Belle II Detector

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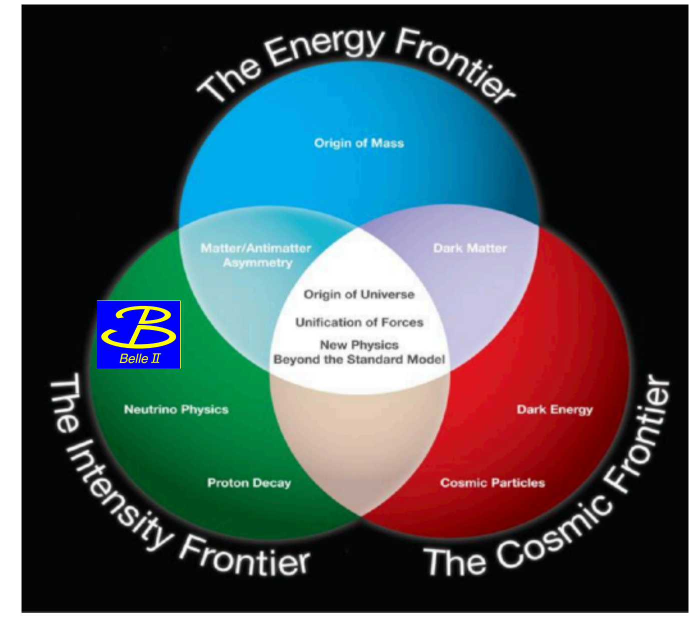
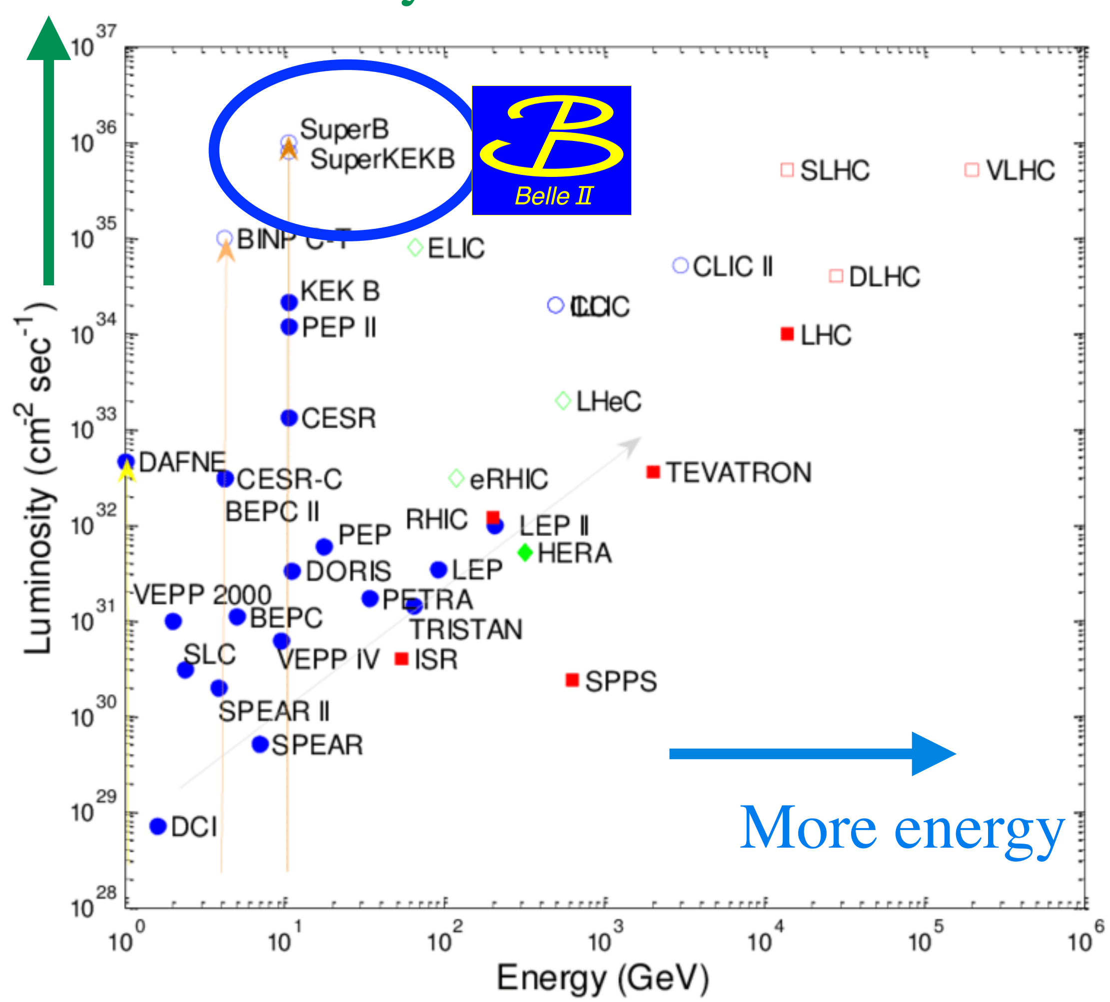
Two directions of physics experiments

1. Challenge for More Luminosity

Try to get **more events**.
Rare event search, precise measurements.
Requires low systematics and precise theory predictions,
since the difference from the theories are the issue.
(Can set upper limits even if nothing is found.)





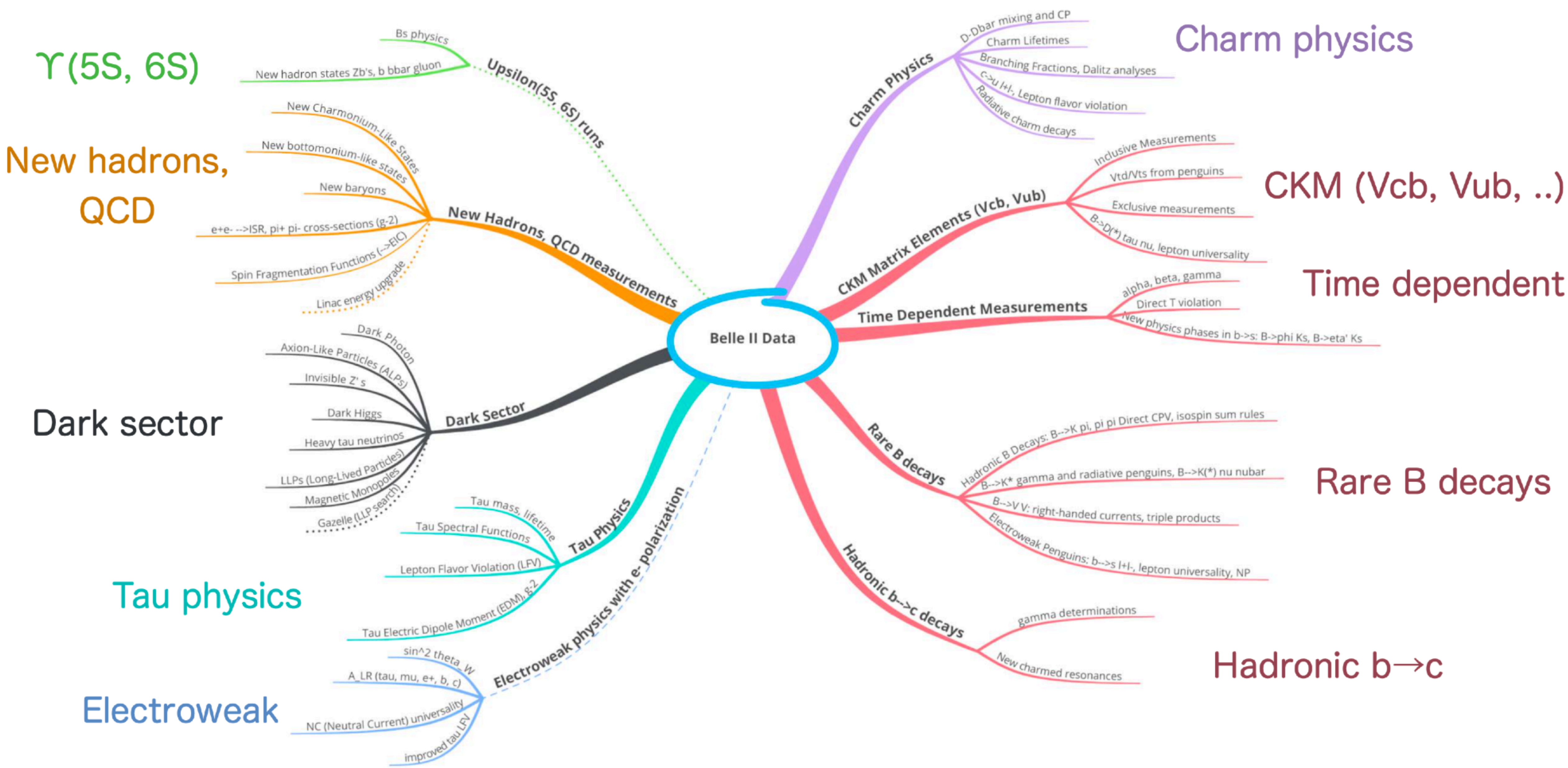
2. Challenge for More Energy

Try to produce **new heavier particles**.
In previously unexplored area.
Requires low systematics, but the result is always
clear = an explicit peak on mass distribution.
(Can expand excluded region in case of no result.)

Belle II - a luminosity frontier experiment

It is unlikely that the GUT scale (10^{16} GeV) will be realized at any accelerator-based experiment even in the distant future. However, there are a few very promising ways to promote our grand challenge. One such approach is to elucidate the nature of quantum loop effects by producing many particle as possible. This provides the rationale to pursue the luminosity frontier.

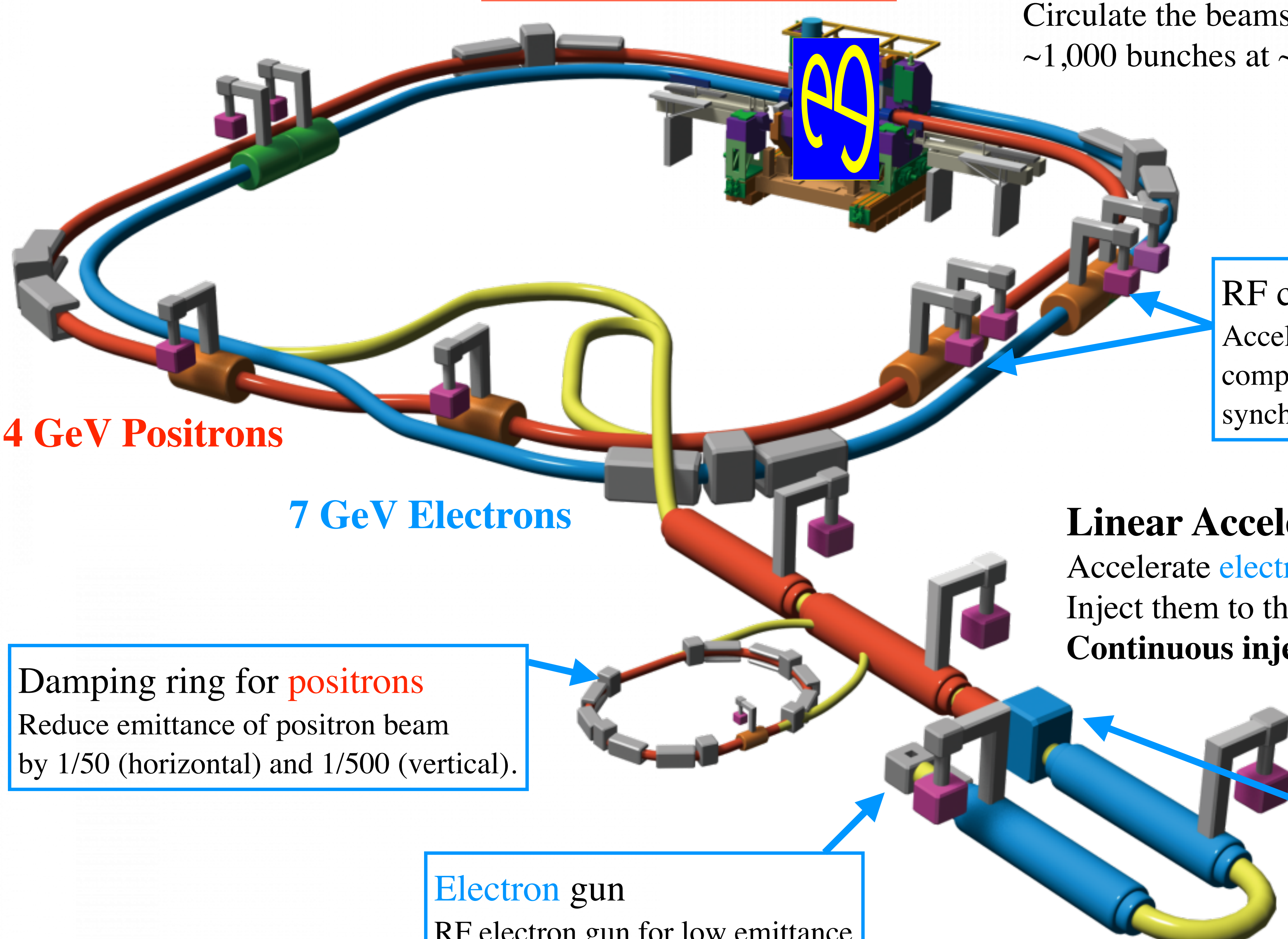
— Letter of Intent for KEK Super B Factory



B factory experiment ~ SuperKEKB accelerator

$$e^+e^- \to \Upsilon(4S) \to BB$$

Storage Rings
Circulate the beams at steady energy.
~1,000 bunches at ~100,000 rev/sec.



RF cavities
Accelerate electrons/positrons to compensate for loss of energy by synchrotron radiation.

Linear Accelerator (LINAC)
Accelerate electrons and positrons.
Inject them to the storage rings.
Continuous injection can be performed.

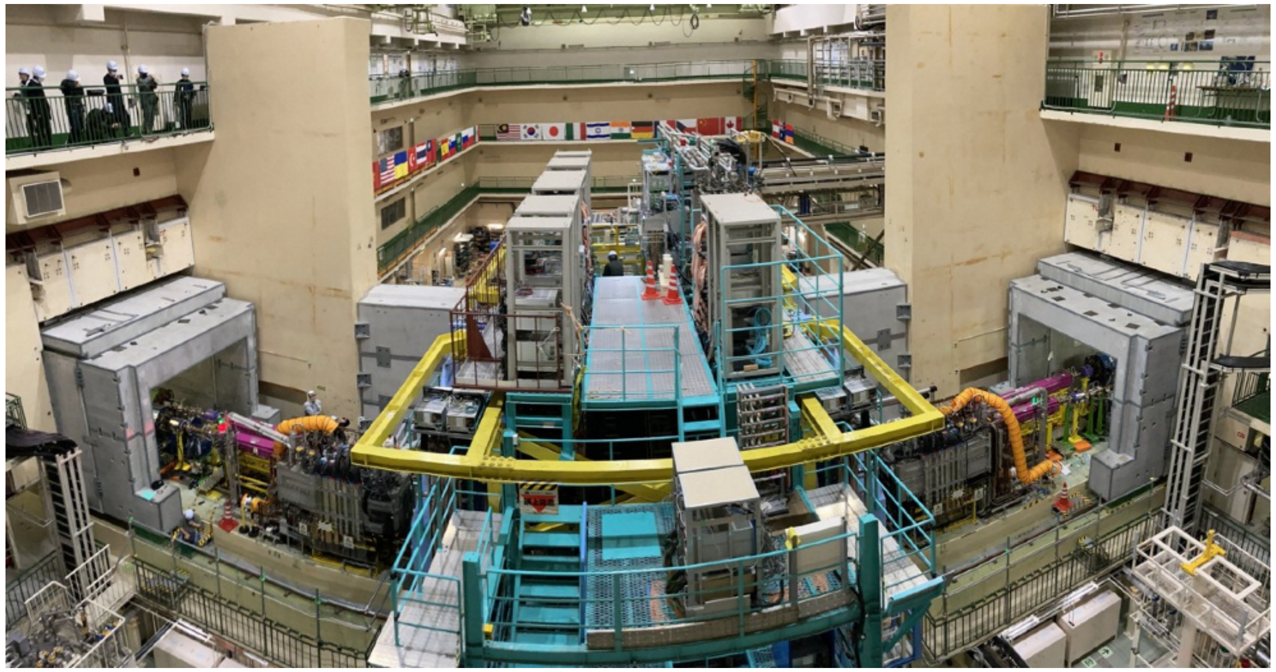
Damping ring for positrons
Reduce emittance of positron beam by 1/50 (horizontal) and 1/500 (vertical).

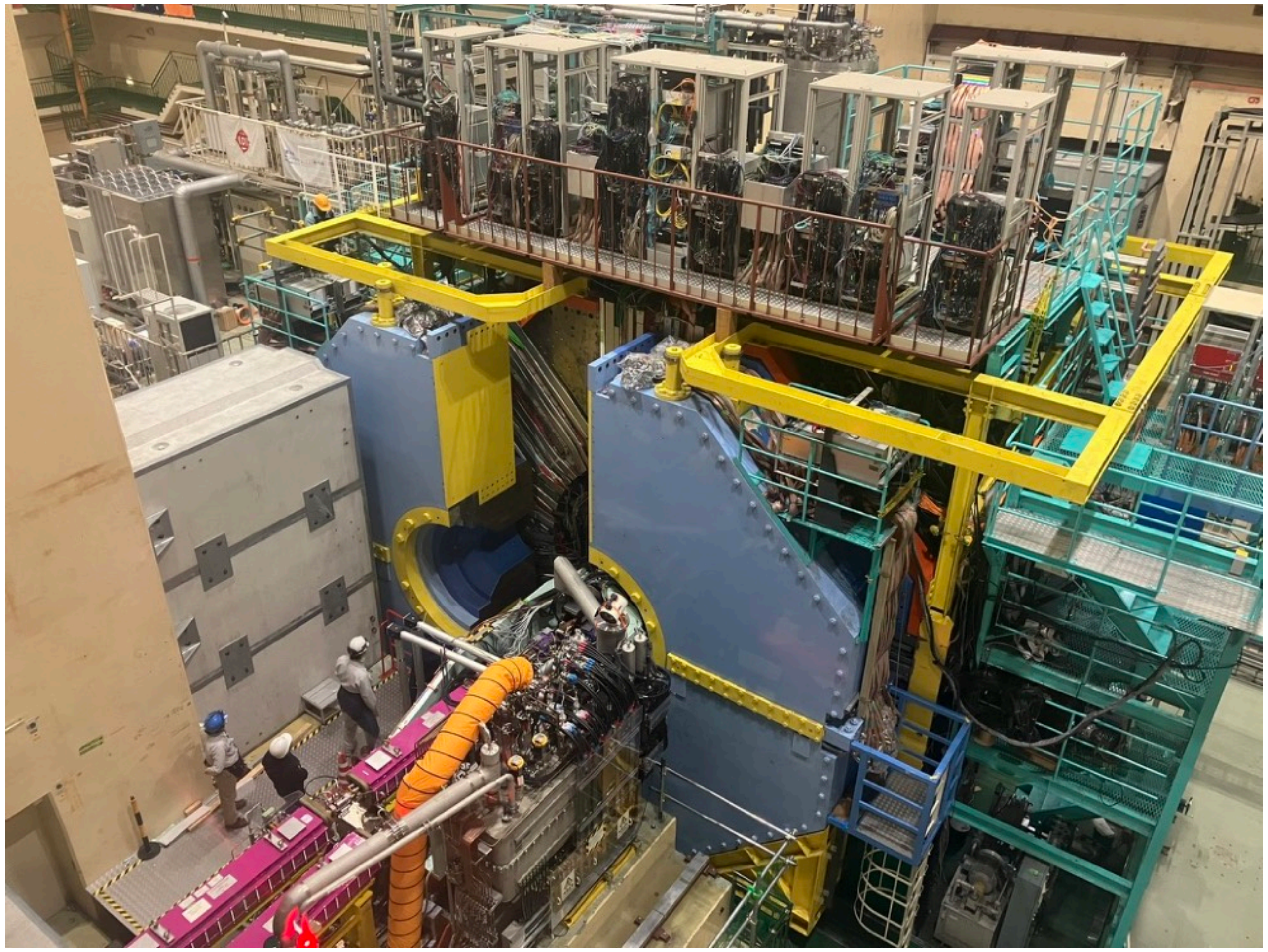
Electron gun
RF electron gun for low emittance and bright injection.

Positron source
Tungsten target to produce positrons by EM shower.

