TOP
Particle ID in the Belle II Barrel

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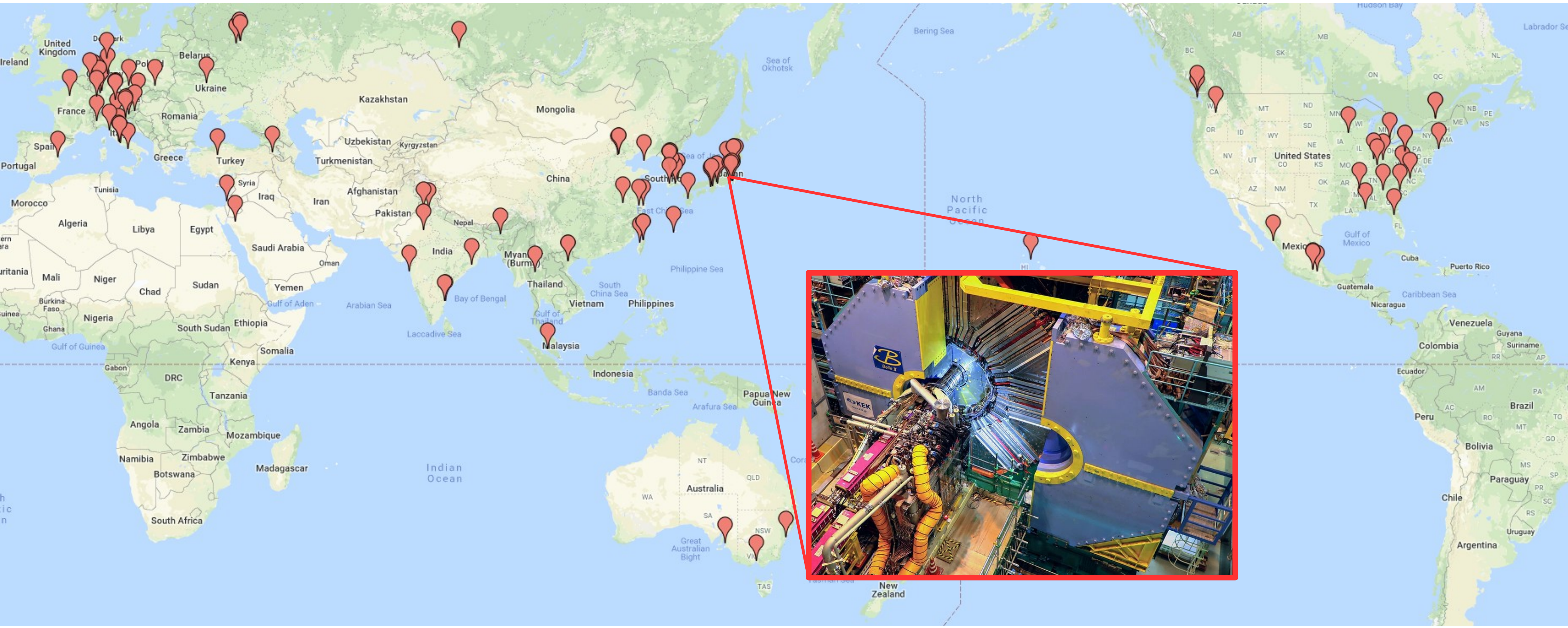
What to Expect

- Overview of Belle II and SuperKEKB
- Key detector technologies in Belle II
- The TOP barrel PID
  - Concept
  - Technologies
  - Experiences
  - Preliminary performance figures

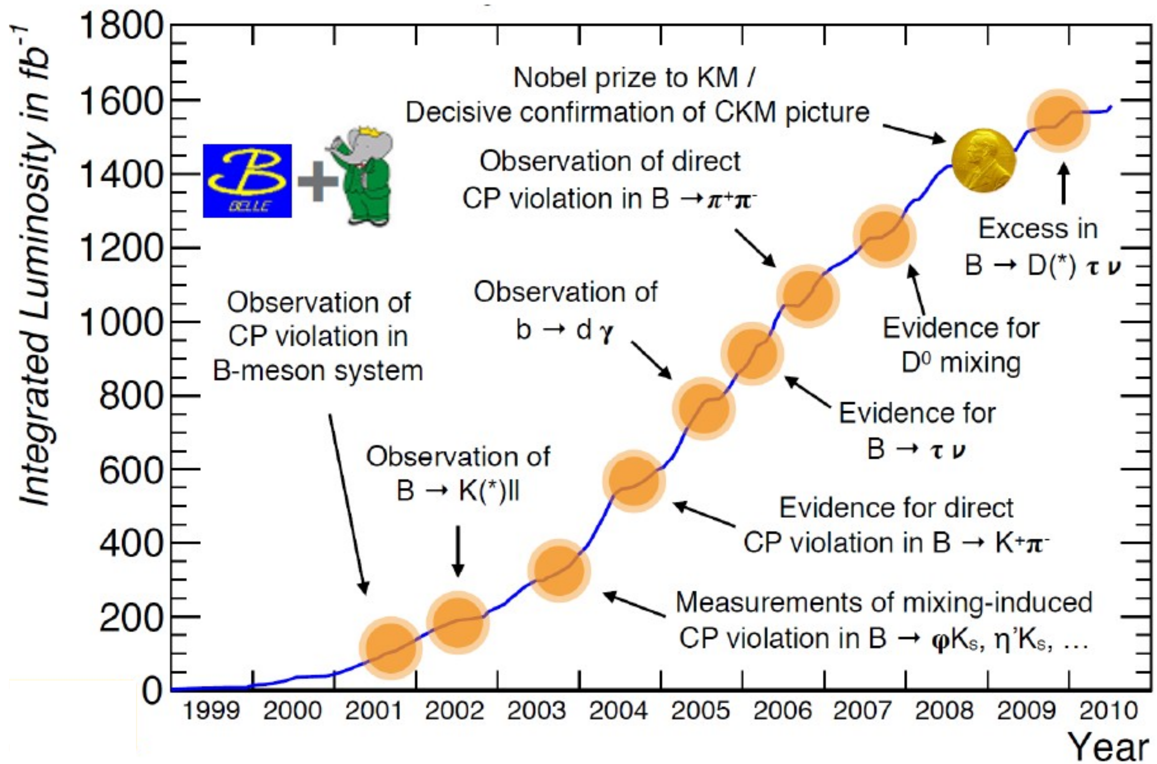
The Belle II Collaboration

- Truly international: now ~980 researchers from 26 countries



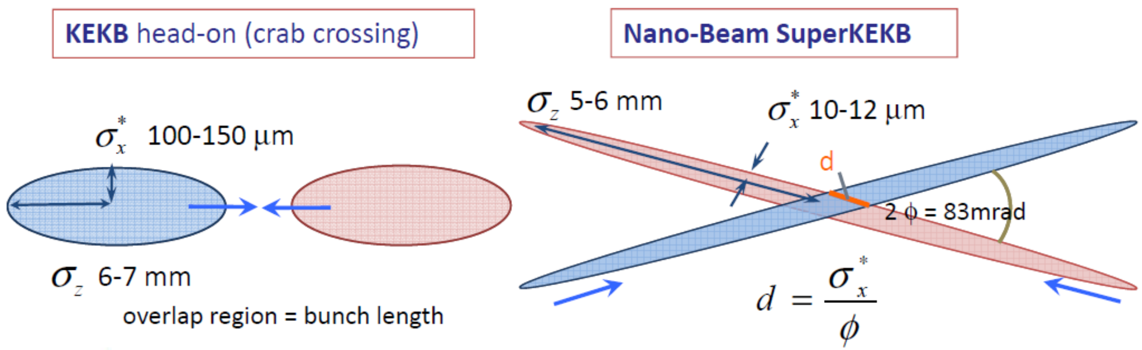
B-Factory Experiments

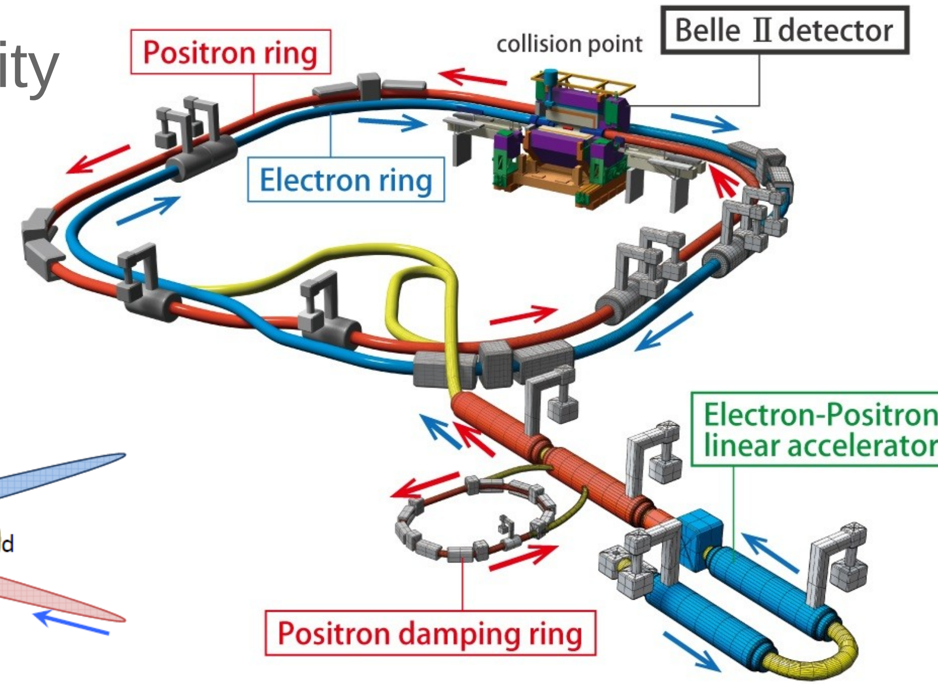
- Asymmetric beam energies, high luminosity
  → High statistics of boosted B, D and τ
- Flavour physics
  - CKM matrix, unitarity triangle
  - CPV in B system
- BSM limits
  - Rare B/D decays
  - $b \rightarrow s\gamma$, $b \rightarrow sl^+l^-$
  - LFV in τ decays
- New particles
  - Tetraquarks



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
Beam current	I	1.64	1.19	3.6	2.6	A
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

x20
x2
x40

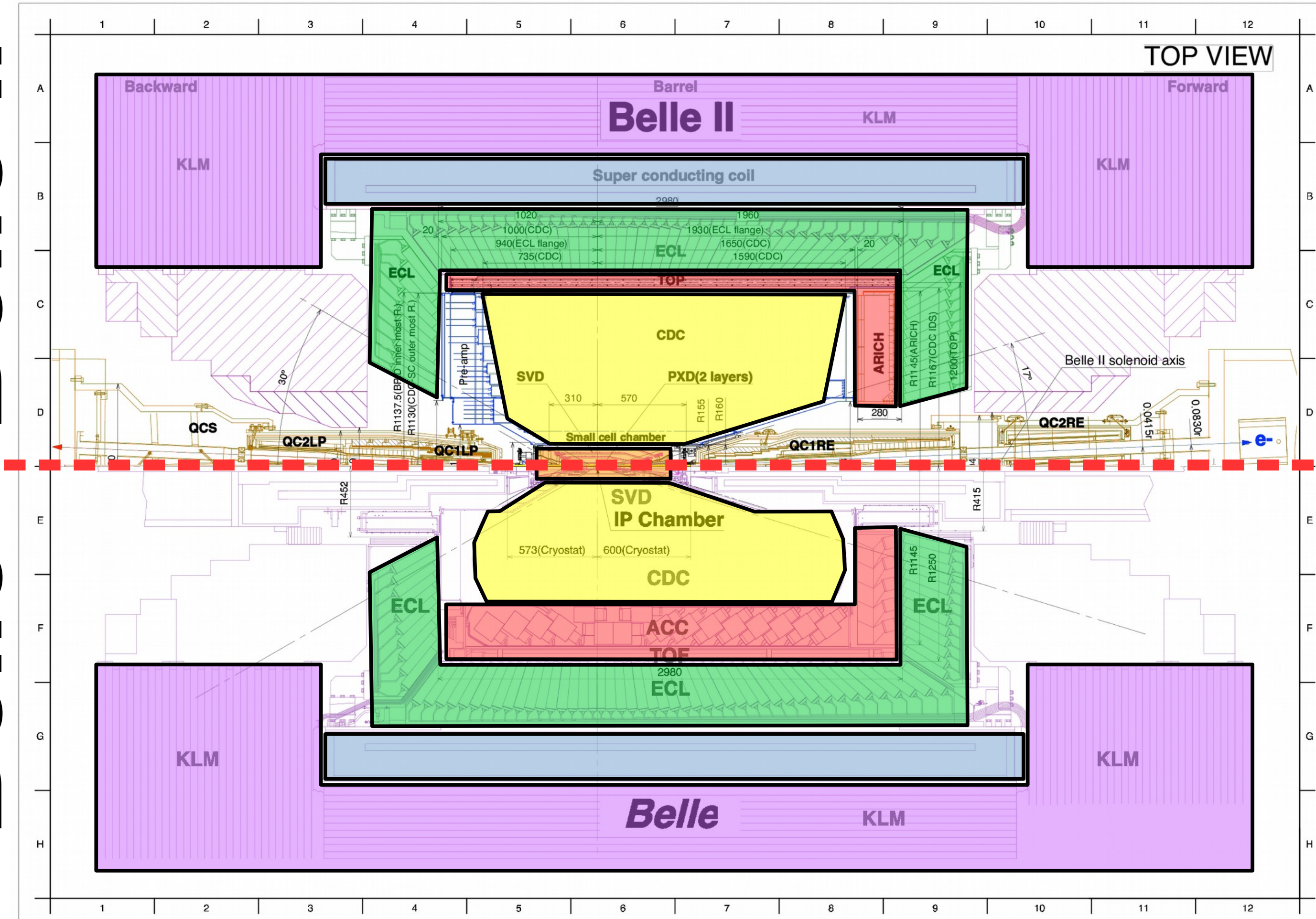
Challenges on the Detector Upgrade

- 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 nodes)
- 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

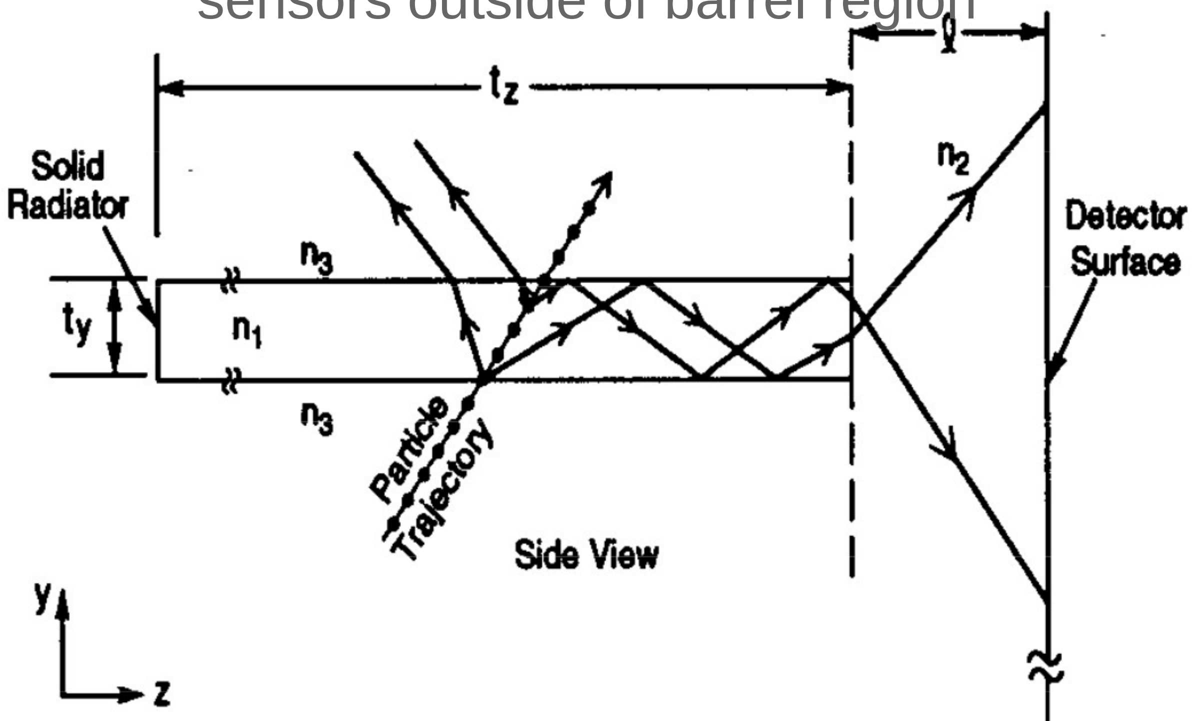
Key Technologies in Upgrade to Belle II

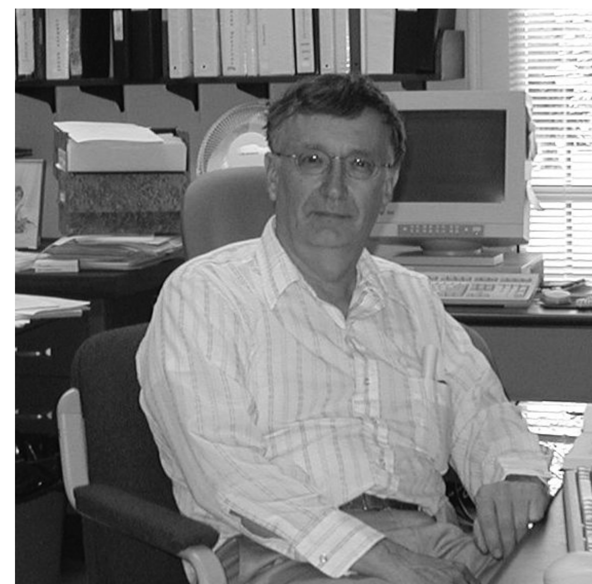
- Pixelated photo sensors
  - MCP-PMTs in TOP (barrel PID) – excellent time resolution
  - HAPDs in ARICH (end cap PID) – large area
  - SiPMs in KLM – low cost

- Waveform sampling readouts
  - TOP: 8192 channels, 2.7GSa/s: IRSX (Hawaii)
  - Sci-KLM: 16800 channels, 1GSa/s: TARGETX (Hawaii)
  - SVD: 224k channels, 40MSa/s: APV25 (adapted from CMS)
  - CDC: 14336 channels, 30Msa/s
  - ECL: 8736 channels, 2MSa/s

Belle II Barrel PID: A DIRC Derivate I

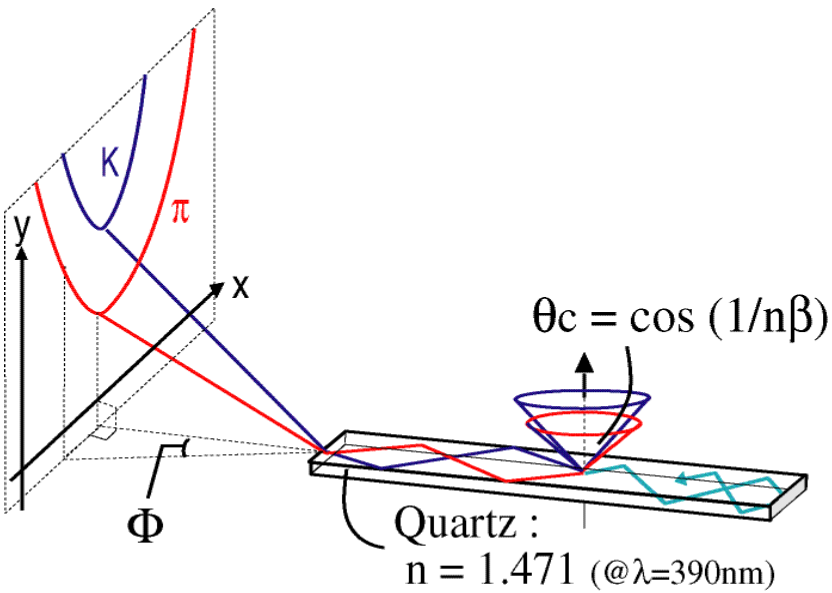
- DIRC: "Detector for Internally Reflected Cherenkov Light"
  - B. Ratcliff, SLAC PUB637 1
- Excellent solution to barrel PID needs in B-factories
  - Thin: Only radiator + casing in front of calorimeter, sensors outside of barrel region

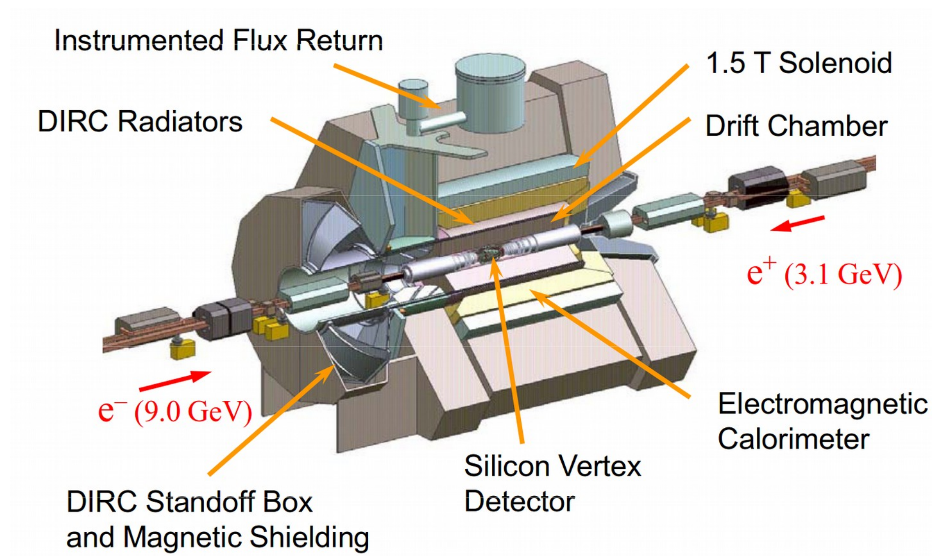




Belle II Barrel PID: A DIRC Derivate II

- 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!

