THE BELLE II EXPERIMENT

MASTERCLASS
Belle II Particle Adventure

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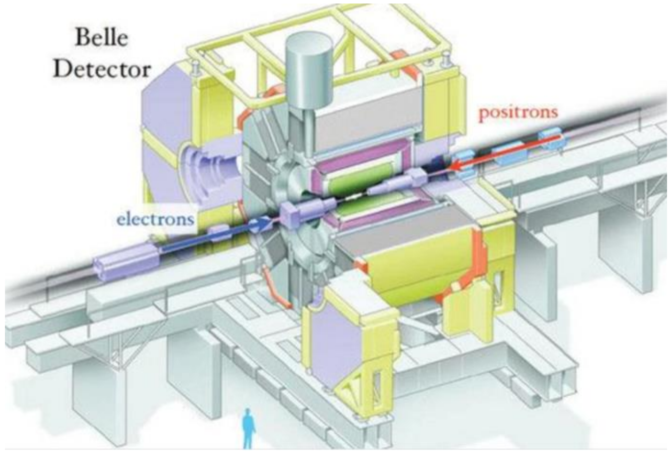
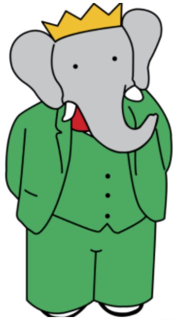
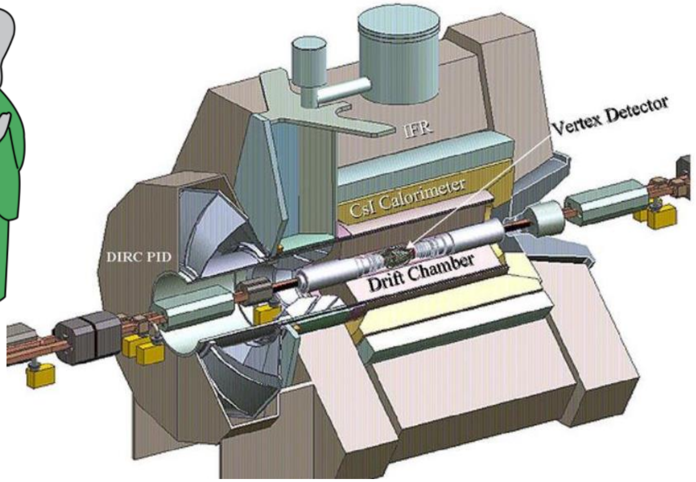
University of Mississippi

Belle II Experiment







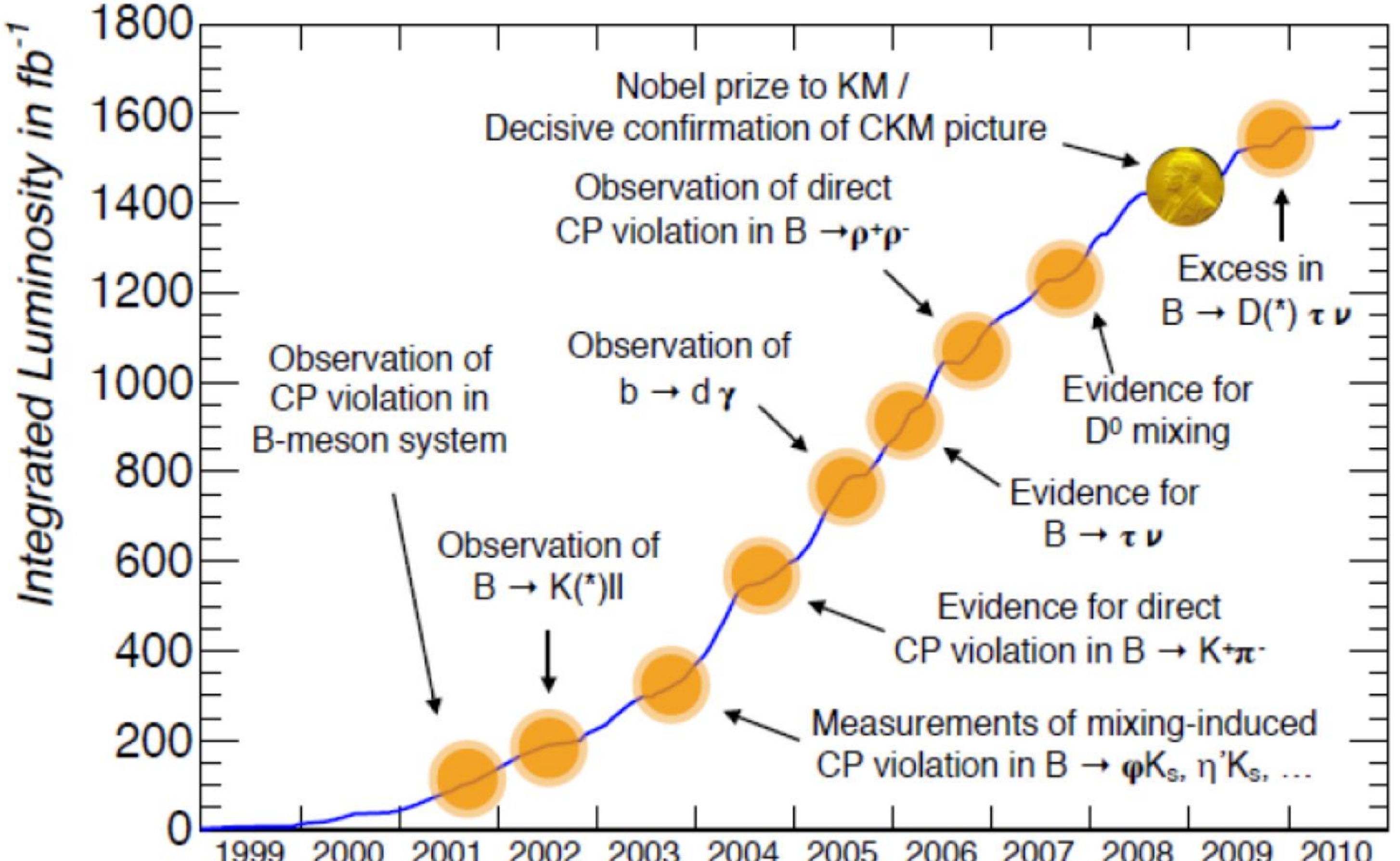
B factories, Belle @ KEKB and BaBar @ PEPII
- Large sample of B mesons ~ 1.5 ab^{-1}

- Operates from 1999 to ~2010

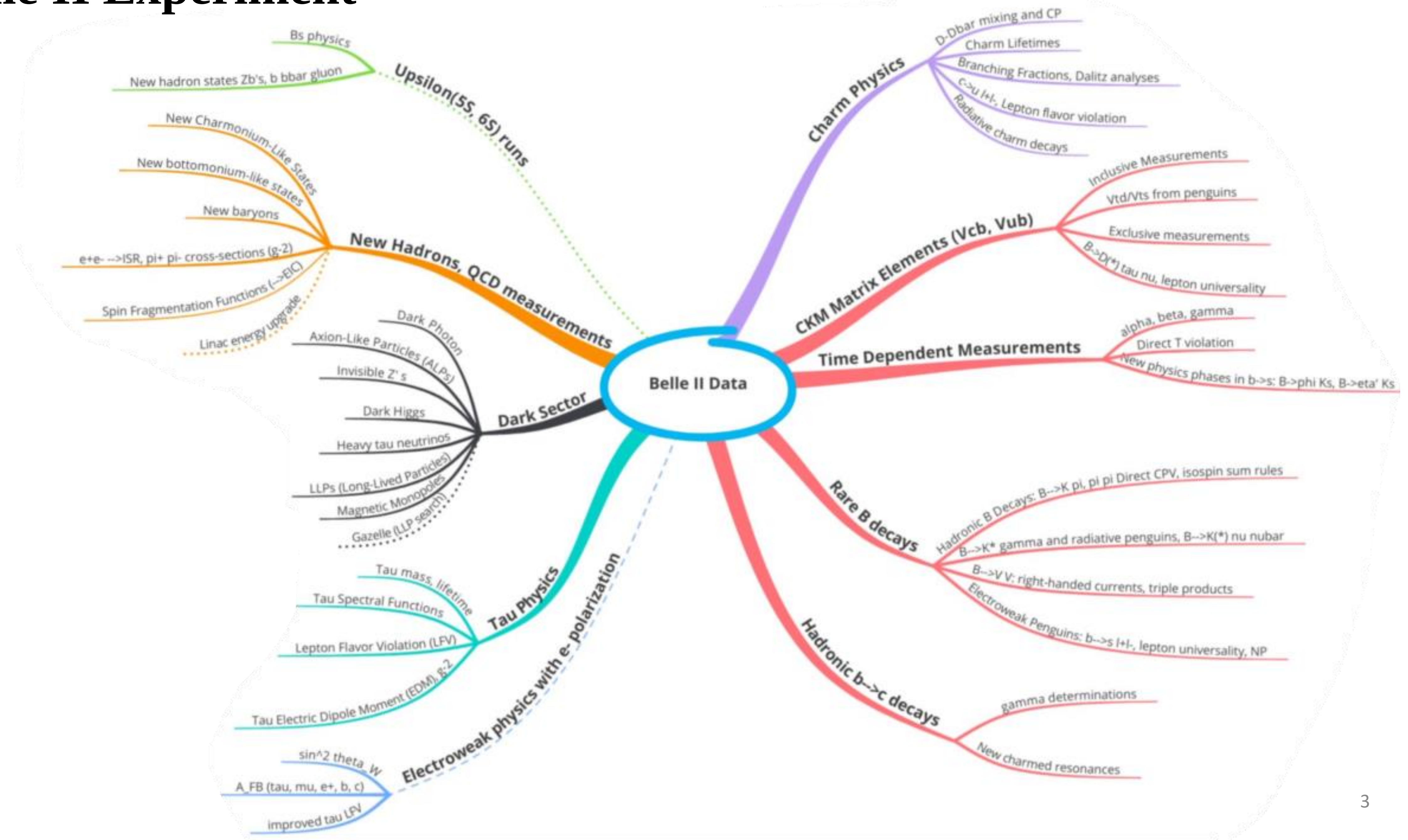
- 2008 Nobel prize for CPV in B meson.
- Published almost 1200,still we are publishing

Belle II @ SuperKEKB

- Expected to record 50 ab^{-1}
- Sofa 420 fb^{-1} collected from 2018 to present

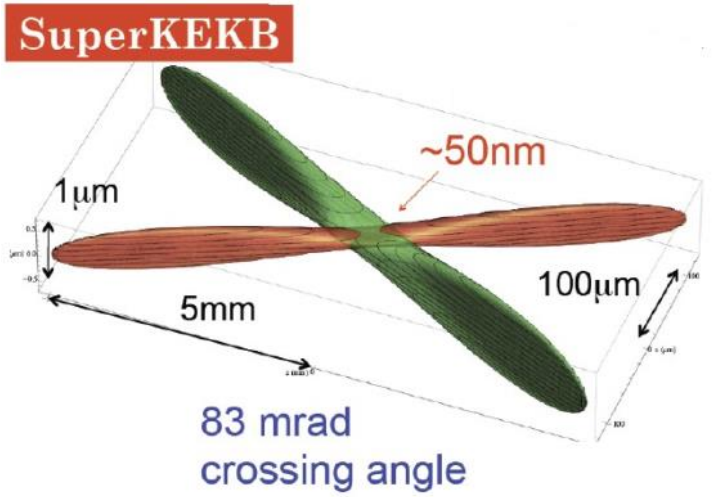


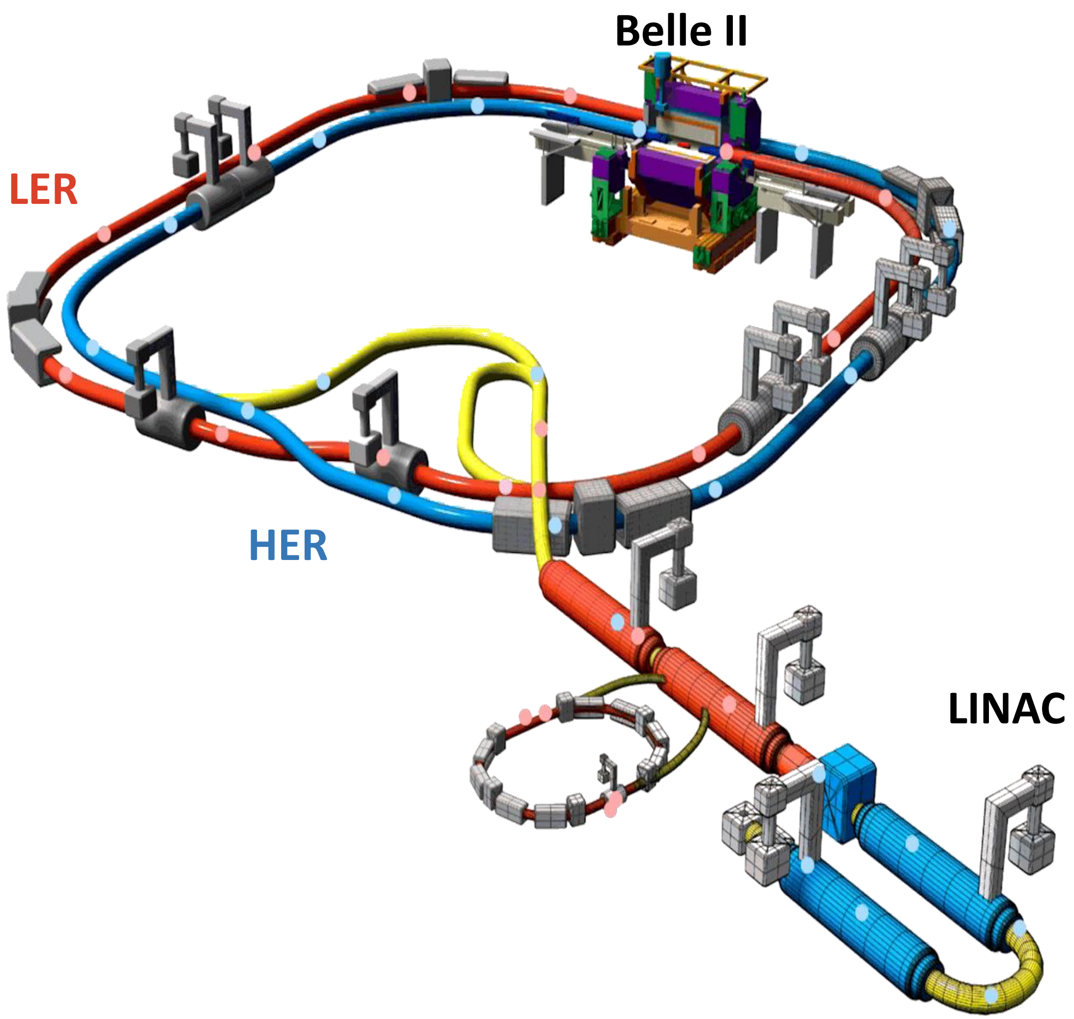
Belle II Experiment



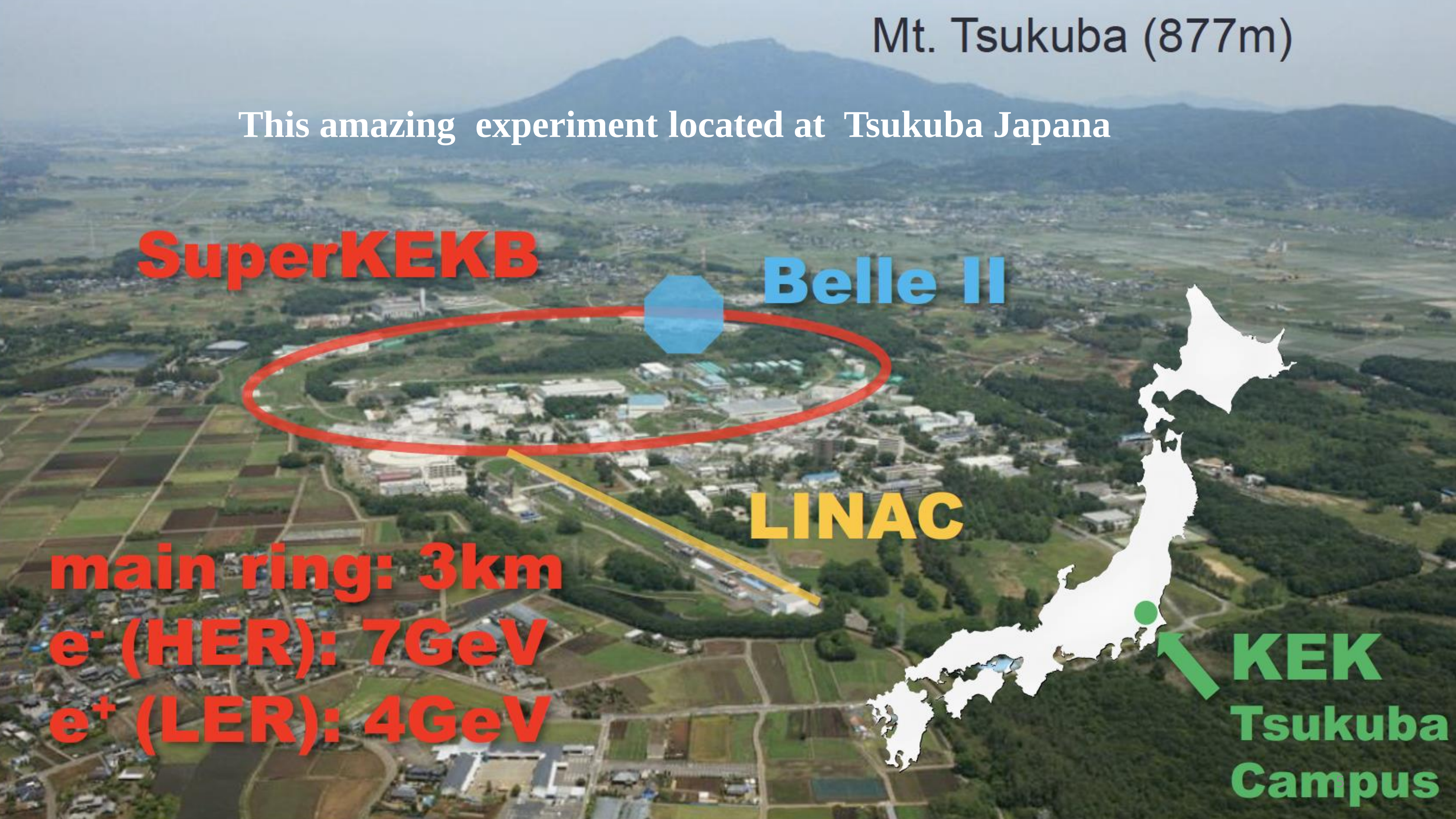
SuperKEKB Accelerator

Particle accelerators can create similar conditions that existed shortly after the Big Bang