[Details](#)

B factory experiment ~ SuperKEKB accelerator





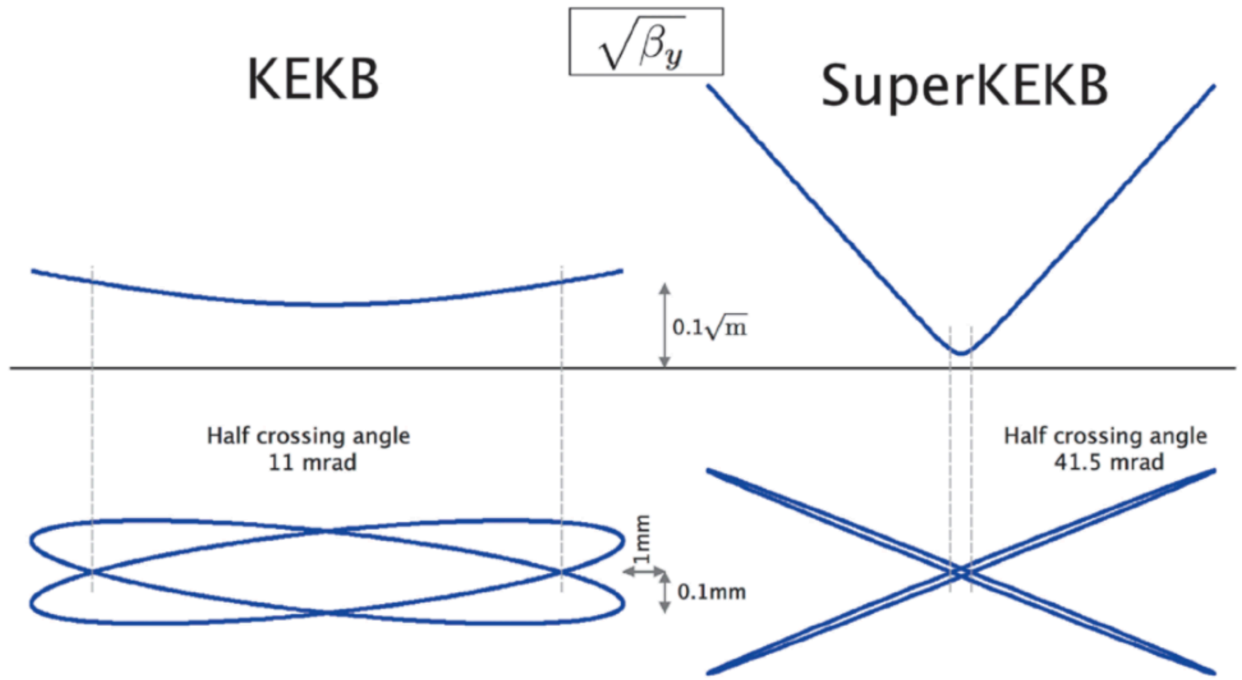
Nano beam scheme for higher luminosity

Details in Tom's talk on Friday

High luminosity = more collisions = more density of particles = well squeezed beams.

However, strong focusing causes shorter DOF (depth of focus).
Density outside of DOF is lower and it does not contribute luminosity.

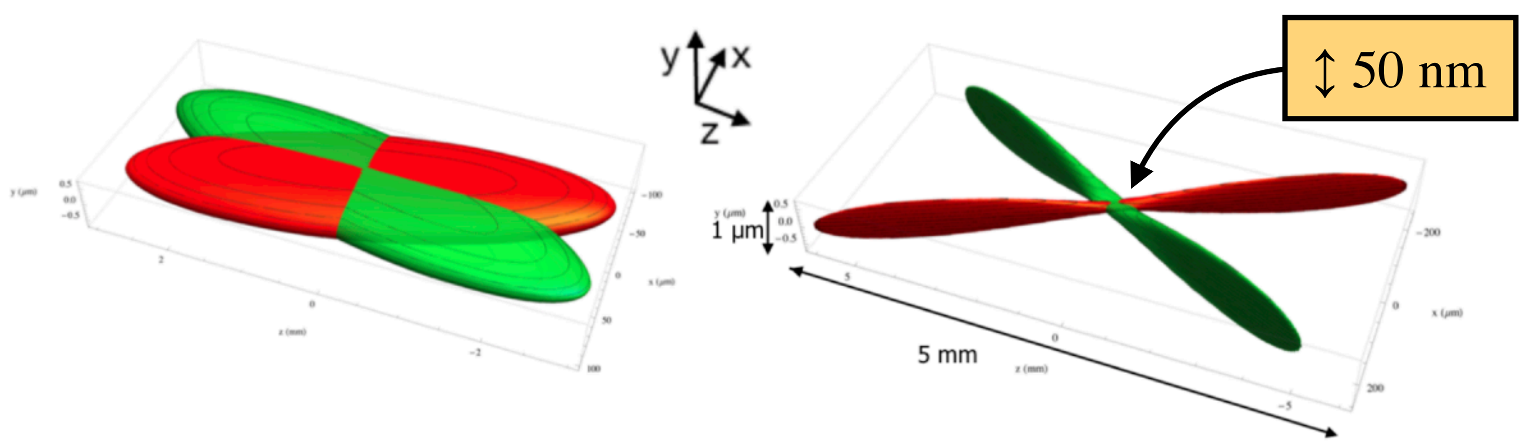
Hourglass Effect



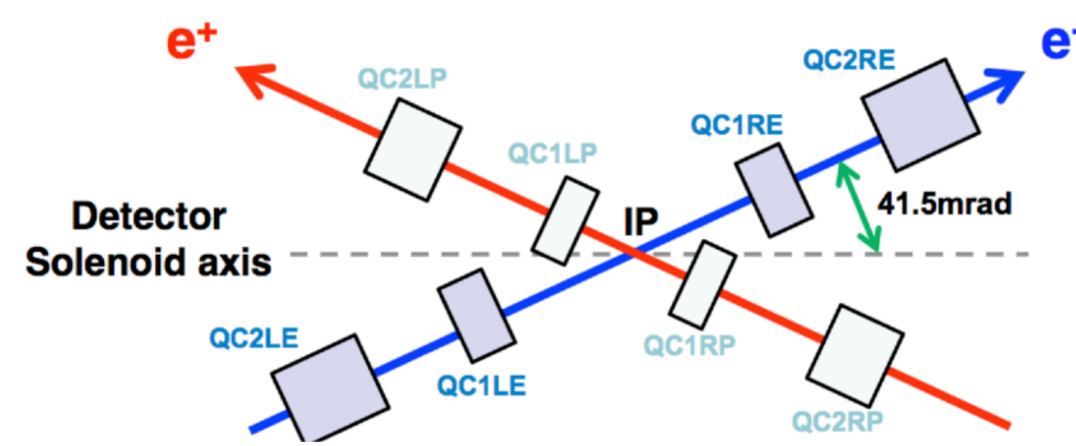
Colliding bunches in the horizontal plane

Nano beam scheme:

1. Change the crossing angle larger
2. Shorten the effective bunch length
3. Squeeze beam vertically to ~50 nm
4. Short effective bunch length still can be within the DOF



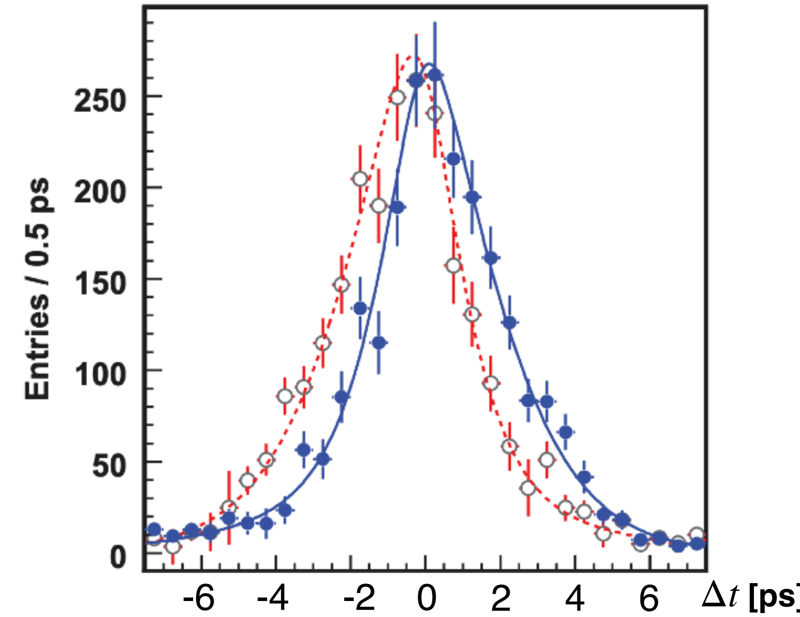
Specialized focusing magnets



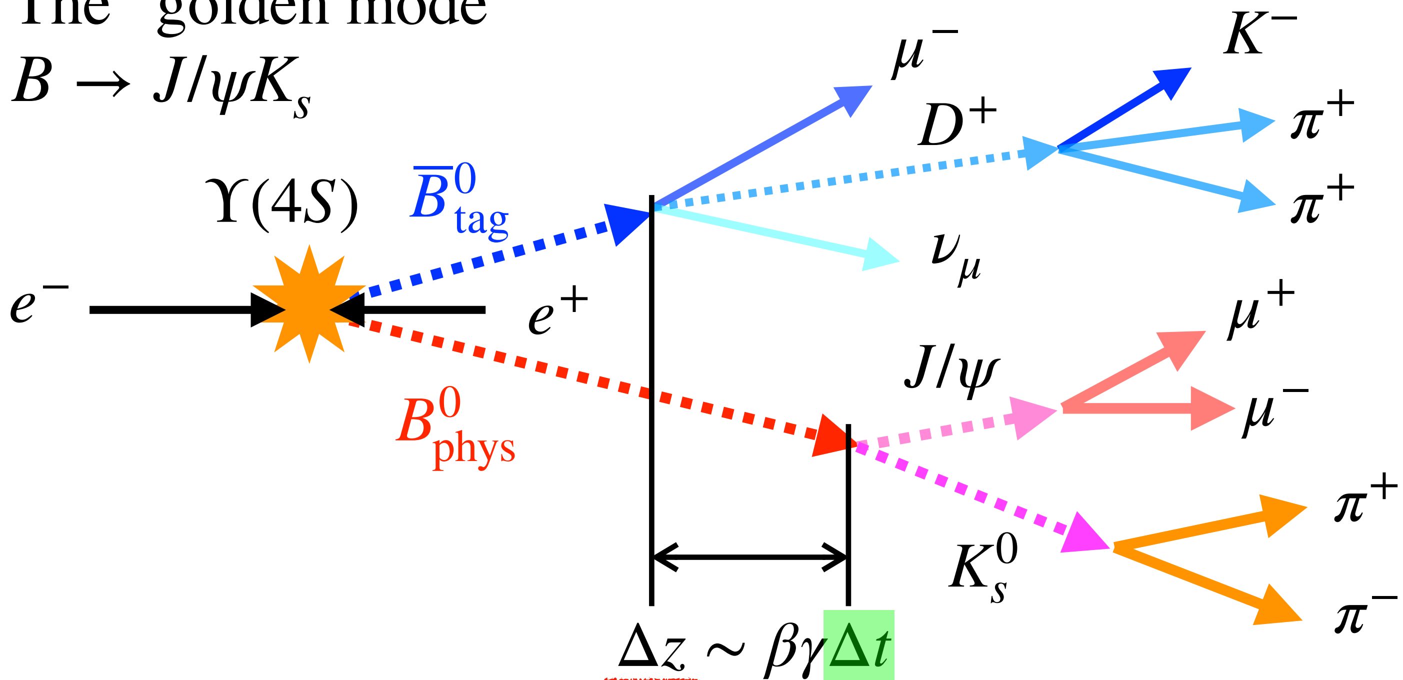
Requirements from physics

$$\Gamma_{B^0 \to f_{CP}} \propto \exp\left[-\frac{|\Delta t|}{\tau_{B^0}}\right] \times (1 - A \cos \Delta m_d \Delta t - S \sin \Delta m_d \Delta t)$$

$$\Gamma_{\overline{B}^0 \to f_{CP}} \propto \exp\left[-\frac{|\Delta t|}{\tau_{B^0}}\right] \times (1 + A \cos \Delta m_d \Delta t + S \sin \Delta m_d \Delta t)$$



The "golden mode"
$B \to J/\psi K_s$



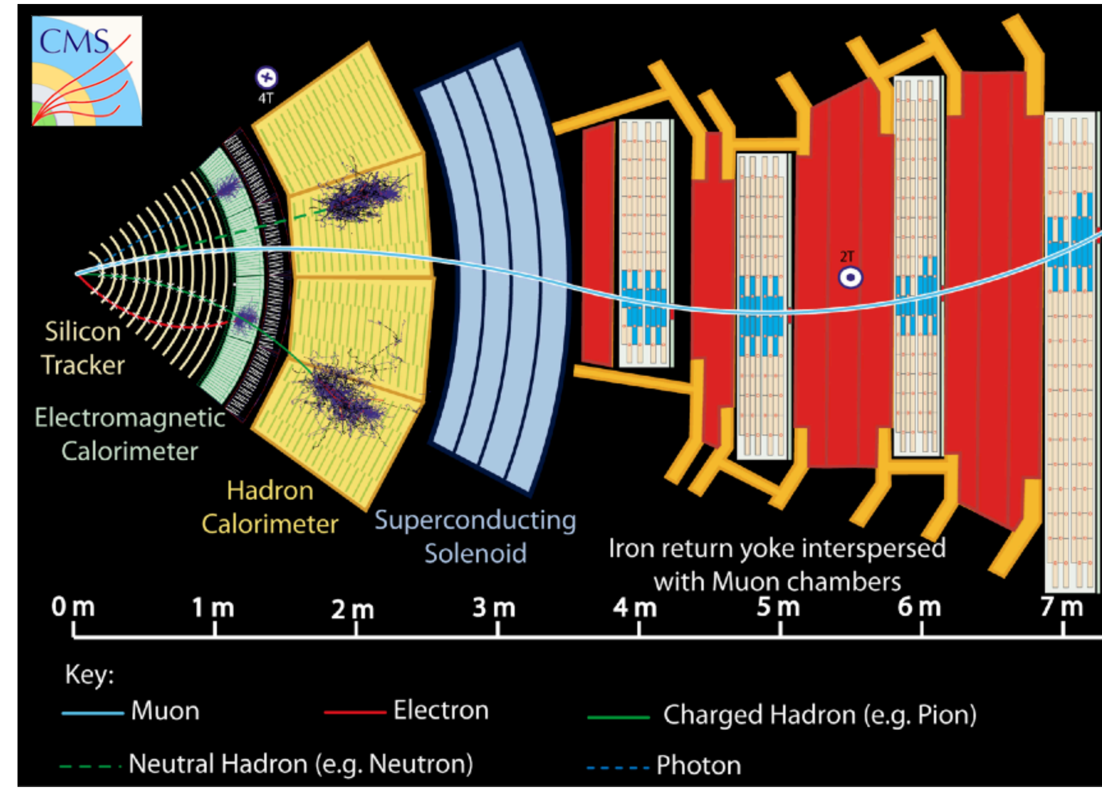
The lifetime of B^0 is about 1.5 ps that is impossible to measure directly.
Using Lorentz boost, it is converted to the flight distance. With the boost of Belle II, the length is 100 μm. (= Required vertex resolution.)

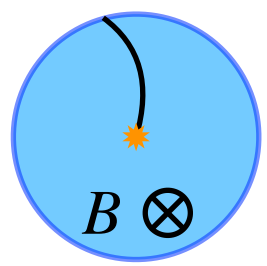
- Detect final state particles ($l^\pm, K^\pm, \pi^\pm$)
  - 3D tracking
  - Momentum measurement
  - Energy measurement
  - Particle identification
- Wide energy range: $\mathcal{O}(10)$ MeV - 6 GeV
- Not miss any particle = hermetic detector
- Radiation tolerance
- High sampling rate

(Common) Fundamental components of detector

- Detect final state particles ($l^\pm$, $K^\pm$, $\pi^\pm$, and γ)
  - 3D tracking
  - Momentum measurement
  - Energy measurement
  - Particle identification → Combination of detectors