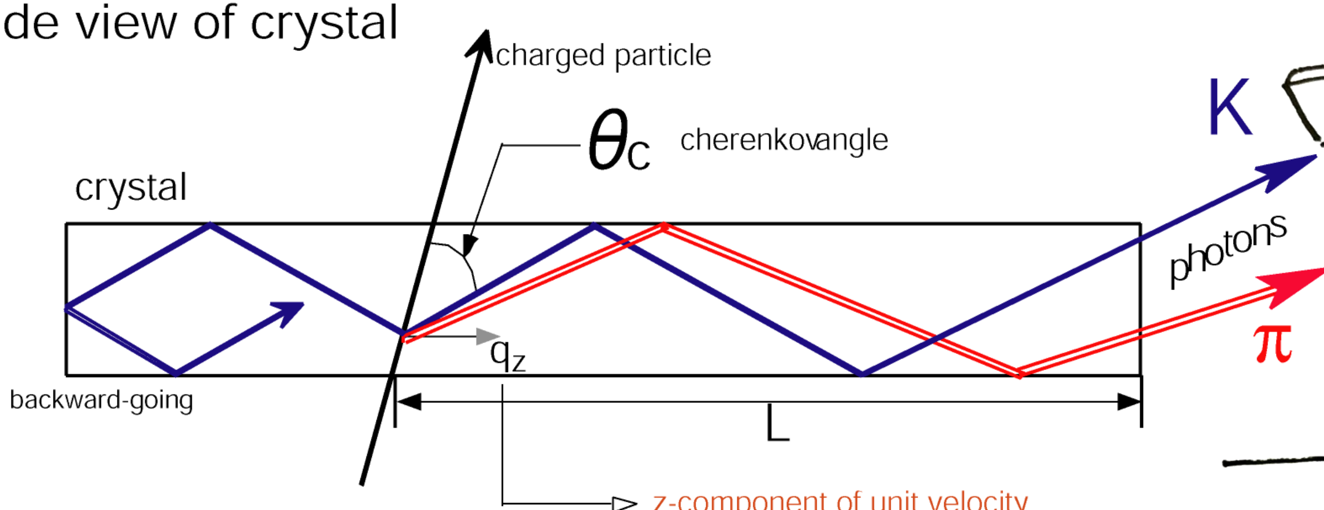


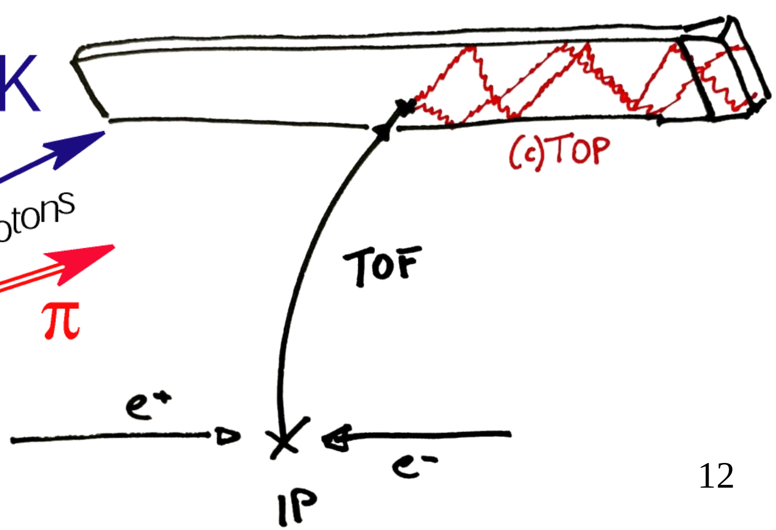


The “Time of Propagation” (TOP) Detector I

- 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...

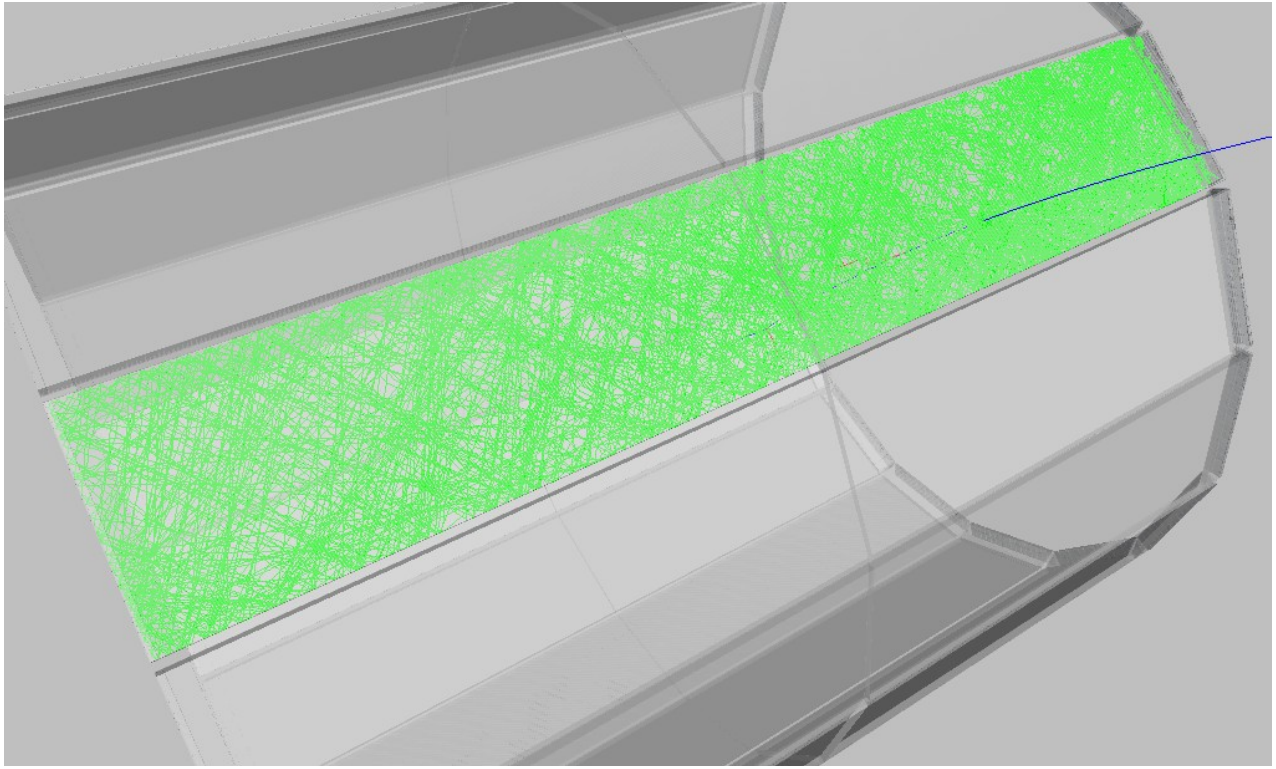
Side view of crystal





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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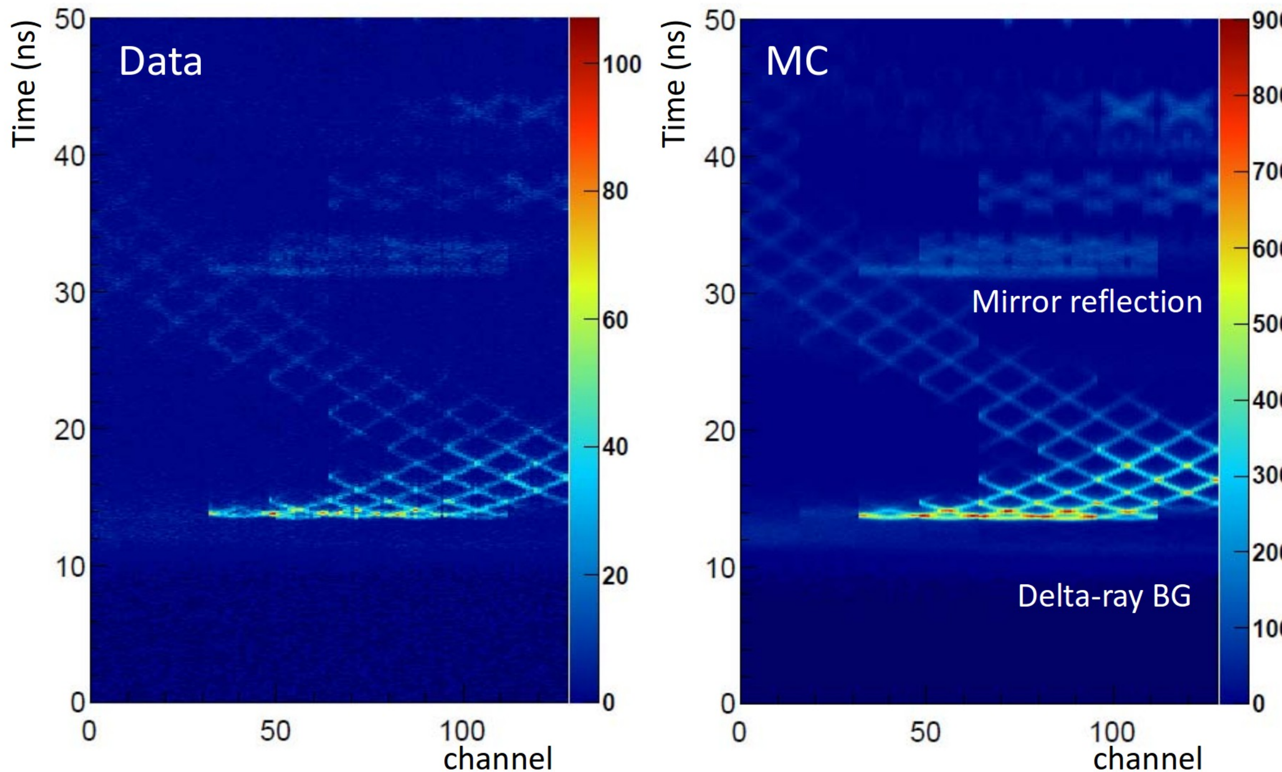
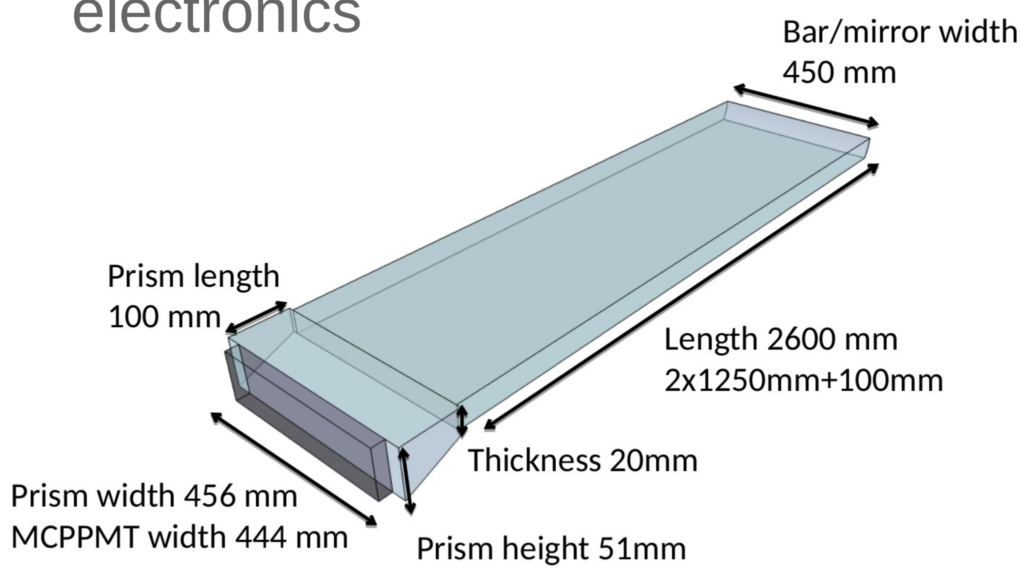
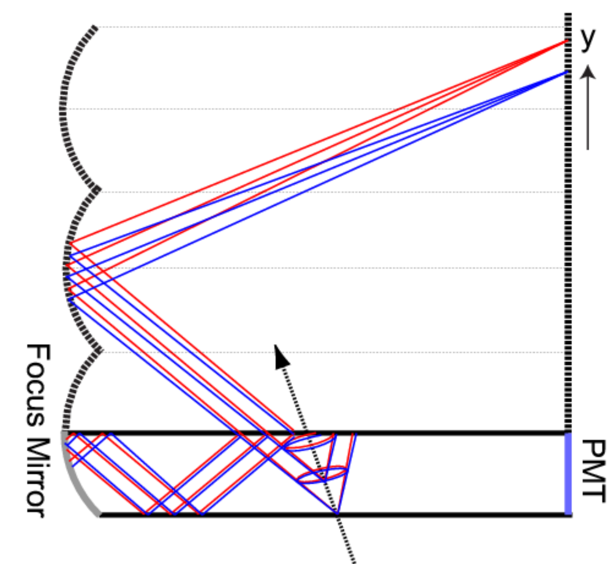
Early electron testbeam:



The “Time of Propagation” (TOP) Detector III

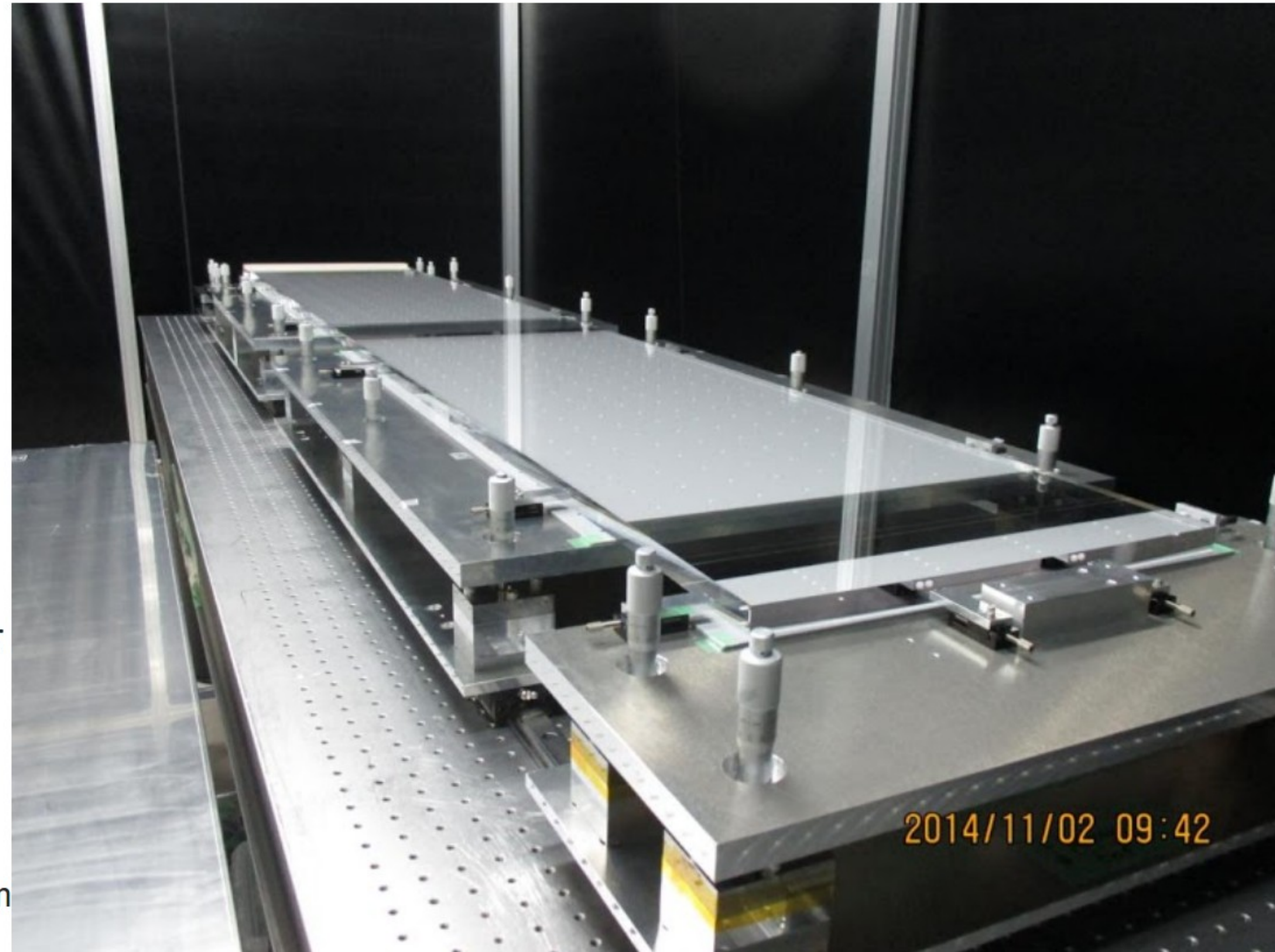
- 16 quartz Cherenkov radiator bars arranged around IP
- Forward side: spherical mirror
  - Effectively removes bar thickness for reflected photons
  - Different wavelengths are focused on slightly different points
- Backward side: small expansion prism, sensors, readout electronics





Quartz & Optics I

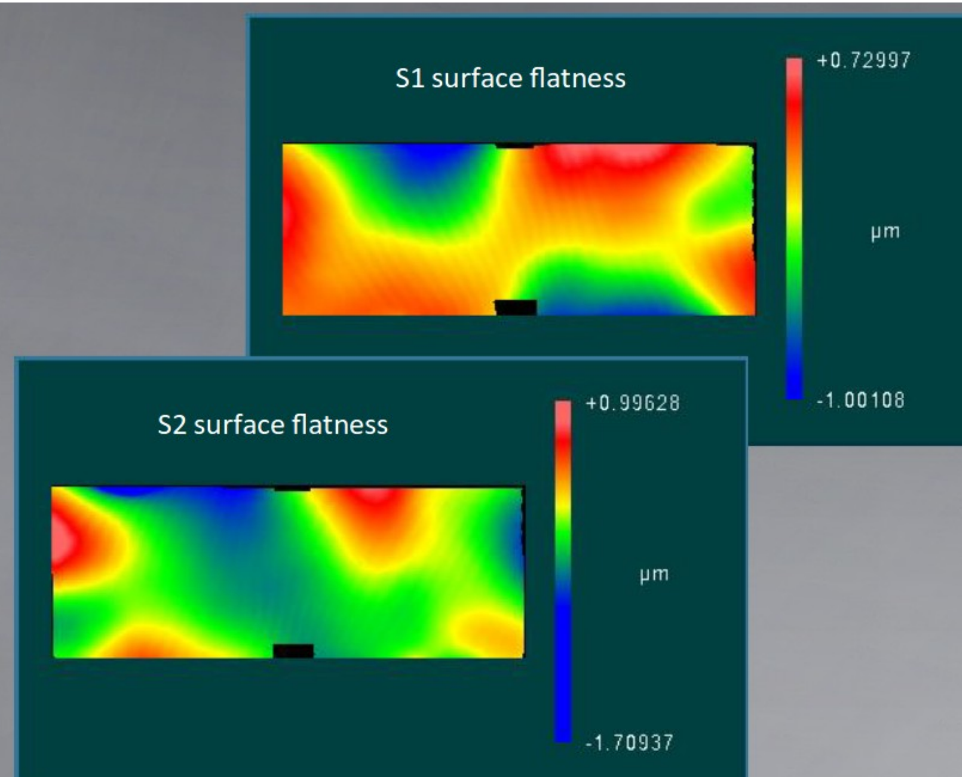
- Bars:
  1250 x 450 x 20 mm^3
  two bars per module
- Mirrors:
  100 x 450 x 20 mm^3
- Prisms:
  100 mm long, 456 x 20 mm^2
  at bar face expanding to
  456 x 50 cm^2 at MCP-PMTs
- Material: Corning 7980
- DIN58927 class 0 material has no inclusions (inclusions ≤0.1 mm diameter are disregarded)
- Grade 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