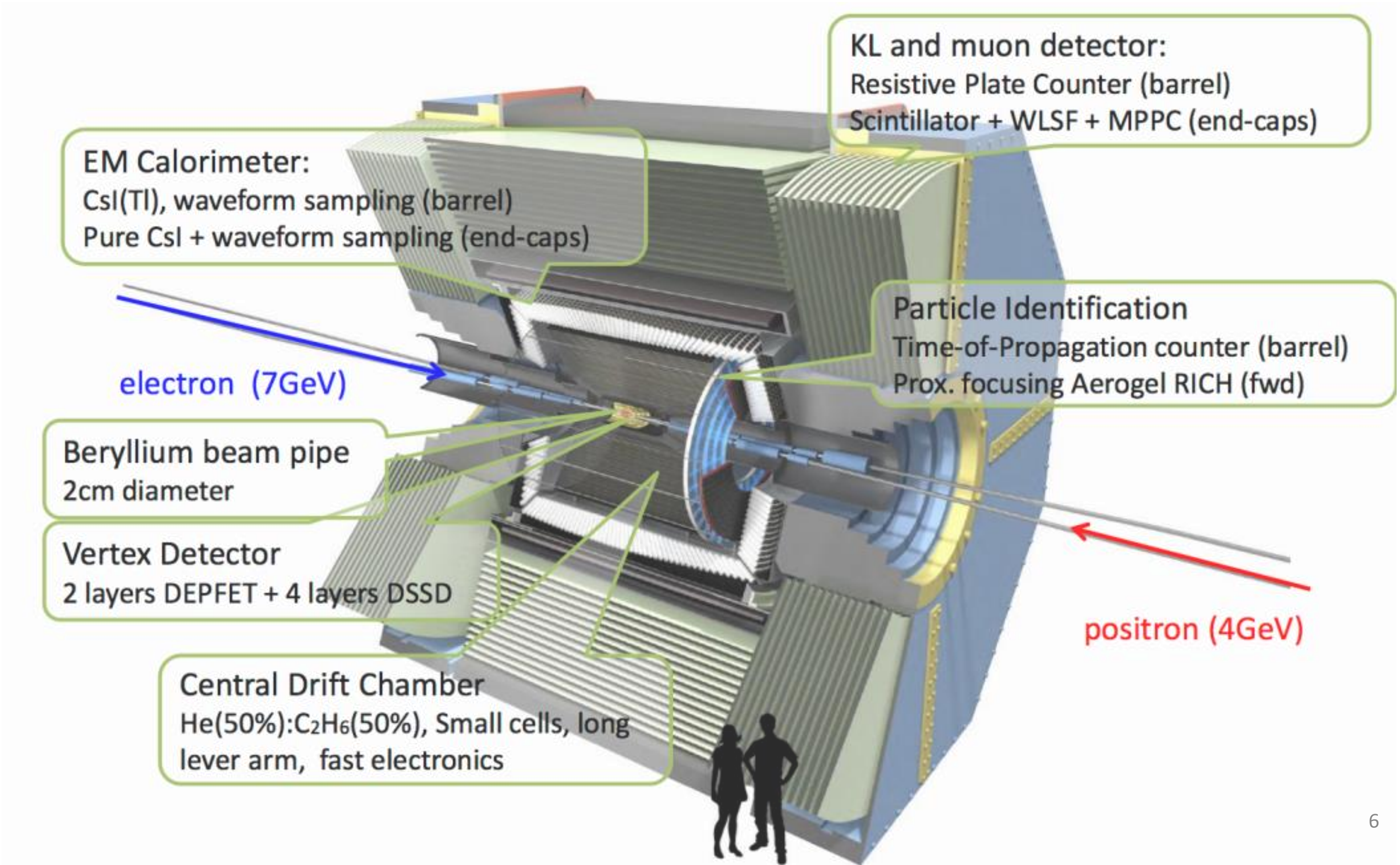




$$c\bar{c},\ u\bar{u},\ d\bar{d},\ \ell^+\ell^- \leftarrow e^+e^- \rightarrow \Upsilon(\mathrm{nS}) \rightarrow B^{(*)}\bar{B}^{(*)}$$


Mt. Tsukuba (877m)
This amazing experiment located at Tsukuba Japana
SuperKEKB
Belle II
LINAC
main ring: 3km
e^- (HER): 7GeV
e^+ (LER): 4GeV
KEK
Tsukuba
Campus

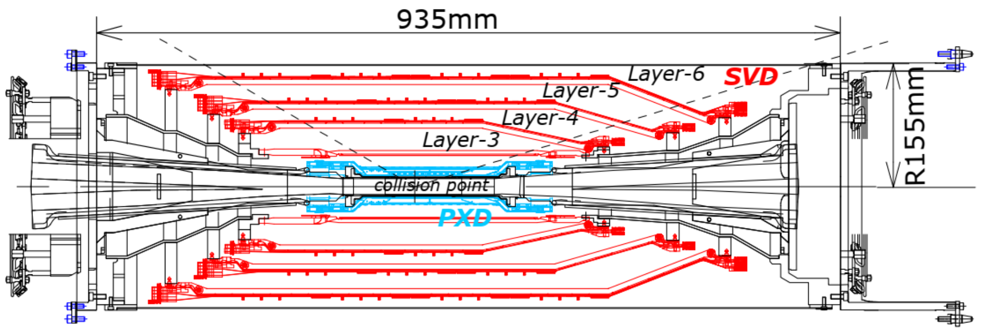
Belle II Detector

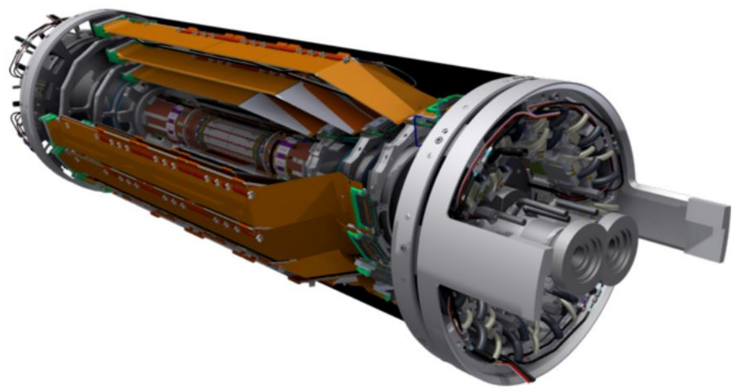


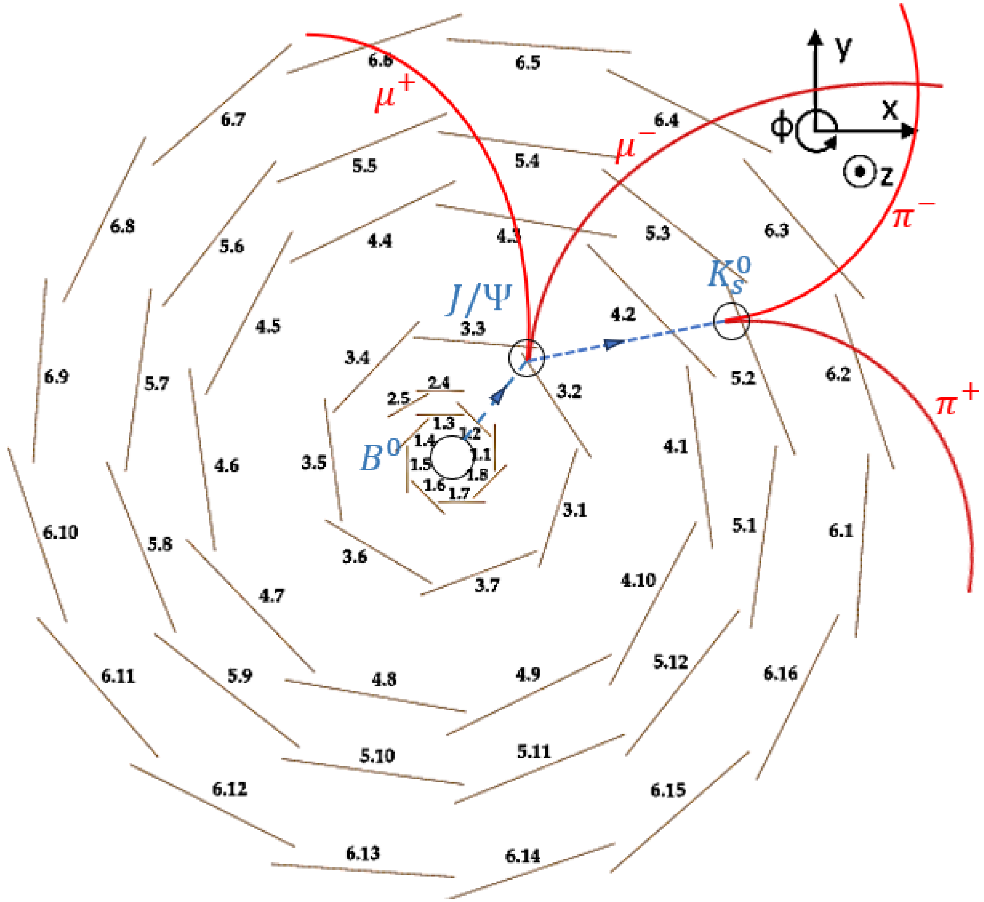
Layer 1:VXD (Vertex Detector)

- **Essential for the precise measurement of decay vertex**

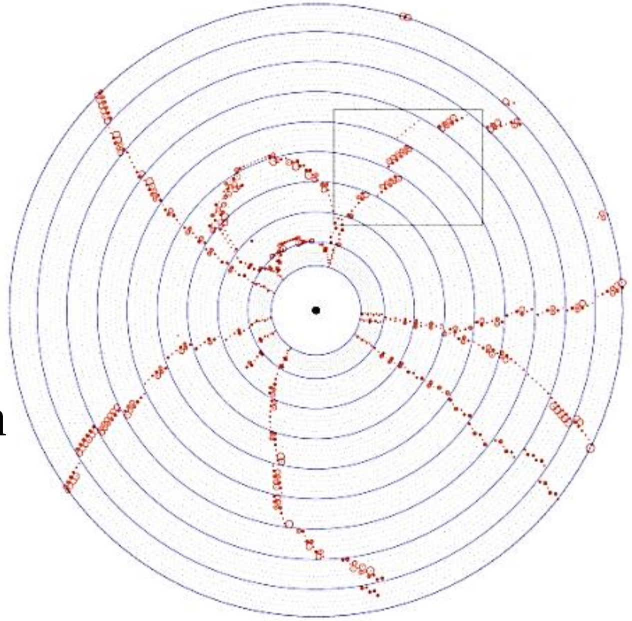
- Combination of two main layers Pixel Detector (PXD) and Silicon Vertex Detector (SVD)



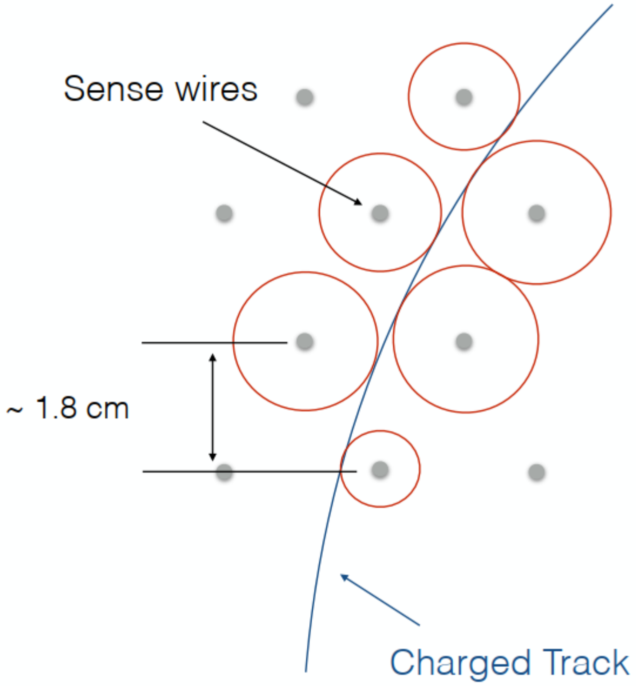


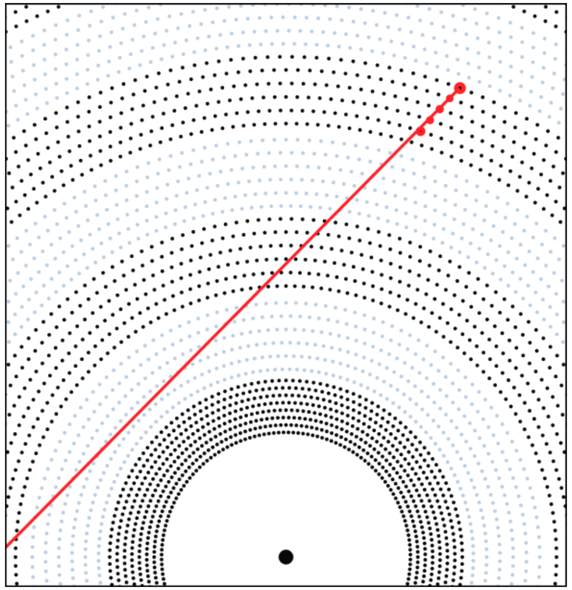


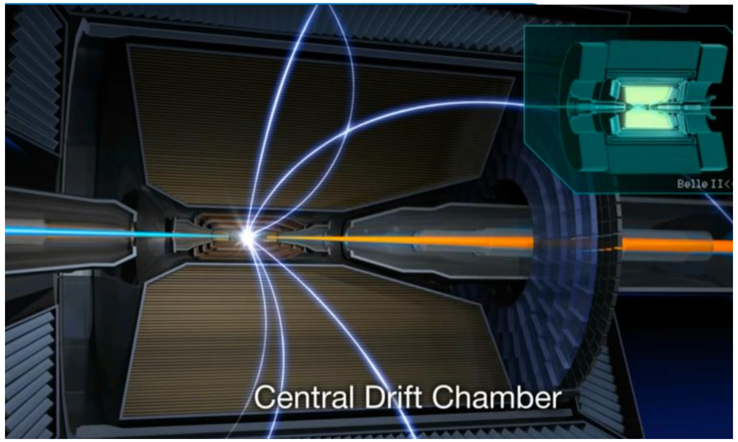
Layer 2: CDC (Central Drift Chamber)



- **Measures the trajectories and energy losses of charged particles**
- Due to strong magnetic field charged particles curve according to their momentum
- Particles pass through easily ionizable gas leaving trails of electron/ion pairs which drift to wires due to strong electric fields





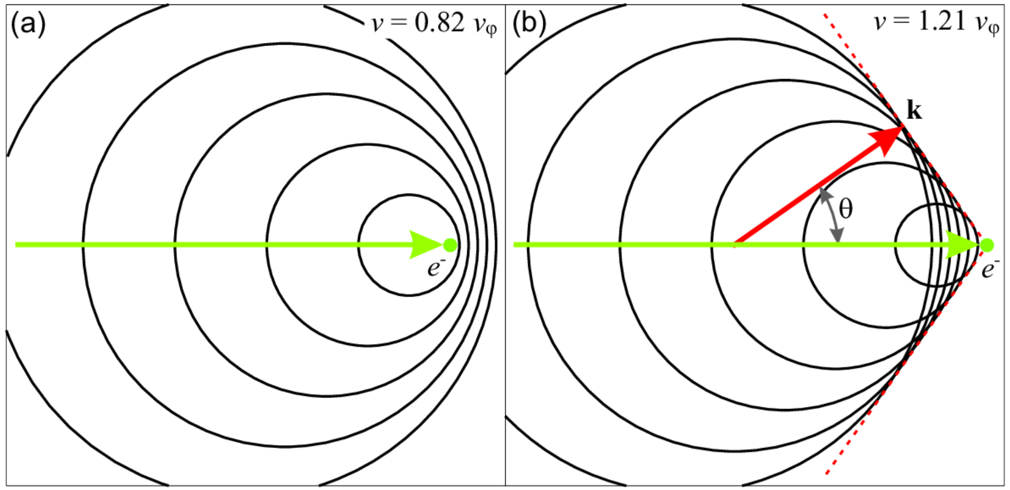


Before we go to next layers lets learn little bit of "Cherenkov" radiation

- **Cherenkov light:** It produced when a charged particle travels through a transparent medium at a speed greater than the speed of light in that medium
- **Range:** Ultraviolet (UV) to blue

Speed of light in a medium (V_φ)

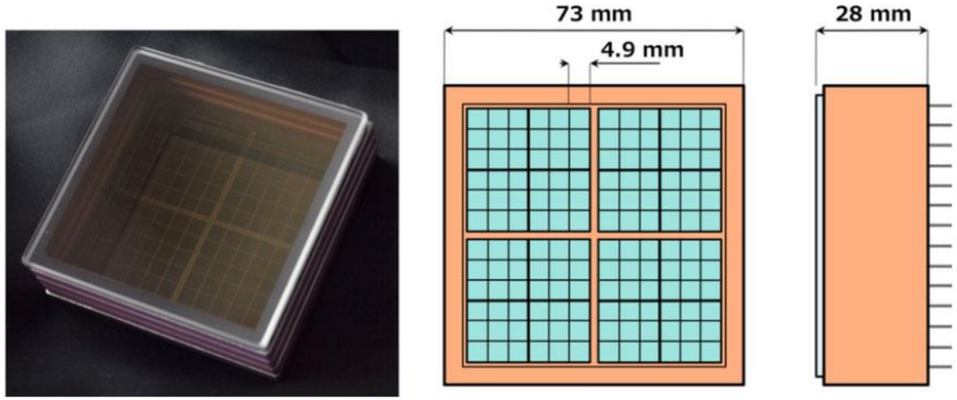
$$V_\varphi = \frac{c}{n} < C$$



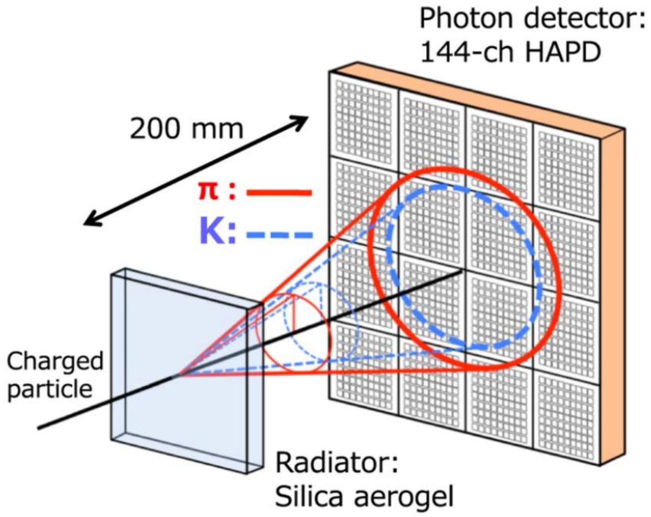
"Cerenkov angle" related to the speed of the particle
Can use this to identify particles

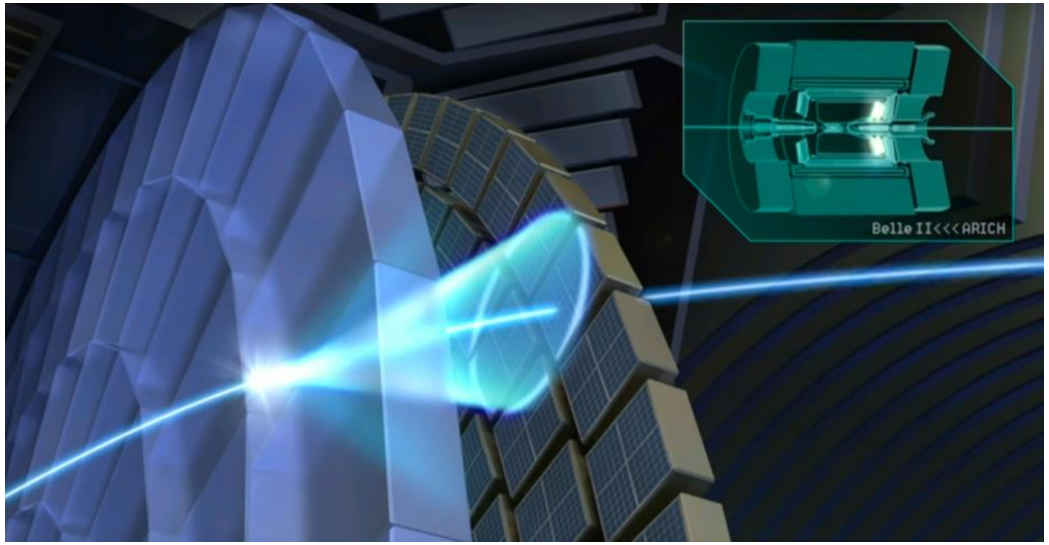
Layer 3.1: ARICH (Aerogel Ring Imaging Cherenkov counter)

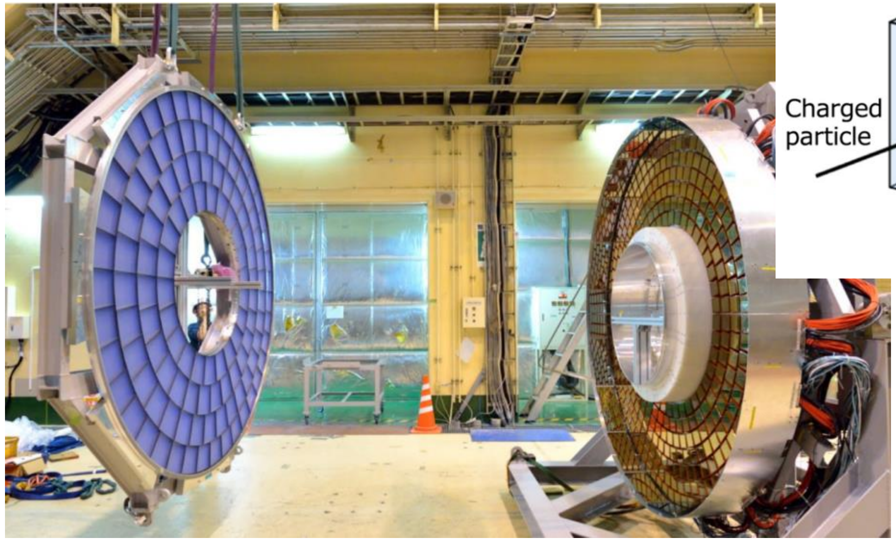
- **Provides a good K/π separation for tracks**
- Covers the forward endcap region
- Cherenkov light → Hybrid Avalanche Photon Detectors (HAPDs)



