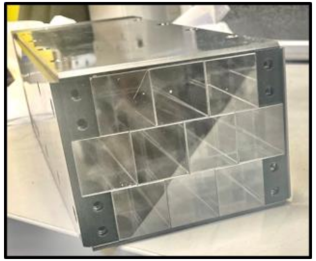
The Case for LYSO - Open Presentation Topics

Omar Beesley & David Hertzog

- **Our Philosophy**:
  - Optimize for physics
  - Use Simulation, 3D printing, Bench, and Beam tests to verify design
  - Closely follow literature and improve on prior efforts
  - Integrate LYSO completely into Sim Framework with waveforms based on measurements and clustering to form events
- **Our Approach:**
  - Take deliberate steps starting with single crystals, simulations, and building a segmented crystal calorimeter that more than meets the specifications of PIONEER
  - Bonus features which will no doubt become critical during actual data analysis stages, providing redundant information to help validate the findings

Prototyping Sequence and Plans



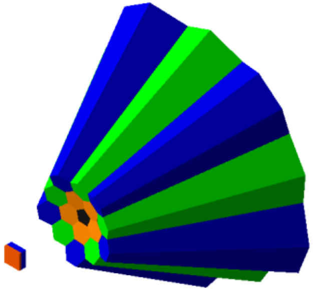
1. Single crystal measurements
2. Small arrays and comparisons of 10 xtals for uniformity of measurements
3. 10-Array in beams from 17.6 to 100 MeV
4. Optimization of PMT divider response for high light yield
5. Geometry optimization through Simulations
6. Acquiring tapered samples per geometry; simulation to determine required longitudinal uniformity
7. Simulations of focussing / roughening effect and calibration against known cases
8. Measurement iteration of uniformity vs roughening for each xtal shape (few months)
9. Acquiring 6-array for tests at PSI and CENPA for a Fall 2025 run
10. Acquiring 16-array for PIONEER Demonstrator for a Fall 2026 run

Ordered: UW/SJTU/ETH

A

3 to order "6-Array"

HexG to order (largest)

