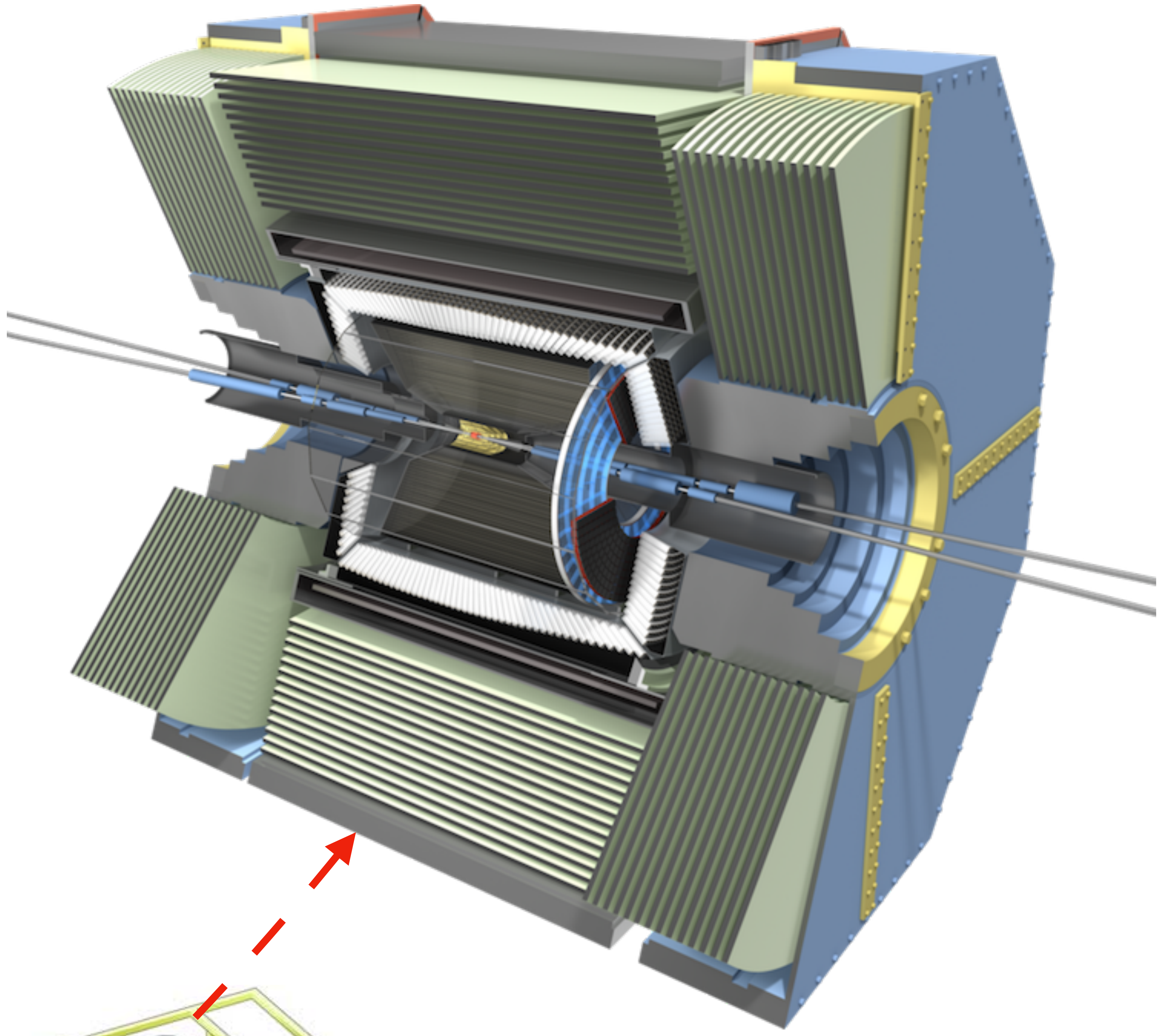
The Belle II Detector

Jake Bennett
The University of Mississippi
Belle II Summer School - July 2019

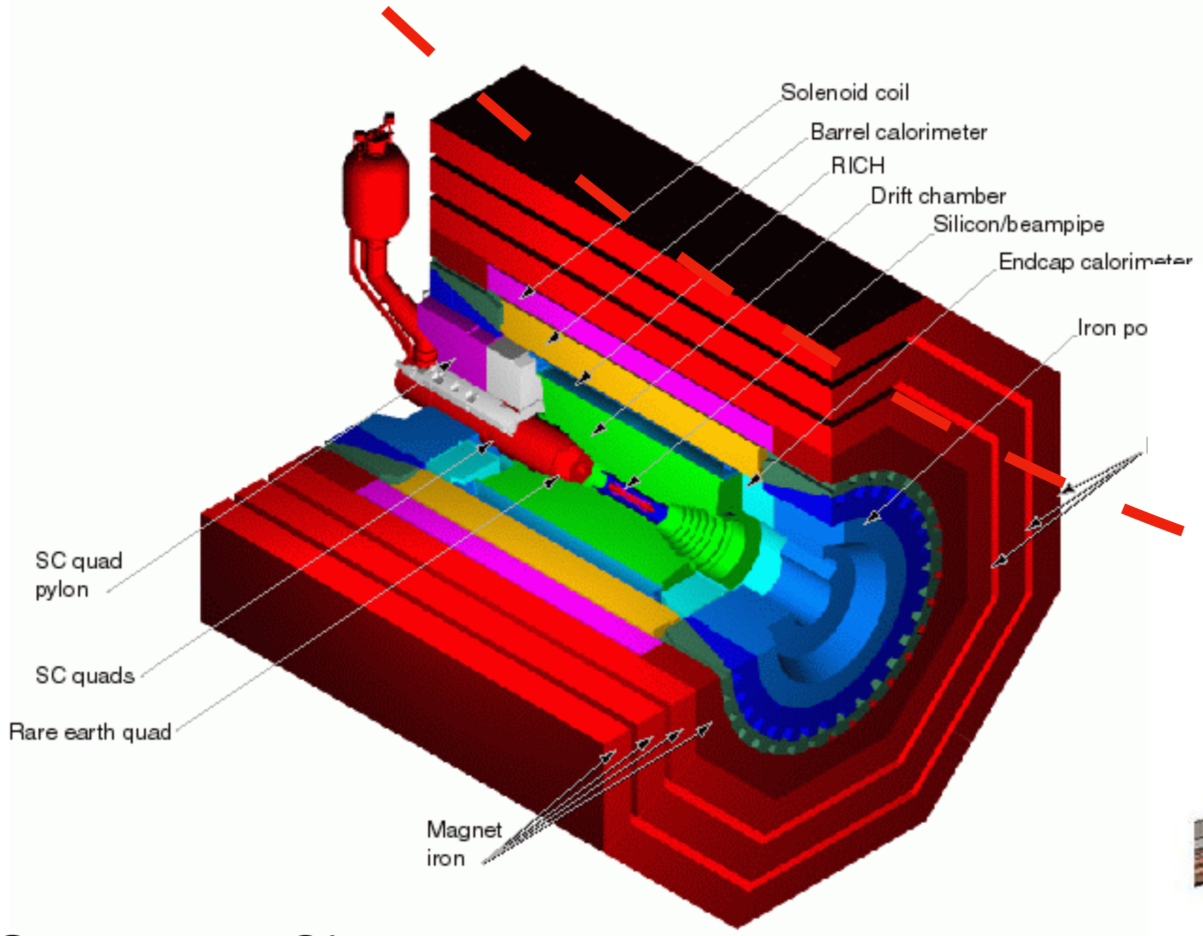
Inheriting a rich history!

ARGUS at DORIS II (DESY, Germany)
1982-1992

Belle II at SuperKEKB (Tsukuba, Japan)
First collisions: 2018

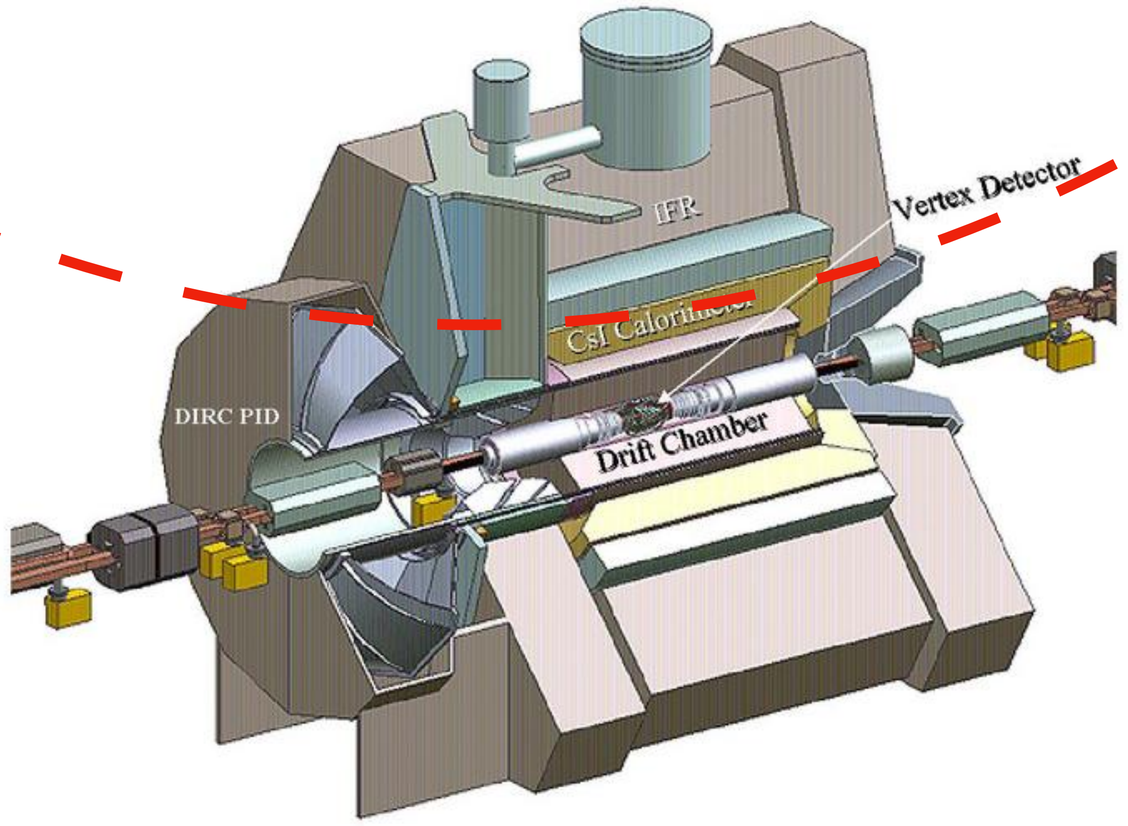


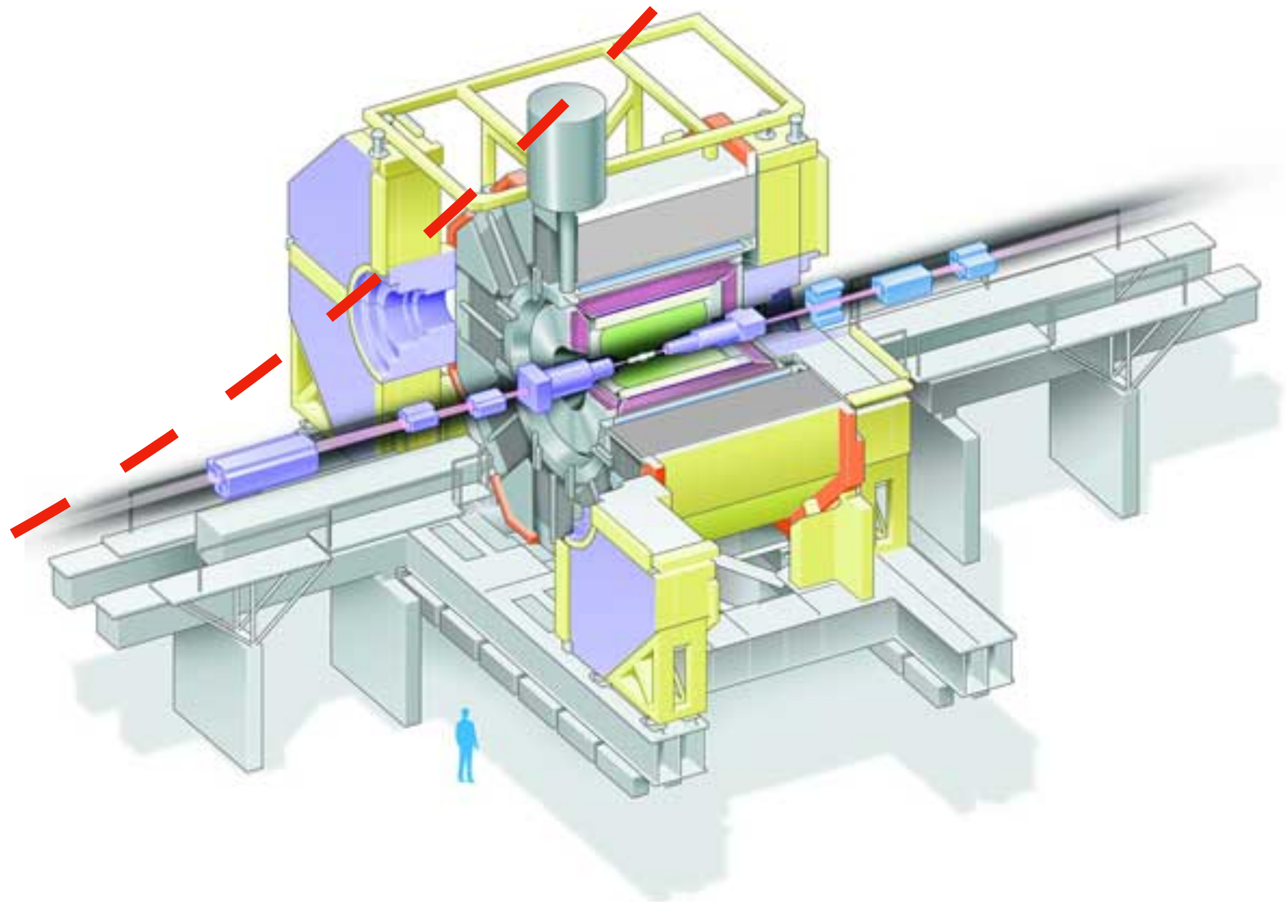
CLEO III



CLEO at CESR (Cornell, US)
1979-2008

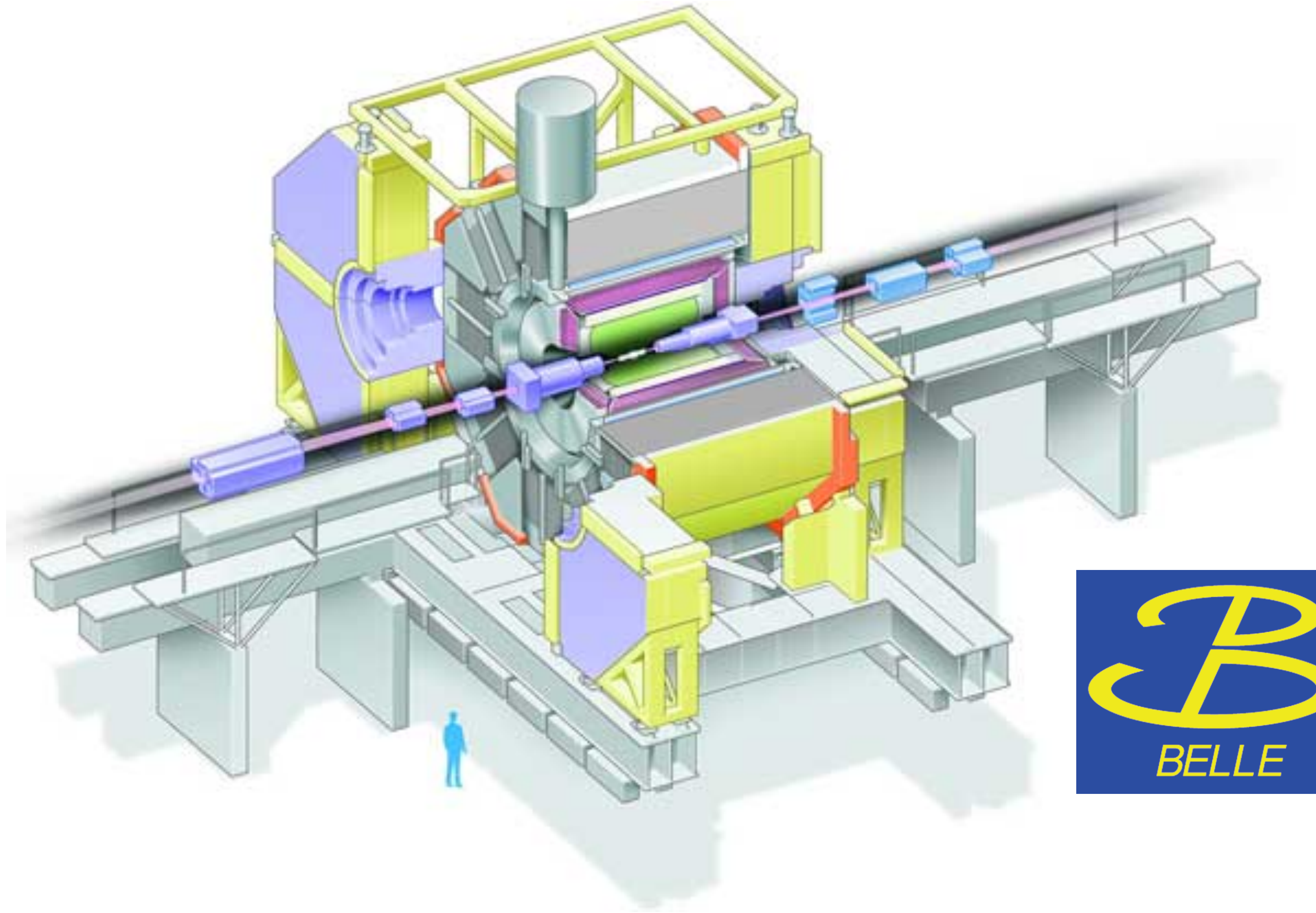
BaBar at PEPII (SLAC, US)
1999-2008

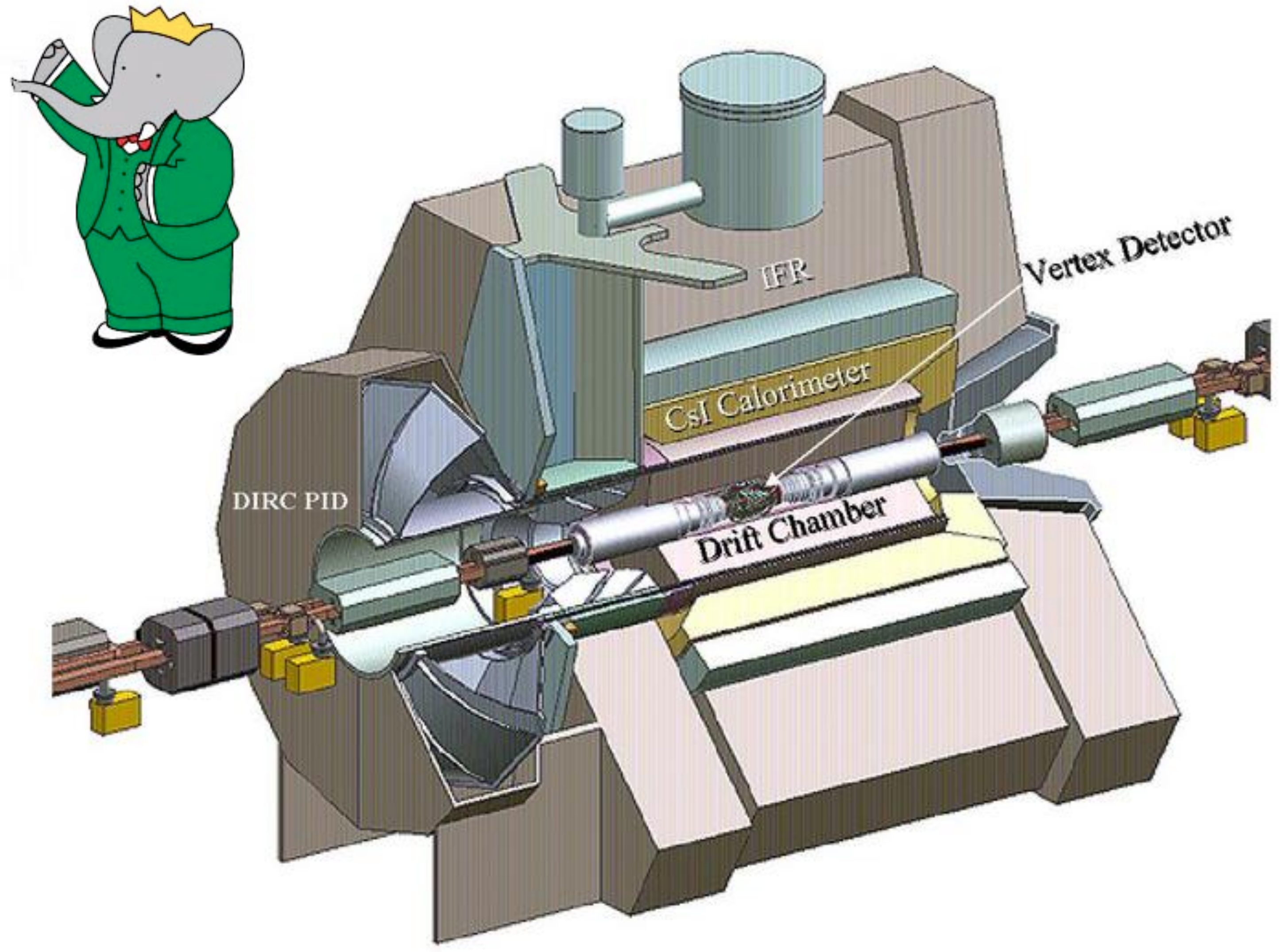




Belle at KEKB (Tsukuba, Japan)
1999-2010

B factories

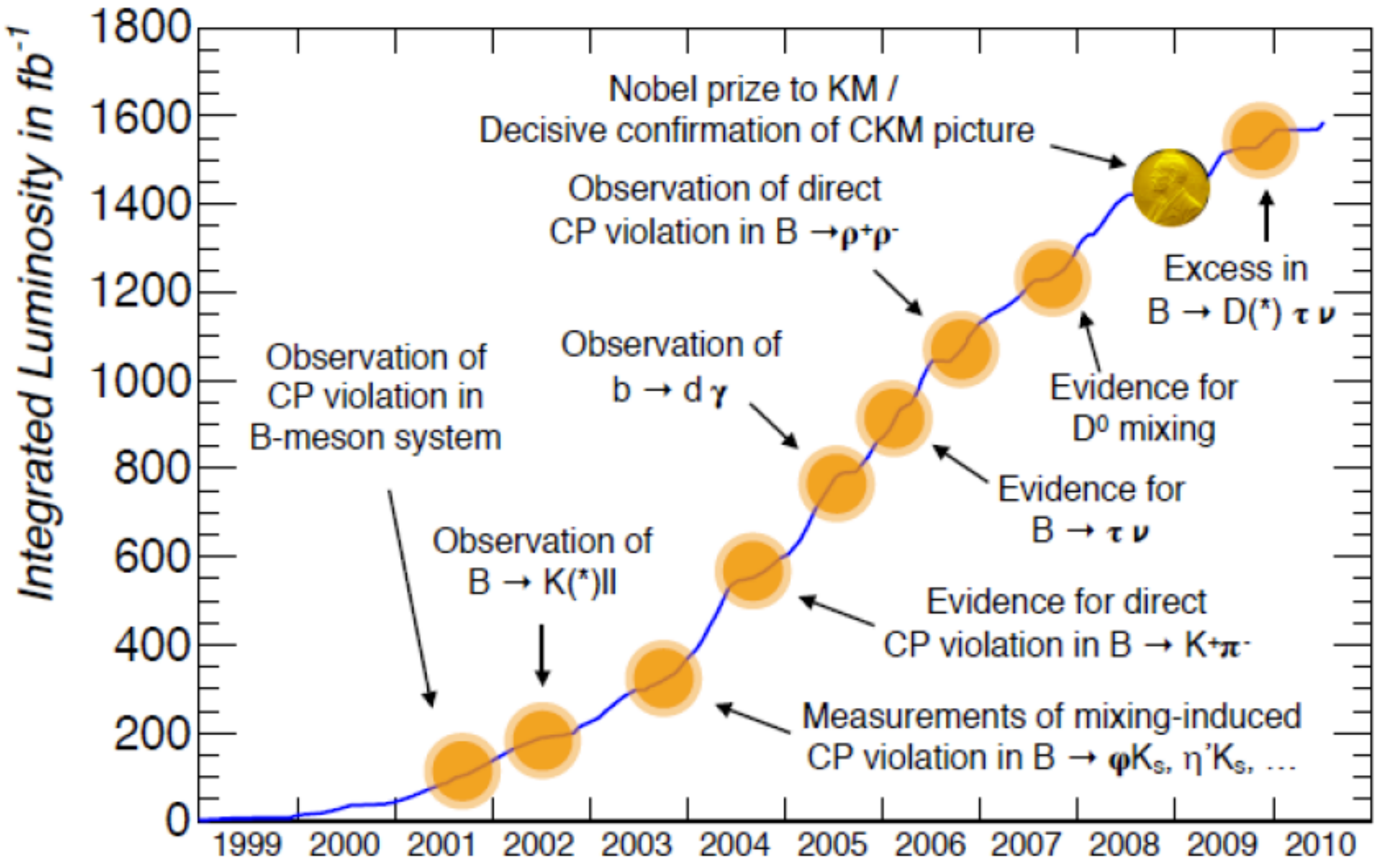




Belle/KEKB (KEK) and BaBar/PEP-II (SLAC)

Very successful physics programs with a total recorded sample over 1.5 ab^{-1} (1.25 x 10^9 $B\bar{B}$)

— Experimental confirmation of CKM mechanism as source of CPV in the SM



Even ~10 years after data taking, Belle is producing new results

~350 papers published since shutdown!

B factories

- Asymmetric beam energies, high luminosity→ high statistics samples of boosted B, D and τ

- Flavor physics
  - CKM matrix, unitarity triangle
  - CPV in B system

- BSM limits
  - Rare B/D decays
  - b→sɣ, b→sl+l-
  - LFV in τ decays

- New particles
  - “Exotic” hadrons (non-qq̄/qqq)

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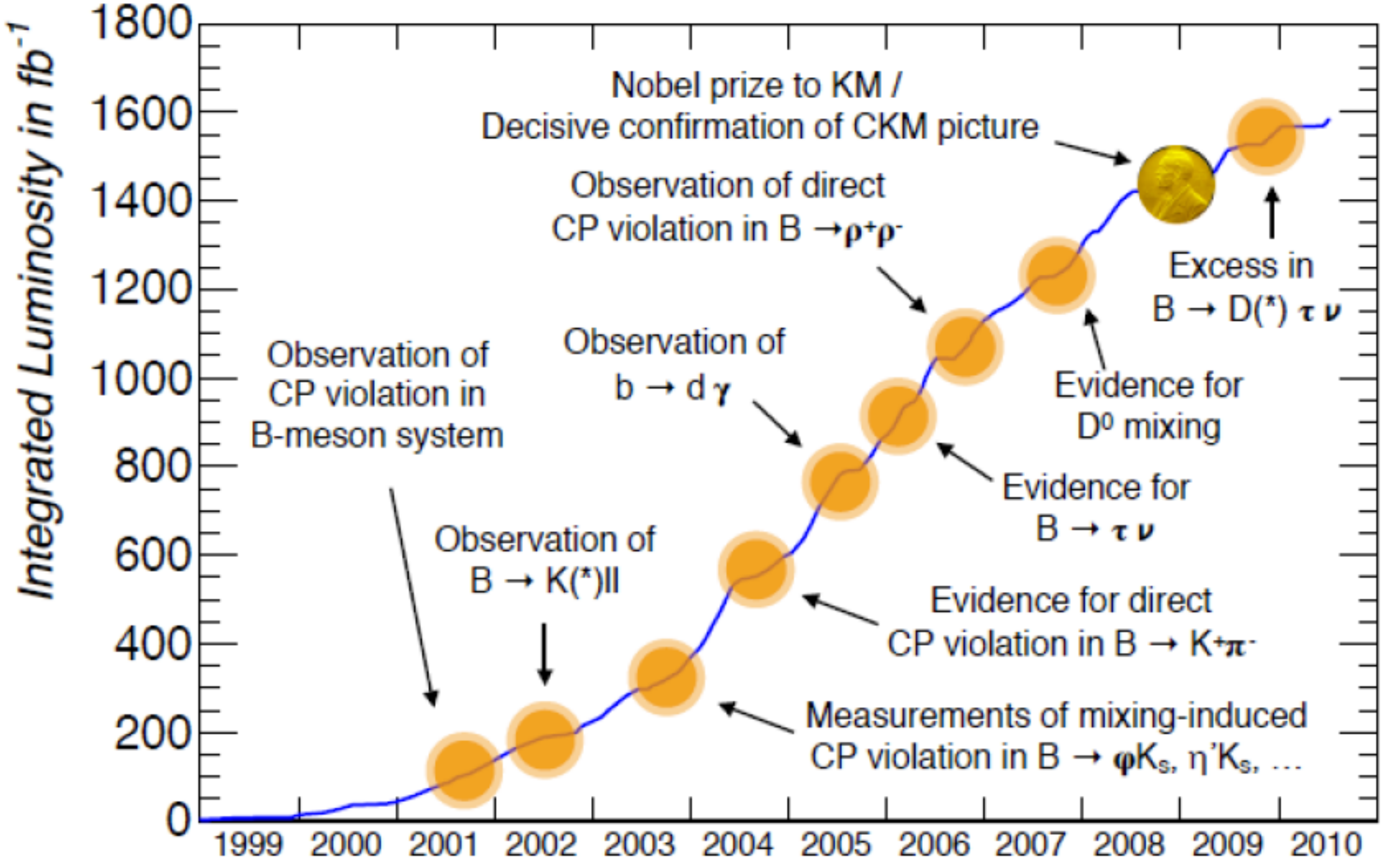

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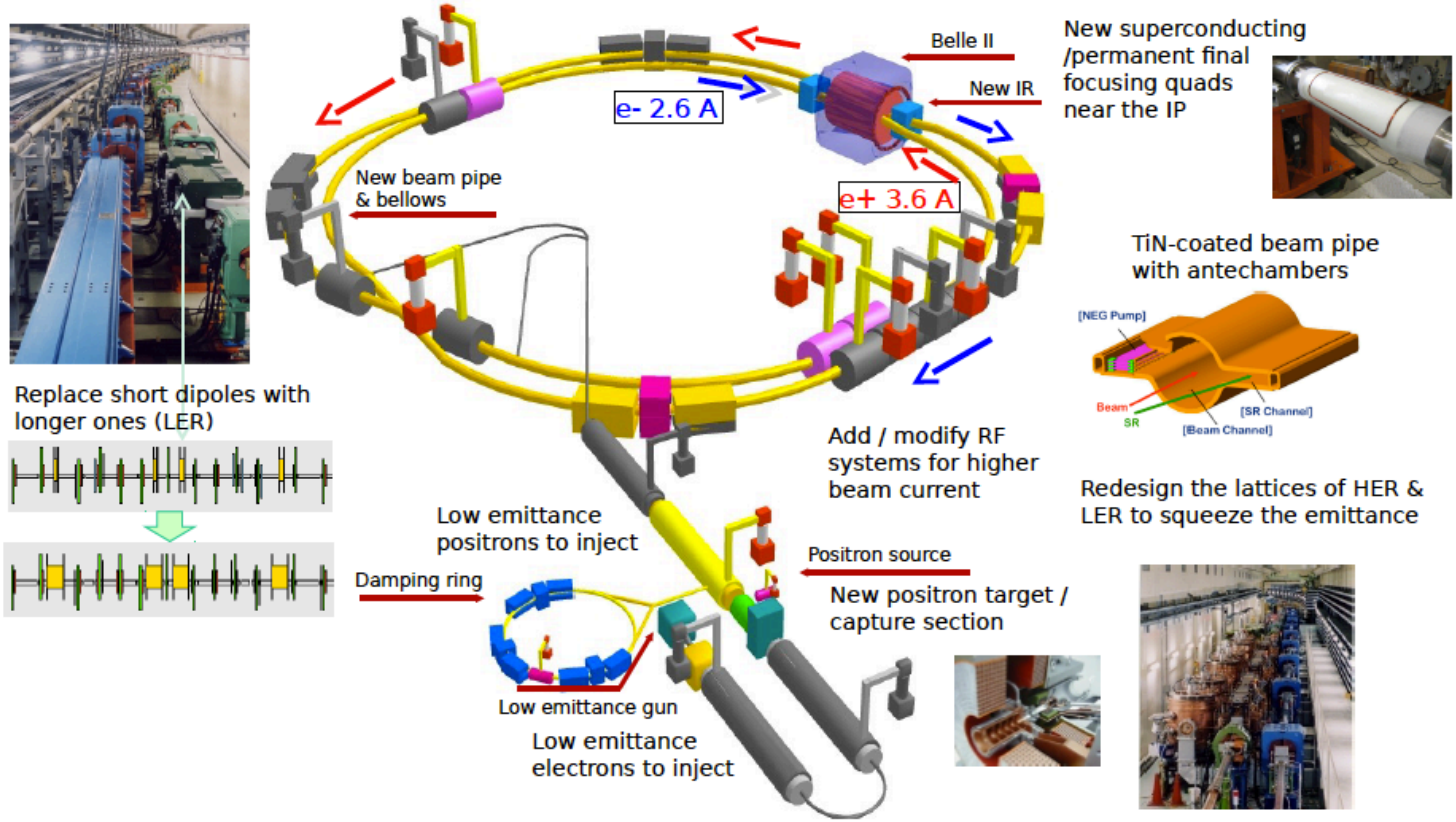
SuperKEKB: the next generation Super B-factory



*gray - recycled, color - new

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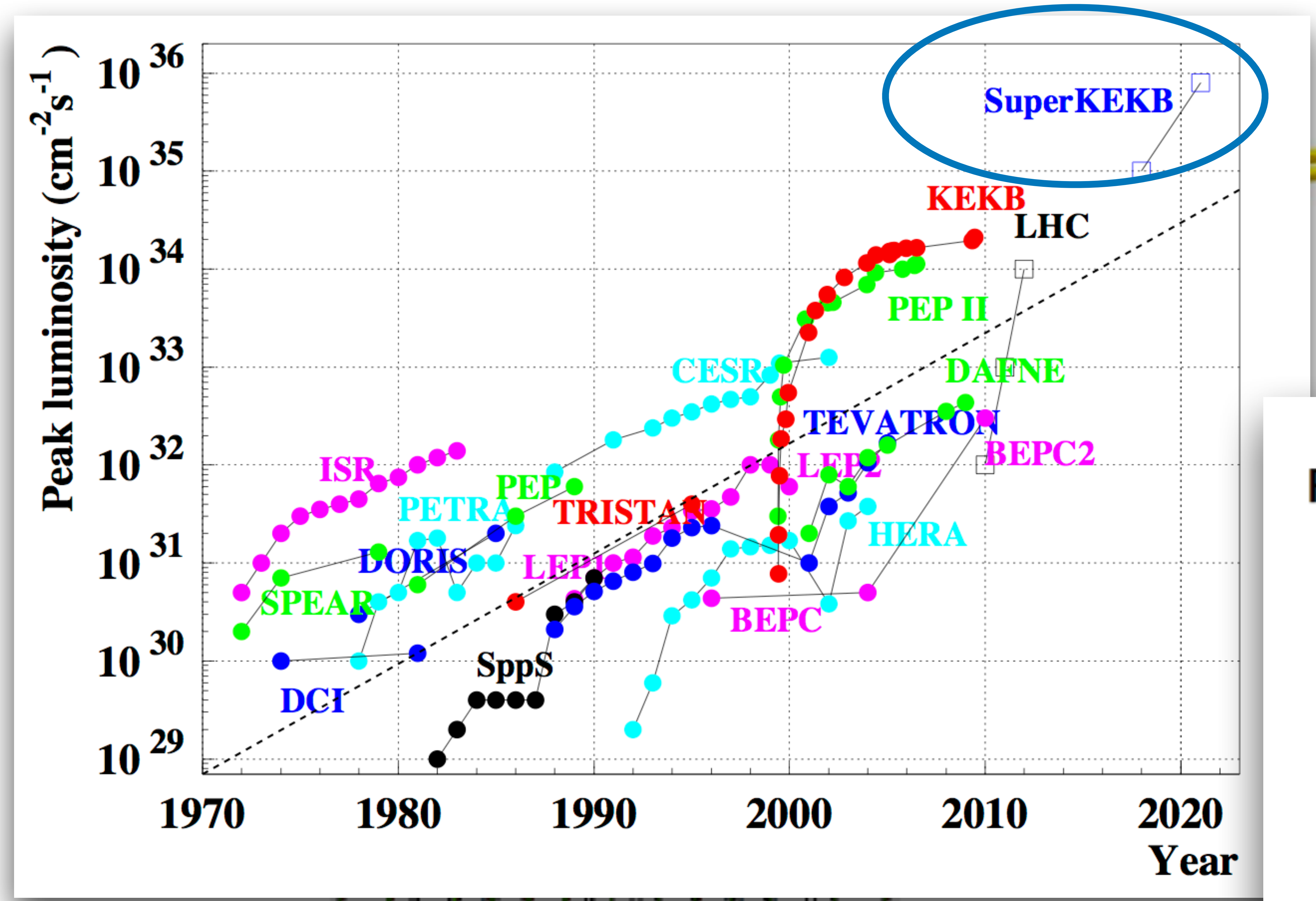

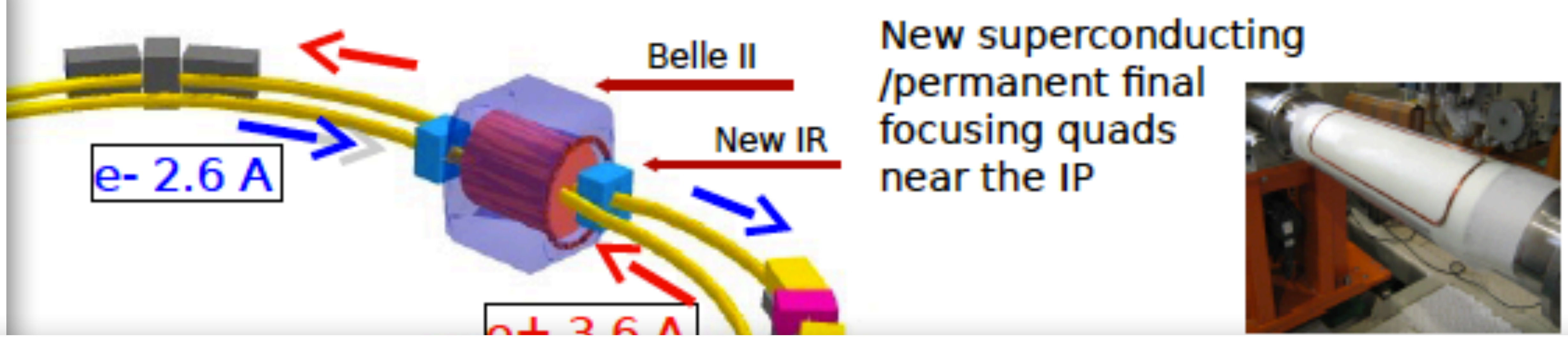

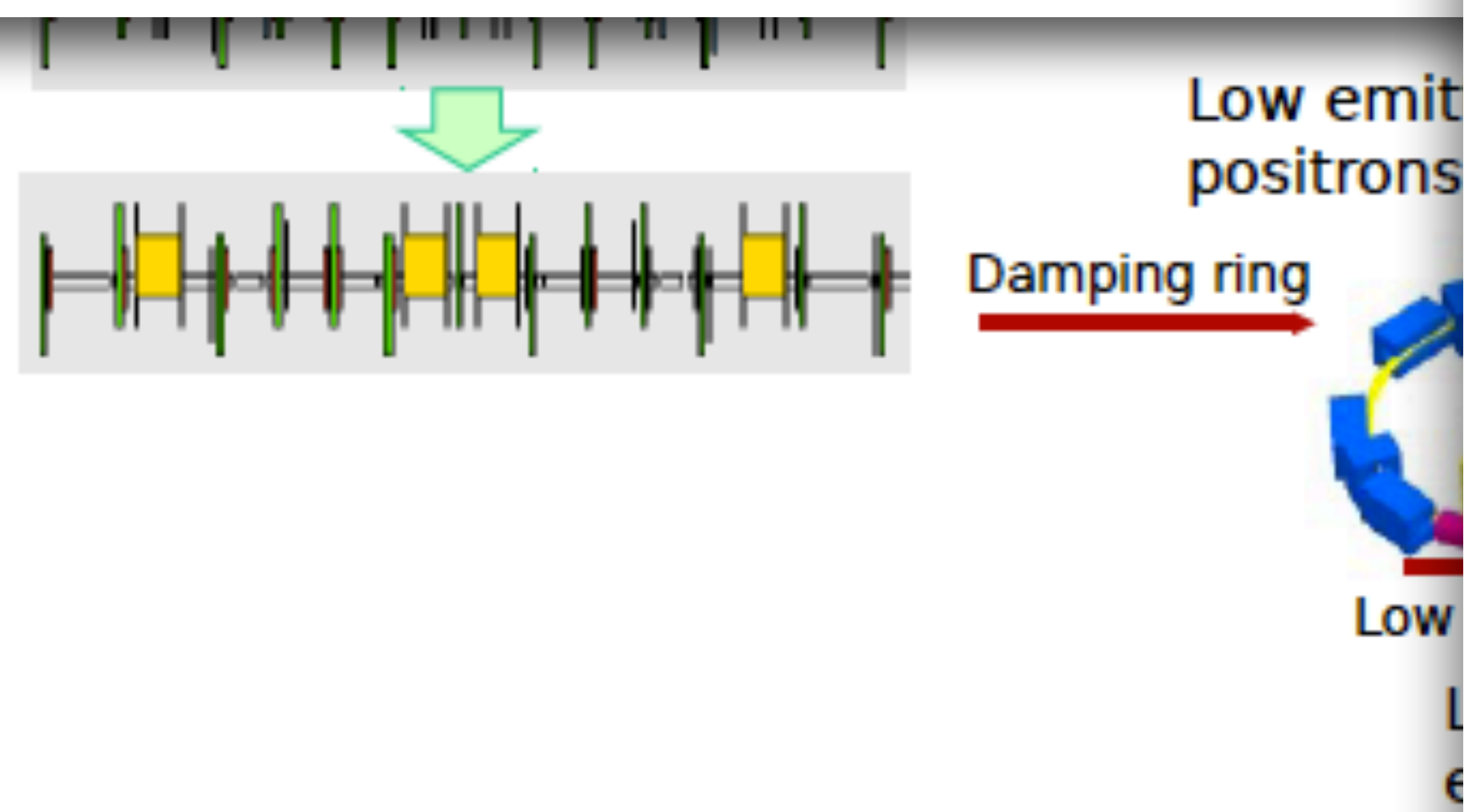

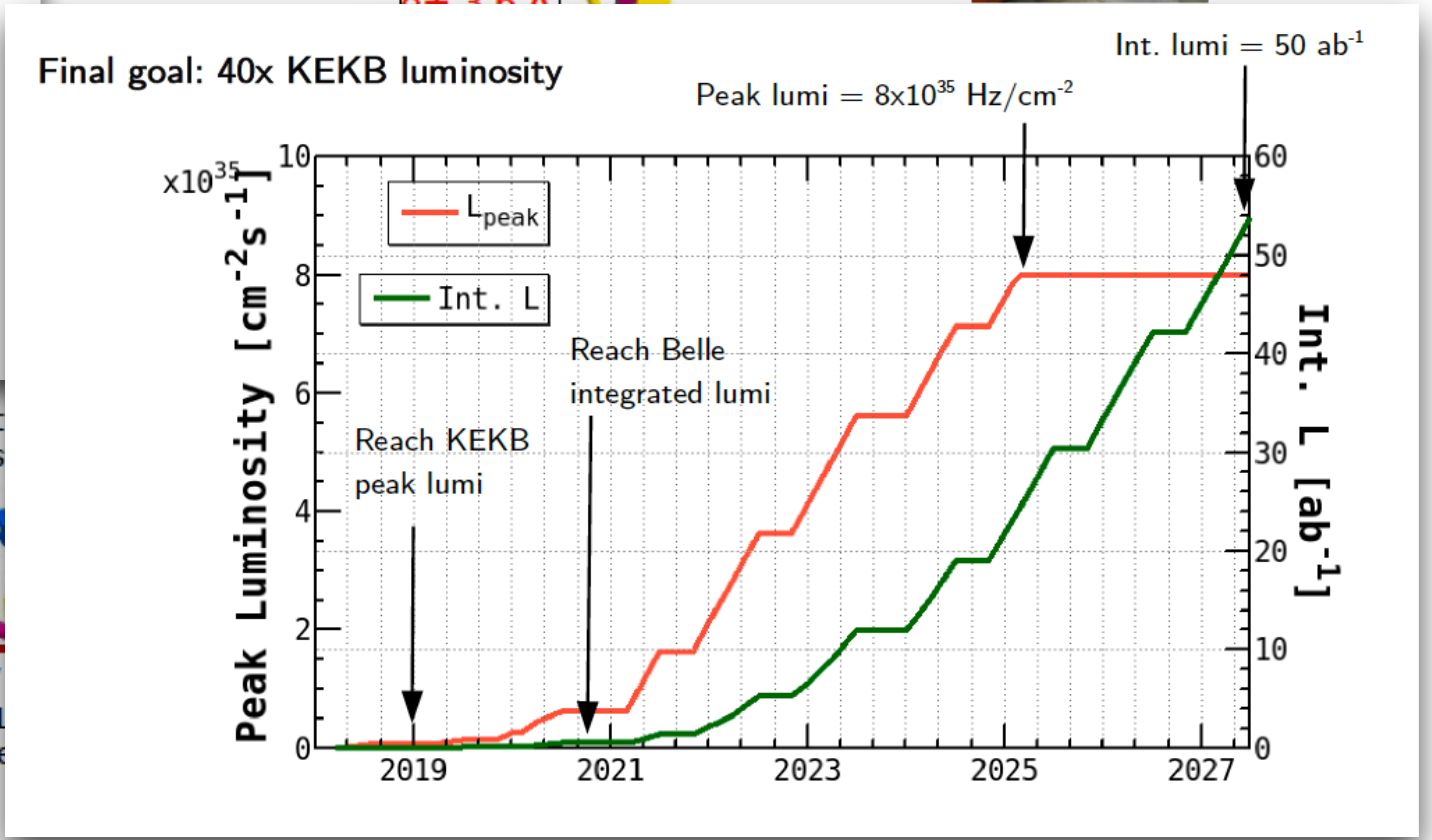

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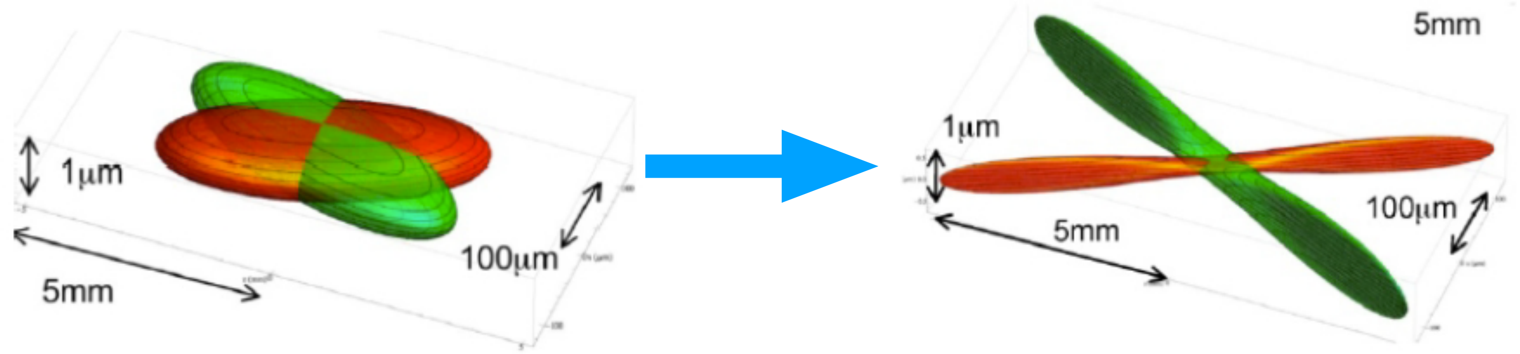
SuperKEKB nanobeams

To get 40x luminosity of KEKB



Reduce beam size to a few 100 atomic layers!

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

Lorentz factor

Beam current

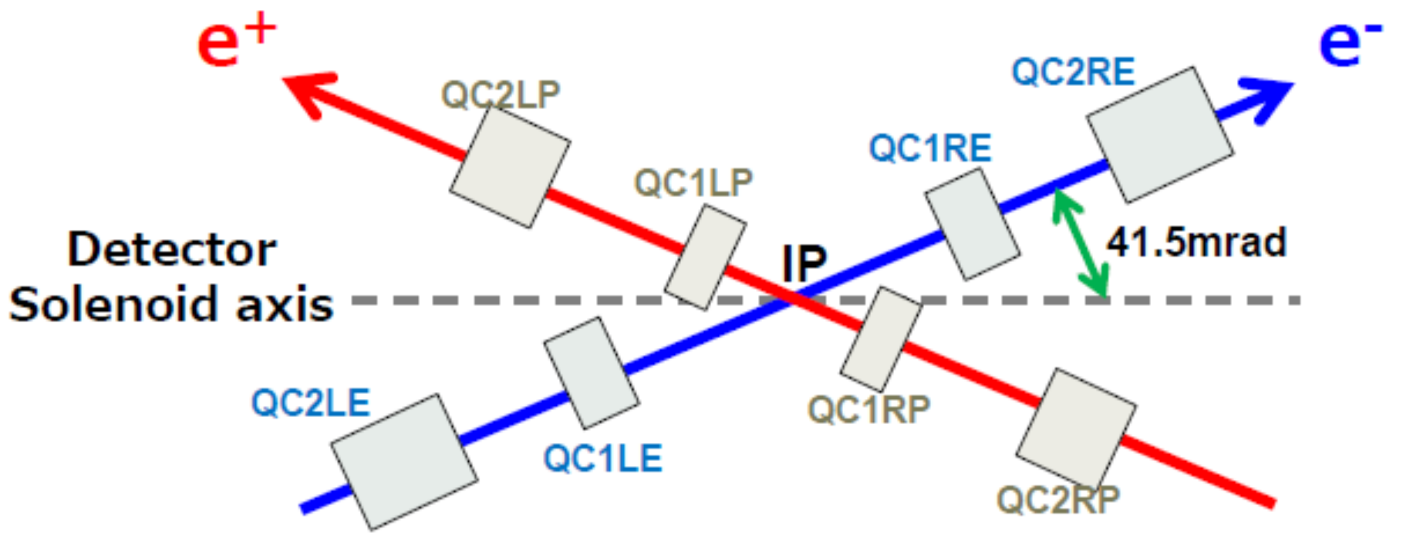
Beam-Beam parameter

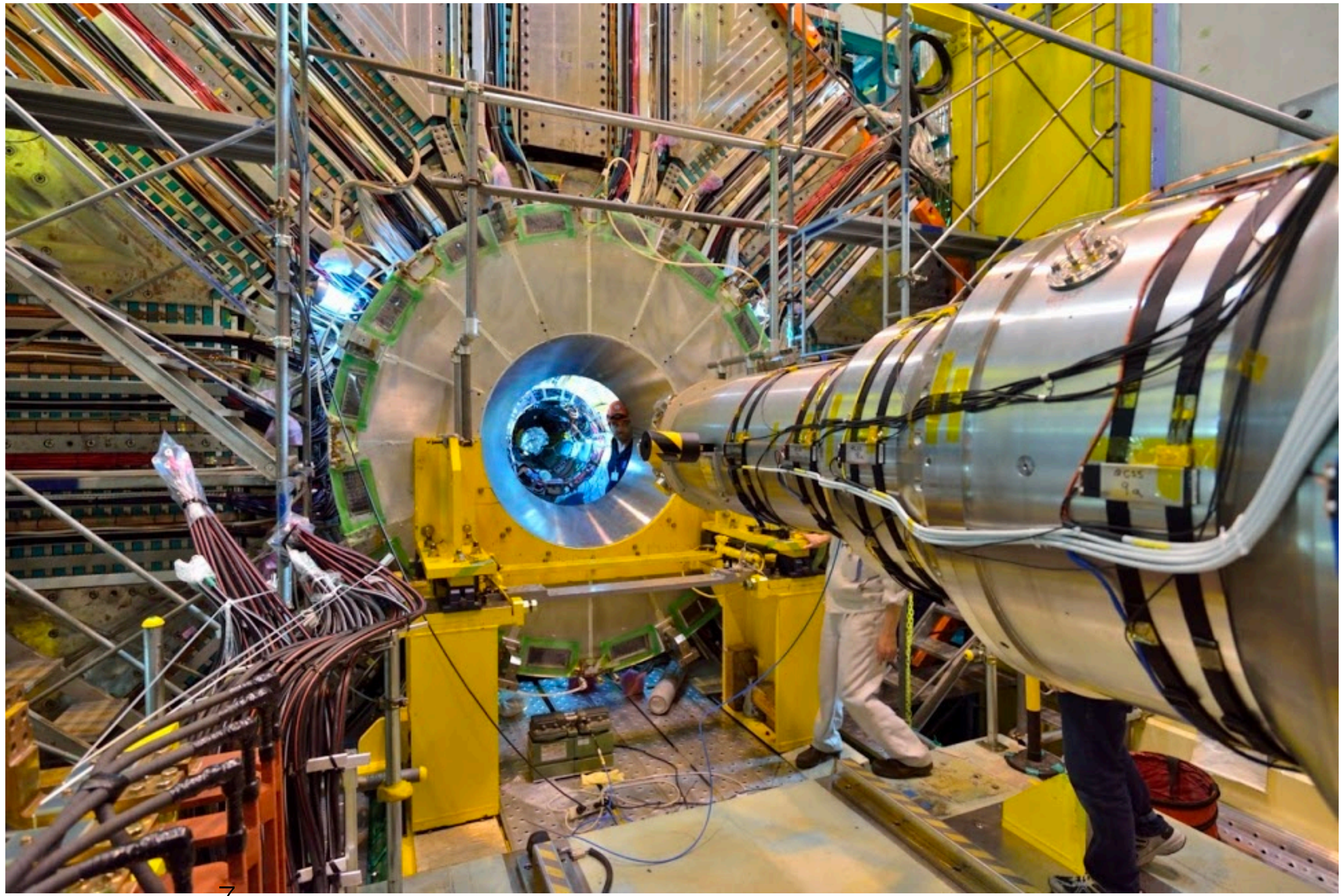
Geometrical reduction factors (crossing angle, hourglass effect)

Beam aspect ratio at IP

Vertical beta function at IP

- 8 superconducting magnets
- Final focusing magnets for each beam





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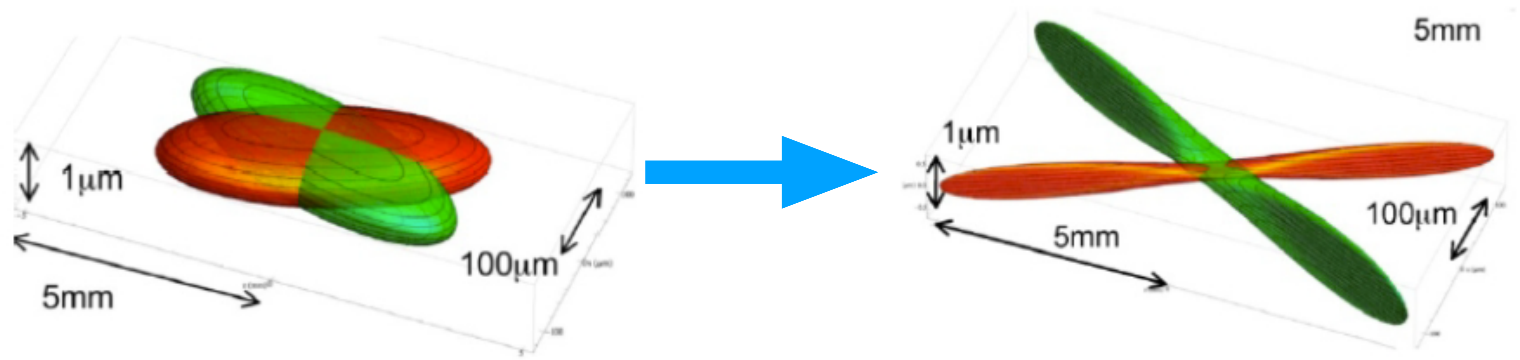

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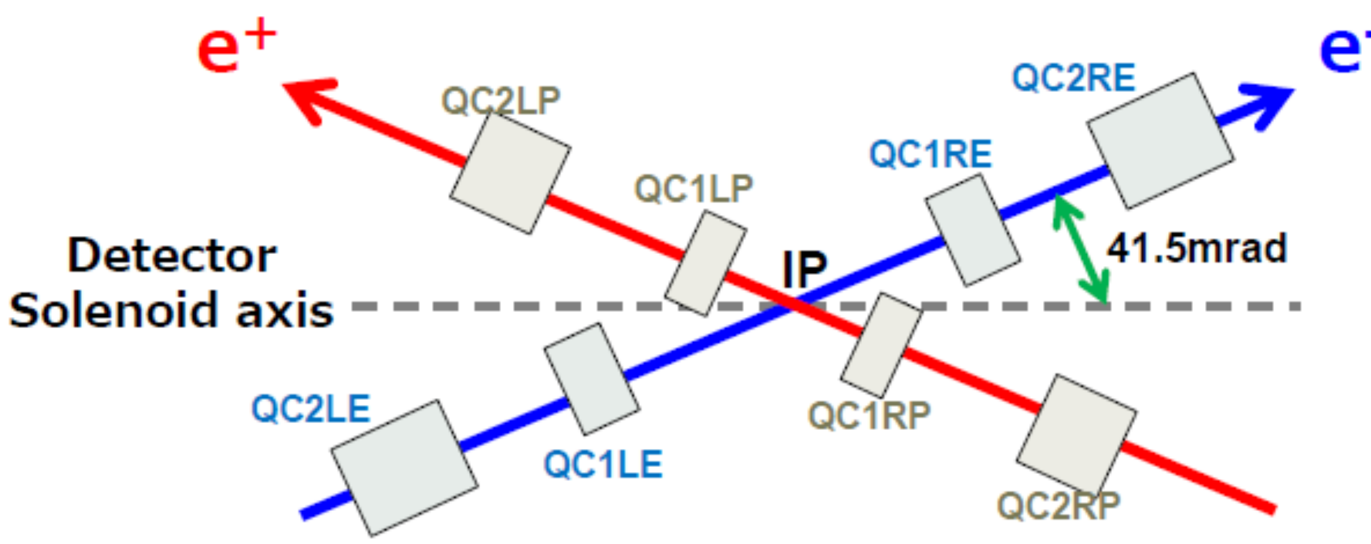

Parameter		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
beam energy	E_b	3.5	8	4	7	GeV
CM boost	$\beta\gamma$	0.425		0.28		
half crossing angle	ϕ	11		41.5		mrad
horizontal emittance	ε_x	18	24	3.2	4.6	nm
beta-function at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam parameter	ξ_y	0.129	0.090	0.0881	0.0807	nm
beam size at IP	σ_x^*/σ_y^*	100/2		10/0.059		μm
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

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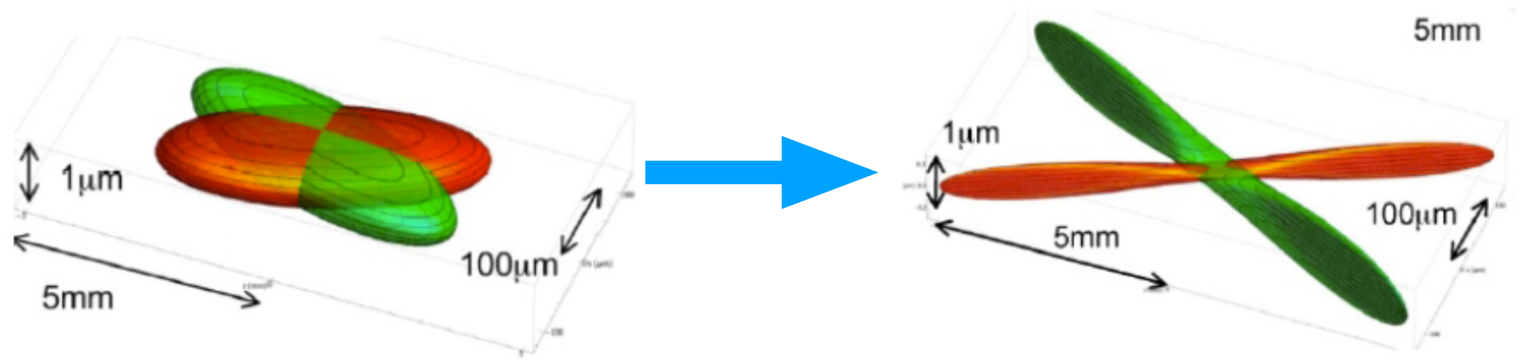

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- Lorentz factor ($\gamma_\pm$)
- Beam current ($I_\pm$)
- Beam-Beam parameter ($\xi_{y\pm}$)
- Geometrical reduction factors (crossing angle, hourglass effect) (R_L / R_{ξ_y})
- Beam aspect ratio at IP (σ_y^* / σ_x^*)
- Vertical beta function at IP ($\beta^*_{y\pm}$)

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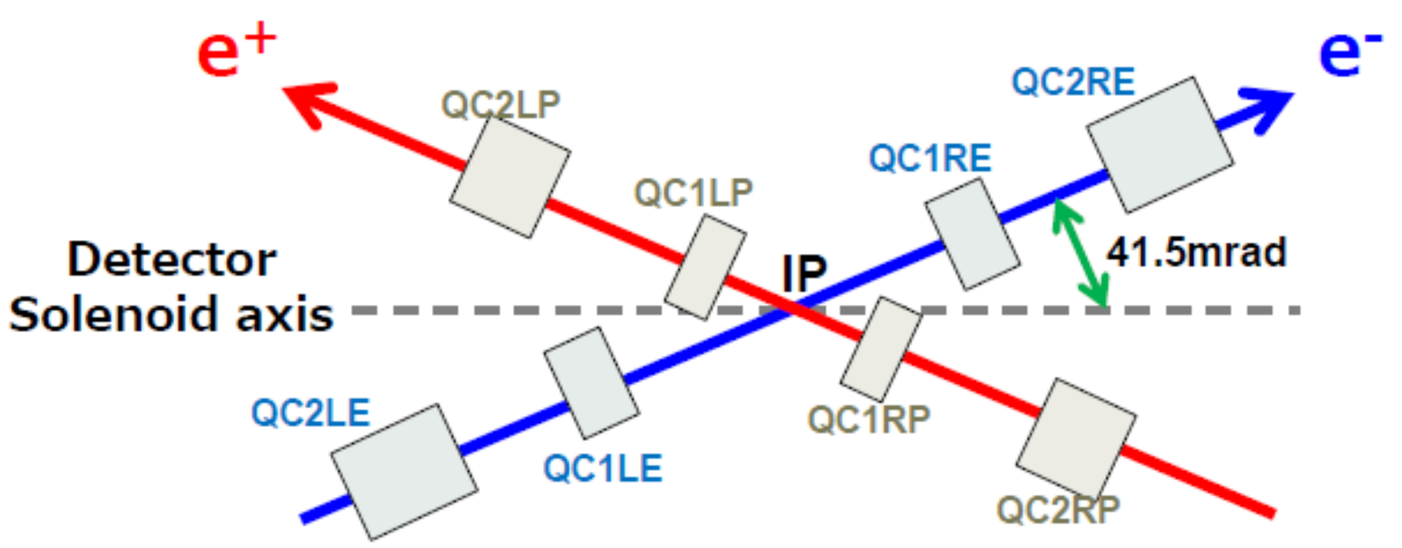
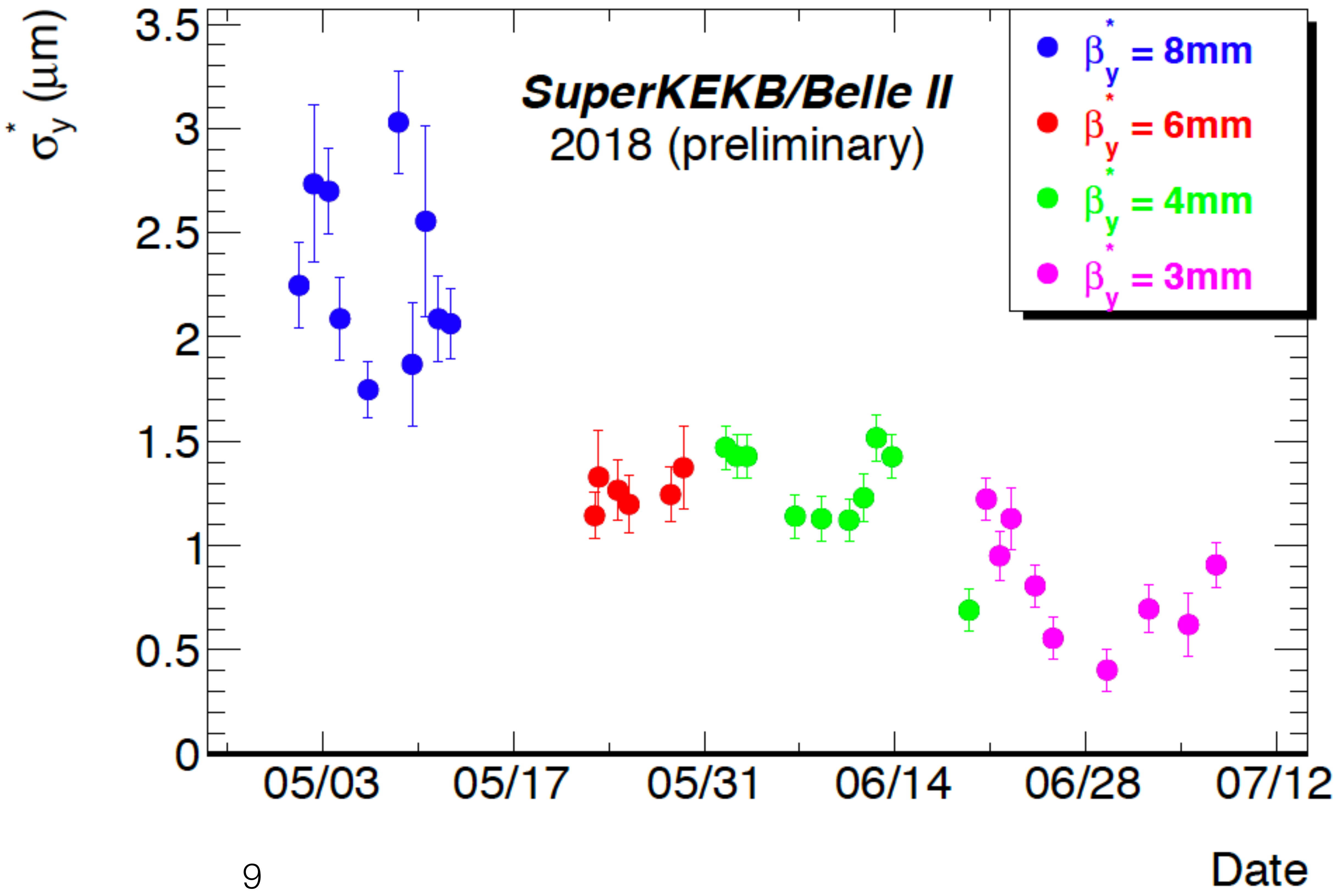
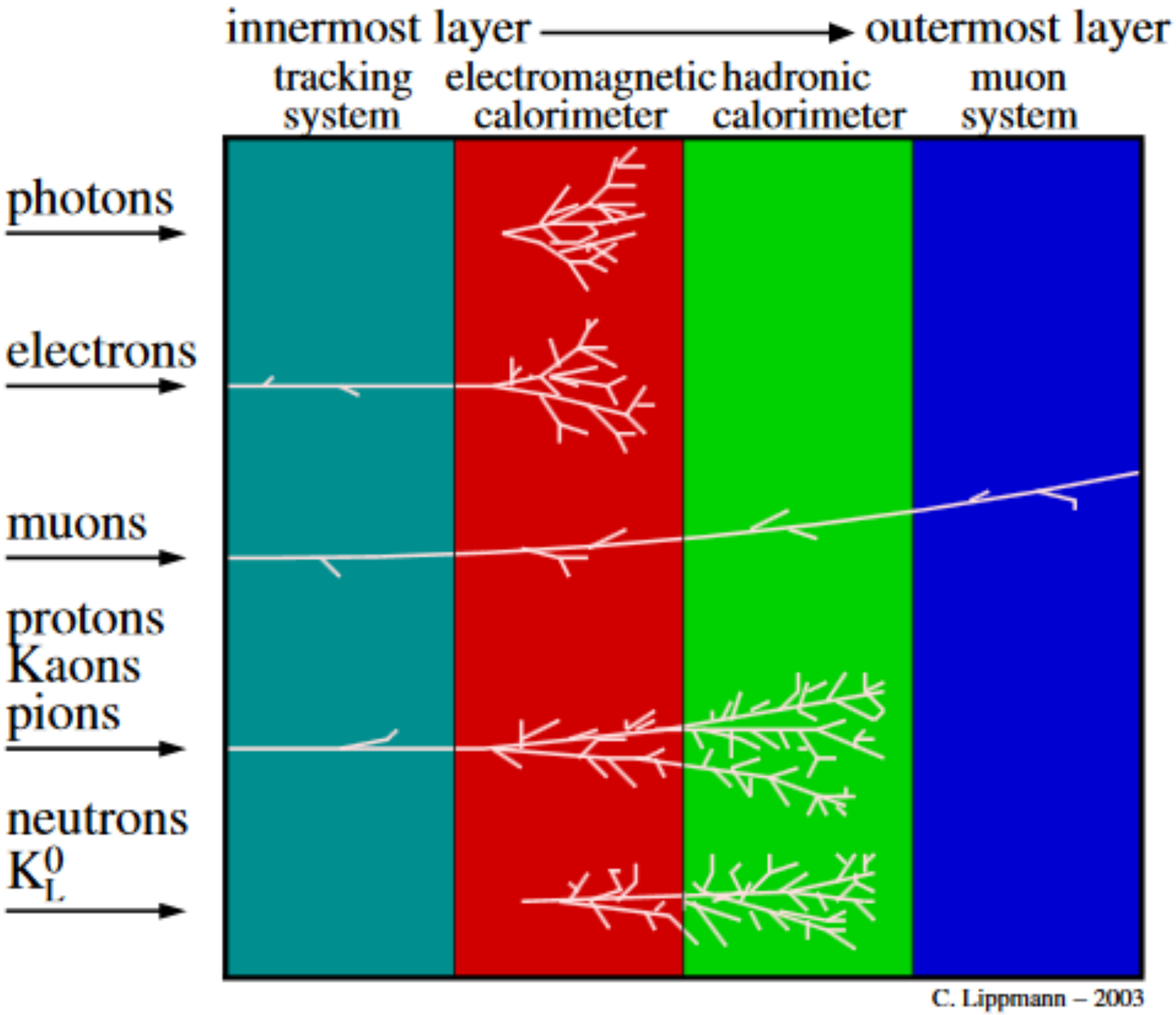