Picture of the exterior and the design of the 144-ch H/

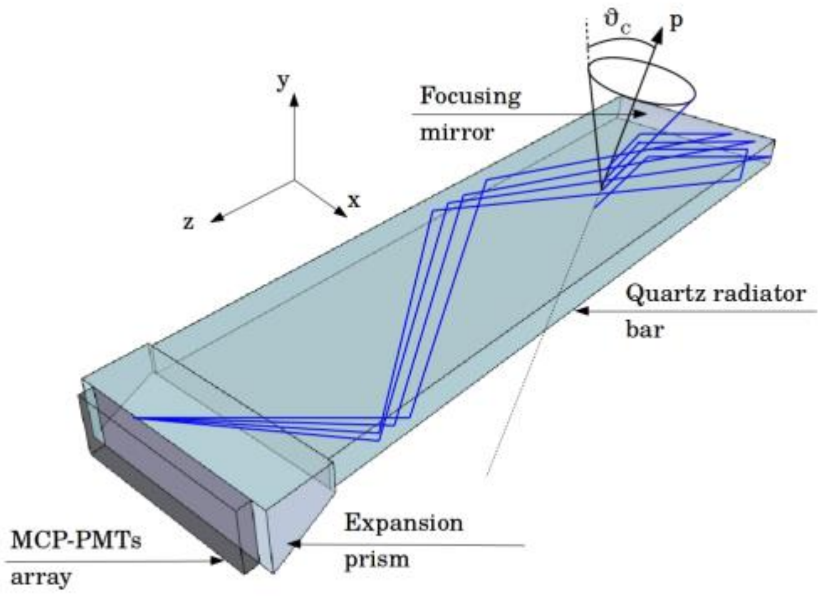


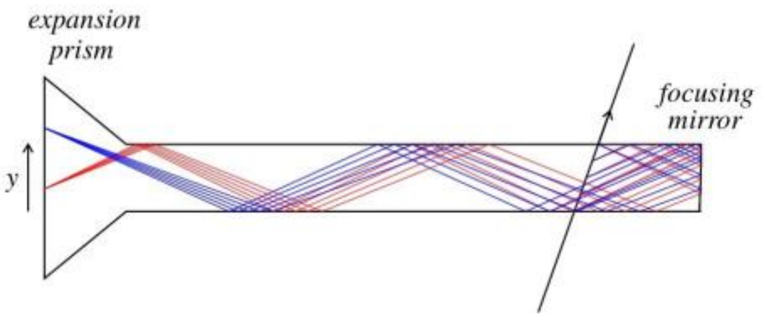


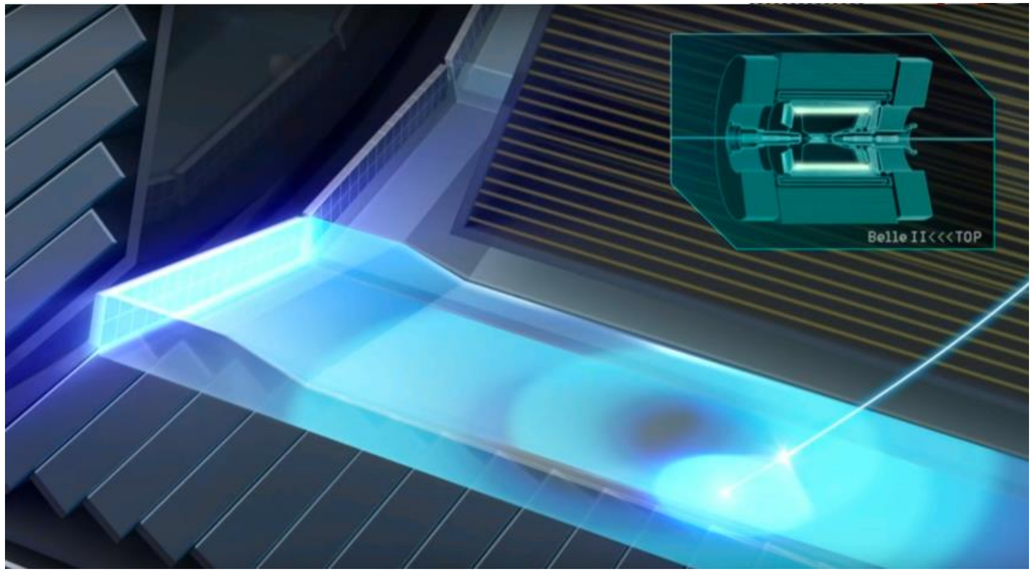


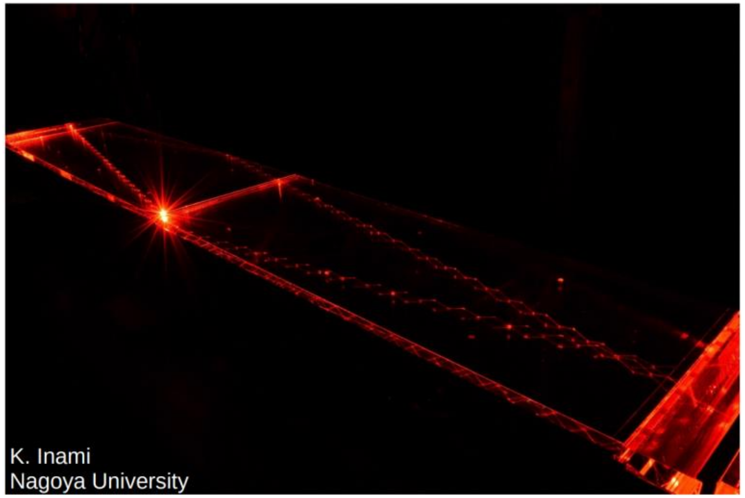
Layer 3.2: TOP (Time of Propagation counter)

- **Particle identification(PID) → Mainly $\pi^{\pm}$ and $K^{\pm}$**



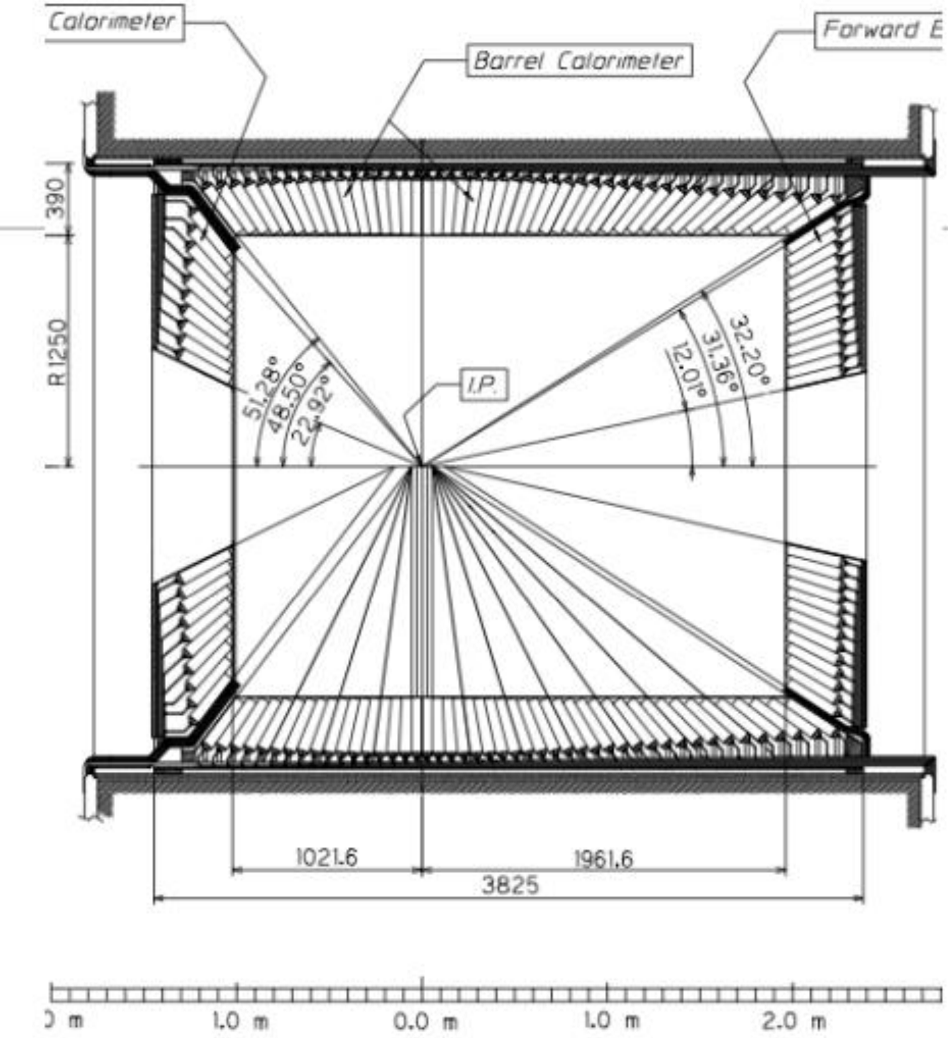


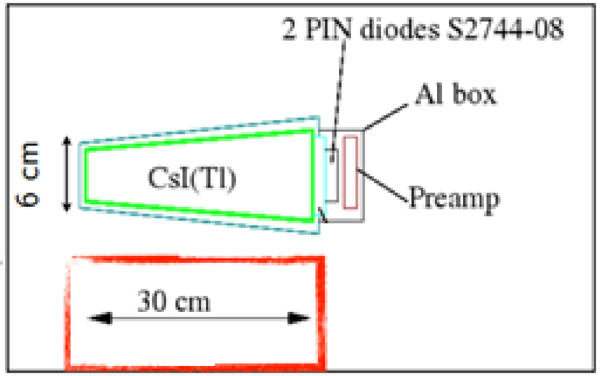


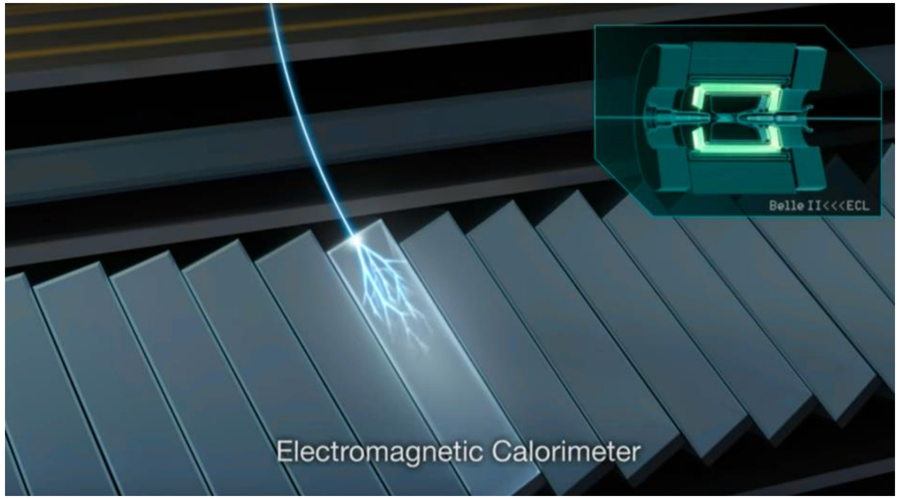


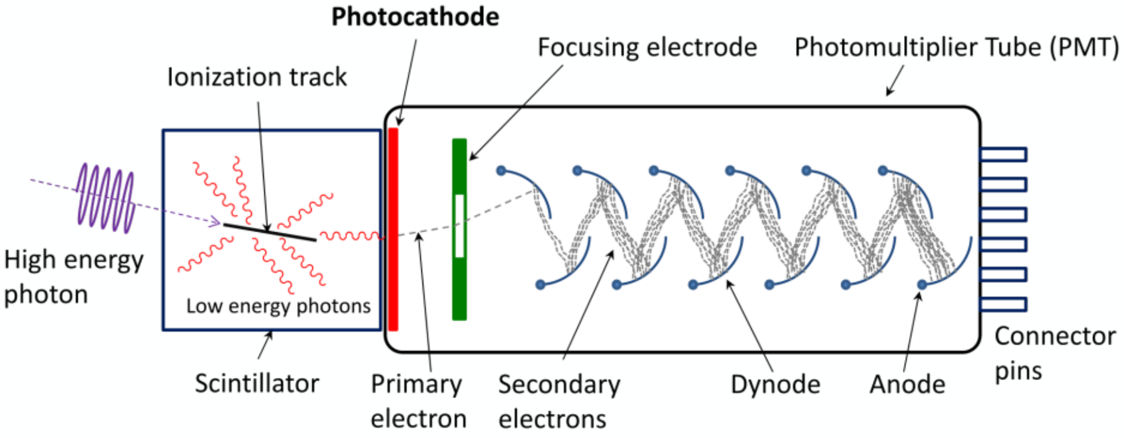
Layer 4: ECL (Electromagnetic Calorimeter)

- **Detect photons and electrons**





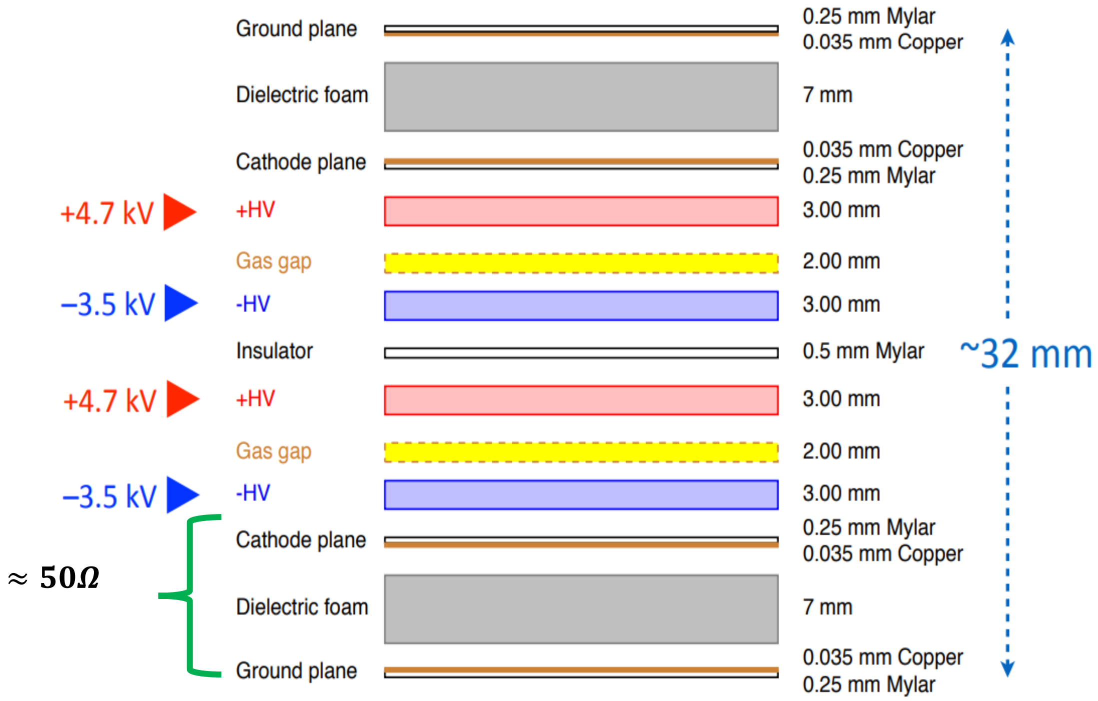


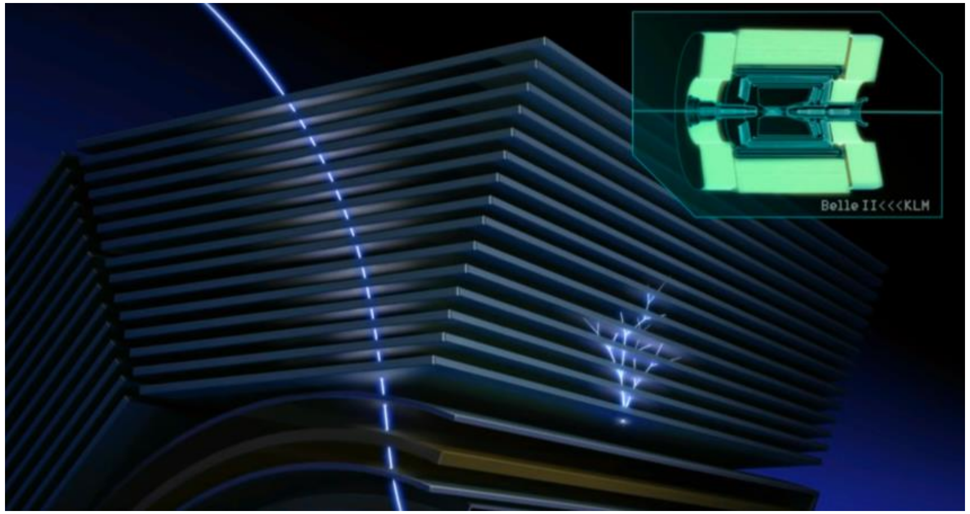


Layer 5: KLM (K_L^0 and μ detector)

- **Detect long Kaons and Muons**

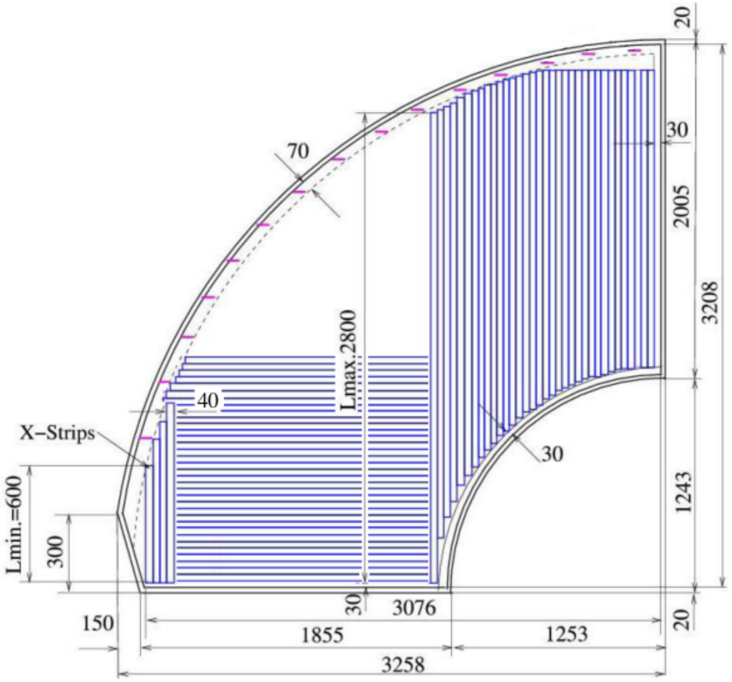
Barrel region covered by alternating layers with RPCs (resistive plate chamber)

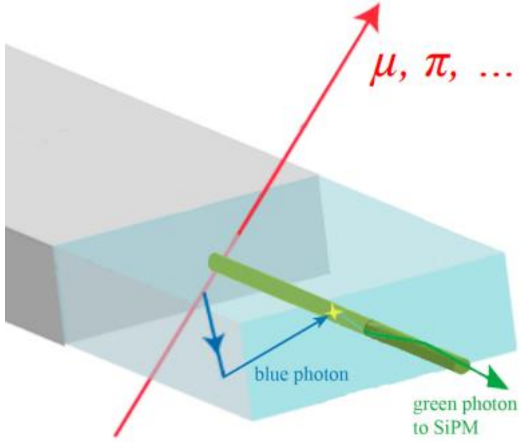


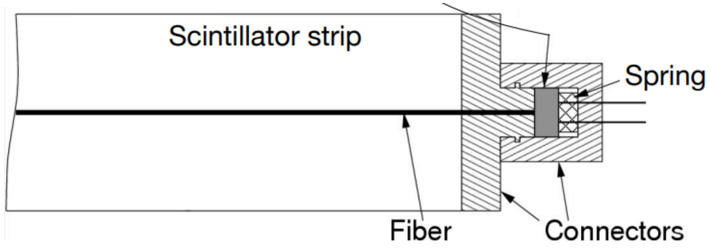


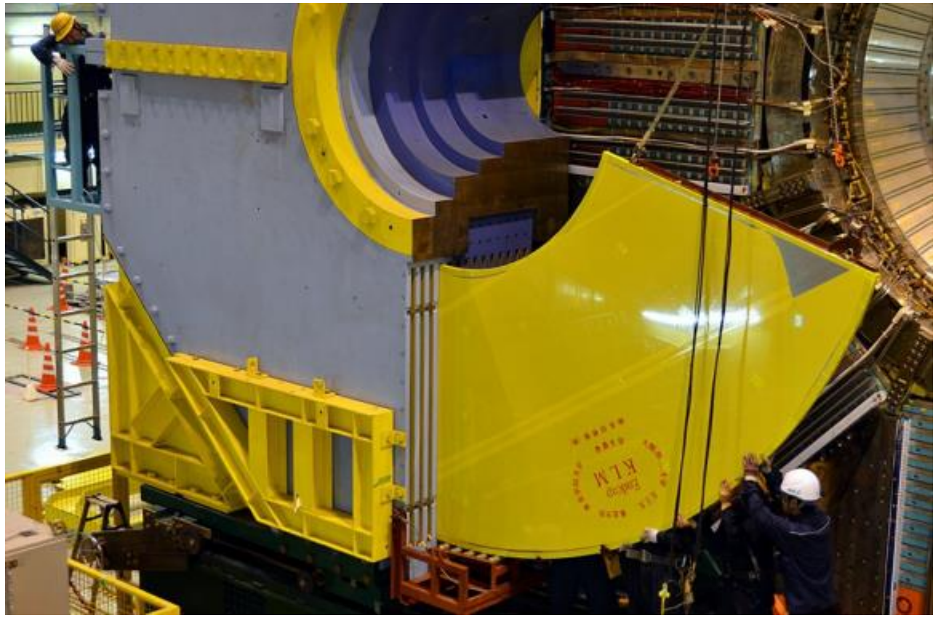
Layer5: KLM (K_L^0 and μ detector)

