EIEIEOO — The Belle II Experiment

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University of Victoria

The Belle II collaboration

2023-05-03

About Myself

Me holding a spare CsI(Tl) crystal.
Belle II's ECL has 8736 of them.

PhD student — UVic

Research:
- Software tools:
  - Simulation generative adversarial networks
  - Identifying events using ML
- Data analysis
  - Measuring QCD in $e^+e^- \rightarrow \pi^+\pi^-$

Outline

1. The Belle II Experiment & International Collaboration
2. The SuperKEKB Subatomic Particle Collider
   - What's so "Super" about it?
3. The Belle II Physics Program
4. The Belle II Particle Detector
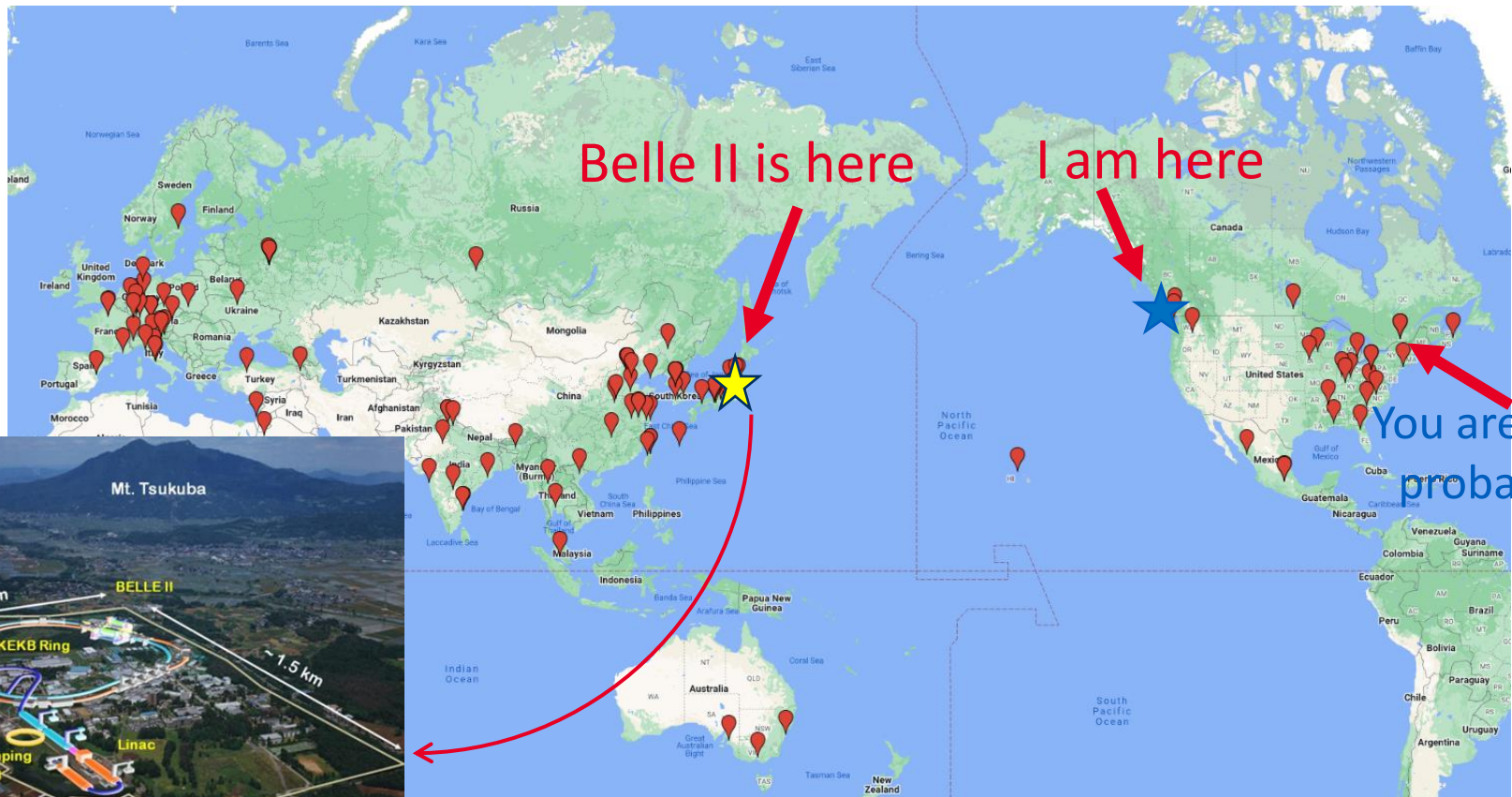   - Purpose, and composition
5. More Belle II!

The Belle II *International* Collaboration

~**1200** collaborators, ~600 authors

- ~500 students, ~450 "Physicists", ~230 technical staff

123 Institutions
27 Countries

Belle II is here

I am here

You are here, probably..?

Previously: *Belle & BaBar*

Previous generation of **experiments** gave the experimental results that led to the 2008 Nobel prize.

-> Experimental observation of CP violation in B-mesons.

© The Nobel Foundation Photo:
U. Montan
Makoto Kobayashi
Prize share: 1/4

© The Nobel Foundation Photo:
U. Montan
Toshihide Maskawa
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That's the "C" and "K" in "CKM Matrix"..!
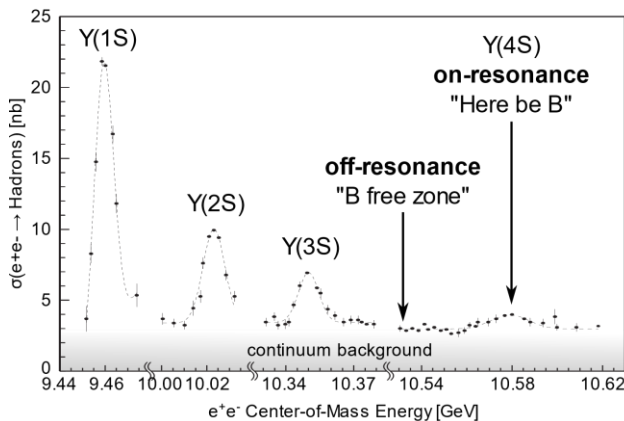
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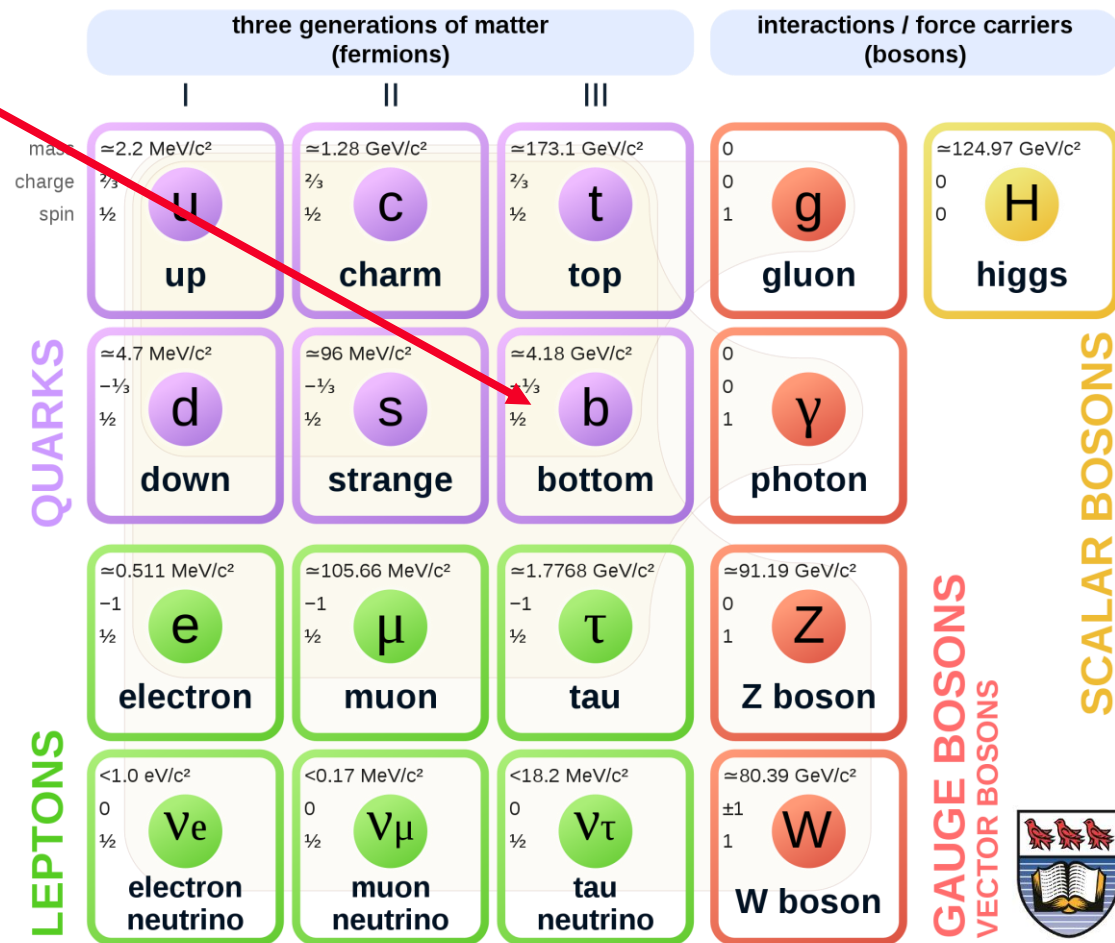# Belle II — a B-Factory

Produce B-mesons:

- $B^+ : u\bar{b}$
- $B^- : \bar{u}b$
- $B^0 : d\bar{b}\,, \bar{d}b$

$$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^+B^-$$

Very relevant for CP violation.
Most present with heavy quarks.

