Particle identification at Belle-II

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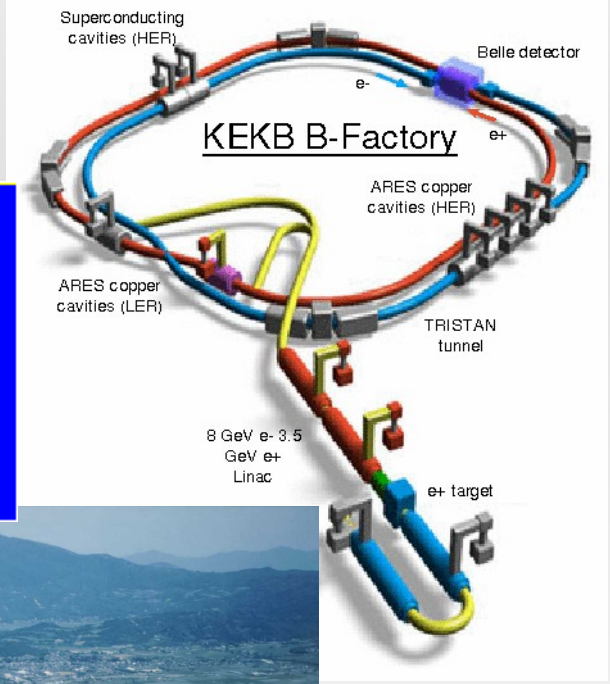
University of Oxford seminar
29 April 2014

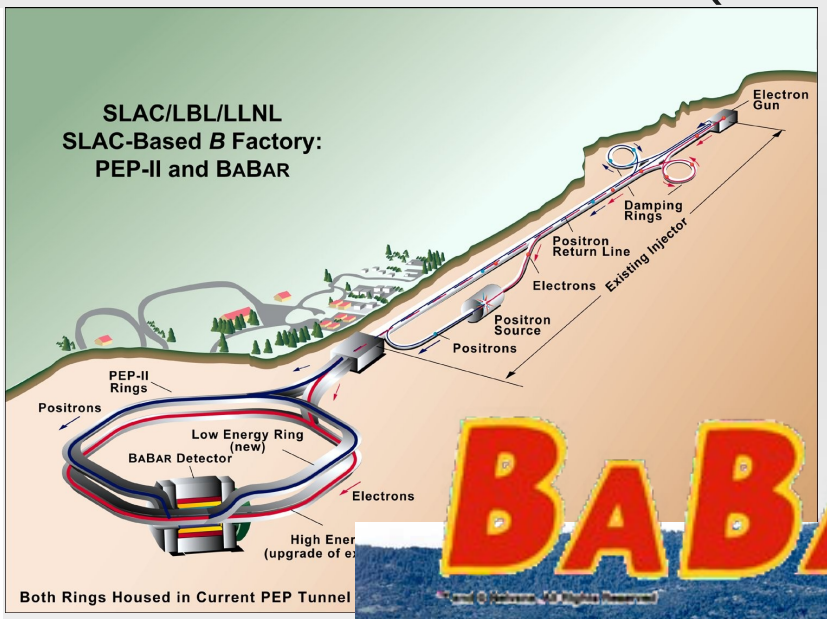
Outline

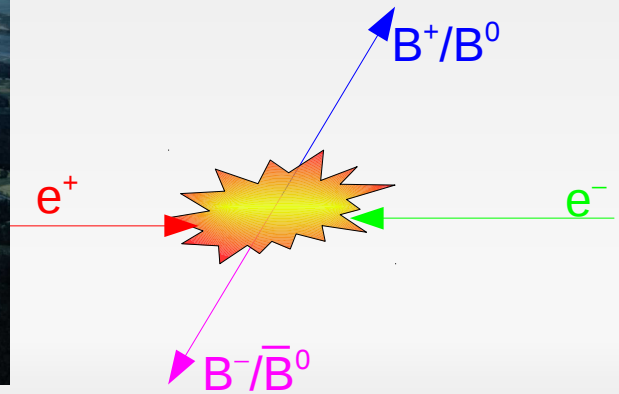
- The B factories
- Belle II and superKEKB
  - The Belle II sub-detectors
- The TOP subdetector
  - Beam test at SPring-8
- Belle II schedule
  - Commissioning detector

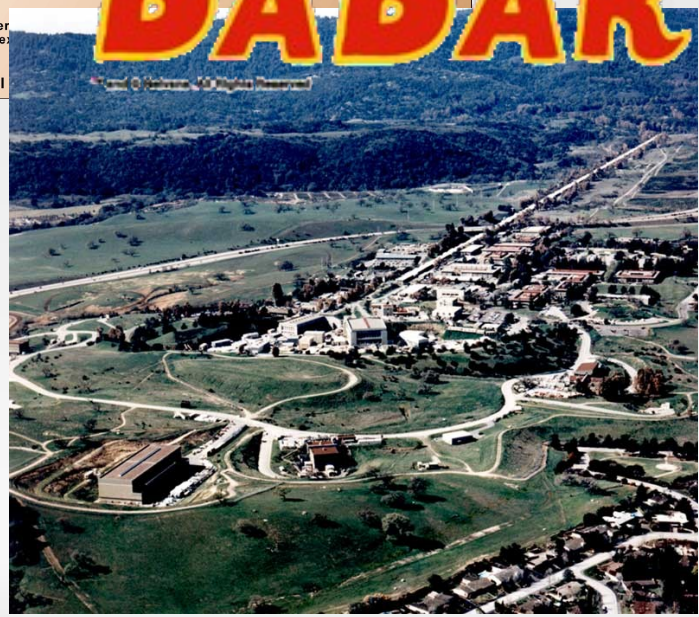
The B factories

- Belle/KEKB at KEK (Japan) and BaBar/PEP-II at SLAC (USA).



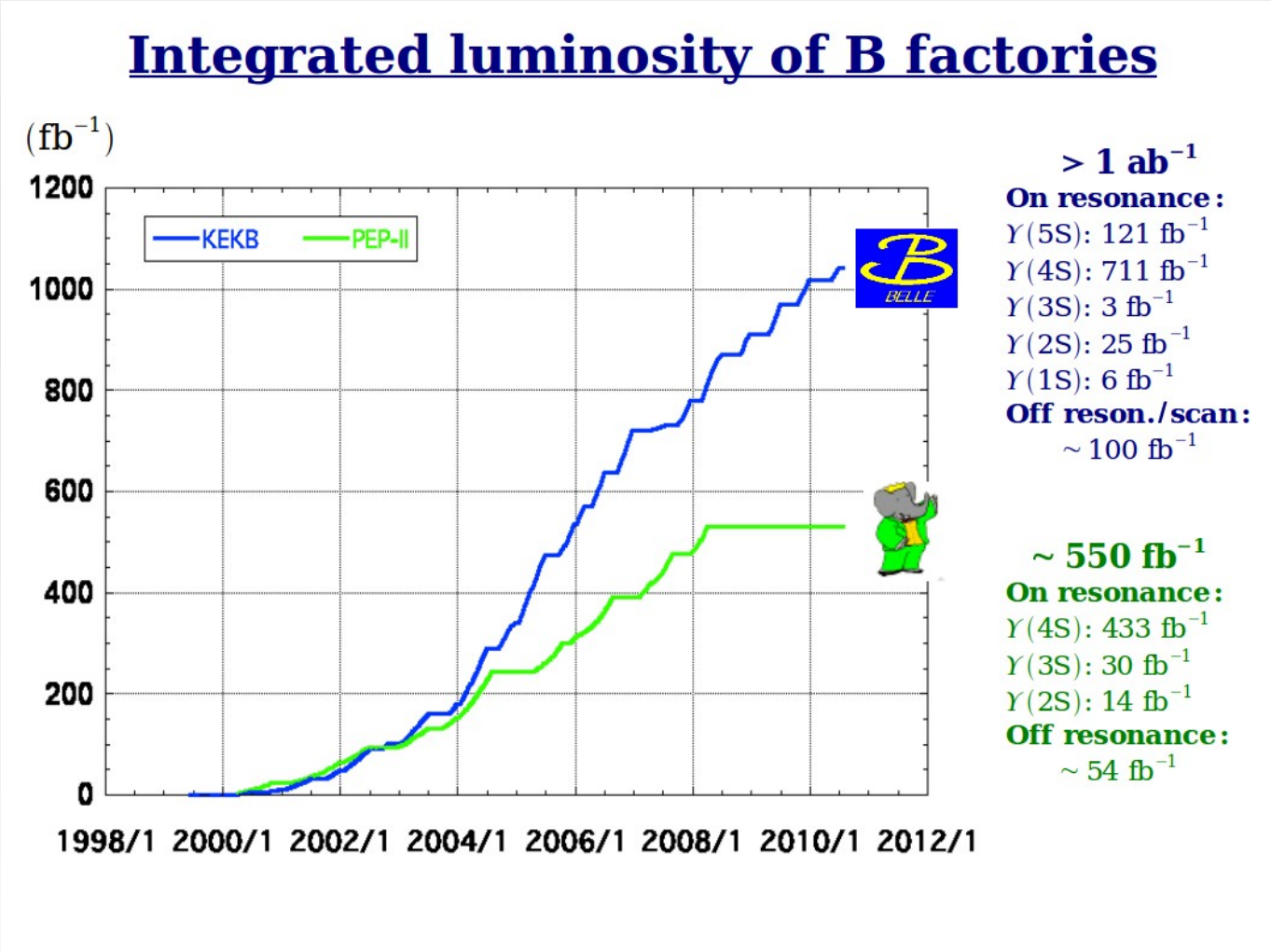






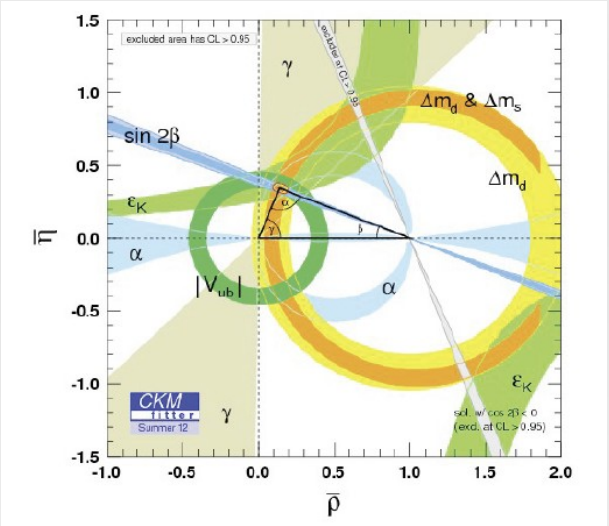
The B factories

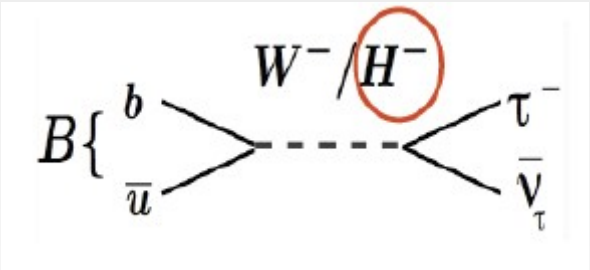
- The B factories: Belle and BaBar ran from 1999 to ~2010.
- They recorded over 1.5ab^{-1} of data.
- And provided the experimental confirmation that lead to the 2008 Nobel prize.



The B factories

- Physics highlights:
- Measurement of the Unitarity triangle, and CKM parameters;
- Observation of D meson mixing;
- Observation of new (X, Y, Z) hadrons;
- Observation of direct CP violation in B decays;
- In addition to being B factories – also τ and charm factories:
  - Search for rare τ decays.
- Constraints on new physics from:
  - e.g $B \rightarrow \tau\nu$ and $B \rightarrow s\gamma$.





B physics prospects

- Is that the end of B-physics?
  Isn't all B-physics done by LHCb now?

B physics prospects

- Is that the end of B-physics?
  Isn't all B-physics done by LHCb now?
- Still many potential sources/signals of new physics:
  - Flavour changing neutral currents;
  - Lepton flavour violating decays;
  - B $\rightarrow \tau$ new physics in loops;
  - Precision CKM measurements/ new sources of CPV

Observable	SM theory	Current measurement (early 2013)	Belle II ($50\,\mathrm{ab}^{-1}$)
$S(B \to \phi K^0)$	0.68	0.56 ± 0.17	± 0.03
$S(B \to \eta' K^0)$	0.68	0.59 ± 0.07	± 0.02
α from $B \to \pi\pi$, $\rho\rho$		$\pm 5.4^\circ$	$\pm 1.5^\circ$
γ from $B \to DK$		$\pm 11^\circ$	$\pm 1.5^\circ$
$S(B \to K_S \pi^0 \gamma)$	< 0.05	-0.15 ± 0.20	± 0.03
$S(B \to \rho\gamma)$	< 0.05	-0.83 ± 0.65	± 0.15
$A_{\mathrm{CP}}(B \to X_{s+d}\,\gamma)$	< 0.005	0.06 ± 0.06	± 0.02
A^d_{SL}	-5×10^{-4}	-0.0049 ± 0.0038	± 0.001
$\mathcal{B}(B \to \tau\nu)$	1.1×10^{-4}	$(1.64 \pm 0.34) \times 10^{-4}$	$\pm 0.05 \times 10^{-4}$
$\mathcal{B}(B \to \mu\nu)$	4.7×10^{-7}	$< 1.0 \times 10^{-6}$	$\pm 0.2 \times 10^{-7}$
$\mathcal{B}(B \to X_s\gamma)$	3.15×10^{-4}	$(3.55 \pm 0.26) \times 10^{-4}$	$\pm 0.13 \times 10^{-4}$
$\mathcal{B}(B \to K\nu\overline{\nu})$	3.6×10^{-6}	$< 1.3 \times 10^{-5}$	$\pm 1.0 \times 10^{-6}$
$\mathcal{B}(B \to X_s\ell^+\ell^-)$ $(1 < q^2 < 6\,\mathrm{GeV}^2)$	1.6×10^{-6}	$(4.5 \pm 1.0) \times 10^{-6}$	$\pm 0.10 \times 10^{-6}$
$A_{\mathrm{FB}}(B^0 \to K^{*0}\ell^+\ell^-)$ zero crossing	7%	18%	5%
$\lvert V_{ub}\rvert$ from $B \to \pi\ell^+\nu$ $(q^2 > 16\,\mathrm{GeV}^2)$	$9\% \to 2\%$	11%	2.1%

Table 3. *The expected reach of Belle II with 50 ab^{-1} of data for various topical B decay measurements. Also listed are the SM expectations and the current experimental results. For $\mathcal{B}(B \to X_s\ell^+\ell^-)$, the quoted measurement [62] covers the full q^2 range. For $|V_{ub}|$ and the A_{FB} zero crossing, we list the fractional errors.*

Report of the Quark Flavor Physics Working Group:
Snowmass – arXiv:1311.1076 [hep-ex]

B physics prospects

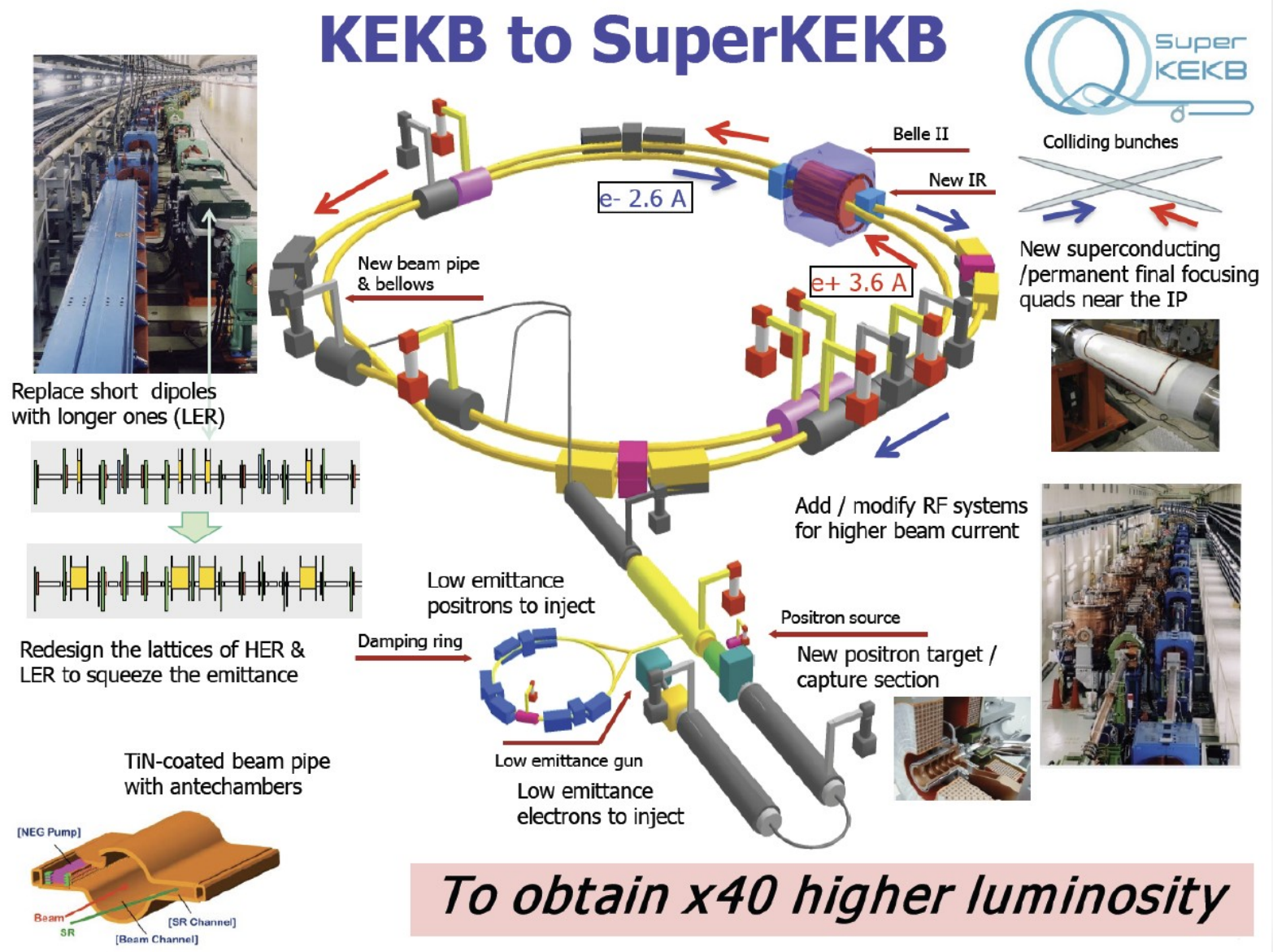
- Is that the end of B-physics?
  Isn't all B-physics done by LHCb now?
- Still many potential sources/signals of new physics:
  - Flavour changing neutral currents;
  - Lepton flavour violating decays;
  - B $\rightarrow \tau$ new physics in loops;
  - Precision CKM measurements/ new sources of CPV
- Different environment leads to complementary capabilities with LHCb.

Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\lvert V_{us}\rvert$ $[K \to \pi\ell\nu]$	**	0.1%	K-factory
$\lvert V_{cb}\rvert$ $[B \to X_c\ell\nu]$	**	1%	Belle II
$\lvert V_{ub}\rvert$ $[B_d \to \pi\ell\nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K^0_S]$	***	$8 \cdot 10^{-3}$	Belle II/LHCb
ϕ_2		1.5°	Belle II
ϕ_3	***	3°	LHCb
CPV			
$S(B_s \to \psi\phi)$	**	0.01	LHCb
$S(B_s \to \phi\phi)$	**	0.05	LHCb
$S(B_d \to \phi K)$	***	0.05	Belle II/LHCb
$S(B_d \to \eta' K)$	***	0.02	Belle II
$S(B_d \to K^*(\to K^0_S\pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A^d_{SL}	***	0.001	LHCb
A^s_{SL}	***	0.001	LHCb
$A_{CP}(B_d \to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B \to \tau\nu)$	**	3%	Belle II
$\mathcal{B}(B \to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d \to \mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb
zero of $A_{FB}(B \to K^*\mu\mu)$	**	0.05	LHCb
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B \to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K \to \pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K \to e\pi\nu)/\mathcal{B}(K \to \mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\lvert q/p\rvert_D$	***	0.03	Belle II
$arg(q/p)_D$	***	1.5°	Belle II

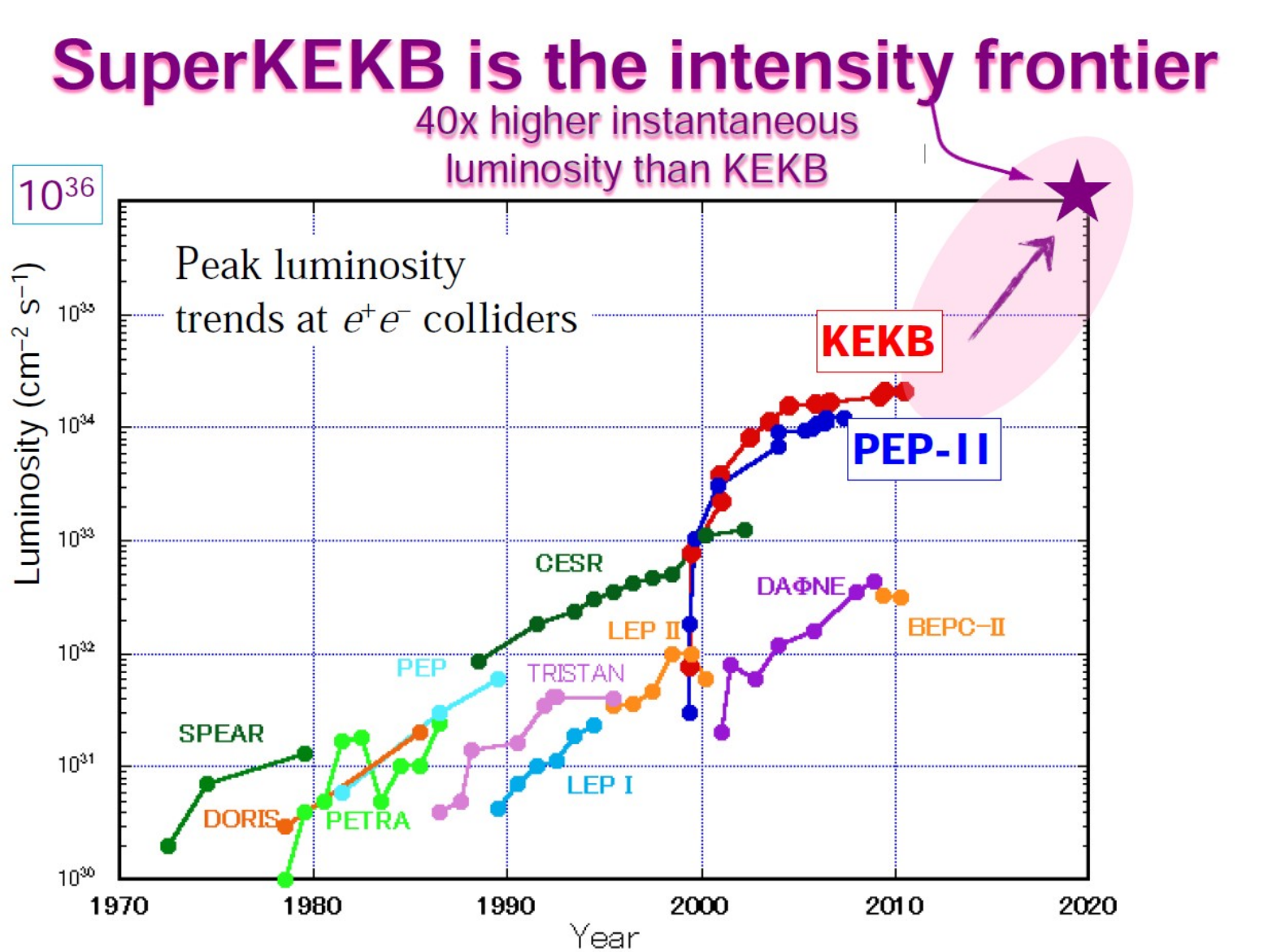
Adapted from G. Isidori et al., Ann. Rev. Nucl. Part. Sci. 60, 355 (2010), by B. Golob KEK-FF2012

