TOP
Particle ID in the Belle II Barrel

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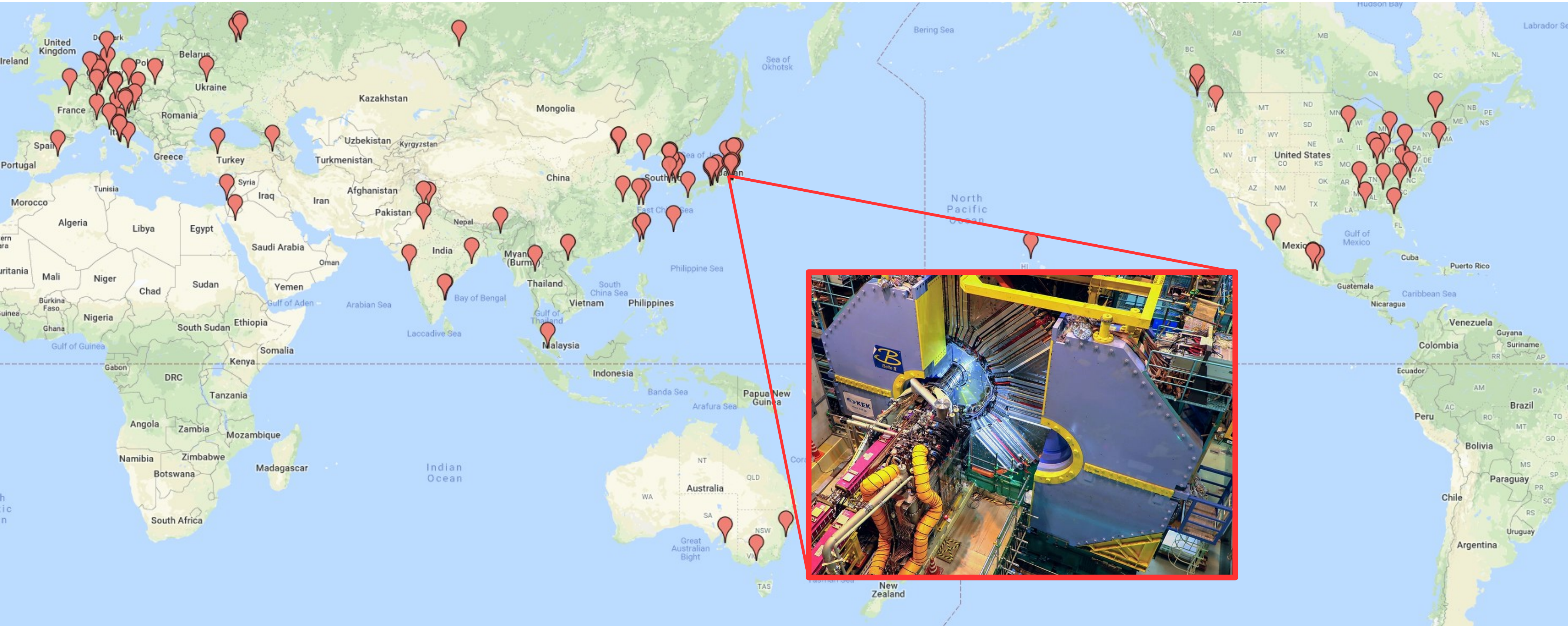
What to Expect

- Overview of Belle II and SuperKEKB
  - Key detector technologies in Belle II
- The TOP barrel PID
  - Concept
  - Technologies
  - Experiences
  - Preliminary performance figures
- Highlights from the first “full Belle II” data

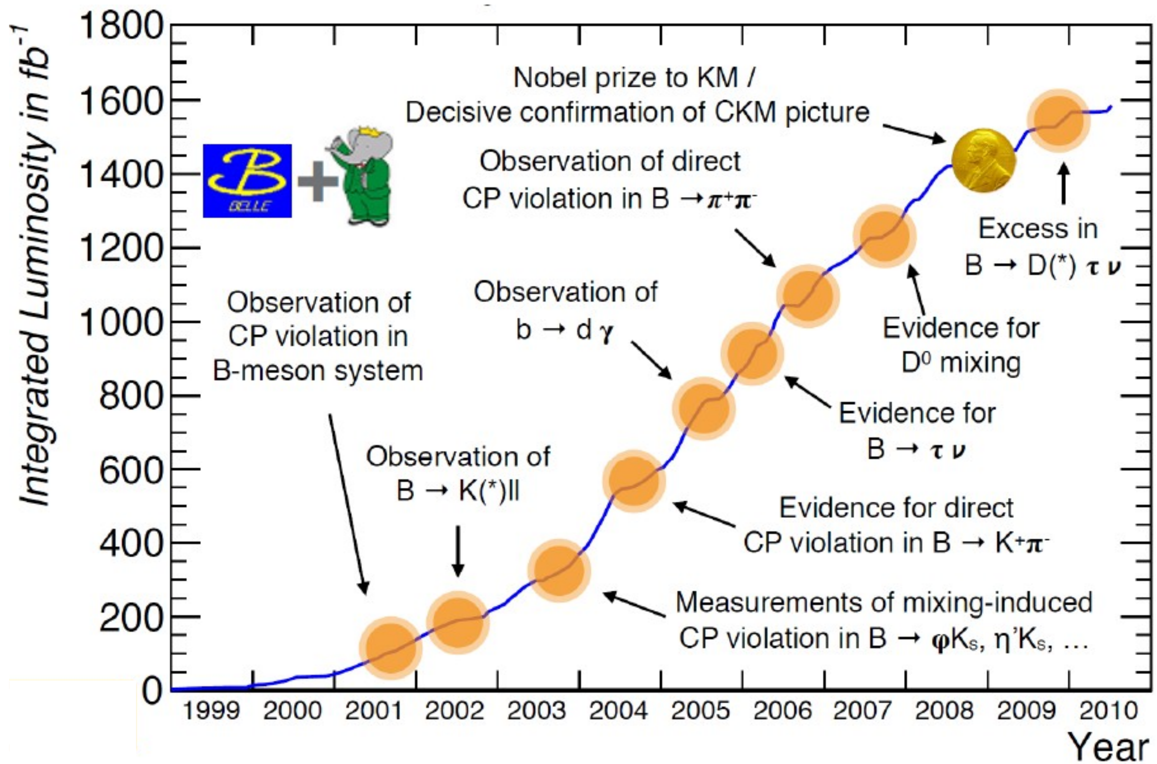
The Belle II Collaboration

- Truly international: now ~980 researchers from 26 countries



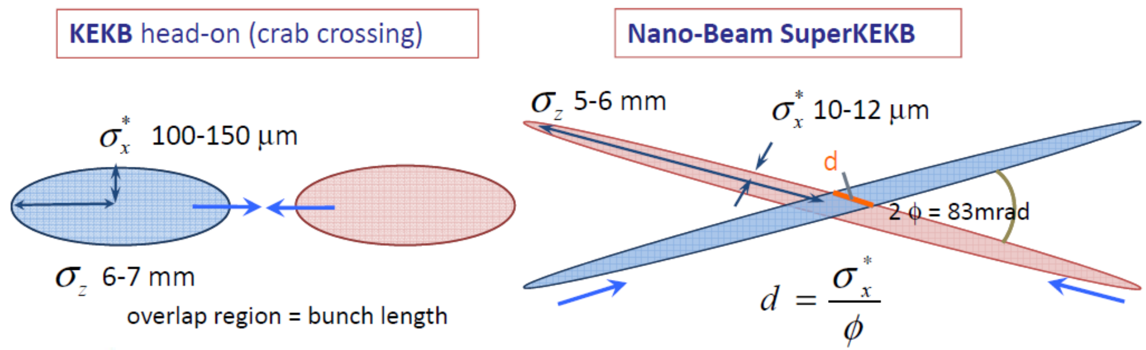
B-Factory Experiments

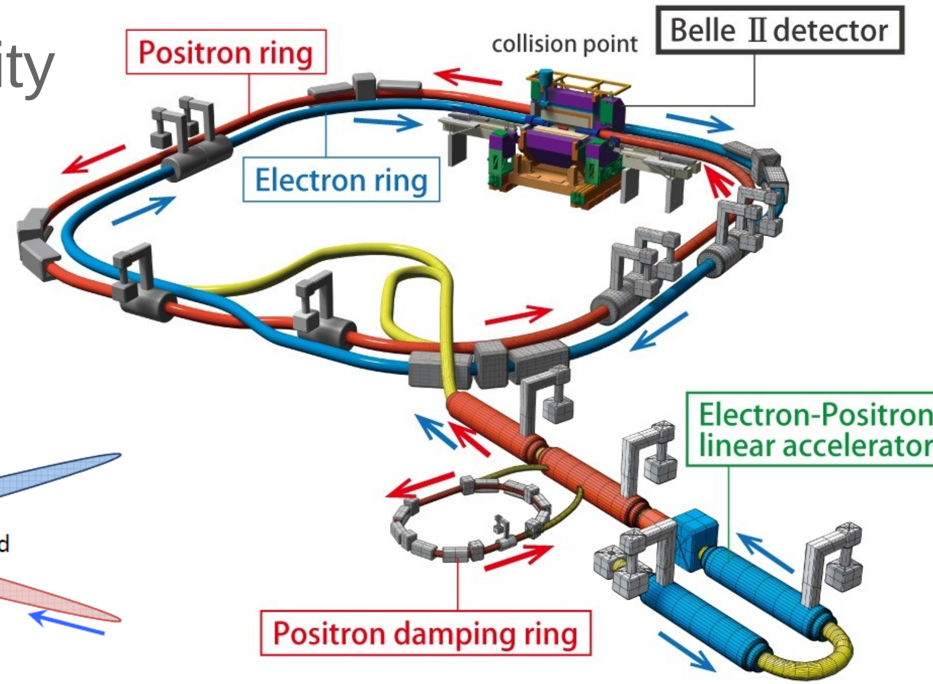
- Asymmetric beam energies, high luminosity
  → High statistics of boosted B, D and τ
- Flavour physics
  - CKM matrix, unitarity triangle
  - CPV in B system
- BSM limits
  - Rare B/D decays
  - $b \to s\gamma$, $b \to sl^+l^-$
  - LFV in τ decays
- New particles
  - Tetraquarks



SuperKEKB

- 40x higher instantaneous luminosity
- Nano-Beam scheme
  - New final focus system





		KEKB		SuperKEKB		units	
		LER	HER	LER	HER		
Beam energy	E_b	3.5	8	4	7.007	GeV	
Beam crossing angle	φ	22		83		mrad	
β function @ IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm	x20
Beam current	I	1.64	1.19	3.6	2.6	A	x2
Luminosity	L	2.1 x 10^{34}		8 x 10^{35}		$cm^{-2}s^{-1}$	x40

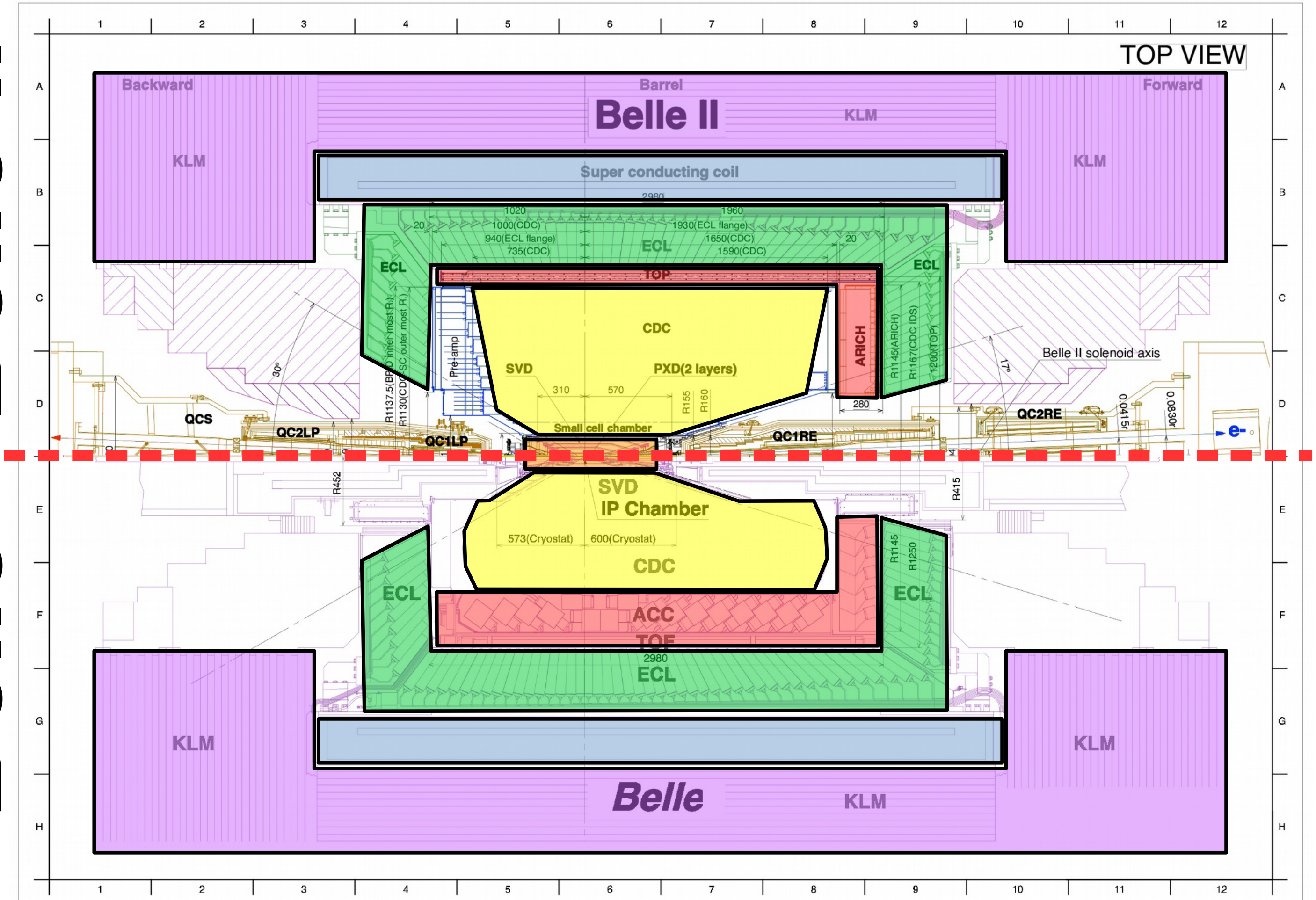
Challenges on the Detector Upgrade

- Significantly increased beam backgrounds (x10-20 x**?**)
  - Faster frontend electronics to reduce background pileup
- Increased trigger rates, data transfer bandwidth (x10-100)
  - Overhauled DAQ system, pipelined readout
  - Full reconstruction in high level trigger farm (~3000 cores)
- Reduced initial state boost (-30%)
  - Higher resolution vertexing detectors
  - Addition of two layers of pixel sensors

Belle II Detector Upgrade

Belle II

Belle



- K_L/Muon System
- Magnet Coil
- EM Calorimeter
- π/K Identification
- Drift Chamber
- Silicon Tracking

Belle II Detector Upgrade

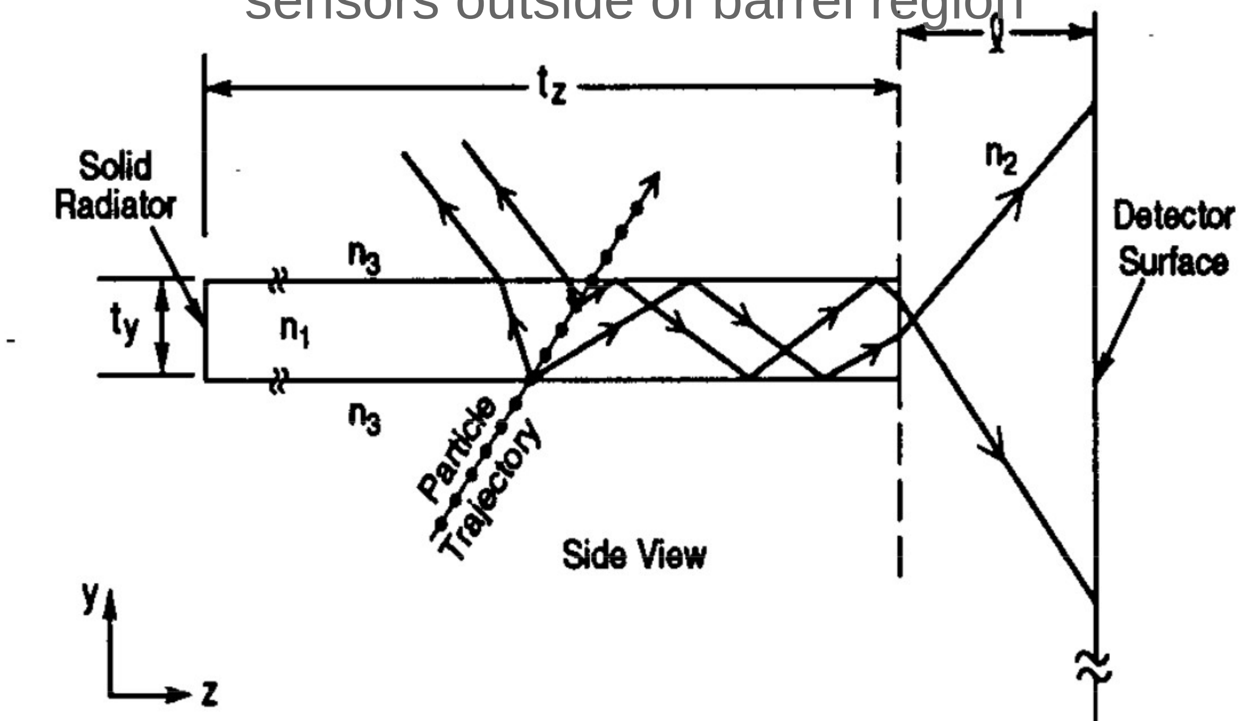
K_L/Muon System	New readout electronics Many RPC layers replaced with scintillator strips + SiPMs
Magnet Coil	No change
EM Calorimeter	New readout electronics (No change to CsI(Tl) crystals)
π/K Identification	Fully replaced
Drift Chamber	Fully replaced Larger outer radius for increased lever arm
Silicon Tracking	Fully replaced 4 layers of double sided silicon strips + 2 layers of DEPFET pixels

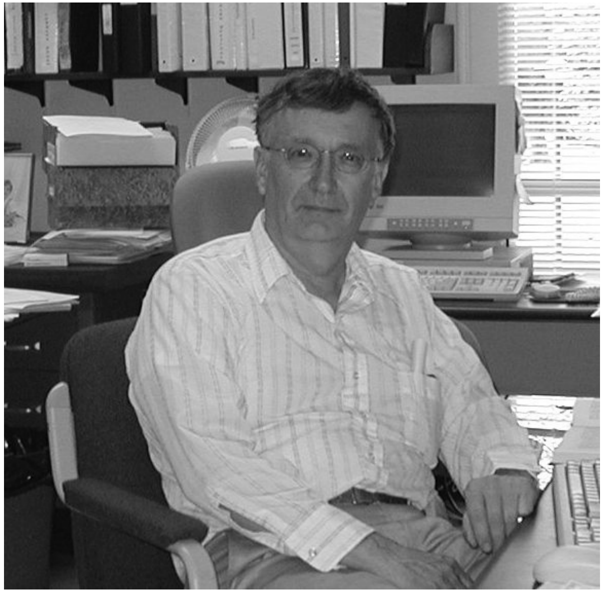
Key Technologies in Detector Upgrade

- State-of-the-art silicon detectors
- Pixelated single photon sensors
  - MCP-PMTs in TOP (barrel PID) – time resolution
  - HAPDs in ARICH (end cap PID) – large area
  - SiPMs in KLM – low cost
- Waveform sampling readouts
  - TOP: 8192 channels, 2.7GSa/s: IRSX (Hawaii)
  - Sci-KLM: 16800 channels, 1GSa/s: TARGETX (Hawaii)
  - SVD: 224k channels, 32MSa/s: APV25 (adapted from CMS)
  - CDC: 14336 channels, 30Msa/s
  - ECL: 8736 channels, 2MSa/s