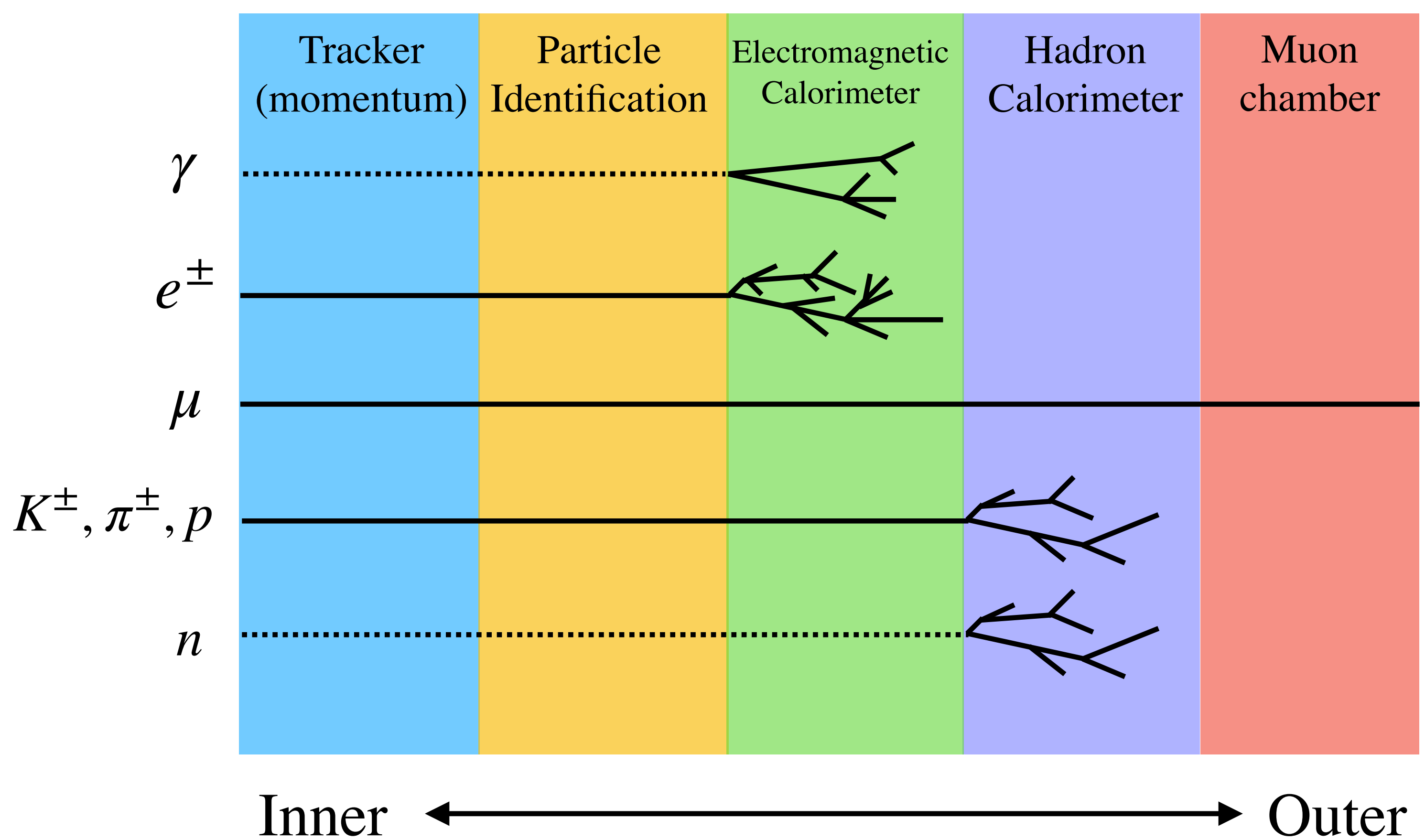
} Done by same detectors

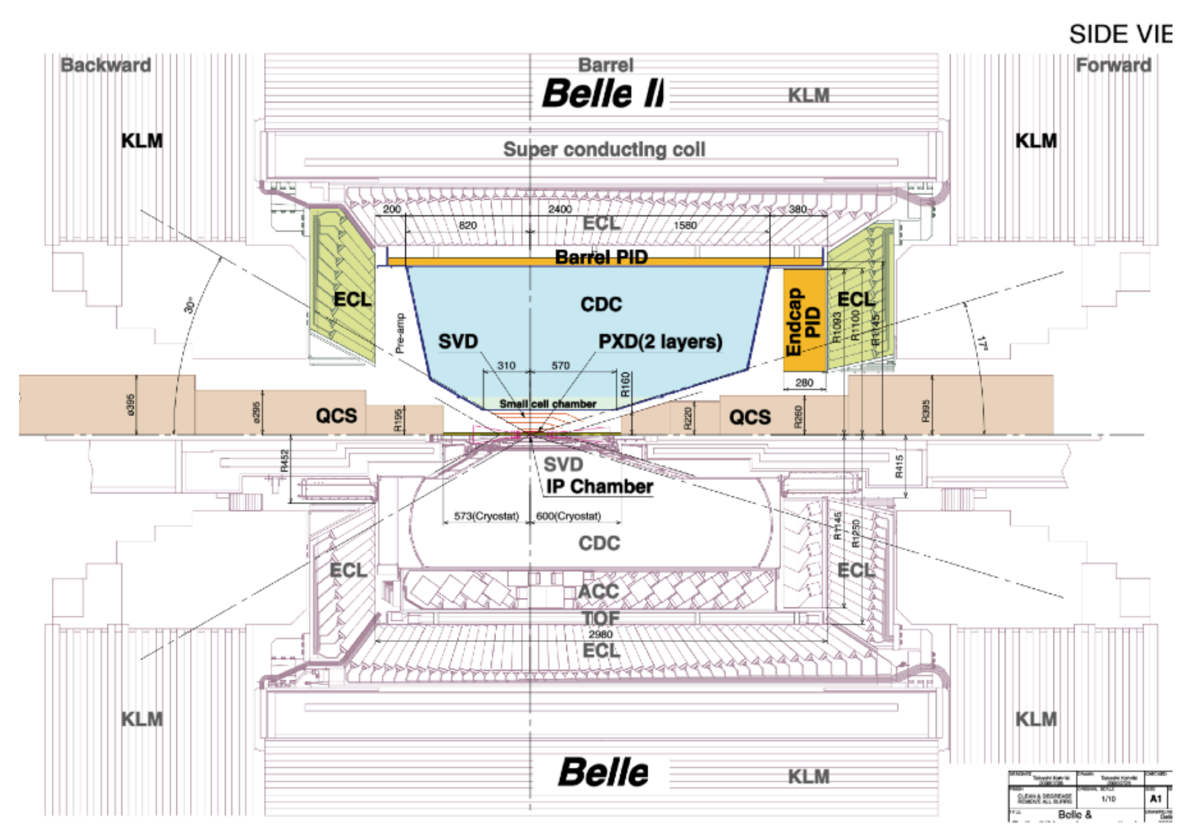




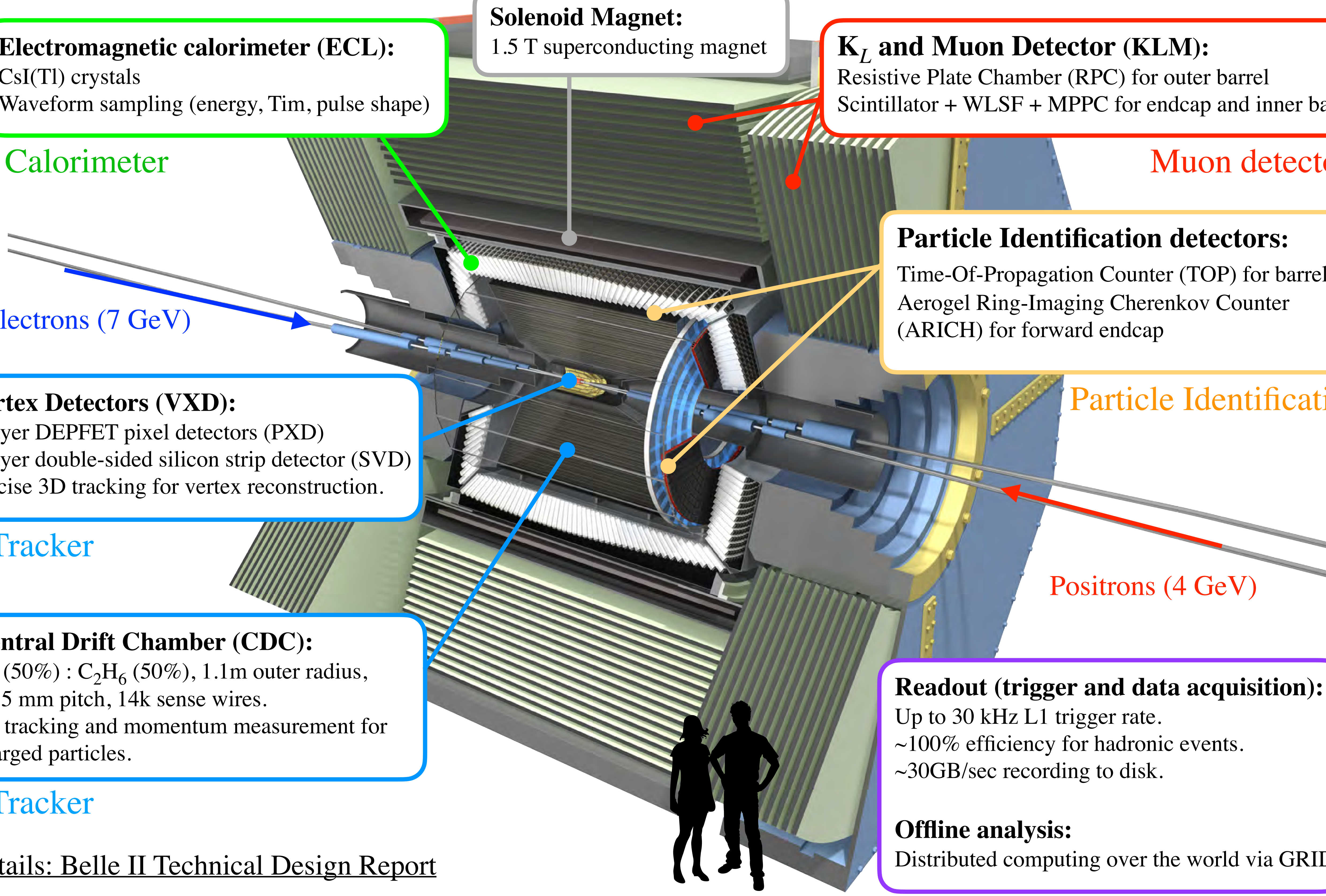
$p_T = 0.3Br$

(r : curvature)





Components of Belle II spectrometer



Electromagnetic calorimeter (ECL):
CsI(Tl) crystals
Waveform sampling (energy, Tim, pulse shape)

Solenoid Magnet:
1.5 T superconducting magnet

K_L and Muon Detector (KLM):
Resistive Plate Chamber (RPC) for outer barrel
Scintillator + WLSF + MPPC for endcap and inner barrel

Particle Identification detectors:
Time-Of-Propagation Counter (TOP) for barrel
Aerogel Ring-Imaging Cherenkov Counter (ARICH) for forward endcap

Vertex Detectors (VXD):
2 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detector (SVD)
Precise 3D tracking for vertex reconstruction.

Central Drift Chamber (CDC):
He (50%) : C_2H_6 (50%), 1.1m outer radius,
8-15 mm pitch, 14k sense wires.
3D tracking and momentum measurement for charged particles.

Readout (trigger and data acquisition):
Up to 30 kHz L1 trigger rate.
~100% efficiency for hadronic events.
~30GB/sec recording to disk.

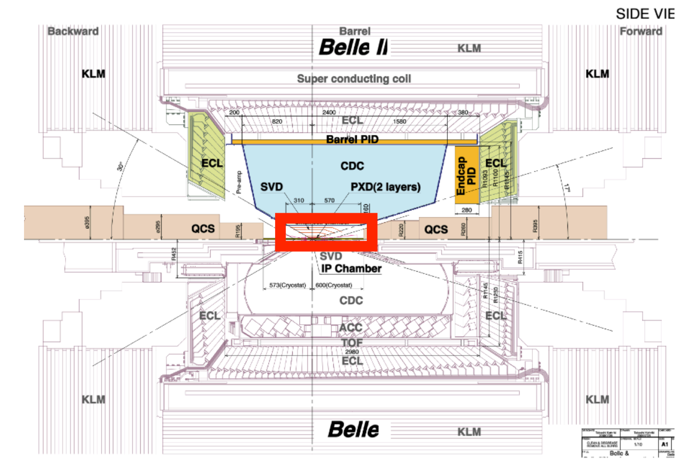
Offline analysis:
Distributed computing over the world via GRID

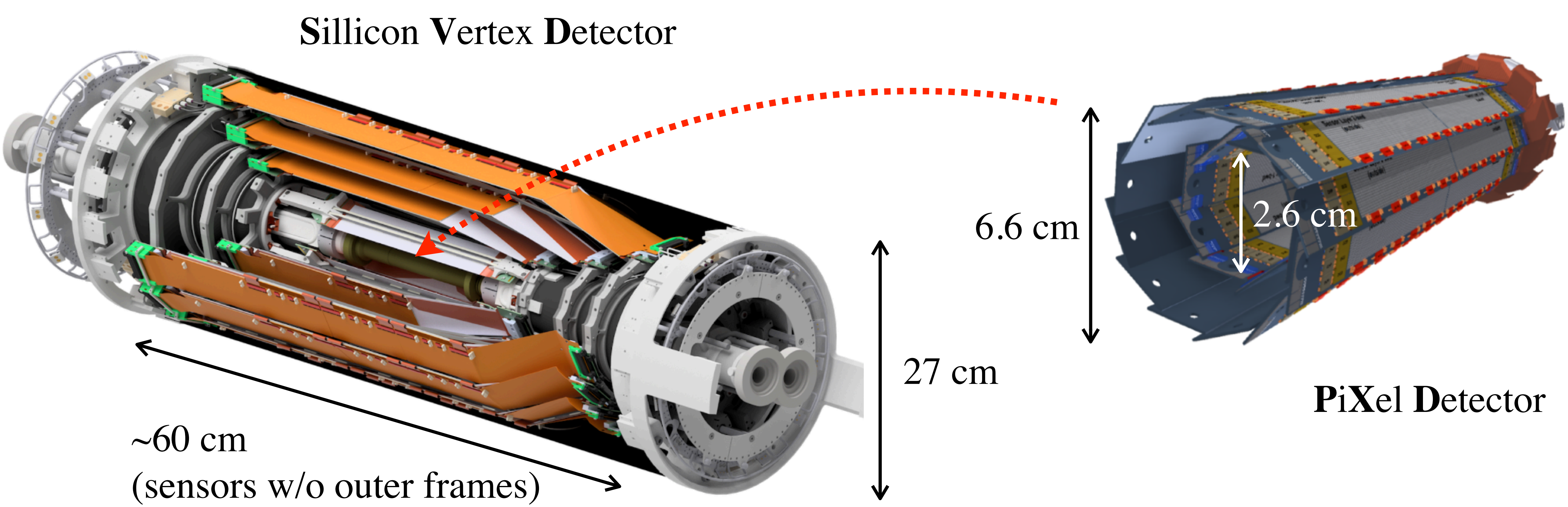
<u>Details: Belle II Technical Design Report</u>

Vertex Detector (PXD, SVD)

- The innermost part of Belle II spectrometer.
- Tracking in combination with CDC, but more precise.

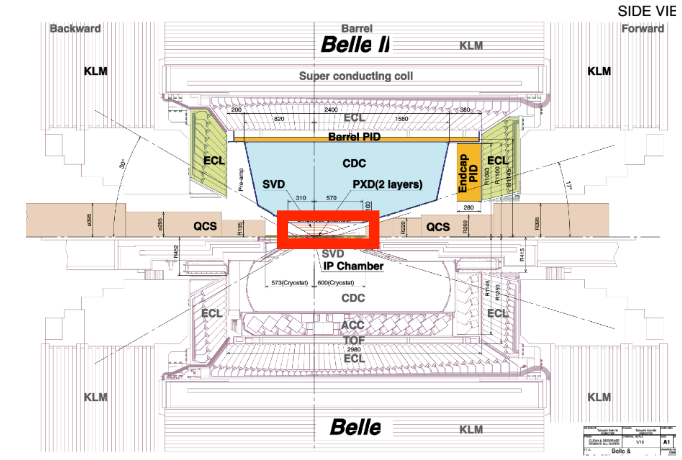
- Combination of 2 + 4 layers of 2D silicon sensors
  - 2 layers of DEPFET pixel sensors
  - 4 layers of double-sided orthogonal silicon-strip sensors





More details: Belle II Technical Design Report

Vertex Detector (PXD, SVD)



- The innermost part of Belle II spectrometer.
- Tracking in combination with CDC, but more precise.

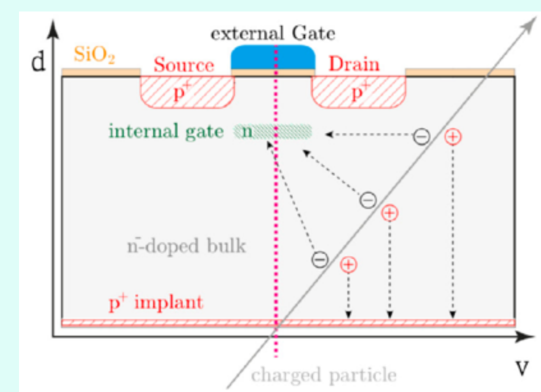
- Combination of 2 + 4 layers of 2D silicon sensors
  - 2 layers of DEPFET pixel sensors
  - 4 layers of double-sided orthogonal silicon-strip sensors

- Semiconductor detector. Reverse-biased PN-junction semiconductor creates a depletion layer, and the holes and electrons generated by charged particles are drifted to the electrode for detection.

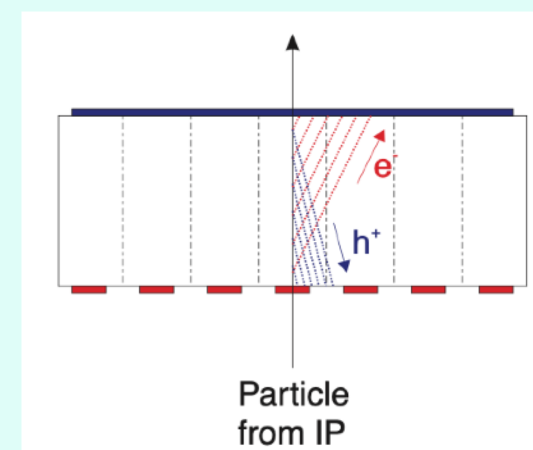
- The position resolution is about 15 μm.

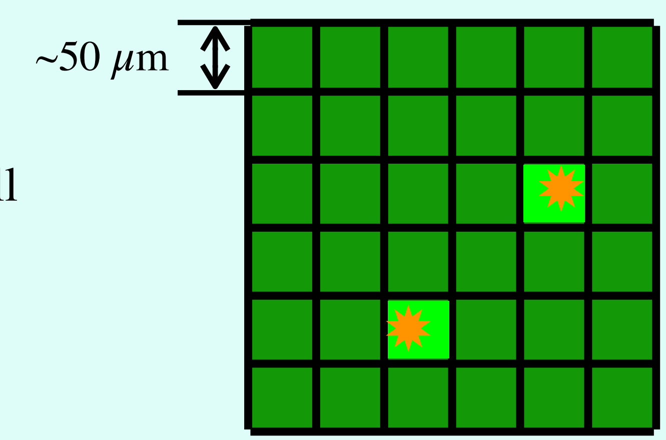
- PXD is a pixel detector and SVD is a 2D strip detector.
  - PXD is more precise and resistant to pile-ups.
  - SVD is faster and its data size is smaller.
  - The inner part is PXD for more resolution.
  - Outer region is SVD to cover larger volume with small data flow.

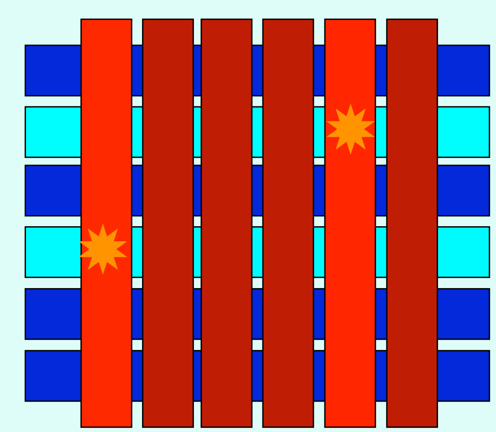
PXD



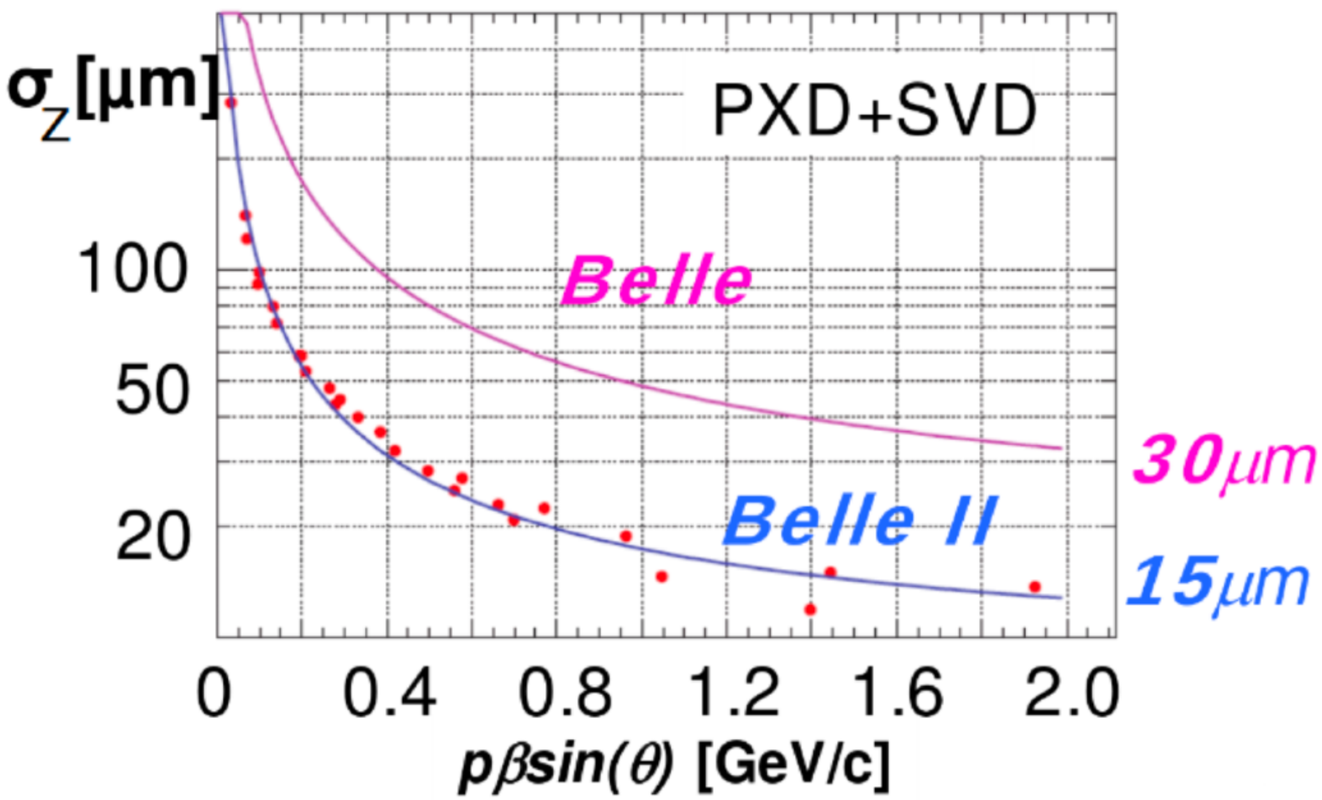
SVD



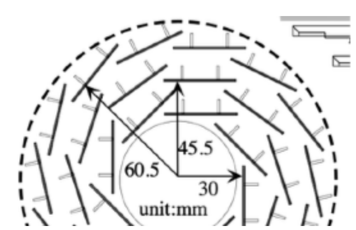




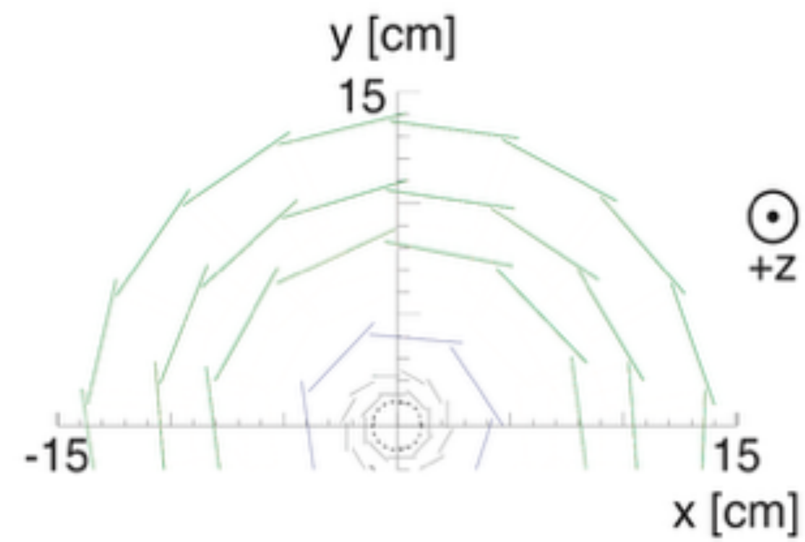
Larger and closer VXD improves vertex resolution σ_z



SVD of Belle



PXD + SVD of Belle II



Closer innermost layer : 30 mm → 13 mm

Larger outermost layer : 60.5 mm → 140 mm

The beam energies are changed from Belle (8.0 / 3.5 GeV) to Belle II (7.0 / 4.0 GeV).

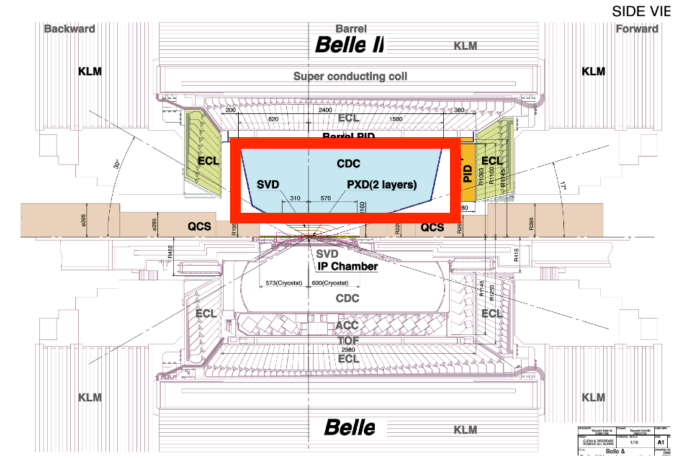
→ Beam related backgrounds are reduced, but boost ($\beta\gamma$) is decreased by 2/3.

