THE UNIVERSITY OF BRITISH COLUMBIA

INSTITUTE OF PARTICLE PHYSICS

The ECL: an overview

Christopher Hearty
University of British Columbia/IPP
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Outline

- Introduction
- Signals from individual crystals
- Reconstructing clusters
- Calibration
- Using the ECL

Introduction

The Belle II calorimeter — ECL

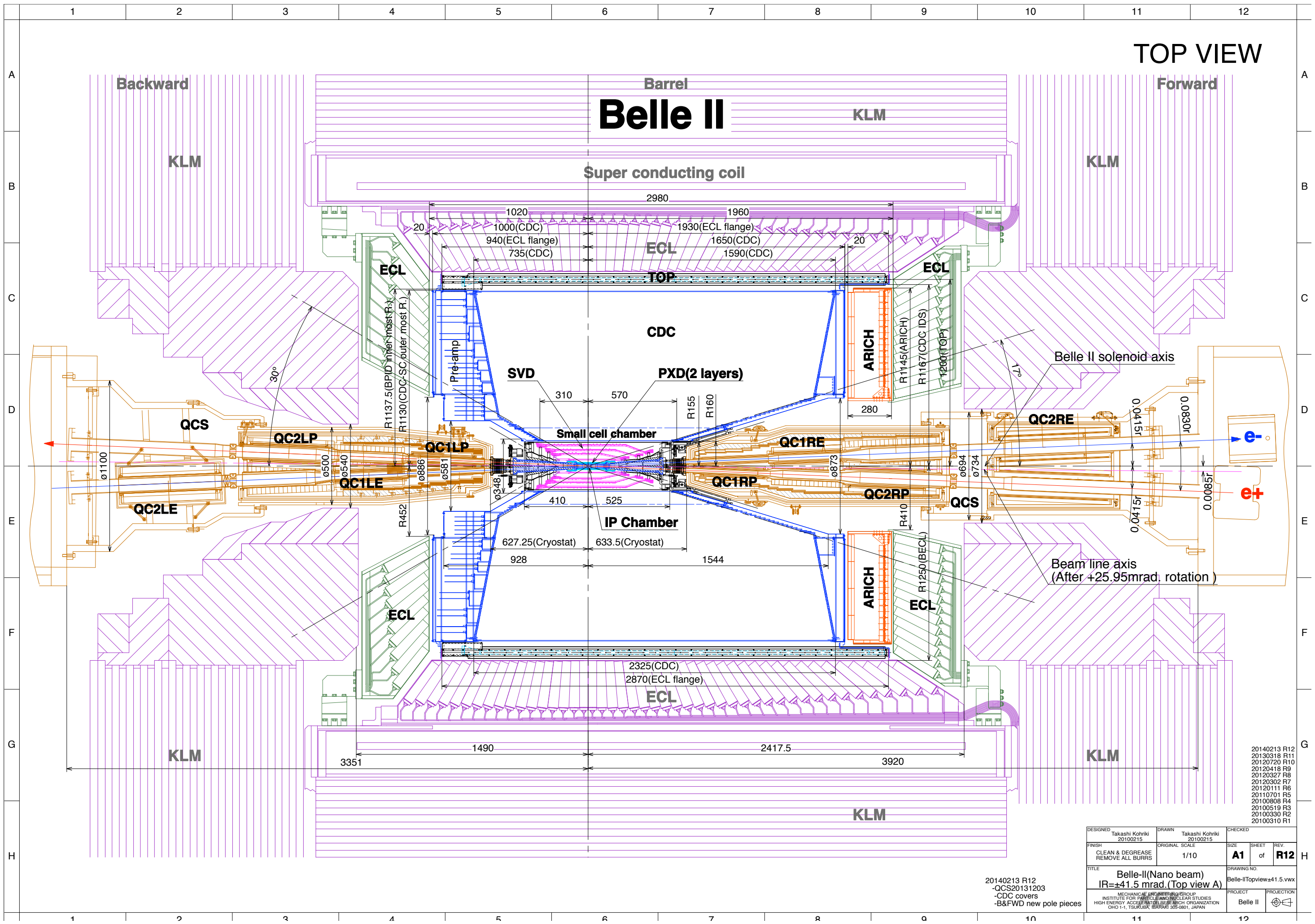
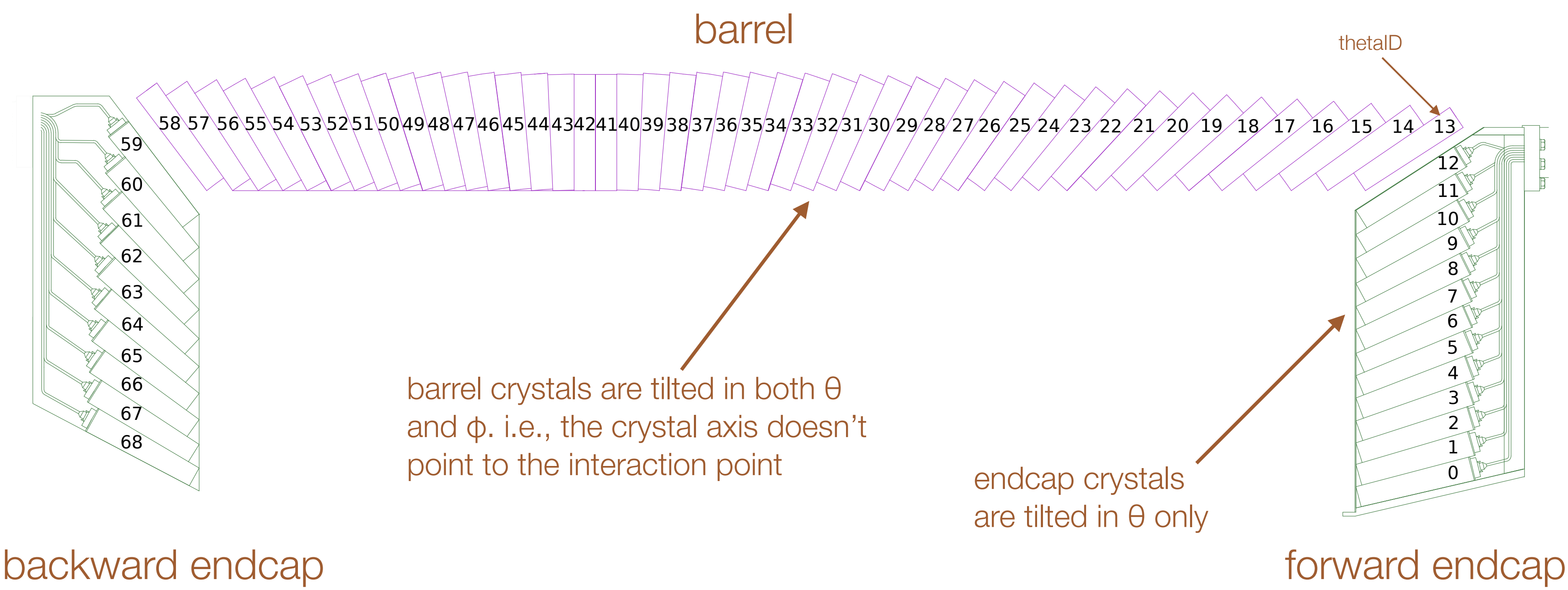


Fig. 3: Belle II top view.

Belle II physics book 1808.10567

- 8736 crystals, CsI(Tl) “Thallium-doped cesium iodide”

- 30 cm long, roughly 5.5 cm × 5.5 cm across



	θ coverage	θ segments	ϕ segments	# of counters
Forward Endcap	12.01° - 31.36°	13	48 - 144	1152
Barrel	32.2° - 128.7°	46	144	6624
Backward Endcap	131.5° - 155.03°	10	64 - 144	960

Hitomi Ikeda PhD dissertation (1999)

- **Question**: why do we tilt the crystals?
- Are there disadvantages to doing this?

Some CsI properties

- Radiation length X_0 = 1.86 cm (our crystals = 16 X_0);
  - characteristic distance for electromagnetic interactions
- Molière radius = 3.53 cm (our crystals ~1.5× this);
  - transverse size of an electromagnetic shower
- Hadronic interaction length for pions = 44 cm
  - about 50% chance of a charged pion undergoing a hadronic interaction in the ECL.

Photon interaction

- The fraction of photons that do **not** interact (pair convert) in X cm of material is $e^{-\frac{7}{9}\frac{X}{X_0}}$.
- For the ECL, $X = 30$ cm, $X_0 = 1.86$ cm, $X/X_0 = 16.1$.
  $\Rightarrow e^{-\frac{7}{9}\frac{X}{X_0}} = 4 \times 10^{-6}$
- **Question**: what fraction of photons do not leave a detectable signal in the ECL?

Photon interaction

- The fraction of photons that do **not** interact (pair convert) in X cm of material is $e^{-\frac{7}{9}\frac{X}{X_0}}$.
- For the ECL, $X = 30$ cm, $X_0 = 1.86$ cm, $X/X_0 = 16.1$.
  $\Rightarrow e^{-\frac{7}{9}\frac{X}{X_0}} = 4 \times 10^{-6}$
- **Question**: what fraction of photons fail to leave a detectable signal in the ECL?
- Ans: about 0.2%.
  - endcap barrel gaps, 90° mechanical structure, crystal wrapping, mechanical structure in ϕ…

Crystals

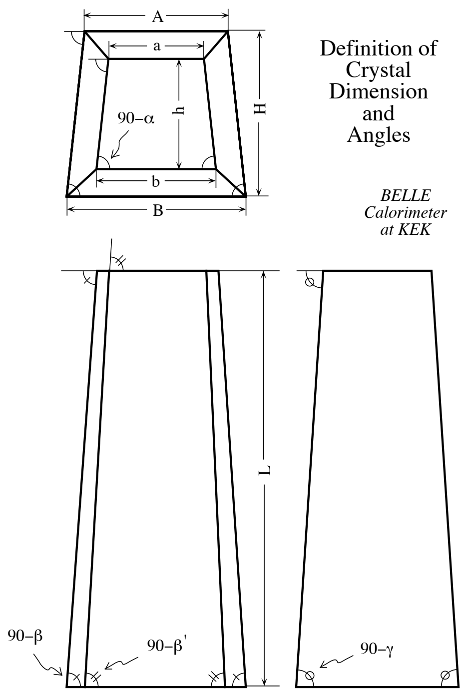
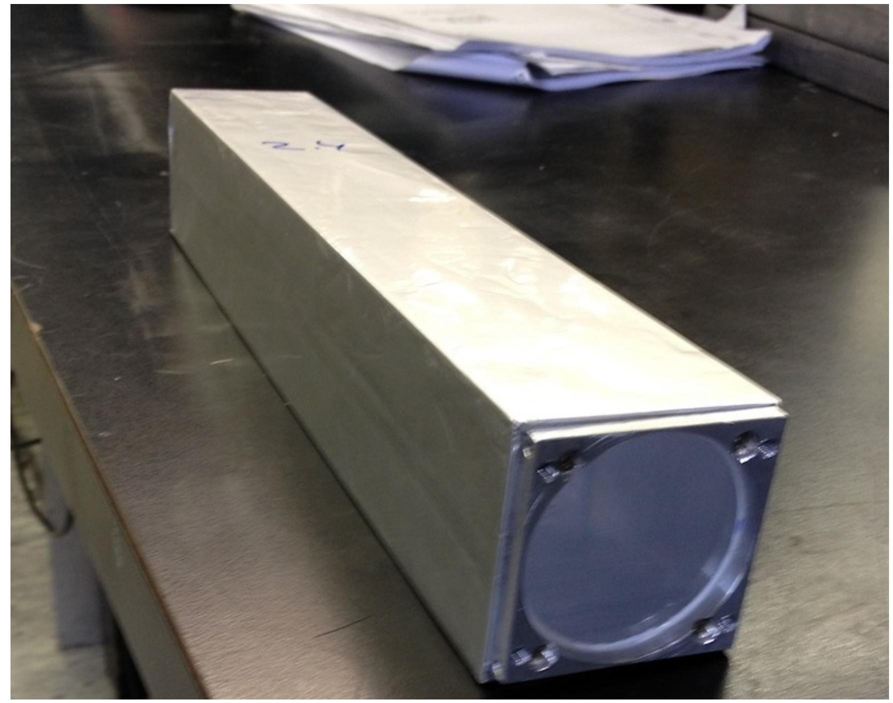


Figure 4.8: Dimension of the barrel CsI(Tℓ) crystal.

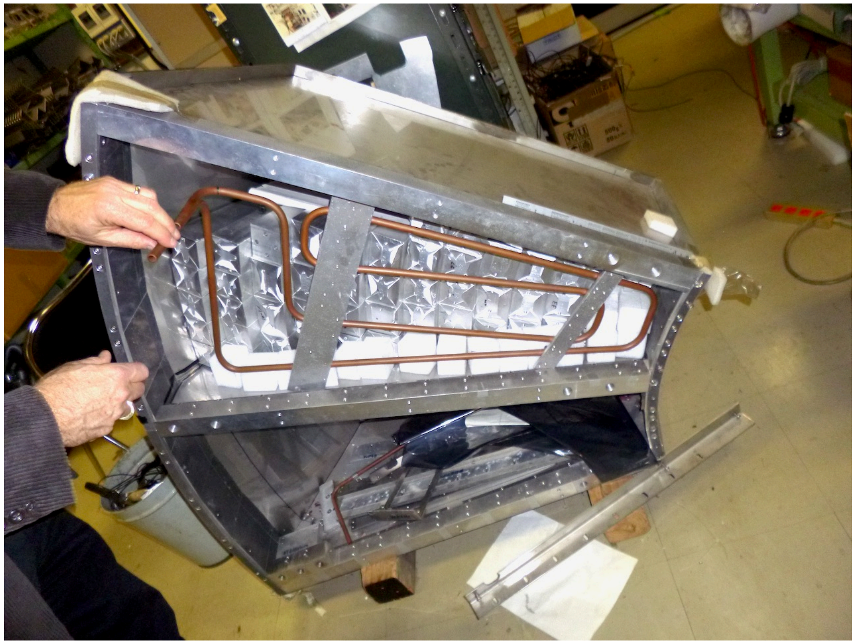
Hitomi Ikeda PhD dissertation (1999)

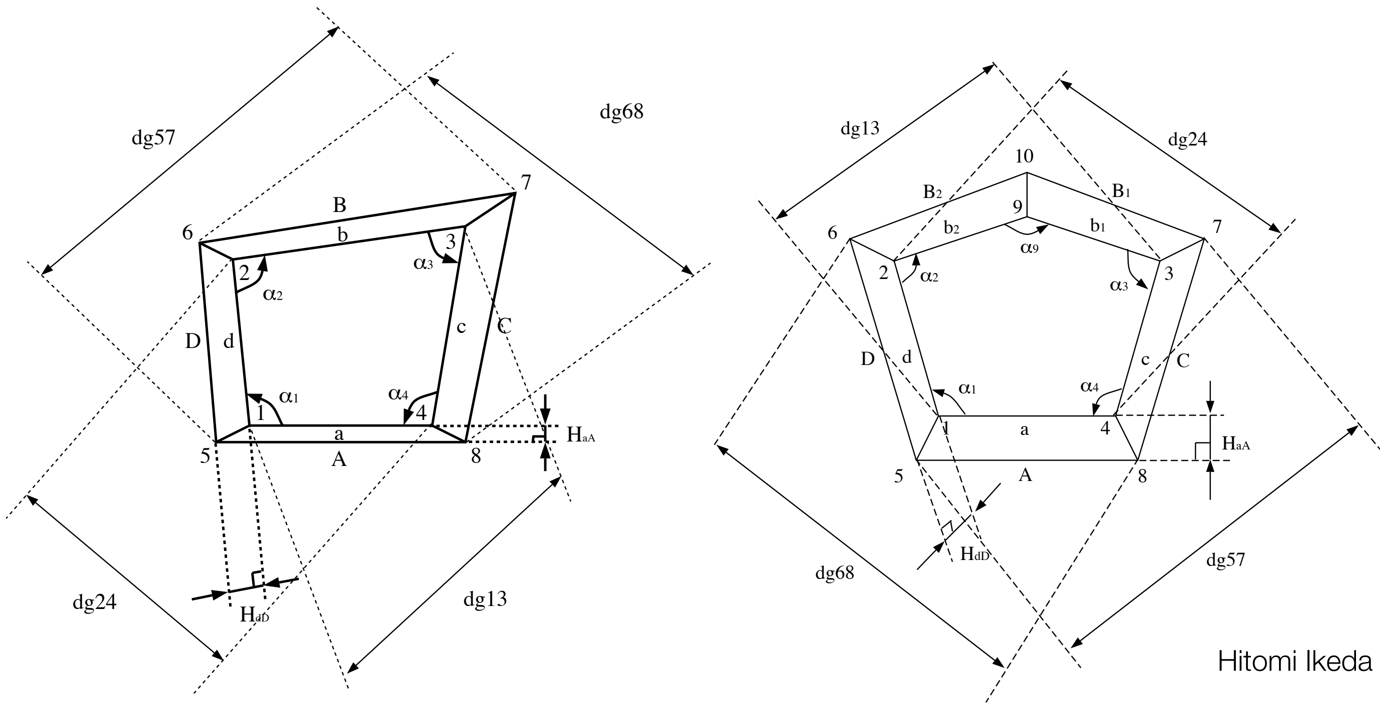


pure CsI, but same size as Belle II crystal

Issue: ECL endcaps

- The endcaps are more complicated:
  - projective gaps;
  - more mechanical structure;
  - wide range of crystal shapes, sizes, and geometries;
  - higher beam background.





