{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu)}$$

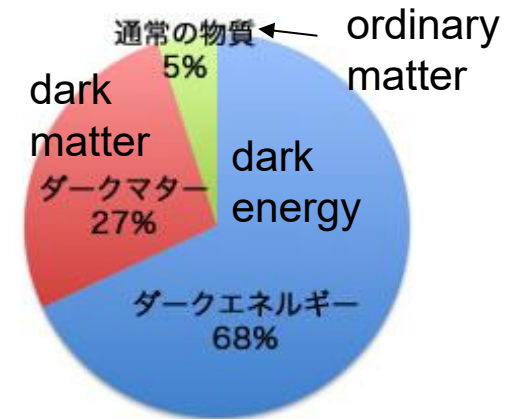
($\ell = e$ or μ)



- Lepton Flavor Universality: Interaction at the SM does not depend on the species of charged leptons.
 - ✓ Branching fractions differ due to phase space or helicity suppression.
 - ✓ SM prediction: $R(D^{(*)}) = 0.30$ (0.25)
- **3.8 σ deviation between the measurement and the theory prediction.**
- Contribution from BSM particles (lepto-quark, charged Higgs)
- Recently, Belle II presented a new measurement. More results will be coming.

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.

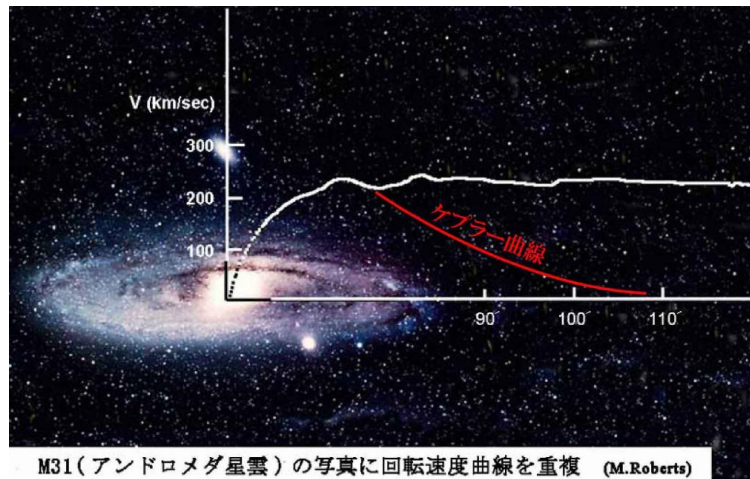
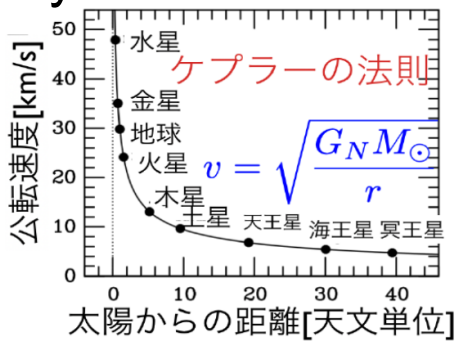


Rotational curve of spiral galaxies

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



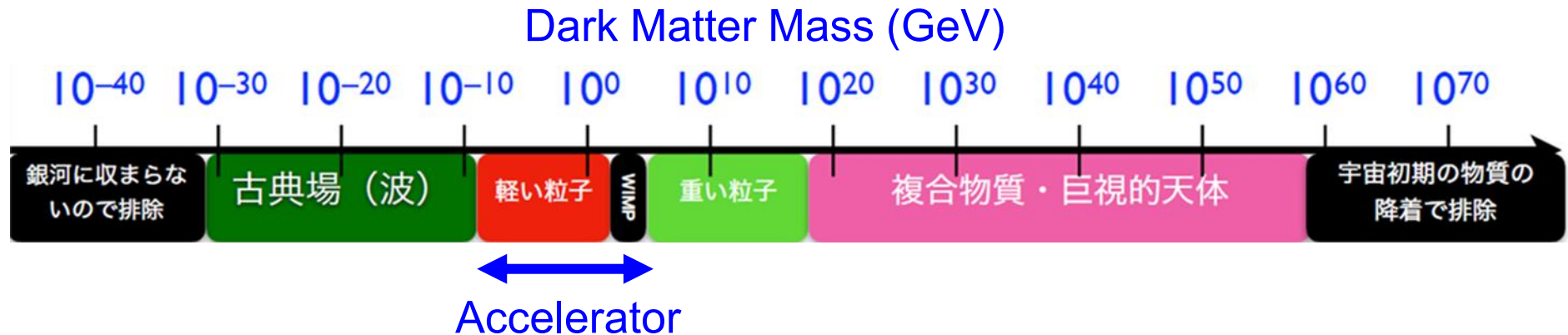
Planet in solar system



Collision of cluster of galaxies.