Belle II Barrel PID: A DIRC Derivate I

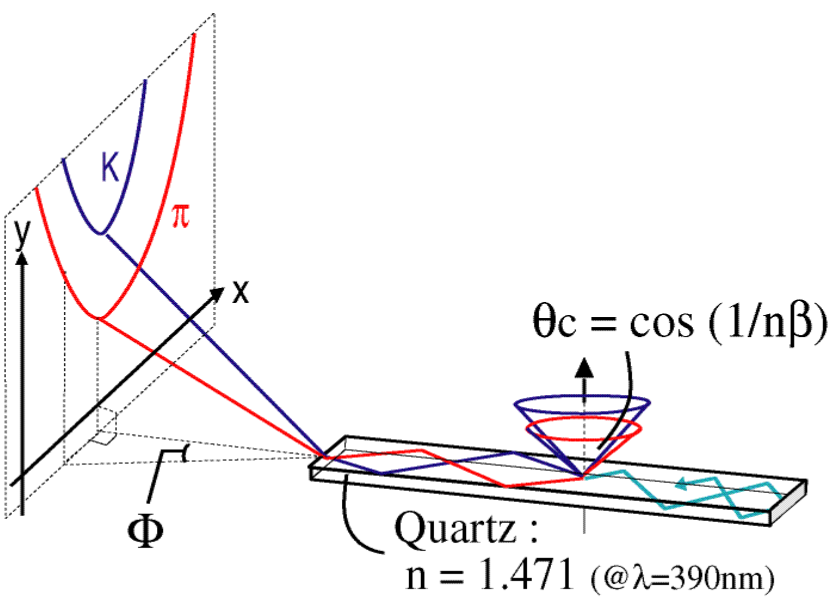
- DIRC: “Detector for Internally Reflected Cherenkov Light”
  - B. Ratcliff, SLAC PUB637 1
- Excellent solution to barrel PID needs in B-factories
  - Thin: Only radiator + casing in front of calorimeter, sensors outside of barrel region

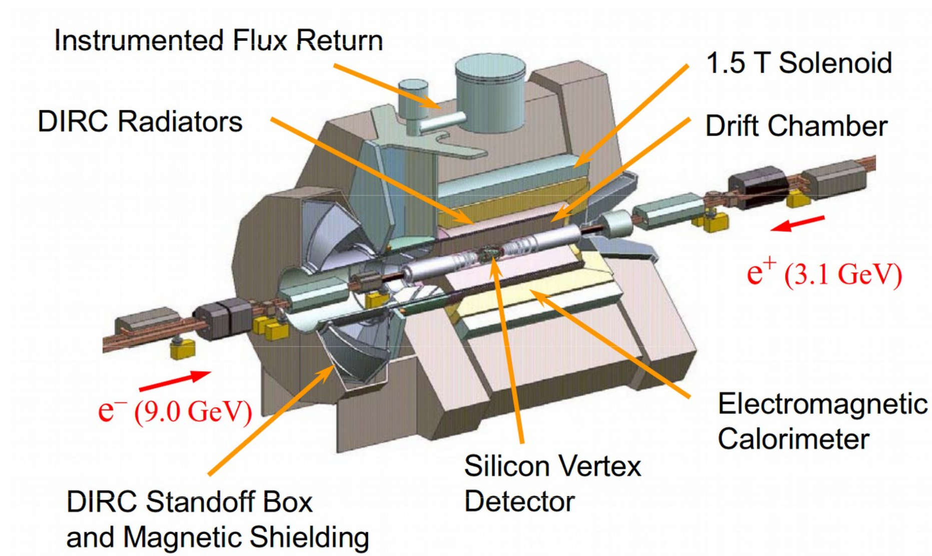




Belle II Barrel PID: A DIRC Derivate II

- DIRC design has huge “stand off box” expansion volume in endcap region
  - Not compatible with the hermeticity requirements of Belle II
- How to evolve on the DIRC concept? Add timing!

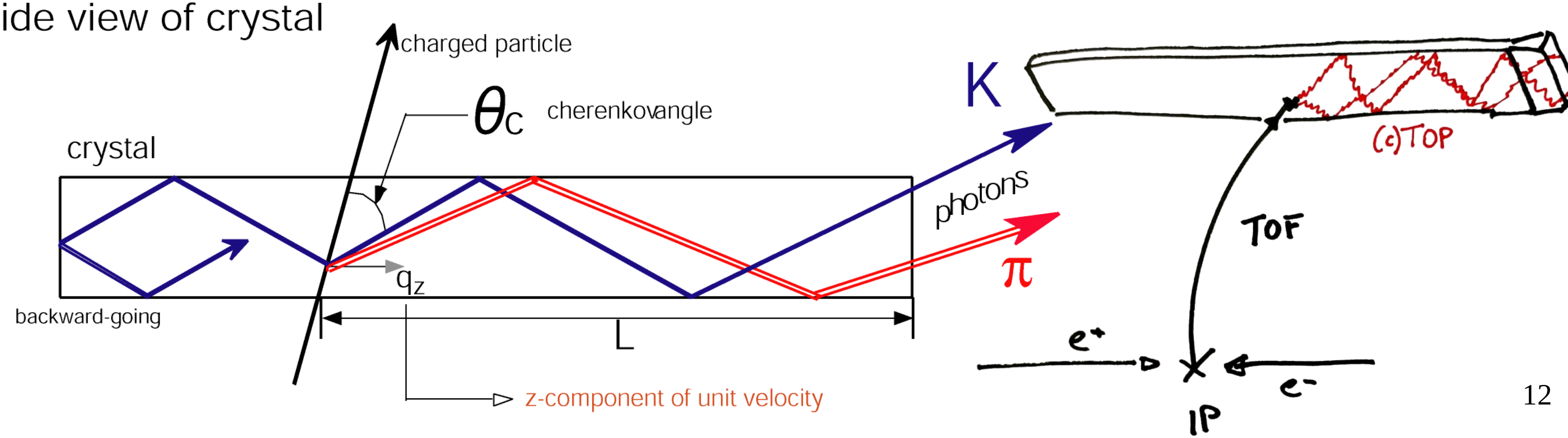




The "Time of Propagation" (TOP) Detector I

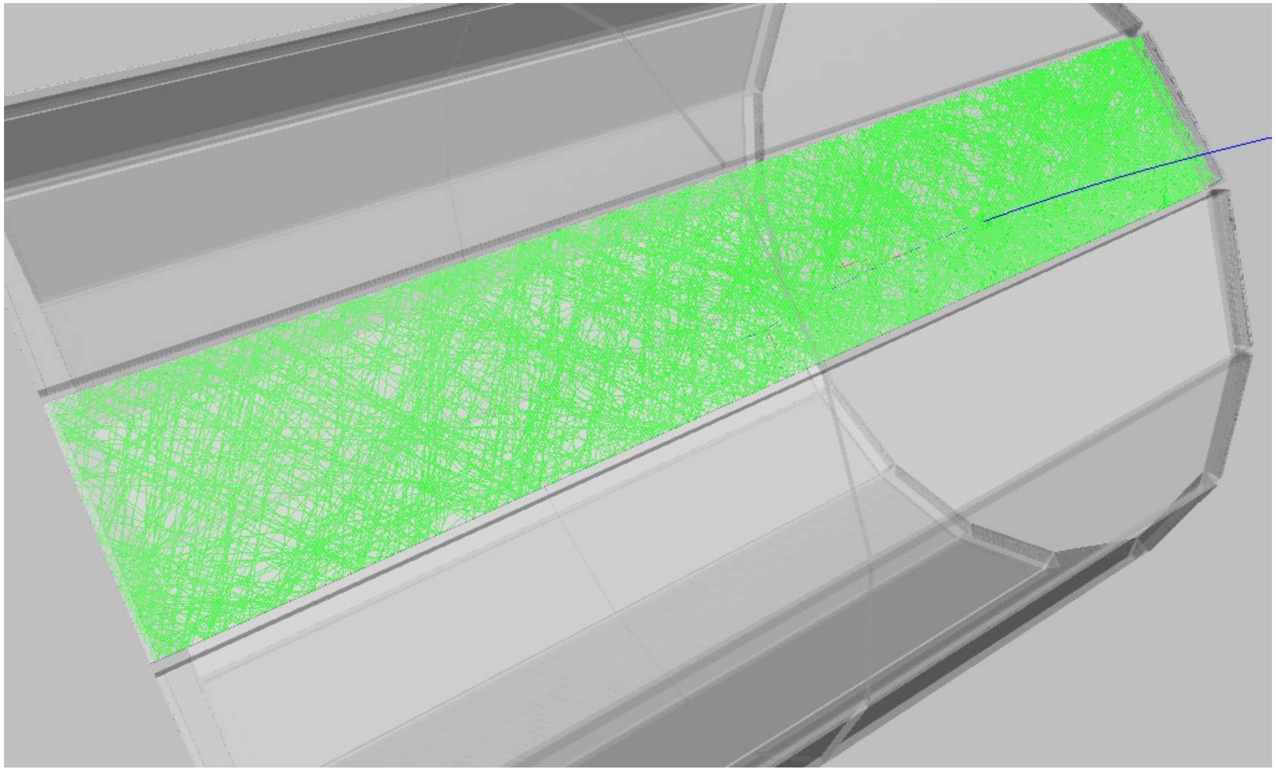
- Instead of reconstructing the full ring image, measure time of propagation (path length) of individual Cherenkov photons.
  - Cherenkov photons from lighter particles arrive earlier on average
  - Since collision timing is well known (in principle), measure ToF at the same time
  - Chromatic dispersion is really not making this easier...

Side view of crystal



The “Time of Propagation” (TOP) Detector II

- Complicated patterns of different photon arrival times in each channel
  - These patterns strongly depend on the particle momentum, angle and position of incidence



The “Time of Propagation” (TOP) Detector II

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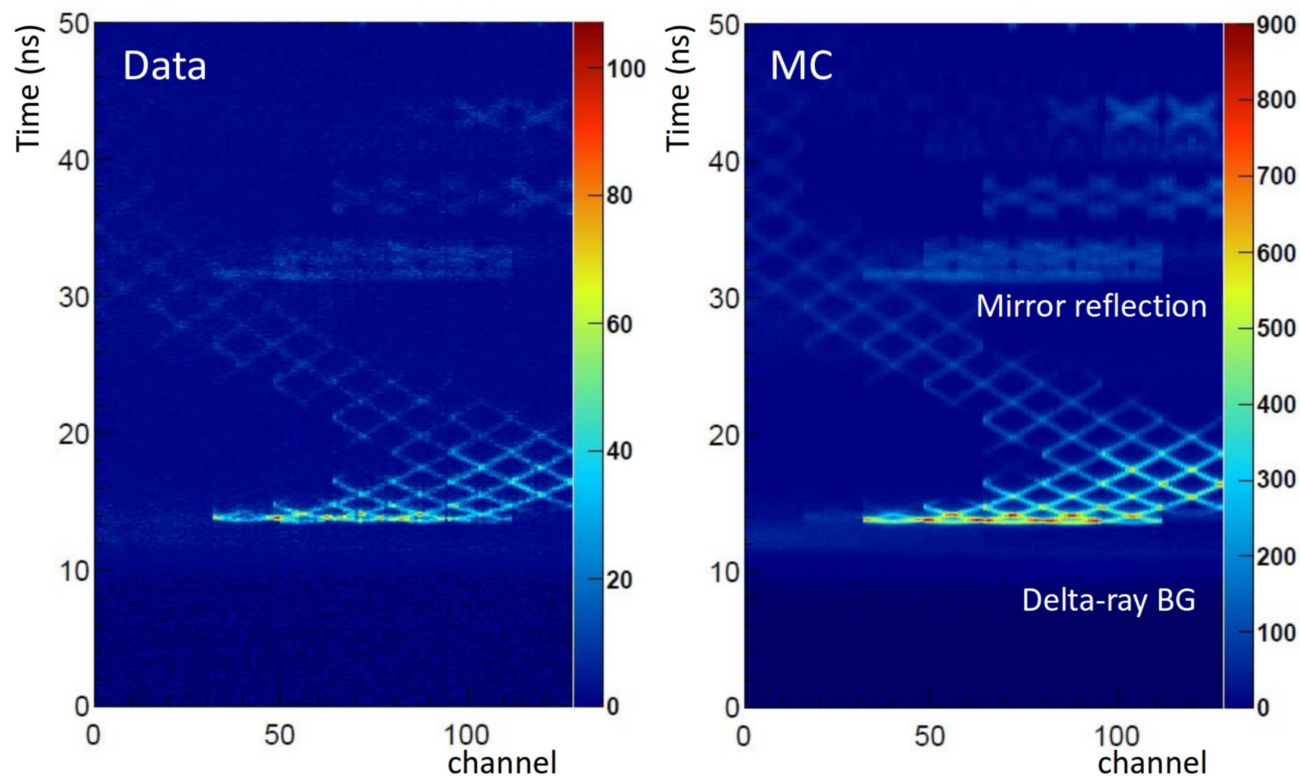
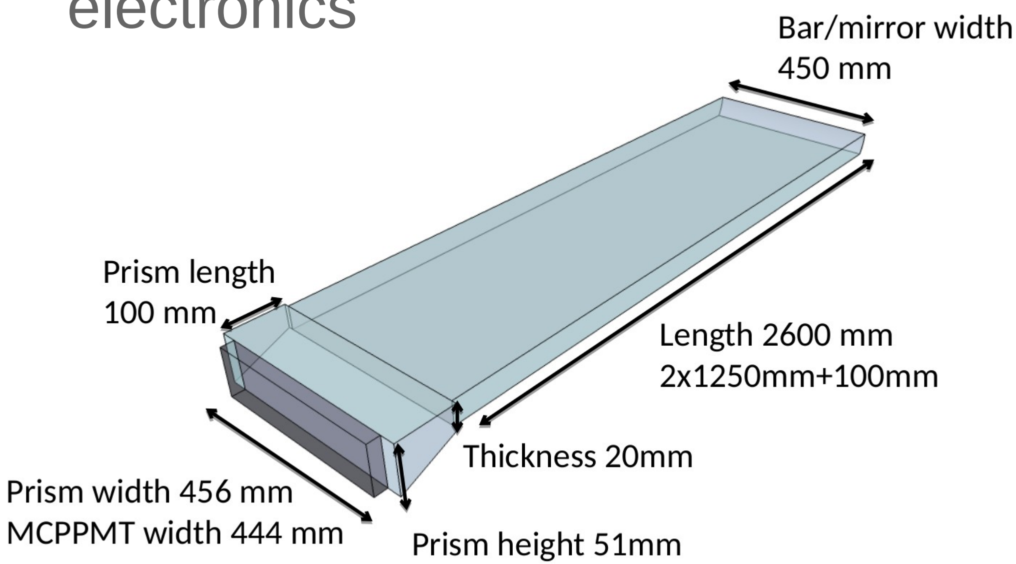
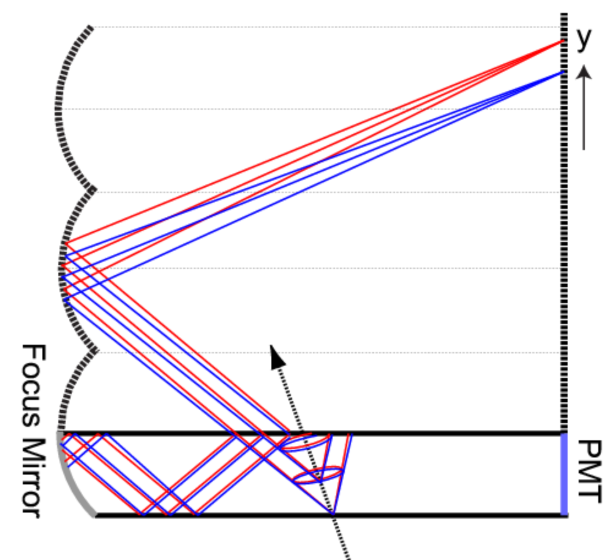
Early electron testbeam:



The "Time of Propagation" (TOP) Detector III

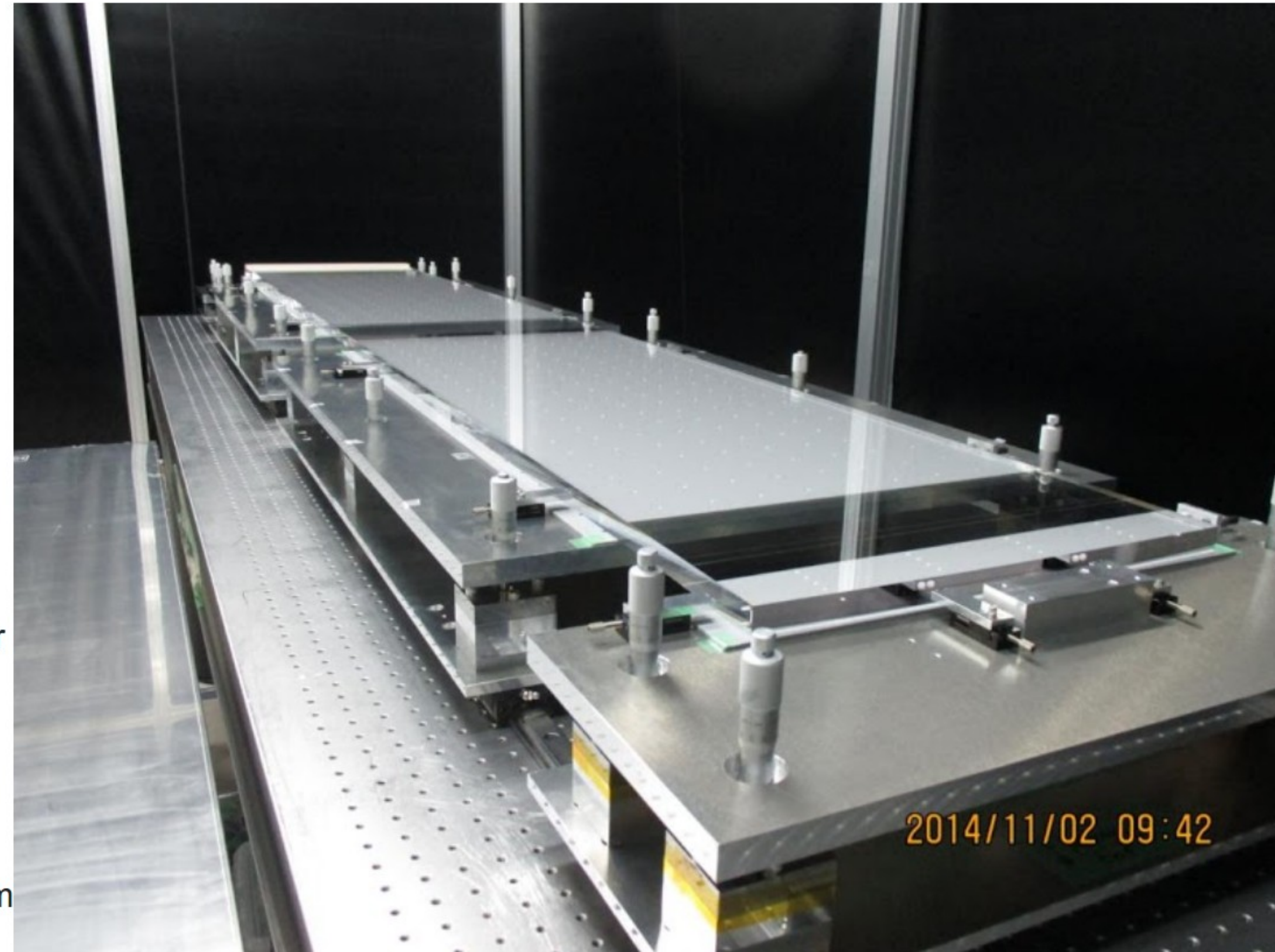
- 16 quartz Cherenkov radiator bars arranged around IP
- Forward side: spherical mirror
  - Effectively removes bar thickness for reflected photons
  - Different wavelengths are focused on slightly different points
- Backward side: small expansion prism, sensors, readout electronics





