The Belle II Experiment

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Outline

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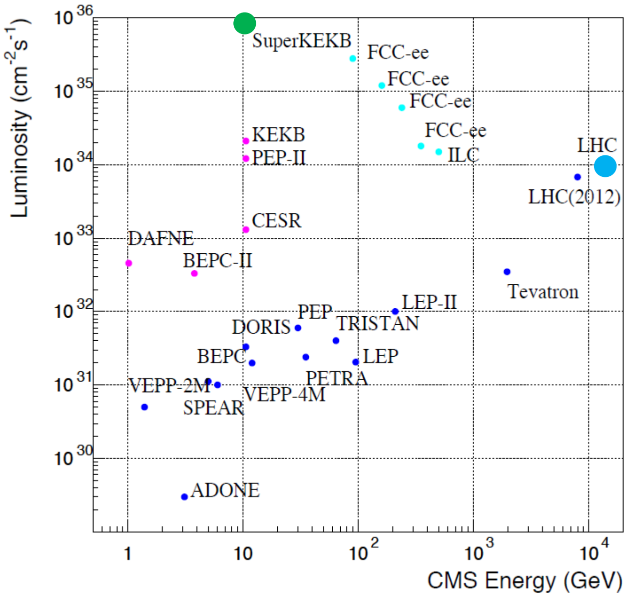
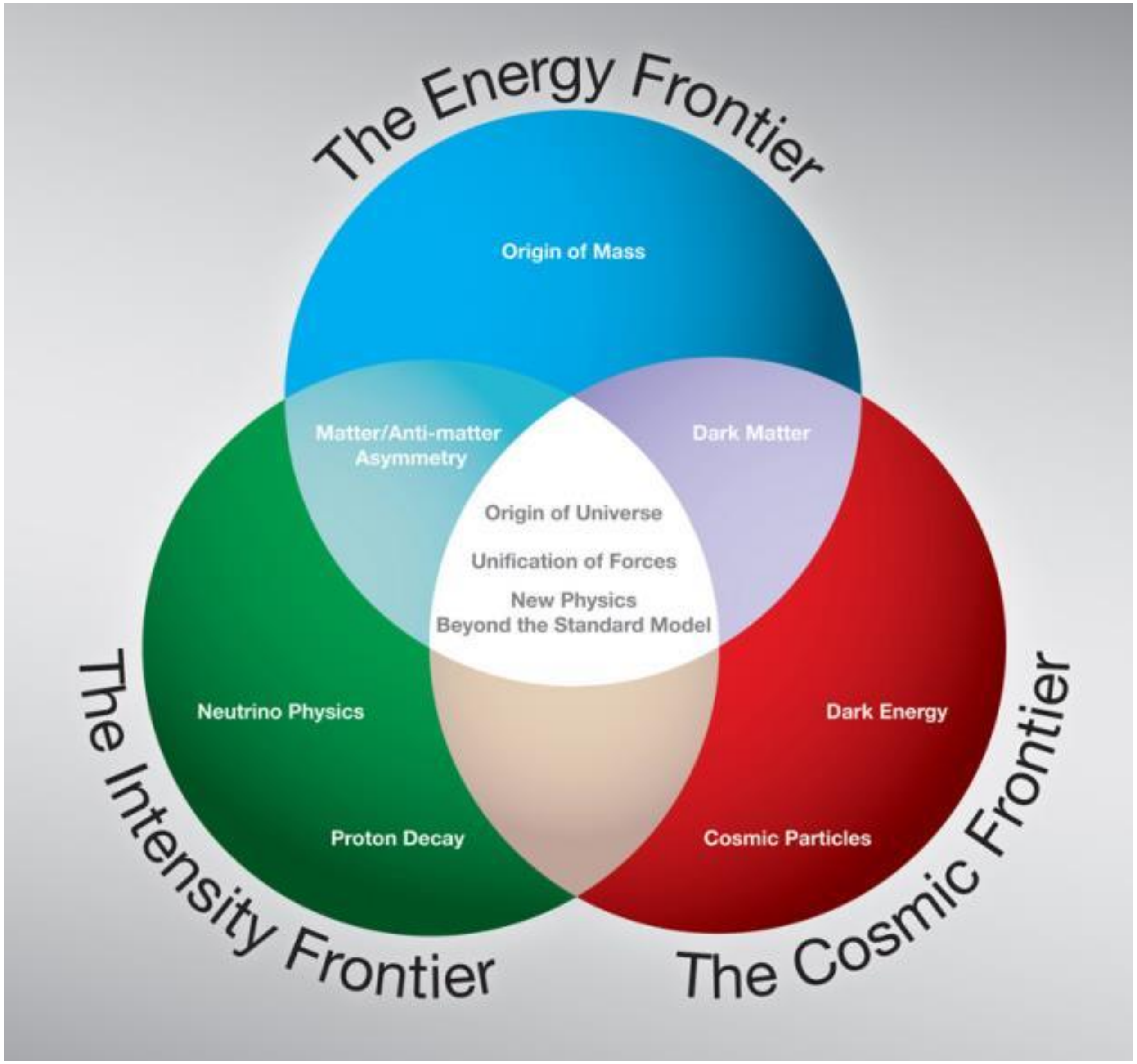
- Flavor Physics Program
- The SuperKEKB Accelerator
- The Belle II Detector

The Three Frontiers



- The **Intensity Frontier**: Search for rare new phenomena using *medium-energy ultra-high-luminosity* machines



Why Super B-Factories?

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50:1

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- Paradigm shift: From 'Is the SM with CKM right?' to **'How is the SM wrong?'**

Why Super B-Factories?

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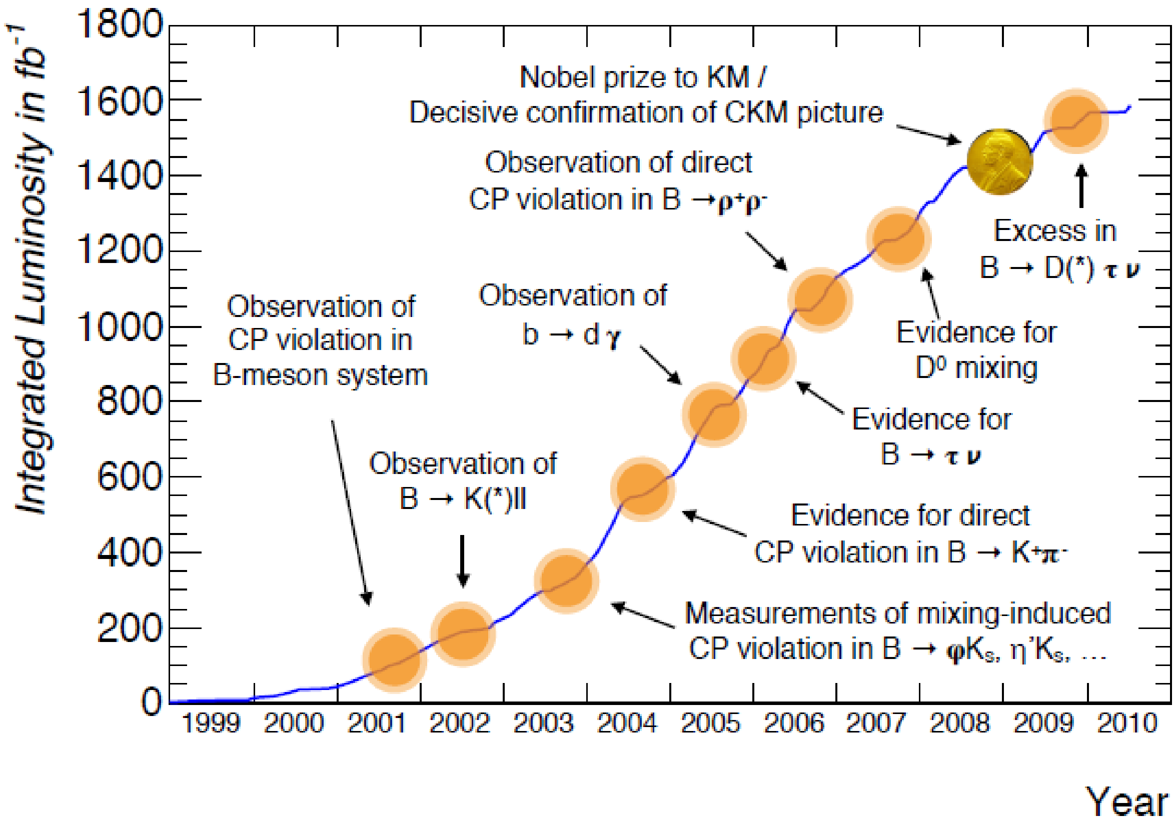
50:1

$$\frac{\text{Belle II data set}}{\text{Belle data set}} \sim 50 \sim \frac{\text{2009 BaBar data set}}{\text{1999 CLEO data set}}$$

- Larger data set will lead to an increase in sensitivity to higher mass scales just by simply redoing existing measurements
- Larger and more precise data sets always spurred new theoretical ideas
- In terms of NP reach this step is as big as going from LHC 8 TeV to LHC 14 TeV

The B Factories: A Success Story

- The B factories Belle and BaBar ran from 1999 to 2010.
- They recorded over 1.5 ab^{-1} of data ($1.25 \cdot 10^9$ BB).
- Both experiments provided the experimental confirmation that led to the 2008 Nobel prize



Super Flavor Factory

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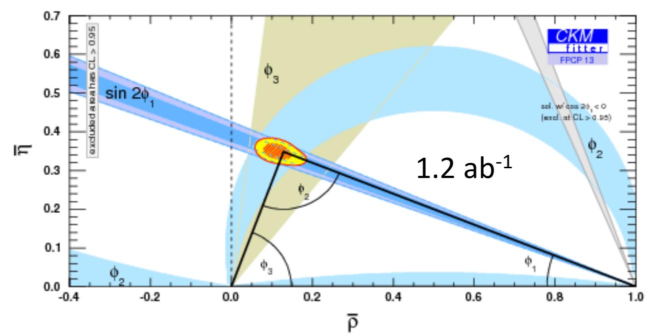
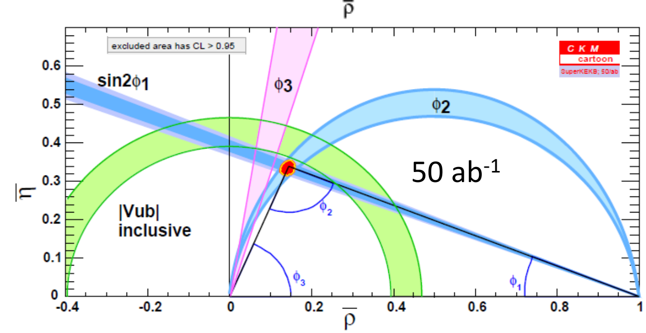
- Search for physics phenomena beyond SM in B, D and τ decays through precision measurements of the CKM sector and studies of rare or forbidden processes
- Many potential NP sources:
  - Flavor changing neutral currents
  - Lepton flavor violating decays
  - B → τ tree level new physics
  - New sources of CPV

1. High luminosity (SuperKEKB)
2. High-resolution and large-coverage detector (Belle II)

Observable	SM theory	Current measurement (early 2013)	Belle II * ($50\,ab^{-1}$)
$S(B \to \phi K^0)$	0.68	0.56 ± 0.17	± 0.018
$S(B \to \eta' K^0)$	0.68	0.59 ± 0.07	± 0.011
α from $B \to \pi\pi, \rho\rho$		$\pm 5.4°$	$\pm 1°$
γ from $B \to DK$		$\pm 11°$	$\pm 1.5°$
$S(B \to K_S \pi^0 \gamma)$	< 0.05	-0.15 ± 0.20	± 0.035
$S(B \to \rho\gamma)$	< 0.05	-0.83 ± 0.65	± 0.07
$A_{CP}(B \to X_{s+d}\gamma)$	< 0.005	0.06 ± 0.06	± 0.005
A^d_{SL}	-5×10^{-4}	-0.0049 ± 0.0038	± 0.001
$\mathcal{B}(B \to \tau\nu)$	1.1×10^{-4}	$(1.64 \pm 0.34) \times 10^{-4}$	$\pm 3\%$
$\mathcal{B}(B \to \mu\nu)$	4.7×10^{-7}	$< 1.0 \times 10^{-6}$	$\gg 5\sigma$
$\mathcal{B}(B \to X_s\gamma)$	3.15×10^{-4}	$(3.55 \pm 0.26) \times 10^{-4}$	$\pm 6\%$
$\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$	3.6×10^{-6}	$< 1.3 \times 10^{-5}$	$\pm 30\%$
$\mathcal{B}(B \to X_s \ell^+\ell^-)$ $(1 < q^2 < 6\,GeV^2)$	1.6×10^{-6}	$(4.5 \pm 1.0) \times 10^{-6}$	$\pm 0.10 \times 10^{-6}$
$A_{FB}(B^0 \to K^{*0}\ell^+\ell^-)$ zero crossing	7%	18%	5%
$\lvert V_{ub} \rvert$ from $B \to \pi\ell^+\nu$ $(q^2 > 16\,GeV^2)$	$9\% \to 2\%$	11%	2.1%





An Example: Leptonic Decays With Missing Energy

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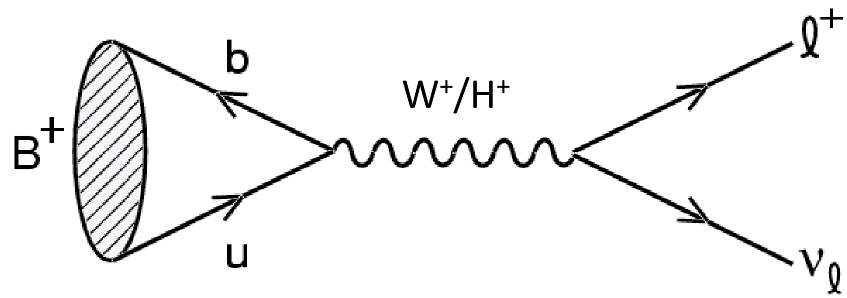
$$B \longrightarrow \tau\nu$$

$\delta(Br) \sim 6\%$ @ 50 ab^{-1}



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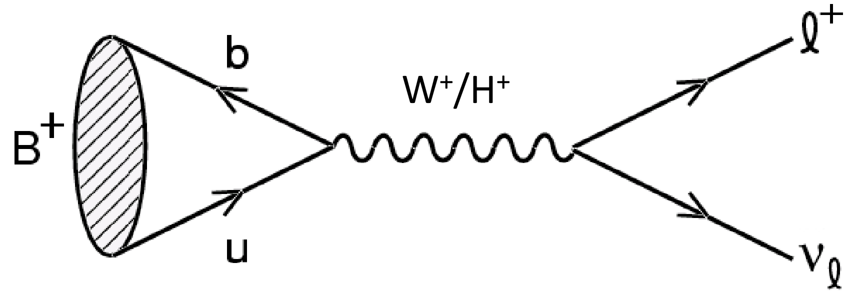
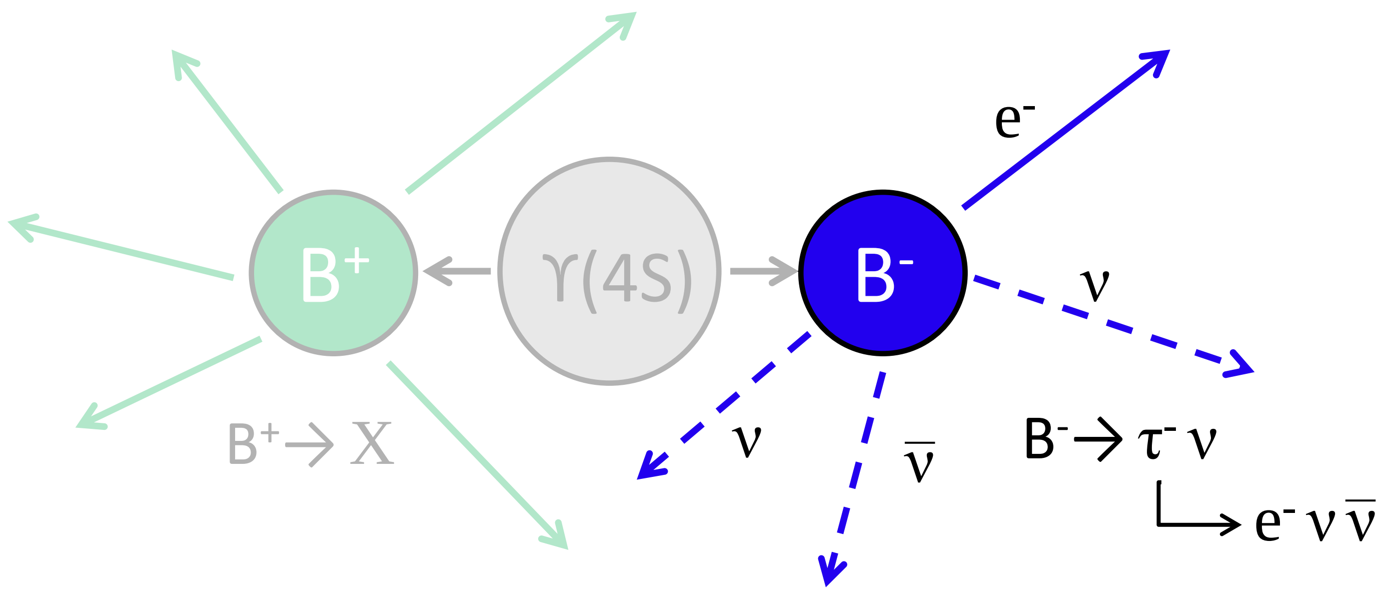


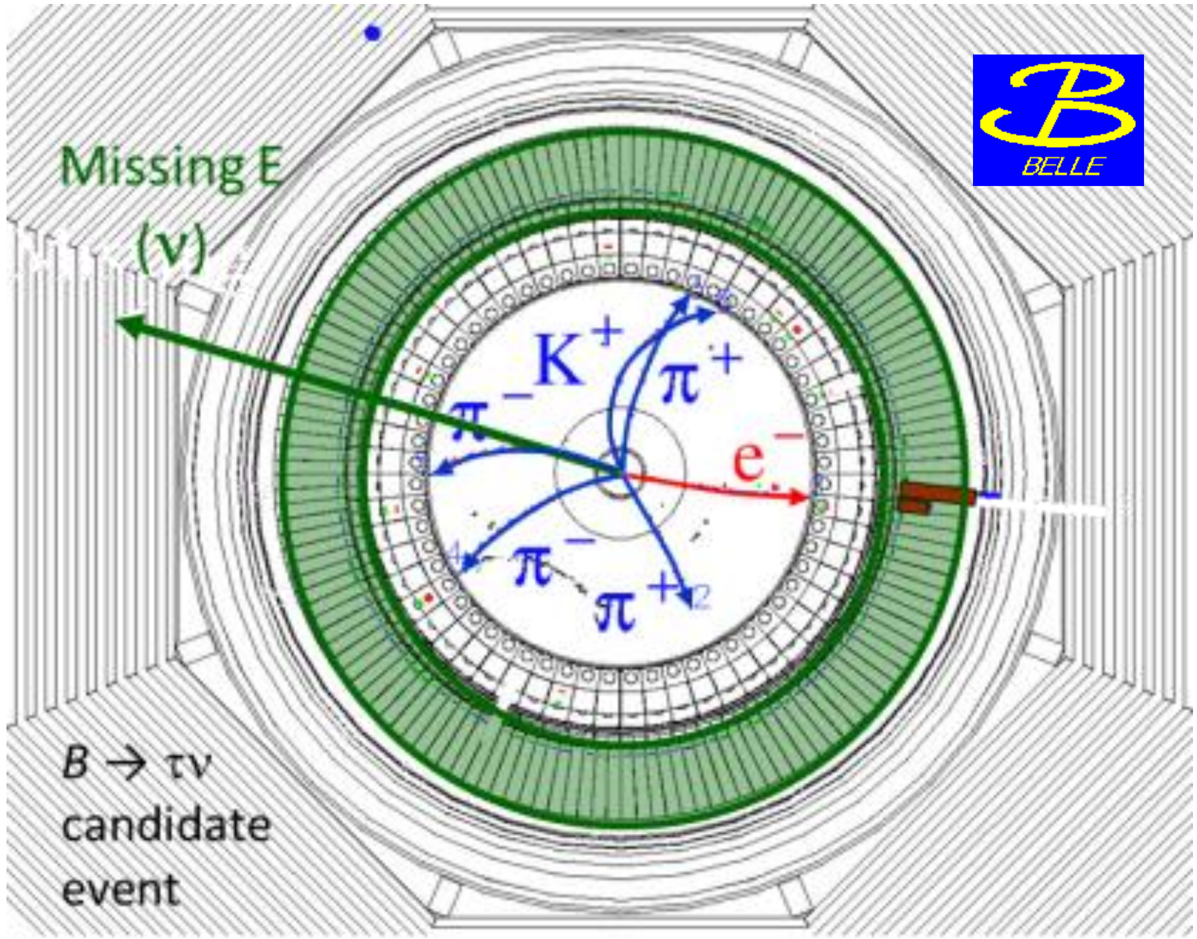
- New physics could significantly modify the SM branching ratio via the exchange of a new charged particle (charged Higgs)
- Experimentally very clean but non-trivial measurement
  → Signal signature: Just a **single charged track + nothing else**



Example: B → τν Candidate Event in Belle Data

$$B^+ \to D^0\pi^+$$
$$(\to K\pi^-\pi^+\pi^-)$$
$$B^- \to \tau(\to e\nu\bar{\nu})\nu$$

Strengths of e⁺e⁻ B factories:
- Final states with neutral particles, in particular neutrinos
- Inclusive measurements



The clean e⁺e⁻ environment makes this possible

The SuperKEKB Accelerator

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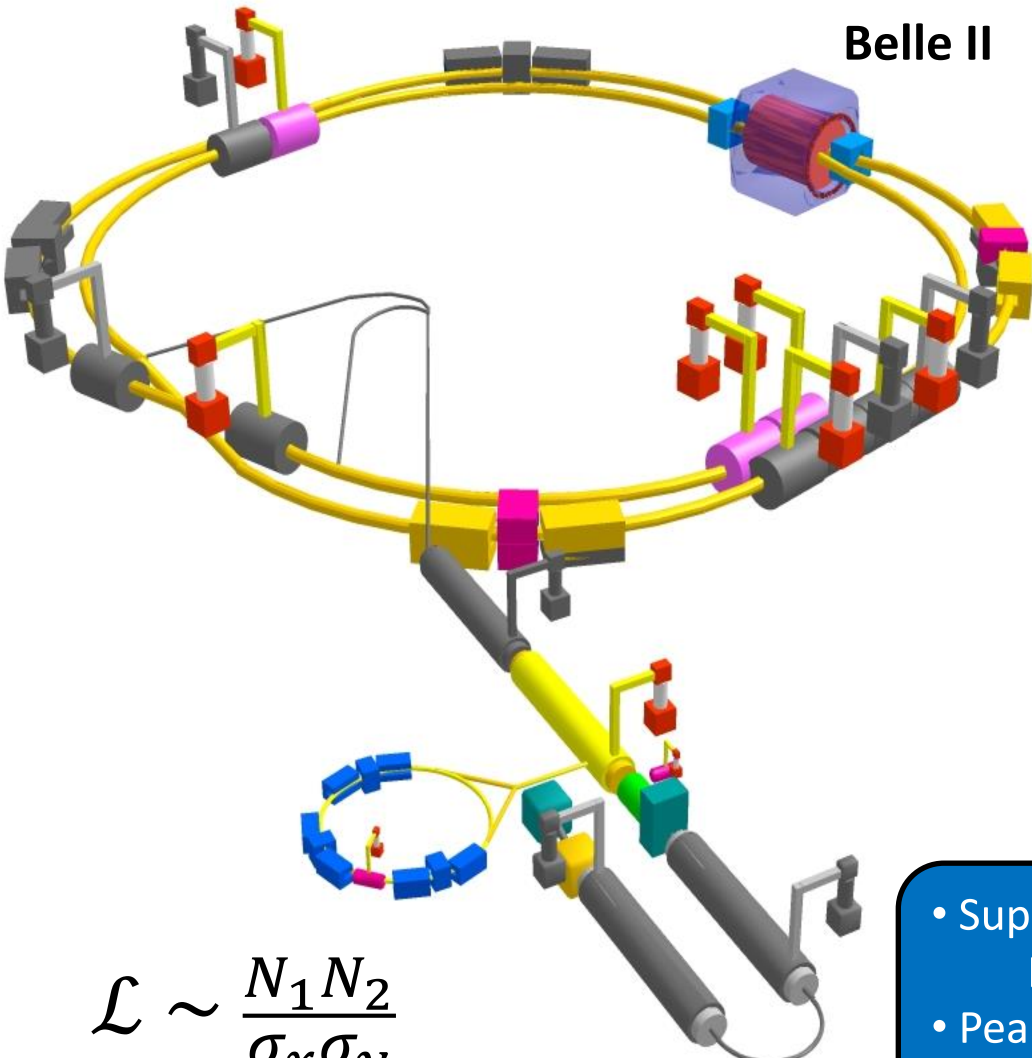
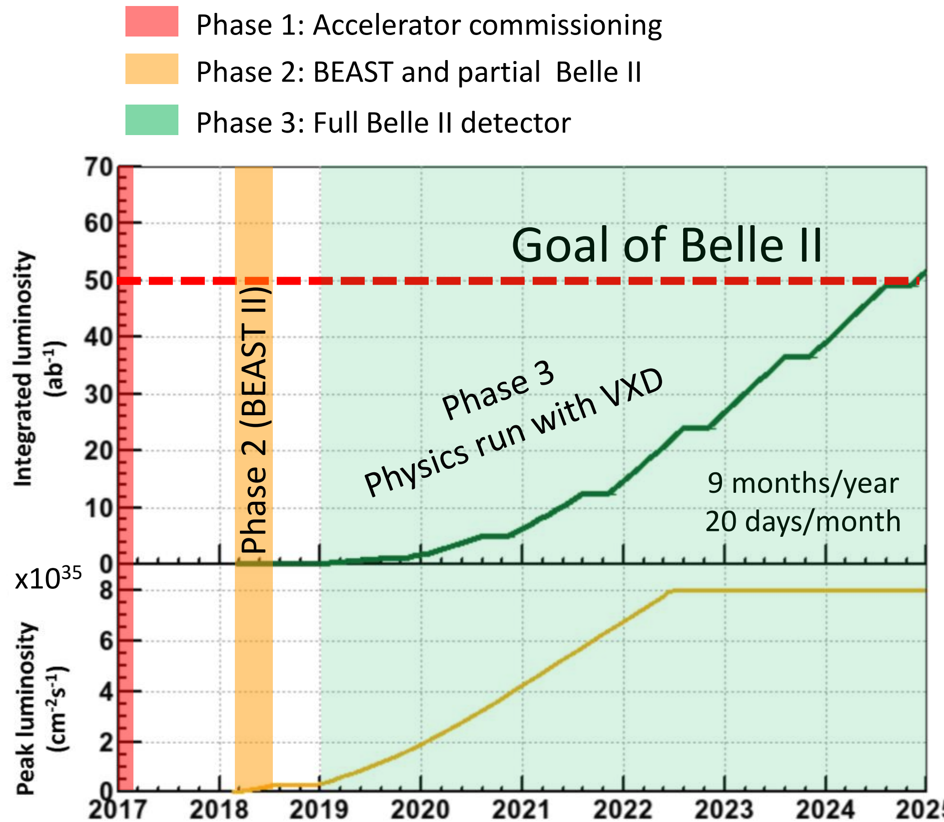
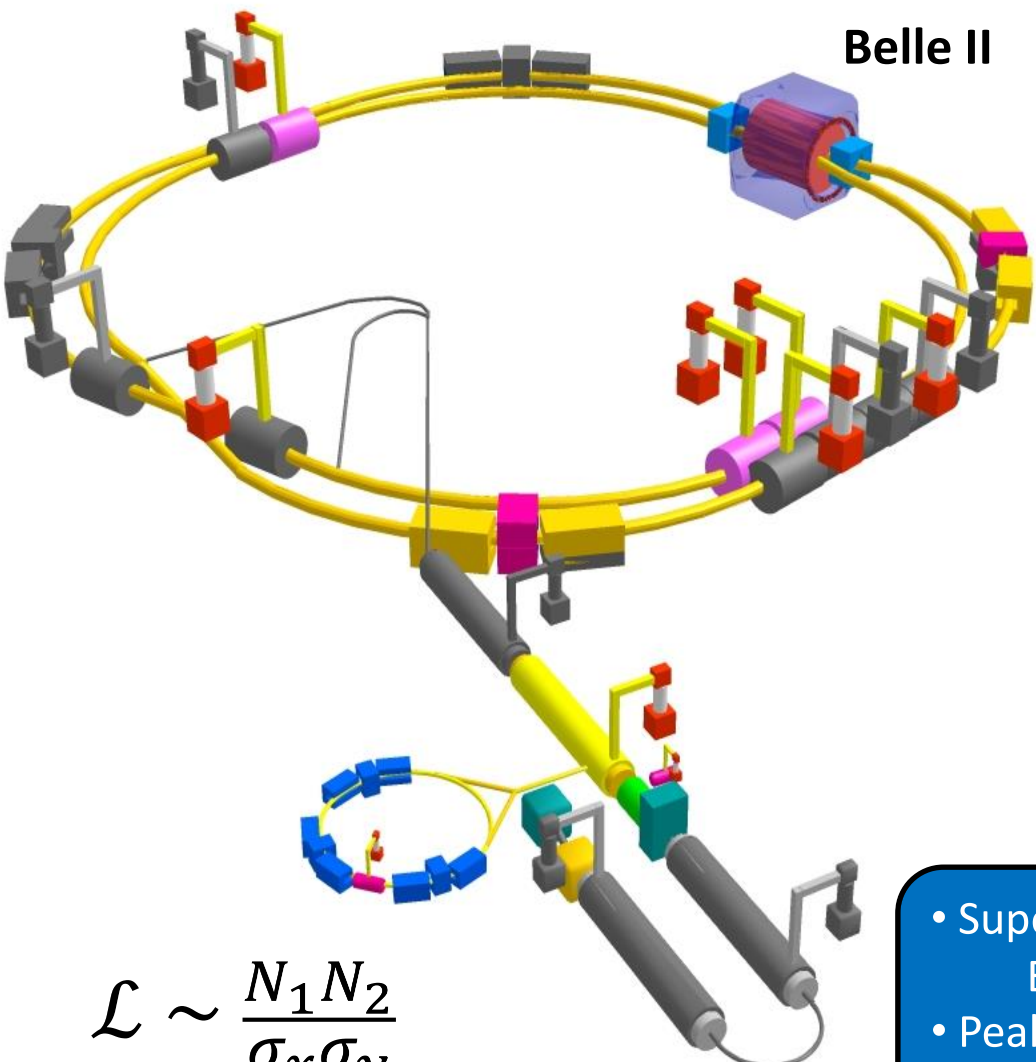