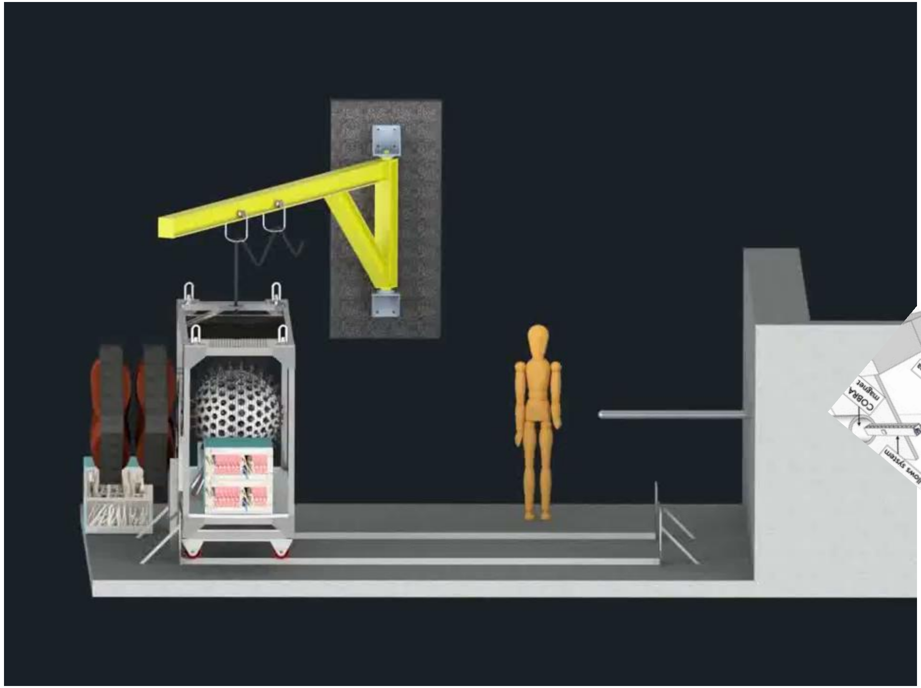


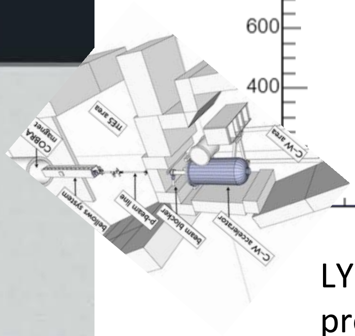
Ideal 16 Array for Demonstrator

Calibration: Absolute energy with p-Li reaction 3x / week @ 17.6 MeV gammas.

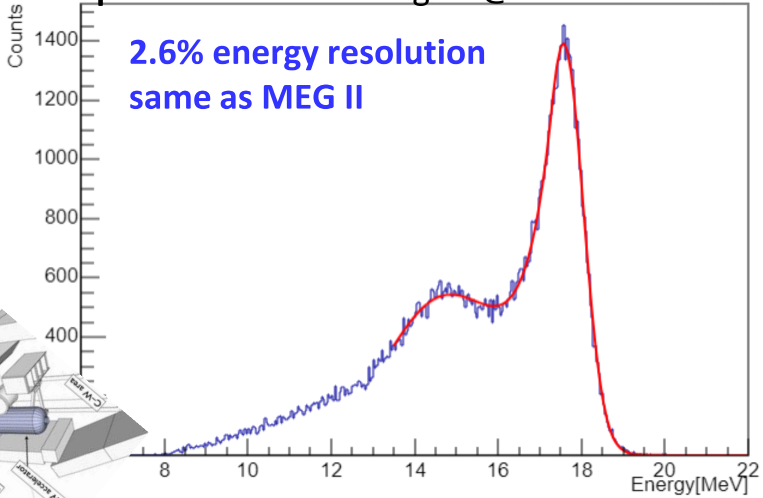
Each crystal will have an individual spectrum so calibration constants can be tuned to guarantee uniform energy response vs (theta, phi)

Assumes we can borrow* or obtain a new Cockroft-Walton proton gun (if new, adds to cost)





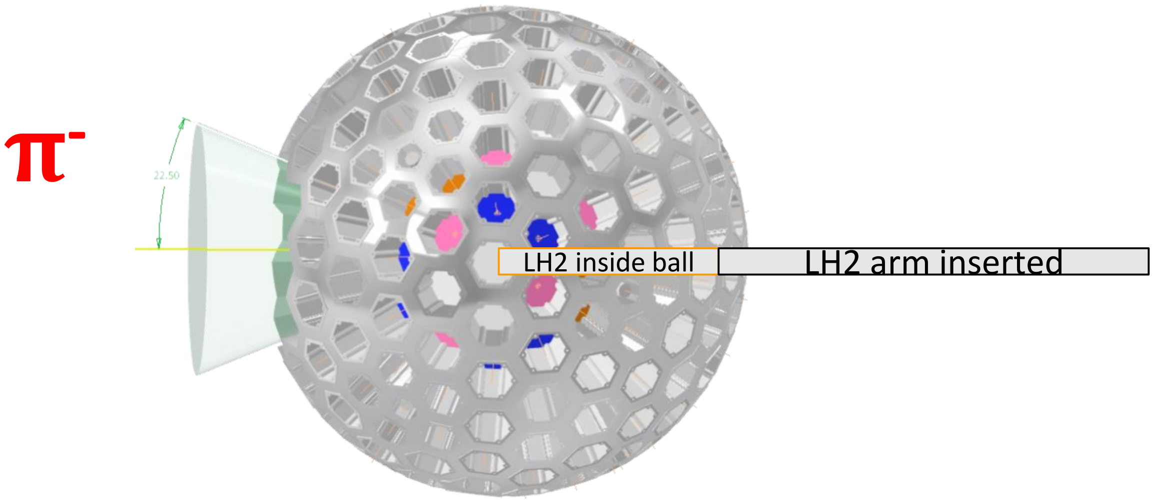
p-Li method following L3 @ LEP and MEG-II