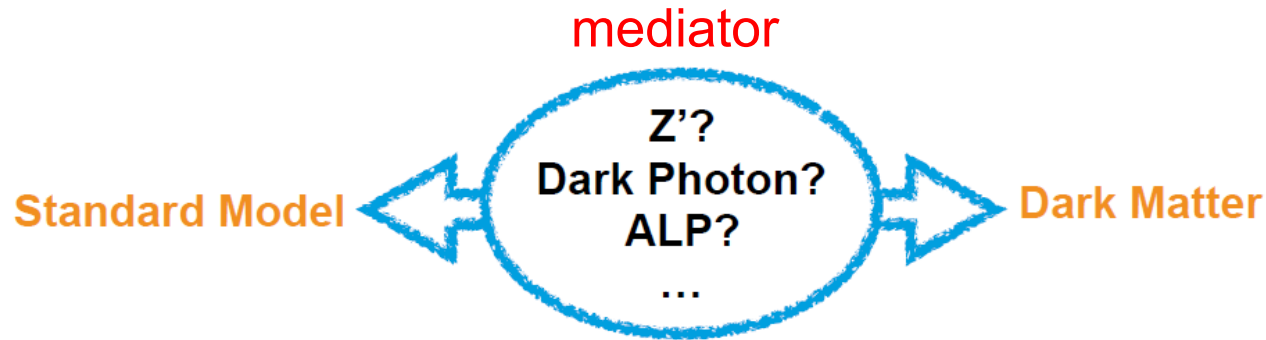


- Red: ordinary matter (stopping due to the friction)
- Blue: dark matter

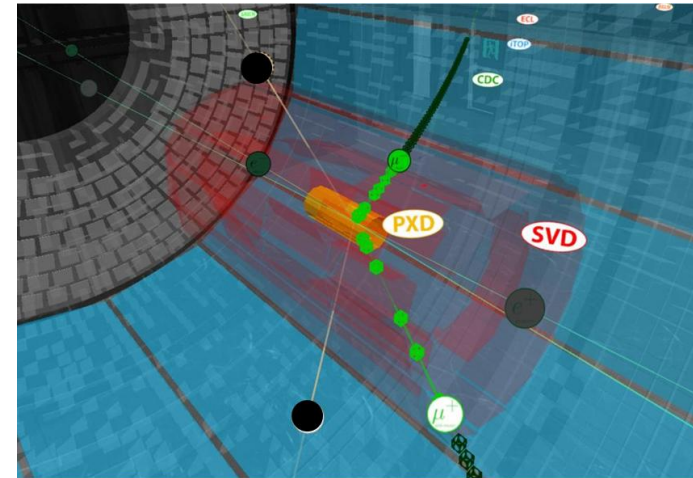
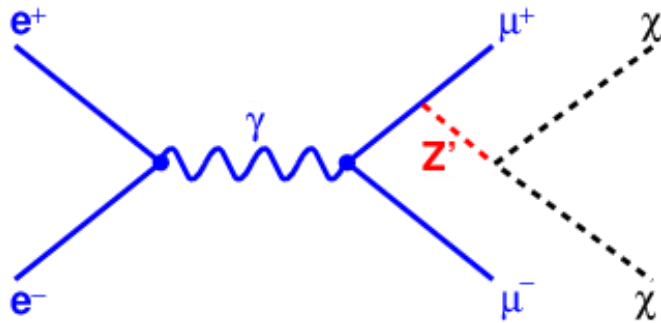


- WIMP (Weak Interacting Massive Particle) was considered to be promising.
 - ✓ Massive particle ($\sim O(10-1000)$ GeV) interacting with a force with similar strength as “Weak Force” in the SM.
 - ✓ New Physics (NP) is expected around this mass scale in relation with hierarchy problem.
 - ✓ LHC or other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

- Search for Dark Matter (DM) at Belle, Belle II.
 - ✓ CM energy is ~ 10 GeV $\rightarrow$ mass region up to $O(1)$ GeV (“light DM”)