Reconstructing long-lived particles

- Particles produced in the e^+e^- collision are often very short lived
  - Strong decays $\sim 10^{-23}$
  - EM decays $\sim 10^{-16}$
  - Weak decays $\sim 10^{-10}$
- Detector is built to reconstruct "final state particles" from the (cascade of) decays

- Which particles are stable?
  - Really stable particles:



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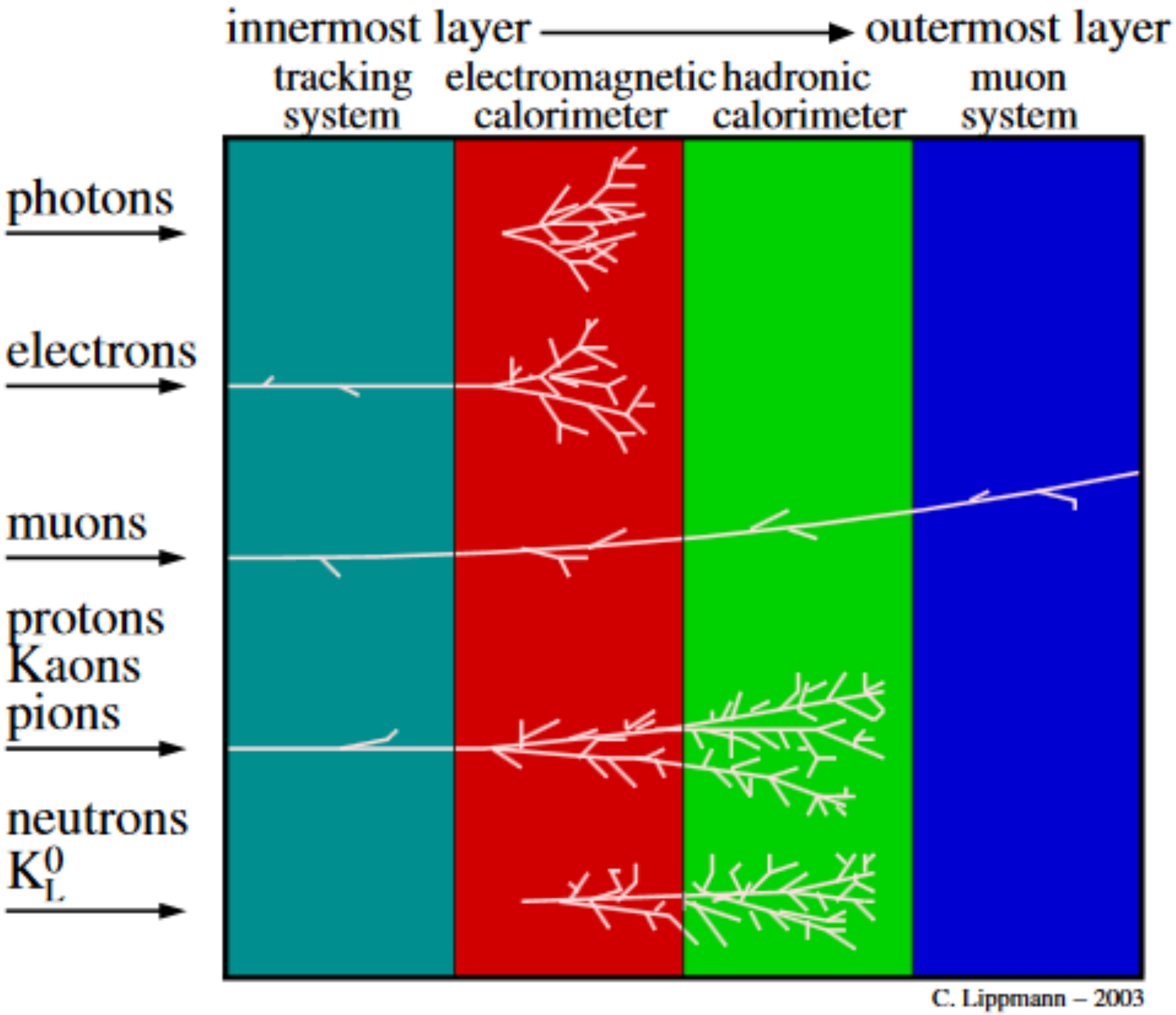
  - Really stable particles: e, p, γ, Fe, d…
  - Almost stable particles:



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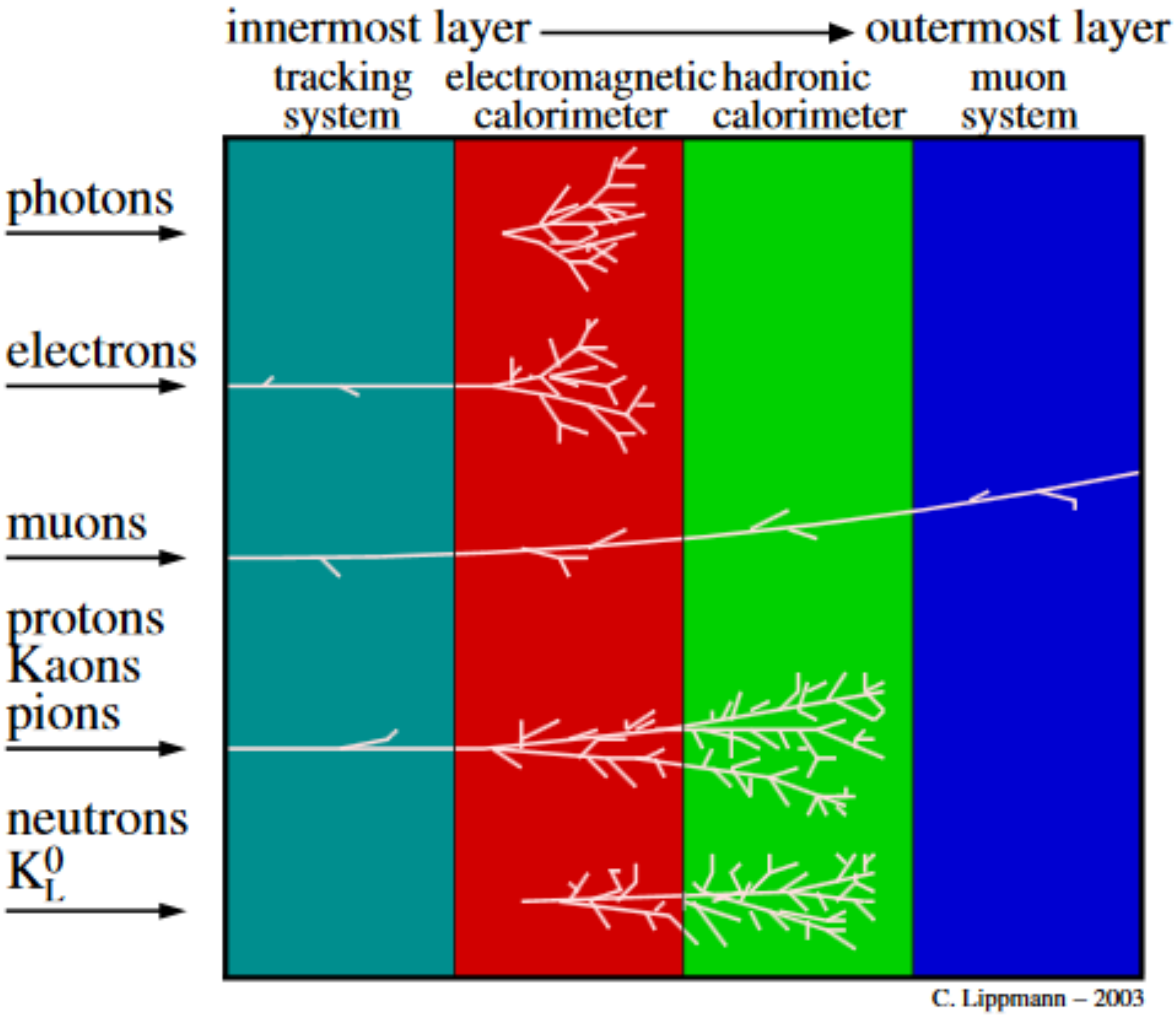
  - Unstable particles:



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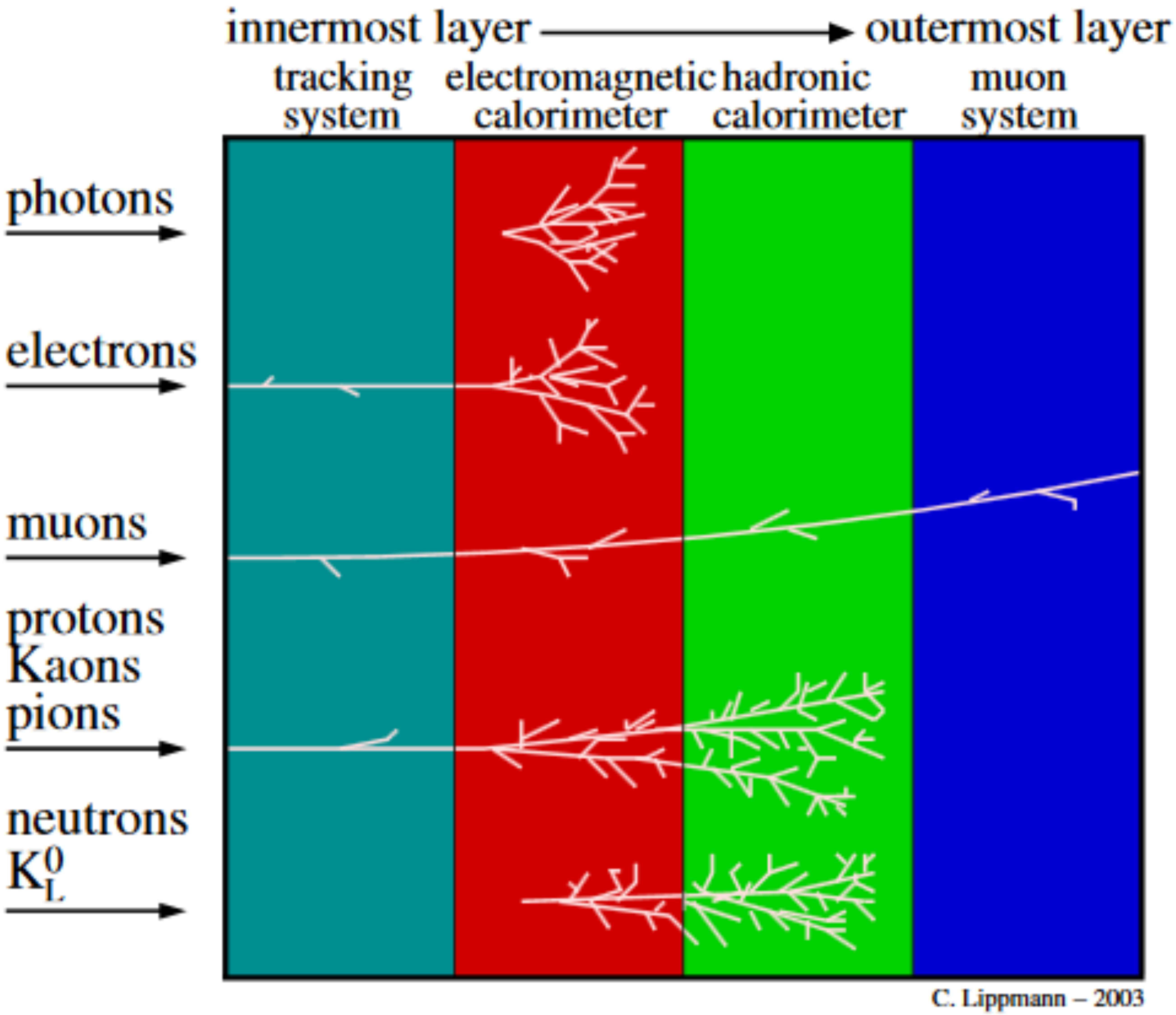
  - Unstable particles: ρ, K*, η, J/ψ, τ D, B, t, Z, W…



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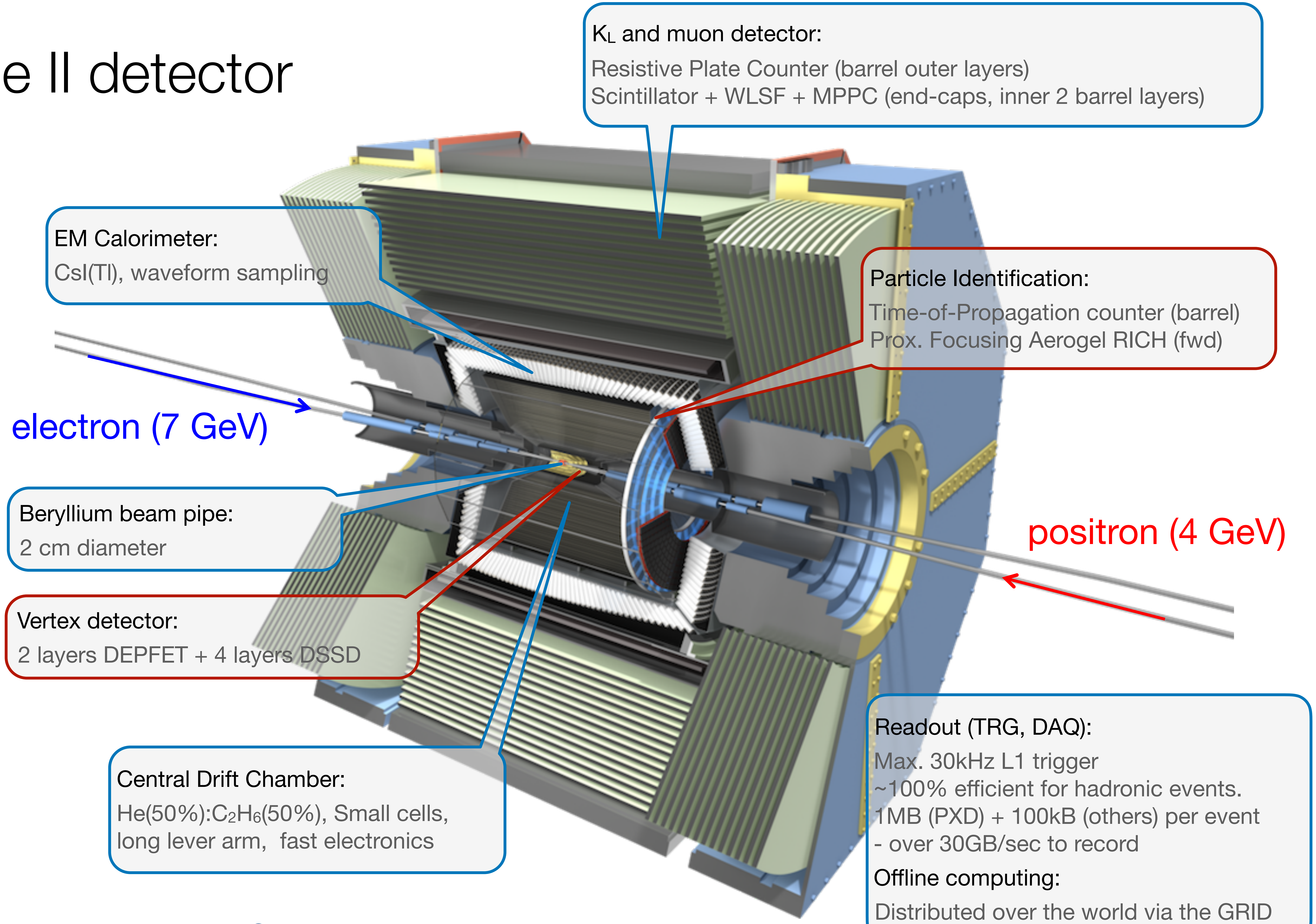
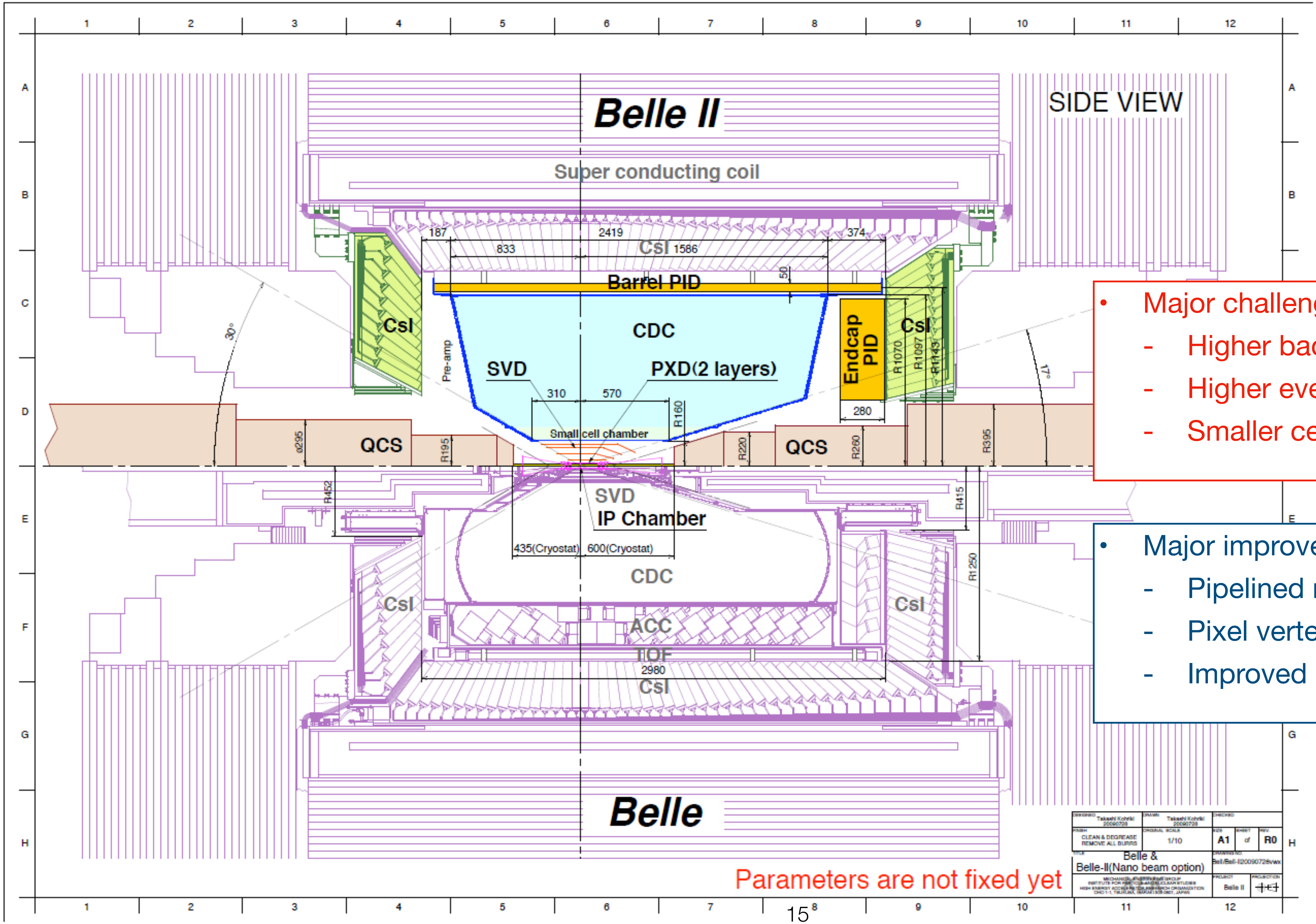


First new particle collider since the LHC
(intensity rather than energy frontier; e^+e^- rather than pp)

arXiv:1011.0352 [physics.ins-det]



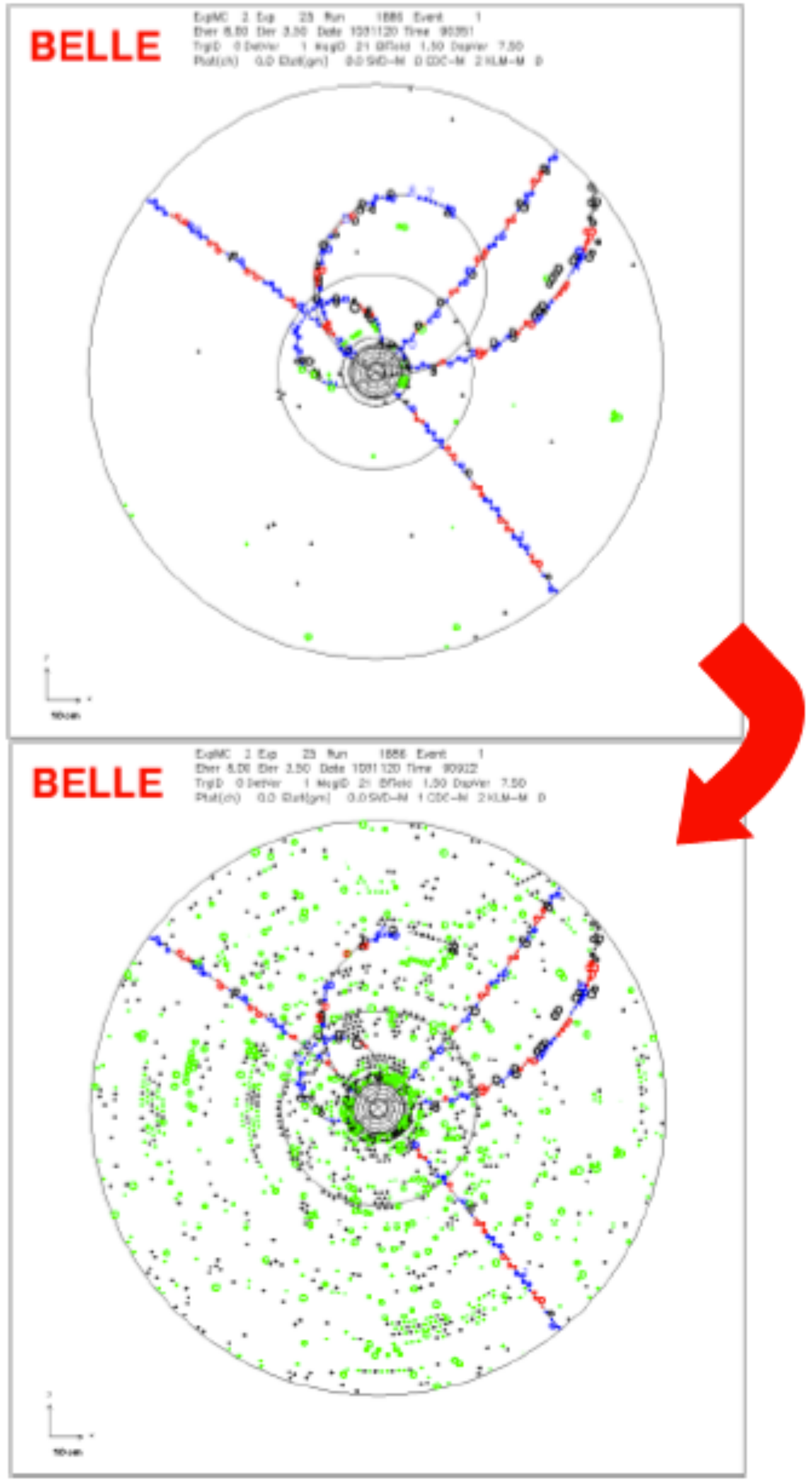
- Major challenges:
  - Higher background (x10-20)
  - Higher event rate (x10-100)
  - Smaller center of mass boost

- Major improvements:
  - Pipelined readout
  - Pixel vertex detector/extend SVD
  - Improved Particle ID

*Jeff Schueler: Wednesday

Beam backgrounds

- In Belle/KEKB, unexpected backgrounds damaged the inner detectors
- Especially dangerous at SuperKEKB (10-20x higher background rate)
  - Temporary damage or faults in electronics
  - Obscure physics processes
  - Fake interesting physics signals
  - Rejecting fake signals also lowers efficiency
- Purpose of BEAST: **B**eam **E**xorcism for **A** **St**able Belle II Experiment



Phase 1 (no collisions)

Touschek scattering:
- intra-bunch scattering process
- dominant with highly compressed beams
- 20 times higher

Beam-gas scattering:
- Bremsstrahlung (negligible) & Coulomb interactions (up to 100 times higher) with residual gas atoms & molecules

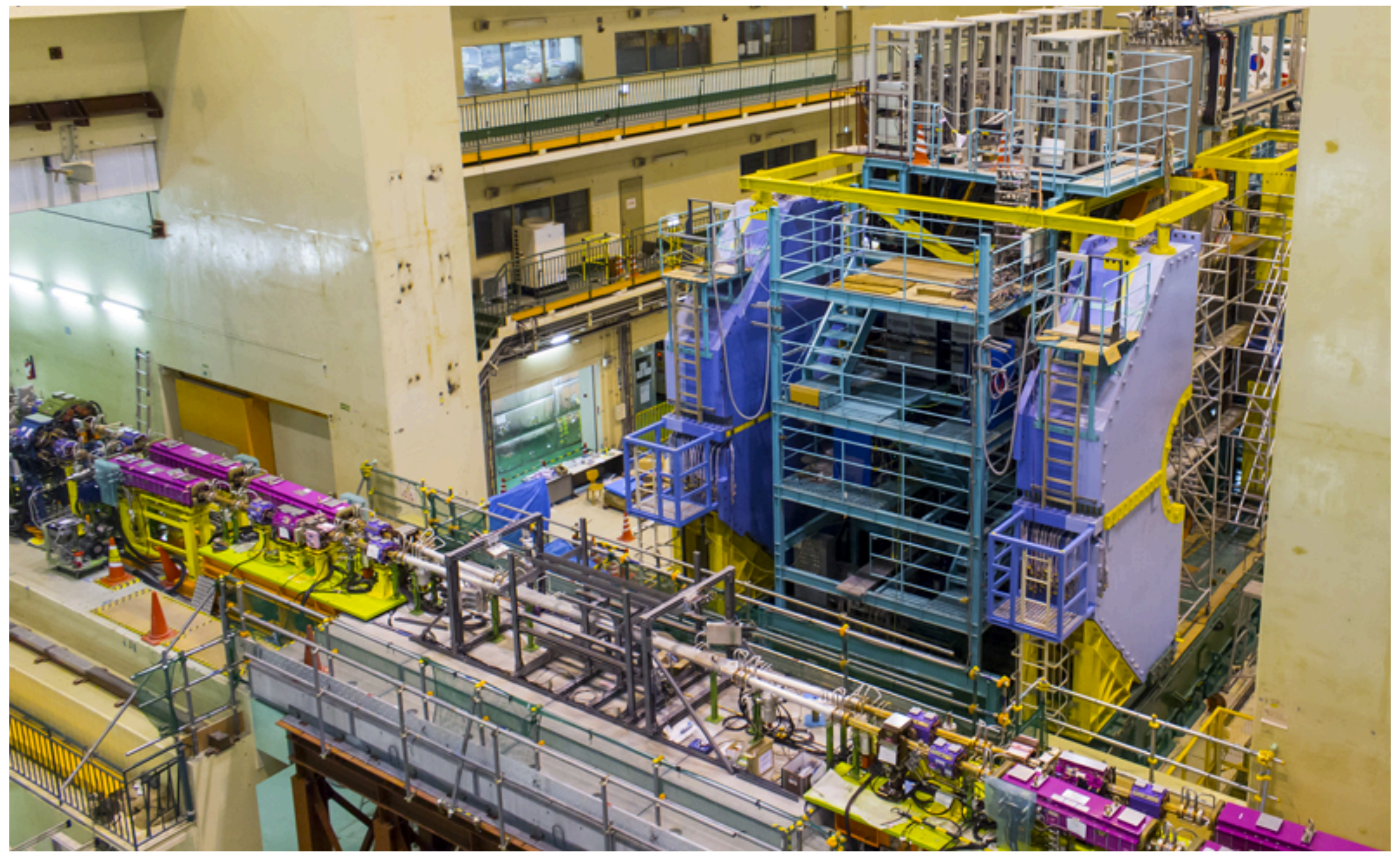
Synchrotron radiation:
- emission of photons by charged particles (e^+e^-) when deflected in *B*-field

Phase 2 (collisions)

***Radiative Bhabha* process:**
- photon emission prior or after *Bhabha* scattering
- interaction with iron in the magnets leads to neutron background

***Two photon* process:**
- very low momentum e^+e^- pairs via $e^+e^- \to e^+e^-e^+e^-$
- increased hit occupancy in inner detectors

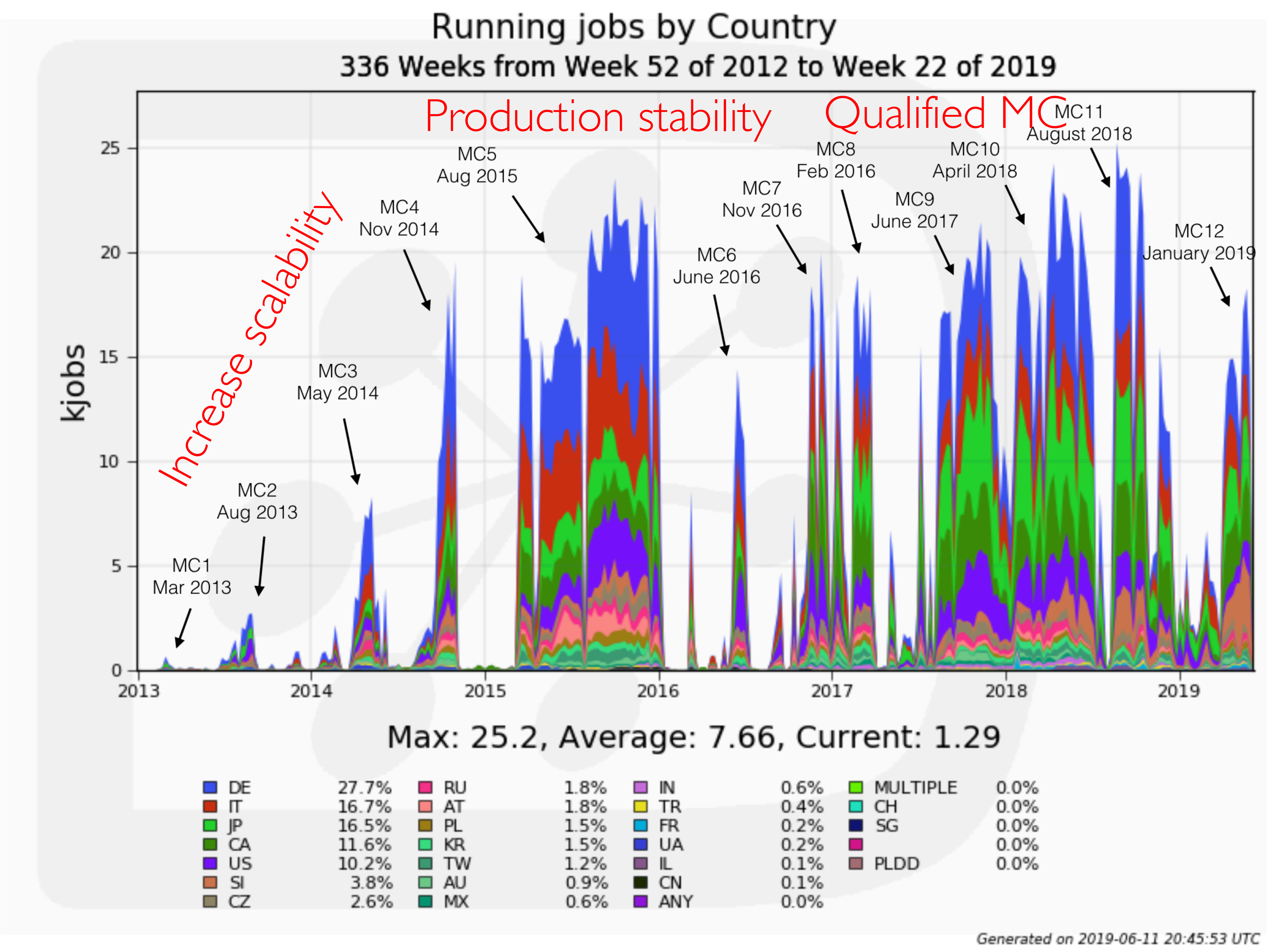
Injection Background:

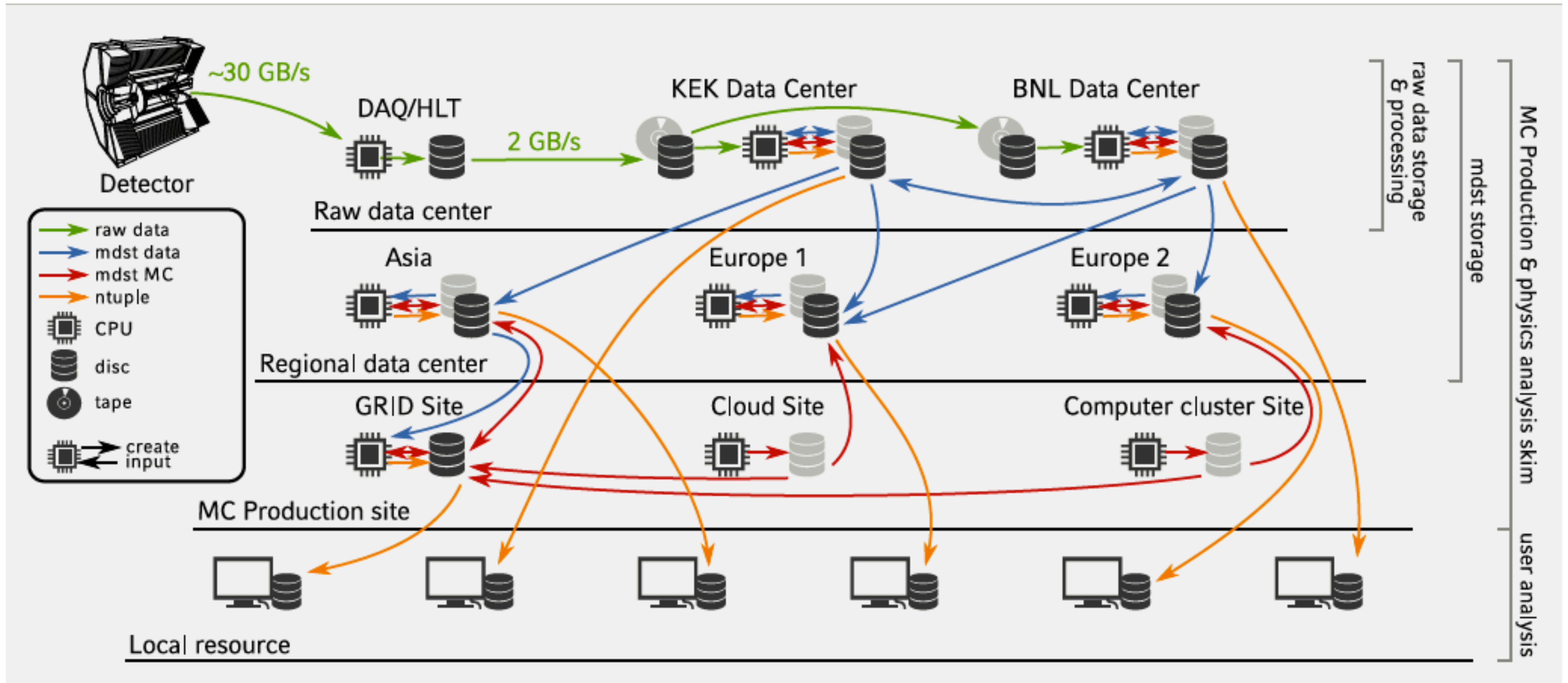


Offline computing

Distributed computing following the LHC model

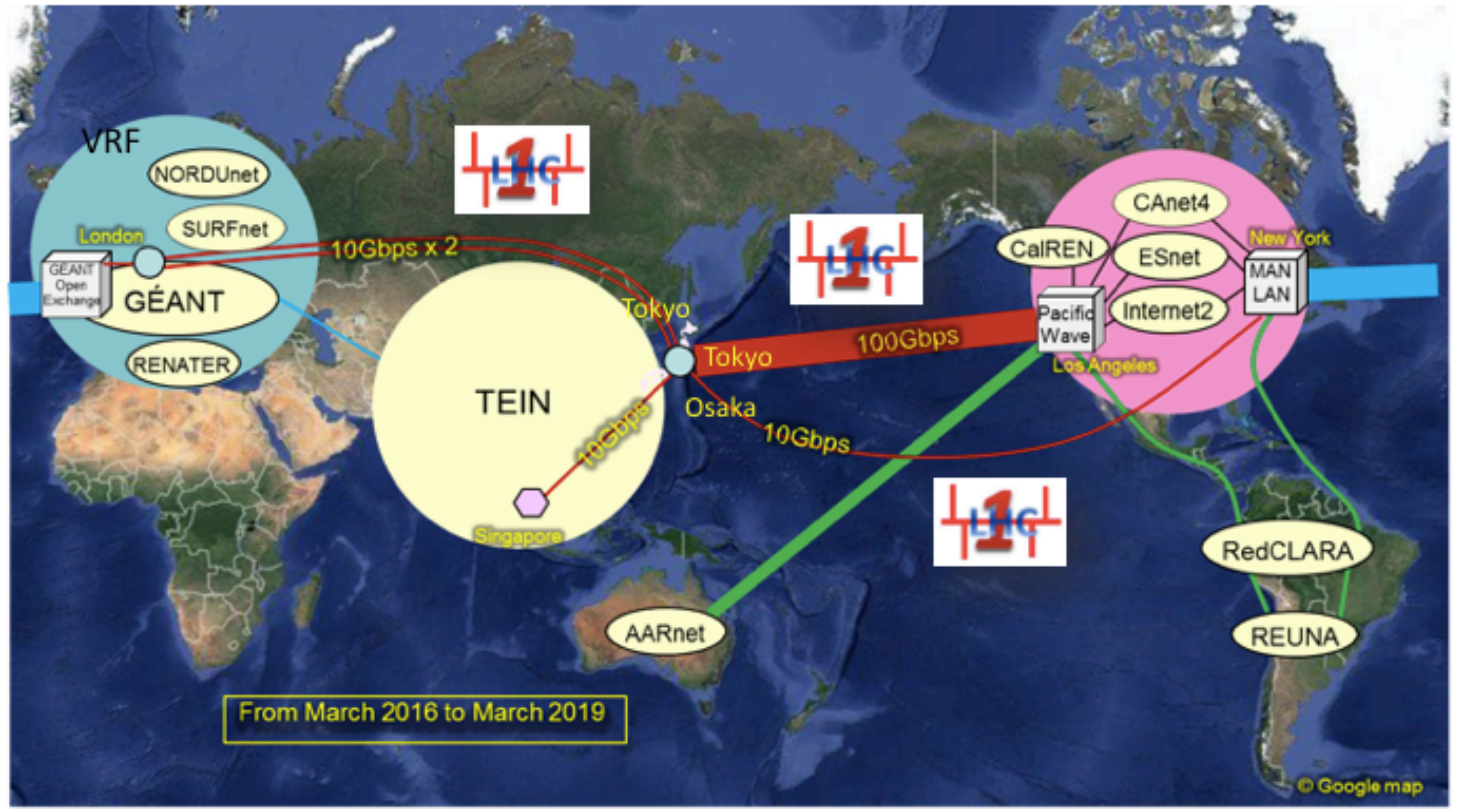
- Manage the processing of massive data sets
- Production of large MC samples
- Many concurrent user analysis jobs





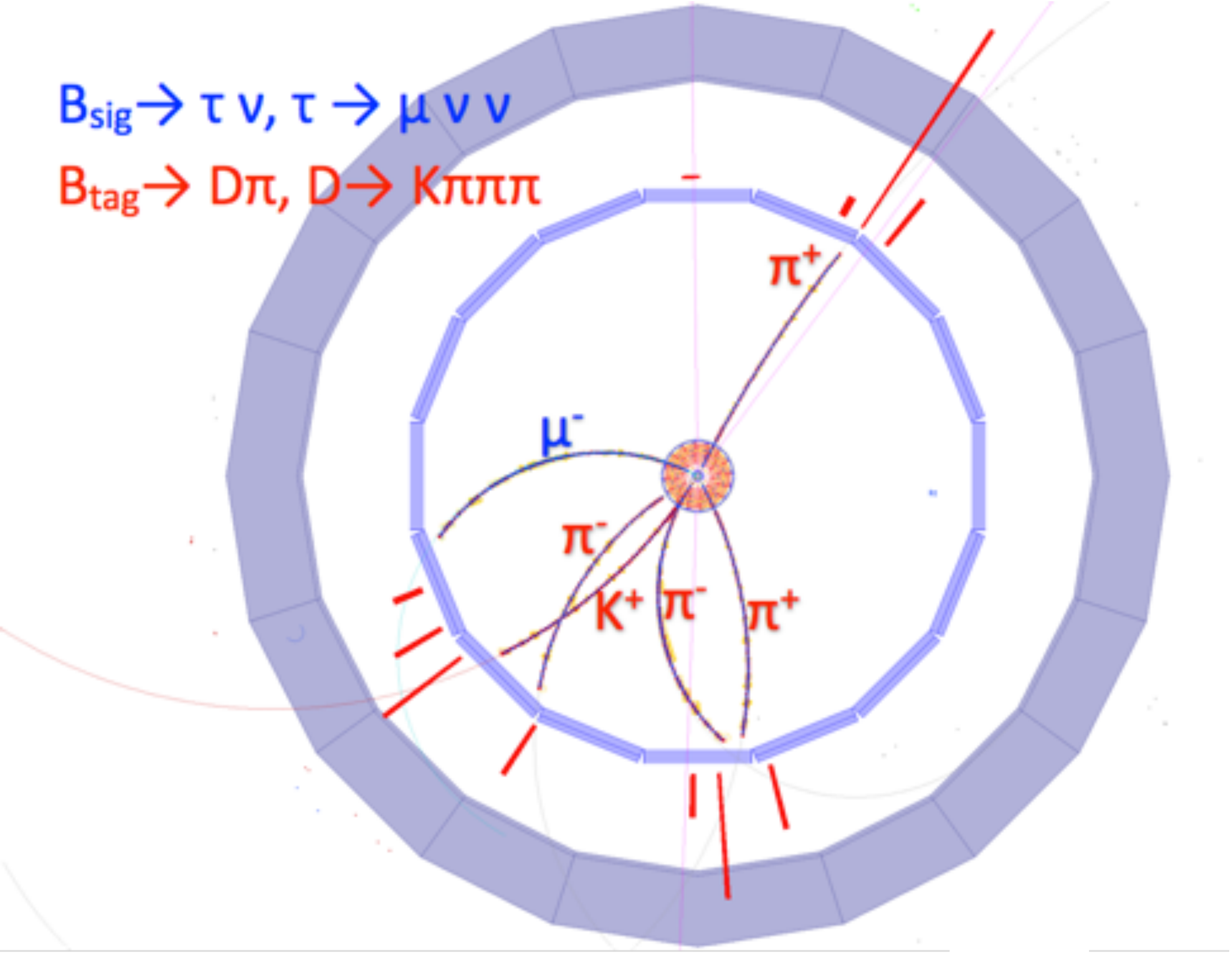
High speed networking data challenge in 2016:

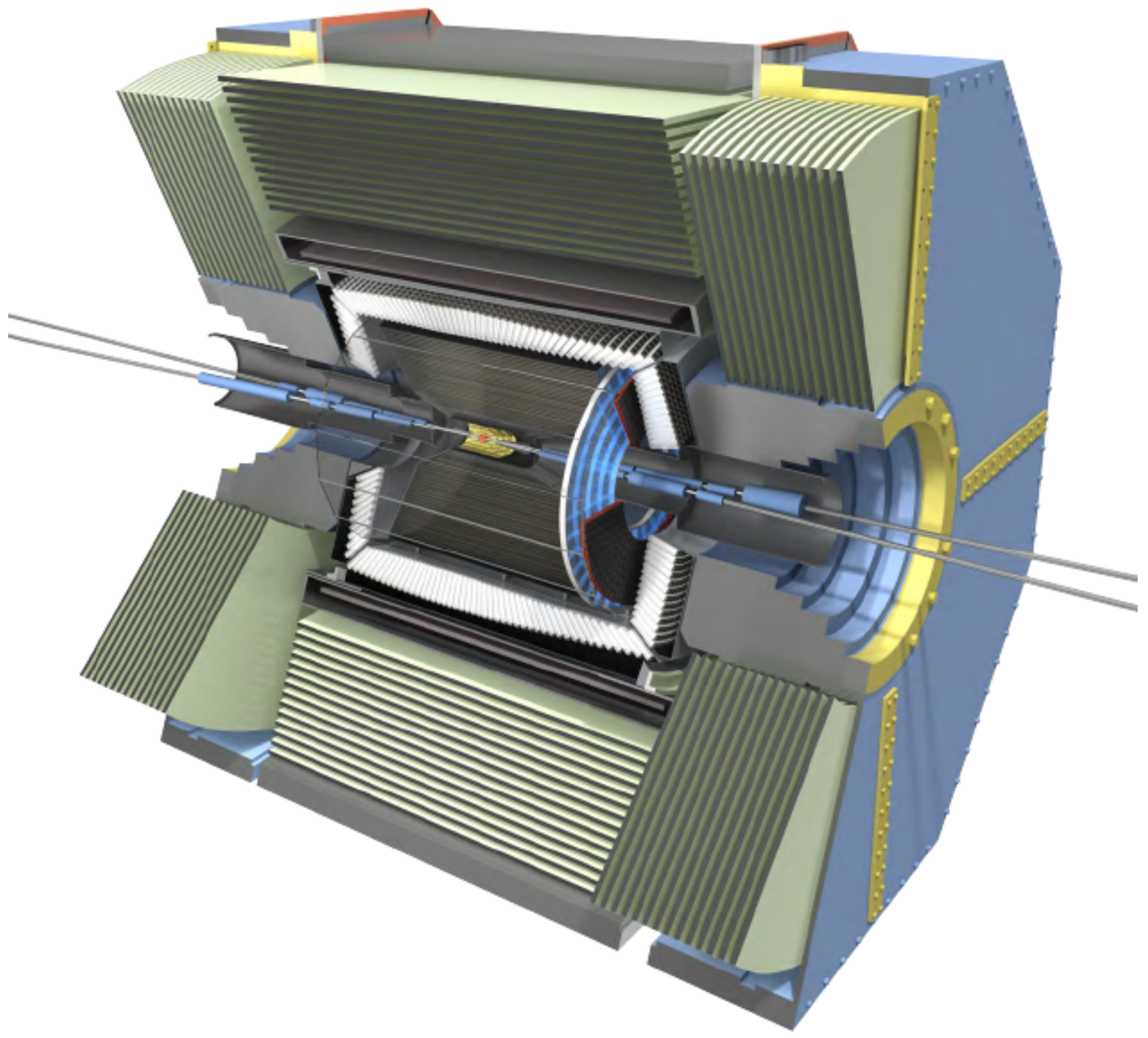
- Belle II networking requirements are satisfied



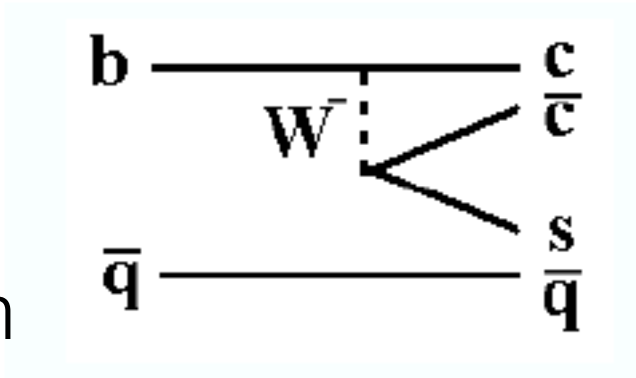
Advantages of SuperKEKB and Belle II

- Very clean sample of quantum correlated $B^0\bar{B}^0$ pairs
- High effective flavor-tagging efficiency
  - Belle II ~34% efficient vs. LHCb ~3%
  - Belle II can also measure K_S and K_L (TD CPV measurements)
- Large sample of τ leptons (rare decays and searches for LFV)
- Efficient reconstruction of neutrals (π^0, η, …)
- Dalitz plot analyses, missing mass analyses straightforward
- Reconstruct single resonance to explore recoiling system (e.g. e+e- → J/ψ X)
- Systematics quite different than those of LHCb
  → NP seen by one experiment should be confirmed by the other
- Variety of production mechanisms available

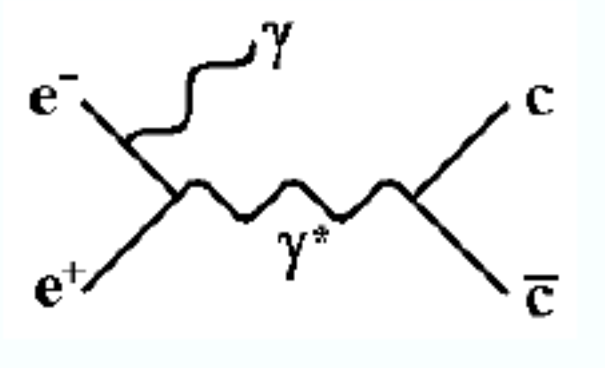




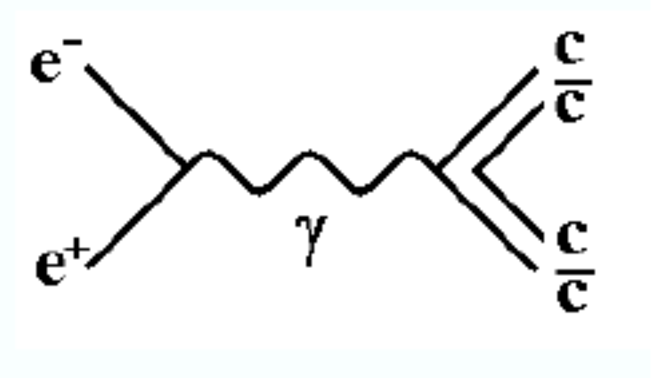
B decays



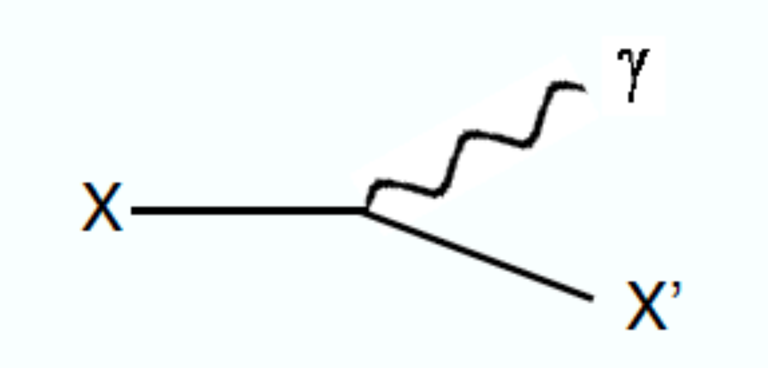
Initial state radiation



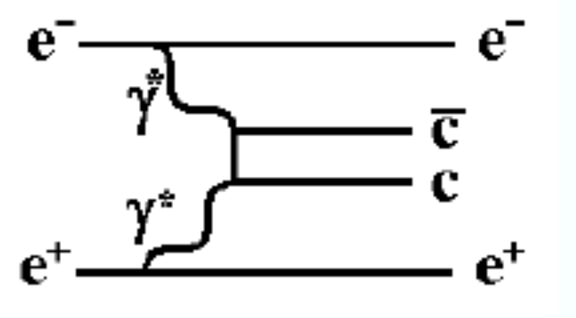
Double charmonium



Quarkonium transitions



Two-photon

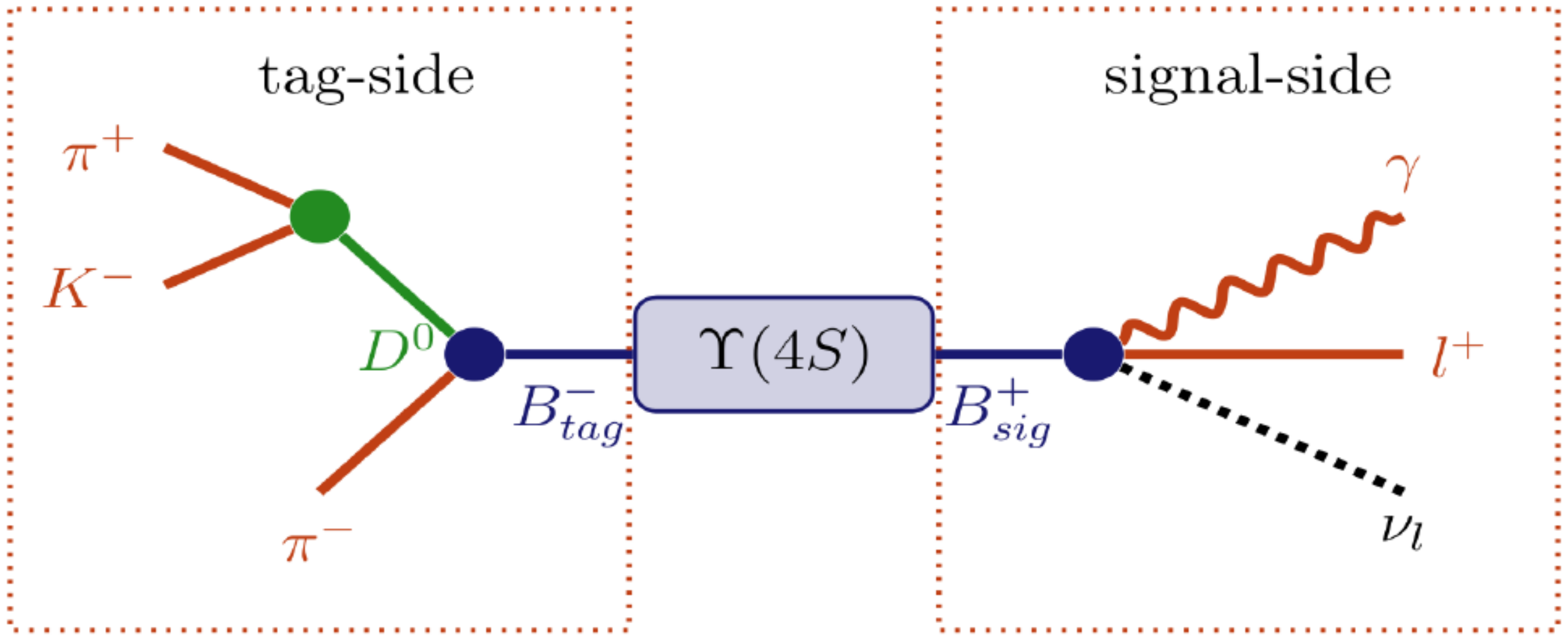


Full reconstruction tagging

- A powerful benefit of physics at B factories: fully reconstruct one B (through > 1000 hadronic/semileptonic modes) to tag the flavor of the other B, determine its momentum, isolate tracks of signal side

Full reconstruction:
($\varepsilon \approx 0.3 - 1.5\%$)

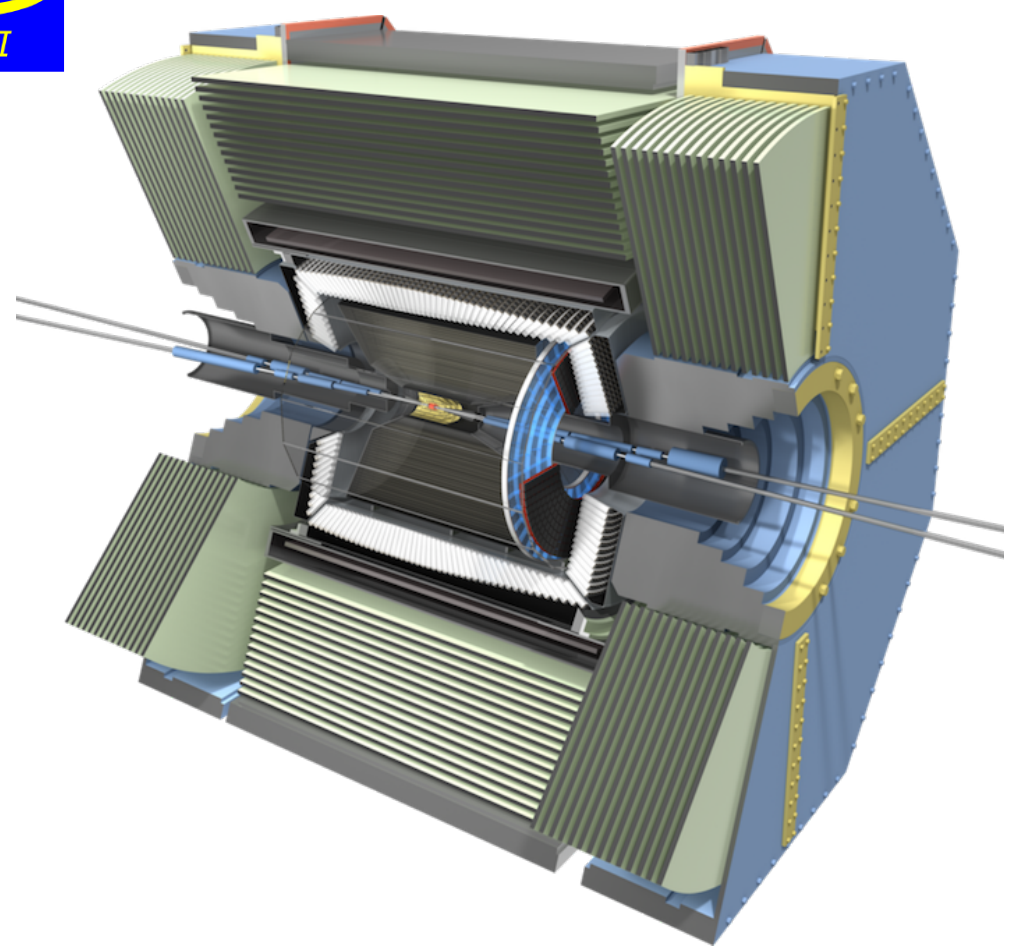
Signal side:
$B \to X\ell\nu$ - Precise meas. of $|V_{ub}|$
$B \to \tau\nu$ - Search for NP
$B \to K\nu\bar{\nu}$ - Search for NP

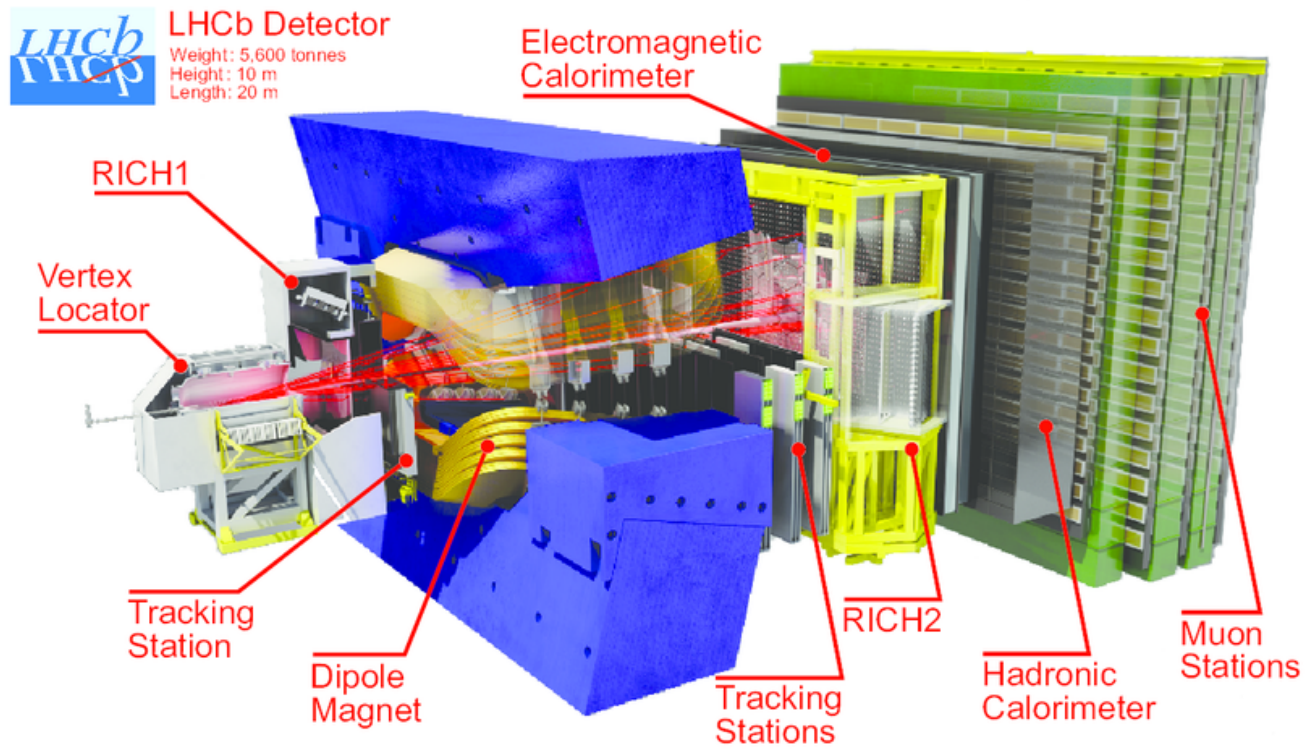


- Excellent tool for missing energy, missing mass analyses!
  - e.g. provide important high-mass sensitivity to the charged Higgs in the multi-TeV range