Belle II and SuperKEKB

SuperKEKB

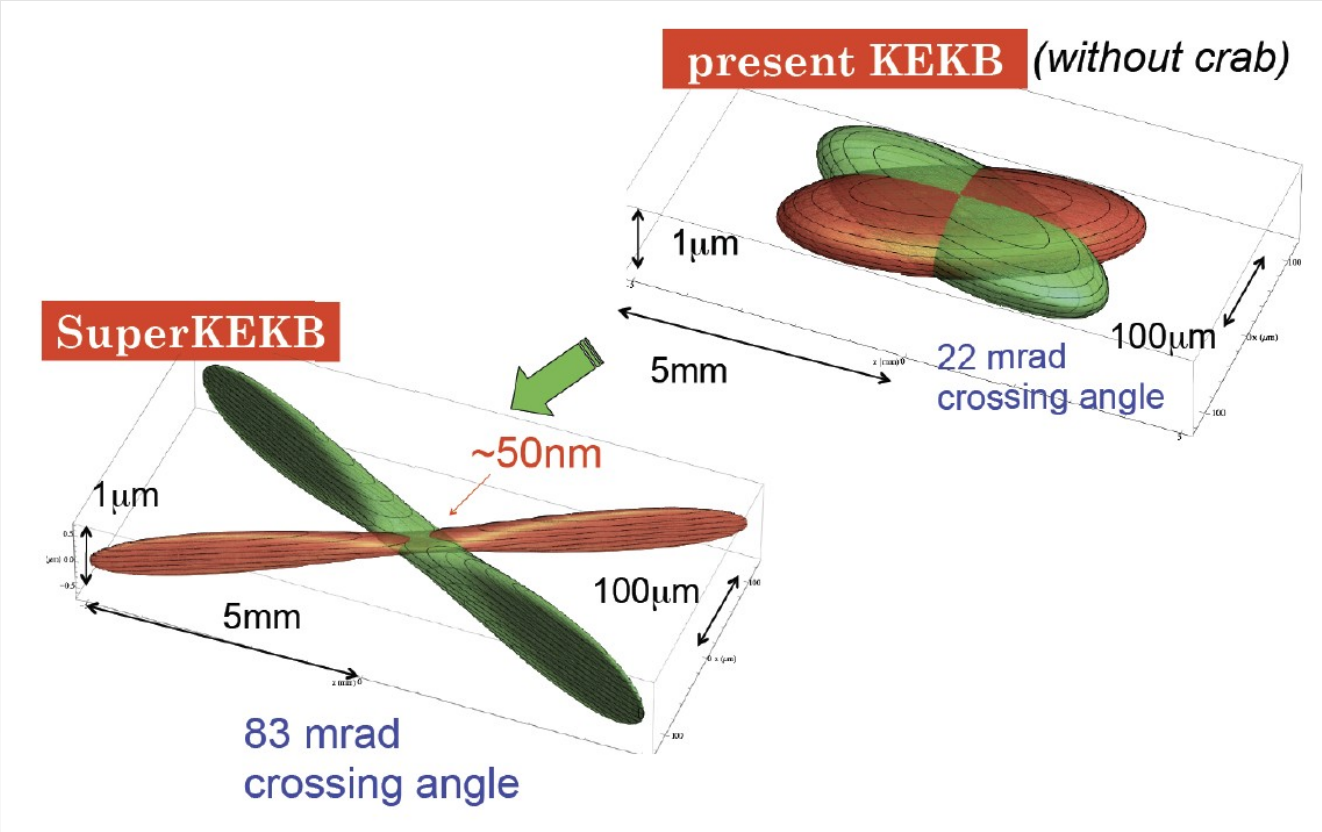

KEKB to SuperKEKB
Super KEKB
Belle II
New IR
Colliding bunches
e- 2.6 A
e+ 3.6 A
New beam pipe & bellows
New superconducting /permanent final focusing quads near the IP
Replace short dipoles with longer ones (LER)
Add / modify RF systems for higher beam current
Low emittance positrons to inject
Positron source
Damping ring
New positron target / capture section
Redesign the lattices of HER & LER to squeeze the emittance
Low emittance gun
Low emittance electrons to inject
TiN-coated beam pipe with antechambers
[NEG Pump]
Beam
SR
[SR Channel]
[Beam Channel]
To obtain x40 higher luminosity

SuperKEKB


SuperKEKB is the intensity frontier
40x higher instantaneous luminosity than KEKB
10^{36}
Peak luminosity trends at e^+e^- colliders
Luminosity (cm^{-2} s^{-1})
10^{35}
10^{34}
10^{33}
10^{32}
10^{31}
10^{30}
KEKB
PEP-II
CESR
DAΦNE
BEPC-II
LEP II
PEP
TRISTAN
SPEAR
LEP I
DORIS
PETRA
1970
1980
1990
2000
2010
2020
Year

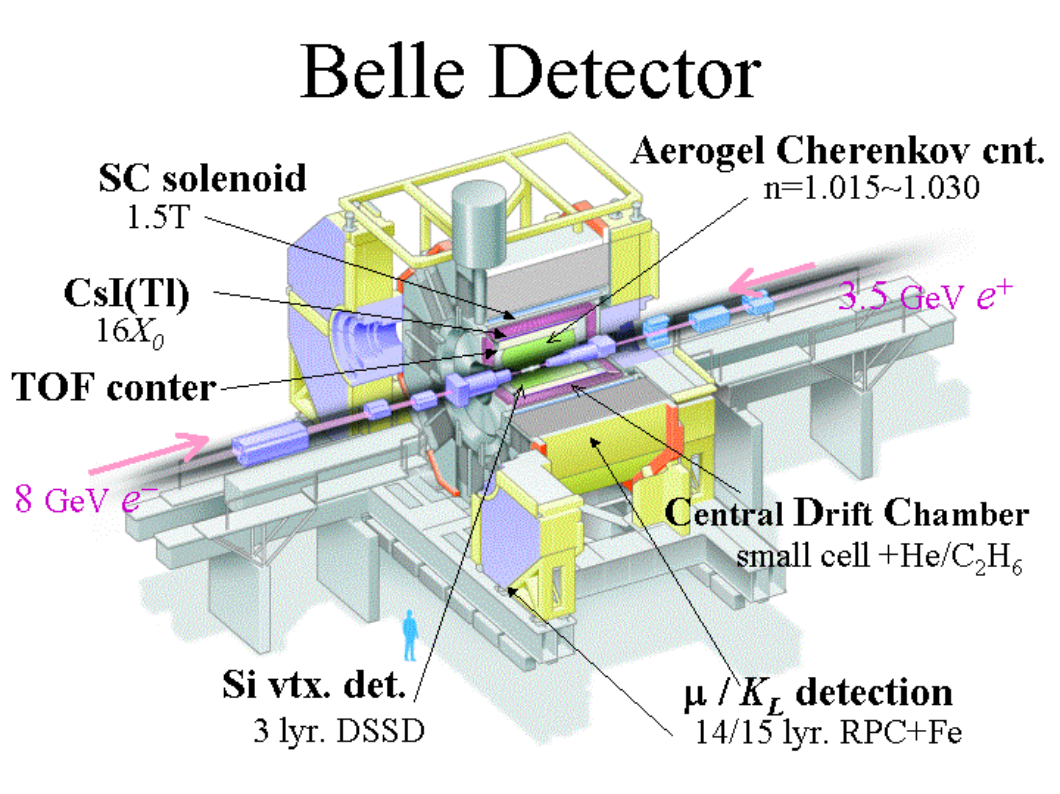
SuperKEKB

- Beam currents are increased by ~2, but the main increase in luminosity comes from the change in beamspot size from using nanobeams, and a crab waist scheme is also being examined.



From Belle to Belle-II

- Belle Detector is being upgraded to the Belle-II detector,
  - which will record data at a Luminosity ~40 times higher.
  - Belle sub-detectors are being upgraded or replaced.
- Belle detector used a time of flight (TOF) counter, and Aerogel Cherenkov counter for PID.



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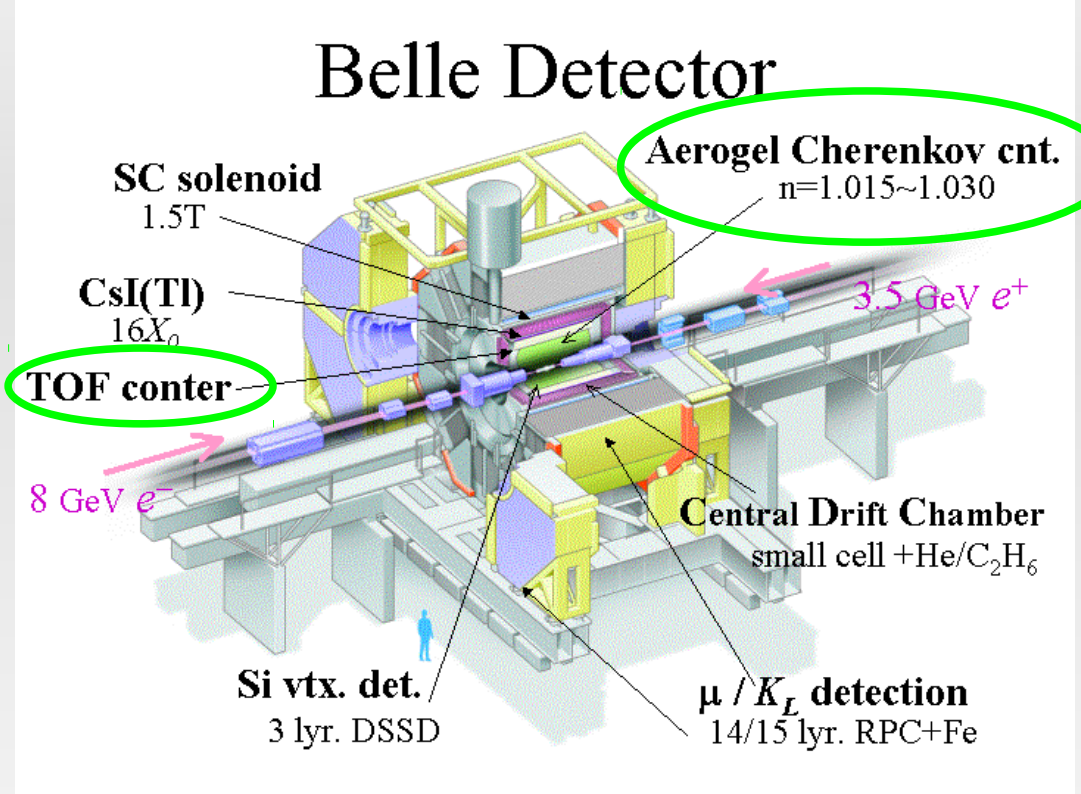

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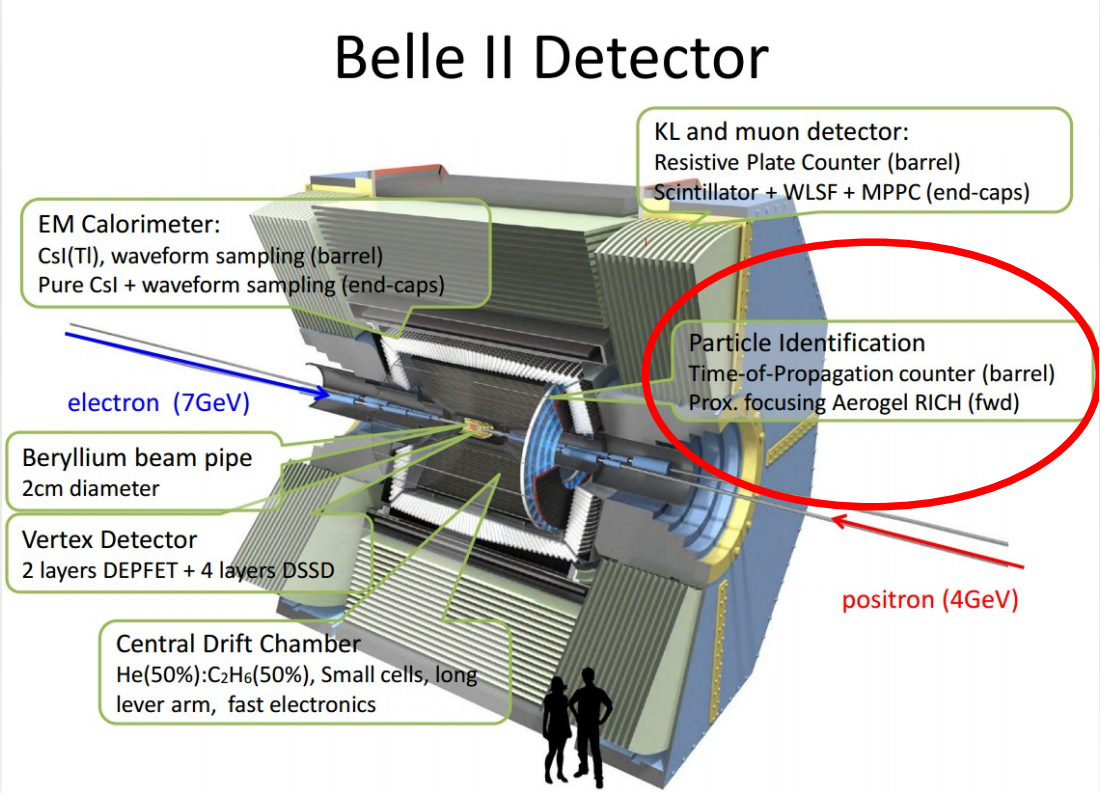
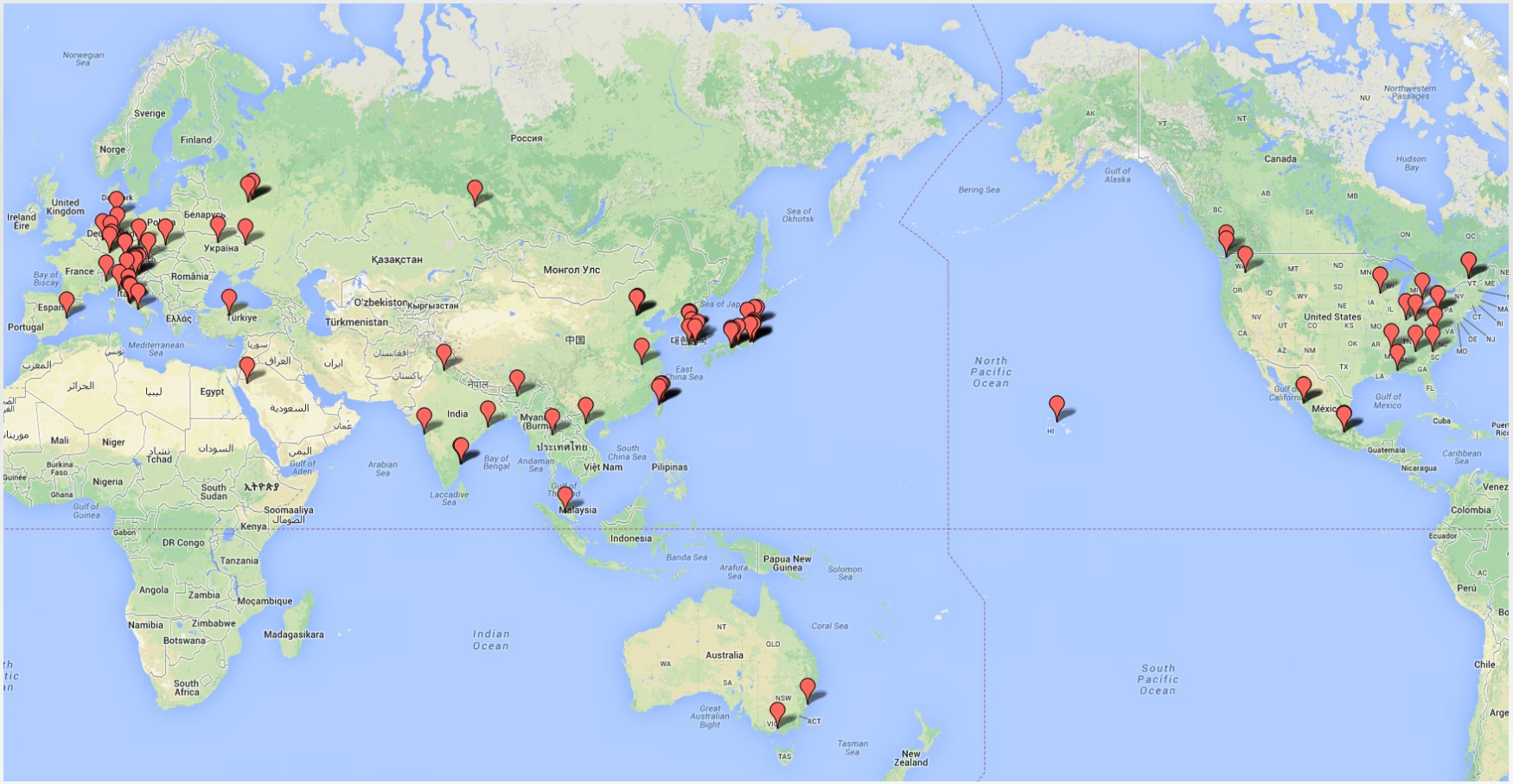


- Belle II will replace these with an Aerogel RICH detector and a Time of Propagation detector.
- Other new sub-detectors include a new backward endcap calorimeter, and new vertex detectors.

Belle II Collaboration

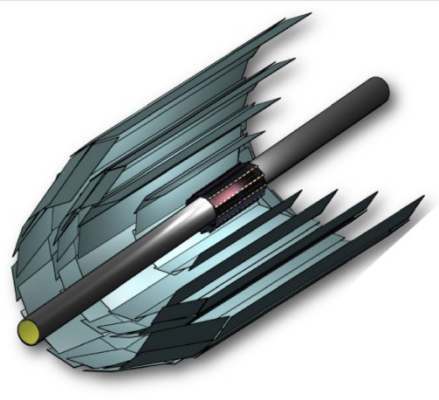


- 599 collaborators, 97 institutions, 23 countries (as of February 2014).

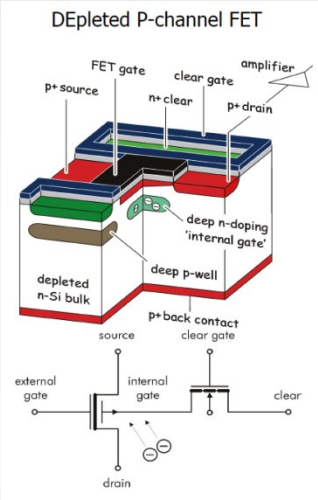
Belle II subdetectors

Vertex detectors

- New vertex detectors: 2 layers of DEPFETs (Depleted P- Channel Field Effect Transistor) and 4 layers of DSSD (Double Sided Silicon Detectors).
- Beam pipe radius reduced from 2cm-1.5cm for Belle to 1cm for Belle II.



Beam Pipe		**r = 10mm**
DEPFET		
	Layer 1	**r = 14mm**
	Layer 2	**r = 22mm**
DSSD		
	Layer 3	**r = 38mm**
	Layer 4	**r = 80mm**
	Layer 5	**r = 115mm**
	Layer 6	**r = 140mm**

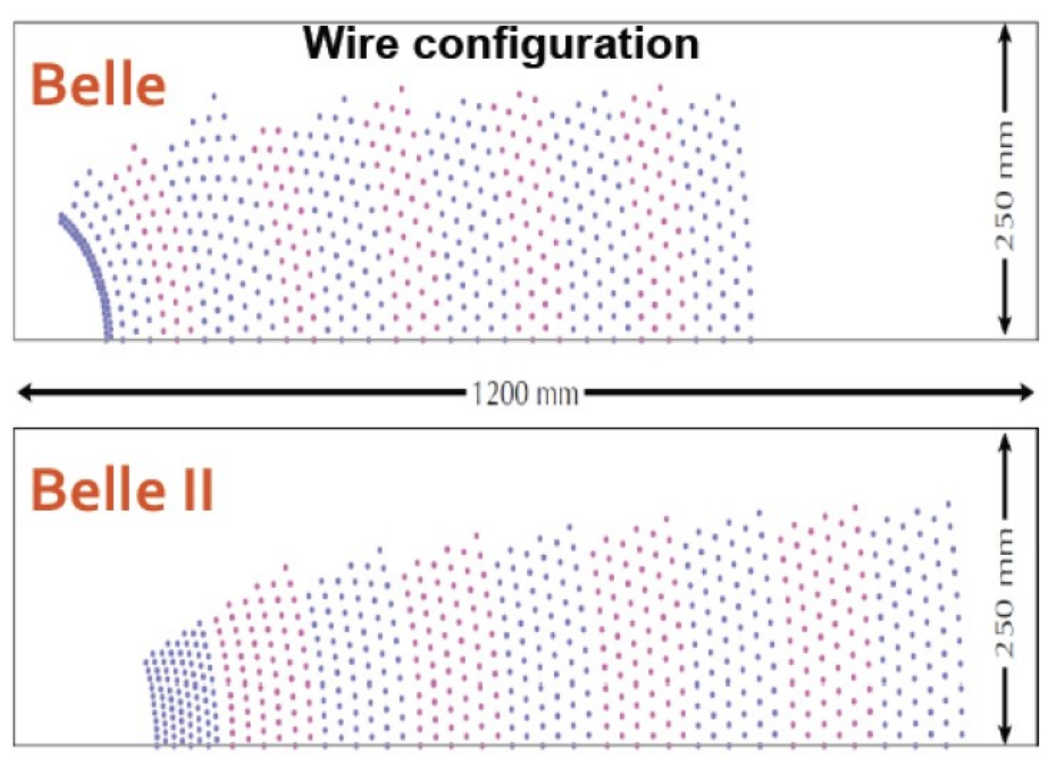


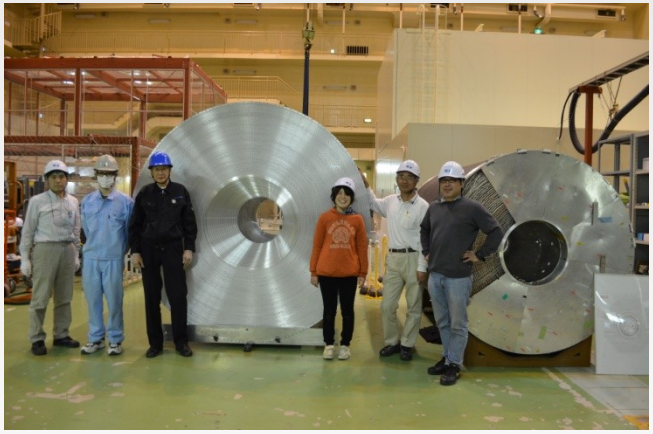
DEPFET pixel sensor

Central Drift Chamber (CDC)

- CDC for Belle II will be larger than Belle CDC.
- Stringing completed in January 2014.
  - 51456 wires.