Quartz & Optics I

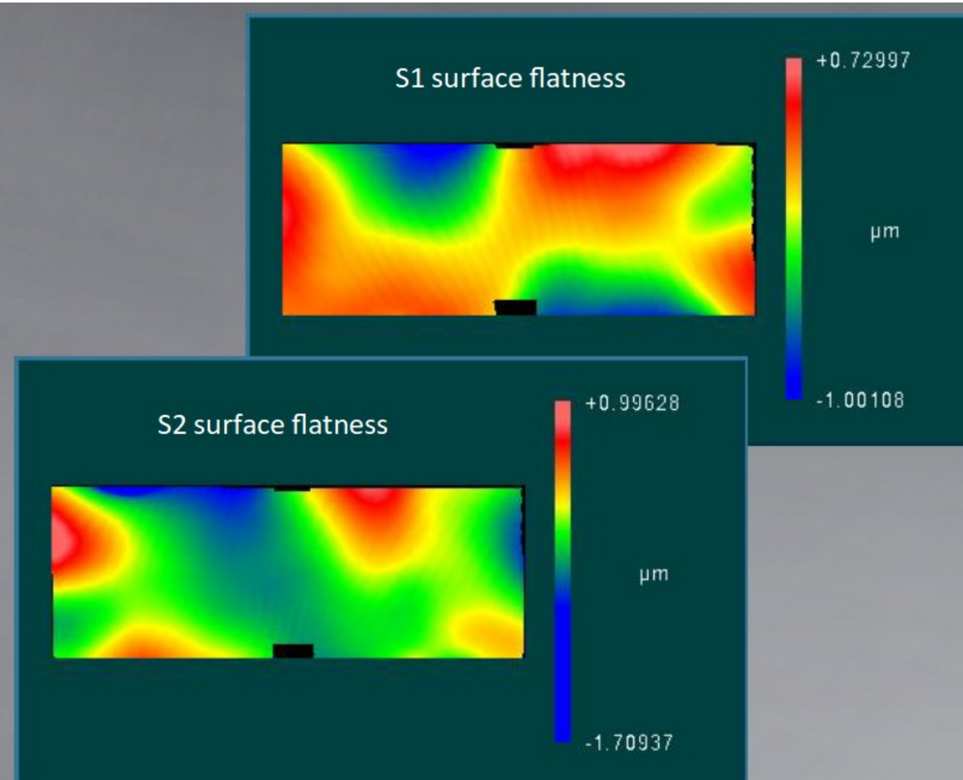
- Bars:
  1250 x 450 x 20 mm^3
  two bars per module
- Mirrors:
  100 x 450 x 20 mm^3
- Prisms:
  100 mm long, 456 x 20 mm^2 at bar face expanding to 456 x 50 cm^2 at MCP-PMTs
- Material: Corning 7980
- DIN58927 class 0 material has no inclusions (inclusions ≤0.1 mm diameter are disregarded)
- Grade F (or superior) material having index homogeneity of ≤5 ppm over the clear aperture of the blank; verified at 632.8 nm
- Birefringence / Residual strain ≤1 nm/cm



Quartz & Optics II

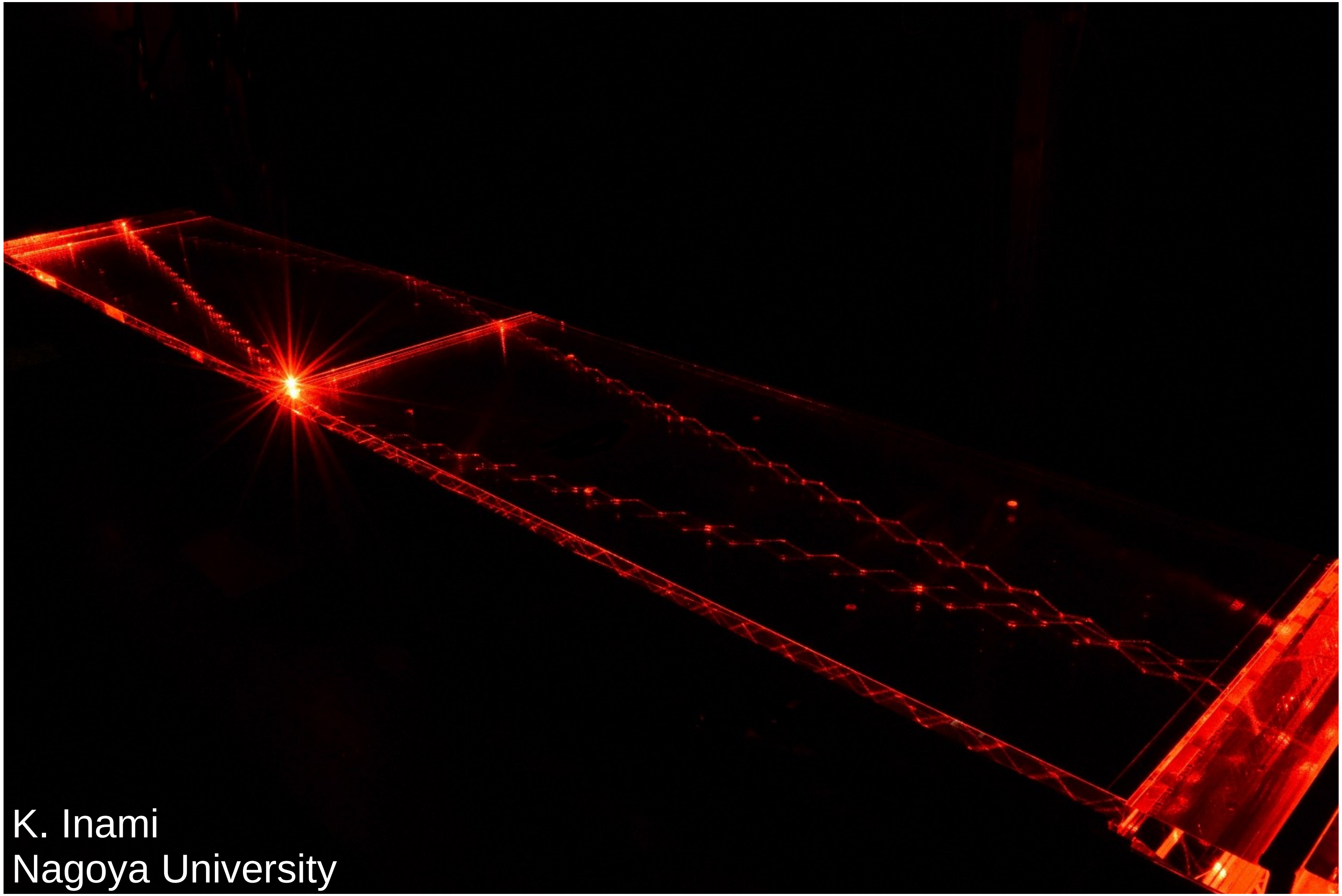
- Quartz most expensive part of the system (~10M$)
- Extreme surface quality requirements

Tolerance	Specification	Measurement	Pass	Fail
S1 Datum A Flatness	≤ 6.3μm	1.731	x	
S1 Local Flatness over 200mm Area	≤ 1.8μm	0.678 Max	x	
S2 Flatness	≤ 6.3μm	2.706	x	
S2 Local Flatness over 200mm Area	≤ 1.8μm	1.462 Max	x	
S3 Datum B Flatness	≤ 6.3μm	2.952	x	
S4 Flatness	≤ 6.3μm	1.472	x	
S5 Datum C Flatness	≤ 25μm	1.425	x	
S6 Flatness	≤ 25μm	2.633	x	
S1 Parallel S2	≤ 4 arcsec	≤ 1.4	x	
S1 Perpendicular S3	≤ 20 arcsec	≤ 5	x	
S1 Perpendicular S4	≤ 20 arcsec	≤ 3	x	
S1 Perpendicular S5	≤ 1 arcmin	≤ 0.083	x	
S1 Perpendicular S6	≤ 1 arcmin	≤ 0.05	x	
S3 Parallel S4	≤ 60μm (10 arcsec)	≤ 7 arc sec	x	
S3 Perpendicular S5	≤ 20 arcsec	≤ 5	x	
S3 Perpendicular S6	≤ 20 arcsec	≤ 5	x	
S5 Parallel S6	≤ 20 arcsec	≤ 10	x	
Surface Roughness S1	≤ 5 Å rms	3.064	x	
Surface Roughness S2	≤ 5 Å rms	3.045	x	
Surface Roughness S3	≤ 5 Å rms	4.035	x	
Surface Roughness S4	≤ 5 Å rms	3.127	x	
Surface Roughness S5	≤ 25 Å rms	13.887	x	
Surface Roughness S6	≤ 25 Å rms	16.991	x	
Length	1250 ±0.50mm	1250.37	x	
Width	450 ±0.15	450.08	x	
Thickness	20 ±0.10	20.09	x	



September 5, 2016 PNNL-SA-120657 11

TOP: Total Internal Reflection

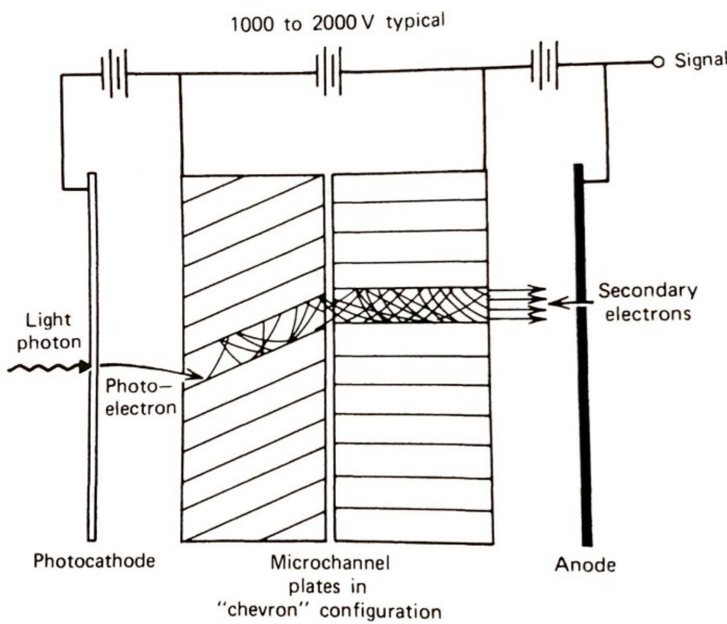


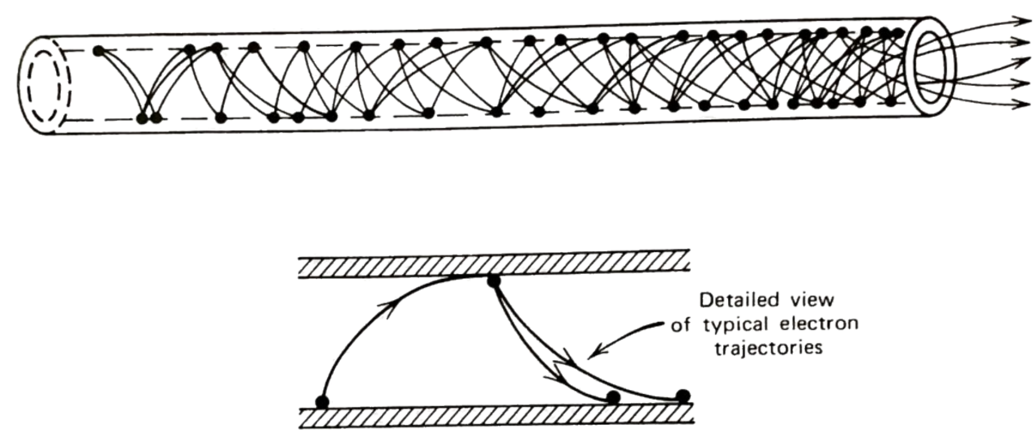
TOP Readout: Requirements

- Goal: <100ps single optical photon time resolution
- Sensor requirements:
  - single photon efficiency
  - <50ps single photon time resolution
  - ~few mm spatial resolution
  - Operation in 1.5T B-field
- Electronics requirements:
  - 30kHz trigger rate
  - <50ps electronics time resolution
  - <30ps clock distribution jitter

TOP Readout: Micro-Channel-Plate PMTs

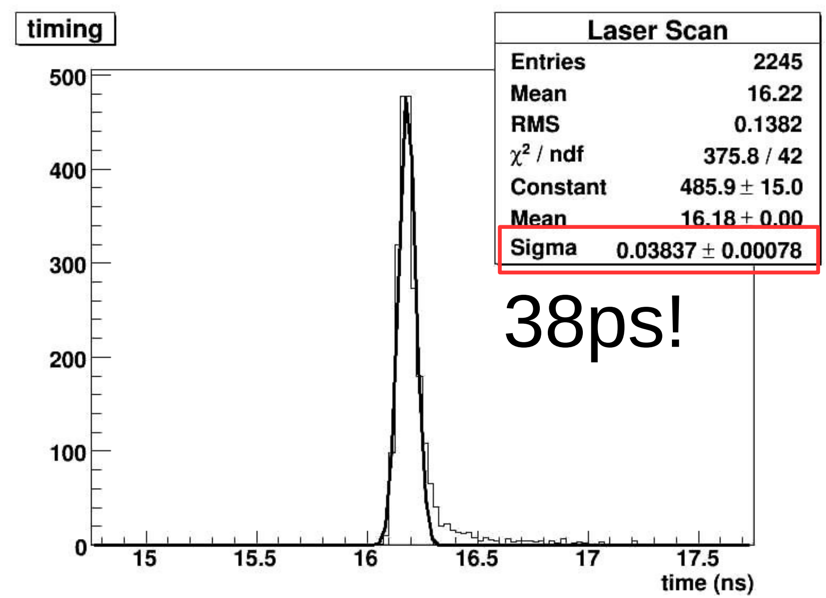
- Very fast amplification, but not well controlled
  - Good time resolution, single photon efficiency, but large output spread
- (Mostly) resistant to B-fields
- Pixelated anodes for spatial resolution





Hamamatsu MCP-PMTs

- Measured single photon time resolution <40ps
- Lifetime (integrated charge) is limited
  - Original version ~1C/cm^2 (~50% of TOP)
  - ALD and LE-ALD versions: >10C/cm^2 (other ~50% of TOP)



TOP Readout: Electronics

- Reads MCP-PMT signals
- Time resolution <50ps
  - ~GSa/s sampling
  - ~500MHz bandwidth

?

TOP Readout: Electronics

- Reads MCP-PMT signals
- Time resolution <50ps
  - ~GSa/s sampling
  - ~500MHz bandwidth
- 8192 channels
- Affordable
- Low power
- Small form factor
- Online data processing
- etc. etc.

Readout: Electronics

- "Oscilloscope on a Chip": IRSX ASIC
  - Designed by IDLAB, UH (Prof. Gary Varner)
- Operated at 2.7GSa/s in TOP
  - ~600MHz analog bandwidth
  - 32k analog buffer cells (~10us)
  - 12 bit digitisation w/o deadtime
- Power budget ~600mW/ch
  - ASIC: ~125mW/ch
  - Preamp: ~150mW/ch
  - FPGAs: ~300mW/ch

Hawaii Waveform Sampling ASICs

- Hawaii Instrumentation Development Lab spinoff: Nalu Scientific
  - Founded by Isar Mostafanezhad (ex-postdoc of IDLab)
- Commercialisation of switched capacitor waveform sampling ASICs based on IDLab designs
- Three ASICs available:
  - SiRead: 32 channels, ~1 GSa/s
  - ASoC: 8 Channels, ~3 GSa/s
  - Aardvarc: 4 Channels, ~14 Gsa/s

Nalu Scientific

Data Acquisition Systems

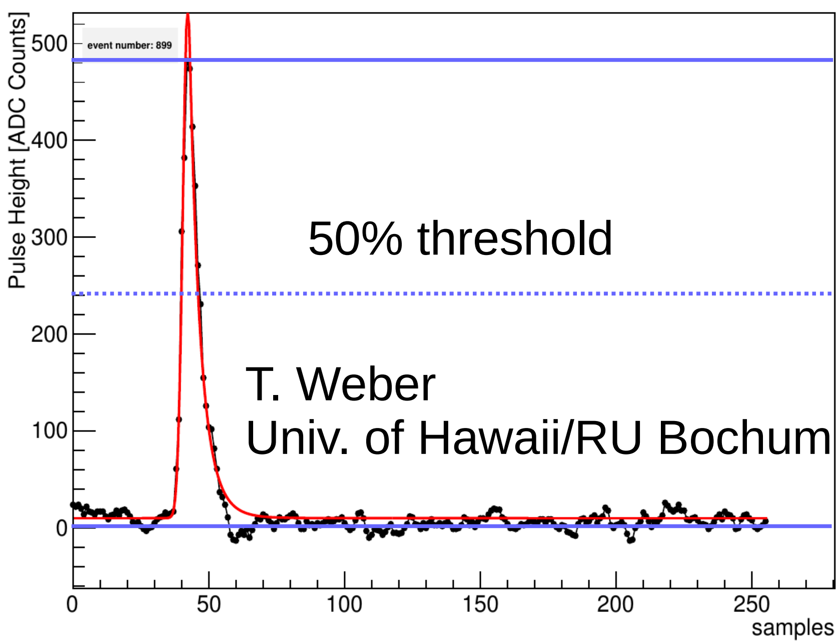
isar@naluscientific.com

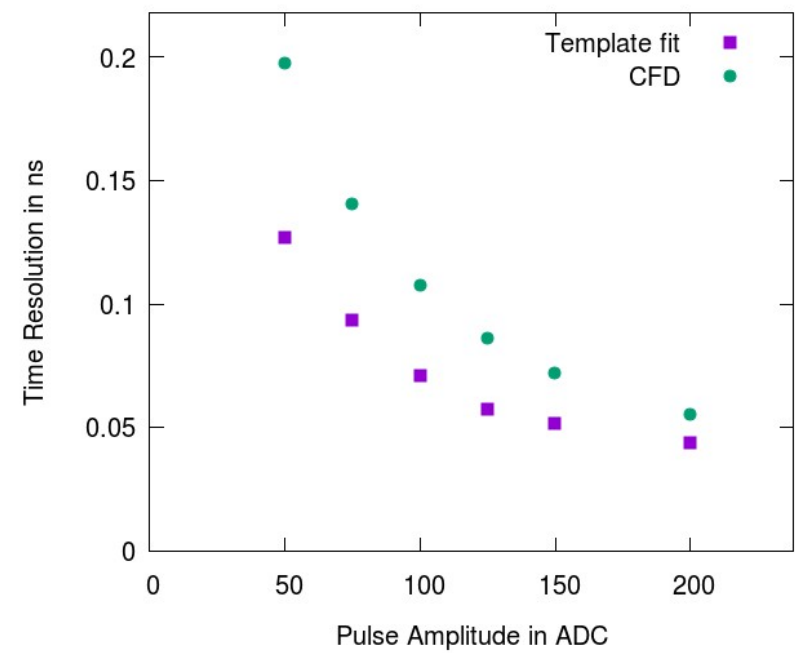
Online Data Reduction

- Whole TOP stores 22×10^{12} samples every second
- Only digitise relevant ASIC samples
  - Based on global trigger, local channel triggers
- Apply all raw data conditioning in frontend
  - Pedestal subtraction
  - Time base calibrations
- Extract waveform features in frontend
  - Photon timing, pulse shape parameters
- Write out only feature parameters
- Powerful frontend processing: 320 FPGAs, 640 ARM cores
  - Based on Xilinx Zynq SoCs