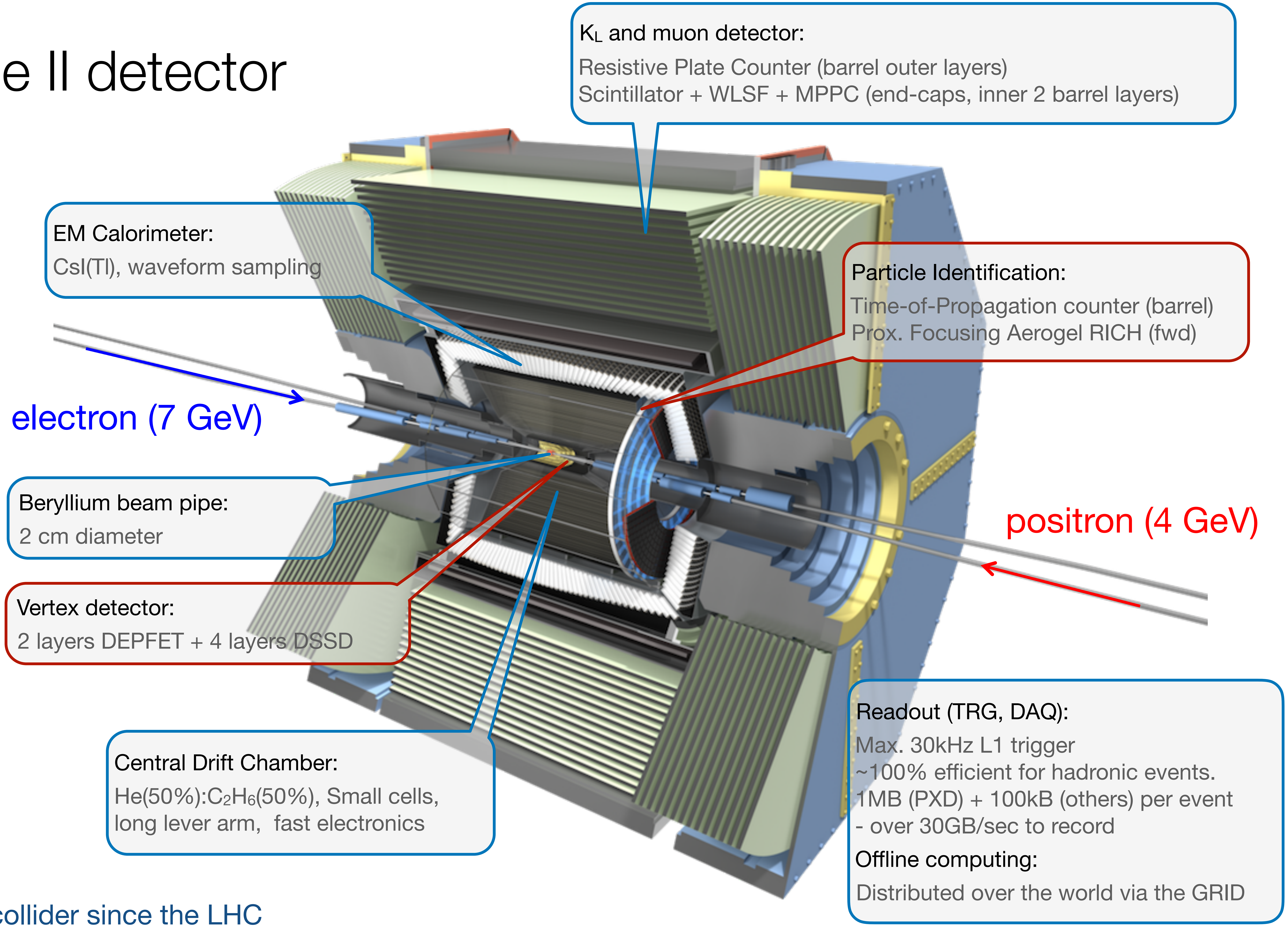
Belle II and LHCb: competition and complementarity

Property	LHCb	Belle II
$\sigma_{b\bar{b}}$ (nb)	~150,000	~1
Integrated luminosity (fb^{-1})	~25	~50,000
Background level	Very high	Low
Typical efficiency	Low	High
Neutral reconstruction	Inefficient	Efficient
Initial state	Not well known	Well known
Decay-time resolution	Excellent	Very good
Collision spot size	Large	Tiny
Heavy bottom hadrons	B_s, B_c, b-baryons	Partial B_s
τ physics capability	Limited	Excellent
B-flavor tagging efficiency	3.5-6%	~36%





The Belle II detector



First new particle collider since the LHC
(intensity rather than energy frontier; e^+e^- rather than pp)

arXiv:1011.0352 [physics.ins-det]

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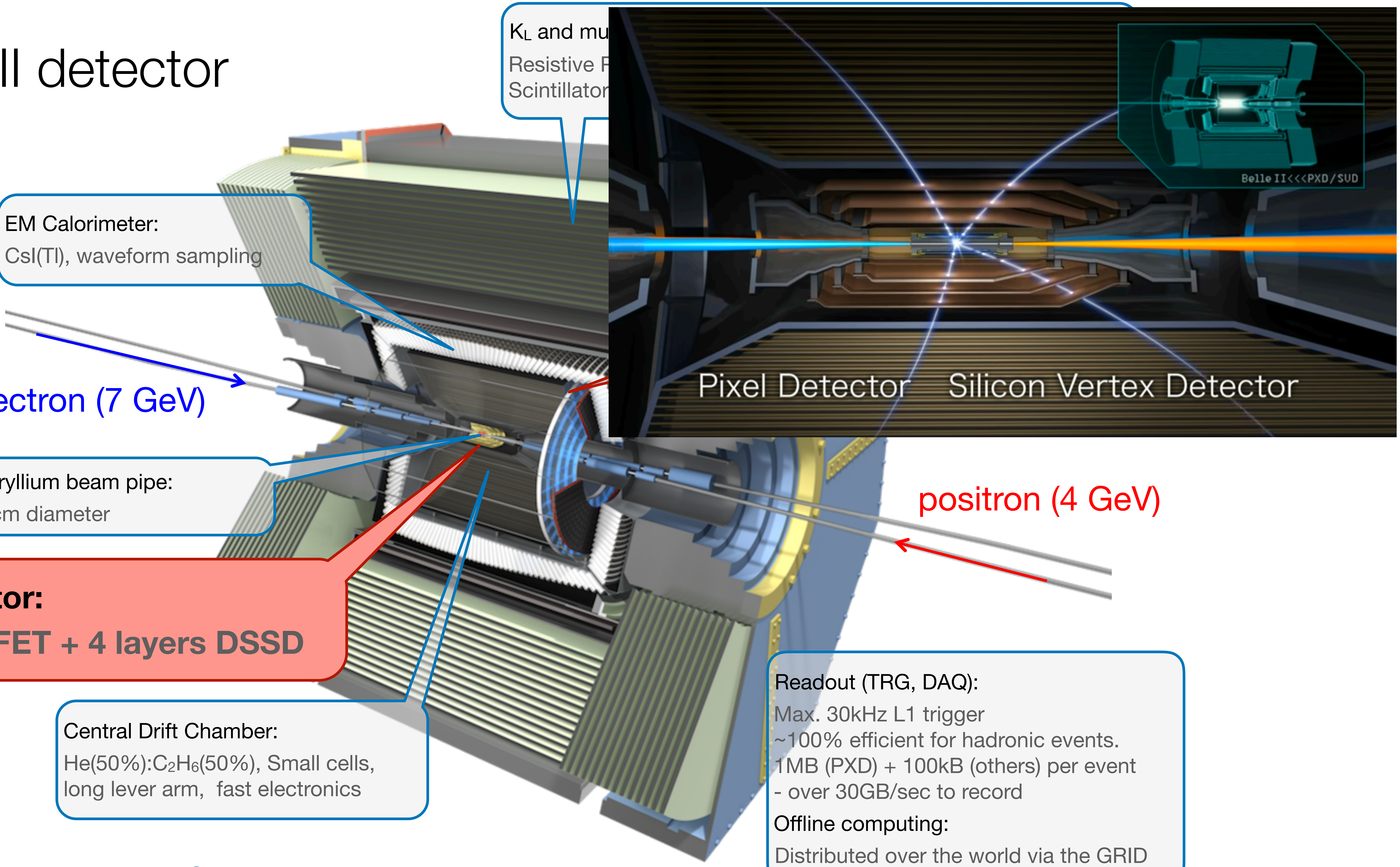

K_L and mu
Resistive P
Scintillator

EM Calorimeter:
CsI(Tl), waveform sampling

electron (7 GeV)

Beryllium beam pipe:
2 cm diameter

Vertex detector:
2 layers DEPFET + 4 layers DSSD

positron (4 GeV)

Central Drift Chamber:
$He(50\%):C_2H_6(50\%)$, Small cells,
long lever arm, fast electronics

Readout (TRG, DAQ):
Max. 30kHz L1 trigger
~100% efficient for hadronic events.
1MB (PXD) + 100kB (others) per event
- over 30GB/sec to record

Offline computing:
Distributed over the world via the GRID

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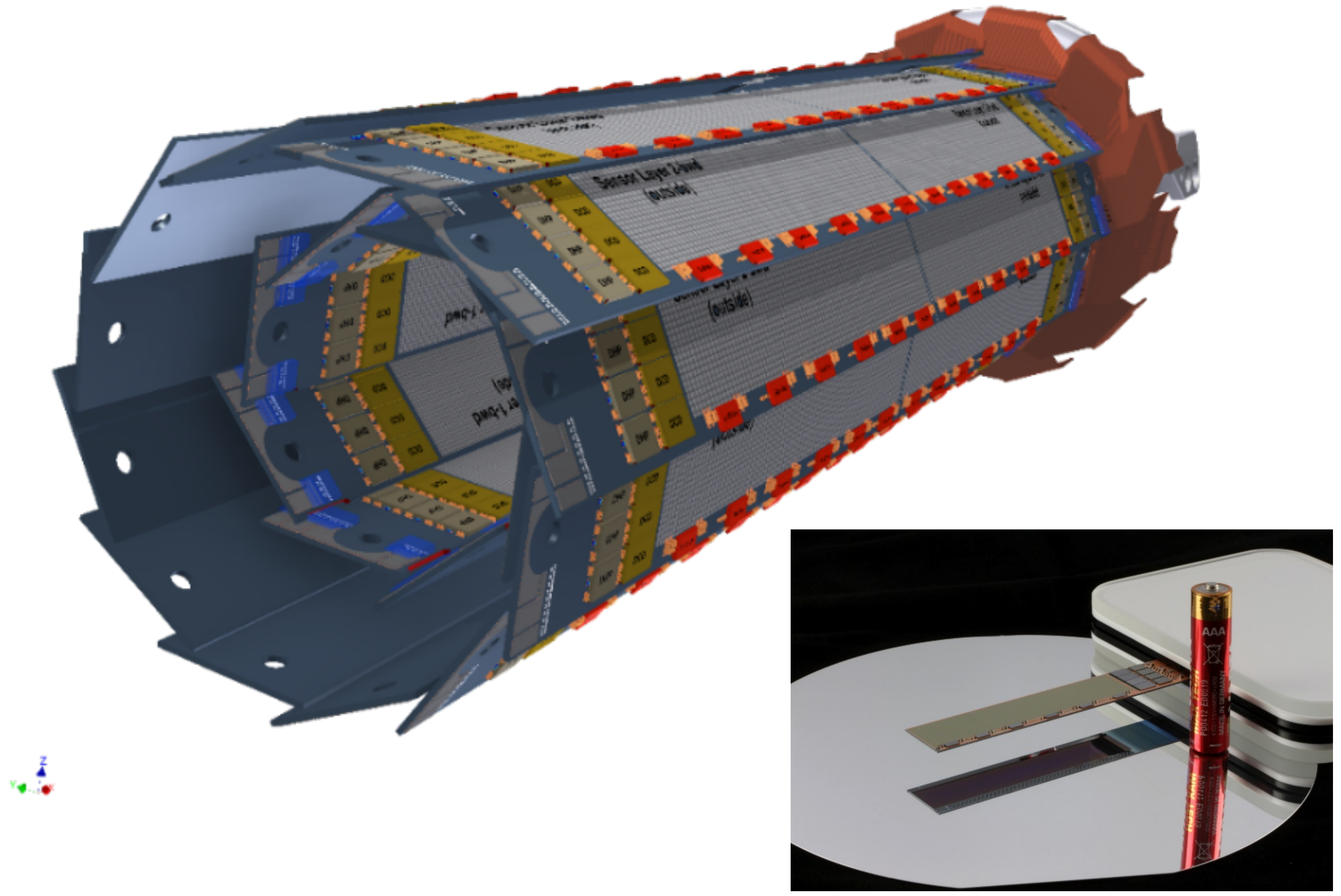
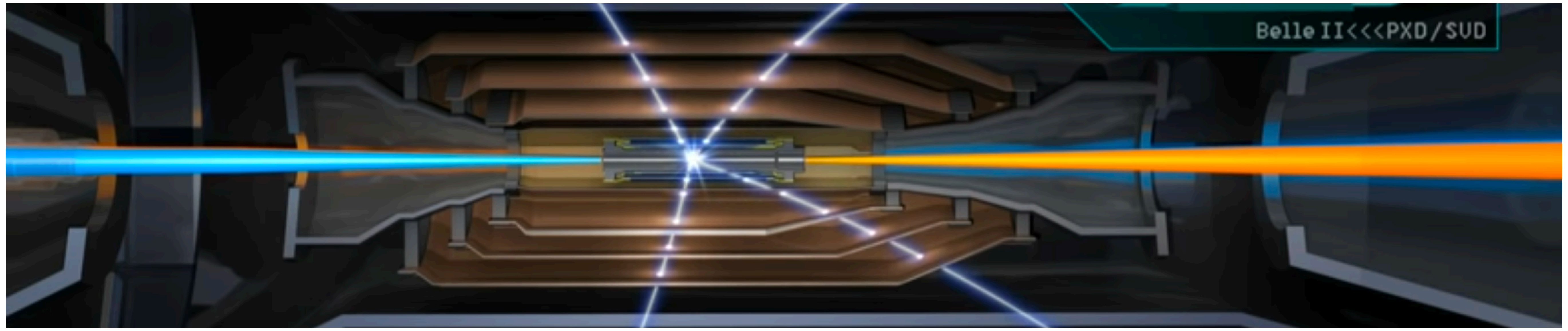
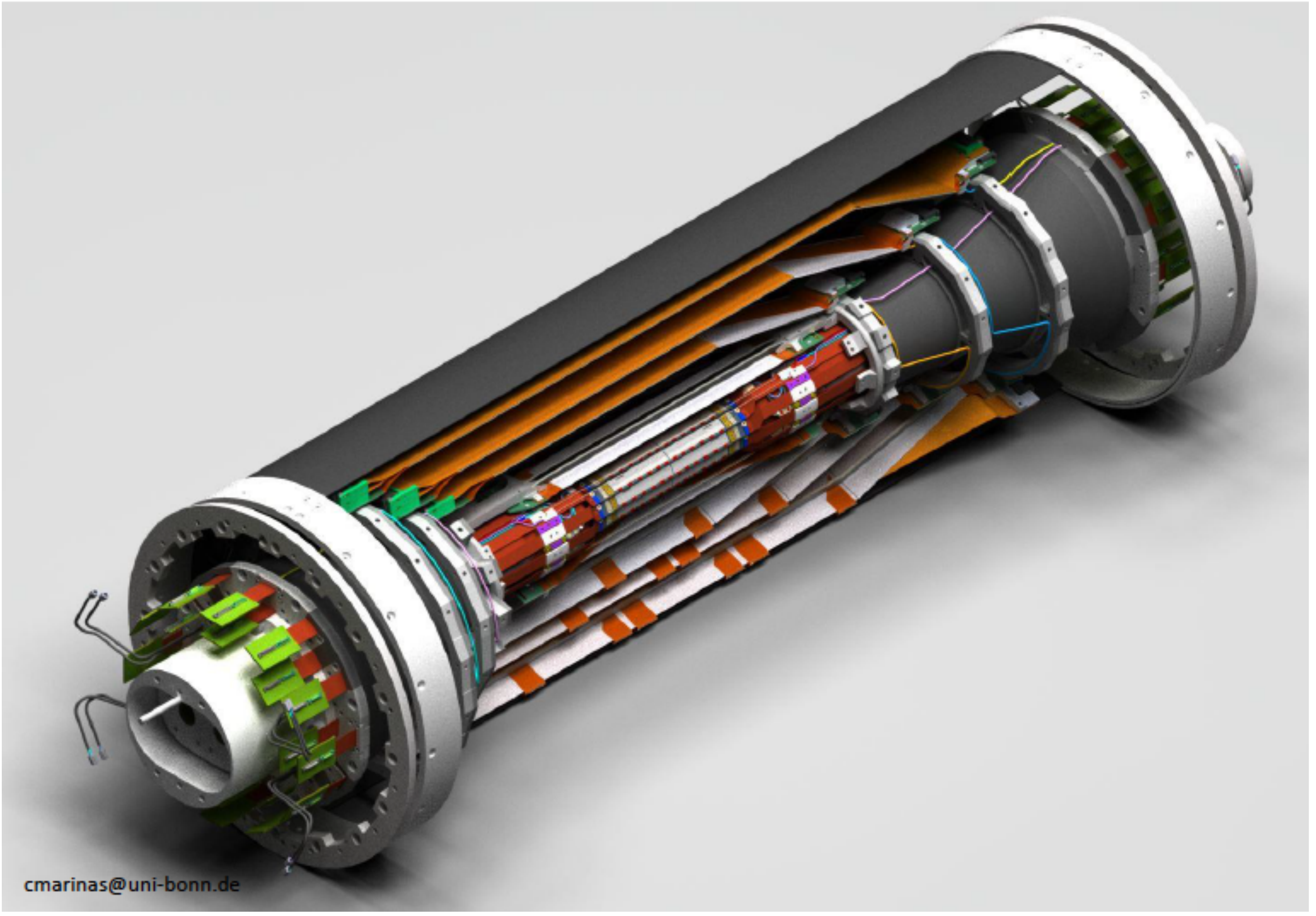
Vertex detector (VXD): SVD + PXD



- Upgraded: 6 layers instead of 4 (outer radius of 14 cm rather than 8 cm)
  - More robust tracking
  - Higher K_S vertex reconstruction efficiency
- Smaller inner radius: 1.3 cm rather than 1.5 cm
  - Better vertex resolution

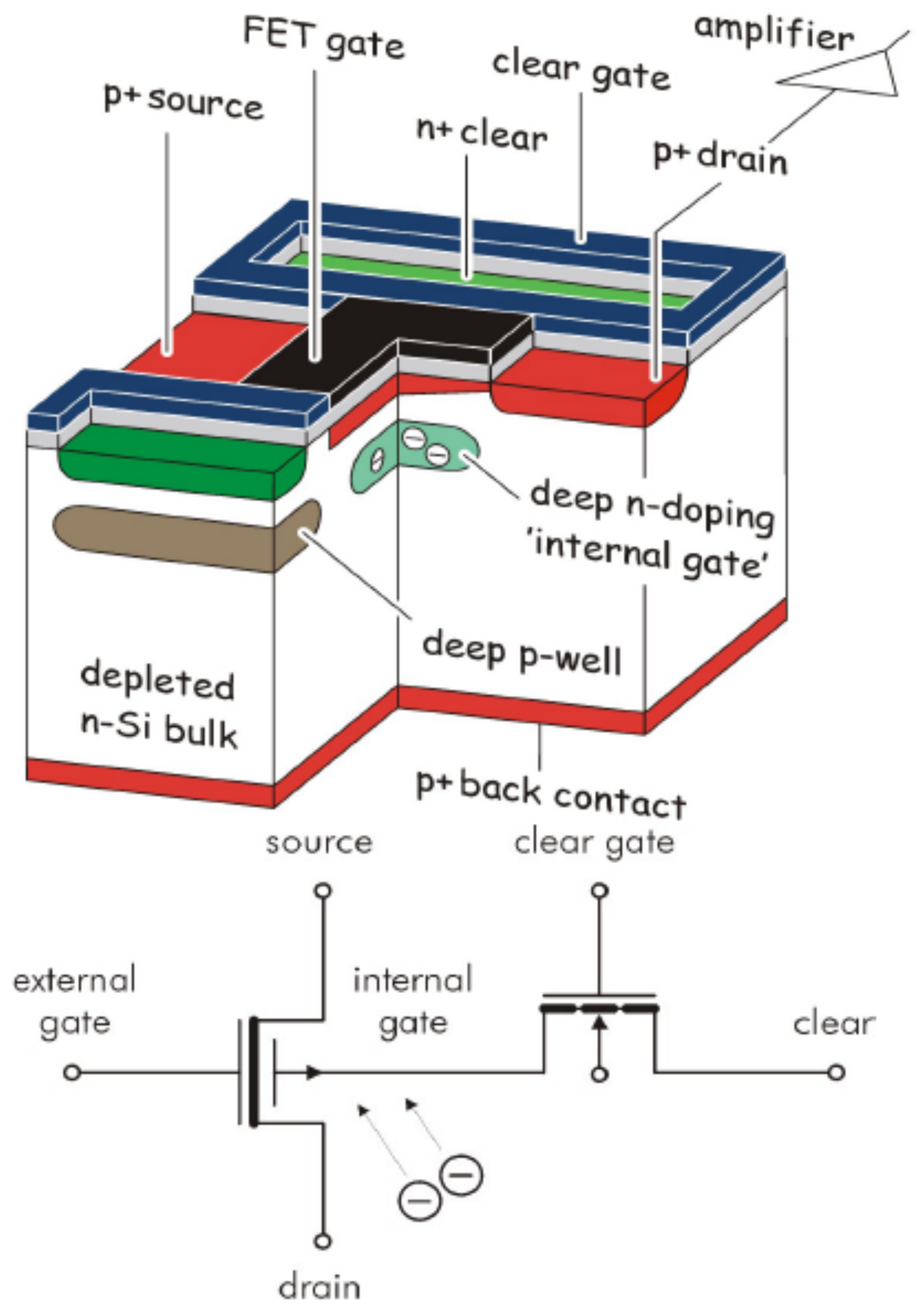
- Inner 2 layers: DEPFET pixel sensors (PXD)
- Outer 4 layers: Double-Sided Silicon Detectors (SVD)
- Strip readout chip also upgraded
  - VA1TA → APV25
  - Pipelined readout to reduce dead time, pile-up rejection





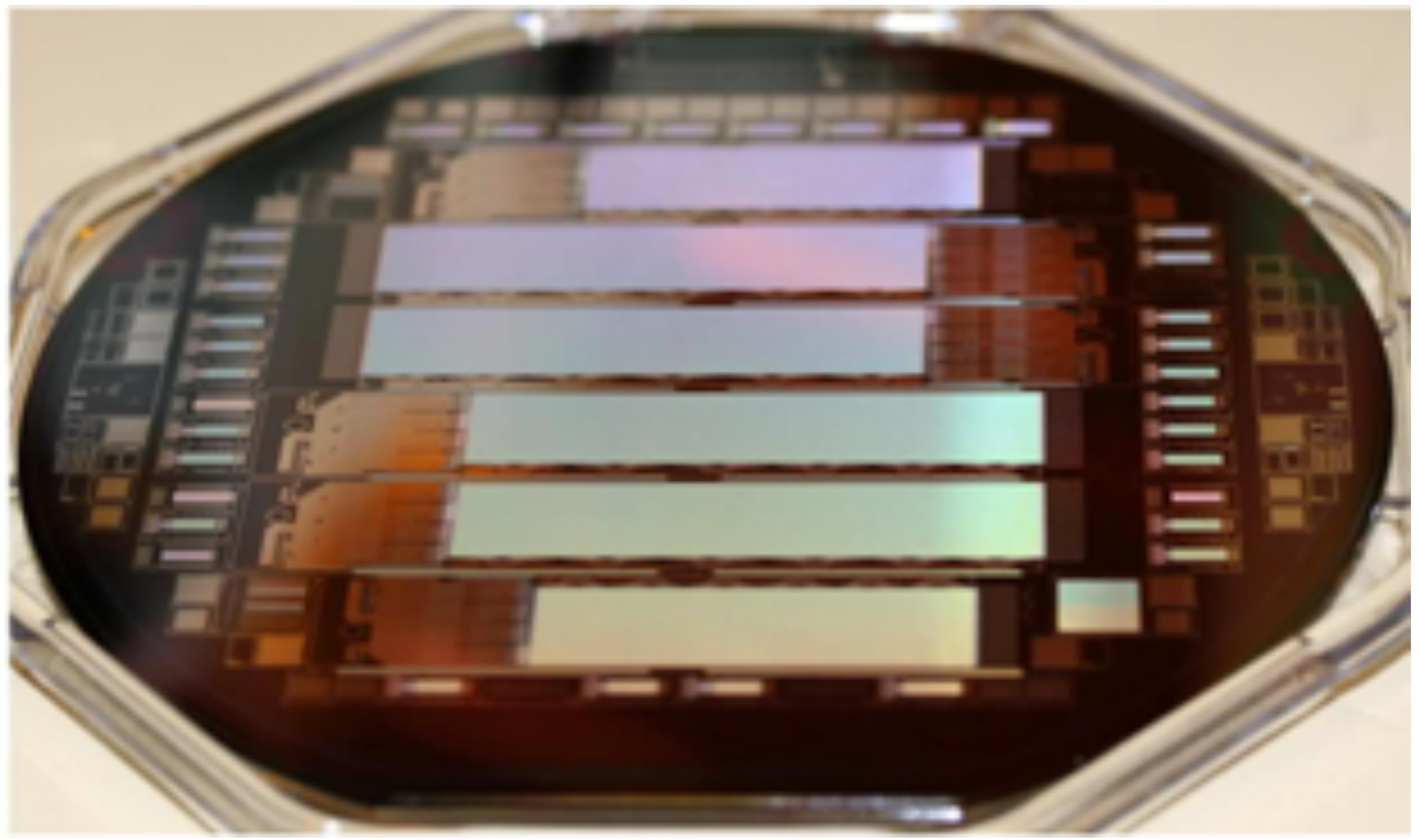
Pixel Detector (PXD)

DEpleted P-channel FET

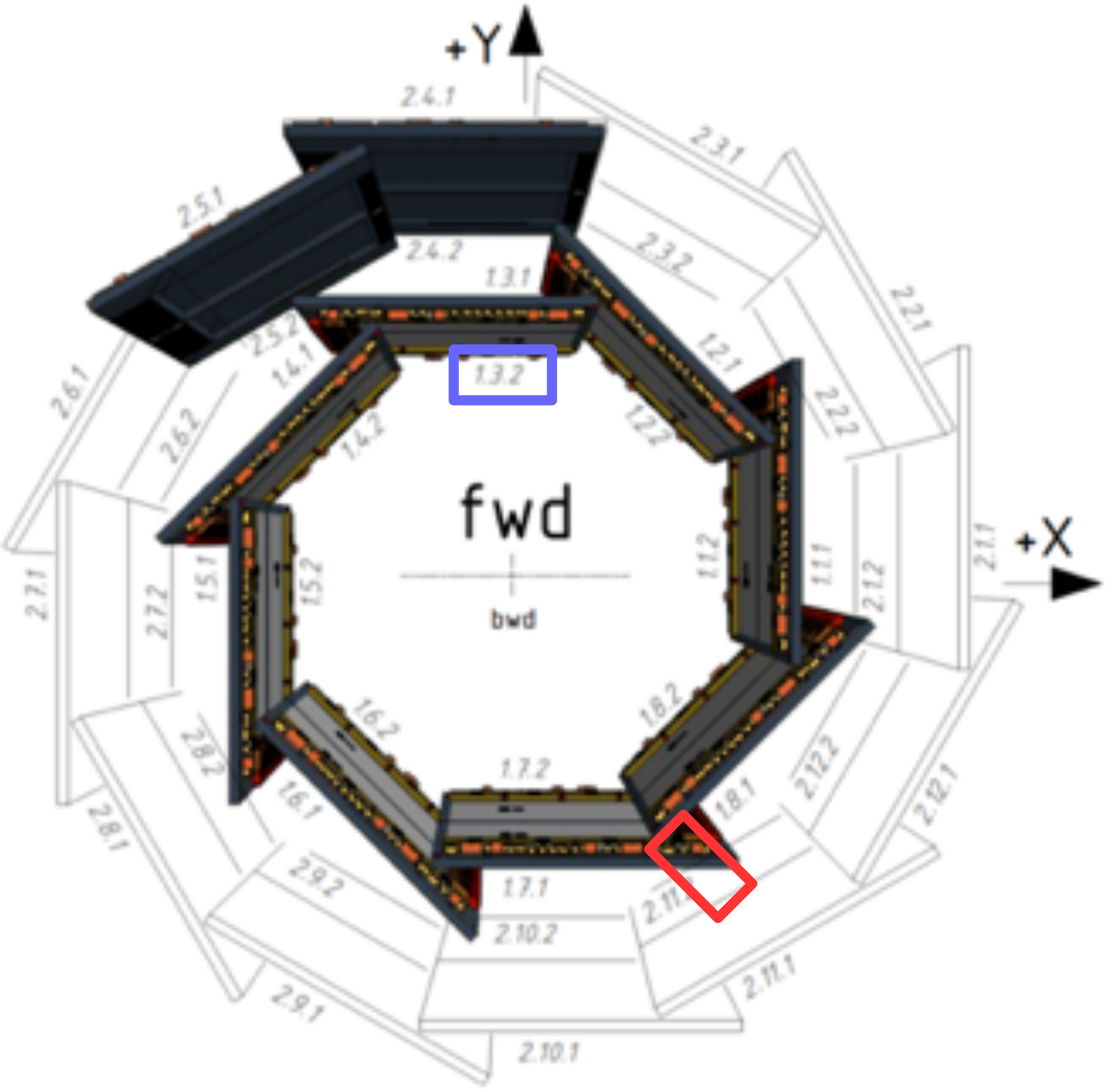


- DEPFET: internal charge to current amplification
  - Each pixel is a p-channel Field Effect Transistor on a completely depleted bulk
  - A deep n-implant creates a potential minimum for electrons under the gate (“internal gate”)
  - Signal electrons accumulate in the internal gate and modulate the transistor current (gq ~ 400 pA/e-)
  - Accumulated charge can be removed by a clear contact (“reset”)
  - Fully depleted: => large signal, fast signal collection
  - Low capacitance, internal amplification: => low noise
  - High S/N even for thin sensors (50 μm)
  - Low power (only few lines powered)

- Sensors thinned to 75 m
  - <0.25% X0 per layer
- Two layers (r = 14 mm, 22 mm)
  - Down to 50*55 μm pixels
  - 40 sensors total, 7.7M pixel

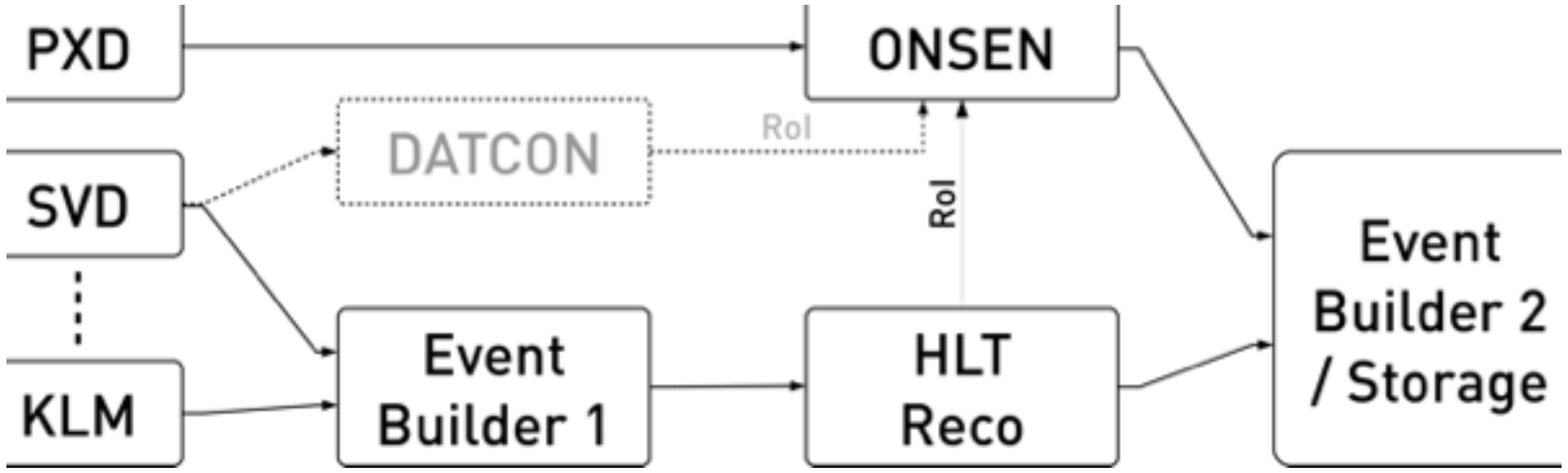


PXD installation/operation

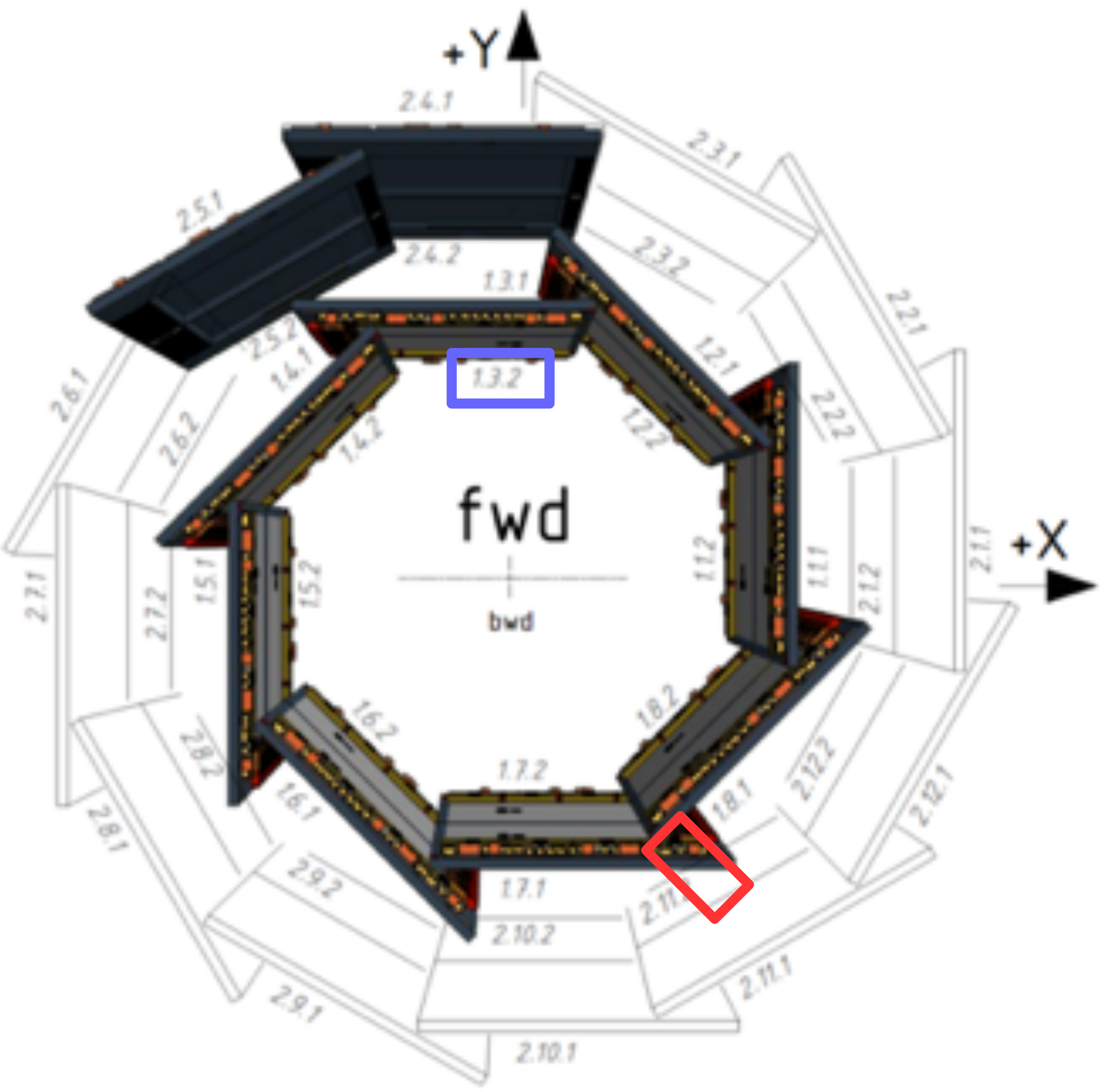


- Technical troubles in module production and assembly: only inner layer installed (+2 ladders on outer layer)
- Restarted production of all sensor types (complete PXD replacement by 2021)
- Two full sensors currently not operational
  - 1.3.2: known B-grade, masked
  - 1.8.1: masked since QCS quench and uncontrolled beam loss

- PXD is virtually noise free, but rather long integration time (20 us, two full accelerator revolutions)
- ONSEN system reads out full PXD on each trigger and keeps data in local buffer
  - Why?



PXD installation/operation



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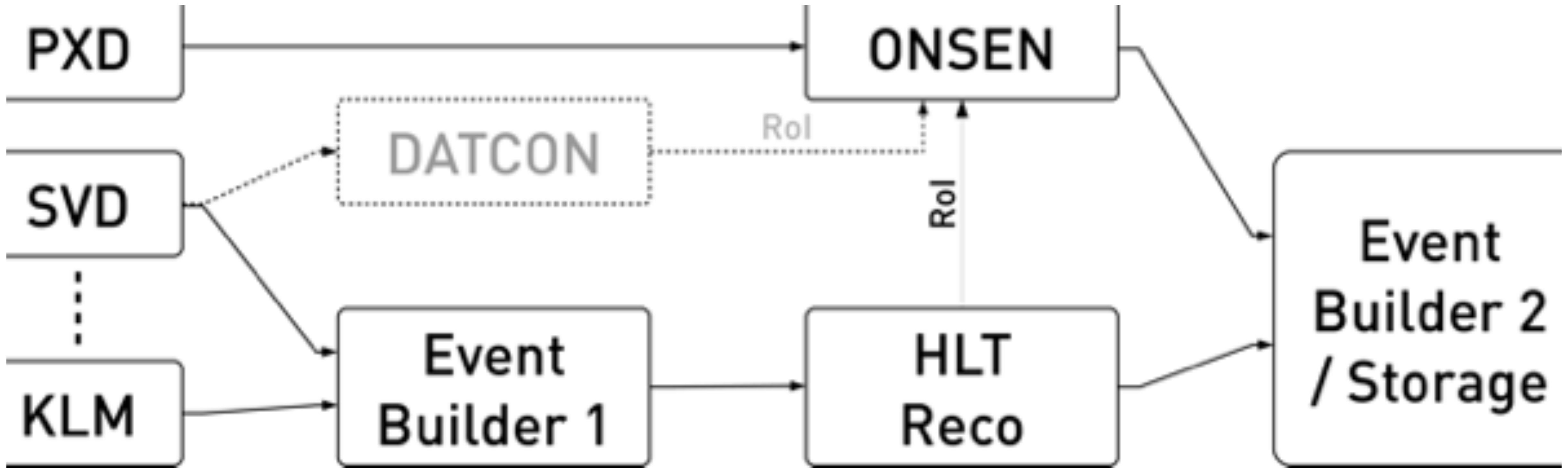
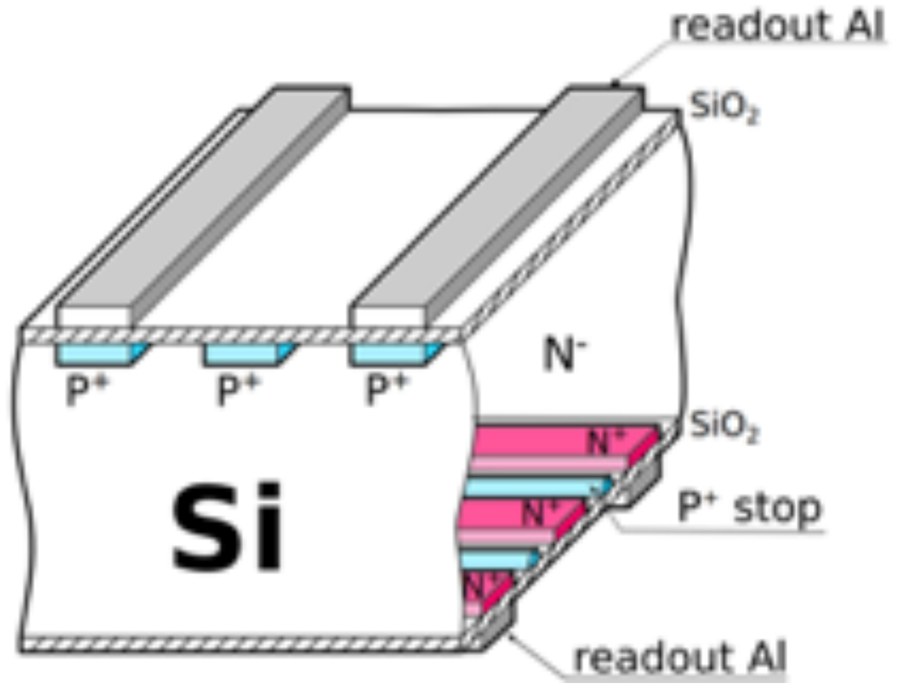
  - 1.8.1: masked since QCS quench and uncontrolled beam loss

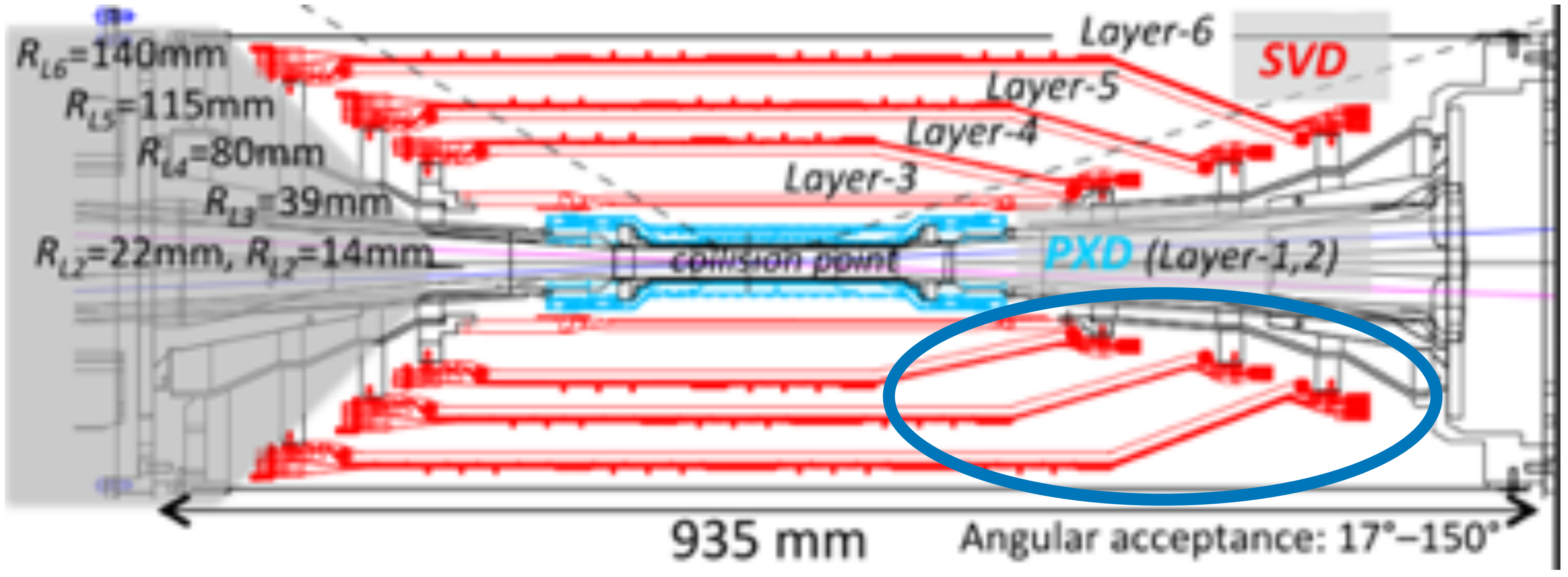
- PXD is virtually noise free, but rather long integration time (20 us, two full accelerator revolutions)
- ONSEN system reads out full PXD on each trigger and keeps data in local buffer
  - HLT reconstruction identifies regions of interest on PXD surface, ONSEN only transfers relevant parts of PXD hitmaps to EB2/storage
  - DATCON: FPGA based tracking to generate RoIs directly from SVD raw data
- Still PXD accounts for ~75% of total Belle II raw data size!



Silicon Vertex Detector (SVD)

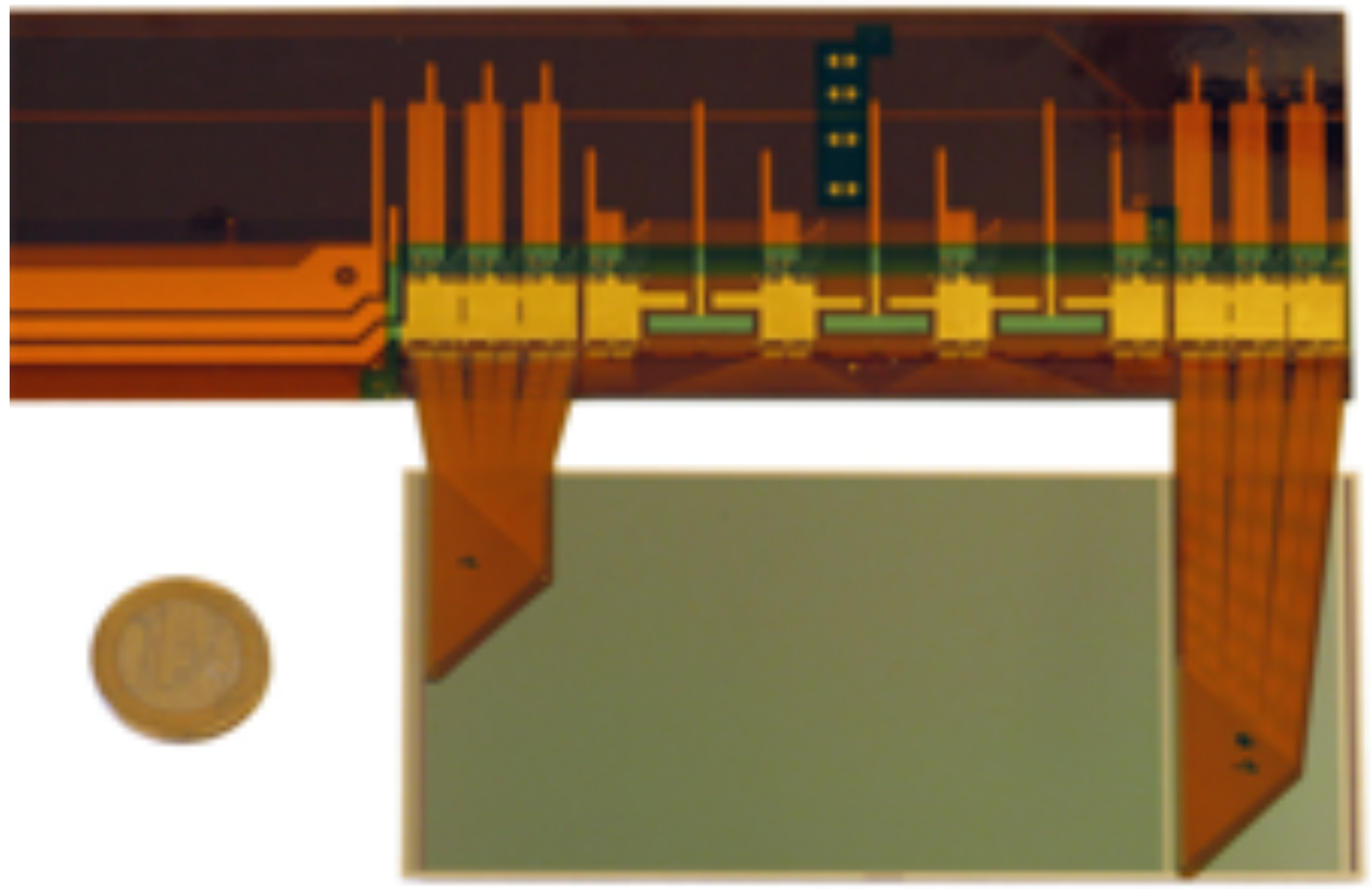
- Four layers of double-sided strip detectors
  - r = 39 mm to r = 140 mm
  - Lampshade geometry
  - 224k strips
- Read out by APV25 ASICs
  - Adapted from CMS
  - 50 ns shaping, 40 MHz sampling
  - Partially thinned to 100 µm





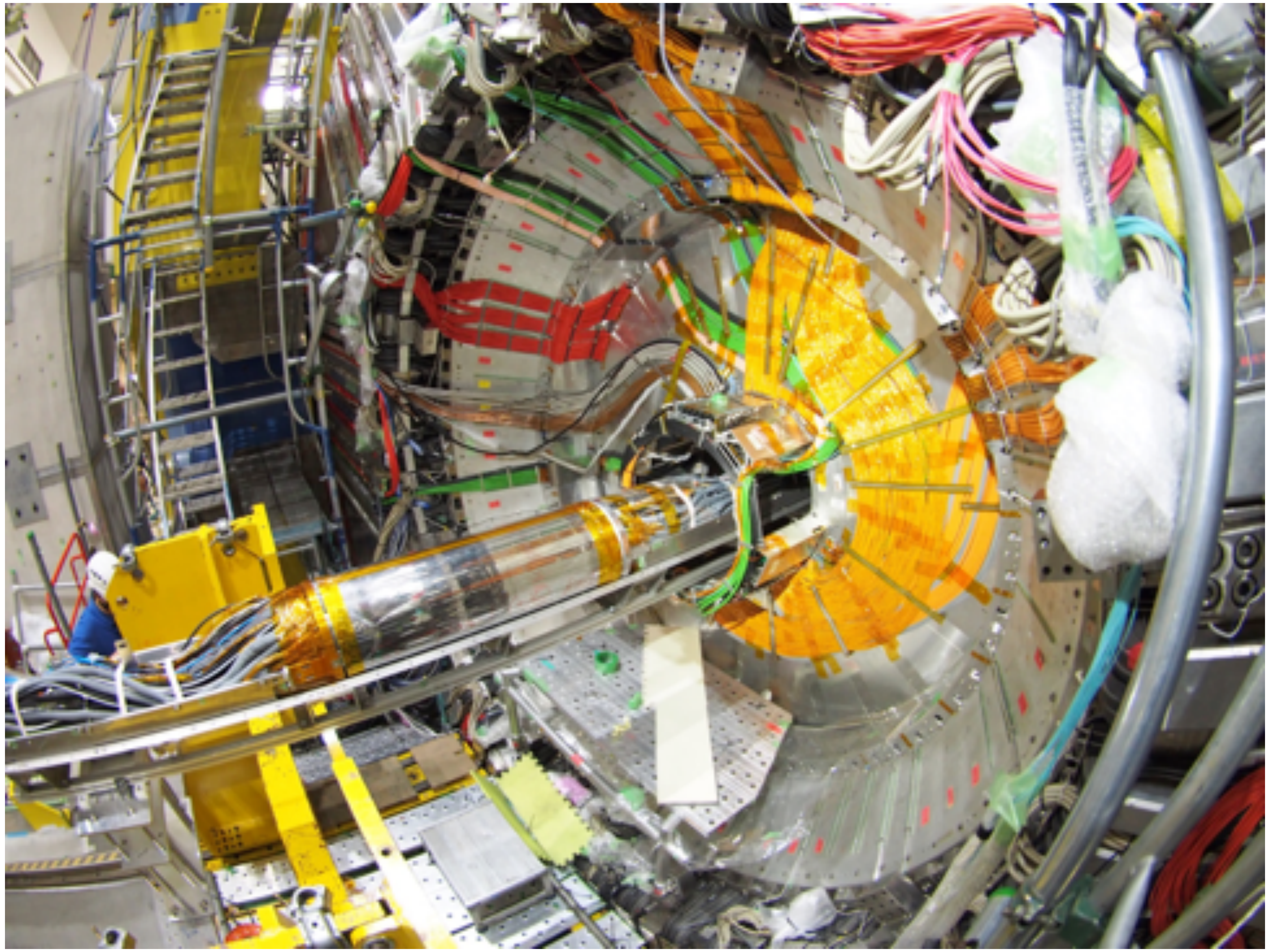
Slanted layers to maintain acceptance in forward region

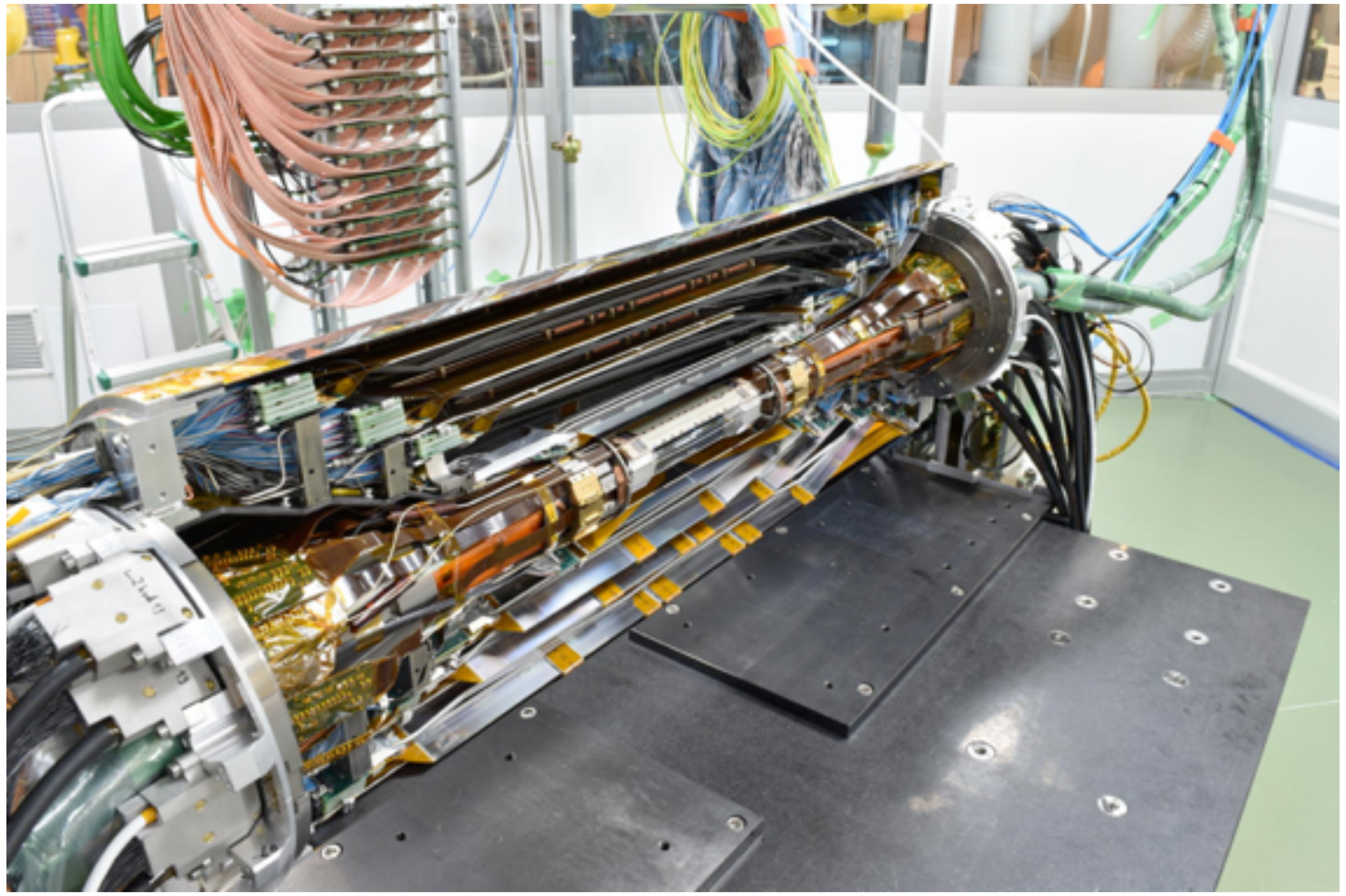
- Readout chips of central sensors bonded to “Origami” Kapton flex
  - Folded around sensors
- Ladders assembled all around the world:
  - Layer 3: Uni Melbourne, Australia
  - Layer 4: TIFR, India
  - Layer 5: HEPHY, Austria
  - Layer 6: Kavli-IPMU, Japan
- Final assembly into half shells and full vertexing system at KEK



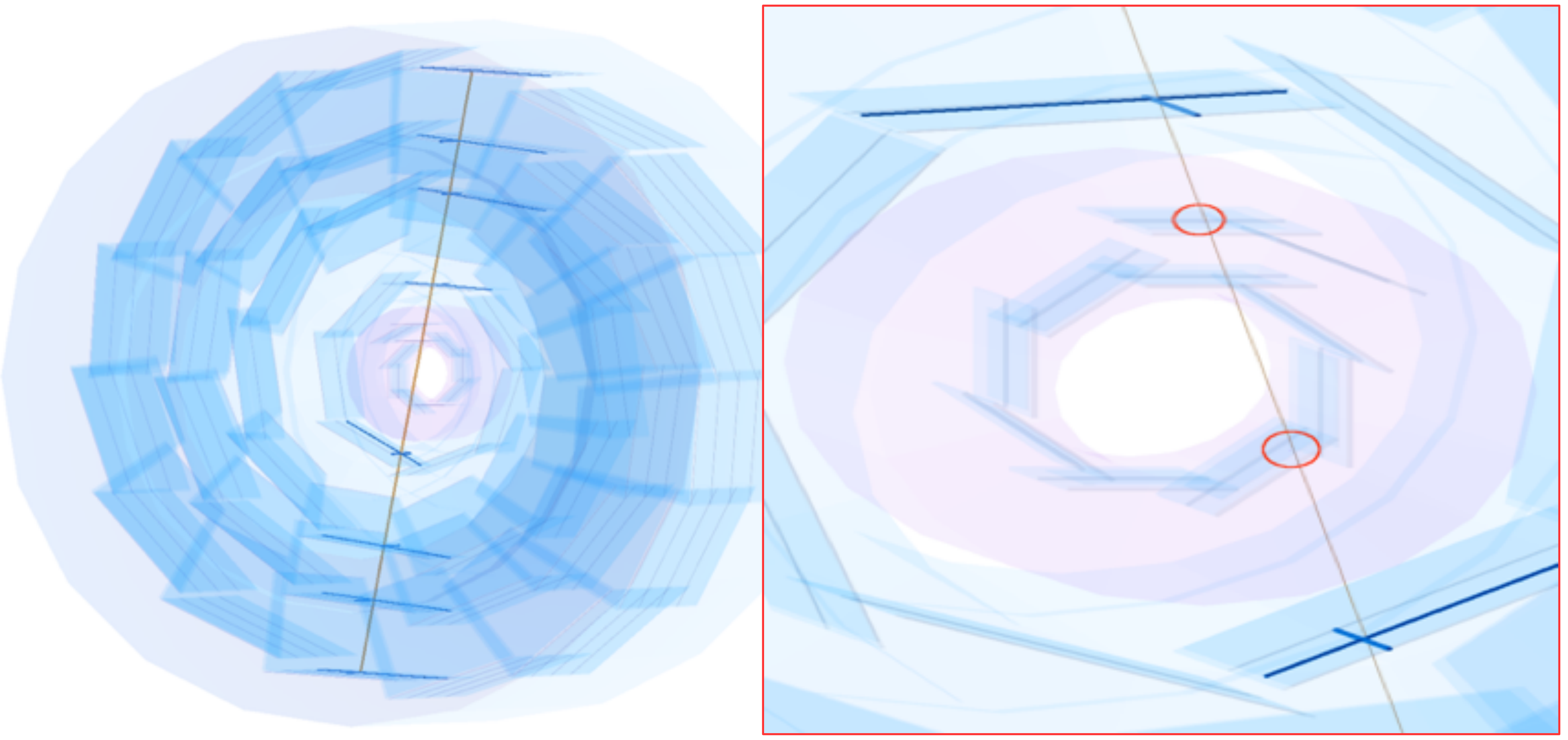
Vertex Detector (VXD)

- PXD & SVD “married” in October 2018
- Installed November 2018





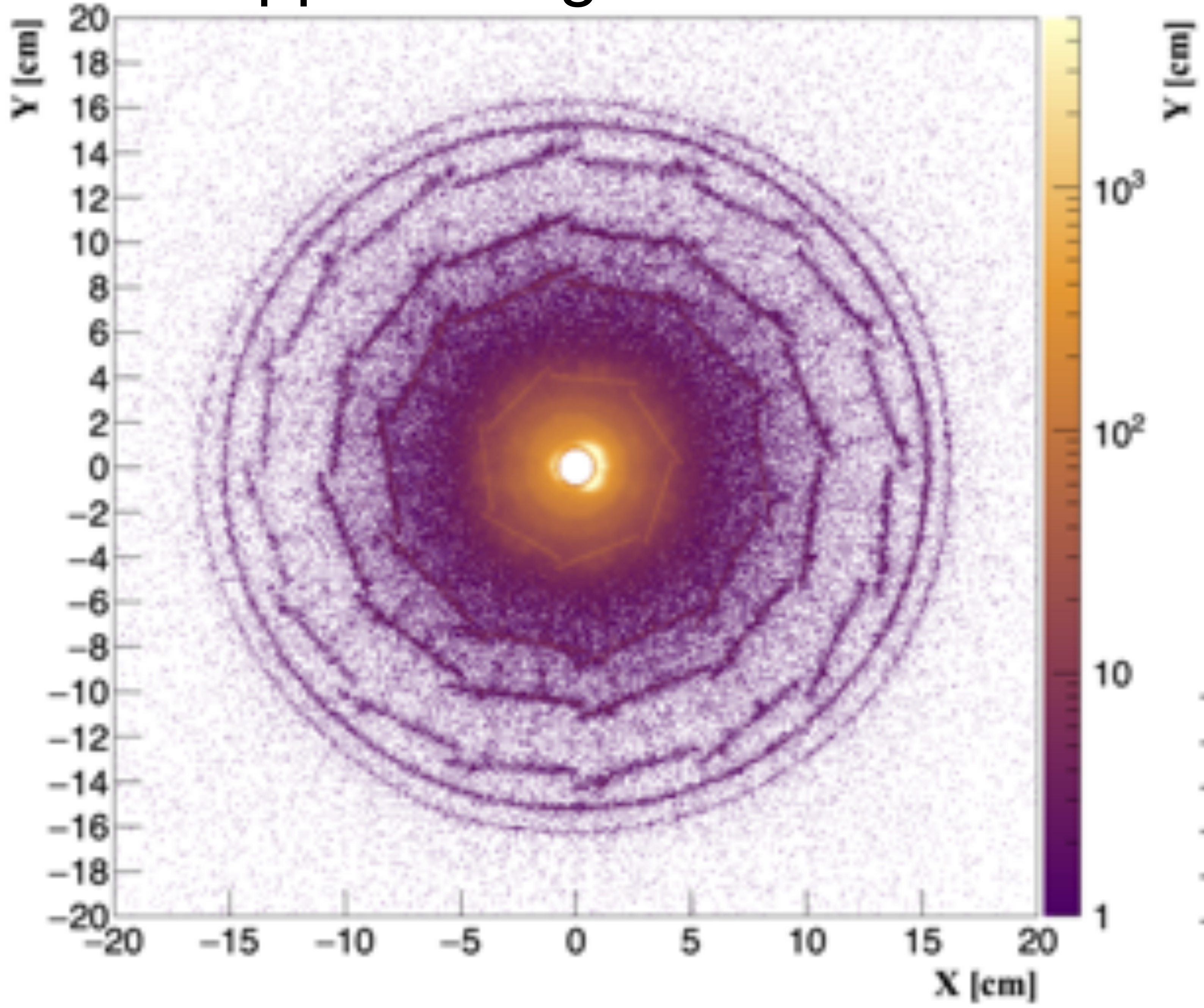
First cosmics



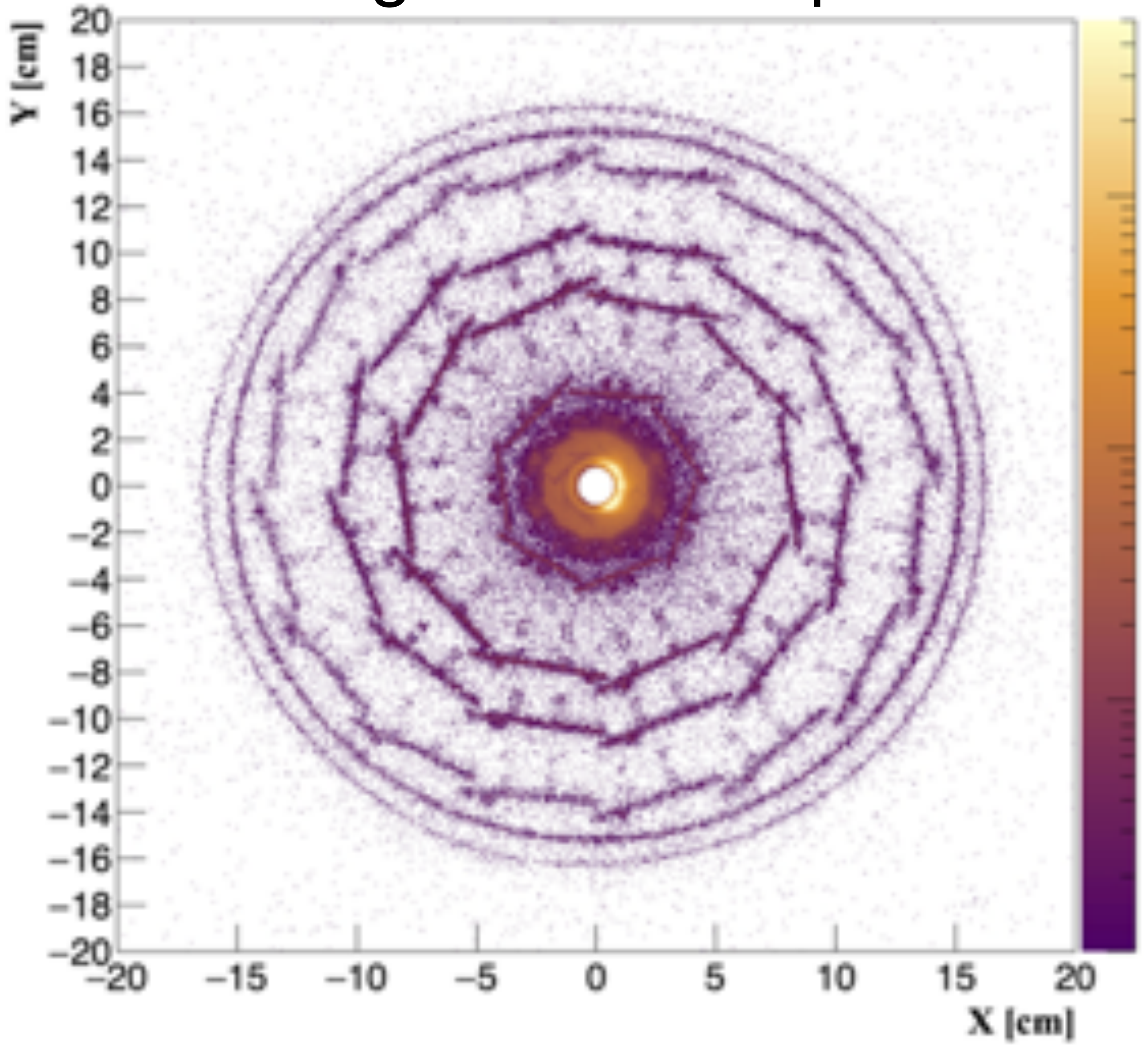
Visualizing the detector

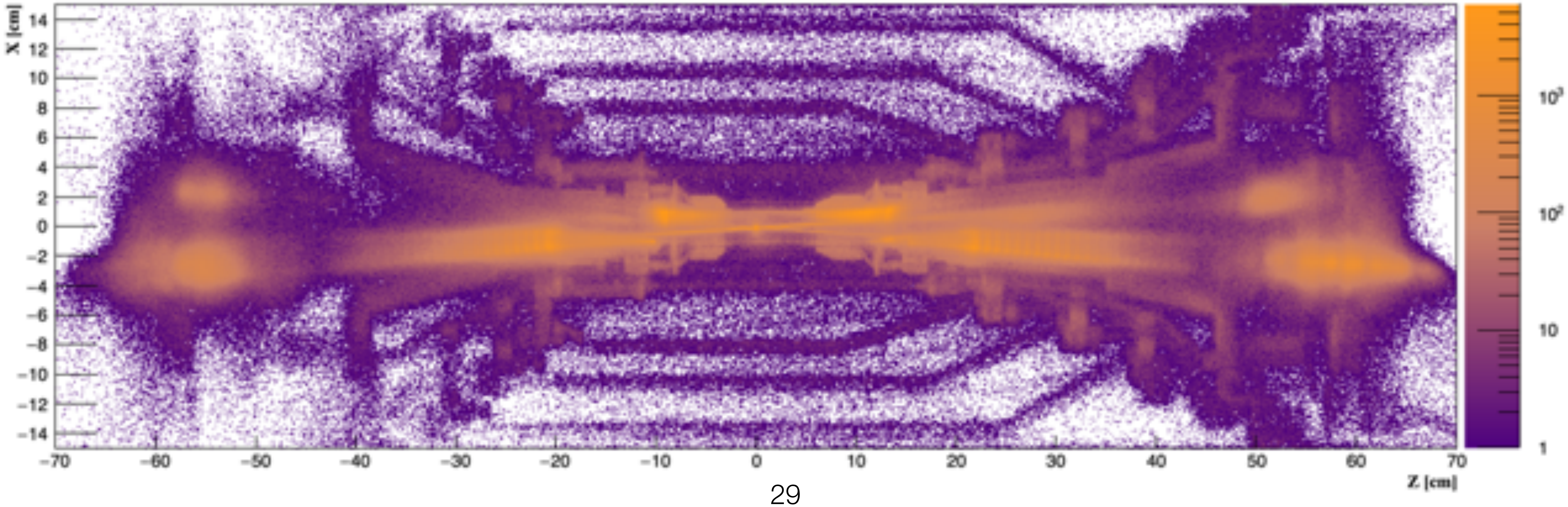
- Particles coming from the beam or IP often strike material and send particles flying through the detector
- Reconstruct tracks coming from a common vertex
  - Plot the number of vertices as a function of position

opposite-sign vertices

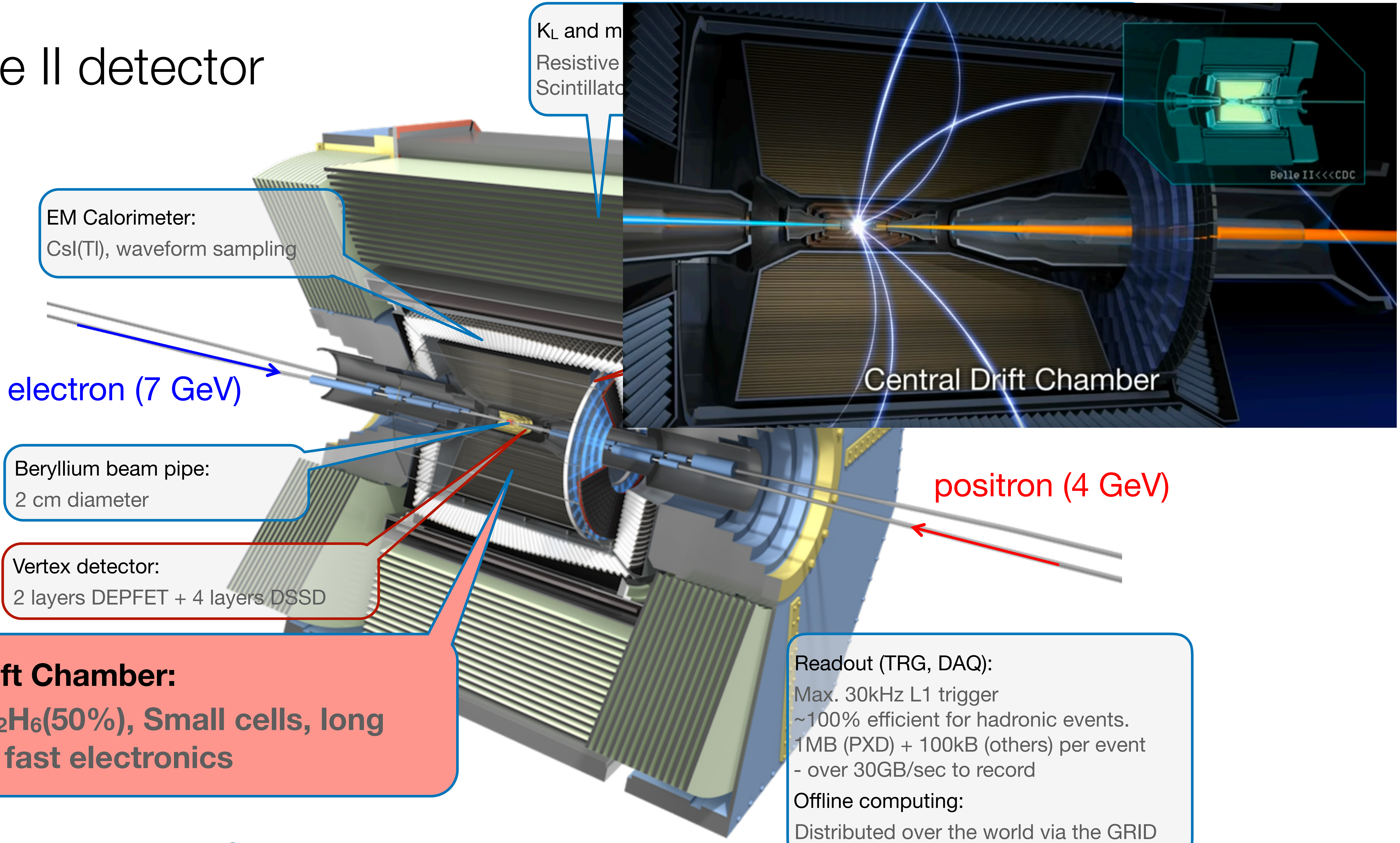


same-sign vertices + protonID





The Belle II detector



Central Drift Chamber:

He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

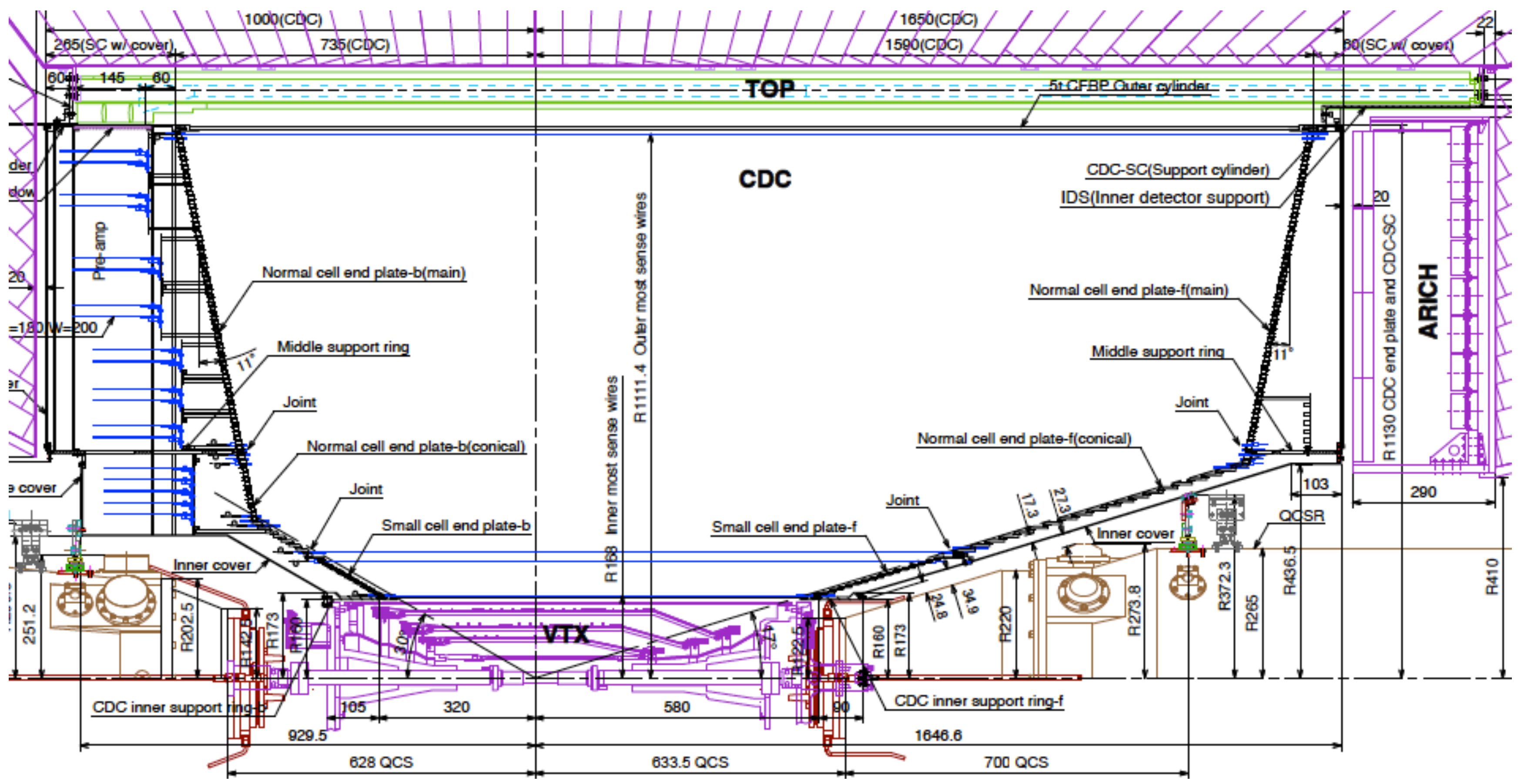
First new particle collider since the LHC
(intensity rather than energy frontier; e^+e^- rather than pp)

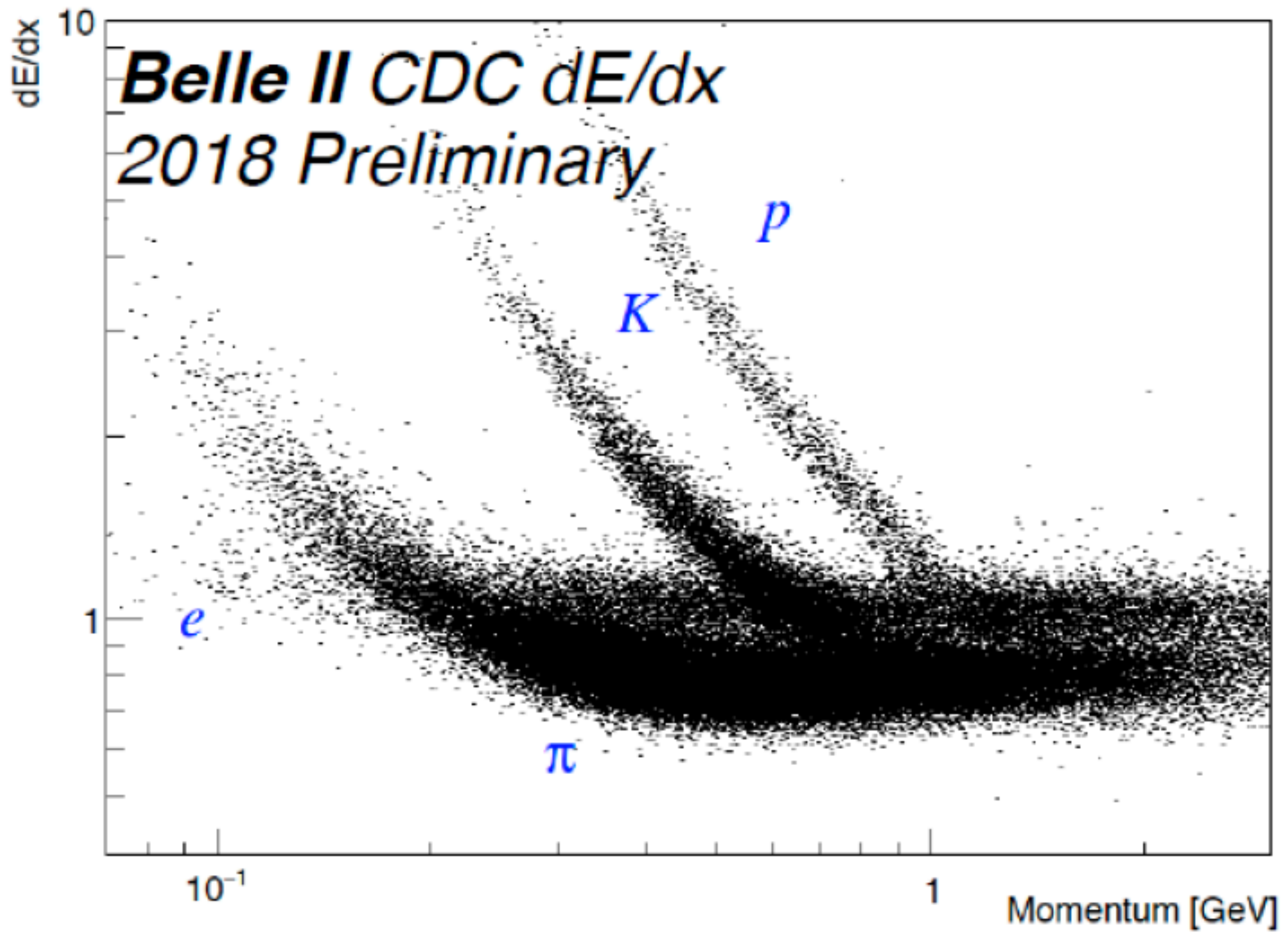
arXiv:1011.0352 [physics.ins-det]

Central Drift Chamber (CDC)

- The CDC plays three important roles
  - Reconstruction of charged tracks with precise momentum measurements
  - Particle identification using ionization energy loss (dE/dx) measurements
  - Efficient and reliable trigger signals for charged particles

- Roughly cylindrical gas-filled chamber with thin wires parallel to the primary axis
- Charged particles ionize the gas along their flight path, giving up a small amount of kinetic energy (few keV/cm)
- Electrical signals with the location (which wire) and drift time of each hit are recorded

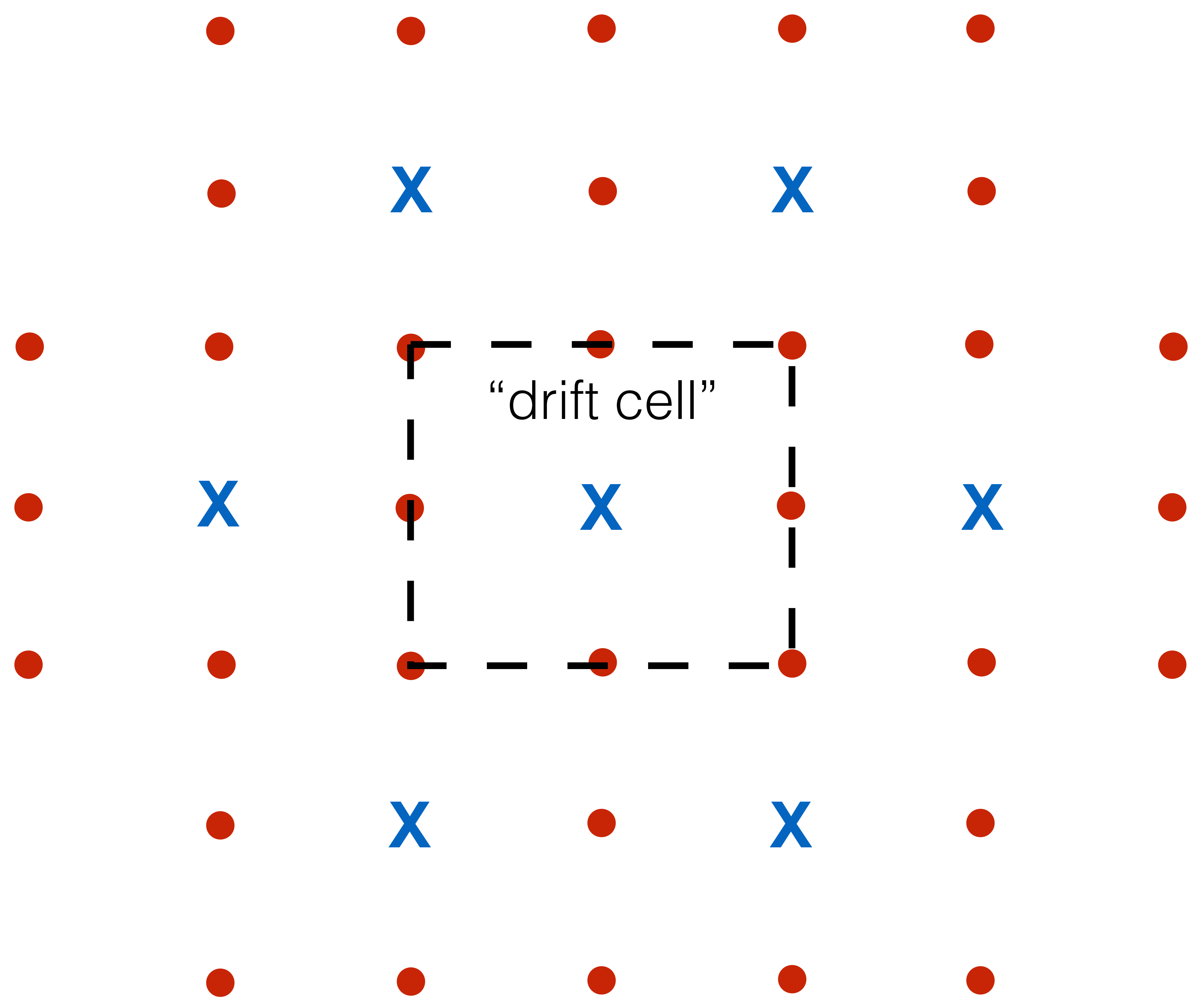




Drift cells

- CDC layers alternate between “field layers” and “sense layers”
  - Sense wires held at a large potential (anode)
  - Grounded field wires help to shape the electric field

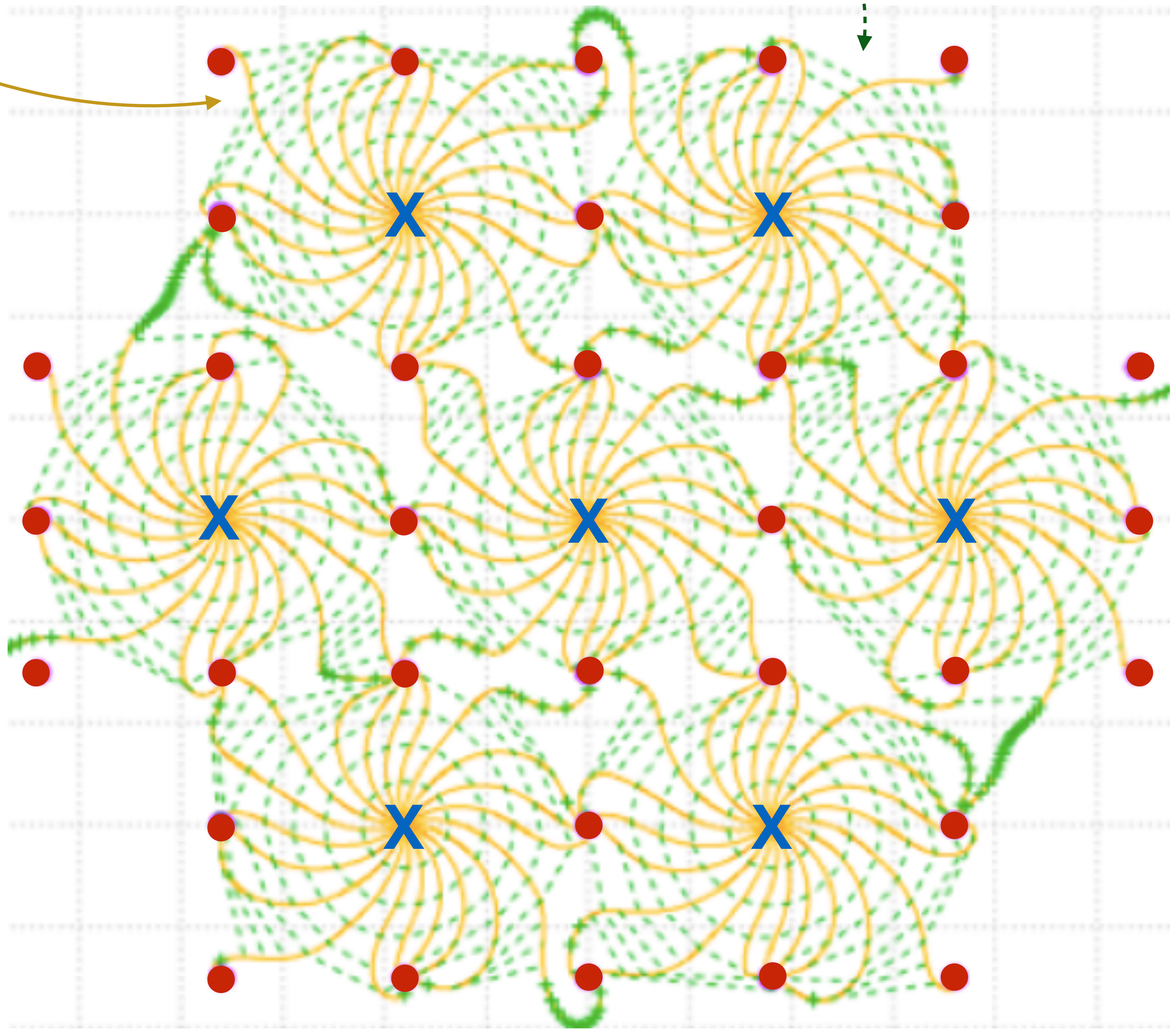
- Electrons liberated by ionization drift toward the sense wires
- Near the wires, the large electric field causes the electrons to gain enough energy per mean free path to ionize at the next collision
- Detectable signal created by avalanche of electrons near sense wires



Q: What does a drift cell *really* look like?

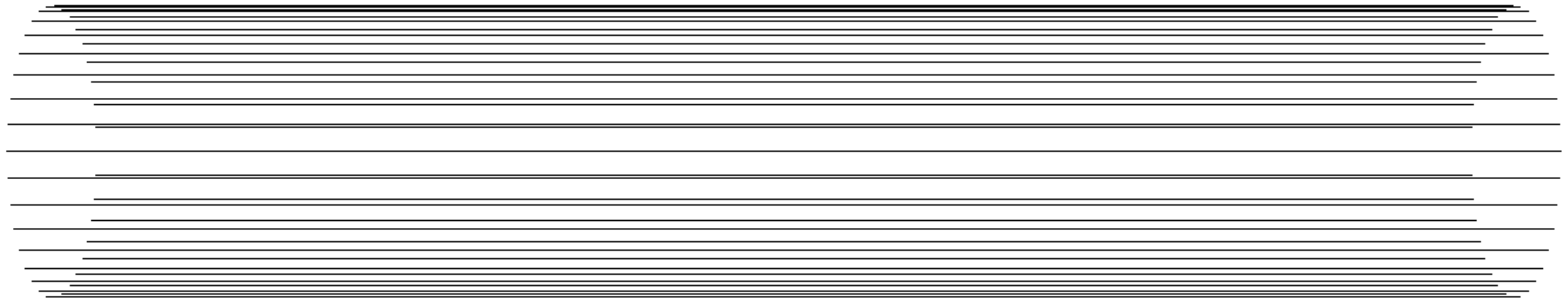
Drift cells

- Presence of magnetic field causes electron trajectories to curve
  - Changes the shape of isochrones (lines of equal drift time)
  - Lorentz Angle: angle between drift path with and without B-field
  - Couples known asymmetries in the radial direction into the ϕ direction (important to properly calibrate!)
  - Degrades electron collection at cell edges
  - Also depends on the gas composition
  - Note: B-field can have a big effect on drift time!

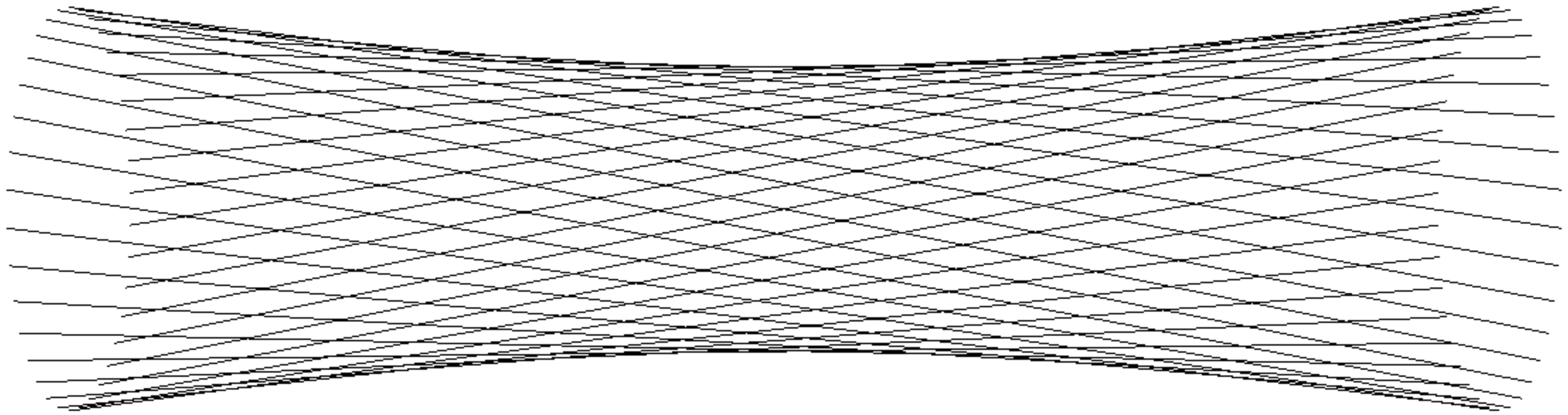


Stereo layers

- Some layers have a stereo angle to measure z information
  - A larger stereo angle provides better z resolution, but a large variation in the radial cell size along the z direction occurs in the boundary region between axial and stereo superlayers
  - Geometrical variations of cells are reduced by implementing half of the full stereo angle in the transition layers (similar procedure used in Belle)
  - The sense wire is then only ~1 mm closer to the field wire so a large gain variation is avoided



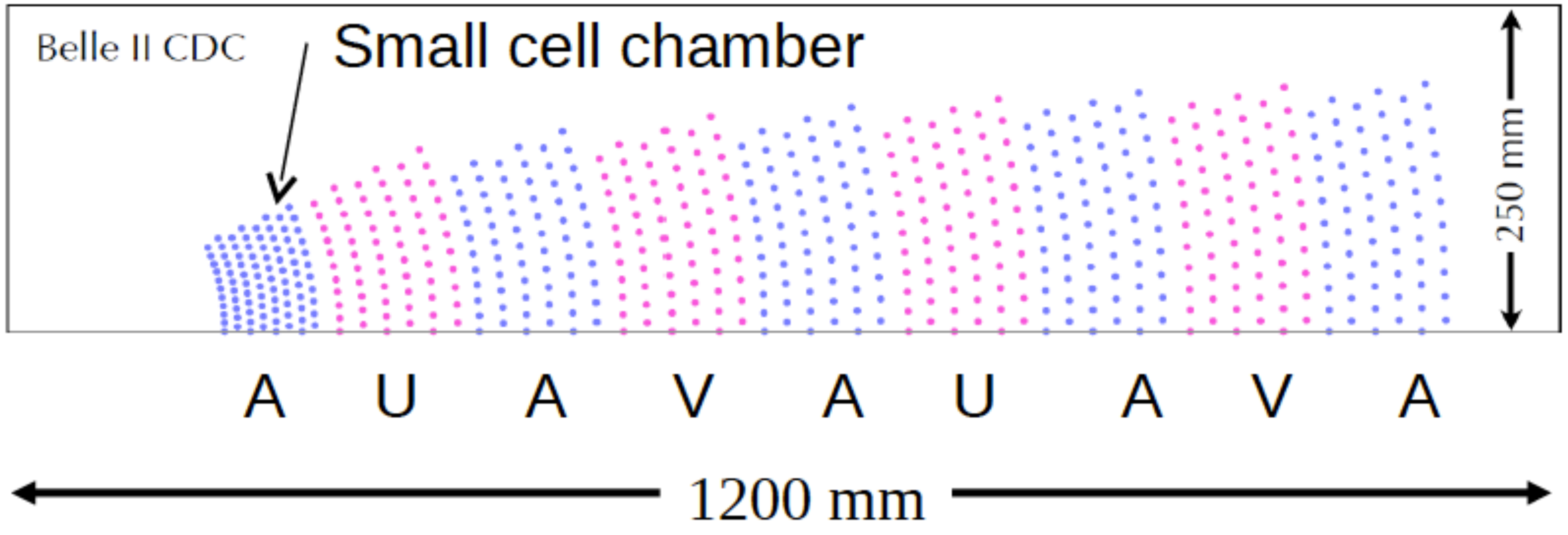
Axial layer



Stereo layer

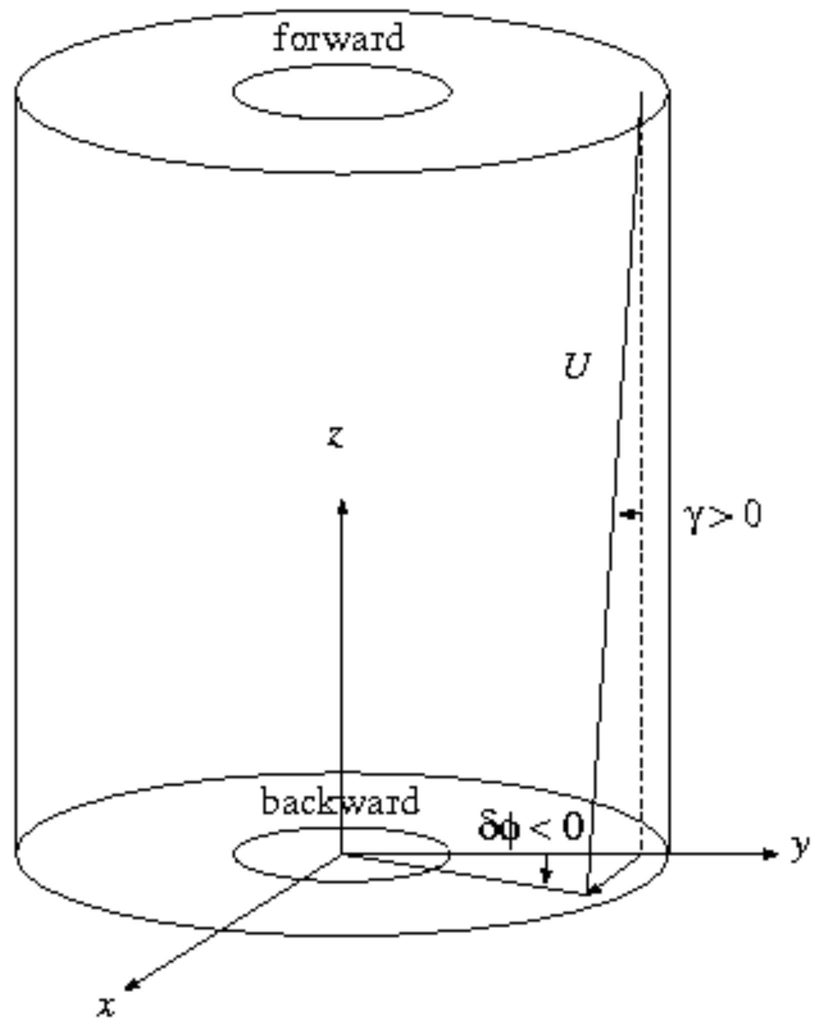
Superlayer structure

- Group layers with similar stereo angles into superlayers
  - Six layers in each superlayer, vs 3-4 layers each in Belle
  - Innermost, outermost super layers contain axial (A) layers, to match the shape of the inner, outer cylinders
  - Superlayers alternate between stereo (U or V) and axial layers
- Innermost superlayer is implemented separately as a small-cell chamber
  - Two additional layers with active guard wires to protect against high occupancy from beam backgrounds



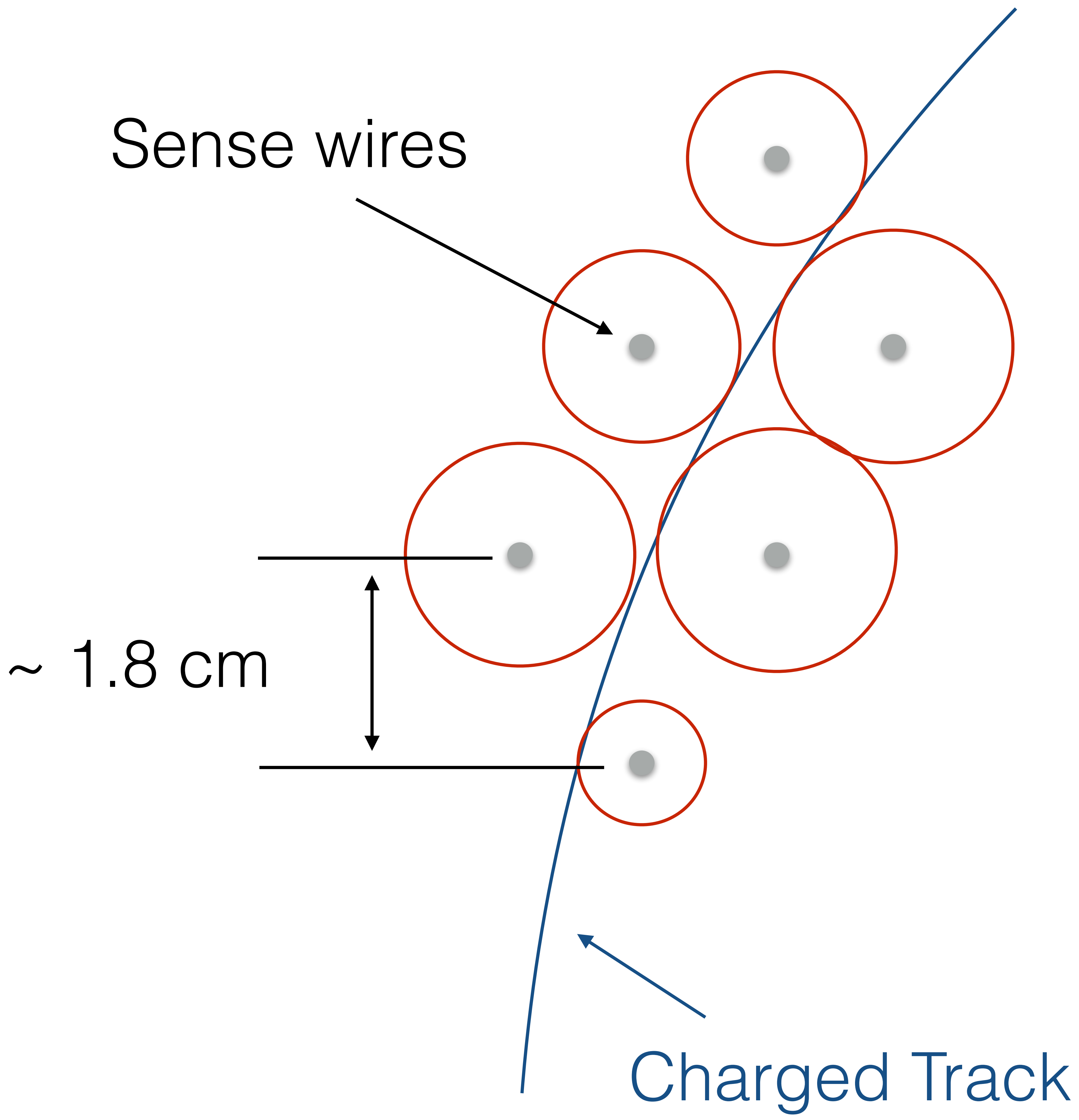
U: $\delta\phi < 0$

V: $\delta\phi > 0$



Very simplistic overview of tracking

- Localize a charged track to be on a ~135 μm resolution drift circle around wire



- Detector hits are collected into a track segments with pattern recognition algorithms
- An approximately helical fit is applied to the track segments, taking into account things like multiple scattering and ionization energy loss
- Track segments are merged into track candidates, which are then fitted to tracks with a particular mass hypothesis

*Gary Varner: Wednesday

Particle IDentification (PID)

- Particle identification is basically measuring mass (measure both p and β simultaneously)
  - $\pi^{\pm}$: 140 MeV
  - $K^{\pm}$: 494 MeV
  - $p^{\pm}$: 938 MeV
  - $\mu^{\pm}$: 106 MeV

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\beta^2}}$$

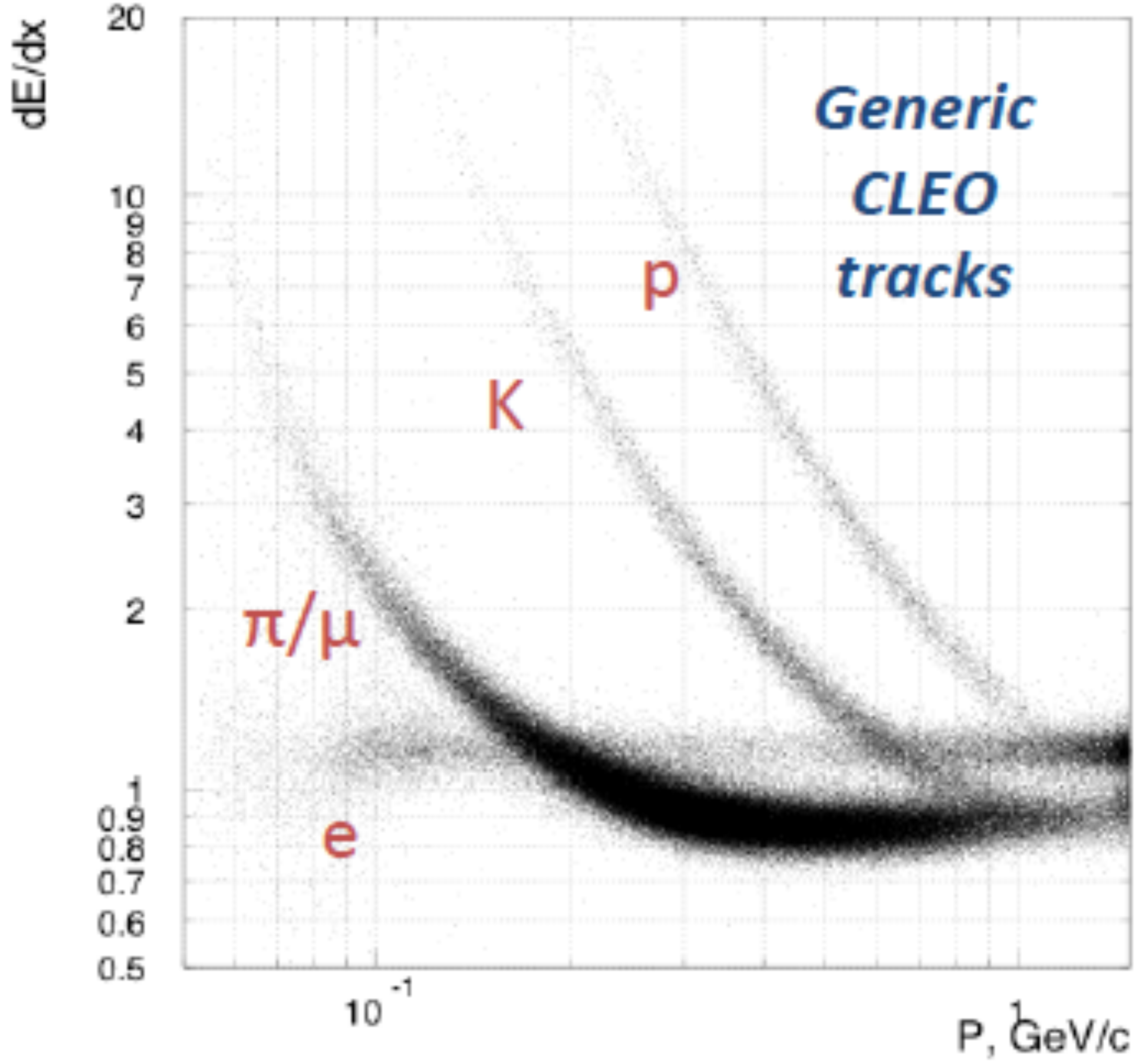
$$\beta\gamma = \frac{p}{m}$$

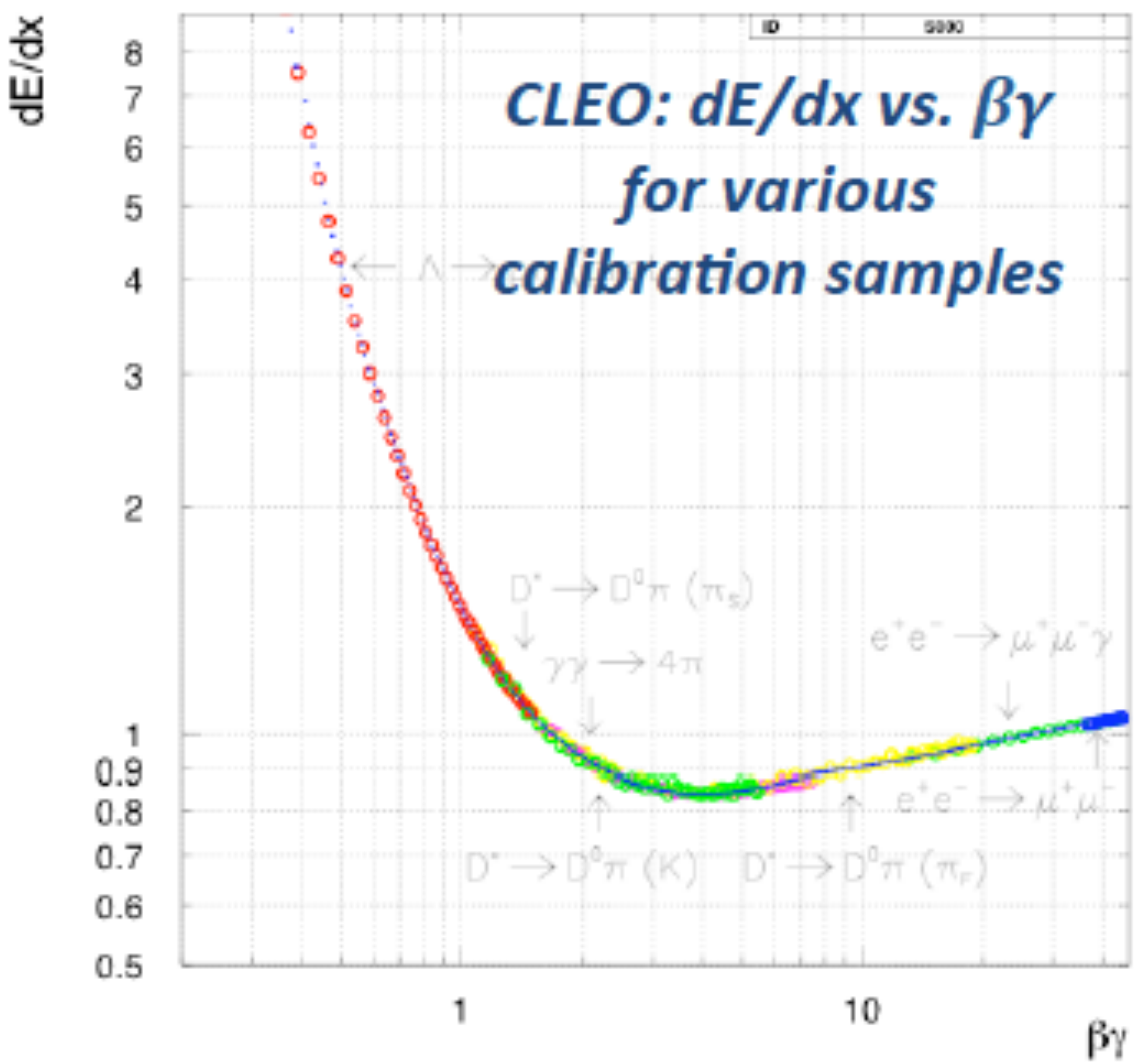
- All depends on the interaction
  - electrons shower in rather light materials (according to X0)
  - hadrons will cross light material and shower in dense ones
  - muons will survive almost everything

- Some options:
  - Specific energy loss: dE/dx
  - Time of flight (ToF)
  - Cherenkov techniques

Basic philosophy

- dE/dx should depend only on βγ = p/m (Bethe-Bloch formula)
- Make this happen by doing low level calibrations well (not arbitrary high level corrections later)

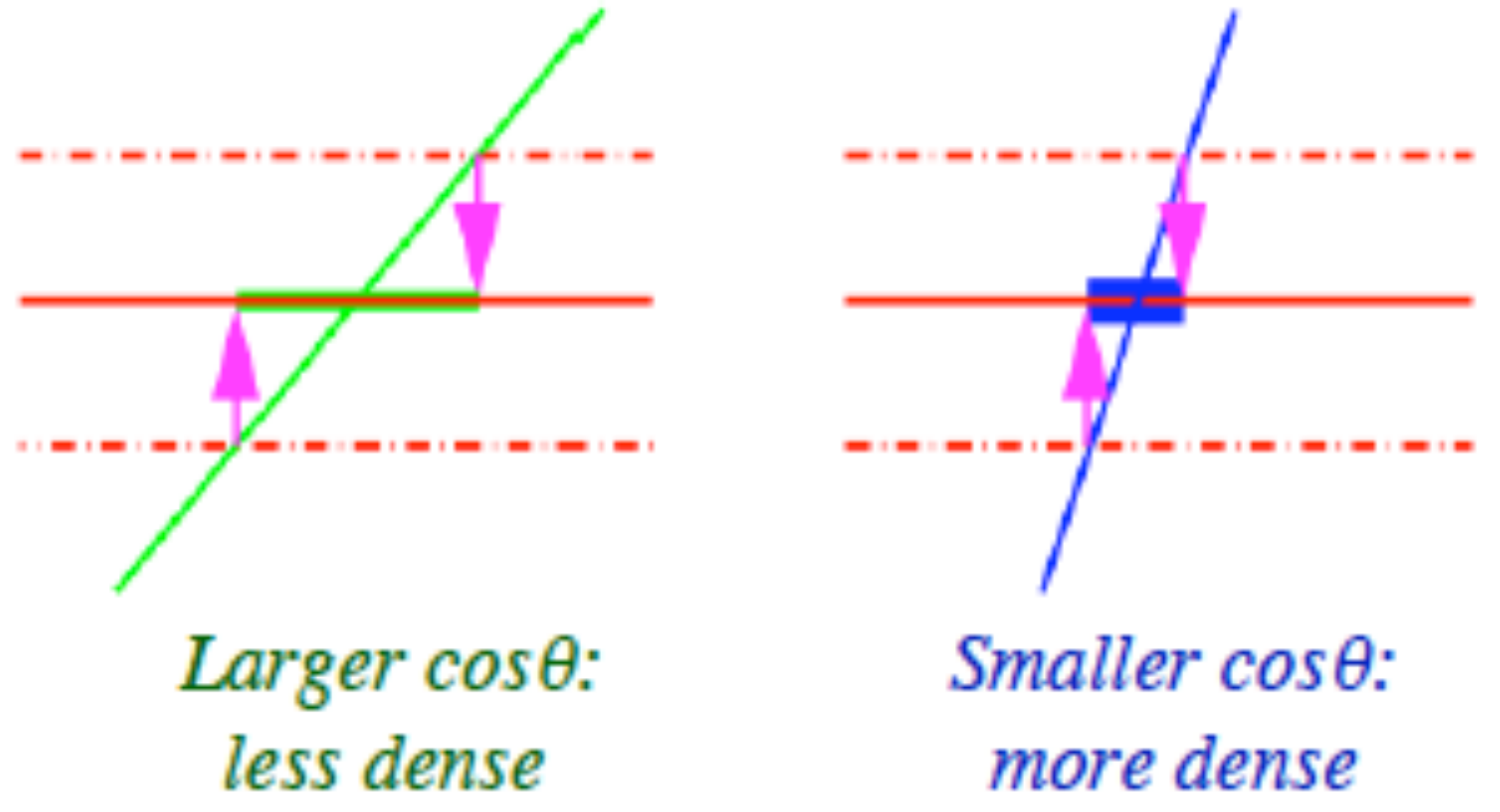


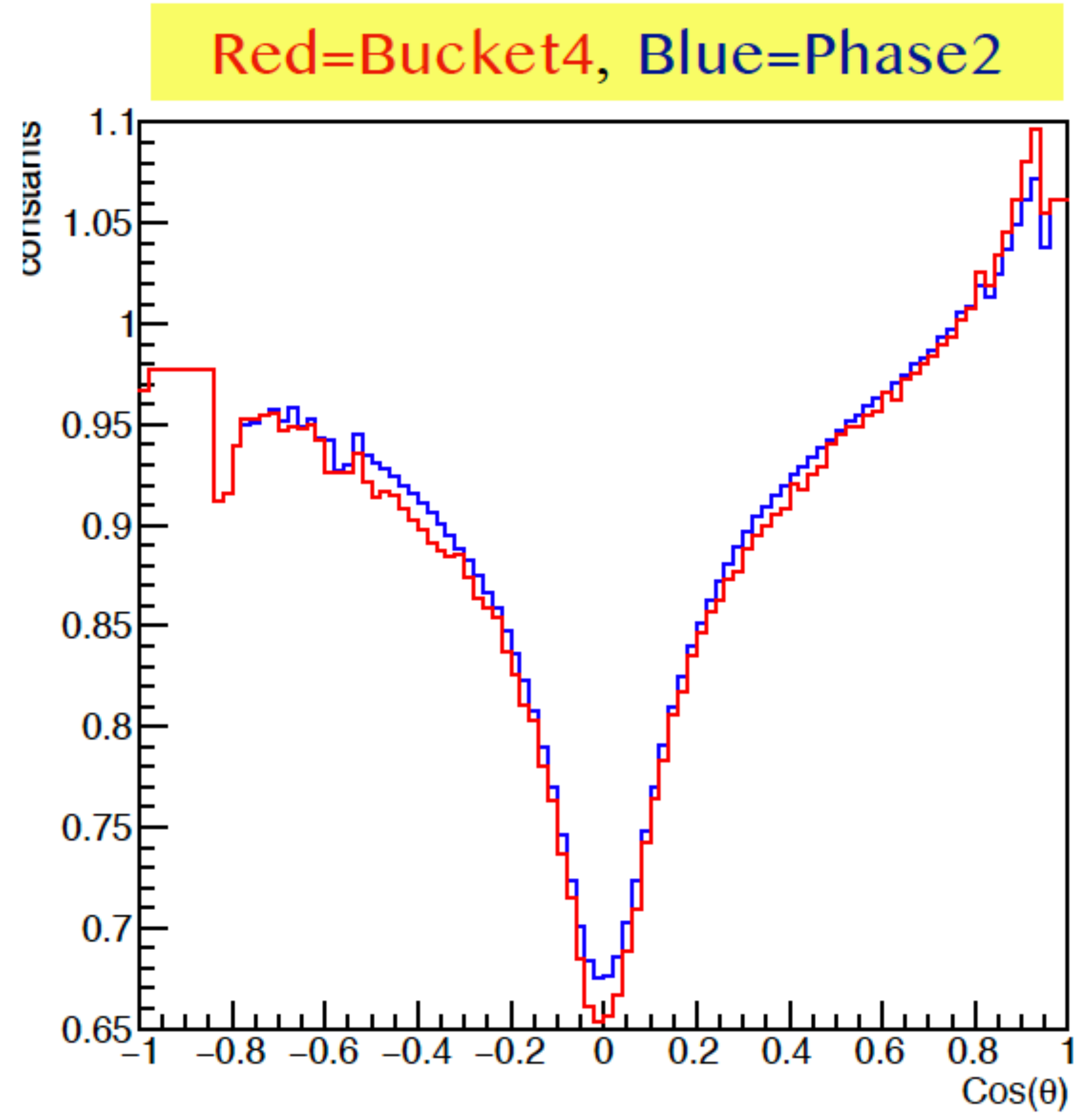


Q: Why is it useful to set dE/dx to 1 for electrons?

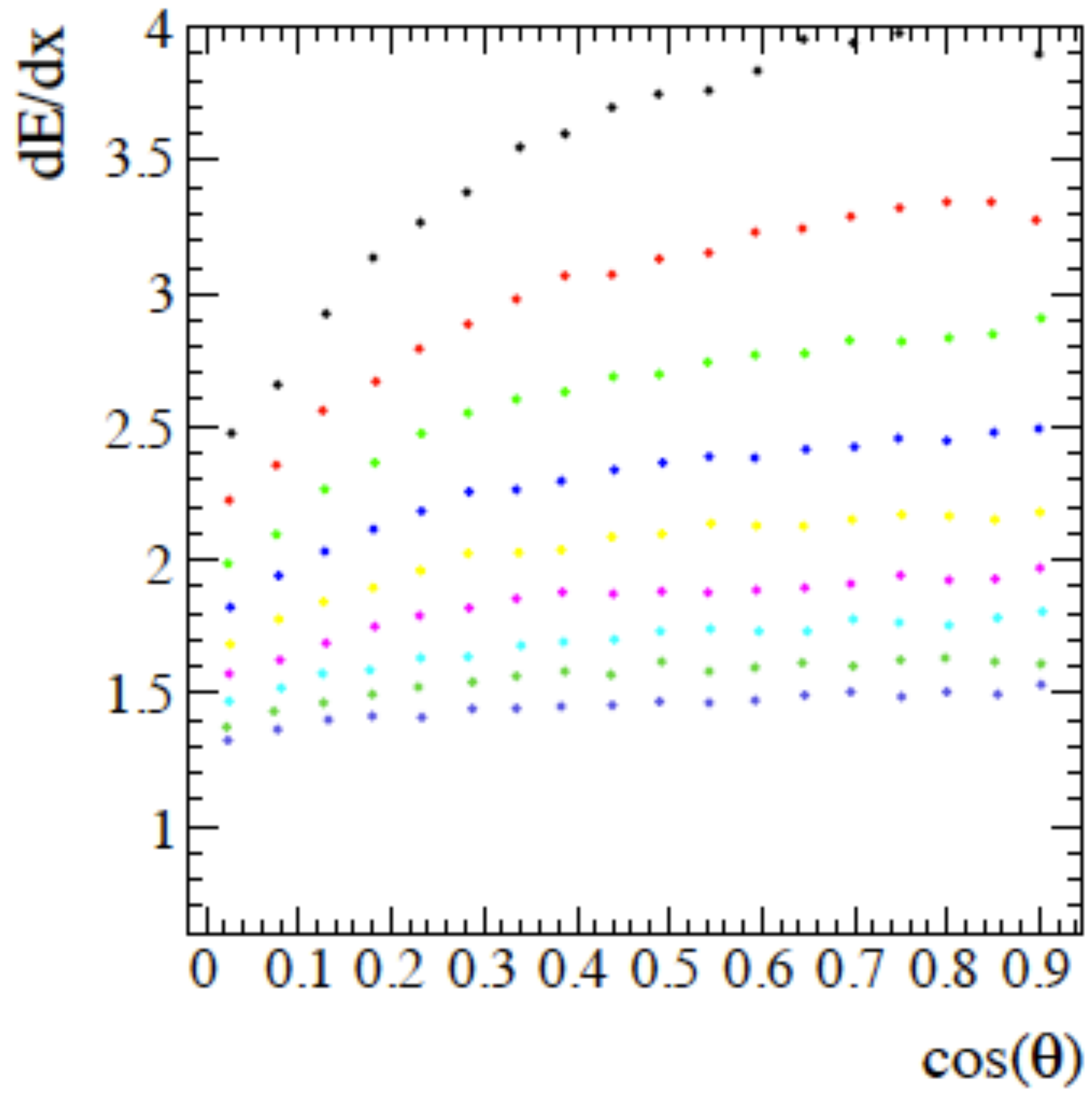
dE/dx calibration

- Variations and non-linearities in running conditions bias and degrade dE/dx measurements
  - Different cell sizes, bad wires, electronics, weather, etc
- Challenging one: charge screening effect - depends on polar angle
  - Avalanche from early electrons screens wire
  - Reduces local field and hence gas-gain for later electrons
  - Gas gain saturation depends on ionization!