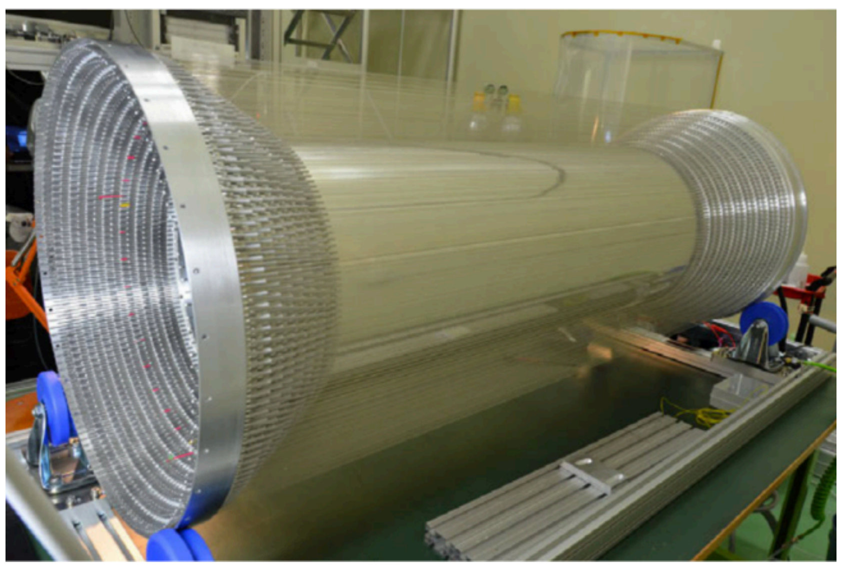
→ Vertex resolution is improved enough to compensate the loss. It is improved by factor of 2.

Central Drift Chamber (CDC)

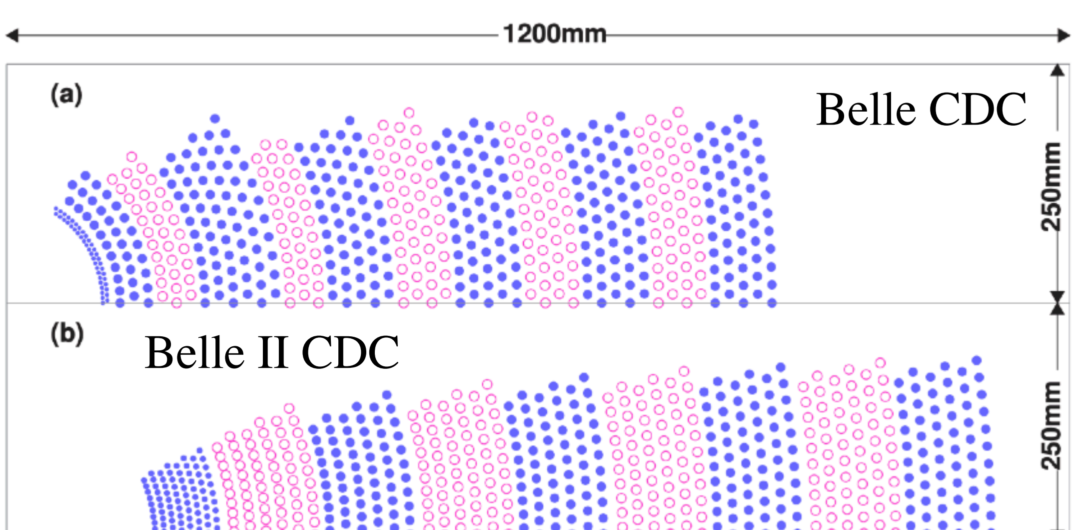
Details in Peter's talk on Wednesday

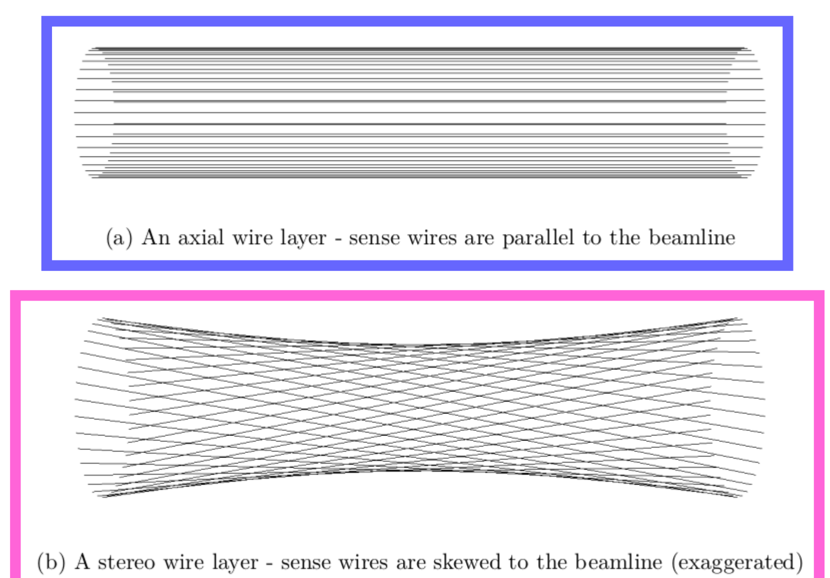
- Gas-filled cylinder in 1.5 T solenoidal magnetic field.
- The main tracking device.
- Additionally, a part of particle identification and momentum measurement
- Data without CDC has little value…the heart of Belle II.





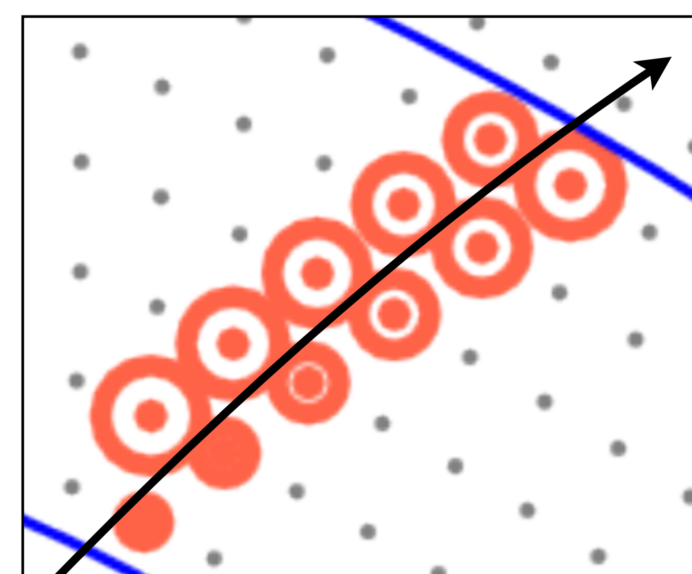
- Drift time for earliest hit on a sense wire gives radius of the tangent circle for that wire.
- Some of layers have wires tilted slightly to measure z position.
- Helical trajectory reconstructed from the circles is converted to 3D momentum using known magnetic field.





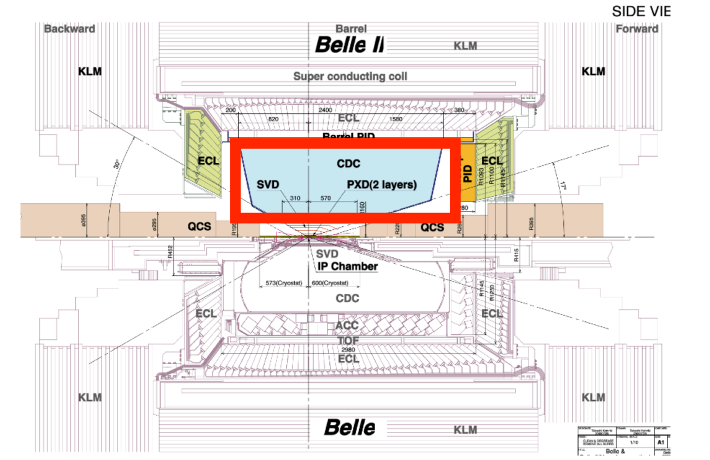
(a) An axial wire layer - sense wires are parallel to the beamline

(b) A stereo wire layer - sense wires are skewed to the beamline (exaggerated)

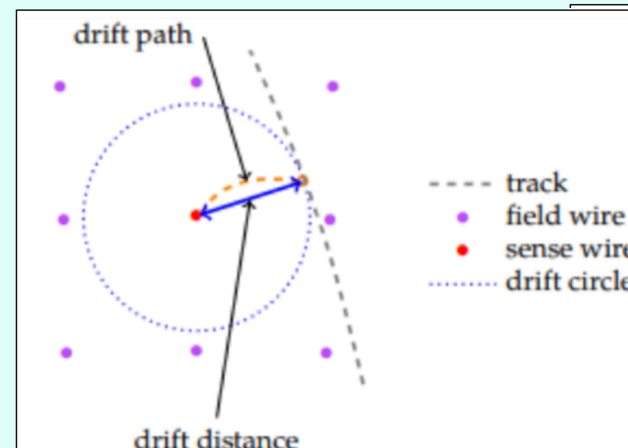


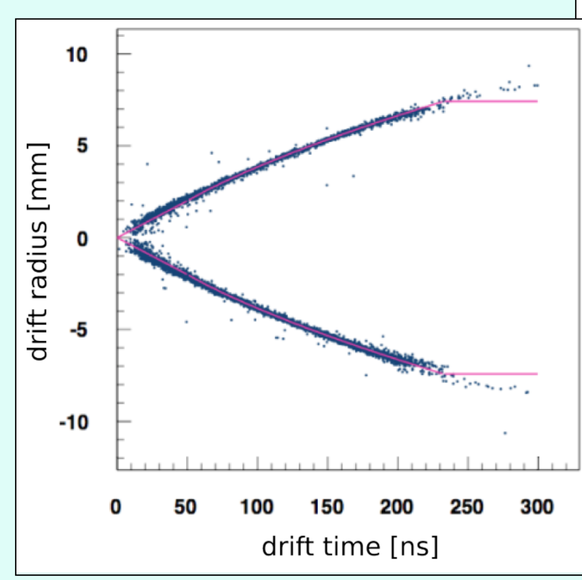
Central Drift Chamber (CDC)

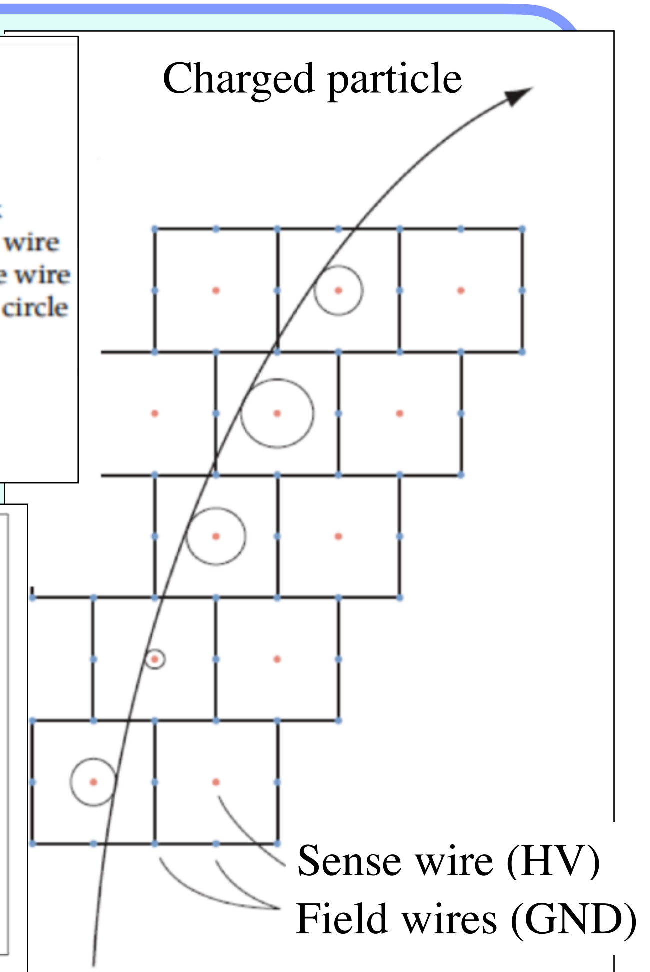
- Gas-filled cylinder in 1.5 T solenoidal magnetic field.
- The main tracking device.
- Additionally, a part of particle identification and momentum measurement
- Data without CDC must be useless…the heart of Belle II.



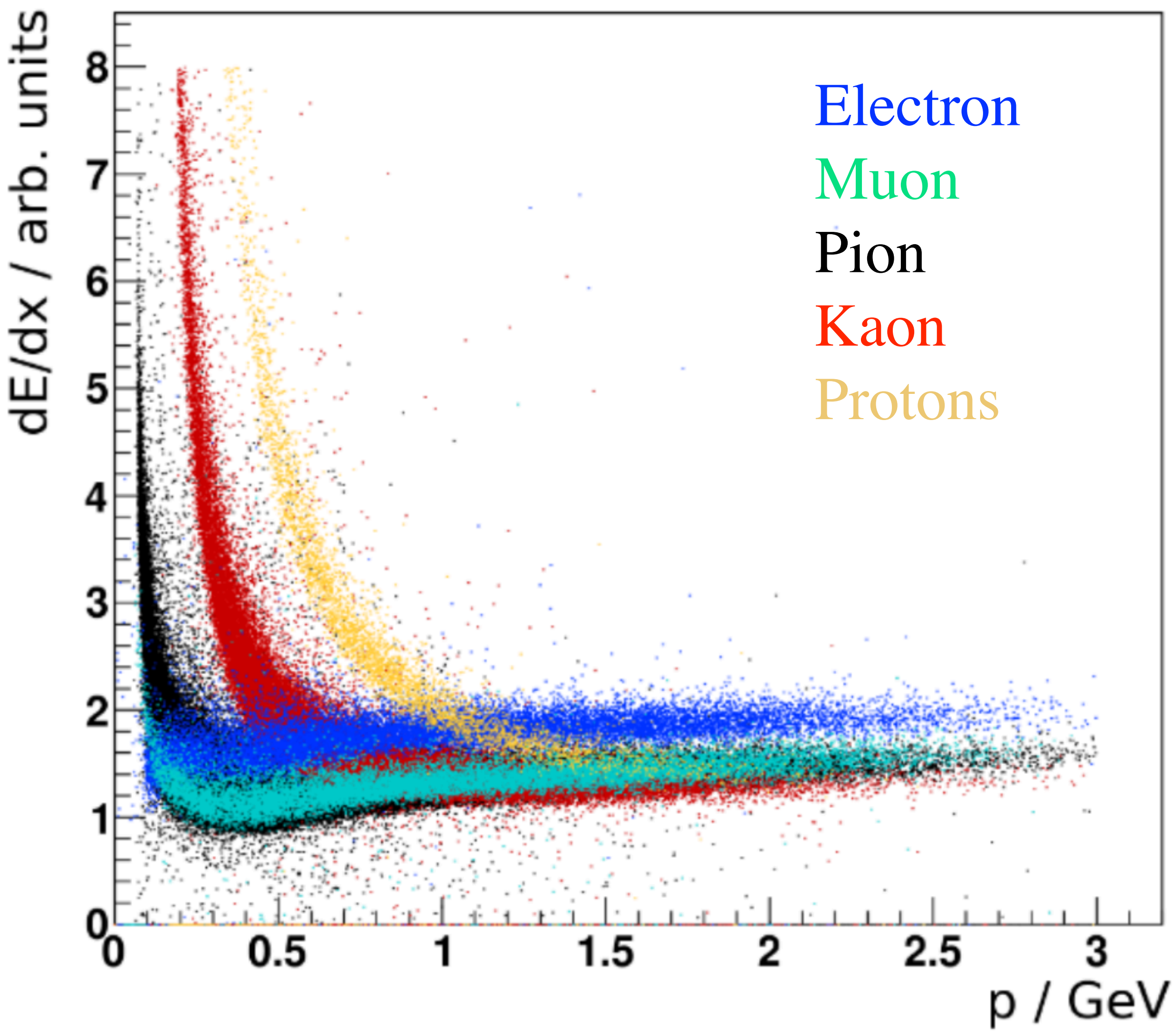
- Consists of "cells" of drift chamber.
  - Each sense wire (HV) is surrounded by field wires (GND). 1 cell = 1 sense wire + 8 field wires.
  - Charged particle ionizes gas and produce electrons.
  - Electrons drift to the sense wire.
  - By electron avalanche, the signal is amplified.
- Based on the relation between the drift radius and time, trajectory is determined.
  - CDC resolution is too coarse to separate two *B* mesons vertices.
  - CDC track is extrapolated to VXD and vertices are determined in combination with VXD.
- Energy deposit on each wire is the key of PID function.







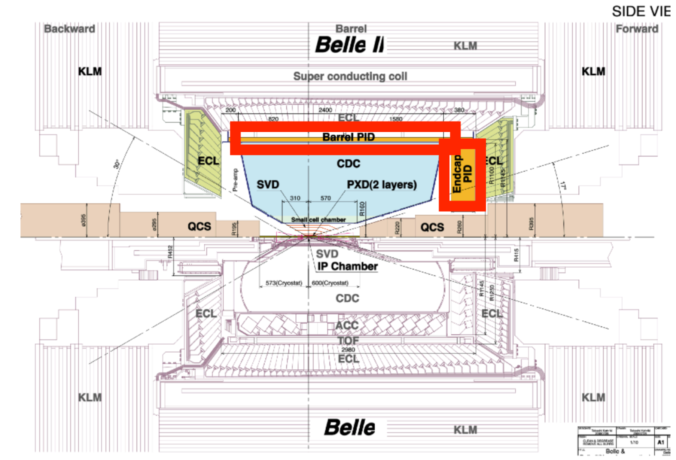
Particle identification in CDC



- CDC also contributes to identify the particle.
- Slight energy loss in gas (dE/dx) for a given momentum differs for each particle.
- dE/dx in this gas depends only on $\beta\gamma = p/m$.
- One of strongest tools for PID in $p < 1$ GeV region

Particle identification detectors (TOP, ARICH)

- Placed in barrel region (TOP) and forward end cap (ARICH).
- Designed to separate kaons and pions in 0.5 - 4.0 GeV.
- Measure velocity of particles using Cherenkov-light cone angle, then calculate mass using momentum provided by CDC.