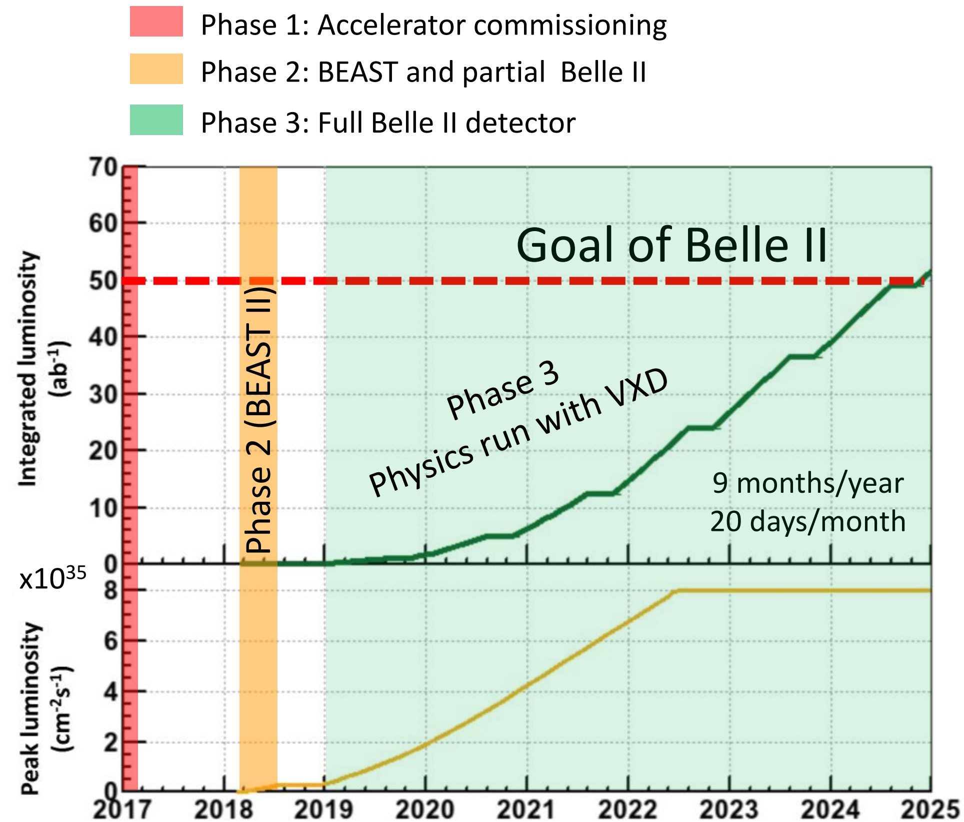


$$\mathcal{L} \sim \frac{N_1 N_2}{\sigma_x \sigma_y}$$

- SuperKEKB: Asymmetric energy e^+e^- collider
  $E_{cm} = m(\Upsilon(4S)) = 10.58$ GeV
- Peak luminosity: $\mathcal{L} = 8\cdot 10^{35}$ cm^{-2} s^{-1} (x40 than KEKB)
  Beam size reduction. Higher current (x2 higher).

The SuperKEKB Accelerator





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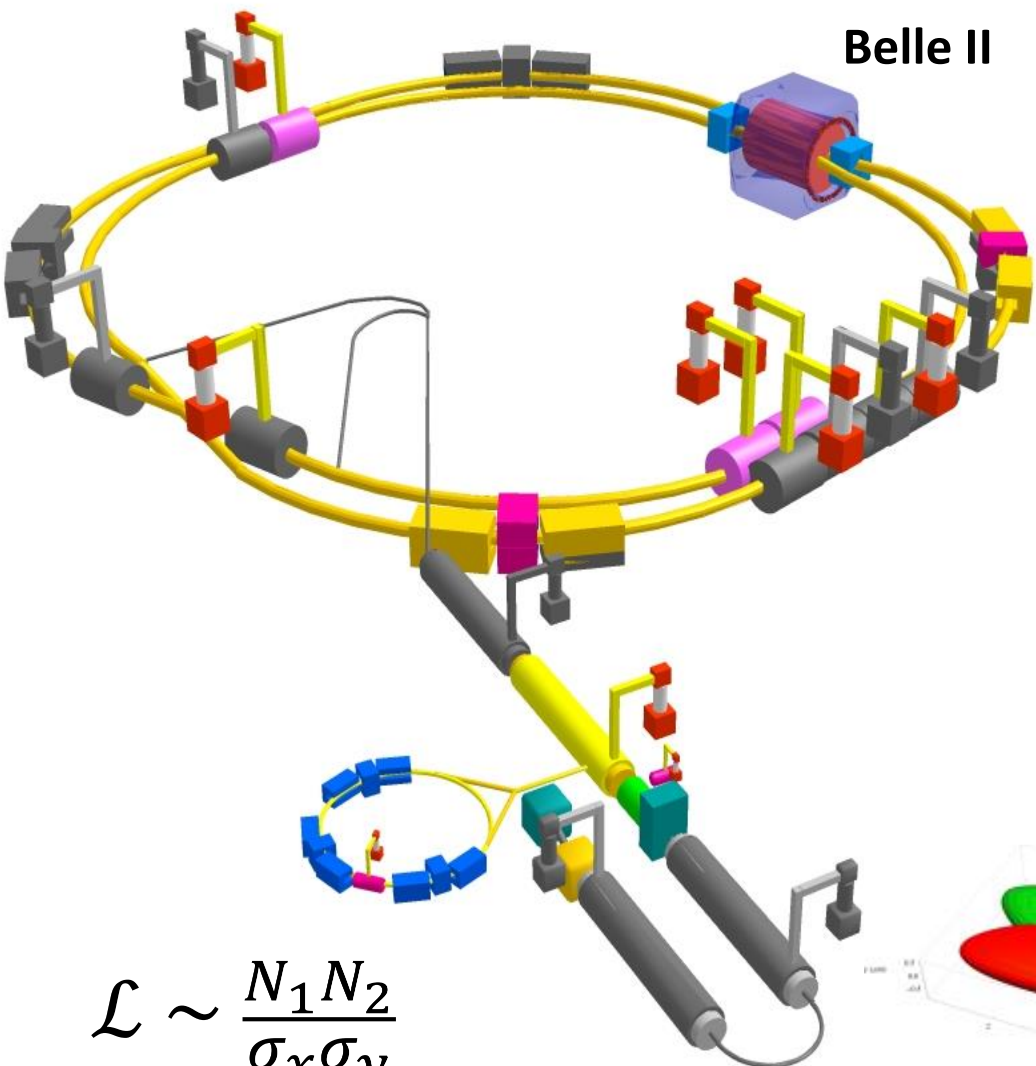

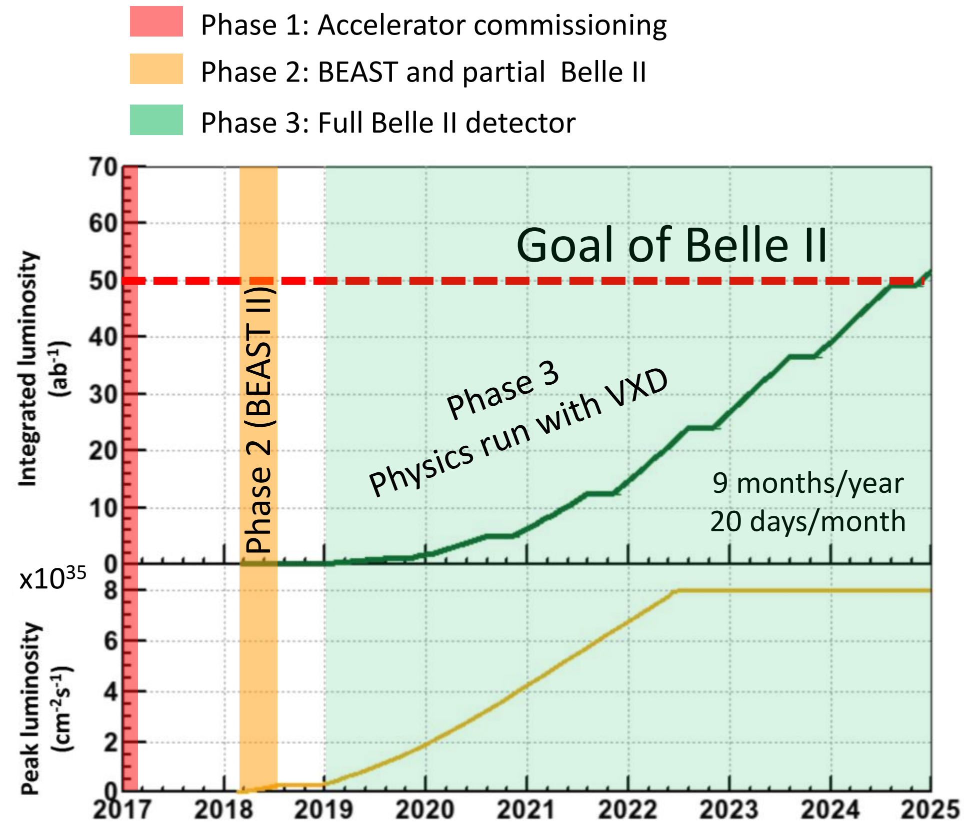

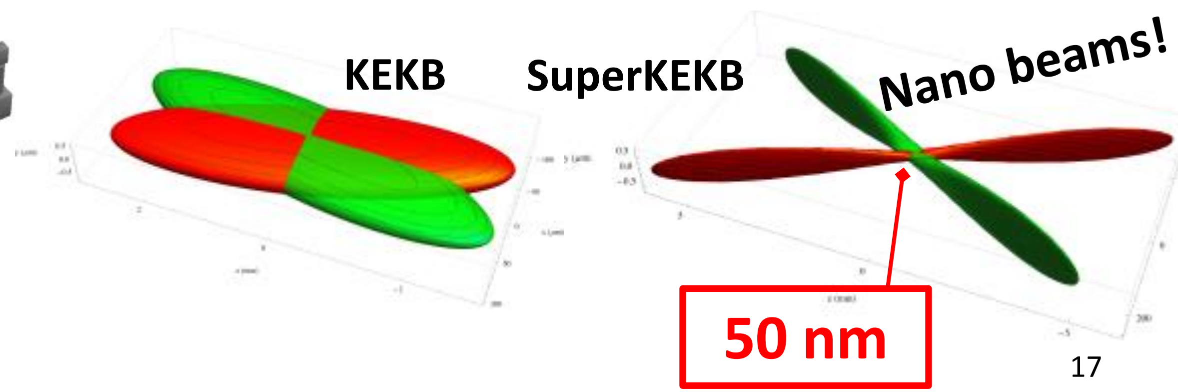

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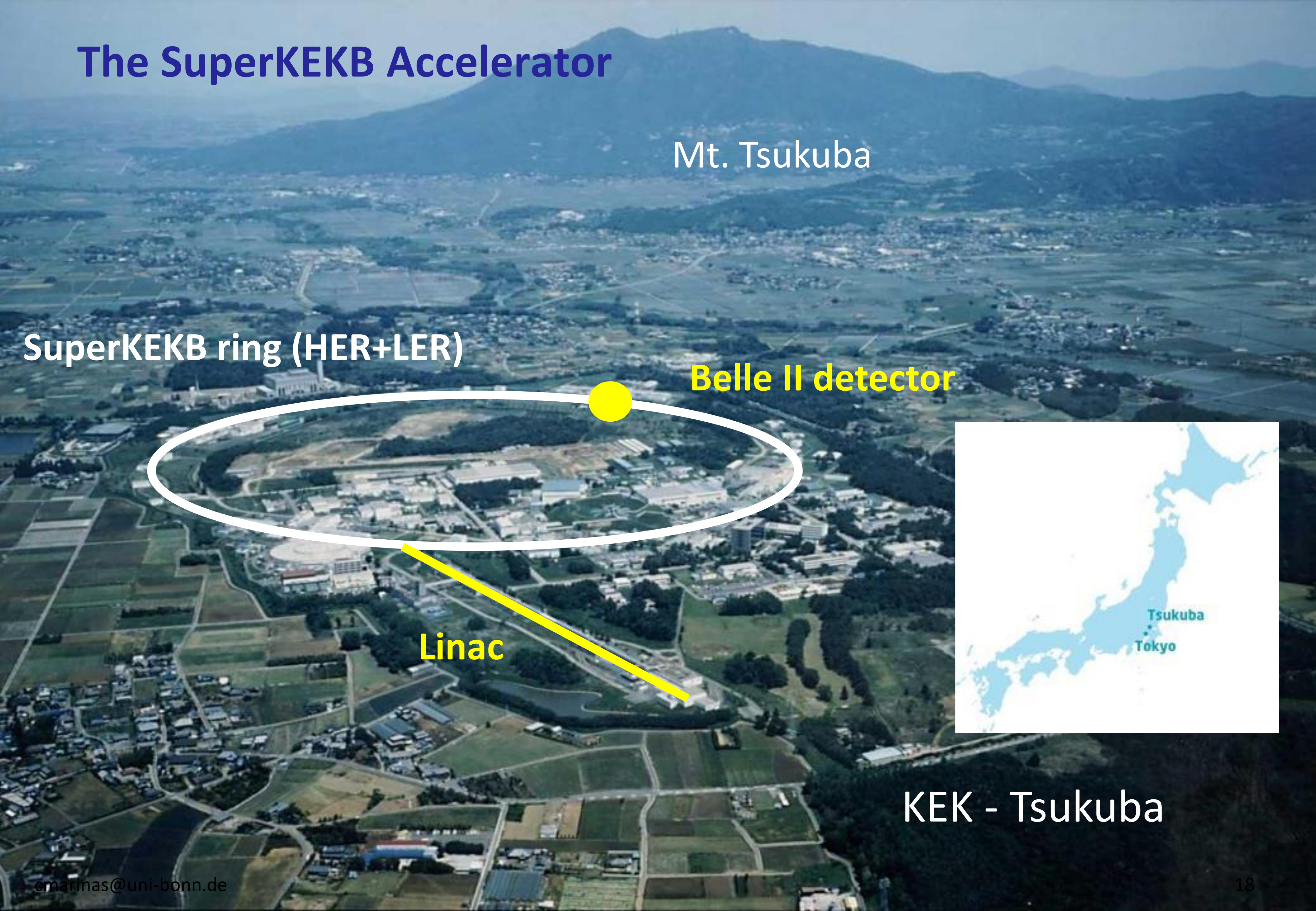
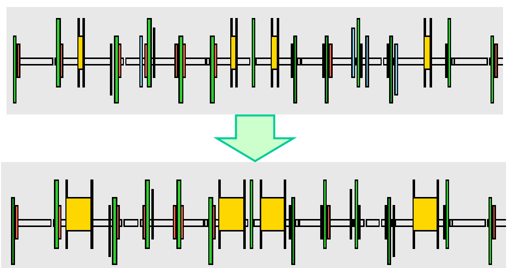


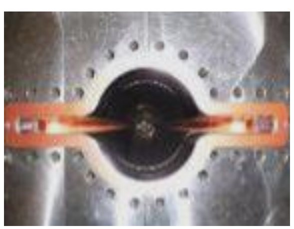
Going For a Super B-Factory: SuperKEKB

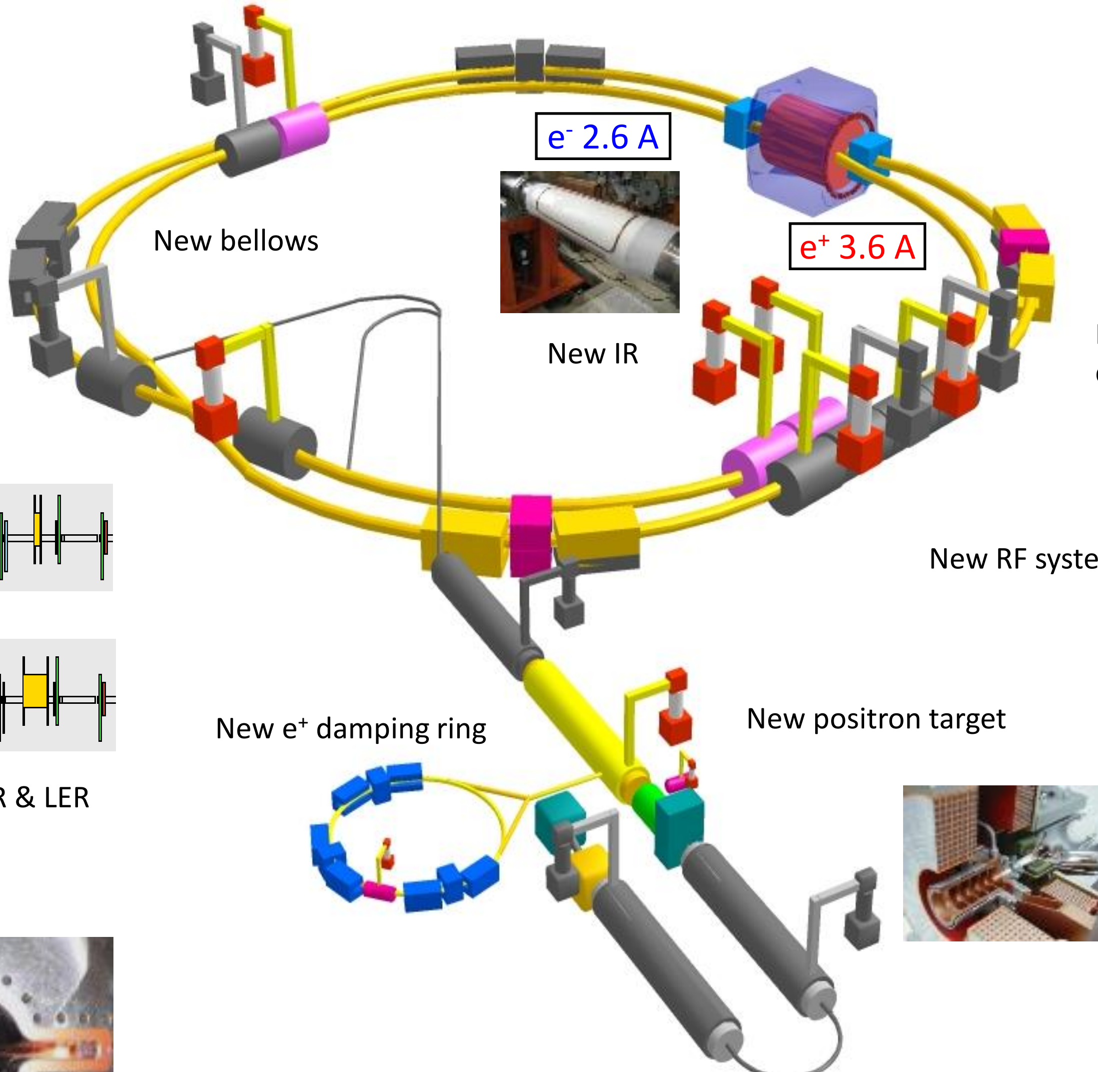
Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers



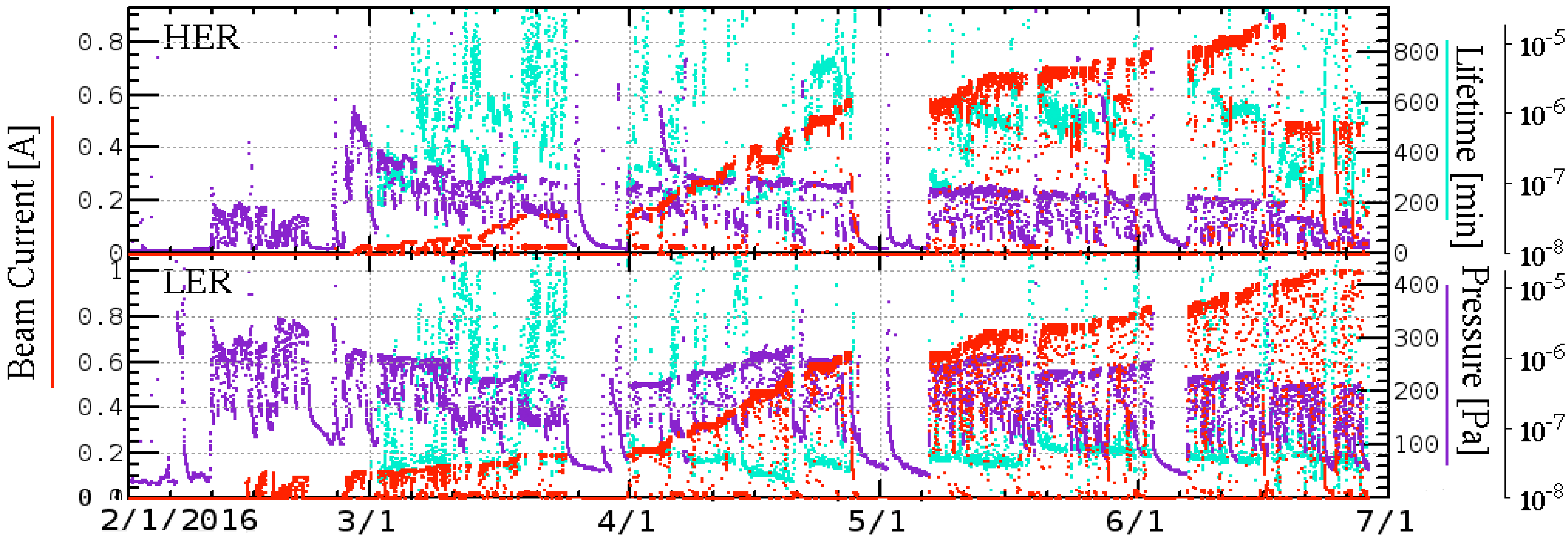


New final focusing quads near the IP

New RF systems

Complete refurbishment to achieve x40 higher luminosity compared to KEKB

Phase 1 Operation



Phase 1 Results:

- First turns at SuperKEKB
- Vacuum scrubbing
- Initial background studies

- HER:
  870 mA
- LER:
  1010 mA

Total beam current

→ Program **completed**!