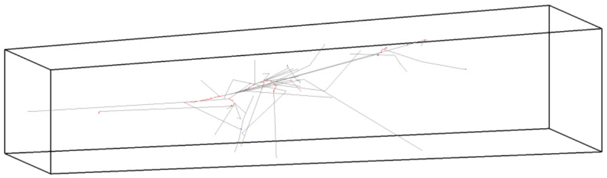
Hitomi Ikeda PhD dissertation (1999)

- When I talk about complications later, it is safe to assume that the endcaps are always worse.

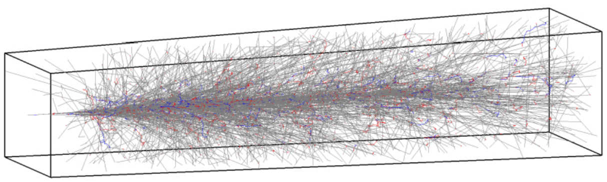
Signals from individual crystals

Signal formation

$100\ \mathrm{MeV}$ photon:



$7\ \mathrm{GeV}$ photon:



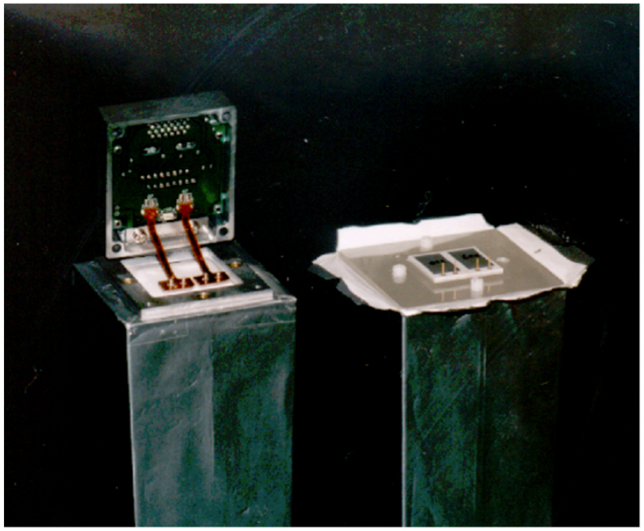
Energy depositions excite metastable states that emit scintillation light.

Thallium doping shifts light from UV to visible, and increases characteristic time to ~1μs.

Two photodiodes with preamps convert the light into electrical signals.

Barrel crystals are not accessible — need redundancy

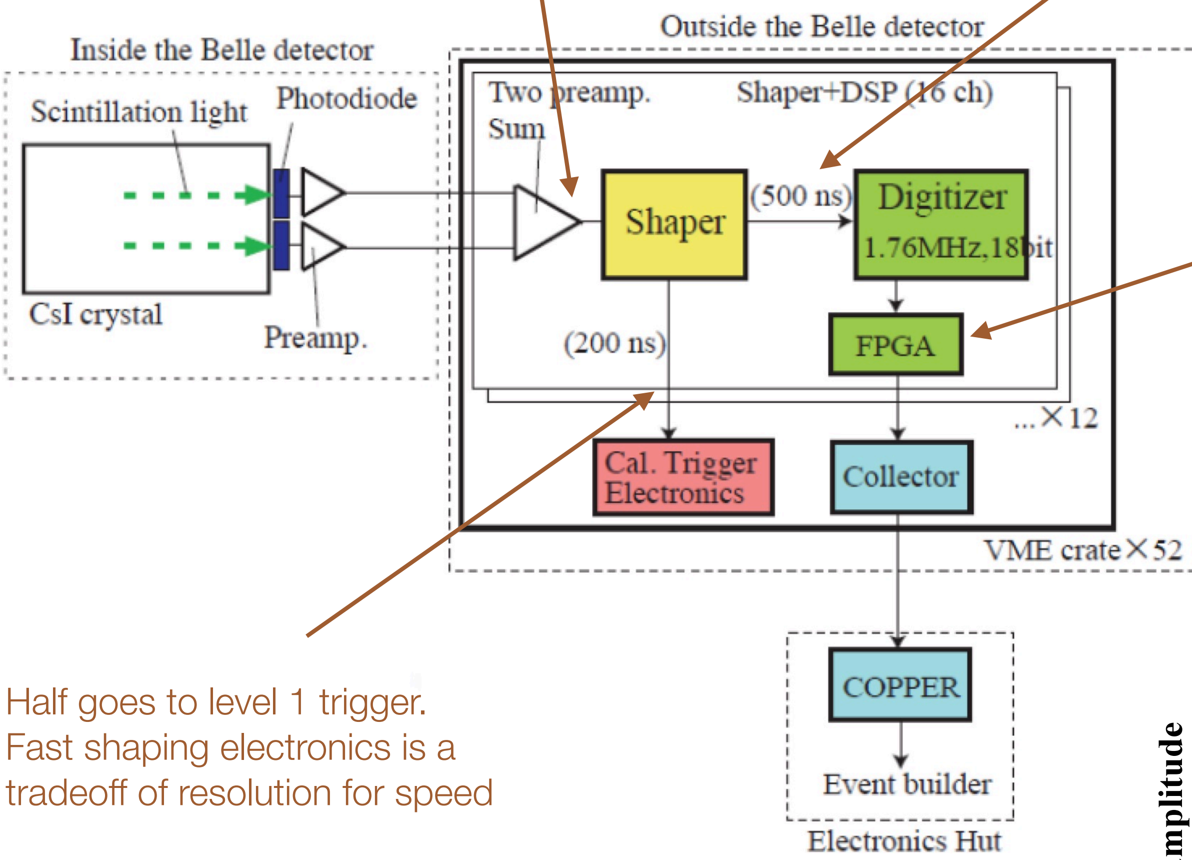
100% of ECL crystals are functional



Hitomi Ikeda PhD dissertation (1999)

Preamp signals are summed in the ShaperDSP board, then split.

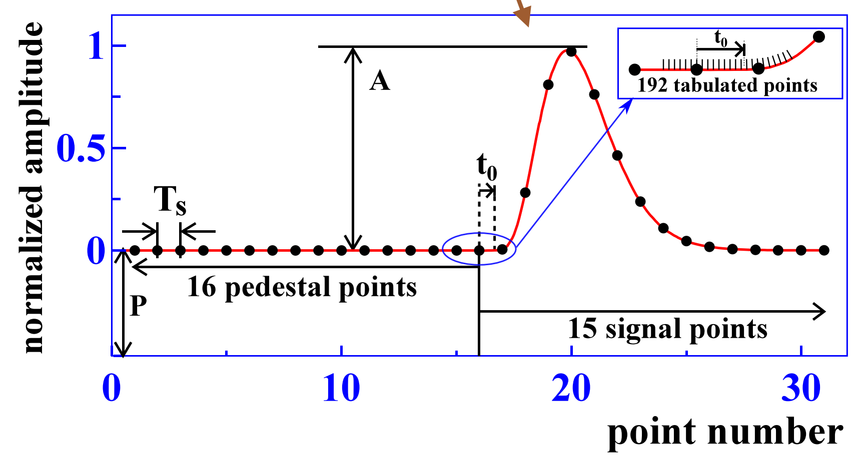
Signal for offline reconstruction uses a longer shaping time



Waveform (i.e. voltage vs time) is fit in FPGA to extract amplitude and time of signal

Half goes to level 1 trigger. Fast shaping electronics is a tradeoff of resolution for speed

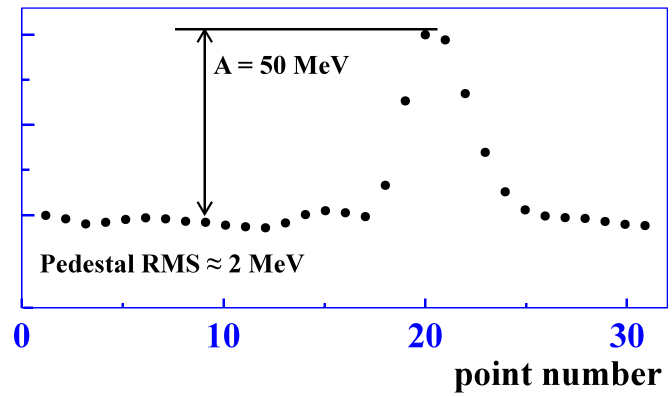
NIM A1030 (2022) 166468



31 points x 567 ns/point = 17.5 µs

Beam backgrounds

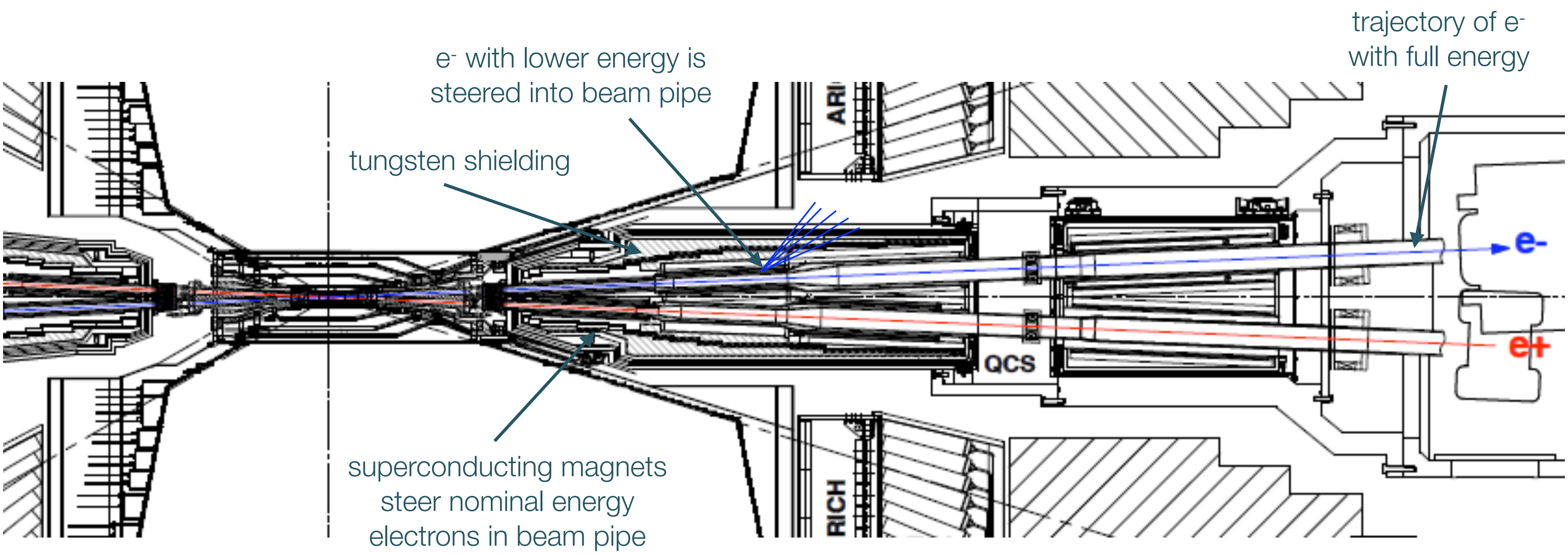
- In reality, the pedestal is not the flat line shown on the previous slide.



- Fluctuations arise from electronic noise, but beam backgrounds are largest contribution.
- Beam backgrounds are energy deposits in a crystal that don't come from the e^+e^- collision of interest.
- Mostly low-energy photons (1–2 MeV) or neutrons, but can be high enough to be reconstructed as a cluster.

- Can be single-beam processes
  - interactions with residual gas in the “vacuum”
  - interactions between electrons in bunch Touschek

- Or from low-angle Bhabha scattering $e^+e^- \rightarrow e^+e^-(\gamma)$.



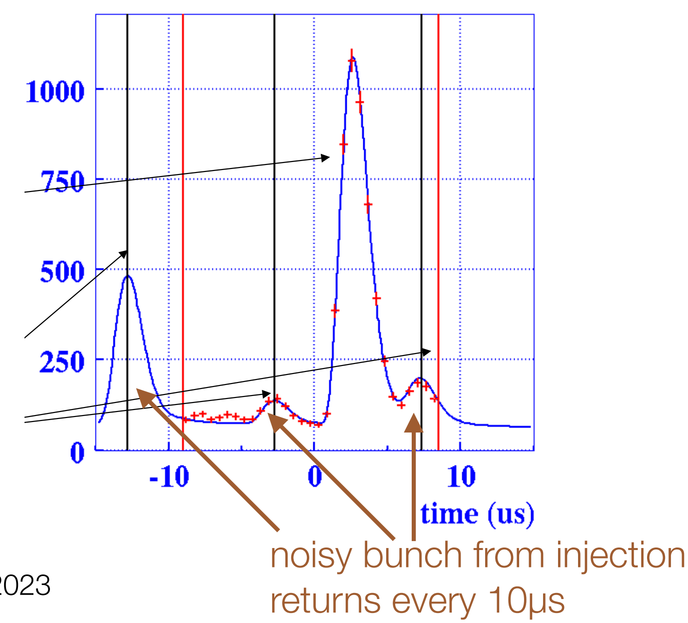
- SuperKEKB on June 8, 2022: 2249 bunches in 3 km ring (10 μs) ⇒ 4000 bunch crossings in 17.5μs window used for waveform fitting.
- There can be hundreds of low-energy photons contributing to the waveform; pedestal fluctuations are due to variations in their number, timing, and energy.