Standard Model of Elementary Particles

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		

≈2.2 MeV/c² ⅔ ½ **u** up	≈1.28 GeV/c² ⅔ ½ **c** charm	≈173.1 GeV/c² ⅔ ½ **t** top	0 0 1 **g** gluon	≈124.97 GeV/c² 0 0 **H** higgs
≈4.7 MeV/c² −⅓ ½ **d** down	≈96 MeV/c² −⅓ ½ **s** strange	≈4.18 GeV/c² −⅓ ½ **b** bottom	0 0 1 **γ** photon	
≈0.511 MeV/c² −1 ½ **e** electron	≈105.66 MeV/c² −1 ½ **μ** muon	≈1.7768 GeV/c² −1 ½ **τ** tau	≈91.19 GeV/c² 0 1 **Z** Z boson	
<1.0 eV/c² 0 ½ **νe** electron neutrino	<0.17 MeV/c² 0 ½ **νμ** muon neutrino	<18.2 MeV/c² 0 ½ **ντ** tau neutrino	≈80.39 GeV/c² ±1 1 **W** W boson	

mass
charge
spin

QUARKS

LEPTONS

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

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Y(1S)
Y(2S)
Y(3S)
Y(4S)
on-resonance "Here be B"
off-resonance "B free zone"
continuum background

σ(e⁺e⁻→ Hadrons) [nb]

9.44 9.46 10.00 10.02 10.34 10.37 10.54 10.58 10.62
e⁺e⁻ Center-of-Mass Energy [GeV]

CP Violation

Ignoring dark matter…

Question: Why is the universe ~100% matter & ~0% anti-matter? Inflation predicts 50%-50%…
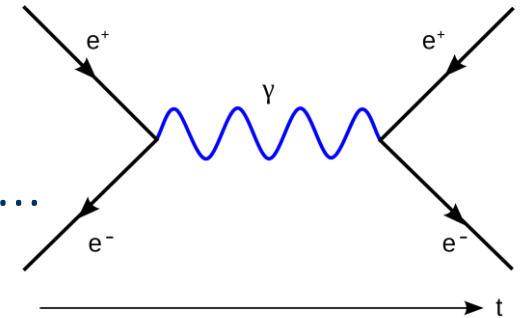
1. Need a process that violates baryon/lepton number
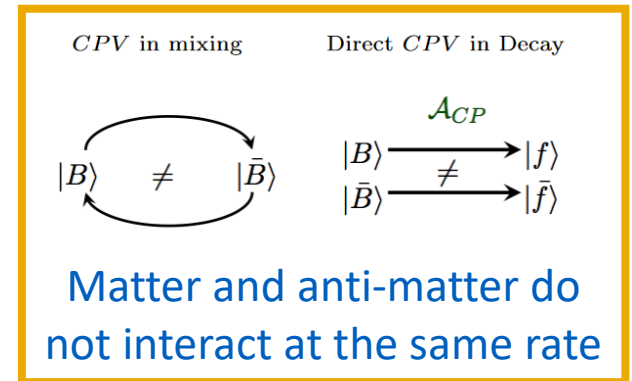   1. matter ⇄ anti-matter
2. Need CP violation
    1. matter ⇄ anti-matter
3. Something about thermodynamics…
    1. See Sakharov conditions

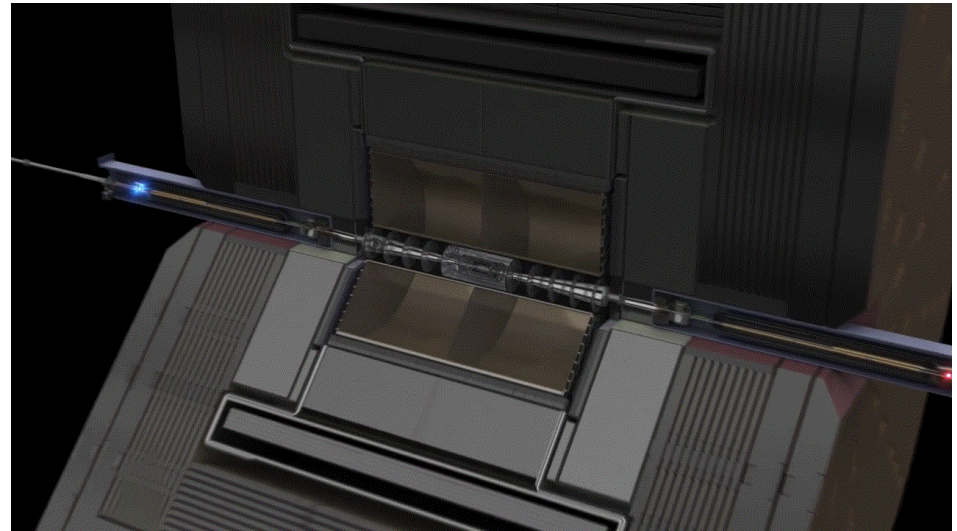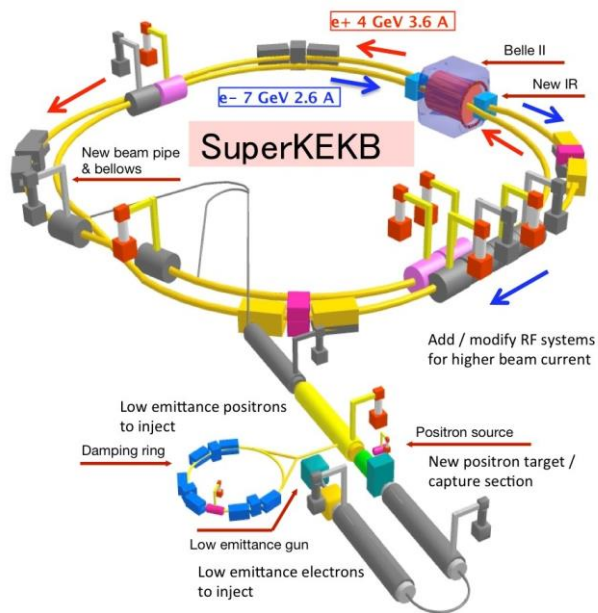Matter and anti-matter do not interact at the same rate

Currently, CPV is much too small to explain the asymmetry.

Measurements are incomplete! Need more precision!

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Matter, anti-Matter Collisions

The SuperKEKB (10.58 GeV) collider collides electrons & anti-electrons for the Belle II experiment.

By looking at what comes out of the collision, we can study the Physics of subatomic interactions.

What's so « Super » about SuperKEKB?

As of 2020, SuperKEKB is the highest luminosity collider **ever**! Target is ~10 to 20 times the cumulative luminosity of HL-LHC

Luminosity $\propto$ intensity of beam.

$$N = \sigma L$$

N = Number of collisions
σ = Cross section (probability)
L = Luminosity

You can think of it as # of particle crossings or # of potential collisions

More luminosity = more events = more precision

What's so « Super » about SuperKEKB?

2 **advantages** of **electron** colliders:

1. Low rate → few pile-up (one event at a time)
2. Known initial state → precise analysis

« clean » collisions

More Precise Physics
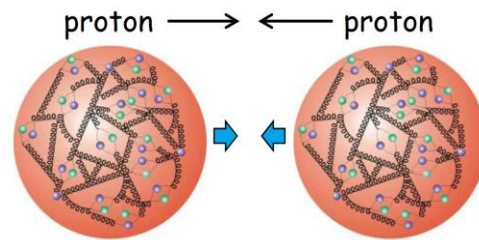
pp Collision
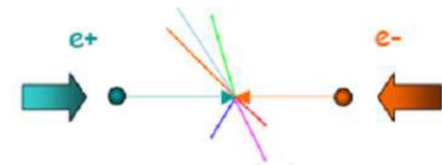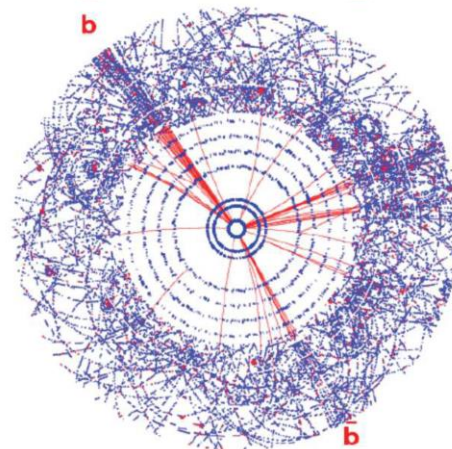
e^+e^- Collision
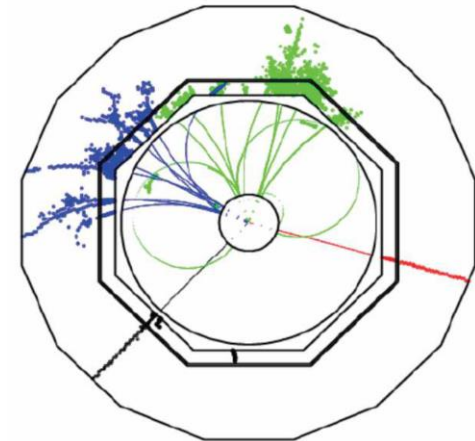
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What is the Advantage of Belle II?