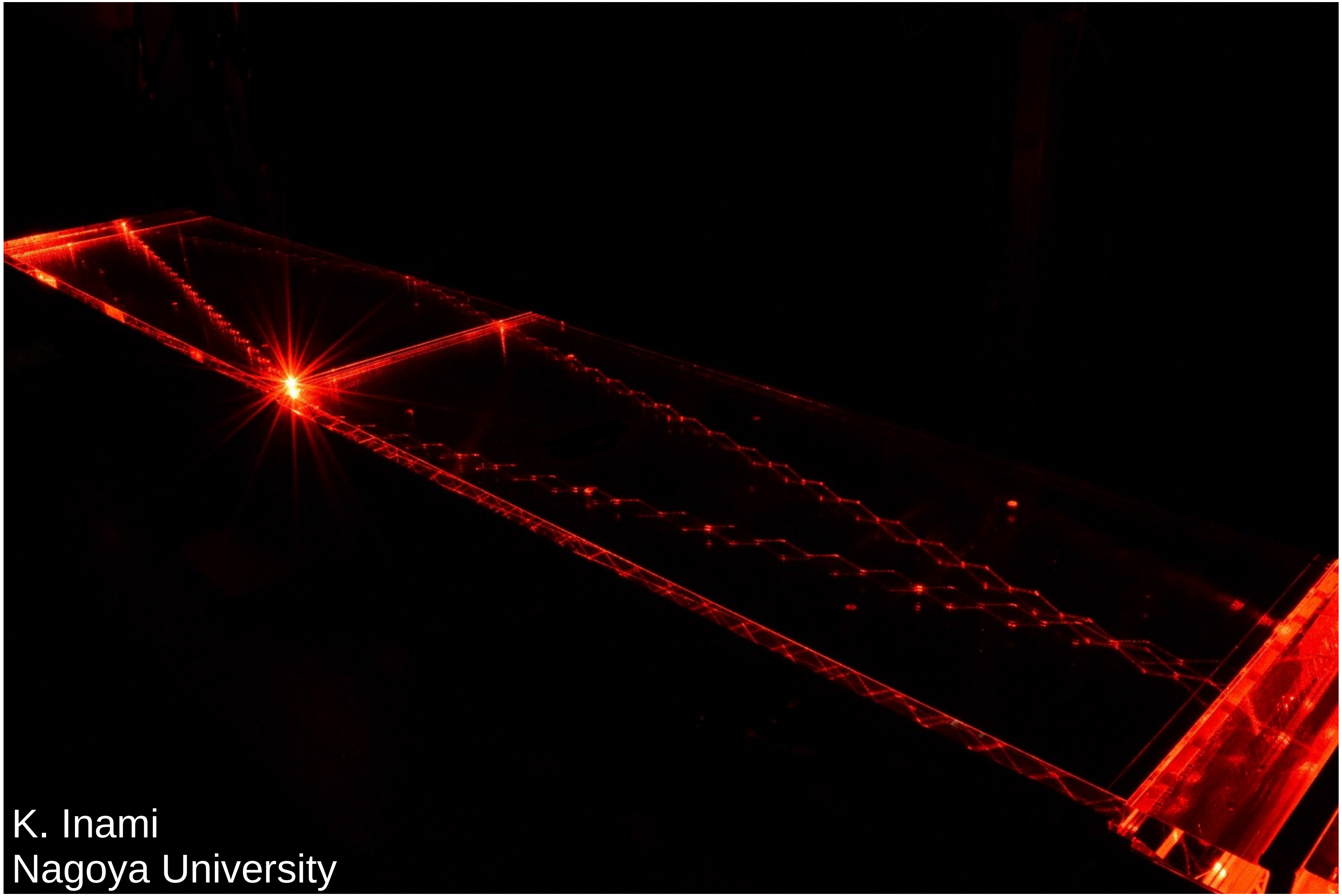
- Quartz most expensive part of the system (~10M$)
- Extreme surface quality requirements

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

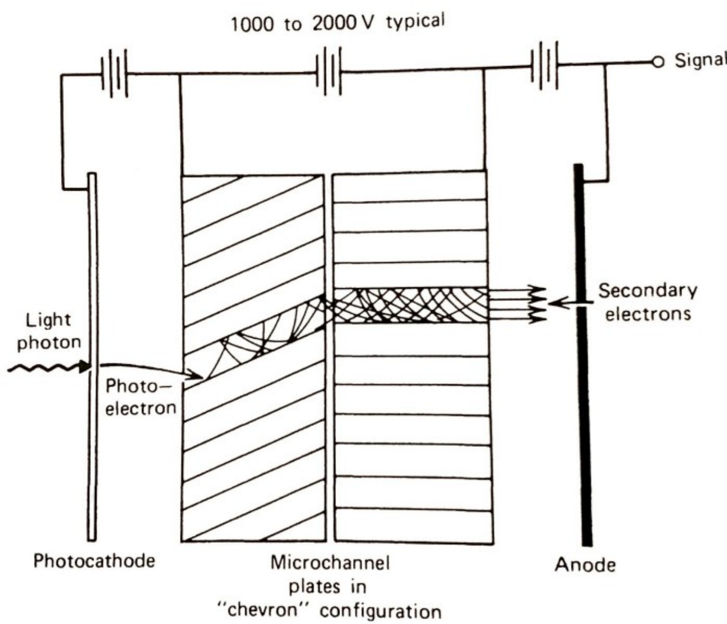


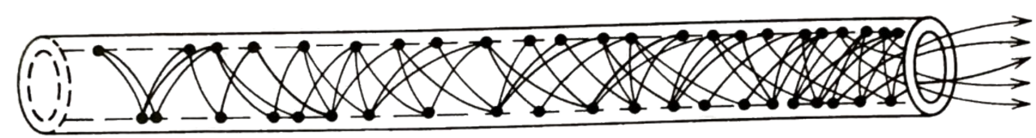
TOP Readout: Requirements

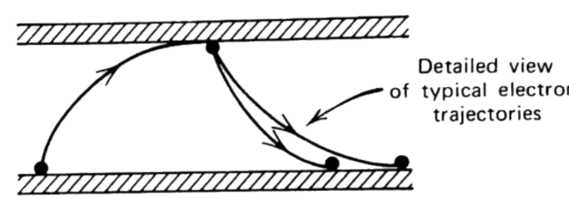
- Goal: <100ps single optical photon time resolution
- Sensor requirements:
  - single photon efficiency
  - <50ps single photon time resolution
  - ~few mm spatial resolution
  - Operation in 1.5T B-field
- Electronics requirements:
  - 30kHz trigger rate
  - <50ps electronics time resolution
  - <30ps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

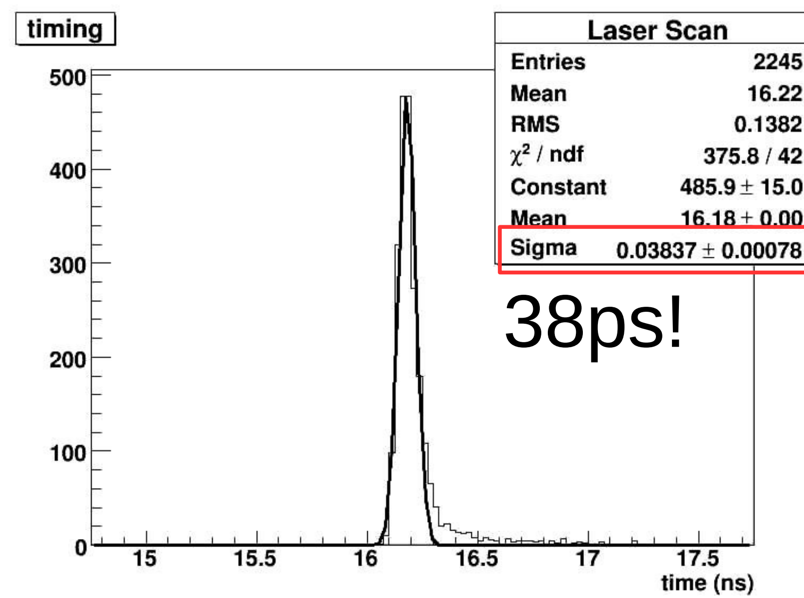






Hamamatsu MCP-PMTs

- 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

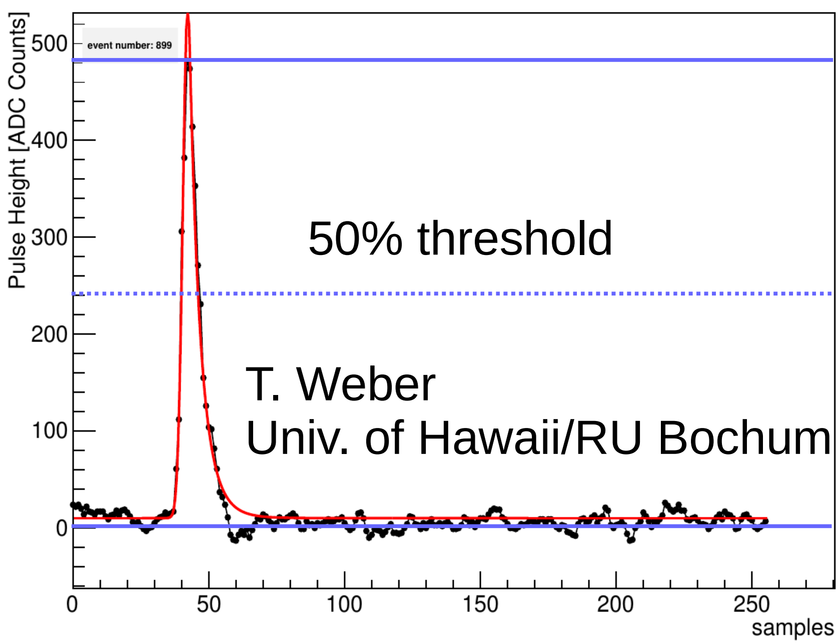
isar@naluscientific.com

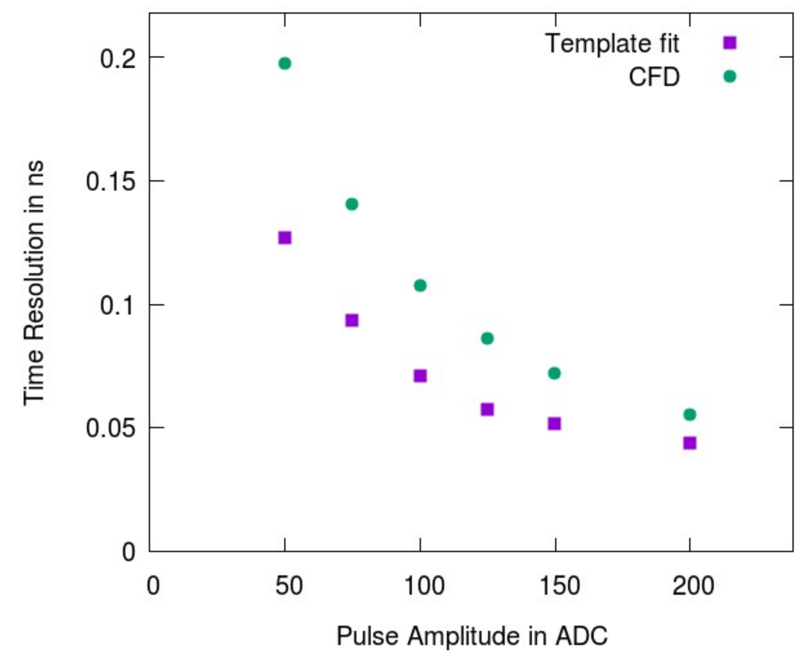
Online Data Reduction

- 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

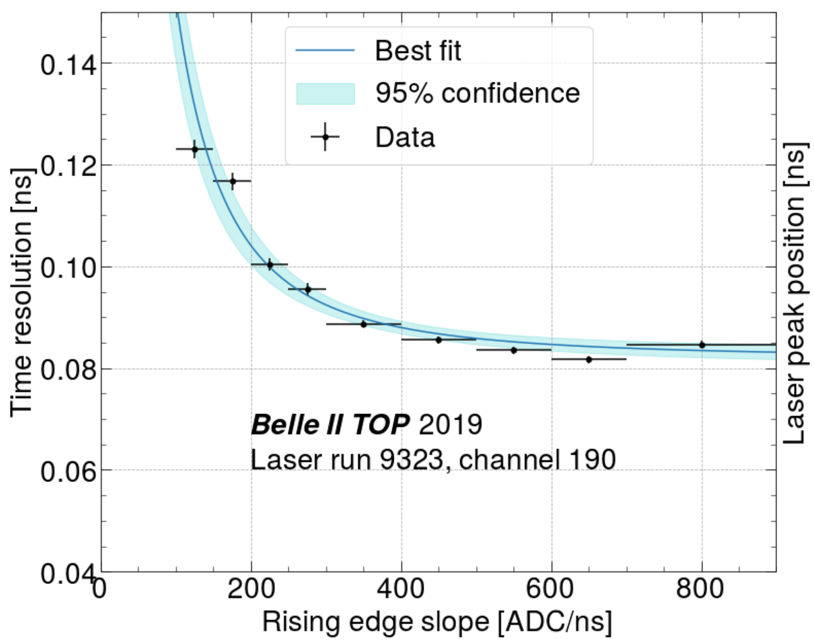
- Constant fraction discrimination
- Template fit to photon pulses
  - Computationally complex, possible on Zynq DSPs?
  - but only needed for low amplitude hits

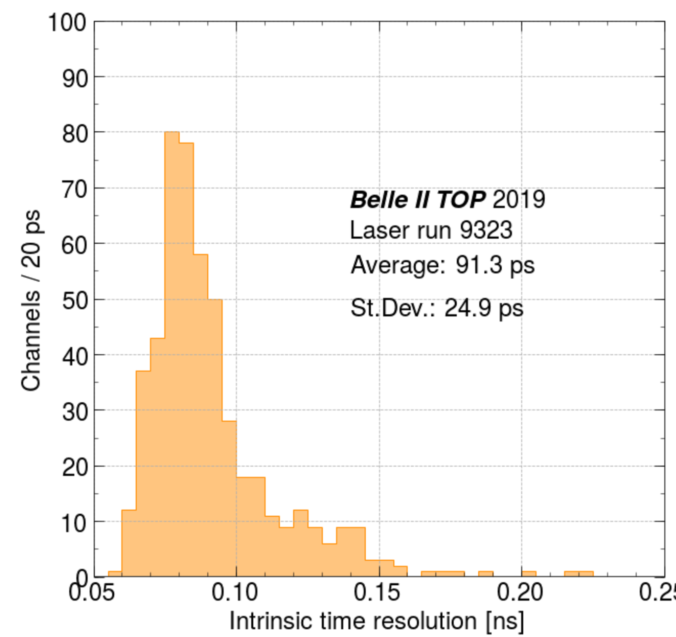




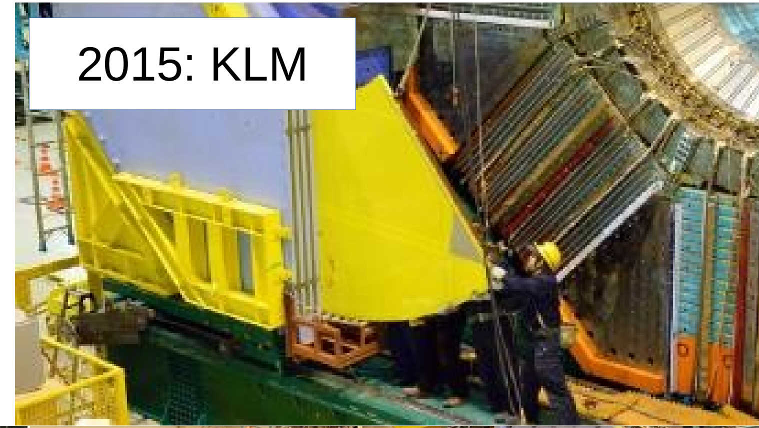
Single Photon Time Resolution

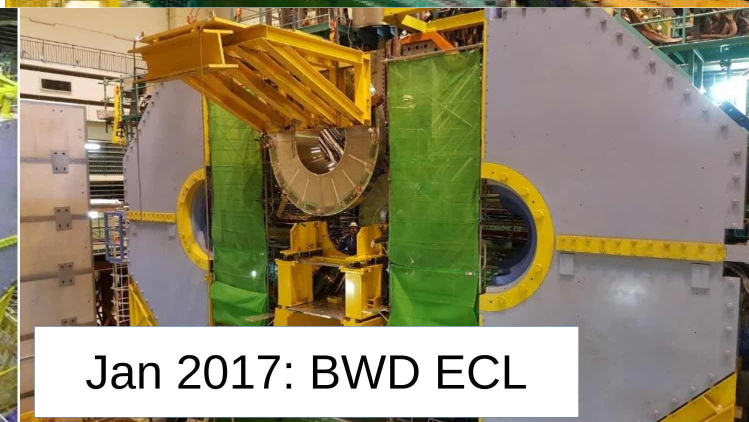
- Intrinsic resolution <100ps on most channels
  - Laser jitter, pulser reference included (but small)
- Dominated by electronic noise in signal chain due to PMT operation at low gain



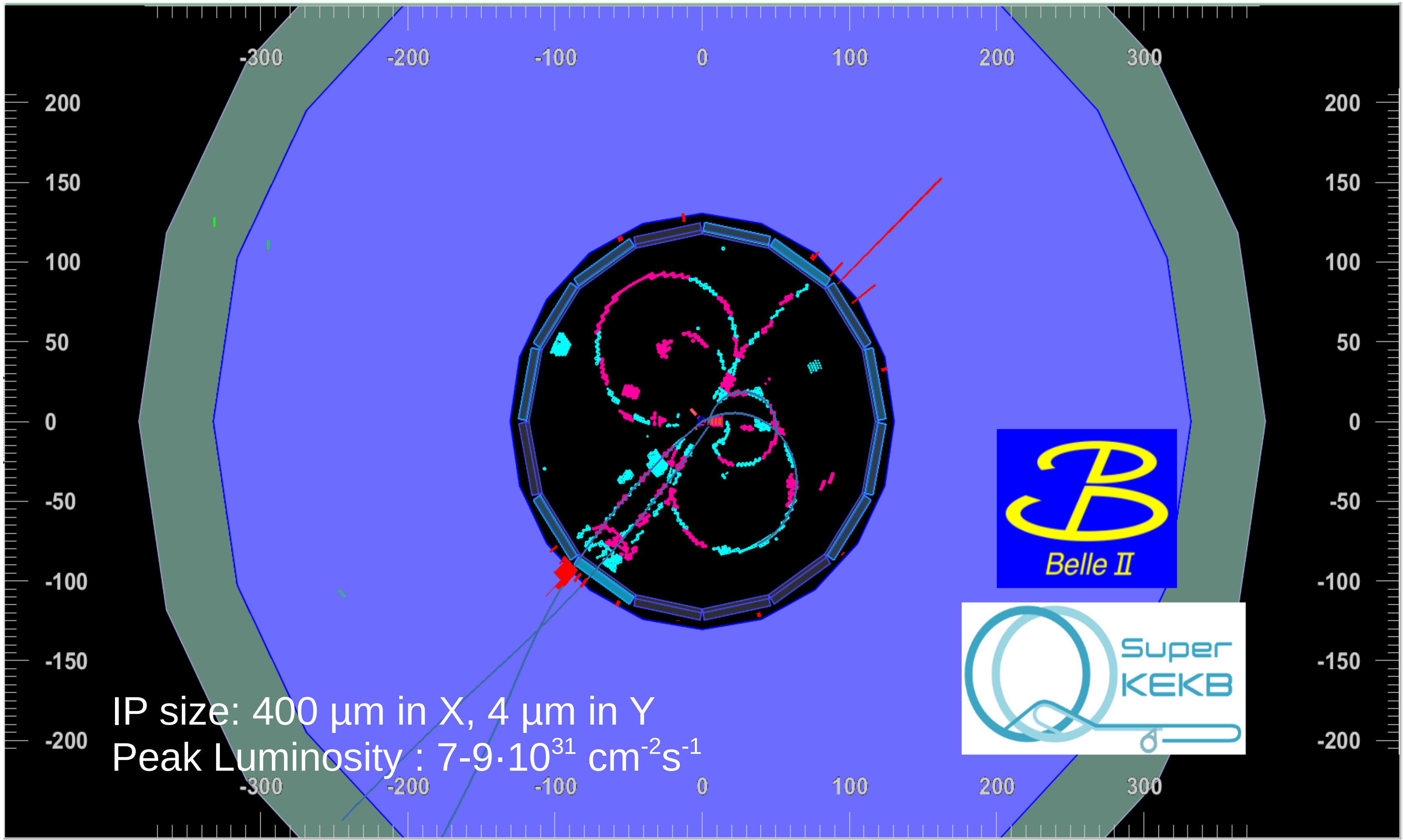


Belle II Installation





First Collision in Belle II - 04/26/2018

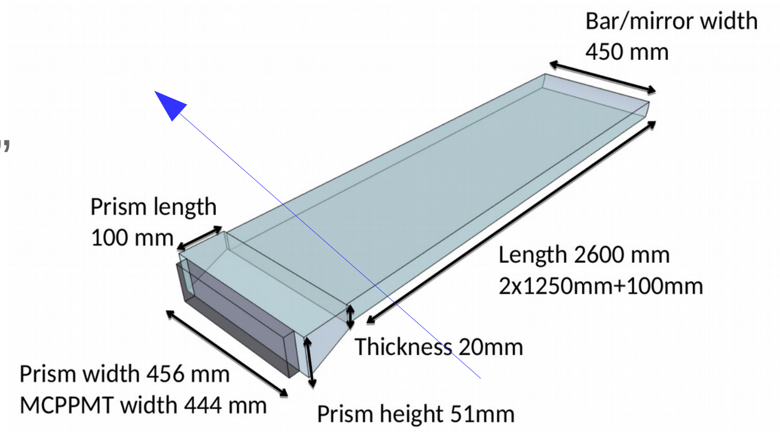


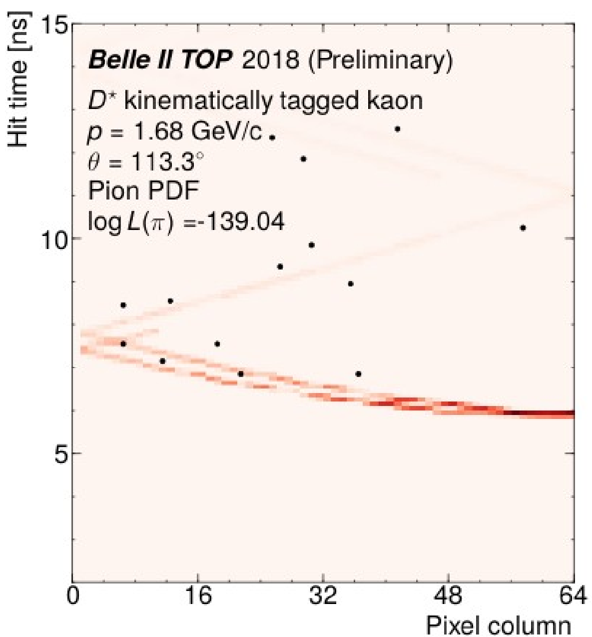
Probably $e+e- \to \gamma^* \to q\bar{q}$