Issue / in progress — injection background

- Additional particles are continually injected into bunches. Very high backgrounds for a while, so we have an "injection veto" that stops triggers during that time.

- But given the slow signal formation, these backgrounds still affect signals outside of the veto window.

- Plan a more-sophisticated fit to detect / improve such issues for future running.



Reconstructing clusters

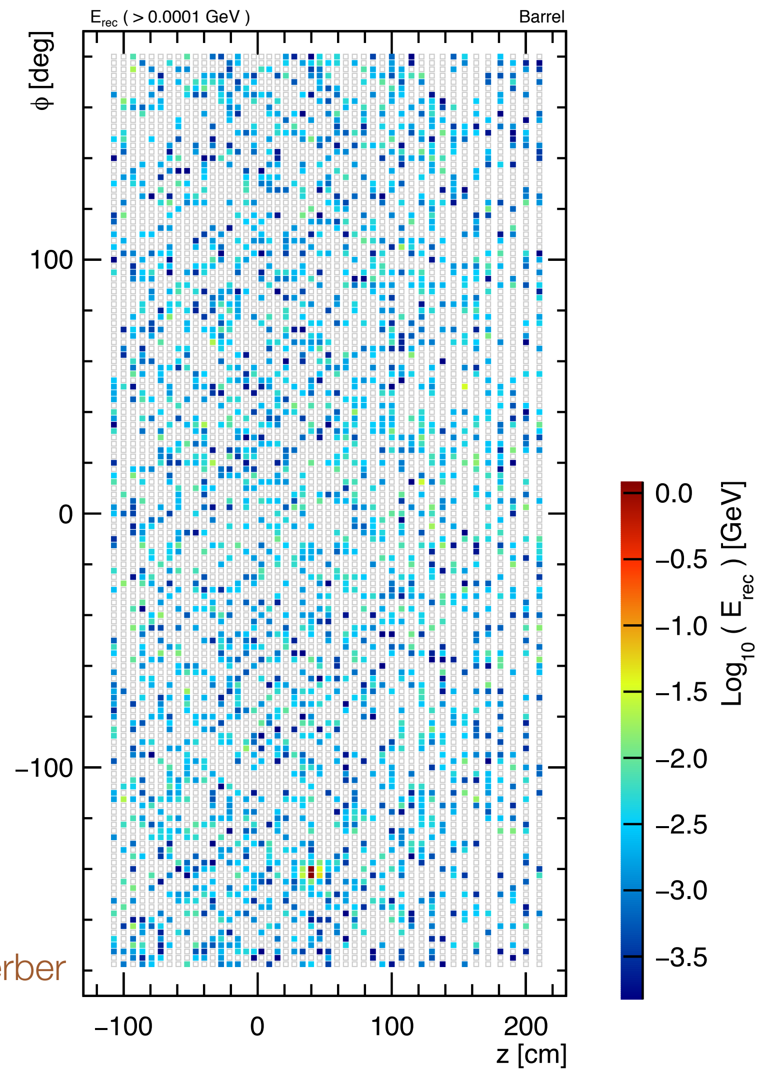
Reconstruction

- Software / algorithms to obtain what we want (e.g. photon energies and directions) from what we have (energy and time of individual crystals).

- We have emphasized high efficiency for reconstructing real photons, even at low energy.
  - high efficiency ⇒ low purity.

- Two considerations:
  - The number of crystals with measurable energy from beam backgrounds (1000's per event) is much larger than the number from physics (<100).
  - Two photons can overlap, i.e., deposit energy in the same crystal.

Energy in each crystal in a simulated event:
>3000 crystals with measurable energy
(beam backgrounds)



Torben Ferber

Reconstruction steps / ECL data objects

- Connected regions (ECLConnectedRegion)
  - set of contiguous crystals with energy above threshold
- Local maximums (ECLLocalMaximum)
- Showers (ECLShower)
  - transient object containing cluster information
- Clusters (ECLCluster)
  - ECL information for particles
  - mdst (i.e., what you use for physics analysis)

Connected region

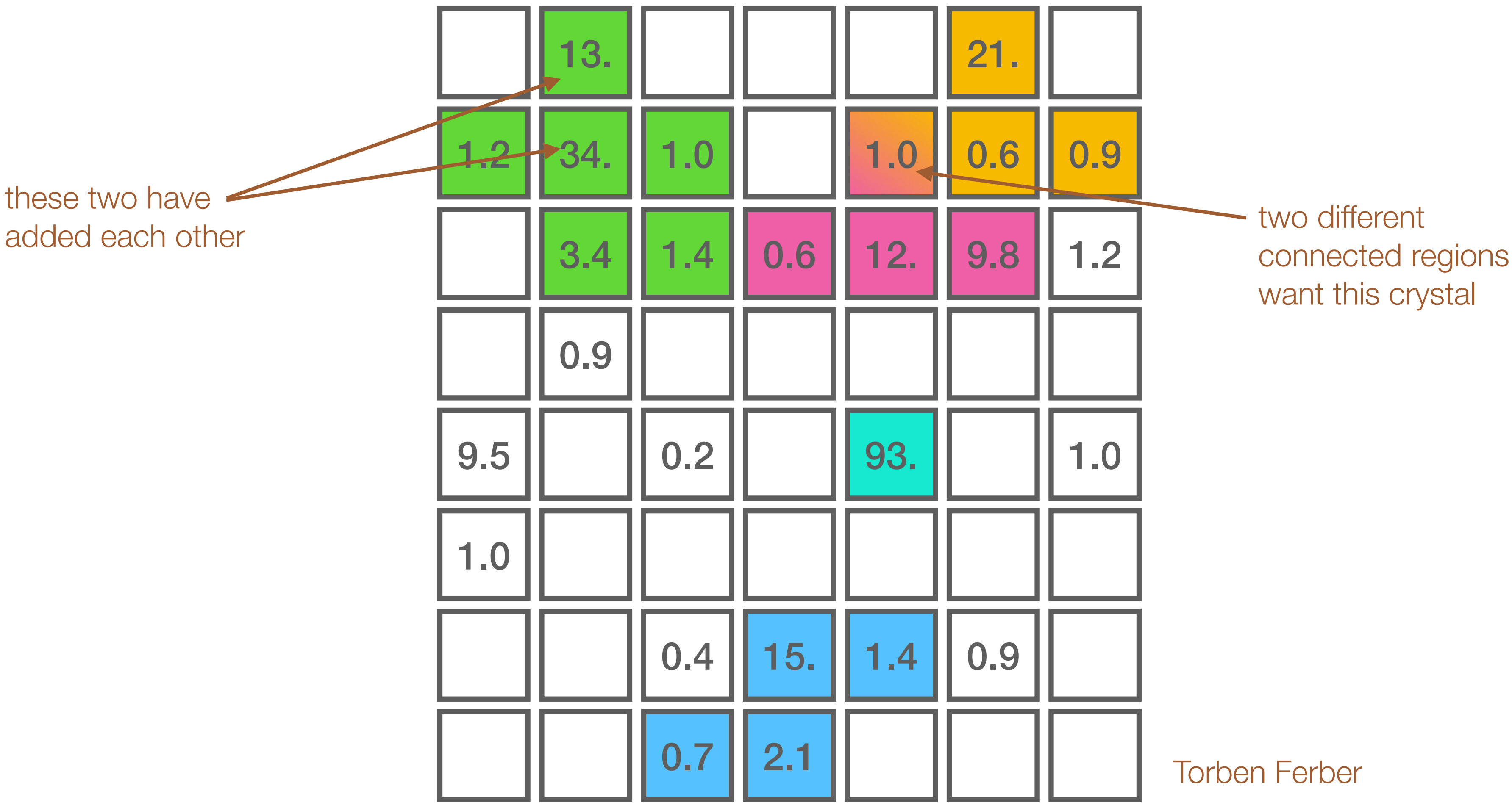
- Idea is that the connected region should contain the information needed to calculate cluster properties, but not more.
  - could be more than one cluster, if overlapped.

- Start by selecting crystals above 10 MeV.

	13.				21.	
1.2	34.	1.0		1.0	0.6	0.9
	3.4	1.4	0.6	12.	9.8	1.2
	0.9					
9.5		0.2		93.		1.0
1.0						
		0.4	15.	1.4	0.9	
		0.7	2.1			

Torben Ferber

- Add all neighbours above 0.5 MeV.
- If the neighbour is above 10 MeV threshold, then add its neighbours that are above 0.5 MeV.



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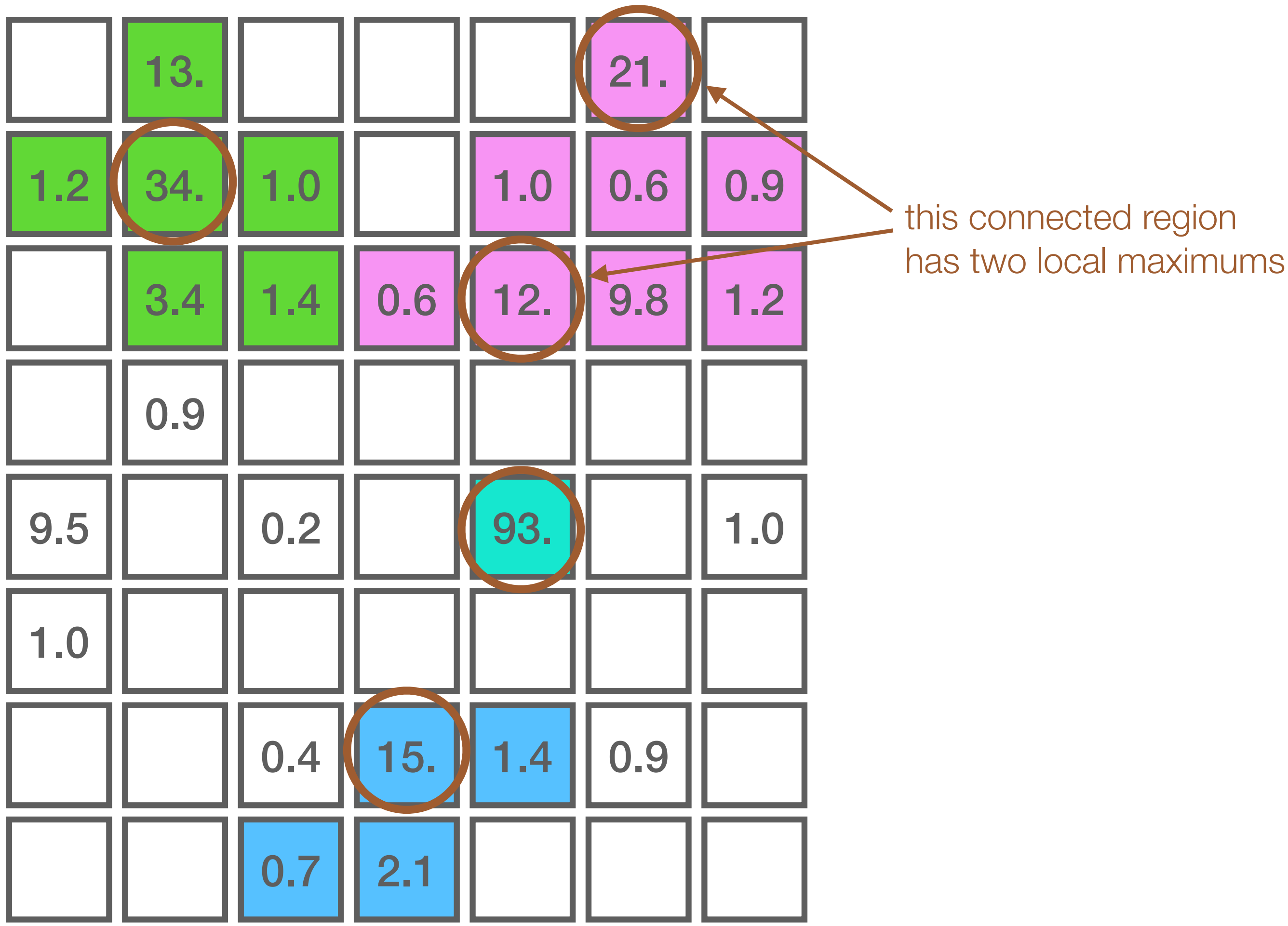
- If two connected regions share a crystal, merge them.
- A local maximum is crystal in a connected region with energy greater than all of its neighbours.



Issue / to do: connected region finder parameters

- There are three different energy thresholds used by the connected region finder. Currently 10 MeV / 10 MeV / 0.5 MeV.
- Can require that crystals below a specified energy satisfy a timing cut. Not yet used.
- These parameters were set before we started data taking. Not obvious to me how to optimize, but seems worthwhile.
  - currently focused on high efficiency

Making ECLShowers

- An ECLShower is created from every local maximum.
- If there is only one local maximum in a connected region, the full energy of each crystal is associated with the corresponding ECLShower.
- If there is more than one, iterative procedure.
  - weight for each crystal depends on the distance of the crystal from the center-of-gravity of each ECLShower
  - center-of-gravity is calculated using weighted energies.

- The point of using connected regions is to minimize the number of times we have to do this computationally intensive splitting procedure.
- The output of this process is a list of crystals and energies (a fraction of the total crystal energy) for each ECLShower.

Calculating ECLShower quantities

- All crystals associated with the ECLShower (up to a 5×5 array) are used to calculate shower shape information.
  - e.g. clusterE1E9, clusterZernikeMVA; quantities that reflect the geometry distribution of the energy.

- The N most-energetic crystals are used to calculate the photon energy.
  - N is from the ECLNOptimal payload (new in release-08)
  - depends on background levels, energy, and location.

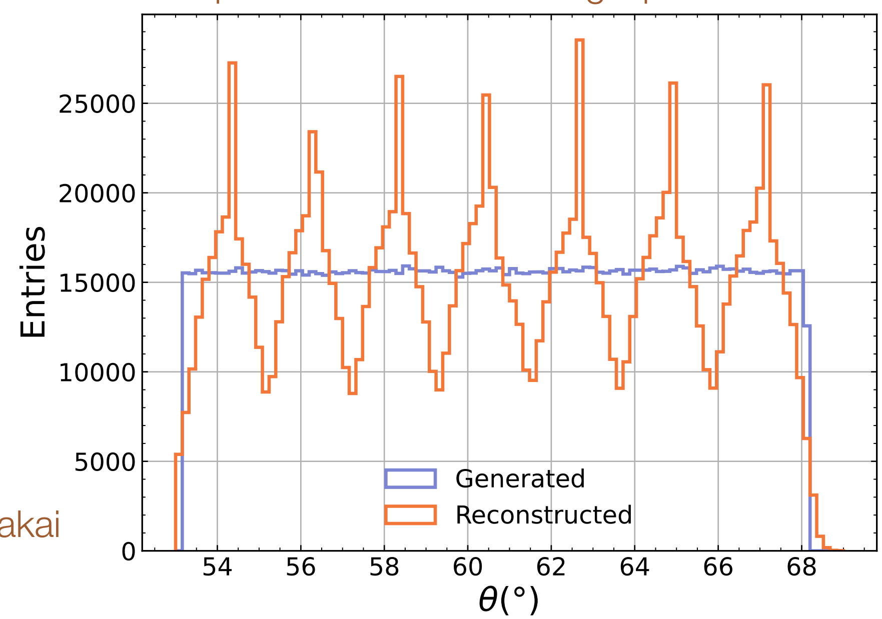
- The most energetic crystal is used for time. Subtract eventT0 (trigger time) from CDC or SVD.