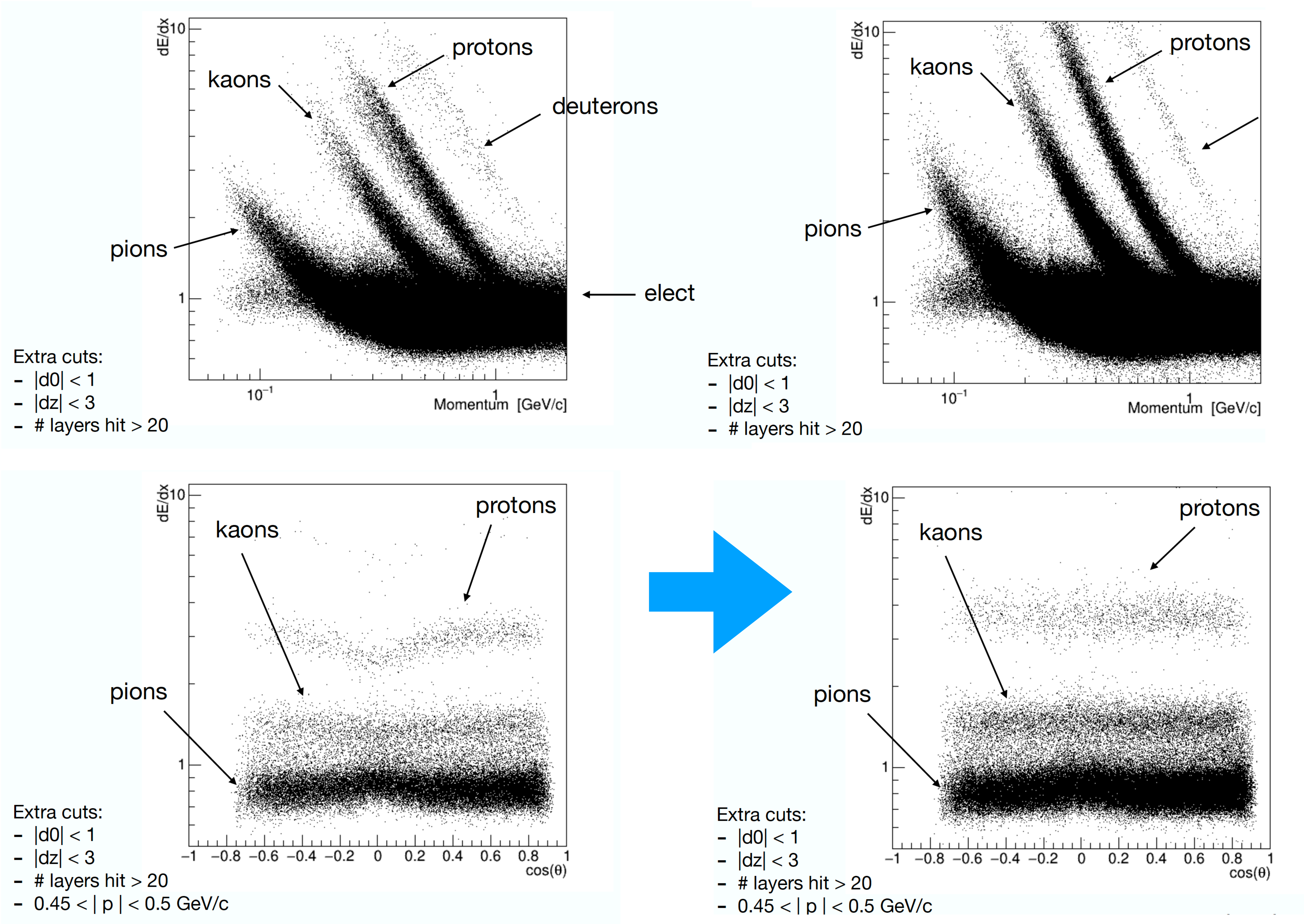


Example from BESIII data

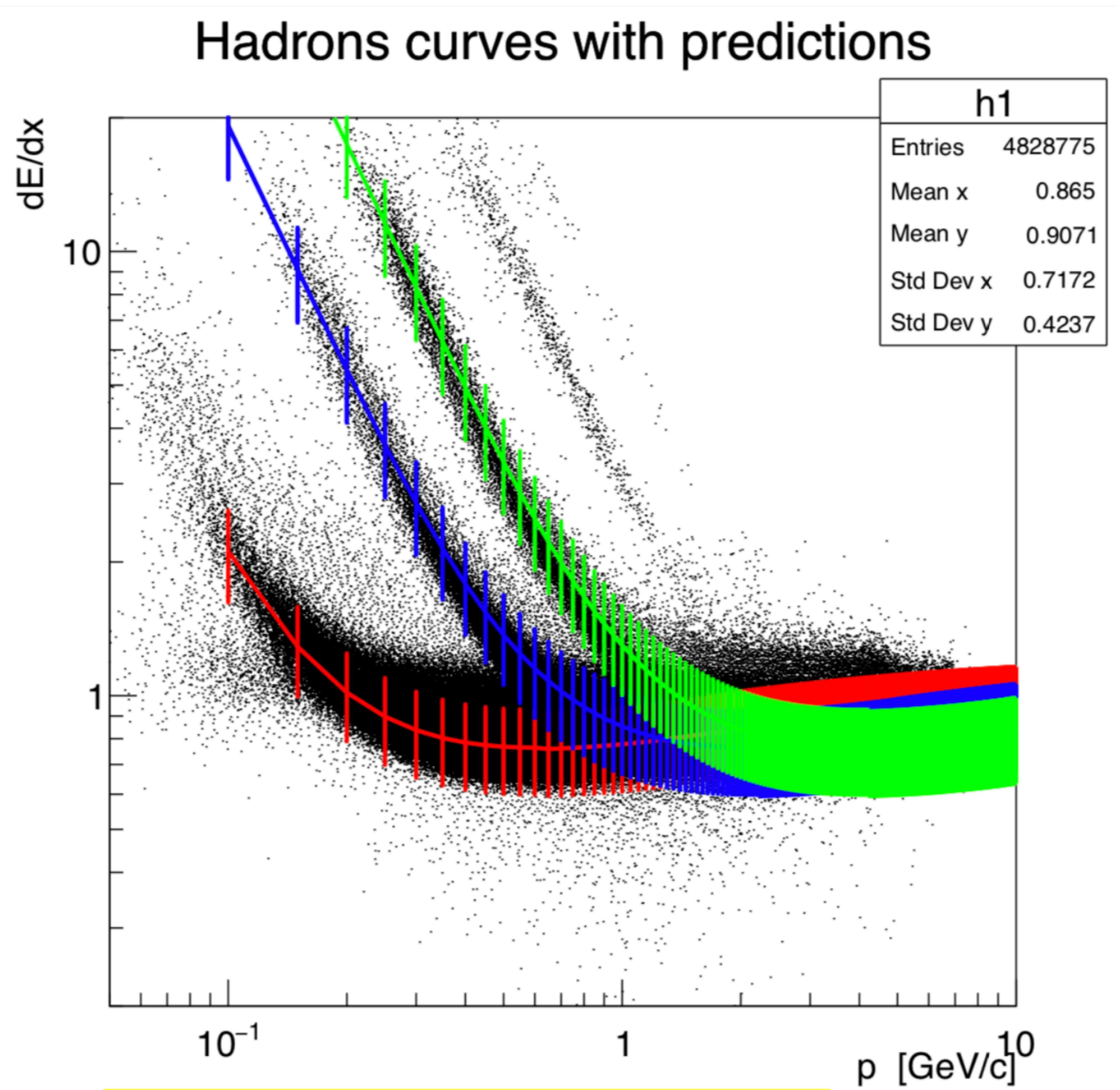


Early “hadron” calibration (by hand!) with Phase 2 data

Prod3 data

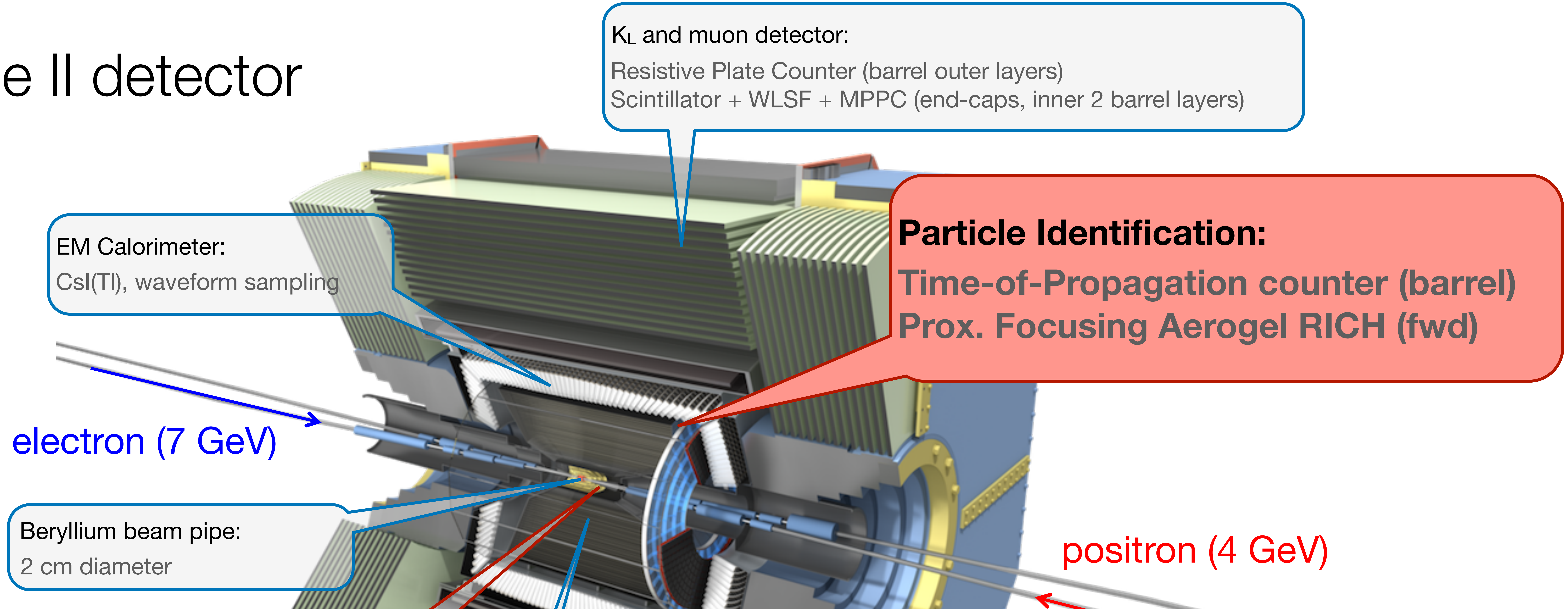


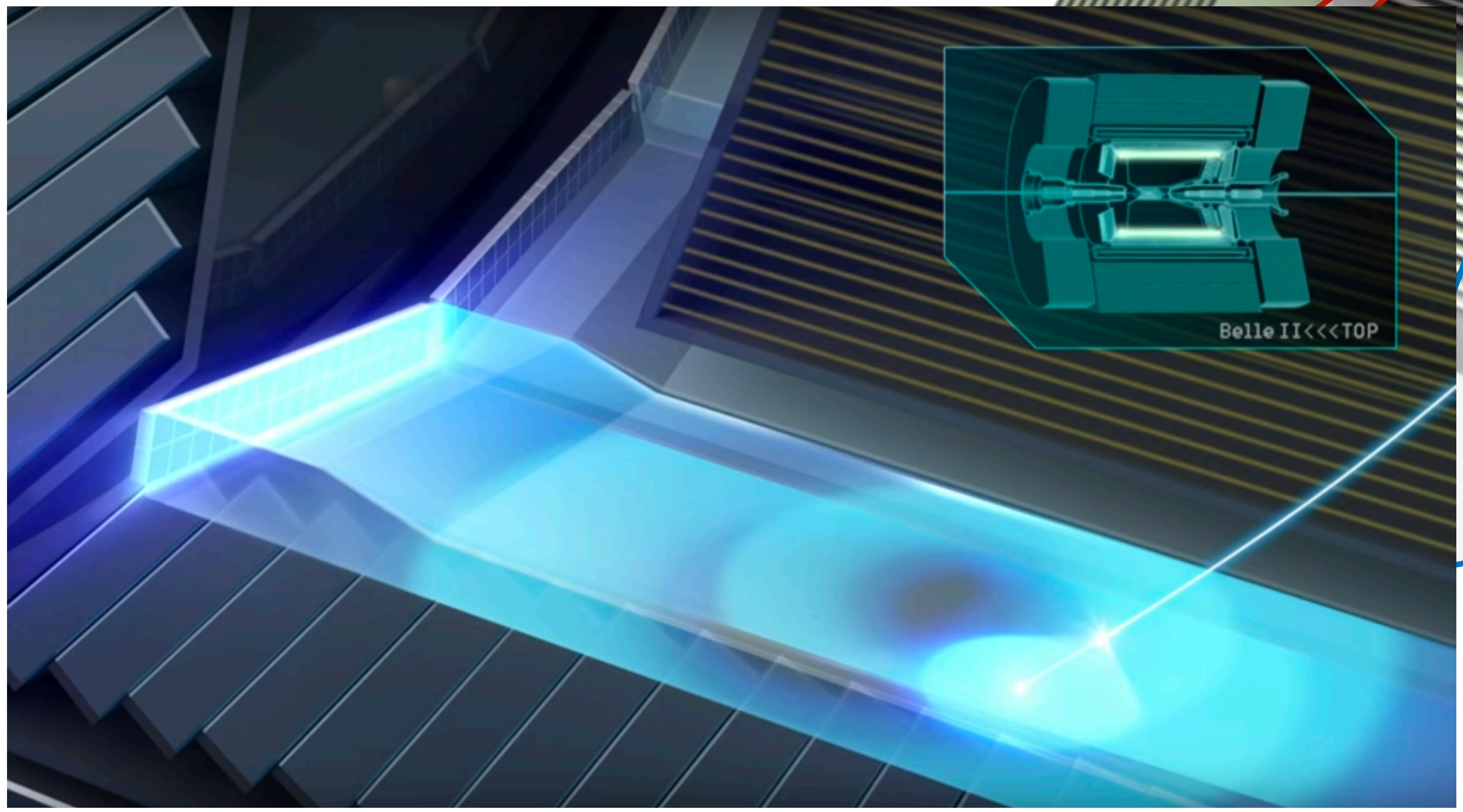
Proc8 data

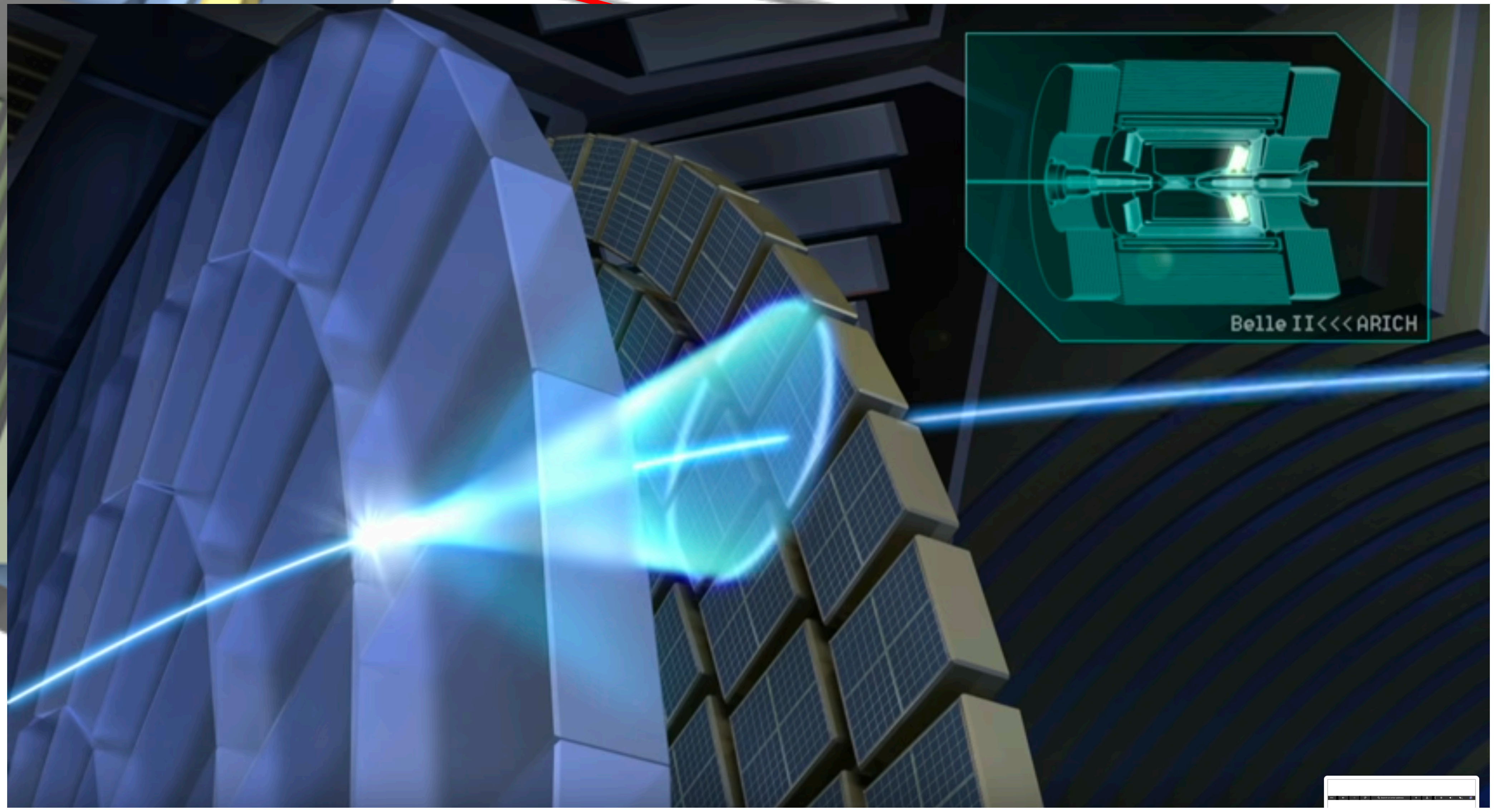


From hlt_hadron skim sample

The Belle II detector





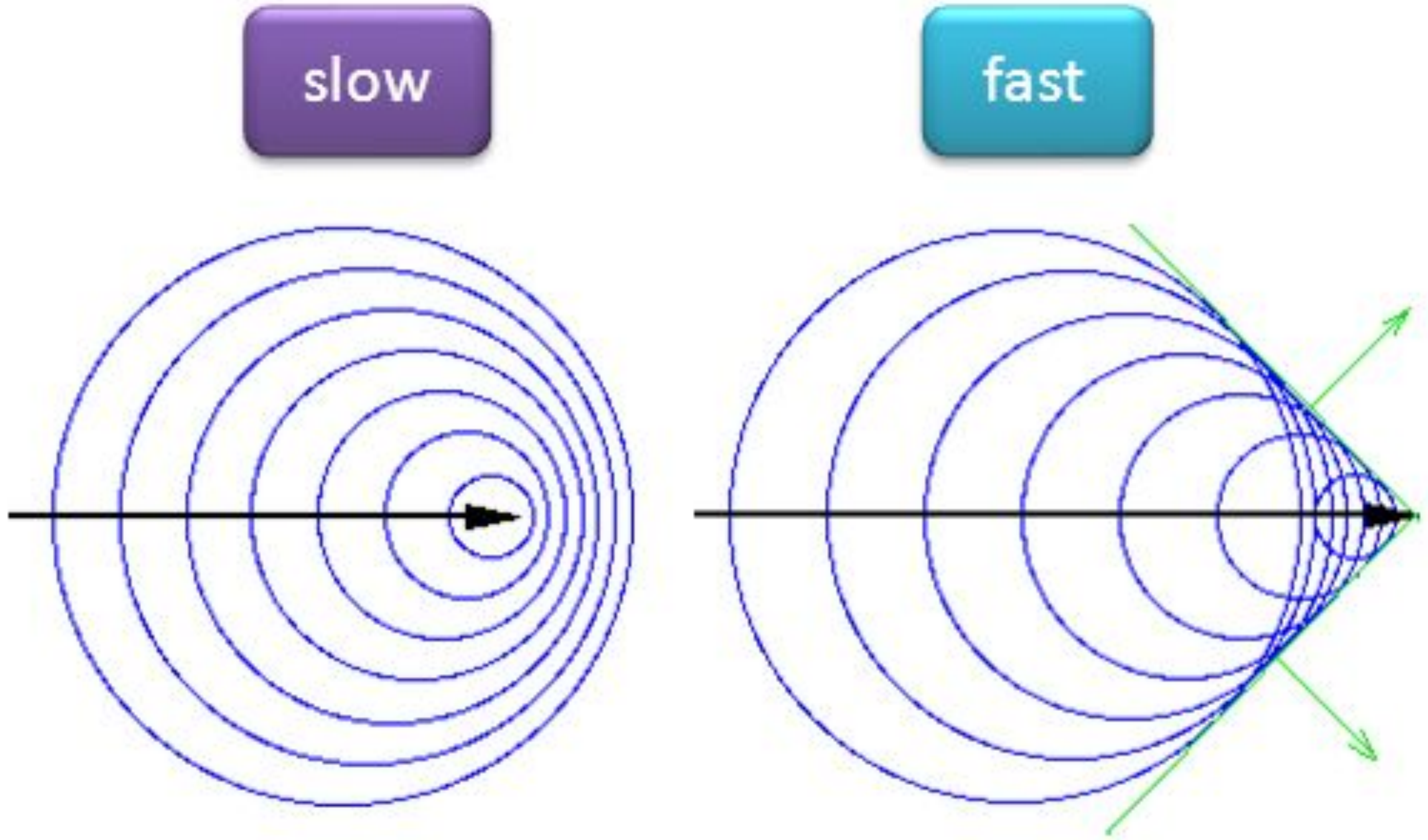


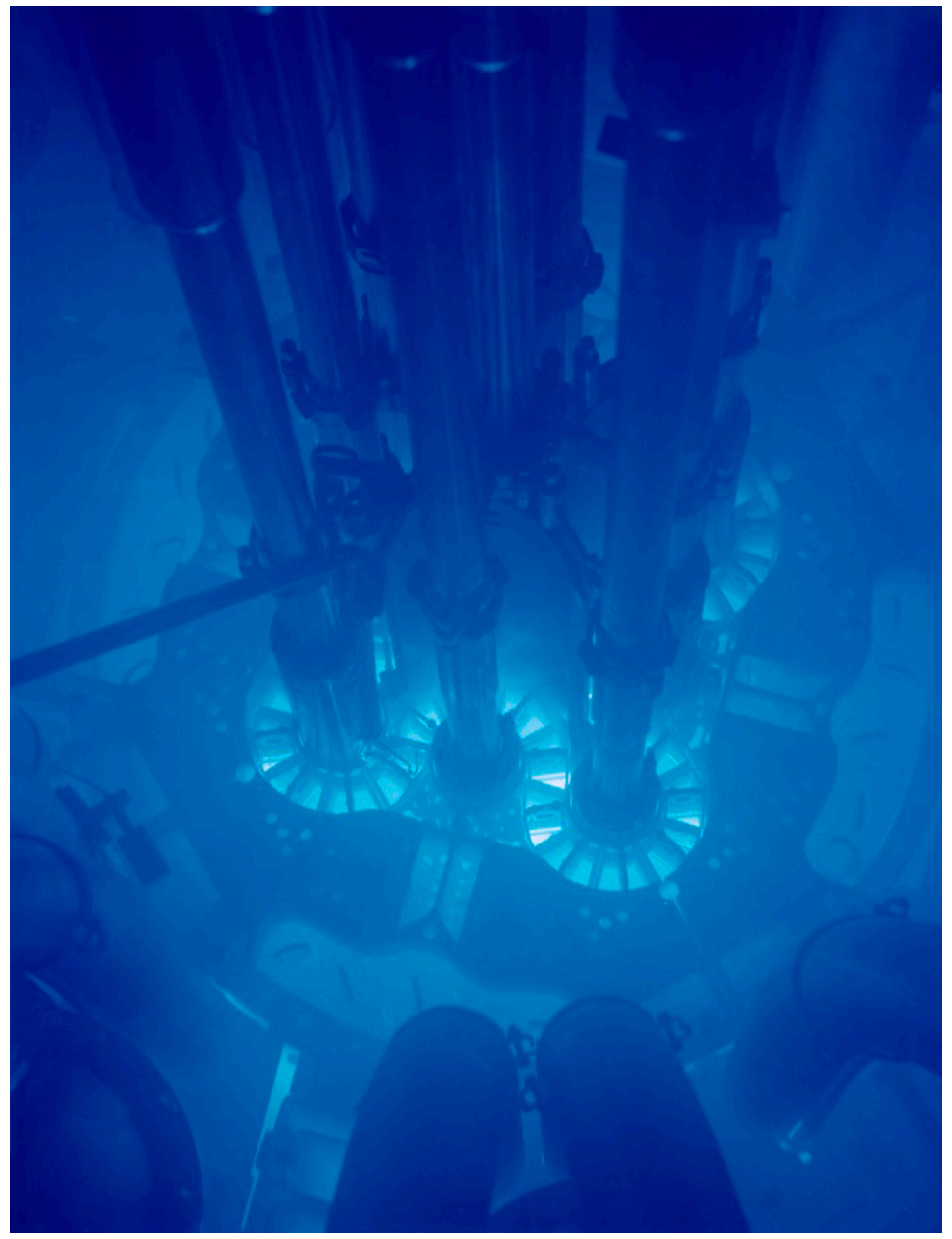
Particle IDentification (PID)

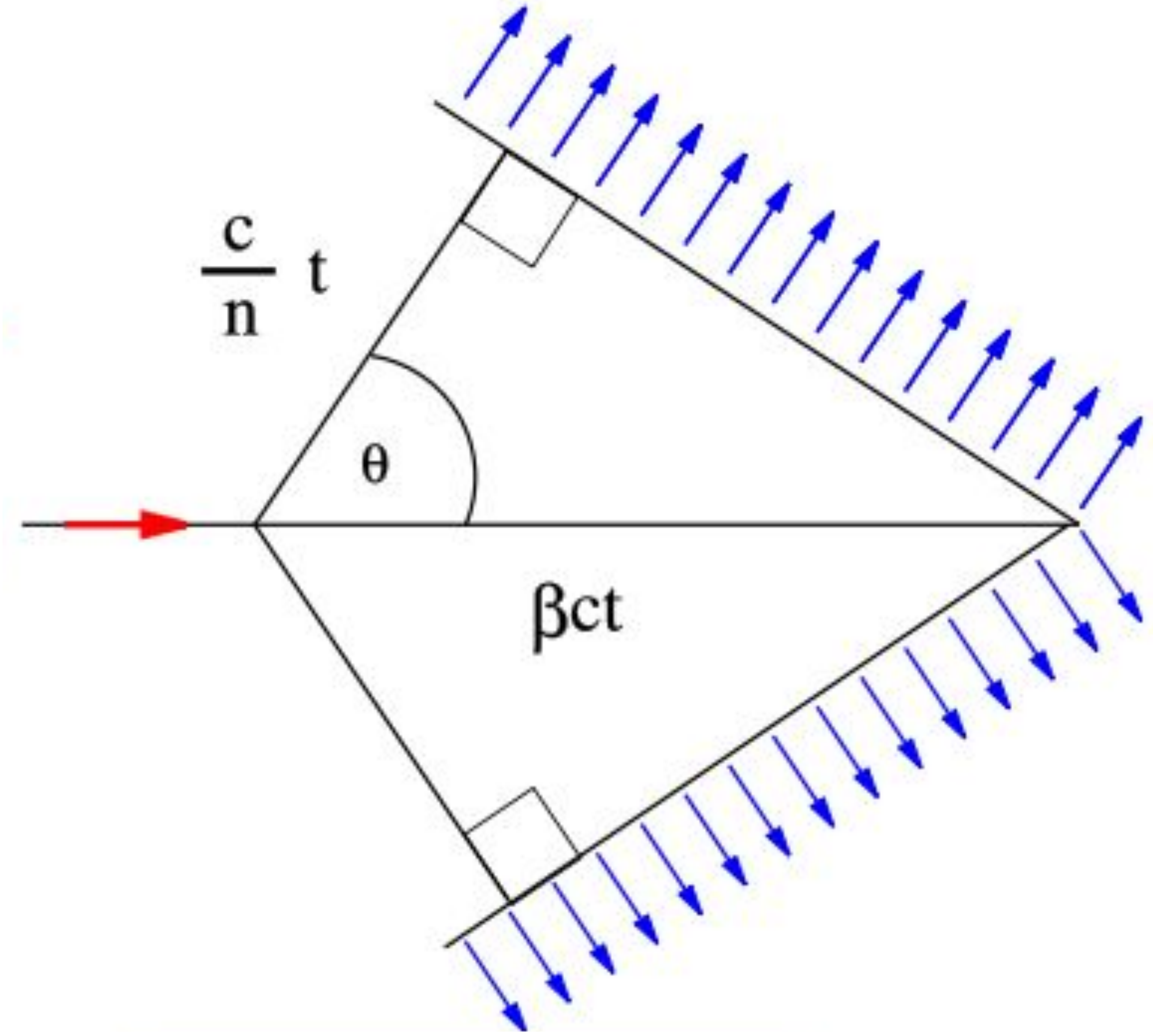
- Use Cherenkov radiation to identify charged particles
- Charged particle moving through a dielectric medium with velocity > the propagation speed of light in the medium will radiate photons
  - Velocity threshold effect (n.b.: Interestingly, this is radiation from constant motion)
- Photons are emitted at a fixed angle:

$$\cos(\theta) = \frac{1}{n(\omega)\beta}$$

- Emission spectrum is ~1/E: mostly in optical range

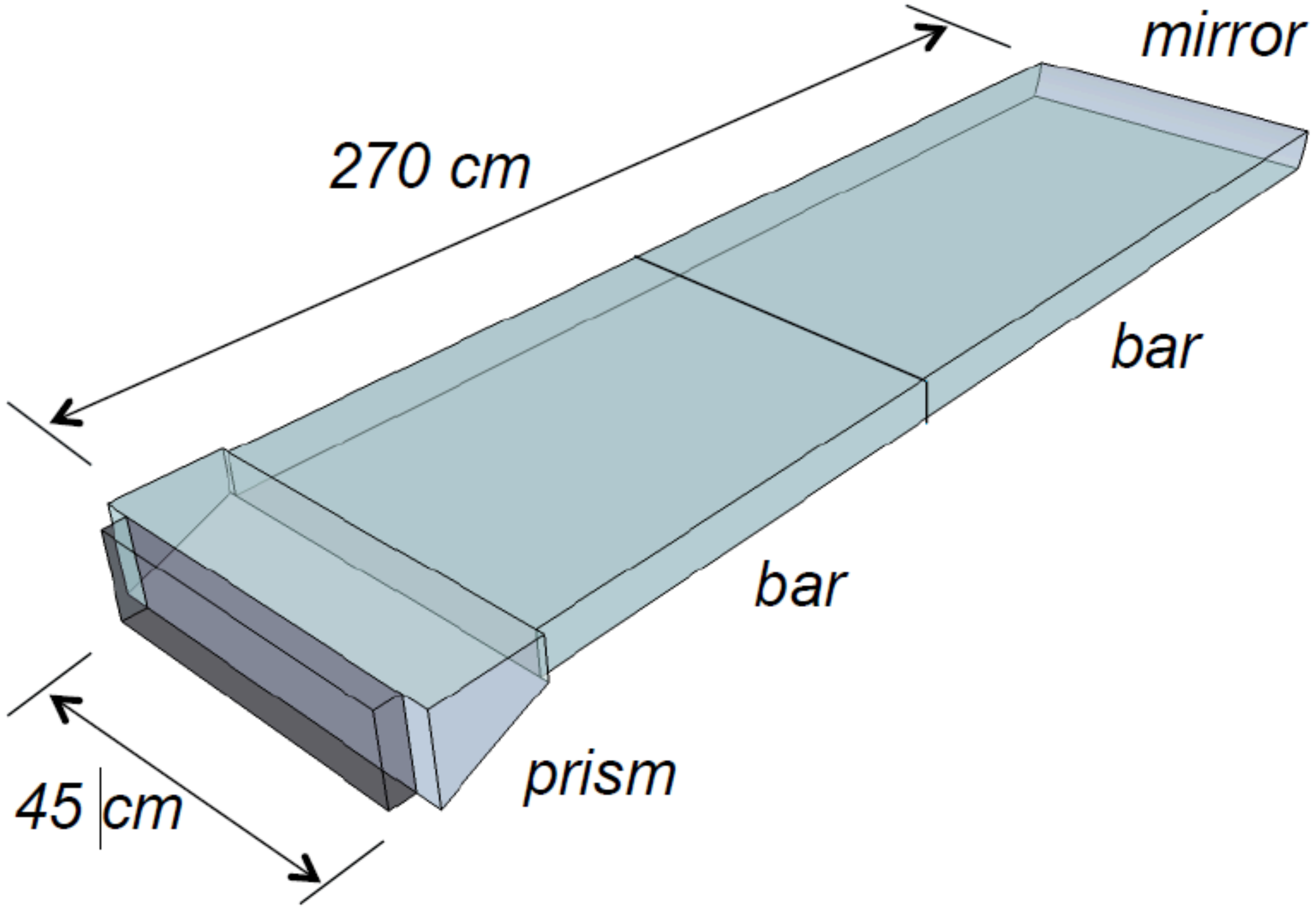


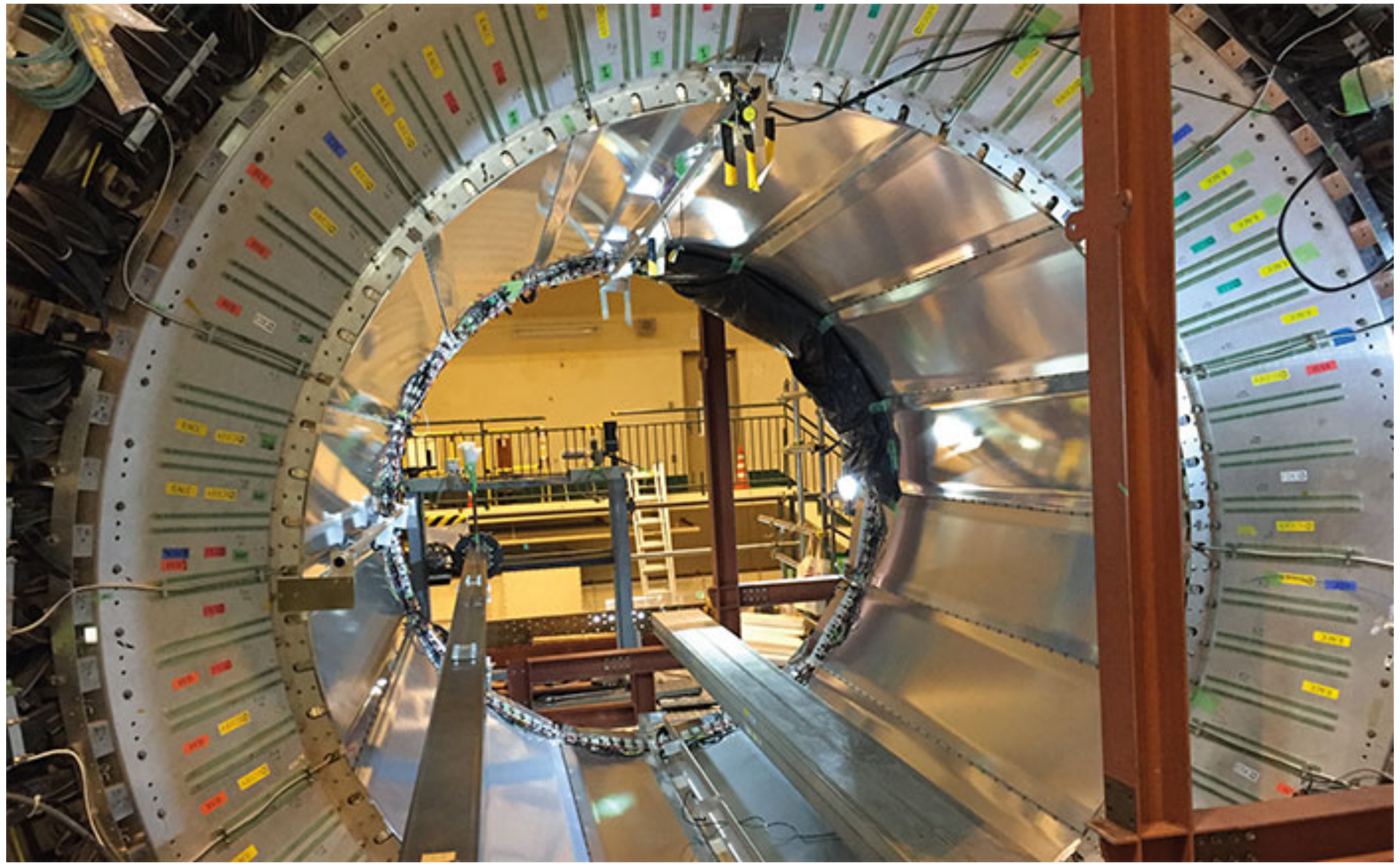




imaging Time Of Propagation counter (TOP)

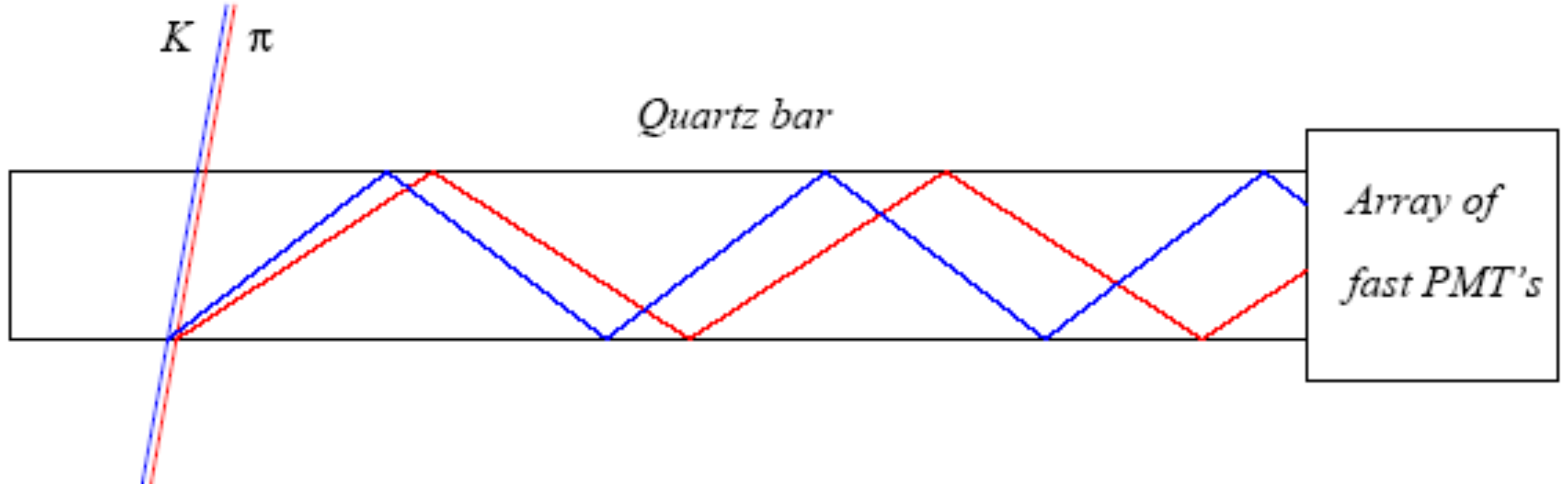
- 16 quartz Cherenkov radiator bars arranged around IP
- Forward side: spherical mirror
- Backward side: small expansion prism, sensors, readout electronics

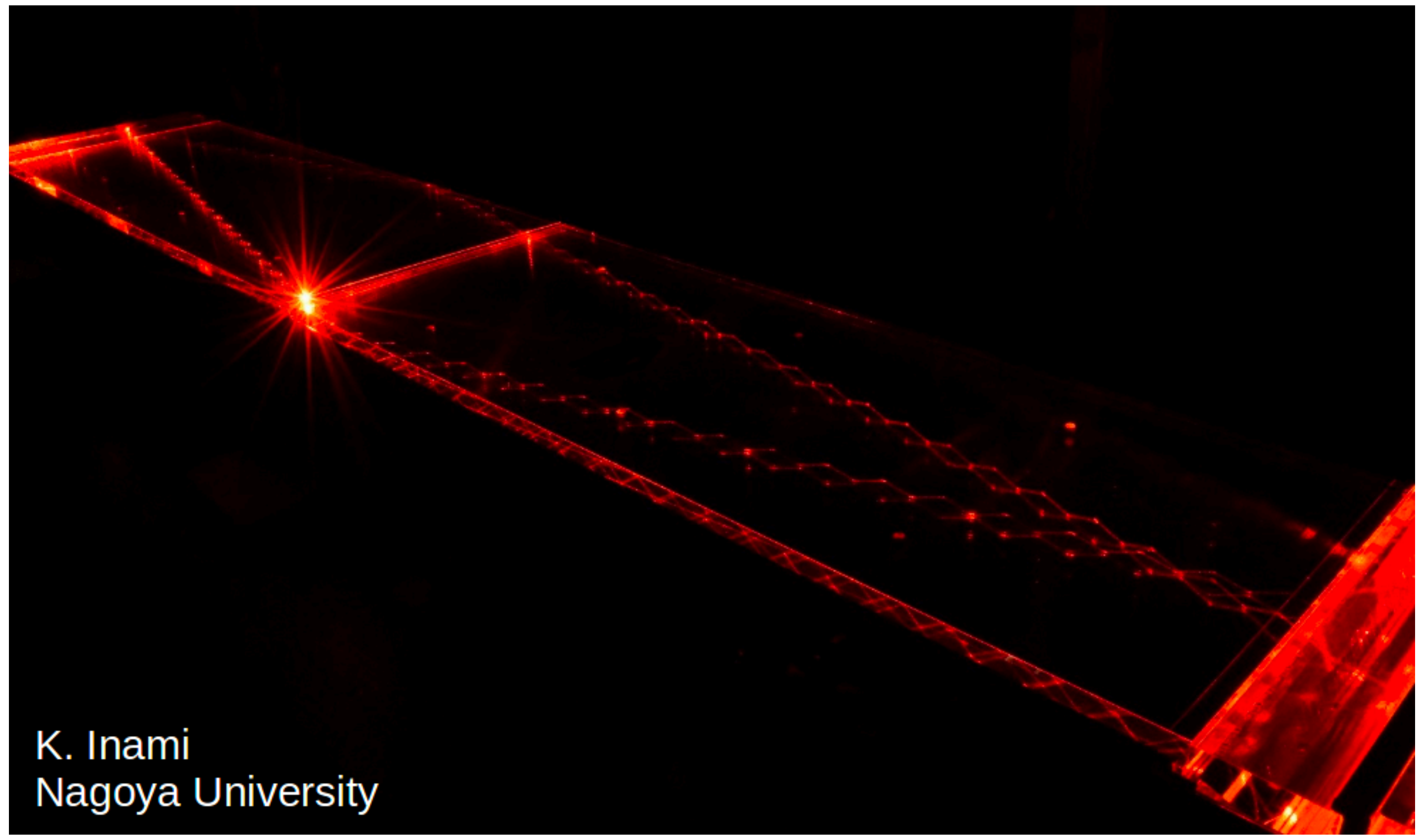


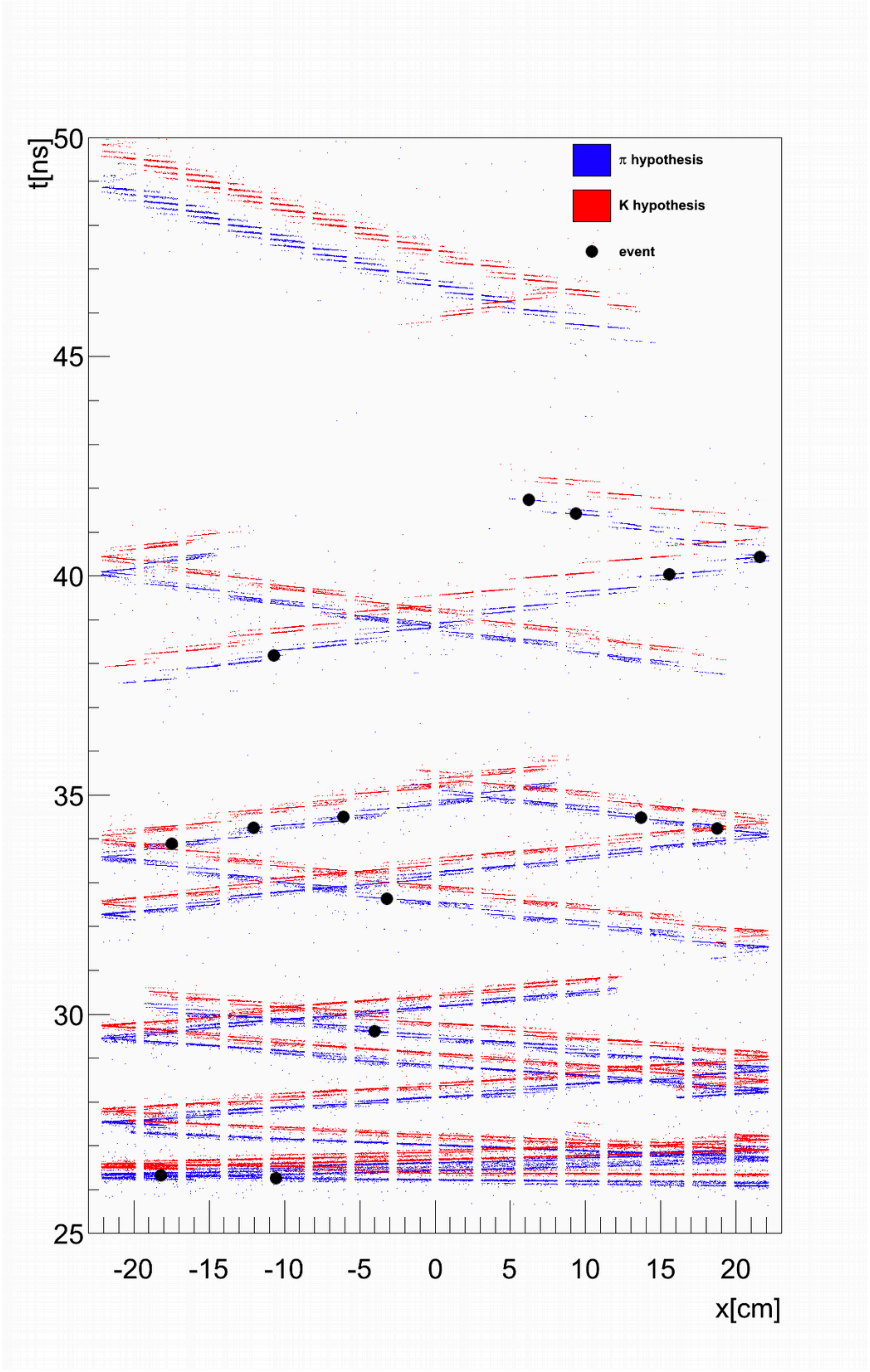


imaging Time Of Propagation counter (TOP)

- Umberto Tamponi: measure the Time And Relative Dimension In Space
- Cherenkov angle is preserved in the time of propagation and light pattern
- Reconstruct angle from two coordinates and the time of propagation of the photon







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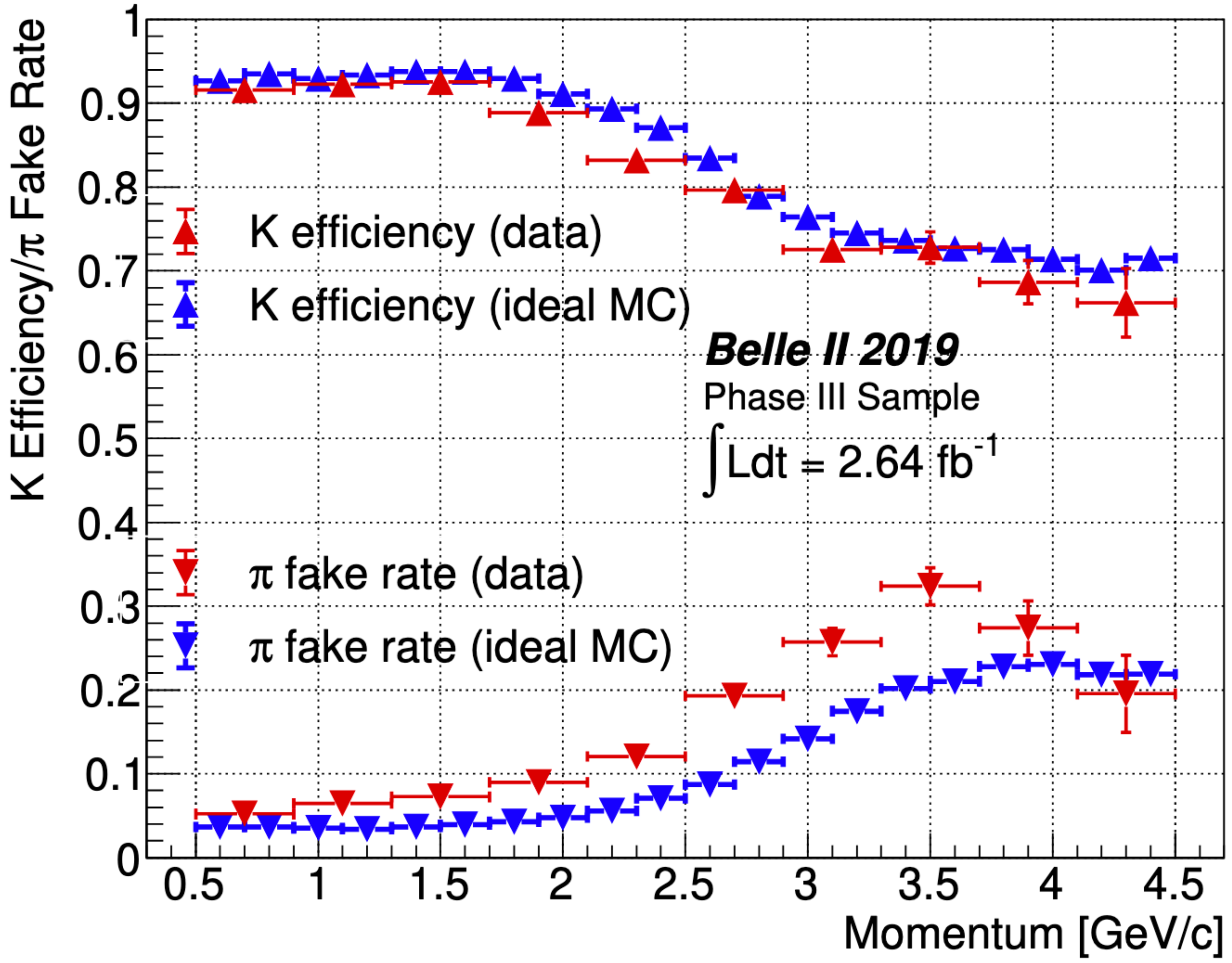
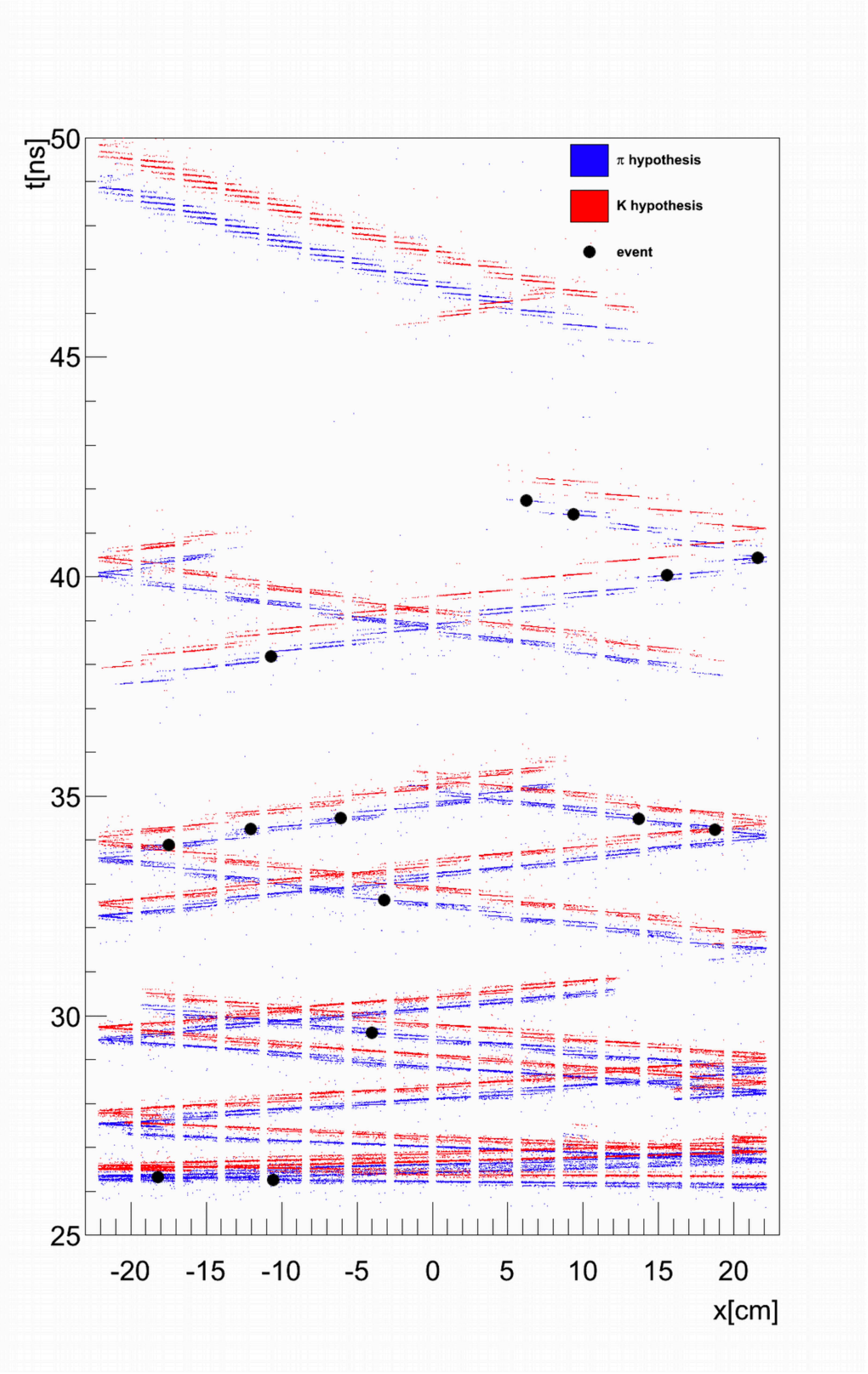


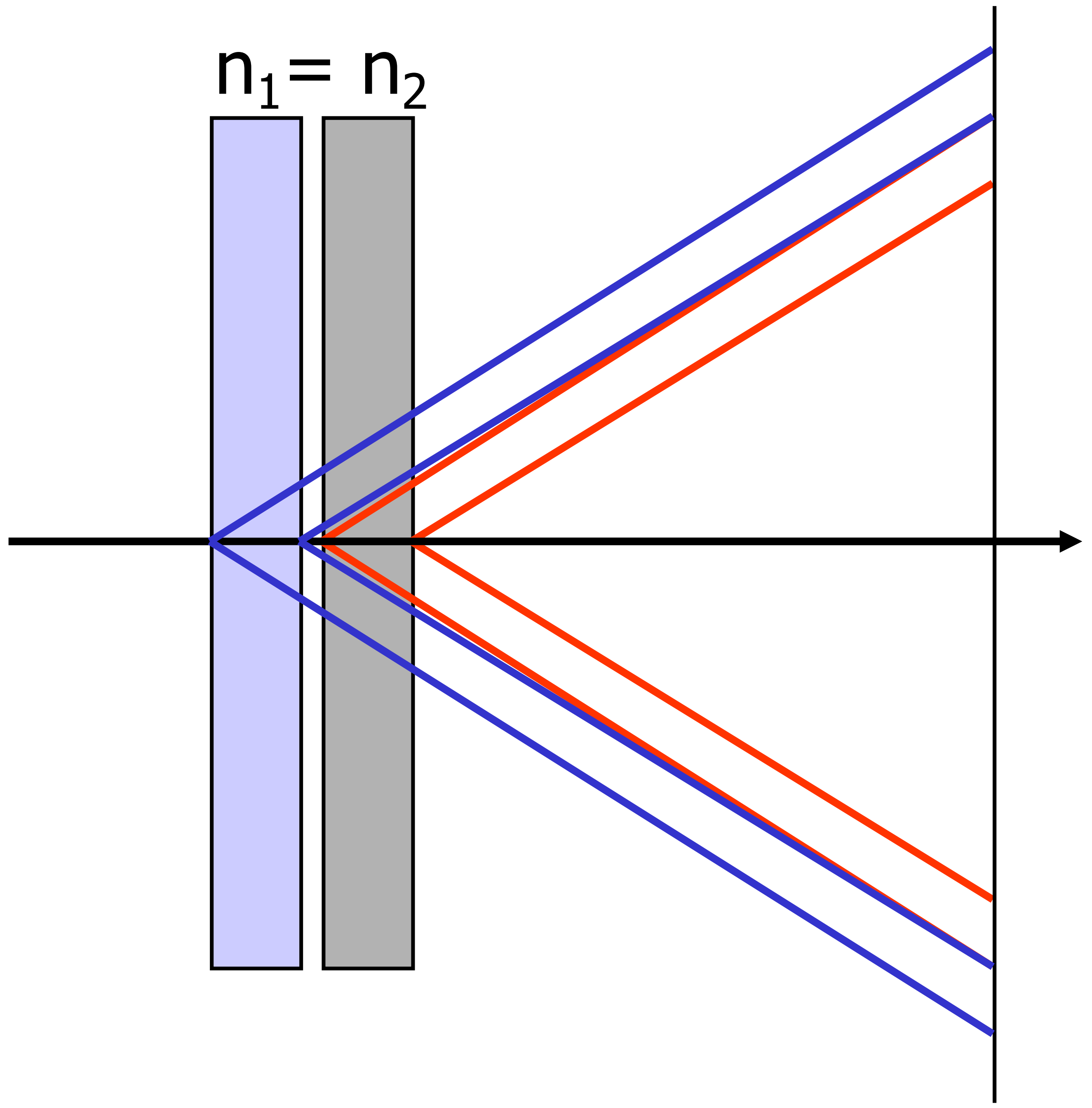
FIG. 4: Kaon efficiency and pion fake rate for the TOP only PID criterion $\mathcal{R}_{K/\pi} > 0.5$ using the decay $D^{*+} \to D^0[K^-\pi^+]\pi^+$ in the bins of momentum of the tracks.



Aerogel Ring Imaging CHerenkov detector (ARICH)

- Q: How can we increase the number of photons without degrading the resolution (“thicker rings”)?
- A: Stack two tiles with different refractive indices: “focusing” configuration

- Great! … but now we need a material with a “tunable” index of refraction…



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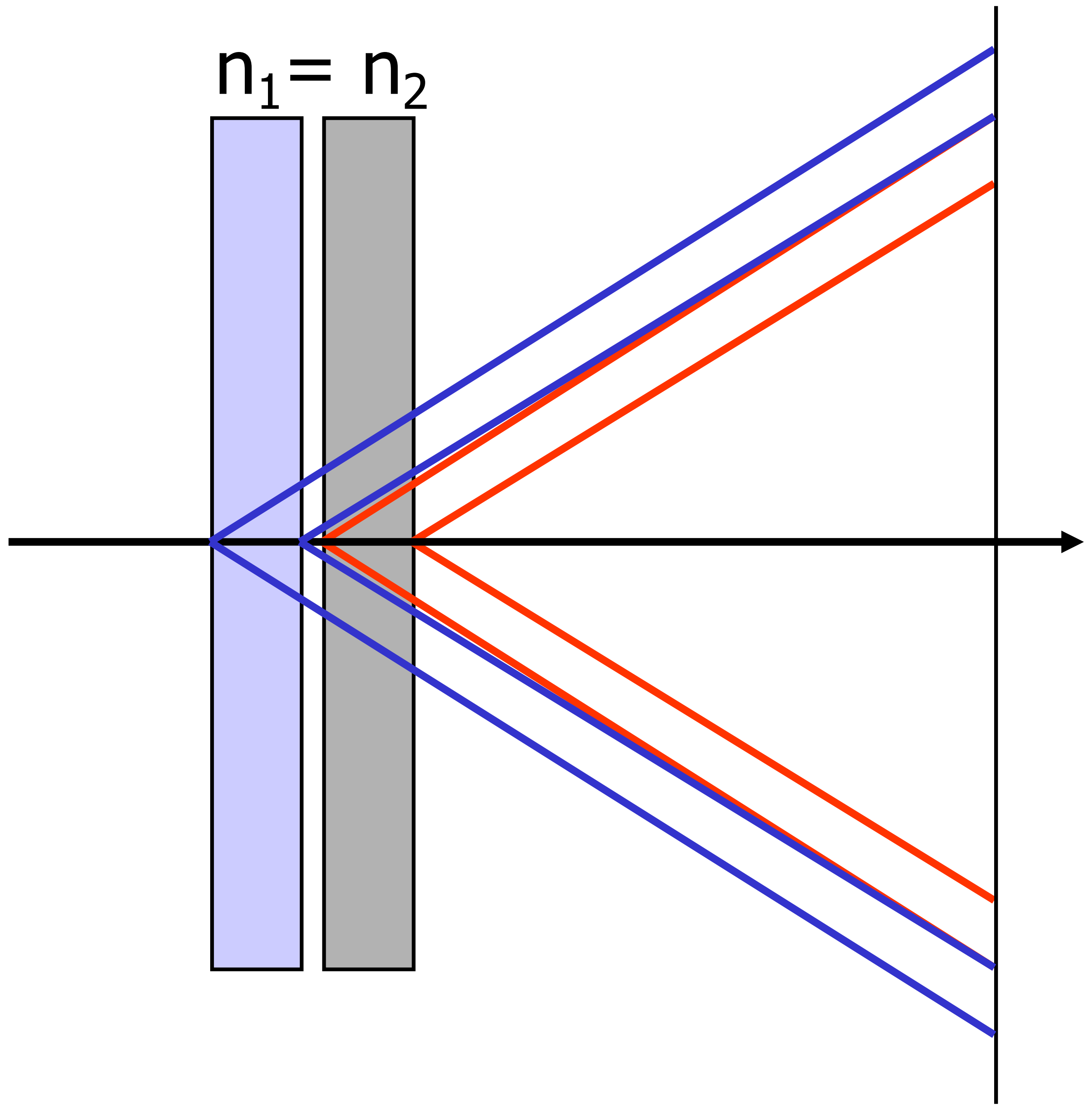
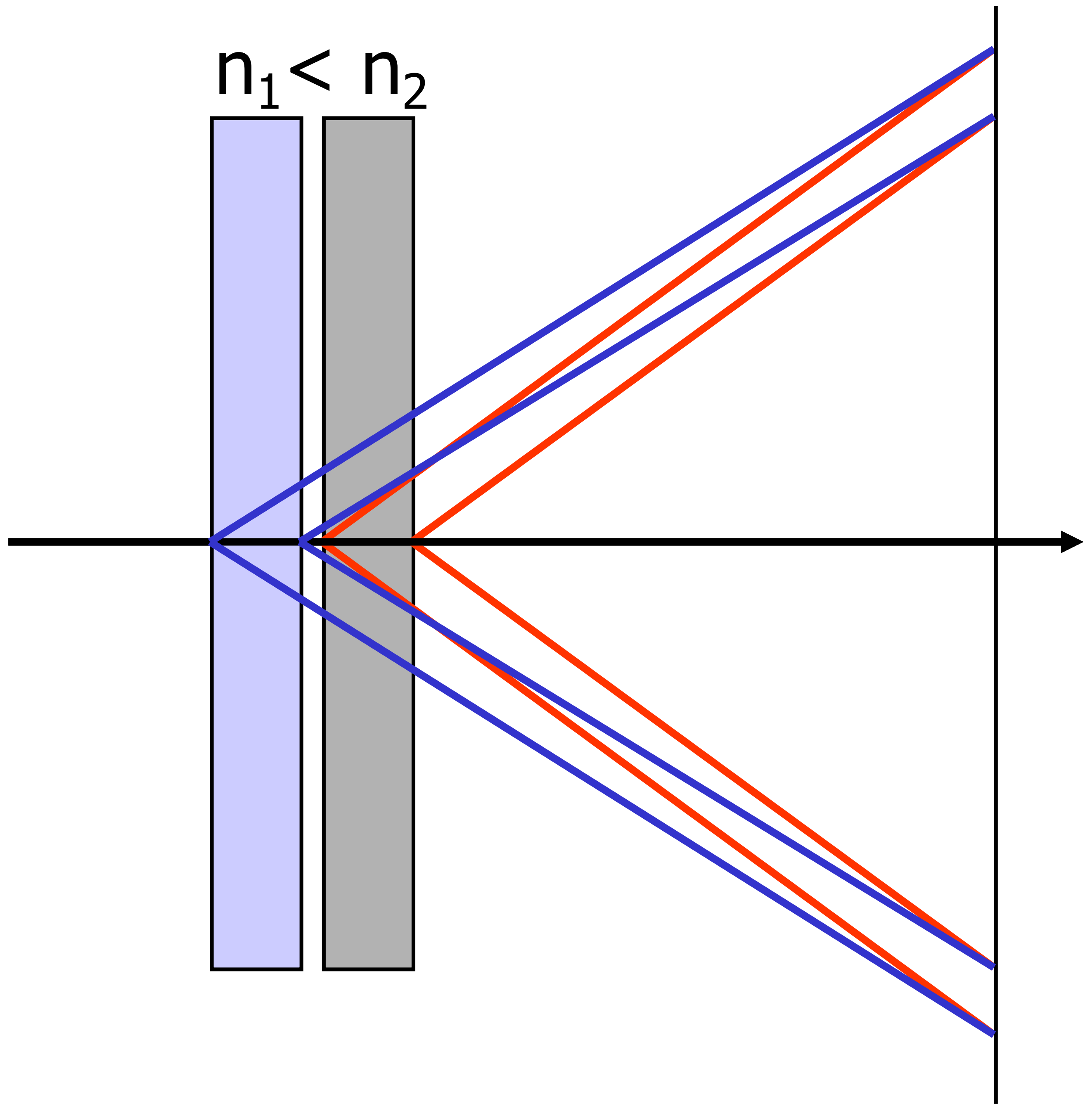
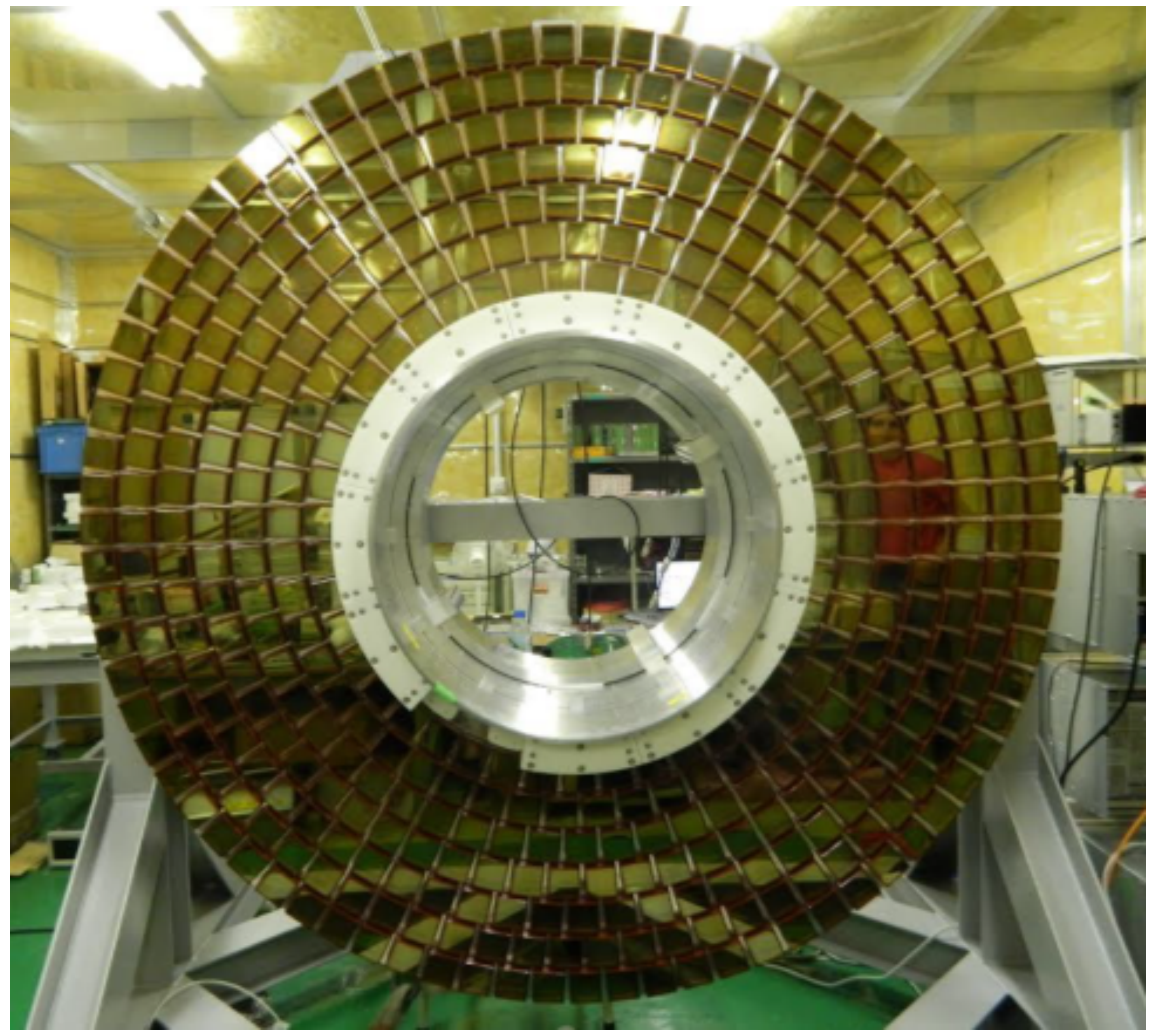
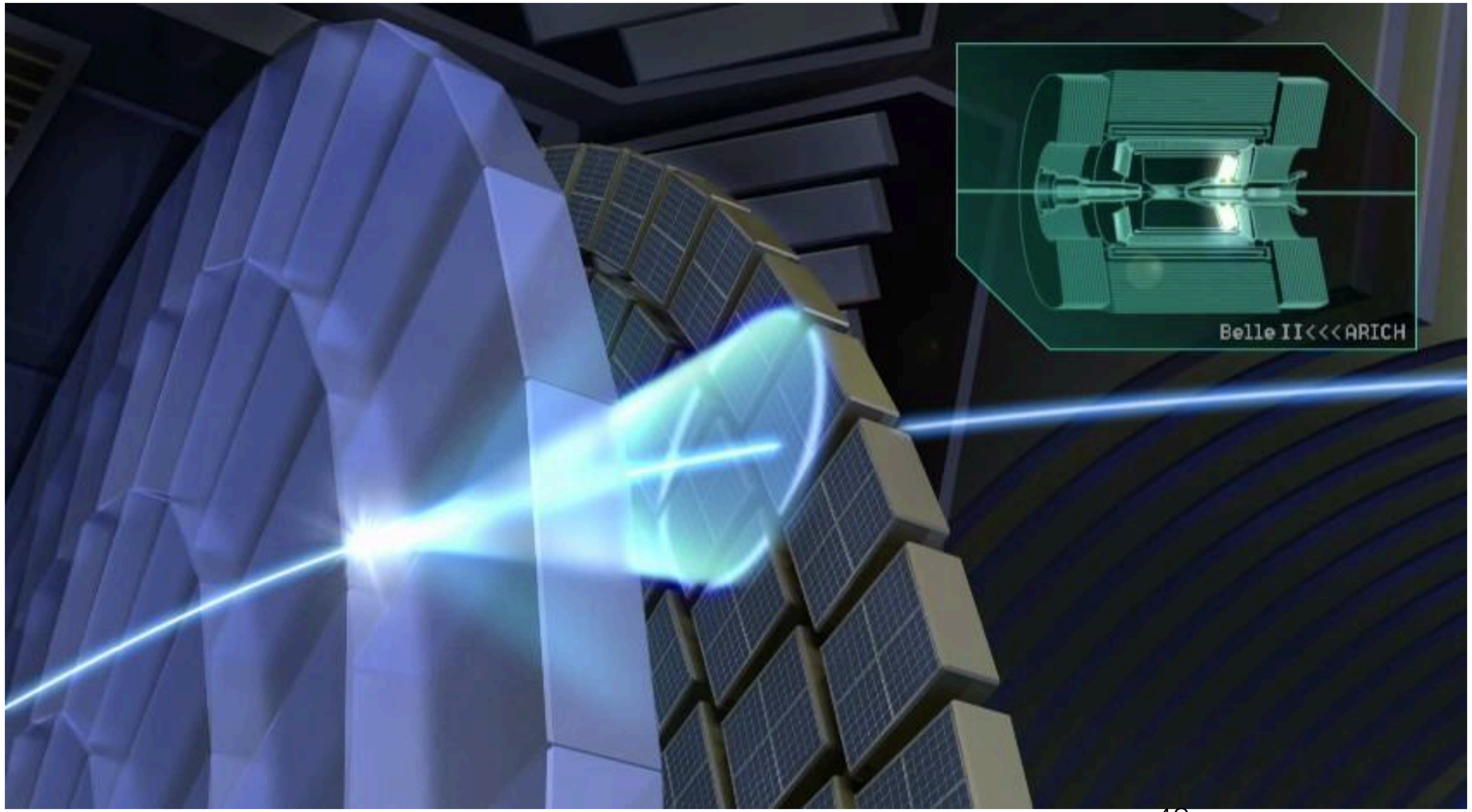


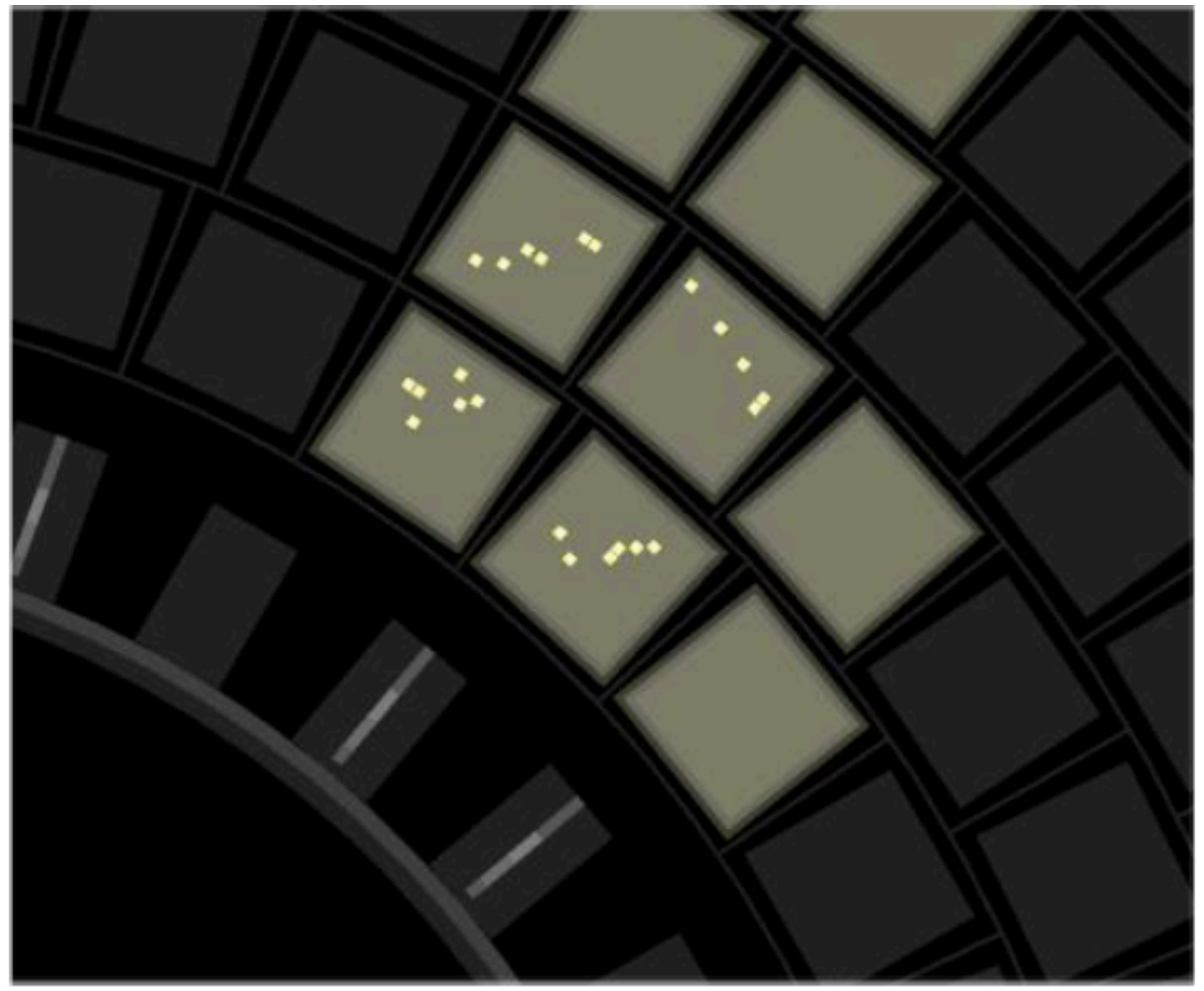


Aerogel Ring Imaging CHerenkov detector (ARICH)