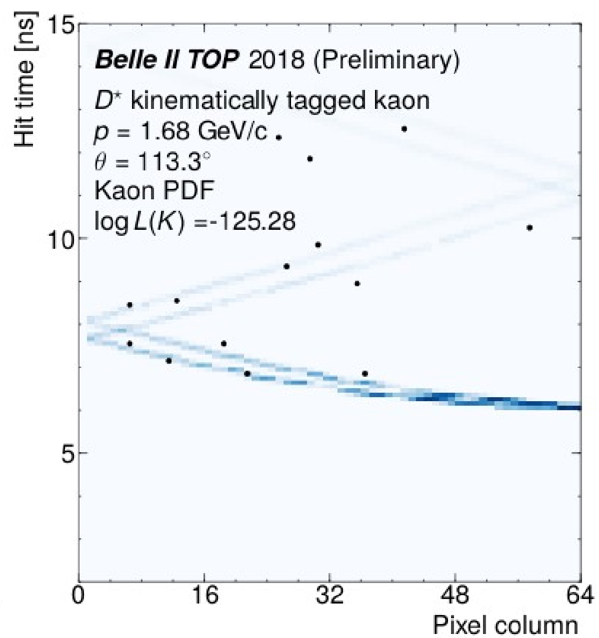
… and the Reaction

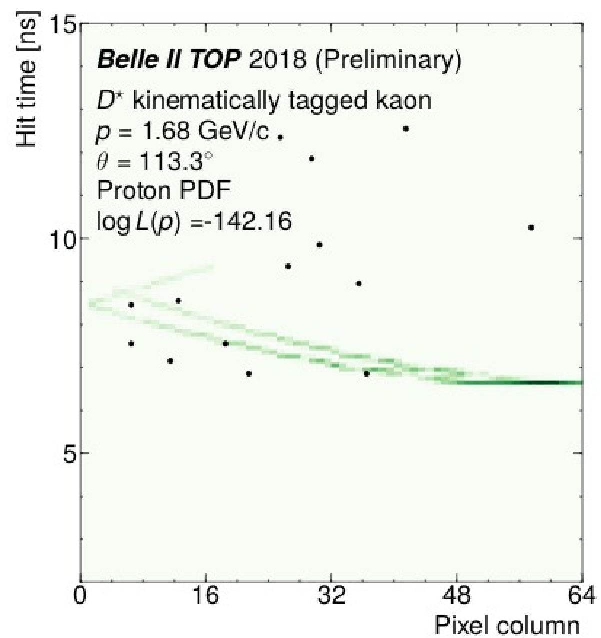
TOP "Cherenkov Rings" I

- $D^{*+} \rightarrow D^0 \pi_s^+ ; D^0 \rightarrow K^- \pi^+$ "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



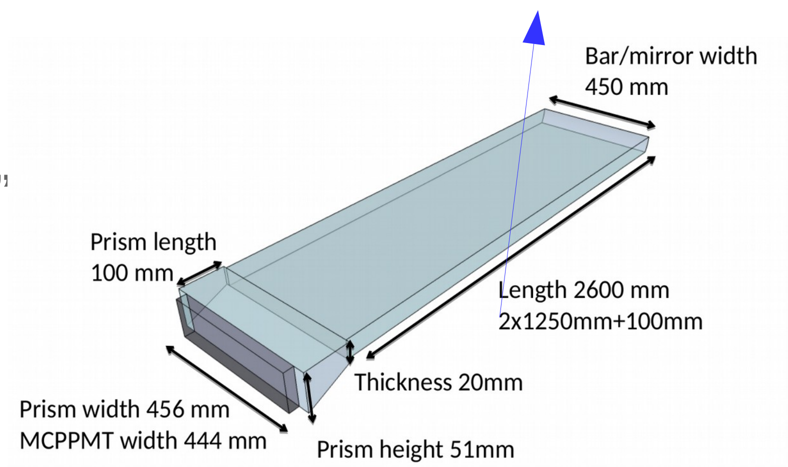


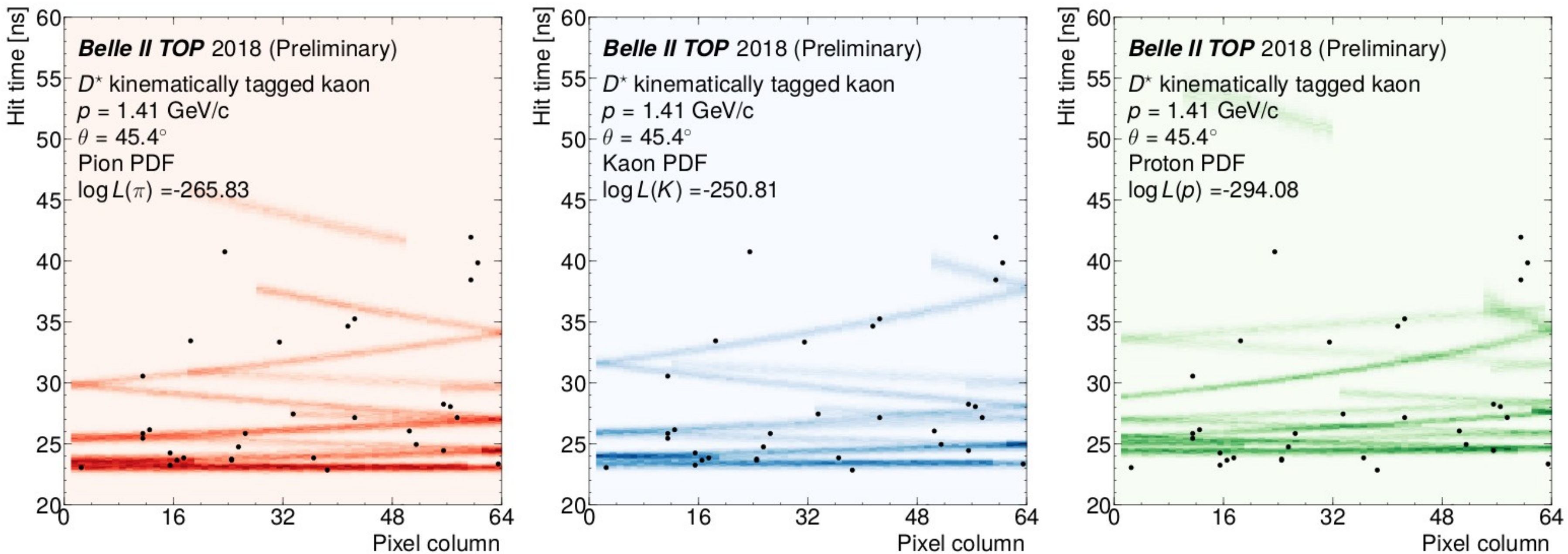




TOP "Cherenkov Rings" II

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

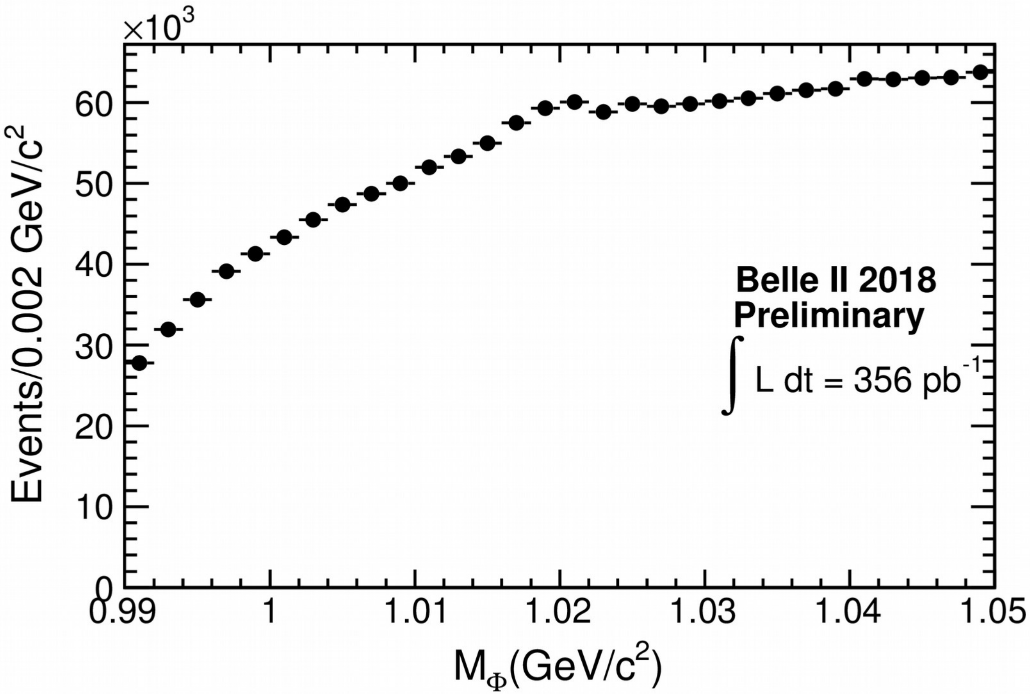




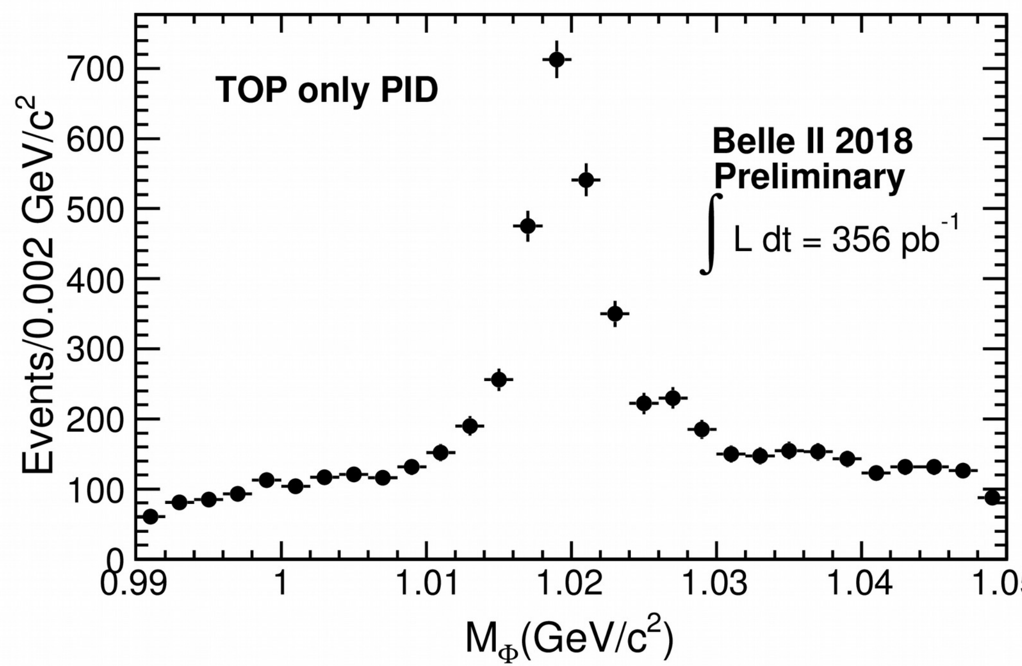
TOP PID Peformance: K-π Separation I

$\phi \rightarrow K^+K^-$ with both the tracks in the TOP acceptance

No PID

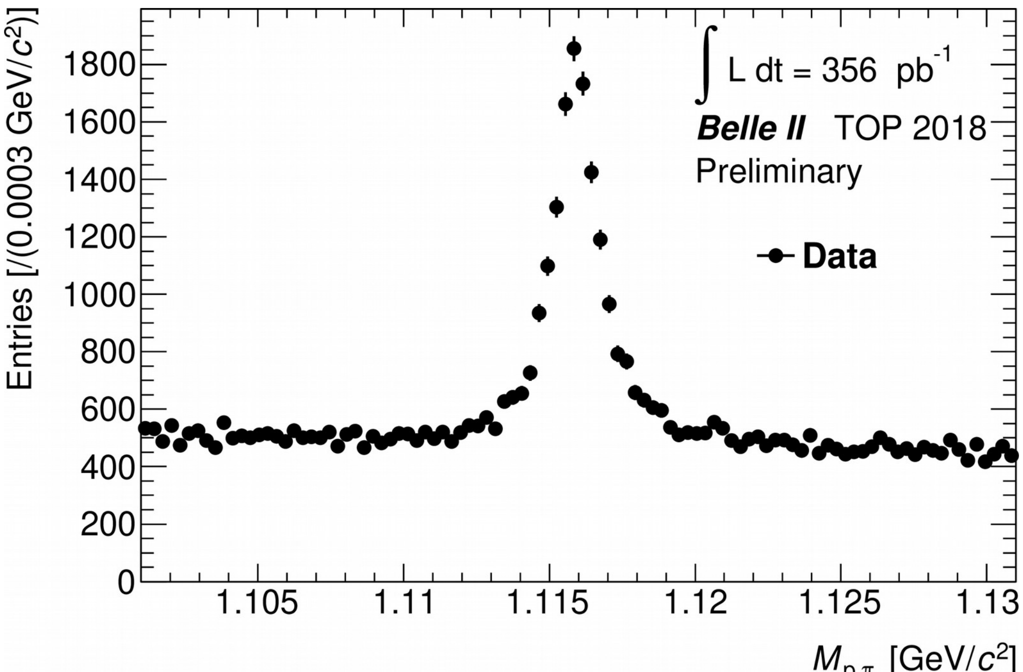


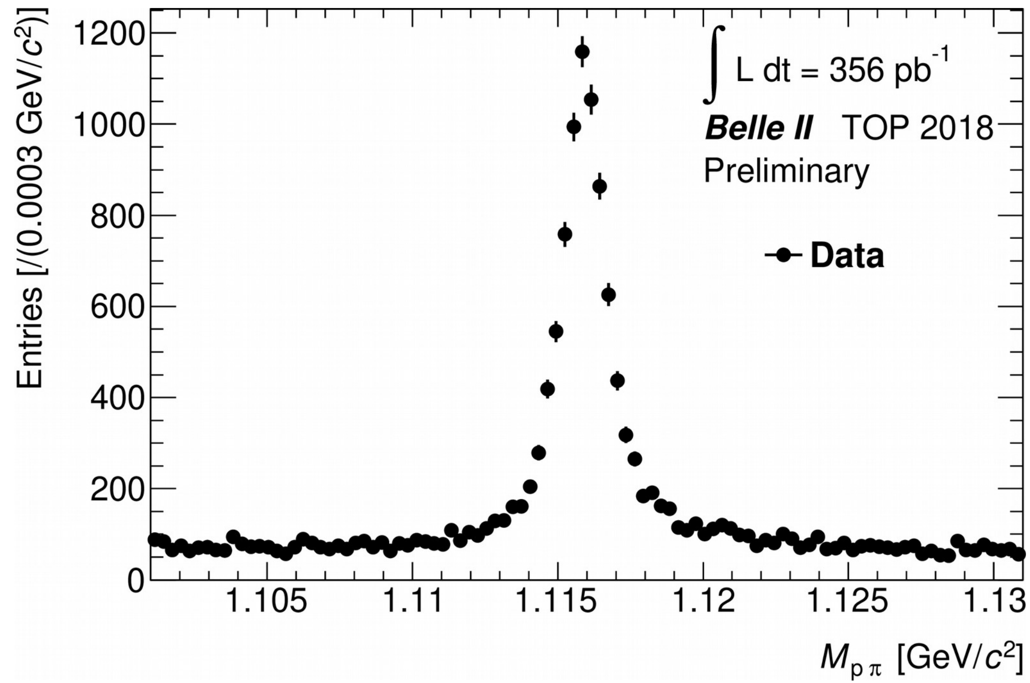
TOP LL(K) > TOP LL(π)



TOP PID Peformance: p-π Separation

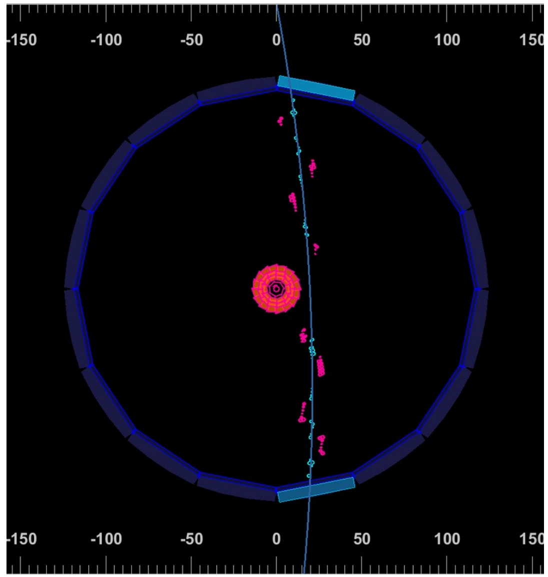
$\Lambda \to p\pi$ with the **proton candidate** in the TOP acceptance