- We can do e.g. **tagging**, **missing mass** measurements
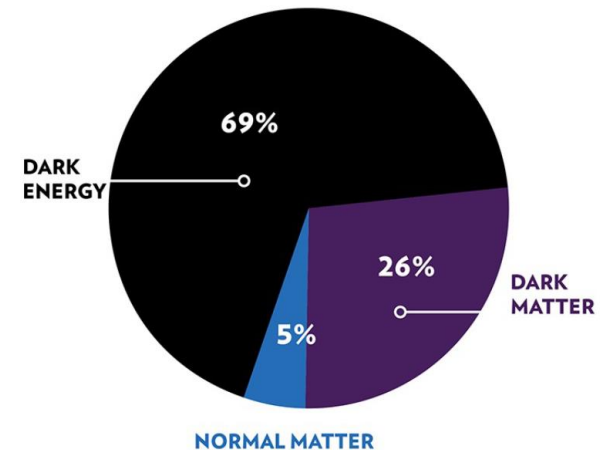 - Use known initial state to understand missing particles
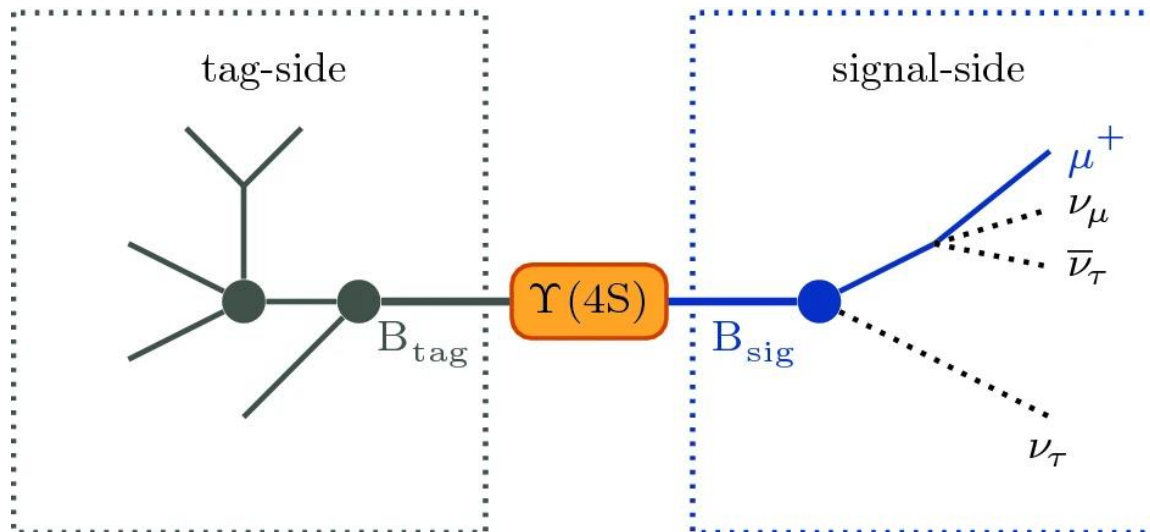
Recoil mass:
How much
energy/momentum
is "taken" by
invisible particles

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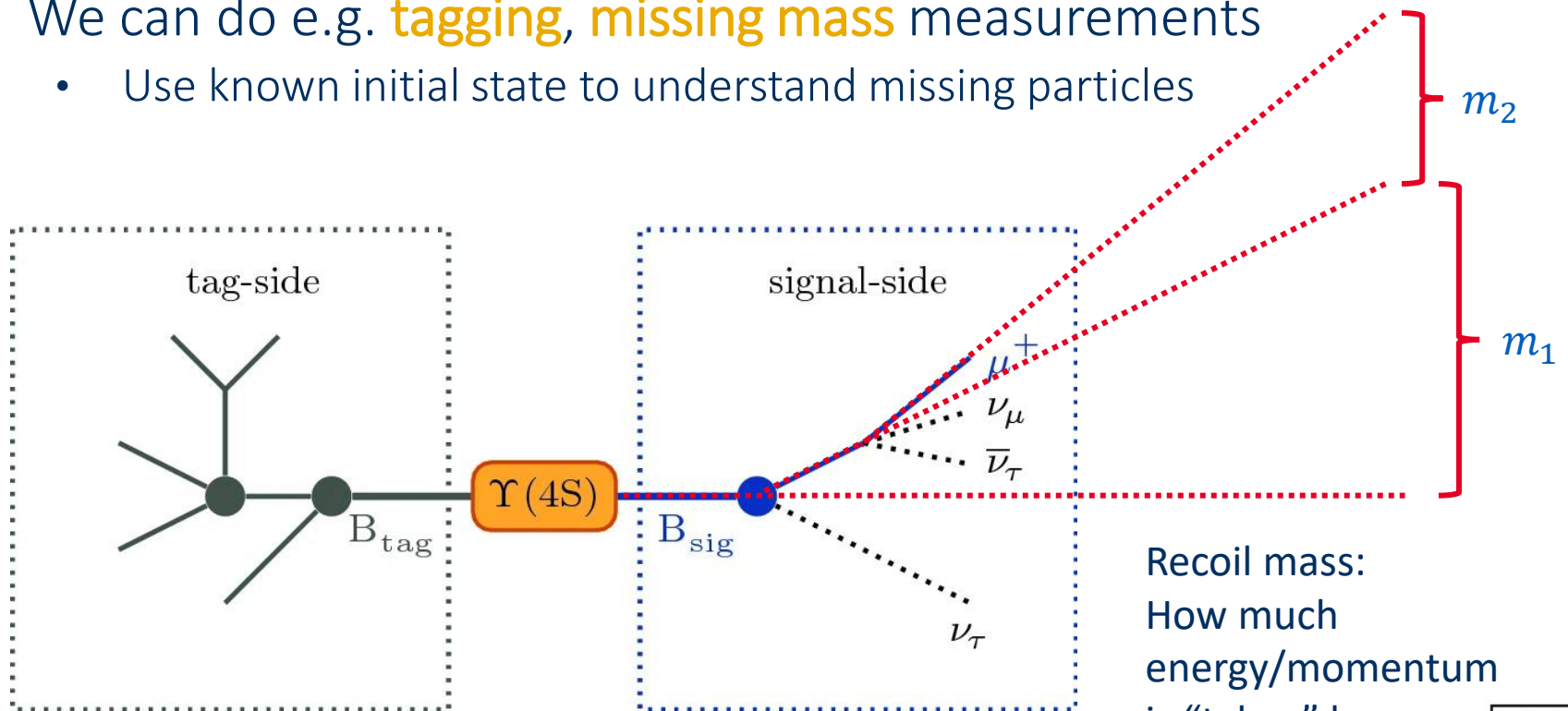
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Dark Sector
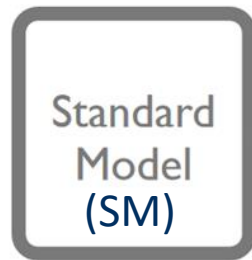
Standard Model (SM)

Dark Sector (DS)

- Dark matter
- Dark forces
- Other dark particles

69% DARK ENERGY
26% DARK MATTER
5% NORMAL MATTER

Dark Sector is a category of dark matter theories. The dark sector is an equivalent to the SM (particles, forces, etc.).

Dark Sector
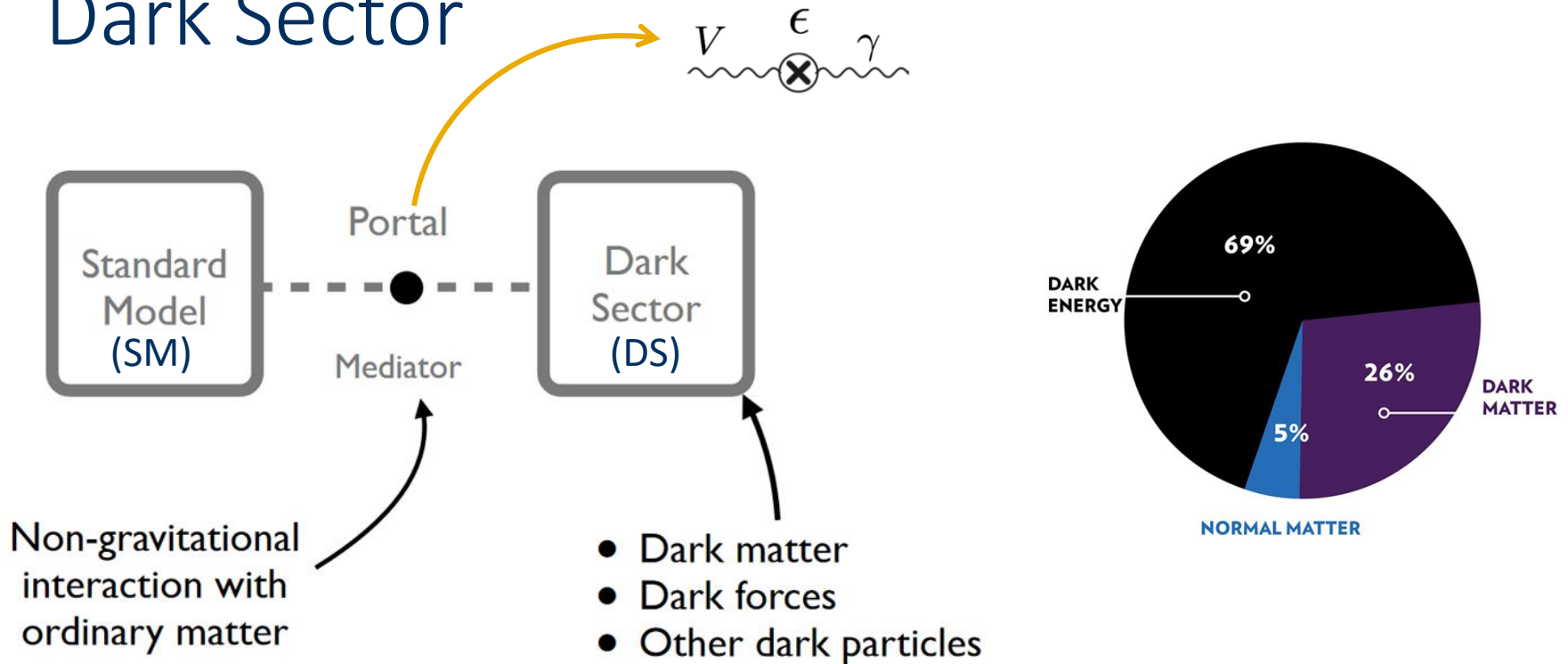
$$V \underset{\otimes}{\overset{\epsilon}{\sim\!\sim\!\sim\!\sim}} \gamma$$

Portal

Standard Model (SM)

Mediator

Dark Sector (DS)

Non-gravitational interaction with ordinary matter

- Dark matter
- Dark forces
- Other dark particles

69% DARK ENERGY

26% DARK MATTER

5% NORMAL MATTER

Dark Sector is a category of dark matter theories. The dark sector is an equivalent to the SM (particles, forces, etc.).