- End-cap RICH device
  - Aerogel tiles are used as a radiator
  - Photons propagate through an expansion volume before detection with HAPD photodetectors





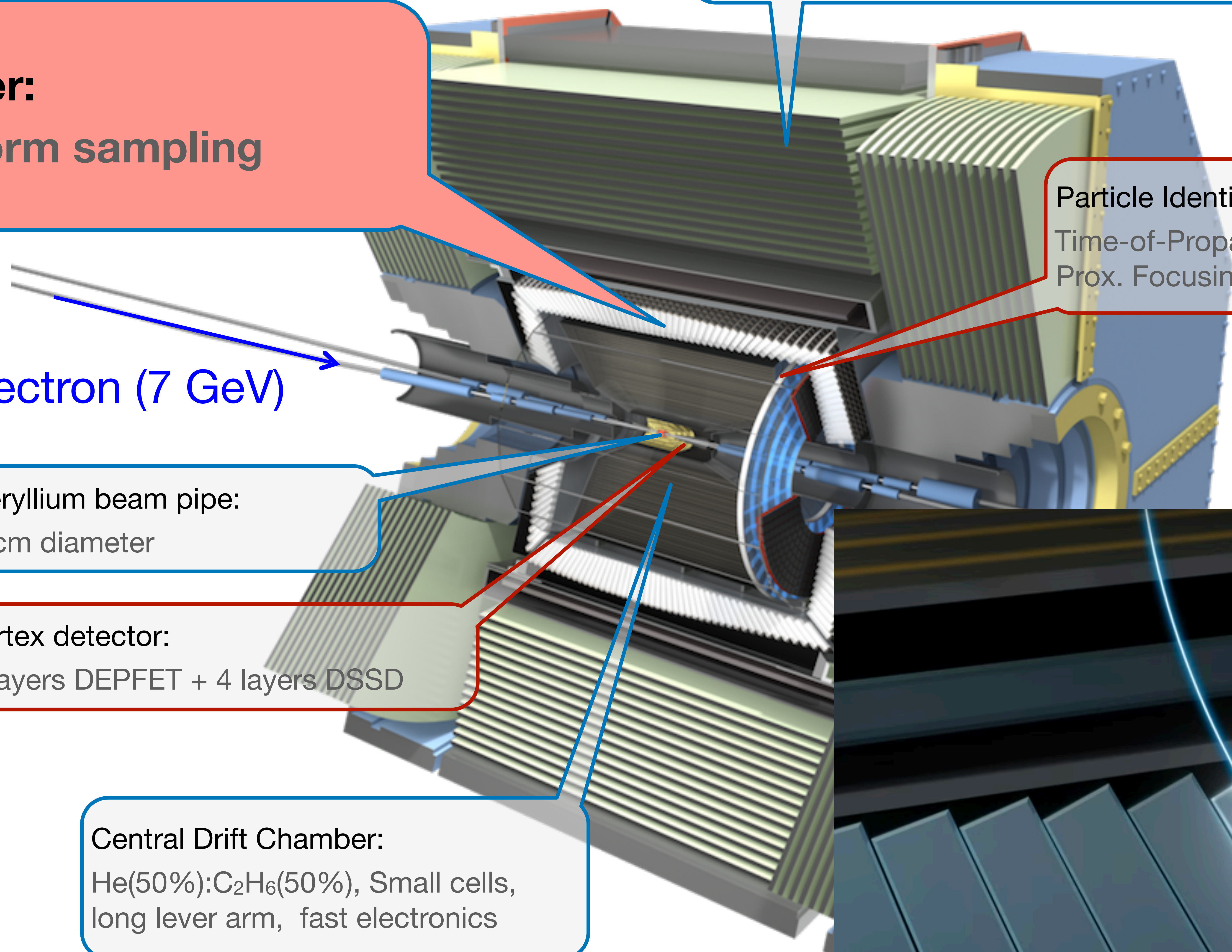


The Belle II detector

EM Calorimeter:
CsI(Tl), waveform sampling

K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

Particle Identification:
Time-of-Propagation counter (barrel)
Prox. Focusing Aerogel RICH (fwd)

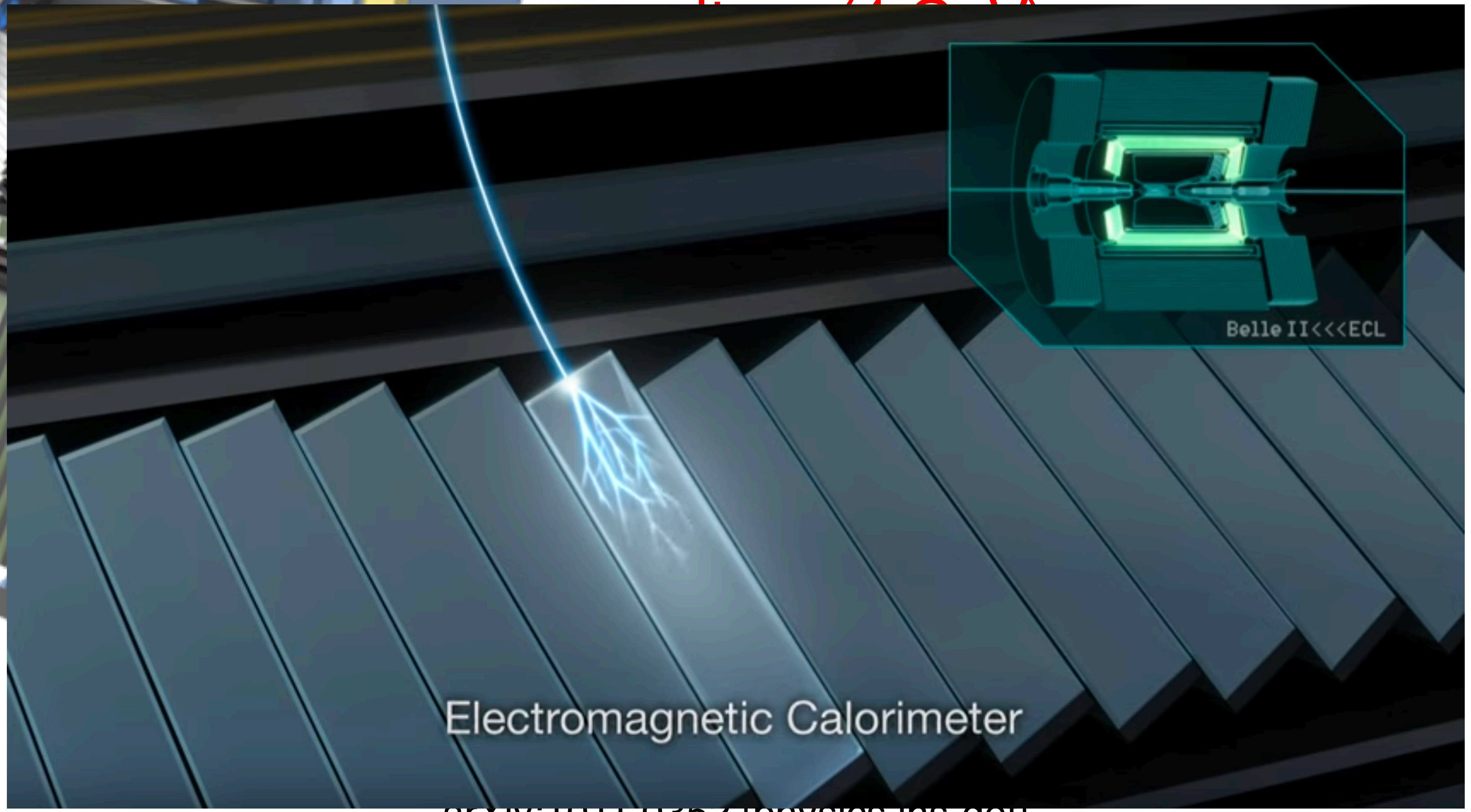


electron (7 GeV)

Beryllium beam pipe:
2 cm diameter

Vertex detector:
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber:
$He(50\%):C_2H_6(50\%)$, Small cells,
long lever arm, fast electronics

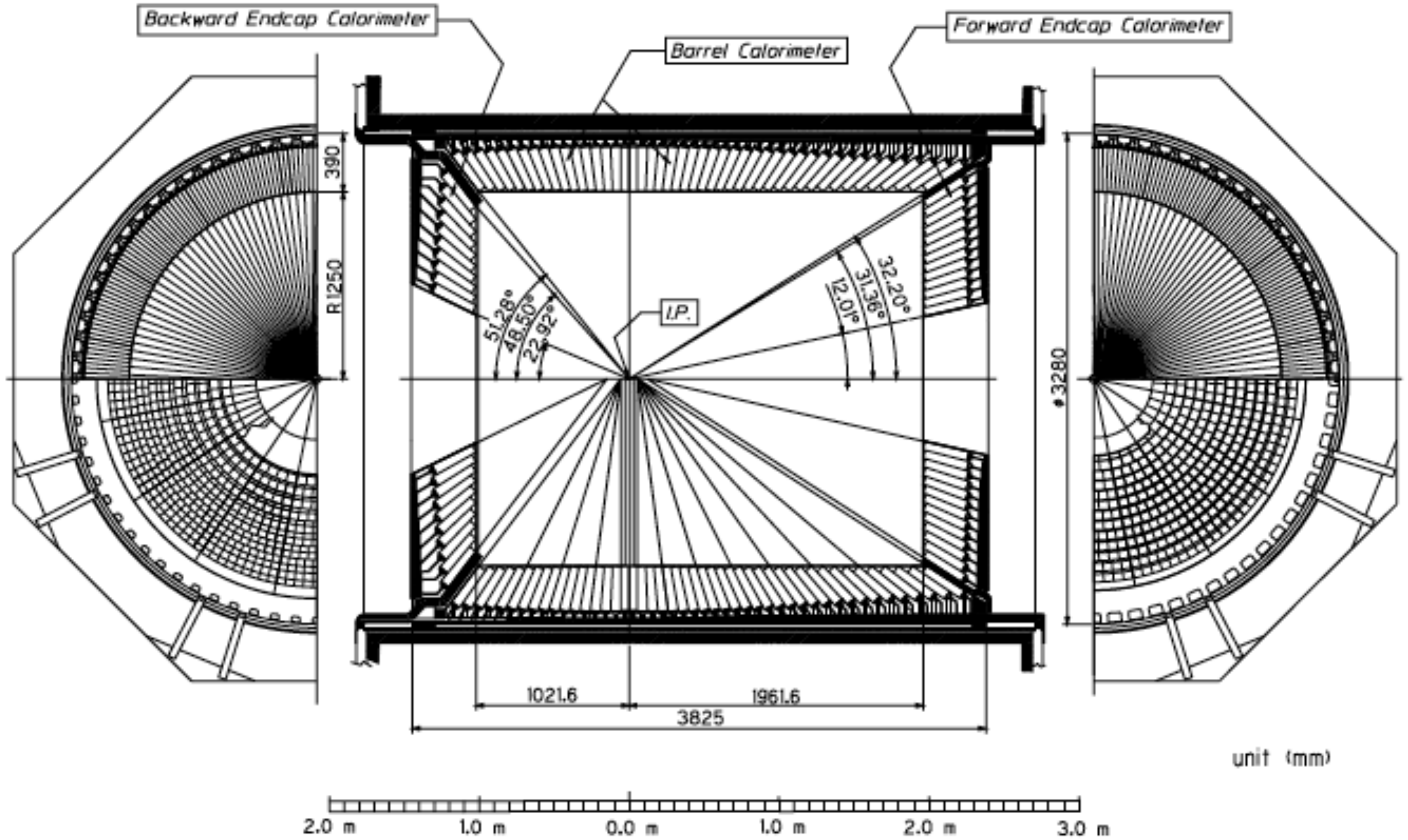


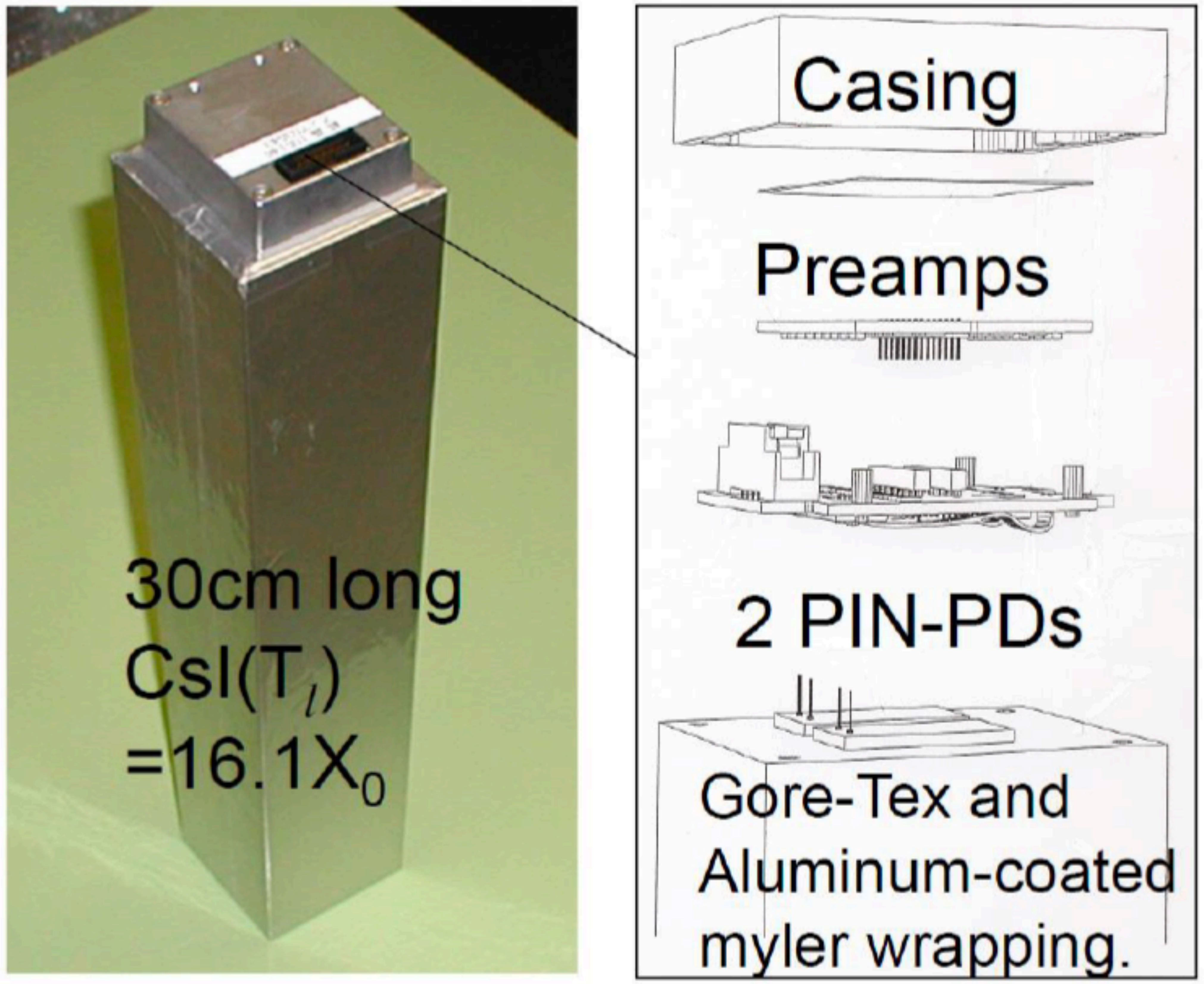
arXiv:1011.0352 [physics.ins-det]

First new particle collider since the LHC
(intensity rather than energy frontier; e^+e^- rather than pp)

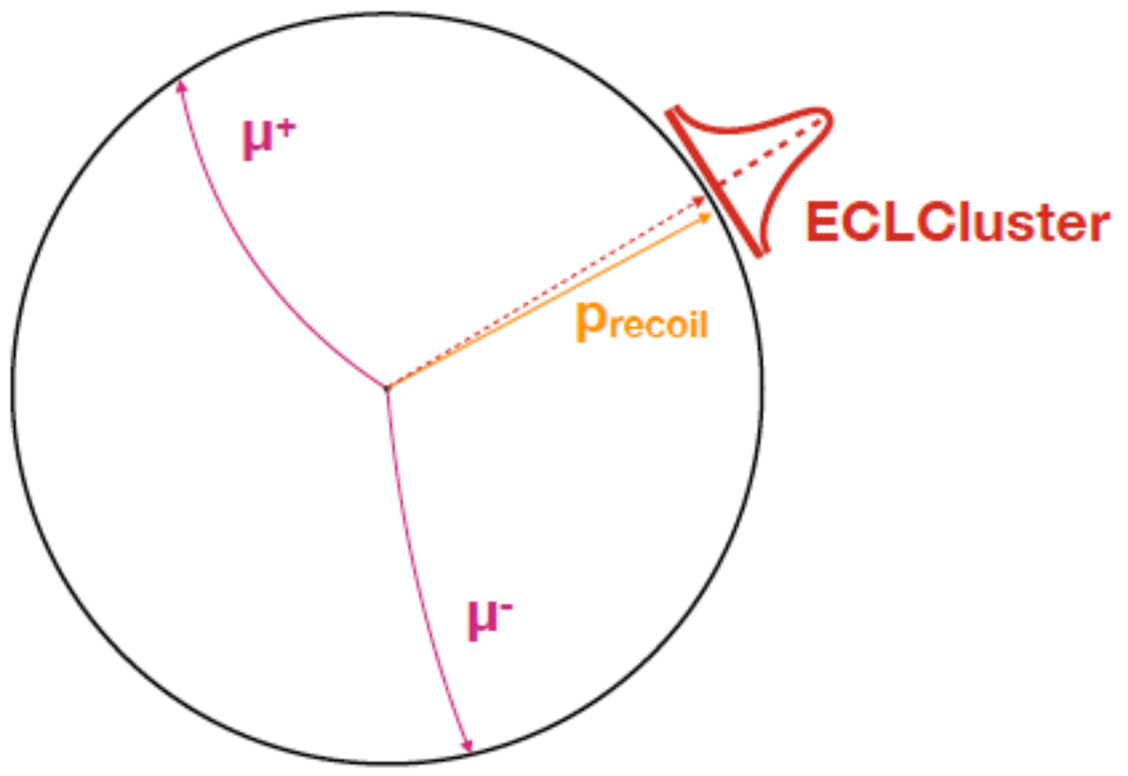
Electromagnetic CaLorimeter (ECL)

- CsI has good stopping power (high density) and fast decay time
  - One of the lowest cost fast scintillators
- CsI(Tl) is one of the brightest known scintillators





Electromagnetic CaLorimeter (ECL)



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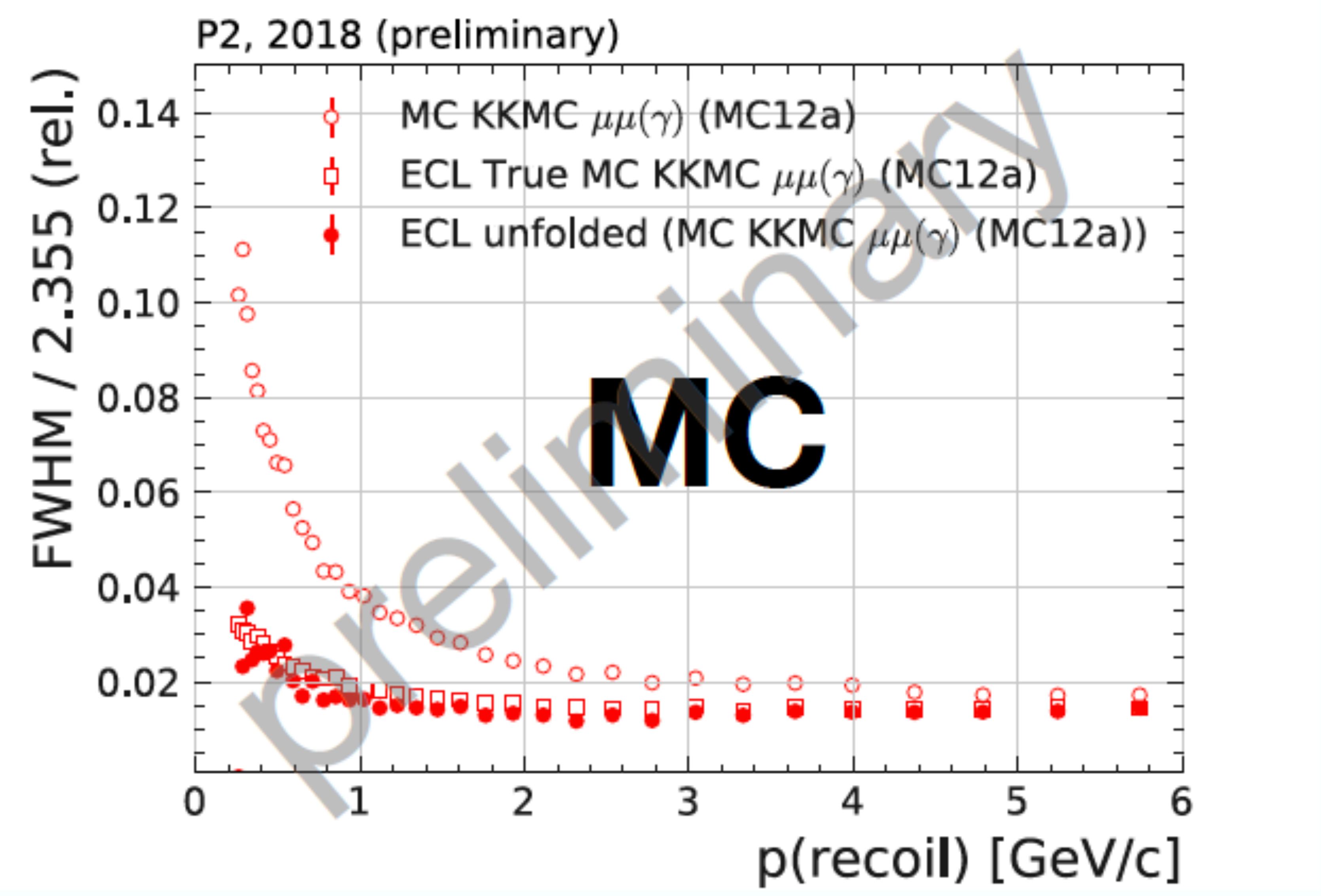
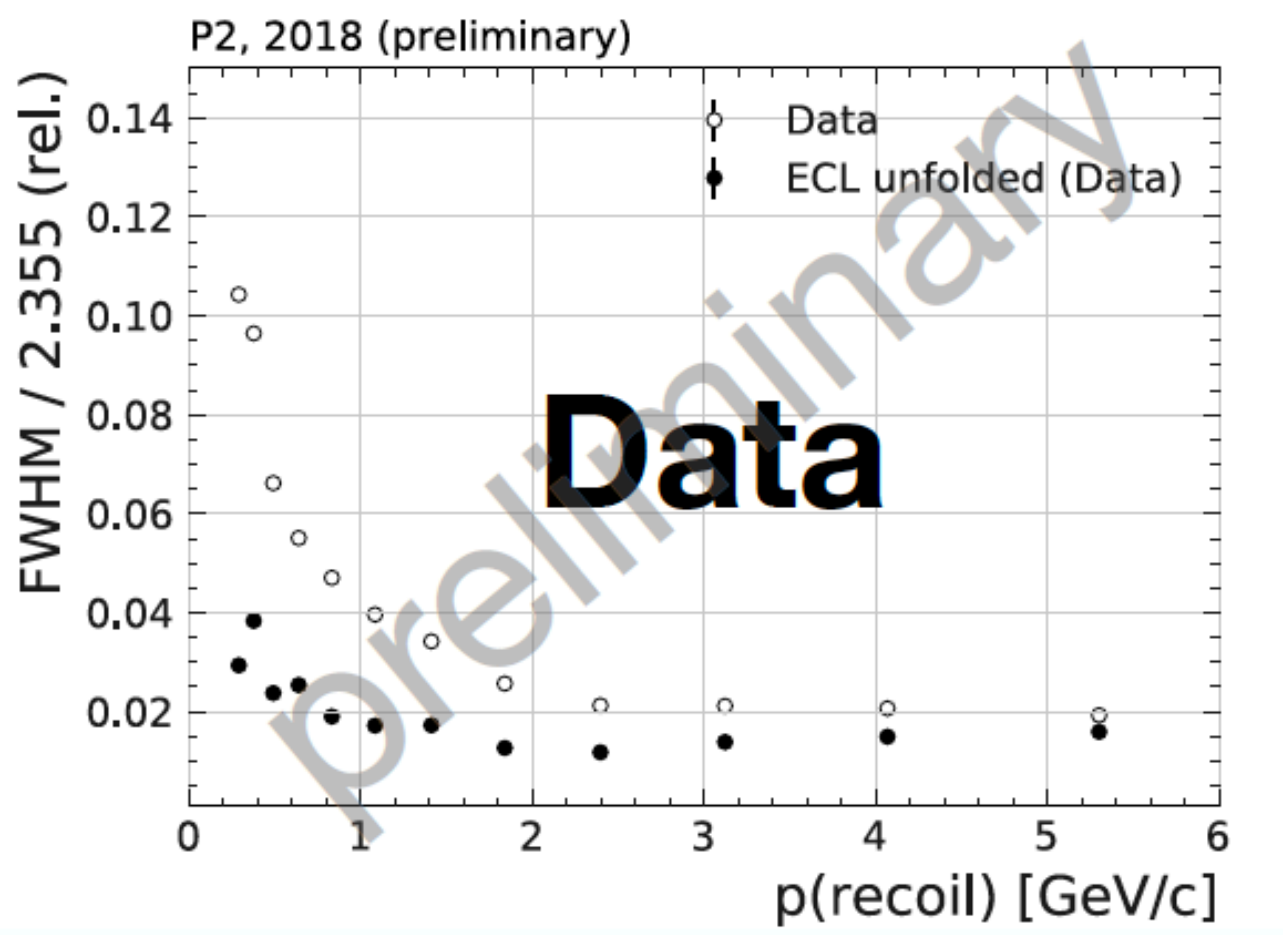
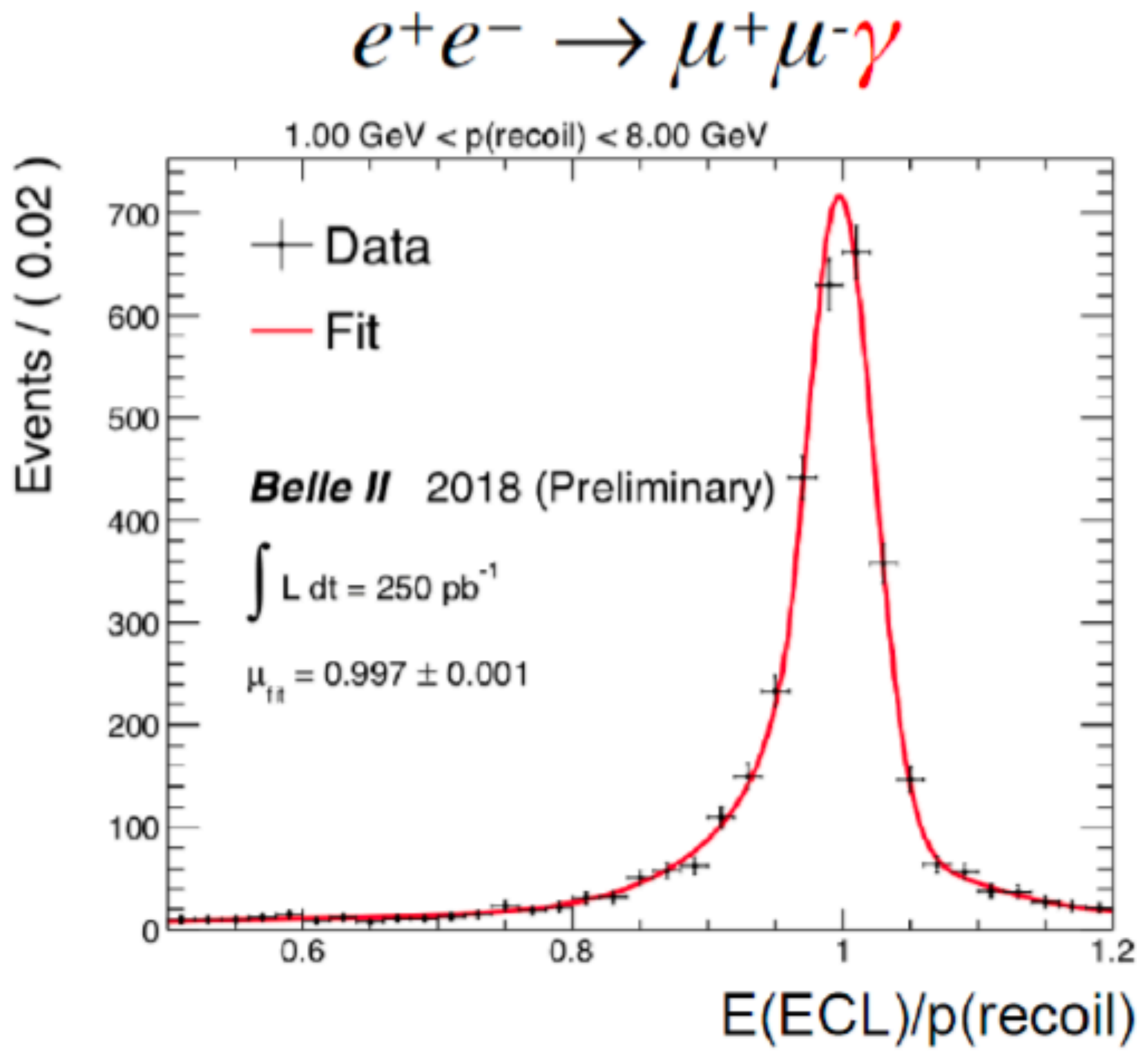
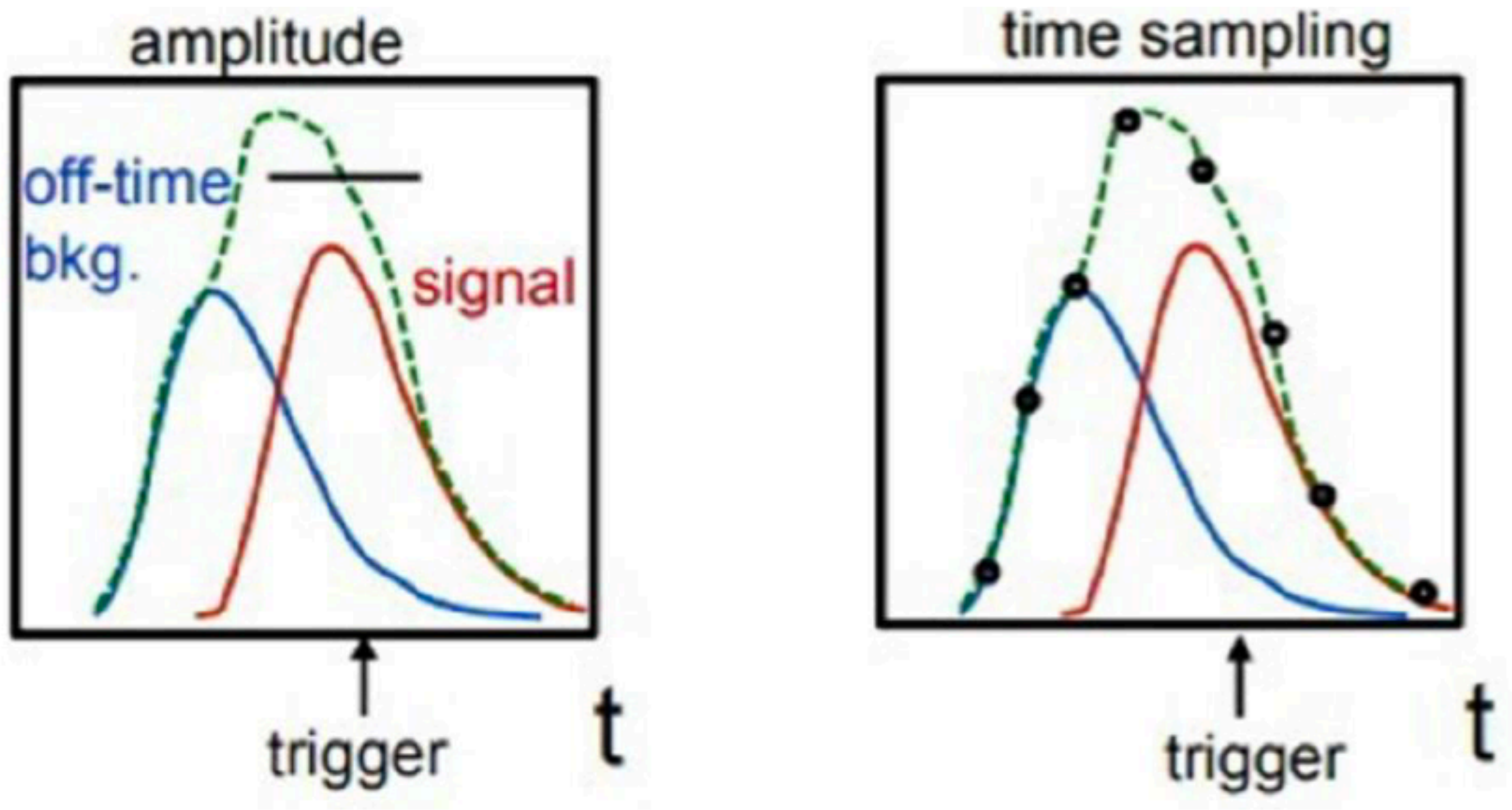




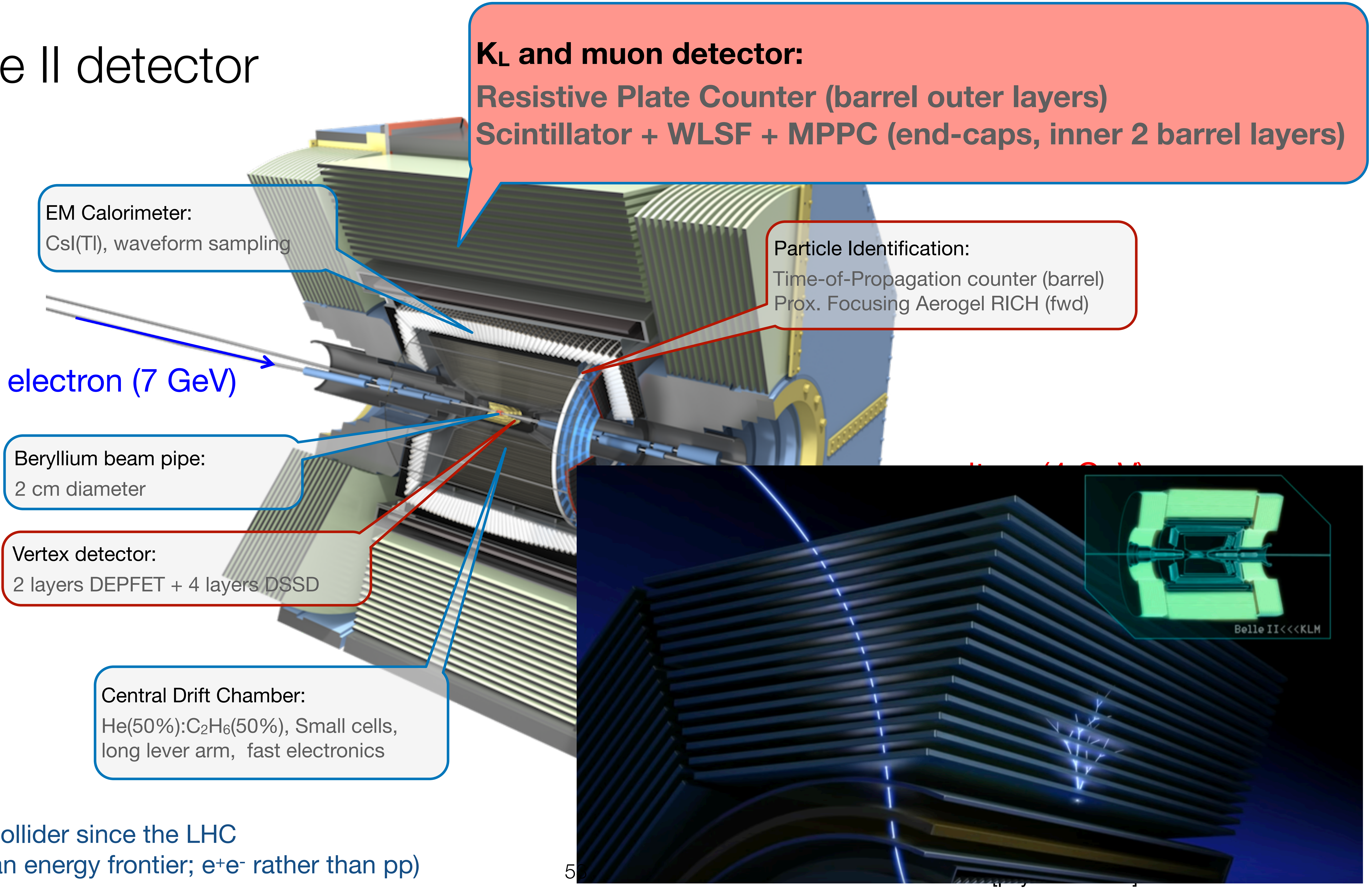


Coping with a high background

- Trigger rate of 30 kHz, background 10 times higher than in Belle
  - Radiation damage will be an issue
- Use waveform sampling (use timing information to discriminate off-timing hits) with a pipelined readout (reduce readout deadtime)
  - Continuous digitization of shaped pulses, fitted to a reference waveform, with baseline restoration and pulse amplitude, time correction
  - Once a trigger is issued, waveform fitting is performed in FPGA using 16 samples to extract timing and amplitude
- 576 Shaper Digitizer boards in 52 VME crates to read out all 8736 crystals



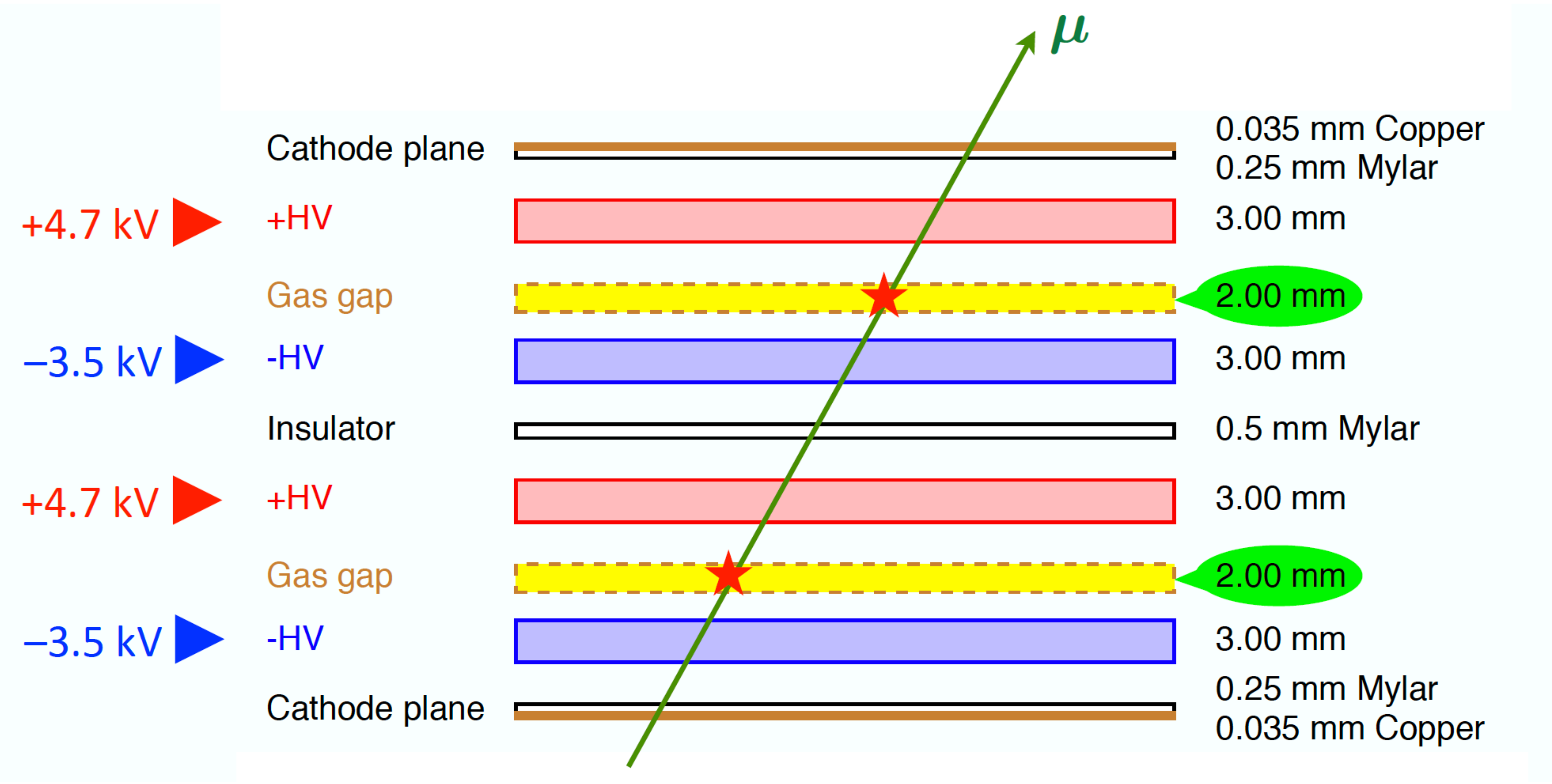
The Belle II detector

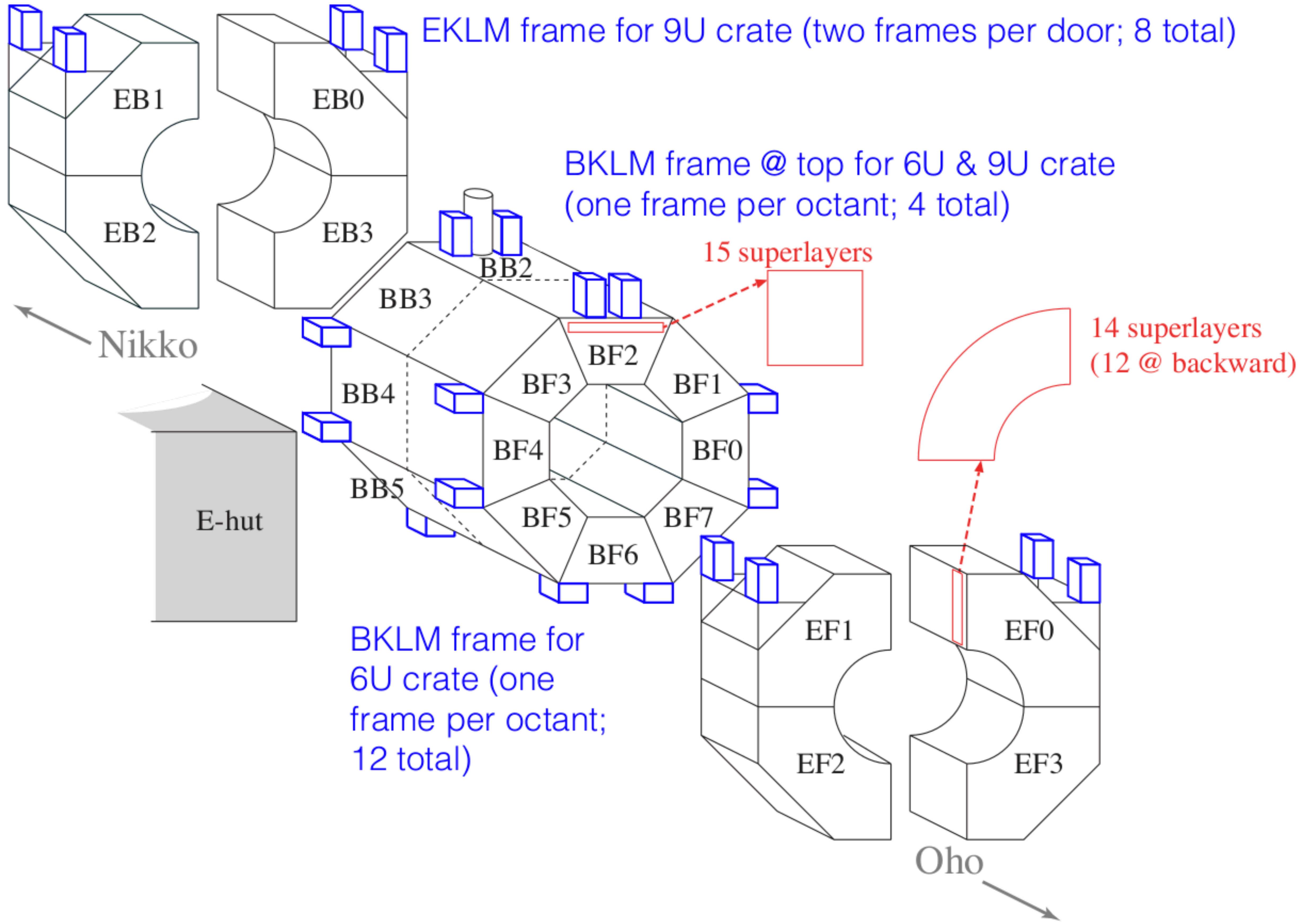


First new particle collider since the LHC
(intensity rather than energy frontier; e^+e^- rather than pp)

K-Long and Muon detector (KLM)

- BKLM has 16 sectors;
  - 15 layers: 2 layers of scintillators and the remaining 13 layers of Resistive Plate Chambers (RPC)
- EKLM has 8 sectors;
  - 14 forward layers, 12 backward of only scintillators
- RPC: A discharge (streamer) in either gas gap induces an image charge on both readout planes



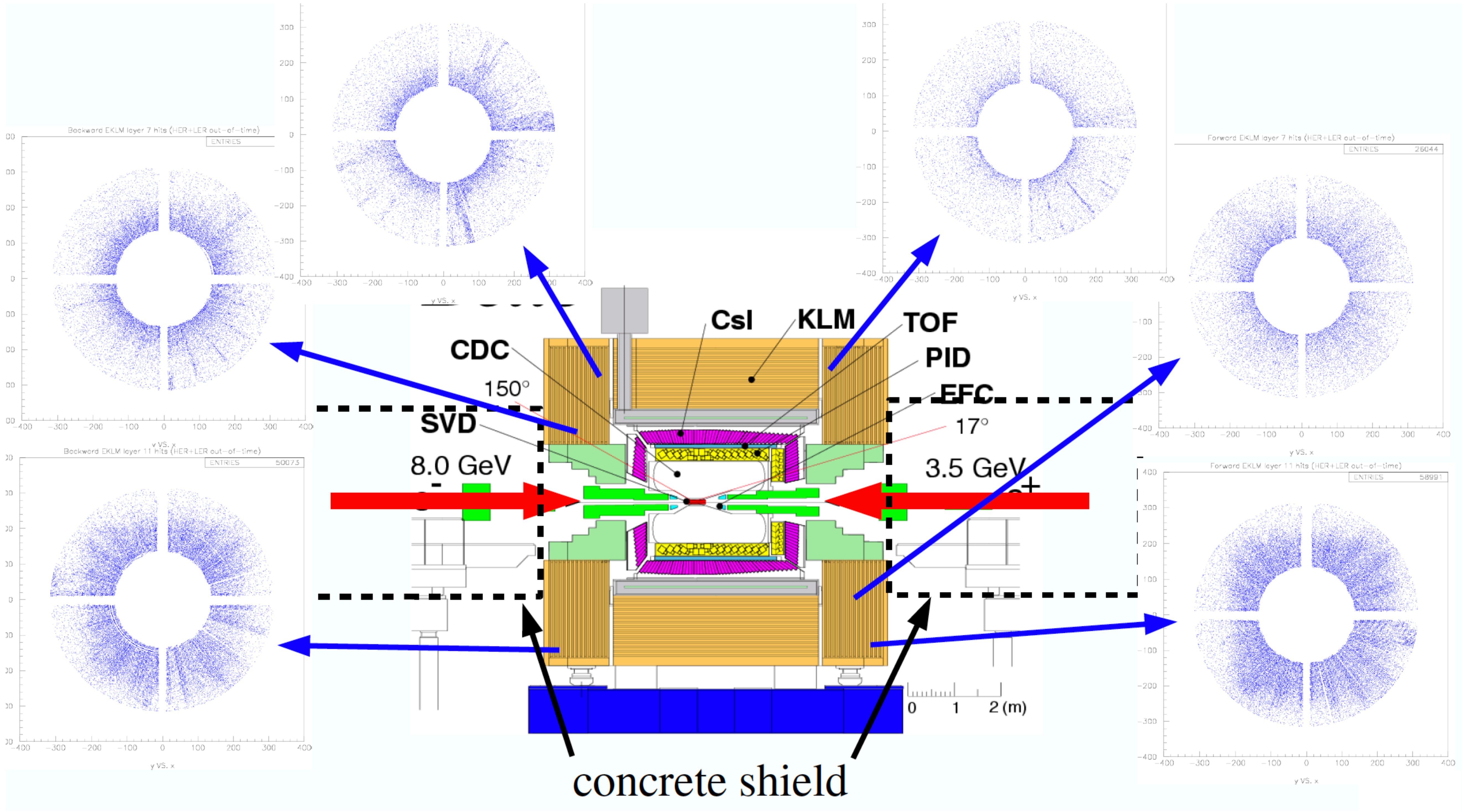


K-Long and Muon detector (KLM)

- Why use scintillators instead of RPCs?

K-Long and Muon detector (KLM)

- Why use scintillators instead of RPCs?
  - RPCs work well at low background rates
  - Ambient neutron rate at Belle II means endcap RPCs would never see muons!



Efficiency in Belle

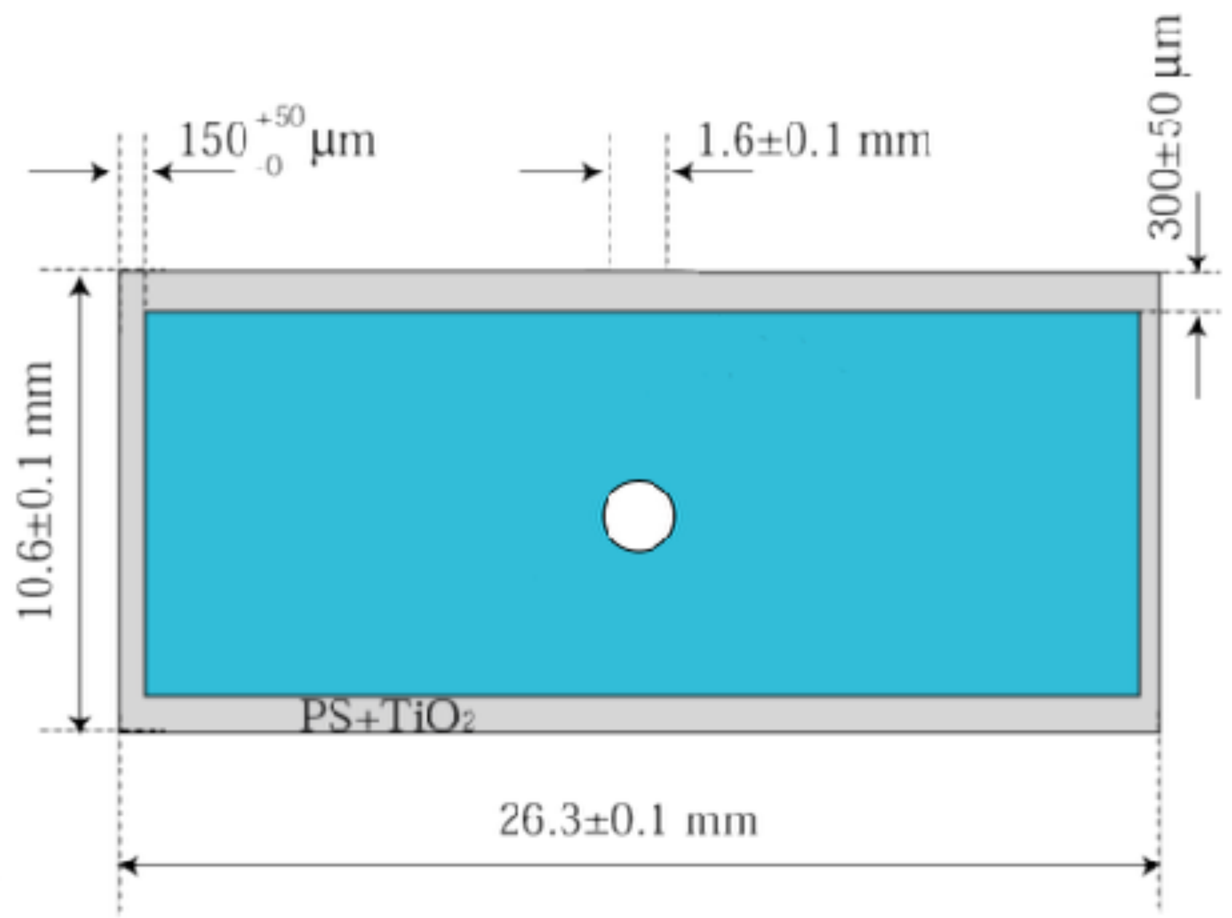
Layer	Barrel	Forward Endcap	Backward Endcap
0	0.97	0.91	0.9
1	0.98	0.93	0.9
2	0.99	0.94	0.9
3	0.99	0.94	0.9
4	0.99	0.94	0.89
5	0.99	0.92	0.88
6	0.99	0.93	0.89
7	0.99	0.92	0.87
8	0.99	0.92	0.86
9	0.99	0.9	0.85
10	0.99	0.87	0.82
11	0.99	0.82	0.8
12	0.99	0.78	0.81
13	0.99	0.77	0.76
14	0.99	—	—

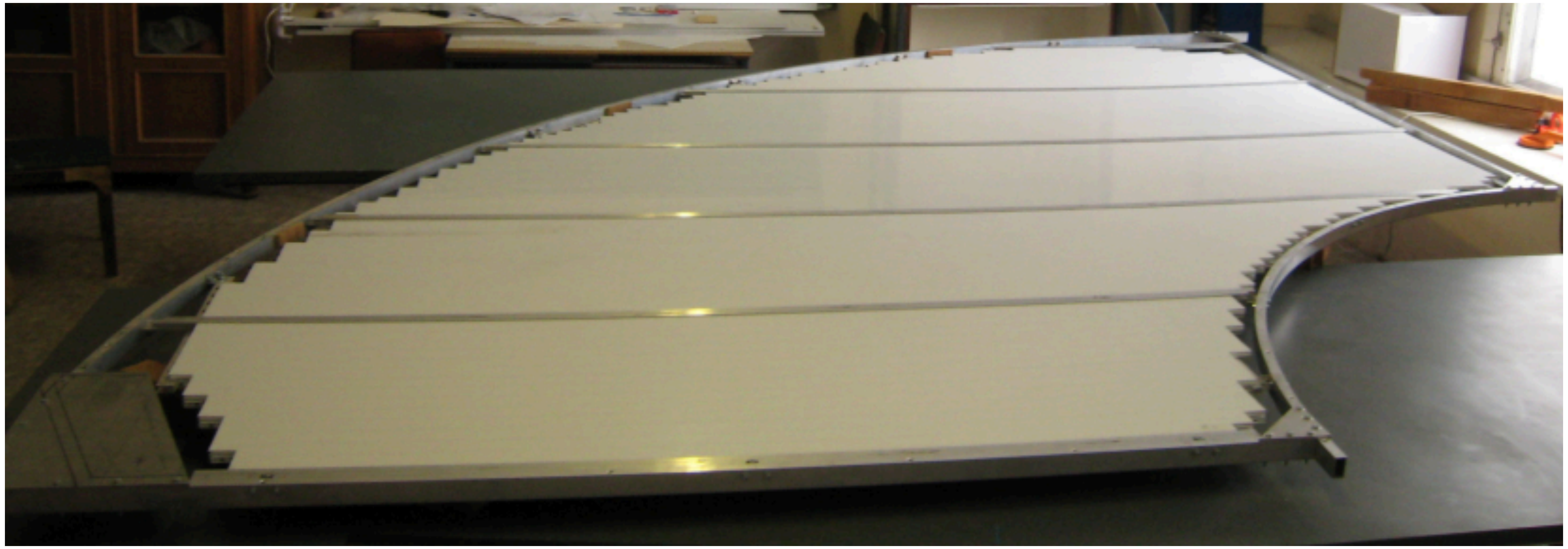
Efficiency in Belle II

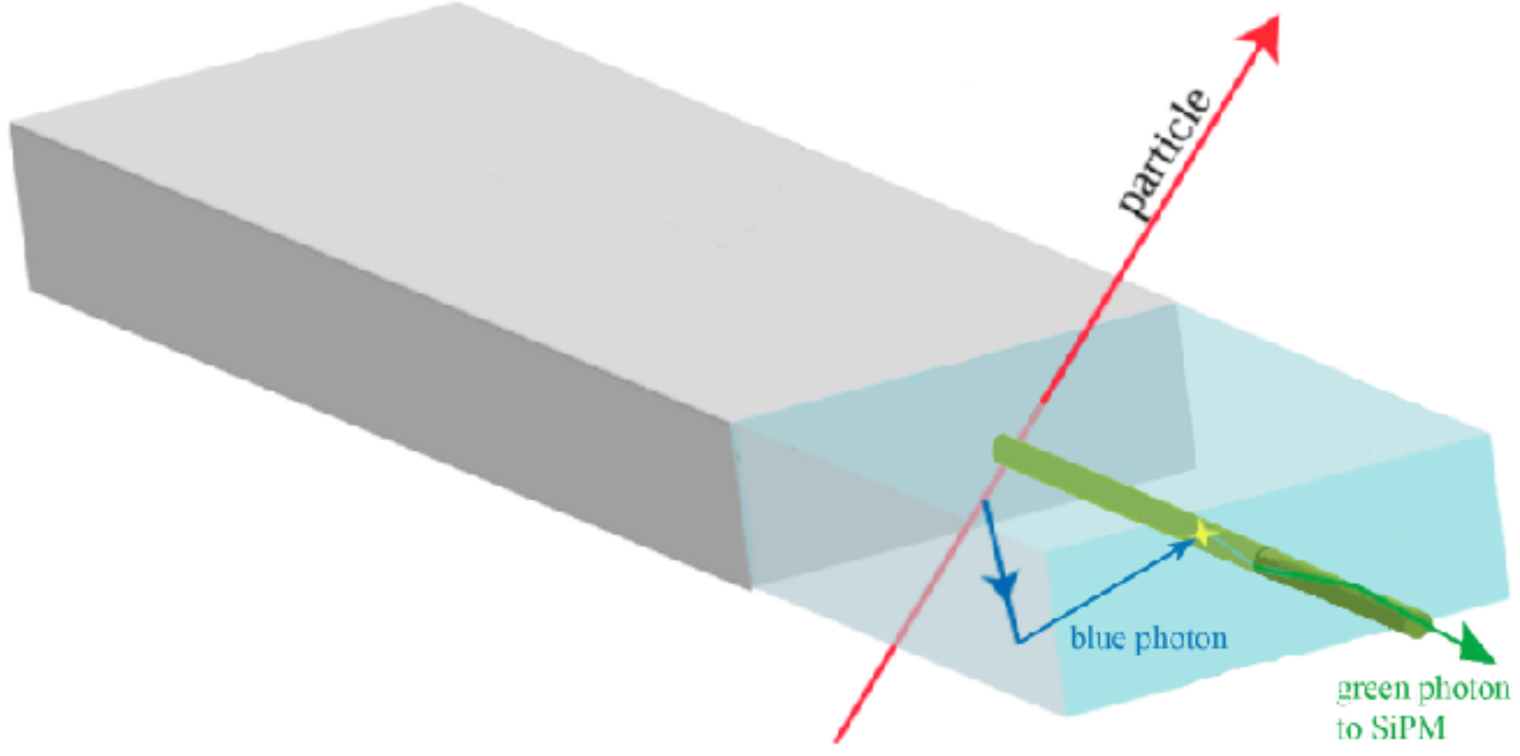
Layer	Barrel	Forward Endcap	Backward Endcap
0	0.13	0	0
1	0.39	0	0
2	0.62	0	0
3	0.78	0	0
4	0.86	0	0
5	0.91	0	0
6	0.94	0	0
7	0.97	0	0
8	0.98	0	0
9	0.99	0	0
10	0.99	0	0
11	0.99	0	0
12	0.99	0	0
13	0.99	0	0
14	0.99	—	—

K-Long and Muon detector (KLM)

- Scintillator (with TiO2 reflective coating) delivers blue light to central-bore fiber
- Light is captured by wavelength-shifting fiber rather than letting the emitted light propagate along the scintillator, why?