LYSO measured at CENPA using VdG proton source and Li target
17.6 MeV gamma

*Owned by INFN and not obviously available after MEG II finished

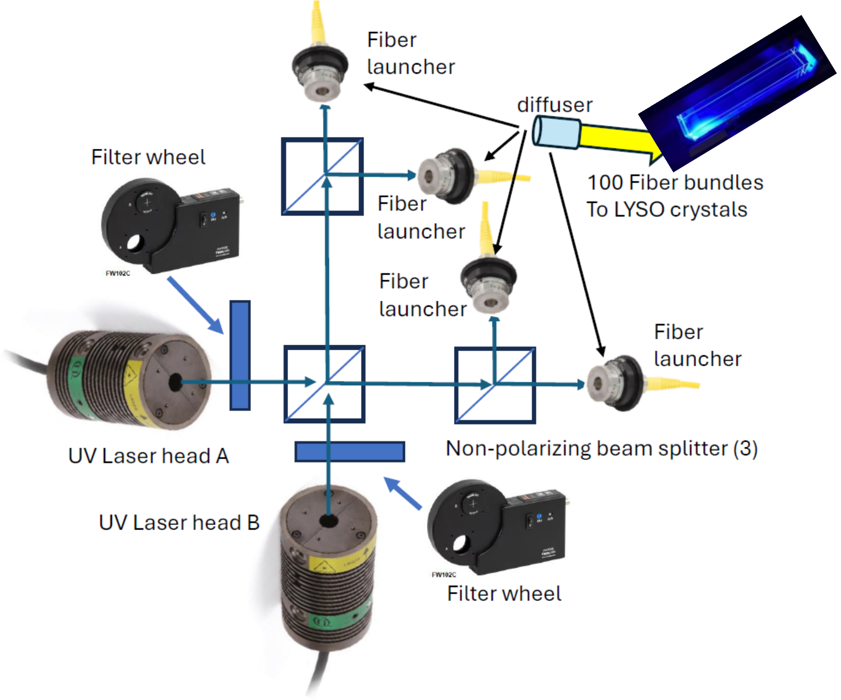
- **For higher energy absolute energy, adopt the successful charge-exchange method used by MEG: $\pi^- p \rightarrow n\pi^0 \rightarrow \gamma\gamma$, employ it once per running cycle;**
  - **Remove 6 downstream crystals to insert LH2 arm; negative pions, remove ATAR**
- **Use direct e+ beam to measure the Tail in downstream crystals**
- **Can build the shell to allow e+ beam to enter at other places, perhaps azimuthal sweep if deemed important**
- **Once calibrated, Michels are used to monitor and observe polar/azimuthal dependence**



(yes, this is just a support shell to illustrate the geometry)

Calibration of xtal light output-, gain-, and timing-stability

Each crystal is excited by an individual fiber from the bundles shown below and all are fired simultaneously to align timing in electronics and offline