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

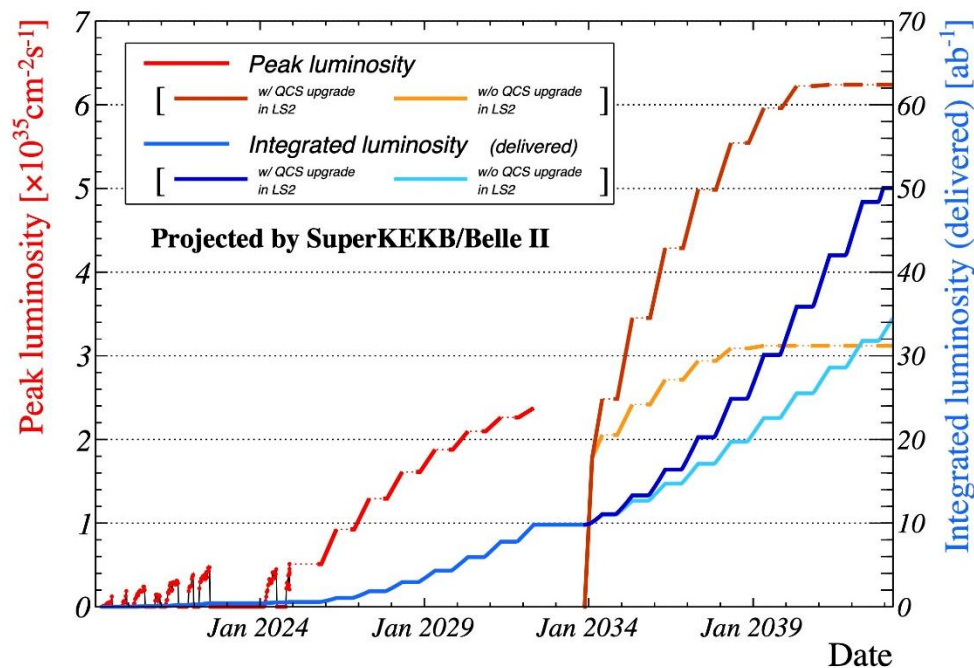


Near term (physics)

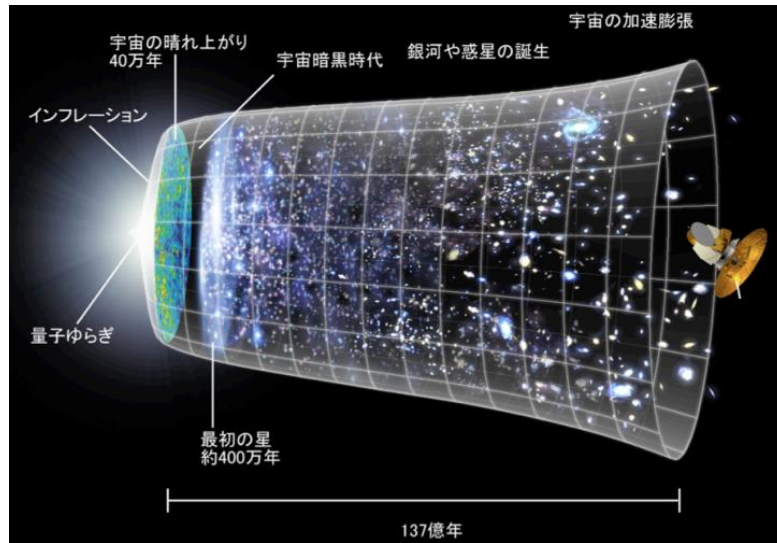
- More results with Run1 data in 2024;
with Run1+Run2 data in 2025
 - ✓ $R(D)$, $R(D^*)$
 - ✓ $B \rightarrow \mu\nu$
 - ✓ $B \rightarrow K\nu\nu$
 - ✓ ...
- World leading results even with smaller
or similar data set compared to Belle.

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
 $\Delta R(D^*) \sim 0.5\%$, $\Delta B(K^*\nu\nu) \sim 9\%$, $B(\tau \rightarrow \mu\mu\mu) < 0.36 \times 10^{-9}$



Backup



- 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: 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



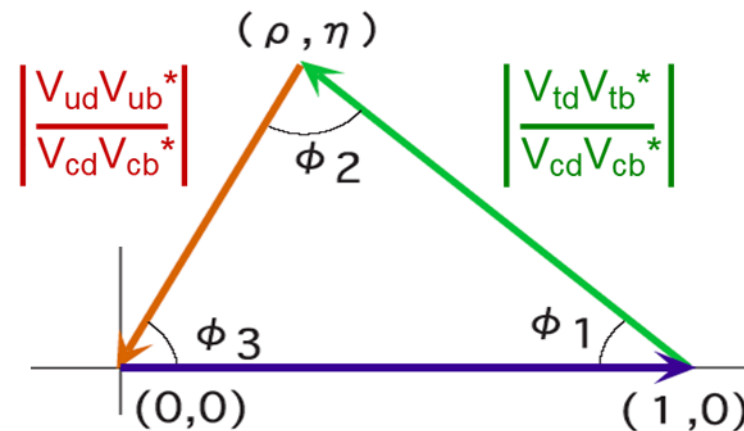
CKM (Cabibbo-Kobayashi-Maskawa) Matrix

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

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.



$$\begin{aligned} \phi_1 &= \beta \\ \phi_2 &= \alpha \\ \phi_3 &= \gamma \end{aligned}$$