The Belle II Detector

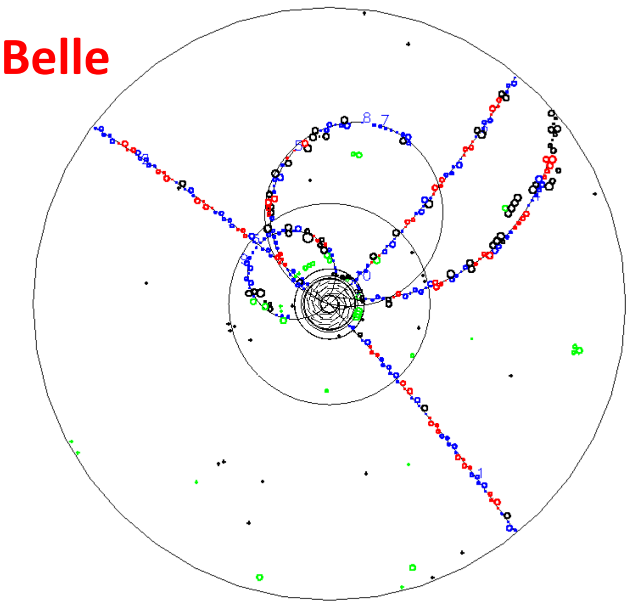
40 times higher luminosity implies

- **Higher event rate**
  - Higher trigger rate
  - Increased DAQ and computing requirements
- **Higher background**
  - Radiation damage
  - Occupancy
  - Fake hits and pile-up
- Changes in detector
  - $\beta\gamma$ reduced by factor 1.5
  - Improved vertexing needed

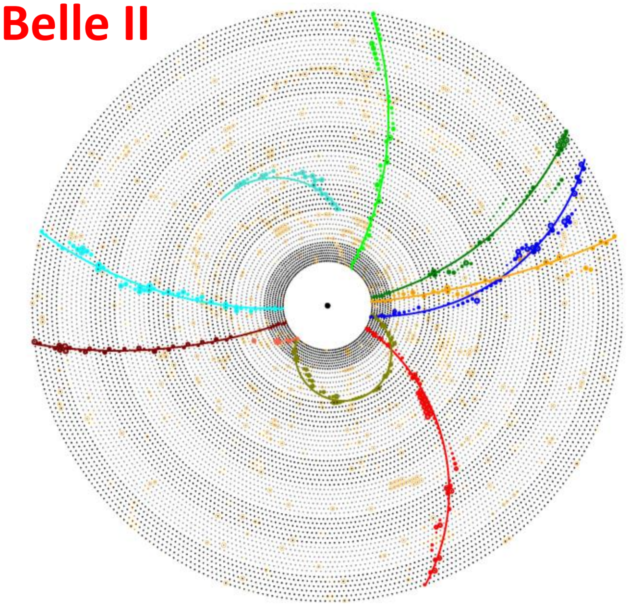
- Results in significant upgrade

→ **Belle II**

Belle



Belle II

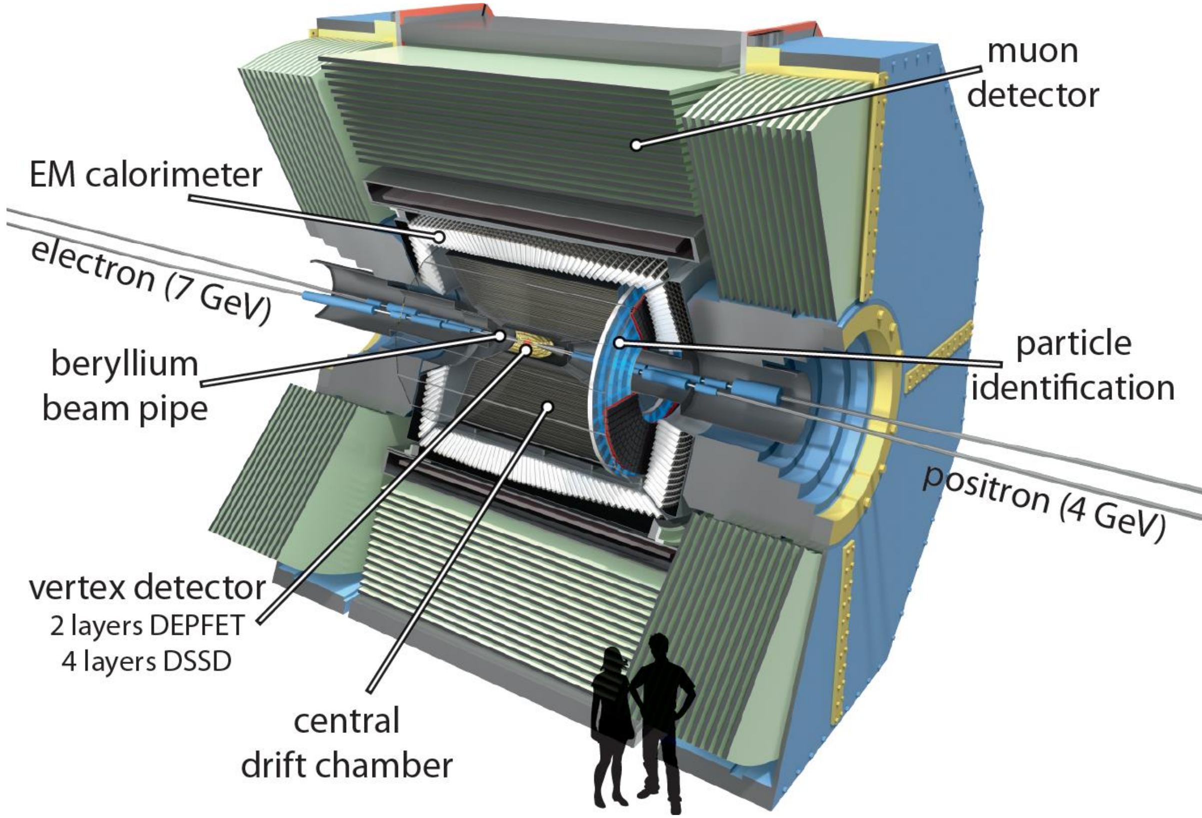


The Belle II Collaboration

101 Institutes
751 Researchers
23 Countries
→ Germany is second largest only after Japan

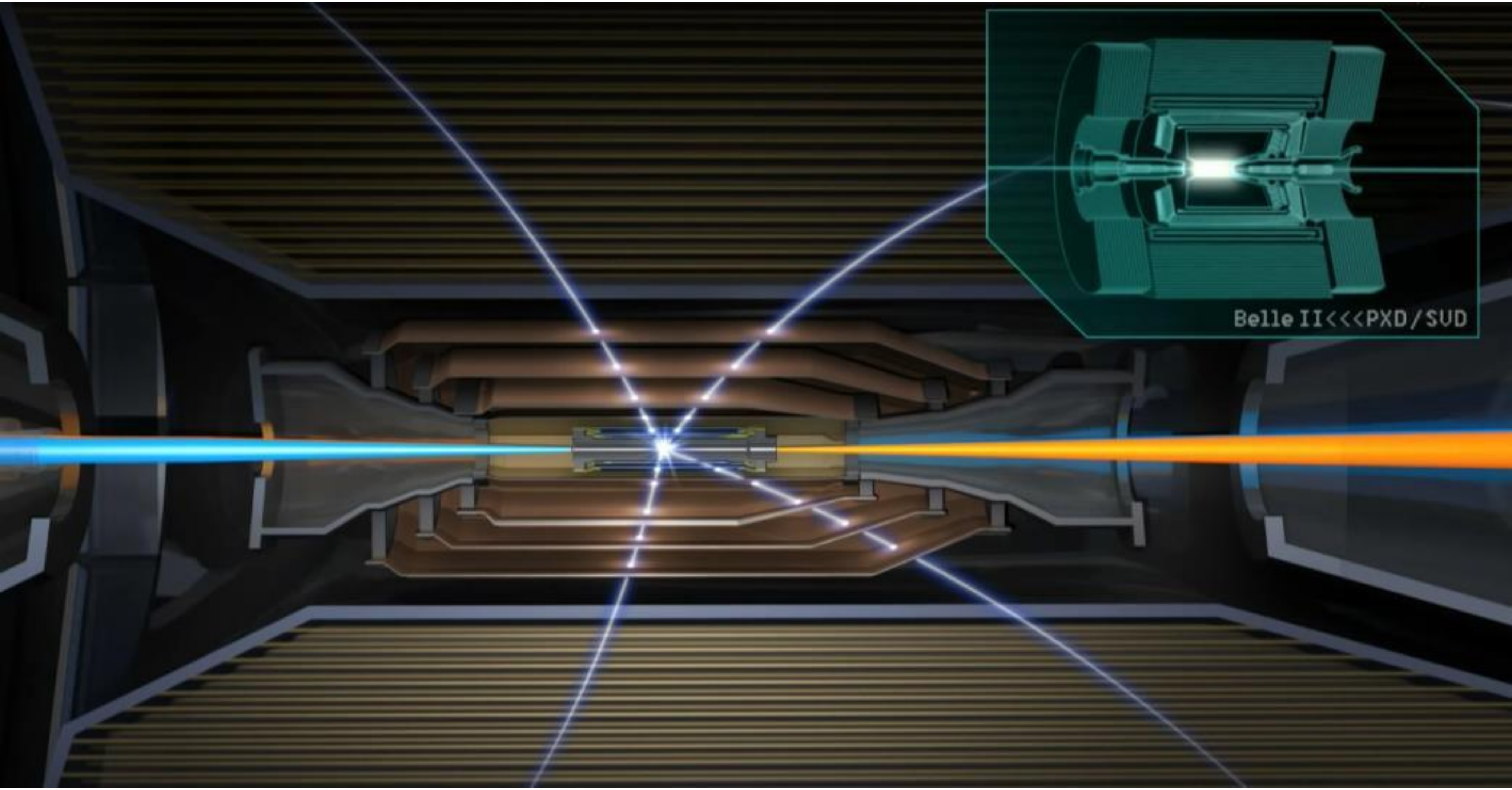
The Belle II Detector

- Areas of improvement:
  - Light inner detector
  - Precise vertexing/tracking
  - Particle identification
  - E.M. calorimetry
  - K^0_L and muon ID
  - Data handling capabilities



Ready for physics run in **2018**

Vertex Detector (VXD)



Typical Event

e^+e^-

E_{cm} = 10.58 GeV

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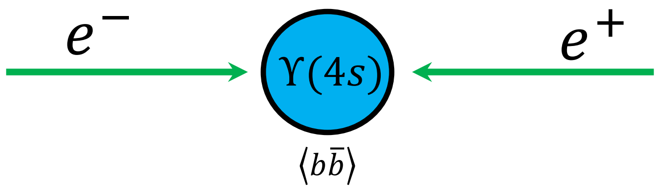
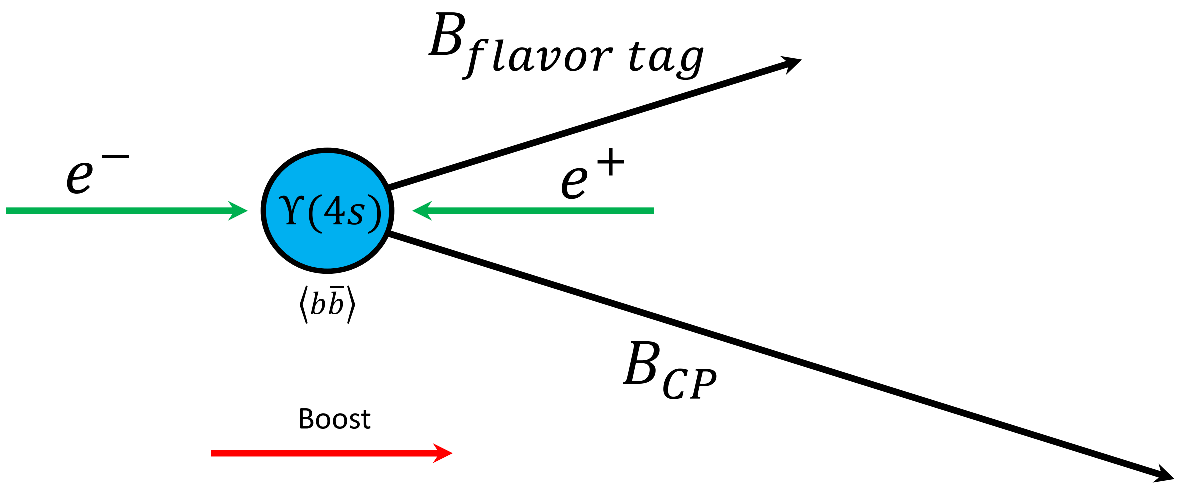
$e^+e^- \rightarrow \Upsilon(4s)$ $E_{cm} = 10.58$ GeV



Typical Event

$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B\bar{B}$ E_{cm} = 10.58 GeV



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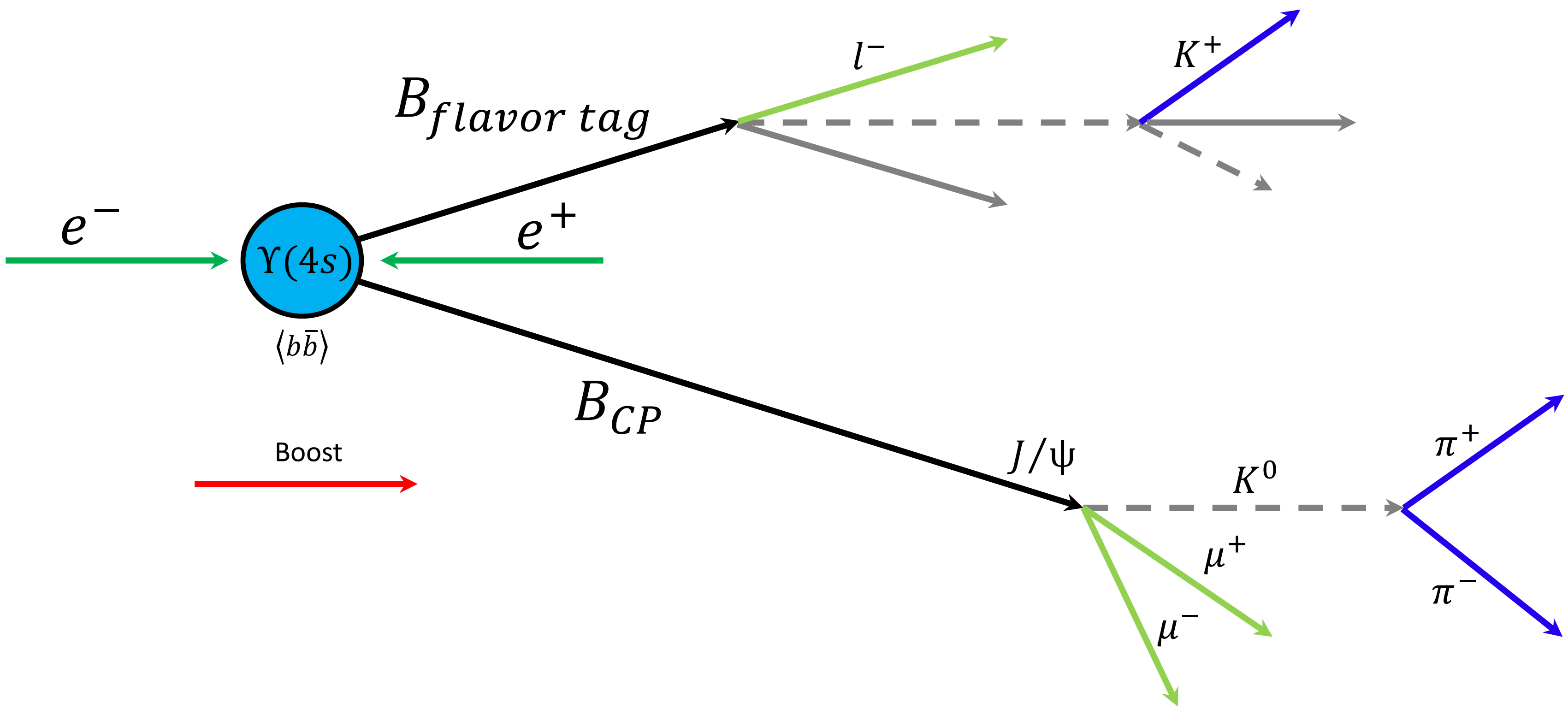

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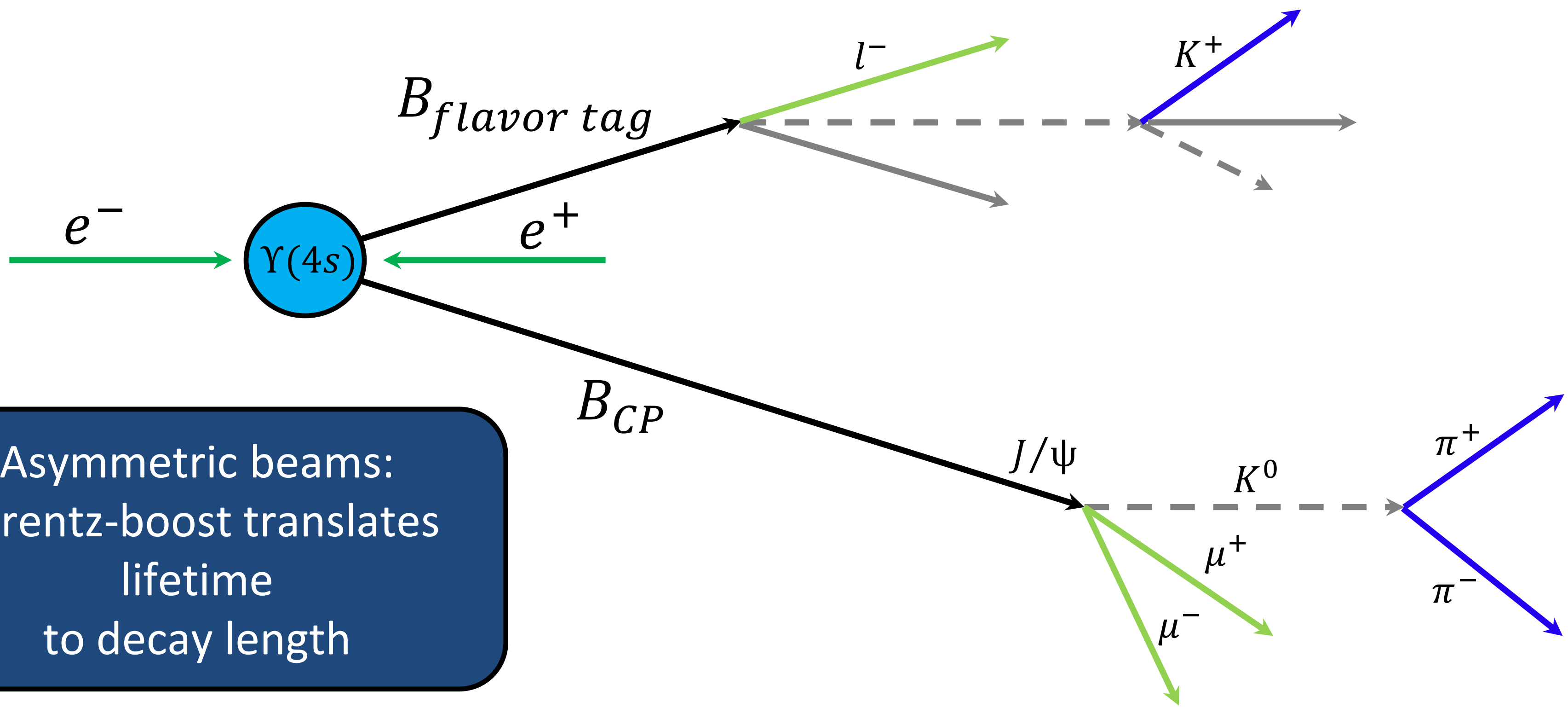

Asymmetric beams:
Lorentz-boost translates lifetime
to decay length

Precise vertexing essential to measure time dependent CP violation and mixing

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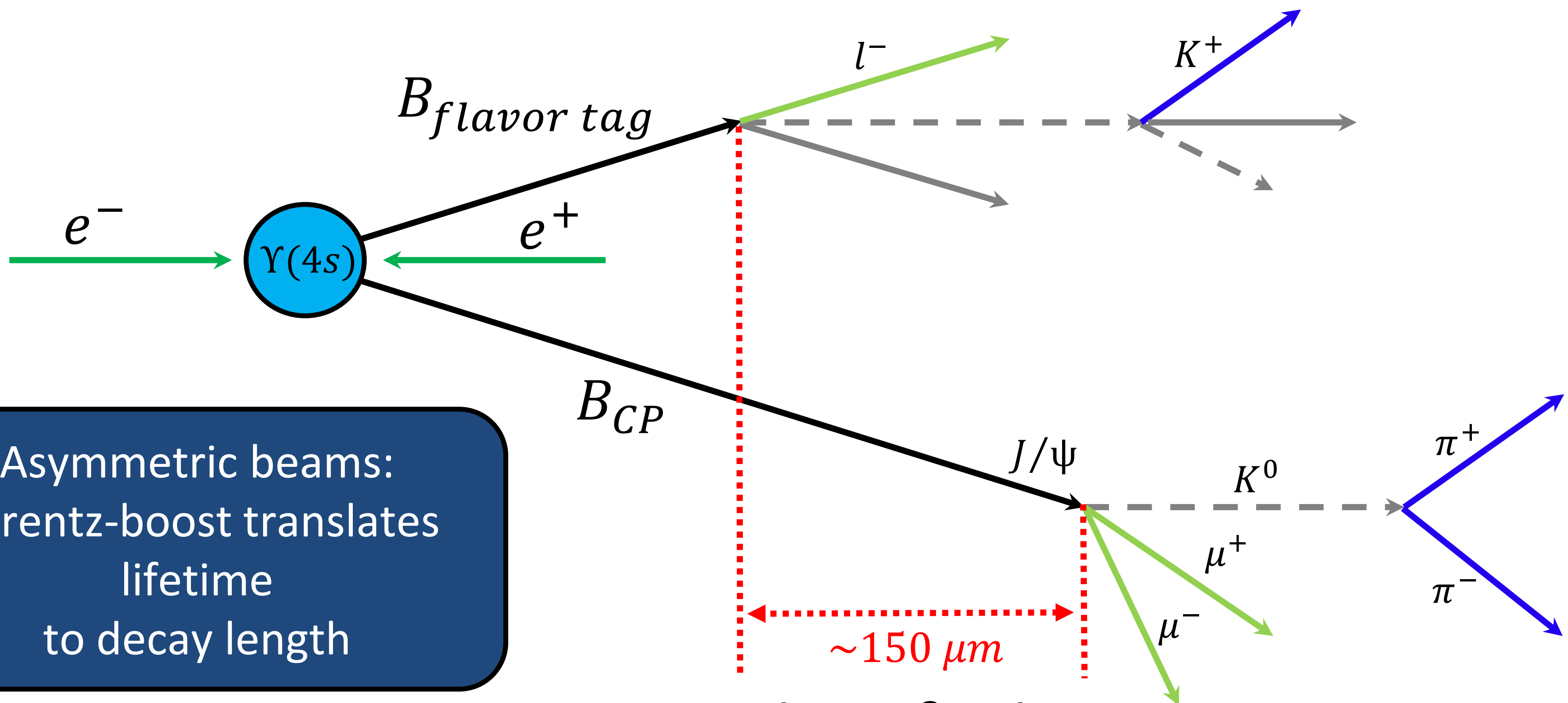
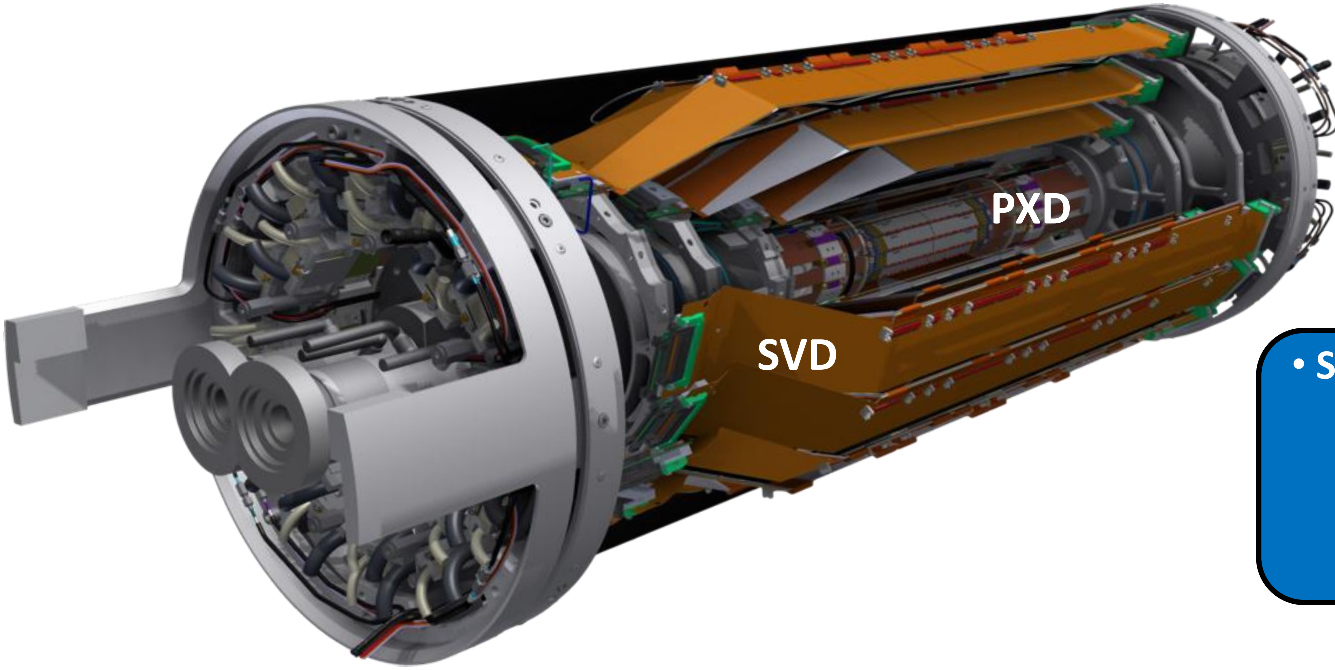