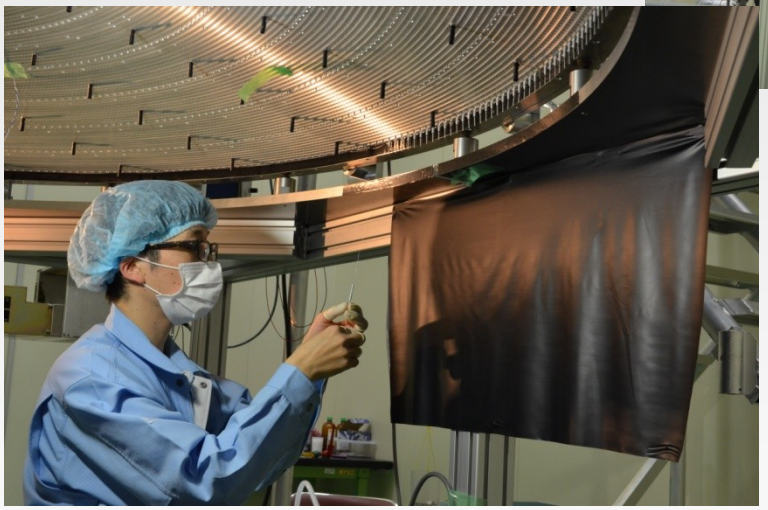
	Belle	Belle II
Innermost sense wire	r=88mm	r=168mm
Outermost sense wire	r=863mm	r=1111.4mm
Number of layers	50	56
Total sense wires	8400	14336
Gas	He:C_2H_6	He:C_2H_6
Sense wire	W(Φ30μm)	W(Φ30μm)
Field wire	Al(Φ120μm)	Al(Φ120μm)



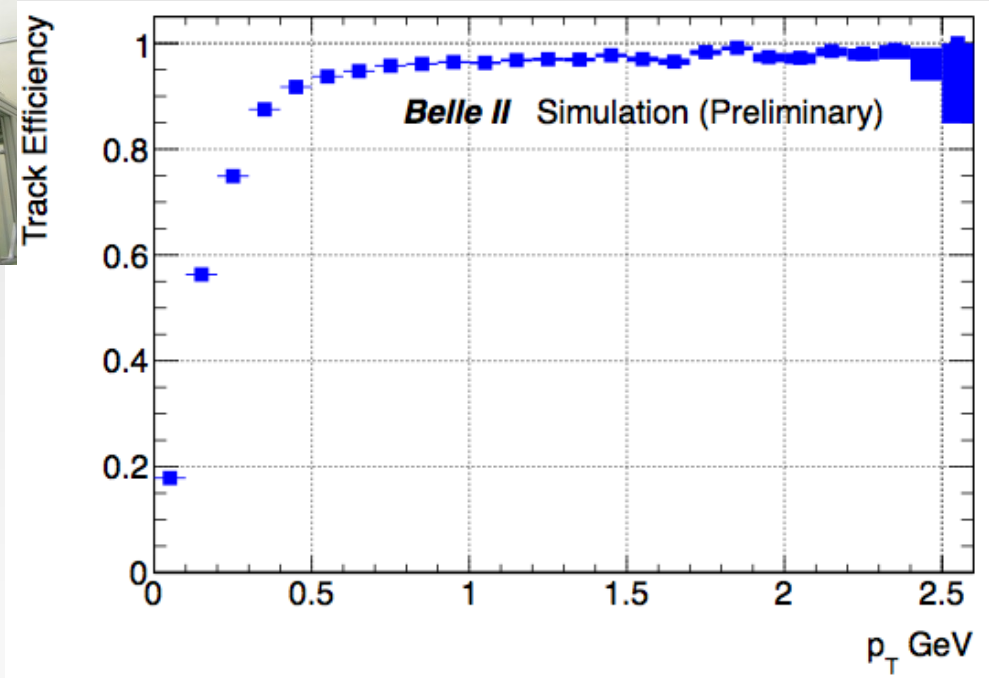


Central Drift Chamber (CDC)

- Stringing in Fuji hall at KEK.

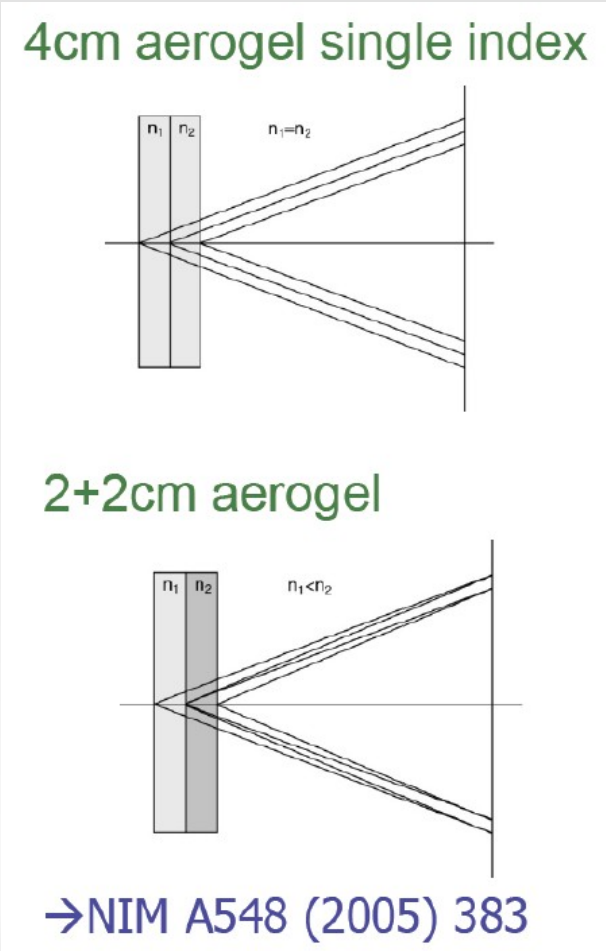


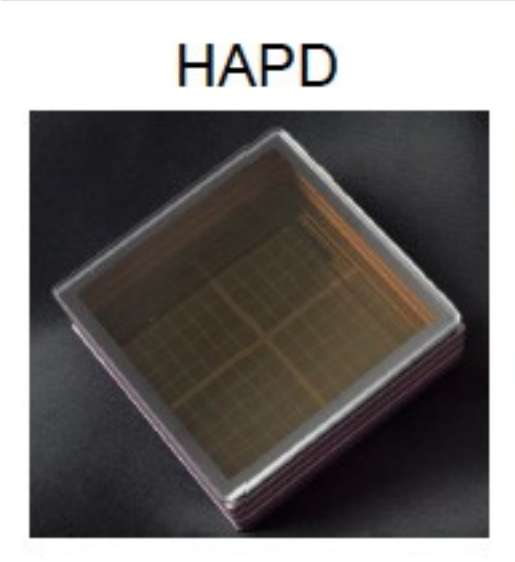
Expected performance from Geant4 simulation and Kalman filter

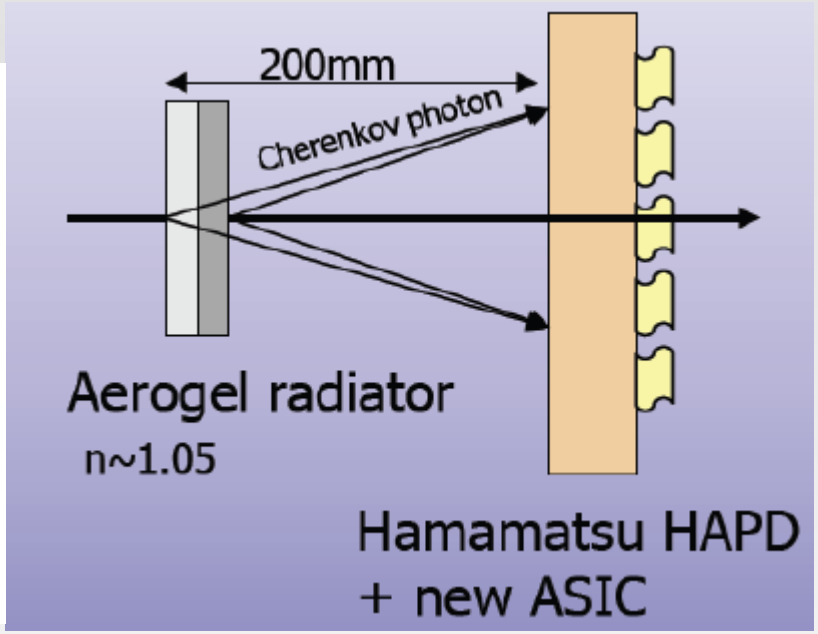


Aerogel RICH

- Aerogel Ring Imaging Cerenkov (ARICH) detector used for particle identification in the forward endcap.

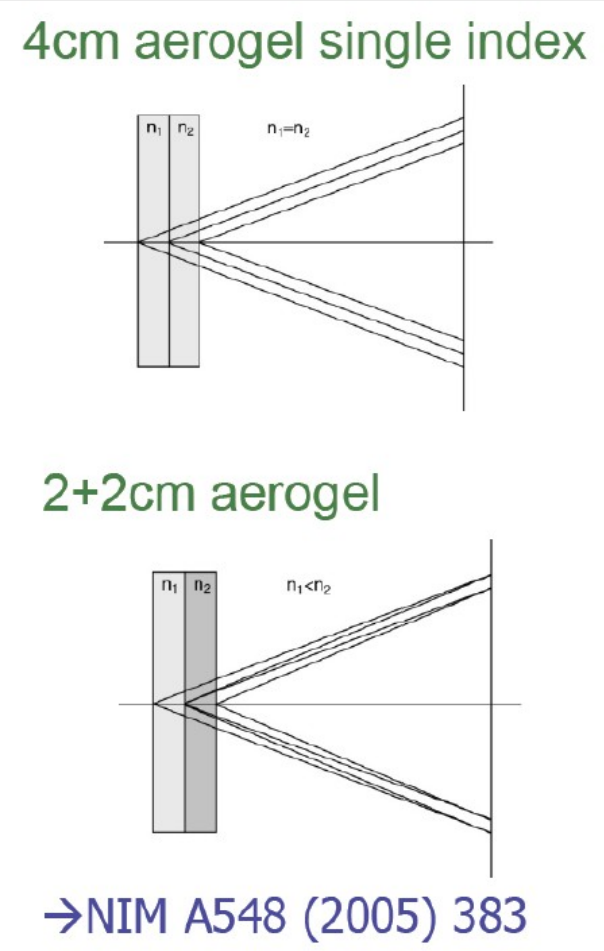


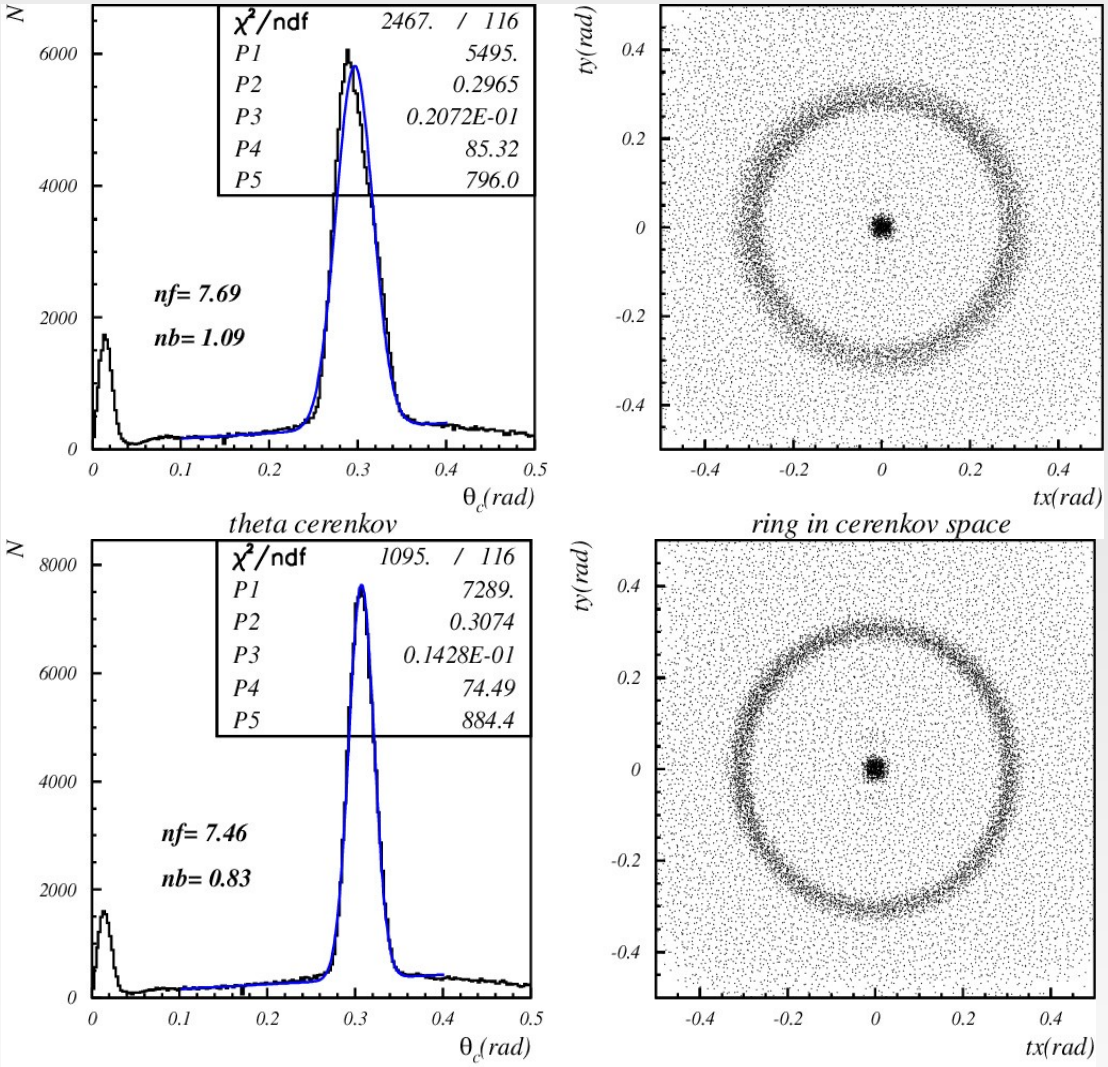




Uses 420 Hybrid Avalanche Photo Detectors (HAPD), each with 144 channels.

Aerogel RICH





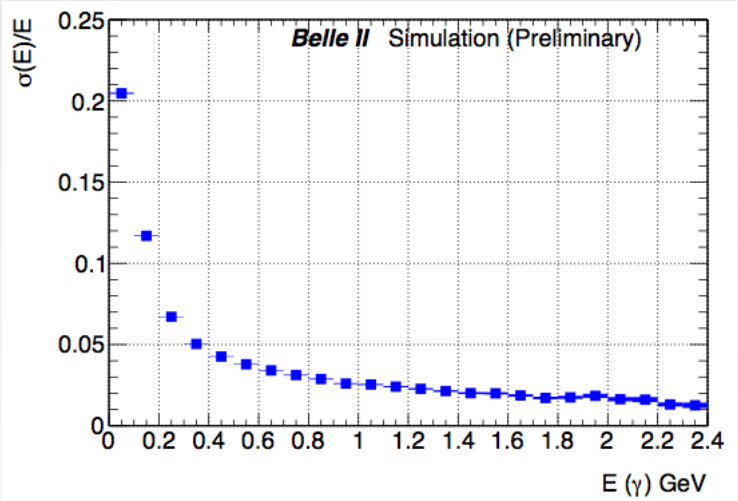
Two layers of aerogel lead to better photon yield, whilst maintaining resolution.

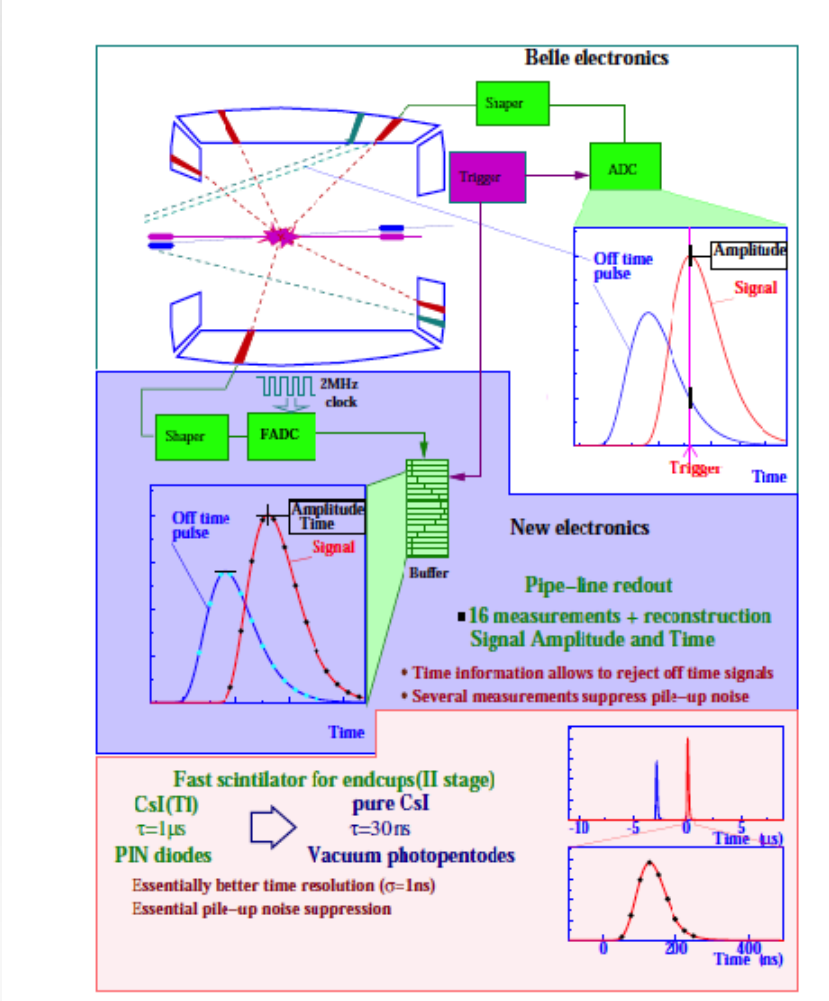
NIM A548 (2005) 383

Electromagnetic Calorimeter (ECL)

- Need upgrade for high backgrounds
- Barrel: CsI(Tl), waveform sampling.
- Endcaps: Pure CsI, waveform sampling.

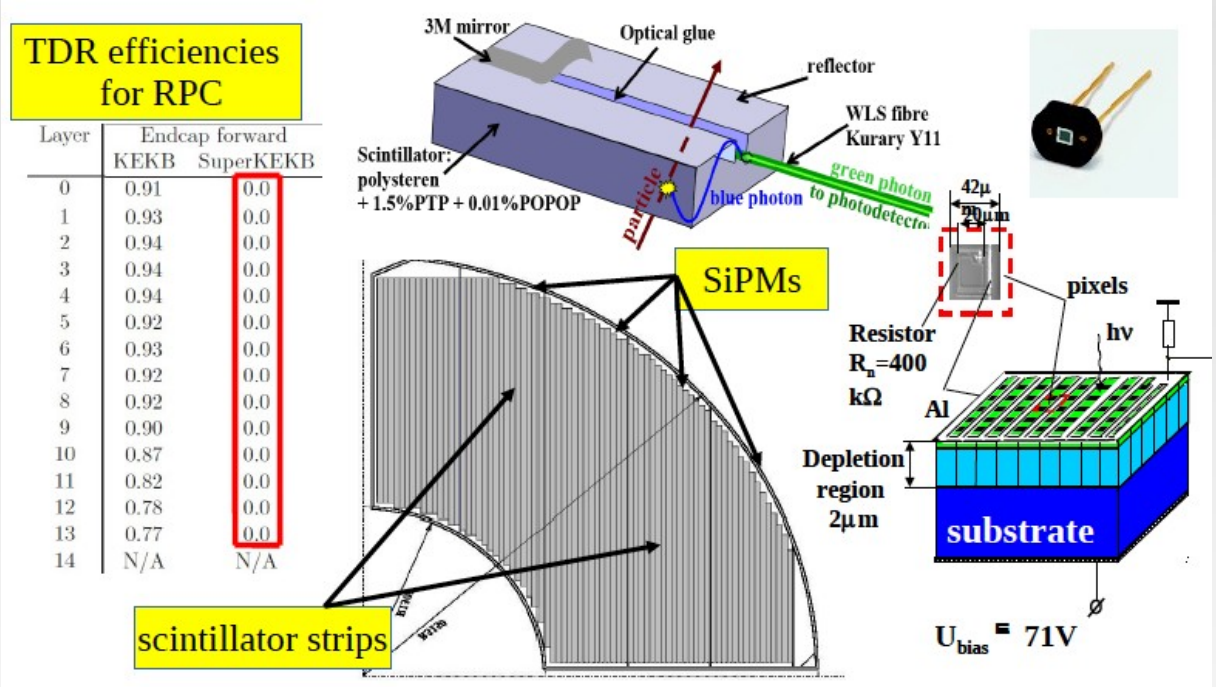
Expected performance from Geant4 simulation.





K_L and Muon systems (KLM)

- Endcaps and parts of the barrel KLM RPCs of Belle needed to be replaced with scintillators due to increased backgrounds expected in Belle II.
- Barrel KLM was the first sub-detector to be installed in Belle II.
- Endcap KLM expected to be installed later this year.