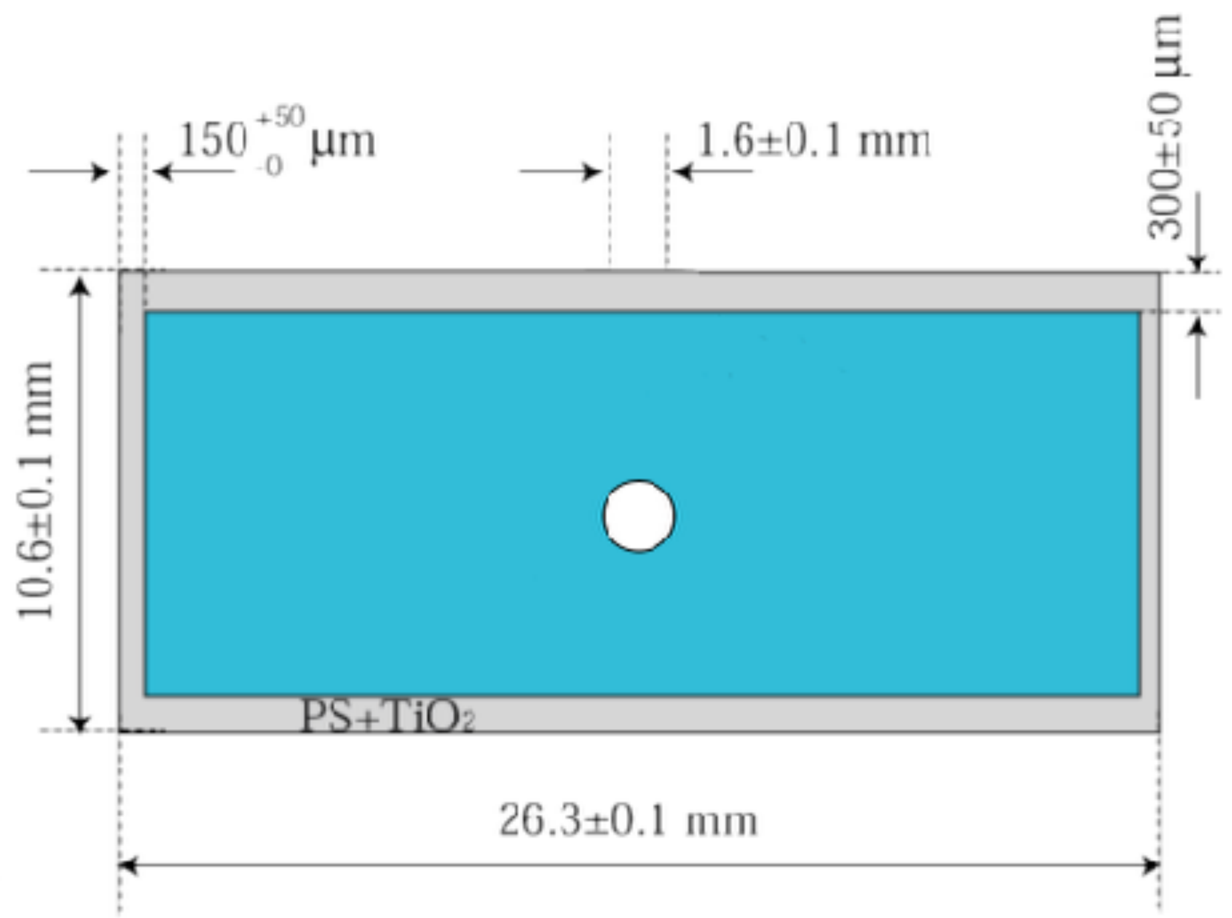


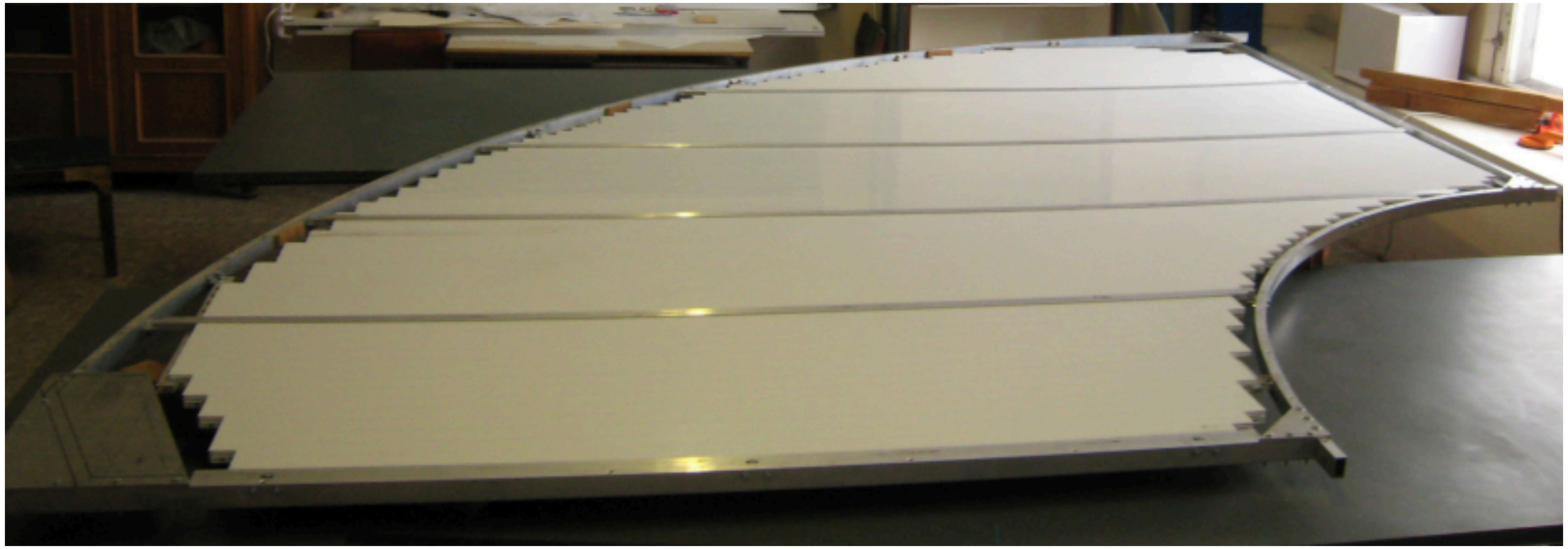


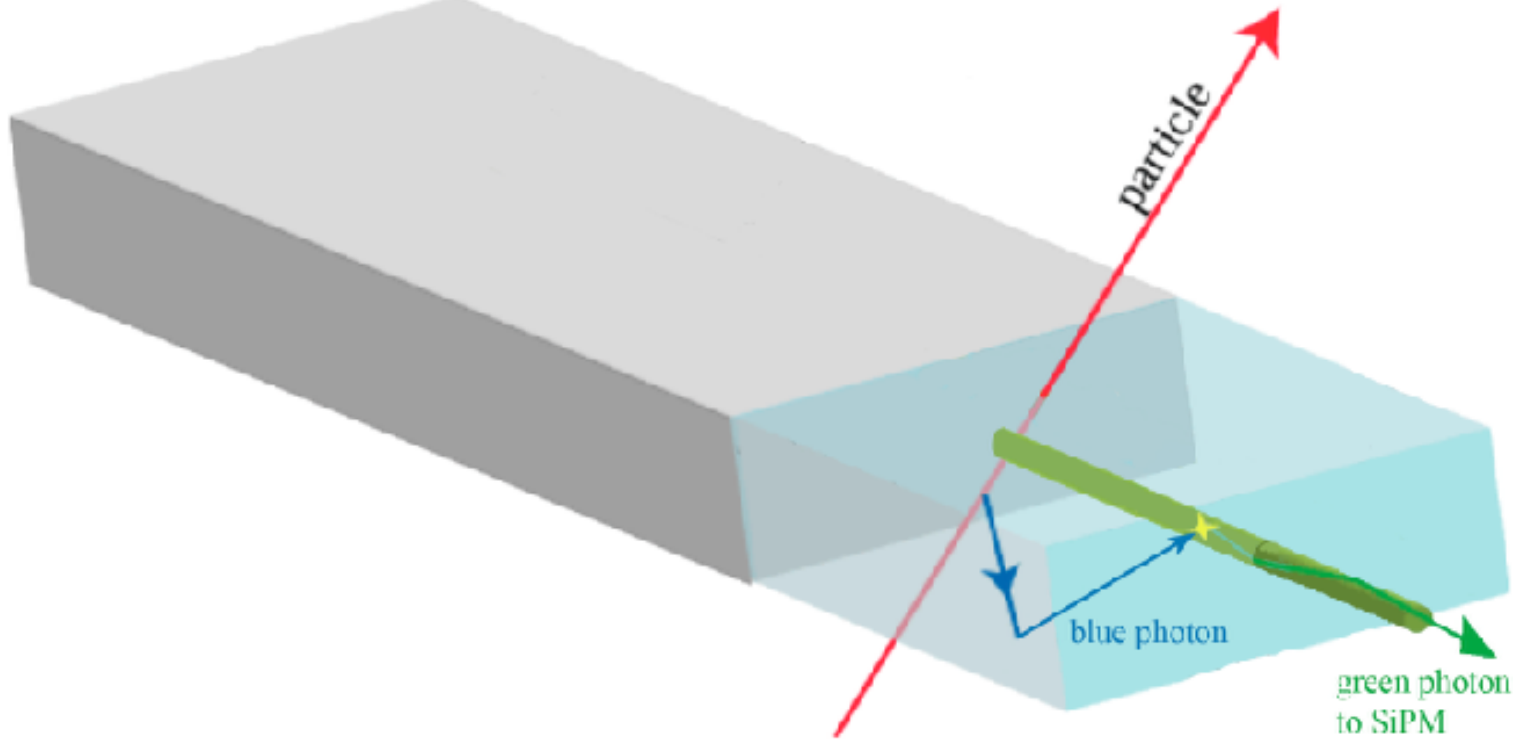


K-Long and Muon detector (KLM)

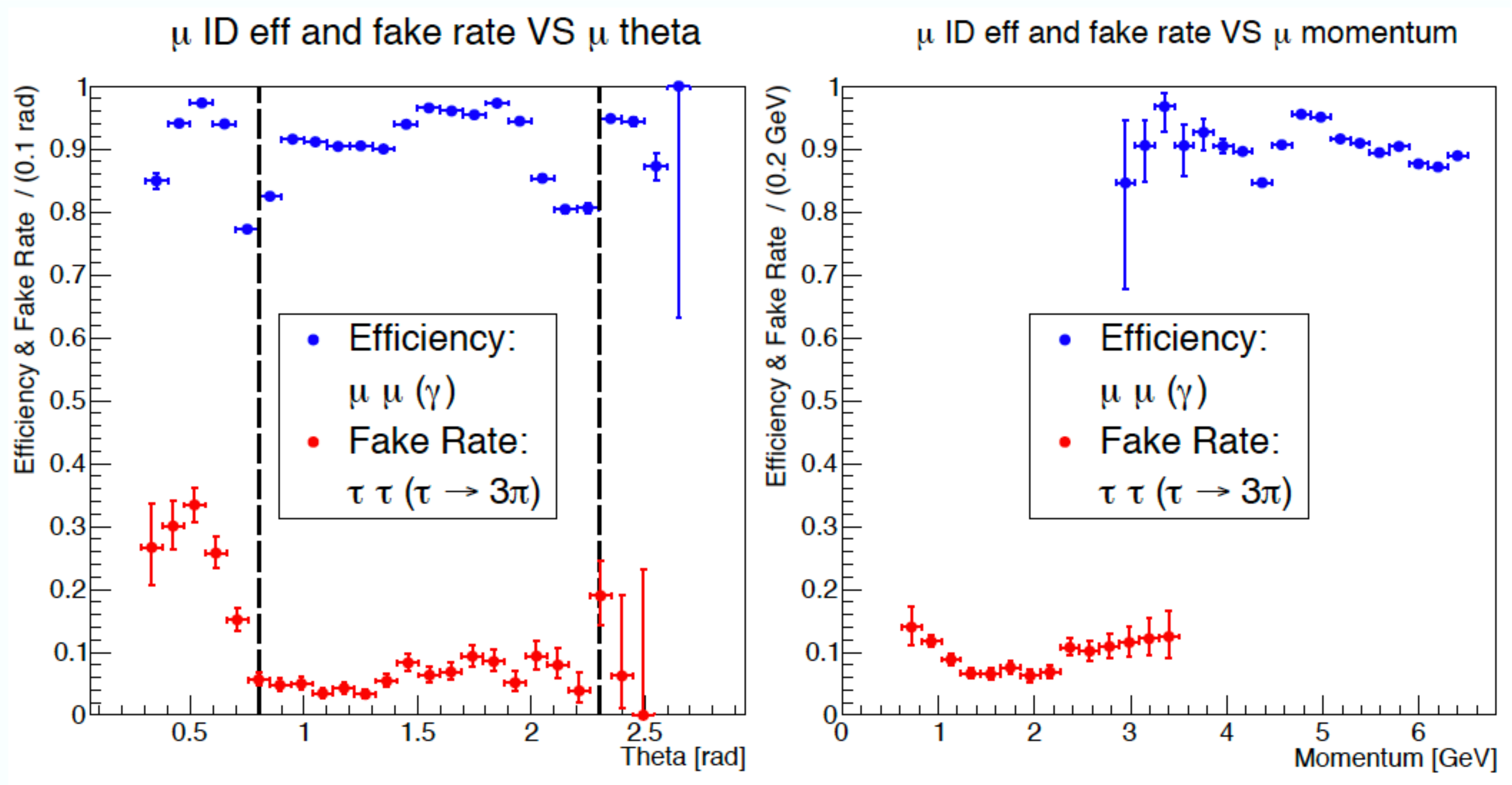
- Scintillator (with TiO2 reflective coating) delivers blue light to central-bore fiber
- Light is captured by wavelength-shifting fiber rather than letting the emitted light propagate along the scintillator, why?
  - Polystyrene is not very pure: mean free path is <10 cm so no signal would reach the photosensor from 10–200 cm away
  - Two layers of cladding around the base fiber trap the light by total internal reflection
  - Scintillation light (blue) is captured by dye and re-emitted in green so it is not recaptured and is better trapped by T.I.R.



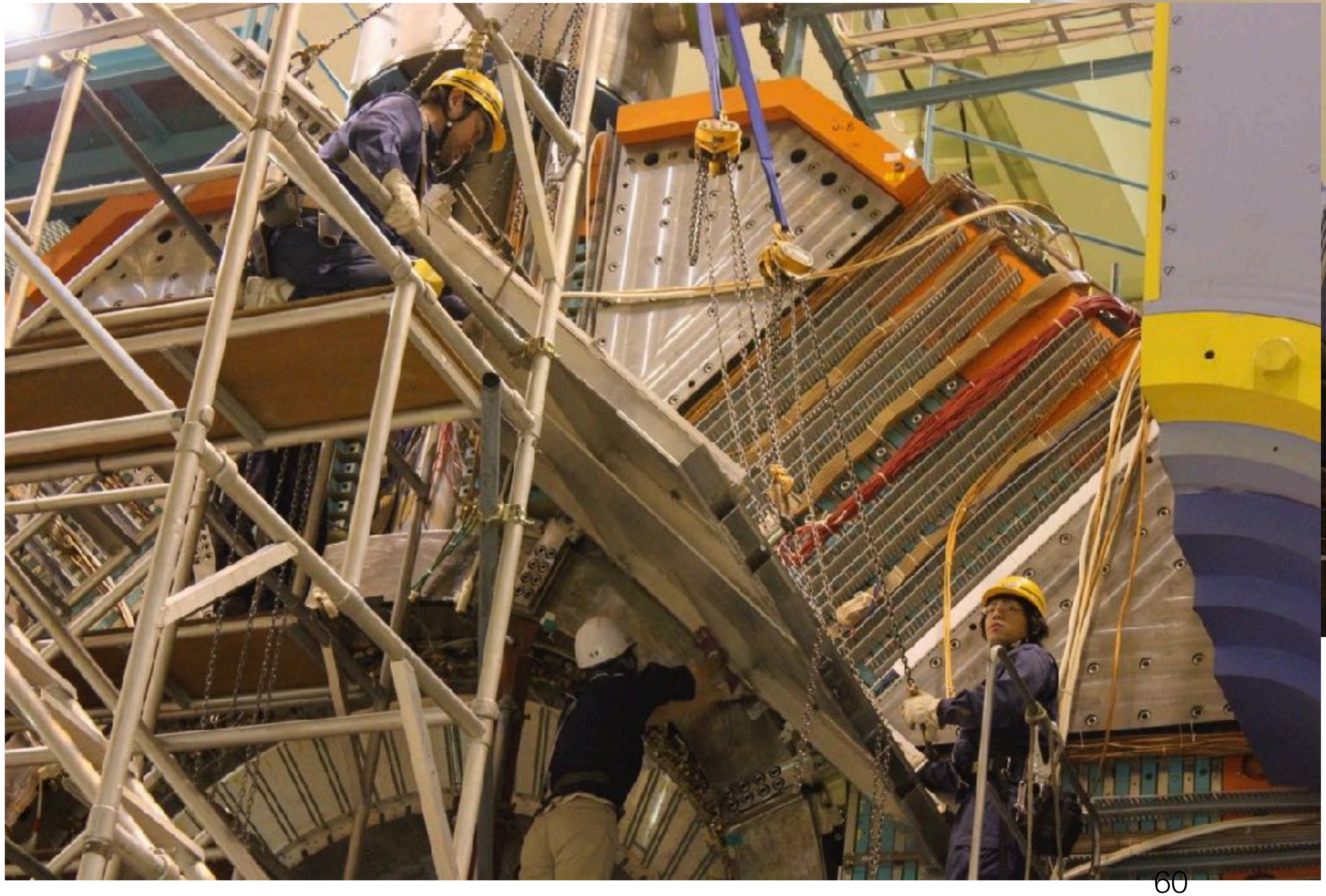


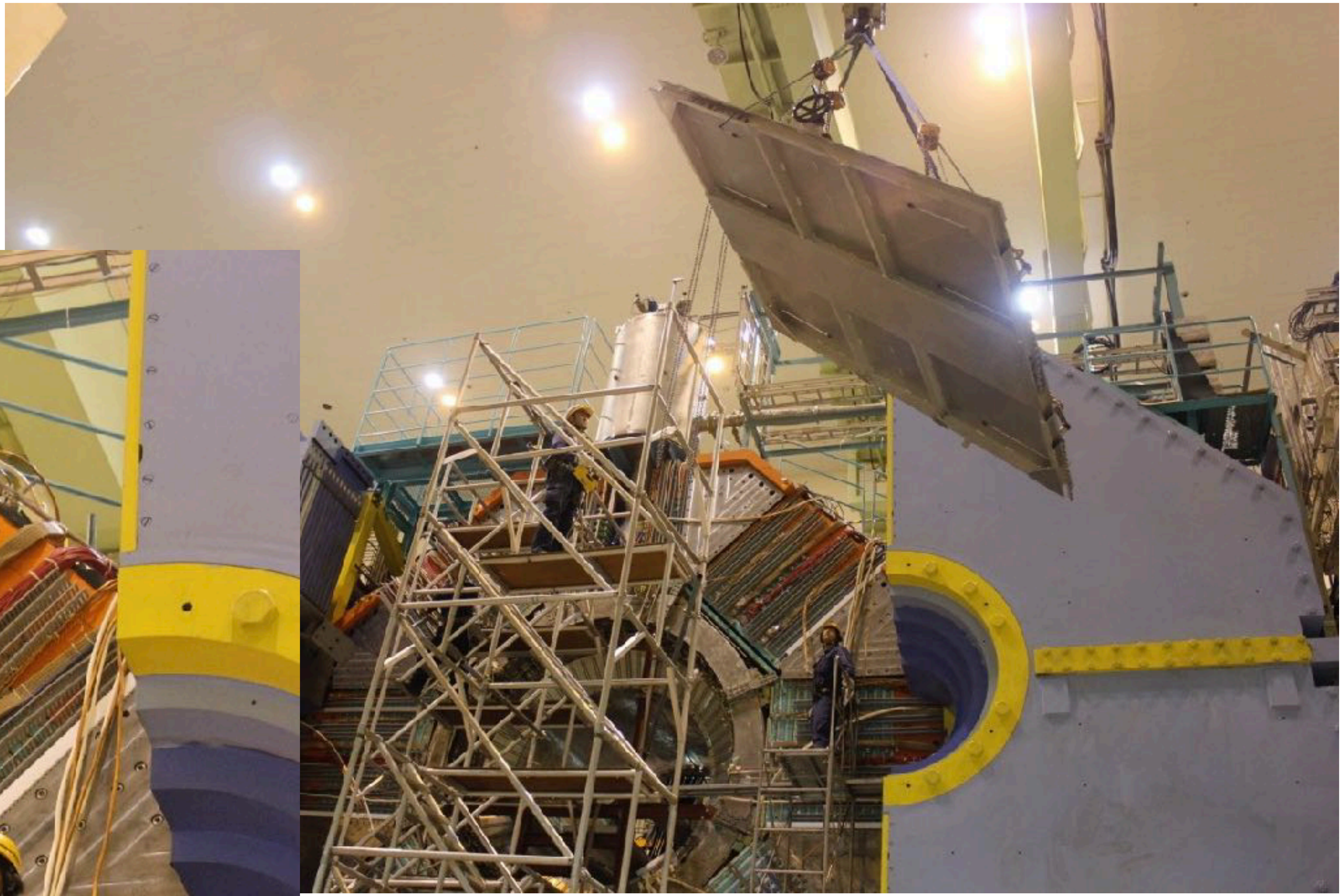


K-Long and Muon detector (KLM)



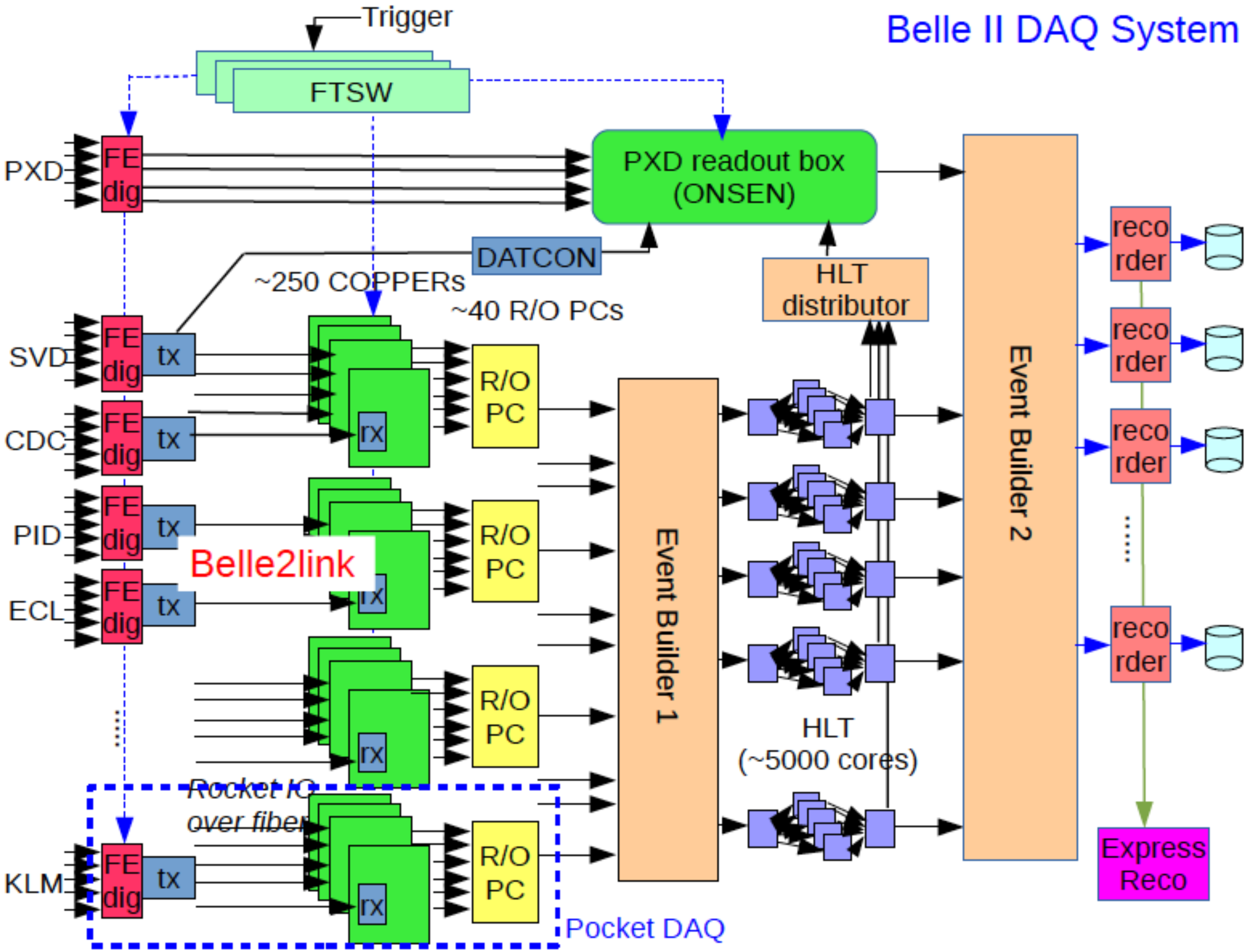
KLM installation



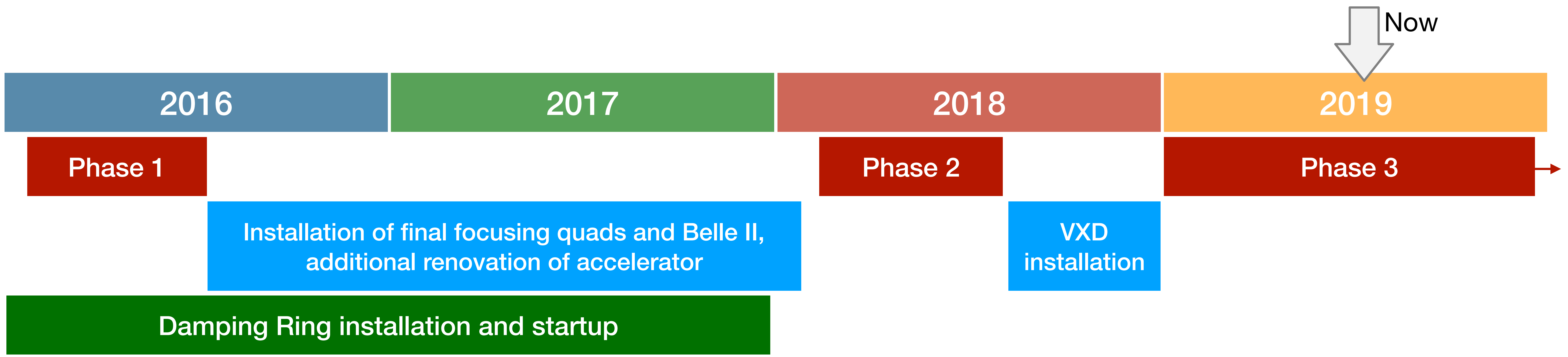


Data AQuisition (DAQ) and readout integration

- Electronics signals from all of the disparate Belle II detectors must be collected together to construct an "event"
- Two stage event builder
  - Construct PXD ROIs
  - Cope with enormous PXD data size
- The full reconstruction chain is performed in the online system
  - Needed for trigger decisions
  - Only "raw data" is saved to be transferred to the offline system
  - Offline data reprocessed later for physics analysis
- Offline data processing will be covered this afternoon



SuperKEKB/Belle II schedule



SuperKEKB/Belle II schedule

Now

2016 | 2017 | 2018 | 2019

Phase 1

Phase 2

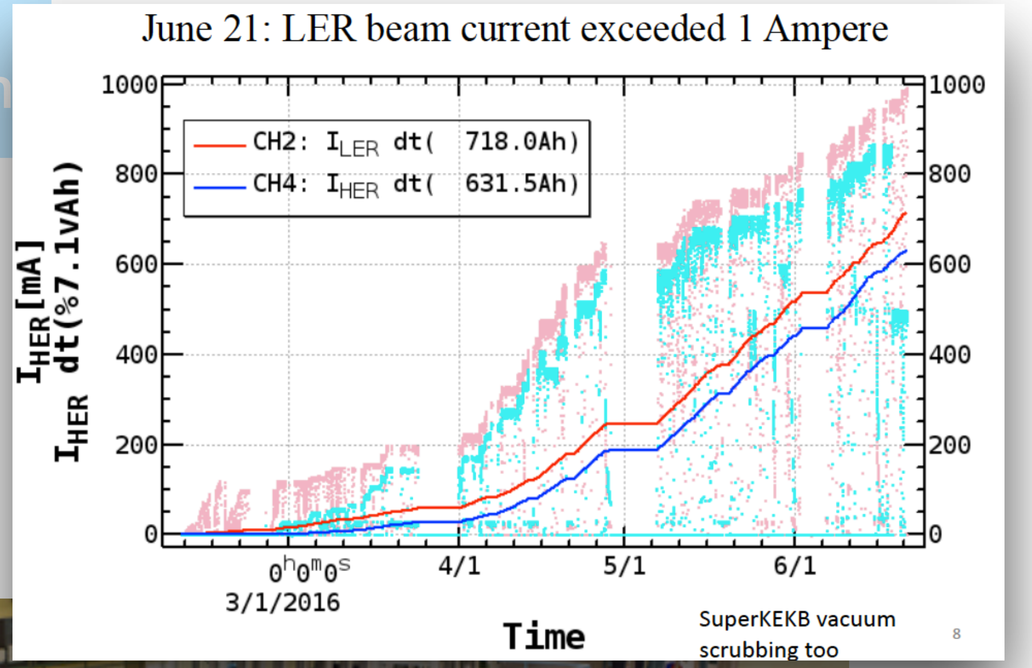
Phase 3

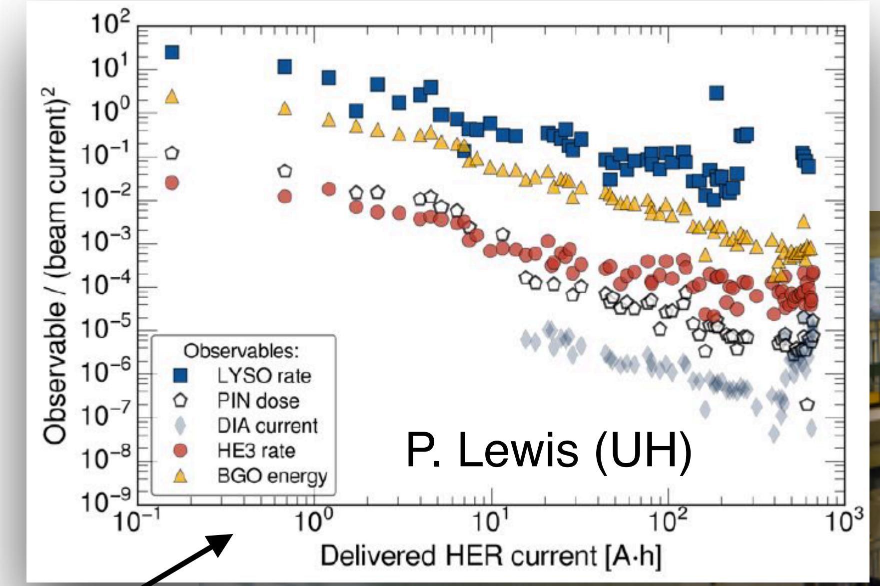
Installation of final focusing quads and Belle II, additional renovation of accelerator

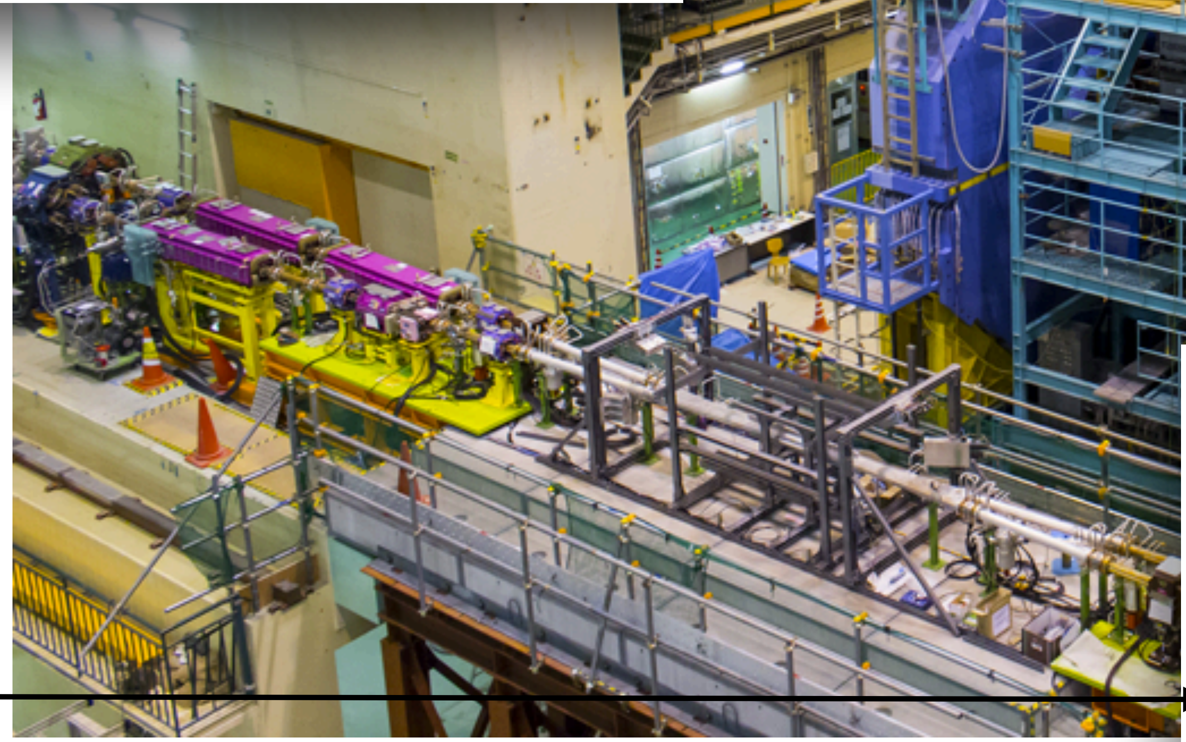
VXD installation

Damping Ring installation and startup

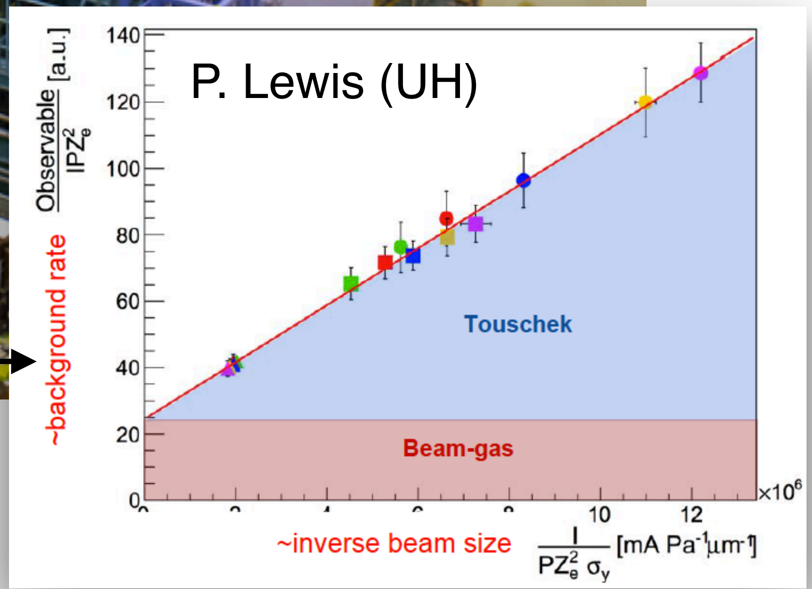
Beam Exorcism for A Stable Experiment
Dedicated background monitors







- **“BEAST” Phase 1: Started in Feb 2016**
  - Simple background commissioning detector (diodes, TPCs, crystals). No final focus. Only single beam background studies possible
  - Tune accelerator optics, etc., vacuum scrubbing, beam studies, validation of Belle II beam background simulations



”First measurements of beam backgrounds at SuperKEKB”, arXiv:1802.01366

SuperKEKB/Belle II schedule

Now

2016 | 2017 | 2018 | 2019

Phase 1

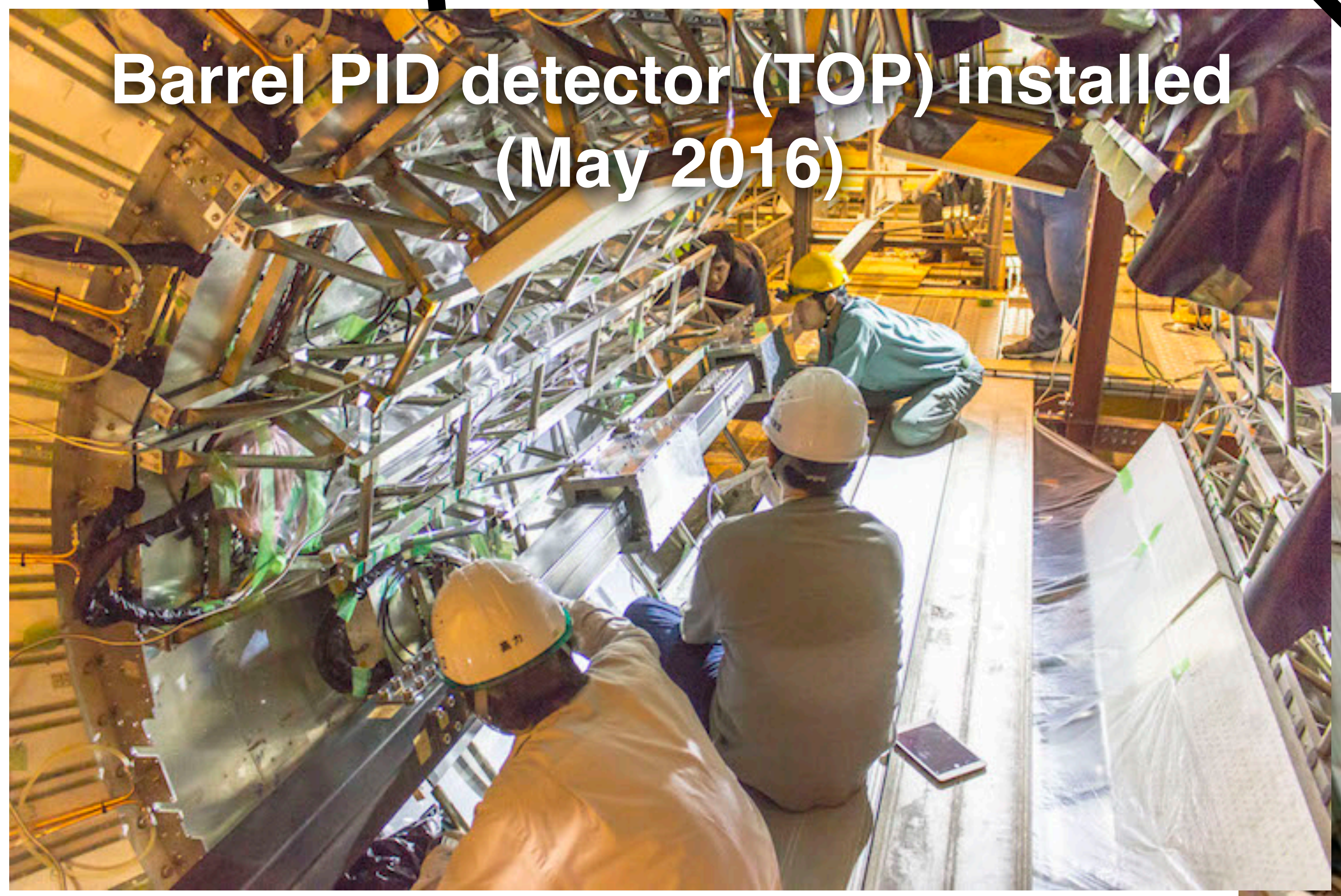
Phase 2

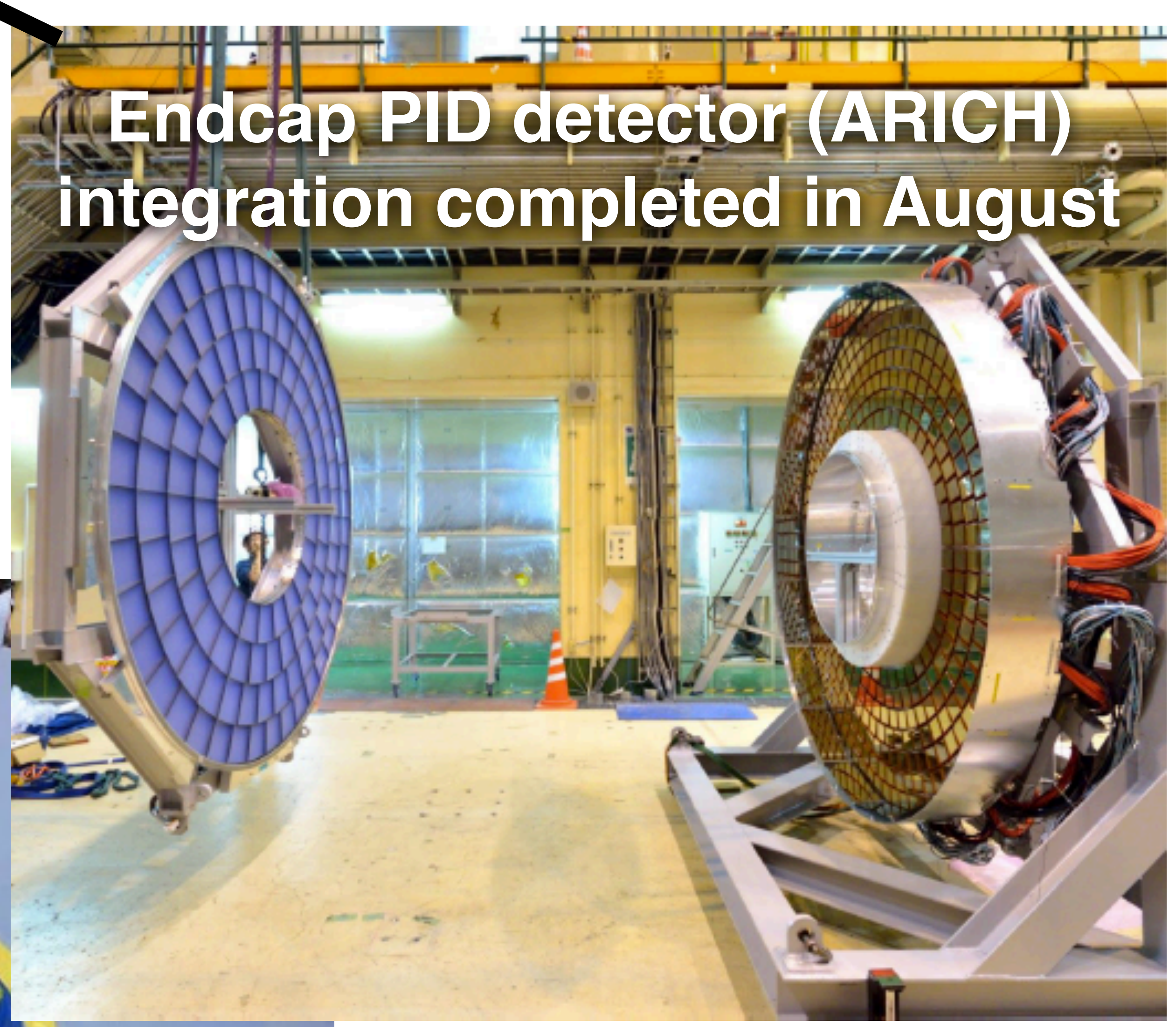
Phase 3

Installation of final focusing quads and Belle II, additional renovation of accelerator

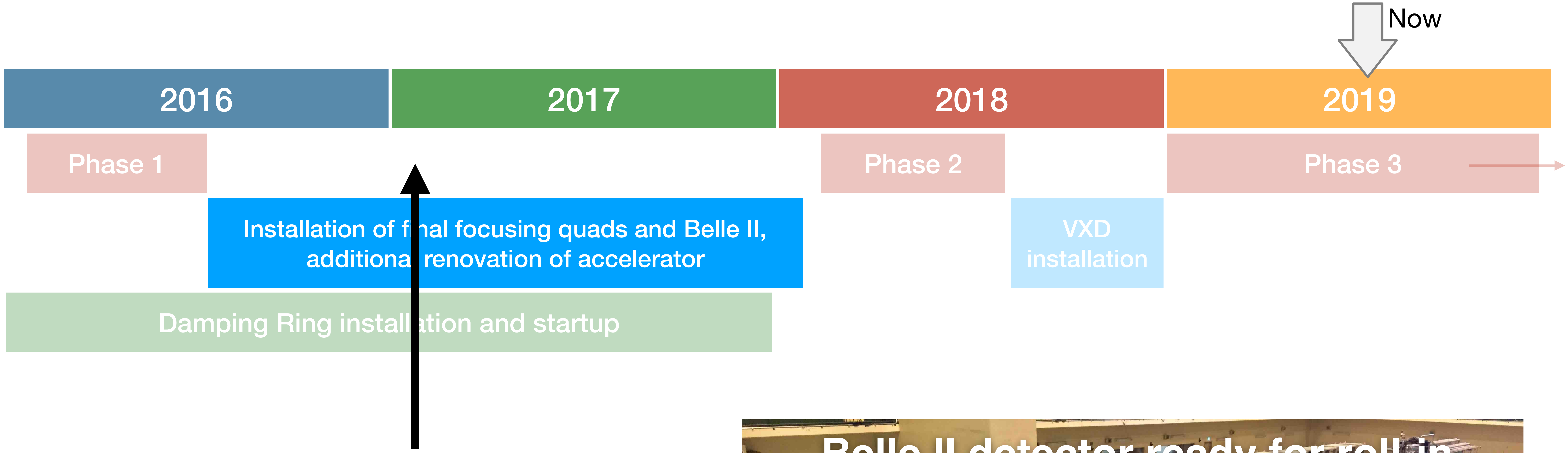
VXD installation

Damping Ring installation and startup



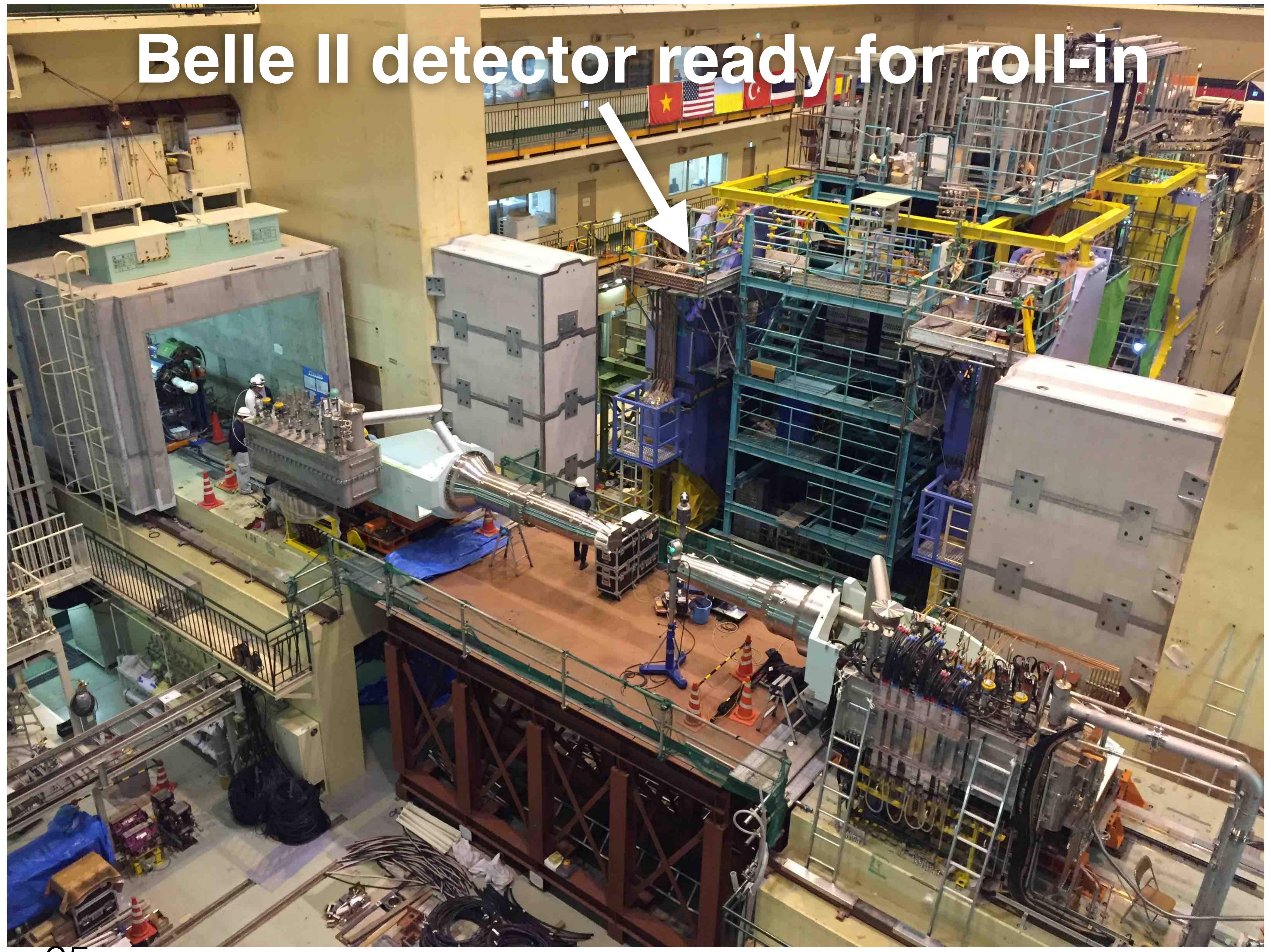


SuperKEKB/Belle II schedule

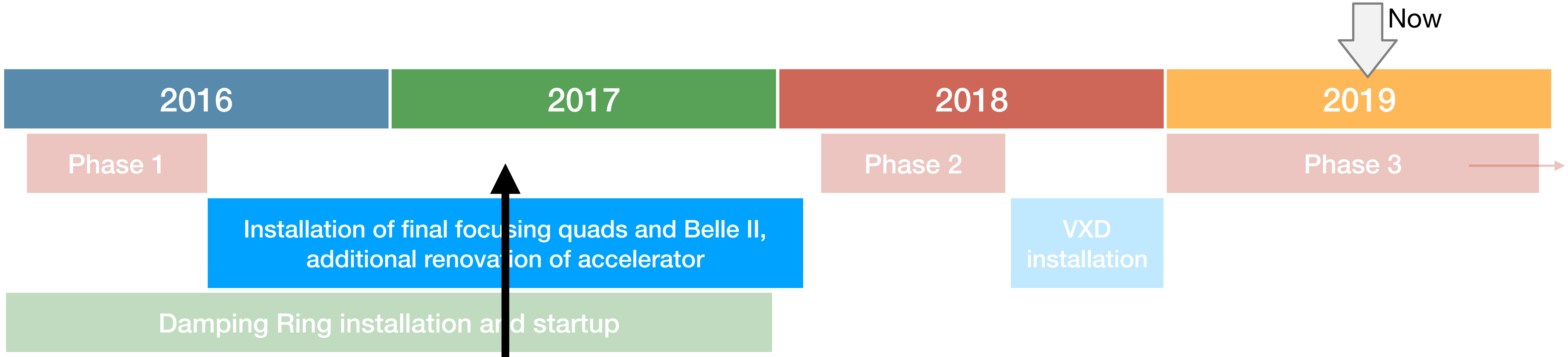


QCSL cooled and excited in Dec. 2016 for the first time

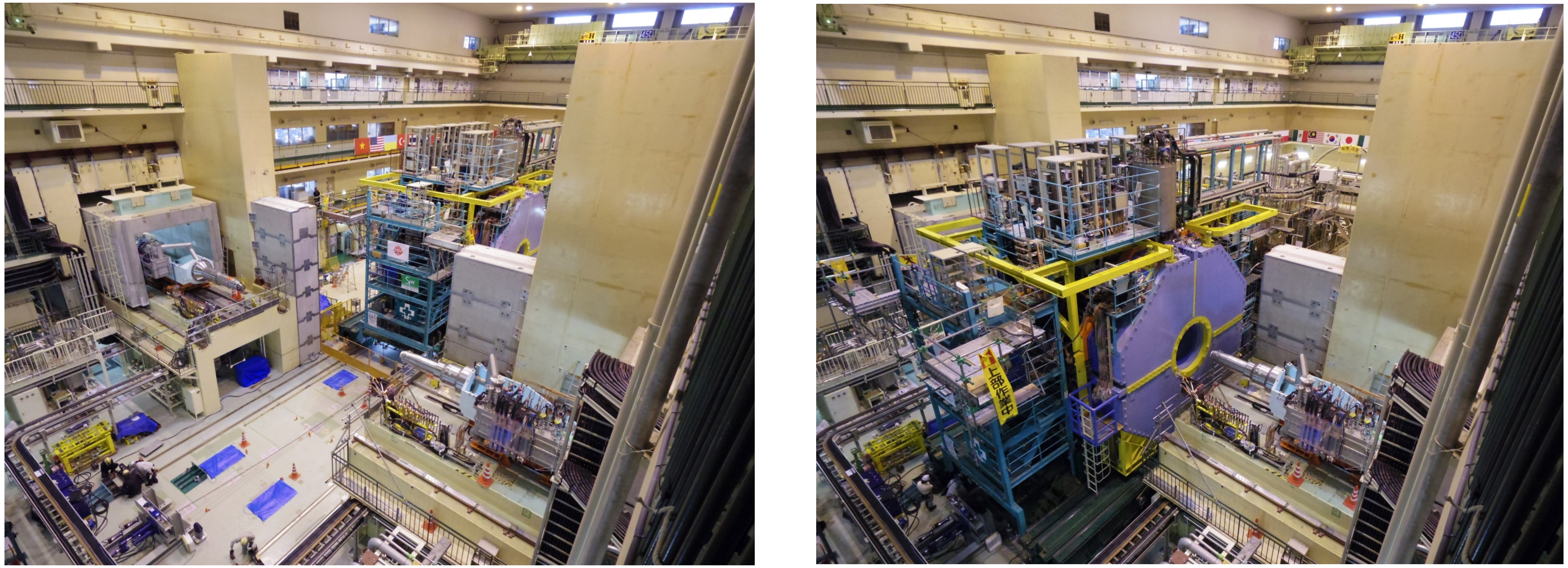
QCSR delivered on Feb. 13, 2017



SuperKEKB/Belle II schedule

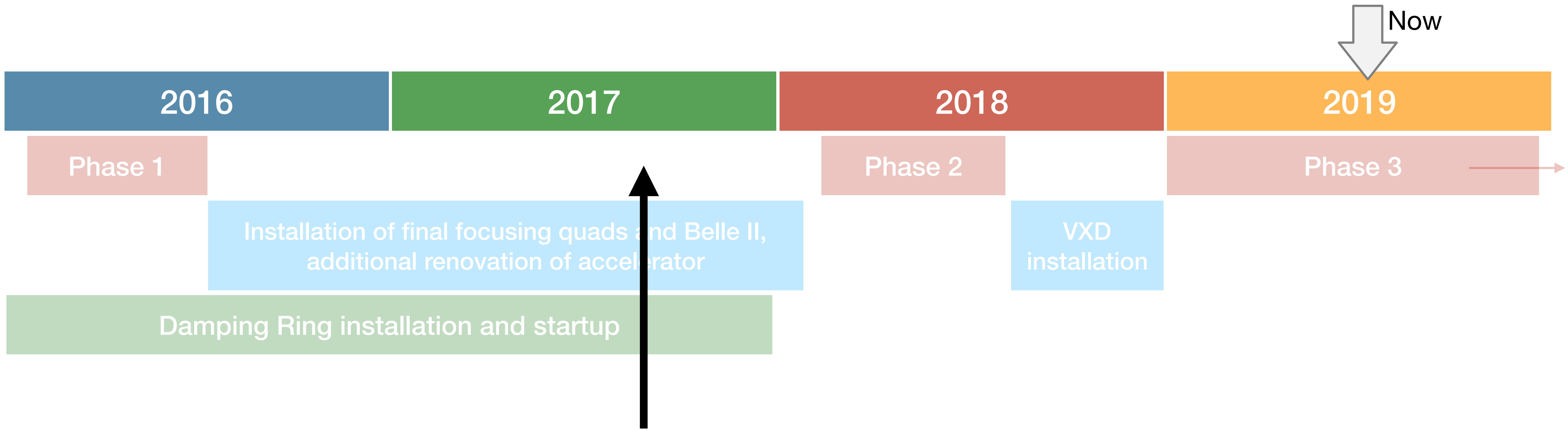


Belle II “roll-in” April 11, 2017

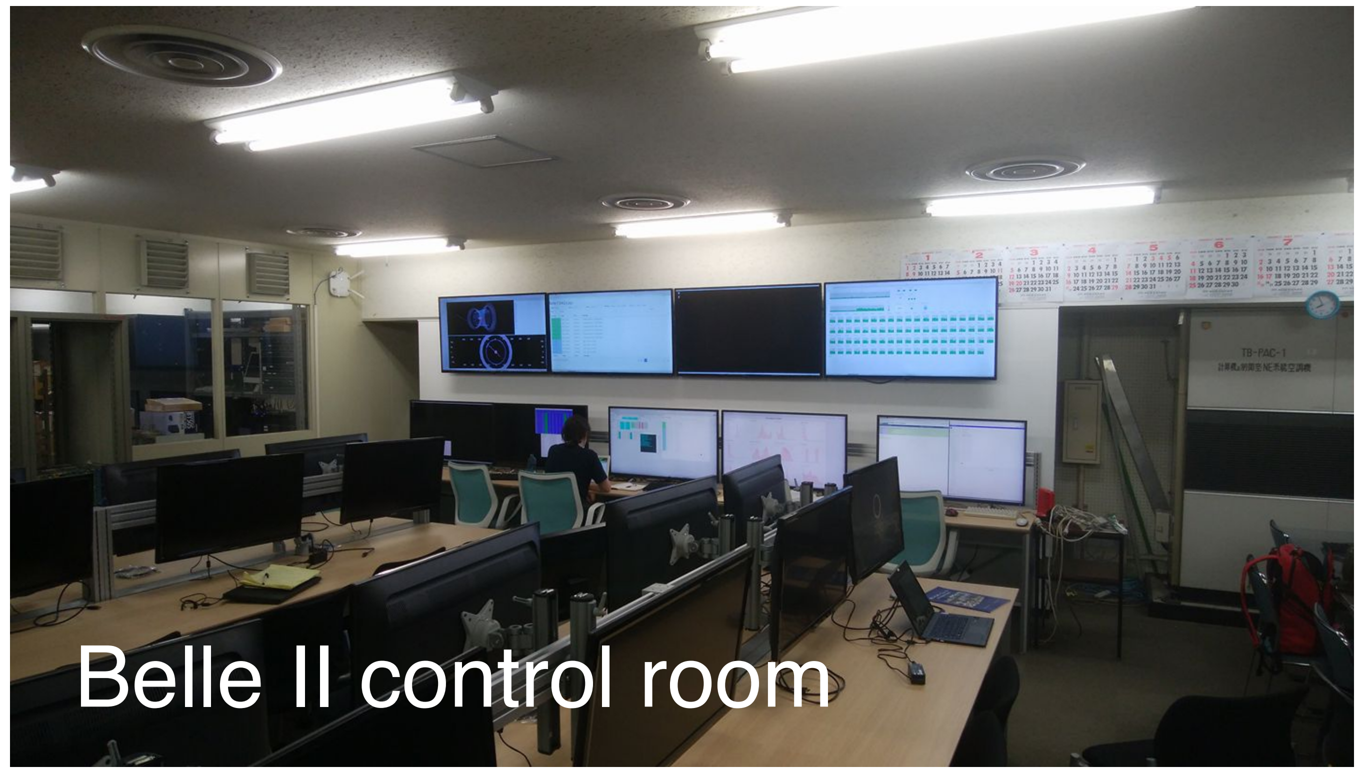


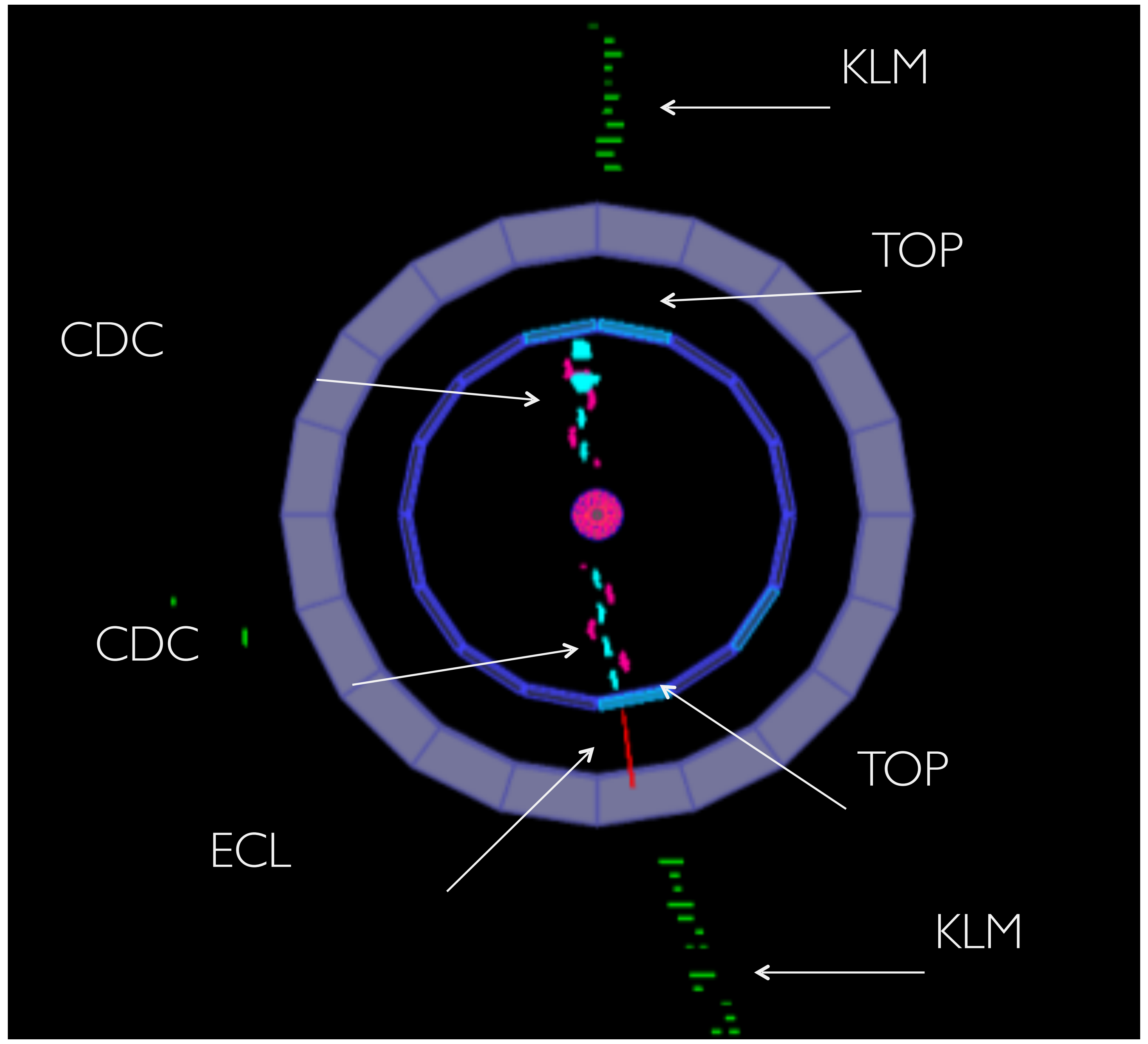
Belle II roll in: 1400 tons, 8m x 8m, moved 13m horizontally

SuperKEKB/Belle II schedule



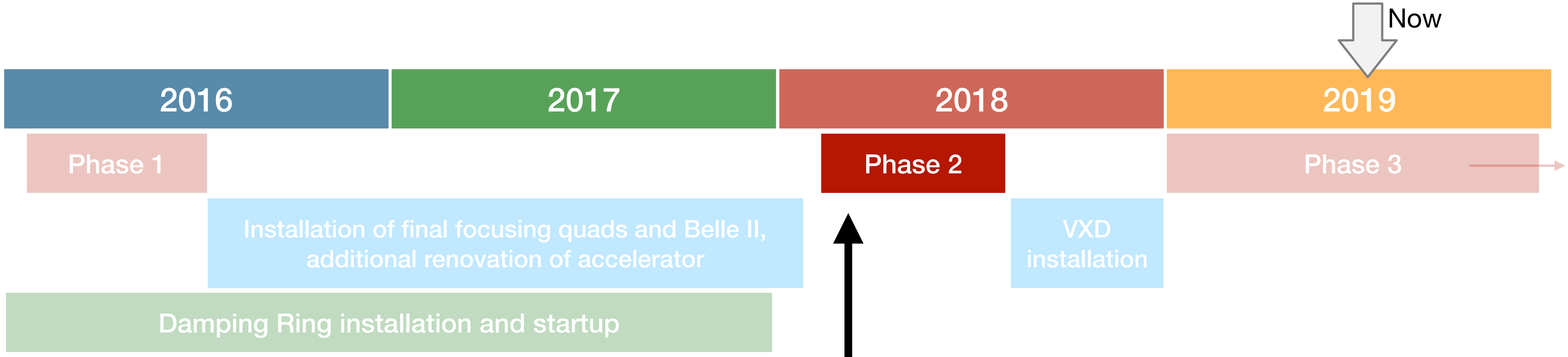
- **Belle II global cosmic run (July - August 2017)**
  - Final 1.5T solenoid field
  - Readout integration of installed sub-detectors and central DAQ in progress



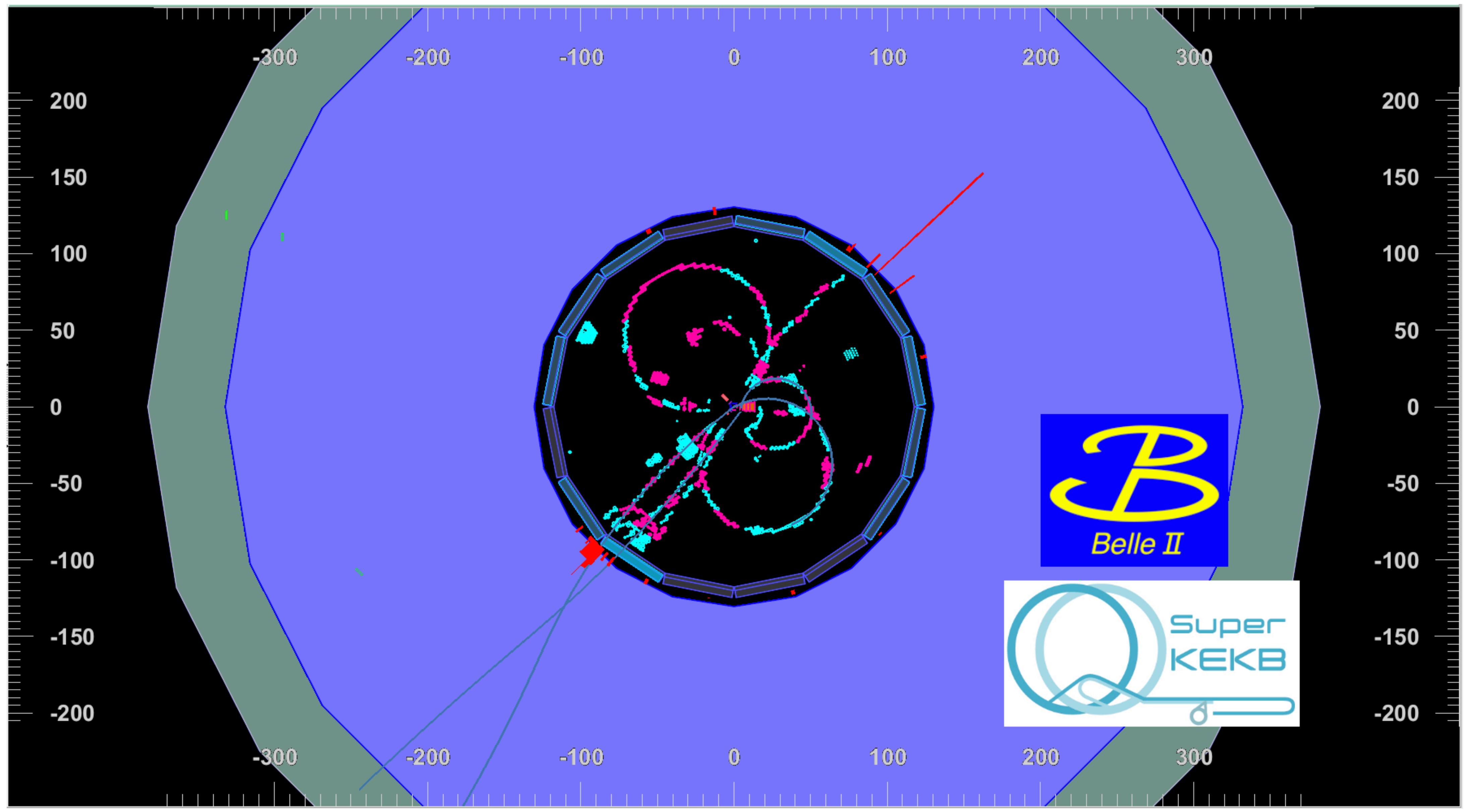


Hits in four outer subdetectors

SuperKEKB/Belle II schedule



One of the first Belle II events!



Probably $e^+e^- \rightarrow \gamma \rightarrow q\bar{q}$

SuperKEKB phase 2 commissioning:

- Dec. 2017 - Damping Ring
- Feb. 2018 - Main Ring
- First collisions April 26, 2018

Phase 2 goals

- Verification of nanobeams (luminosity > 10^{34} $cm^{-2}s^{-1}$)
- Beam background study, especially in VXD volume
- First physics!

SuperKEKB/Belle II schedule

Inside the Belle II control room

2016	201
Phase 1	
Installation of final focusing qua additional renovation of ac	
Damping Ring installation and startu	

elle

(luminosity > 10^{34} $cm^{-2}s^{-1}$)

- Beam background study, especially in VXD volume
- First physics!