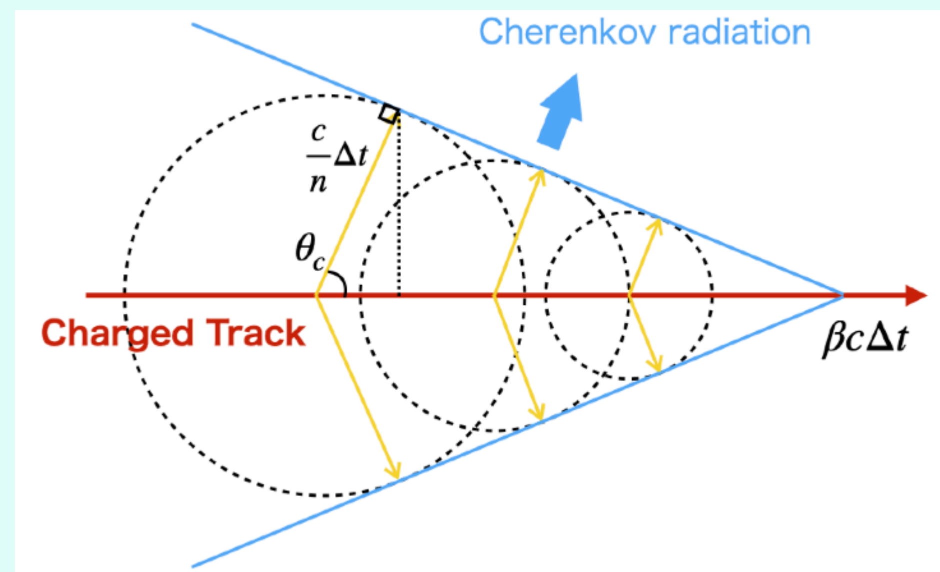


Time **O**f **P**ropagation / **A**erogel **R**ing **I**maging **CH**erenkov

$$\cos\theta_c = \frac{c/n}{\beta c} = \frac{1}{n\beta}$$

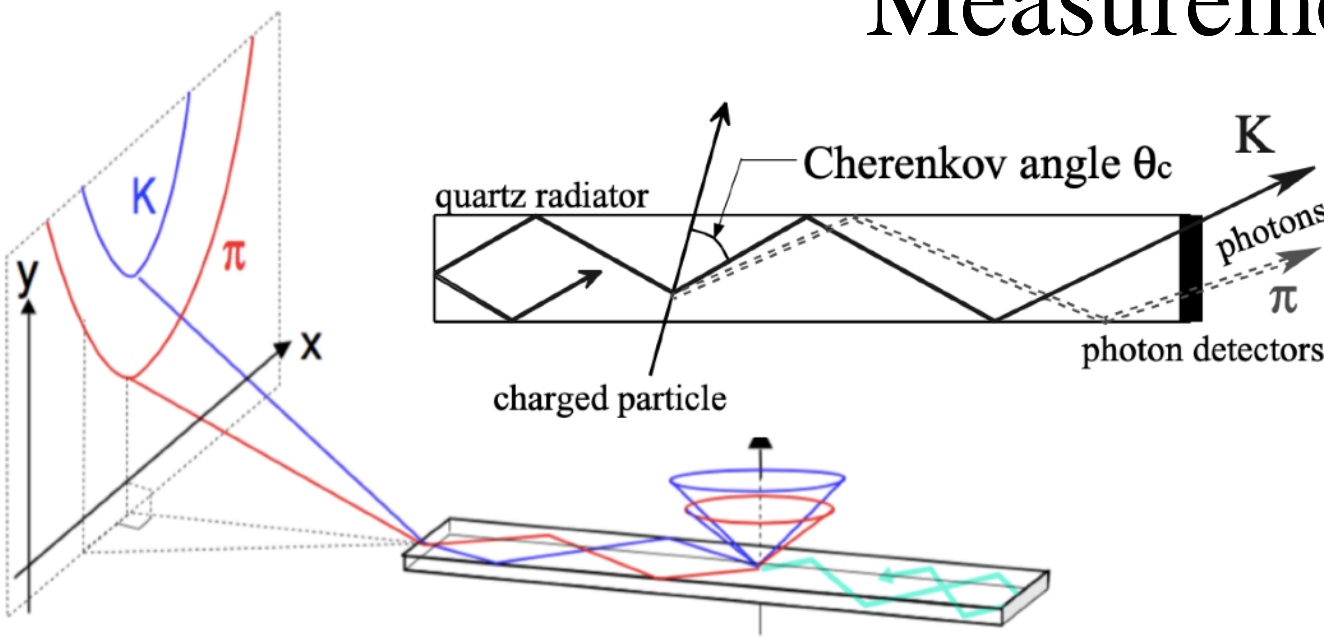
$$p_{\mathrm{min}} = \frac{m}{\sqrt{n^2\cos^2\theta_c - 1}} > \frac{m}{\sqrt{n^2 - 1}}$$

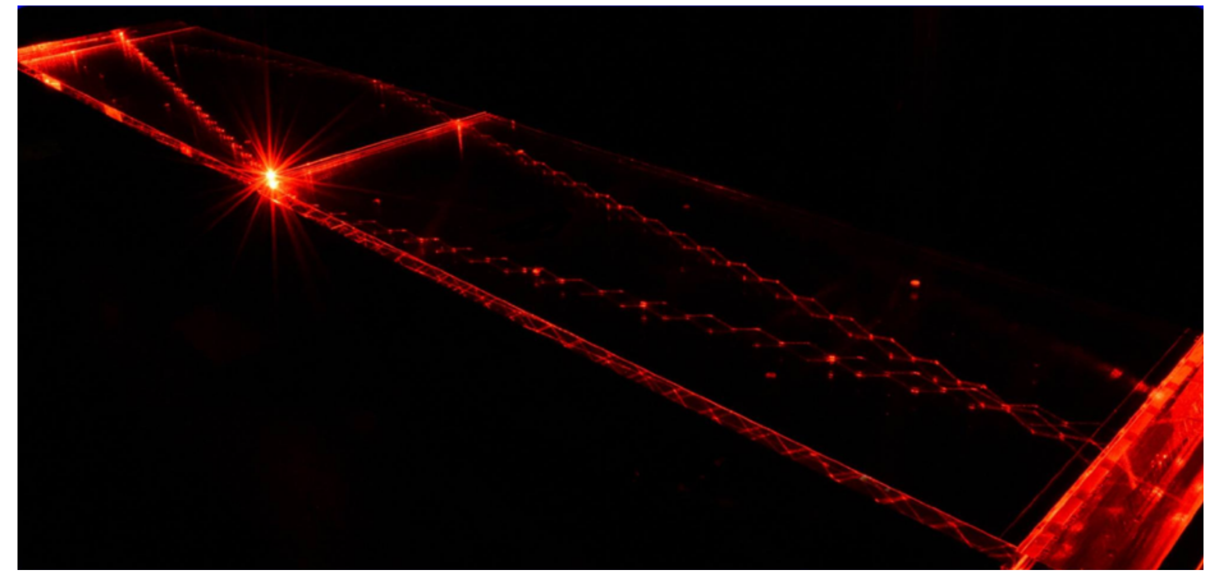
- Cherenkov radiation - "Light shock wave"
  - When a charged particle moves faster than the speed of light in a certain material ($v = \beta c > c/n$), a light shock wave called Cherenkov radiation is generated.
  - The angle of radiation depends on the velocity and refractive index.
  - Larger angle = faster velocity = lighter particle.

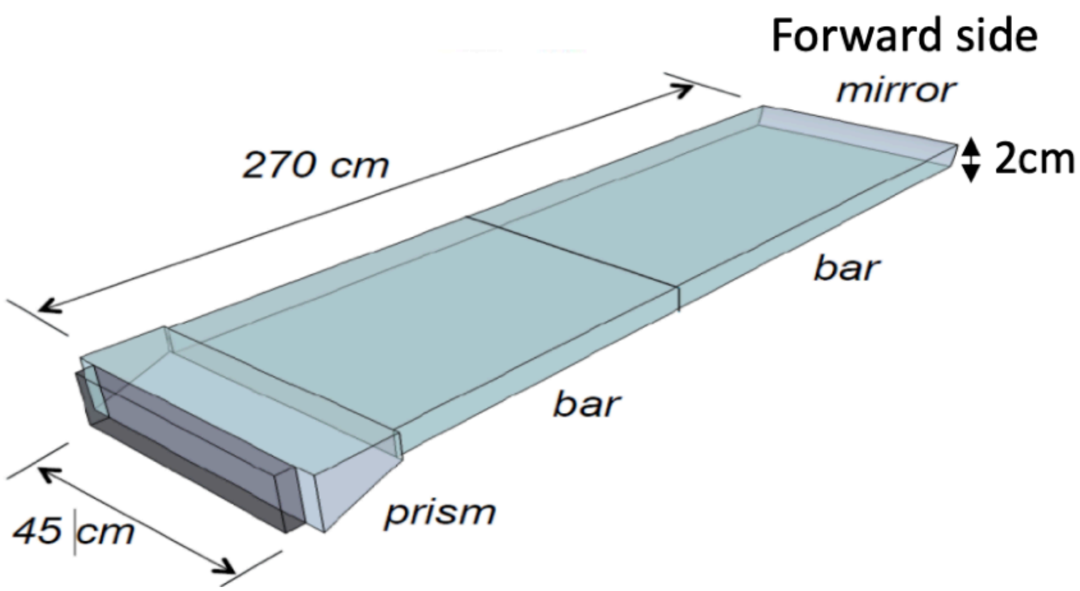


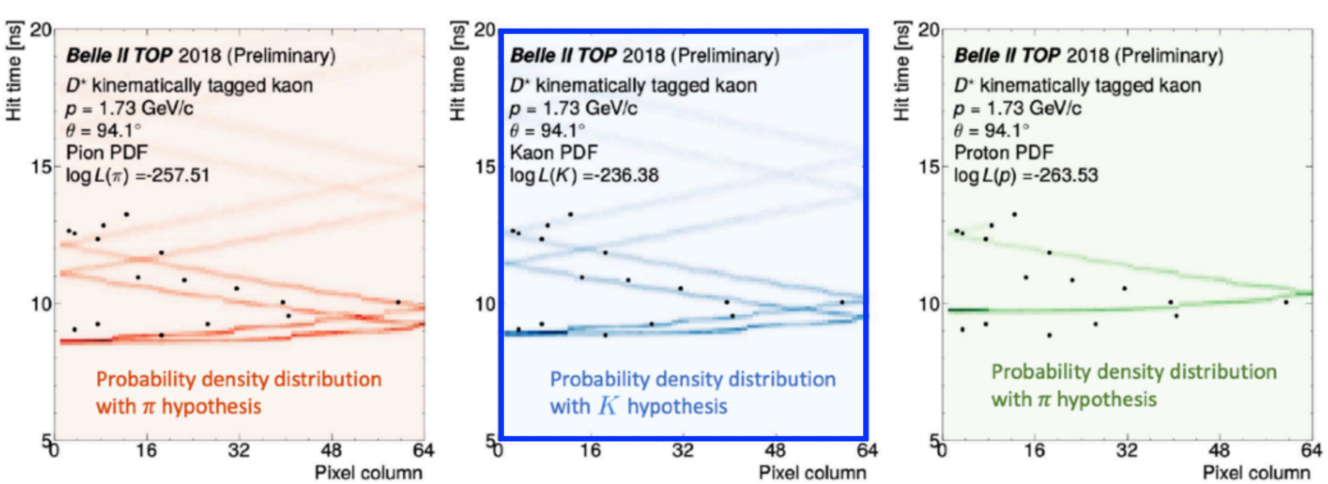
- Because momentum is known by CDC, mass can be calculated from the velocity.
  - TOP calculate the angle from propagation time.
  - ARICH calculate the angle from ring image.
  - The refractive indices are tuned for K/π separation.

Measurement of TOP



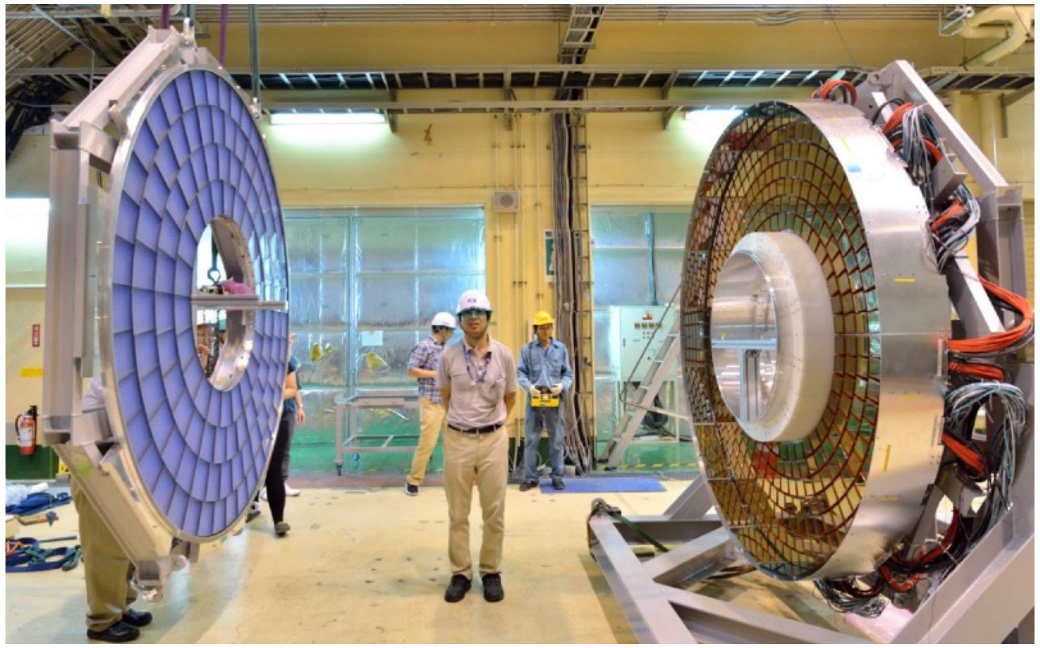


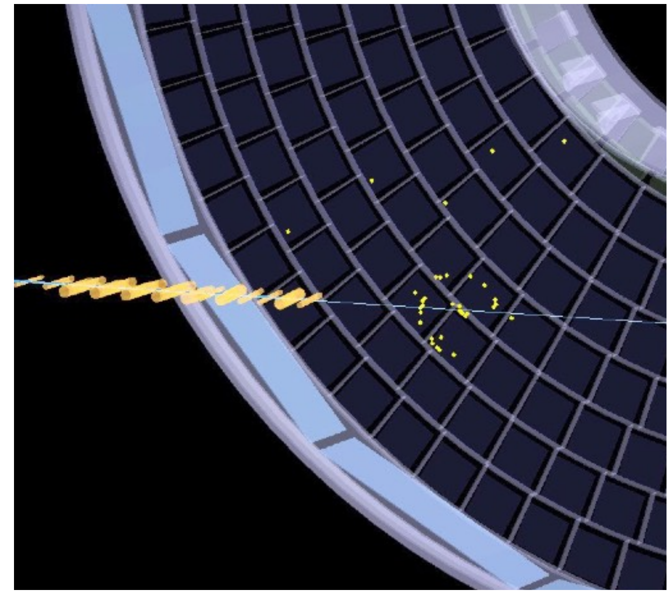


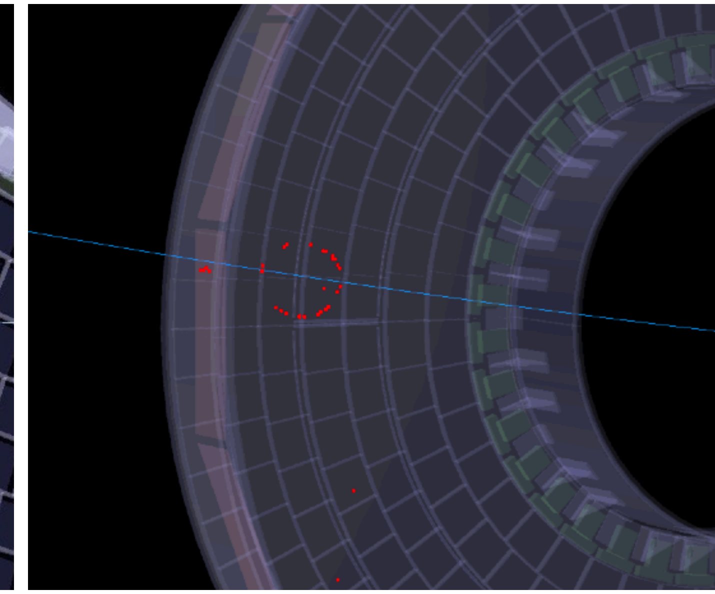


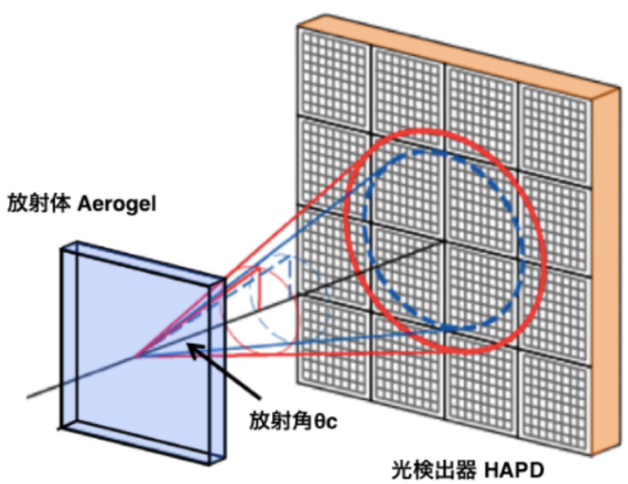
- Cherenkov light is generated in a quartz bar.
- Photons propagate to the sensor while reflecting inside the quartz bar.
- Photons arrive at sensors at different time and location but preserve information about Cherenkov angle.
- Fit the angle distribution by each hypothesis and take the most suitable one.
  (In the example, the particle looks like a kaon.)

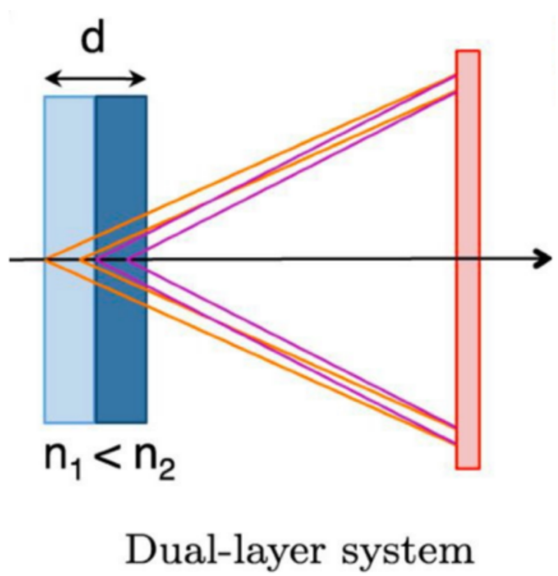
Measurement of ARICH

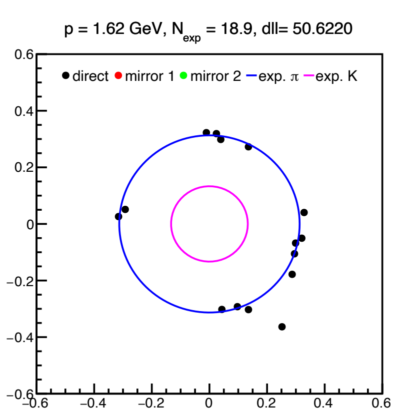


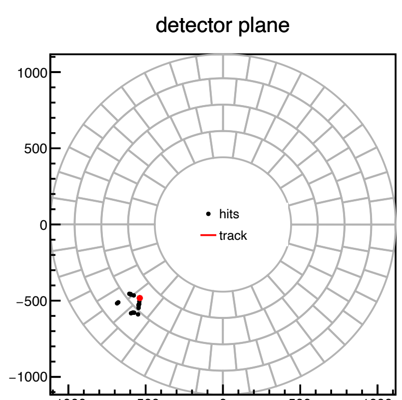


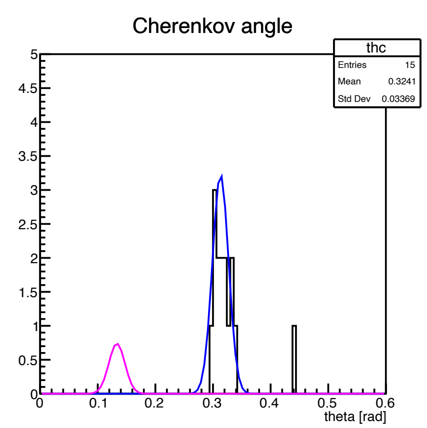








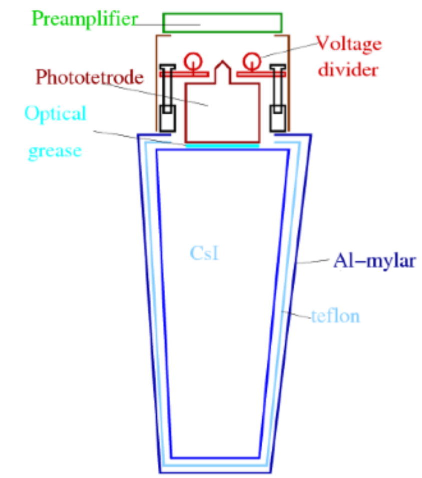


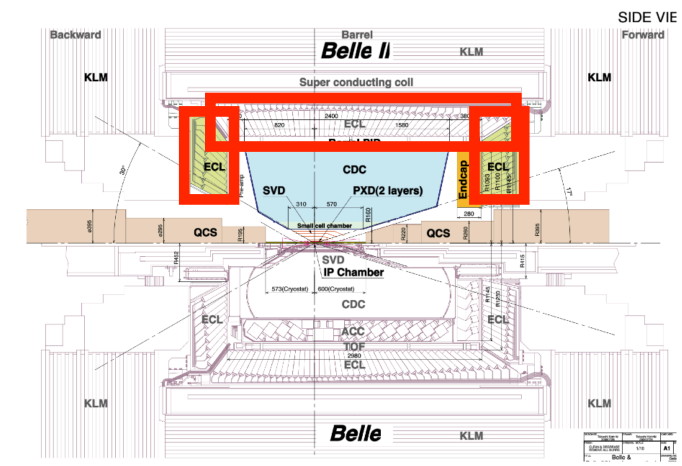


- Cherenkov light is generated in aerogel tiles and directly incident on the sensors.
- Dual layer of aerogel focuses light onto sensors: double the light without a blurry image.
- Fit the angle distribution by each hypothesis and take the most suitable one.
  (In the example, the particle looks like a pion.)

Electromagnetic Calorimeter (ECL)

- Outside of PID detectors, covering all directions.
- The most important role is photon detection. Trigger generation, e/K_L identification, and luminosity measurement.



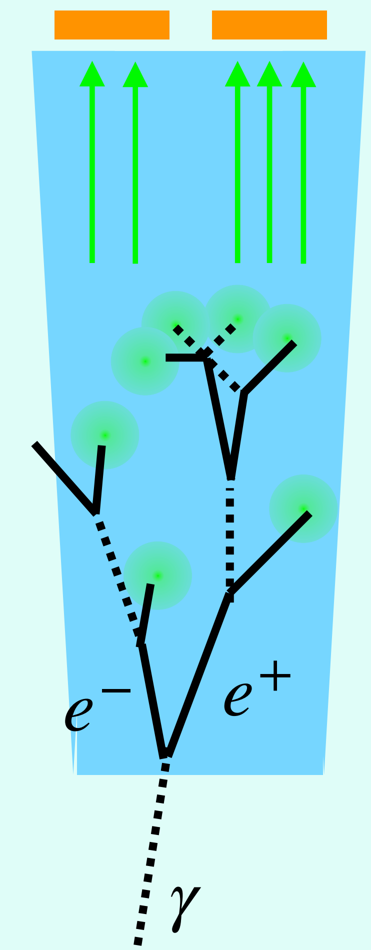


- Consists of CsI (TI) Crystal bars (scintillator) and photon sensors.
  - Incident photons or electrons generate an electromagnetic shower: branches of bremsstrahlung (γ production) and e^+e^- pair production.
  - Ionized atoms emit scintillation light on de-excitation. This visible light is corrected
  - The energy deposit is well proportional to the particle energy. (The ratio depends on the type of particle.)