It interacts with the SM through mixing of mediators.

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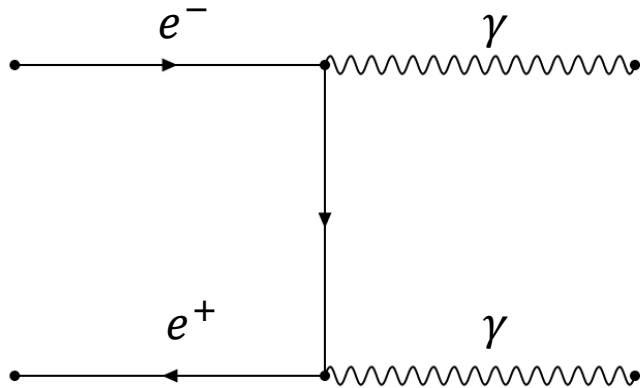
Dark Sector Searches w/ Missing Mass

Dark Sector processes look quite **similar** to Standard Model processes

SM process: annihilation into **2 photons**

DS process: one of the **photons mixes** with a DS particle (e.g. dark photon)


DM particles Invisible

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Dark Sector Searches w/ Missing Mass

Dark Sector processes look quite **similar** to Standard Model processes

SM process: annihilation into **2 photons**

e^- $\qquad$ γ

e^+ $\qquad$ γ

DS process: one of the **photons mixes** with a DS particle (e.g. dark photon)

e^- $\qquad$ γ

e^+ $\qquad$ $A'^{(*)}$ $\qquad$ χ $\quad$ $\bar{\chi}$
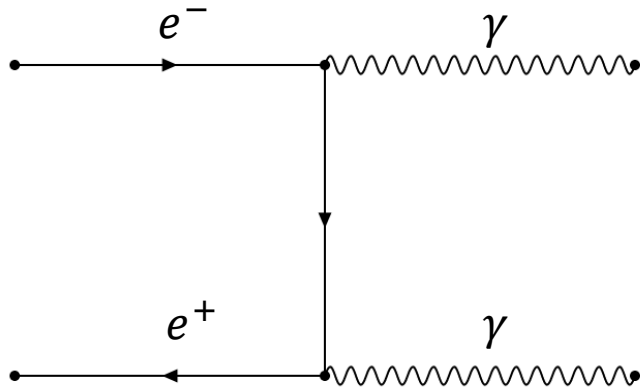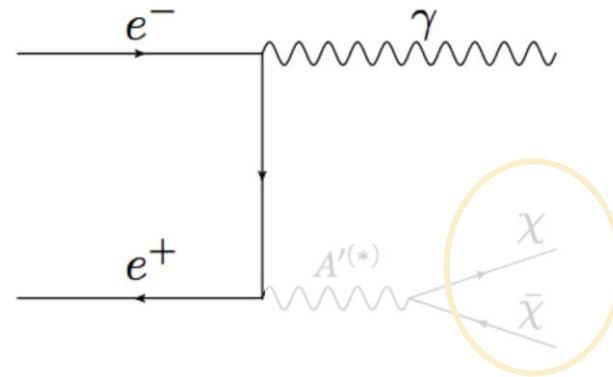
For our detector:
Looks like a SM process with a **missing particle**

Belle II Physics Program

1. Probe the limit of Standard Model (SM) with high precision
2. Search for new Physics
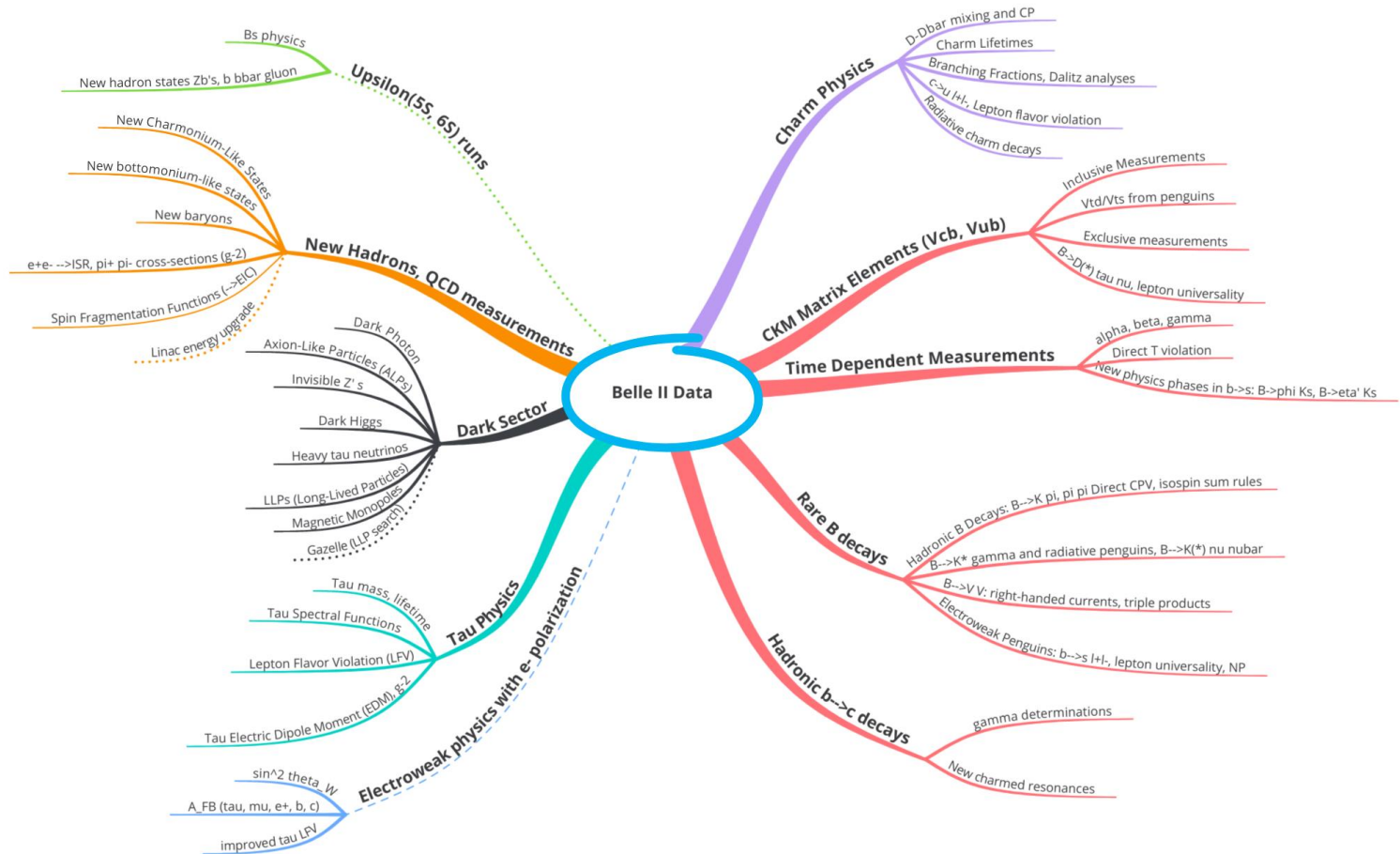
Belle II Physics Program

1. Probe the limit of Standard Model (SM) with high precision
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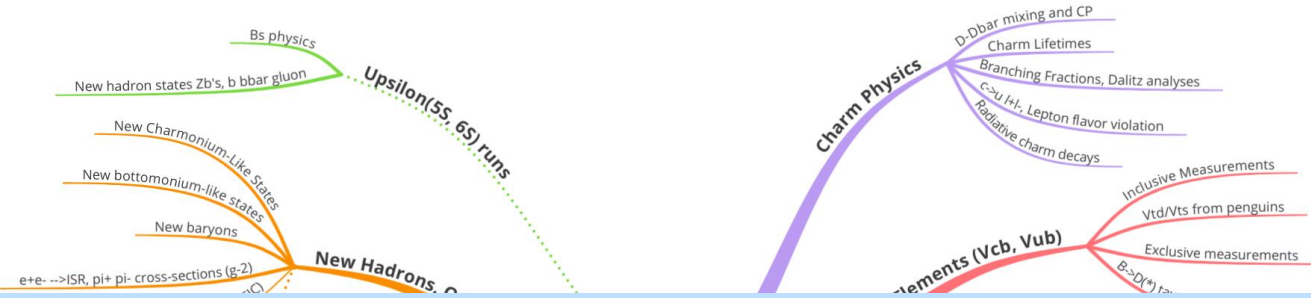
Belle II produces much more than B-mesons
A versatile **flavor-Factory**!