- **Detect long Kaons and Muons**



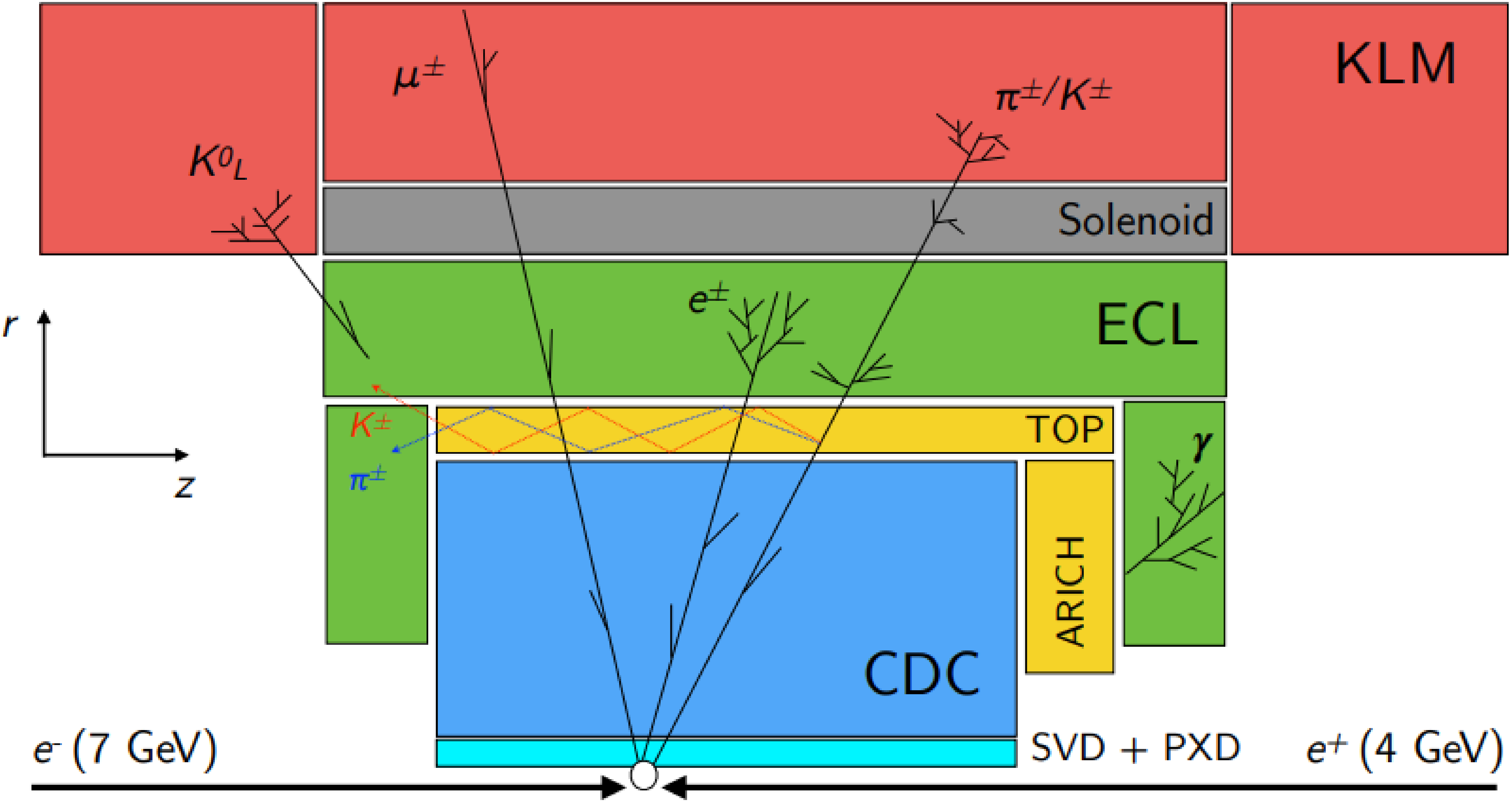




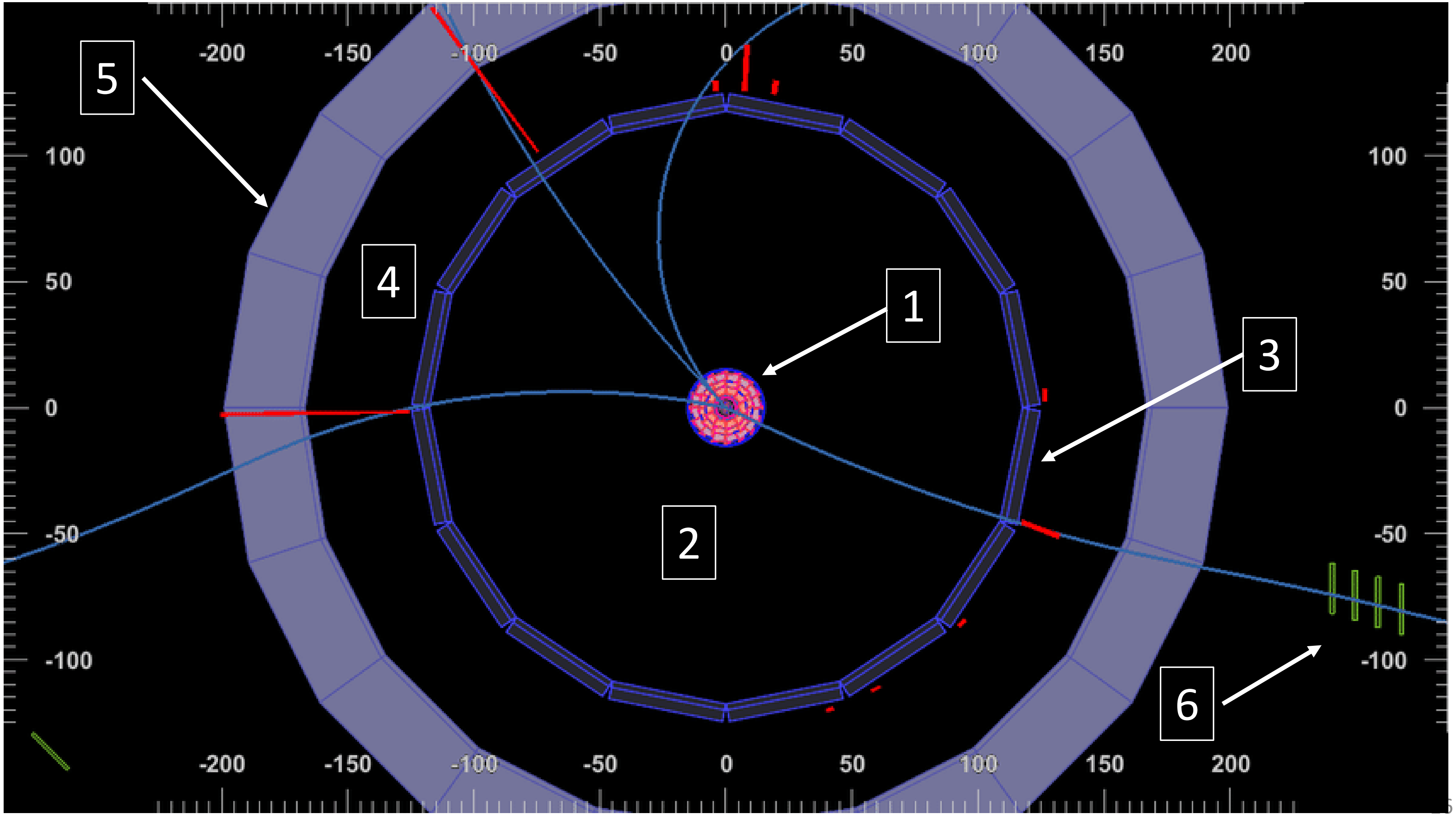


Blue light emits from $\frac{dE}{dx}$ process in scintillator is captured by wavelength-shifting fiber and re-emitted as green

(Sub-detectors not to scale)

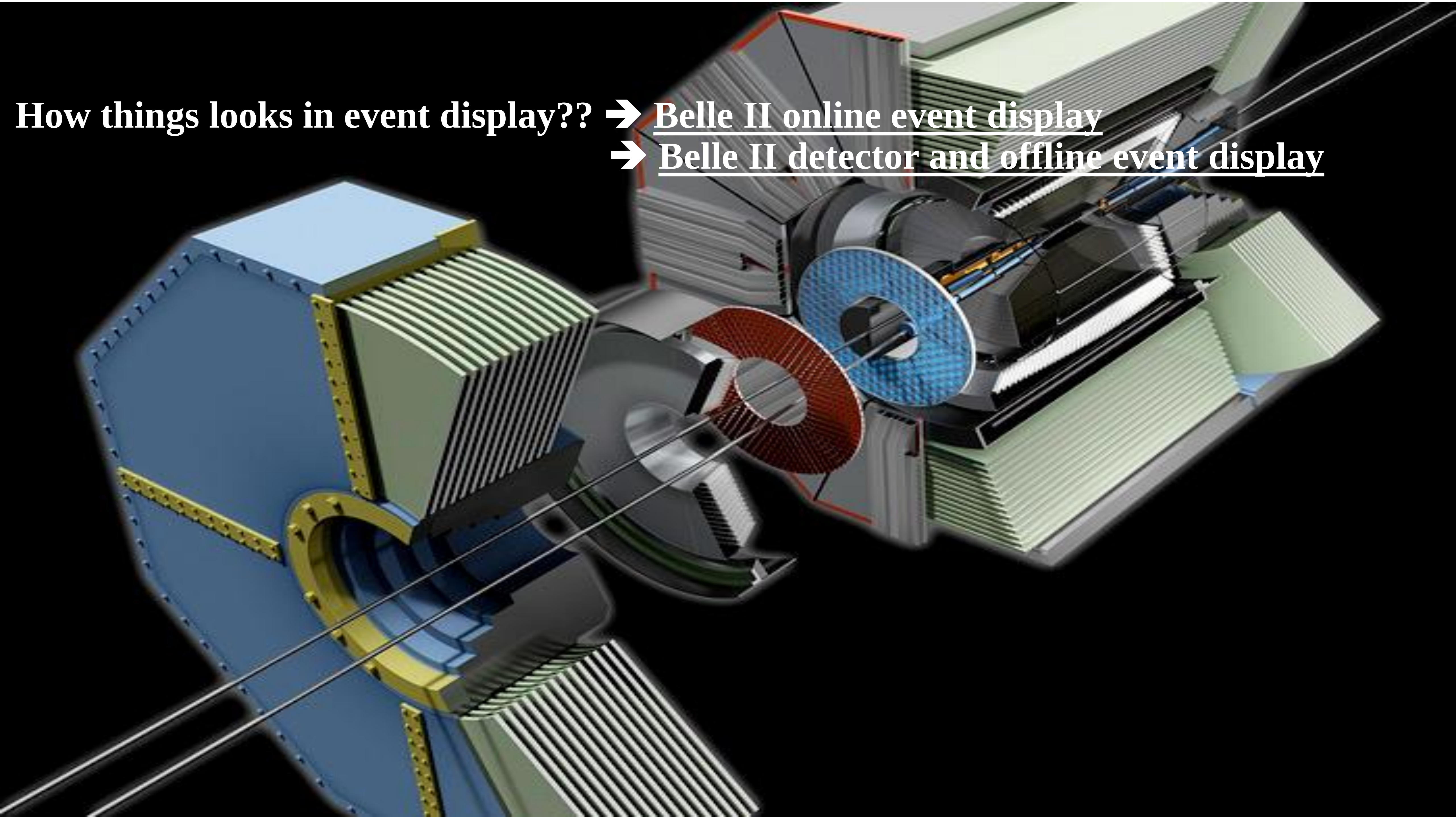


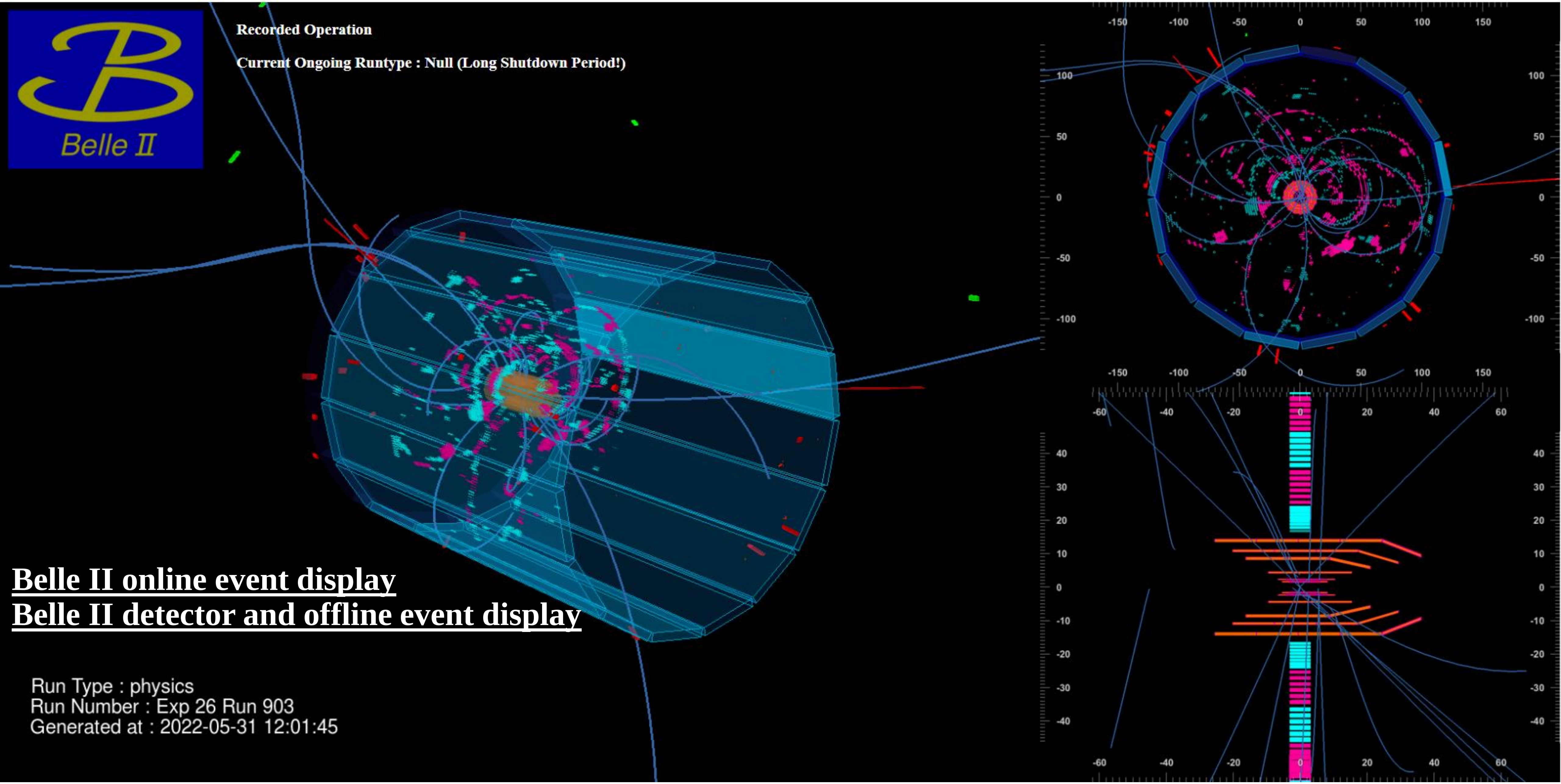
Now you tell me what are these???