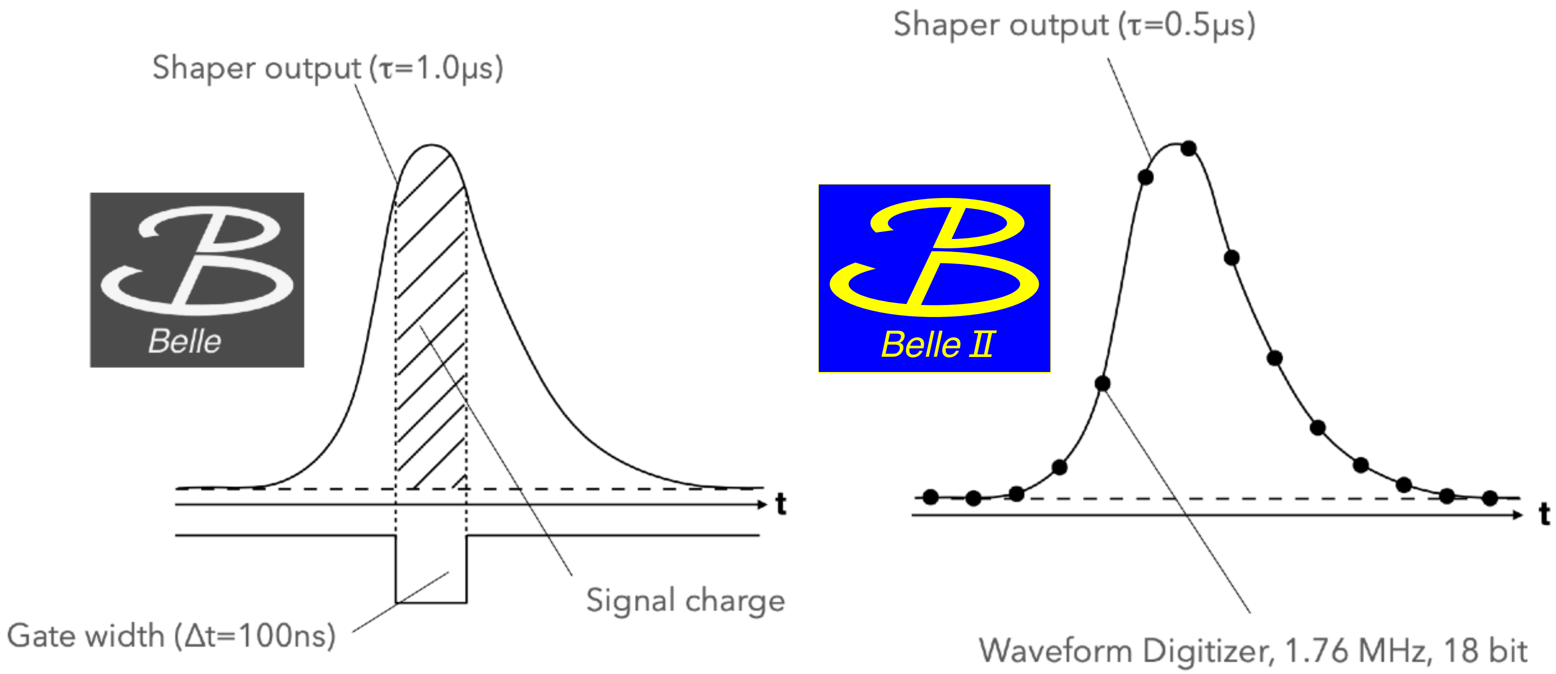
- The "shower shape" = width and depth varies depending on the incident particles.
  - Because of directions of initial bremsstrahlung photons.
  - In general, hadrons create wider showers.

- **Only ECL can detect photons.** ISR, FSR, and π^0 detection depend on ECL.
  - Required energy range is 20 MeV - 7 GeV.
  - To reconstruct π^0, energy resolution need to be < 5 MeV and position resolution need to be <10 mm.

Loop of pair production and bremsstrahlung.

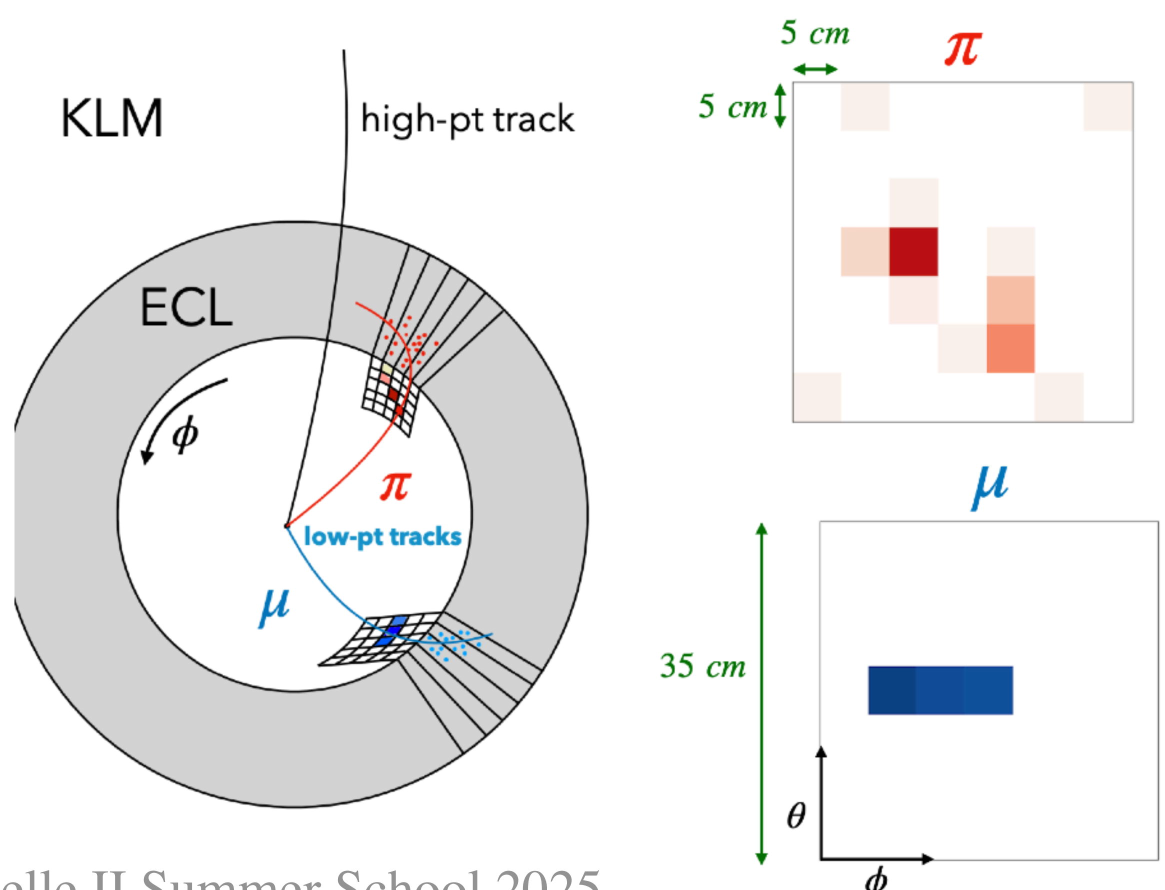


Electromagnetic Calorimeter (ECL)

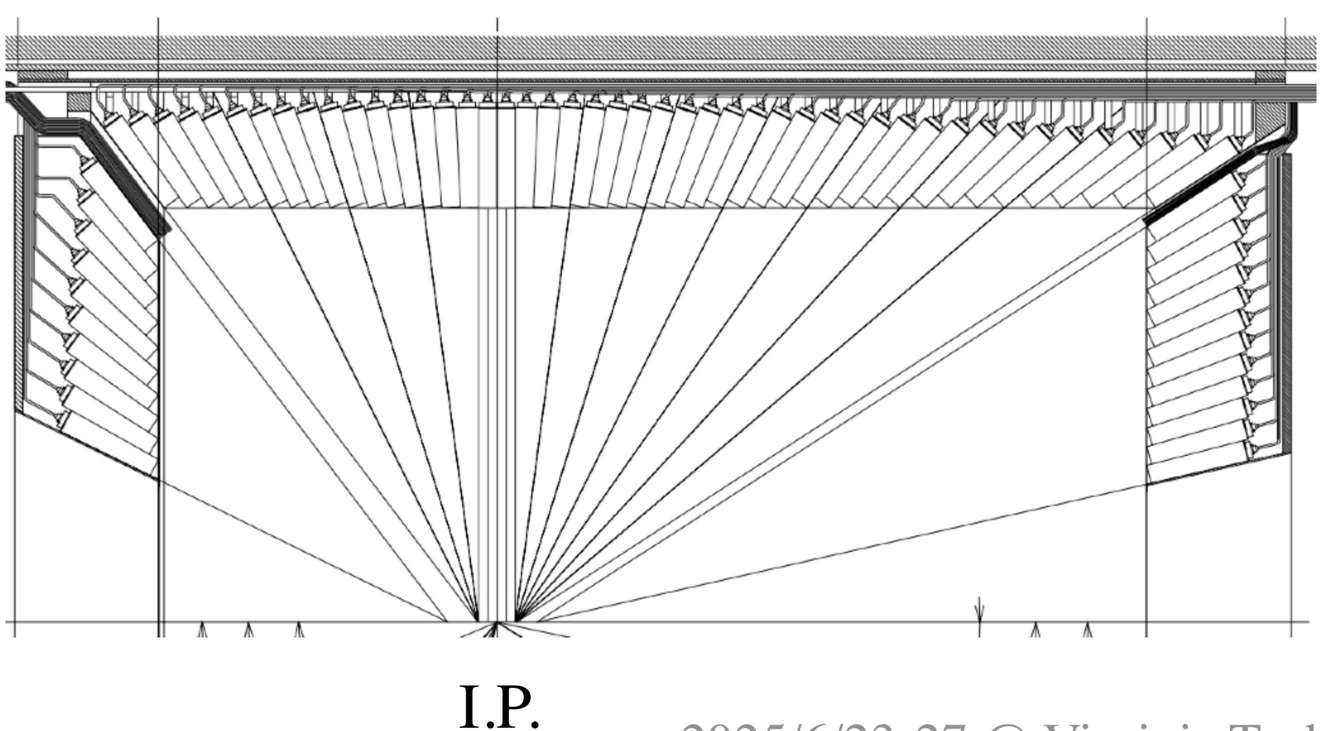


- Waveform sampling is implemented in Belle II ECL.
- It allows better noise rejection.

PID for Low p_T track by shower shape



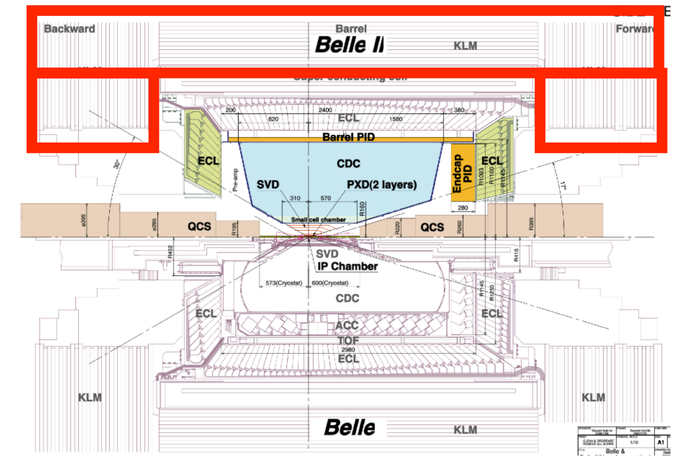
There are ~ 10,000 crystals, but no one looks I.P. directly. To prevent particles from flying along the crystal walls and passing through ECL without generating a signal.



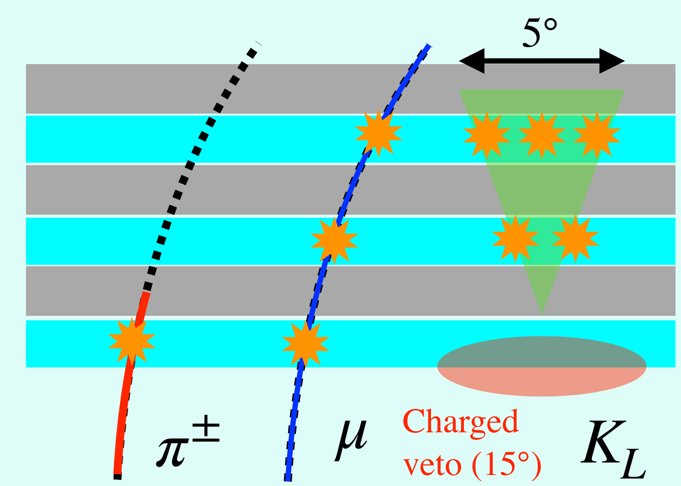
K_L^0 and μ (K-Long and Muon) detector

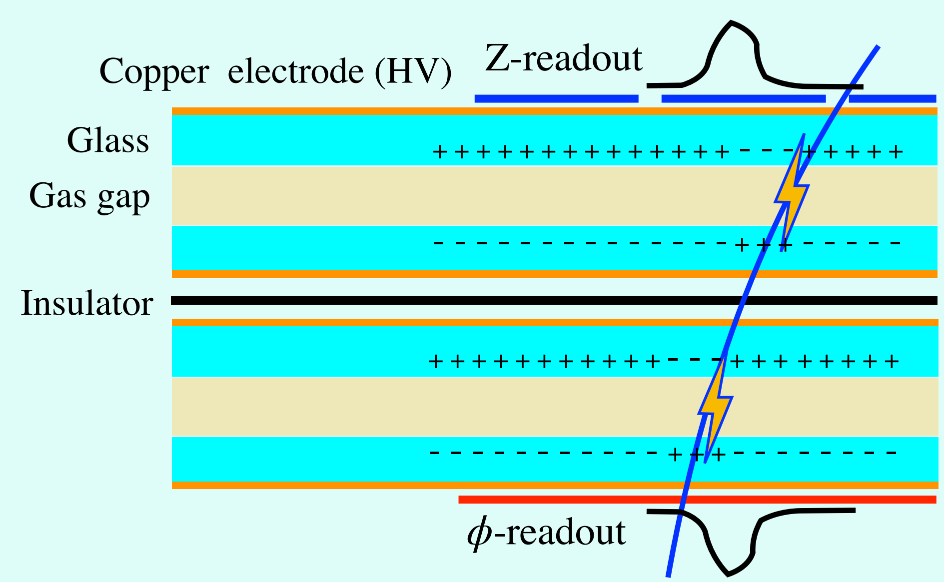
Koninklijke Luchtvaart Maatschappij

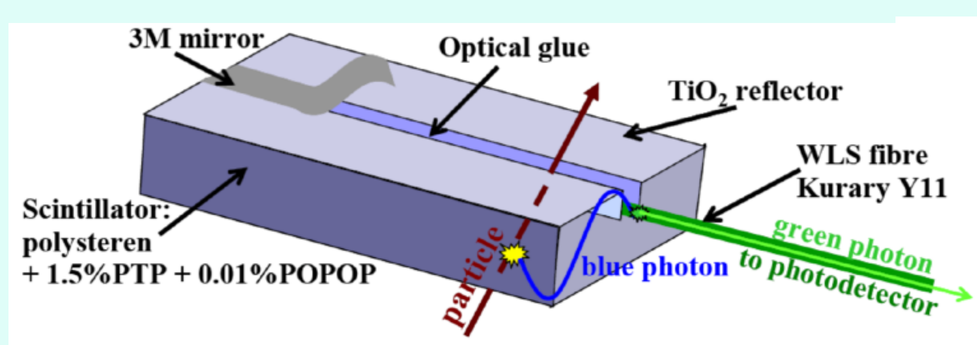
- Outermost layer of Belle II. For long-lived particle detection.
- Layered structure of steel plates and RPC / Scintillator.
- Detect secondary particles from a shower generated in a steel plate
- Originally built in Belle. Big, sturdy, and cheap.



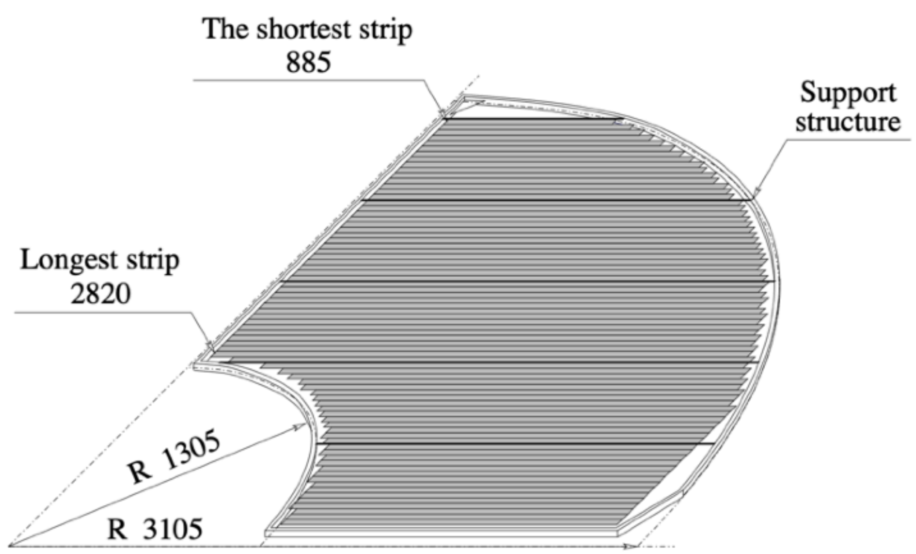
- Typically, only muons can penetrate steel plates and leave signals on detectors.
  - Muons can be easily distinguished, since other particles stop in inner layers.
  - Need track information from CDC.
- For K_L, secondary particles from hadronic shower in steel are used, since neutral particles give no signal.
  - Clustering hits in a specific region, vetoing charged tracks.
  - In combination with ECL clusters, identify K_L.
- The detector layers consist of RPC (barrel) and scintillators (end caps.)