Issue: ECLShower position

- The location of the photon in the ECL is calculated using the logarithmically-weighted energies of all crystals (up to 5×5) associated with the ECLShower.

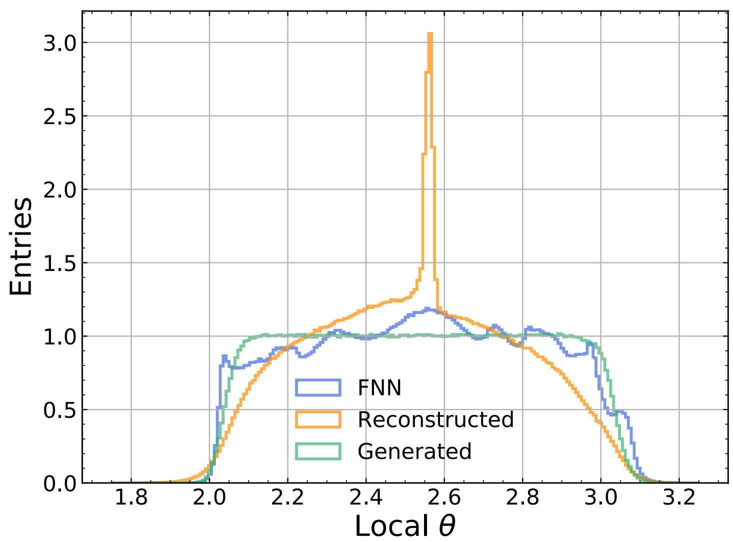
- Result is significantly biased towards the center of the most-energetic crystal.

Generated and reconstructed positions for mc15ri single photon MC

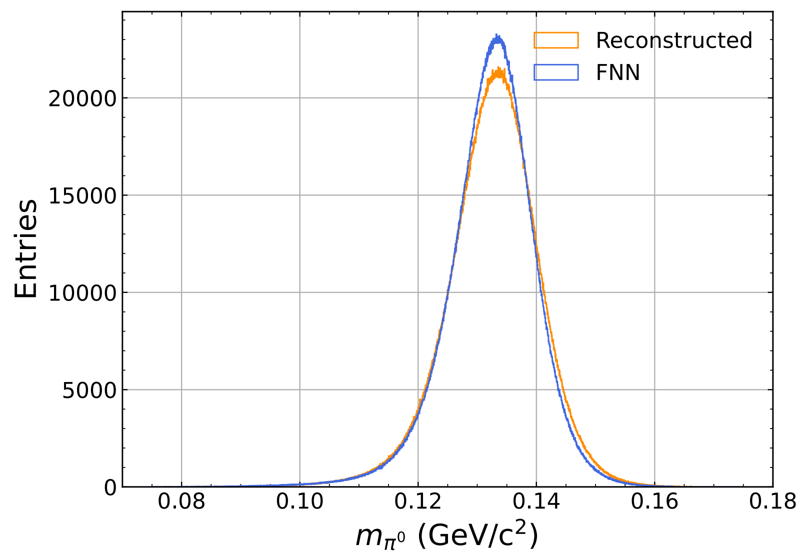


Miho Wakai

- Miho Wakai has been studying an neural-net alternative. Significantly reduces bias in position reconstruction, but physics benefits (e.g. π^0 mass resolution) are marginal.



reconstructed mass for high-momentum π^0



Matching things to ECLShowers

- Tracks are extrapolated to the ECL and various distances to the centroid are used to associate the ECLShower to the track.
  - apparently failures are a major source of E_{ECL}.
- For MC, the true energy in each associated crystal is used to decide whether or not the cluster is "truth matched" to an MC particle.
- These are both much more complicated than you might think.

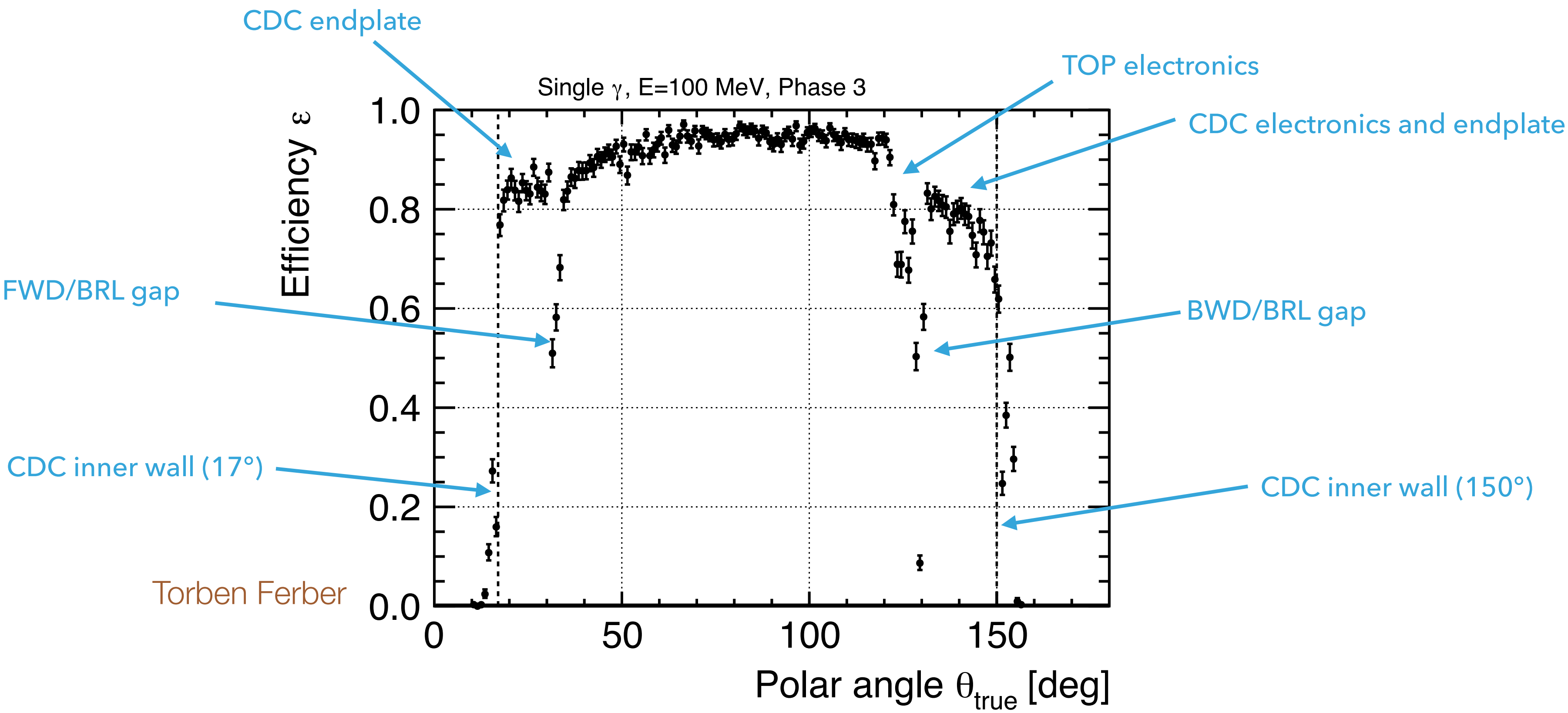
Making ECLClusters

- ECLShowers with energy above 50 MeV, or with energy between 20 MeV and 50 MeV with good times ($|t| < dt99$), are turned into ECLClusters.
  - the object available for physics in the mdst.

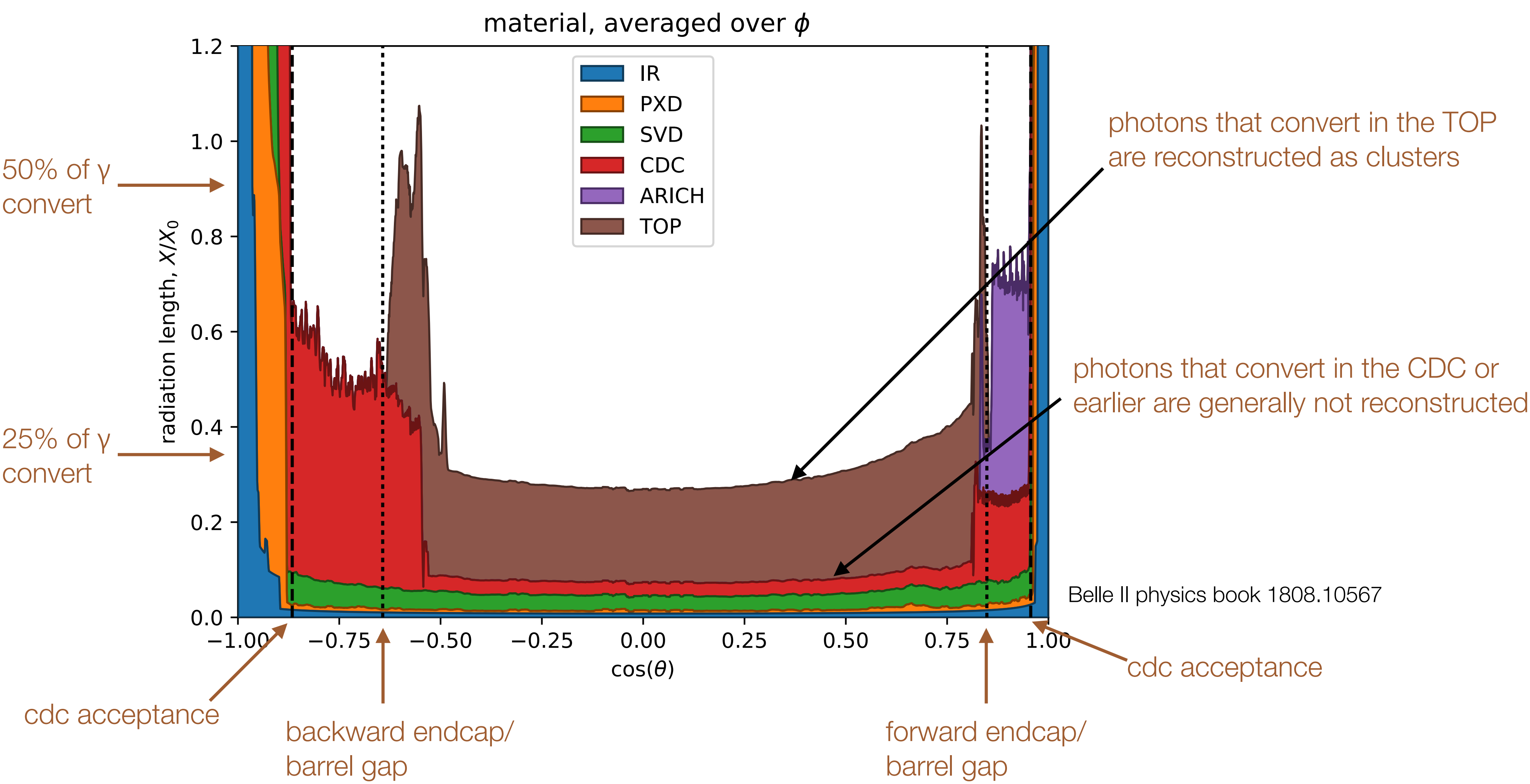
- **Question**: why don't we just keep all of them?

Photon efficiency

- How often is there an ECLCluster associated with a photon?



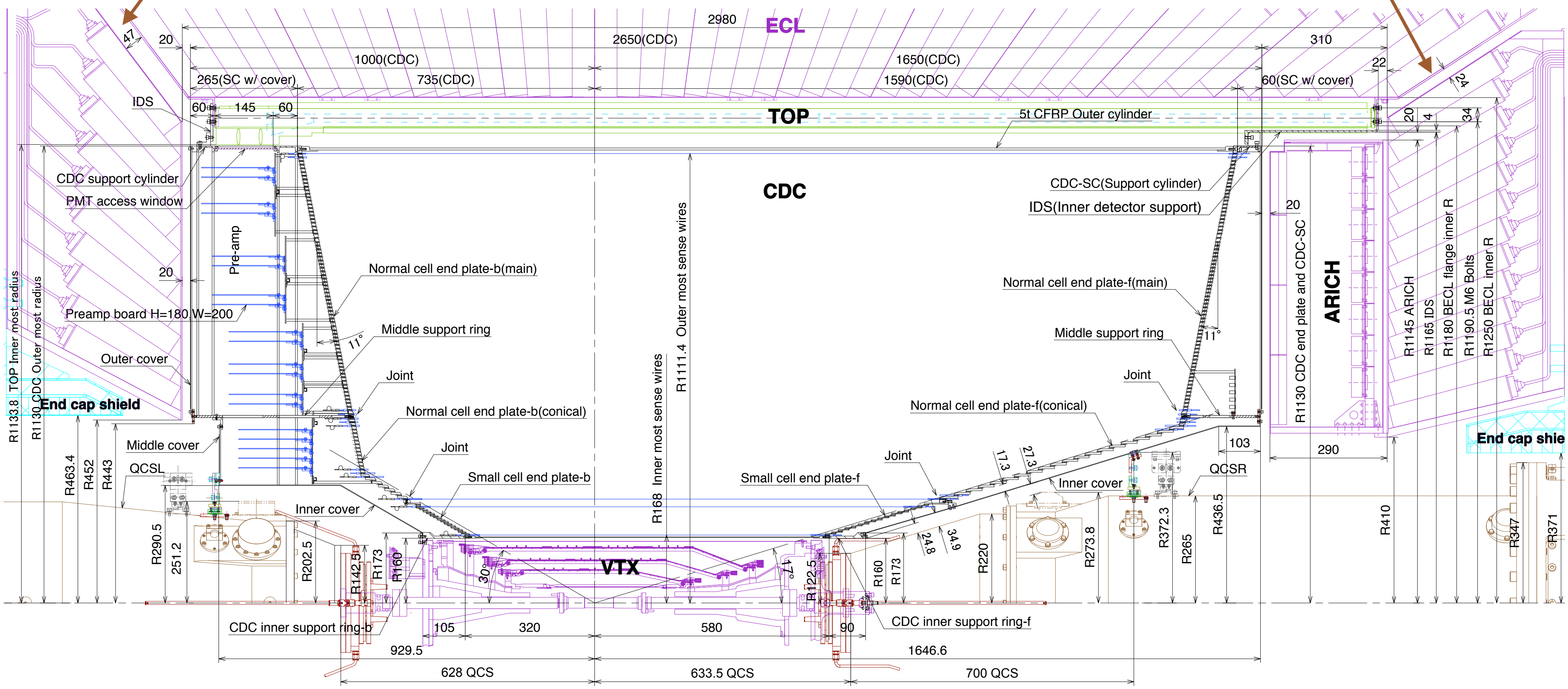
- Inefficiency is primarily due to photon conversions $\gamma \rightarrow e^+e^-$, except barrel/endcap gaps.