How things looks in event display?? ➔ Belle II online event display

➔ Belle II detector and offline event display





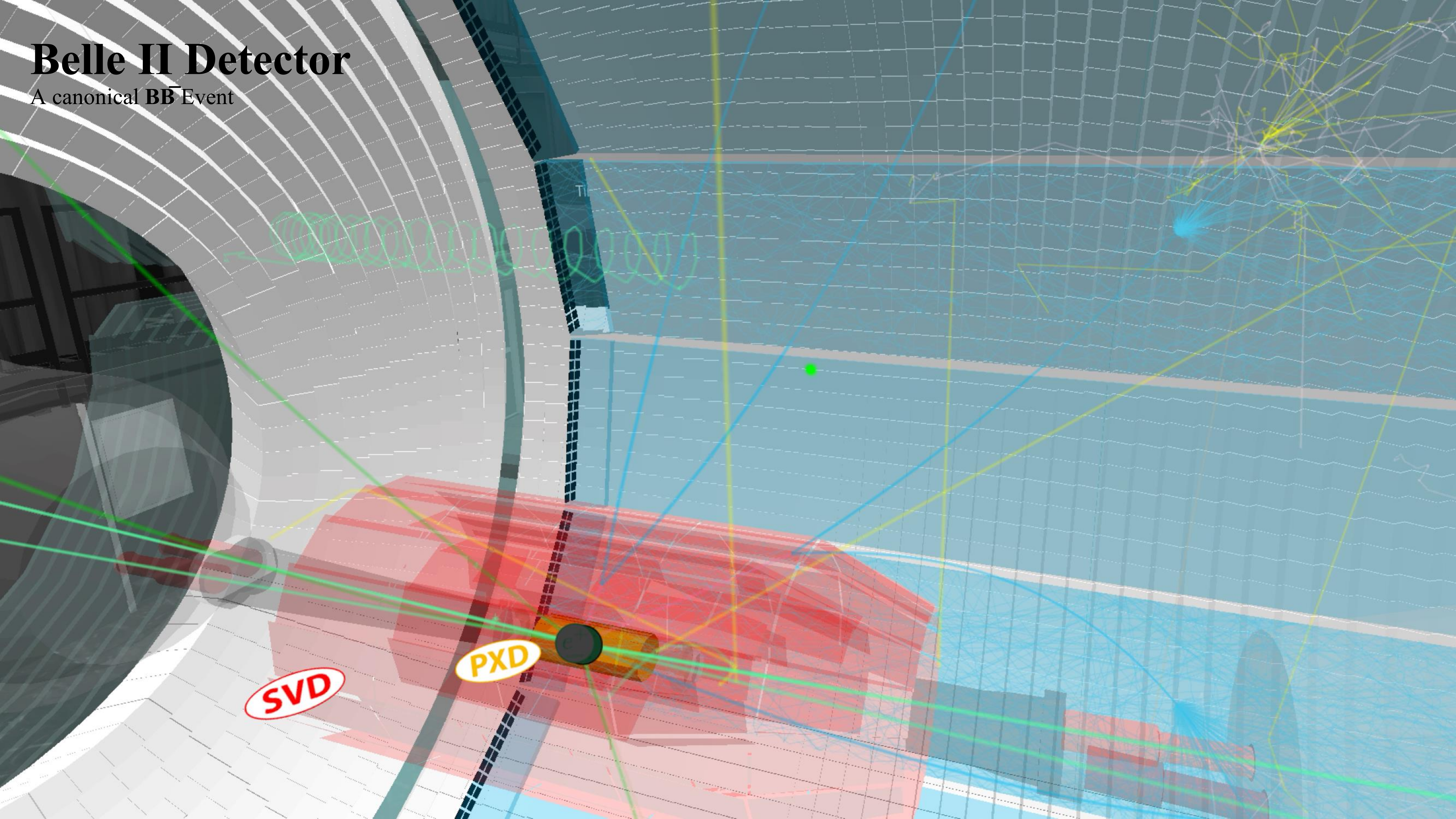
Belle II online event display

Belle II detector and offline event display

BACK UP

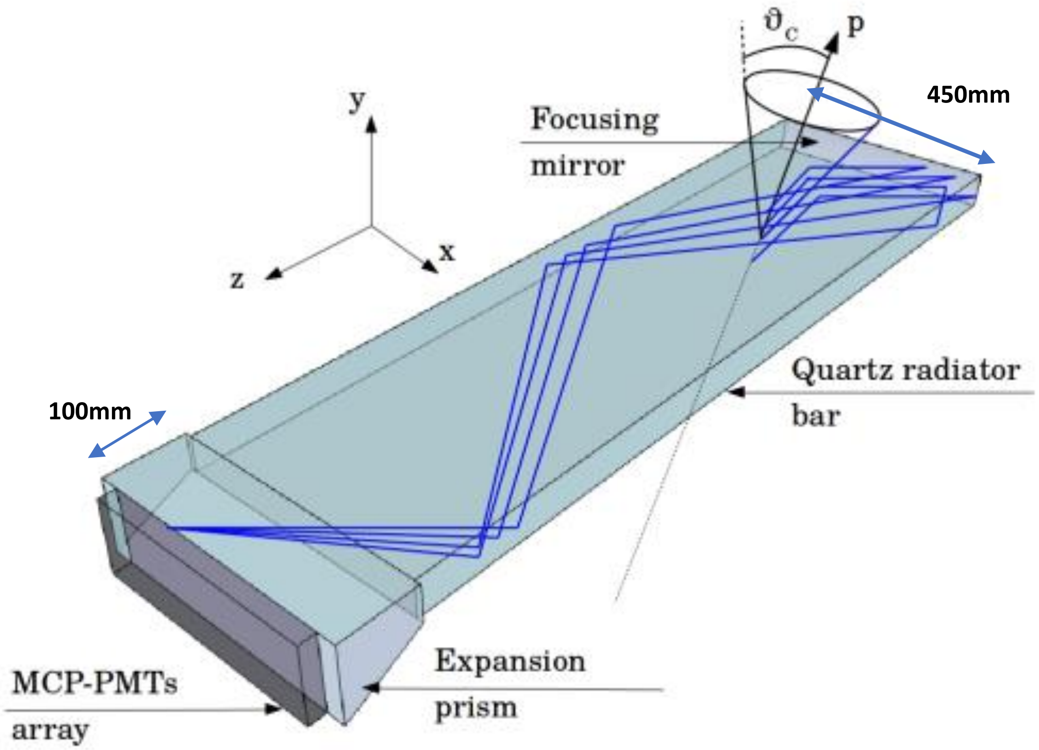
Belle II Detector

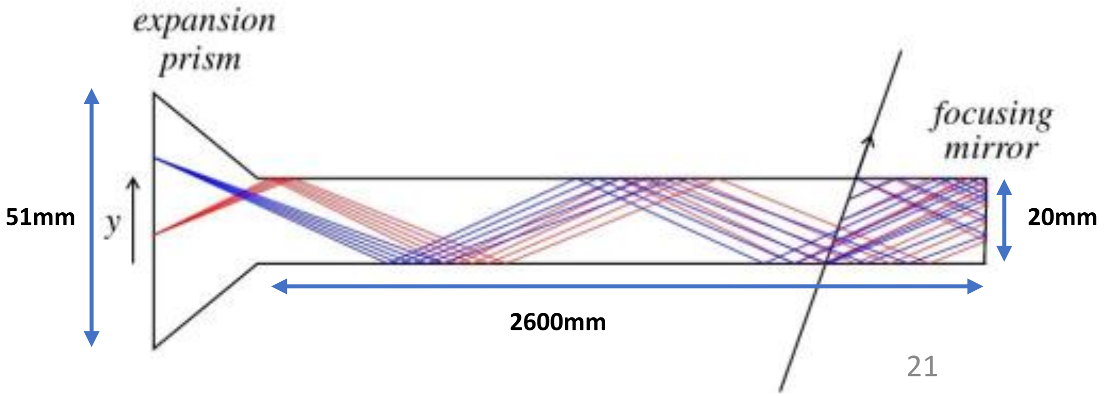
A canonical $B\bar{B}$ Event



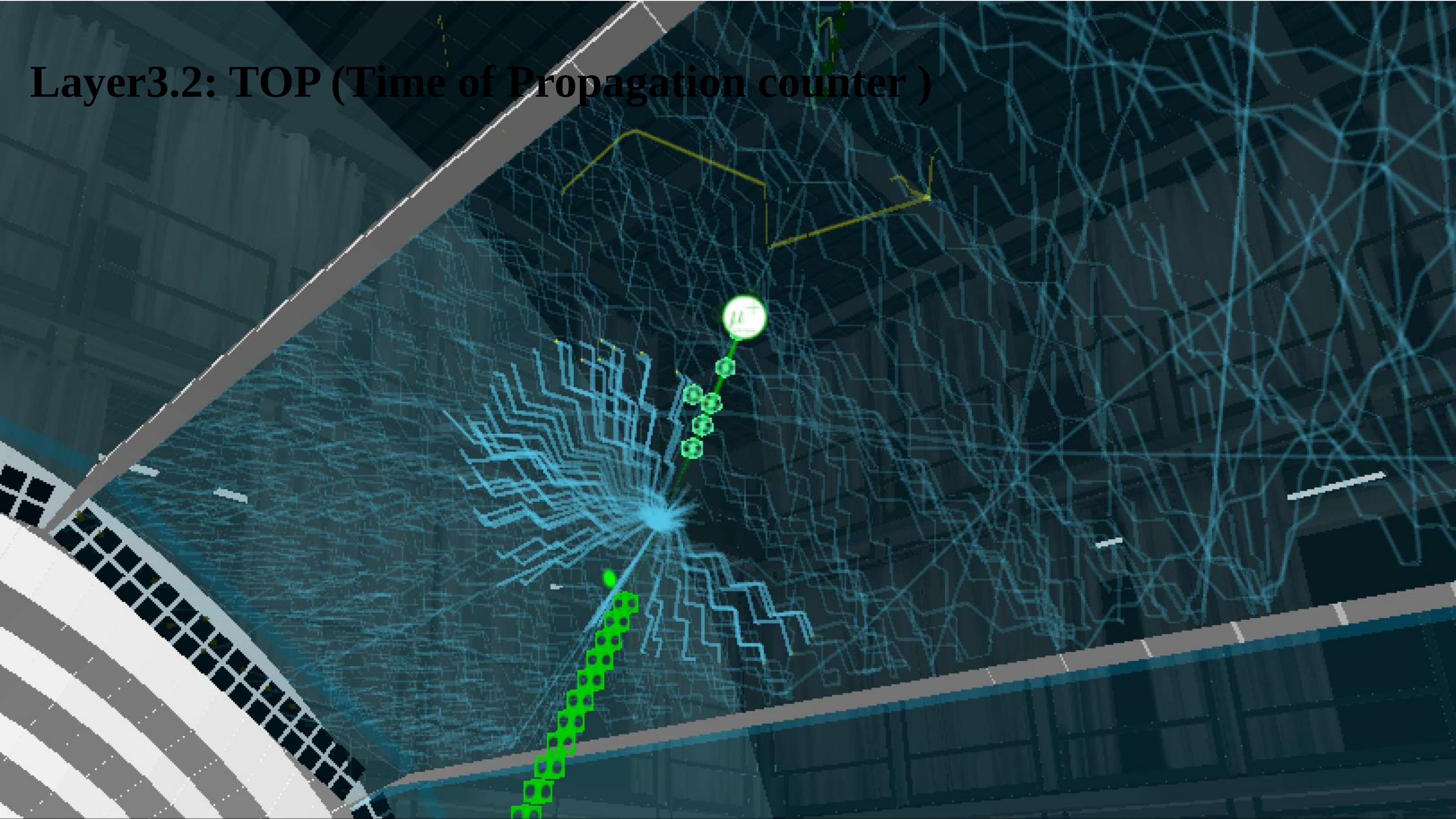
TOP (Time of Propagation counter)

- **Base on ring-imaging Cherenkov radiation**
- Particle identification(PID) → **Mainly $\pi^{\pm}$ and $K^{\pm}$**
- 16 modules → 2.6 m-long quartz radiator
- Right end → Mirror
- Left end → micro channel plate photomultipliers (MCP-PMTs)
- 2 × 16 matrix of MCP-PMTs
- **MCP-PMTs → time of propagation and arrival (x,y) coordinates of the photons.**

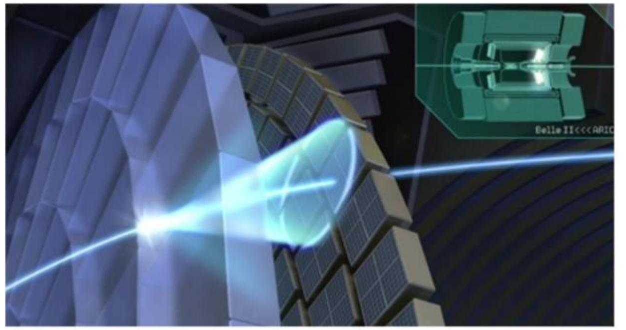




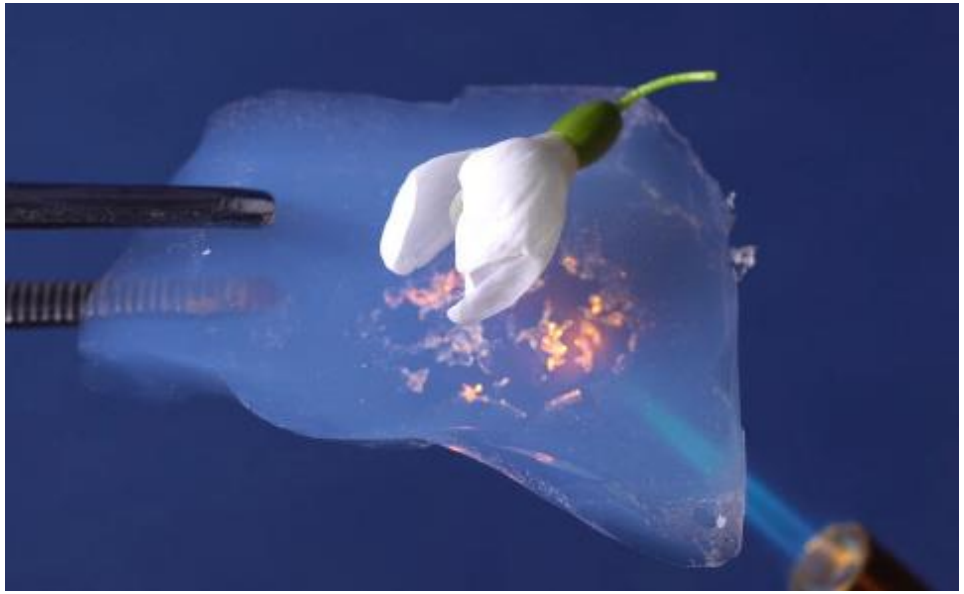
Layer3.2: TOP (Time of Propagation counter)



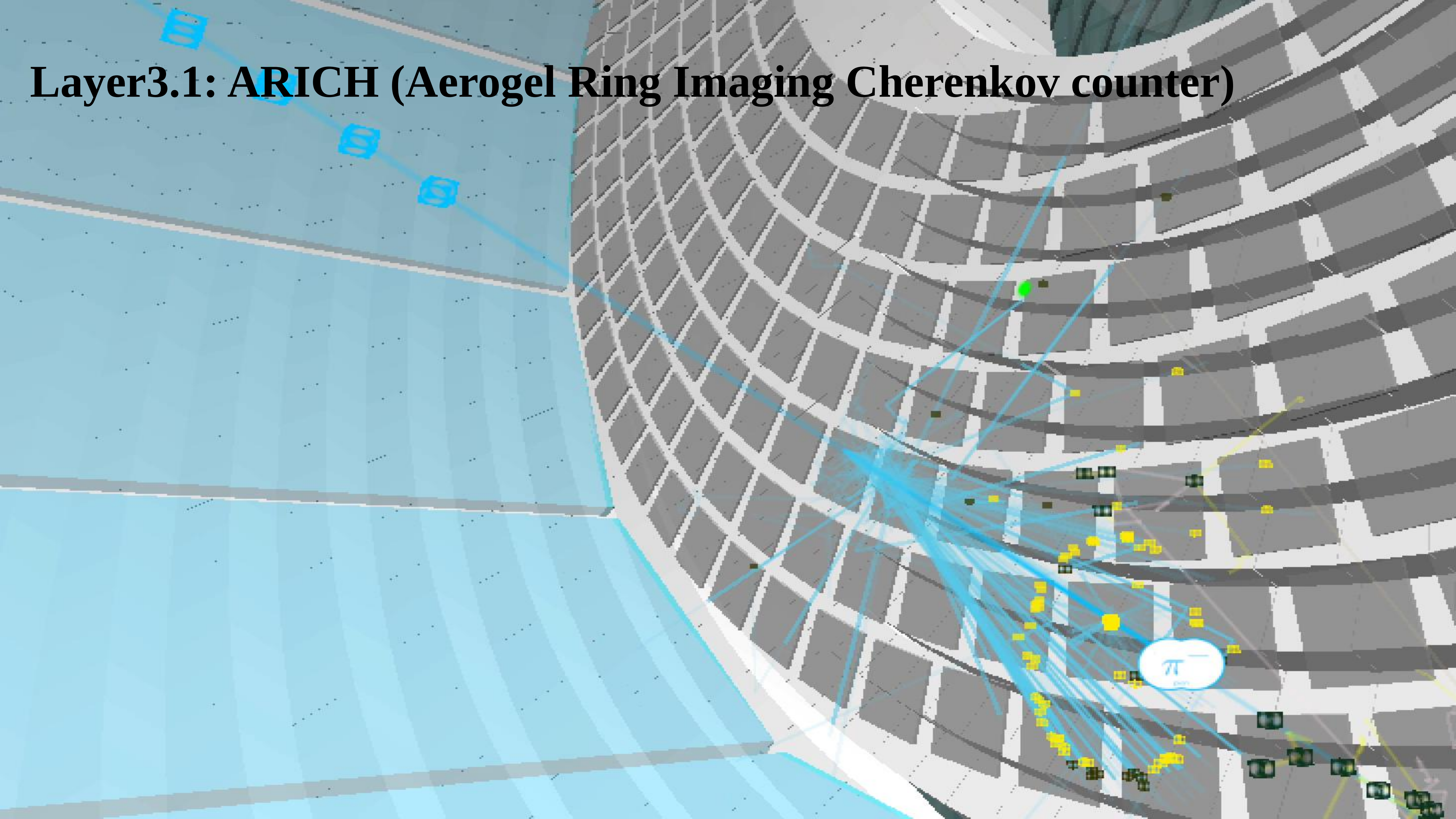
ARICH (Aerogel Ring Imaging Cherenkov counter)



- Covers the forward endcap region
- **Cherenkov light** → Hybrid Avalanche Photon Detectors (HAPDs)
- Inner / Outer radius → 410 / 1140 mm
- **Provides a good K/π separation for tracks**
- **n_1 = 1.046 and n_2 = 1.056**

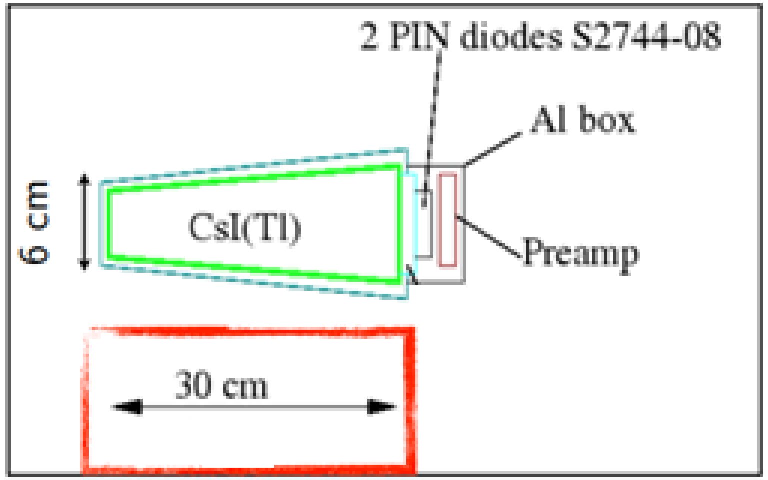


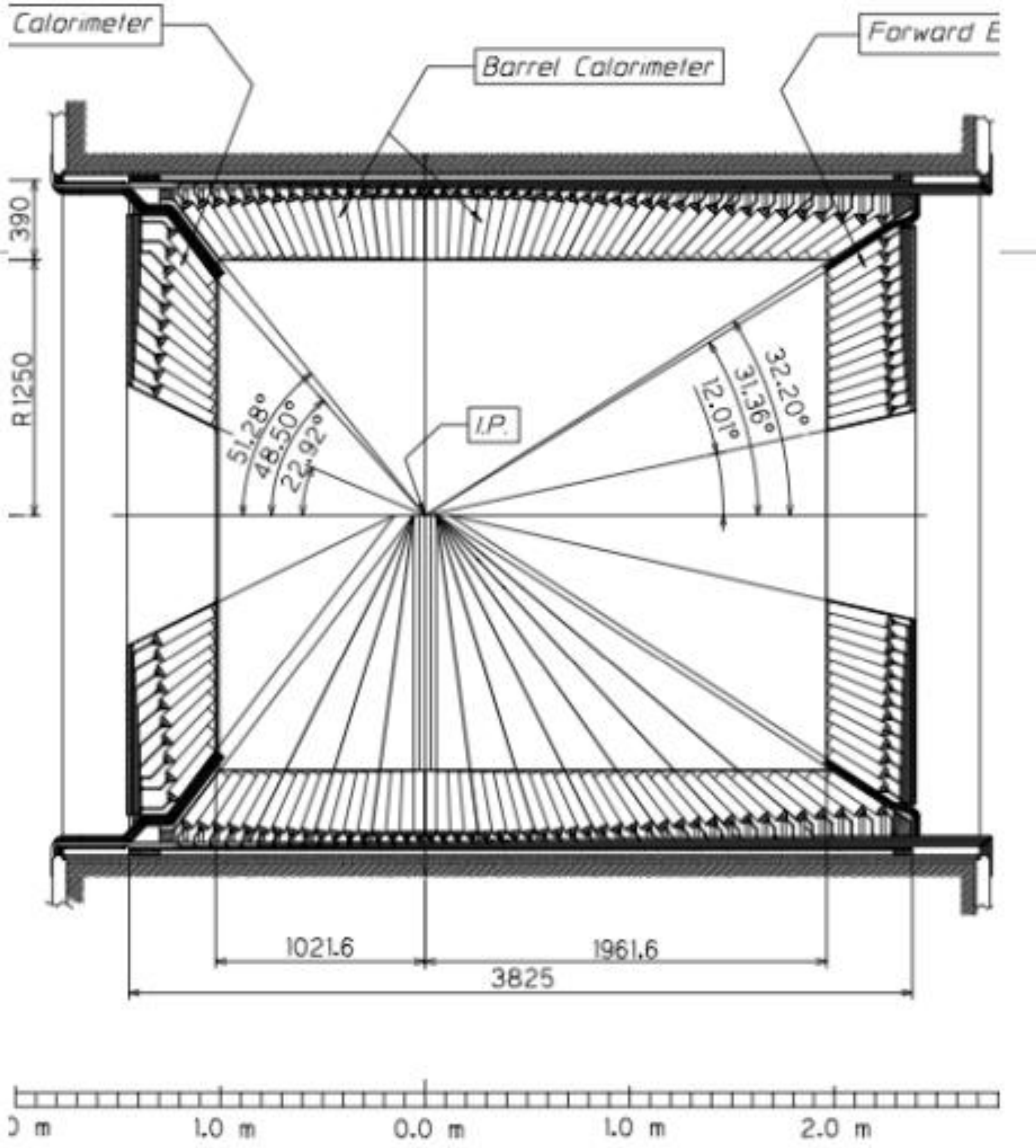
Layer3.1: ARICH (Aerogel Ring Imaging Cherenkov counter)



ECL (Electromagnetic Calorimeter)