Layer	Endcap forward KEKB	Endcap forward SuperKEKB
0	0.91	0.0
1	0.93	0.0
2	0.94	0.0
3	0.94	0.0
4	0.94	0.0
5	0.92	0.0
6	0.93	0.0
7	0.92	0.0
8	0.92	0.0
9	0.90	0.0
10	0.87	0.0
11	0.82	0.0
12	0.78	0.0
13	0.77	0.0
14	N/A	N/A

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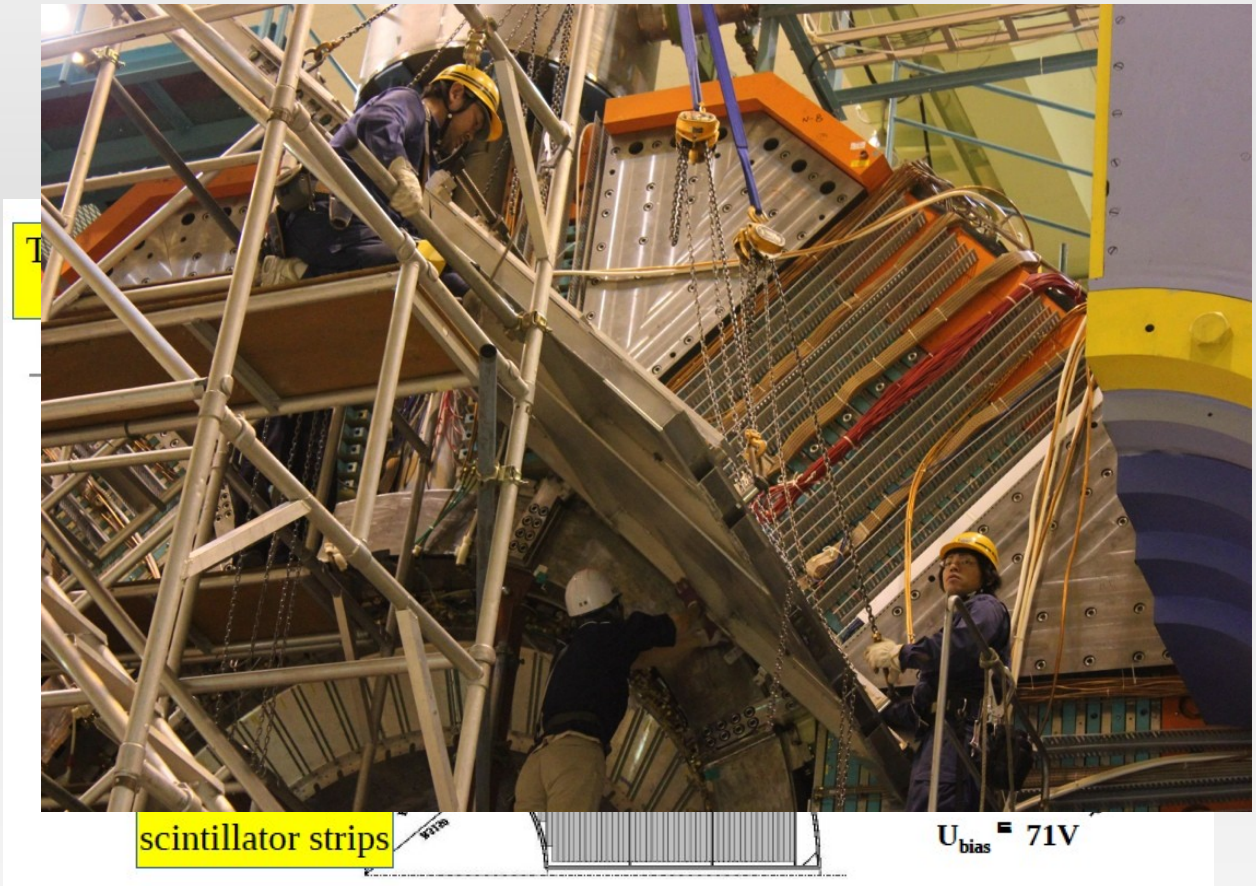

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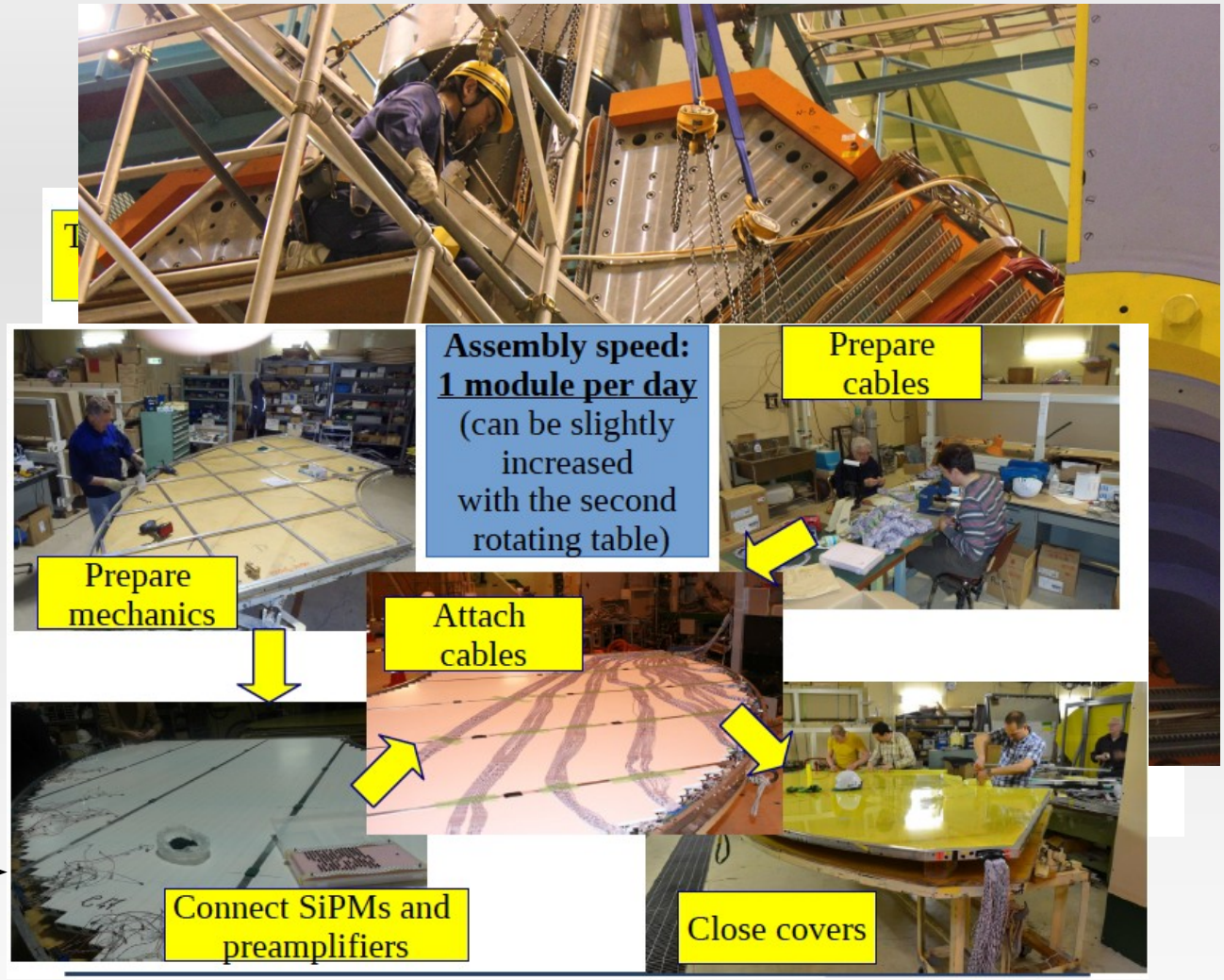
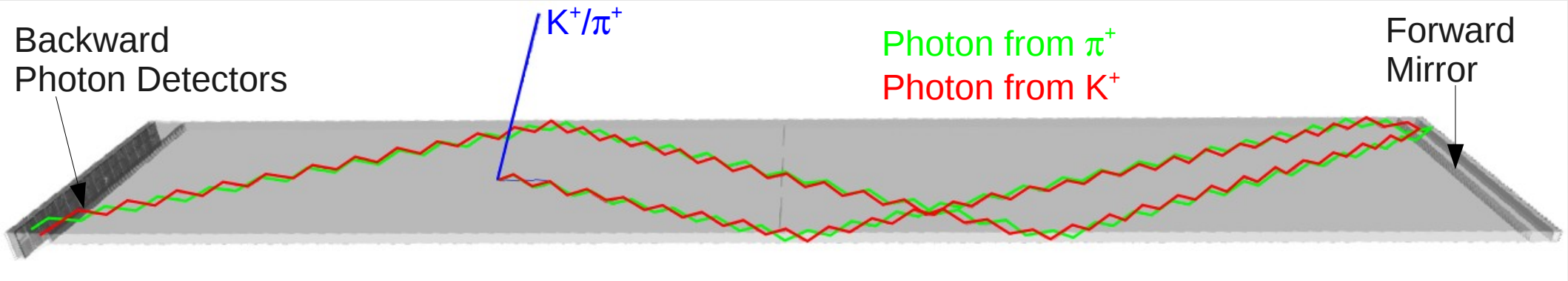


The TOP detector

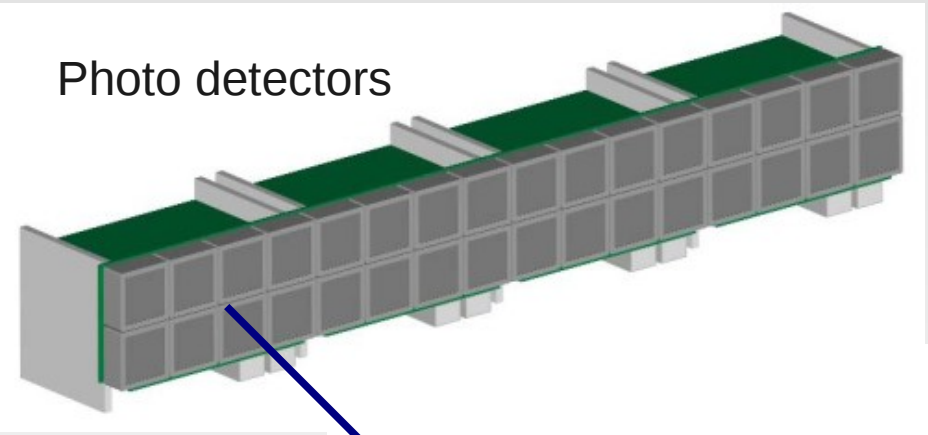
- The (imaging) Time of Propagation subdetector (TOP or iTOP) will be used for particle identification in the barrel region of Belle II.
- Each TOP module contains two quartz bars (~2.5m in length), and expansion volume, mirror, and array of photodetectors.

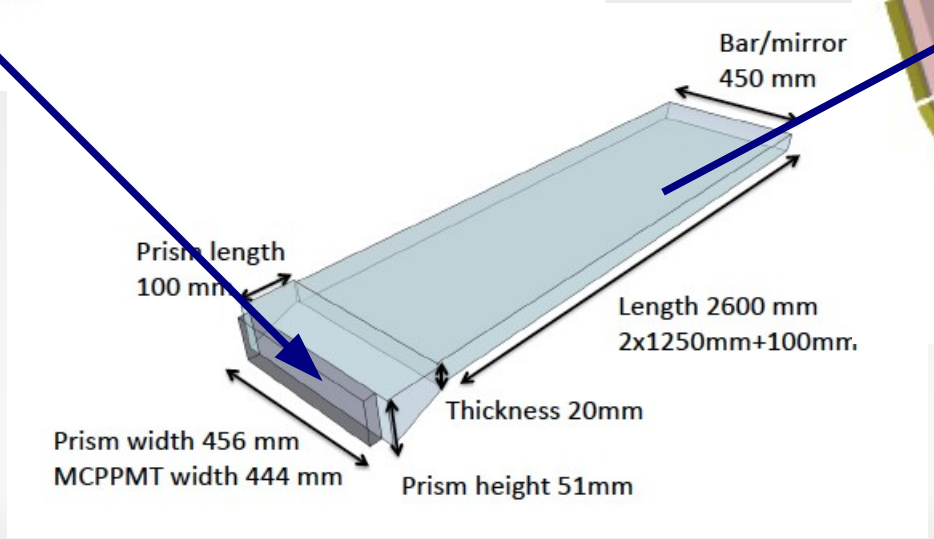


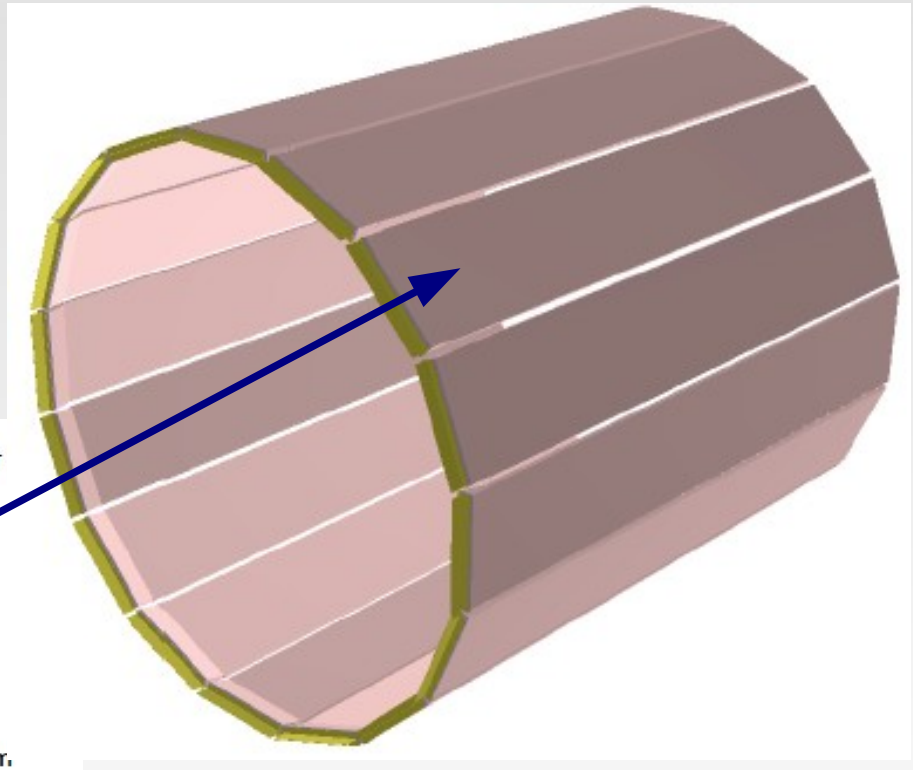
- When a charged particle passes through the quartz, it emits Cherenkov photons:
  - The Cherenkov angle, and hence detection time/position depends on the mass of particle (for given track parameters).

TOP modules

- There are 16 TOP modules to be installed in Belle II,
  - Forming a “Roman Arch” structure.

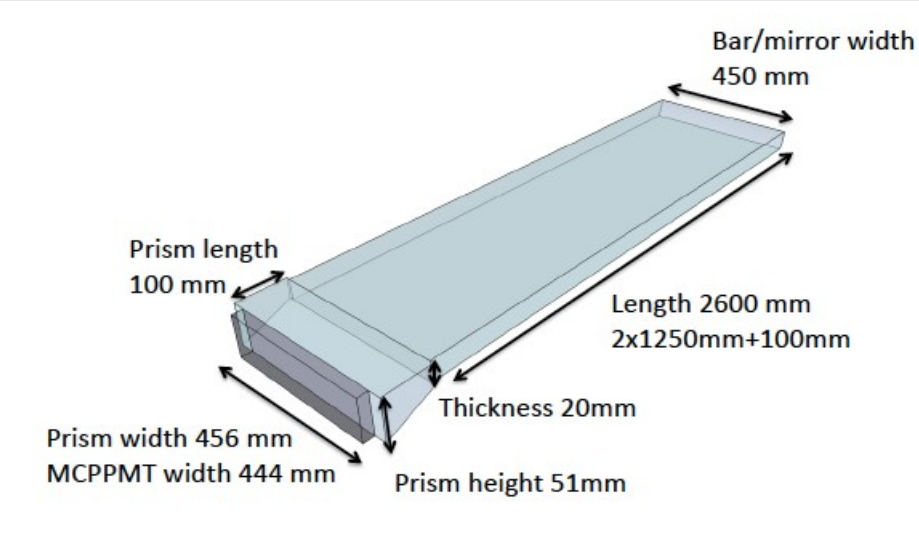






Quartz

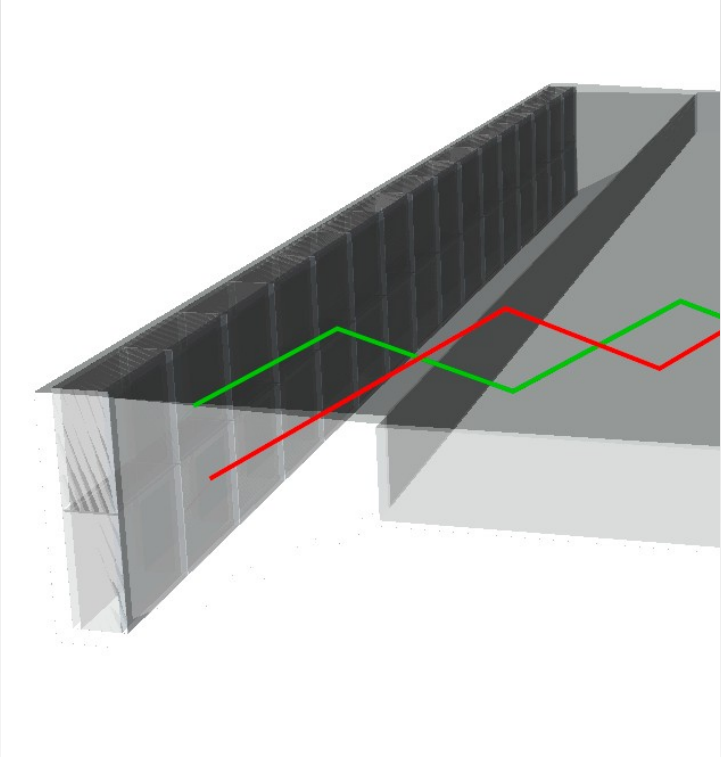
- 32 quartz bars are needed for the full Belle-II detector, each 20×450 ×1250mm^3, with two per module.
- The quartz needs to be of high quality to ensure that photon losses are minimised, and that the Cherenkov photon reflection angles are maintained.



Quartz Property	Requirement
Flatness	<6.3μm
Perpendicularity	<20 arcsec
Parallelism	<4 arcsec
Roughness	< 0.5nm (RMS)
Bulk transmittance	> 98%/m
Surface reflectance	>99.9%/reflection

Photon Detection

- Photons are detected by an array of 32 Micro Channel Plate Photomultipler Tubes (MCP-PMT) in each module.
- Each MCP-PMT has an active area of ~23×23mm^2.
  - NaKSbCs photocathode.
  - Readout via 4×4 channels – 512 total channels per TOP module.
- PMTs required to have a peak quantum efficiency of >24%, and a collection efficiency of ~55%.
  - PMTs have a gain of ~2×10^6 at operating HV, and an intrinsic transit time spread of ~40ps.



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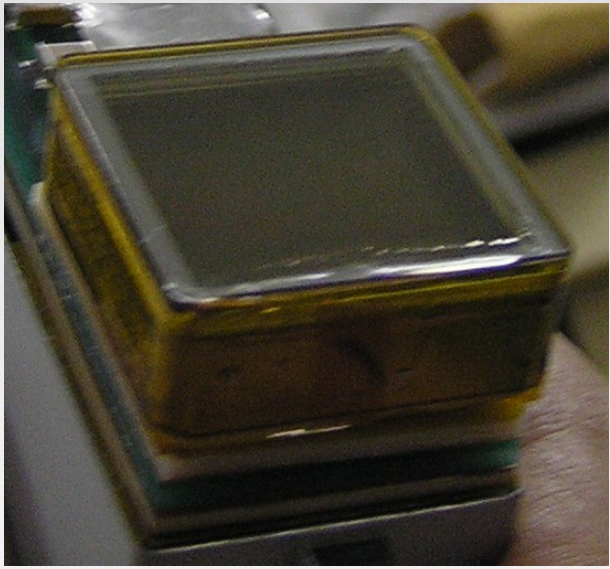
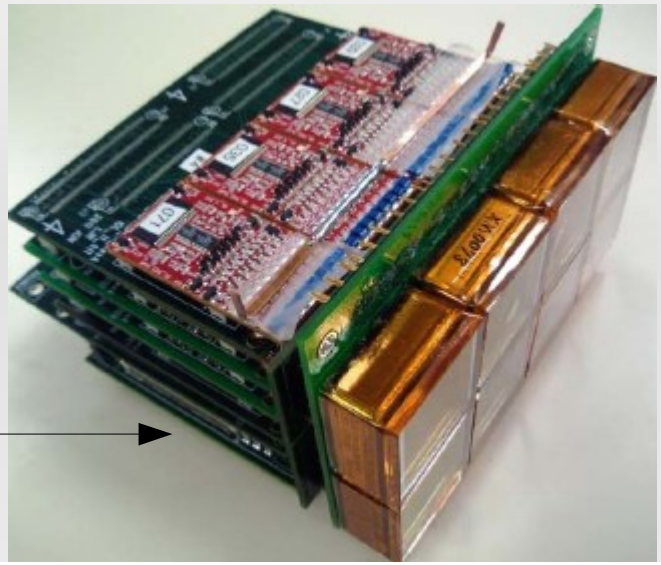
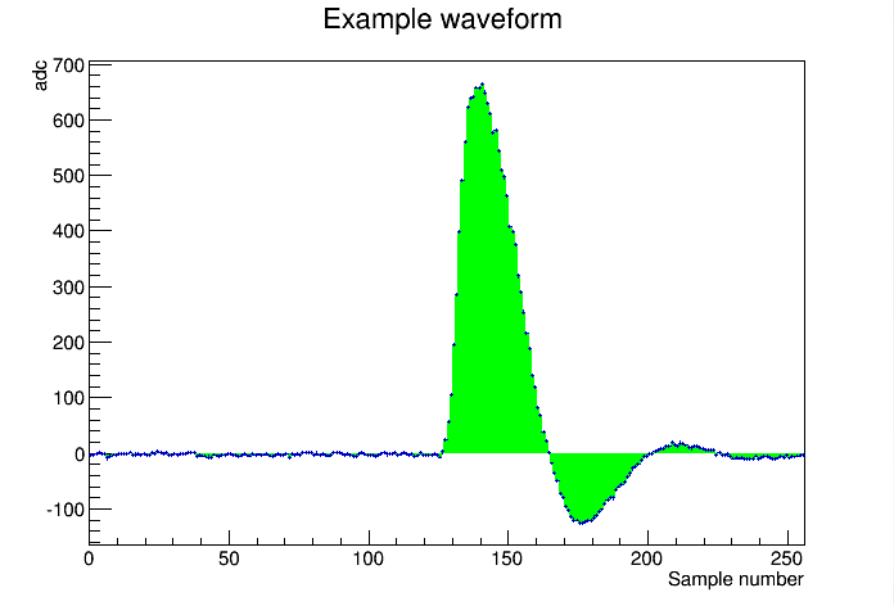


Electronics

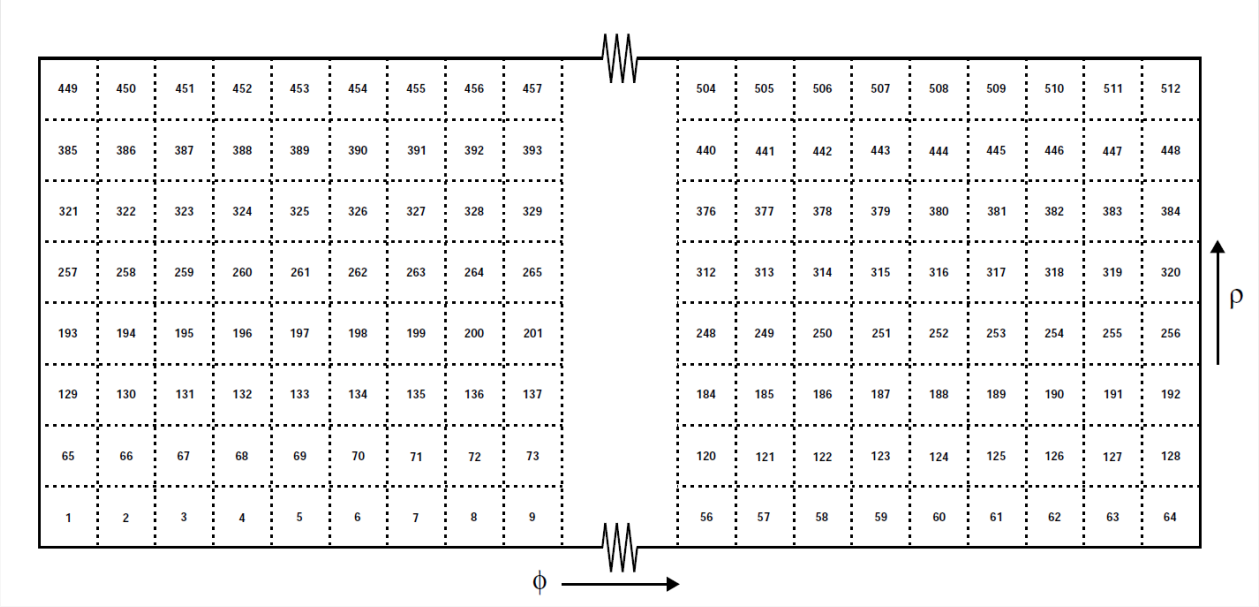
- The PMTs are readout by electronics including waveform sampling ASICs (IRS3B).
  - Two ASICs are used to readout each PMT.
  - These are assembled into readout modules, each with 8 PMTs/16ASICS.
  - 4 readout modules per iTOP module.
- Deposited charge on the PMT anode is converted into a waveform.
  - Used to determine photon detection time.
  - Time resolution goal of 50ps.
- System needs to be calibrated for optimum performance.