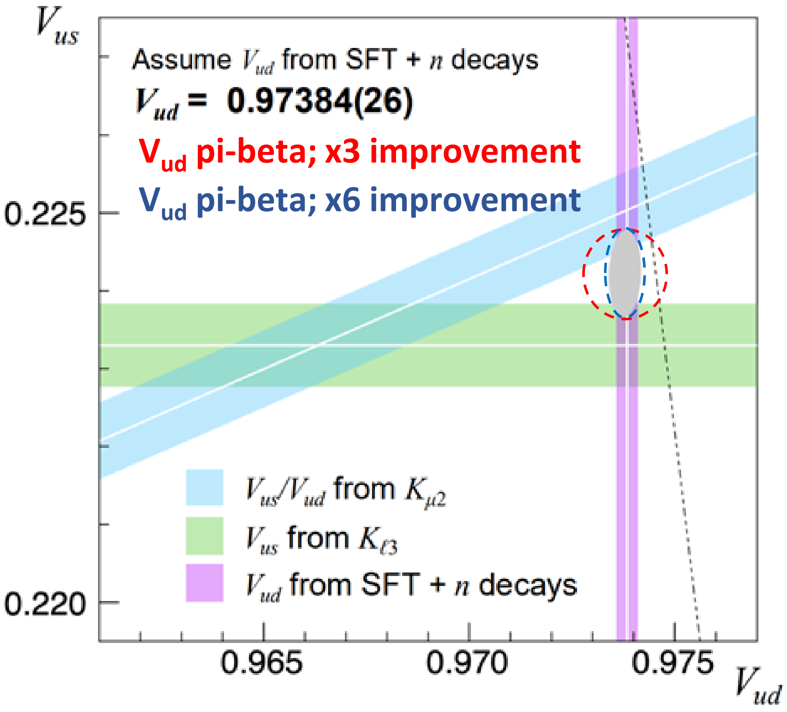
The scintillation light is excited by photons with wavelengths in a band around 360 nm and de-excites by emitting photons in the visible. This process can be monitored by injecting 355 nm photons from a laser and recording the true pulse shape and light intensity in the normal DAQ.

The system is conceptually similar to g-2 experiment for 1296 crystals (A. Anastasi et al JINST 14 P1125)

Two lasers allow double pulsing with any pulse to pulse separation.

Laser light is split into 4 equal paths by 3 50/50 beam splitters. These are collimated by fiber launchers into 100 channel fiber bundles for distribution to individual crystals. The 4 light distribution fiber bundles include diffuser sections to uniformly spread out the gaussian input beam to all fibers in the bundle. For best efficiency the number of fibers in the bundle is the square of an integer. The custom fiber distribution bundles in the figure have a length of 4 meters with FC connectors for connecting to the crystals. They can be purchased from SQS Vláknová optika a.s.. The optical breadboard is contained in a light tight ventilated box mounted in the vicinity of the

High Precision unitarity test with pion beta decay



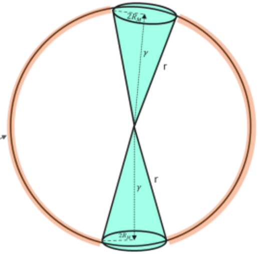
From Matt Moulsen

- Appealing measurement to the NP and HEP community
- V_{ud} measurement in super-allowed beta decays limited by theoretical uncertainties on hadronic form factors
- Pion beta decay is the cleanest (theoretically)reaction to measure V_{ud}
- PiBeta: $\Gamma(\pi^+ \to \pi^0 e^+ \nu)/\Gamma(\pi^+ \to \text{all}) = 1.036\ \ (0.006) \times 10^{-8}$