Feature Extraction in TOP

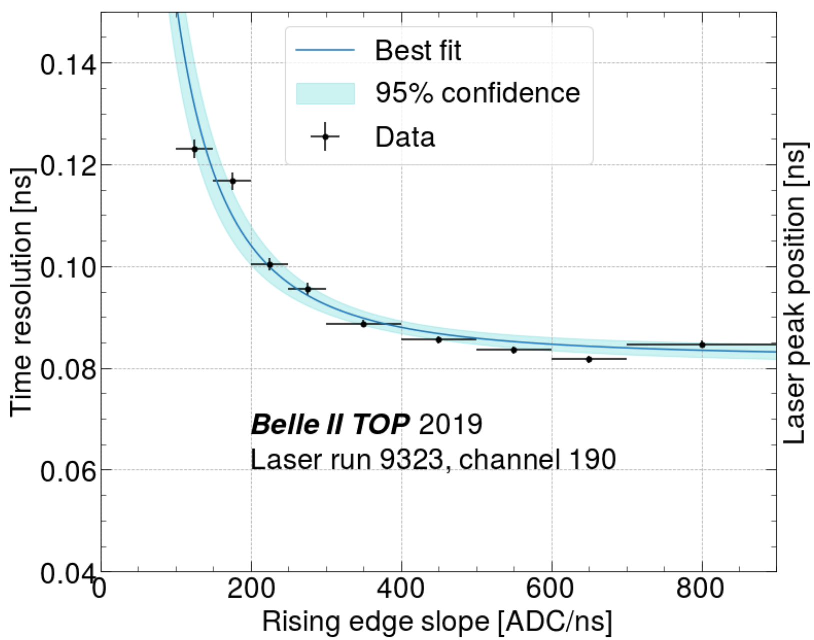
- Constant fraction discrimination
- Template fit to photon pulses
  - Computationally complex, possible on Zynq DSPs?
  - but only needed for low amplitude hits

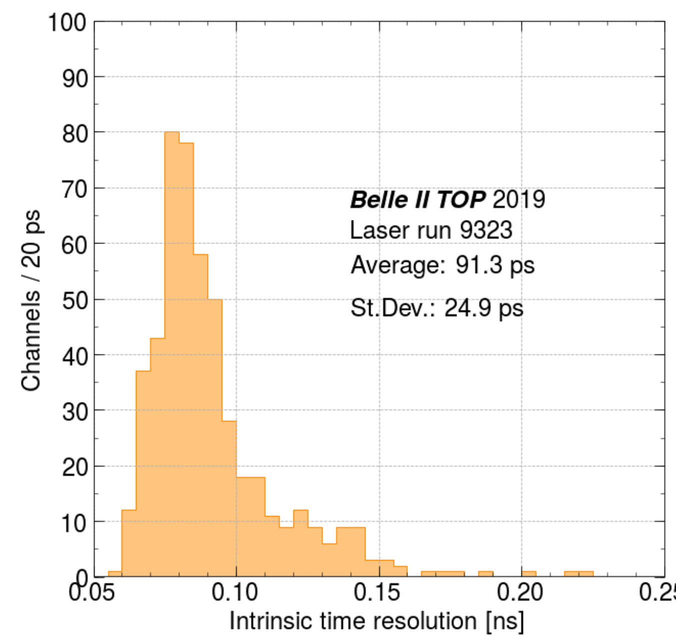




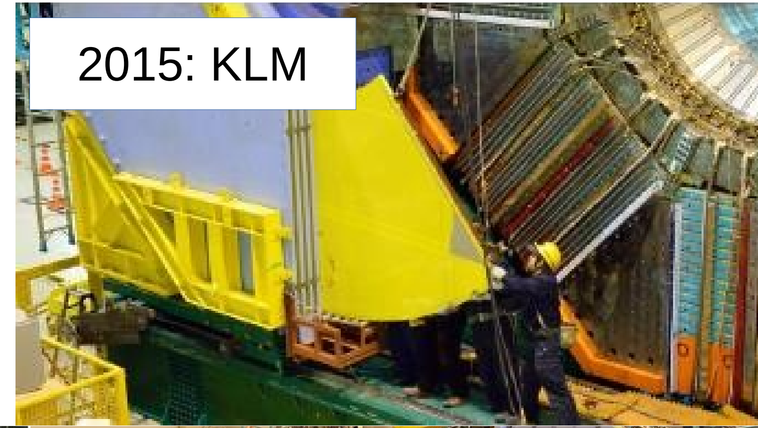
Single Photon Time Resolution

- Intrinsic resolution <100ps on most channels
  - Laser jitter, pulser reference included (but small)
- Dominated by electronic noise in signal chain due to PMT operation at low gain



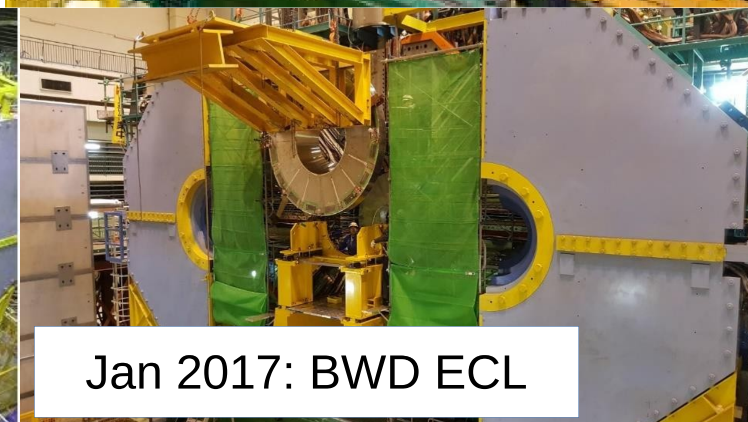


Belle II Installation


2015: KLM

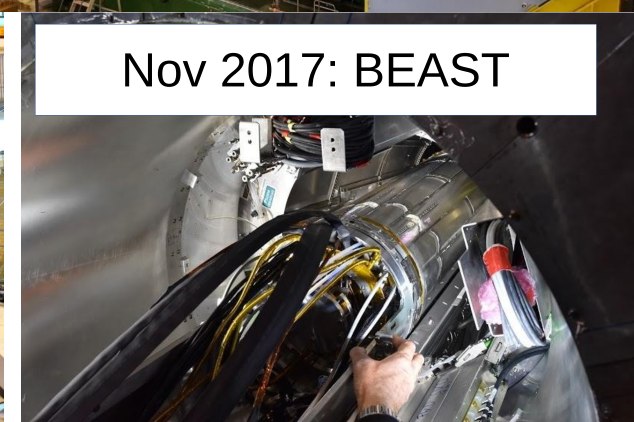

May 2016: TOP


Oct 2016: CDC


Jan 2017: BWD ECL

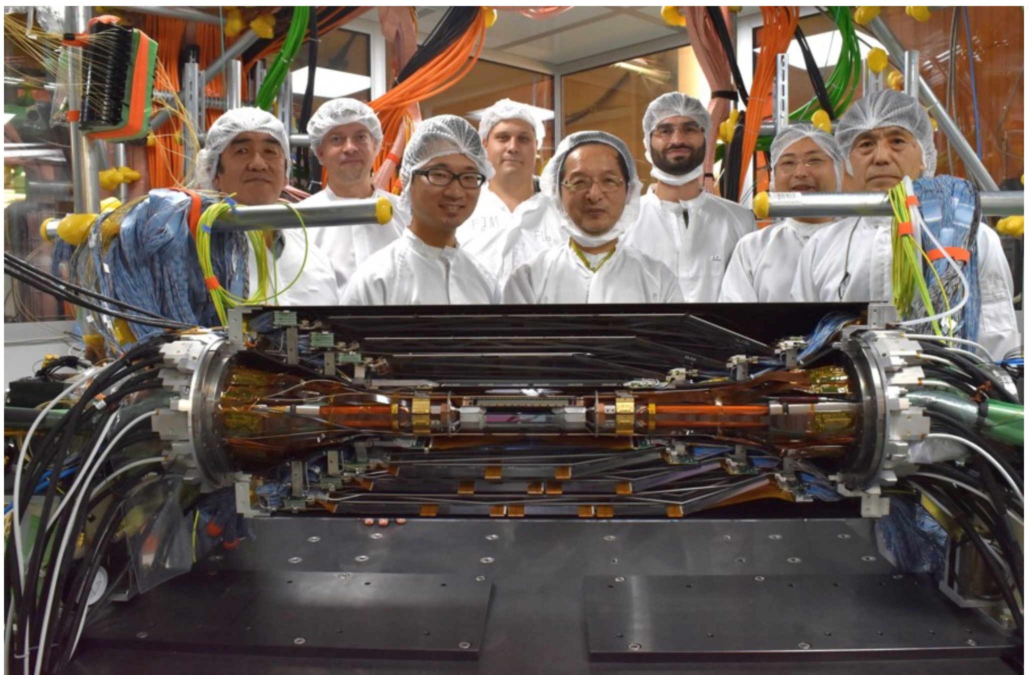
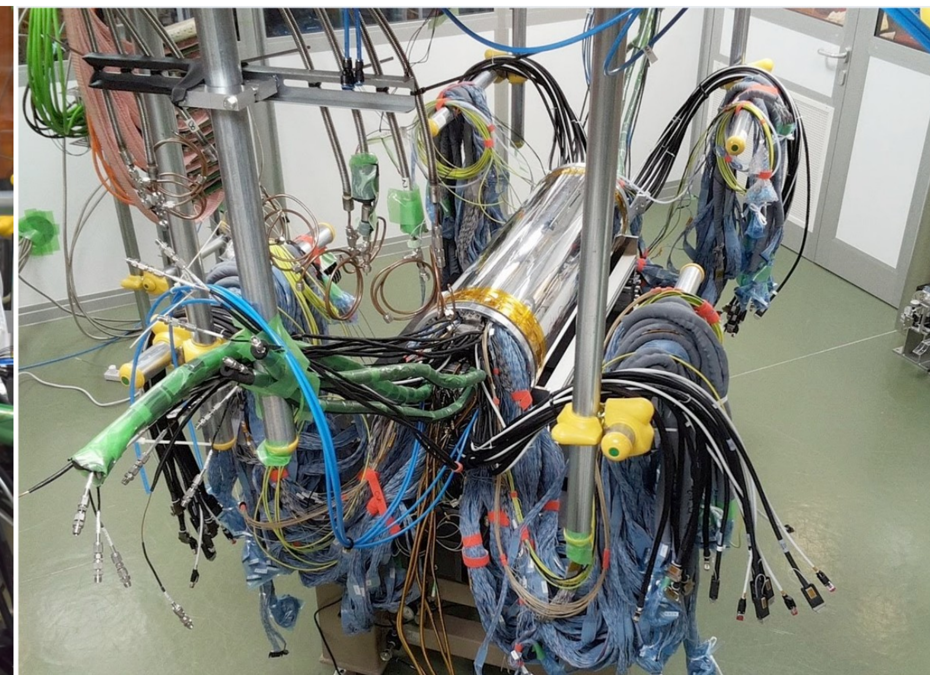

Apr 2017: Roll-in


Aug 2017: ARICH


Nov 2017: BEAST

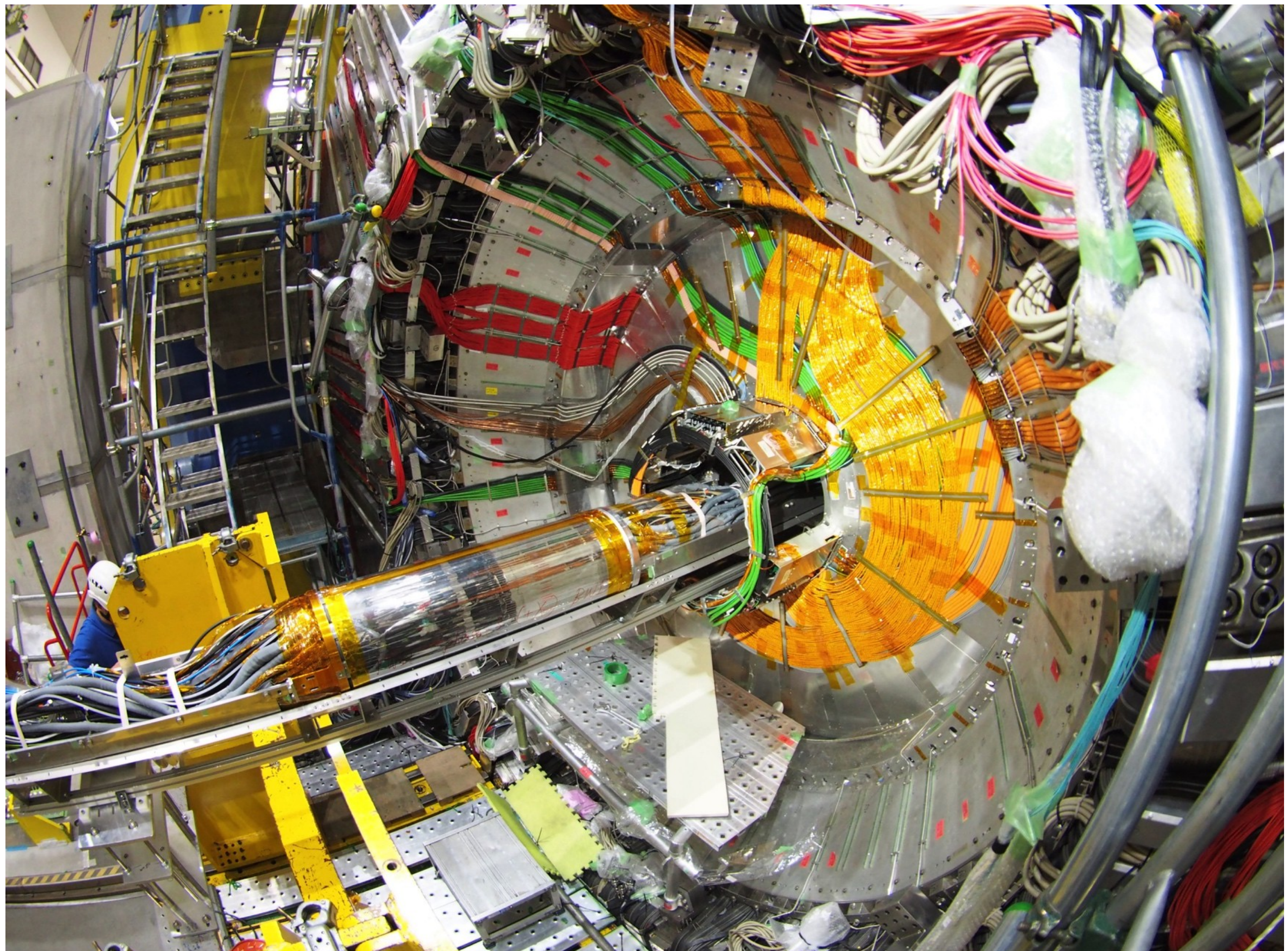
VXD Assembled

- PXD & SVD “married” since October 2018

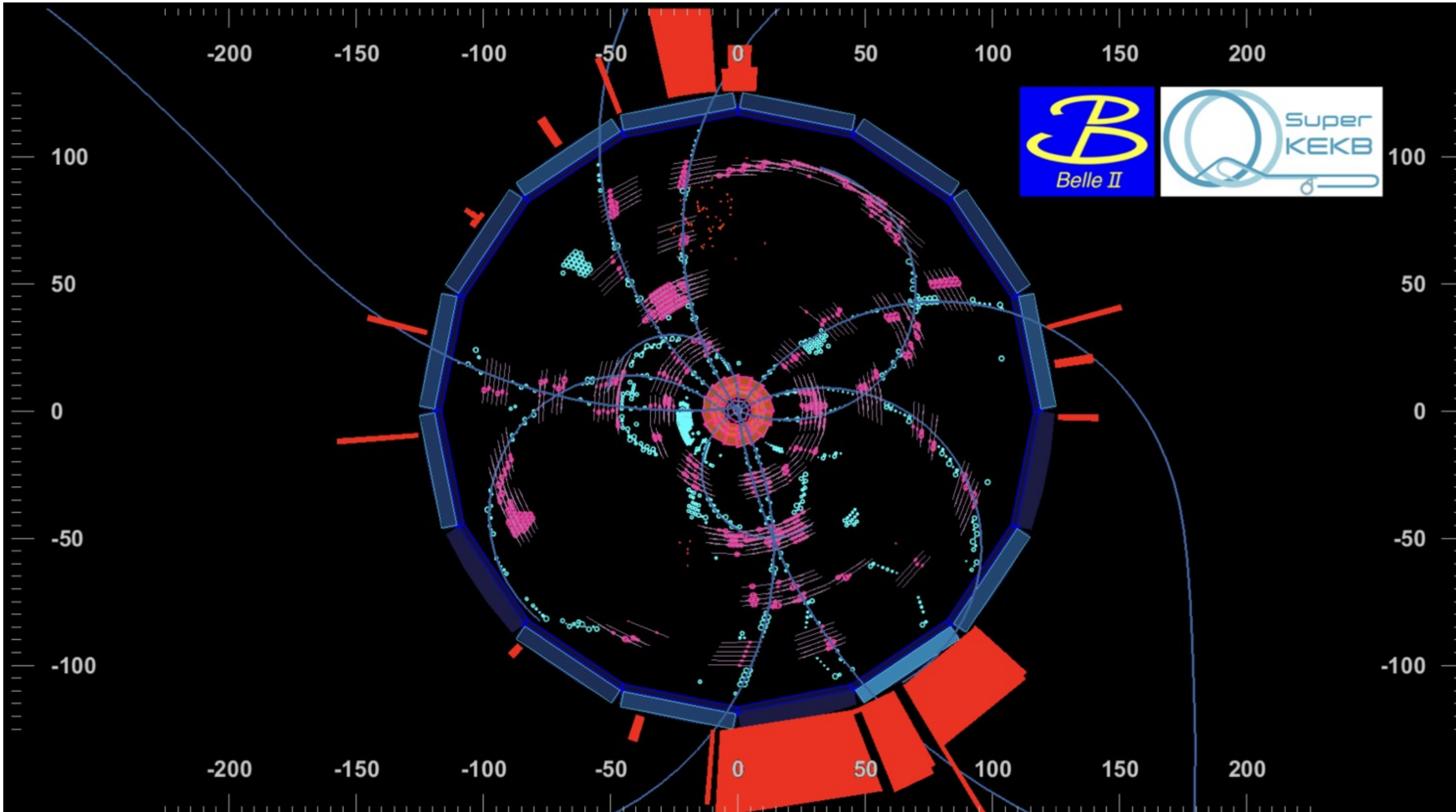



VXD Installation

- VXD installed November 21st 2018, Belle II detector complete!