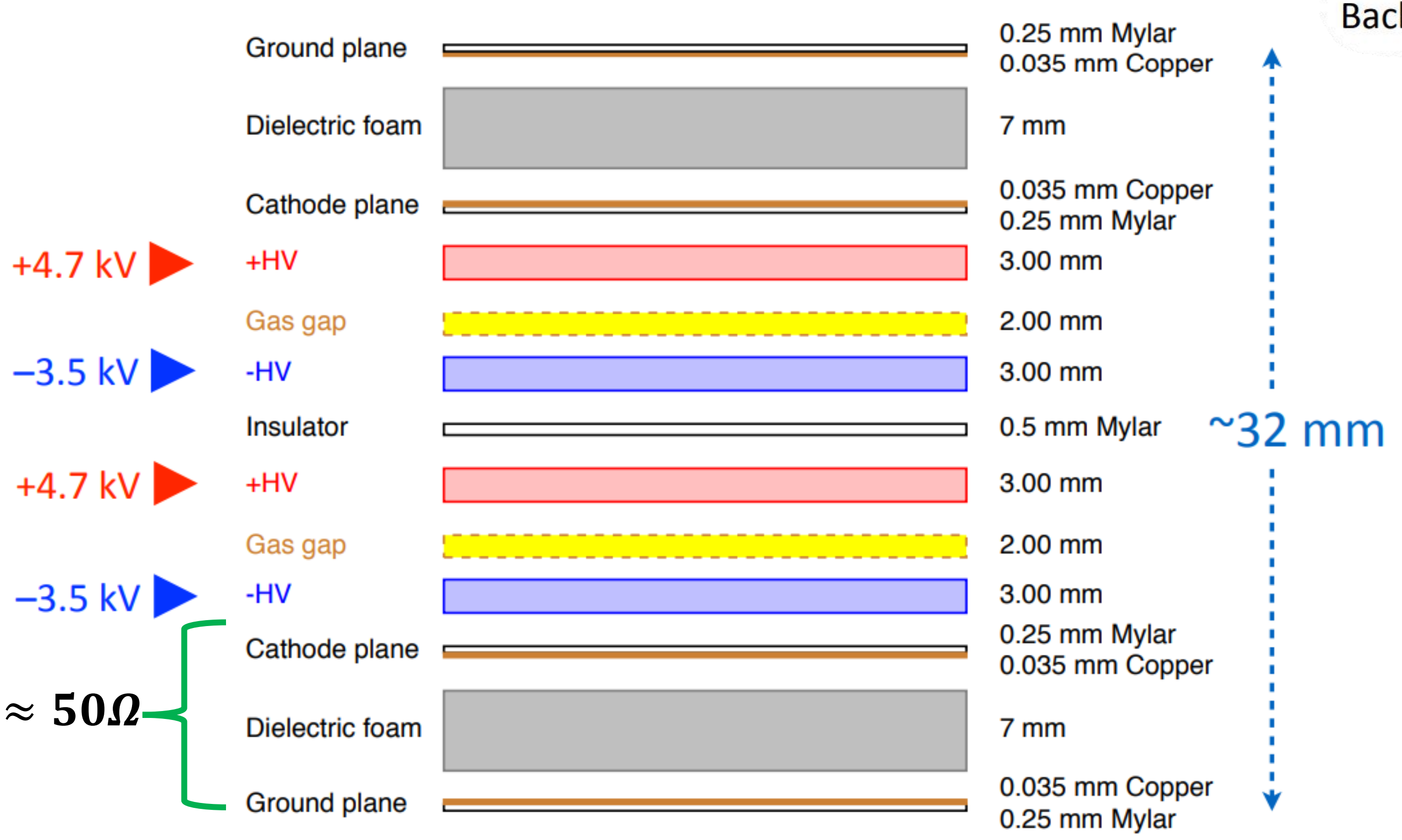
- Energy deposit range → 20 MeV to 4 GeV
- Size → Crystal about $6 \times 6\ cm^2$ in cross section and $30\ cm$ in length.
- Two sections
  - Barrel → $3m$ long with R = $1.25m$
  - Forward/backward endcaps → Z = $1.96m$ and Z = $-1.02m$

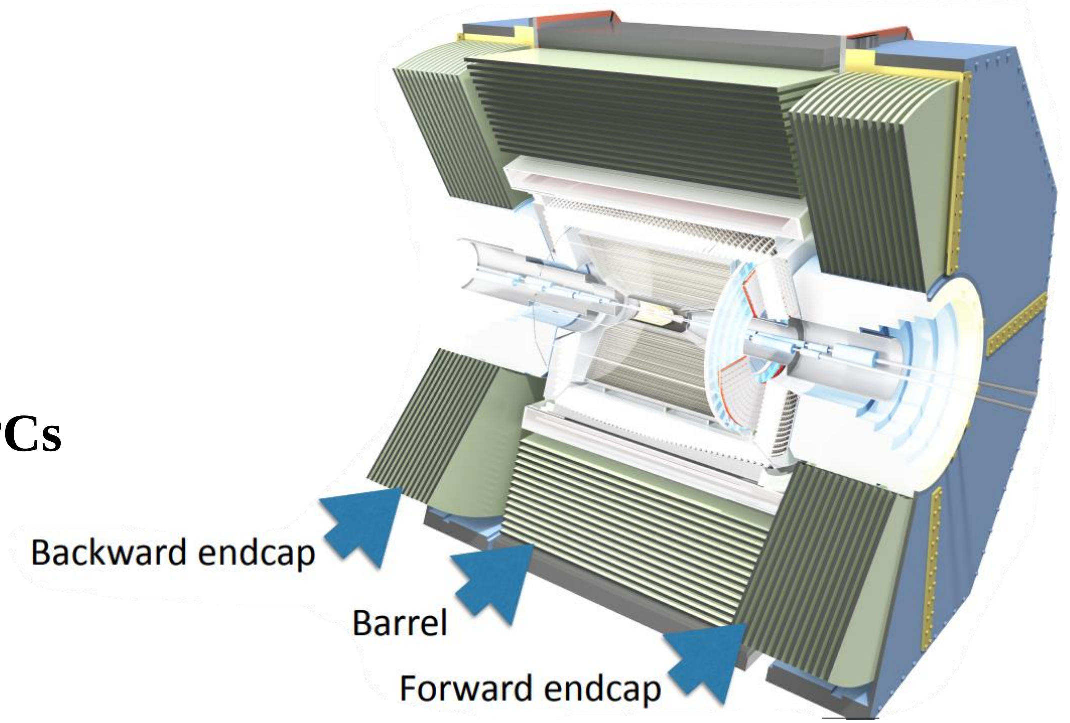




KLM (K_L^0 and μ detector)

One panel has alternating layers and two independent RPCs
(resistive plate chamber)





Gas mixture → 62% HFC-134a freon
30% argon
8% butane-silver

Float-glass electrodes → $\rho \cong 10^{12} \Omega \cdot cm$

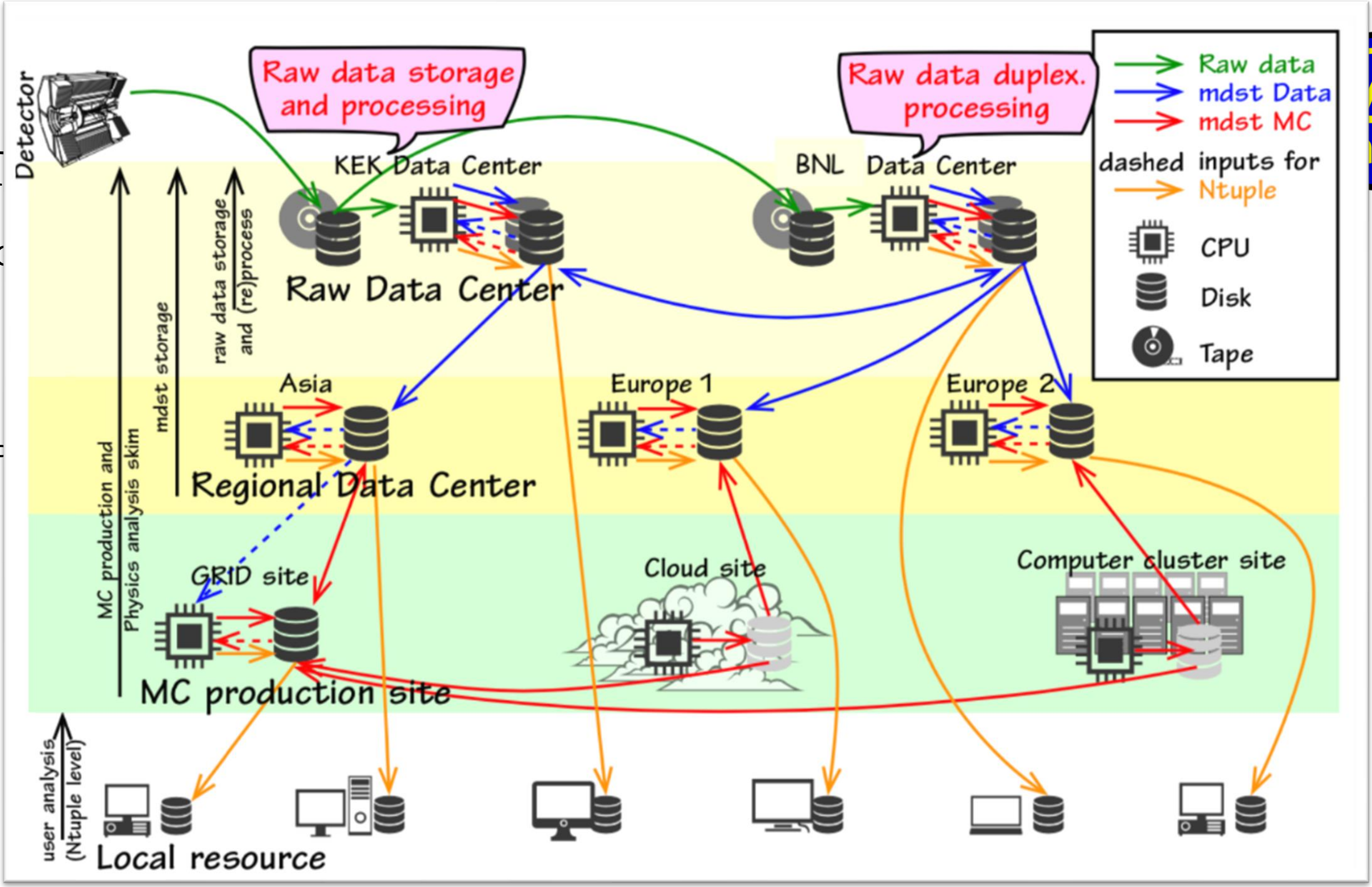
The Belle II software and computing

- Belle II analysis software framework (**basf 2**)

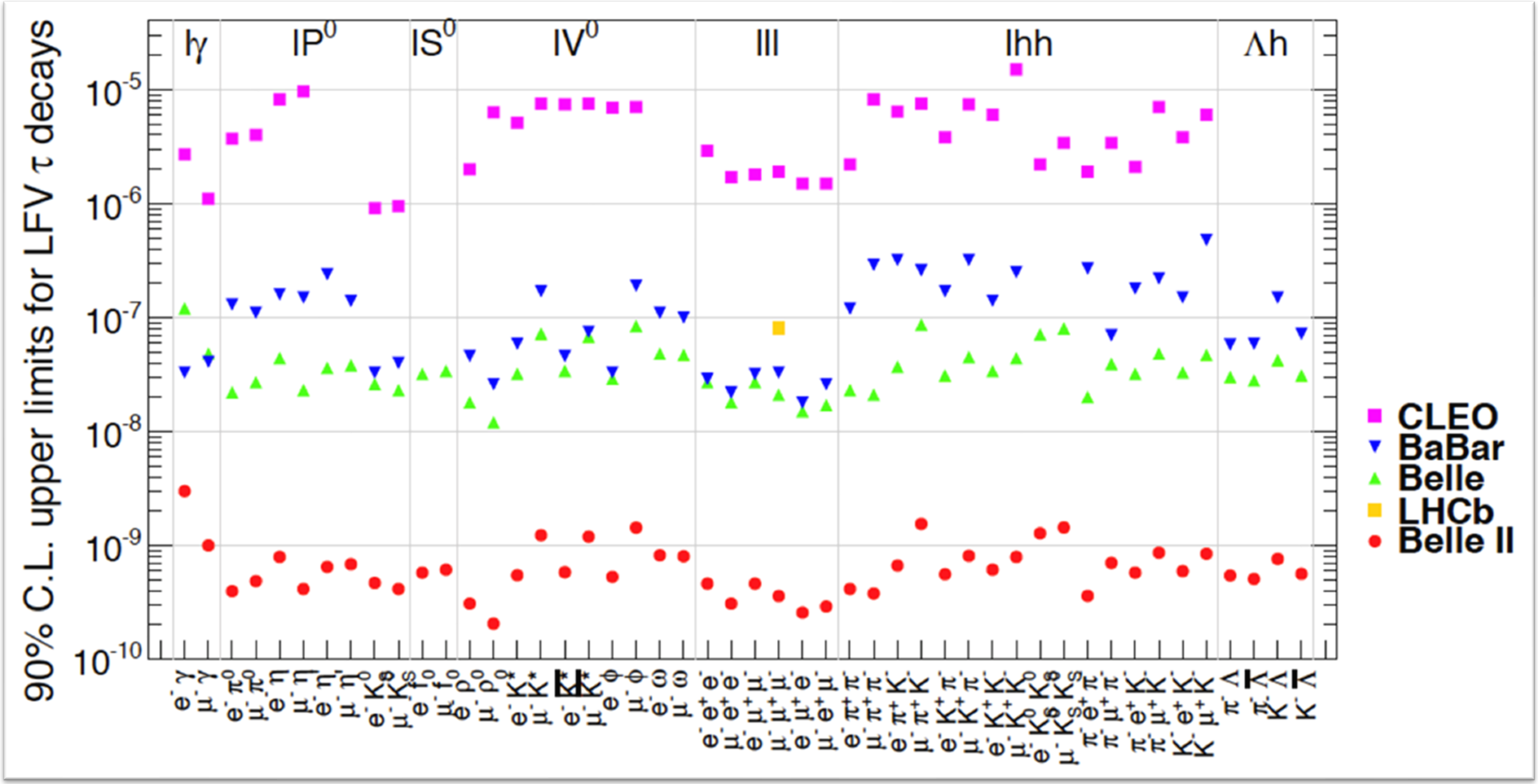
- **Around 40 packages** for different purposes such as for sub-detectors, reconstruction, and etc.

- Grid Belle II analysis software framework (**gbasf 2**) distributed computing among members of the Belle II

- Performs several tasks such as →
    - Raw data processing
    - Monte Carlo event production
    - Physics analysis

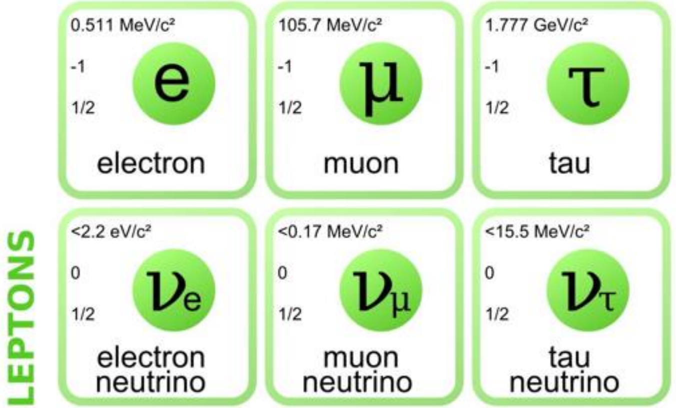


Detector
Raw data storage and processing
Raw data duplex. processing
KEK Data Center
BNL Data Center
Raw data
mdst Data
mdst MC
dashed inputs for
Ntuple
CPU
Disk
Tape
Raw Data Center
raw data storage and (re)process
mdst storage
MC production and Physics analysis skim
Asia
Europe 1
Europe 2
Regional Data Center
GRID site
Cloud site
Computer cluster site
MC production site
user analysis (Ntuple level)
Local resource



90% C.L. upper limits for LFV τ decays
10-5
10-6
10-7
10-8
10-9
10-10
lγ
lP0
lS0
lV0
lll
lhh
Λh
CLEO
BaBar
Belle
LHCb
Belle II

Charged Lepton Flavor Violation (CLFV)



Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu\eta$	BR < 6.5 E-8	
$\tau \rightarrow \mu\gamma$	BR < 6.8 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \rightarrow \mu\mu\mu$	BR < 3.2 E-8	
$\tau \rightarrow eee$	BR < 3.6 E-8	
$K_L \rightarrow e\mu$	BR < 4.7 E-12	
$K^+ \rightarrow \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \rightarrow e\mu$	BR < 7.8 E-8	
$B^+ \rightarrow K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \rightarrow e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \rightarrow eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

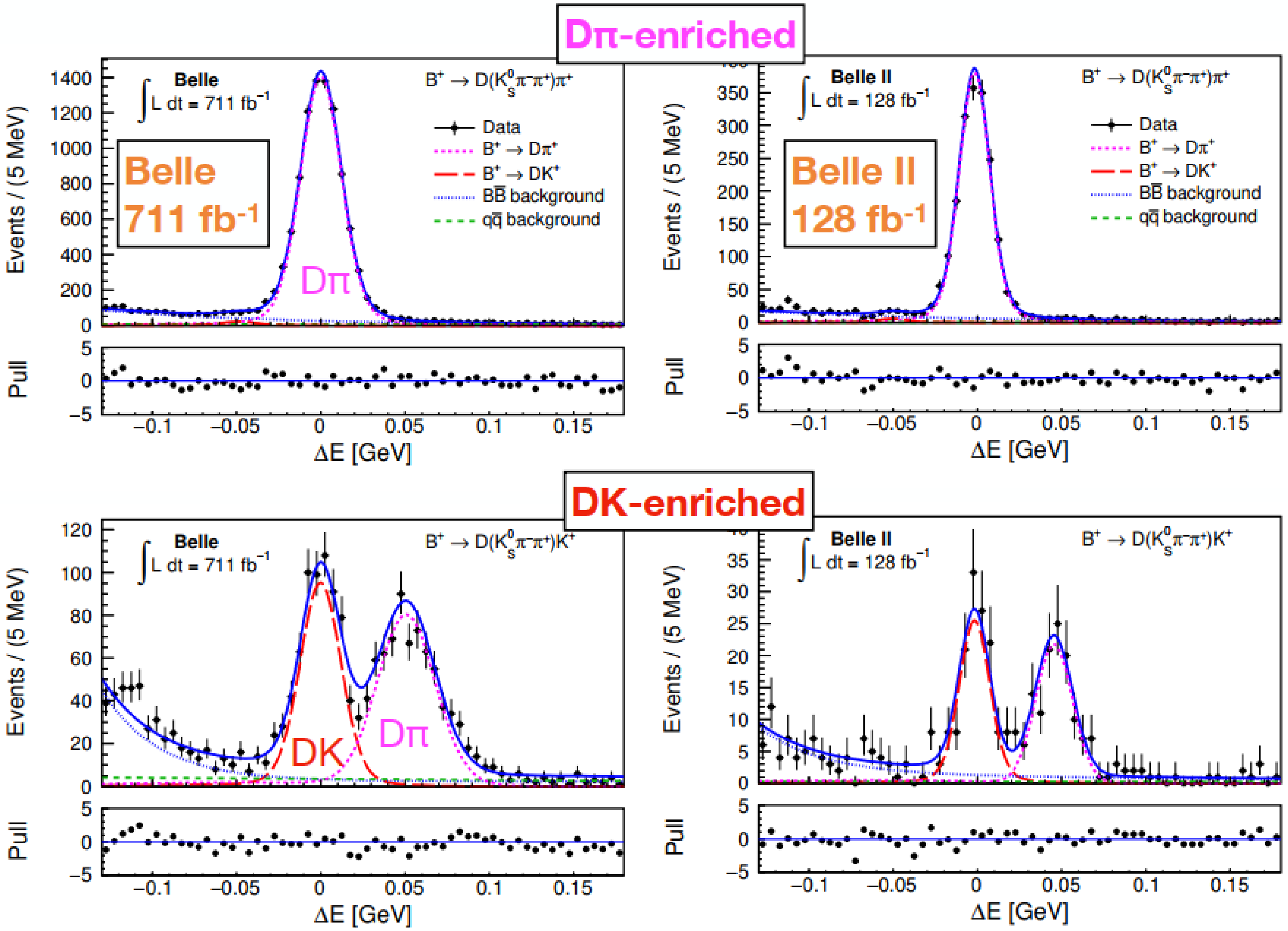
Hadronic B decays
CKM angle $\Phi_3 \equiv \gamma$ with Belle and Belle II