Ring images

- Each detected photon is identified by a time and a position within a module (plus charge and waveform quality values).
- Plotting time against position gives a representation of the Cherenkov ring.
- The two dimensional array of PMT channels is mapped to a single channel/pixel number parameter (1 to 512).
  - Seven discontinuities between rows.



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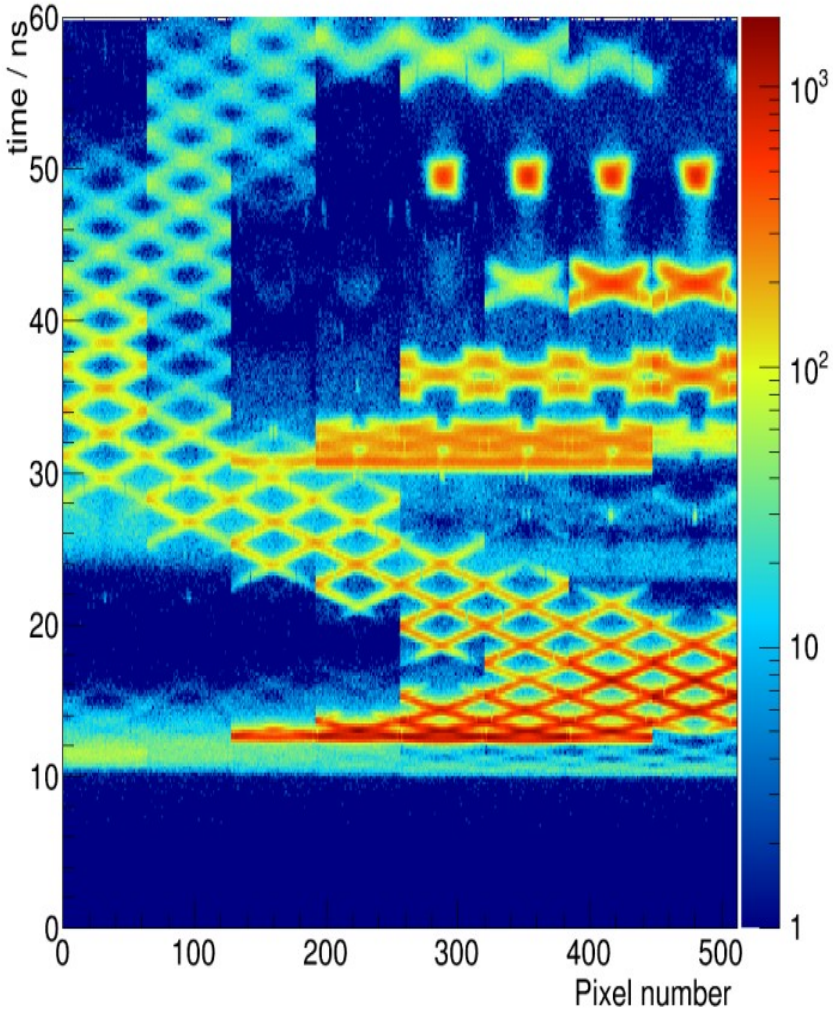
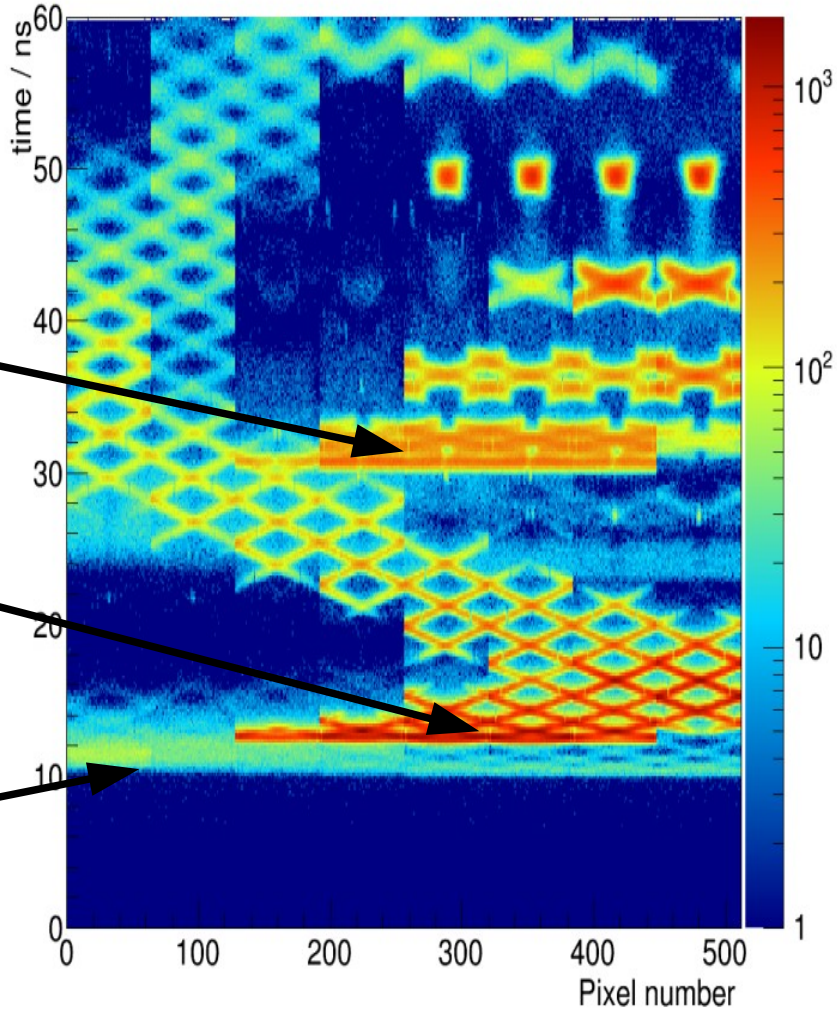
Example ring image



Ring images

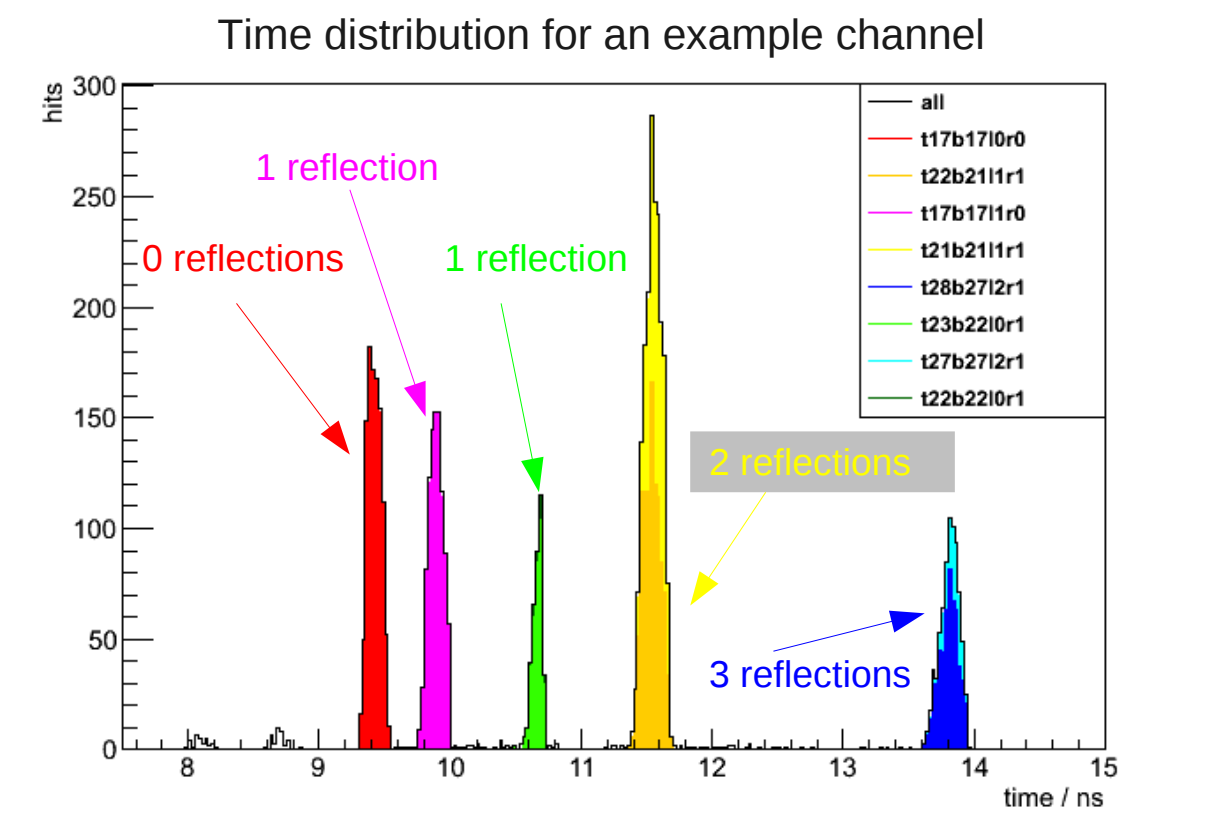
- Example ring image is shown for tracks hitting the quartz bars at normal incidence.
- It includes both photons that have reflected back from the mirror.
- And photons that have travelled to the PMTs directly.
- For other incident angles only direct photons or “mirror” photons may be present.
- There is also a contribution from delta rays.

Example ring image



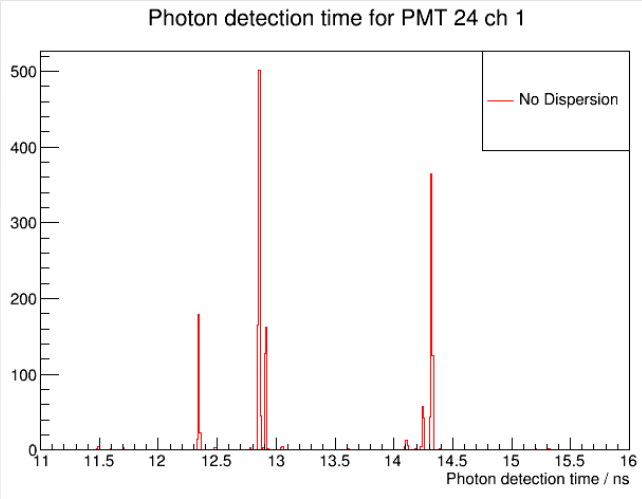
Channel time distributions

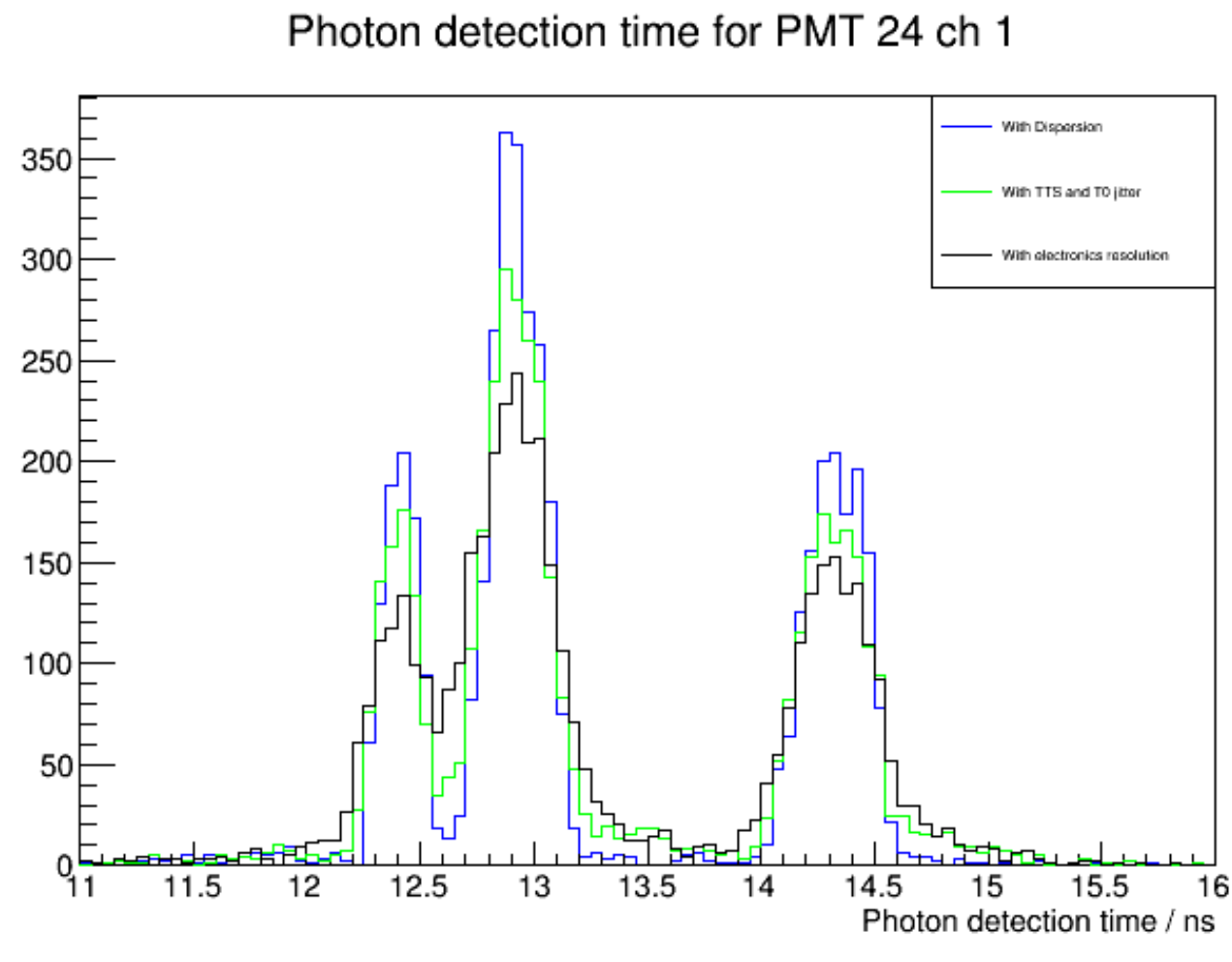
- For each channel there is a time distribution.
- The peaks correspond to different numbers of reflections on the long thin sides of the quartz bar.



Channel time distributions – direct photons

- Individual channels have a time distribution with peaks, corresponding to different numbers of reflections.



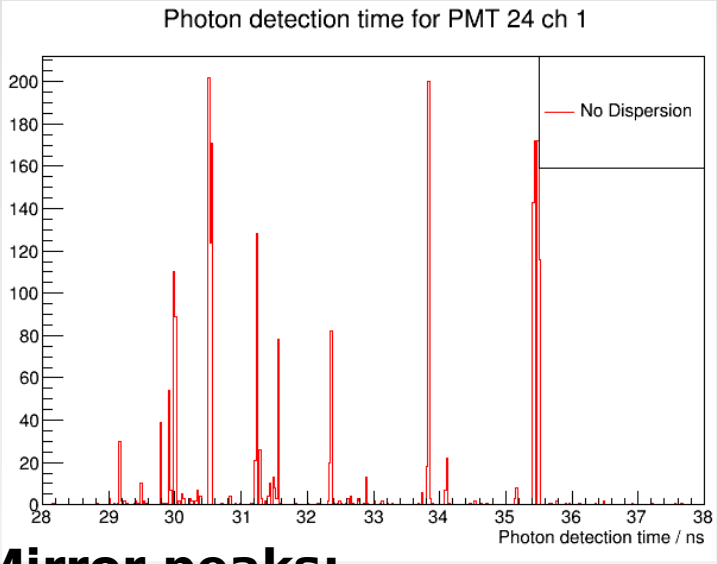


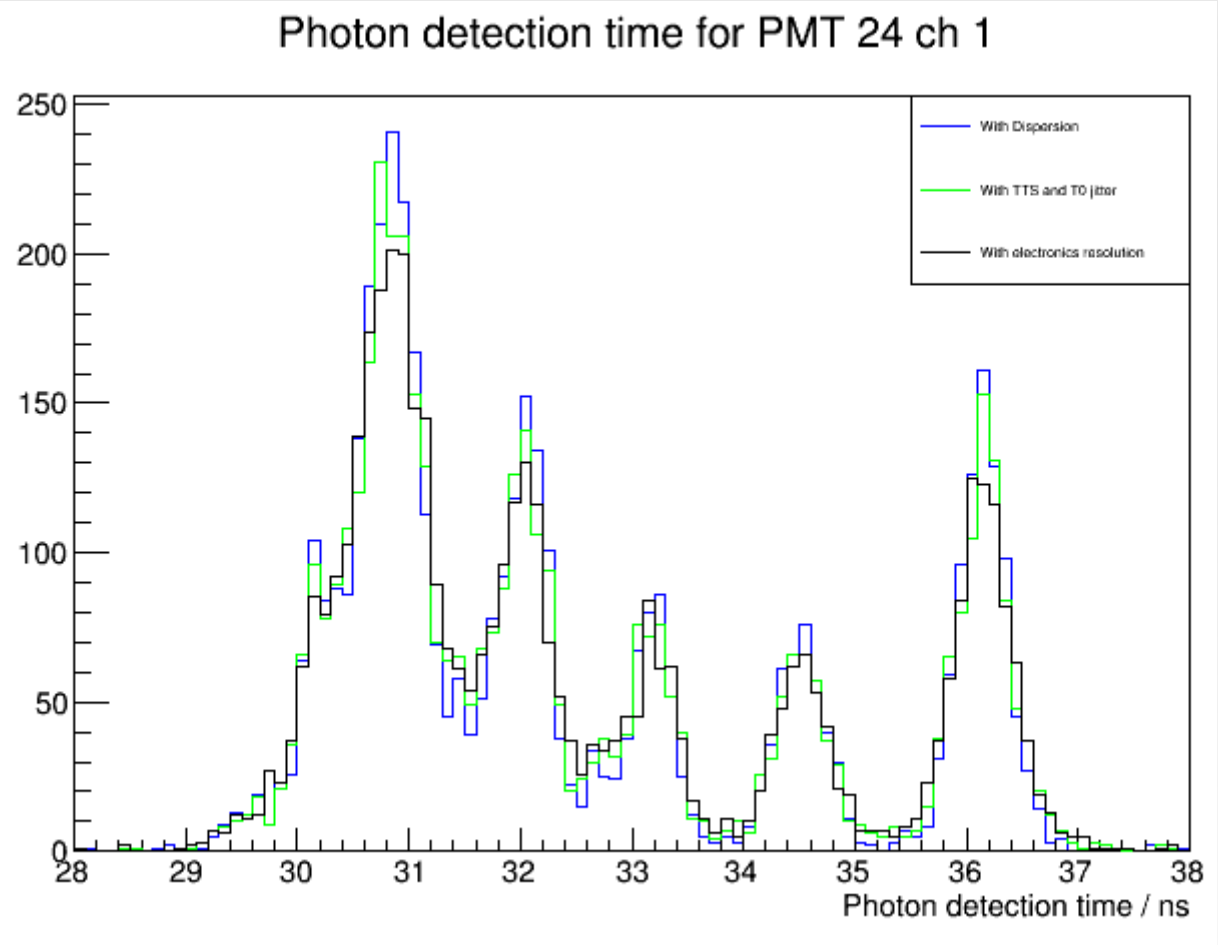
Normal Incidence
1st peak width:

No dispersion:	6-8ps
With dispersion:	90-100ps
+TTS/T0 jitter:	110-120ps
+ electronics:	120-150ps

Channel time distributions – “mirror” photons

- Individual channels have a time distribution with peaks, corresponding to different numbers of reflections.