The Belle II Detector

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The Belle II Detector

General-purpose detector — Built like an onion around collision point

7 sub-detectors

~7m

~7.5m

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The Belle II Detector

General-purpose detector — Built like an onion around collision point

7 sub-detectors

~30 000x the Earth's magnetic field

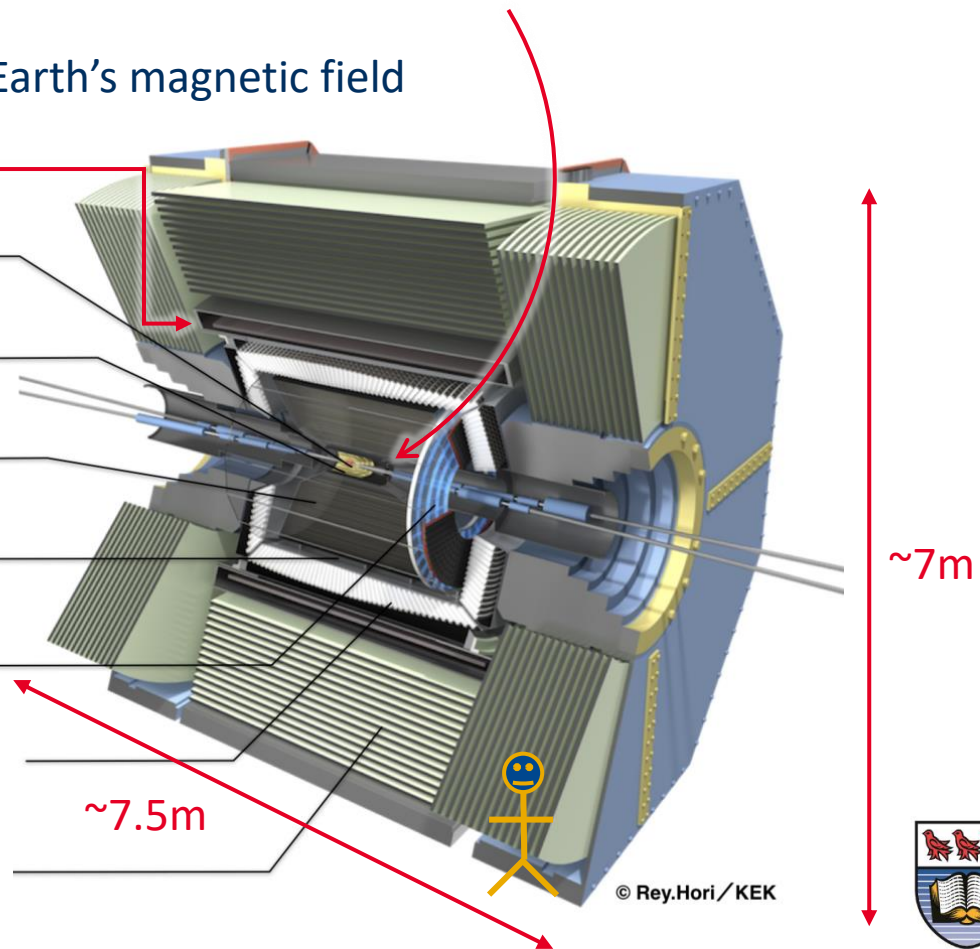Also, a 1.5T magnet!

Particle Position & Tracks

Pixel Detector（PXD）

Silicon Vertex Detector（SVD）

Central Drift Chamber（CDC）

~7m

~7.5m

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The Belle II Detector

General-purpose detector — Built like an onion around collision point

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Pixel Detector（PXD）

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Central Drift Chamber（CDC）

Particle Type

TOP counter（TOP）

Aerogel RICH counter（ARICH）

~7m

~7.5m

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Particle Position & Tracks
- Pixel Detector (PXD)
- Silicon Vertex Detector (SVD)
- Central Drift Chamber (CDC)

Particle Type
- TOP counter (TOP)
- Aerogel RICH counter (ARICH)

Particle Energy
- Electromagnetic Carolimeter (ECL)
- K_L^0／Muon Detector (KLM)

~7m

~7.5m

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Event Viewer — Collisions

3D **visualization** of Belle II **collision**.

Tracks are left by **charged particles** traveling through the detector.

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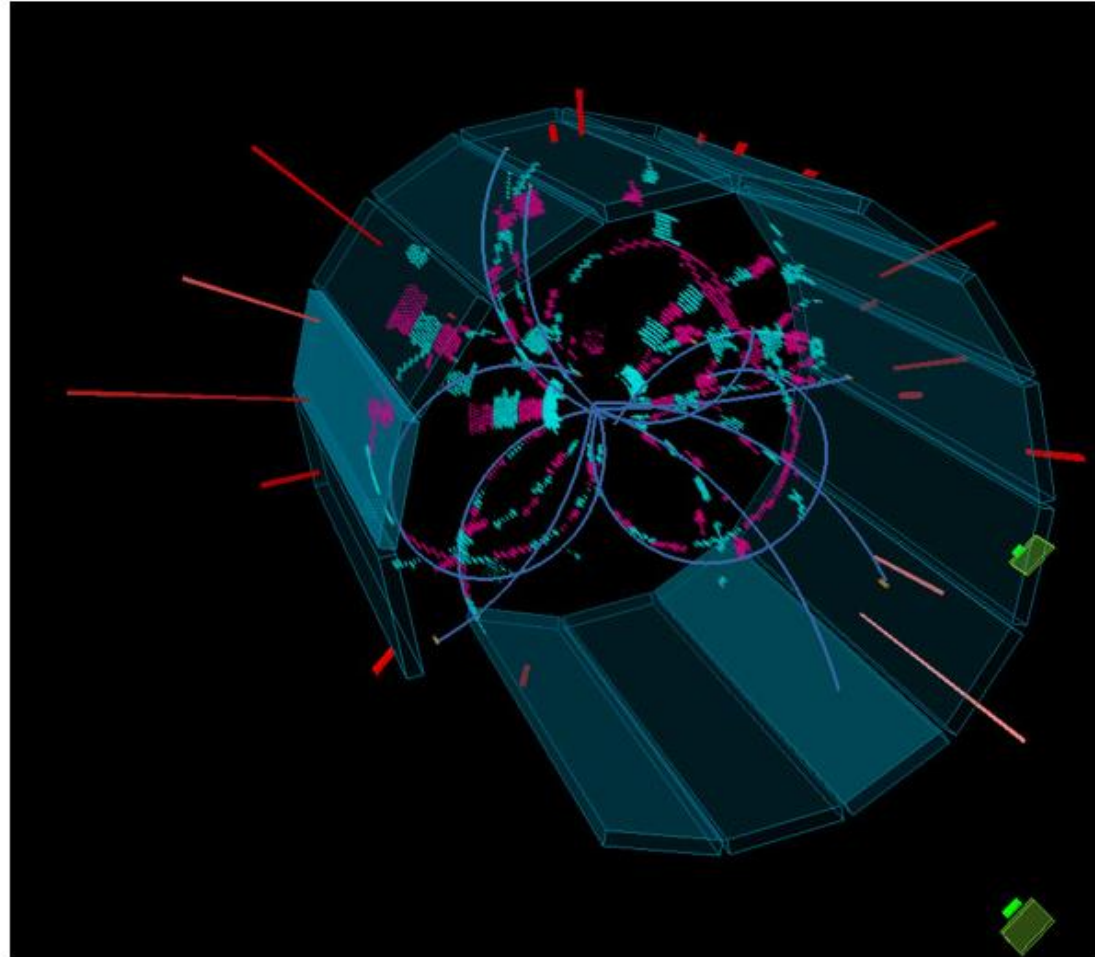
Belle II Tracking & Vertexing
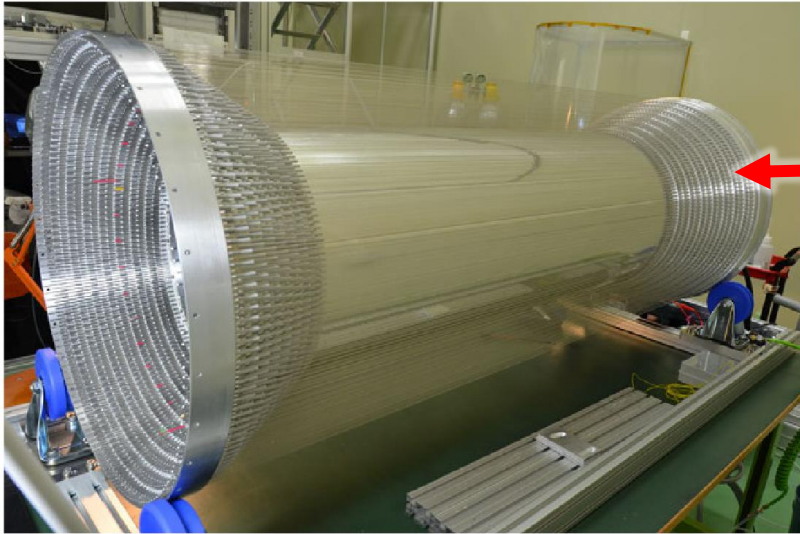
The **drift chamber** tracks the trajectory of charged particles.

**14336 wires** of diameter 30 μm track charged particles through space.

The **vertex detector** find where particles decay.

Each shell is made of **« pixels »** with resolution on the order of 10 μm
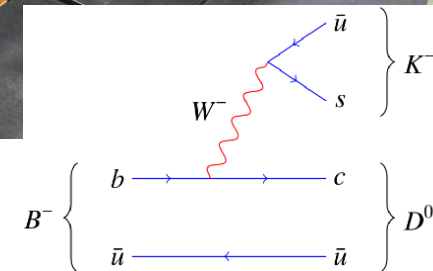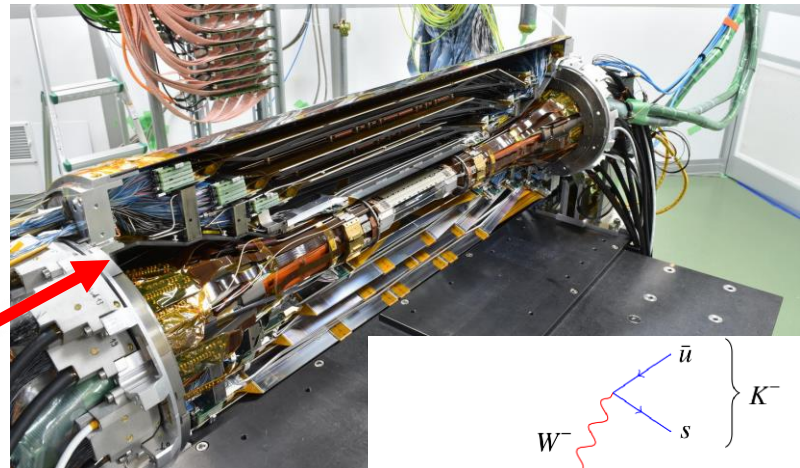
ARICH and TOP

The **TOP** and **ARICH** identifies charged particles using **Cherenkov radiation** (sonic boom for light).