First Collision in Physics Run - 03/25/2019

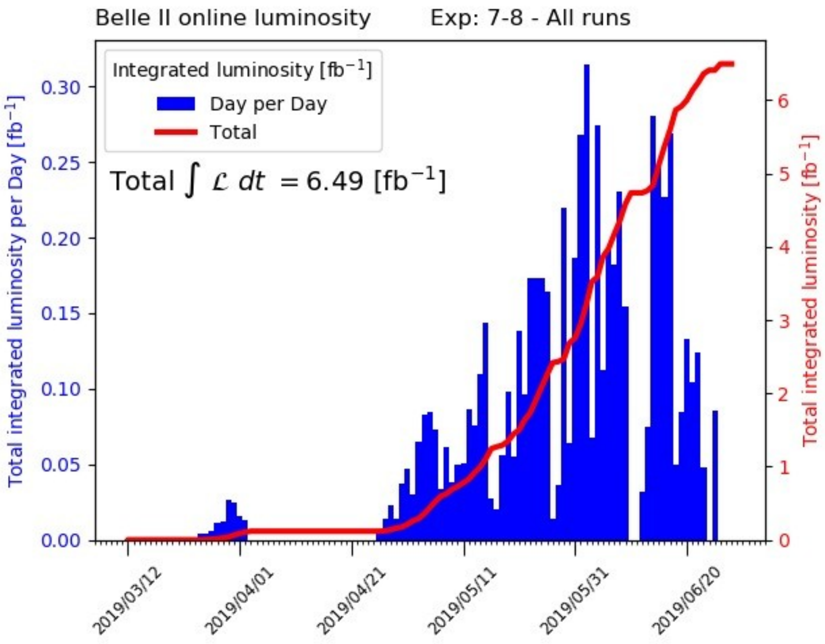


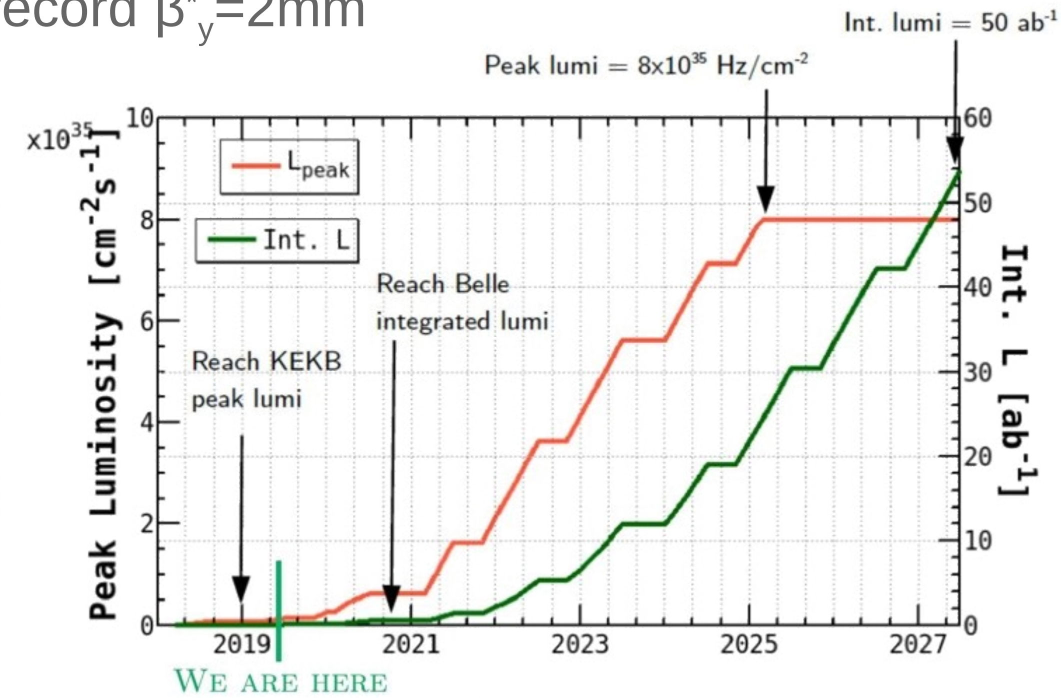
Probably e+e $\rightarrow$ Y(4s) $\rightarrow$ $B\overline{B}$

… and the Reaction

Luminosity in 2019

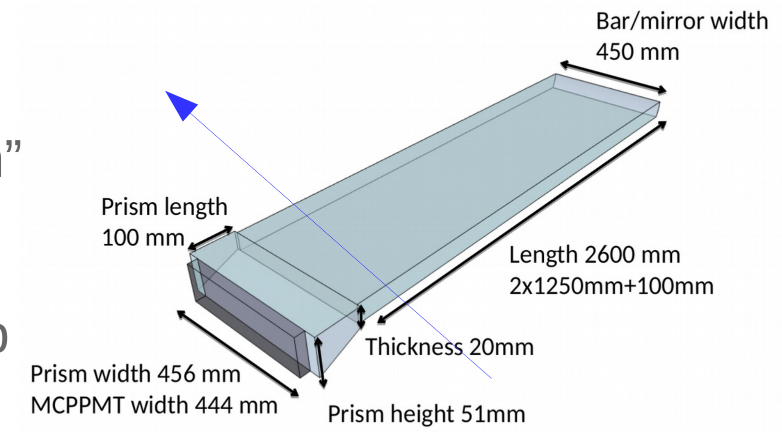
- 6.5fb^{-1} integrated from March 25th to July 1st 2019 (410pb^{-1} for EPS-HEP)
  - L_{peak}: 6.1x10^{33} cm^{-2} s^{-1} (12x10^{33} with Belle II off)
  - Limited by backgrounds, beam-beam blowup
- New machine, entirely new concept, requires tuning
  - Already running at world record β^*_y=2mm

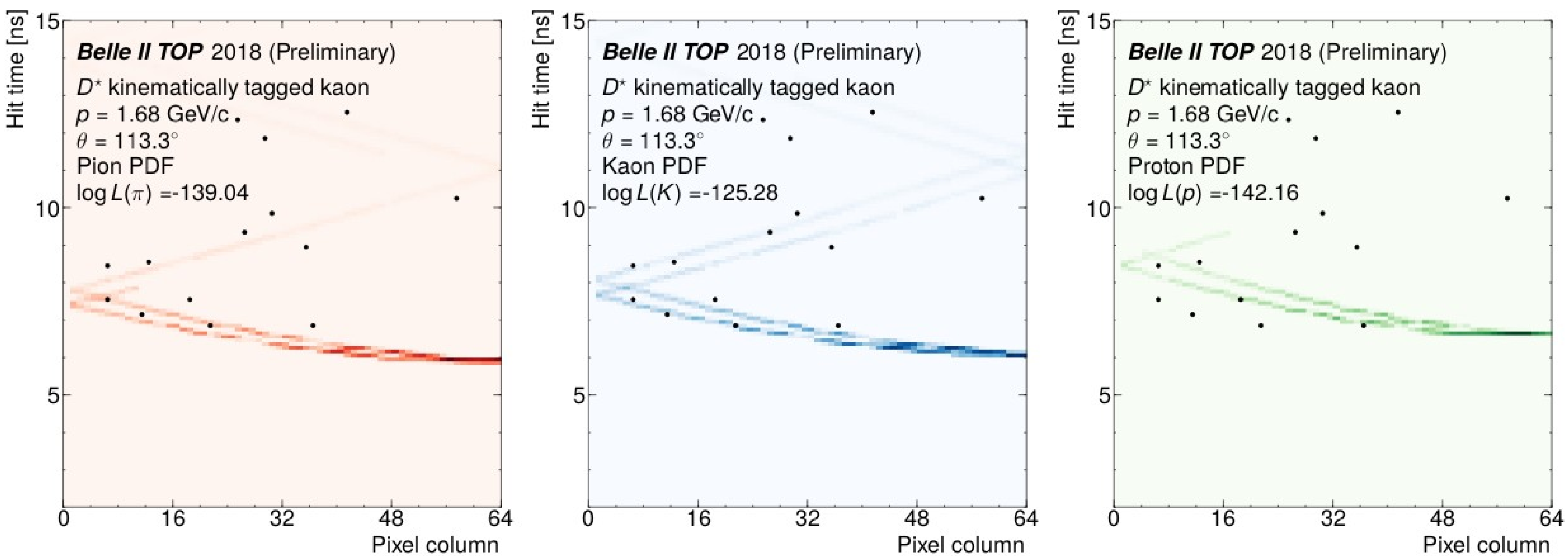




TOP "Cherenkov Rings" I

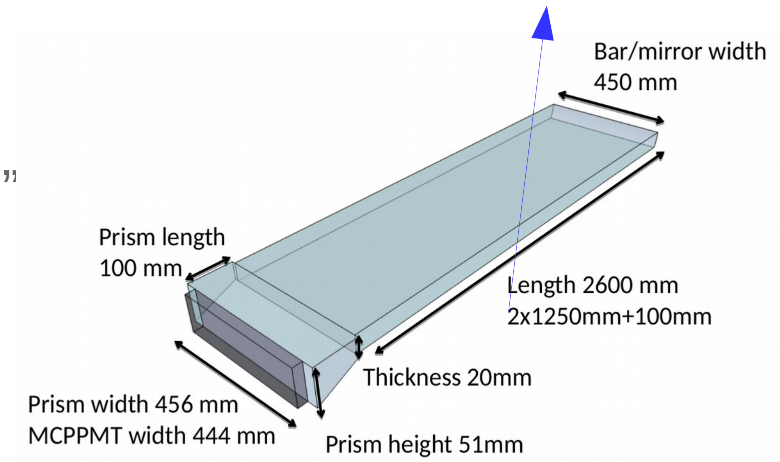
- $D^{*+} \rightarrow D^0 \pi_s^+ ; D^0 \rightarrow K^- \pi^+$ "Nature's MC truth"
- Kaon facing prism-side of TOP bar
  - Little room for Cherenkov cone to open up
  - PDF differences dominated by ToF offset

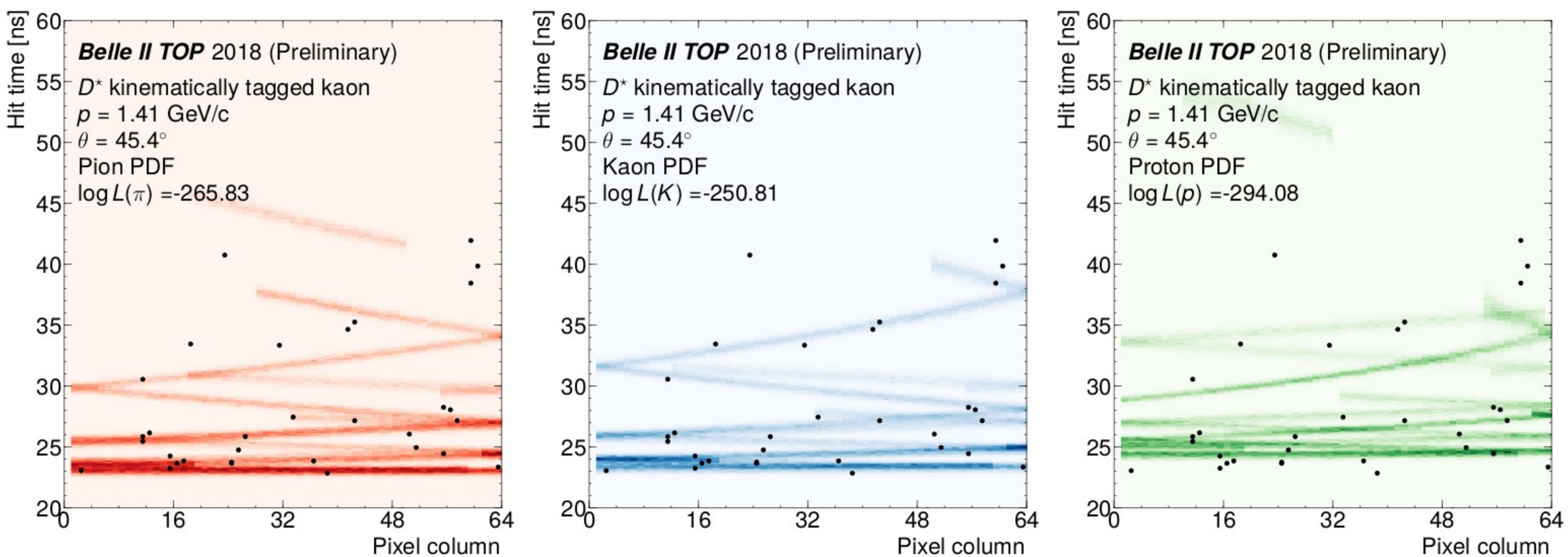




TOP "Cherenkov Rings" II

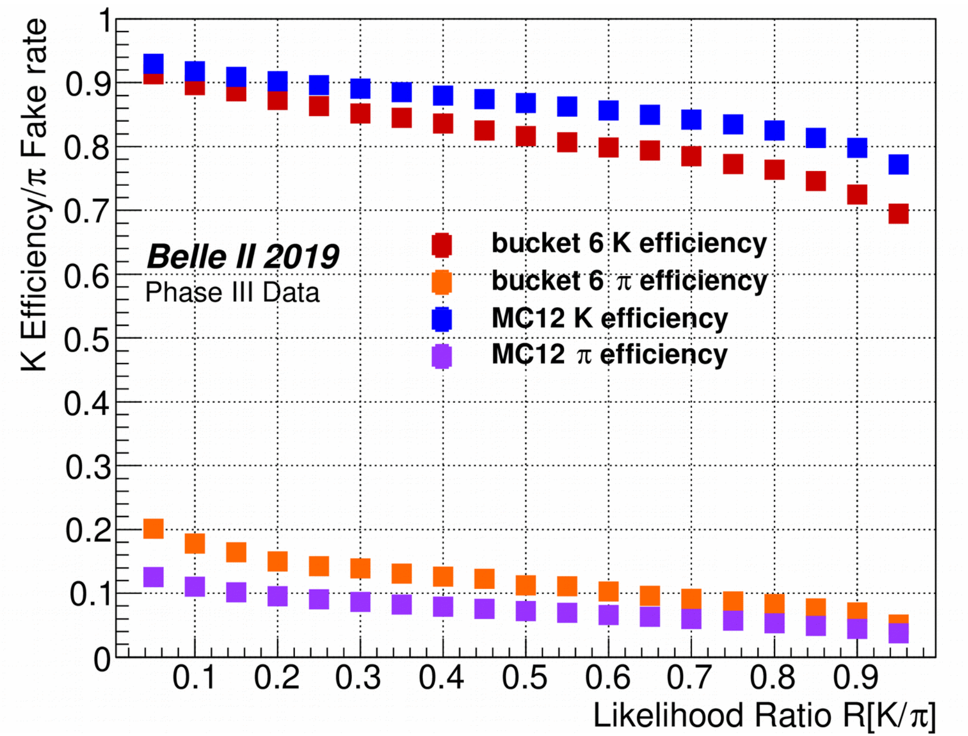
- $D^{*+} \to D^0 \pi_s^+; D^0 \to K^- \pi^+$ "Nature's MC truth"
- Kaon facing mirror-side of TOP bar
  - PDF differences dominated by shape





TOP PID Peformance: K-π Separation

VERY PRELIMINARY



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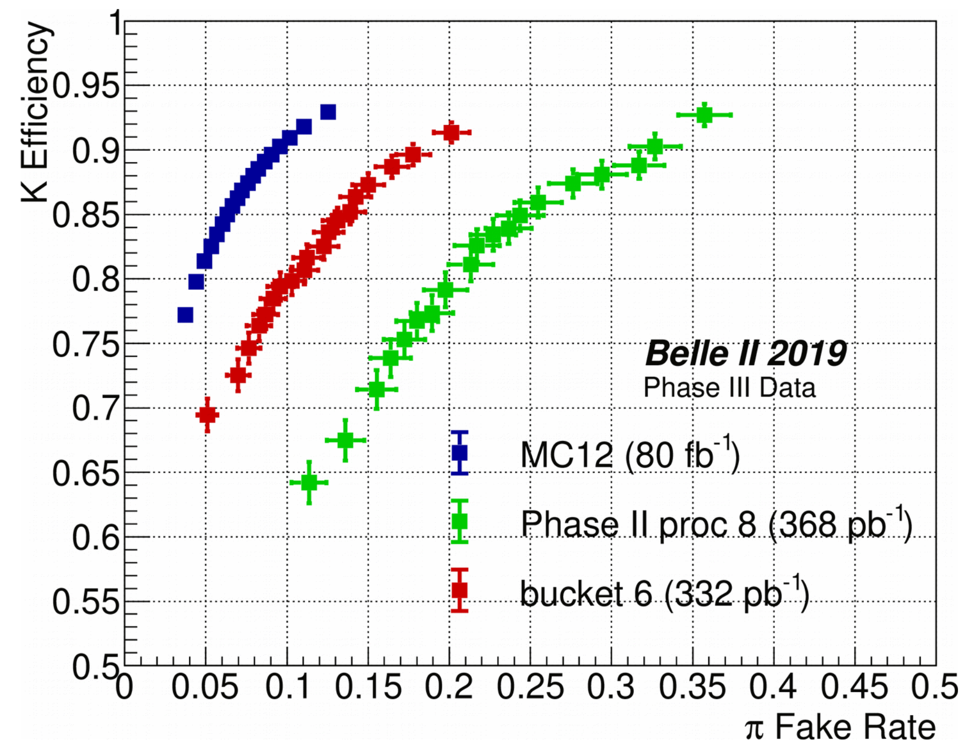
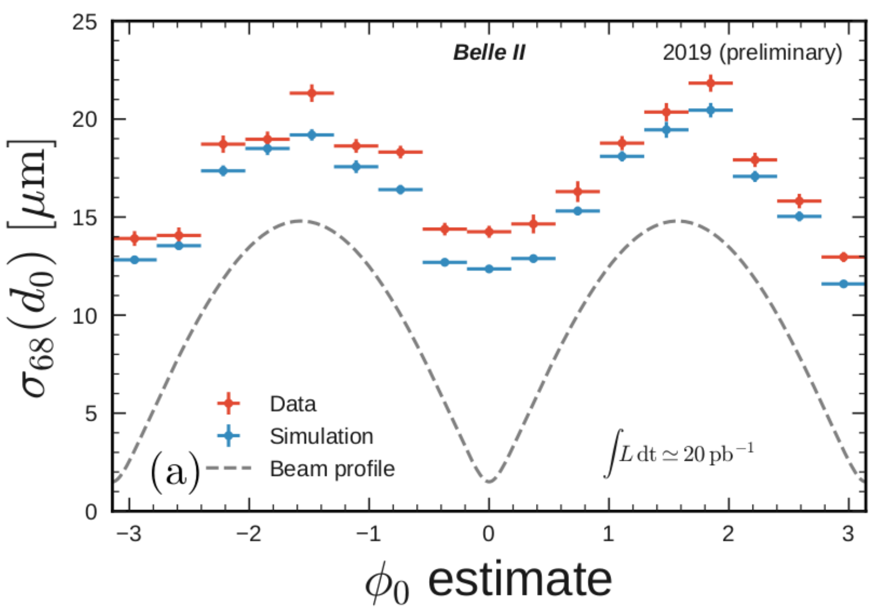
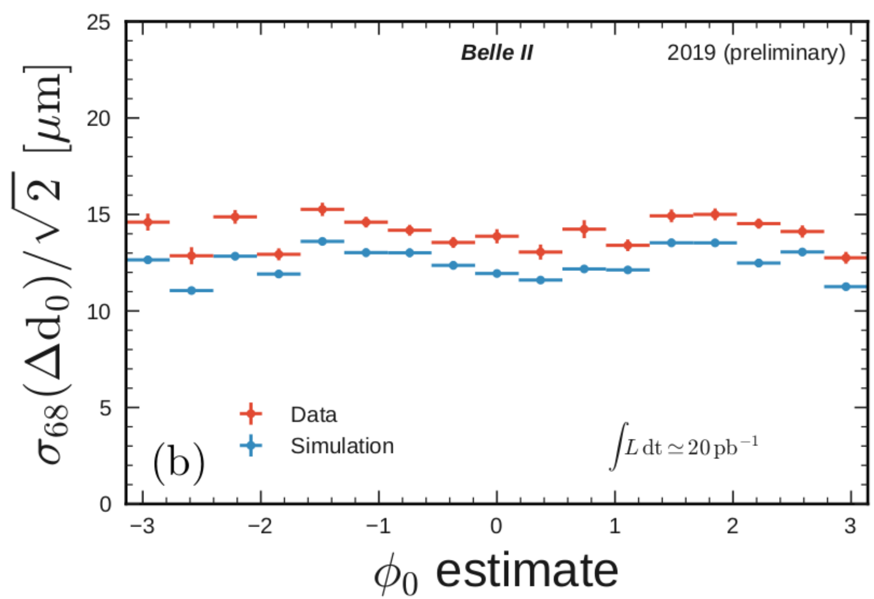