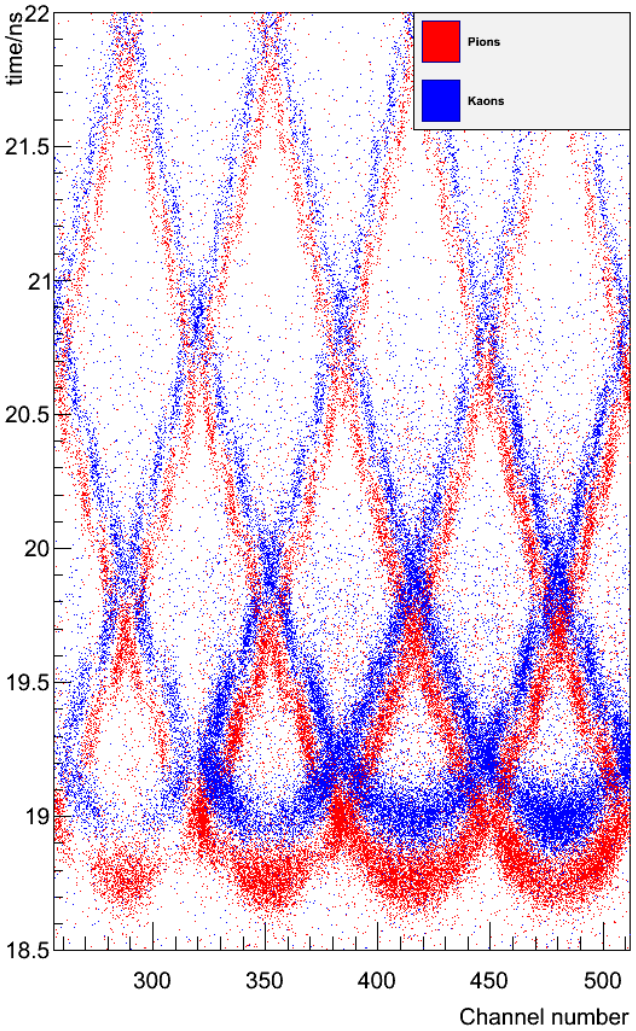
Mirror peaks:

No dispersion: 6-8ps
With dispersion: 300-350ps
+TTS/T0 jitter: 300-350ps as above plus 0-10ps
+ electronics: 300-350ps as above plus 10-20ps

Kaon/Pion separation

- The primary use for the TOP will be to discriminate between kaons and pions.
- A 2-dimensional PDF can be constructed based on detection time and detection position of Cherenkov photons.
- The different Cherenkov angle for photons from kaons leads to a later arrival time than for photons from pions.
- The TOP readout needs to have excellent time resolution to distinguish between particle types, with a requirement of better than 100ps, and a goal of 50ps.
- Final PID performance will also include information from other subdetectors, e.g. dE/dx to form a likelihood for each particle hypothesis.

Photon detection time vs channel number (zoom)



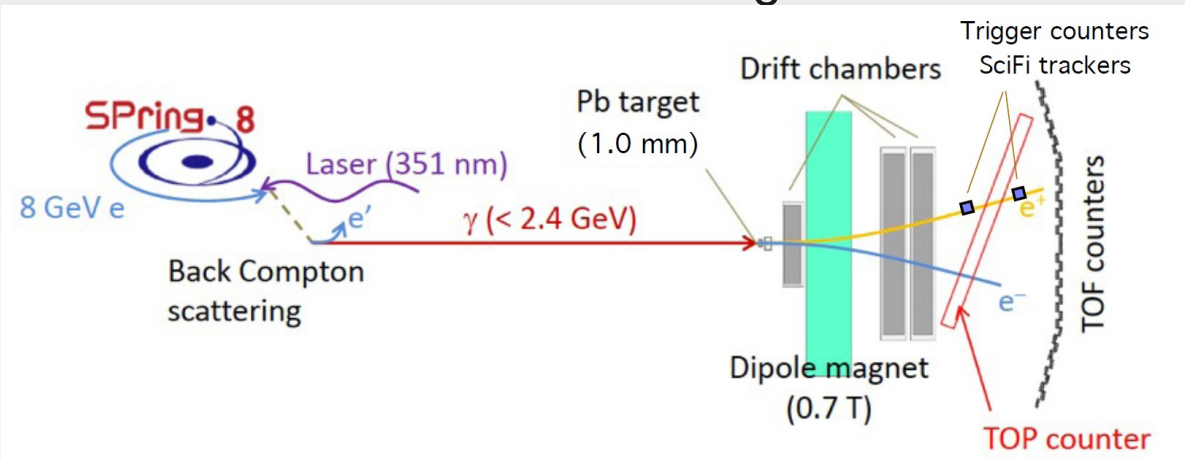
TOP performance

- Preliminary estimates of the TOP performance from Belle II Geant 4 simulation.

Decay mode Preliminary	π efficiency with 2% K fakes π rate 100ps electronics jitter	π efficiency with 4% K fakes π rate 100ps electronics jitter
$B \to \pi\eta\gamma$ vs $K\eta\gamma$	84.28 +/- 0.91	94.13 +/- 0.57
$B^+ \to \rho\gamma$ vs $K^*\gamma$	80.71+/-1.07	93.19+/-0.67
$B^0 \to \rho\gamma$ vs $K^*\gamma$	81.50+/- 0.78	92.63+/-0.49
$B^+ \to \pi\pi\pi^0\gamma$ vs $K\pi\pi^0\gamma$	83.55+/-0.76	94.03+/-0.46
$B^0 \to \pi\pi\pi\gamma$ vs $K\pi\pi\gamma$	79.50 +/- 0.67	91.48+/-0.45
$B^+ \to \pi\pi\pi\pi^0\gamma$ vs $K\pi\pi\pi^0\gamma$	75.00+/-0.72	90.50 +/-0.44
$B^0 \to \pi\pi\pi\pi\gamma$ vs $K\pi\pi\pi\gamma$	76.33+/-0.37	90.00+/-0.33

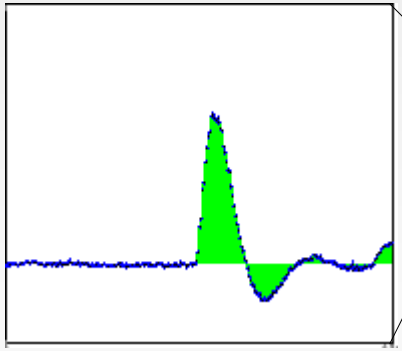
Beam test at SPring-8

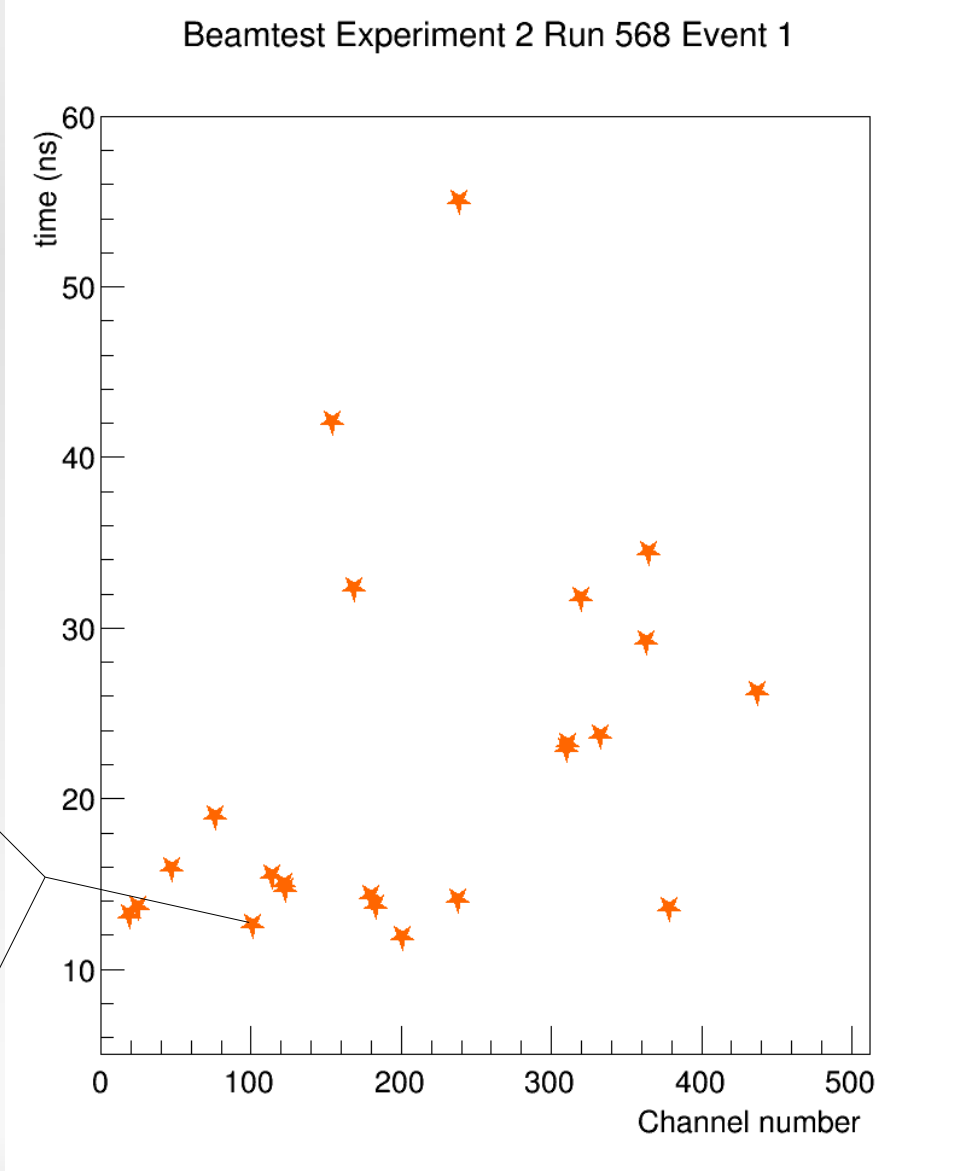
- Beam test in June 2013 at the LEPS beamline at SPring-8 in Japan.
- Used a positron beam with energy ~2.1GeV.
- Prototype iTOP module was placed in LEPS experiment – LEPS subdetectors used to provide tracking and momentum information.
- Data taken with beam hitting module at normal incidence and at forward angles.



Beam Test Single Event

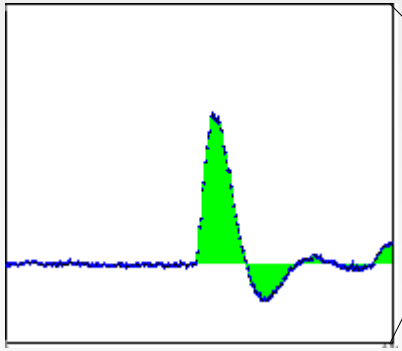
- Single events have a mean of ~30 Cherenkov photons detected.
  - Each waveform yields a hit time.
  - Multiple events are required in order to see a ring image.

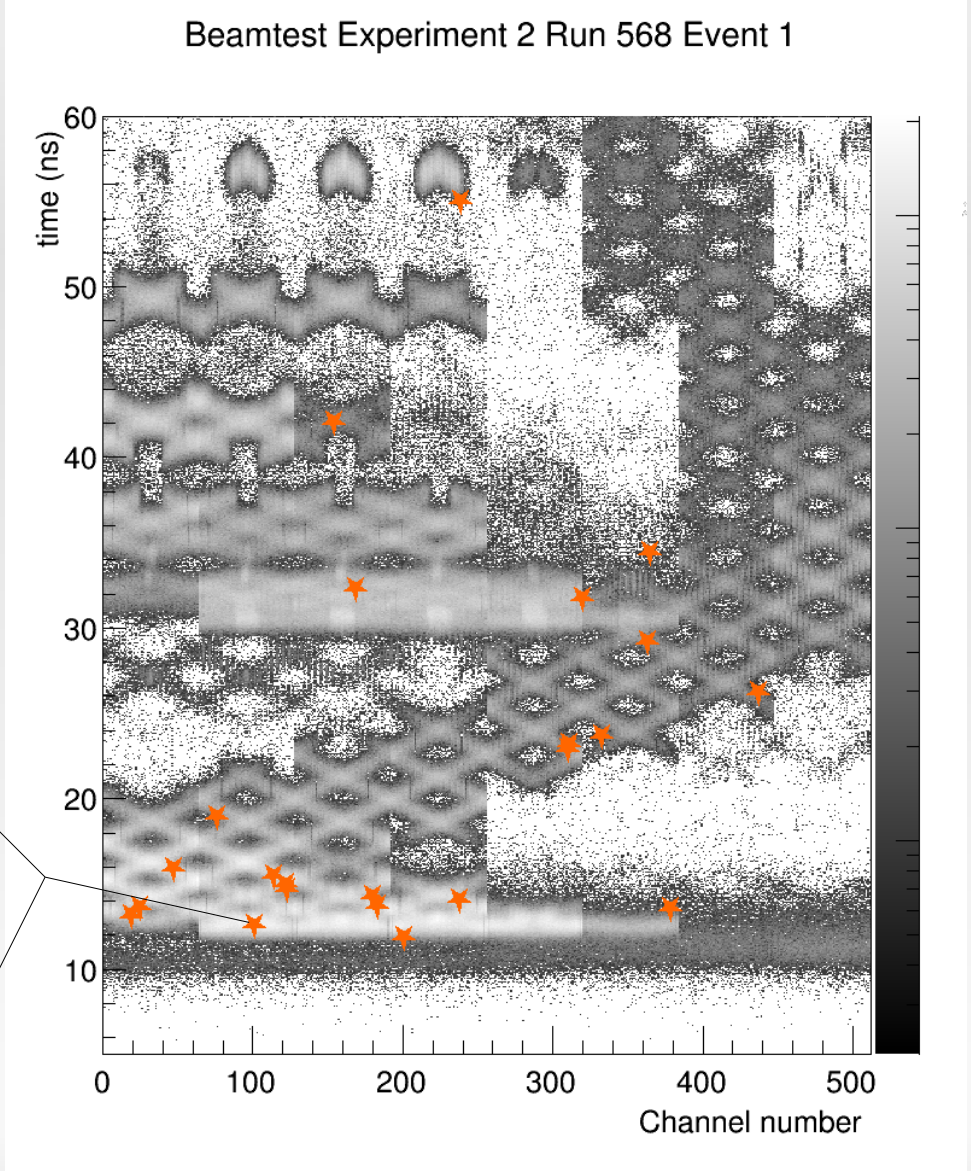




Beam Test Single Event

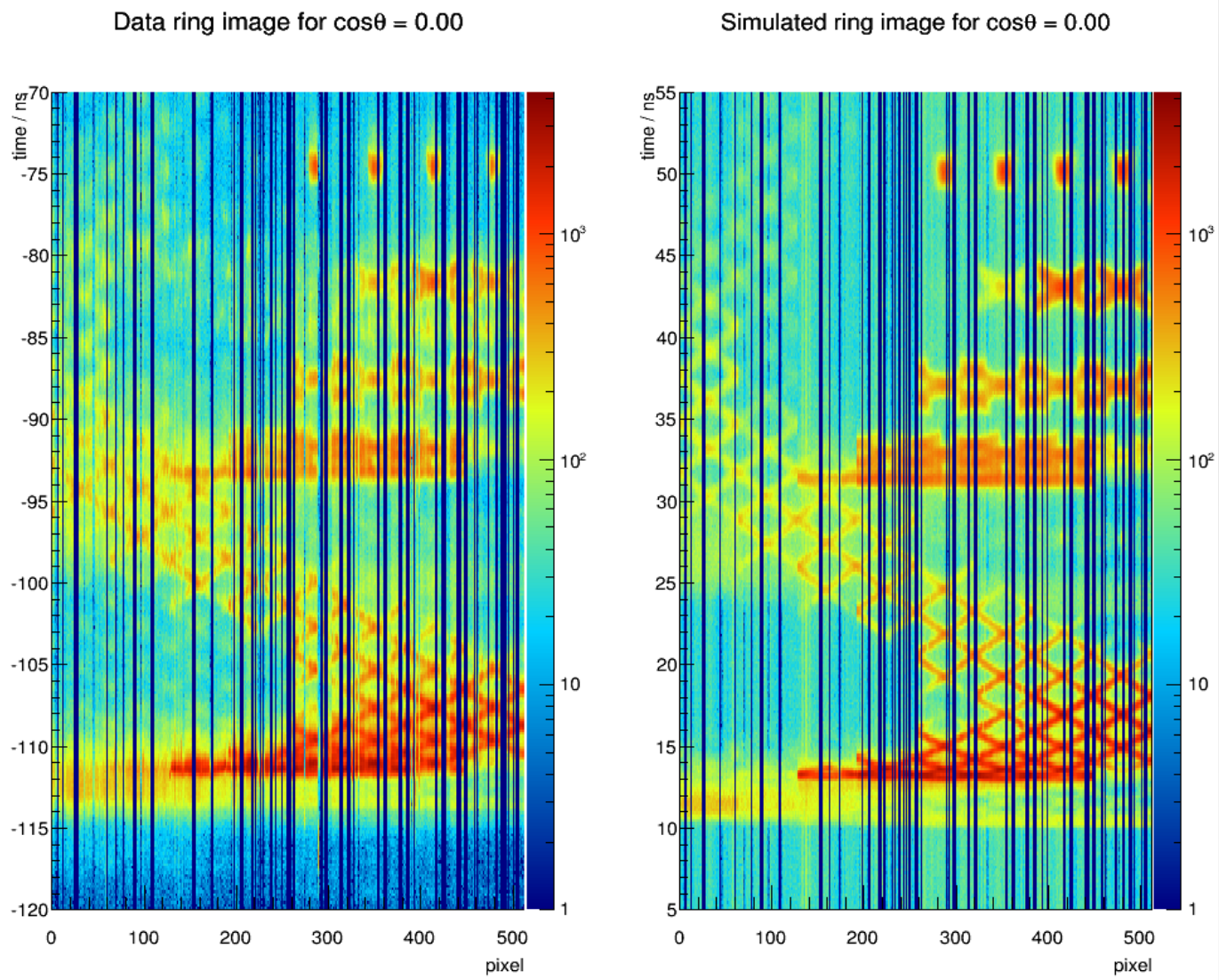
- Single events have a mean of ~30 Cherenkov photons detected.
  - Each waveform yields a hit time.
  - Multiple events are required in order to see a ring image.
- Greyscale image shows expected distribution from simulation.





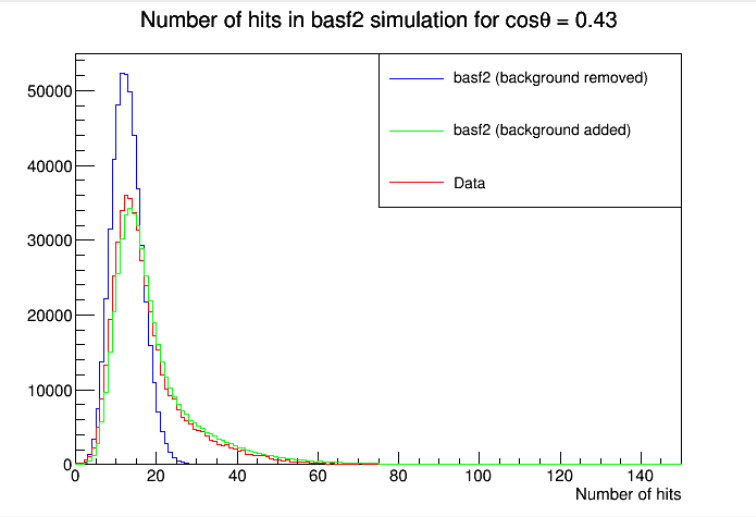
Beam test data/MC comparison

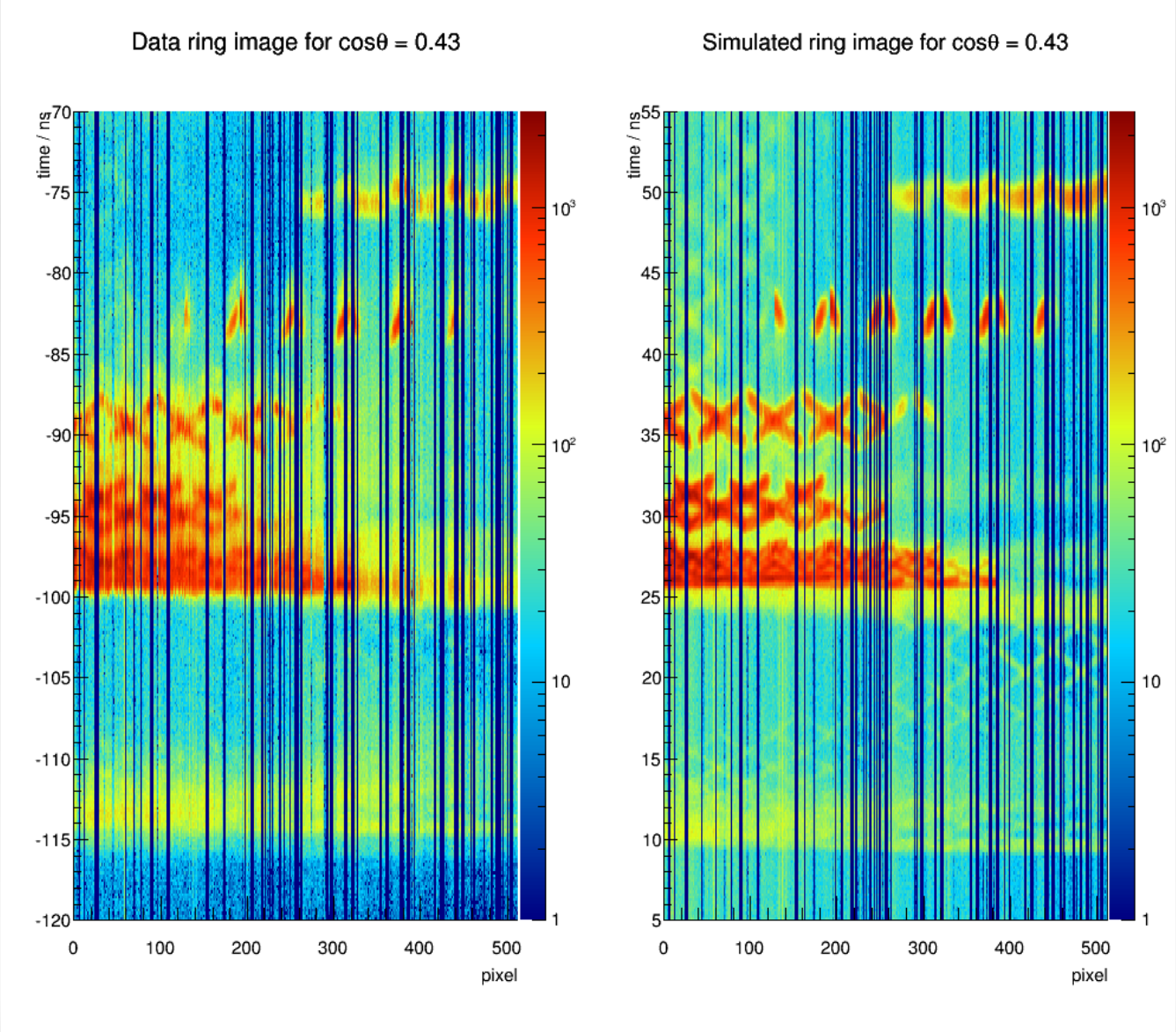
- Comparison between data and MC for beamtest with normally incident beam.
- The MC consists of events generated with Belle II Geant4, with additional backgrounds simulated using data driven background estimates.