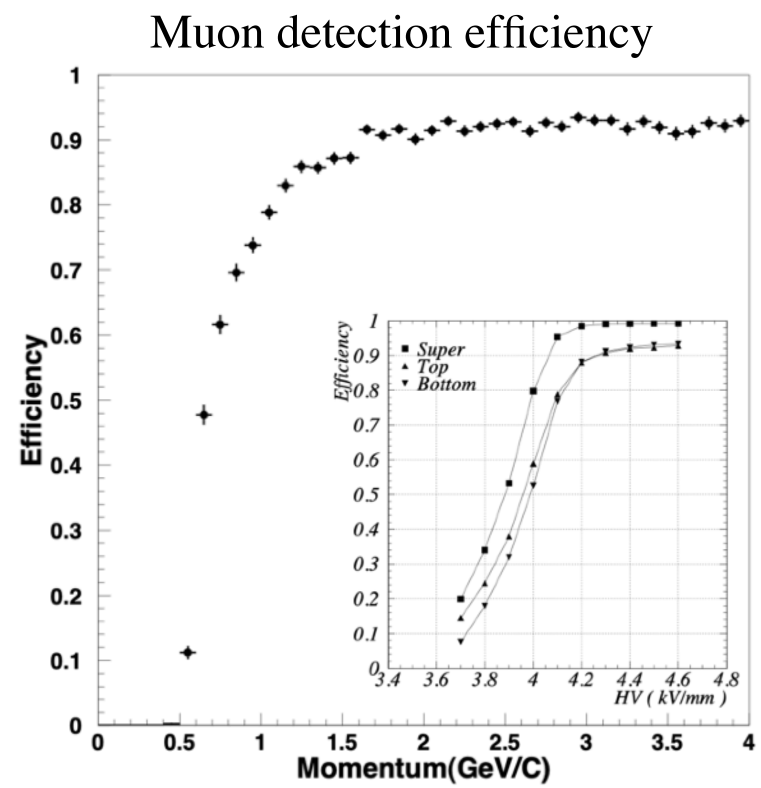




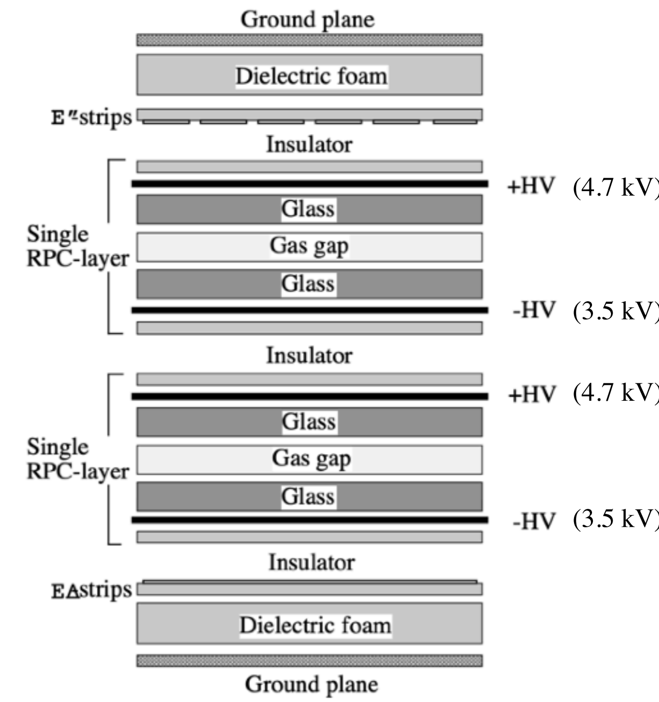
長寿命粒子検出 (KLM)



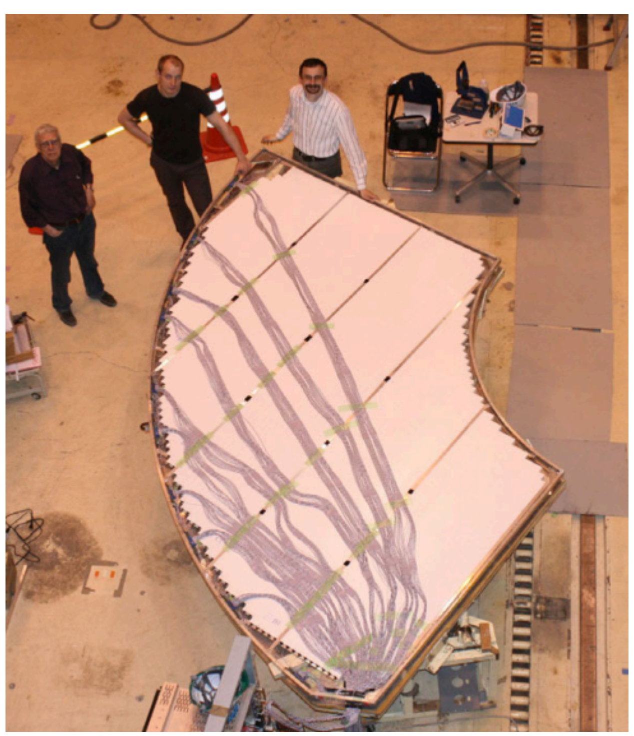
The shortest strip
885
Support
structure
Longest strip
2820
R 1305
R 3105

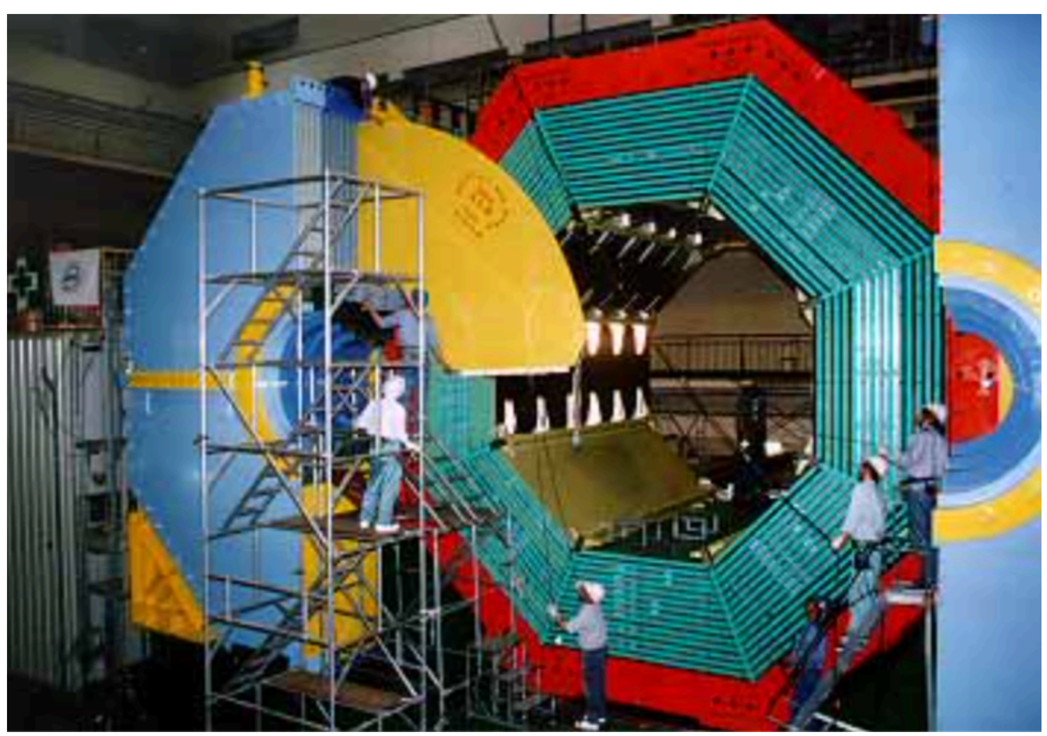


Muon detection efficiency
Efficiency
Momentum(GeV/C)
0
0.5
1
1.5
2
2.5
3
3.5
4
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Super
Top
Bottom
HV (kV/mm)
3.4
3.6
3.8
4
4.2
4.4
4.6
4.8



Ground plane
Dielectric foam
Insulator
Single
RPC-layer
Glass
Gas gap
Glass
+HV (4.7 kV)
-HV (3.5 kV)
Insulator
Single
RPC-layer
Glass
Gas gap
Glass
+HV (4.7 kV)
-HV (3.5 kV)
Insulator
Dielectric foam
Ground plane



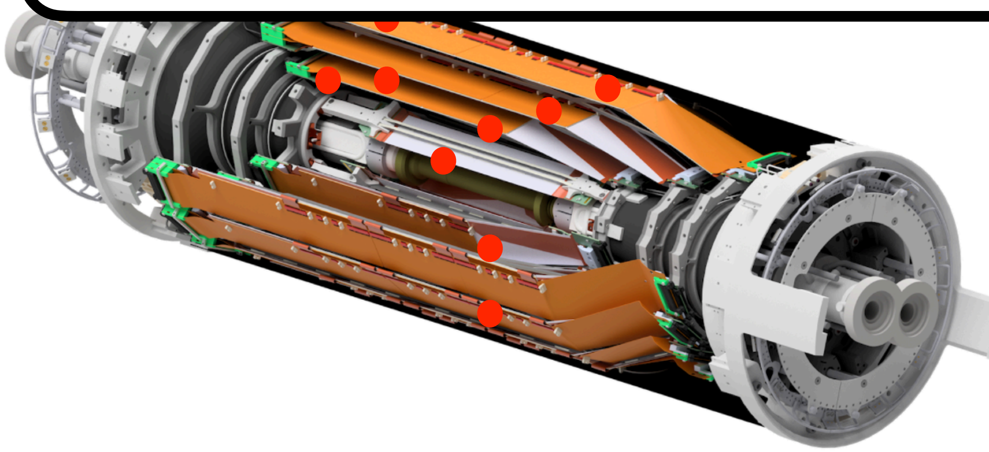


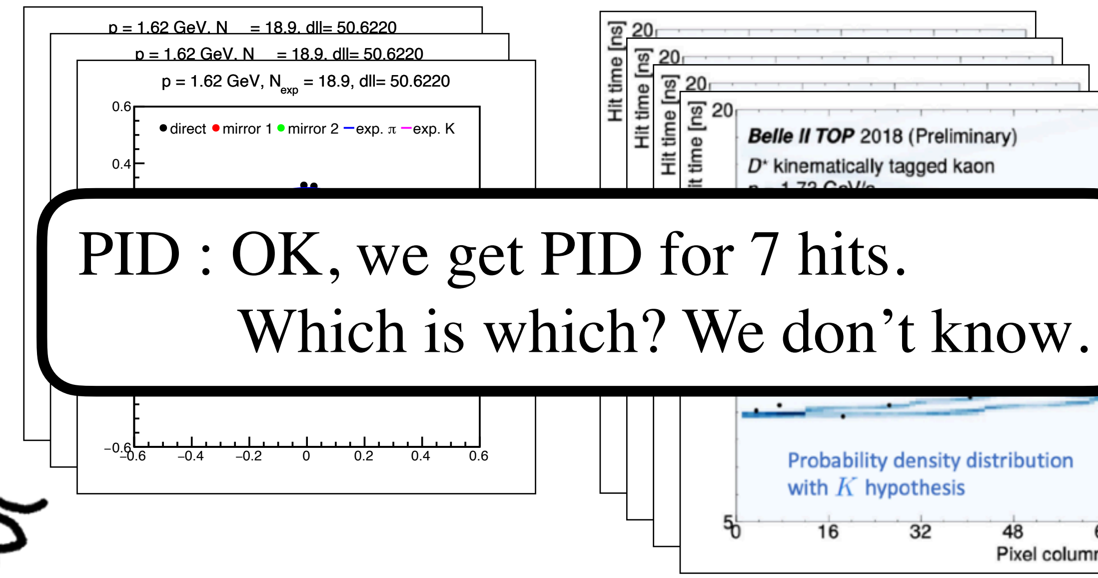
WATER LEAK
SENSOR

Data Acquisition and Trigger (DAQ & TRG)

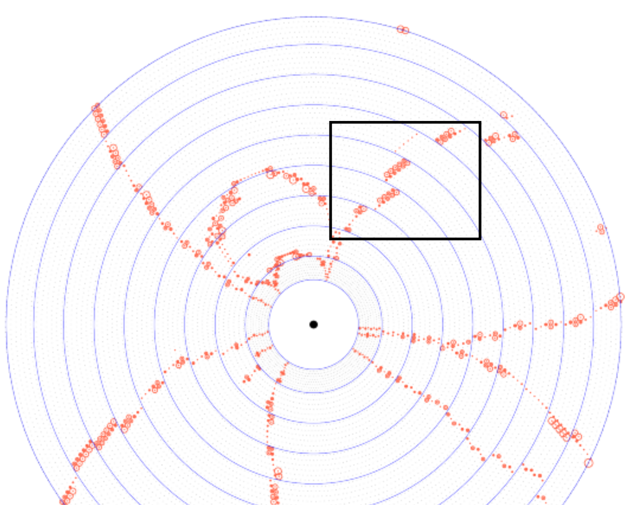
- **Integrate information from all detectors and build a snapshot of an “event”.**
- Select valuable events excluding “useless” (= well known and too many) events such as Bhabha.

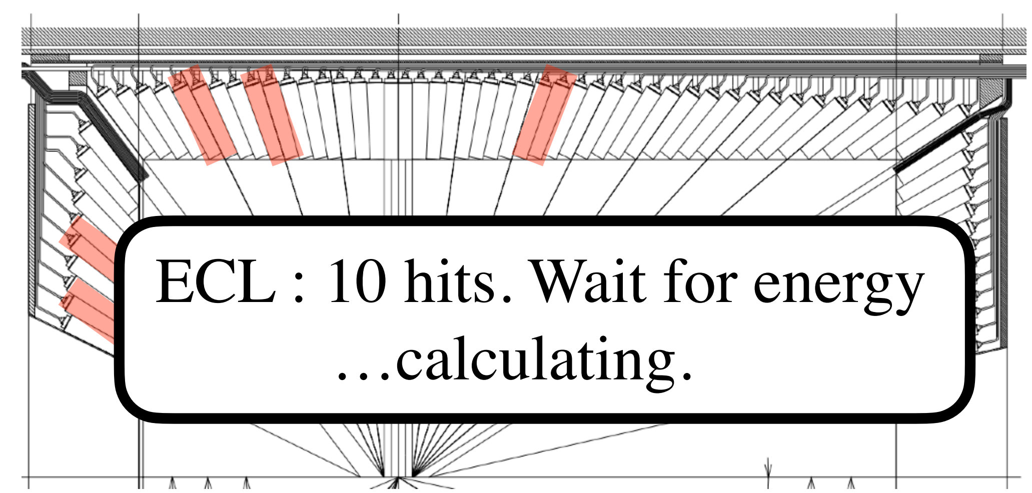
VXD: Wait. Too much raw data…
OK, 9 hits. The coordinates are…





PID : OK, we get PID for 7 hits.
Which is which? We don’t know…





ECL : 10 hits. Wait for energy
…calculating.

CDC : Here is the hit map.
There seems to be 8 tracks.

KLM

2 muon-like hits.
Give me track information.
Then, I will check other hits…

Data Acquisition and Trigger (DAQ & TRG)

- Integrating information from all detectors and build a snapshot of an "event".
- **Select valuable events excluding "useless" (= well known and too many) events.**

- The rate and data size of each "event" is a big issue.
  - [PXD (1 MB) + Others (100 kB)] × 30 kHz = 33 GB/sec (raw data)
  - For reference; USB 3.2 Gen 2 = 10 Gbps. = 1.25 GB/sec. HDD writing < 200 MB/sec.

(1) Event selection is essential **(2) Selection rate must be < 30 kHz (= 33 μsec/event)**

- The rate of important physics events are much less than others (Bhabha, $\gamma\gamma$, etc…)

Cross sections and event rates at the target luminosity ($8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

Physics process	Cross section (nb)	Rate (Hz)	
$\Upsilon(4S) \to B\bar{B}$	1.2	960	Keep every one of these
Hadron production from continuum	2.8	2200	
$\mu^+\mu^-$	0.8	640	
$\tau^+\tau^-$	0.8	640	
Bhabha ($\theta_{\mathrm{lab}} \geq 17°$)	44	350 [a]	
$\gamma\gamma$ ($\theta_{\mathrm{lab}} \geq 17°$)	2.4	19 [a]	
2γ processes ($\theta_{\mathrm{lab}} \geq 17°$, $p_t \geq 0.1\,\mathrm{GeV}/c$)	~ 80	~ 15000	
Total	~ 130	~ 20000	

[a] rate is pre-scaled by a factor of 1/100

Structure of DAQ & TRG - Three layers

- **No dead time is allowed.** However, maximum rate can exceed 30 kHz.
- Necessary to “wait” for processing at each stage.
  - Collision information from the accelerator, synchronization of signals among detectors, L1 trigger generation…

① **Level 1 trigger**

FPGA based trigger ~5 μsec response.

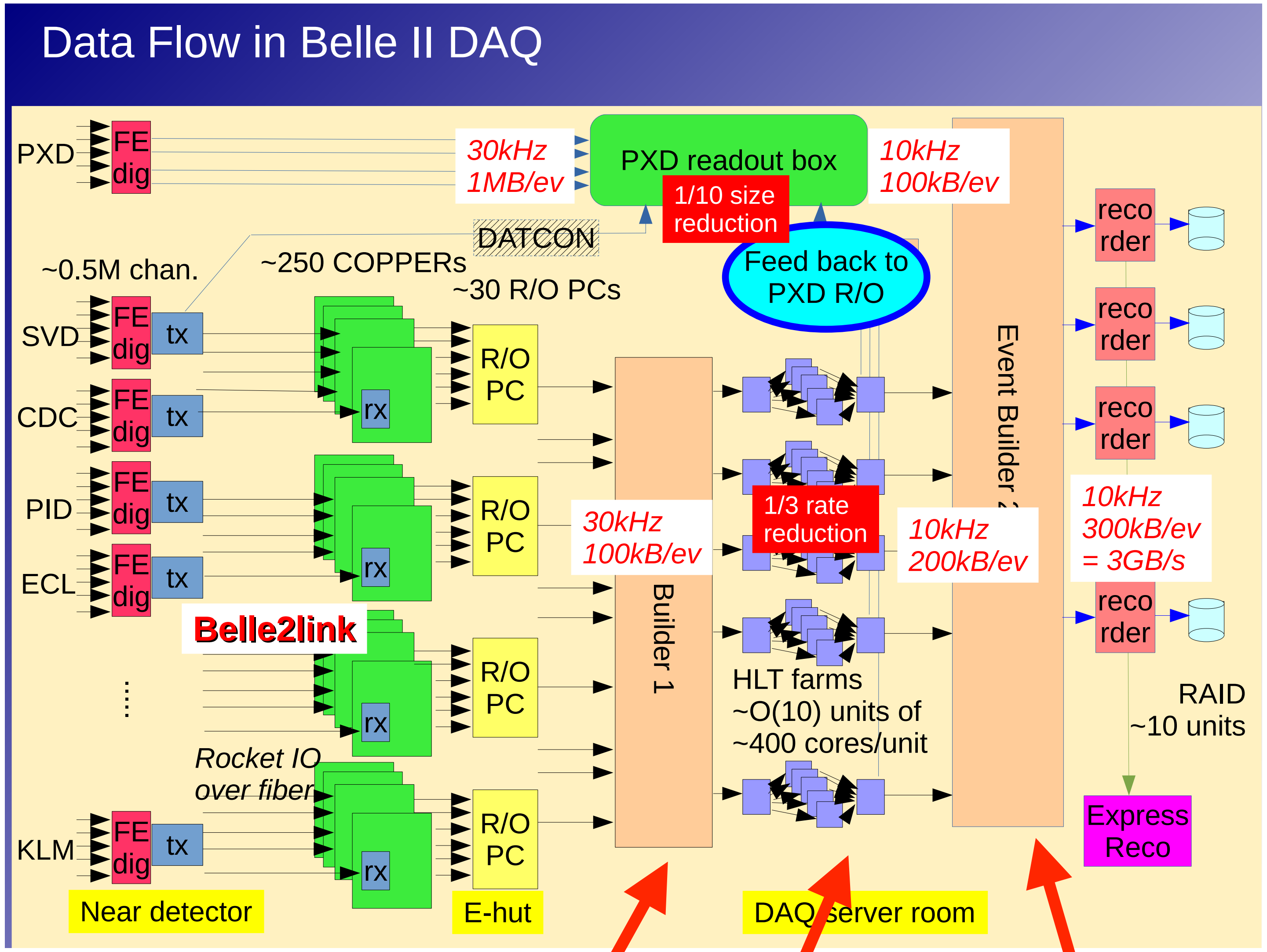
② **High Level Trigger (HLT)**

CPU based. Event building.
Check if “physical” events or not.
Event-by-Event parallel processing.

③ **Event builder**

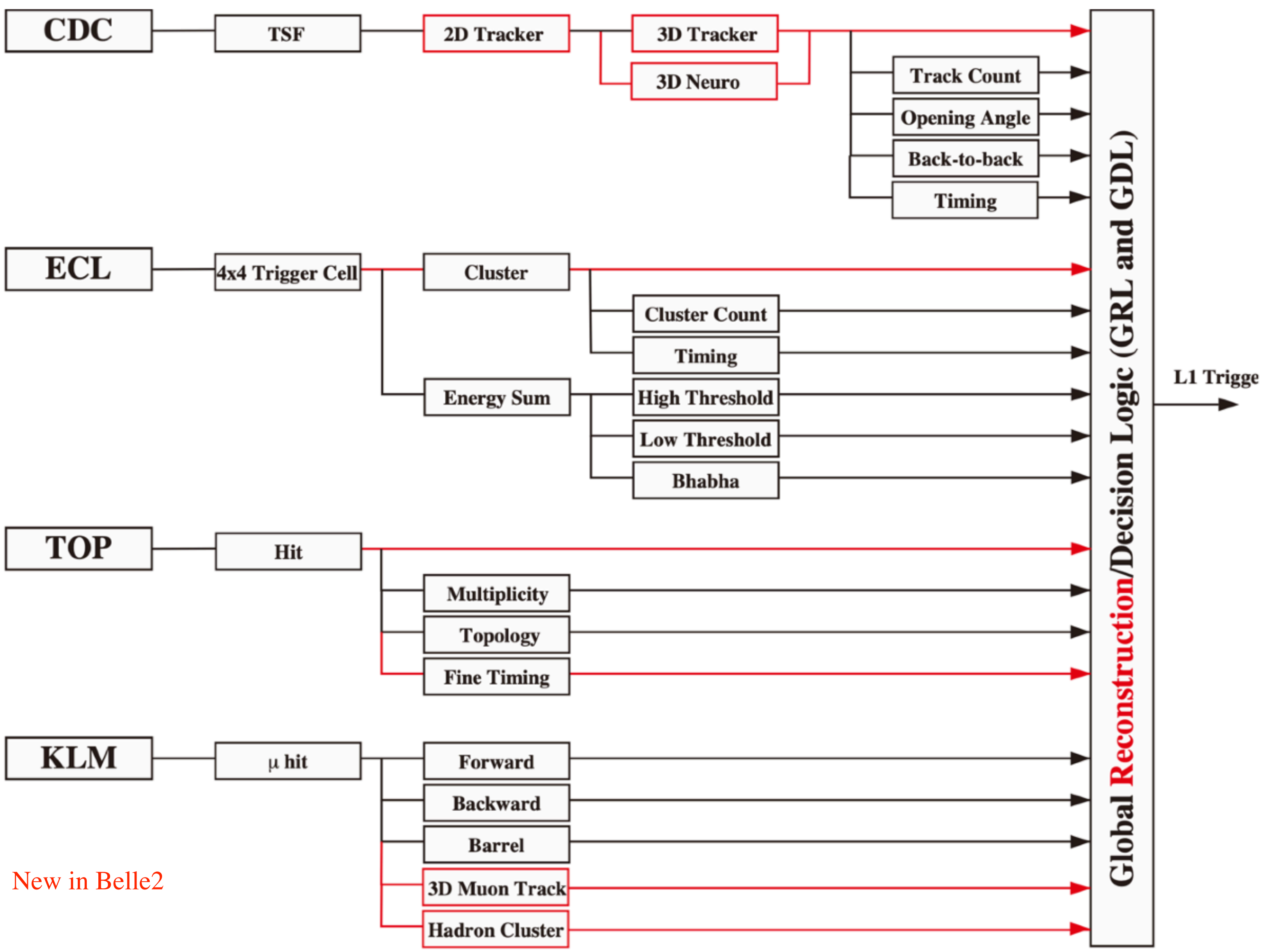
Integrate PXD information.
Event building is finalized.