Asymmetric beams:
Lorentz-boost translates lifetime
to decay length

$$\Delta z = \beta\gamma c\Delta t$$

Precise vertexing essential to measure time dependent CP violation and mixing

Vertex Detector: PXD and SVD



- **Silicon Vertex Detector (SVD)**
  4 layers of DSSD
  r = 3.8 cm, 8.0 cm, 11.5 cm, 14 cm
  L = 60 cm
  $\sim 1\ m^2$

Vertex Detector: PXD and SVD

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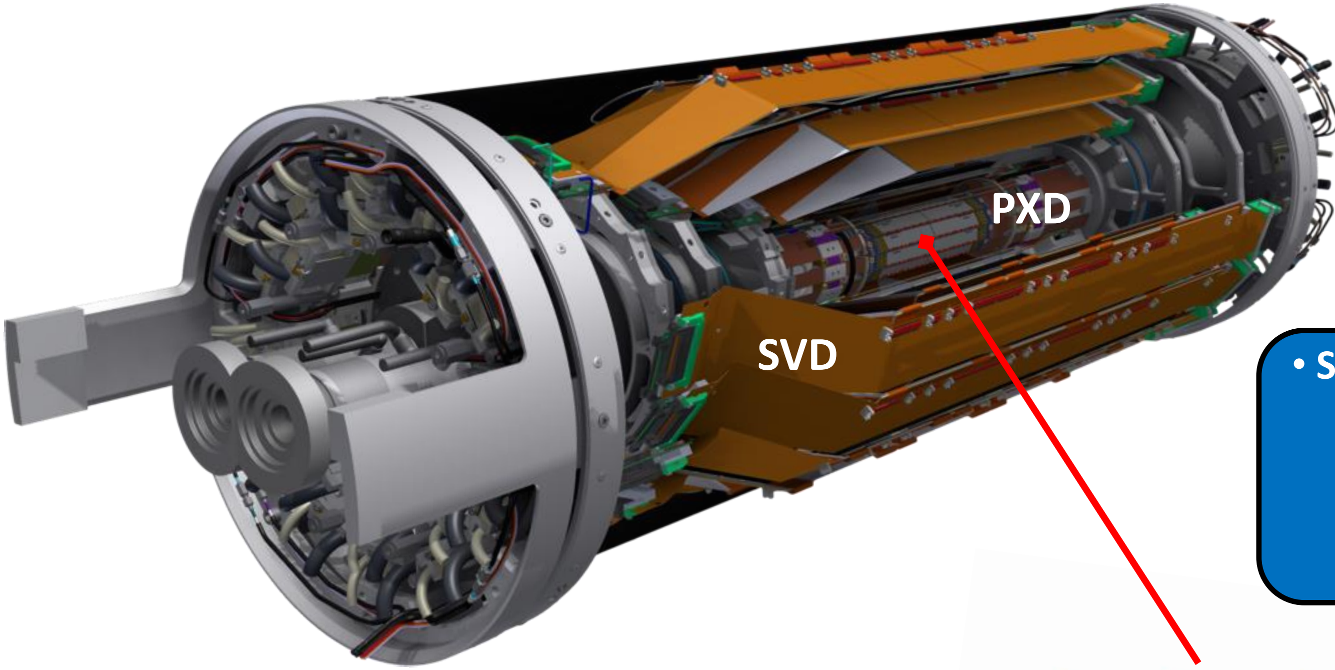

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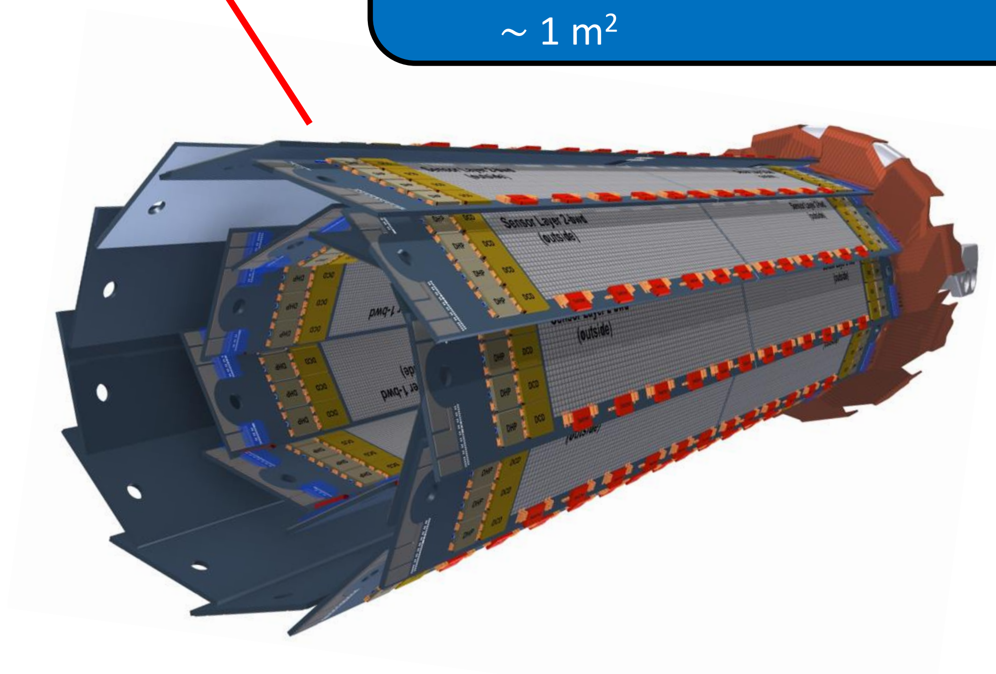
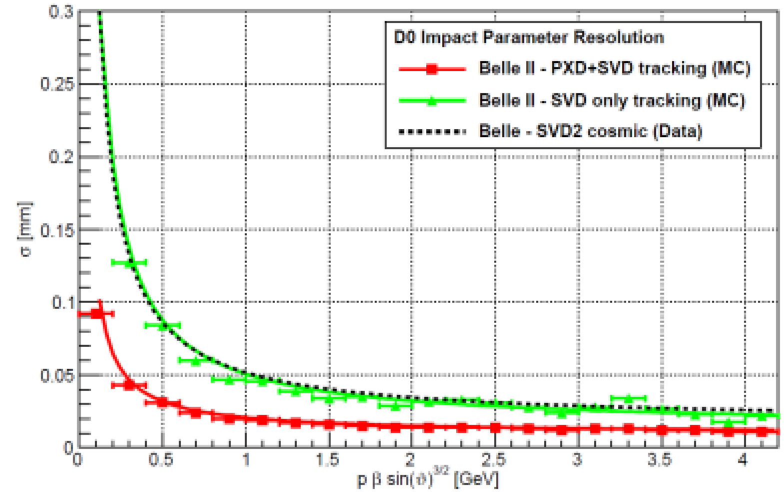
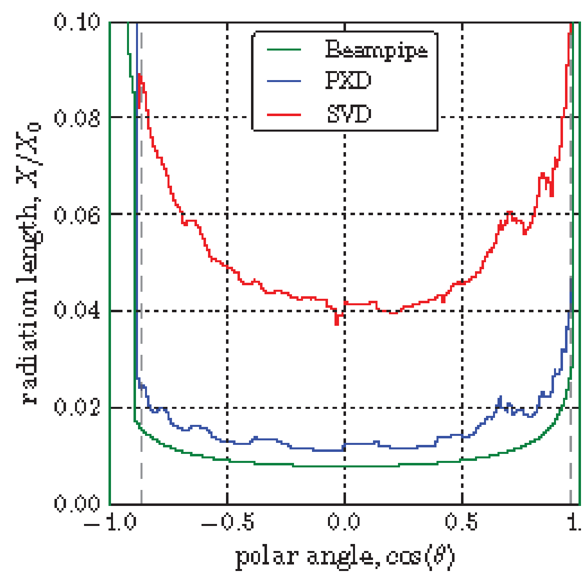


- **Pixel Detector (PXD)**
  - 2 layers of DEPFET pixels
  - r = 1.4 cm, 2.2 cm
  - L = 12 cm
  - $\sim 0.027\ m^2$

Belle II VXD Requirements and Parameters

	Belle II PXD
Occupancy	0.4 hits/μm^2/s (3% max)
Radiation	2 Mrad/year
	$2 \cdot 10^{12}$ 1 MeV n_{eq} per year
Integration time	20 μs
Momentum range	Low p (50 MeV - 3 GeV)
Acceptance	17º-155º
Material budget	0.21% X_0 per layer
Resolution	15 μm (50x75 μm^2)

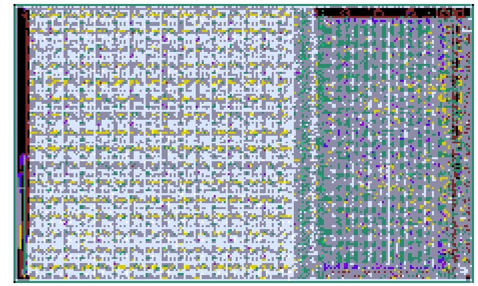




- Impact parameter resolution (15 μm), dominated by multiple scattering mainly in BP → Pixel size (50 x 75 μm²)
- Lowest possible material budget (0.21% X_0/layer)
  - Ultra-transparent detectors
  - Lightweight mechanics and minimal services in physics acceptance

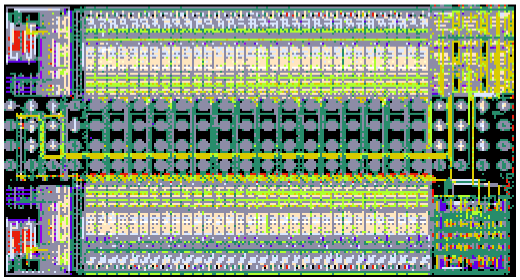
The DEPFET Ladder

DCDB (Drain Current Digitizer)
Analog frontend

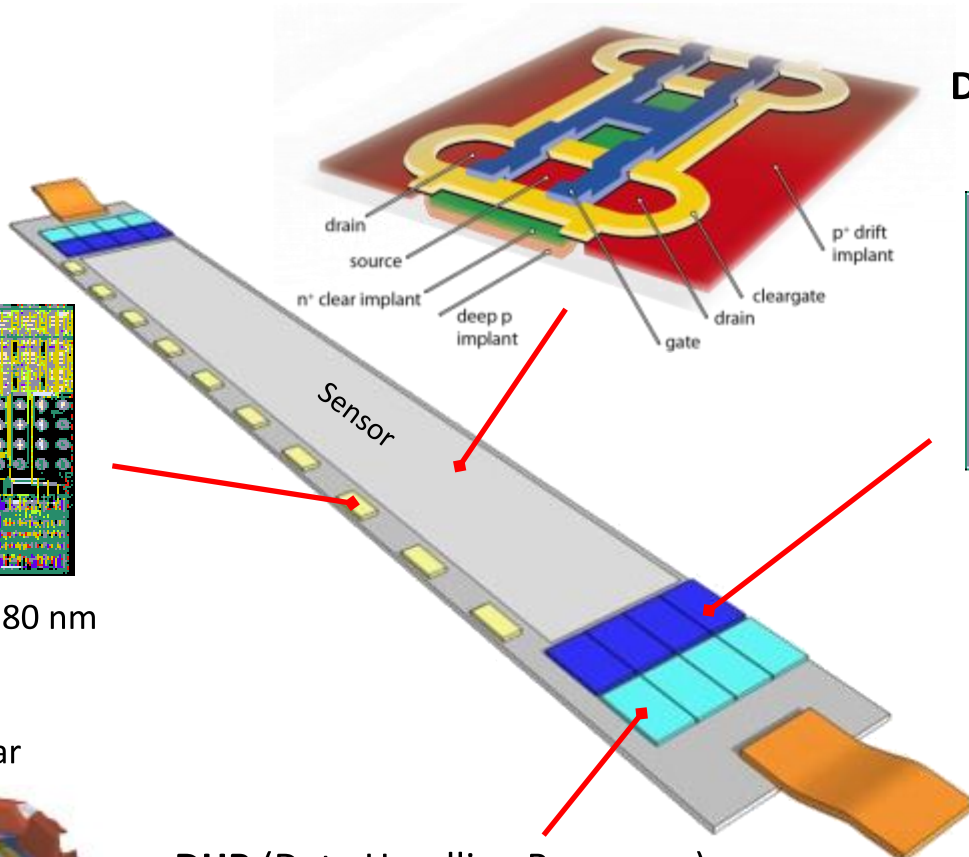


UMC 180 nm
Size 5.0 × 3.2 mm^2
TIA and ADC
Pedestal compensation

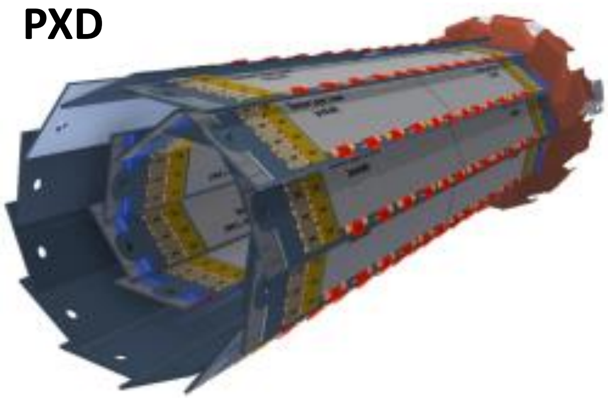
SwitcherB
Row control



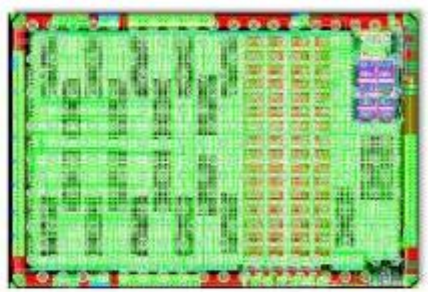
AMS/IBM HVCMOS 180 nm
Size 3.6 × 1.5 mm^2
Gate and Clear signal
Fast HV ramp for Clear



PXD



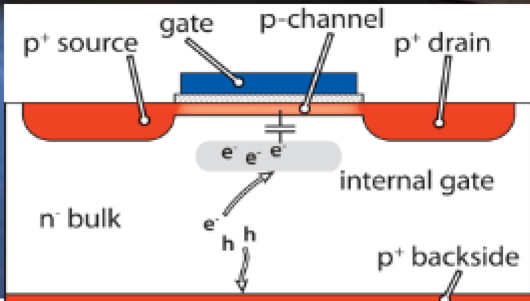
DHP (Data Handling Processor)
First data compression



TSMC 65 nm
Size 4.0 × 3.2 mm^2
Stores raw data and pedestals
Common mode and pedestal correction
Data reduction (zero suppression)
Timing signal generation

Belle II PXD Module

- 768x250 DEPFET Pixels
- 50x75 µm^2 pixel pitch
- 75 µm thickness



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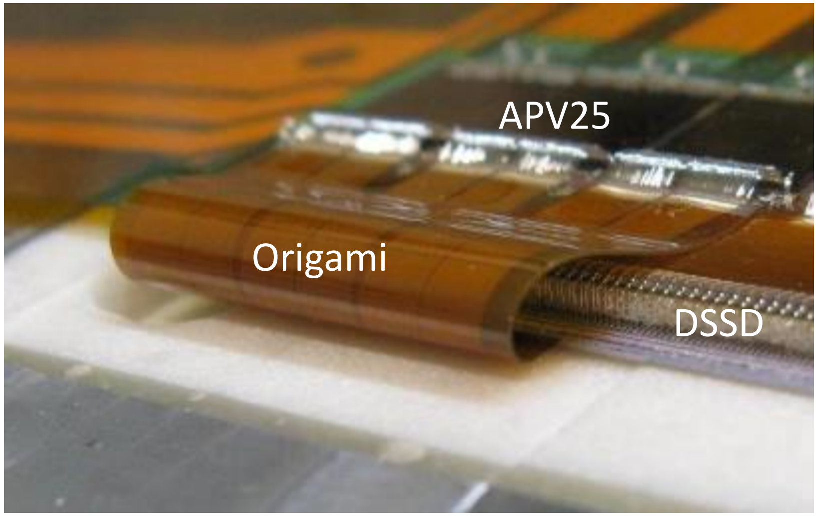
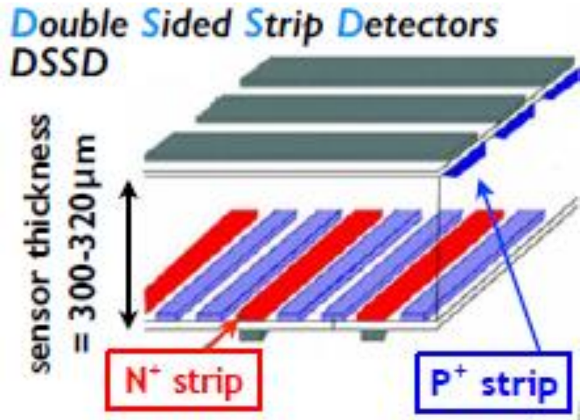
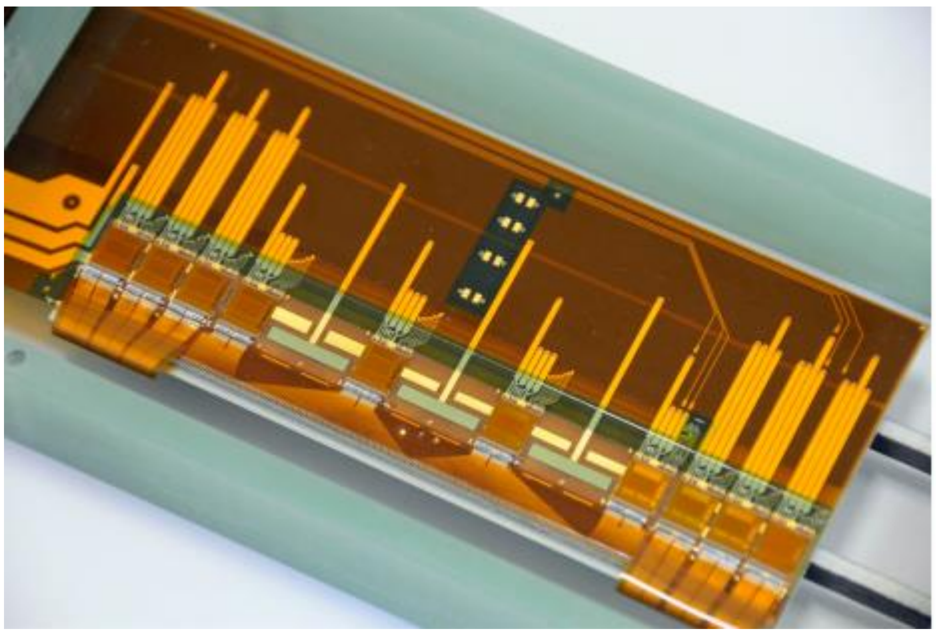
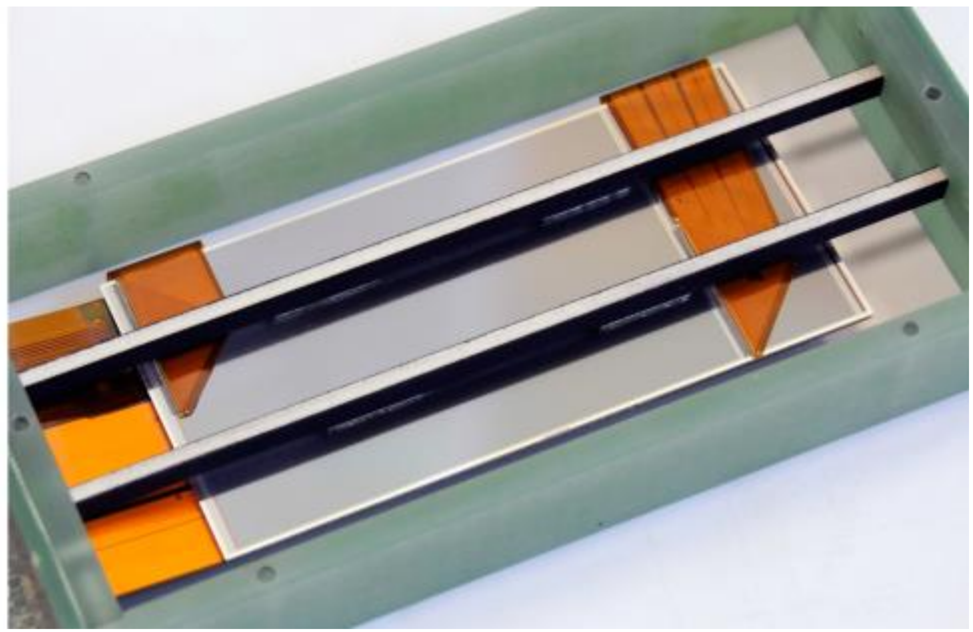
Belle II SVD Module