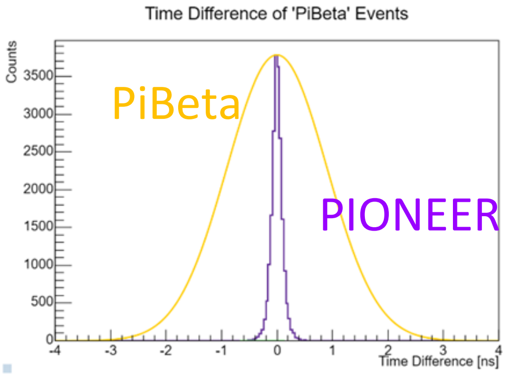
PIONEER aims to improve

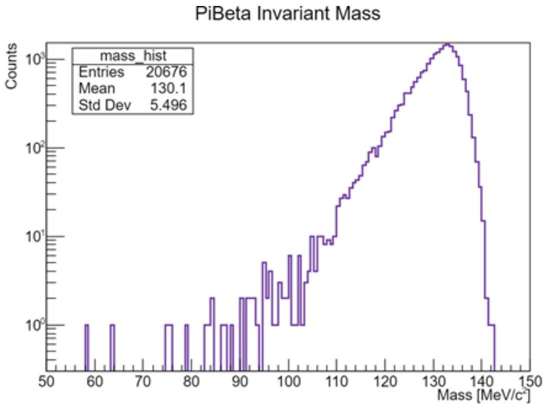
- **x3 as proof of concept** (~1 year)
- **x6 as a competitive cross-check of the historical approach** (~3 years)
- x10 would become the reference (aspirational) but at present limited by π^+ - π^0 mass difference that might be measured in the future

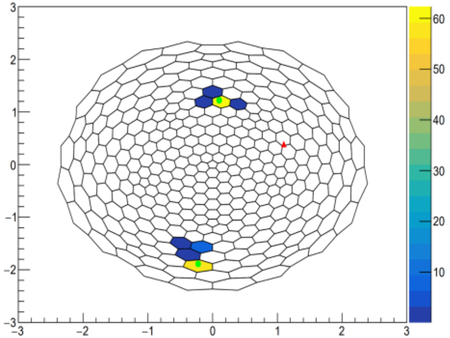
We carefully studied PiBeta method and systematics to learn if we have advantages



- LYSO array in Full Simulation.
  - Michels, & p+ n → p pi0 prompt reactions studied (momentum dependent).
  - Realistic 10x higher rate at 85 MeV/c (not 110 MeV/c)
- LYSO vs CsI: timing & energy resolution greatly improved → lower backgrounds
- Events identified by the invariant mass Sqrt[$2E_1E_2(1\text{-}\cos\alpha)$] =134.9769 MeV







PiBeta Spectrum (work in progress)

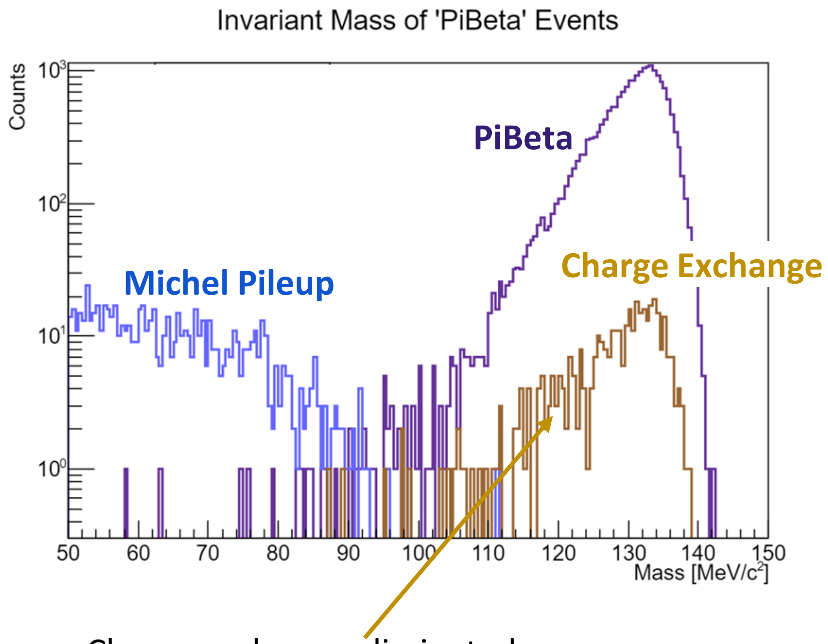
- Mass > 90 MeV
- Alpha > 130°
- Time Difference < 0.8 ns
- Time < 250 ns

Sensitivity: 99.94%
Specificity: 100%

Michel pileup are never IDd as PiBeta

We know there are challenges to work out, like normalization and systematics.