Beam test data/MC comparison

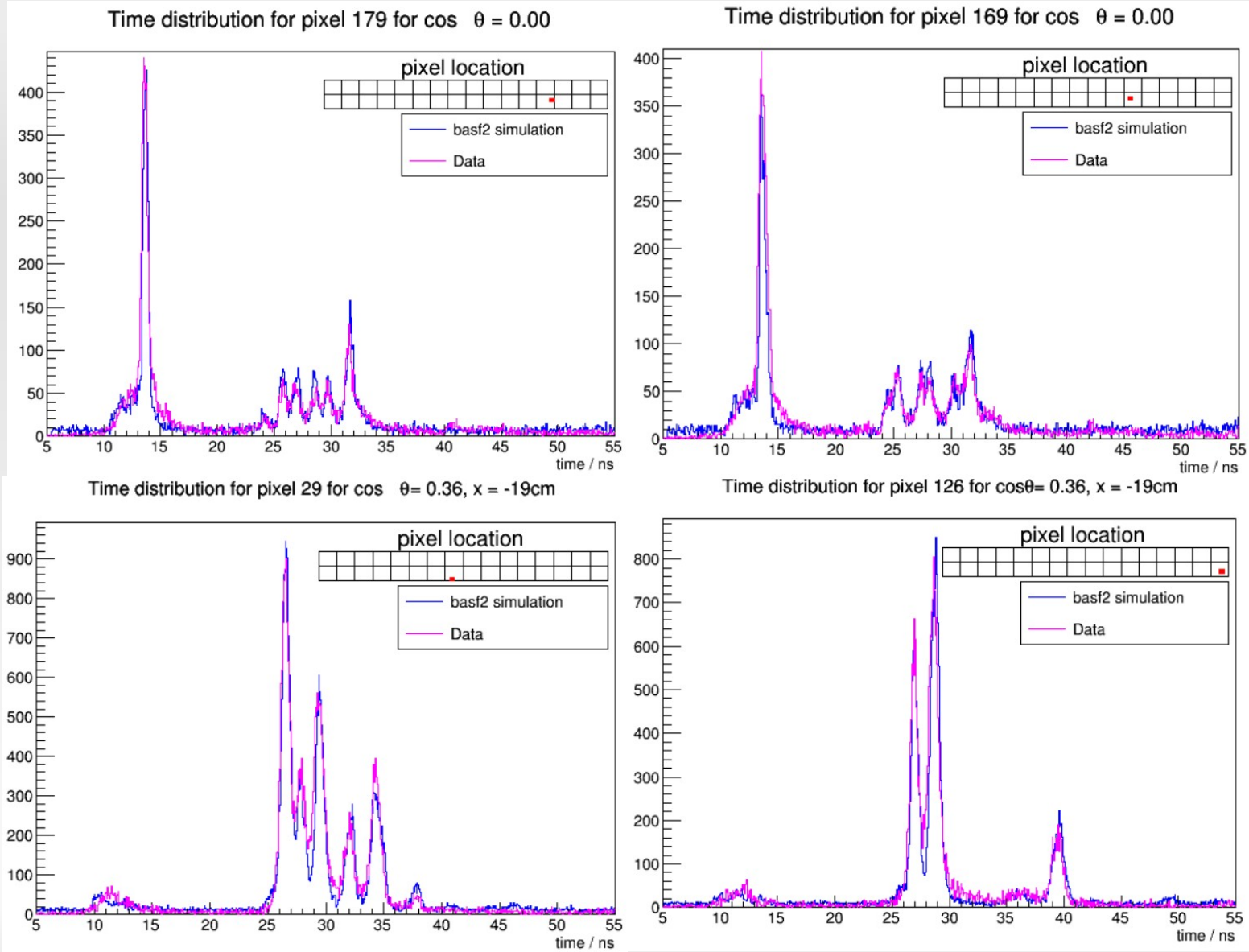
- Comparison between data and MC for beamtest with a beam hitting the quartz at a forward angle.





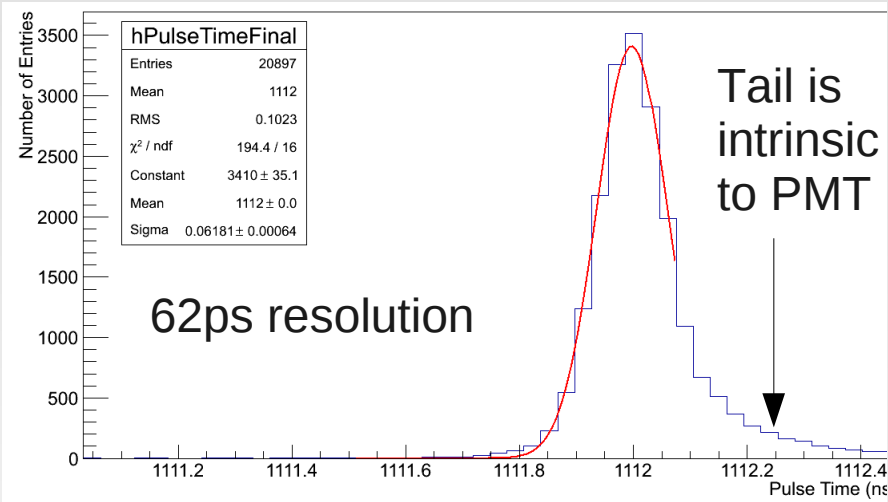
Channel Time distributions

- Time distributions for individual channels recorded during the beam test.
- Comparison is between data and Belle II Geant4 simulation with additional backgrounds simulated using data driven methods.



Beam test summary

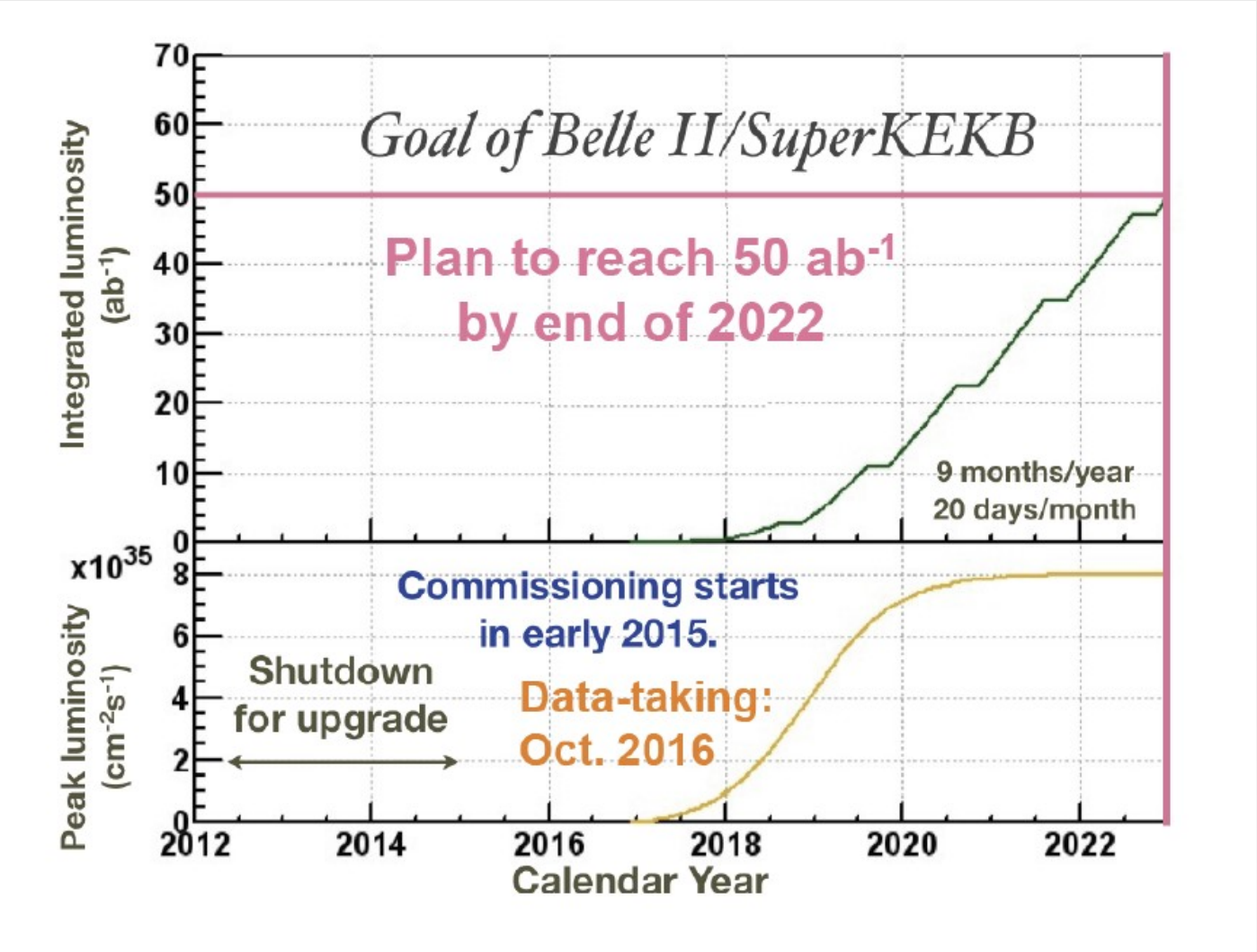
- The beam test at SPring-8 was the first test of the full TOP system.
  - Both electronics and optics were tested.
  - Electronics had a timing resolution of 100ps, meeting requirements.
  - Subsequent testing of the electronics with a laser has achieved close to goal of 50ps resolution.



- The prototype module has been moved to KEK where it is being tested with cosmic rays.
- A cosmic ray test stand is being commissioned which will be used to test every TOP module before installation.

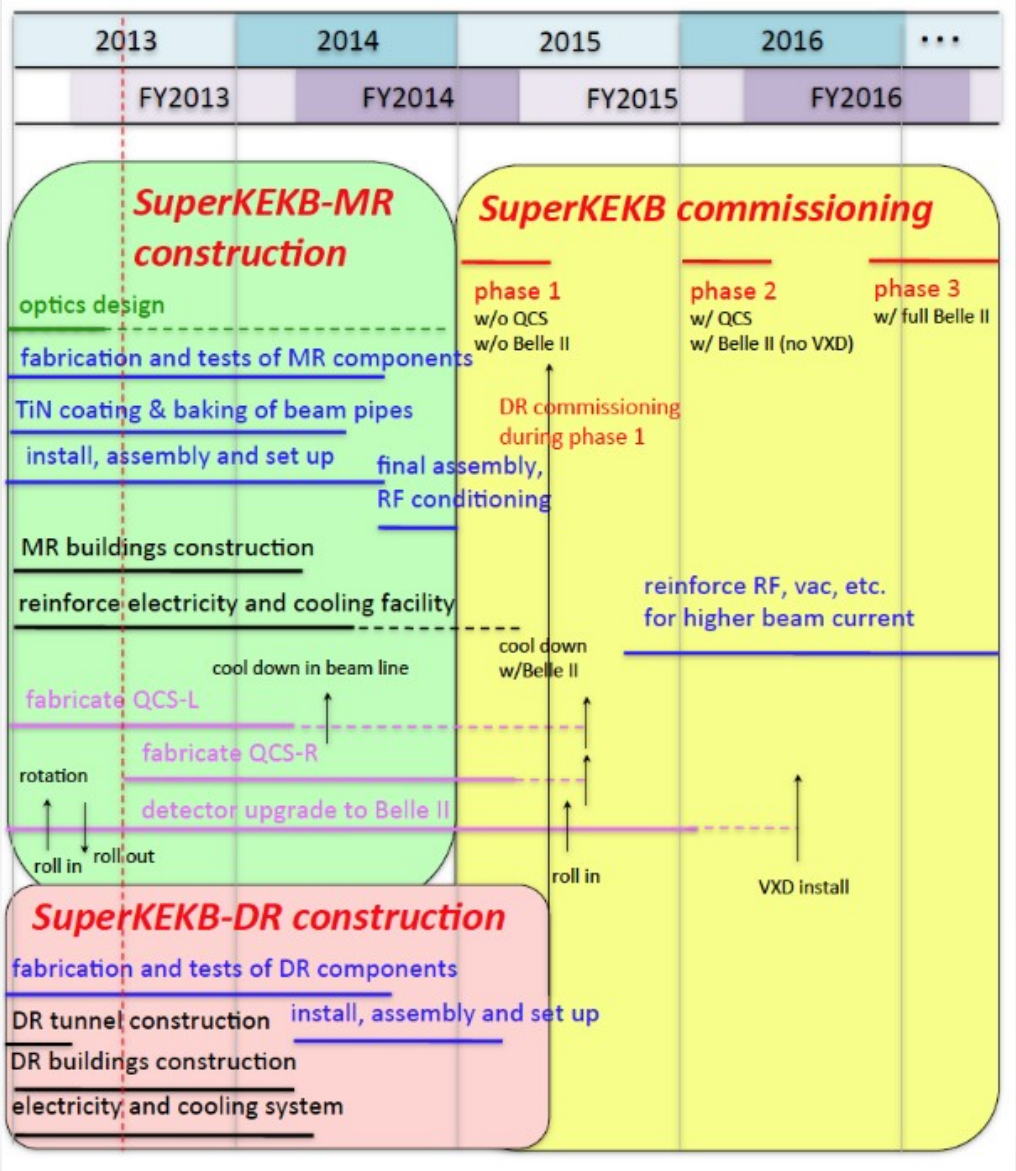
Schedule

Schedule


Goal of Belle II/SuperKEKB
Plan to reach 50 ab-1
by end of 2022
9 months/year
20 days/month
Integrated luminosity
(ab-1)
70
60
50
40
30
20
10
0
x10^35
8
6
4
2
0
Peak luminosity
(cm-2s-1)
Commissioning starts
in early 2015.
Shutdown
for upgrade
Data-taking:
Oct. 2016
2012
2014
2016
2018
2020
2022
Calendar Year

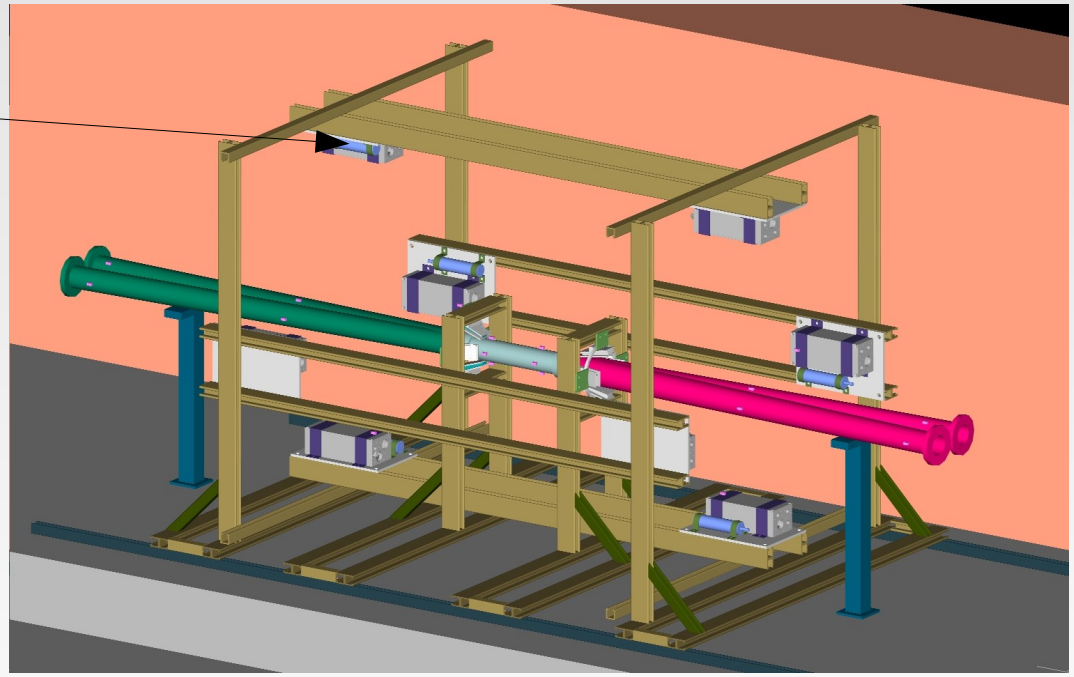
Schedule

- SuperKEKB will start circulating beams in 2015.
- Phase 1: Without Belle II.
- Phase 2: Belle II is rolled in, but without vertex detector.
- Phase 3: With full Belle II.
- Physics data taking will start in late 2016.



Commissioning Detector

- During phases 1 and 2 a commissioning detector will be used – BEAST II (Beam Exorcisms for A Stable ExperimenT).
- Will be used to measure beam backgrounds, before Belle II is rolled in and fully installed.
- Phase 1: 2 MicroTPCs in 8 positions used to measure neutron backgrounds, and PIN diodes used to measure ionising particle backgrounds.
- Every other PIN diode coated in gold paint, to allow for separation of charged particle and x-ray contributions.



Commissioning Detector

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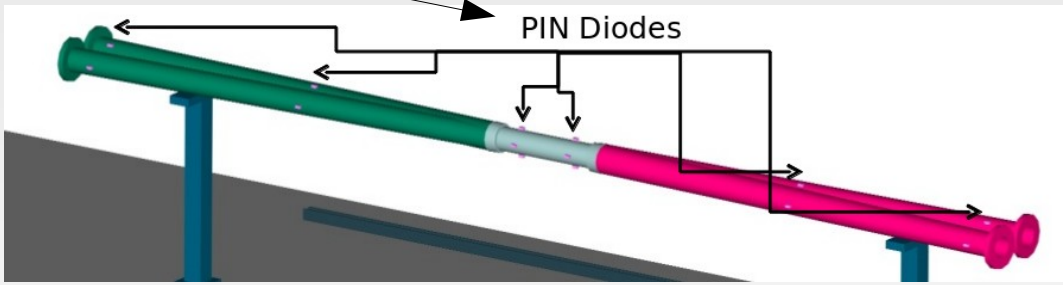
- Will be used to measure beam backgrounds, before Belle II is rolled in and fully installed.
- Phase 1: PIN diodes.
- Phase 2: 8 MicroTPCs and pin diodes used alongside Belle II – vertex detector will not be installed until Phase 3.



Summary

- Belle II will operate at an instantaneous luminosity 40 times higher than its predecessor.
- It is projected to record 50ab^{-1} of data during its lifetime.
  - Allowing for precision measurements with sensitivity to many new physics models.
- The construction of Belle II and superKEKB is well under way,
  - The first sub detectors have been installed.
  - TOP sub detector has been tested at beam test.
- The first beams in superKEKB will be in 2015,
  - And the first physics run is due to start in late 2016.

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ありがとうございました

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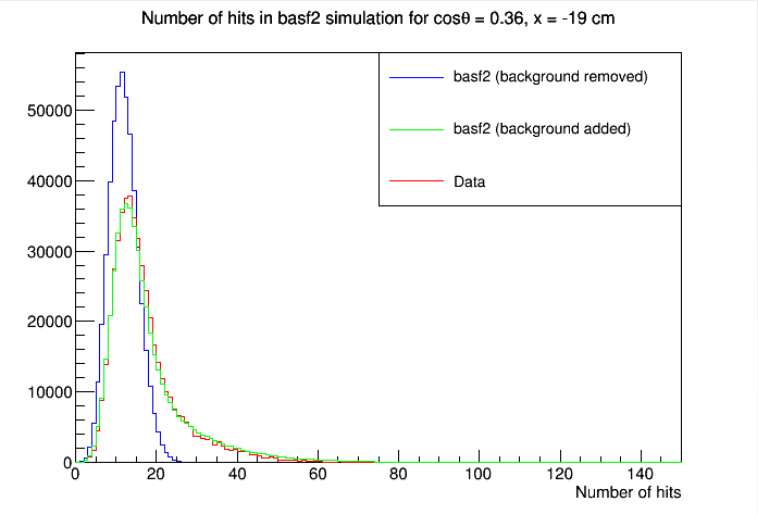
- Thank you for listening,
- And thank you to the many Belle II collaborators whose plots I have shown, including:
  T Browder, S Vahsen, L Piilonen, K Matsuoka, M Petric, T Hara, M Rosen, B Kirby, G Varner, and many others...