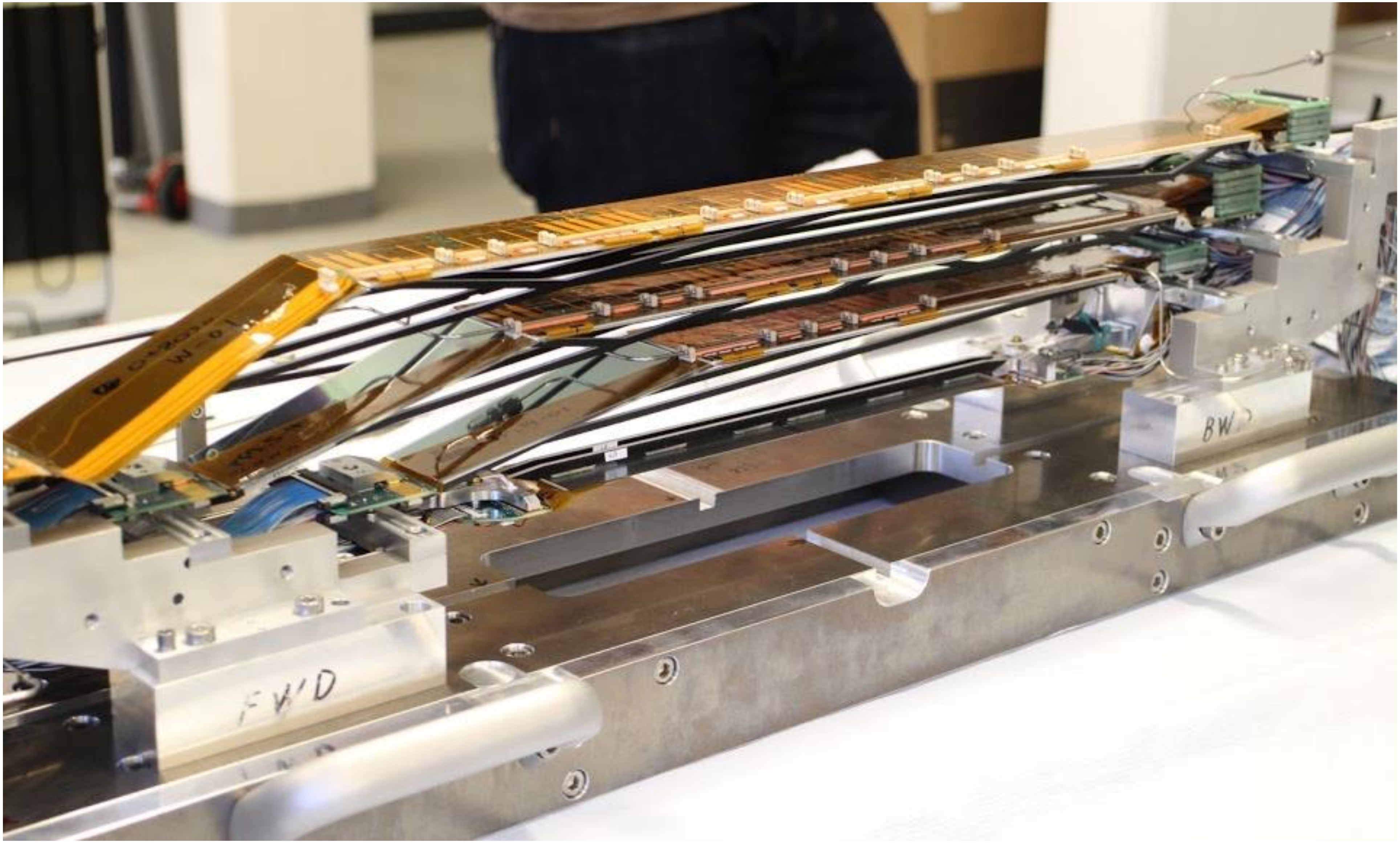








Belle II Vertex Detector Beam Tests



PXD and SVD Combined Operation

Small sector of final PXD and SVD under electron beam and 1 T magnetic field

PXD Performance

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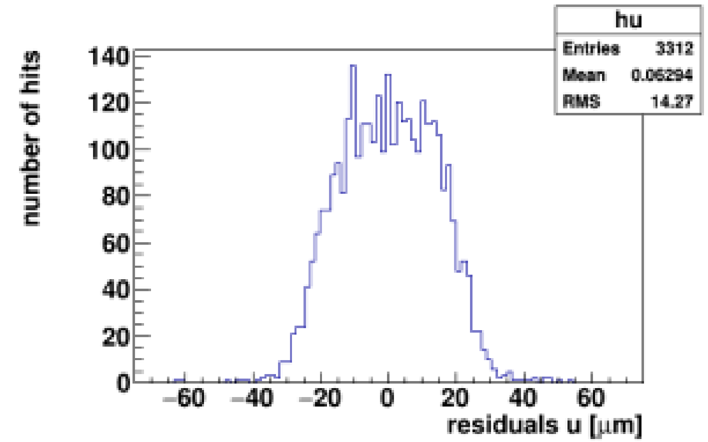
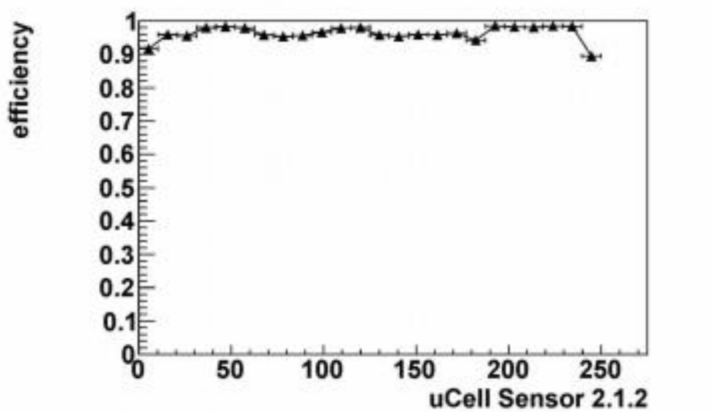
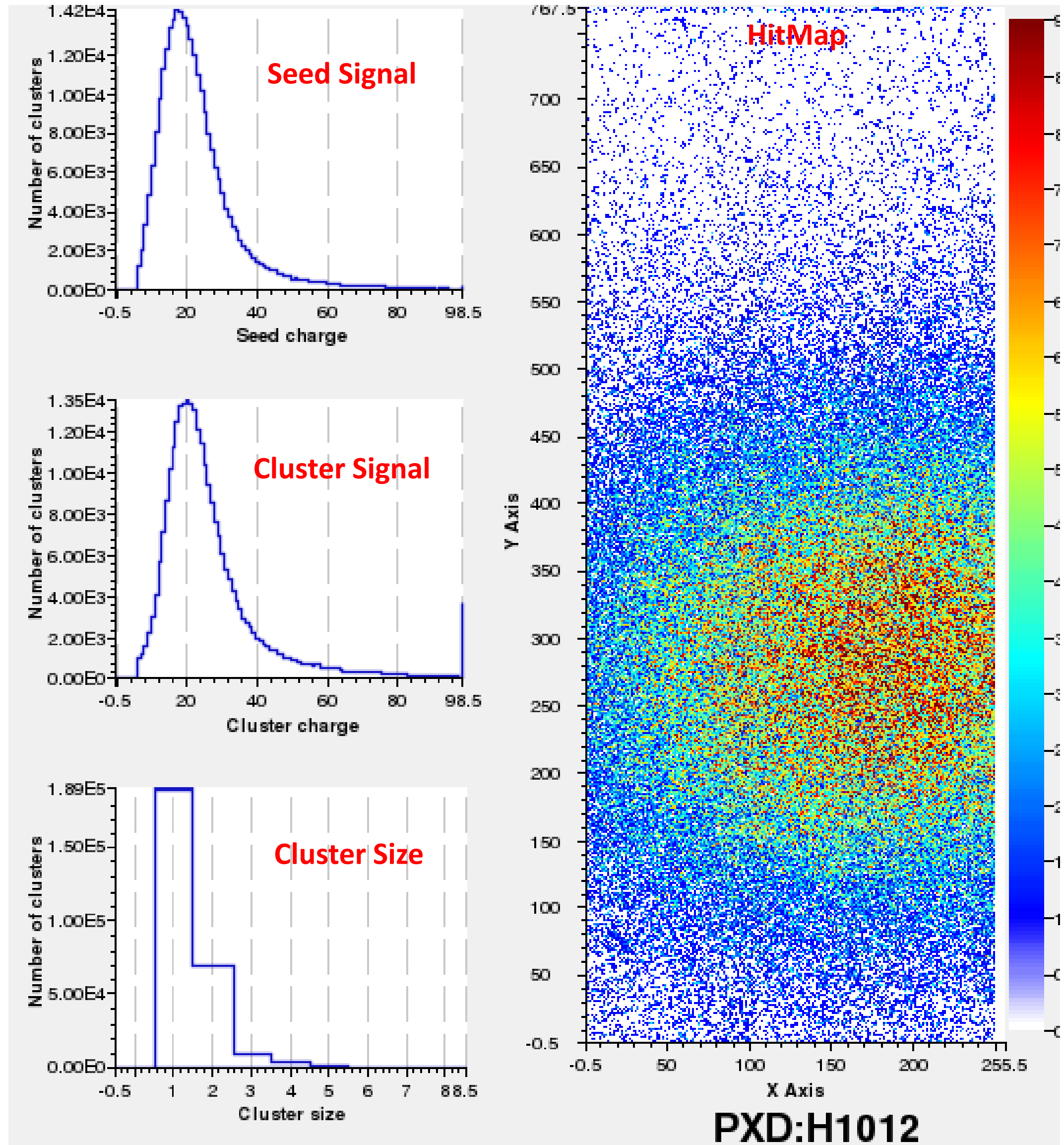
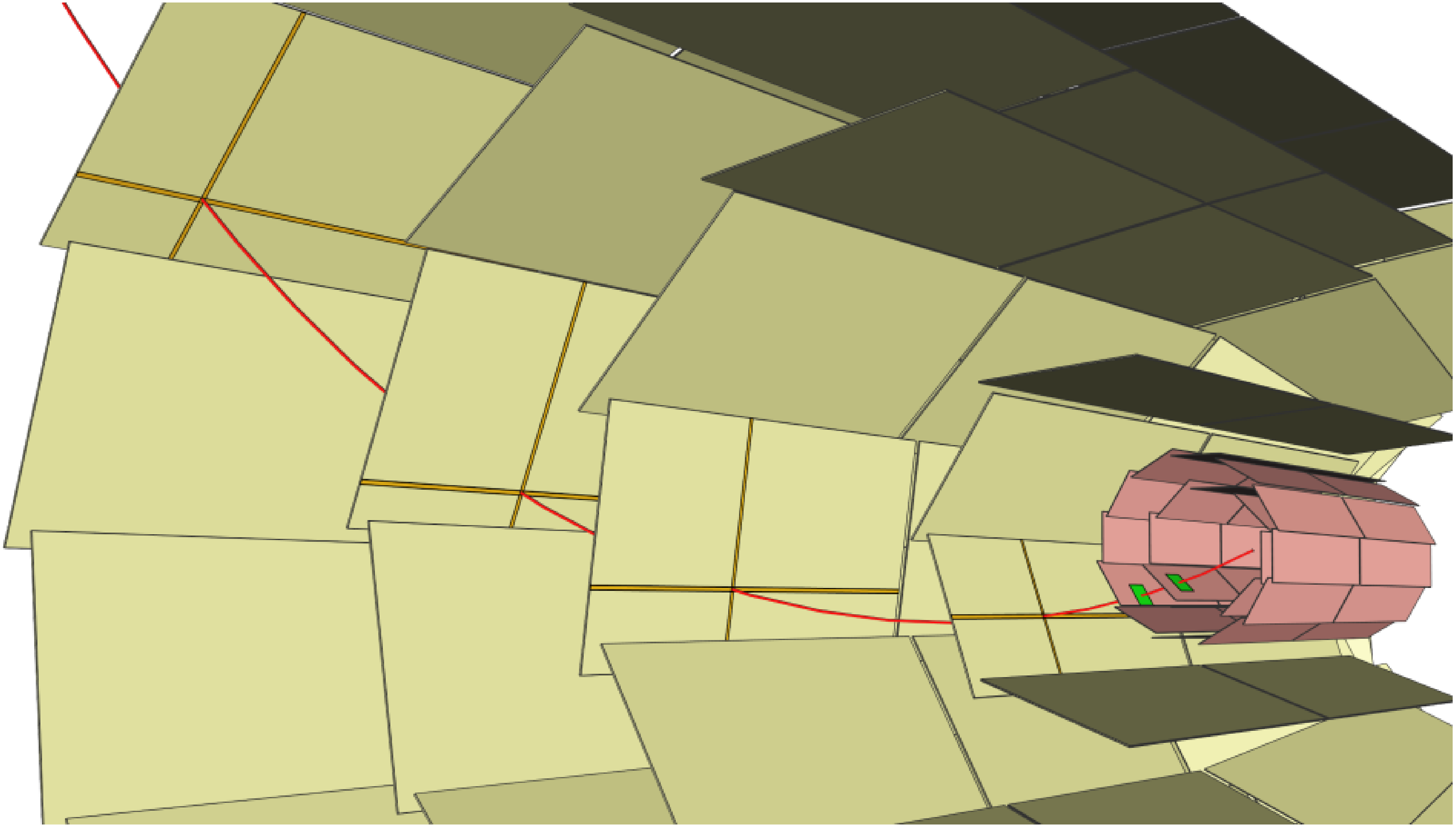






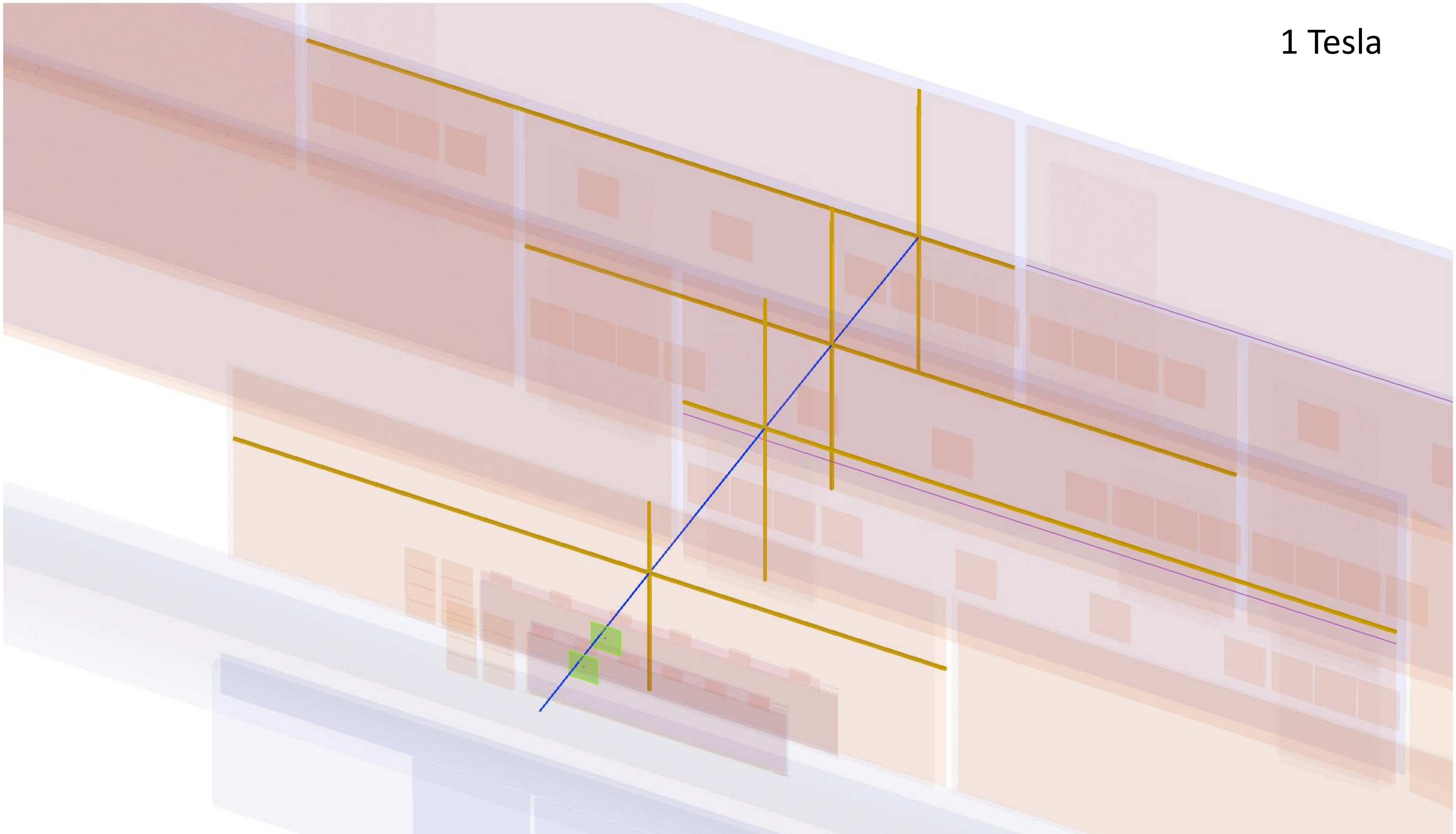
- Homogeneous sensor response
- SNR ~ 30
- 14 μm resolution (50 μm)
- ε > 99%

VXD Online Data Reduction

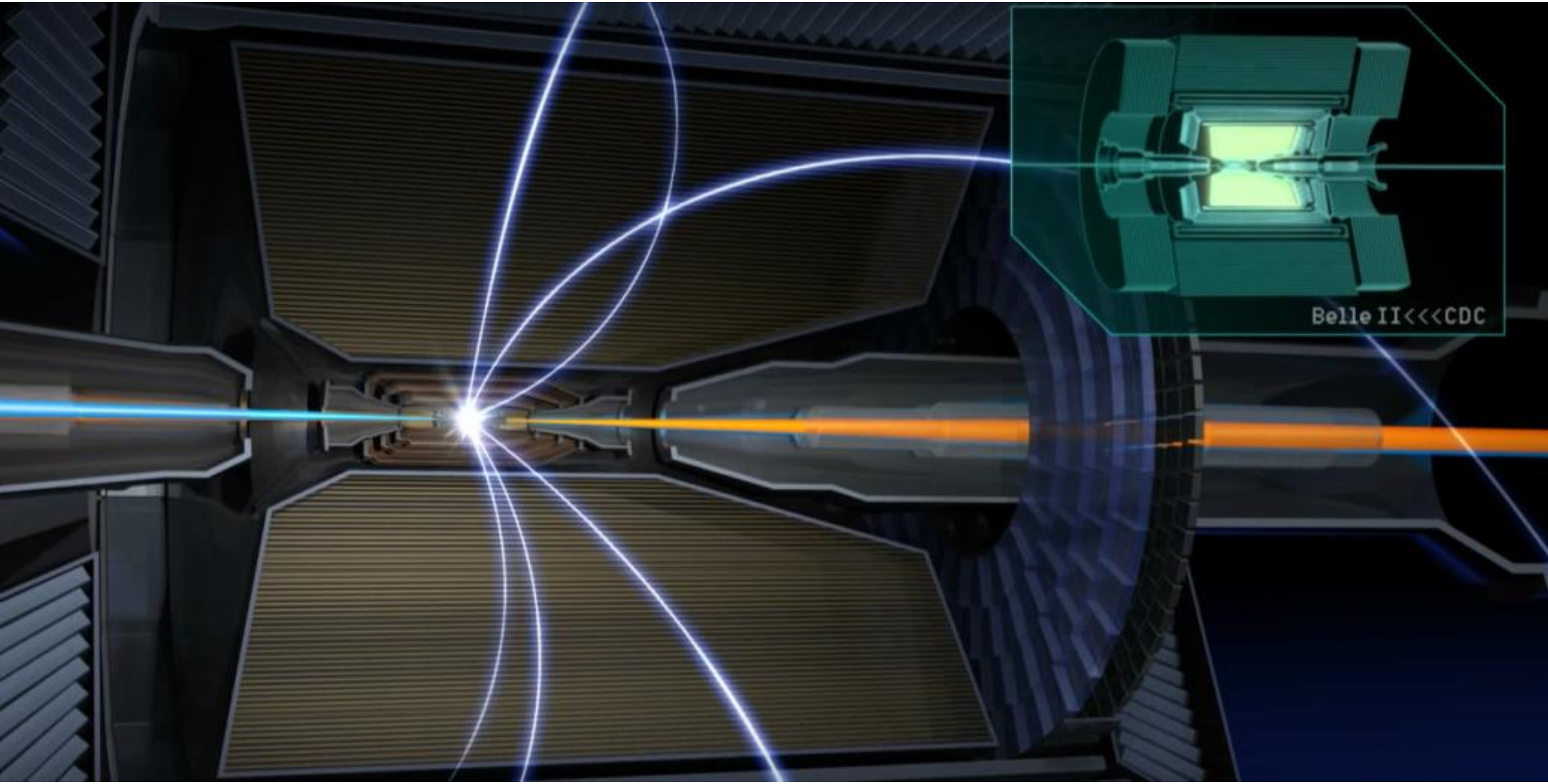


- Amount of data created by PXD is larger than the data generated by all other subdetectors
- Only reduced PXD data is written to tape
- Use tracks in SVD (and CDC) to find PXD regions of interest

Online Data Reduction



Central Drift Chamber (CDC)

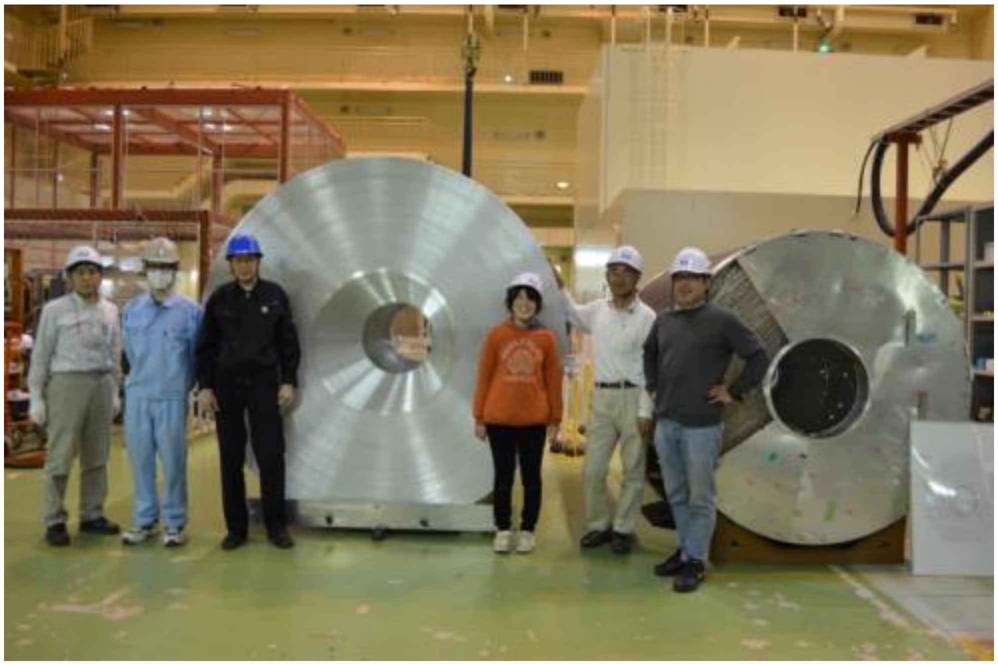


Central Drift Chamber (CDC)

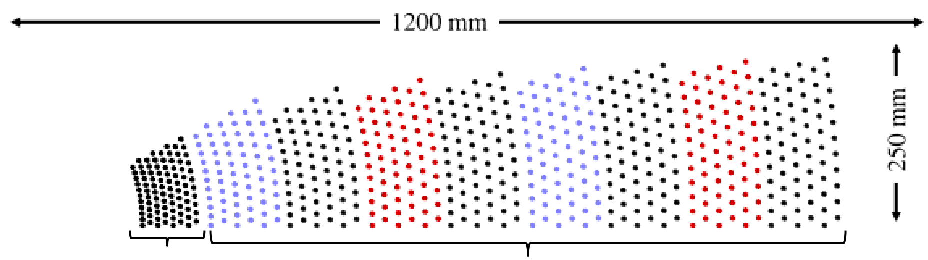
Three important roles:

- Track reconstruction and momentum determination
- Particle identification via dE/dx
- Trigger for background rejection

	Belle II CDC
Number of layers	56
Total sense wires	14336
Gas	He:C_2H_6 (1:1)
Sense wire	Au-W (ø30 μm)
Field wire	Al (ø126 μm)



Stereo and axial layers



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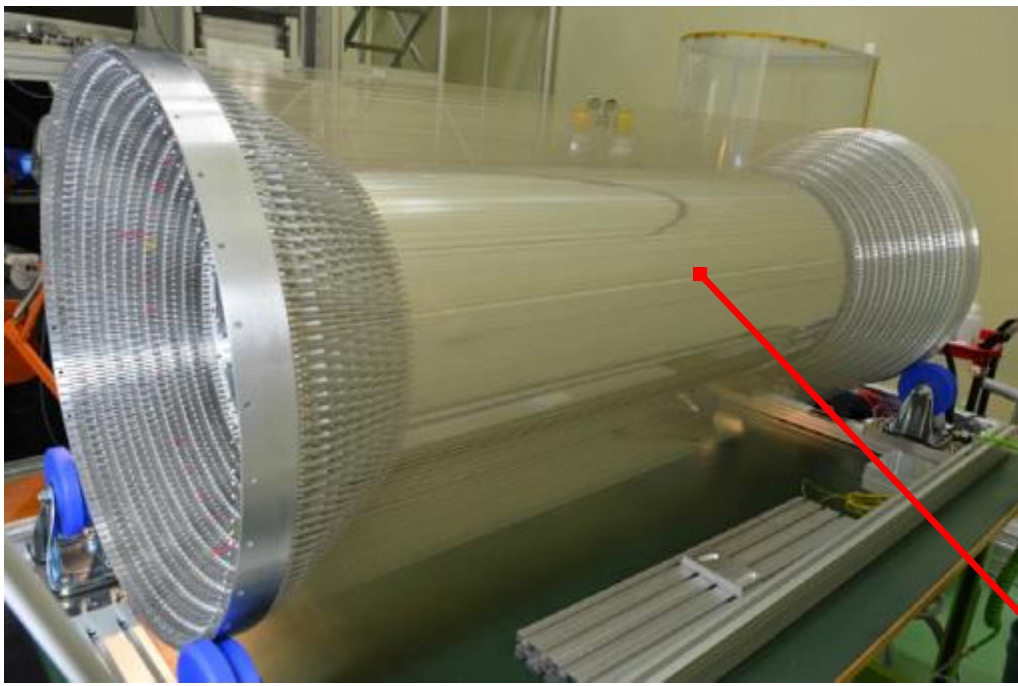
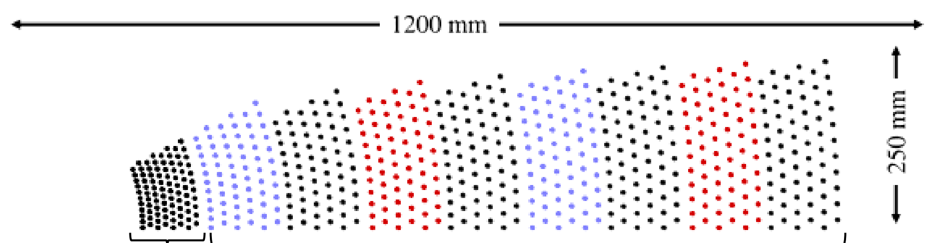


Stereo and axial layers



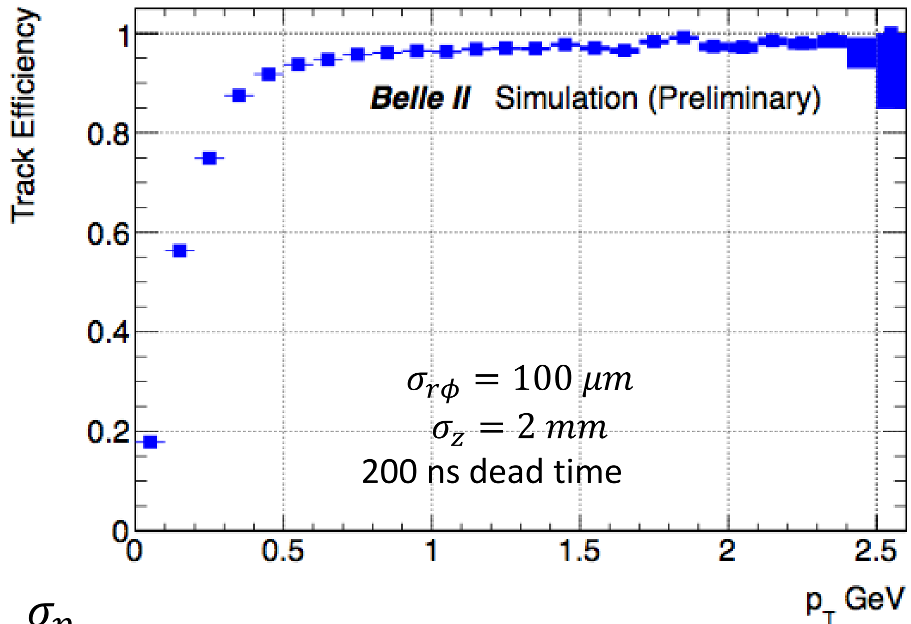
Small cell chamber

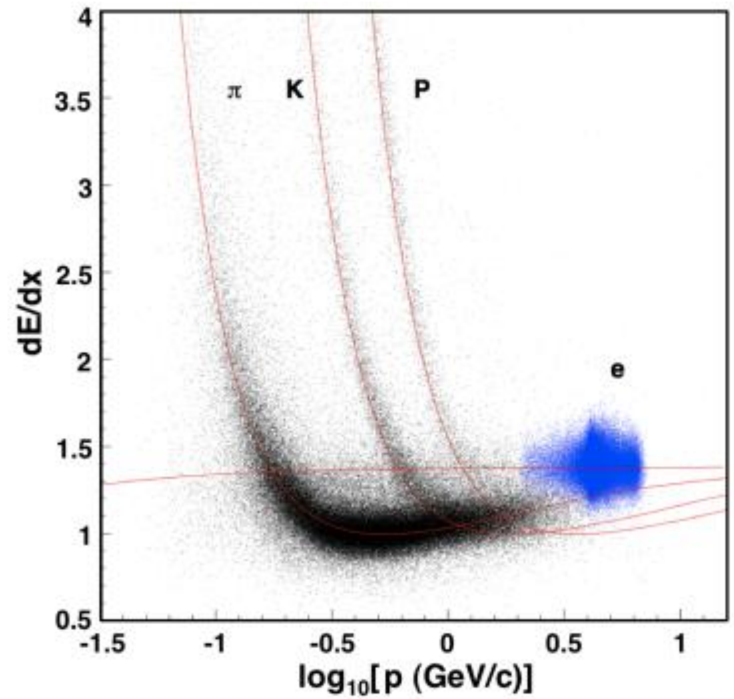
Large tracking volume

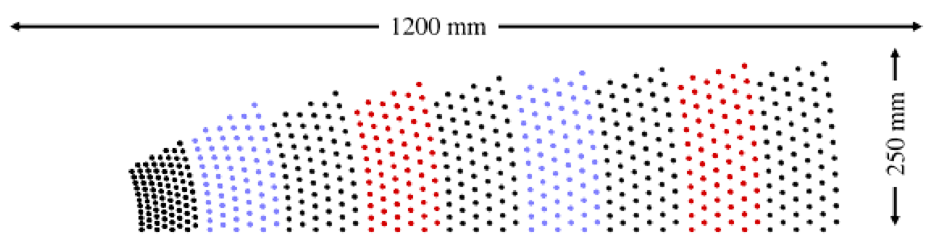
Central Drift Chamber (CDC)

Three important roles:

- Track reconstruction and momentum determination
- Particle identification via dE/dx
- Trigger for background rejection