Belle II physics book 1808.10567

backward endcap/
barrel gap

forward endcap/
barrel gap



Calibration

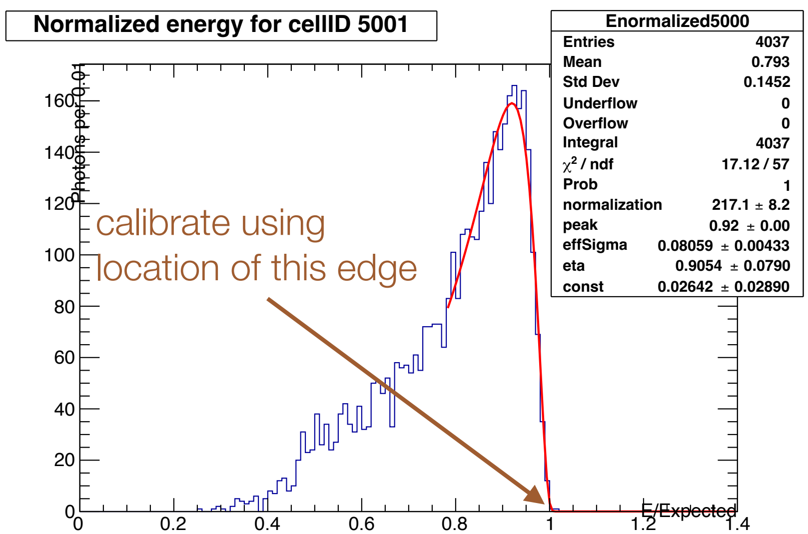
Calibration of individual crystals

Single crystal calibration

- Individual crystals have different light yield per deposited MeV, different electronics gain, and different cable lengths.
- We use a pulser calibration to verify the stability of the electronics chain, and to correct for changes when we replace an electronics board.
  - otherwise, extremely stable.

Single crystal energy calibration using $e^+e^- \to \gamma\gamma$

- Absolute energy calibration for each crystal comes from back-to-back $e^+e^- \to \gamma\gamma$ events (beam-energy photons).
  - most energetic crystal associated with each photon.



Energy in the most energetic crystal normalized to MC

- Upper edge does not depend on material between interaction point and ECL (unlike location of peak).

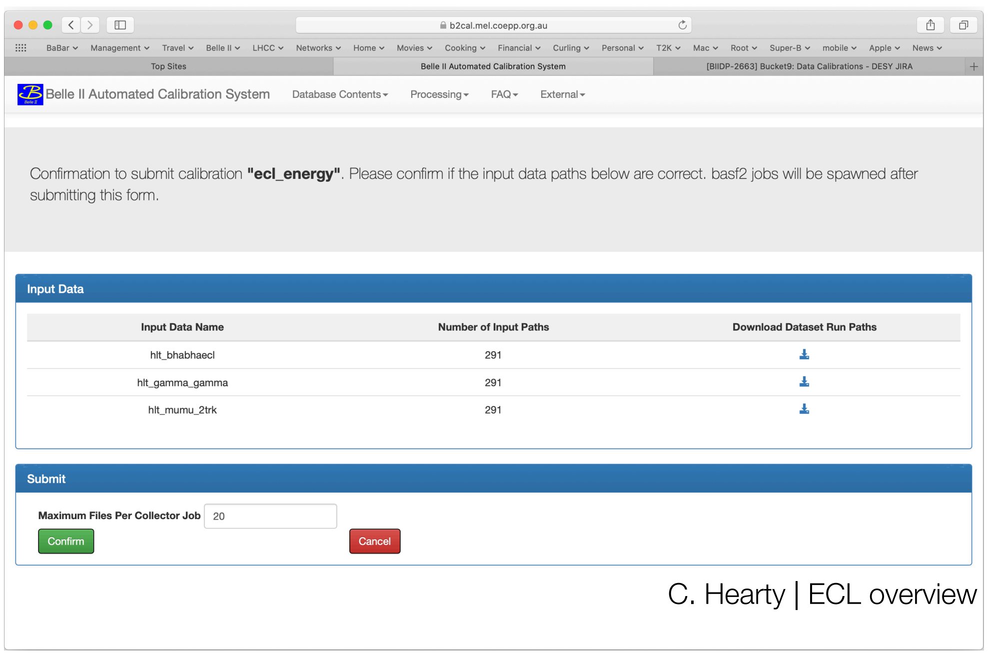
Single crystal timing calibration using Bhabhas

- Timing is calibrated such that a photon from the IP has t = 0.
- Use Bhabhas for timing calibration. Need tracks to get the event time (eventT0) from the CDC.
  - will be SVD in release-08.

Prompt calibration

- The single crystal energy and time calibrations are run on “data buckets” shortly after the data is recorded. Not sensitive to changes within the bucket.

- Buckets are of order 20 fb^{-1}. Typically time between maintenance days.



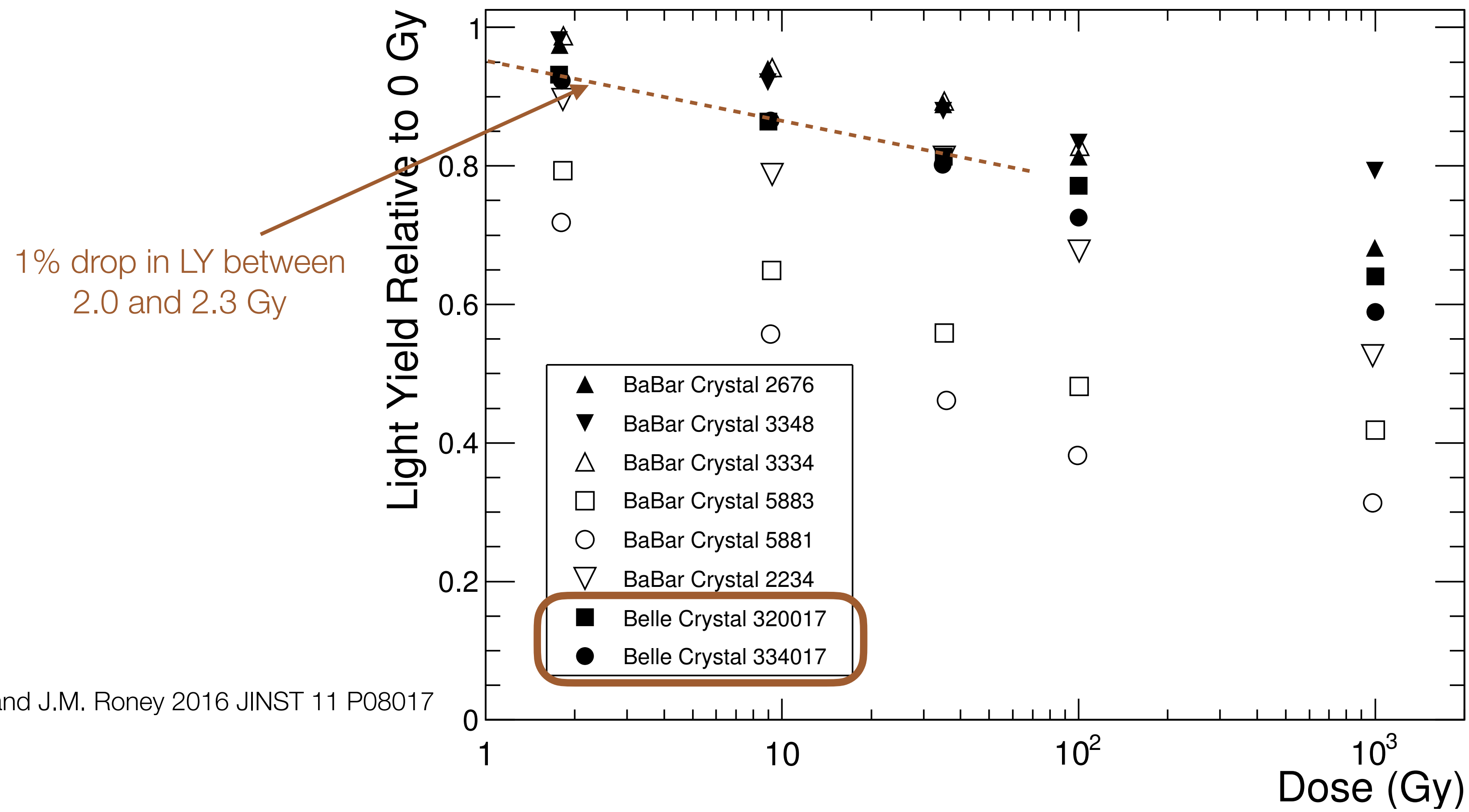
- Airflow: almost entirely automated process

- **Question**: I previously said that pulser calibration is extremely stable. So why do we need to recalibrate every two week?

Issue: radiation damage

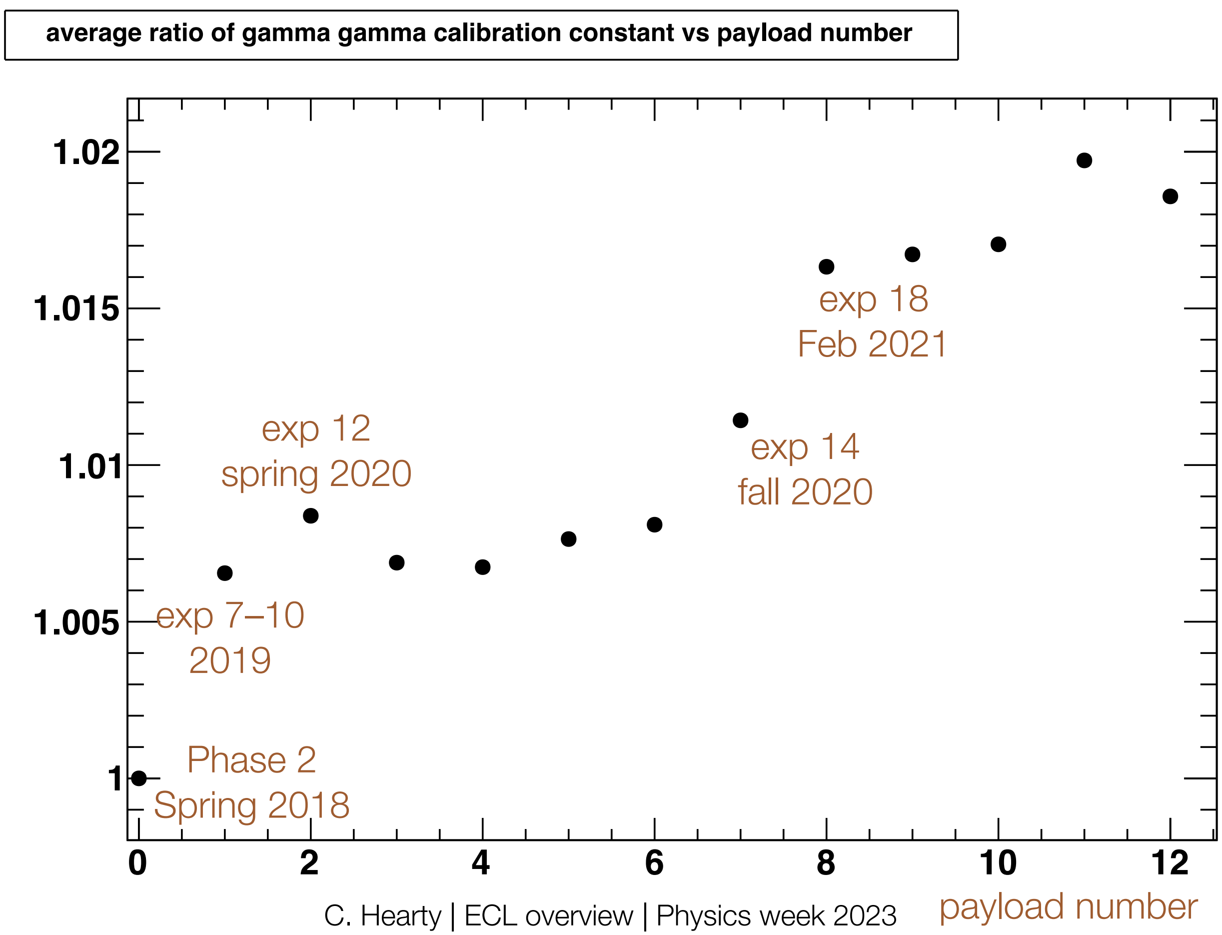
- The light output of crystals decreases as they age

Drop in light yield of CsI(Tl) crystals versus dose



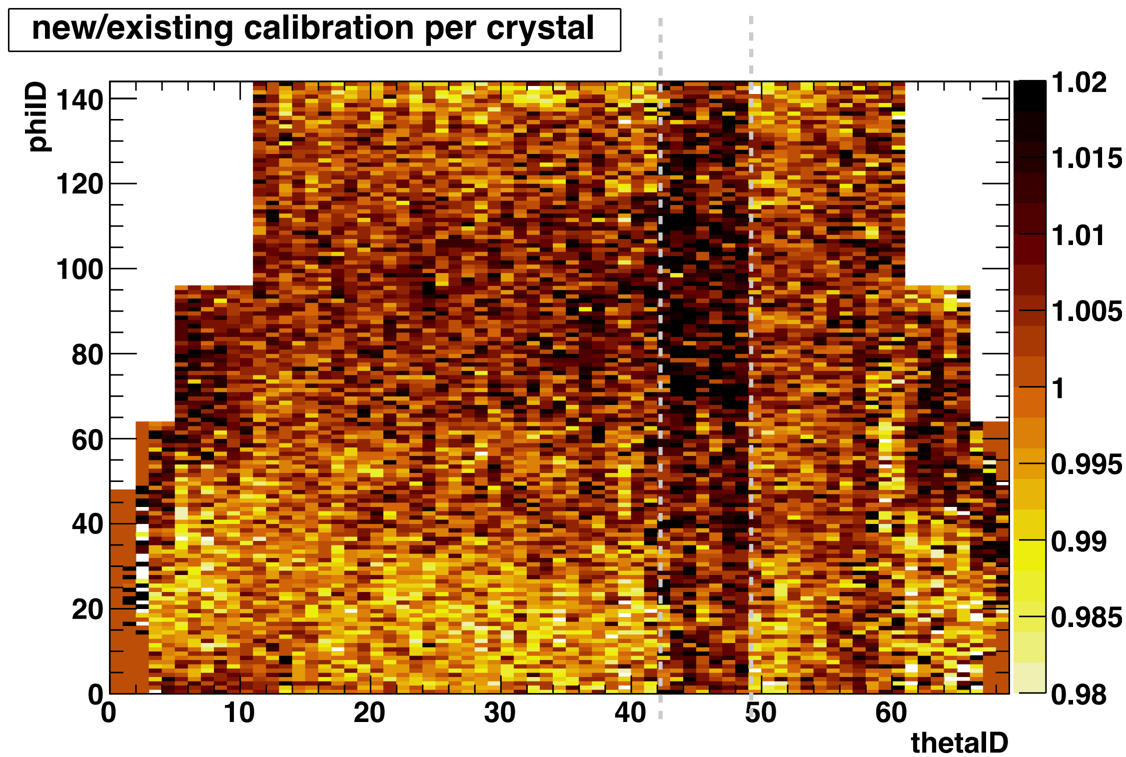
S. Longo and J.M. Roney 2016 JINST 11 P08017

- Barrel calorimeter dose during Belle operations was 0.8 Gy, 5% drop in light yield (Miyabayashi-san).
- Through end of 2021, we have seen ~2% decrease.