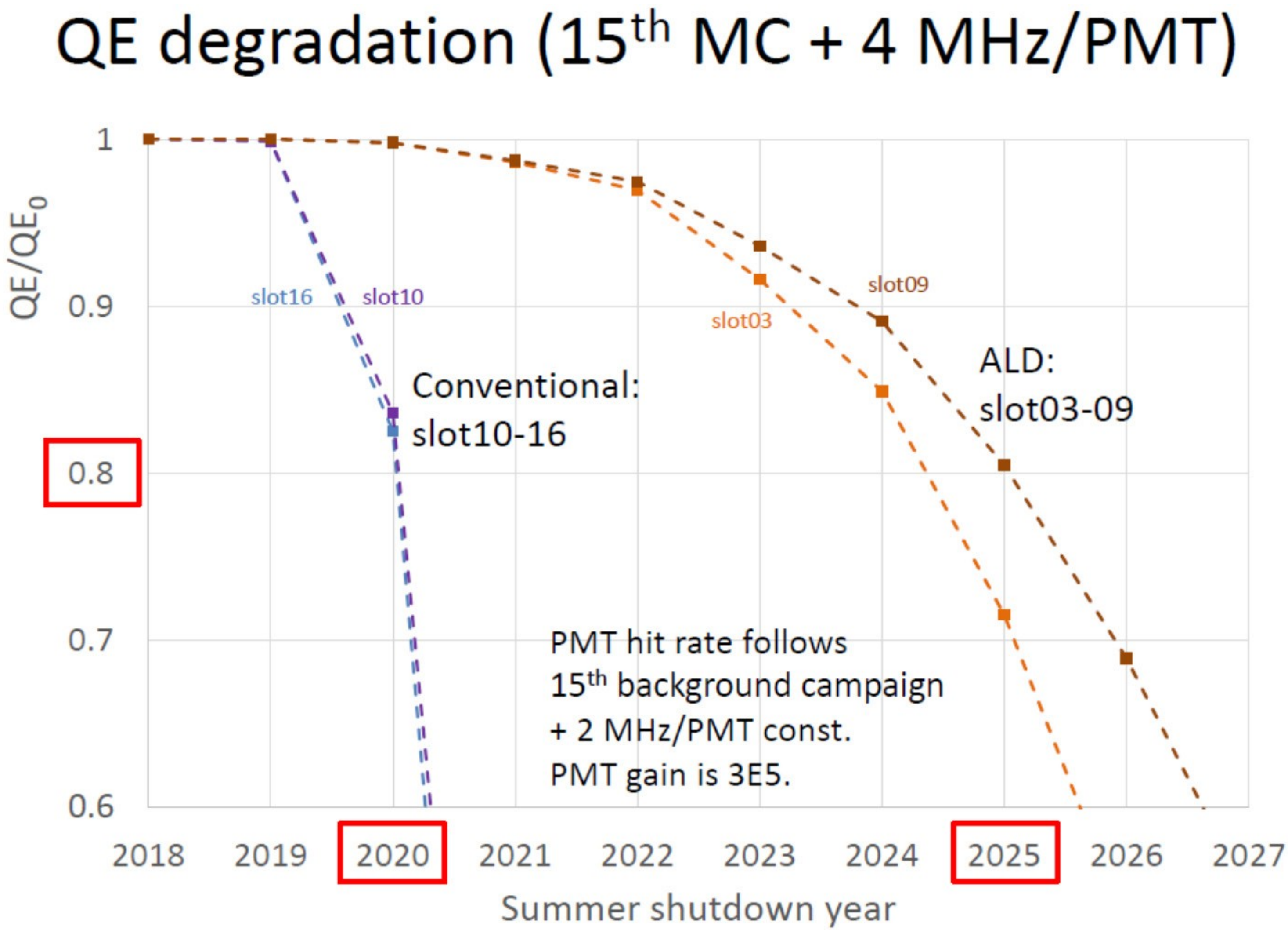


TOP Event Timing for Trigger

- Event starting time: relatively easy to fit offline, more difficult on trigger level
  - ECAL and drift chamber can give a live estimate, but resolution is ~tens of ns
  - Precise event time is important for SVD readout: 25ns frame spacing, can afford only few ns of jitter
- 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 geometry available)
  - Full FPGA implementation
  - Estimated to produce <3ns T0 resolution (eventually)
  - Infrastructure is set up, successfully used TOP timing for cosmics trigger



PMT Degradation and Replacement Plans

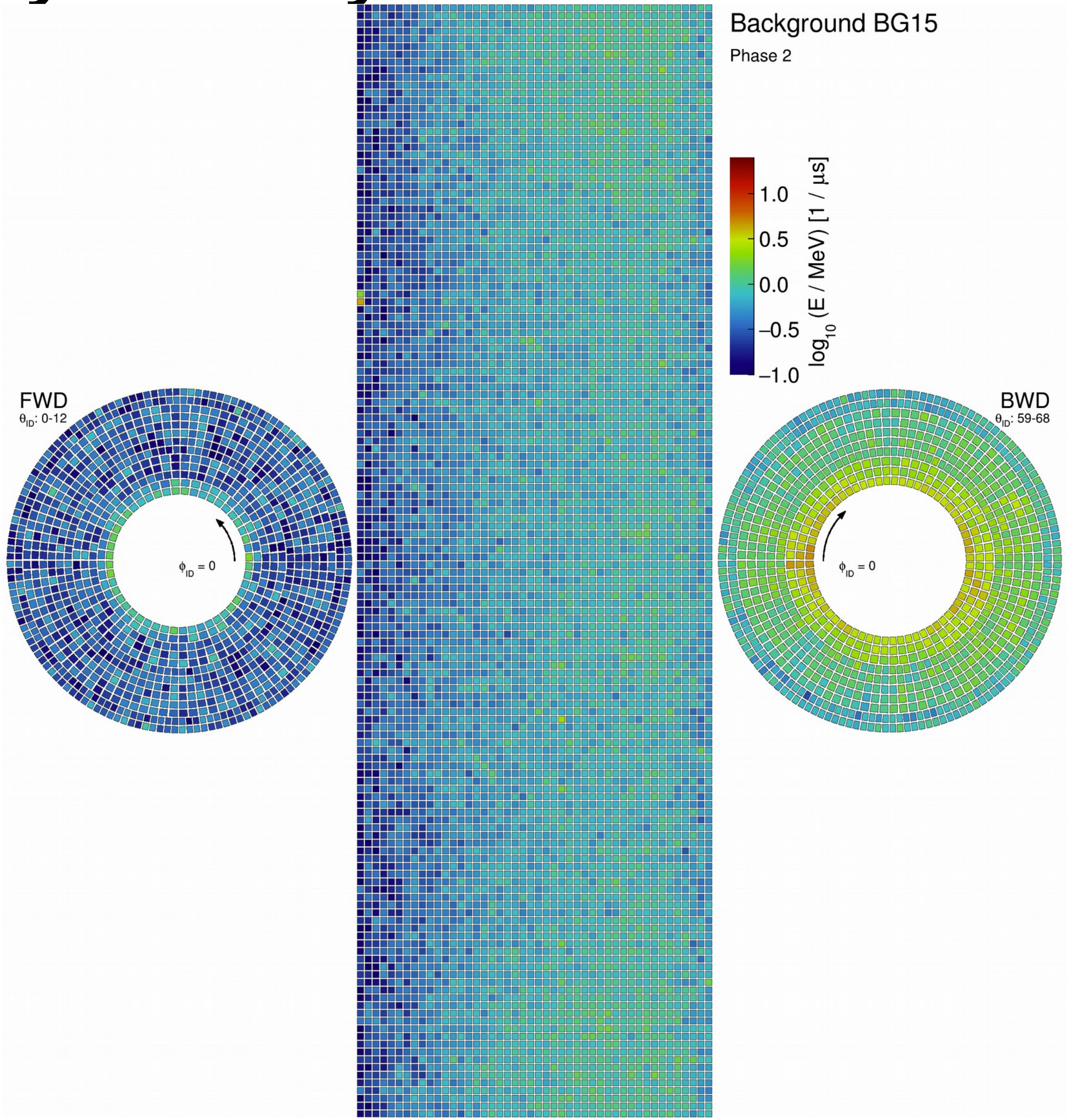


Summary

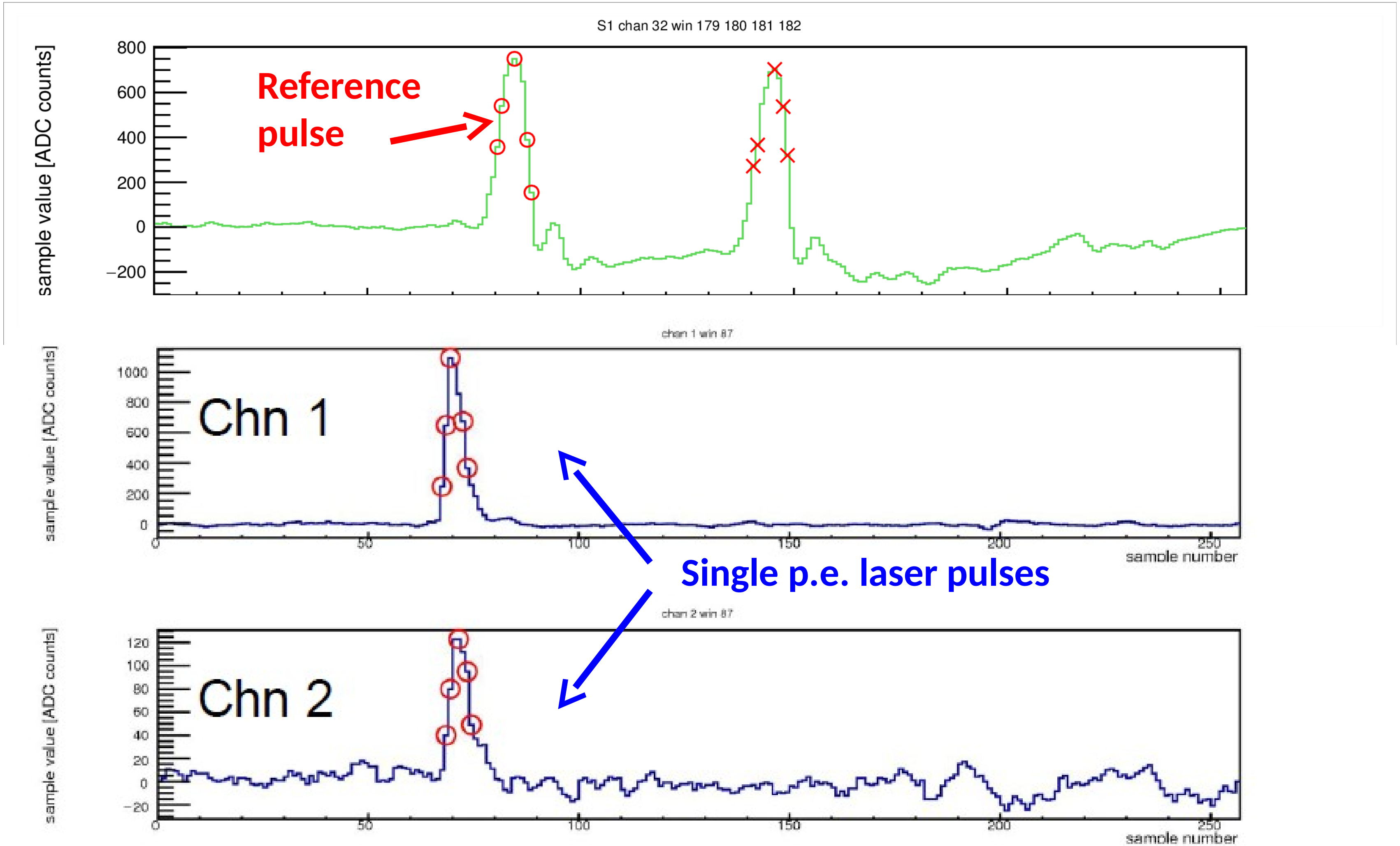
- Belle II has successfully started its first physics run period earlier this year

- 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

Radial Asymmetry

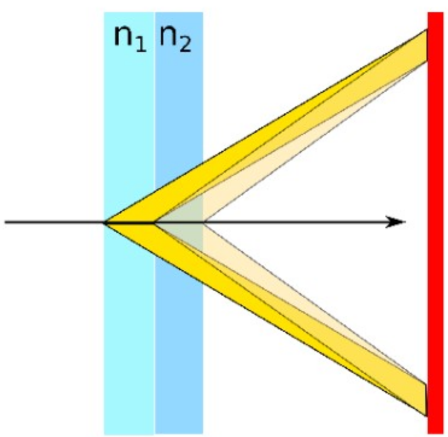


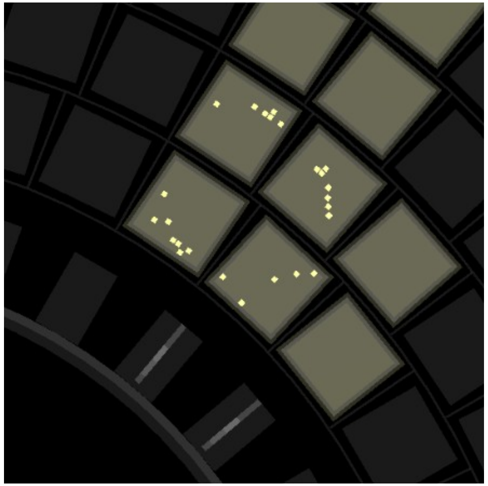
Feature Extraction Implementation Status