Impact Parameter Resolution

- Can measure vertexing resolution from the known small "nanobeam" spot
  - Resolution driven by DEPFET pixel detector

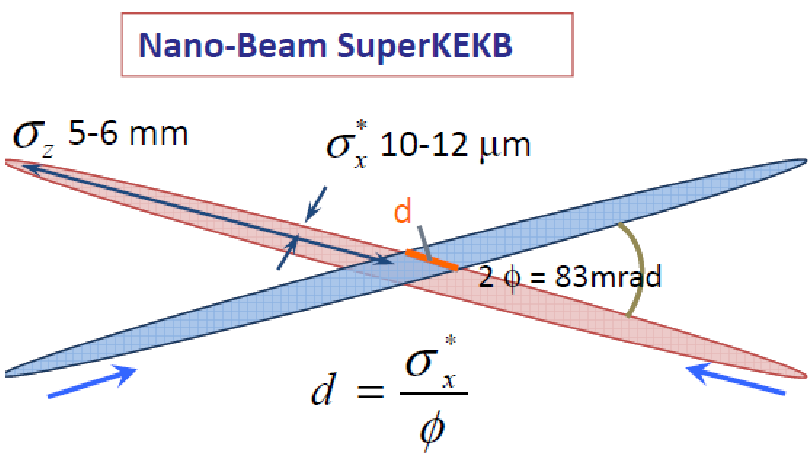


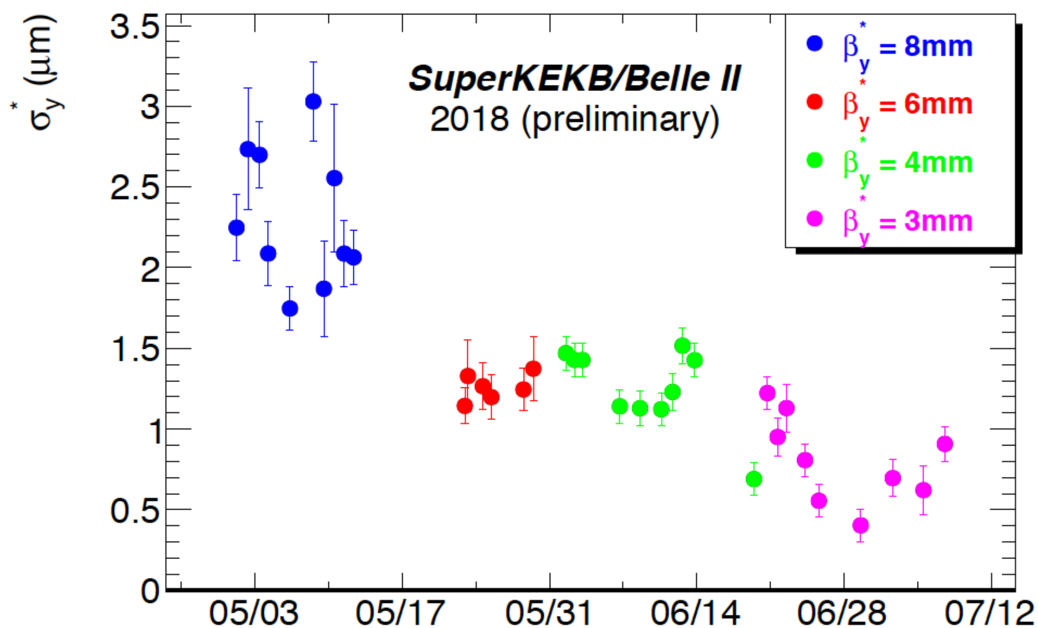


SuperKEKB Beam Spot Size

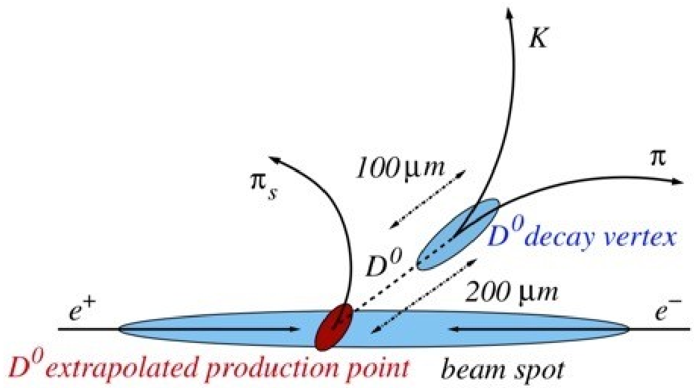
- Measurement for all three dimensions
- Nanobeam scheme works as intended

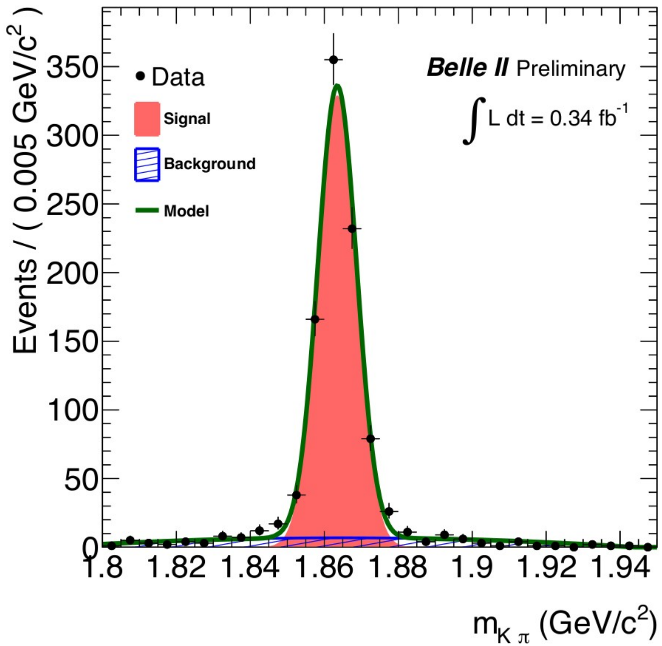
	Data
$\hat{\sigma}_x$ [μm]	$14.6 \pm 0.4\,(\text{stat}) \pm 0.2\,(\text{syst})$
$\hat{\sigma}_z$ [μm]	$346.9 \pm 1.8\,(\text{stat}) \pm 0.1\,(\text{syst})$



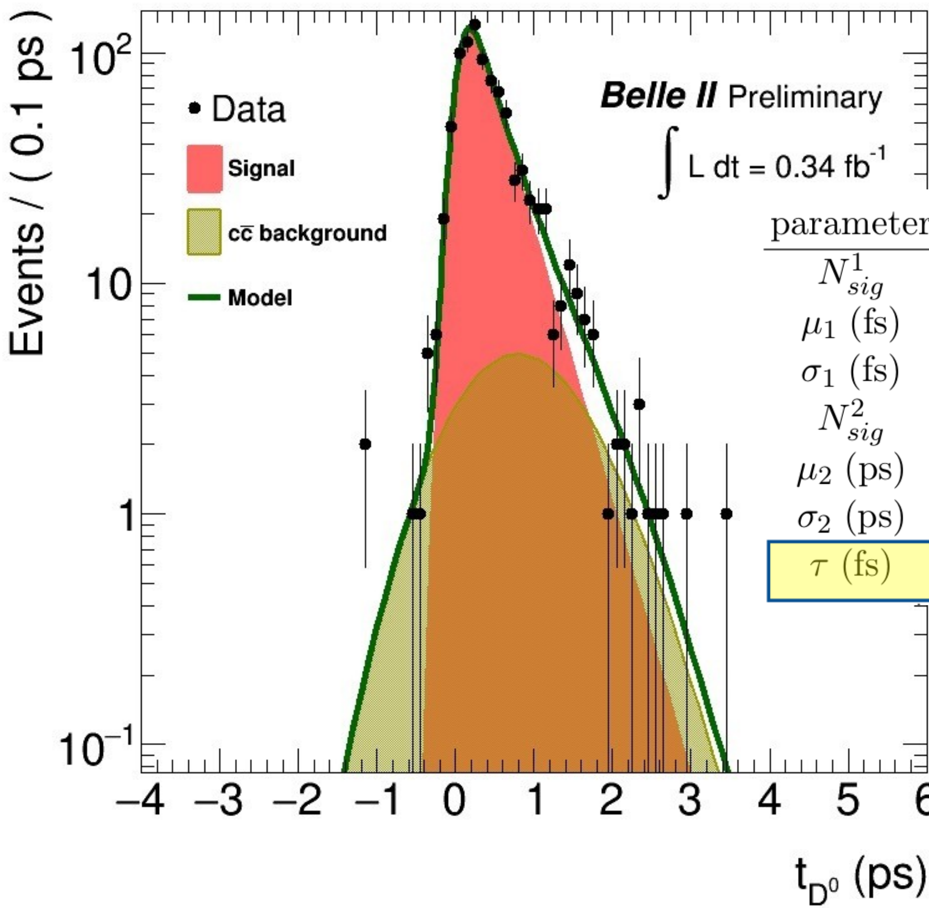


D0 Lifetime Measurement





m_{D0}=(1864.83±0.05) MeV/c^2 (PDG - 2018)

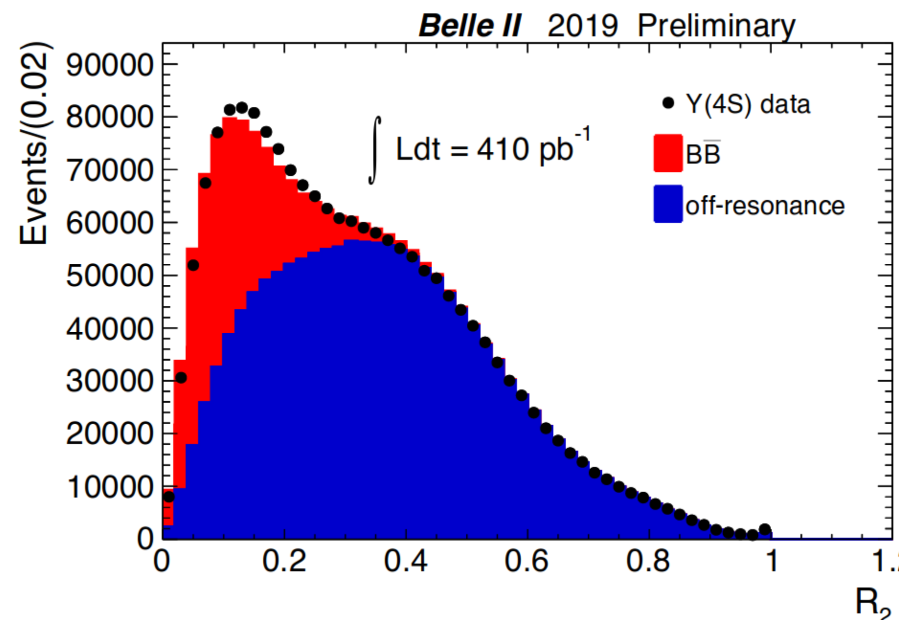


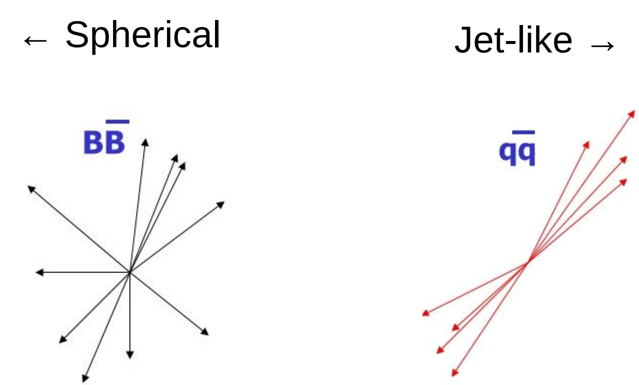
parameter	extracted value
N^1_{sig}	$(81 \pm 6) \cdot 10$
μ_1 (fs)	31 ± 16
σ_1 (fs)	127 ± 15
N^2_{sig}	$(10 \pm 5) \cdot 10$
μ_2 (ps)	(0.48 ± 0.17)
σ_2 (ps)	(0.73 ± 0.13)
τ (fs)	(370 ± 40)

τ_{D0}=(410.1±1.5) fs (PDG - 2018)

$B\bar{B}$ Pairs in First Data

- Decompose measured R2 distribution into $B\bar{B}$ and continuum components
- Using off-resonance data to model continuum distribution
  - some discrepancies in continuum MC likely due to incomplete machine background modeling
- Many $B\bar{B}$ pairs in first data set
  - We are stably operating on on the Y(4s) resonance

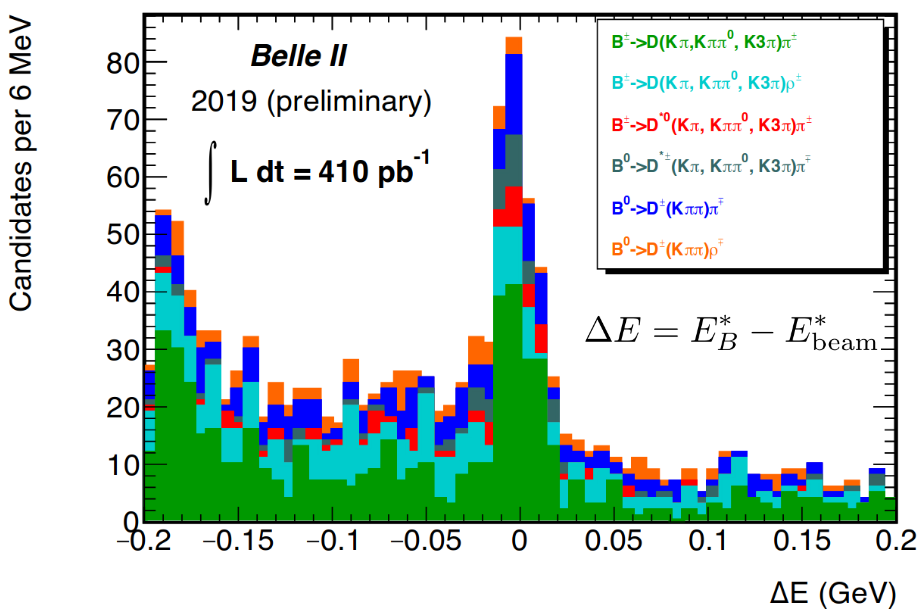


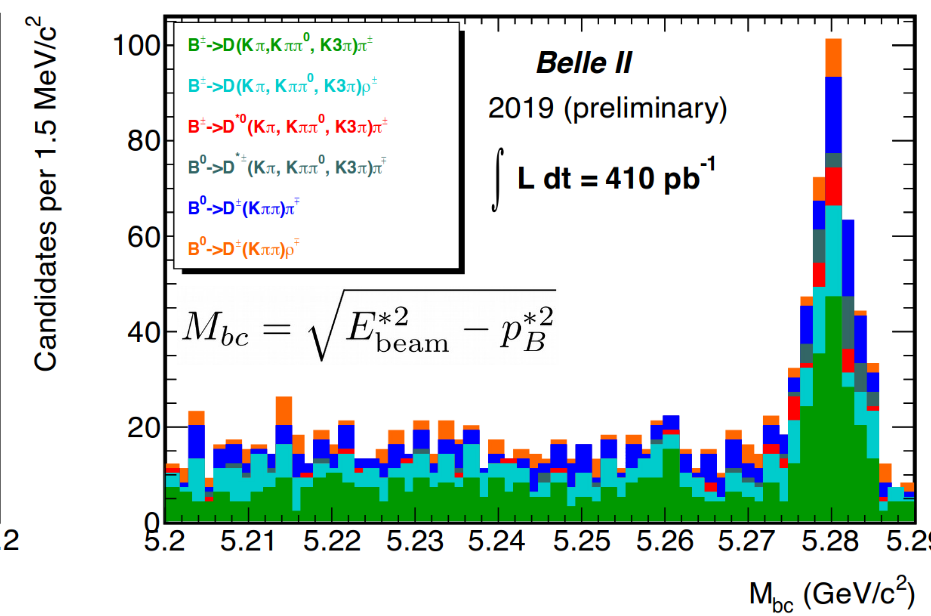


Reconstructed B decays

- B → D(*)h exclusive (h=π,ρ)
  - Various D decays
- ~300 selected event candidates in first 410pb^{-1}

Mode	Exp7
$B \to D\pi$	140 ± 13
$B \to D\rho$	58 ± 11
$B \to D^{*0}\pi$	24 ± 5
$B^0 \to D^{*\pm}\pi$	32 ± 6
$B^0 \to D^-\pi^+$	31 ± 7
$B^0 \to D^-\rho^+$	14 ± 7