LG: “can include pibeta triggering in phase 1 to allow development / fine tuning of strategy”



Charge exchange eliminated through early time cut

Bradley Taylor (now UW grad)

Time needed for precision goals is reasonable

- Event Goal: 6.25×10^5 PiBeta Events
  - → 3 times statistical improvement
- Beam Rate: 10^7 Hz
- PSI/Expt Uptime: 80%
- Geometric Acceptance: 50%
- Time Acceptance after Pi stop: about 80% (77% to 95%)
- → **7.1 Months of running**
-

PIONEER Uncertainty: **2.1×10^{-11}**
PiBeta Uncertainty: **6.4×10^{-11}**

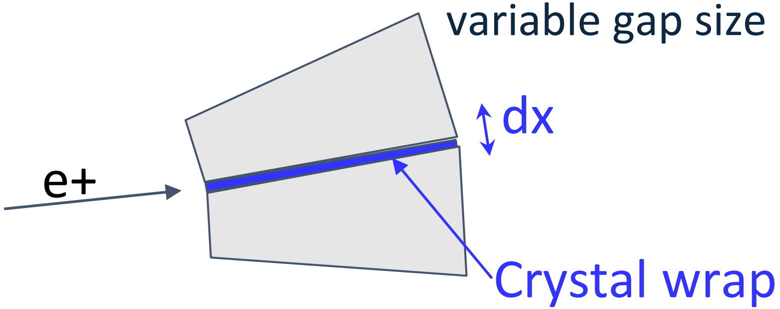
This looks promising and we will continue to study it as the detector evolves. It's worth stating we have a plan of x3 and x6

Addressing concerns for a LYSO calorimeter

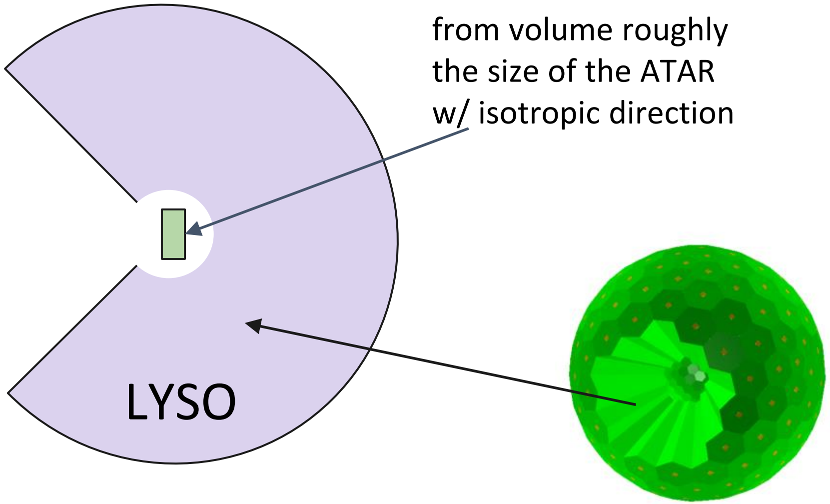
- Losses at gaps between LYSO crystals
- Energy resolution degradation due to LYSO intrinsic radioactivity
- Performance issues due to tapered crystal shapes

Effects of gaps between the crystals

Simulate calorimeter performance for variable gap size dx



70 MeV e+ started from volume roughly the size of the ATAR w/ isotropic direction



Crystal calorimeters (Mu2e, CMS, Belle-2, etc.) typically have a gap size of 0.1-0.3mm

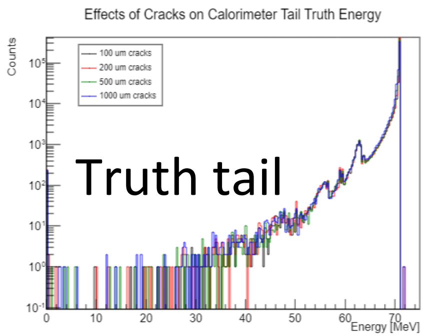
- <0.1mm can be achieved using reflective sprays
- 0.1-0.15mm can be achieved with aluminum foil or ESR