- Current measurement $66.2^{+3.4}_{-3.6}{}^{0}$

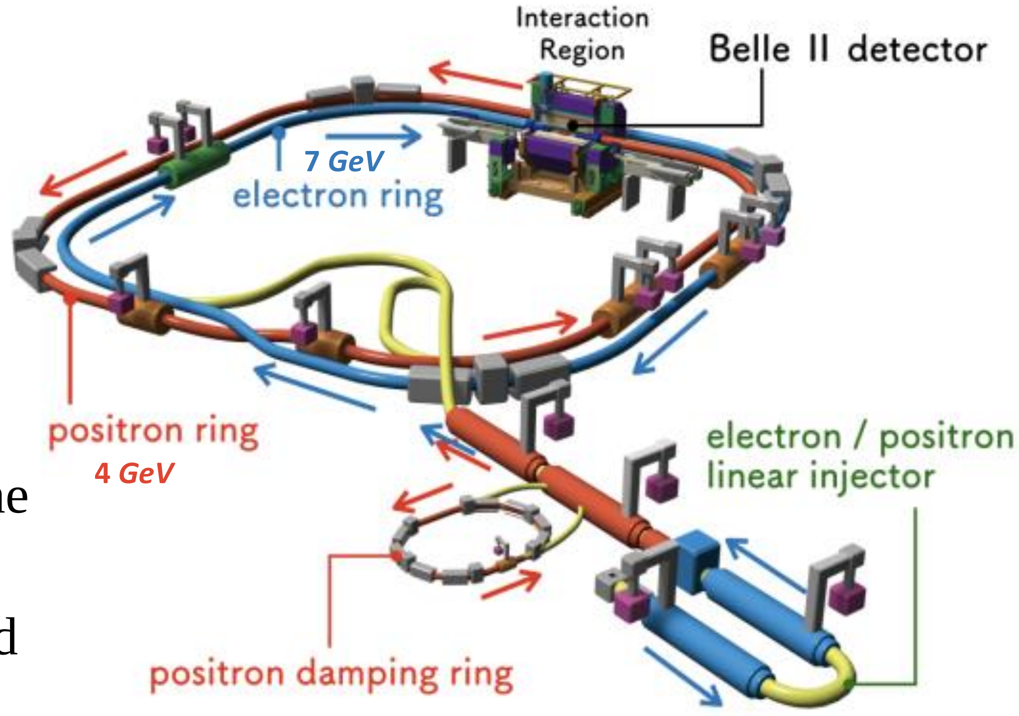
$$\frac{A_{sup}(B^+ \to \bar{D}^0 h^+)}{A_{fav}(B^+ \to D^0 h^+)} = r_B e^{i(\delta_B - \phi_3)}$$

$\delta_B \to strong\ phase$
$r_B \to ratio\ of\ amplitudes$
$\phi_3 \to CKM\ angle$

$$\begin{aligned} \phi_3 &= (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ\,, \\ r_B^{DK} &= 0.129 \pm 0.024 \pm 0.001 \pm 0.002, \\ \delta_B^{DK} &= (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ\,, \\ r_B^{D\pi} &= 0.017 \pm 0.006 \pm 0.001 \pm 0.001, \\ \delta_B^{D\pi} &= (341.0 \pm 17.0 \pm 1.2 \pm 2.6)^\circ\,. \end{aligned}$$

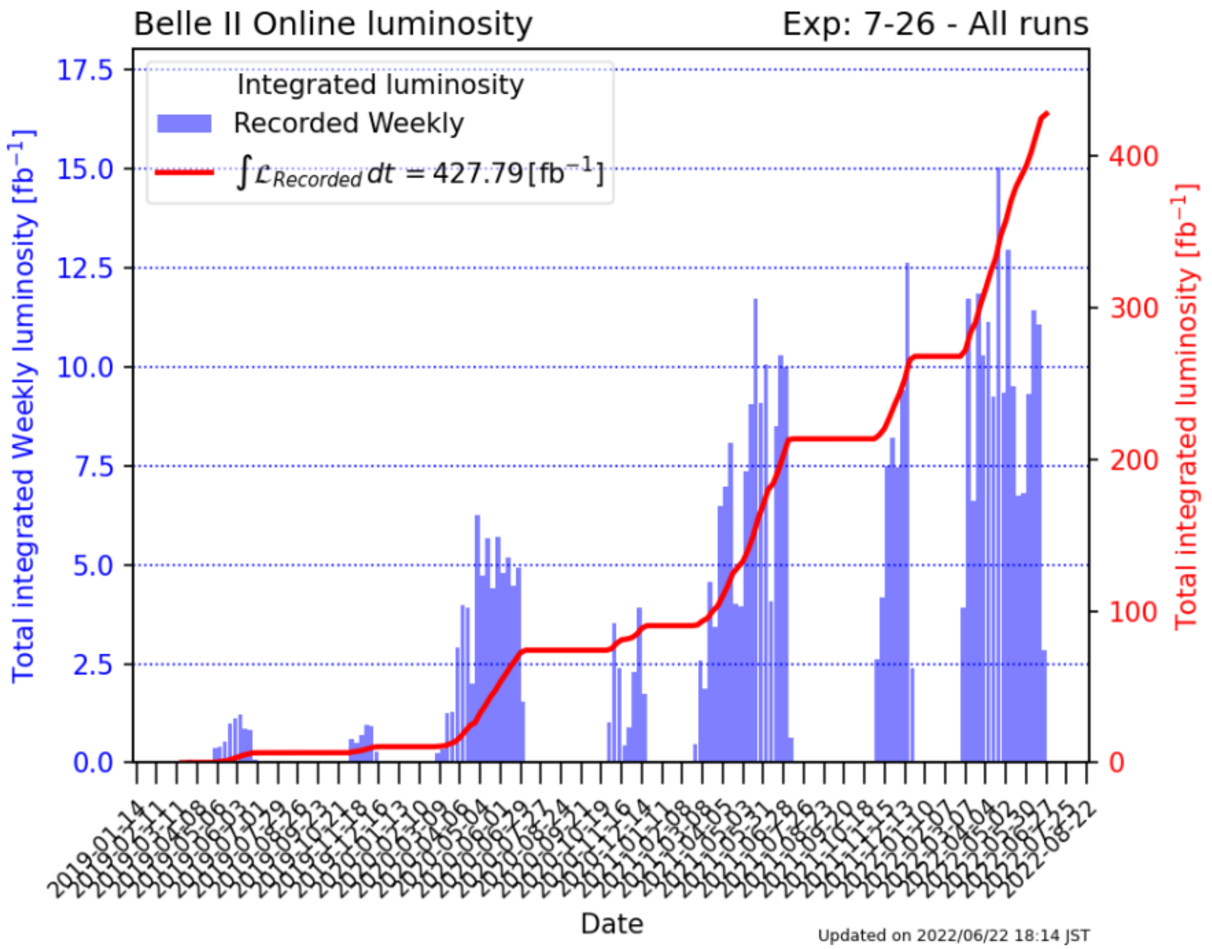


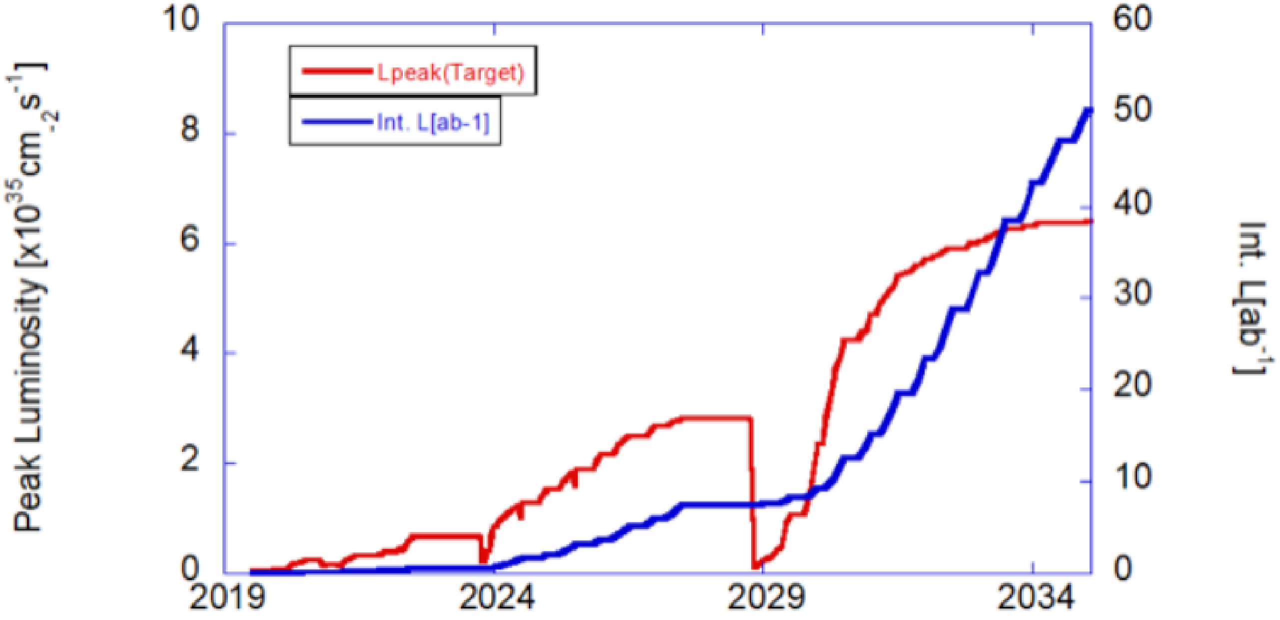
SuperKEKB Accelerator



- The linac is responsible for producing a beam of high-energy electrons. Electrons are generated from a metal photocathode by shining laser light on it, which causes the release of electrons via the photoelectric effect.
- After the electrons are generated, they need to be grouped together in tightly packed "bunches." Radiofrequency (RF) cavities are used to accelerate the electrons and create these electron bunches. The RF cavities are timed to accelerate the electrons at the right moment to form bunches with a specific spacing.
- Positrons, are generated using a process called "pair production." High-energy photons from a target material interact with atomic nuclei, creating electron-positron pairs. The positrons are then captured and accumulated in another storage ring called the positron ring.

SuperKEKB Accelerator





The Belle II software and computing

Belle Analysis Framework 2 (*basf* 2) →

- Online (example for the HLT in DAQ) and offline (physics analysis or detector studies) use.
- Event generation (EvtGen and PYTHIA) and simulation of the detector (Geant4)
- ROOT, used for analysis, installation and setup of *basf* 2 and externals.

~40 packages for →

- Base-level framework
- One package for each sub-detectors
- Packages dedicated to reconstruction and simulation
- Analysis package containing the tools used in the analysis

It allows →

- Generation of MC samples to simulation of all detector and to reconstruction of tracks
- Unpacking of raw data to physics analysis
- Extracting all parameters required by the user and saving them in appropriate files

The Belle II software and computing

Grid Belle Analysis Framework 2 (g*basf* 2) →

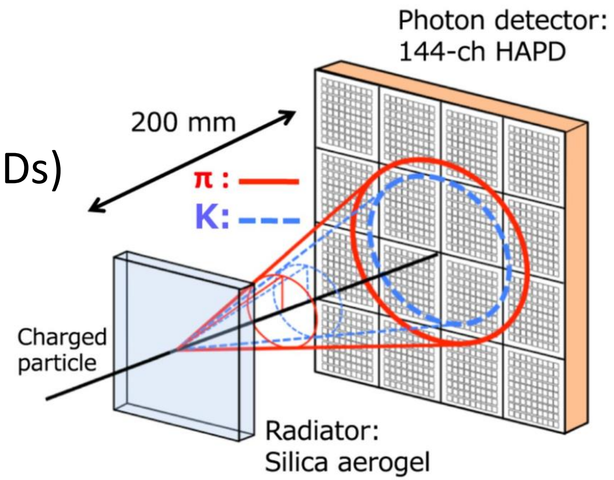
- Grid-based approach
- Distributed among members of the Belle II
- Common software for process the huge amount of data production

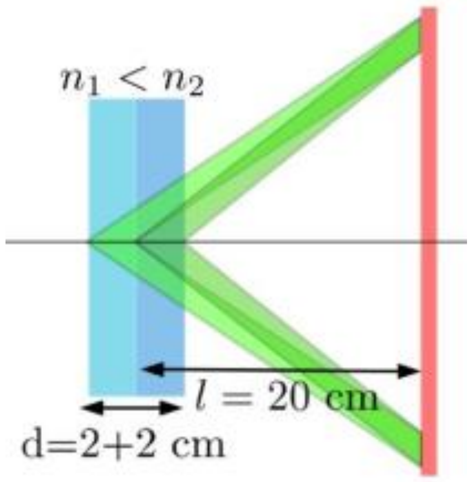
Performs several tasks such as →

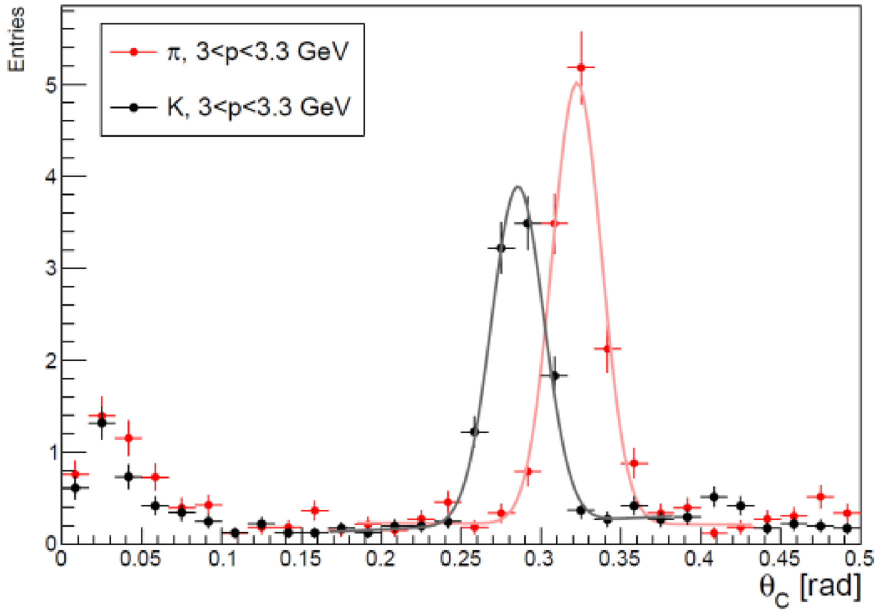
- raw data processing
- Monte Carlo event production
- physics analysis

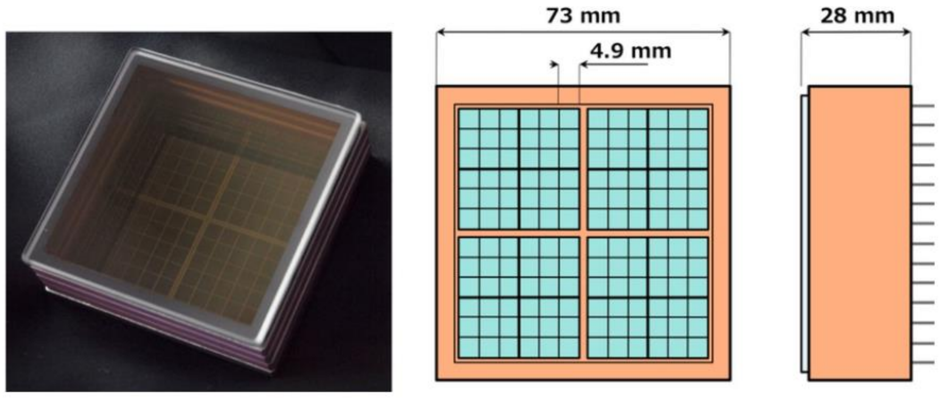
ARICH (Aerogel Ring Imaging Cherenkov counter)

- Covers the forward endcap region
- Cherenkov light → Hybrid Avalanche Photon Detectors (HAPDs)
- Inner / Outer radius → 410 / 1140 mm
- Provides a good K/π separation for tracks
- n_1 = 1.046 and n_2 = 1.056









Picture of the exterior and the design of the 144-ch HAPD.

ARICH (Aerogel Ring Imaging Cherenkov counter)

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

- (… dcap region
- (… brid Avalanche Photon Detectors (HAPDs)
- I
- I
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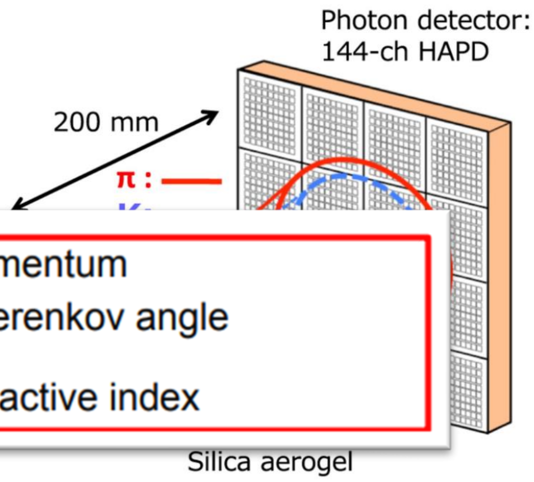
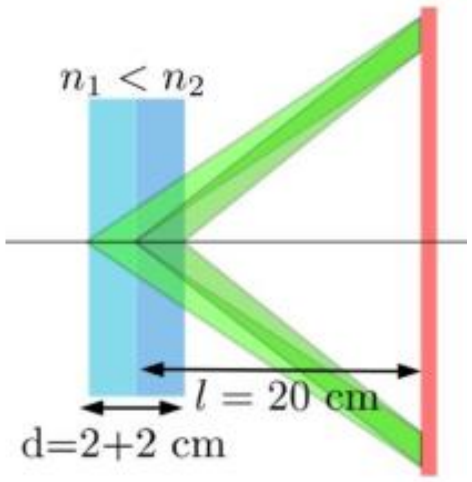
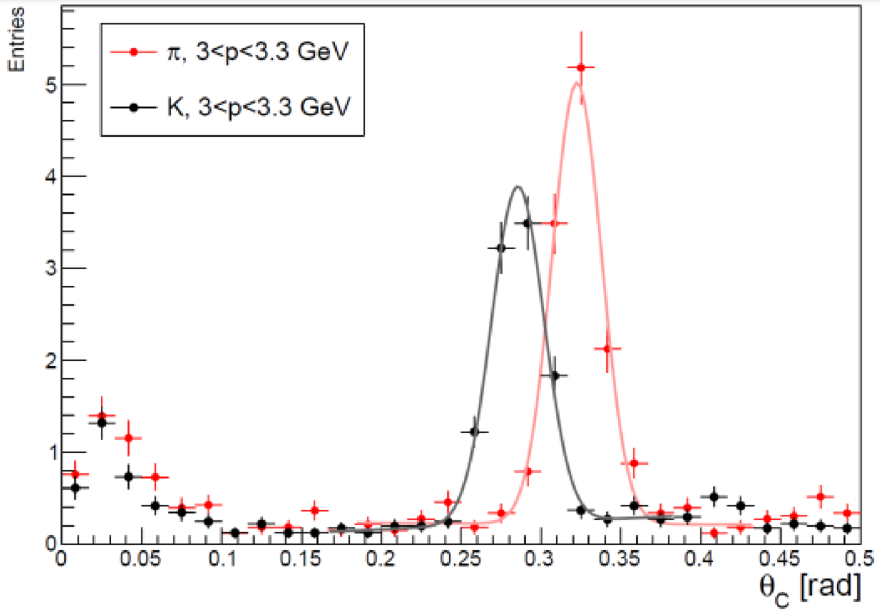
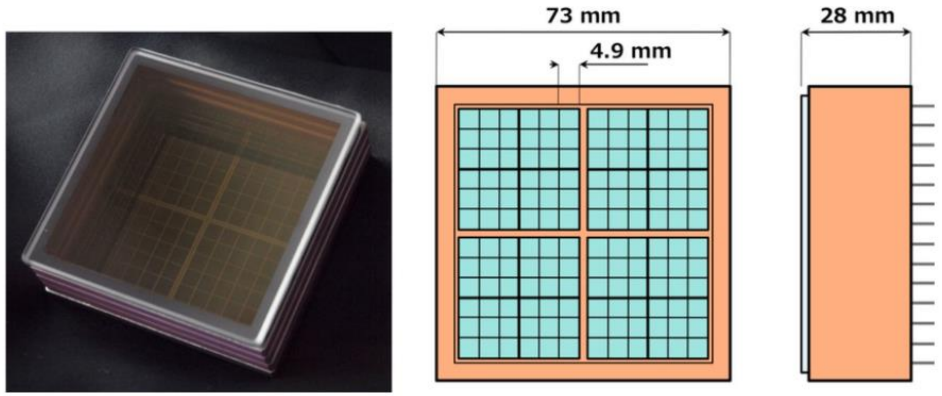
$$m = \frac{p}{c}\sqrt{n^2\cos^2\theta_c - 1}$$

Particle mass ← m; p → Particle momentum; θ_c → Particle Cherenkov angle; n → Aerogel refractive index









Picture of the exterior and the design of the 144-ch HAPD.