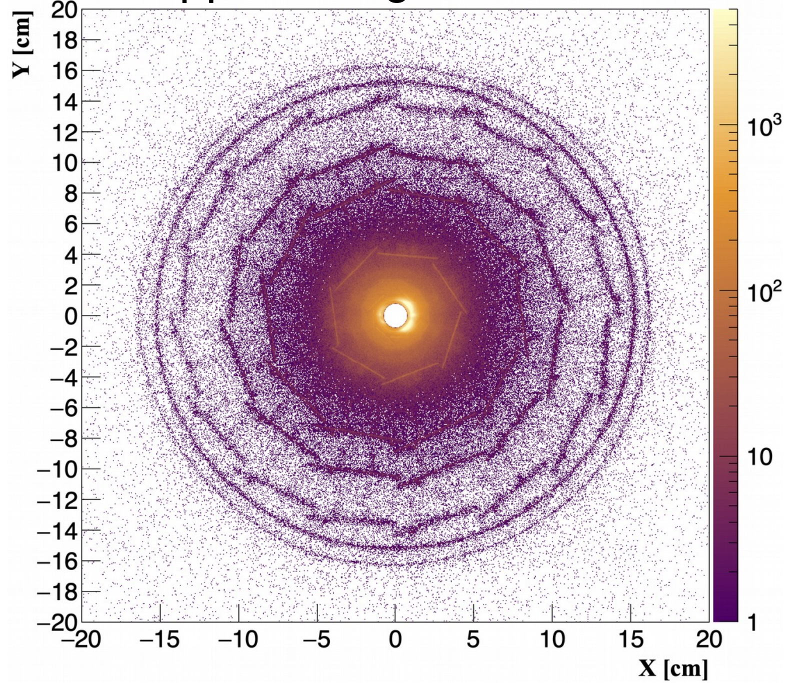


Summary

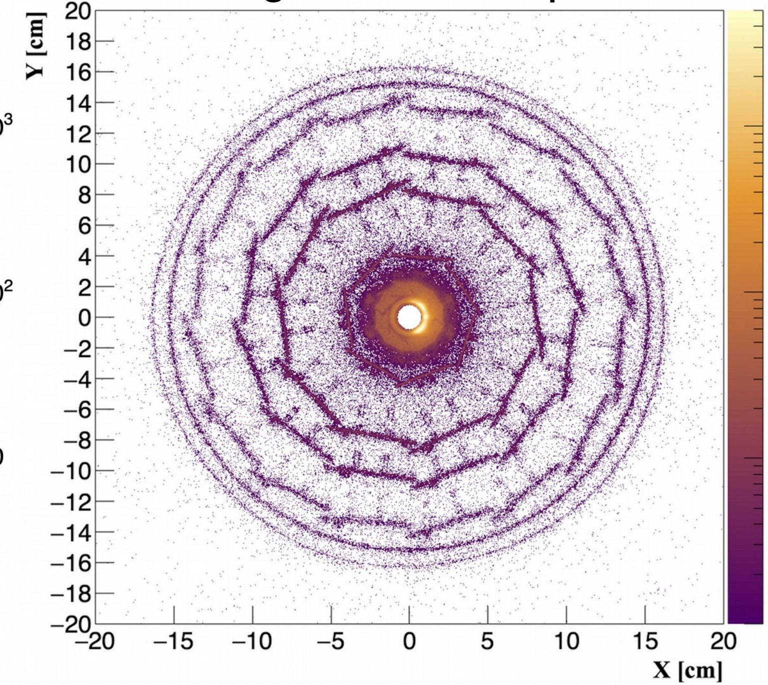
- The TOP detector is a novel particle identification system for the Belle II barrel region
  - Strong requirements on sensors, readout electronics, calibration
  - It actually works

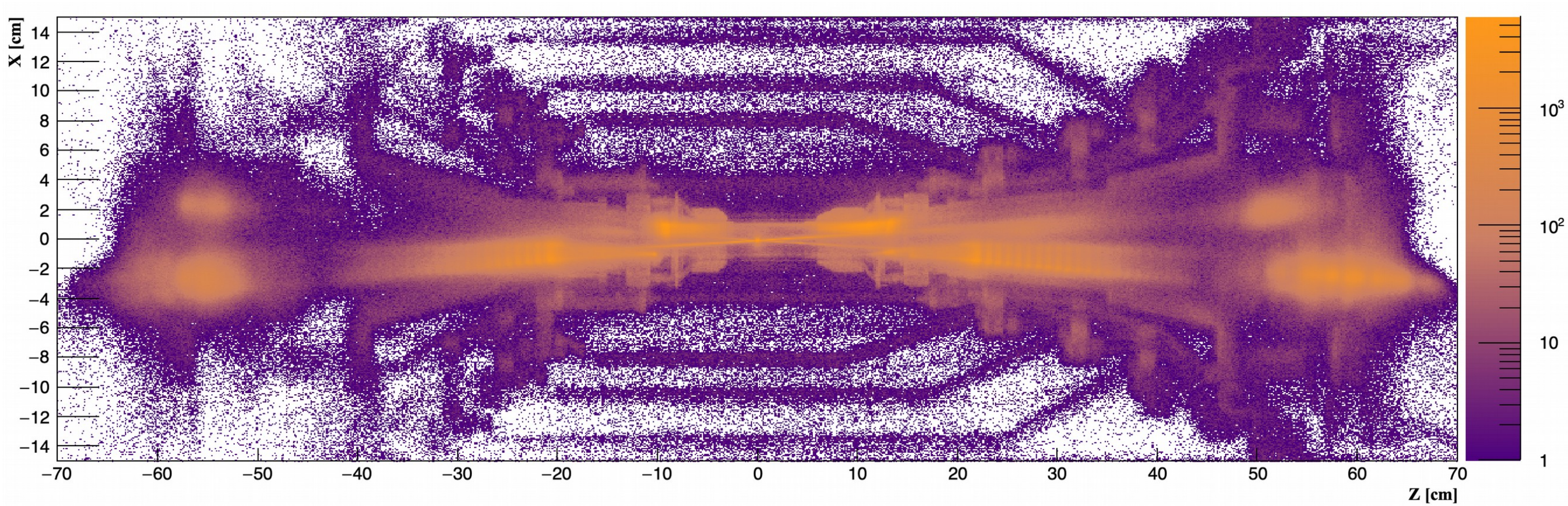
- Belle II has successfully started its first physics run period earlier this year
  - Relatively slow luminosity rampup gives us some time to really understand the fine details of the detector

opposite-sign vertices

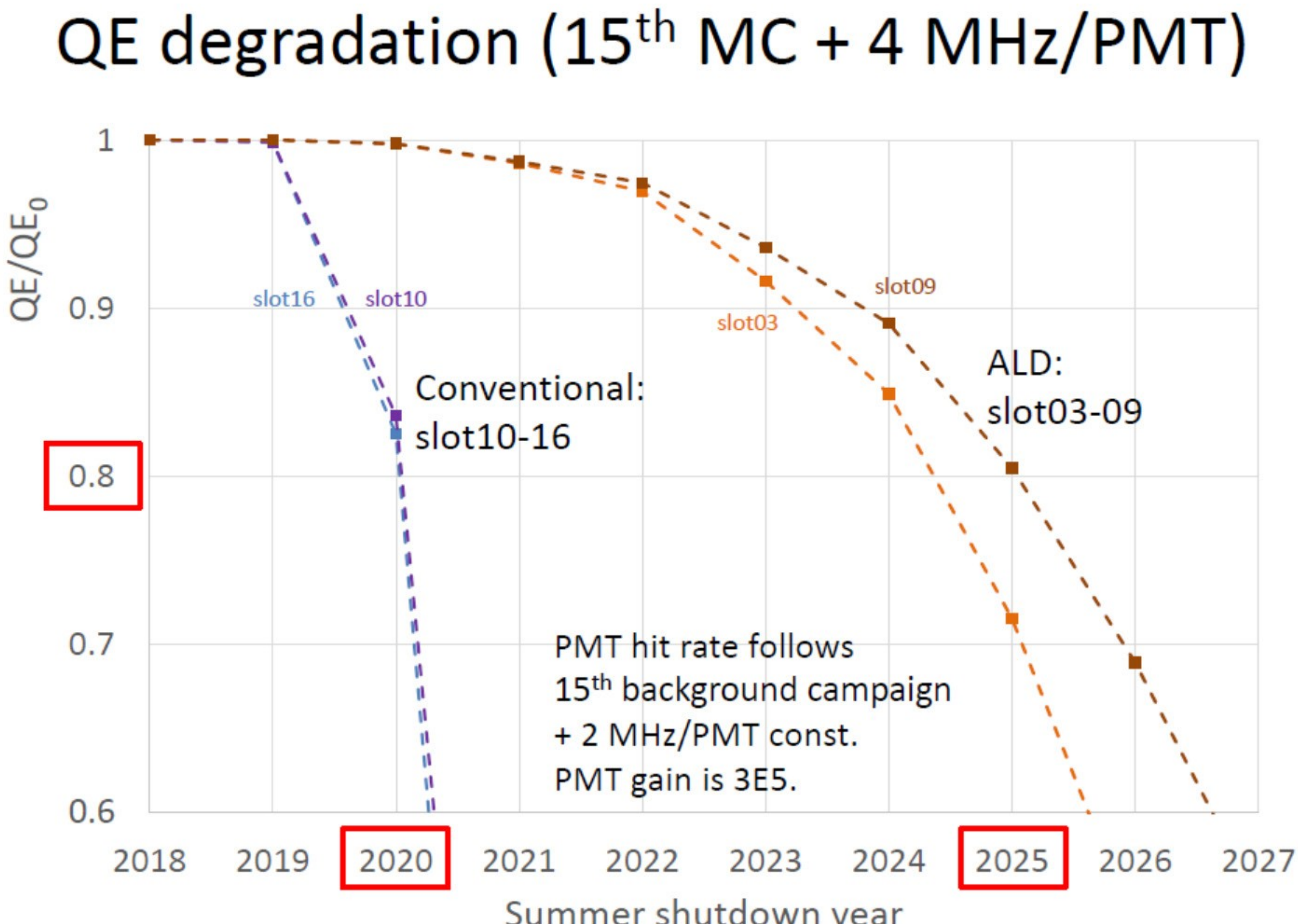


same-sign vertices + protonID



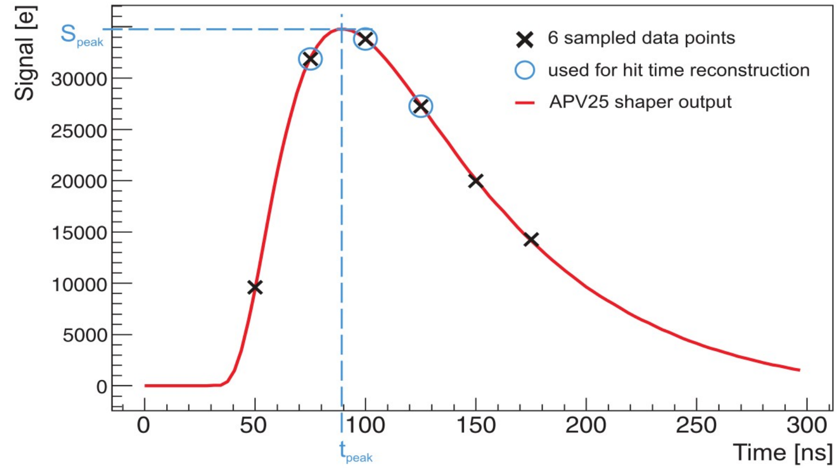


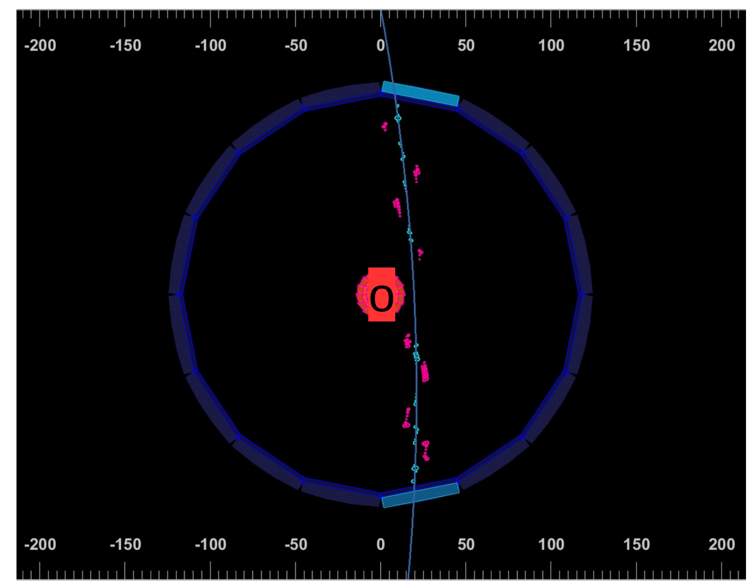
PMT Degradation and Replacement Plans



TOP Event Timing for Trigger

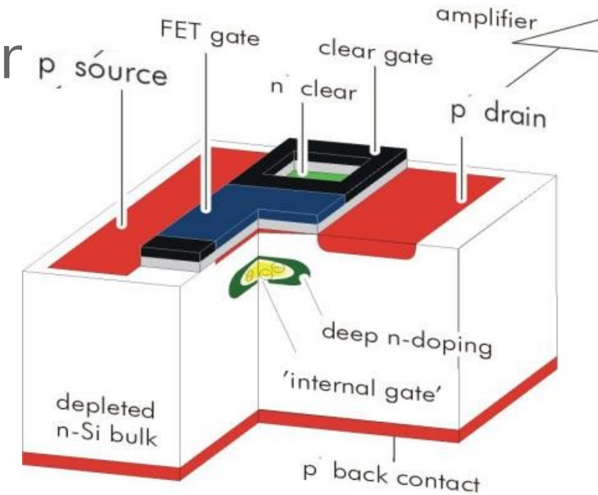
- Precise event time is important for SVD readout: 25ns frame spacing, can afford only few ns of jitter
  - ECAL and drift chamber trigger timing but resolution is ~tens of ns
- Why not use TOP information for L1 T_0 estimate?
- Complicated photon timing structure due to reflections etc.
  - Live likehood analysis of streamed TOP hit timings (no geometric info available)
  - No tracking information on trigger level
  - Estimated to produce <3ns T0 resolution (eventually)
  - FPGA Infrastructure is set up, successfully used TOP timing for cosmics trigger

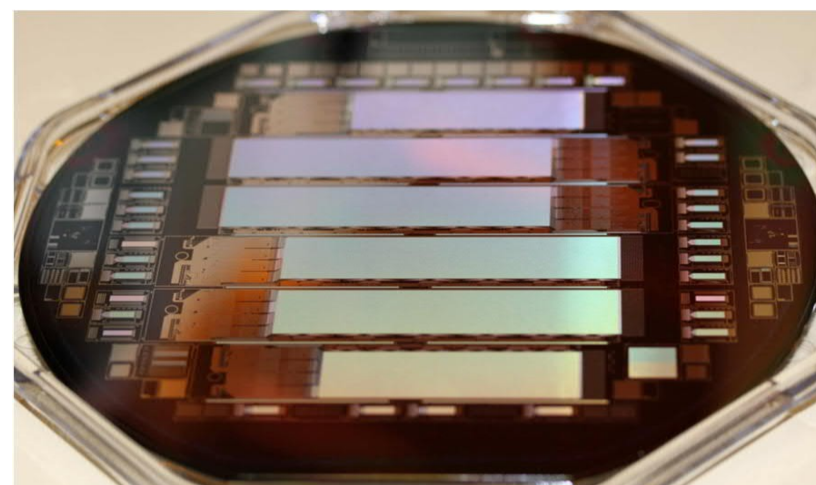




PXD: Inner Vertexing with DEPFET Pixels

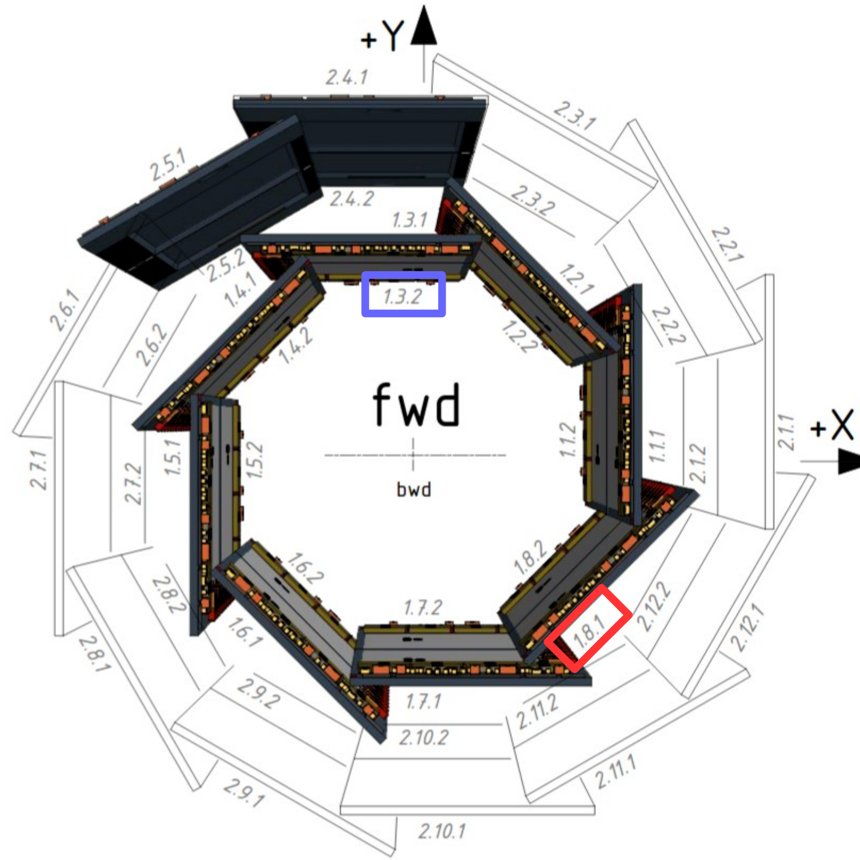
- DEPFET: internal charge to current amplification
  - Very good S/N for thin sensors
  - Relatively low power (no cooling in active area)
  - Rolling shutter readout (20us frame time)
- Sensors thinned to 75um
  - <0.25% X_0 per layer
- Two layers (r=14mm, 22mm)
  - Down to 50*55um pixels
  - 40 sensors total, 7.7Mpixel





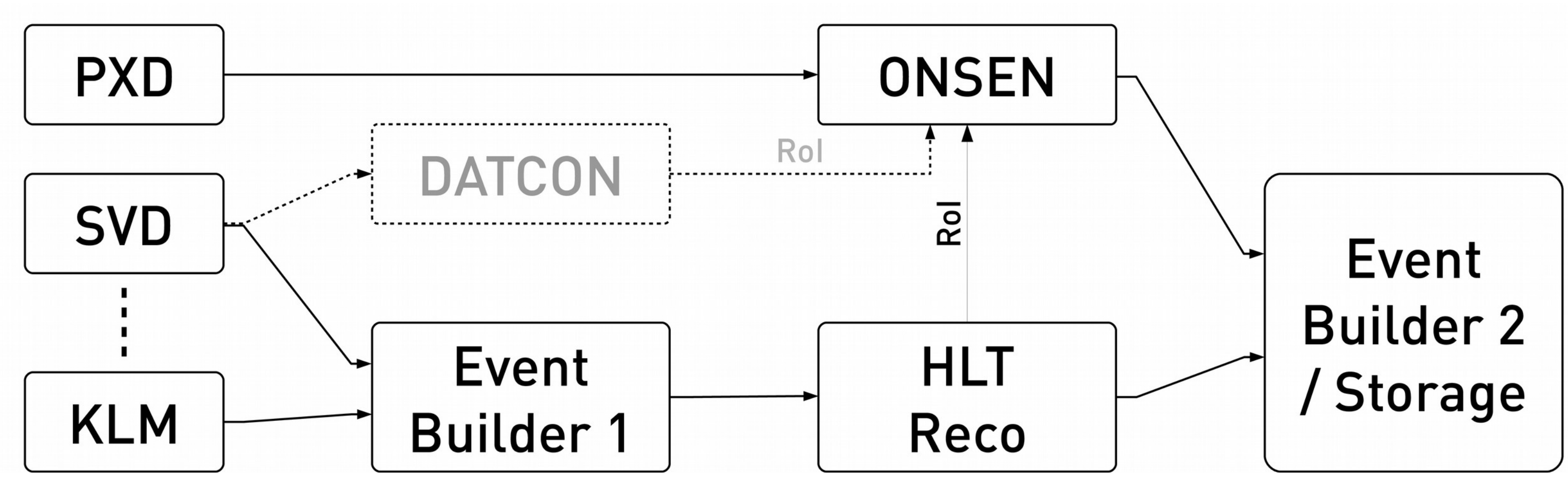
PXD: Current Installation

- After technical troubles in module production and assembly: only inner layer installed
  - +2 ladders on outer layer
  - 10/20 sensors (3.8Mpixel)
- Restarted production of all sensor types to provide modules for a complete replacement of the currently installed PXD 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