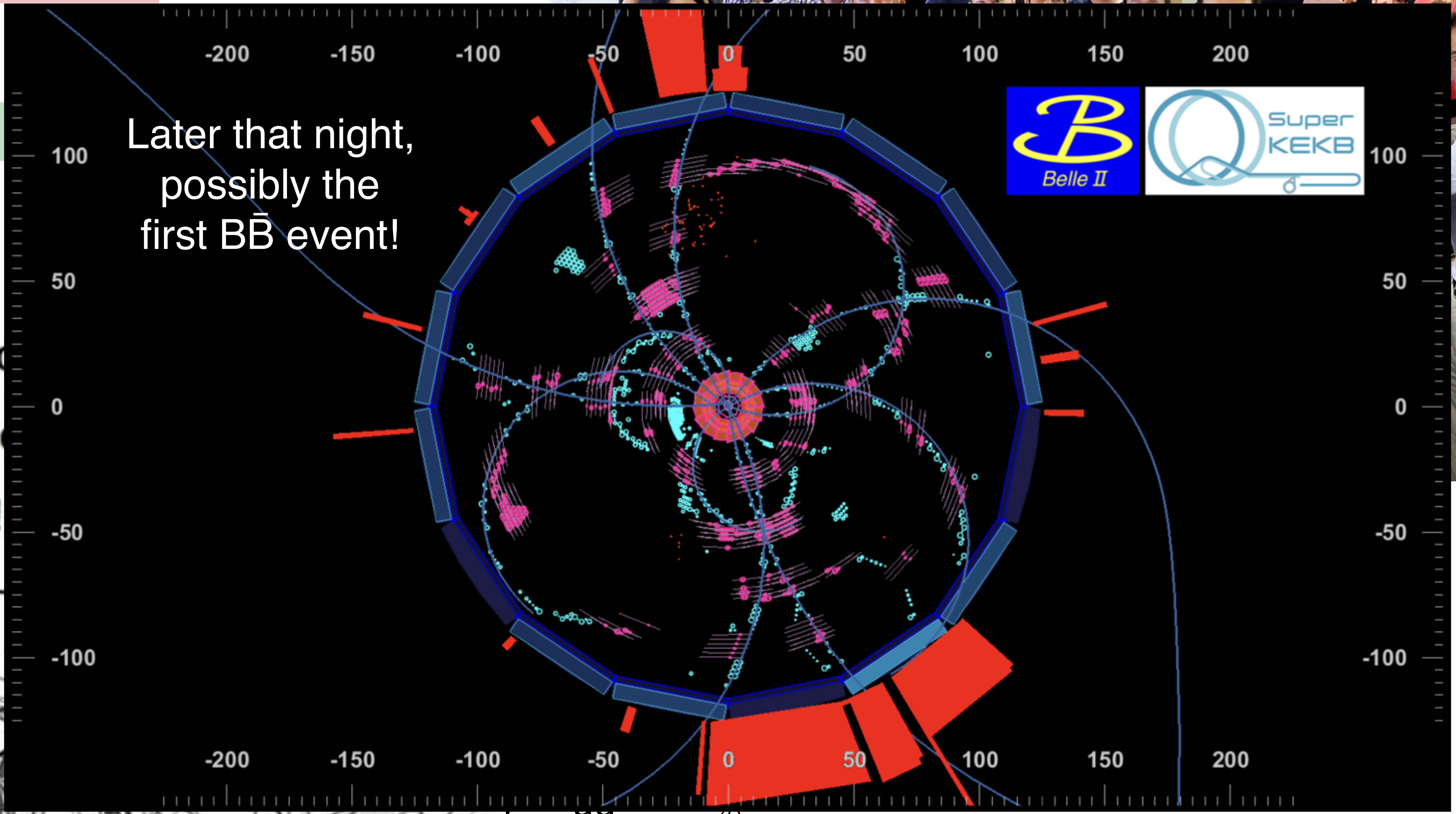
$\gamma \rightarrow q\bar{q}$

SuperKEKB/Belle II schedule

2016 | 201

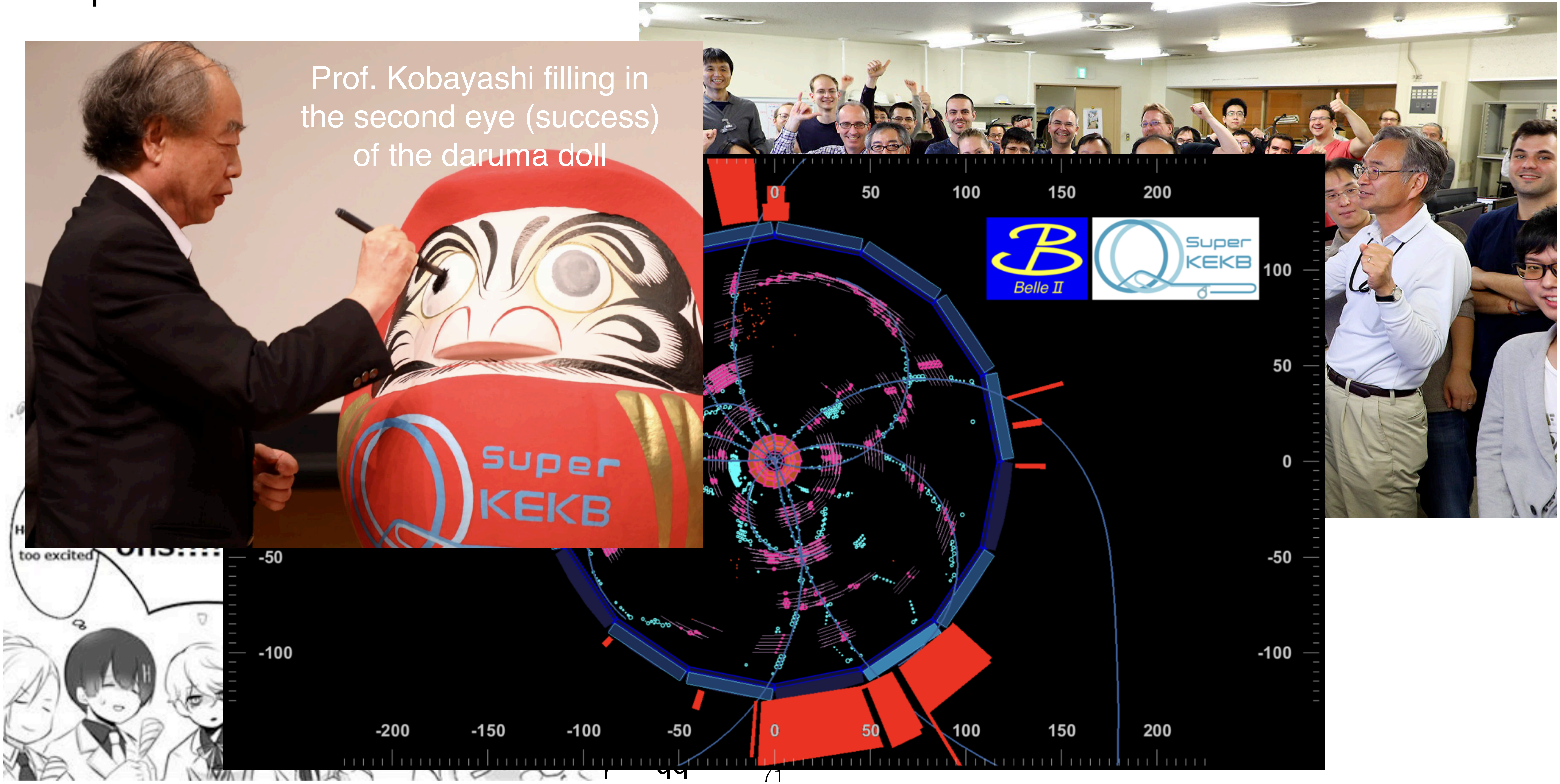
Phase 1

Inside the Belle II control room



SuperKEKB/Belle II schedule

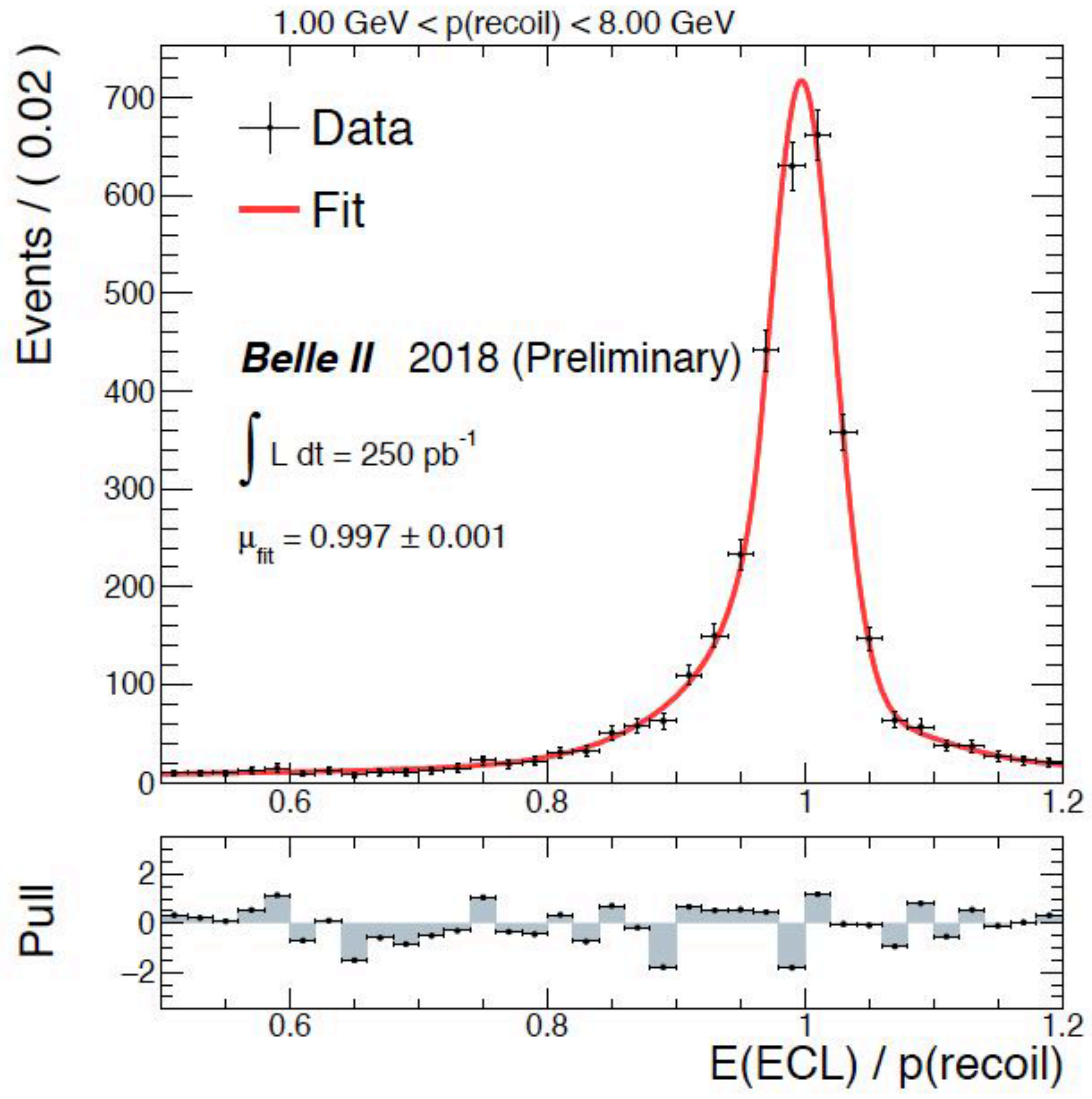
Inside the Belle II control room



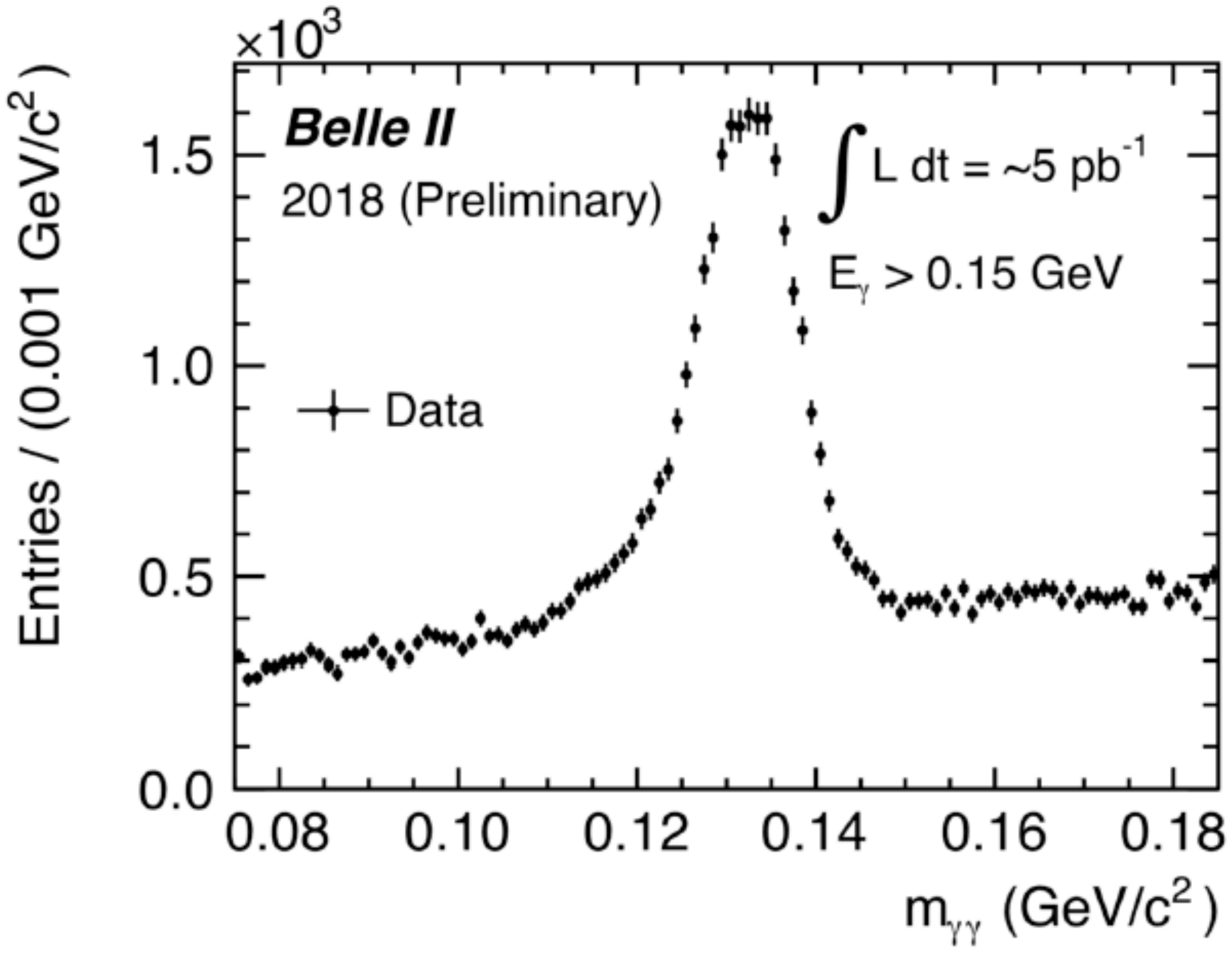
Some results from phase 2

- First physics!
  - Neutral reconstruction

$e^+e^- \rightarrow \mu^+\mu^-\gamma$

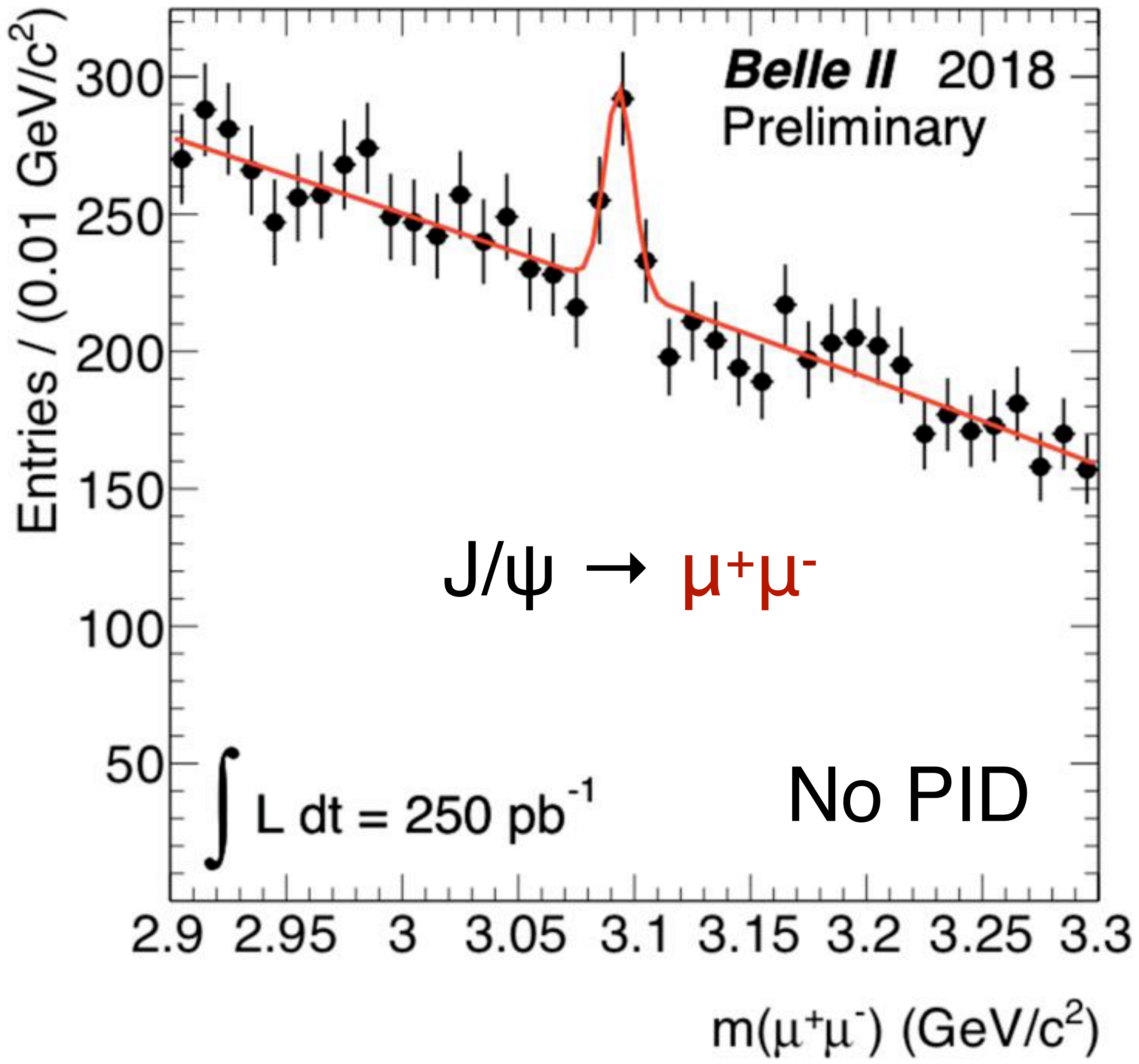


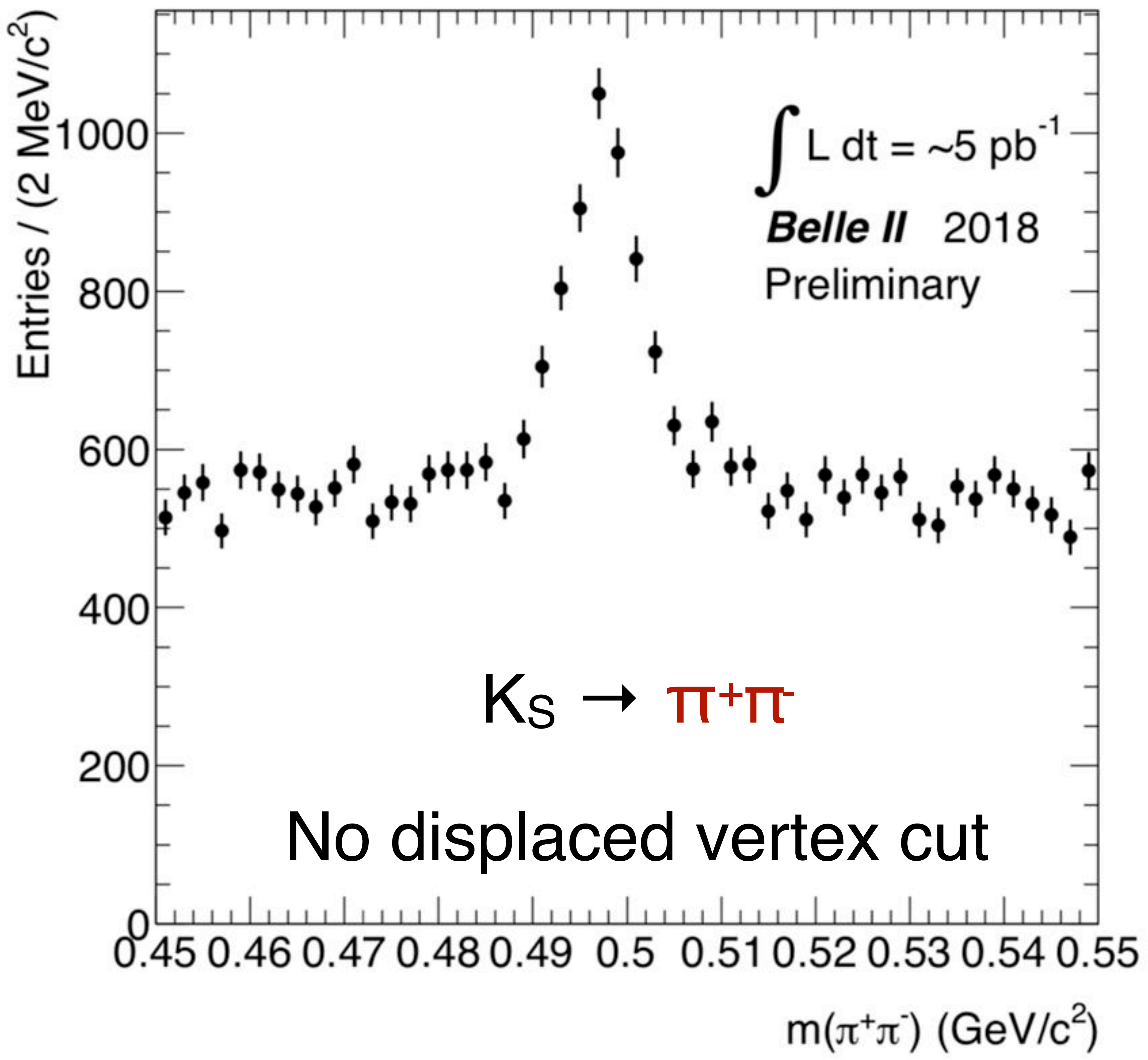
$\pi^0 \rightarrow \gamma\gamma$

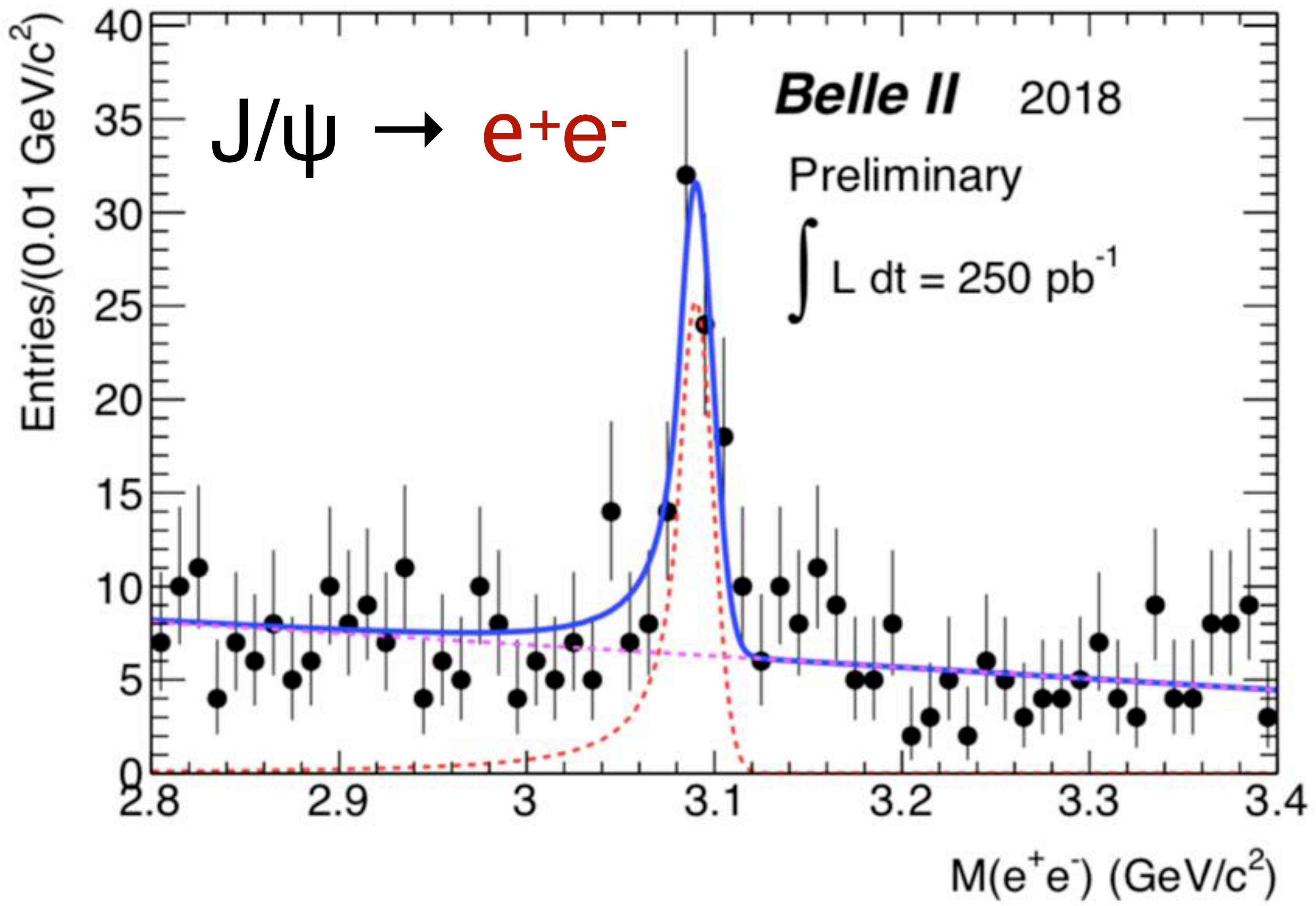


Some results from phase 2

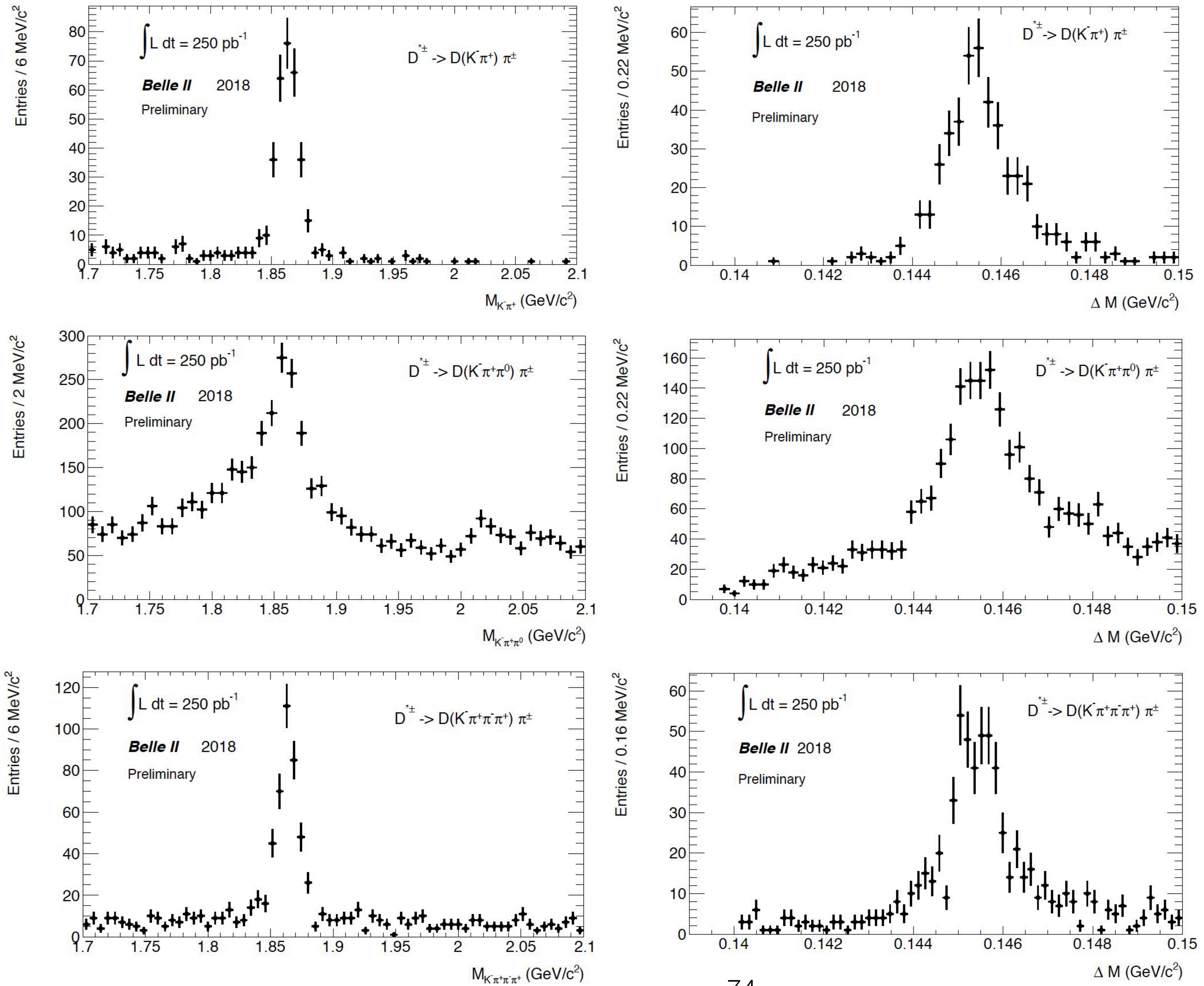
- First physics!
  - Neutral reconstruction
  - Tracking







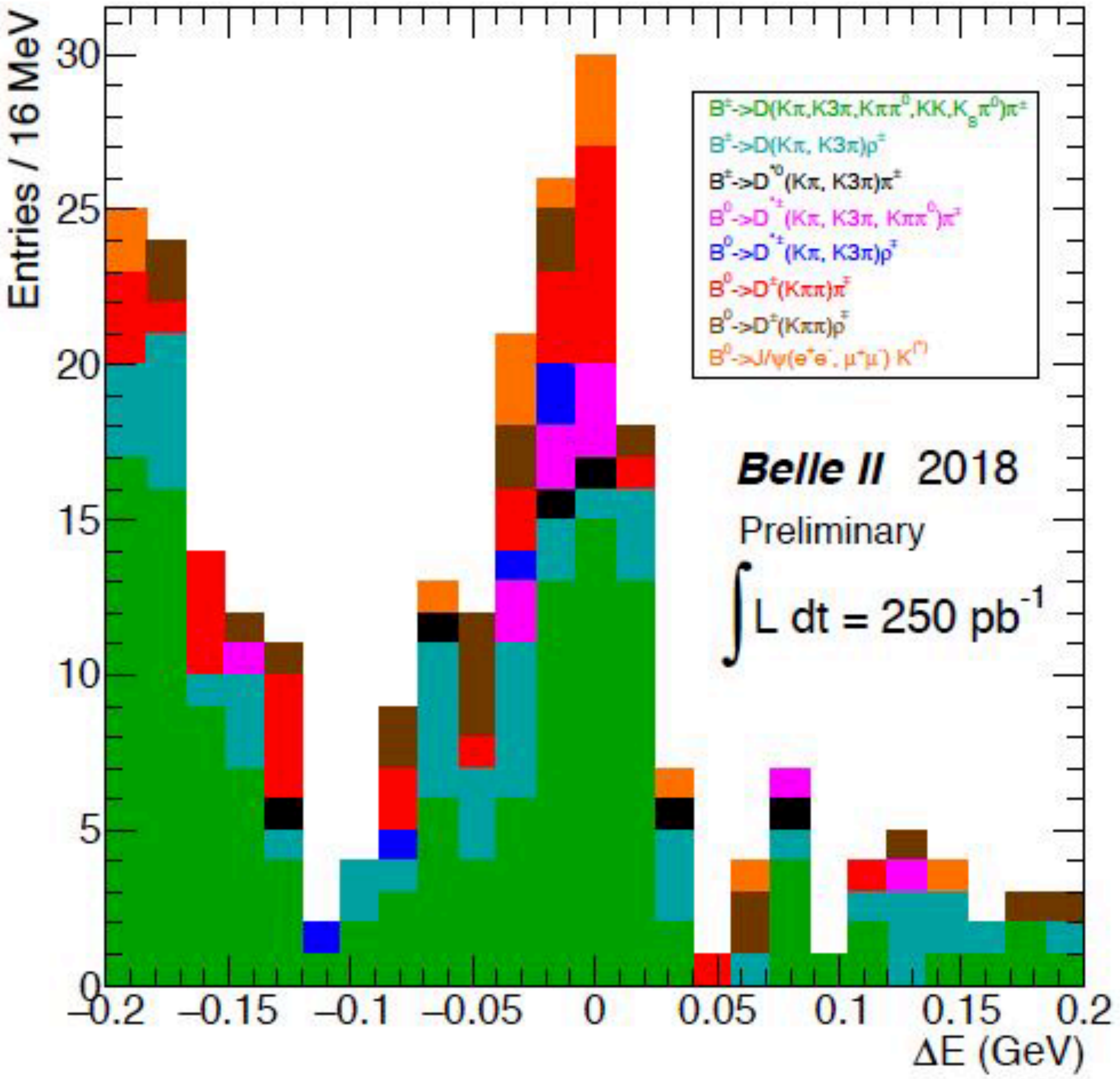
Some charming results from phase 2

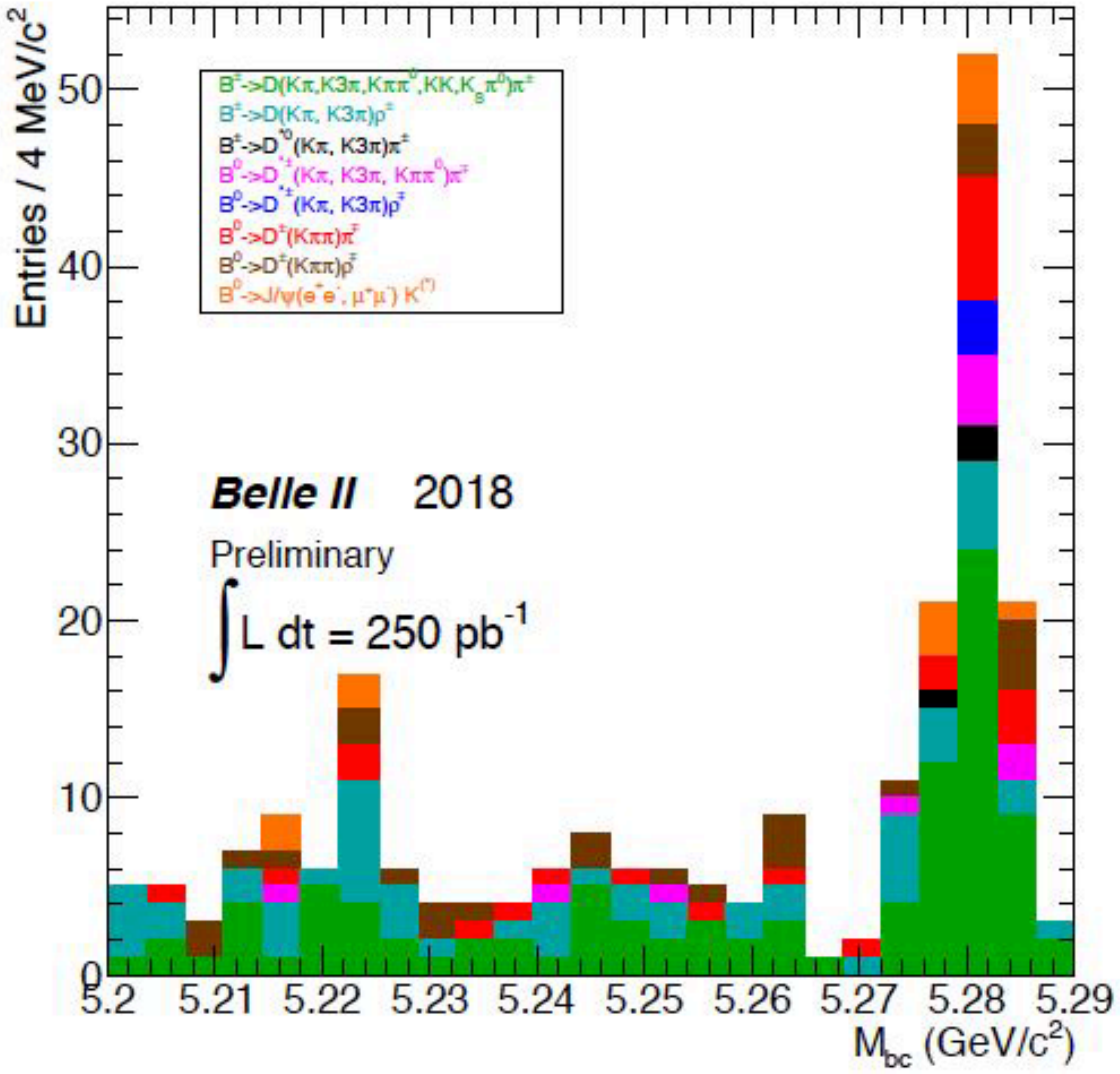


With PID cuts

Belle II is ready for charm physics, a building block for B physics!

Some beautiful results from phase 2

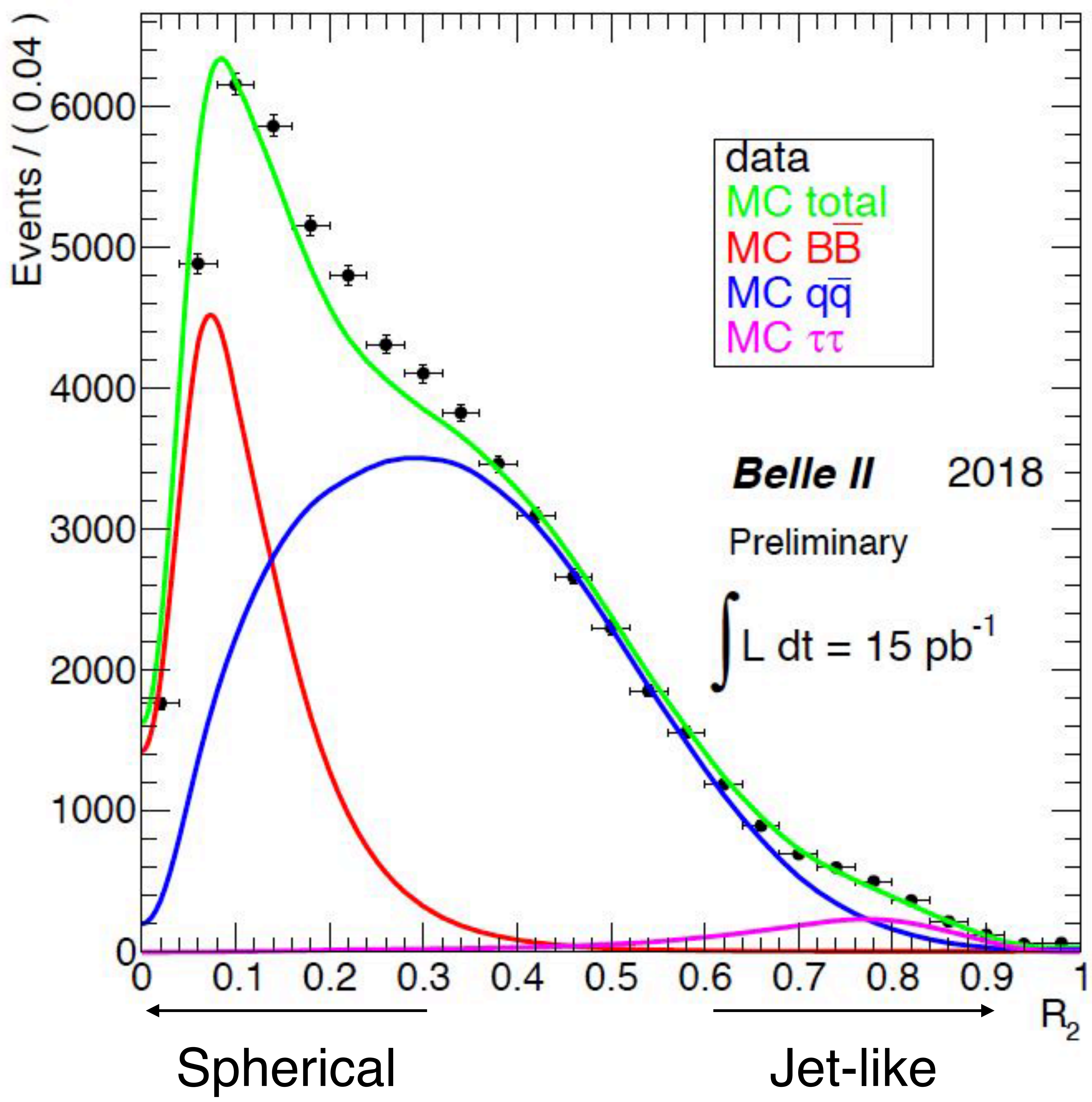


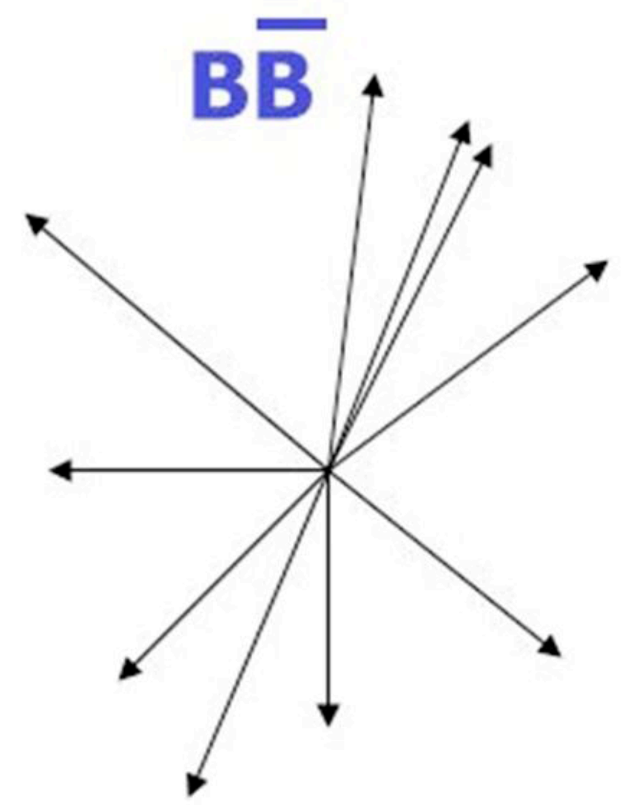


$$\Delta E = E_B - E_{beam}$$

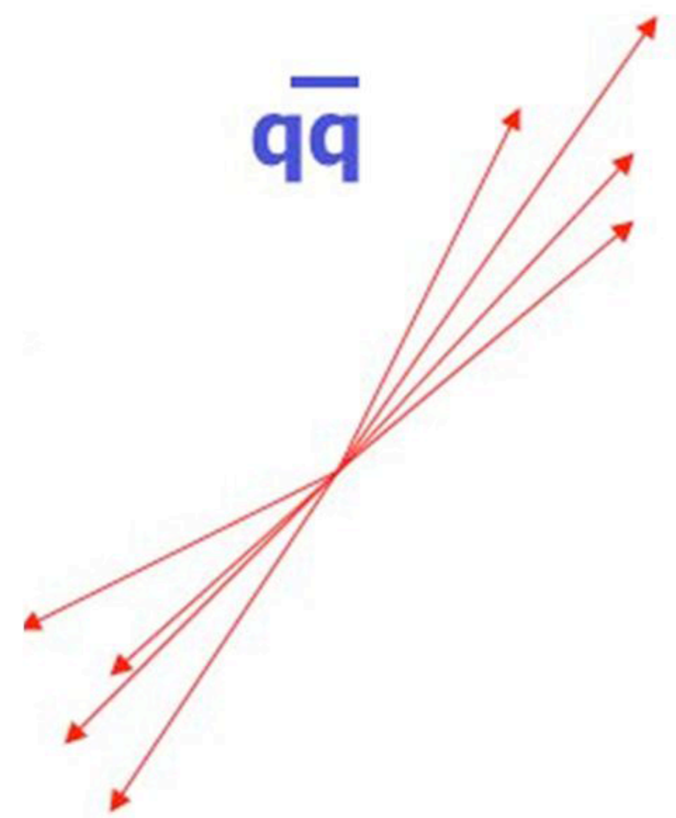
$$M_{BC} = \sqrt{(E_{beam})^2 + (p_B)^2}$$

Confirmation of B “rediscovery” from event topology





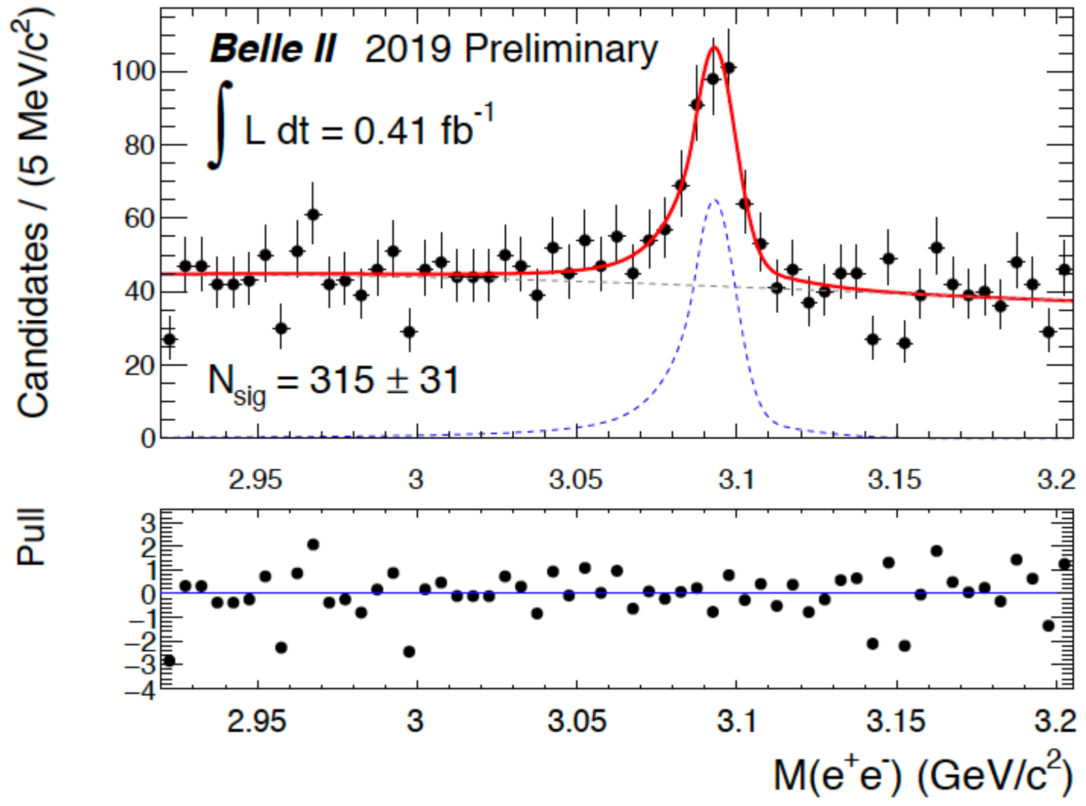
At the Υ(4S), BB̄ pairs are produced at rest in the CM with no extra particles

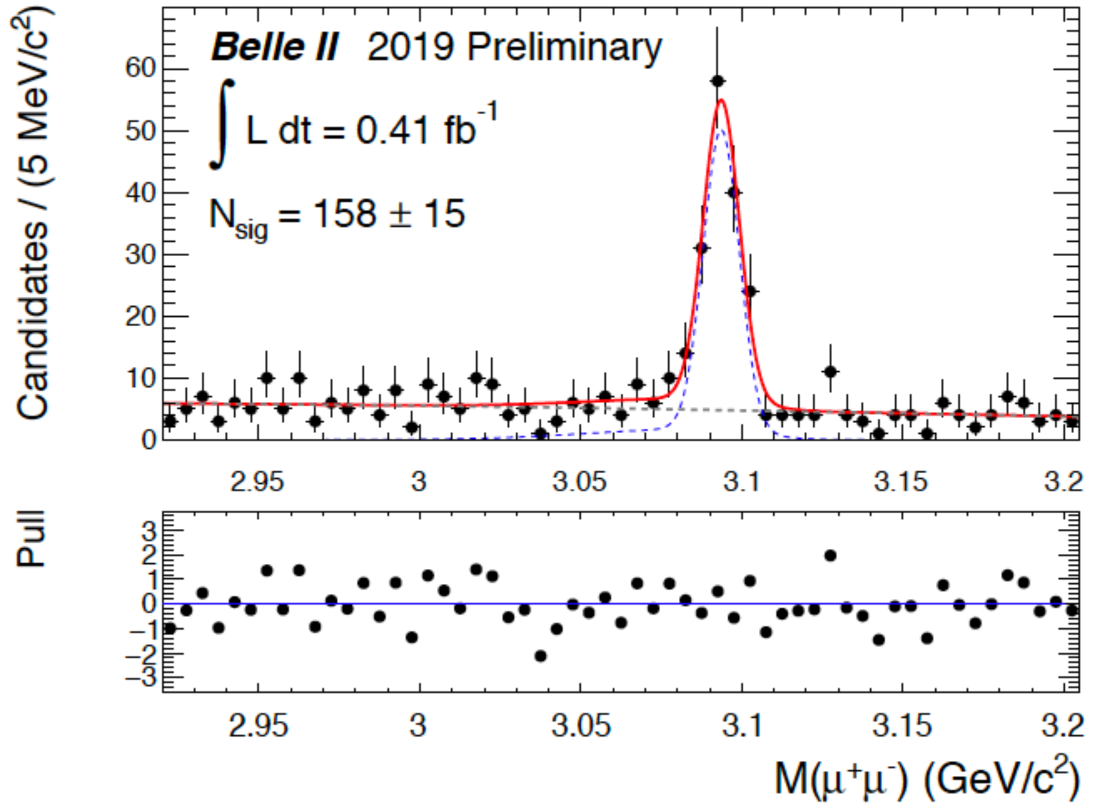


We are on the Υ(4S) and recording BB̄ pairs with ~99% efficiency!

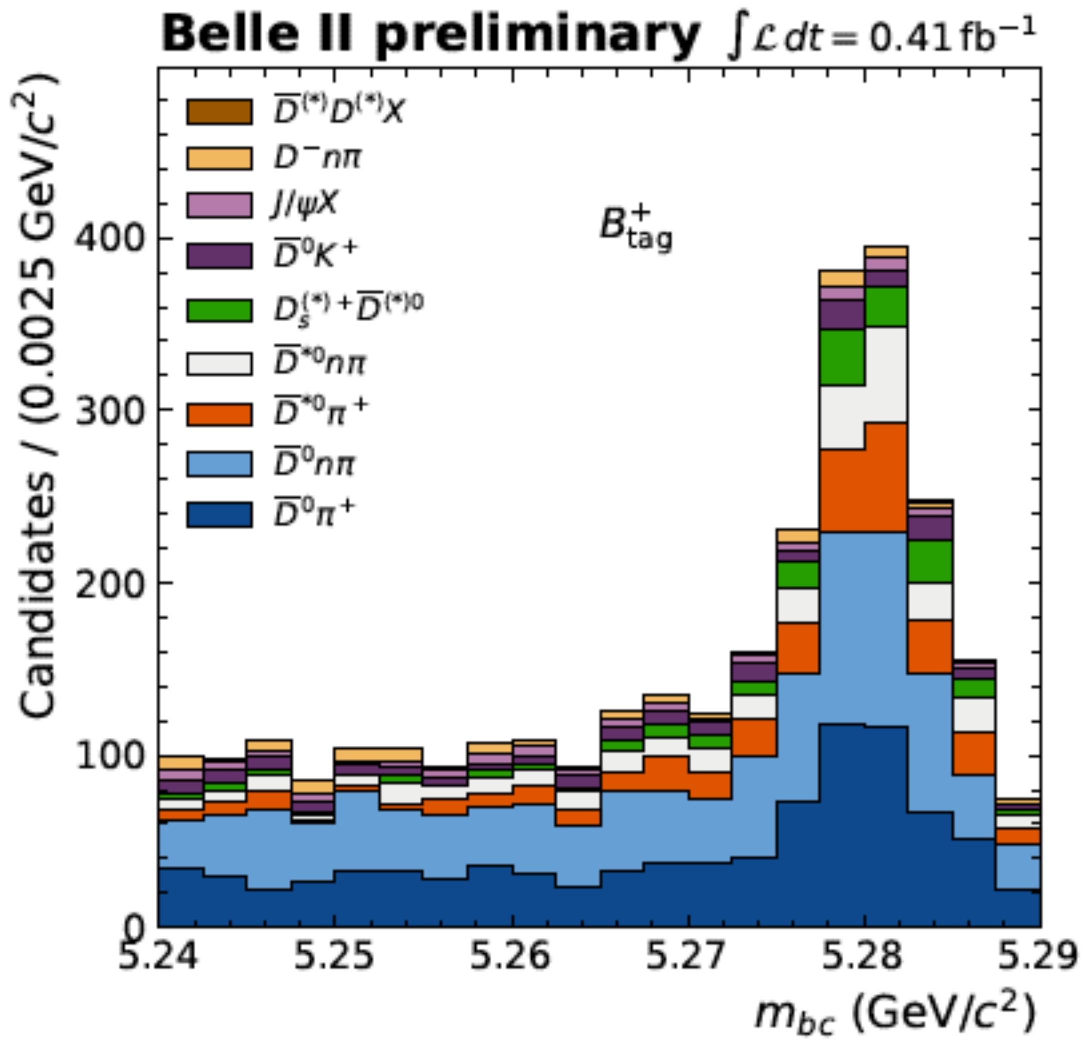
Phase 3 results

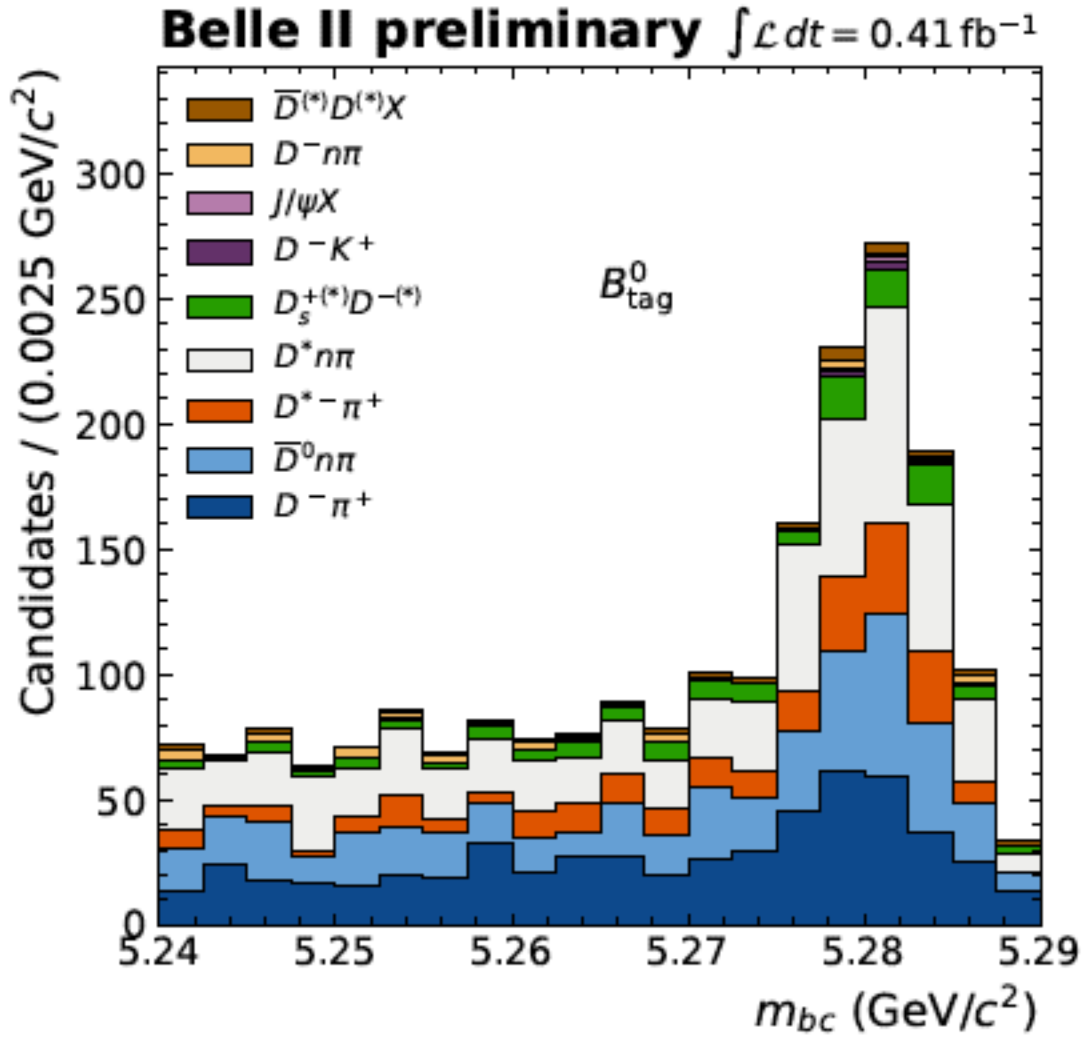
- Working lepton ID!

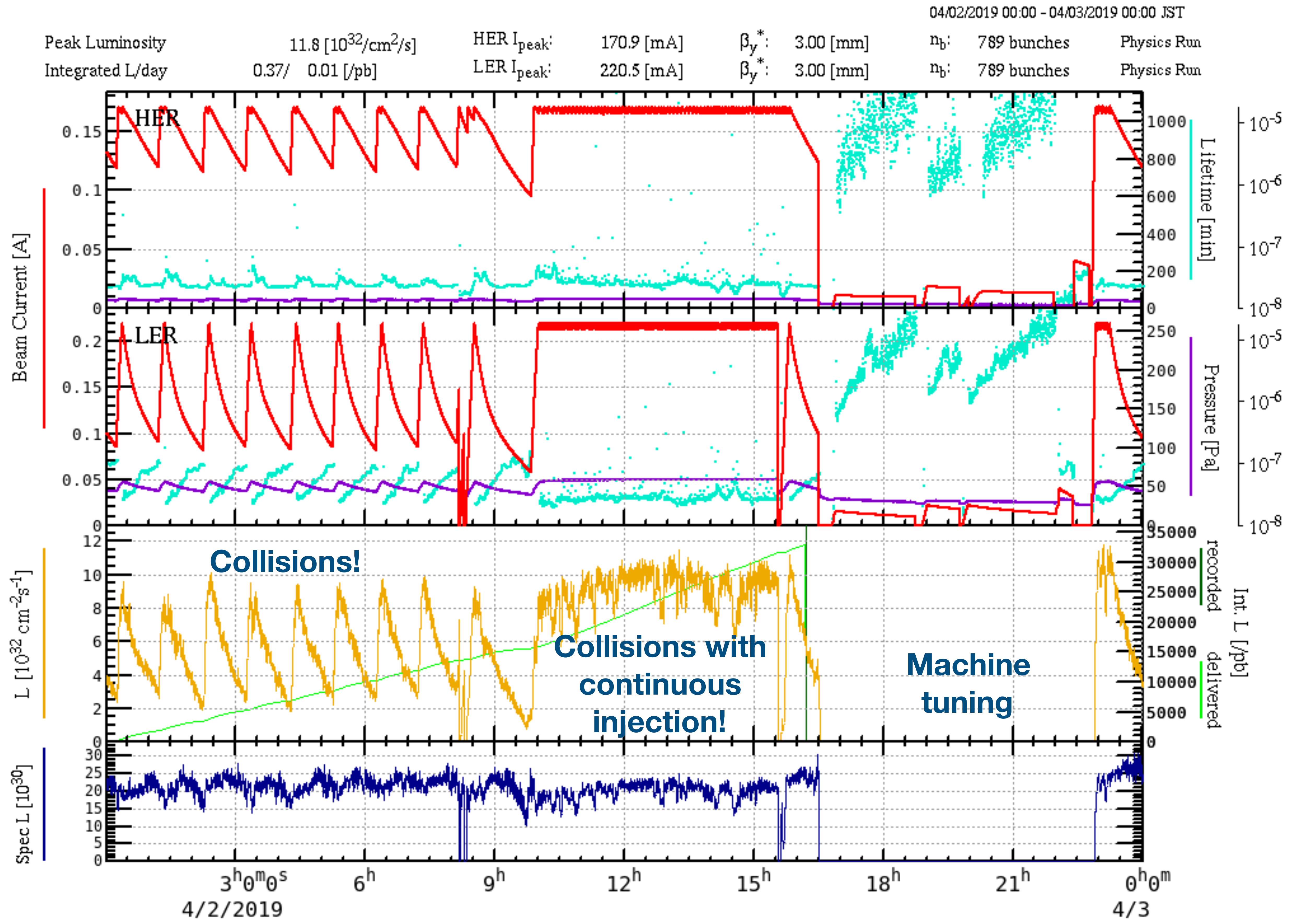




- Working Full Event Interpretation!







Closing remarks

- Major upgrade at KEK for the next generation B-factory
    - Many detector components and electronics replaced, software and analysis tools also improved!
- Belle II has a rich physics program, complementary to existing experiments and the energy frontier program
- Successful Phase 1 (2016) and 2 (2018) operation!
- Very exciting start to Phase 3 in spring 2019!

- Too much information for a single talk!
    - More details coming in later talks
    - Plenty of other resources
        - Belle II Technical Design Report (TDR): https://arxiv.org/ftp/arxiv/papers/1011/1011.0352.pdf
        - Belle II document database: https://docs.belle2.org/
        - Belle II video: https://www.youtube.com/watch?v=nGCrrgXSEOk
        - Definition of acronyms: https://confluence.desy.de/display/BI/Main+Glossary

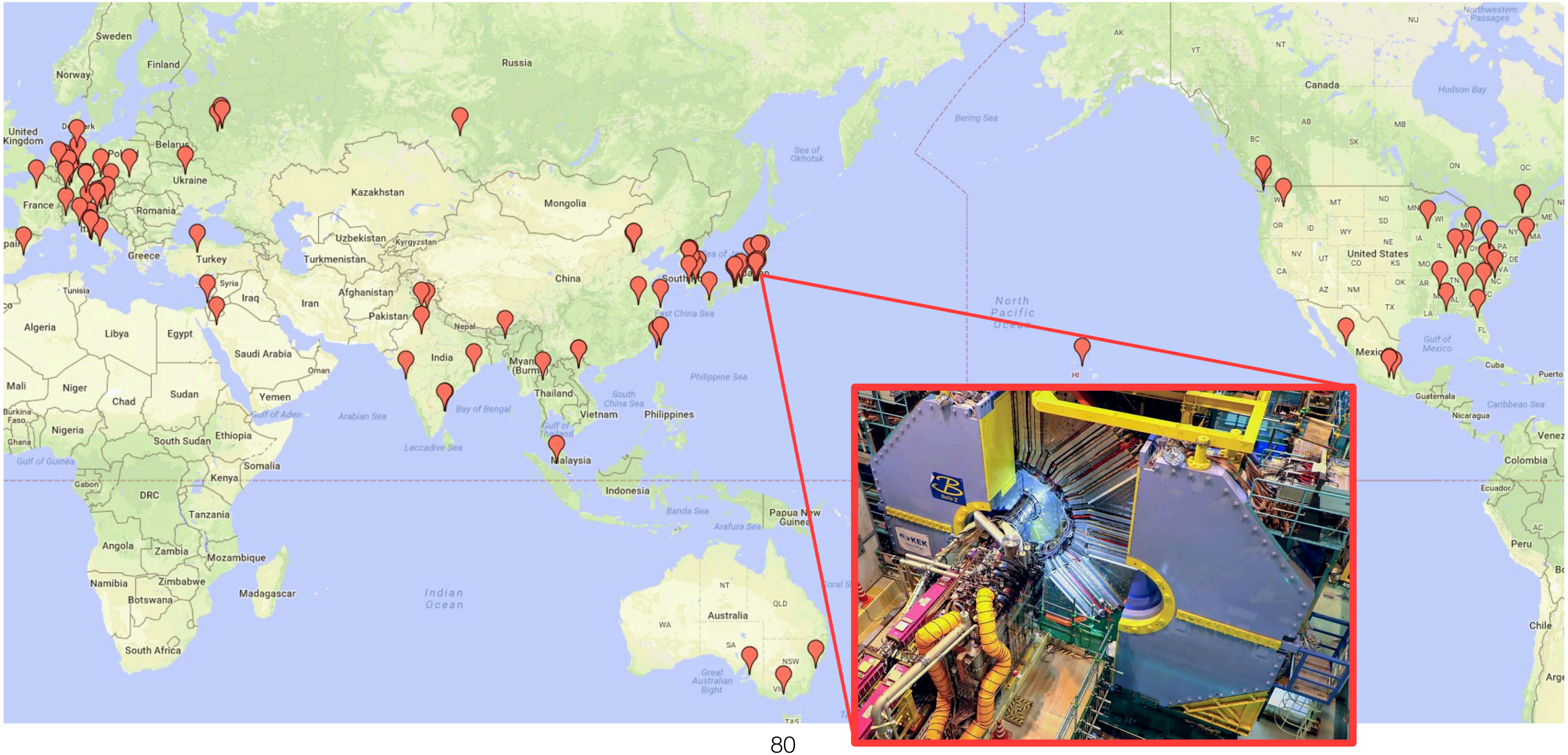
Belle II detector jargon/acronyms

- KLM = KLong-Muon detector
  - EKLM = Endcap KLM: Scintillator
  - BKLM = Barrel KLM: Scintillator and Resistive Plate Chamber (RPC)
- ECL = Electromagnetic CaLorimeter
  - CsI(Tl) crystals (measures energies of photons et al.)
- TOP (iTOP) = (imaging) Time Of Propagation
  - Barrel PID - distinguishes hadrons (mostly)
- ARICH = Aerogel Ring Imaging Cherenkov
  - Endcap PID - distinguishes hadrons (mostly)
- CDC = Central Drift Chamber
  - Tracking, momentum measurements, PID
- SVD = Silicon Vertex Detector
  - 4 layers of double sided silicon detectors
  - Tracking and vertexing
- PXD = PiXel Detector
  - ~2 layers of DEPFET pixels
  - Tracking and vertexing

- DAQ = Data AQuisition
- HLT = High Level Trigger

The Belle II Collaboration

- ~900 researchers from 25 countries (some institutions not shown)




Mt. Tsukuba (877m)
SuperKEKB
Belle II
LINAC
main ring: 3km
e- (HER): 7GeV
e+ (LER): 4GeV
KEK
Tsukuba
Campus