Cherenkov radiation tells you what your particle **velocity** is. Mix with spectrometer and you get **mass**!
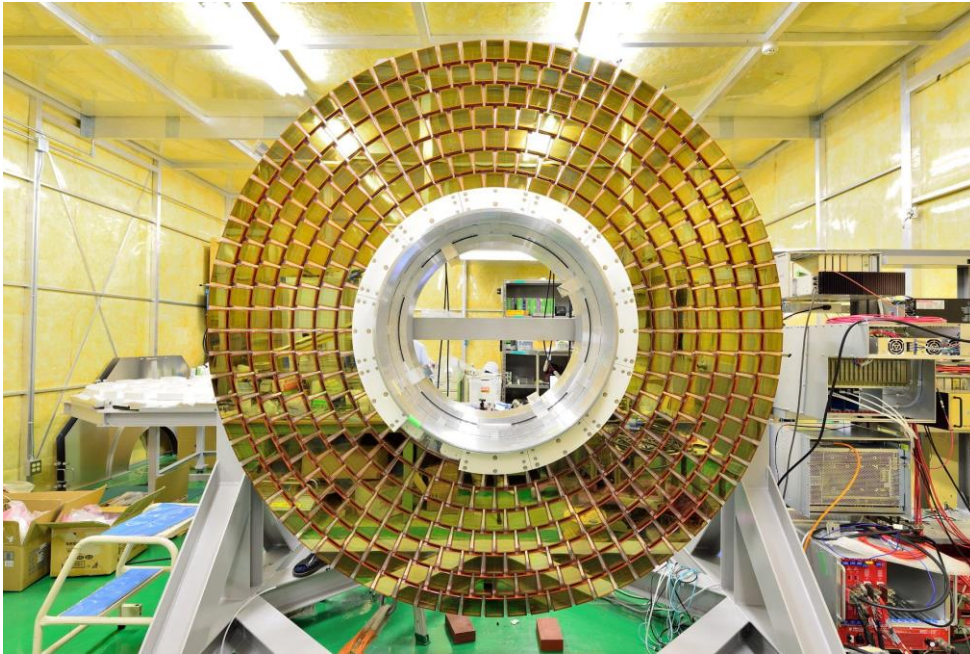

TOP

ARICH

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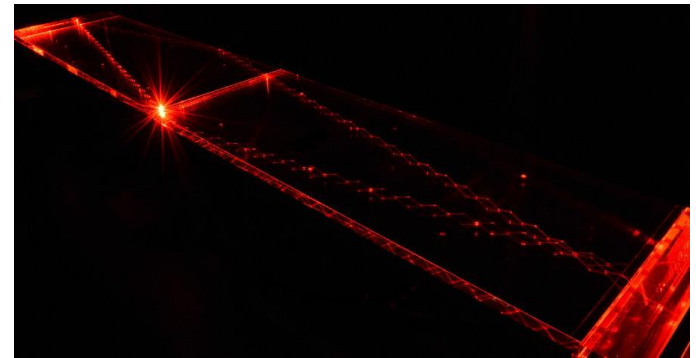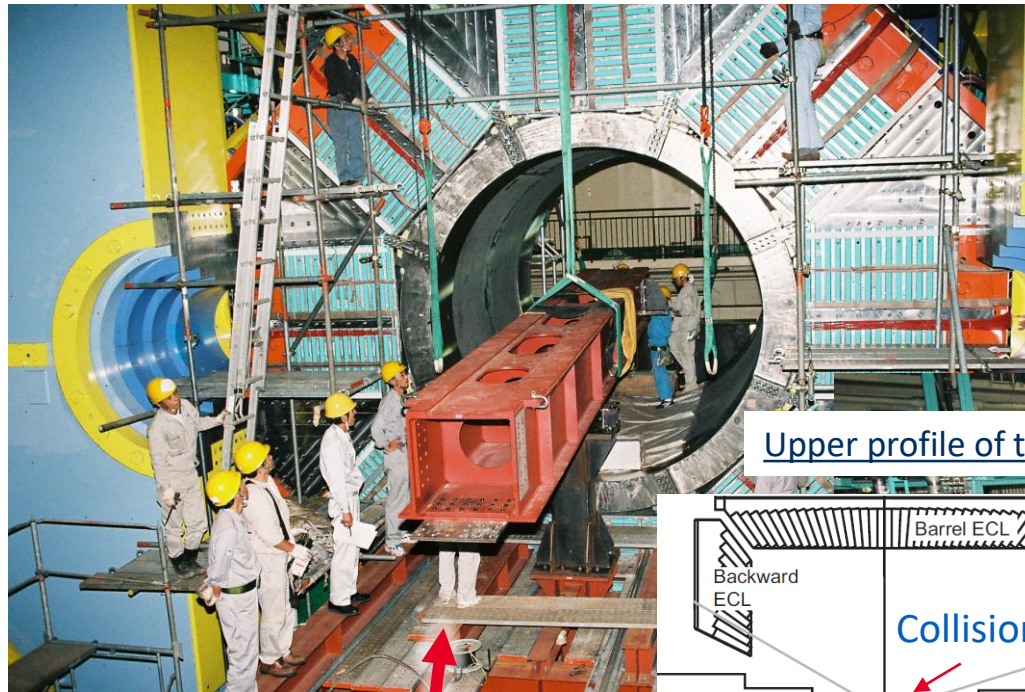
ARICH and TOP
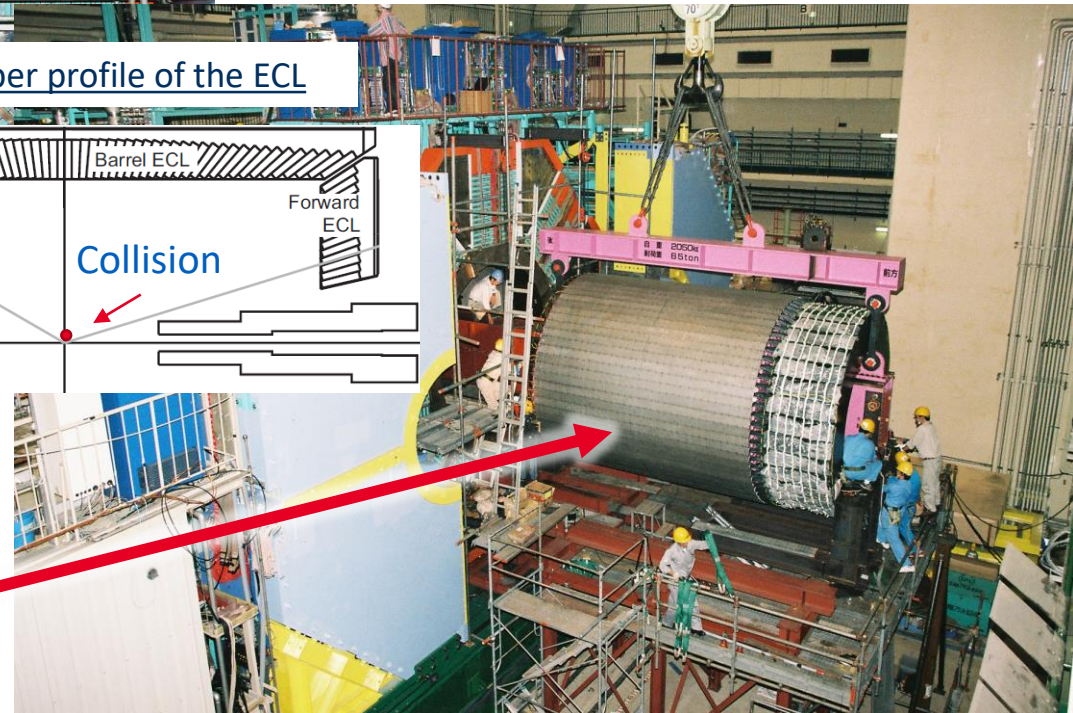
ARICH