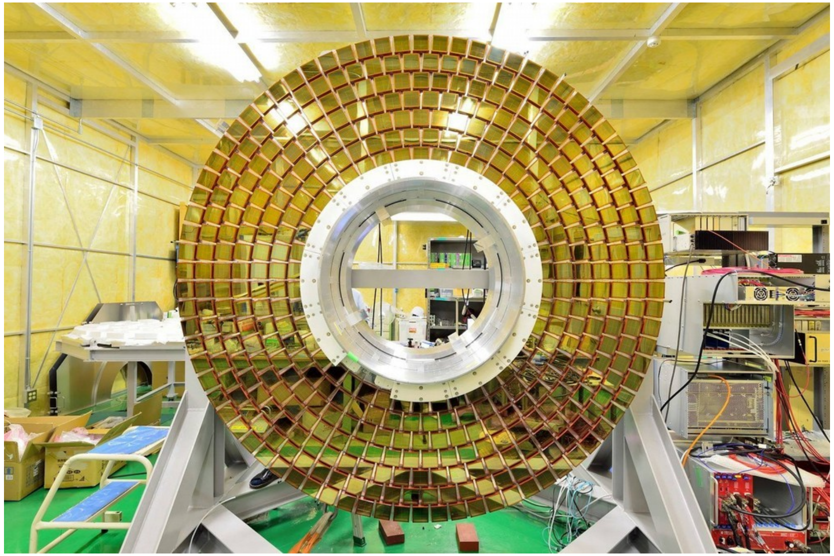


Endcap Particle ID: ARICH

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



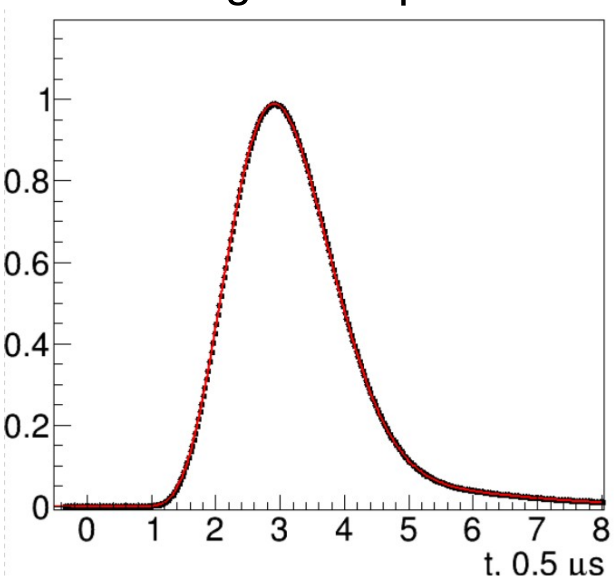




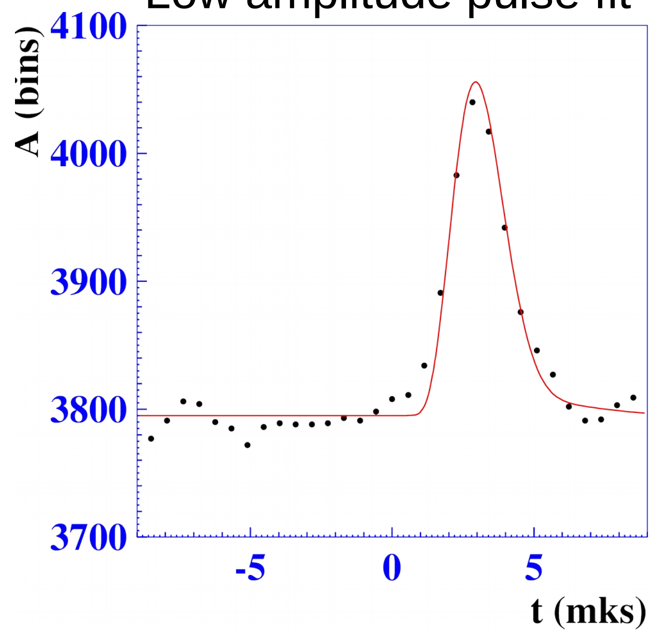
Feature Extraction in ECL

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

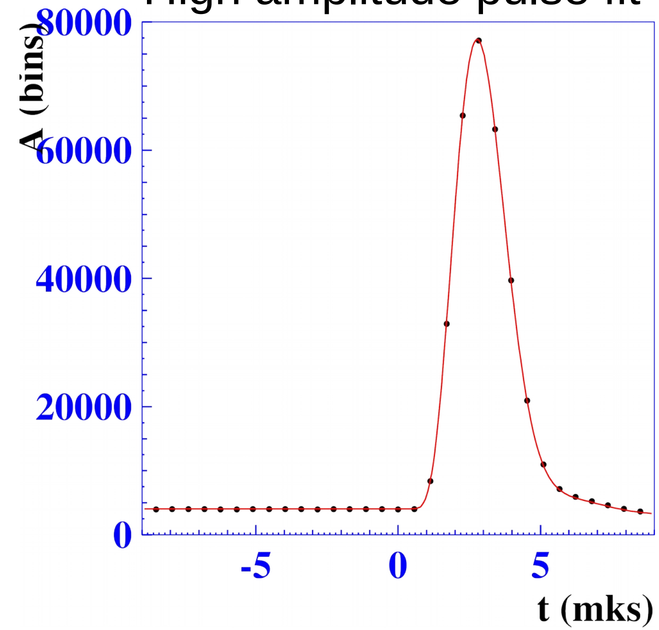
Averaged template



Low amplitude pulse fit

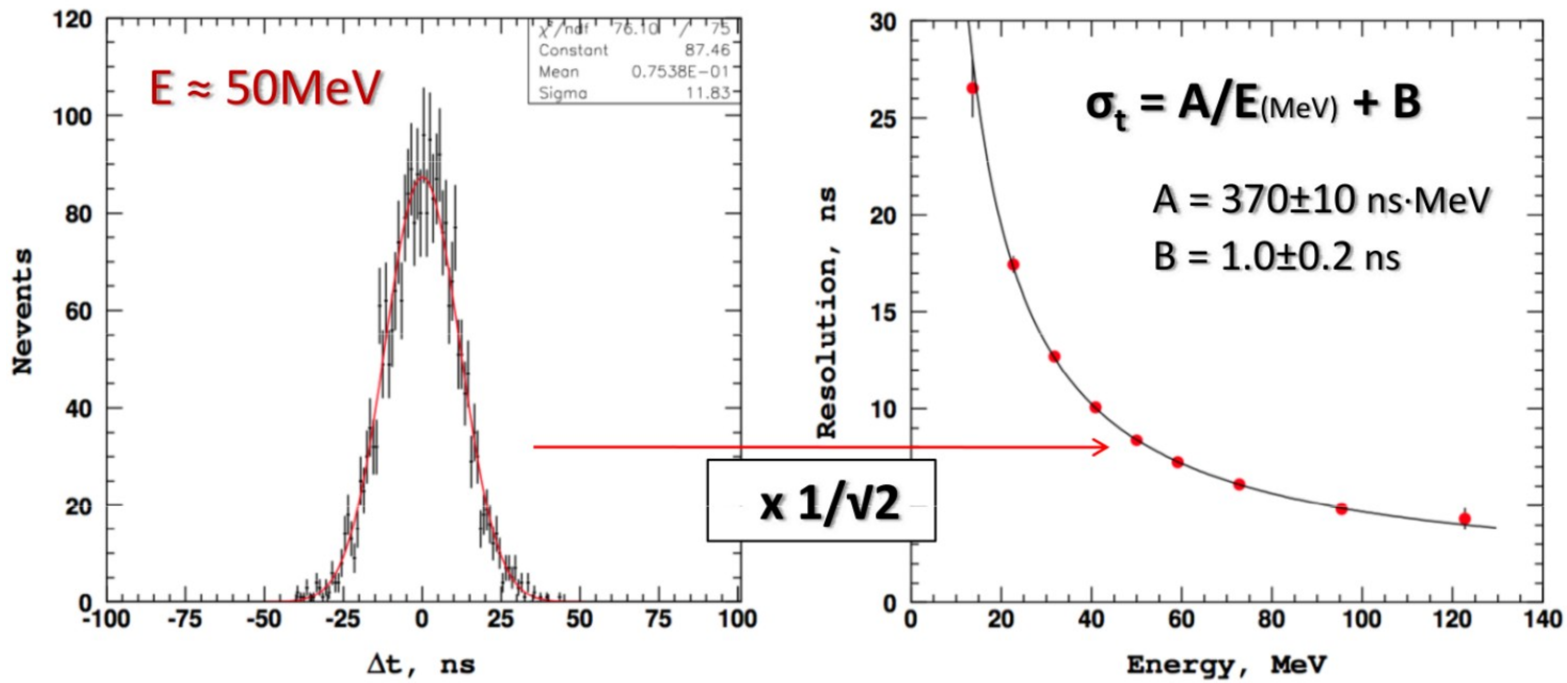


High amplitude pulse fit



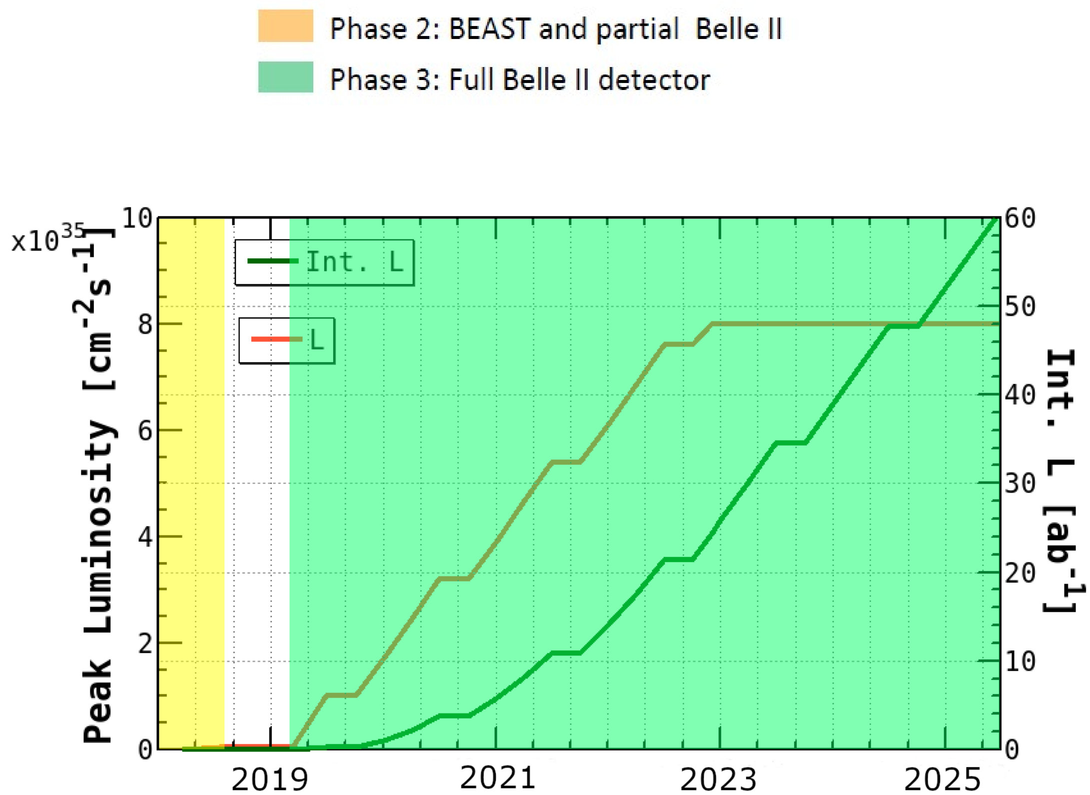
Feature Extraction in ECL

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



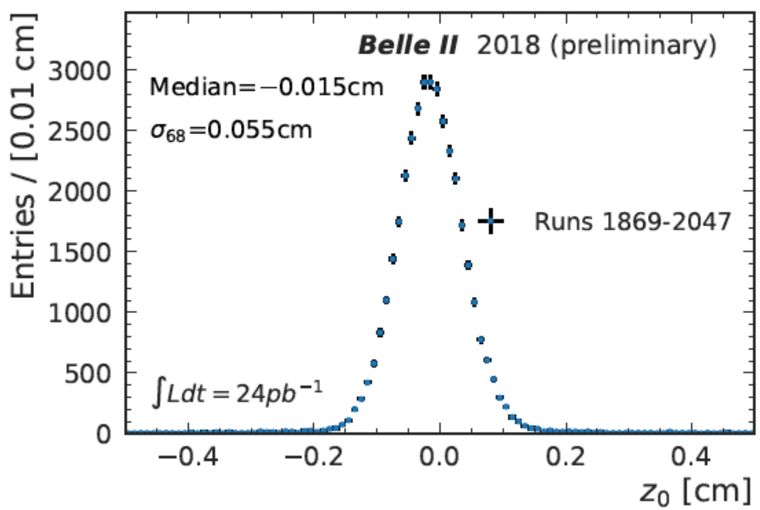
SuperKEKB + Belle II Commissioning

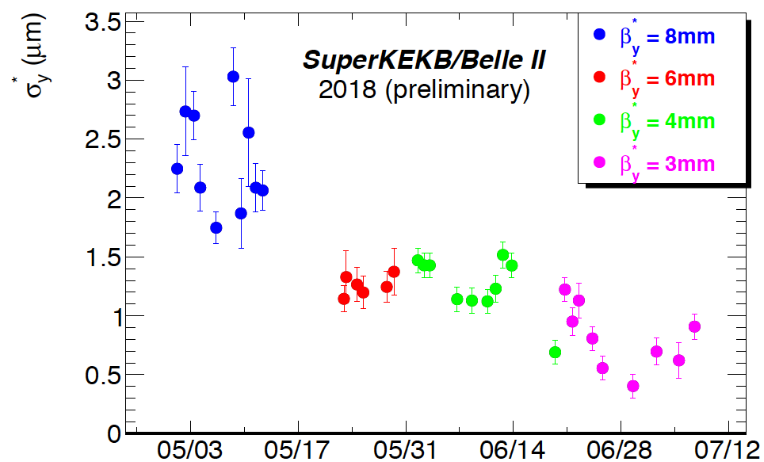
- Phase 1: Operation without Belle II and without final focus system
  - Completed in June 2016
- Phase2: Start data taking with first collisions
  - Full outer Belle II detector
  - BEAST beam background detector instead of inner tracking, contains one ladder each of strip and pixel detectors
  - Luminosity goal ~1x10^{34} cm^{-2} s^{-1}
  - Completed in July 2018
- Phase3: Full Belle II operation
  - Final detector configuration
  - Luminosity goal ~8x10^{35} cm^{-2} s^{-1}
  - Starting Spring 2019



SuperKEKB Phase 2 Beam Size

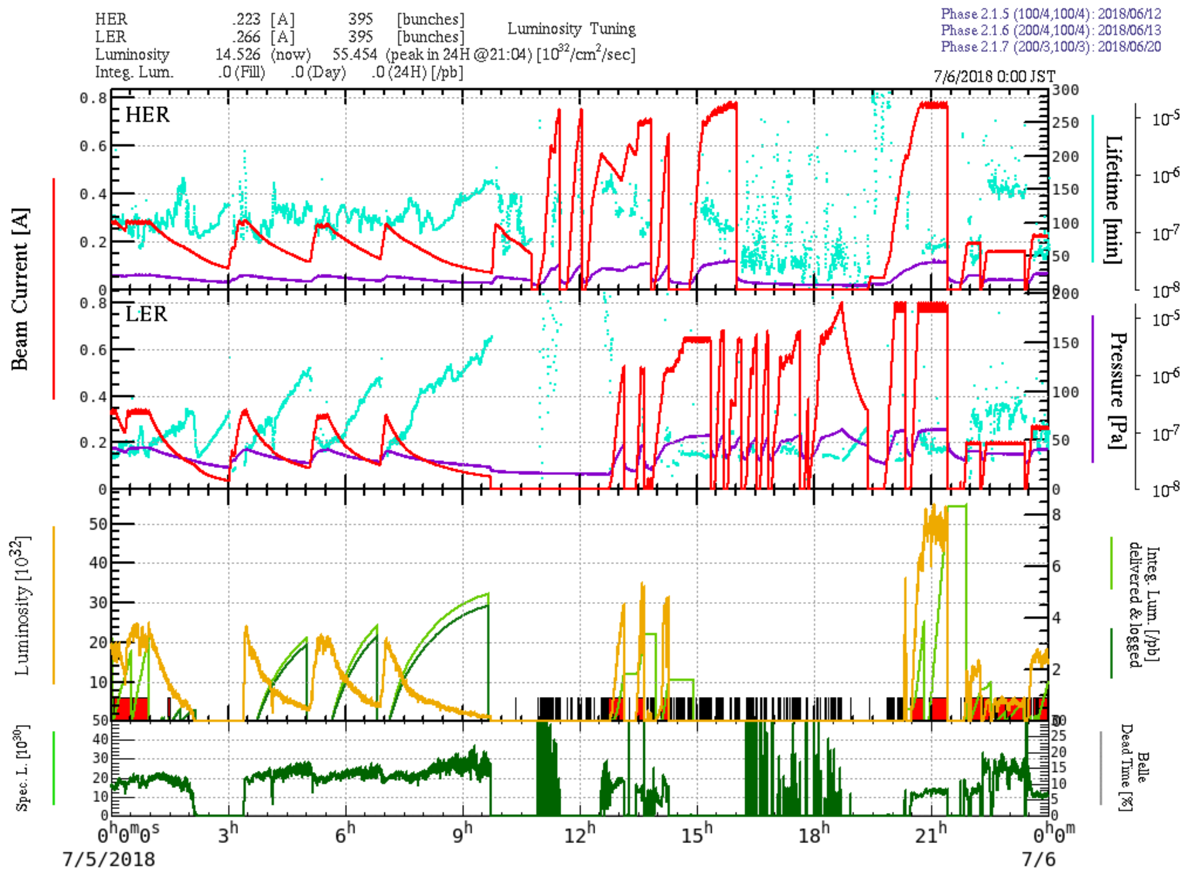
- Effective bunch length is **0.5mm**! (x20 smaller than KEKB)
  - Measured by Belle II using two track events
- Vertical beam spot size down to 330nm
  - Some beam-beam blowup observed at higher currents, increases up to ~700nm
  - Will decrease by another order of magnitude with focus tuning





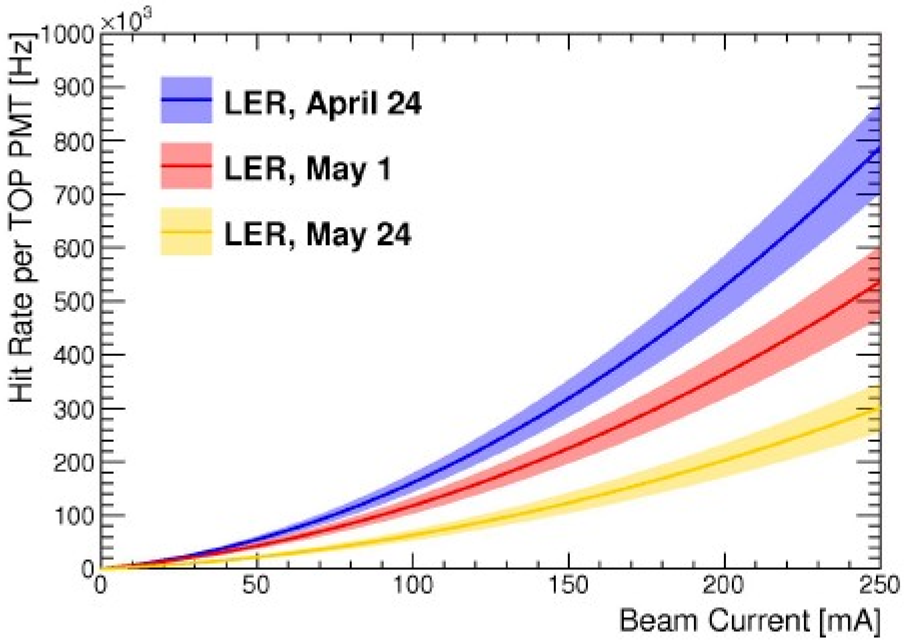
SuperKEKB Phase 2 Luminosity

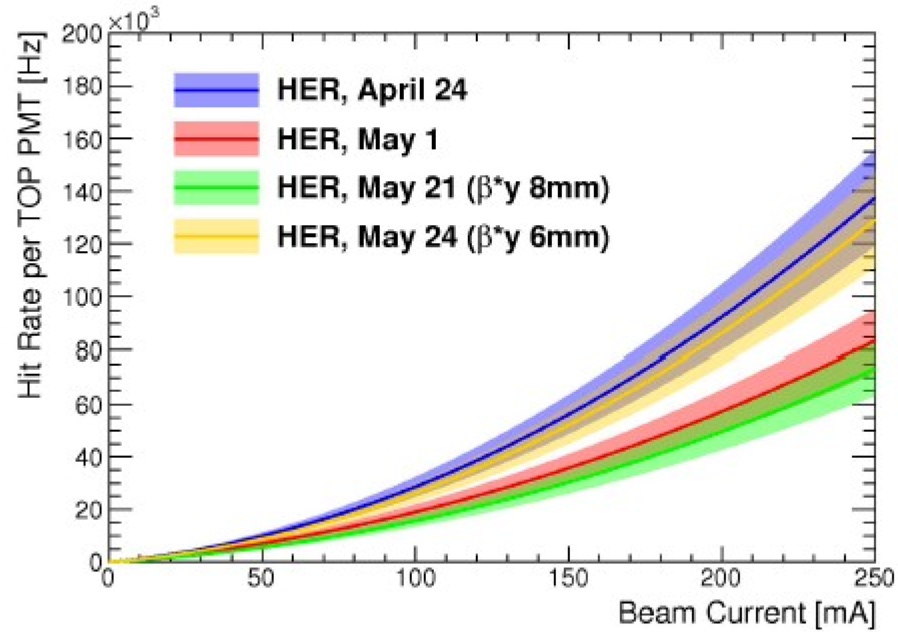
- Up to ~5.5×10^{33} cm^{-2} s^{-1}, 500 pb^{-1} recorded in Phase 2
  - Focus on machine and detector commissioning



SuperKEKB Phase 2 Beam Backgrounds

- Measured beam backgrounds x5-100 higher than simulated
- Major concern for various subdetectors
  - TOP PMTs will not survive long at these background levels
  - CDC HV sometimes hit its current limit already

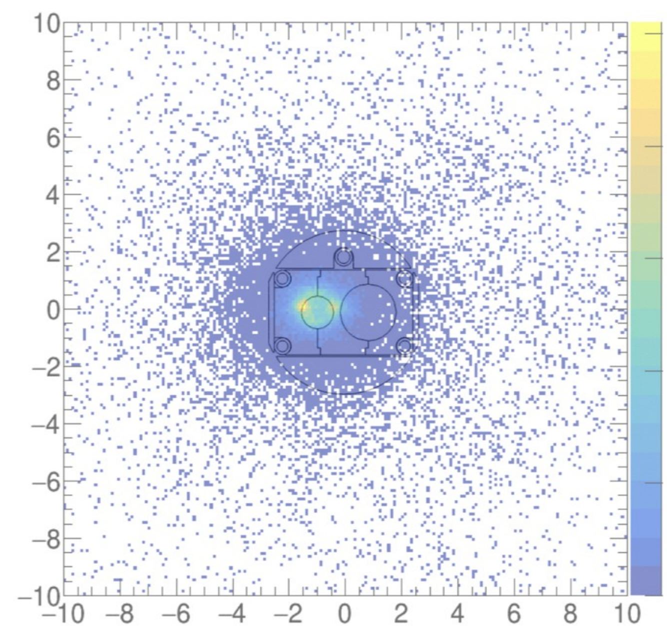




SuperKEKB Phase 3 Beam Backgrounds

- Fear not! More dedicated study time at the start of Phase 3
  - Belle II is the best beam background detector
  - Background rates and levels in inner tracking were acceptable
- Additional collimators installed during shutdown
  - Collimator tuning takes time
- Possibly beam is still “scraping” the beam pipe near the IP

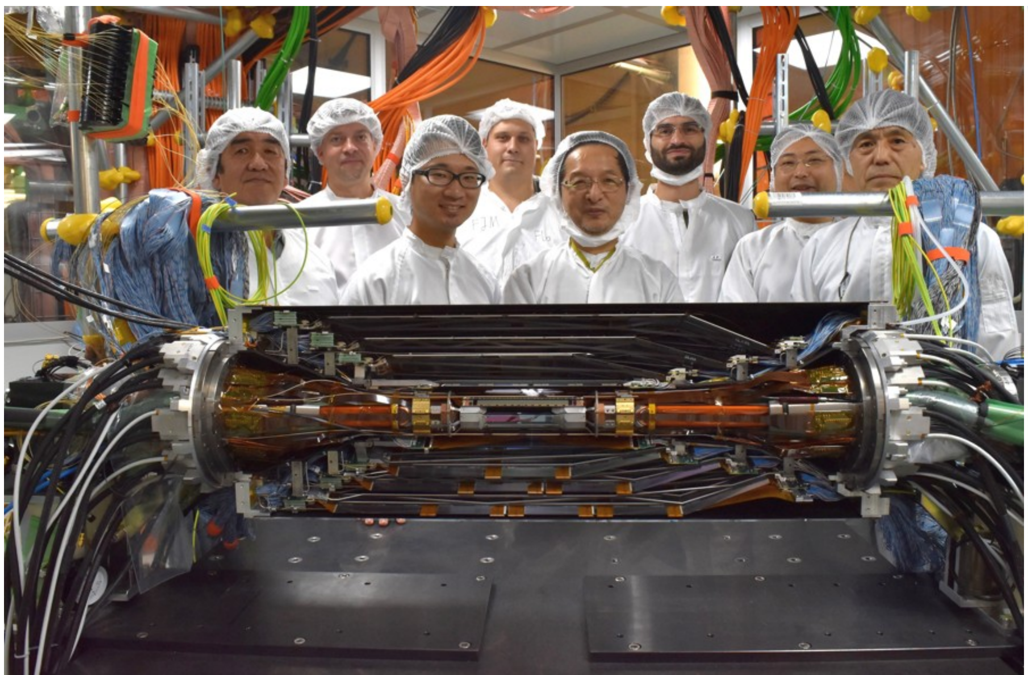
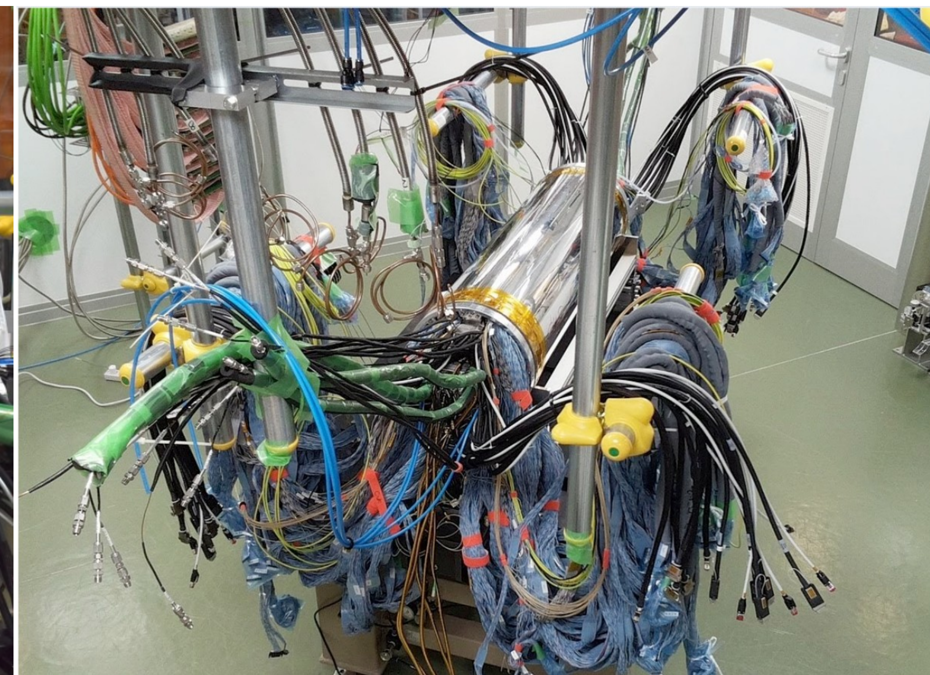
Z = -22.5cm