The B

Grid Belle

- C
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- C

Performs

- r
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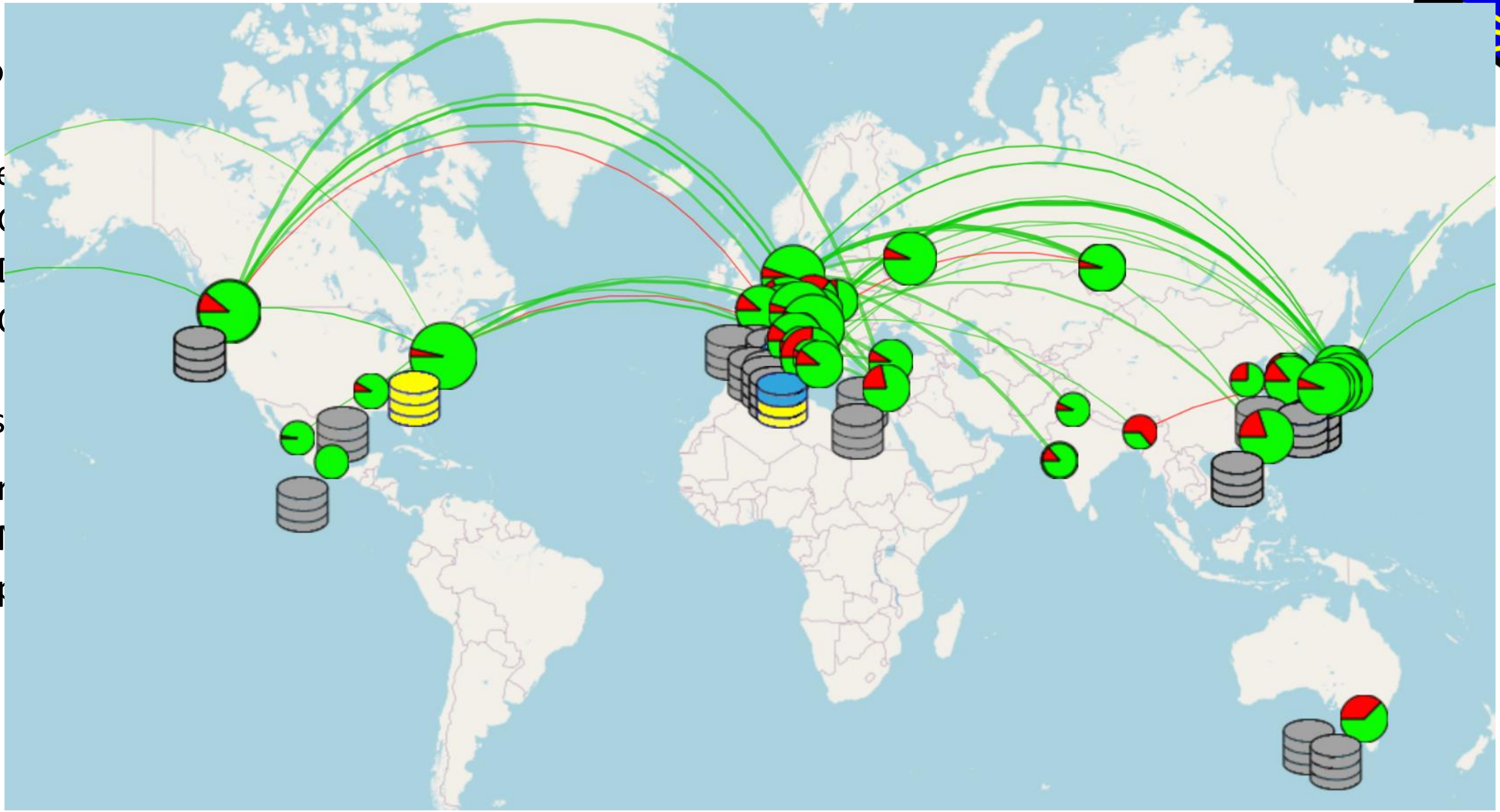
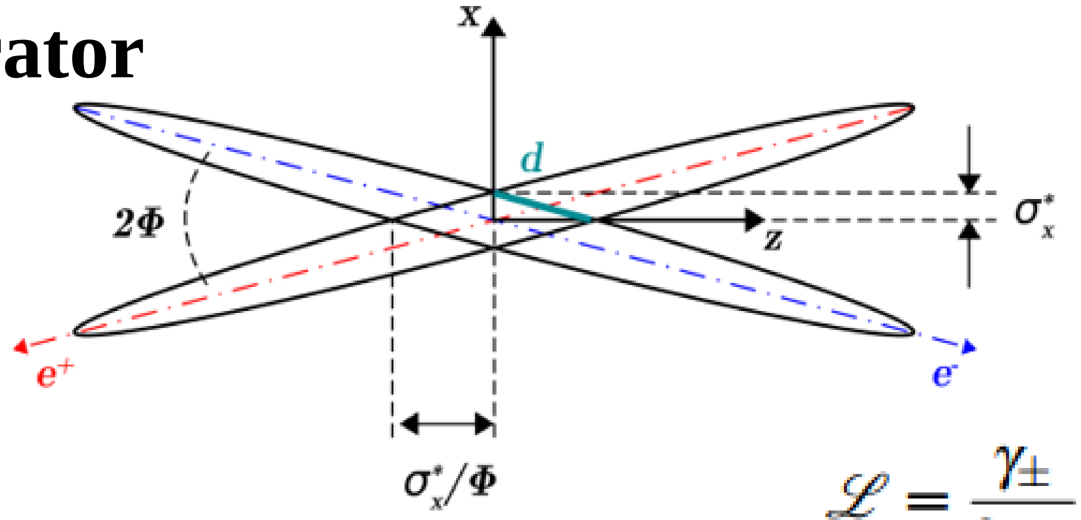
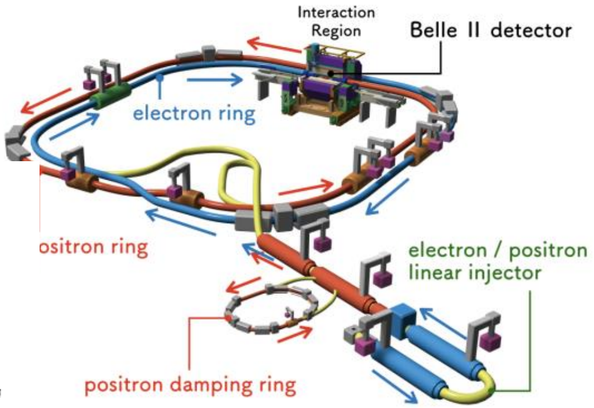
- p



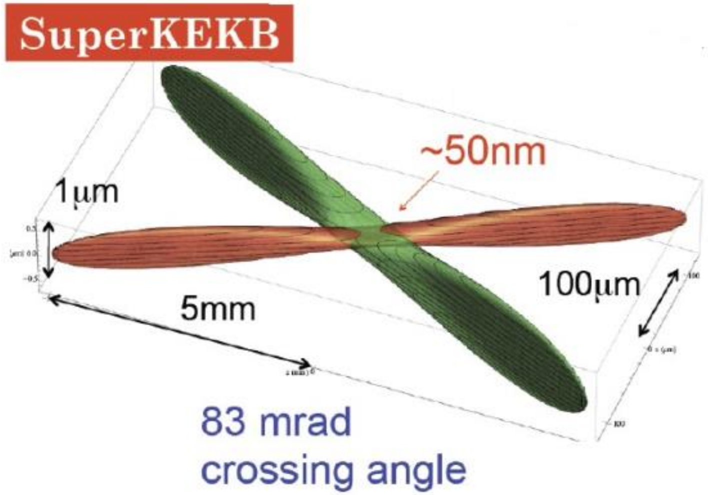
SuperKEKB Accelerator

- Nano beam used
- σ_x^* horizontal beam size
- d size of the overlap region
- 2Φ horizontal crossing angle 83mrad

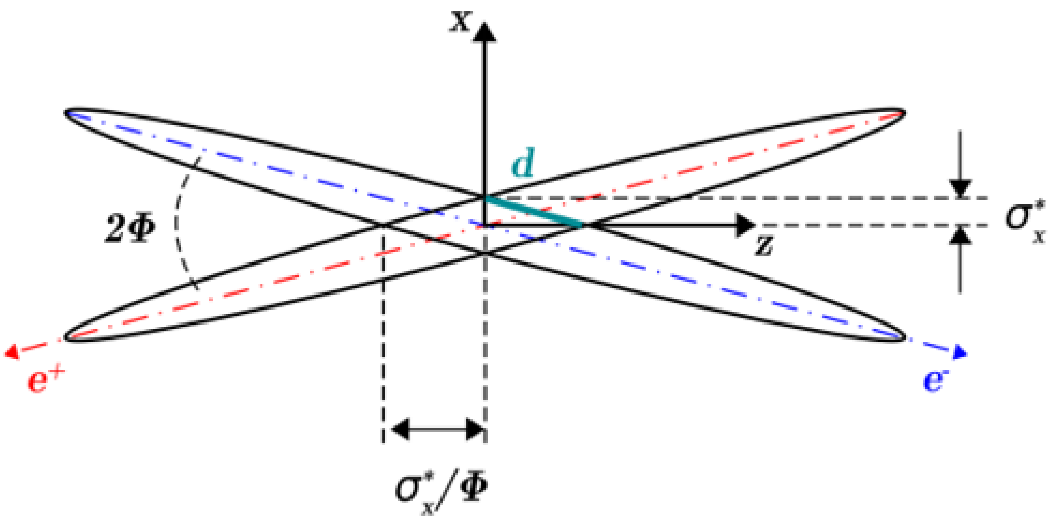




$$\mathscr{L} = \frac{\gamma_\pm}{2 e r_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\frac{R_L}{R_{\xi_y}}$$



SuperKEKB Accelerator

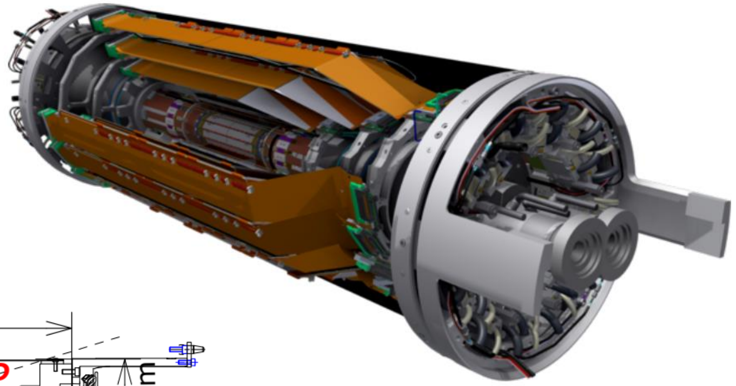


$$\mathscr{L} = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\frac{R_L}{R_{\xi_y}}$$

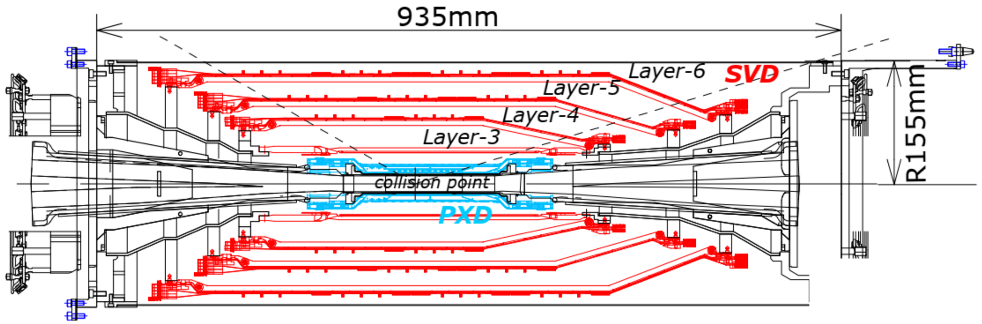
- γ Lorentz factor
- e electron charge
- r_e electron classical radius
- I total beam current
- $\xi_{y\pm}$ vertical-beam parameter
- $\beta_{y\pm}^*$ vertical betatron function
- R_L and R_{ξ_y} reduction factor and vertical beam-beam parameter (This ratio is approximately 1)
- Electron beam current 2.6A
- Positron beam current 3.6A
- Equipped with a final focus system→ QCS → four quadrupole magnets installed very close to the IP to reducing $\beta_{y\pm}^*$ up to 0.3mm

SuperKEKB Accelerator

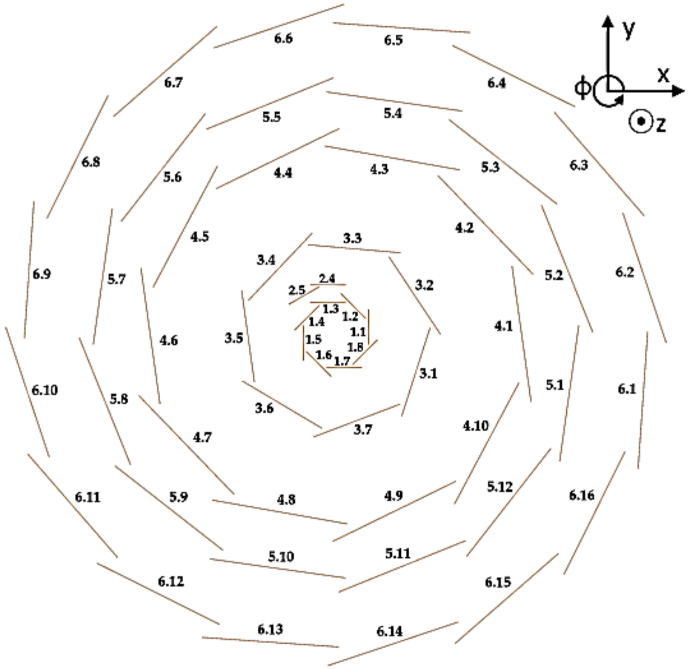
Parameters		Units	PEP-II achieved (LER/HER)	KEKB achieved (LER/HER)	SuperKEKB (LER/HER)
Beam Energy	E	GeV	3.1/9	3.5/8	4/7
Beam Current	I	A	2.7/1.8	1.6/1.2	3.6/2.62
Beam sizes at the IP	σ_x^*	μm	140	80	10.2/11.2
	σ_y^*	μm	3	1	0.048/0.062
	σ_z	mm	8.5	5	6/5
Betatron function	β_y^*	mm			0.3/0.3
Lorentz boost factor	$\beta\gamma$		0.56	0.43	0.28
Number of bunches	N_b		1732	1584	2503
Beam crossing angle	2ϕ	mrad	0	22	83
Beam-beam parameter	ξ_y^*			0.129/0.090	0.090/0.088
Horizontal emittance	ε_x	nm			3.2/5.1
Emittance ratio	$\varepsilon_y/\varepsilon_x$	%			0.27/0.25
Luminosity	$\mathscr{L}(\cdot 10^{34})$	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.2	2.11	65



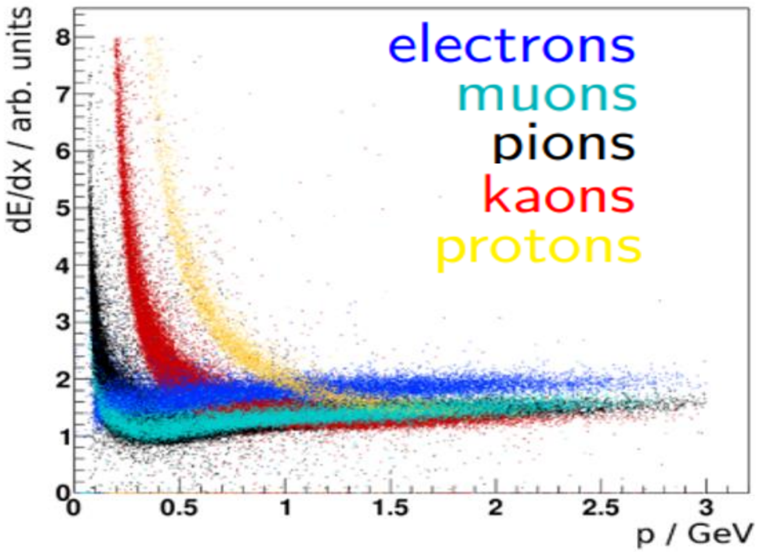
VXD (Vertex Detector)

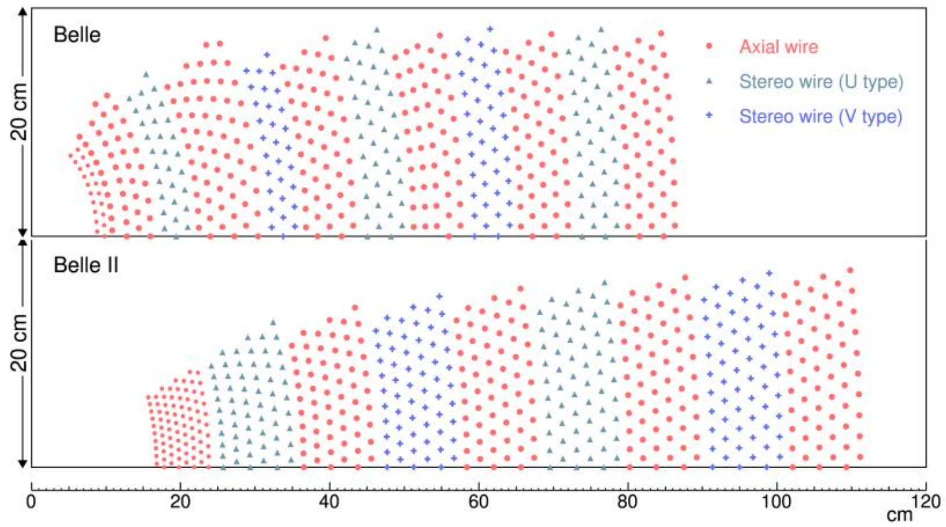


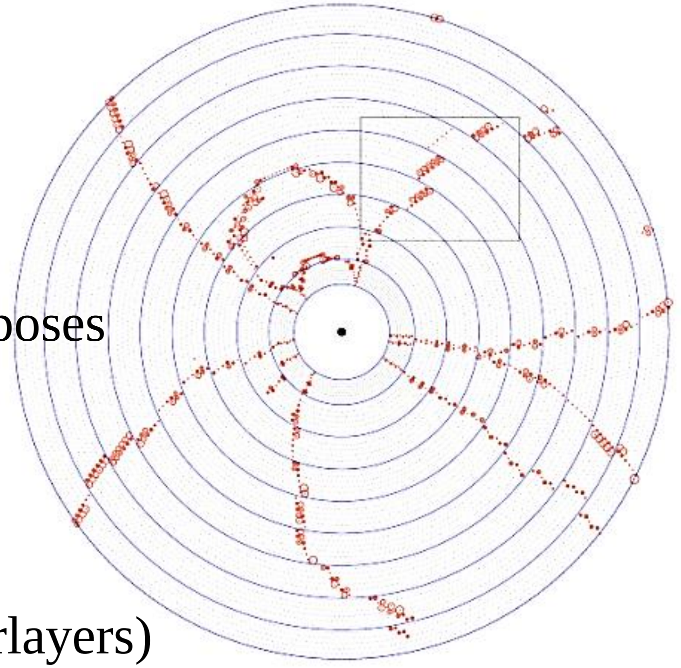
- **Layer 1,2 →Pixel Detector (PXD) →** DEPFET (Depleted P-channel Field Effect Transistor).
- **Layer 3 – 6 → Silicon Vertex Detector (SVD) →** DSSDs (Double-sided Silicon Strip Detectors).
- Installed in → $R_1 = 14mm,\ R_2 = 22mm,\ R_3 = 39mm,\ R_4 = 80mm,\ R_5 = 104mm,\ R_6 = 135mm$
- Essential for the precise measurement of K_S^0 decay vertex position



Layer2: CDC (Central Drift Chamber)







- Measures the trajectories and energy losses of charged particles for three purposes
  - **Measurement of the momenta of the tracks**
  - **PID using dE/dx**
- **Gas mixture → 50 % He and 50 % C_2H_6**
- Sense wires → Total 14,336 in 56 layers (grouped into nine parts called superlayers)
- There are 5 superlayers of axial wires and four superlayers of stereo wires (U and V)

Let's Summarize

- Final states charged particles → $e^{\pm}, \mu^{\pm}, \pi^{\pm}, K^{\pm}, p, and\ \bar{p}$ → VXD, CDC
- Charge particle identification → TOP, ARICH and CDC
- TOP → $K^{\pm}\ and\ \pi^{\pm}$
- KL and muon → Detection of $K_L\ and\ \mu^{\pm}$
- Neutral particles → $\gamma,\ K_L^0, \pi^0$ → energy deposit → ECL and KLM