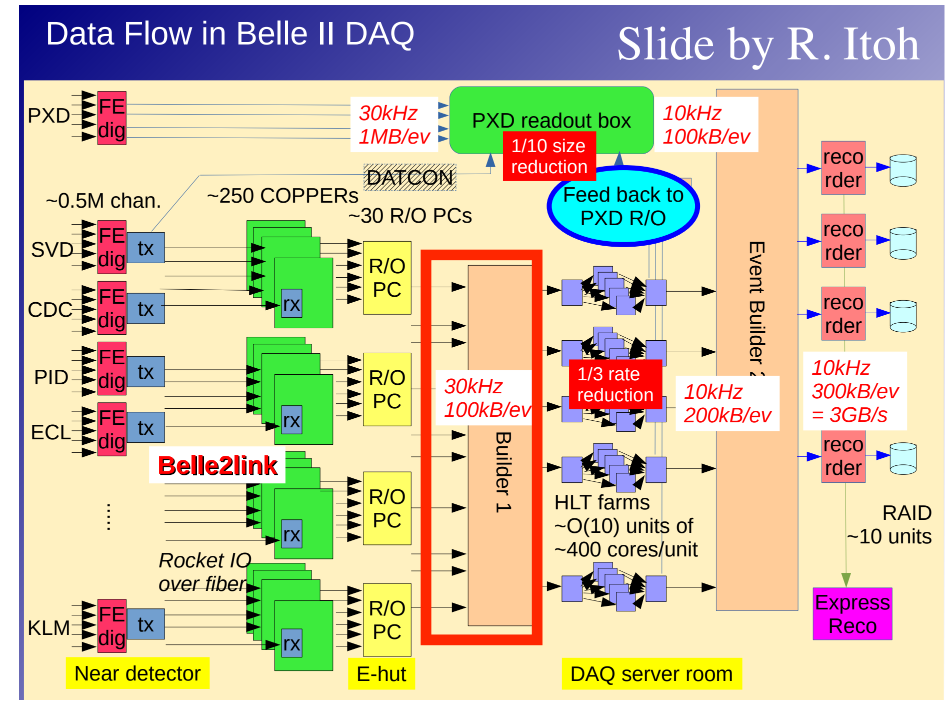
Firmware experts needed…
(to program, test, and debug the FPGA codes)



① **L1 trigger** ② **HLT** ③ **Event builder**

Level 1 Trigger - selection by logic circuits





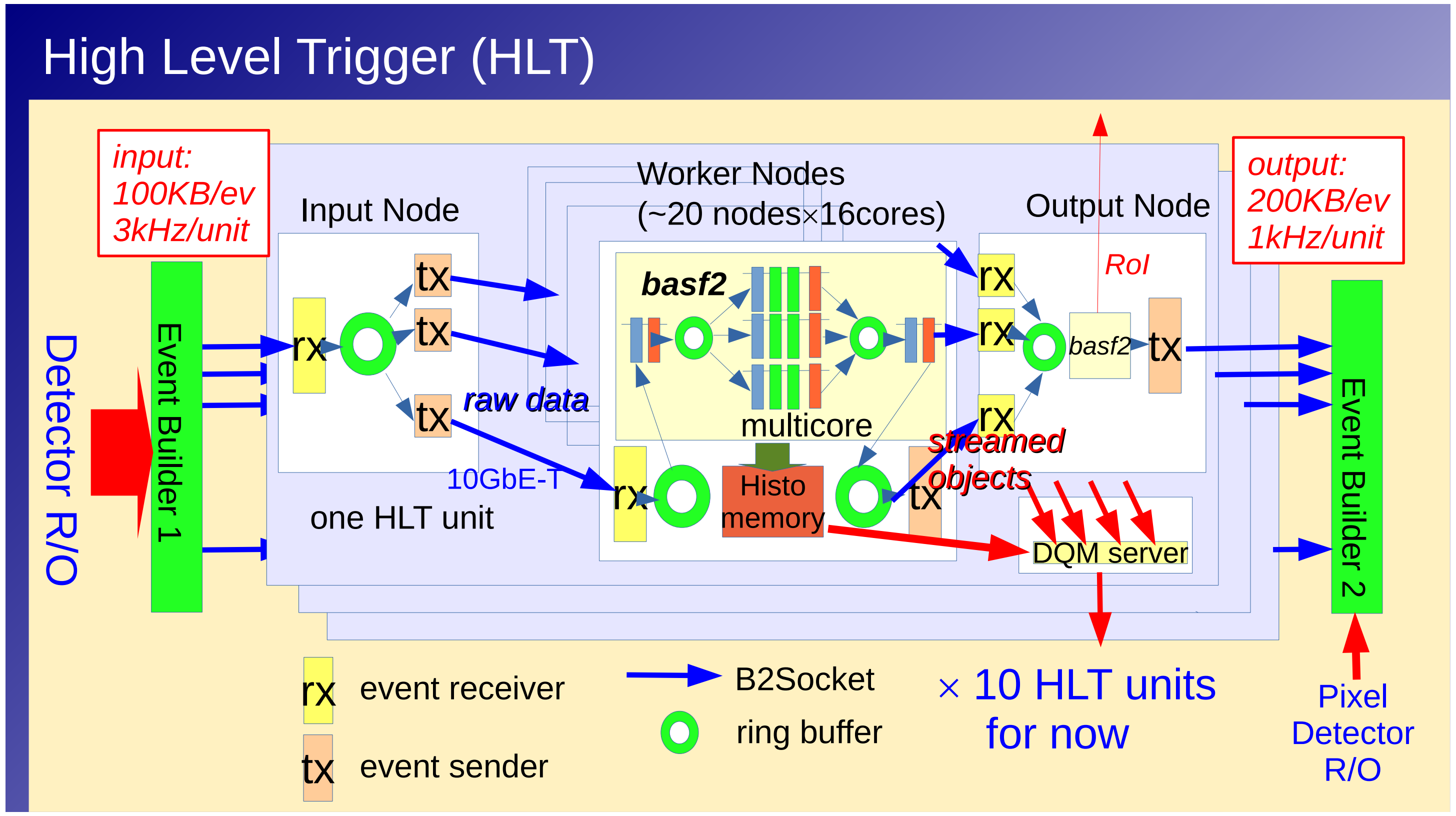
① L1 trigger

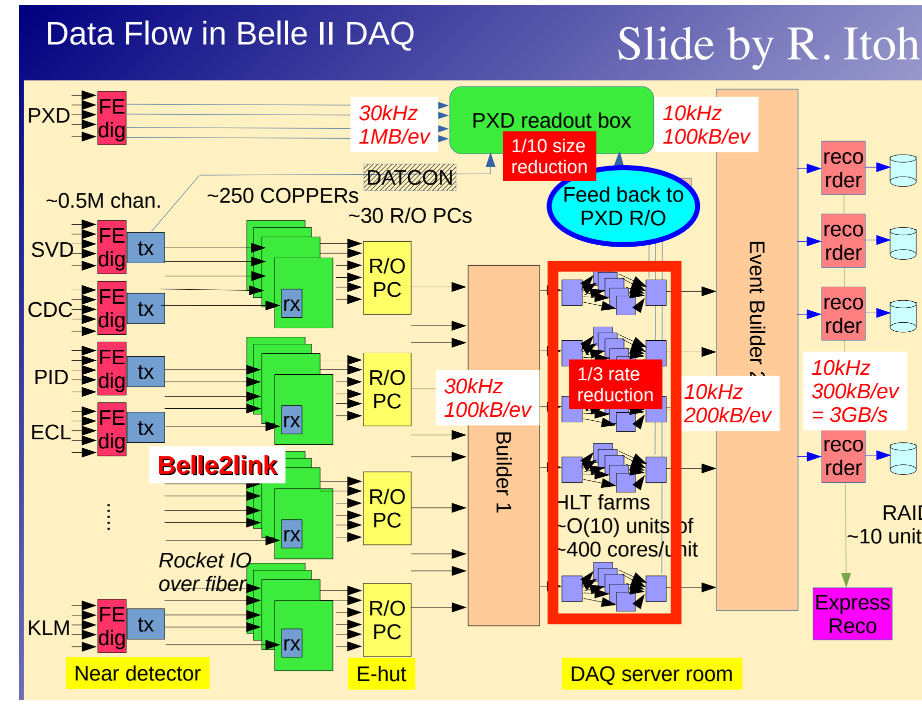
- Input the number of tracks, angles, energy, and timing to Global Decision Logic (GDL).
- Only when one of criteria is fulfilled, trigger is generated.
- Typical physics event satisfies multiple criteria.

- **Physics (PS=1)**
  - **ffo : 2D track > 1 & opening angle > 90° & !Bhabha**
  - **fff : 2D track > 2**
  - **hie : energy > 1 GeV & !Bhabha**
  - **c4 : isolated cluster > 3 & !Bhabha**
- **Calibrations (PS>1)**
  - **ff(PS=20), c2(PS=150), bhabha(PS=1), 3D bhabha(PS=1), many others**
- **MC background overlay**
  - **Pseudo random(1Hz), revolution(1Hz)**
  - **Delayed bhabha logic had a bug (PS=0)**
- **Triggers for the dark sector**
  - **c1 & hie/lum, c3 & hie/lum, n1 & hie/lum, n3 & hie/lum**
- **Timing decision**
  - **ECL timing only**

Slide by A. Ishikawa

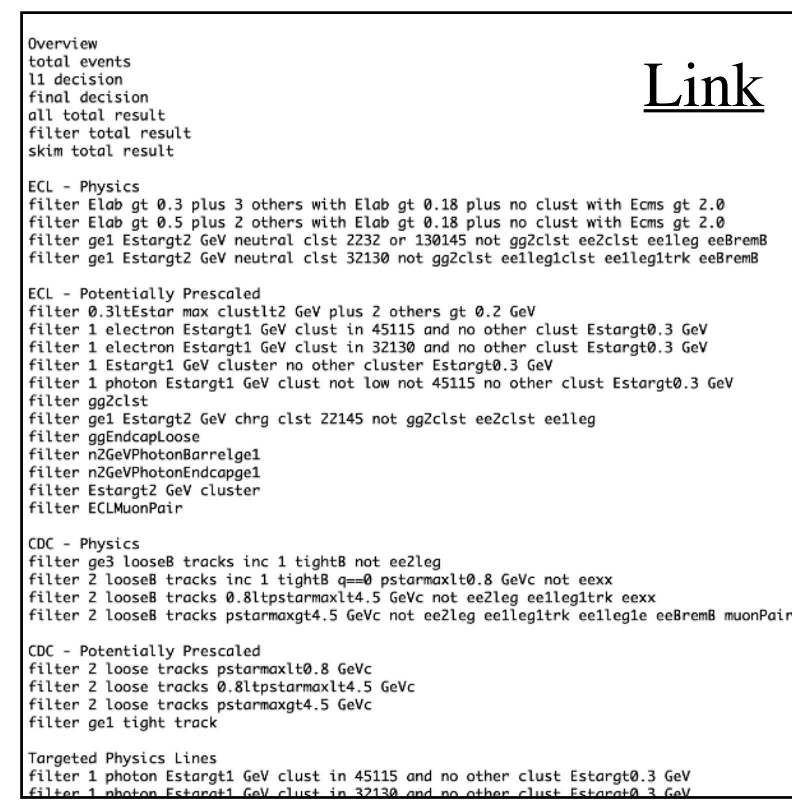
High Level Trigger - Event building





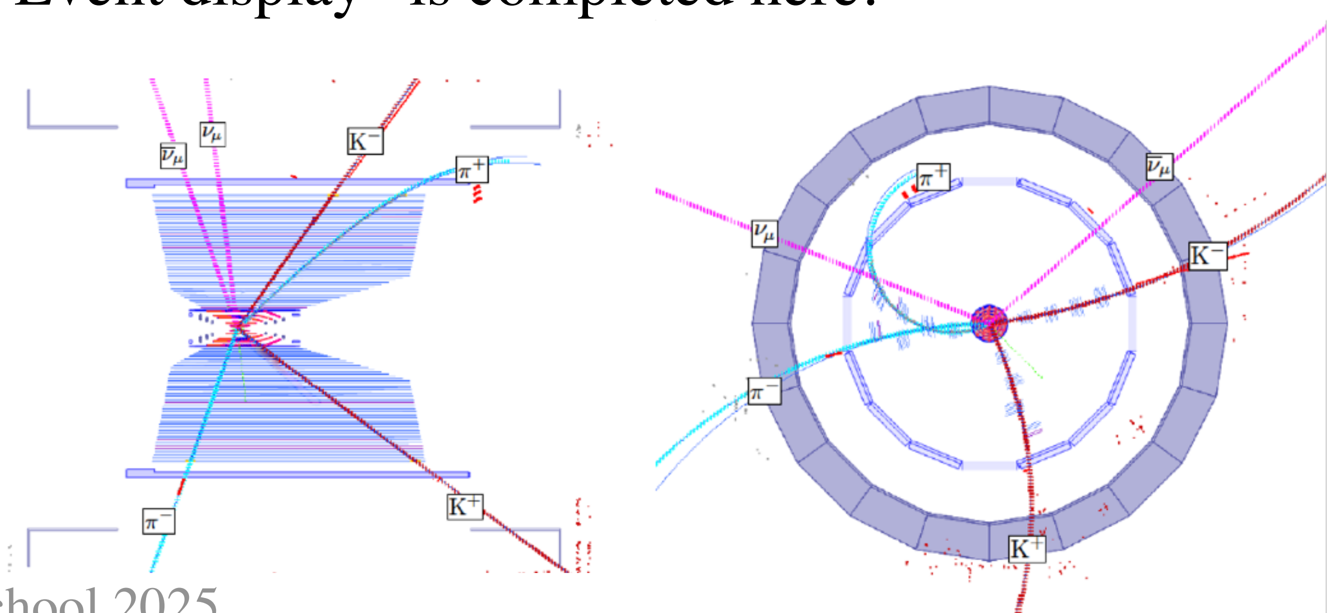
② High level trigger

- Event-by-Event reconstruction
- Track quality and PID information are connected to each track.
- There is a list of target events and corresponding trigger conditions
- Snapshot or "Event display" is completed here.



Link

```
Overview
total events
l1 decision
final decision
all total result
filter total result
skim total result

ECL - Physics
filter Elab gt 0.3 plus 3 others with Elab gt 0.18 plus no clust with Ecms gt 2.0
filter Elab gt 0.5 plus 2 others with Elab gt 0.18 plus no clust with Ecms gt 2.0
filter ge1 Estargt2 GeV neutral clst 2232 or 130145 not gg2clst ee2clst ee1leg eeBremB
filter ge1 Estargt2 GeV neutral clst 32130 not gg2clst ee1leg1clst ee1leg1trk eeBremB

ECL - Potentially Prescaled
filter 0.3ltEstar max clustlt2 GeV plus 2 others gt 0.2 GeV
filter 1 electron Estargt1 GeV clust in 45115 and no other clust Estargt0.3 GeV
filter 1 electron Estargt1 GeV clust in 32130 and no other clust Estargt0.3 GeV
filter 1 Estargt1 GeV cluster no other cluster Estargt0.3 GeV
filter 1 photon Estargt1 GeV clust not low not 45115 no other clust Estargt0.3 GeV
filter gg2clst
filter ge1 Estargt2 GeV chrg clst 22145 not gg2clst ee2clst ee1leg
filter ggEndcapLoose
filter n2GeVPhotonBarrelge1
filter n2GeVPhotonEndcapge1
filter Estargt2 GeV cluster
filter ECLMuonPair

CDC - Physics
filter ge3 looseB tracks inc 1 tightB not ee2leg
filter 2 looseB tracks inc 1 tightB q==0 pstarmaxlt0.8 GeVc not eexx
filter 2 looseB tracks 0.8ltpstarmaxlt4.5 GeVc not ee2leg ee1leg1trk eexx
filter 2 looseB tracks pstarmaxgt4.5 GeVc not ee2leg ee1leg1trk ee1leg1e eeBremB muonPairVB

CDC - Potentially Prescaled
filter 2 loose tracks pstarmaxlt0.8 GeVc
filter 2 loose tracks 0.8ltpstarmaxlt4.5 GeVc
filter 2 loose tracks pstarmaxgt4.5 GeVc
filter ge1 tight track

Targeted Physics Lines
filter 1 photon Estargt1 GeV clust in 45115 and no other clust Estargt0.3 GeV
filter 1 photon Estargt1 GeV clust in 32130 and no other clust Estargt0.3 GeV
```

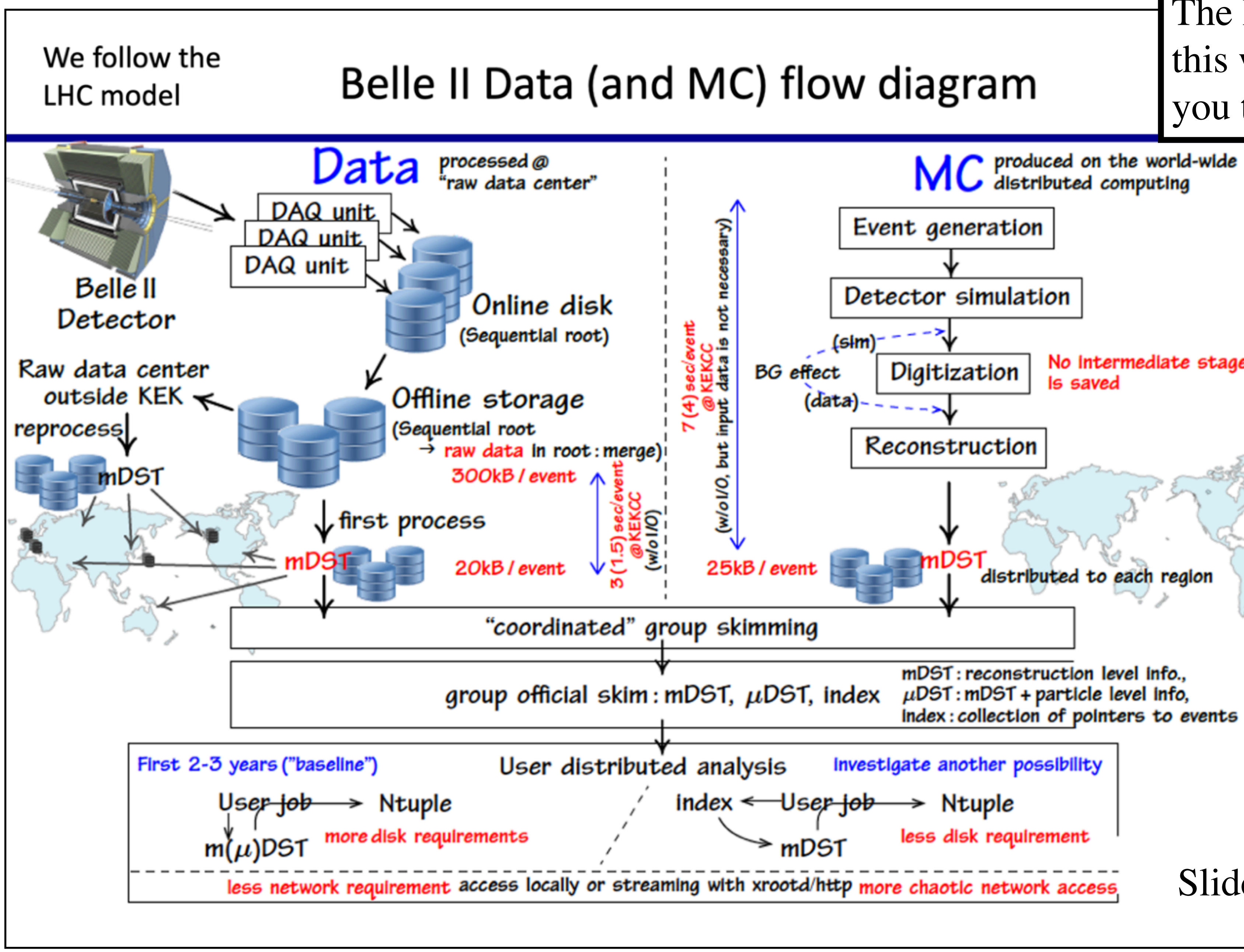


Offline analysis - world wide collaboration

- Final processing is done by distributed computing called GRID system。

  （Processing by KEK alone requires CPU power far beyond what is currently available.）

- Raw data is stored in KEK and several additional data centers.
  Usually, only the processed data files (mDST, μDST) are available for users.



The hands-on exercises in this workshop will help you to do this analysis!

Slide by T.Browder

Summary

- Belle II and SuperKEKB will explore physics beyond the Standard Model and make precision measurements of the Standard Model with 50x more data than Belle.

- Belle II has unique sensitivity to various fields of physics by clean environment in a multi-purpose hermetic detector with efficient DAQ and trigger system.

- Belle II Technical Design Report - KEK Report 2010-1 (2010), arXiv:1011.0352 - provides details of each system; IR design, detectors, trigger, and DAQ.

- For more, Belle II Physics Book - PTEP 2019, 123C01 (2019) provides a wealth of detail on the machine, detector, analysis tools, and physics.