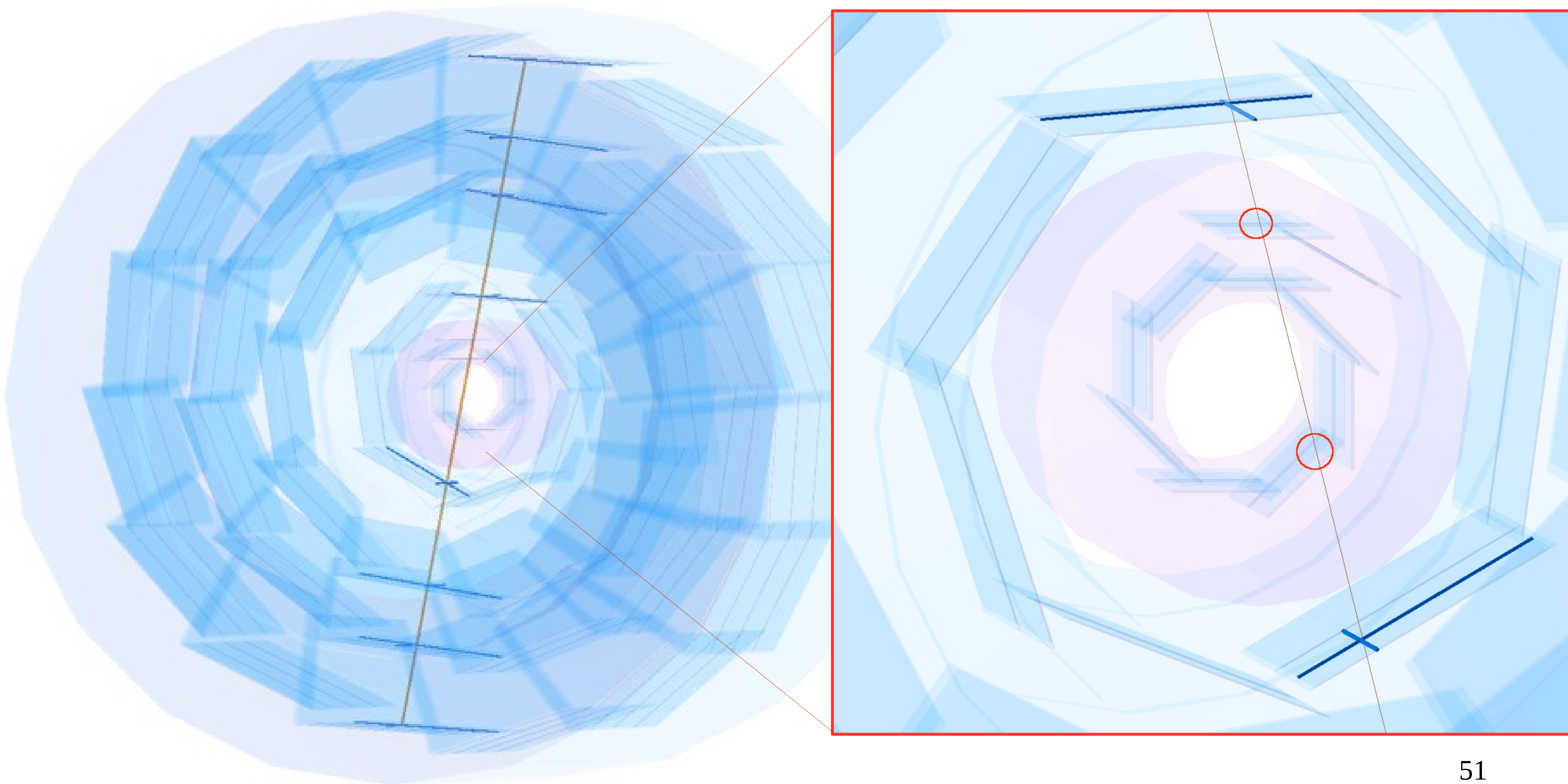
Vertex distribution in X-Y plane

Inner Tracking Status – VXD Assembled

- PXD & SVD “married” since October
  - PXD only installed L1 + 2 ladders of L2

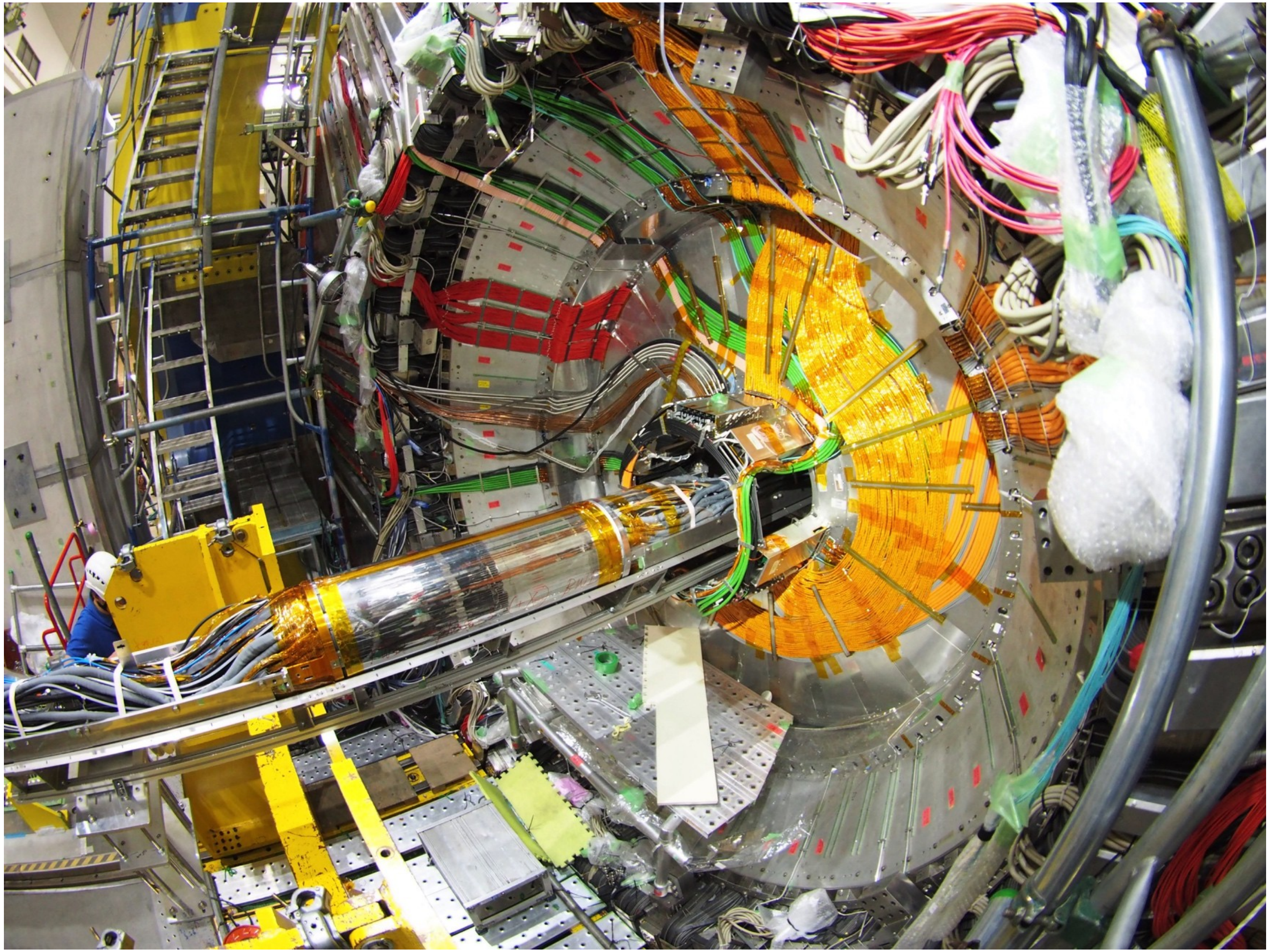



Inner Tracking Status – First Cosmics



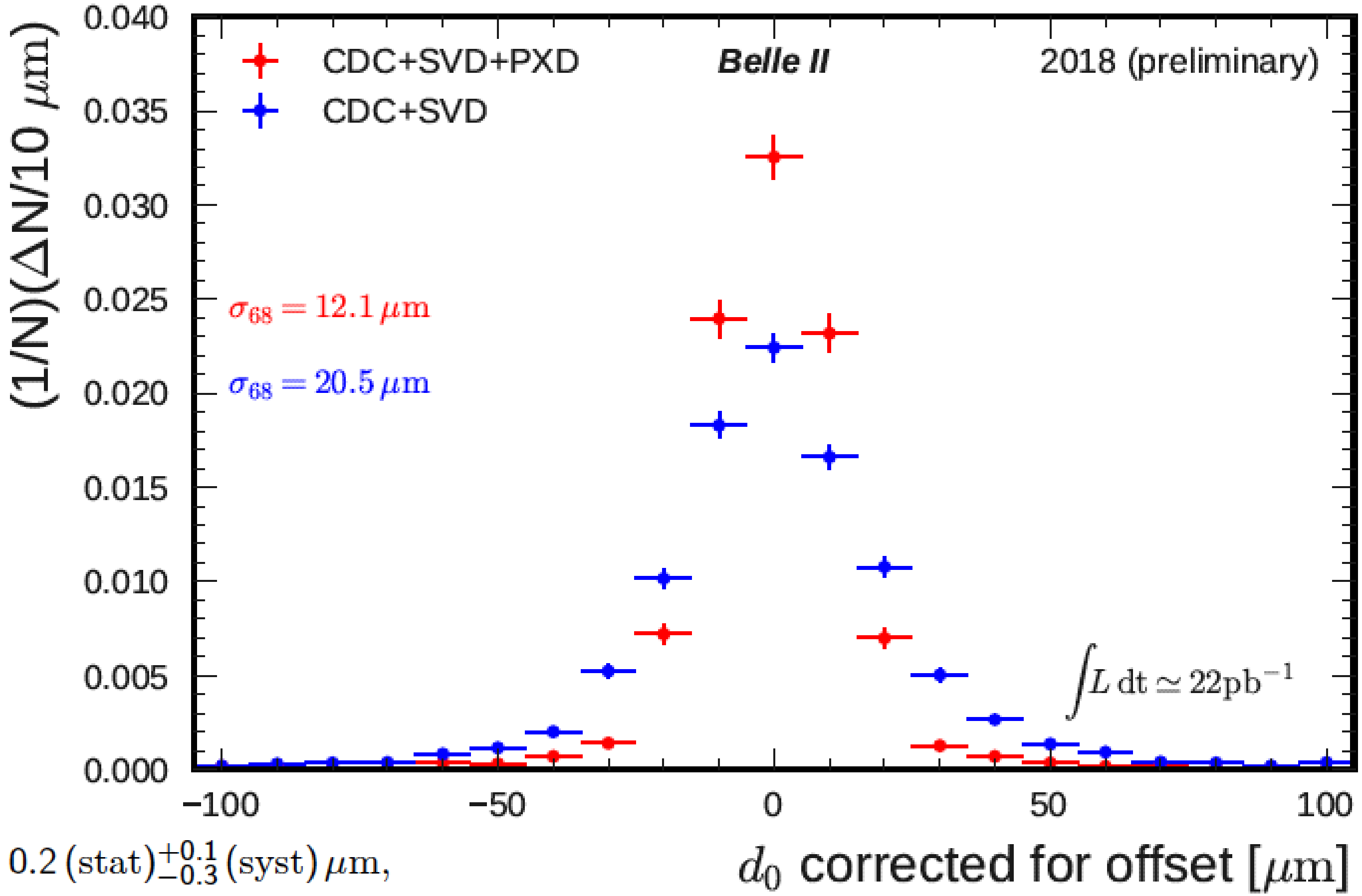
Inner Tracking Status – Installation

- Belle II VXD installed November 21st



VXD Impact Parameter Resolution

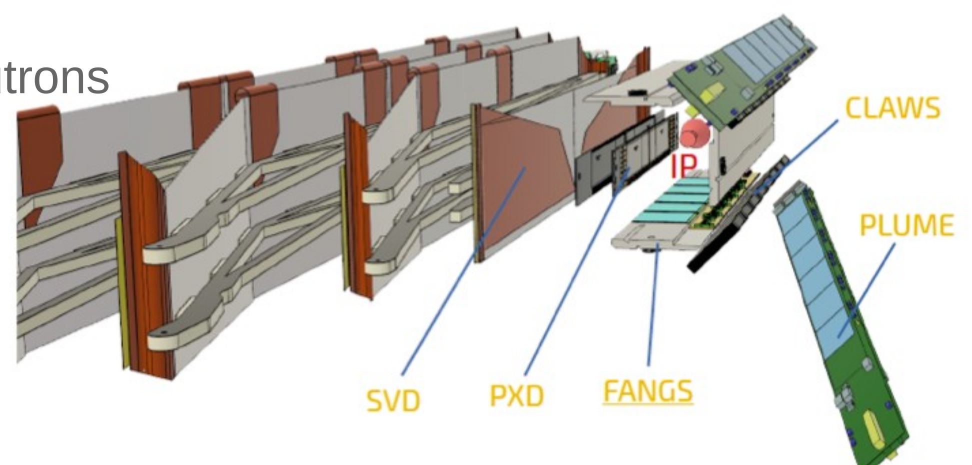
- From Phase 2 data (BEAST2 VXD layers)



$$\sigma_{68}^{\mathrm{measured}} = 12.1 \pm 0.2\,(\mathrm{stat})^{+0.1}_{-0.3}\,(\mathrm{syst})\,\mu\mathrm{m},$$
$$\sigma^{\mathrm{expected}} = 9.9 \pm 0.2\,(\mathrm{stat})\,\mu\mathrm{m}.$$

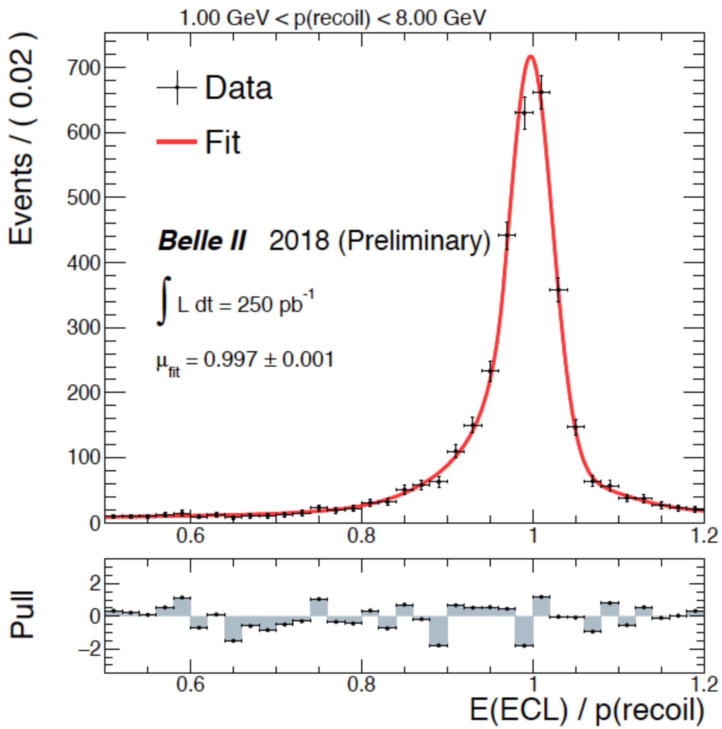
SuperKEKB Phase 2: BEAST

- Dedicated beam background detector: BEAST II instead of inner tracker
  - FANGS: ATLAS FEI4 pixels
  - CLAWS: plastic scintillators + SiPMs
  - PLUME: ILC style CMOS pixels
  - Diamond dose rate monitors
  - PiN dose rate monitors on QCS
  - 3He for thermal neutrons
  - Gas TPC for directional fast neutrons
  - One ladder of each type of PXD and SVD



Photons in Belle II

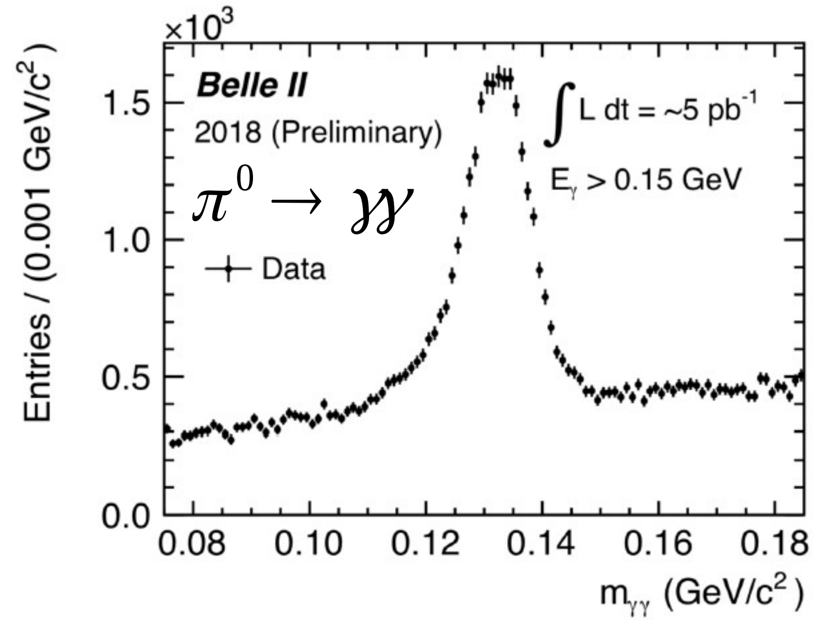
$$e^+e^- \rightarrow \mu^+\mu^-\gamma$$

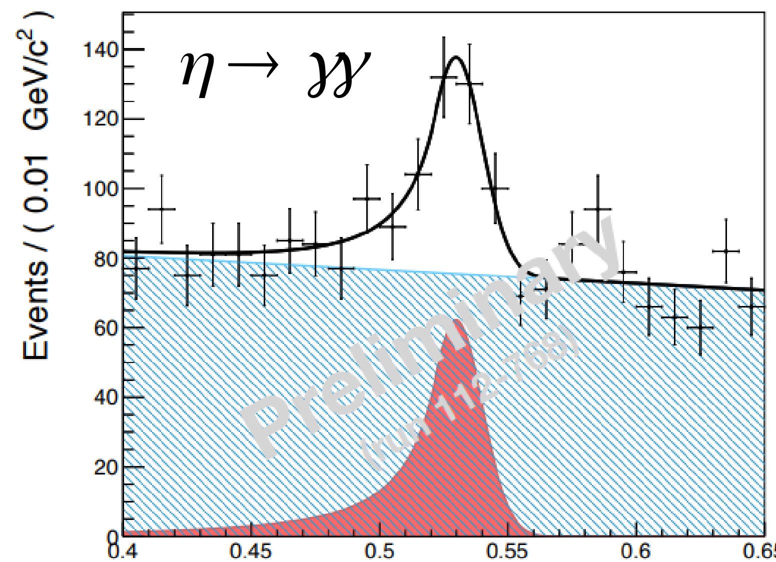


Ready for the dark sector !

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

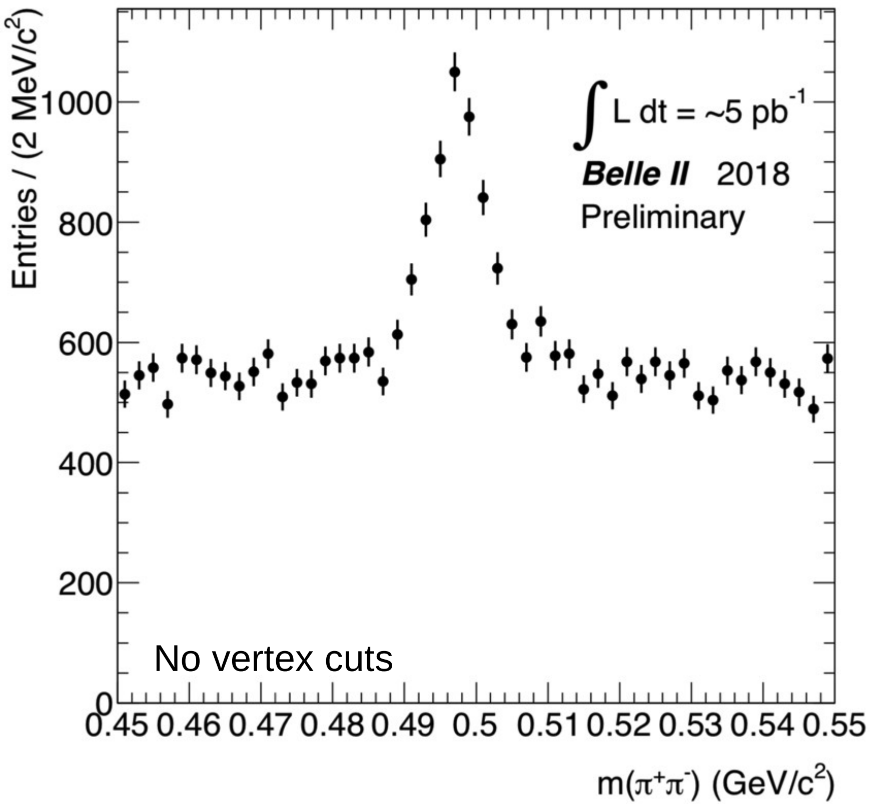
$$e^+e^- \rightarrow \gamma ALP \rightarrow \gamma(\gamma\gamma)$$