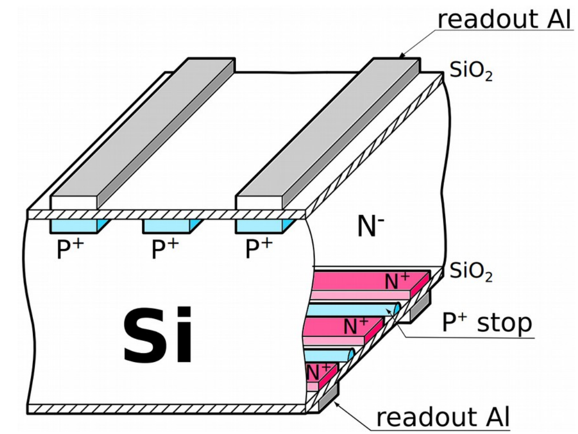
PXD: Readout

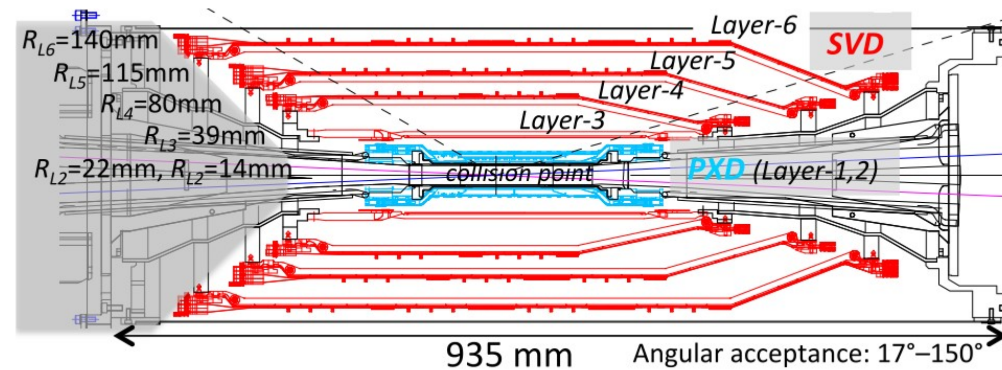
- PXD is virtually noise free, but rather long integration time (20us, two full accelerator revolutions)
- ONSEN system reads out full PXD on each trigger and keeps data in local buffer
  - HLT reconstruction identifies regions of interest on PXD surface, ONSEN only transfers relevant parts of PXD hitmaps 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



SVD: Silicon Vertex Detector

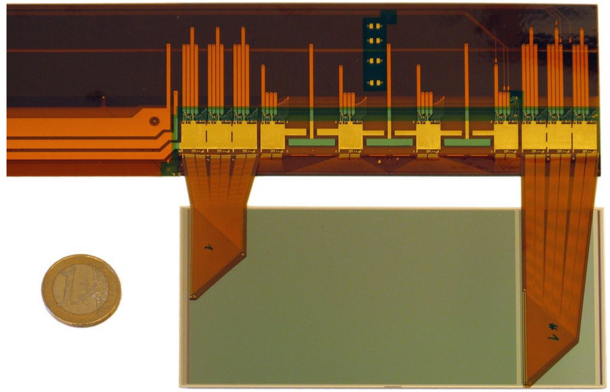
- Four layers of double-sided strip detectors
  - r=39mm to r=140mm
  - Lampshade geometry
- 224k strips
  - 50-75um pitch tangential
  - 160-240um pitch axial
- Read out by APV25 ASICs
  - Adapted from CMS
  - 50ns shaping,40MHz sampling
  - Partially thinned to 100um

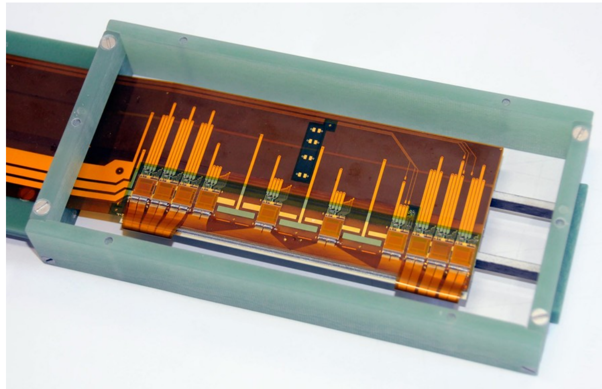


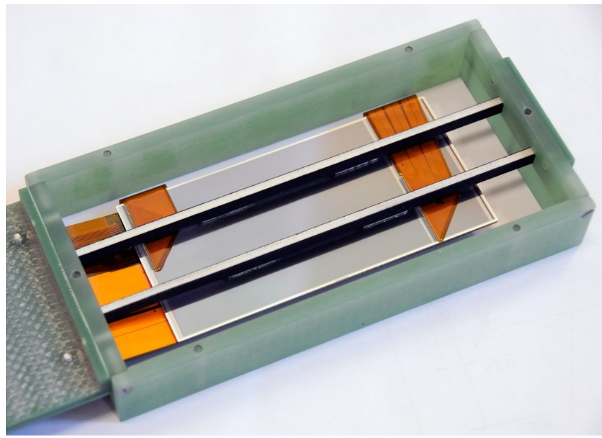


SVD: Production

- 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

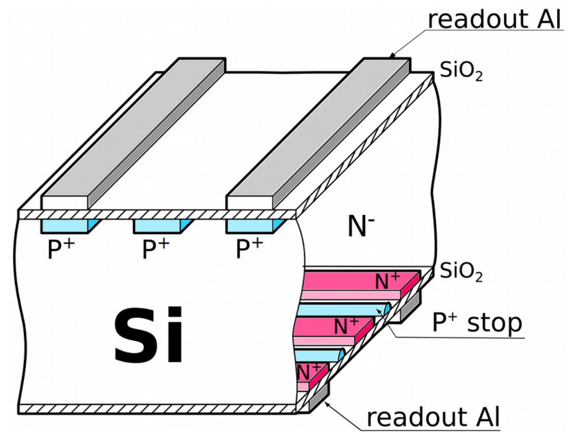


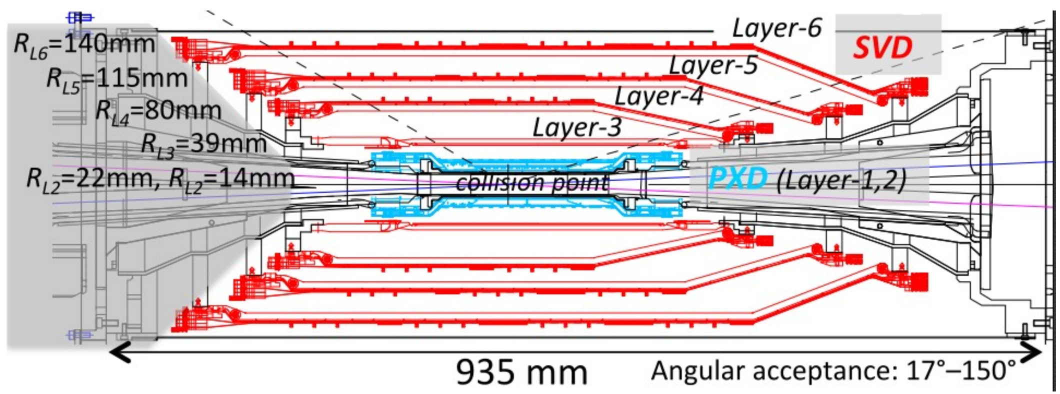




VXD Assembled and Installed

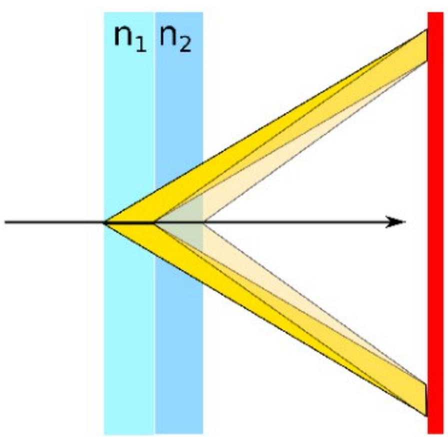
- Four layers of double-sided strip detectors
  - r=39mm to r=140mm
  - Lampshade geometry
- 224k strips
  - 50-75um pitch tangential
  - 160-240um pitch axial
- Read out by APV25 ASICs
  - Adapted from CMS
  - 40MHz signal sampling
  - Partially thinned to 100um

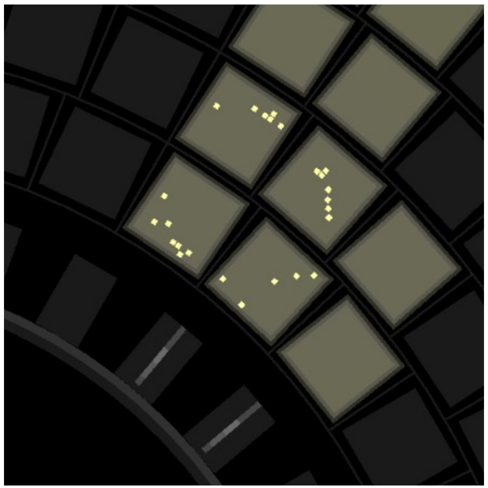


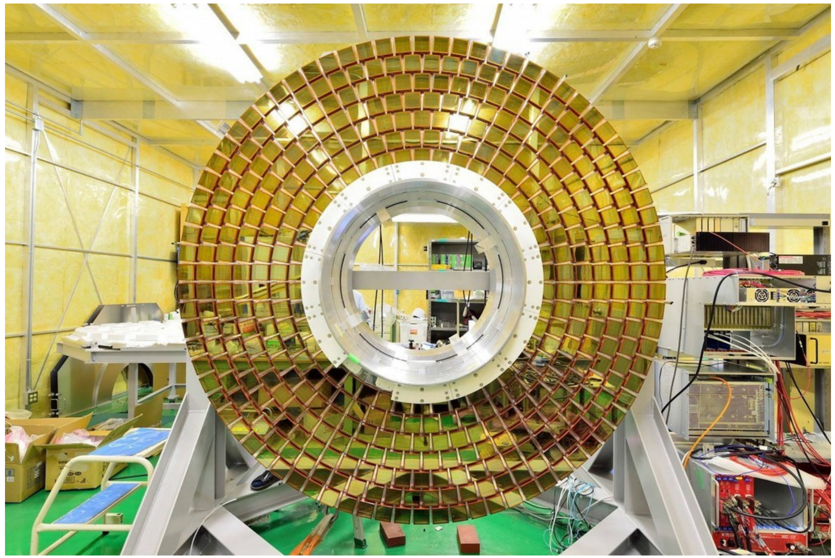


Endcap Particle ID: ARICH

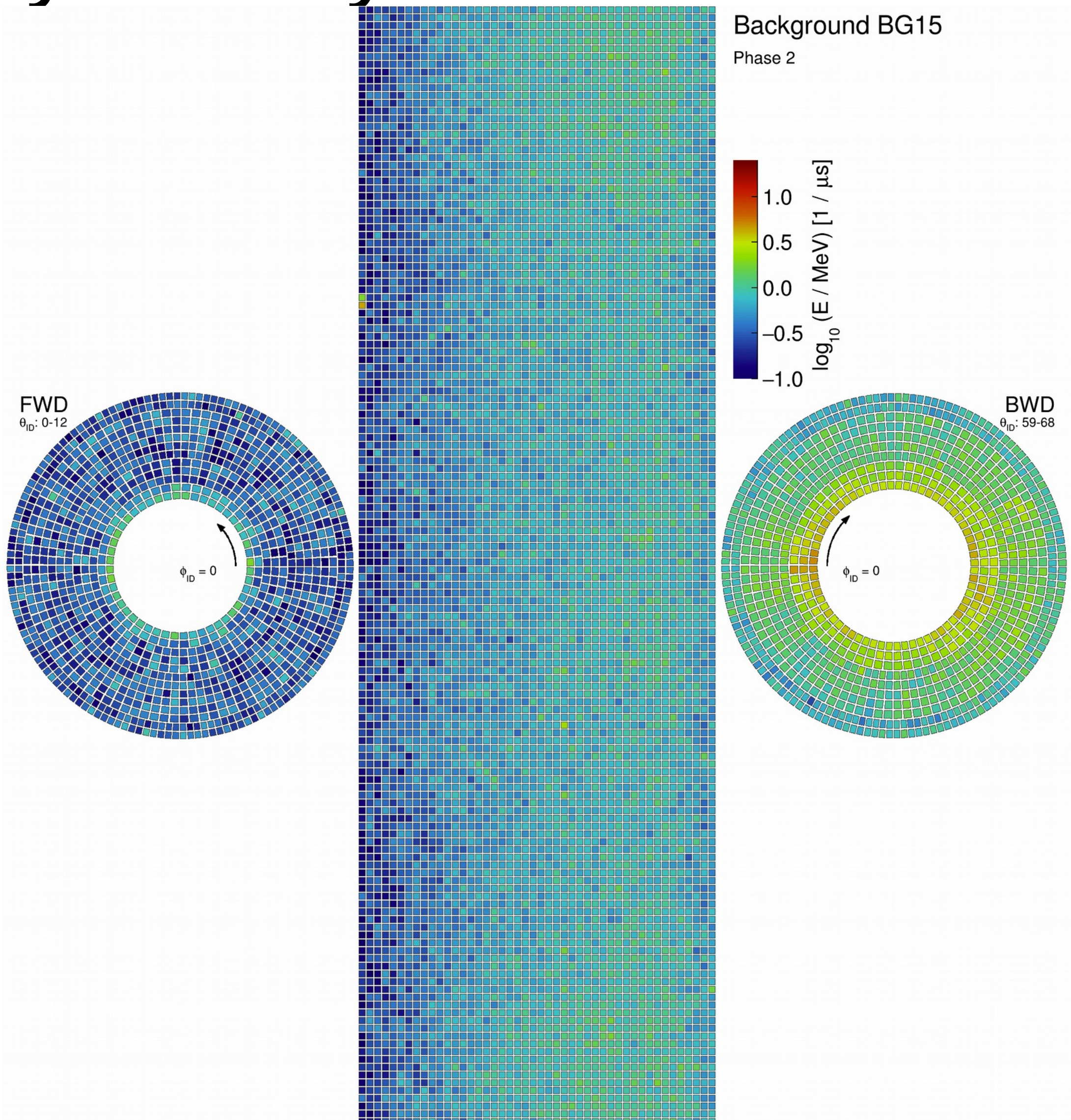
- Aerogel ring imaging Cherenkov detector
  - Double aerogel layer for focusing
- Very large sensor area: pixelated, single photon sensitive
  - instrumented with HAPDs (Hamamatsu)







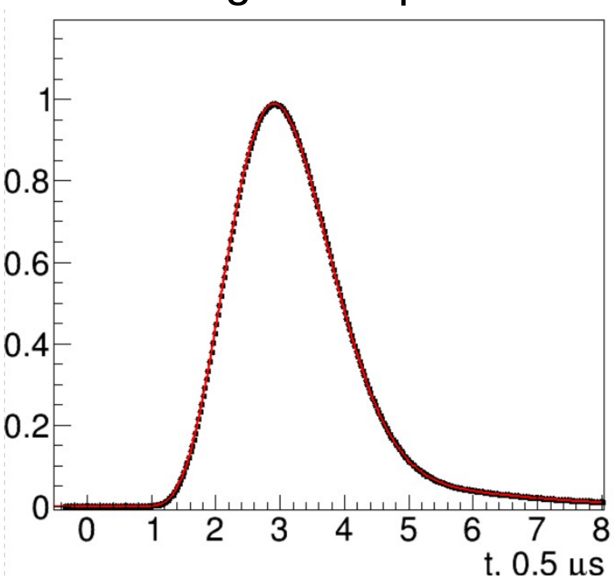
Radial Asymmetry



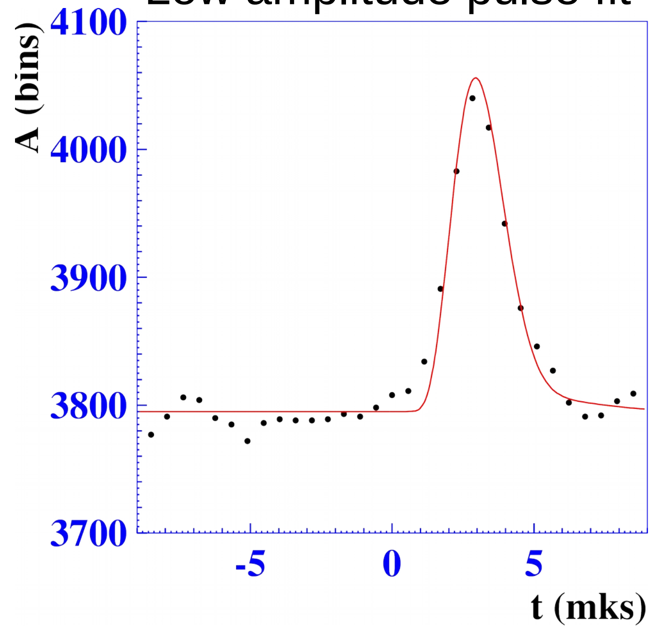
Feature Extraction in ECL

- 128 sample template fit in ECL frontend FPGA
  - Extracting hit amplitude and timing

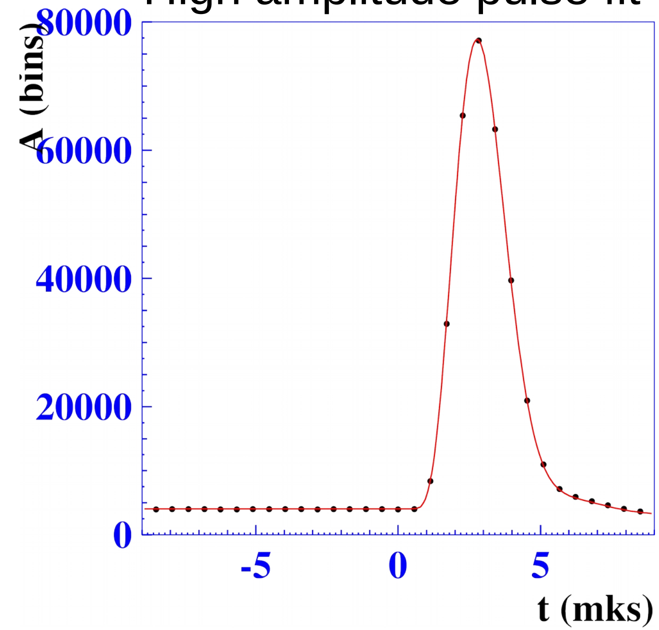
Averaged template



Low amplitude pulse fit



High amplitude pulse fit



Feature Extraction in ECL

- Achieves <10ns timing resolution with 500ns sample distance