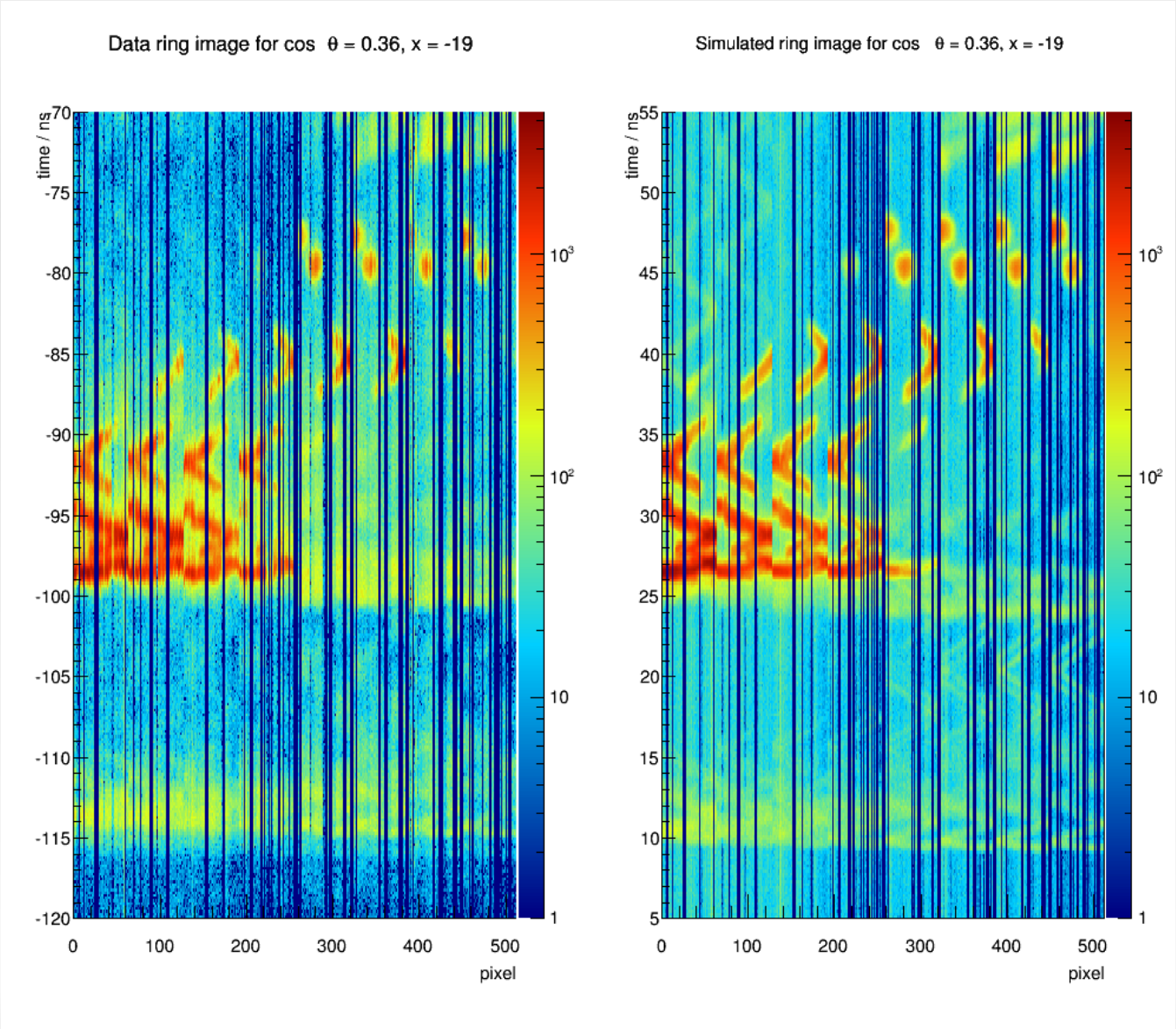

15th Belle II collaboration meeting at VPI, Virginia

Backup

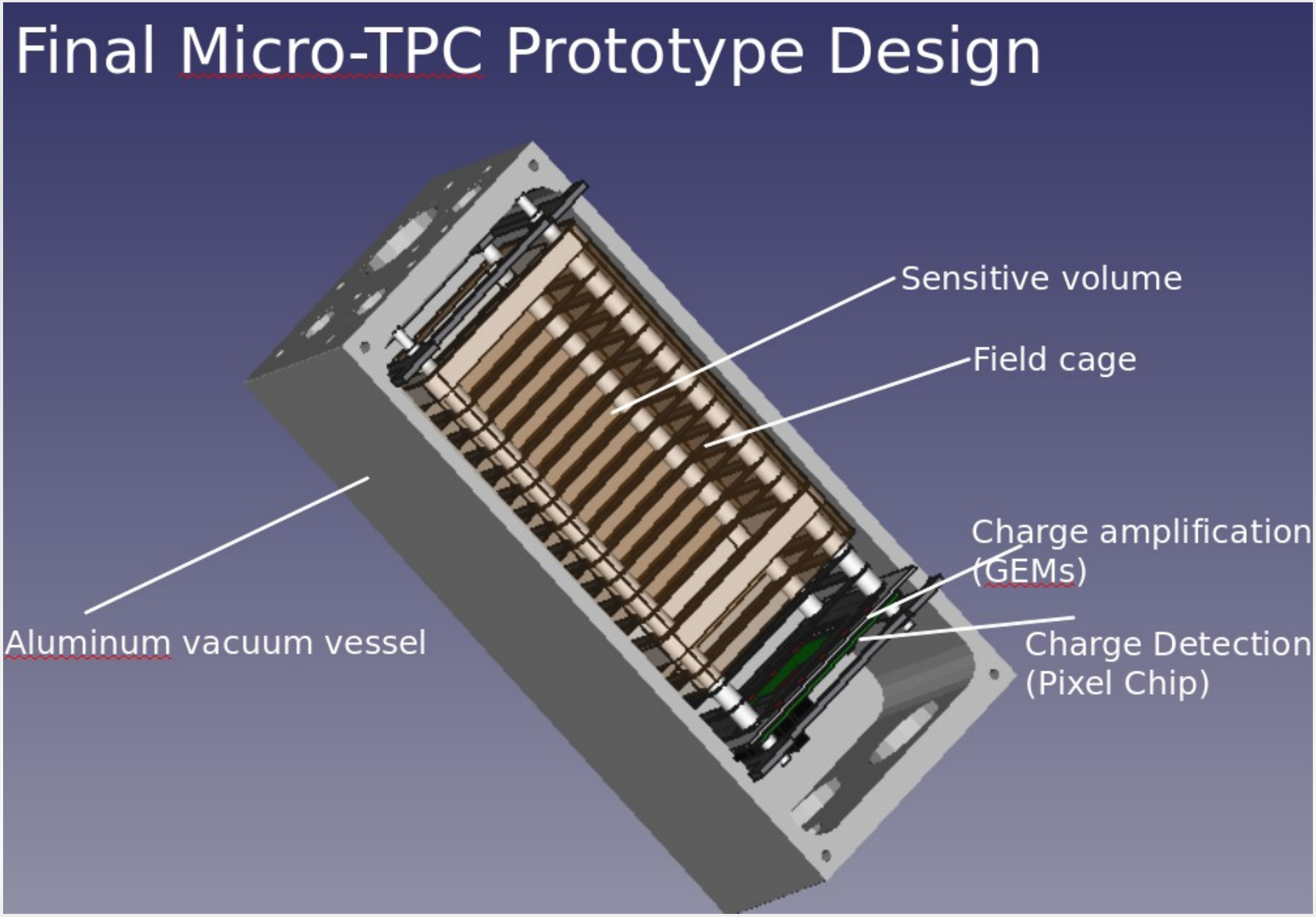
Beam test data/MC comparison

- The comparison between data and MC for beamtest with a beam hitting the quartz at a forward angle is shown.





MicroTPC

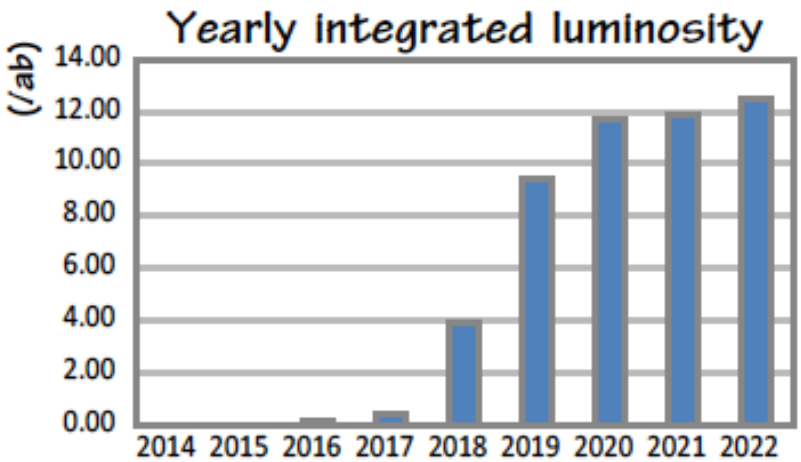

Final Micro-TPC Prototype Design
Sensitive volume
Field cage
Charge amplification
(GEMs)
Charge Detection
(Pixel Chip)
Aluminum vacuum vessel

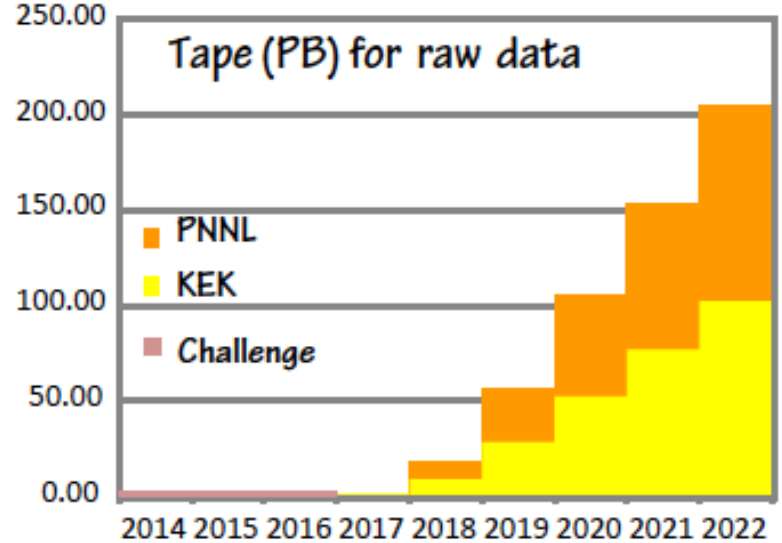
SuperKEKB

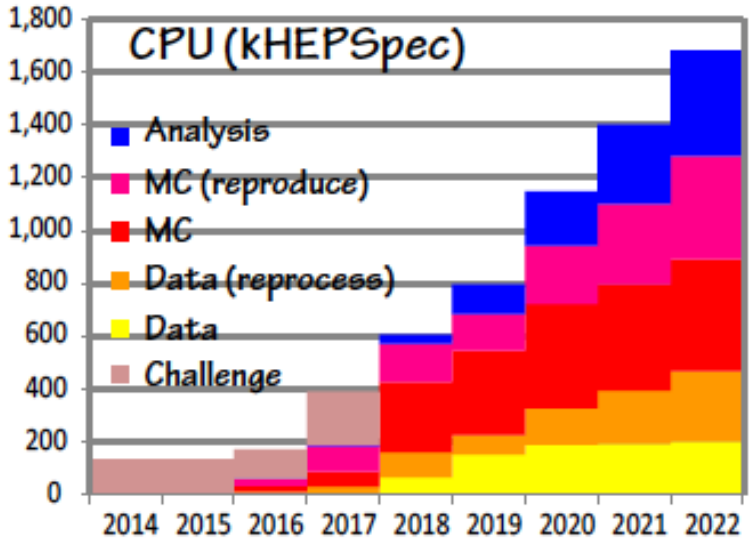
Machine design parameters

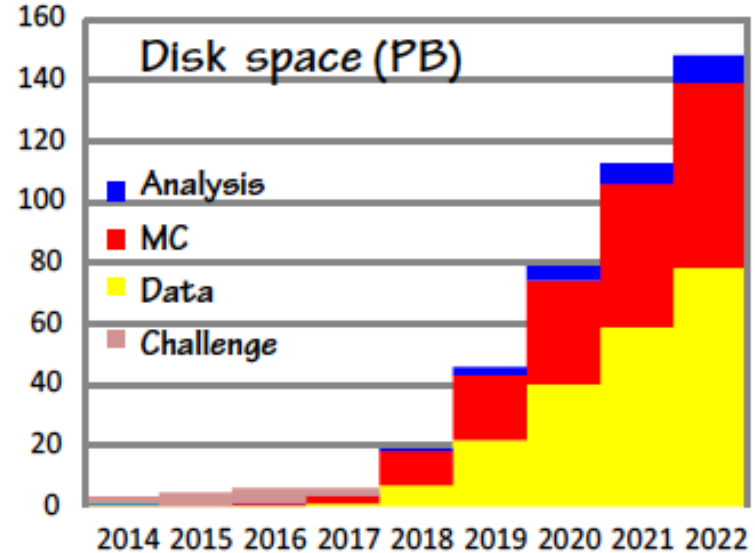
parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7	GeV
Half crossing angle	φ	11		41.5		mrad
Horizontal emittance	ε_x	18	24	3.2	4.6	nm
Emittance ratio	κ	0.88	0.66	0.37	0.40	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
Beam currents	I_b	1.64	1.19	3.60	2.60	A
beam-beam parameter	ξ_y	0.129	0.090	0.0881	0.0807	
Luminosity	**L**	**2.1×10^{34}**		**8×10^{35}**		**$cm^{-2}s^{-1}$**

Hardware Resources for Belle II



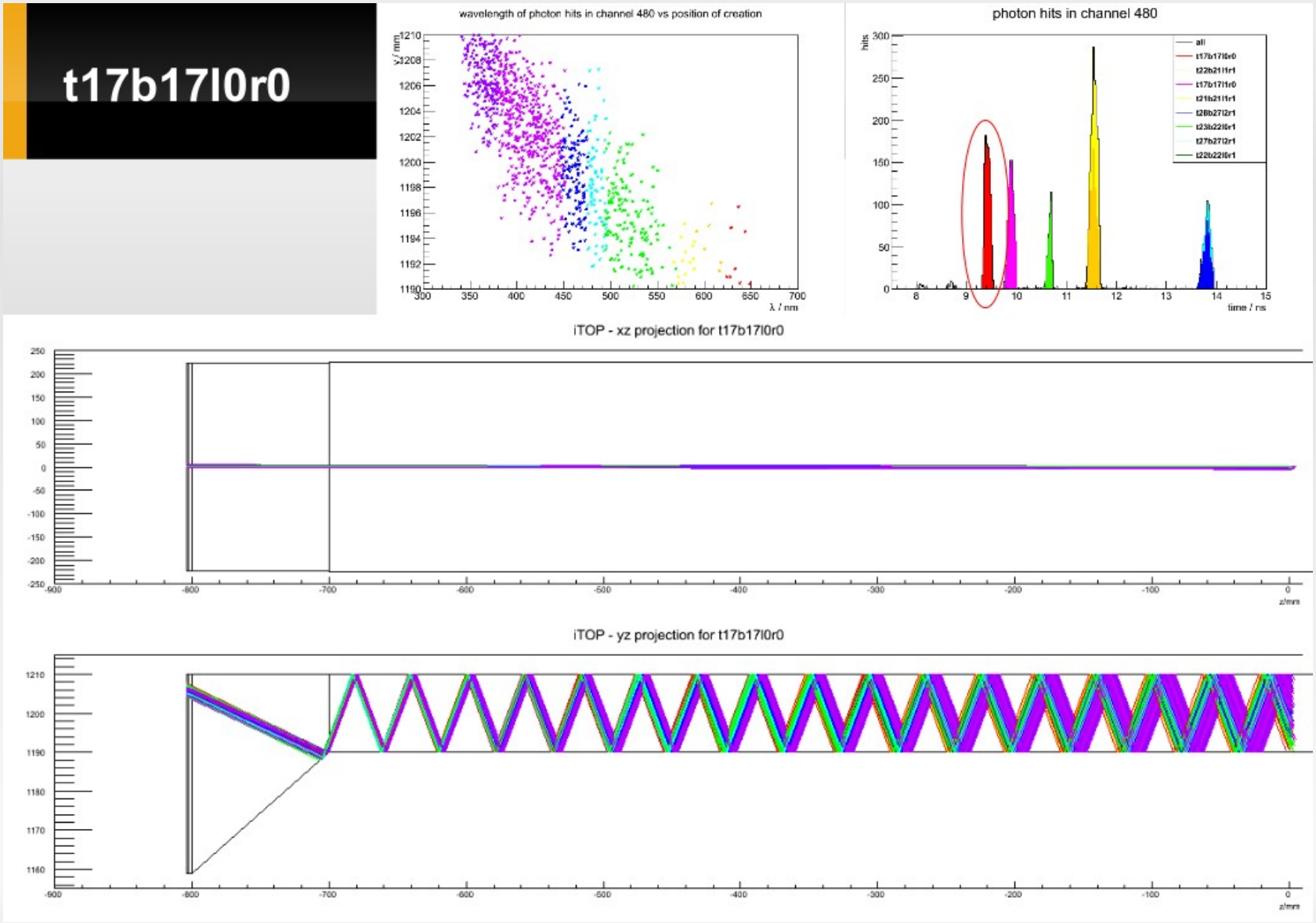




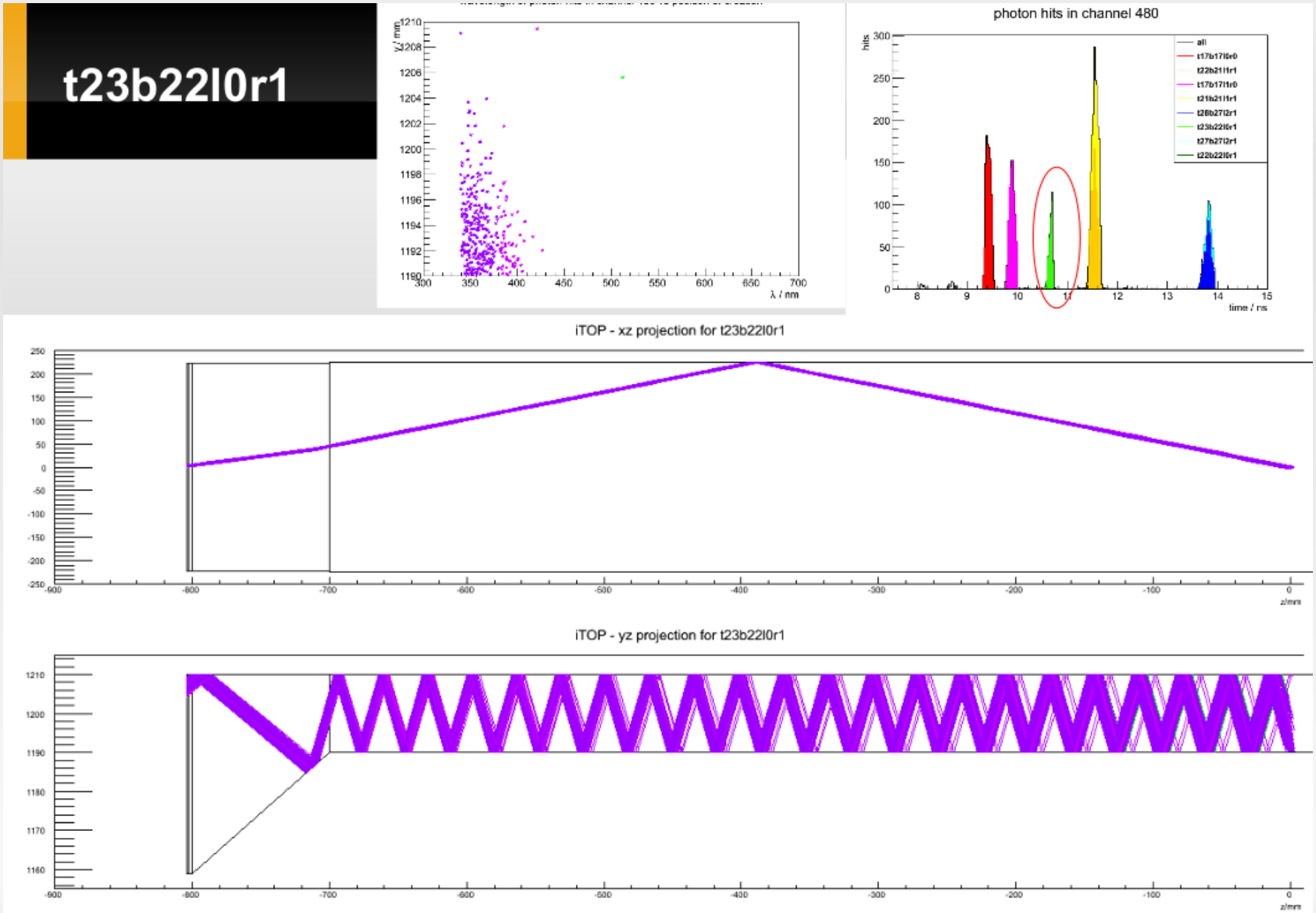


T. Hara et al. (Belle II Computing Steering Group)

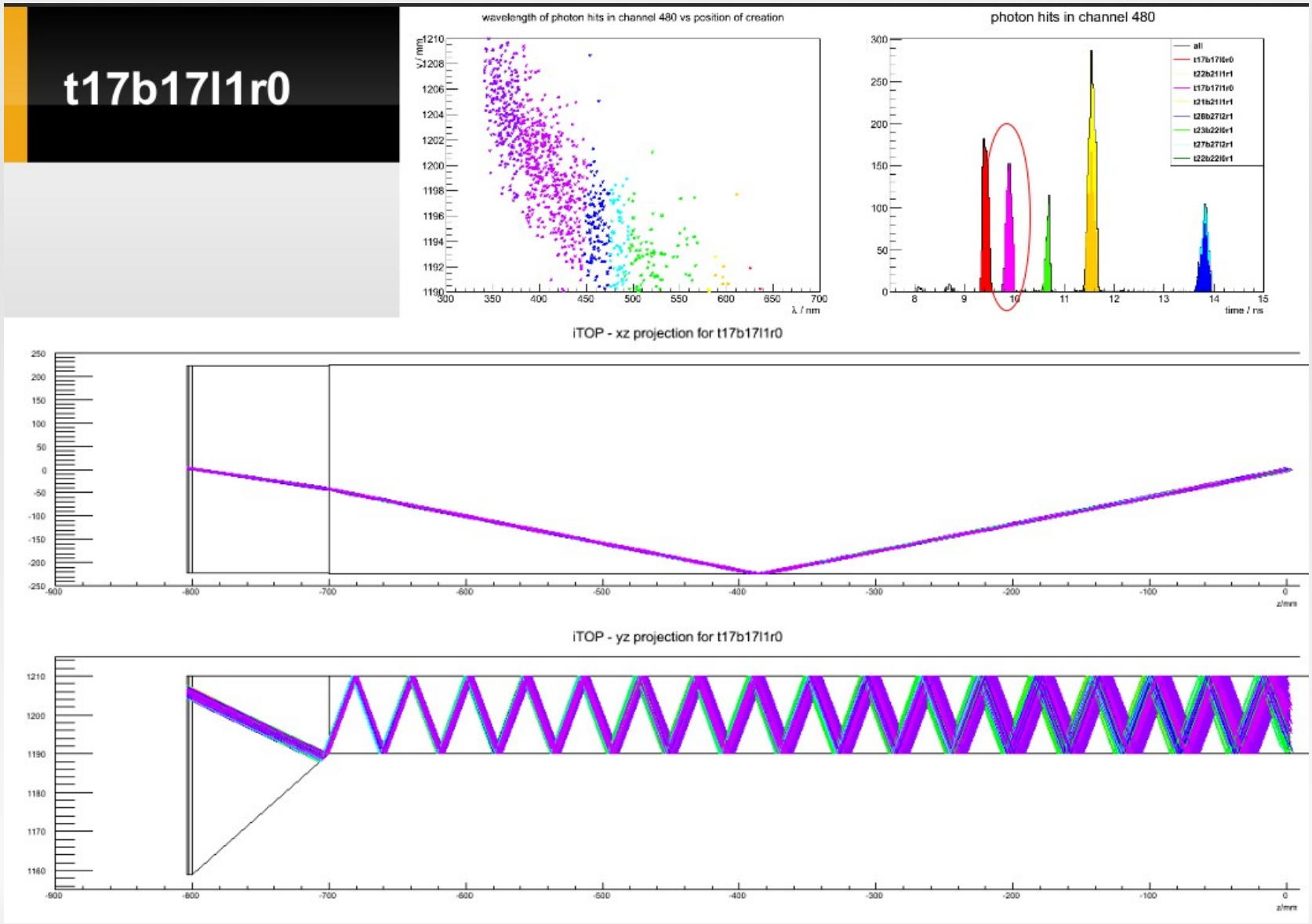
Photon reflections in module



Photon reflections in module



Photon reflections in module



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