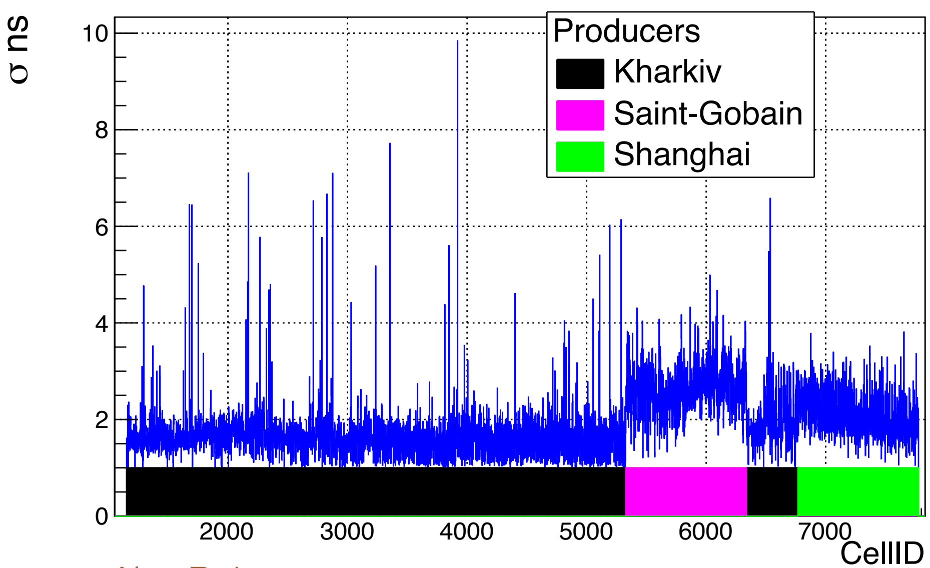
Issue: temperature variation

- Fall 2021: new chiller; couple of months to stabilize.
- Changes in light yield of up to 2%, depending on crystal manufacturer.
- Variations within a bucket cannot be corrected.

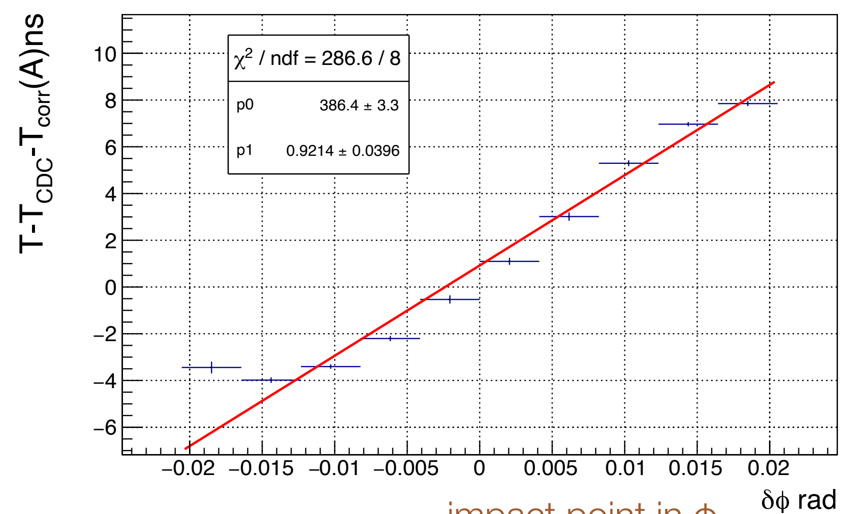


Issue / to do: dependence of time measurement on location in crystal

- Time resolution for beam-energy electrons is significantly worse for crystals made by Saint Gobain. Alex Bobrov has traced this to a dependence on the location in the crystal. Variation in Thallium doping concentration?
  - aim for a correction in release-09



Alex Bobrov



impact point in φ

12 ns variation across crystal

Alex Bobrov

- **Question**: is this effect simulated in our GEANT model?

Issue / to do: smear MC timing resolution

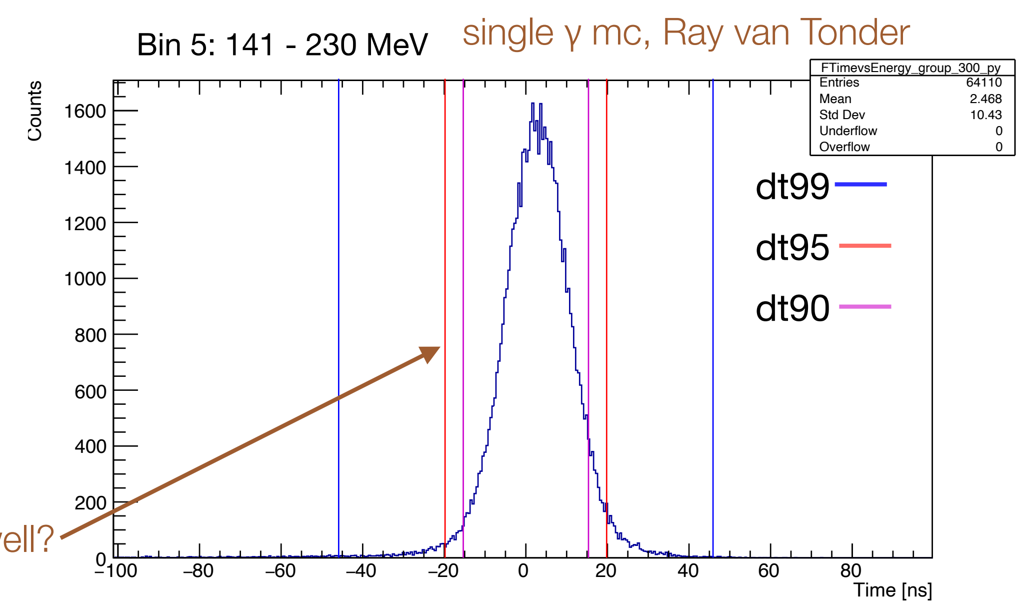
- Perfect MC crystals have better timing resolution than real crystals.
- Goal for release-09: implement smearing of MC timing.
  - does smearing depend on background level?
- Started by Ching-Hua Li, but he has since left Belle II.

Issue / to do: timing resolution calibration

- For analysis, we characterize timing resolution using "dt99". 99% of signal photons should have |t| less than this value. Depends on energy, backgrounds, location.

- Currently, tabulated values found before we started taking data.

- Goal: new calibration for release-09.



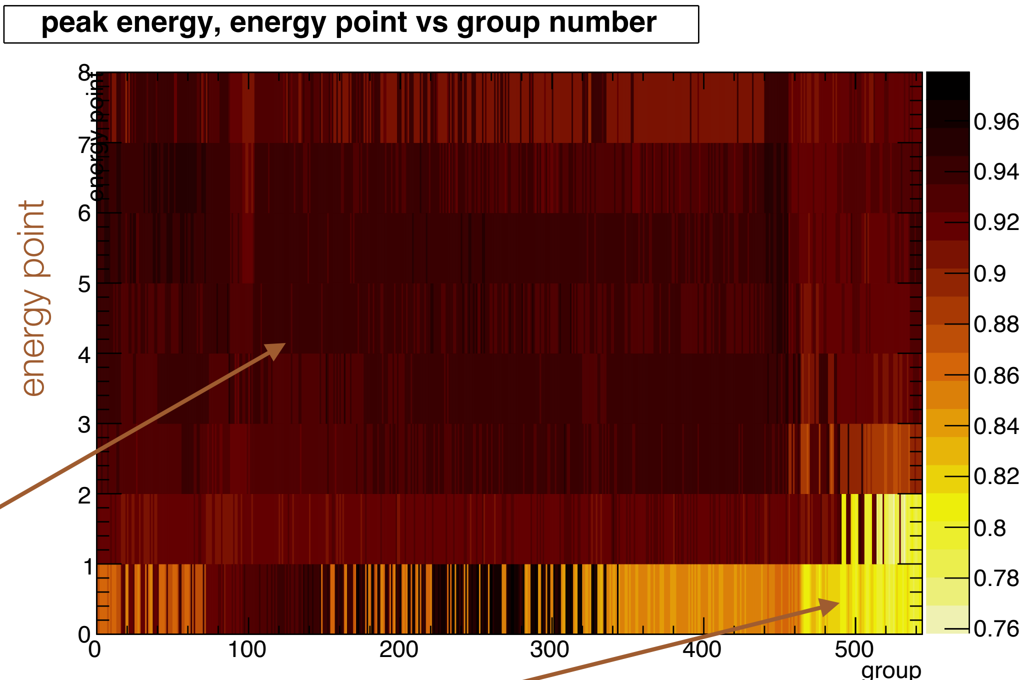
maybe dt95 would be useful as well?

Calibration of photon clusters

Photon cluster energy calibration

- “Raw” energy is the sum of the energies in the N highest-energy crystals in the cluster. What we want (for physics) is the incident energy of the photon.

- The “nOptimal” payload includes the first-order correction for the ratio of these two energies.



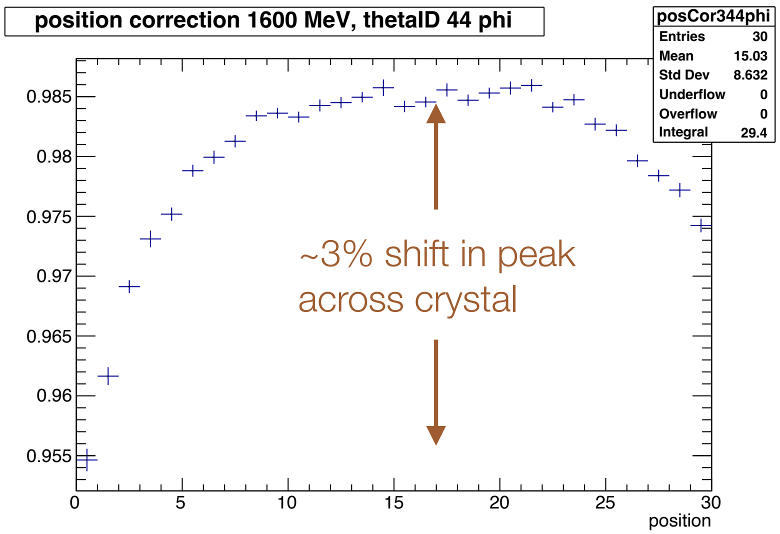
typically ~92% of photon energy is in the N crystals

as low as 80% for low energies in the backward endcap (high backgrounds)

- Second-order correction: a smaller energy fraction is contained if the photon strikes the crystal near the edge.
  - inactive material, mechanical structure.

- eclLeakageCorrection payload.

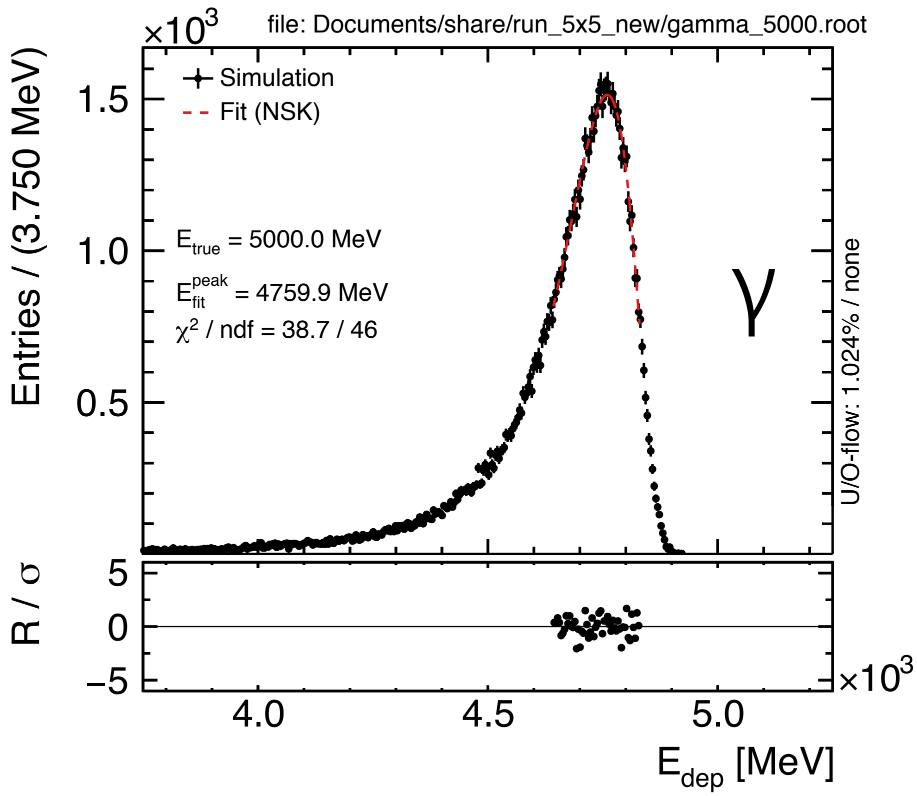
- Obtained (with nOptimal) for each data bucket using run-dependent single γ MC.



Photon energy resolution

- Reconstructed energy distribution has a low-side tail due to leakage. σ of a Gaussian fit is not a useful parameter.
  - use FWHM/2.335 or half of 68.3% range.

Torben Ferber

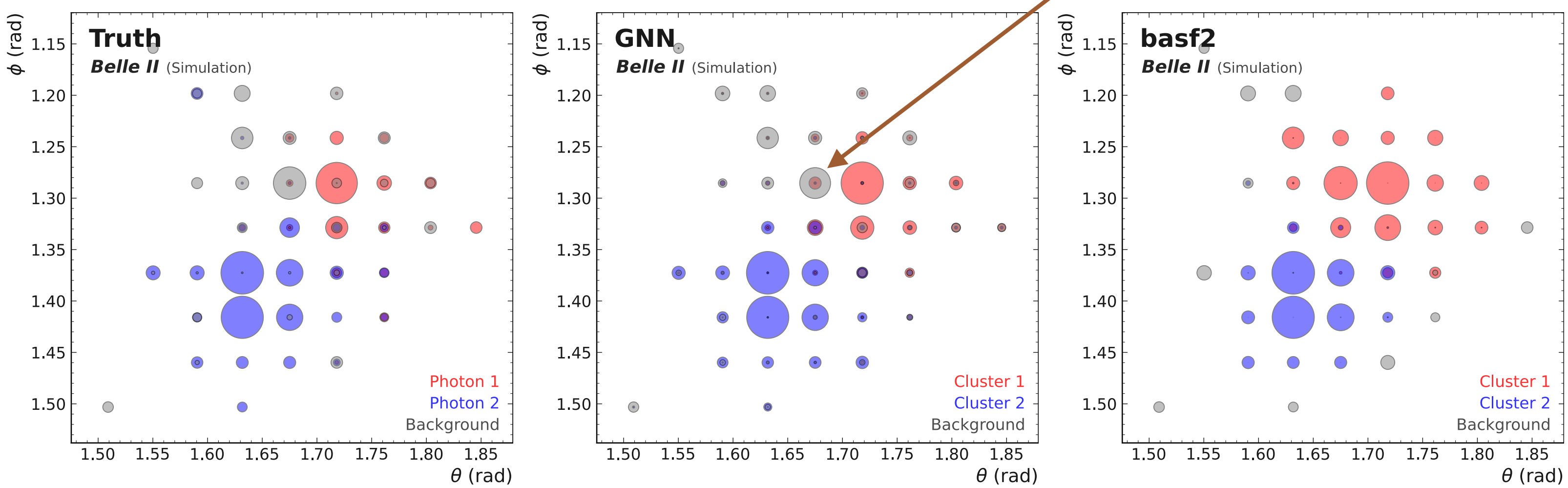


- Resolution is dominated by variations in the amount of leakage, and variations in beam background.
    - not light yield or electronic noise.