ECL

TOP

TOP

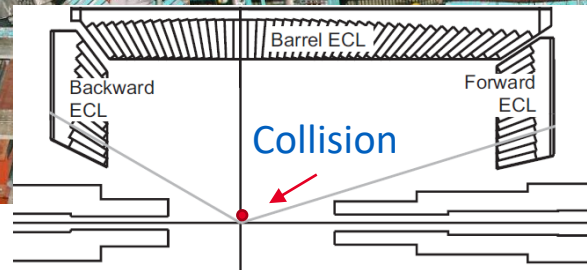University of Victoria
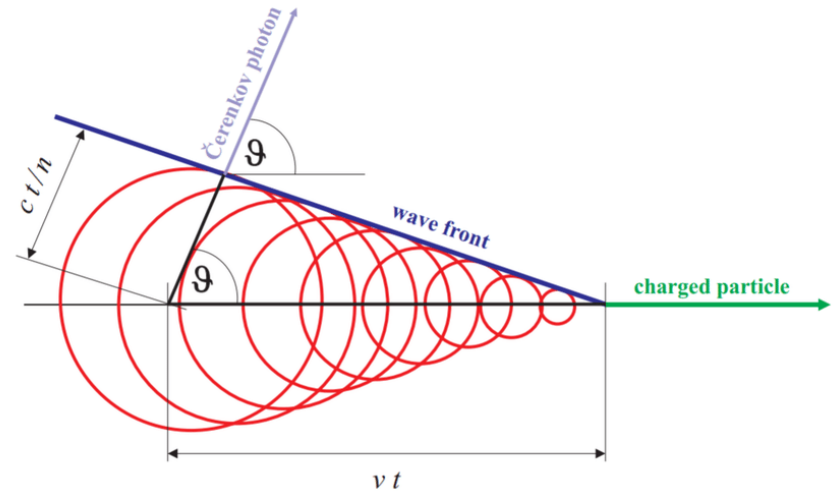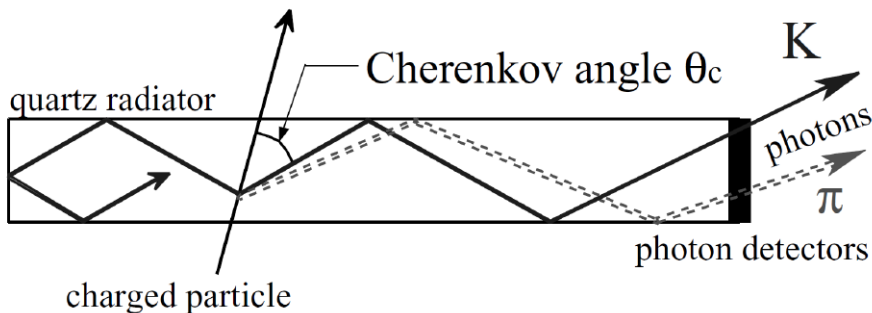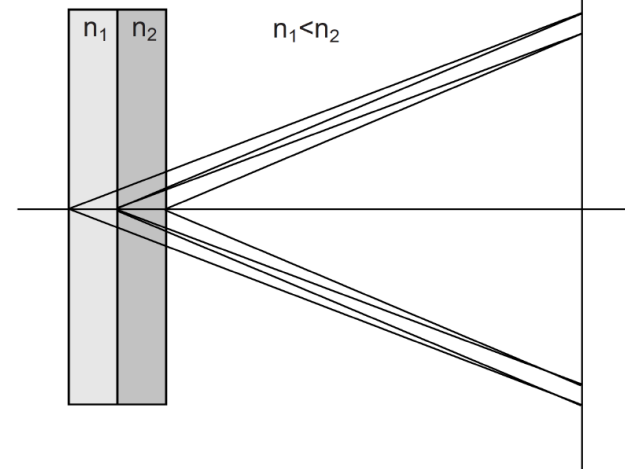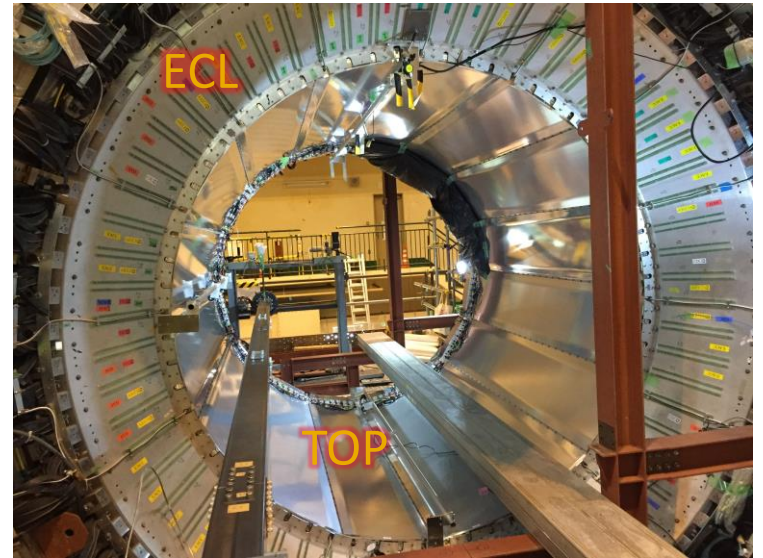
ECL Installation (old)

The **Electromagnetic Calorimeter** measures particle's energies deposited in 8736 **CsI(Tl)** crystals

Upper profile of the ECL
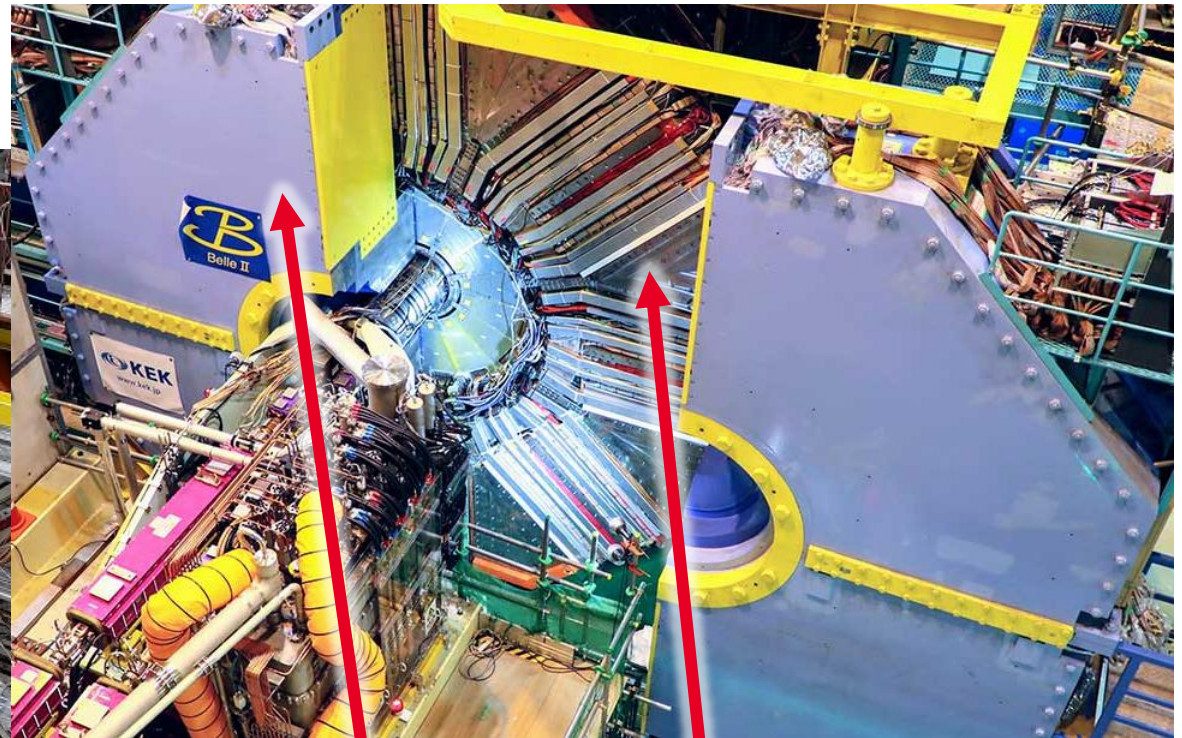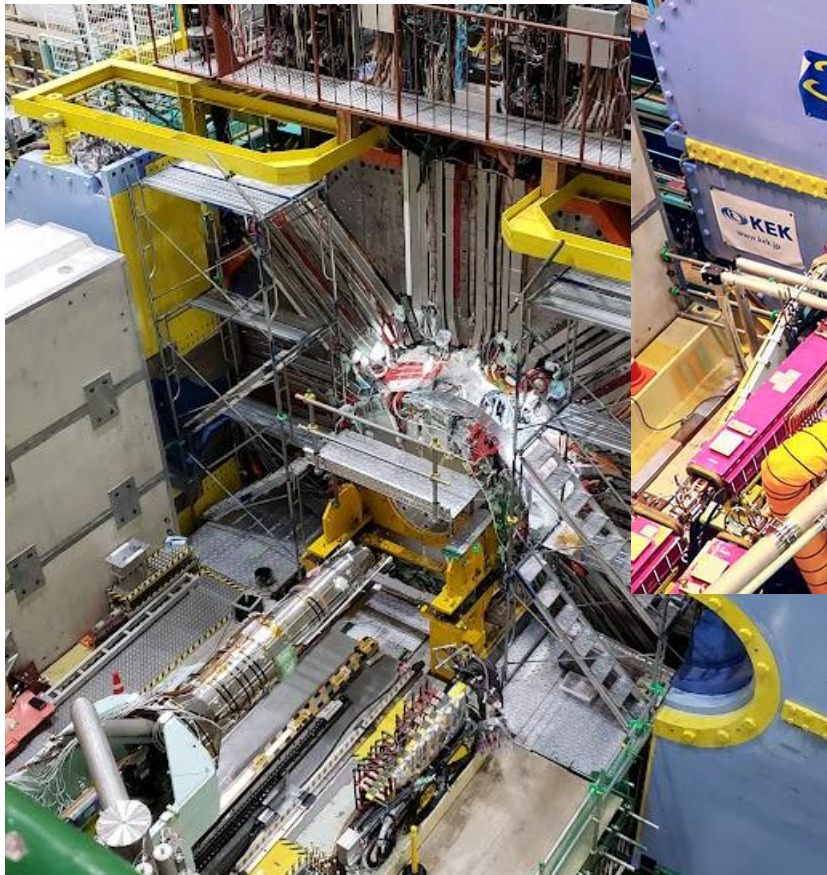
Barrel ECL