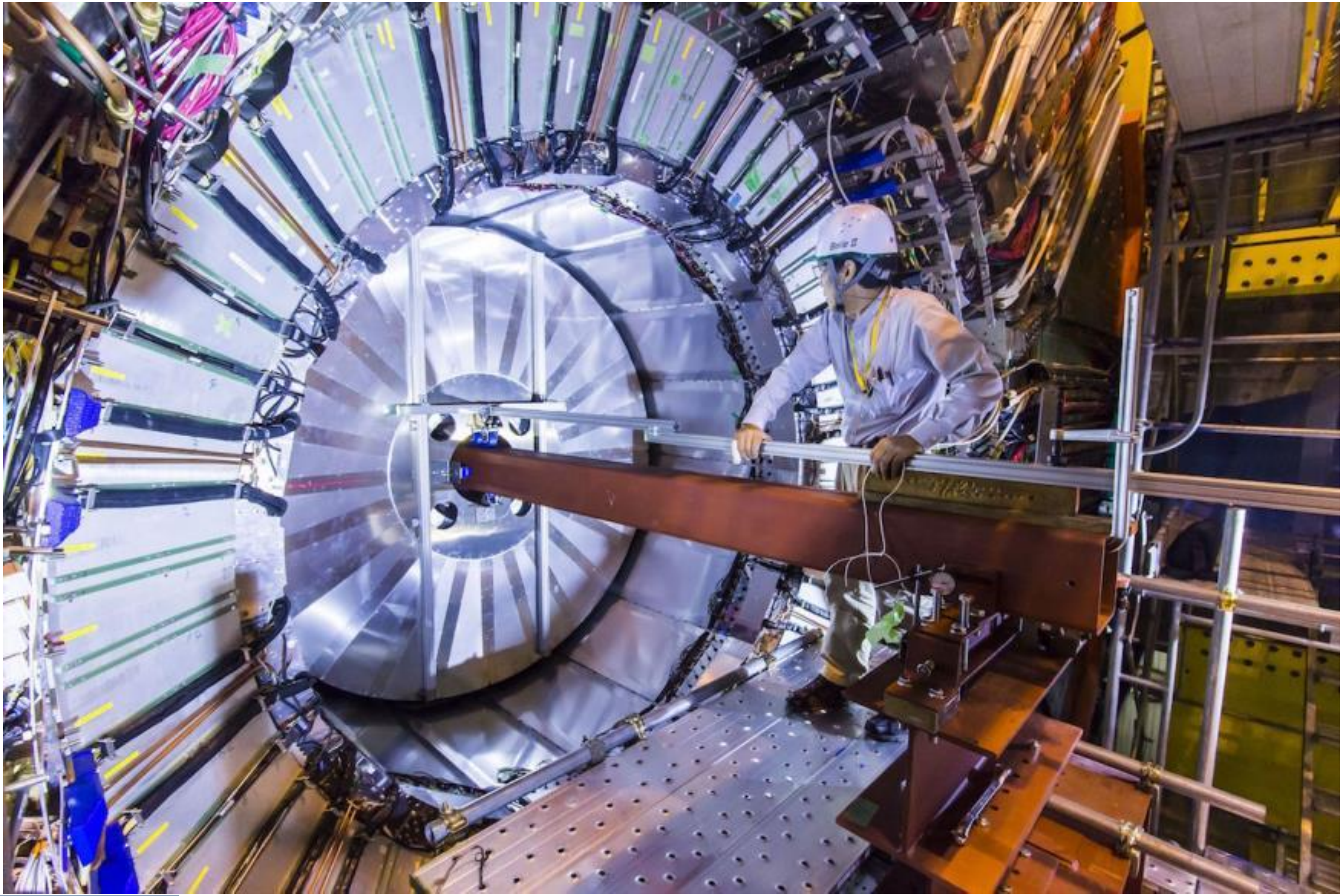




$$\frac{\sigma_{p_t}}{p_t} \sim 0.3\%/\beta \oplus 0.1\% \cdot p_t[GeV/c]$$

$$\sigma\left(\frac{dE}{dx}\right)\Big|_{\text{MIP}} \sim 5\%$$

Central Drift Chamber (CDC)



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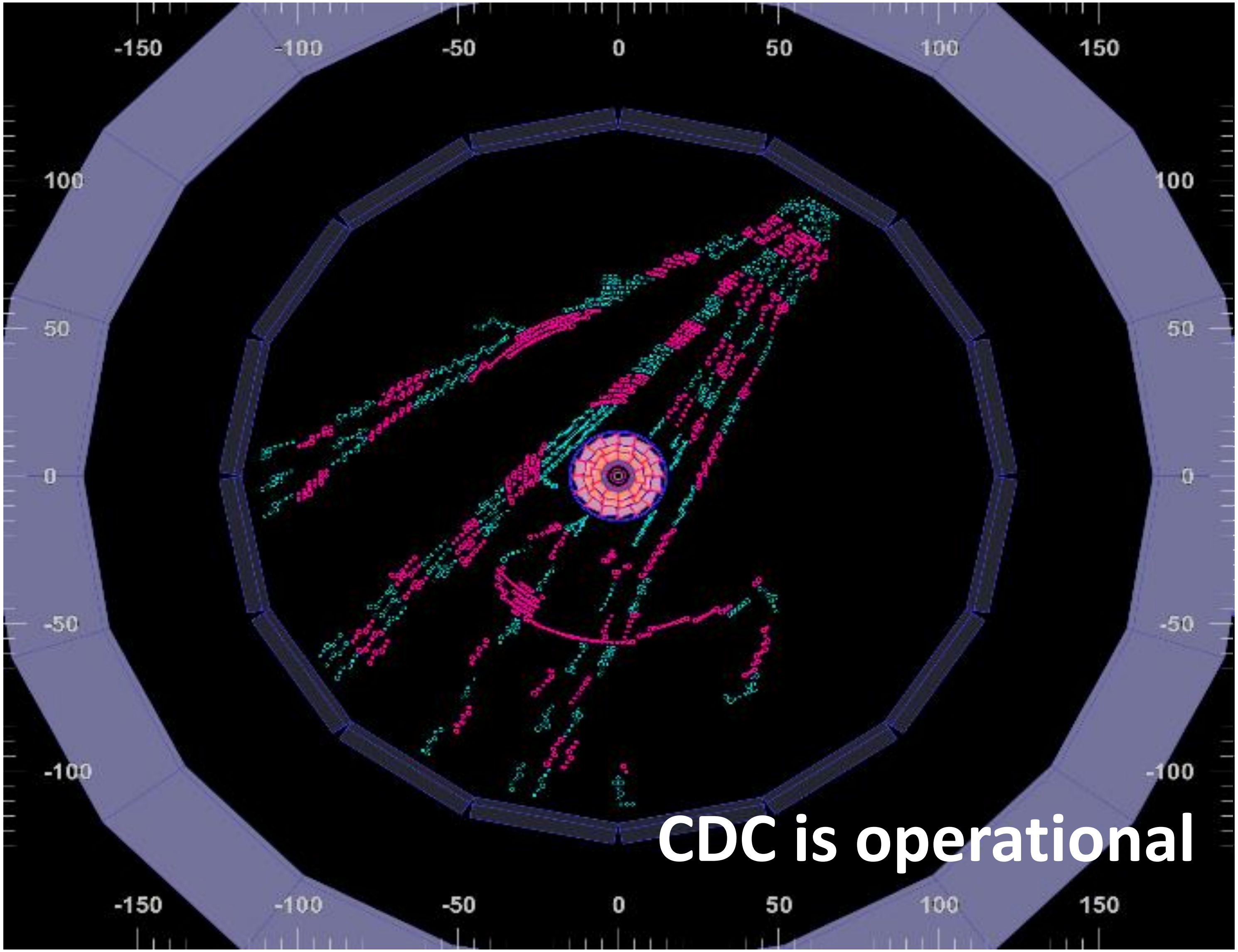
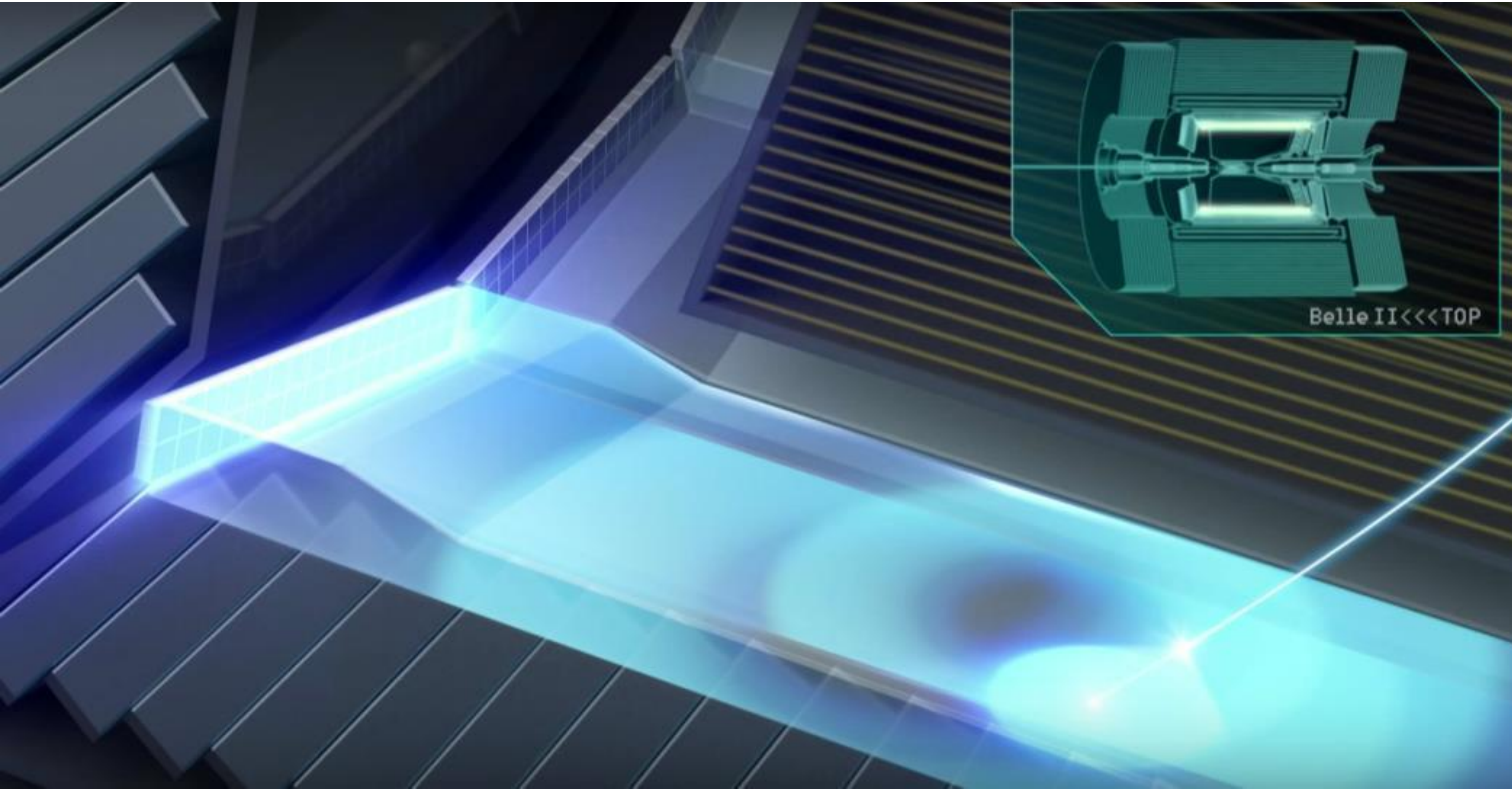


Time Of Propagation (TOP)



Time Of Propagation (TOP)

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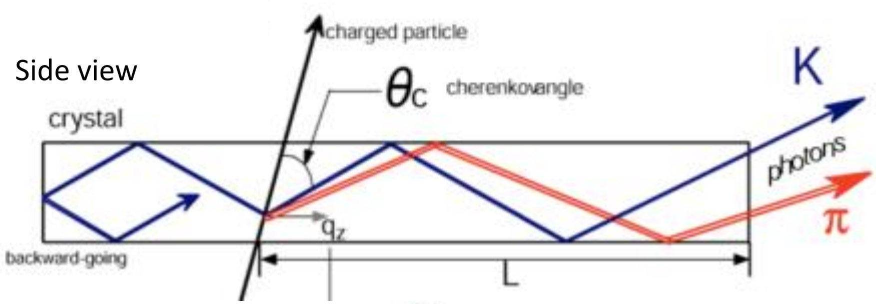
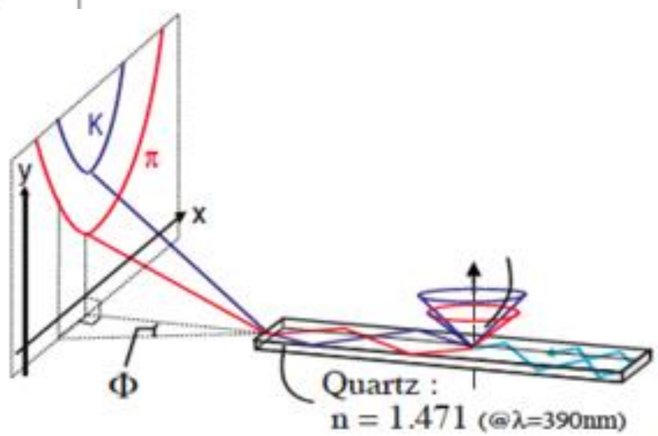
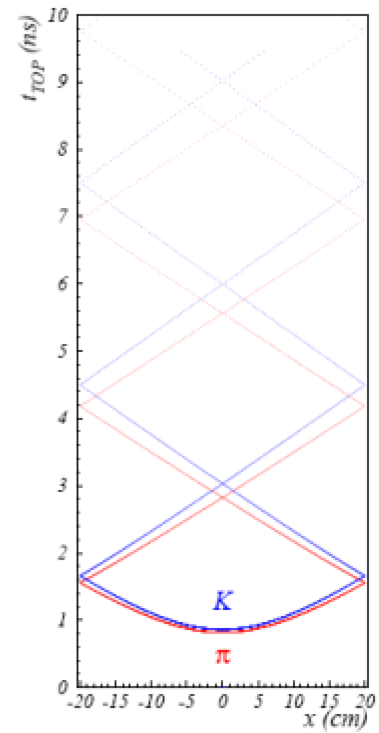
TOP will be used for PID in the barrel region

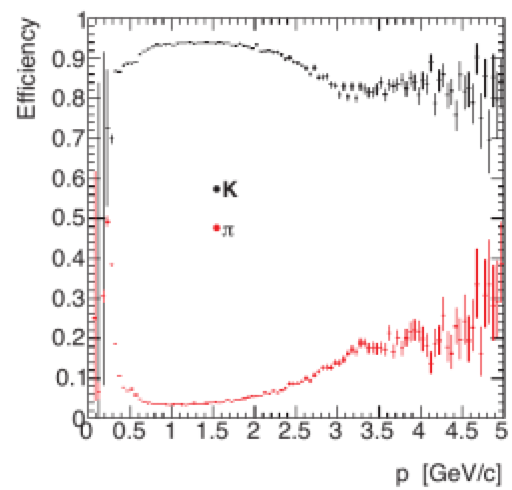
- When a charged particle passes through the quartz, it emits Cherenkov photons
- The Cherenkov angle, and hence detection time/position depends on the mass of particle (for given track parameters).



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

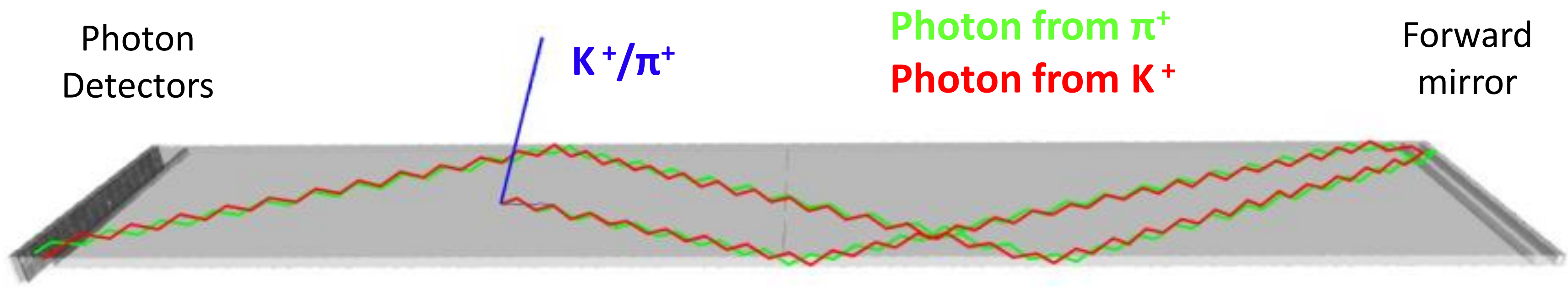






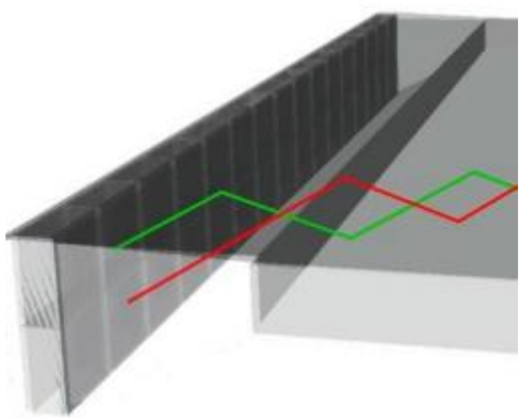
Time Of Propagation (TOP)

- Each TOP module contains two quartz bars (2.5 m x 0.45 m x 2 cm), mirror, and array of photodetectors.



32 (segmented 4x4) Micro-channel plate PMT
Hamamatsu SL-10 MCP PMT
They can operate in a magnetic field
Gain = $2{\cdot}10^6$
Time resolution σ = 35 ps
QE > 24% at 380 nm

Quartz property	Belle II TOP
Flatness	< 6.3 μm
Roughness	< 0.5 nm (RMS)
Bulk transmittance	> 98% /m
Surface reflectance	> 99.9% /reflection



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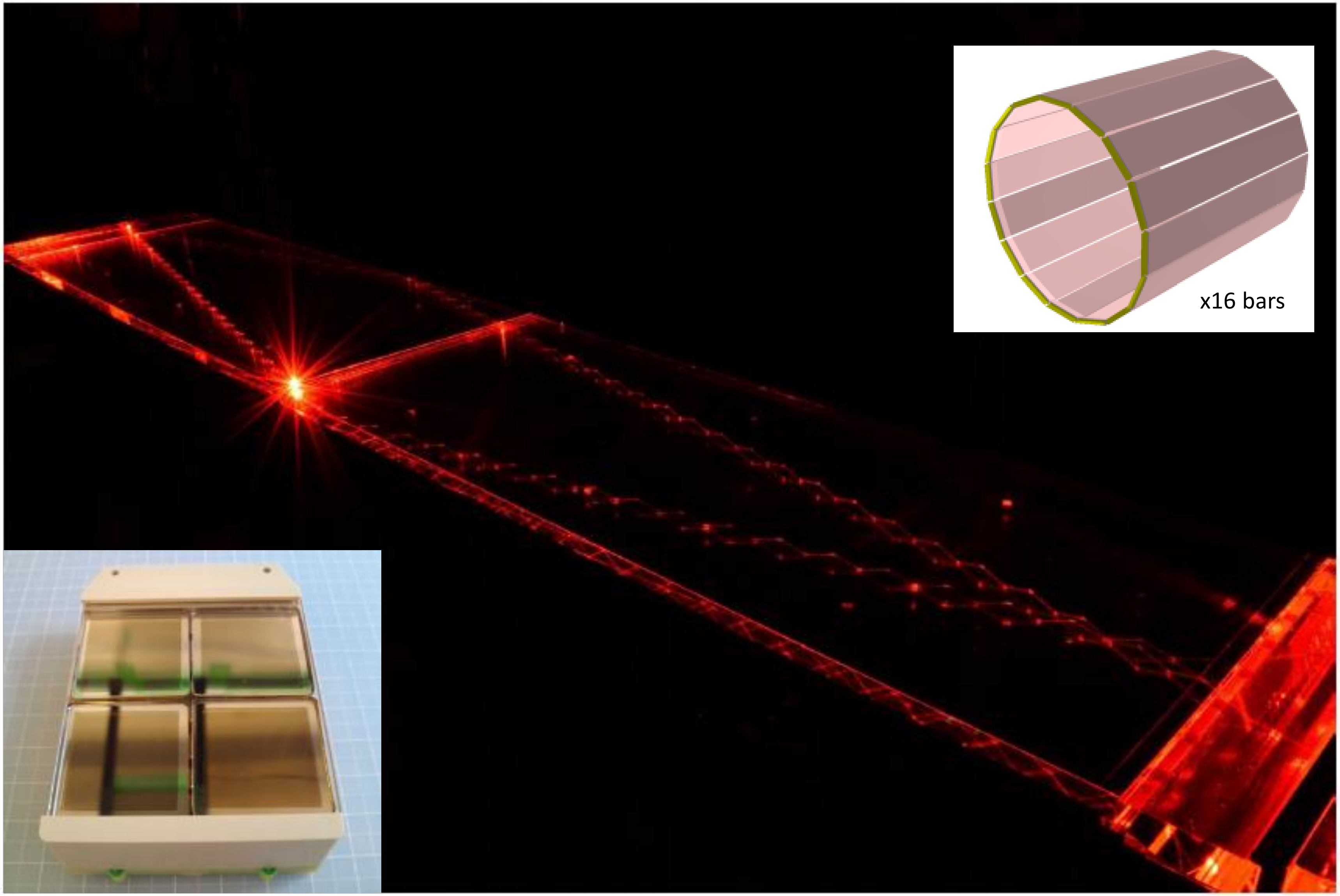

Time Of Propagation (TOP)

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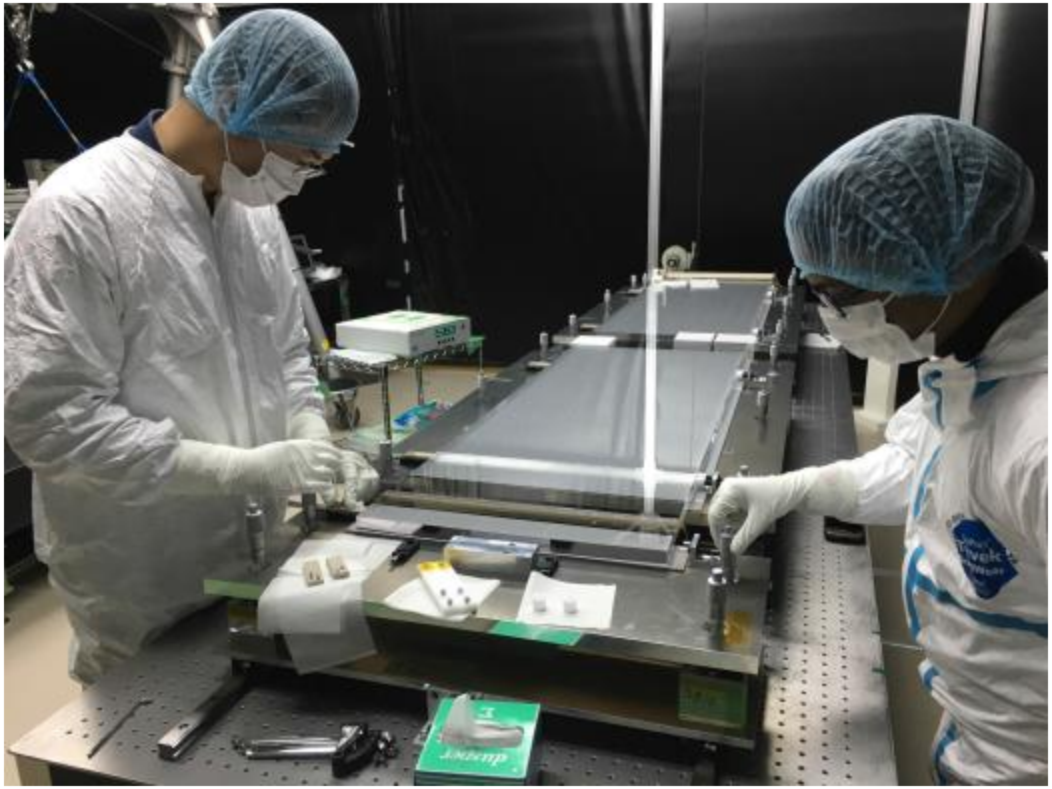
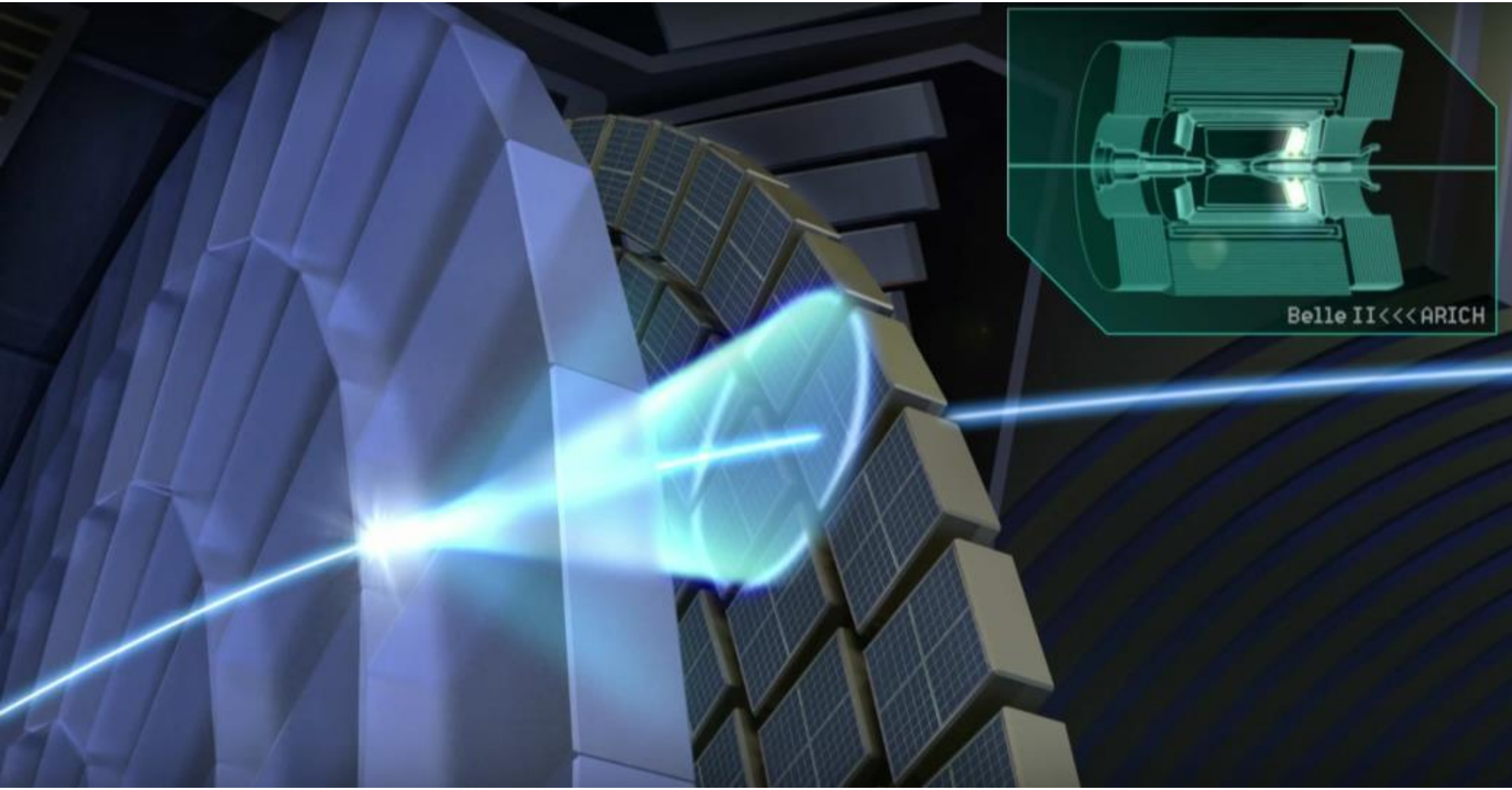