The future: reconstructing photons using graph neural networks

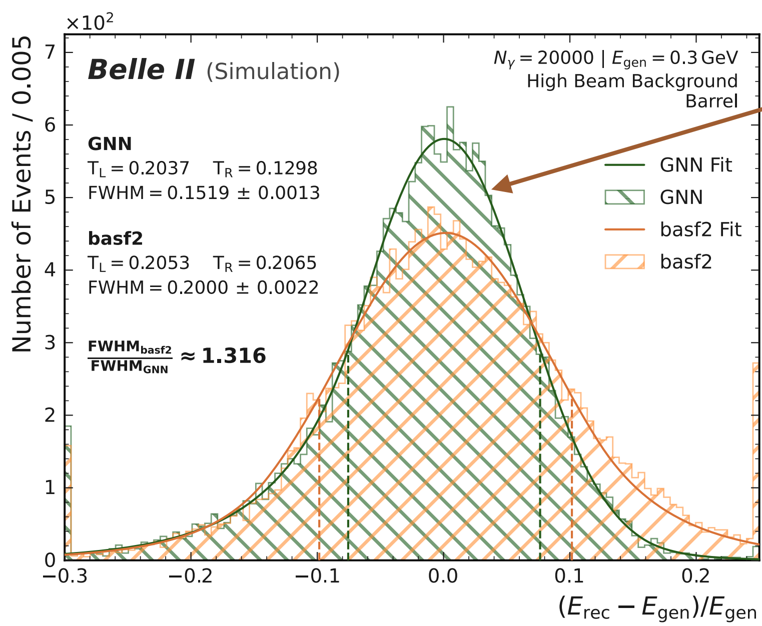
- F. Wemmer, I. Haide, J. Eppelt, and T. Ferber
- Graph neutral net trained using crystal time and pulse-shape discrimination information (later) as well as energy. Separates overlapping photons and distinguishes beam background contributions.
  - uses a 9×9 set of crystals, large enough to include backgrounds even for overlapping photons.

crystal energy split between 2 photons and background



(a) Truth (b) GNN (c) `basf2`

30% better resolution at high backgrounds

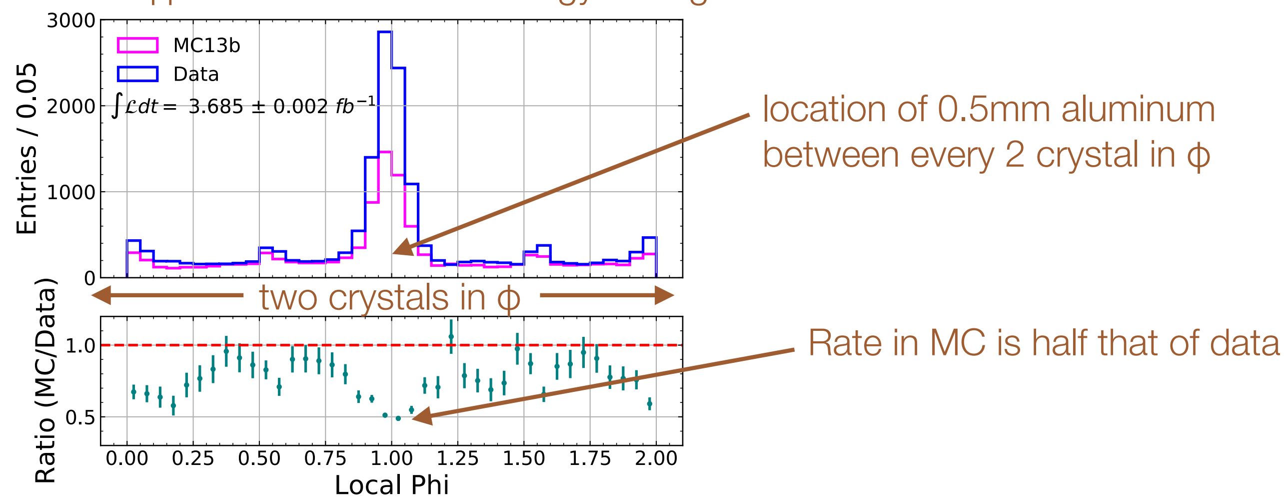


Photon Reconstruction in the Belle II Calorimeter Using Graph Neural Networks, arXiv:2306.04179

Issue / to do: final correction for data/MC differences

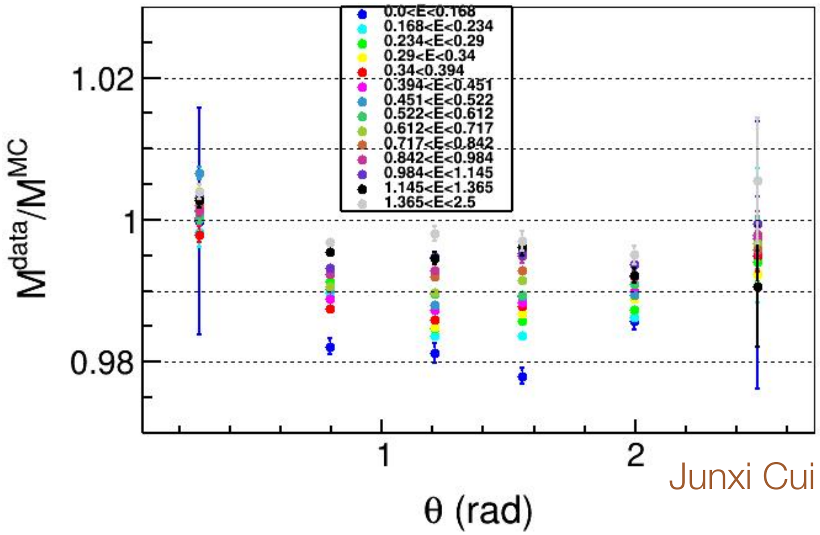
- Currently, final calibration step uses single photon MC to correct for leakage in the GEANT model.
- But we know from Miho Wakai MSc studies that the actual leakage is higher ⇒ data/MC difference in calibration.

Rate of γγ events with >50% energy leakage



Miho Wakai

- Neutrals group finds a photon energy correction using π^0 mass peaks.



- Two related goals for release-09

  - Improve GEANT model by increasing leakage.
    - will help data/MC agreement in both calibration and energy resolution.

  - Implement a crystal-by-crystal correction for data/MC differences in leakage.
    - corrects data calibration (but does not improve MC description of resolution).

Photon cluster timing calibration

- Cluster time = time of most-energetic crystal, so only the single crystal calibration is required.

Using the ECL in physics analysis

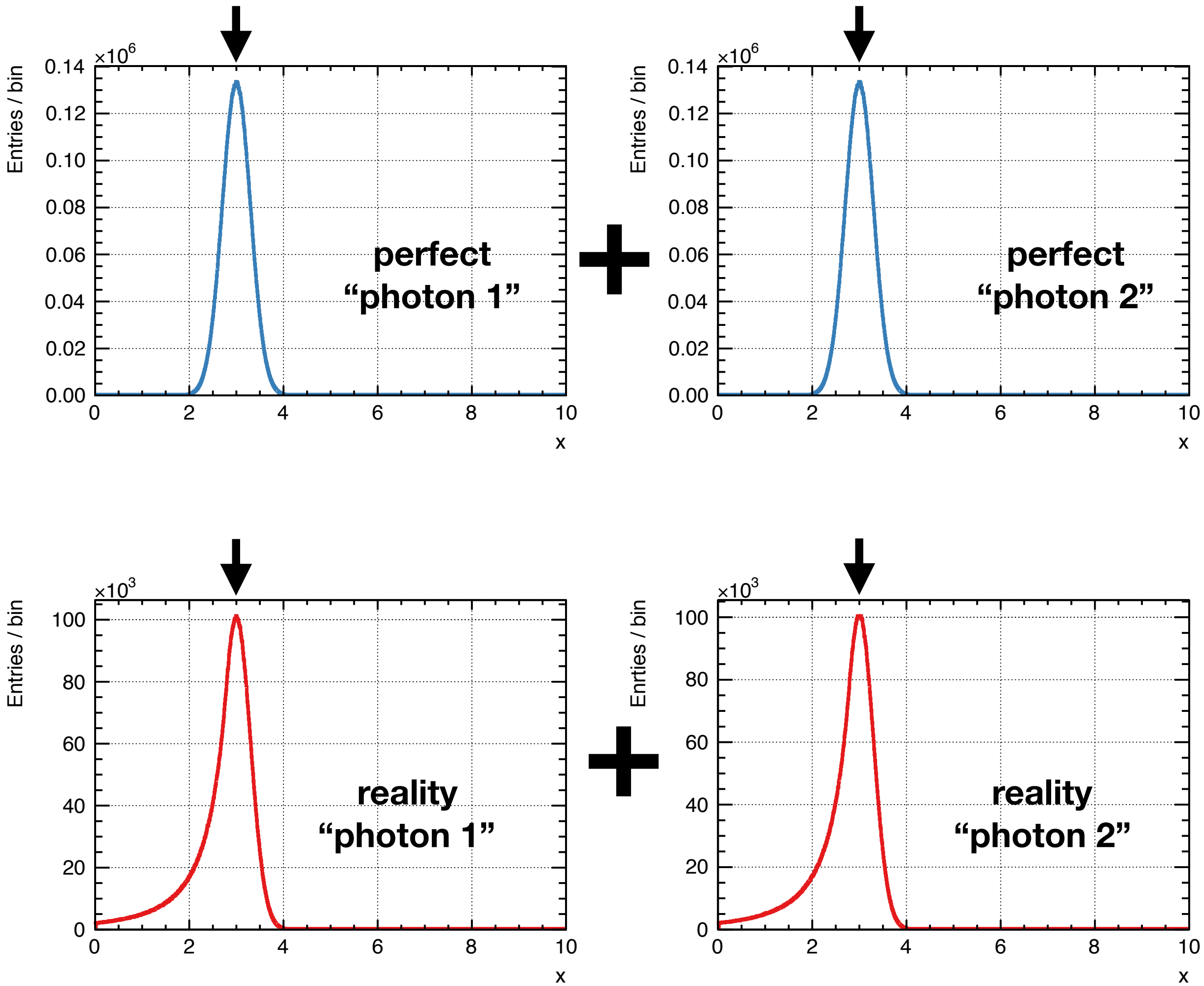
Common uses of the ECL

- Photons → skip
- π^0 reconstruction
- E_{ECL} → see Gaetano's talk on Friday
- Particle identification

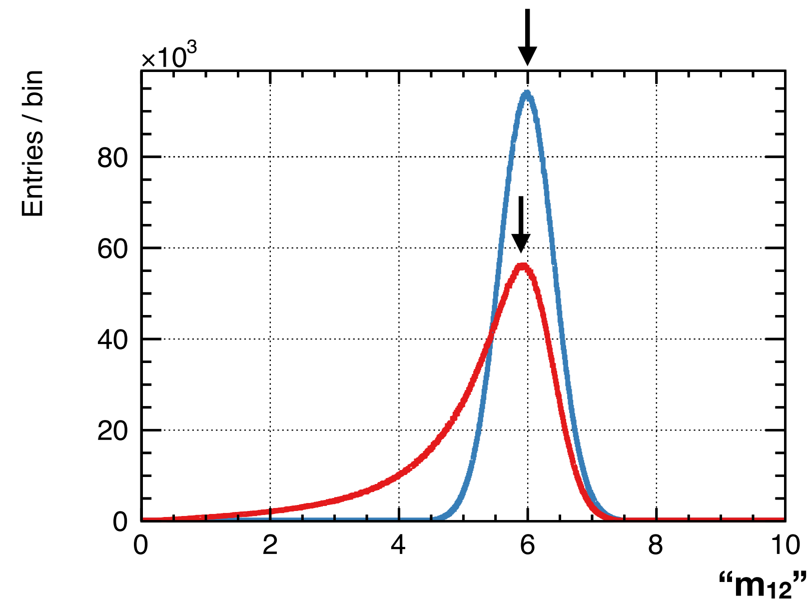
π^0 reconstruction

π^0 mass

- For B physics, one of the primary uses of the ECL is in making π^0 mesons.
- Perhaps you have noticed that the reconstructed mass is not at the PDG value.
- This happens even when photon energies are correctly calibrated. Measured photon energies do not have a Gaussian distribution; they have a low-side tail.



Torben Ferber

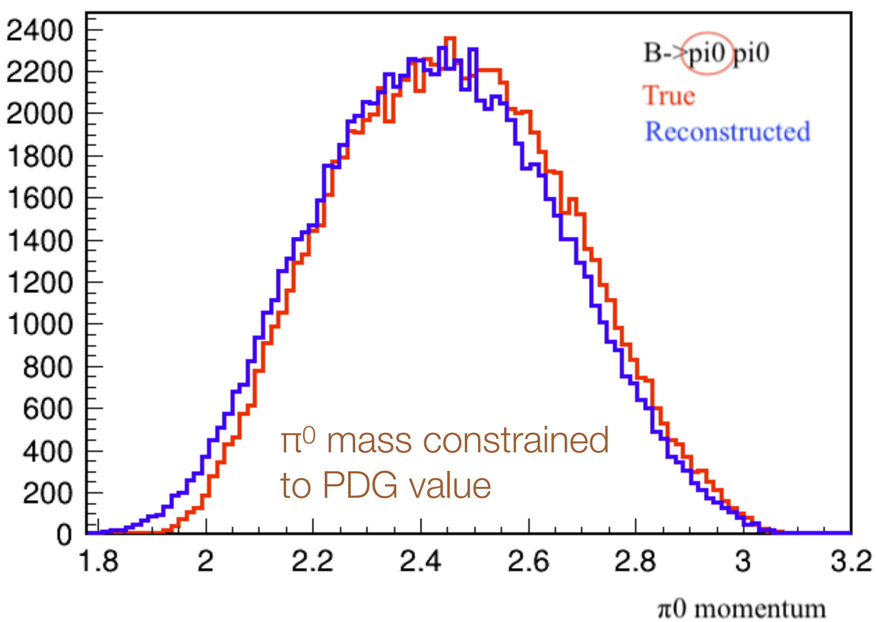


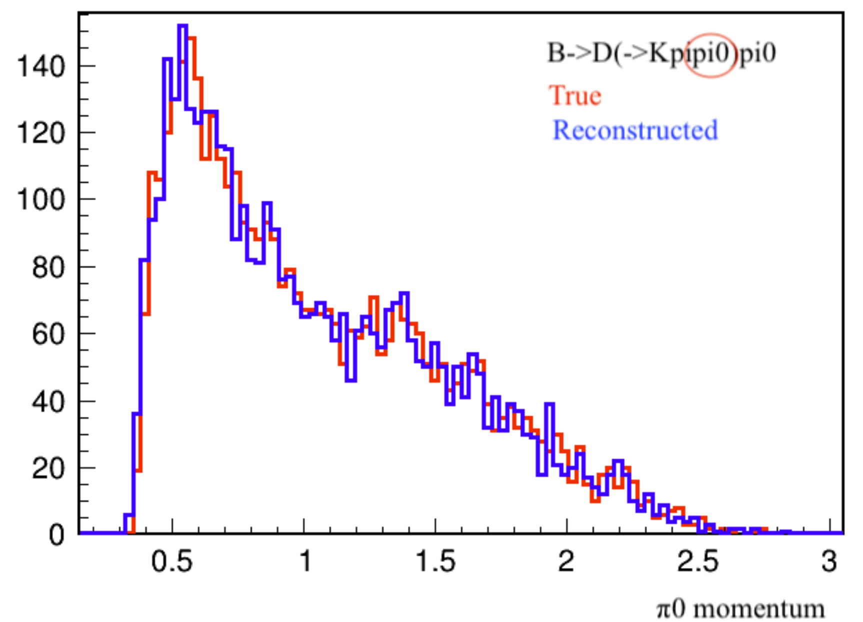
→ The π^0 mass peak in data must be at the same position as in MC. Both must be ~1-2% below the PDG value.