Backward ECL

Forward ECL

Collision

Installing the Electromagnetic Calorimeter (Belle) – circa 20th century.
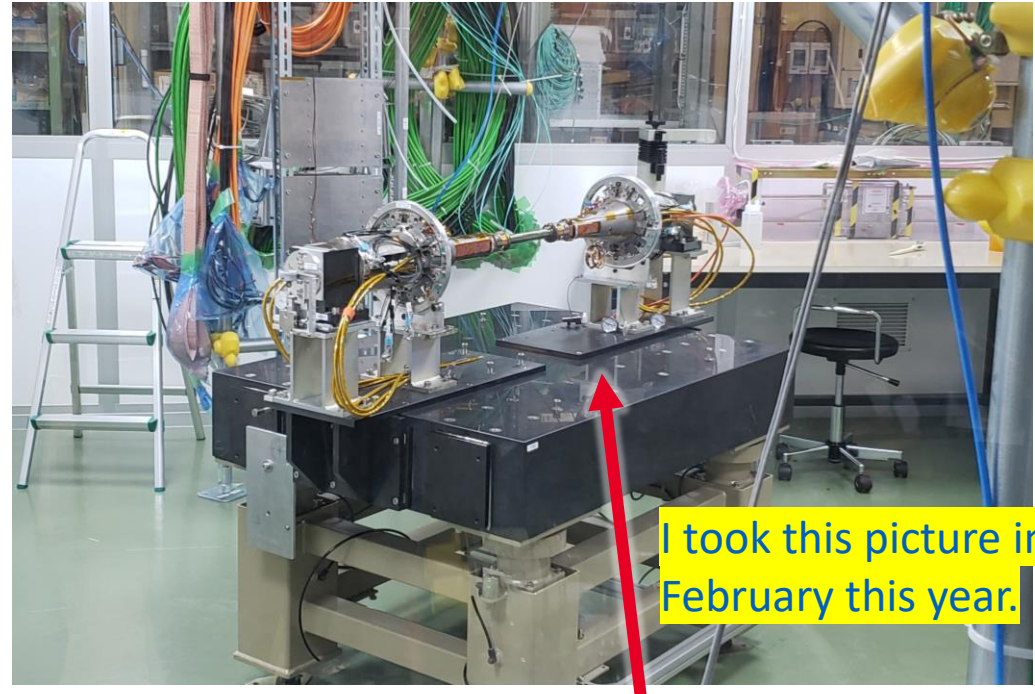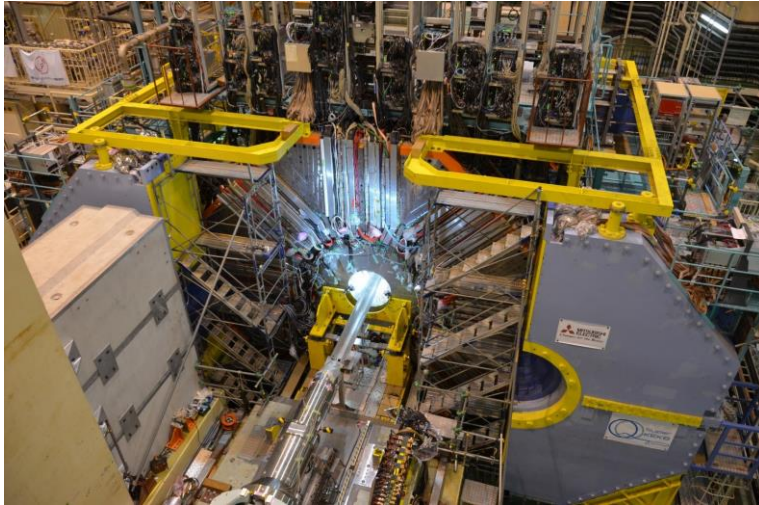
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K-Long and Muon detector (KLM)

The KLM measures long-lived particles: μ, K_L
Large Metal & Scintillator plates for particles to interact

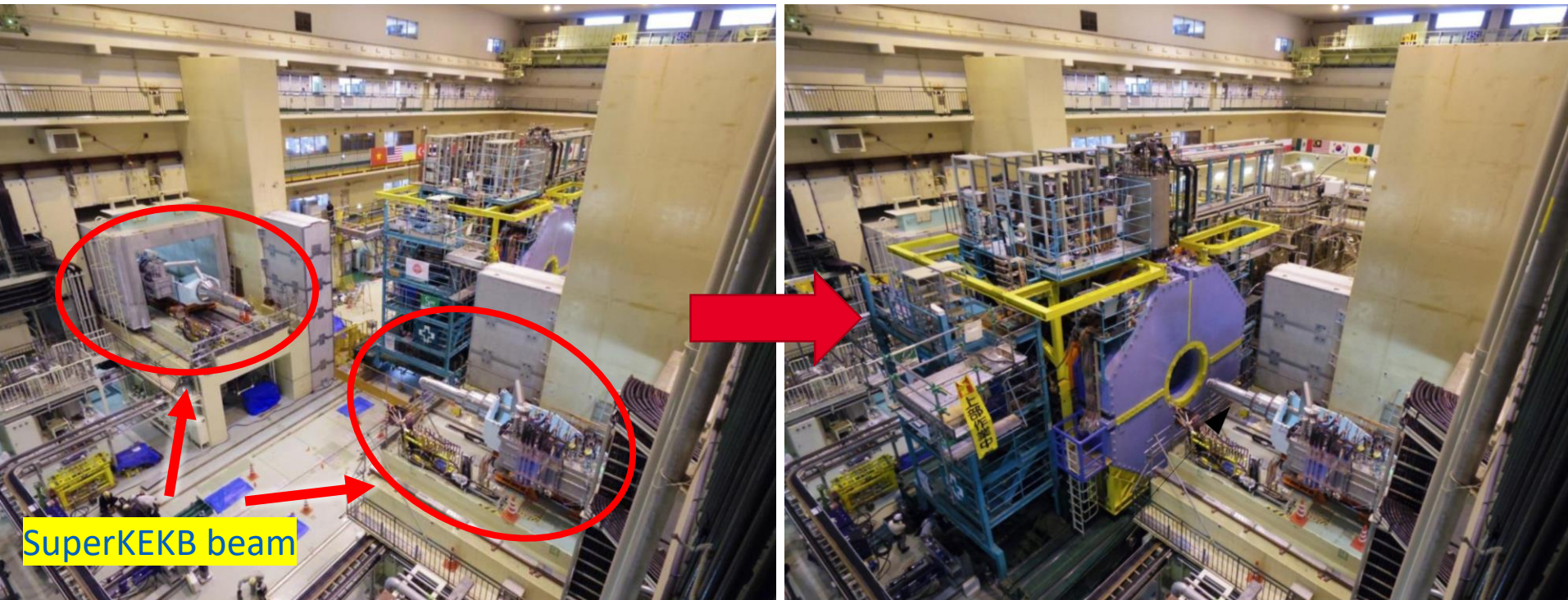# Installing the Belle II Vertex Detector

I took this picture in February this year.

Detector is due for its final **upgrade** in 2023 (now!).

Installing the vertex detector in 2019.

Rolling-in the Detector

SuperKEKB beam

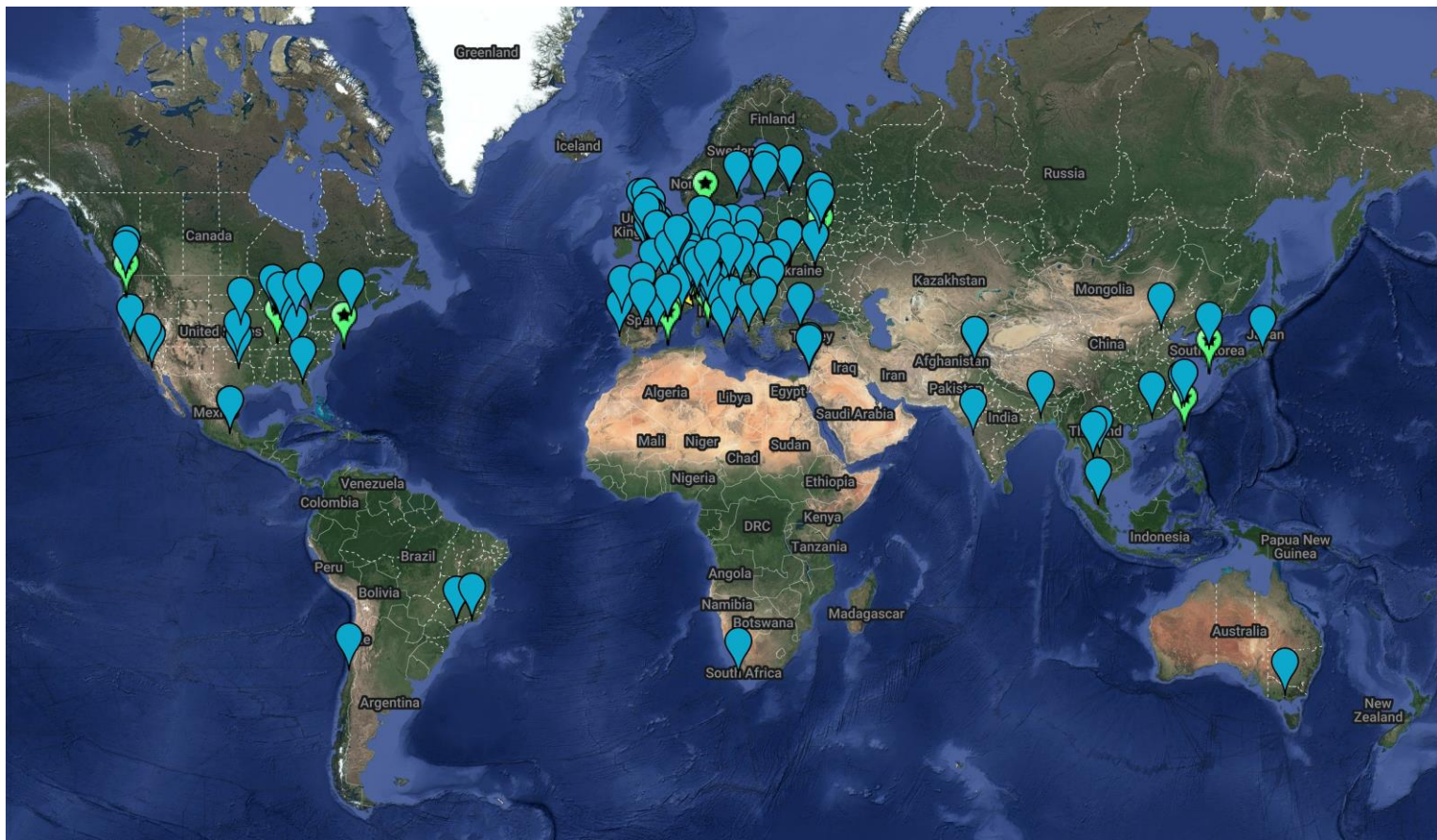We **roll-in** the detector to the **collision area** after it is fully built.

Control Room

Belle II control room →

← SuperKEKB control room

Much More Than That…

A large computing infrastructure to handle data processing, analysis and simulations. 40+ countries, 170+ computing centers.

Much More Than That…

Advanced software is needed to run the experiment.
Hundreds of collaborators contribute to the open source software in one capacity or another:

https://github.com/belle2/basf2

It includes many advanced computing techniques
e.g. A.I., machine learning, etc.
Used for Physics tools, computing tools, …

Conclusion

Belle II is a highly international effort to push understanding of Physics beyond the Standard Model.

It utilizes the highest luminosity collider ever, SuperKEKB, to obtain the ~50 billion B-meson events it targets.

Its world class detector is complemented by a world class software and computing infrastructure.

Fin