TOP is operational

Aerogel Ring Imaging Cherenkov (ARICH)



Aerogel Ring Imaging Cherenkov (ARICH)

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Particle identification in the forward endcap

- Radiator: Silica Aerogel

n = 1.045-1.055

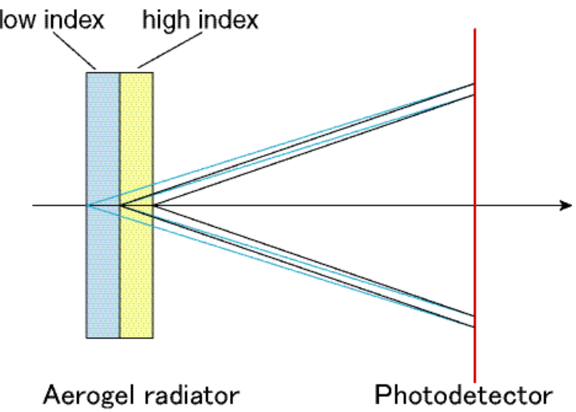
Transmission length > 40 mm

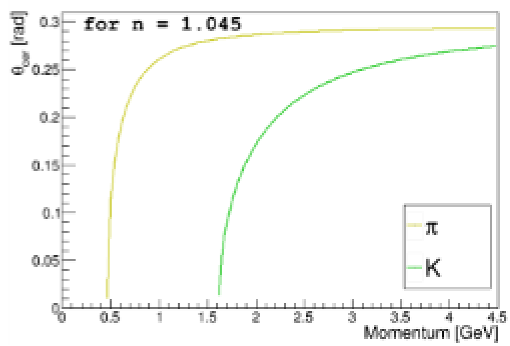
- Photon detection: Hybrid Avalanche Photo Detectors

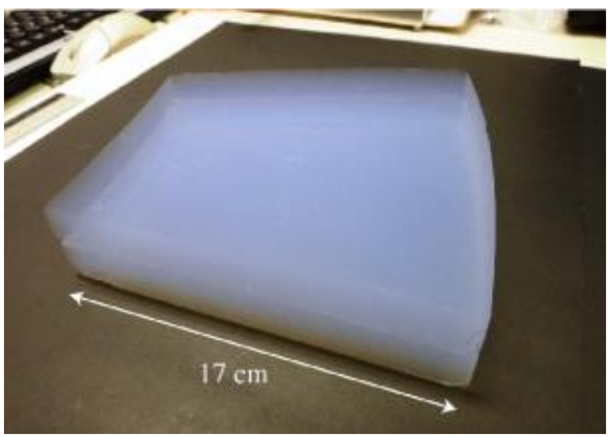
420 units, 144 channels each, 5 mm pixelated

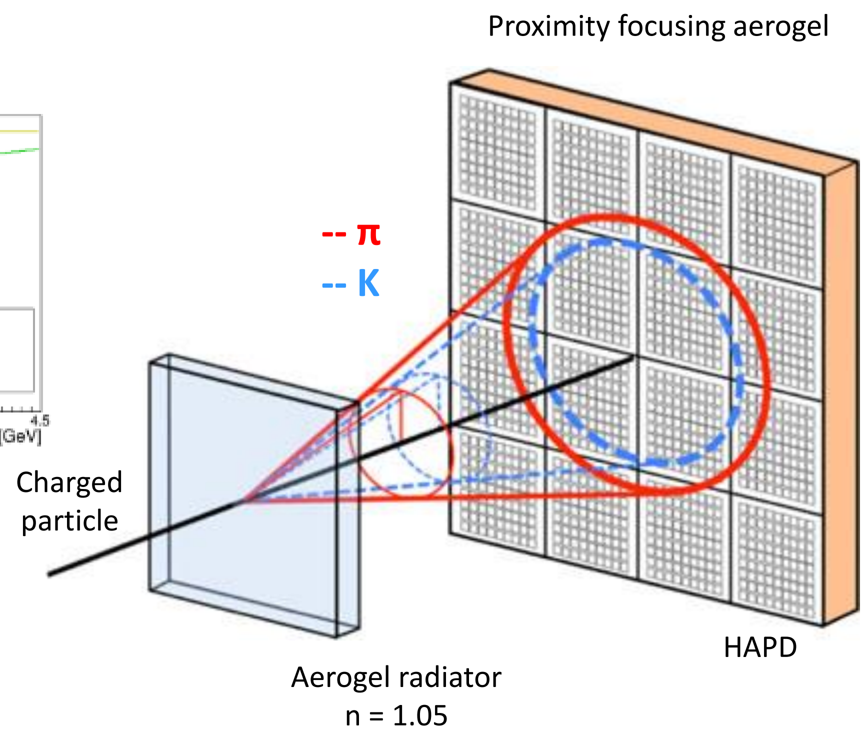
Gain = $7 \cdot 10^5$

QE > 28%









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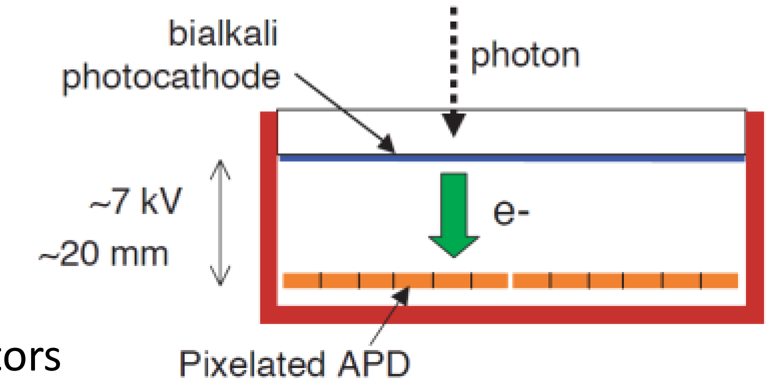
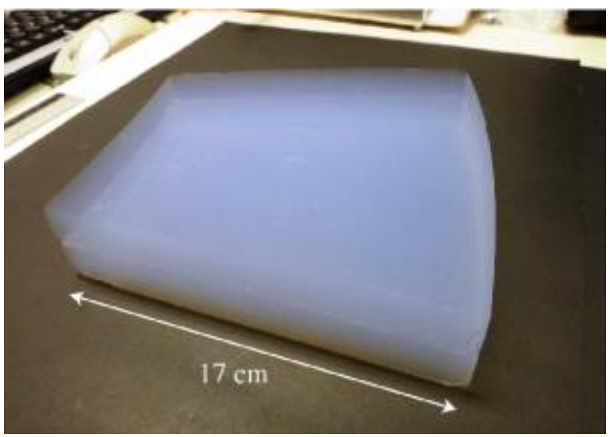
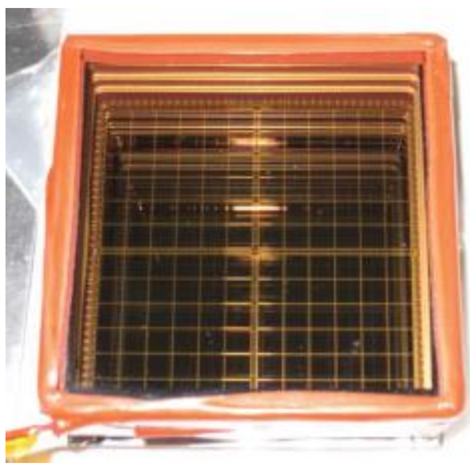
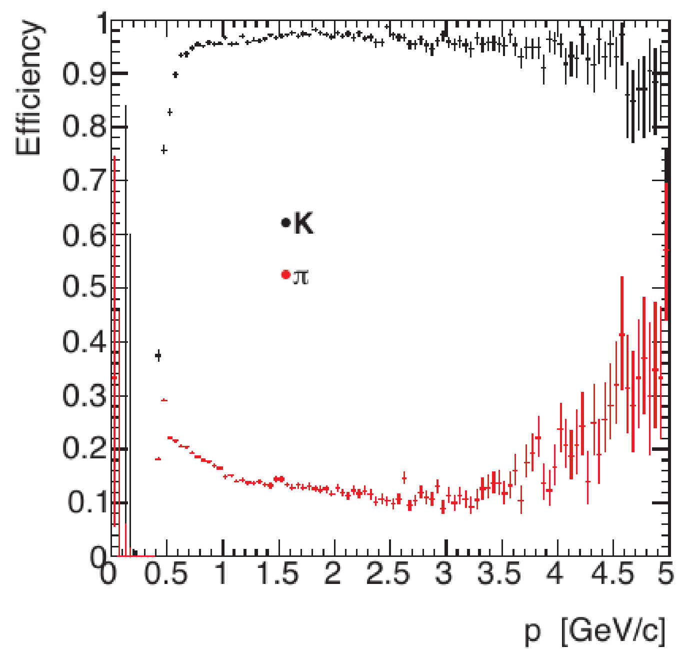
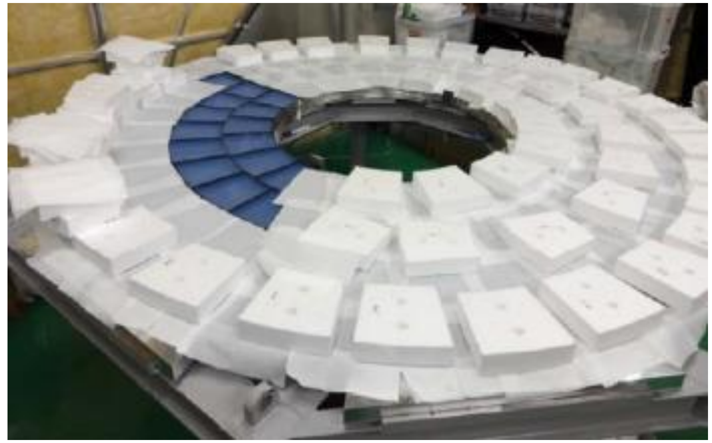


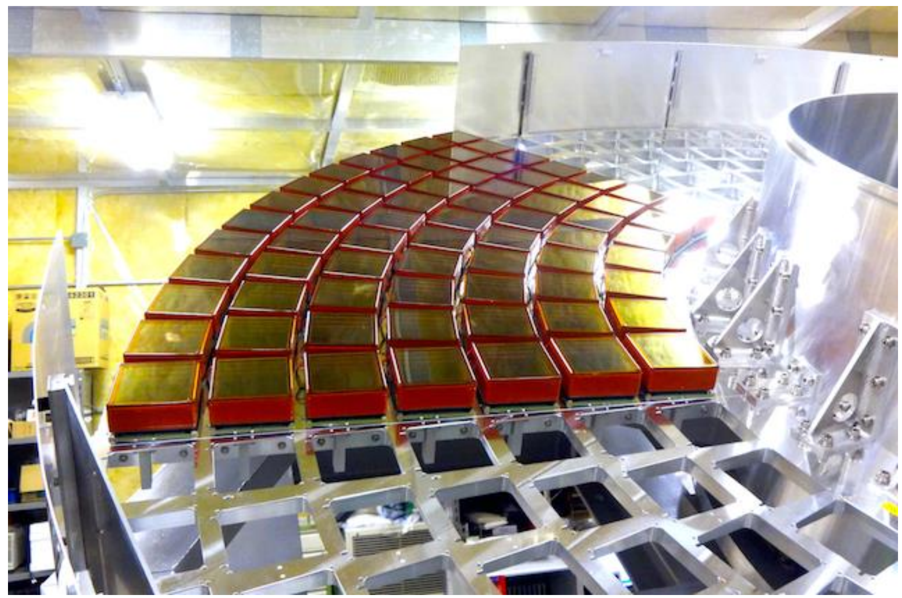






Aerogel Ring Imaging Cherenkov (ARICH)

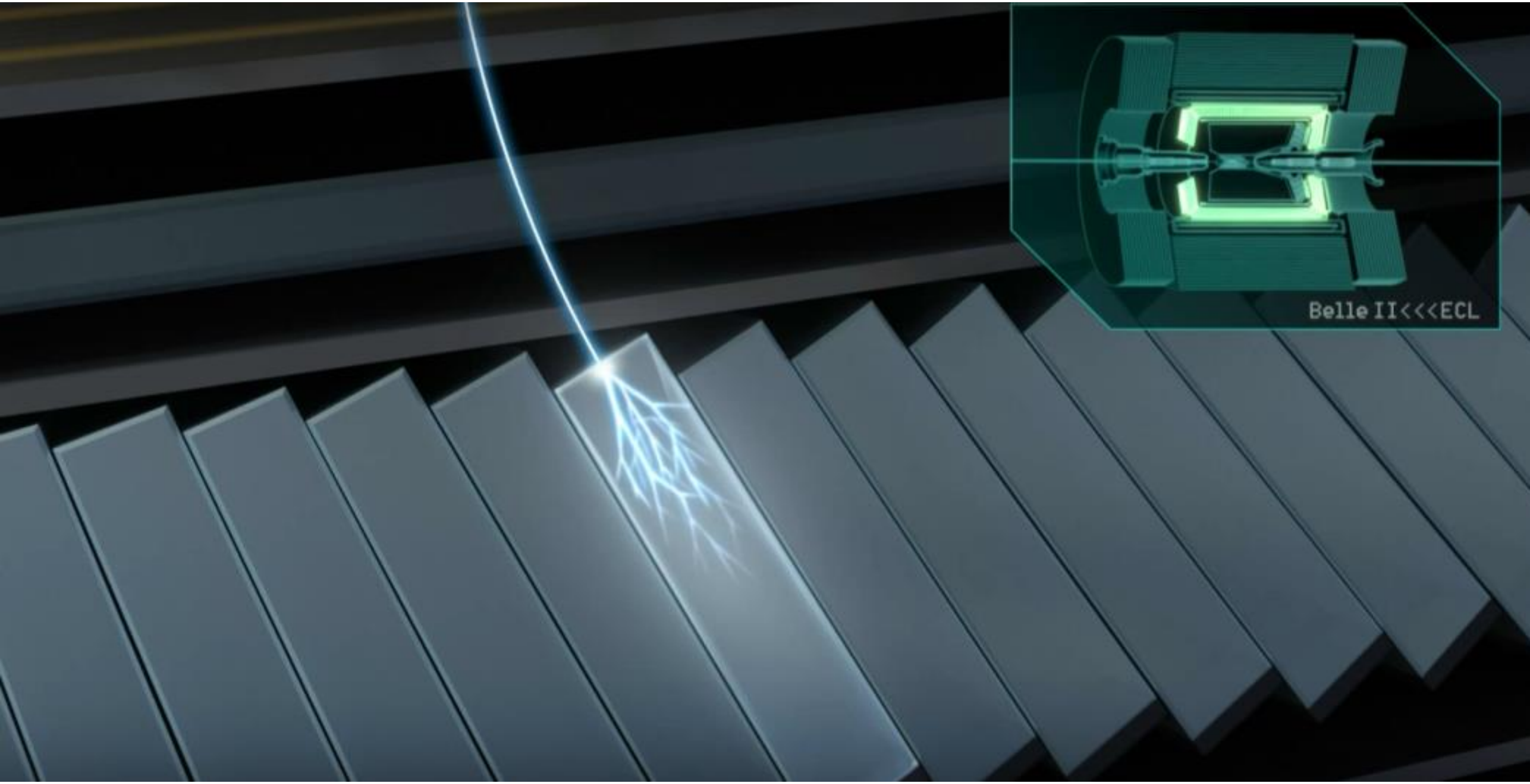




ARICH:

- Aerogel sectors completed
- HAPDs being installed

Electromagnetic Calorimeter (ECL)



Electromagnetic Calorimeter (ECL)

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E.M. Calorimeter to measure:

Energy and angle of electrons/photons

Luminosity

Need upgrade due to high backgrounds:

- Barrel:

CsI(Tl) crystals reused

16.1 X_0 (30 cm)

New electronics 2 MHz waveform sampling

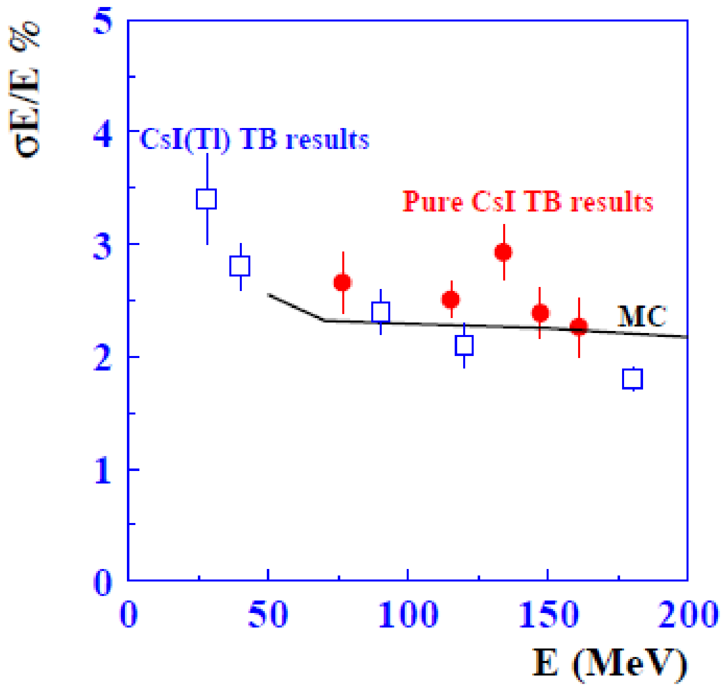
- Endcaps:

CsI(Tl), crystals reused

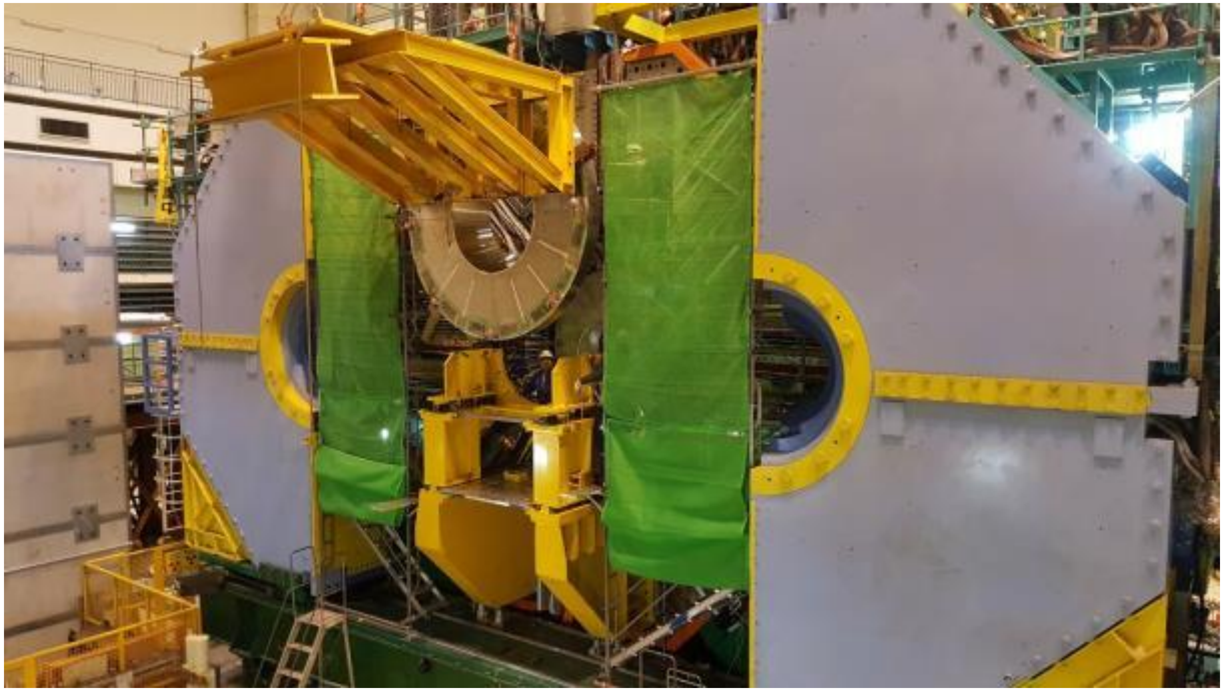
16.1 X_0 (30 cm)

Replacement with pure CsI in future (under study)

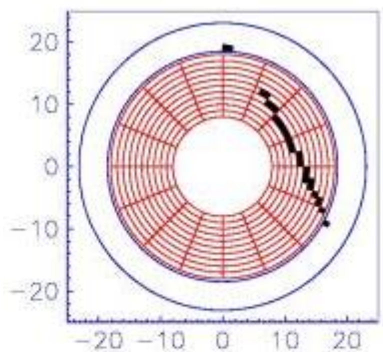
Time constant (shaping) 30 ns



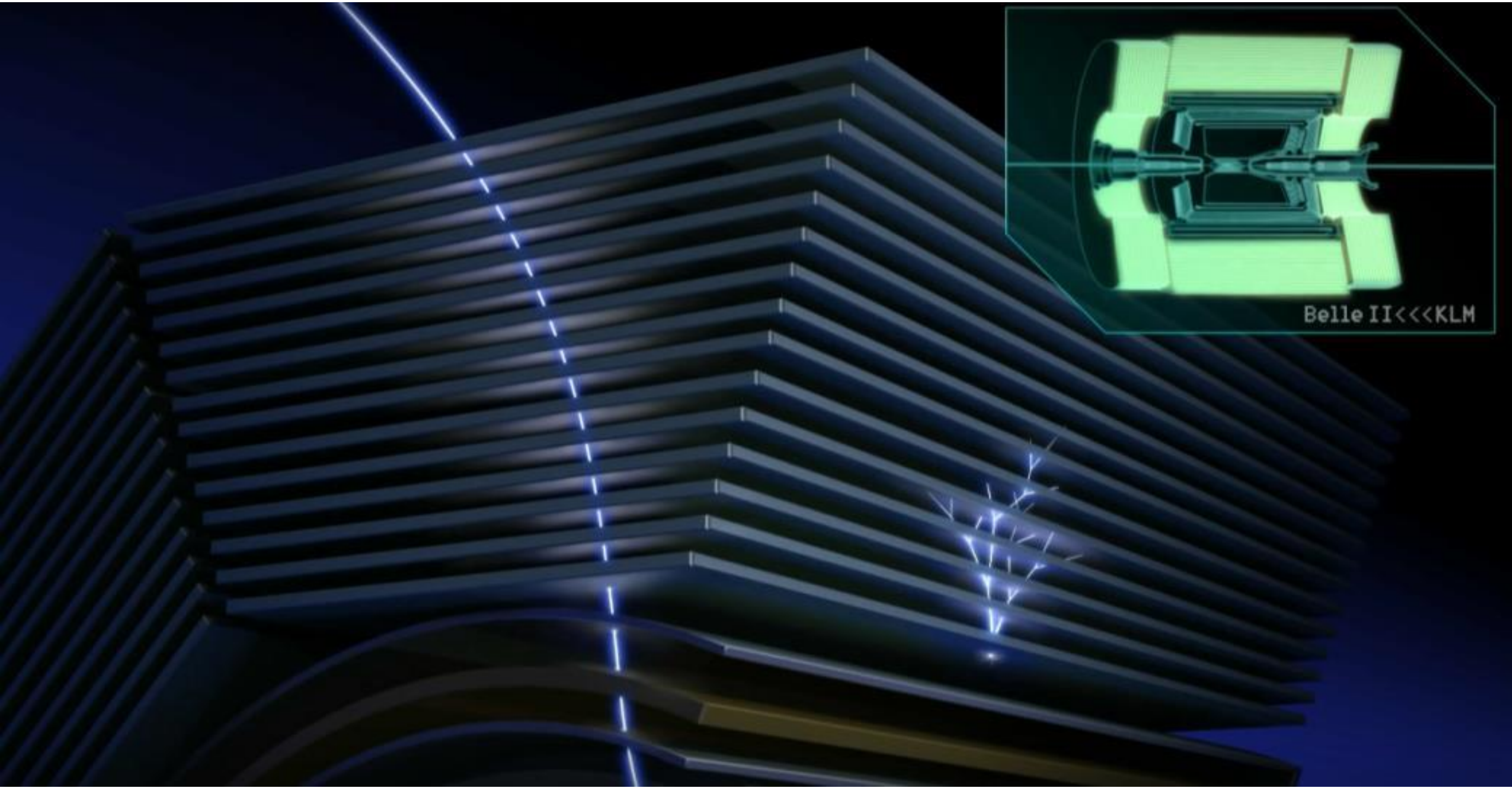
Electromagnetic Calorimeter (ECL)



ECL is operational



K_L and Muon Systems (KLM)

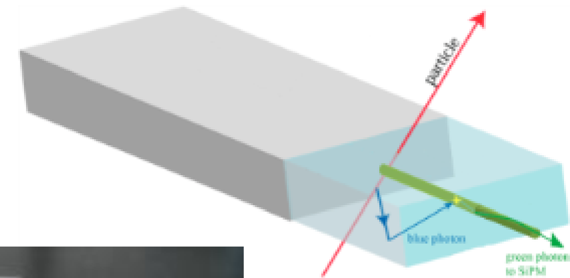


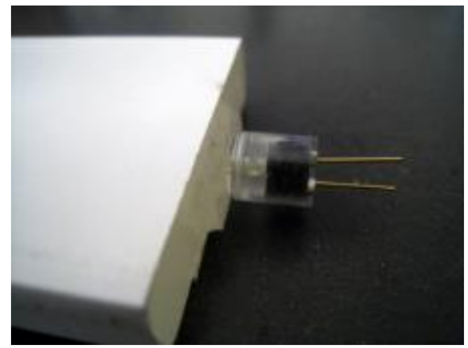
K_L and Muon Systems (KLM)

Large area thin planar detectors interleaved with the iron plates of the flux return yoke.