- Constraining your π^0 candidates to the PDG mass may be helpful.

Issue / to do (?): π^0 momentum calibration

- Even after the mass constraint, the π^0 momentum is biased as a result of the photon low-side tail.
- Would it be worth developing a calibration to correct for this? Needs study.



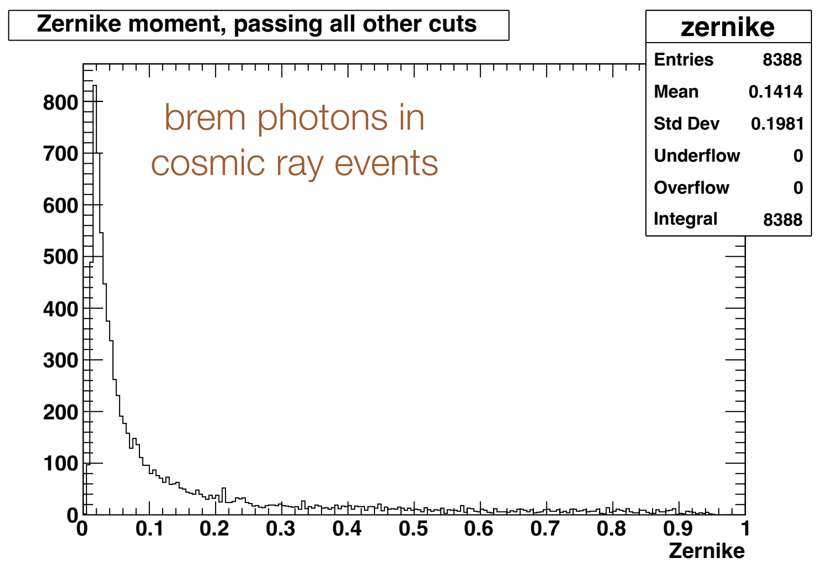


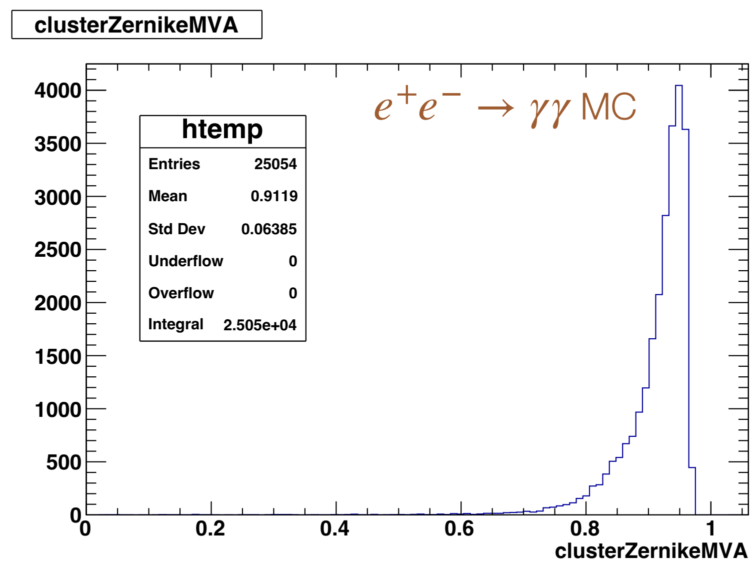
Sebastiano Raiz

Particle identification

Neutral particle ID: shower shapes for photon / hadron separation

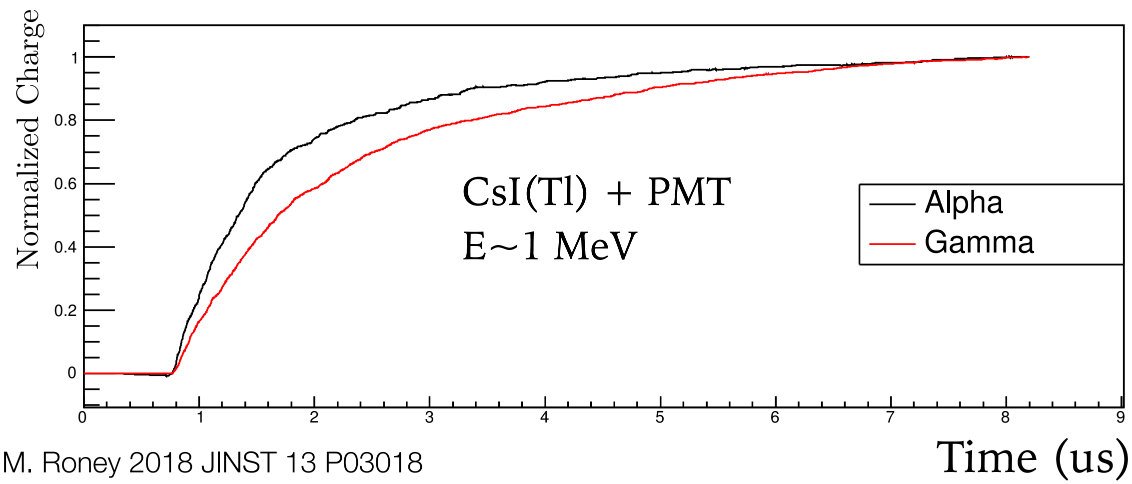
- Distinguish photon showers from hadronic showers, or from photons originating far from the IP.
- Characterize the energy distribution among the (up to) 21 crystals in an ECLCluster. e.g., clusterSecondMoment, clusterZernikeMVA, clusterE1E9





Neutral particle ID: pulse shape discrimination for photon/hadron separation — Savino Longo

- In CsI(Tl), highly-ionizing particles produce a faster scintillation signal than electromagnetic showers.
  - protons or α produced in hadronic showers.



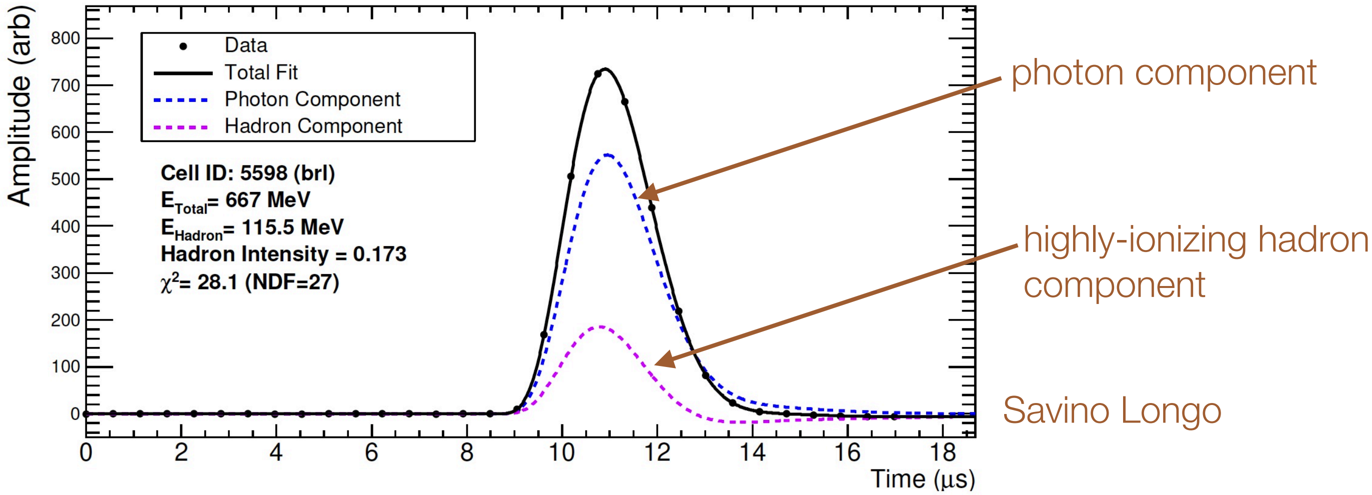
Savino Longo

S. Longo and J. M. Roney 2018 JINST 13 P03018

- We record waveforms of crystals above 50 MeV to look for such signals in offline reconstruction.

- **Question**: Many of the crystals in a cluster have energy <50 MeV; why don't we record their waveforms as well?

- Offline waveform fit extracts the fraction of the signal that is due to highly-ionizing hadrons.

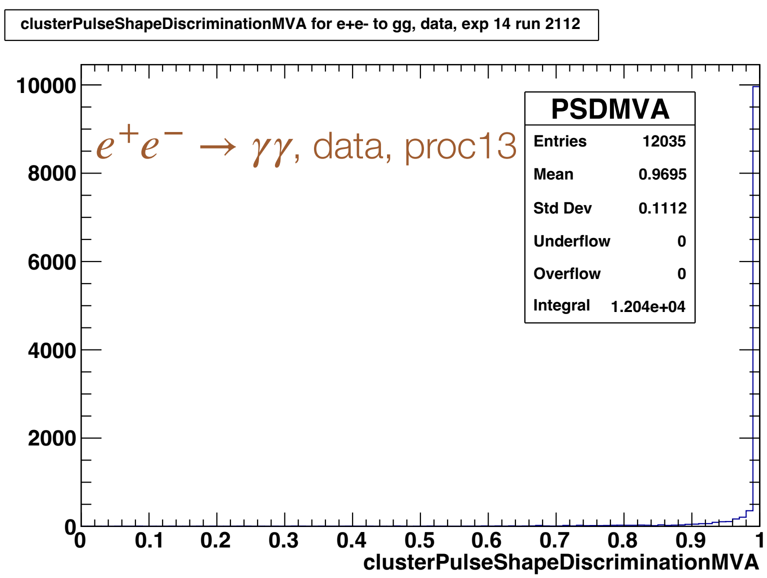


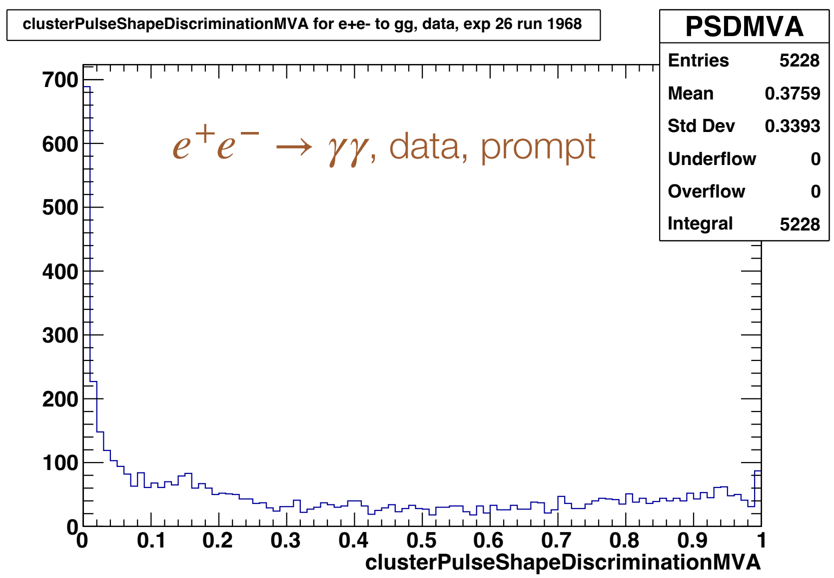
- Information from all crystals in a cluster is combined in an MVA "clusterPulseShapeDiscriminationMVA".

- Note that not all hadrons produce such highly-ionizing particles in the ECL.

Issue: pulse-shape-discrimination calibration

- Offline fit uses database payloads that depend on the level of beam backgrounds.
- Prior to release-08, these payloads were not calculated during prompt reconstruction ⇒ MVA is not usable in existing prompt data.



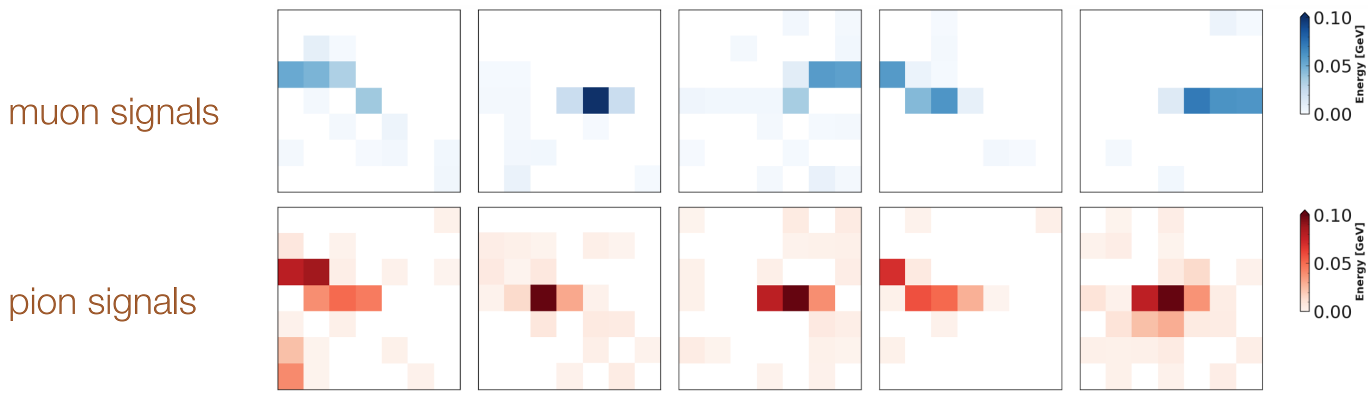


Charged particle identification: ECLChargedPIDMVA — M. Hohmann, M. Milesi, and P. Urquijo

- Original likelihood-based particle identification relies primarily on E/p (cluster energy / track momentum).
- ECLChargedPIDMVA adds many shower shape and per-crystal variables in a boosted decision tree.
  - trained in 18 categories: 3 momenta × 3 θ × 2 charge
- At low momentum, reduces $\pi^{\pm} \to e^{\pm}$ misID by 10×; $\pi^{\pm} \to \mu^{\pm}$ by 2×.
- As of release-07.

Future: convolutional neutral net — Abtin Charan and Torben Ferber/Anja Novosel

- Analyze a 7×7 set of crystals in the barrel as an image with the particular goal of distinguishing low-momentum muons and pions.



- Does not rely on track/cluster matching.

- Should get another factor of 2 reduction in misID.

Summary

- A lot of material, but a lot I didn't cover — just ask!
- Many opportunities to get involved. Talk to me if you would be interested in taking on a project in this area.

For additional information…

- Details of original construction
  - Hitomi Ideka, PhD dissertation (1999)

- Overview of planned Belle II upgrades
  - Belle II Technical Design Report, 1011.0352 [physics.ins-det]

- ECL data acquisition
  - V. Aulchenko et al, Development of data acquisition system for Belle II electromagnetic calorimeter, Nucl.Instrum.Meth.A 1030 (2022), 166468

- Radiation hardness
  - S. Longo and J.M. Roney, Radiation Hardness of 30 cm Long CsI(Tl) Crystals, JINST 11 (2016) 08, P08017

- Hadronic pulse shape discrimination
  - S. Longo and J.M. Roney, Hadronic vs Electromagnetic Pulse Shape Discrimination in CsI(Tl) for High Energy Physics Experiments, JINST 13 (2018) 03, P03018

- GNN clustering
  - F. Wemmer et al, Photon Reconstruction in the Belle II Calorimeter Using Graph Neural Networks, 2306.04179 [hep-ex]

- Convolutional neural net for particle ID
  - Anja Novosel et al, Identification of light leptons and pions in the electromagnetic calorimeter of Belle II, Nucl.Instrum.Meth.A 1056 (2023), 168630