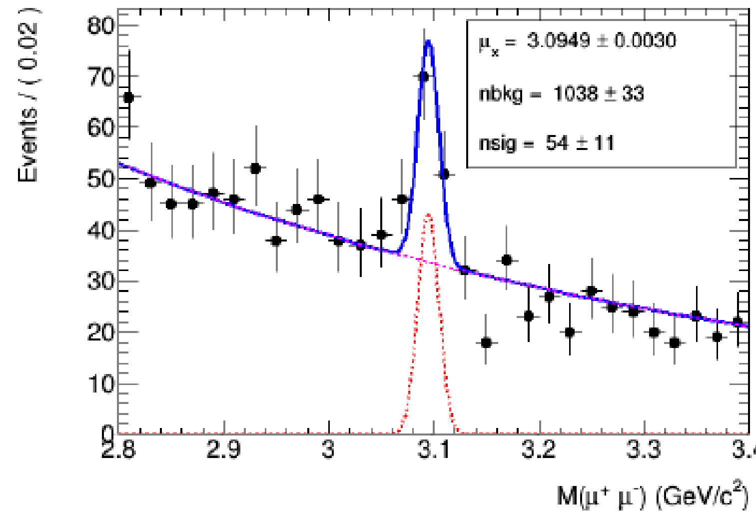


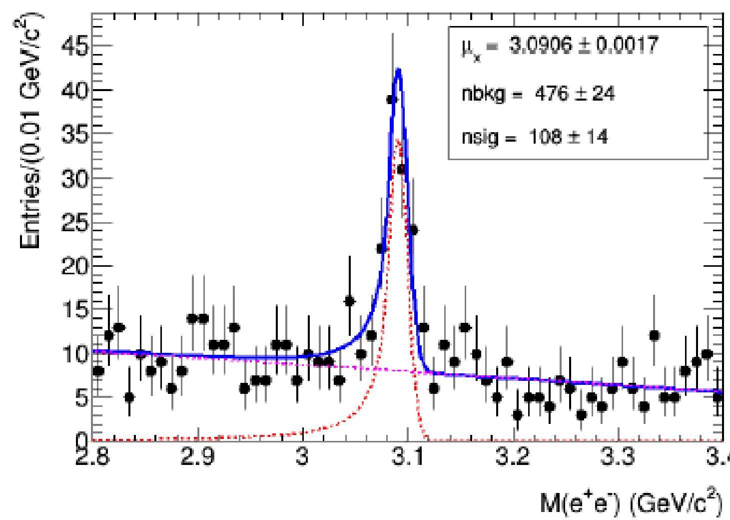
Tracks in Belle II

$K_S \to \pi^+\pi^-$



$J/\psi \to \mu^+\mu^-$, $J/\psi \to e^+e^-$

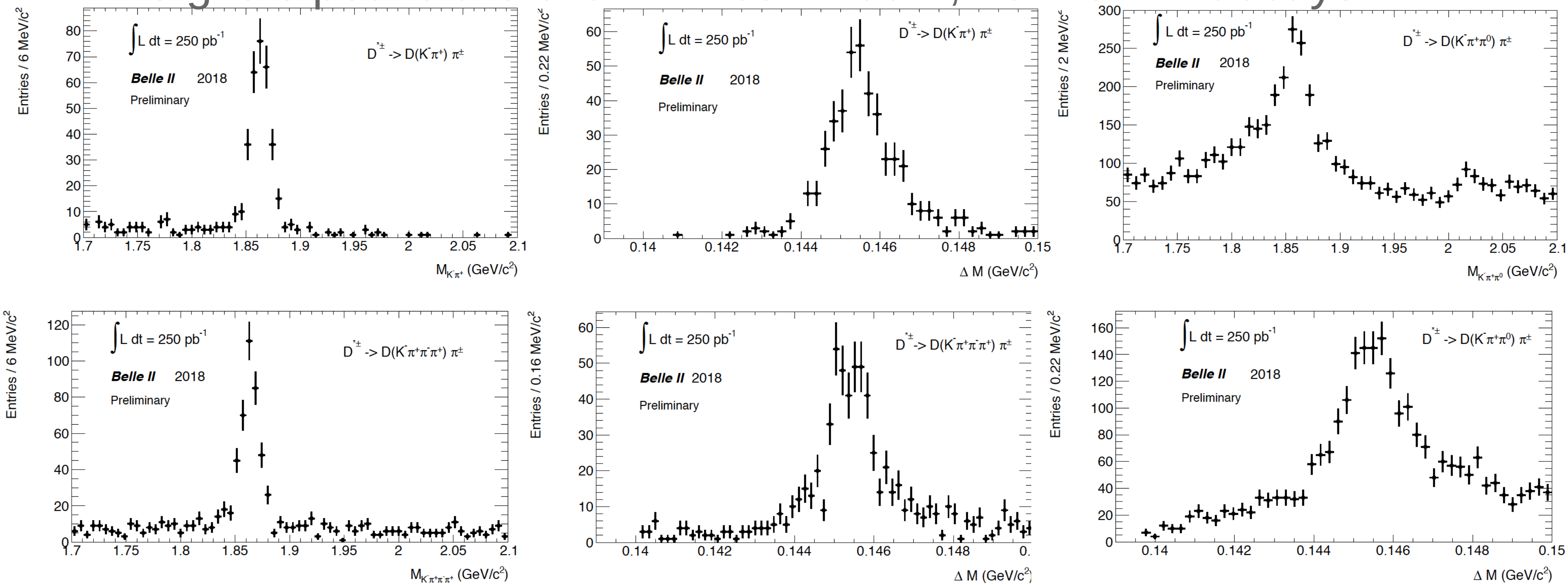




$e^+e^- \to c\bar{c}$ in Belle II

$$D^{*+} \to D^0\pi^+,$$
$$D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+$$

- Building blocks of B mesons
- Signals peaks are charm in continuum, not from B decays



Neutral Final States $D^0 \to K_S\pi^0$

- Pair of pions with a displaced vertex and two photons measured with good resolution and low background
  - Quite impossible at LHCb

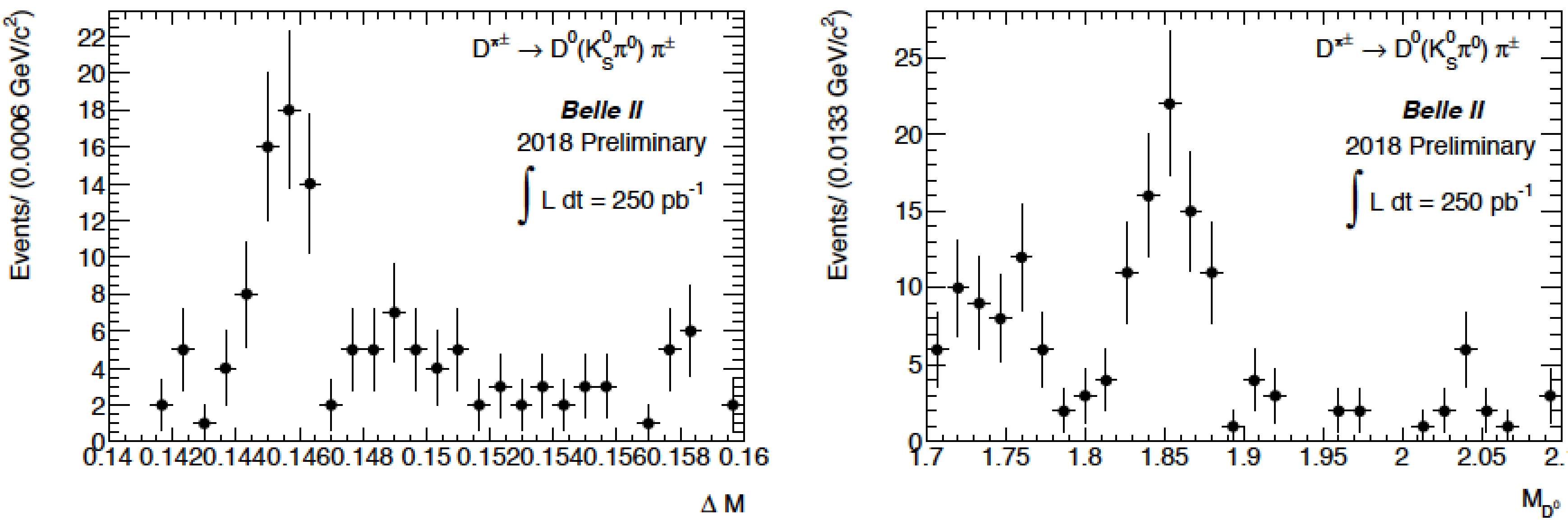
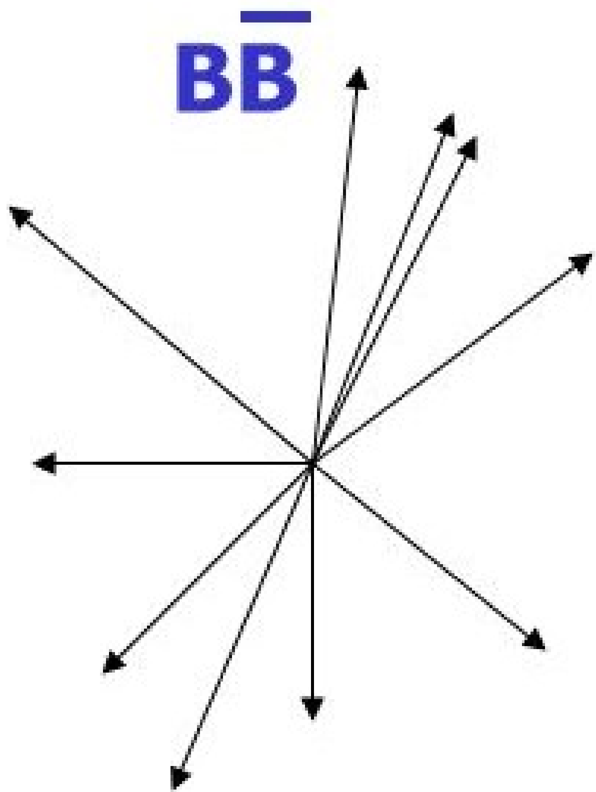
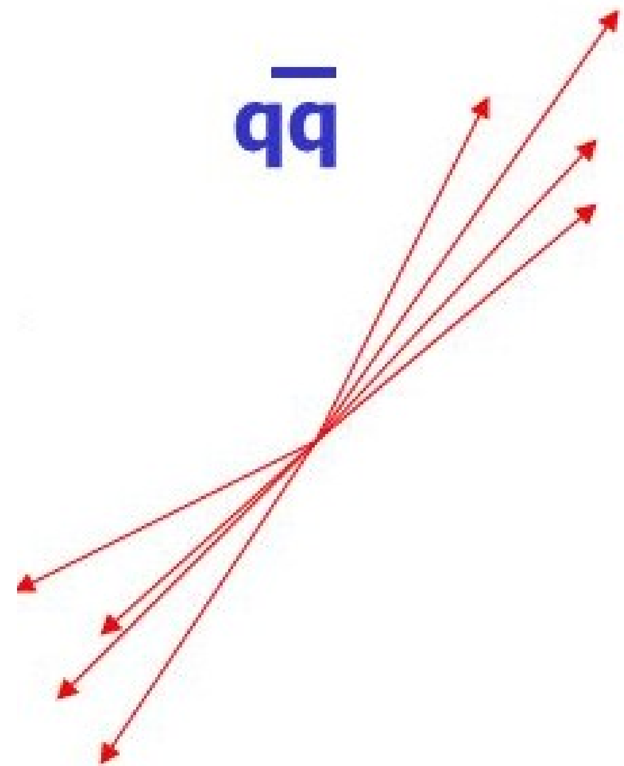


FIG. 36: ΔM (left) and M_D (right) signal-enhanced projections in 250 pb^{-1} prod4 data sample for $D \to K_S^0\pi^0$ final state.

Event Topology of B's

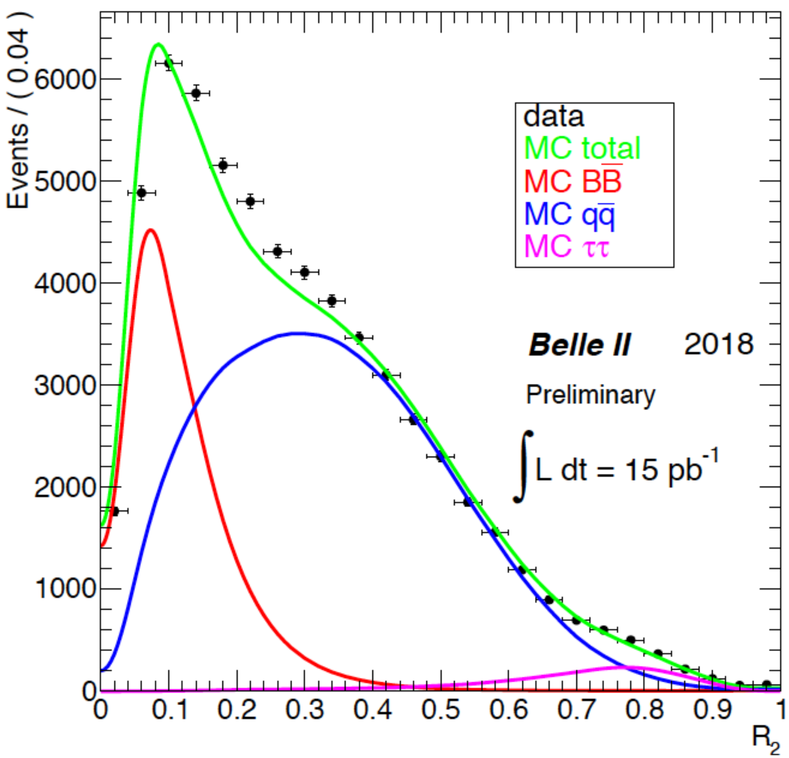
- In CM frame: $B\bar{B}$ look "spherical", $q\bar{q}$ looks "jetty"
  - Quantified by "R_2" variable



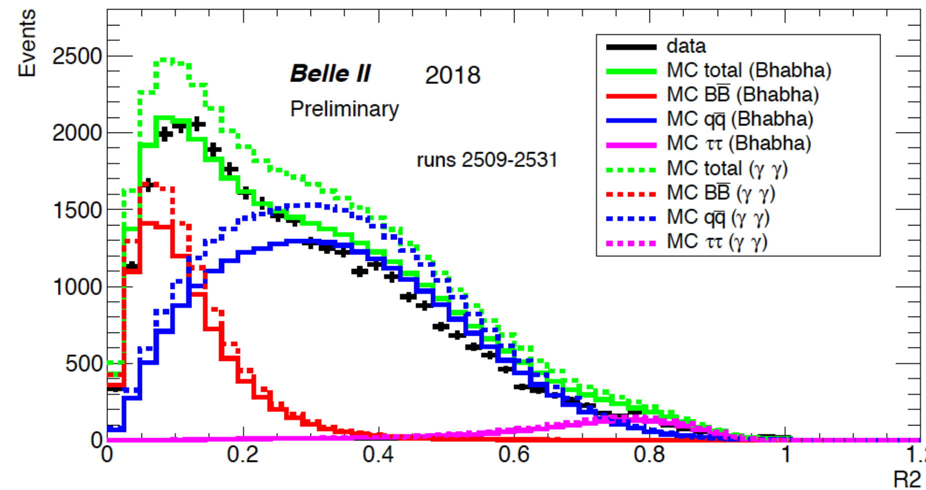


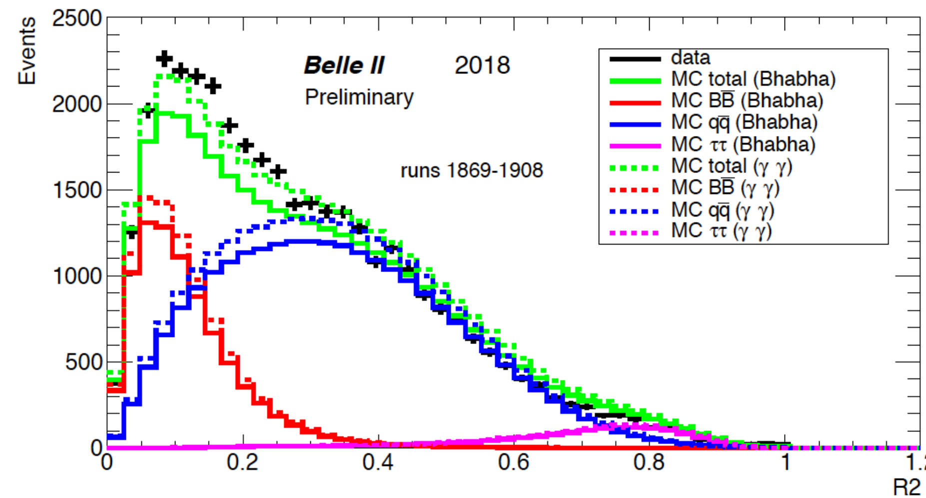
Many Bs in Belle II

- We are and stay on Y(4s) resonance

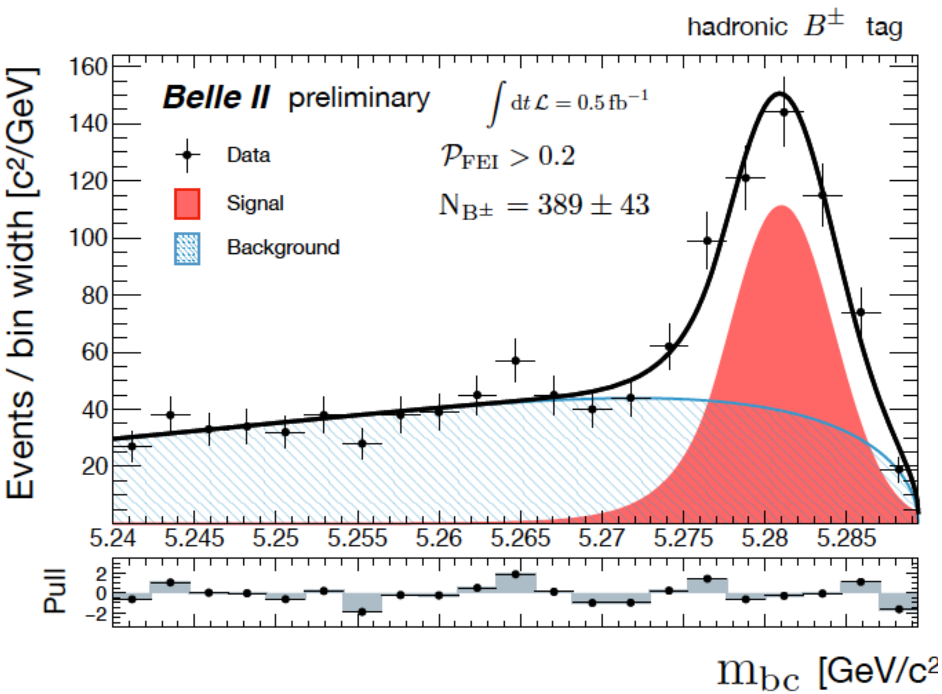


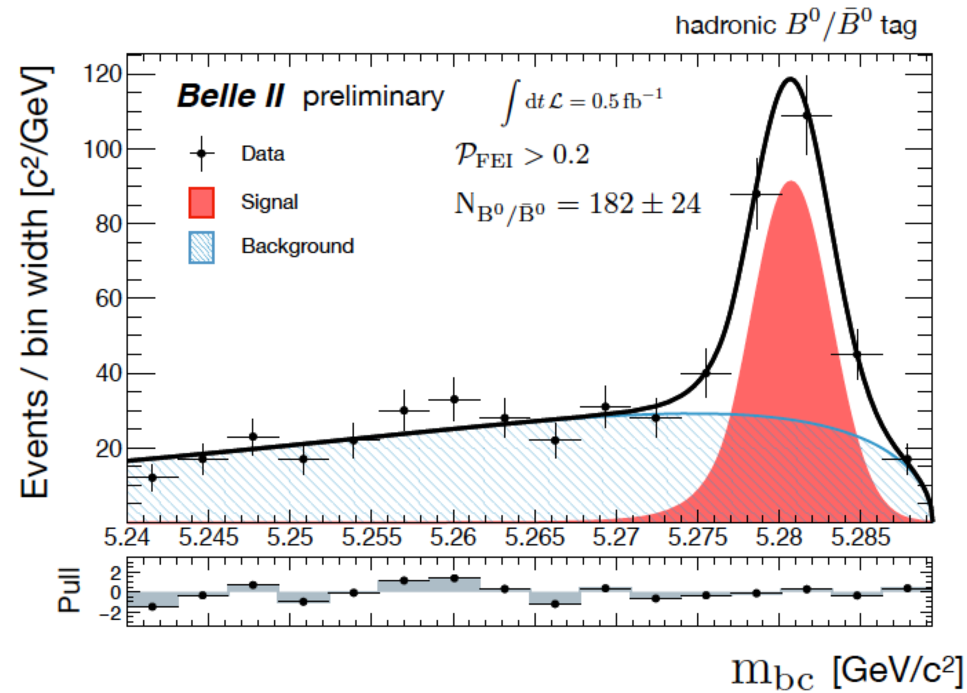
Spherical R_2 Jet-like





Single Bs in Belle II





~571 (389+182) fully reconstructed B mesons

VOLUME 50, NUMBER 12 PHYSICAL REVIEW LETTERS 21 MARCH 1983

Observation of Exclusive Decay Modes of *b*-Flavored Mesons **40.7 pb^{-1}**

B-meson decays to final states consisting of a D^0 or $D^{*\pm}$ and one or two charged pions have been observed. The charged-B mass is $5270.8 \pm 2.3 \pm 2.0$ MeV and the neutral-B mass is $5274.2 \pm 1.9 \pm 2.0$ MeV.