- Barrel:

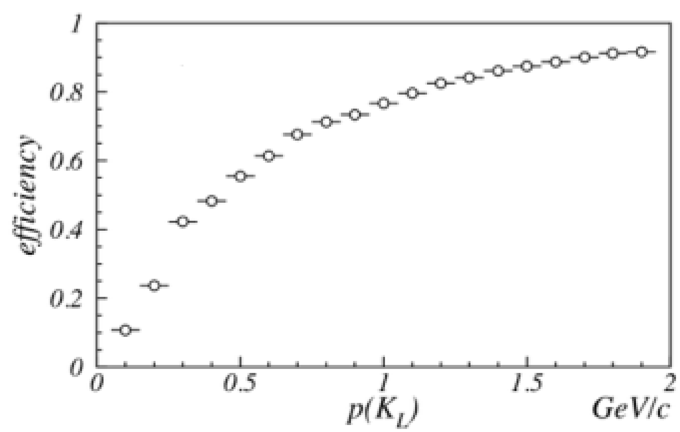
Belle RPCs reused
Two inner layers replaced by scintillator strips (BKG)
Scintillator strips with WLS fibers
Hamamatsu SiPM S10362

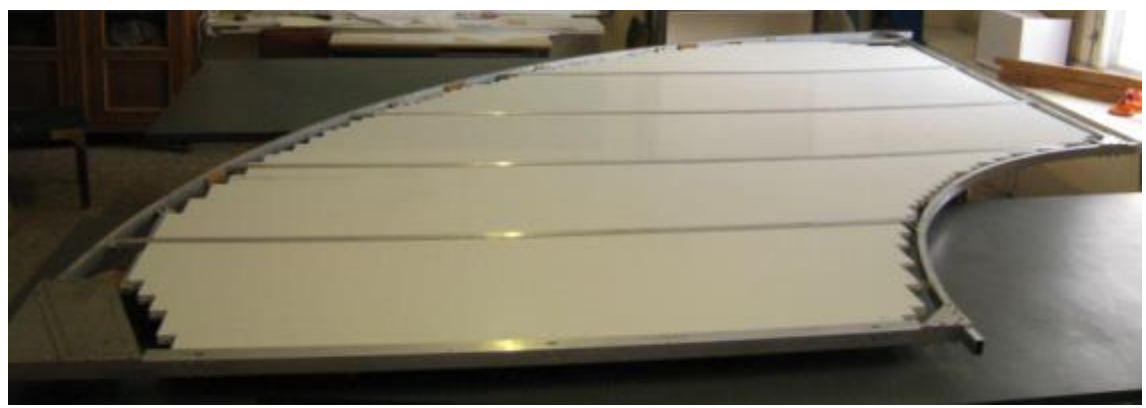




- Endcap:

RPCs replaced with polystyrene scintillators
99% geometrical acceptance. σ ~ 1ns





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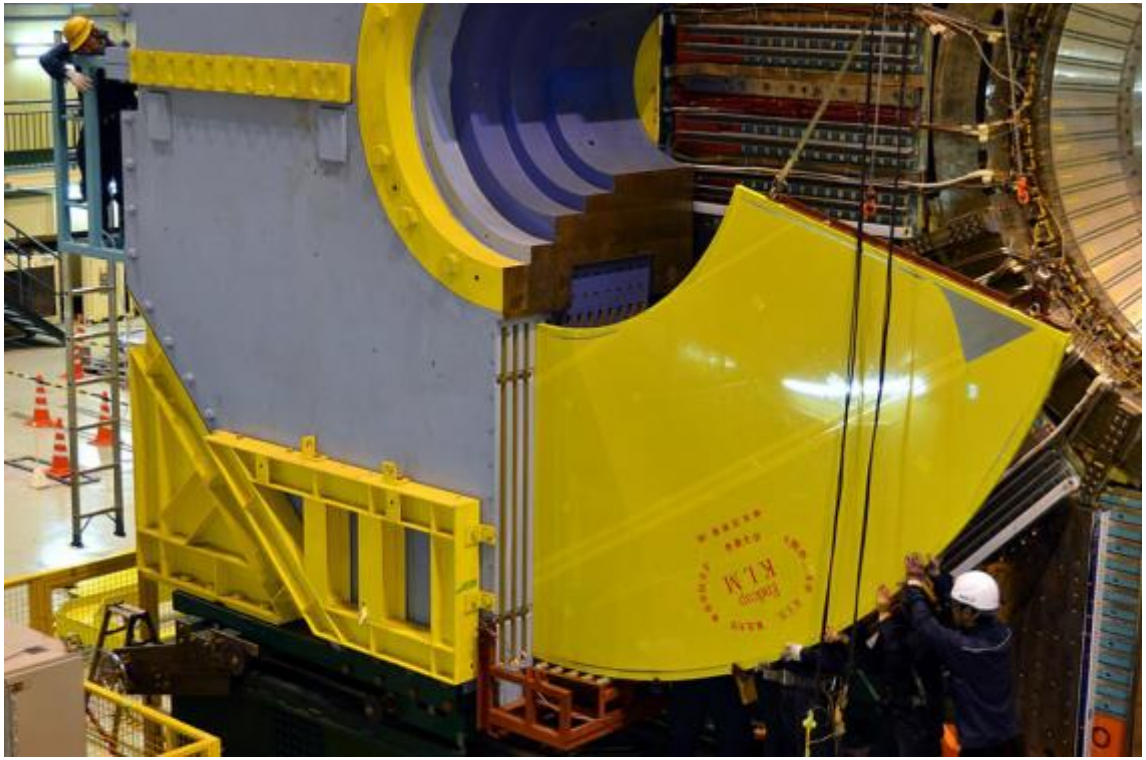
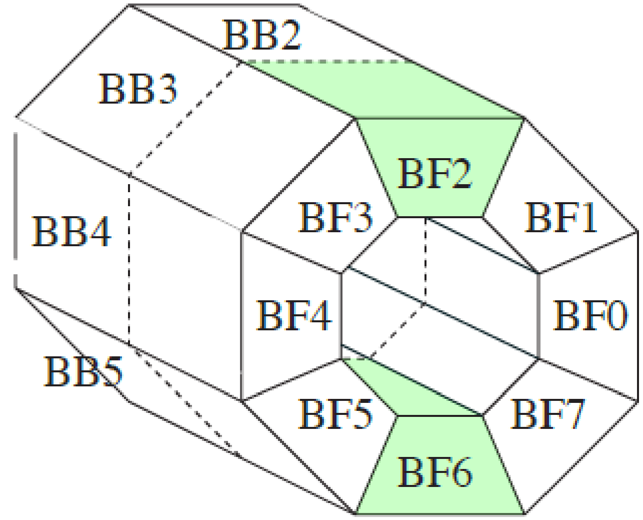
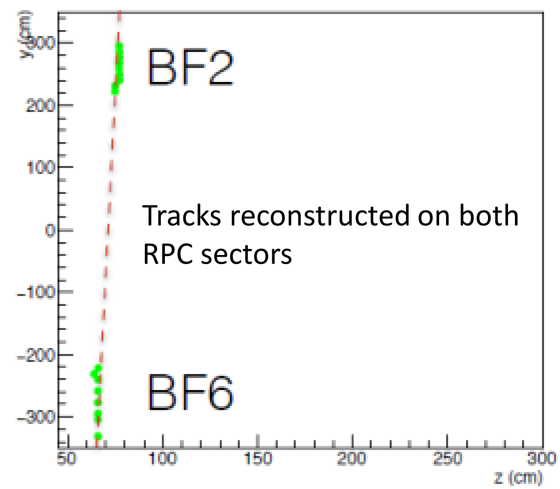
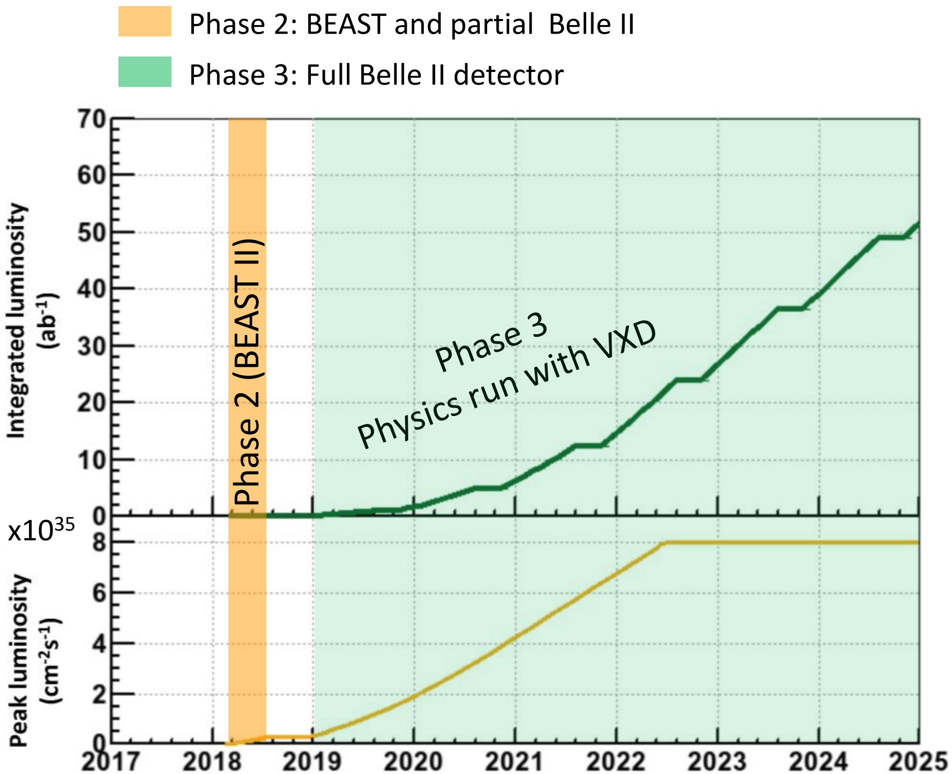






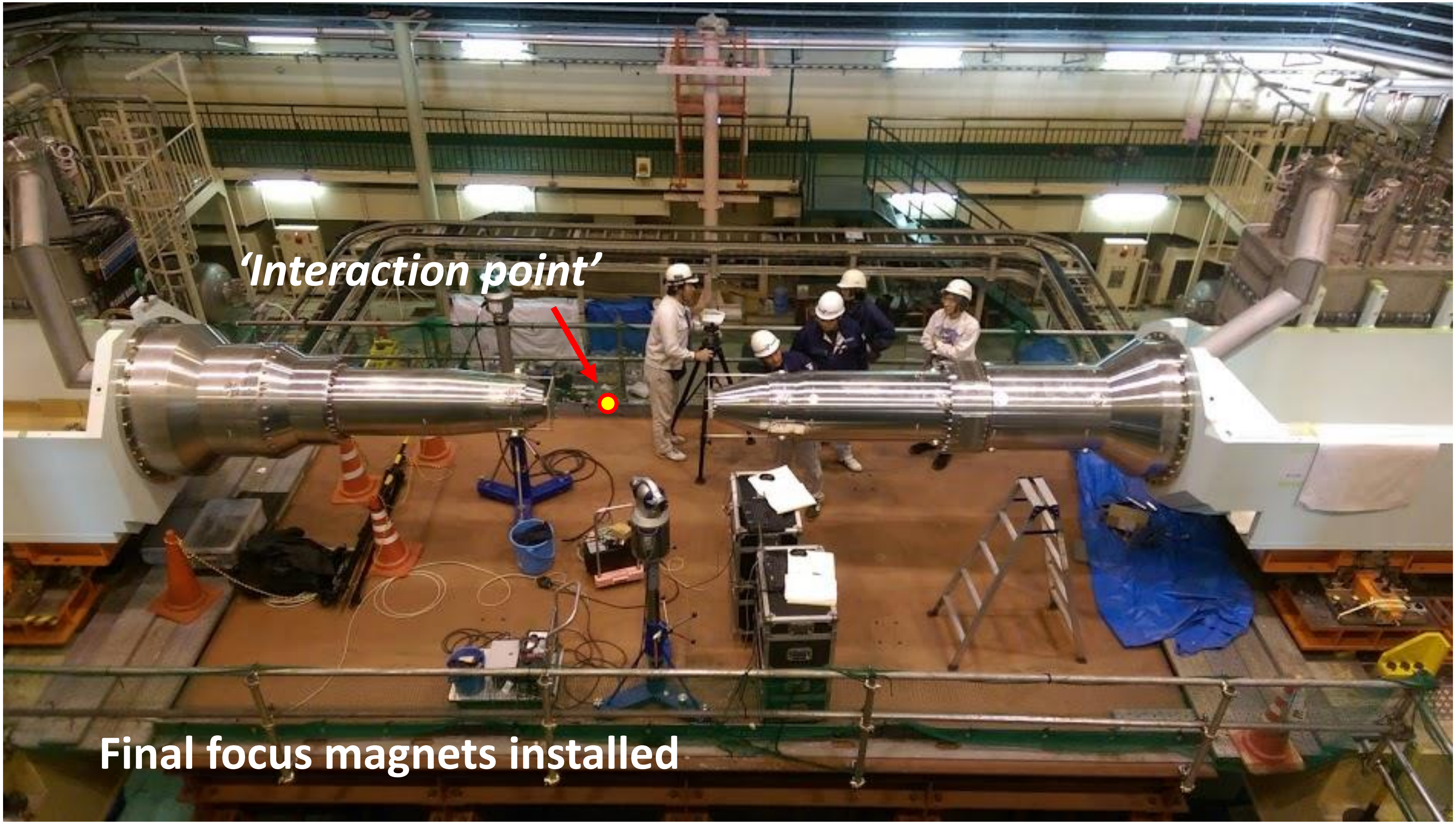
KLM is operational

Getting Ready for Phase 2

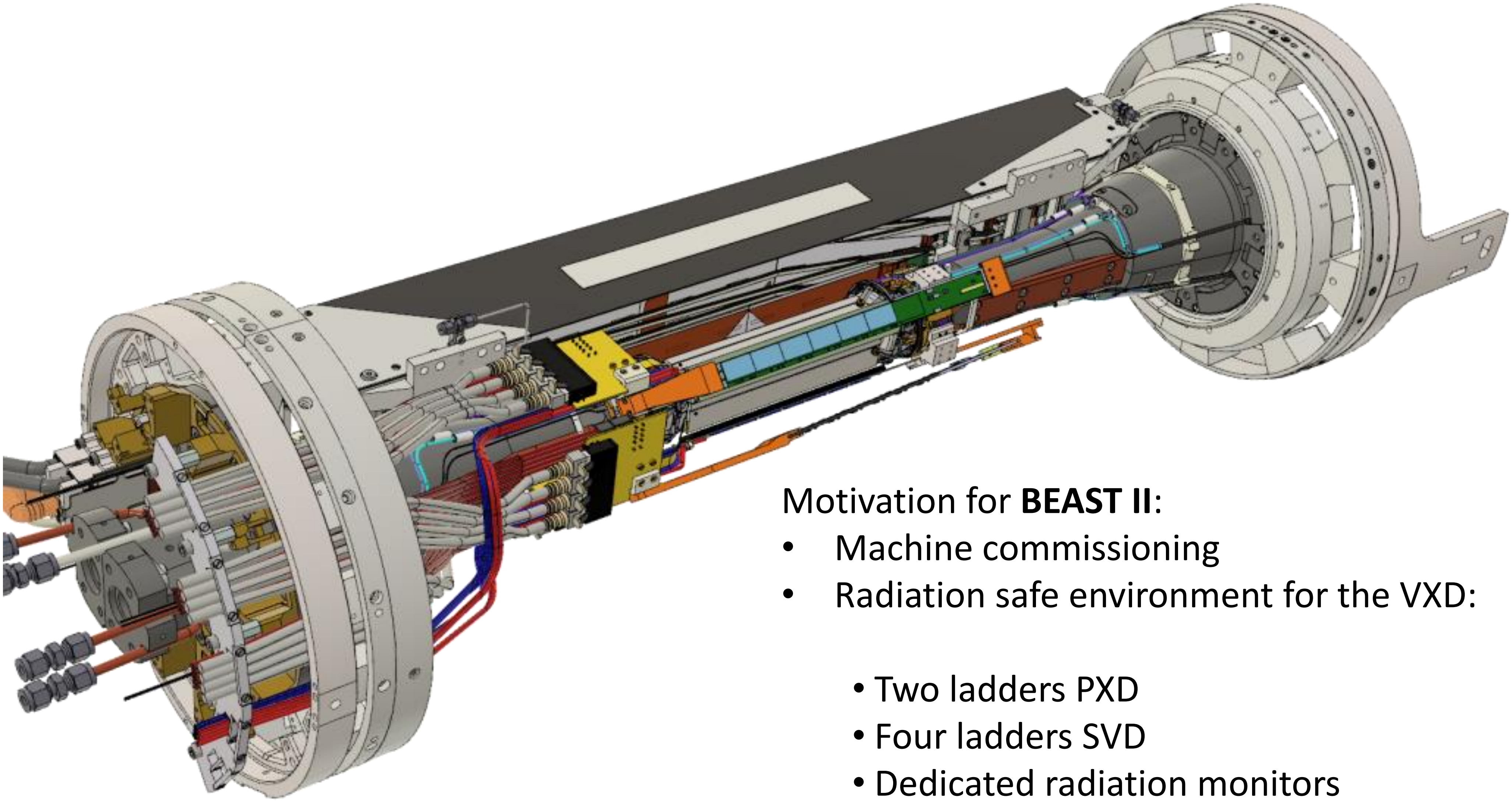


- The SuperKEKB accelerator will be operating, for the first time, with QCS magnets
  - First operation with focused beams
  - First beam collisions
- The Belle II detector, minus the vertex detectors (VXD), will have rolled into the beam line (11.4.17)

Getting Ready for Phase 2



Getting Ready for Phase 2



Motivation for **BEAST II**:

- Machine commissioning
- Radiation safe environment for the VXD:
  - Two ladders PXD
  - Four ladders SVD
  - Dedicated radiation monitors
    FANGS, CLAWS, PLUME

Getting Ready for Phase 2

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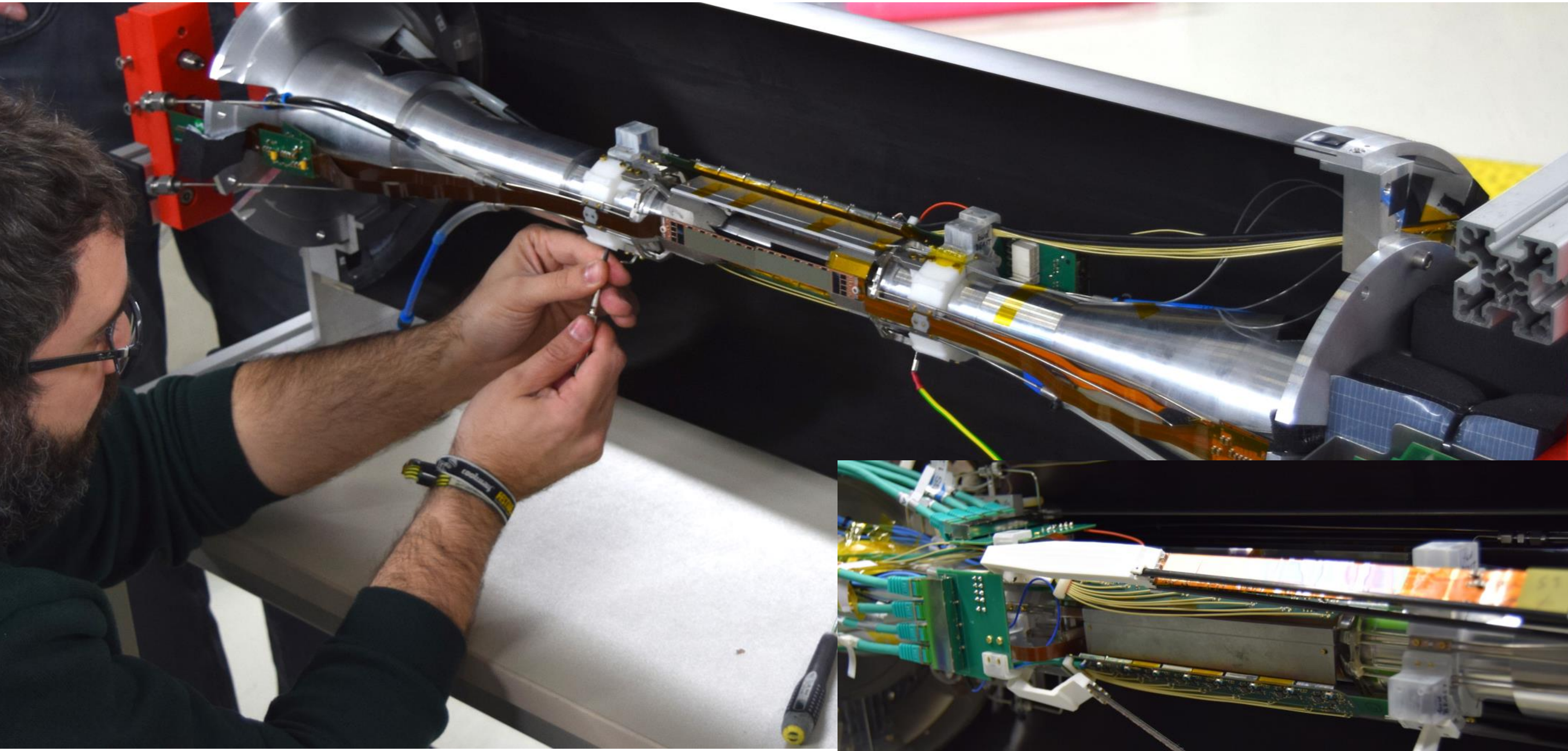

- Combined operation demonstrated
- Getting ready for installation in November 2017

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German Contribution

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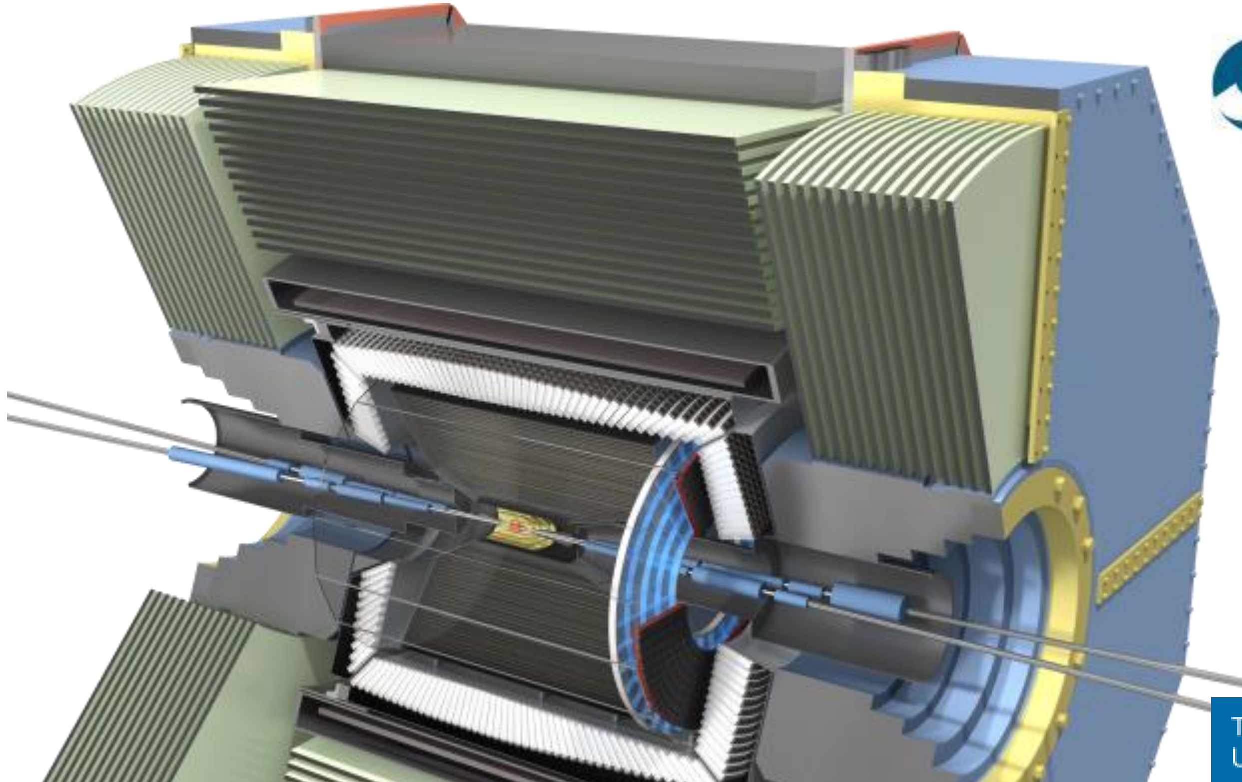

- DESY
- JOHANNES GUTENBERG UNIVERSITÄT MAINZ
- Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
- UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
- universitätbonn
- JÜLICH FORSCHUNGSZENTRUM
- KIT Karlsruher Institut für Technologie
- LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN
- MPG HLL
- Technical University of Munich TUM
- JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
- GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

- Physics analysis
- Vertex detector
- BEAST
- Tracking
- Computing

Outlook

- The B-Factory experiments have played an pivotal role in understanding the SM and are a unique tool to search for New Physics

- Belle II will further explore these opportunities with a target integrated luminosity of 50 ab^{-1}

- Detector to start **operation in early 2018** (Phase 2) and start taking **physics data beginning 2019** (Phase 3)

- Stay tuned!


ル検出器
B-ファクトリー
Thank you