Gaps <1 mm have minimal effect

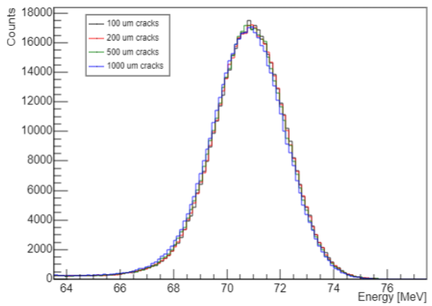
- The intrinsic calorimeter tail fraction is only about half of the total expected tail fraction (which is 0.5-0.7%) based on other detectors
- An ATAR offset of 0.5 cm almost completely eliminates effects of losses at gaps (1 in 10^4 e+ go through 200um gaps)

Gap Size (mm)	Tail Fraction (Calo Only)	Energy Resolution
0	0.19%	1.83%
0.1	0.21%	1.85%
0.2	0.24%	1.86%
0.5	0.25%	1.86%
1	0.25%	1.87%

Likely gap size



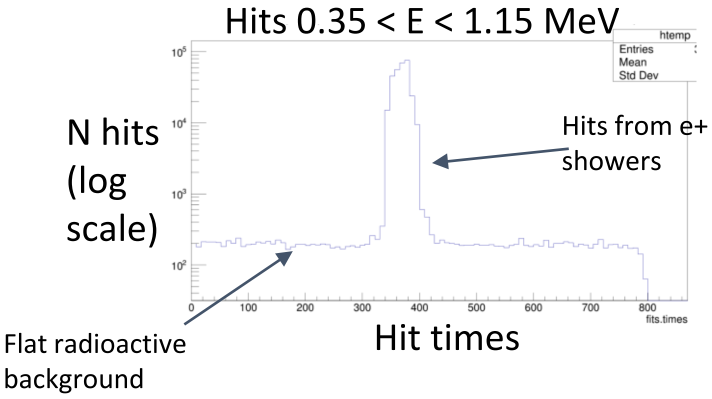
Smeared 1.8%

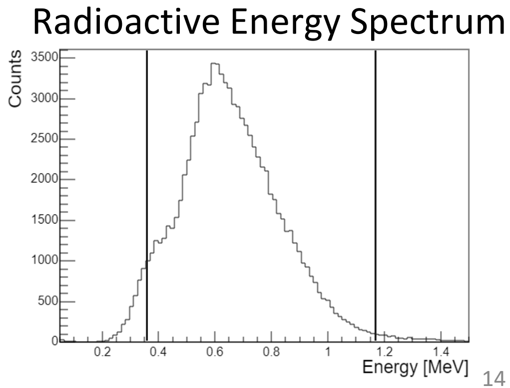


Takeaway: **Gaps between crystals will have a minimal effect on PIONEER calorimeter performance with the ATAR offset 0.5 cm in z. The current default offset in the PIONEER sim is 0.3 cm.**

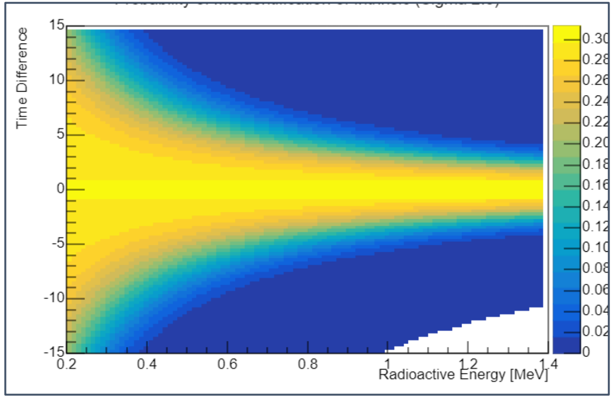
LYSO Intrinsic radioactivity rate, as measured using the PSI test beam data

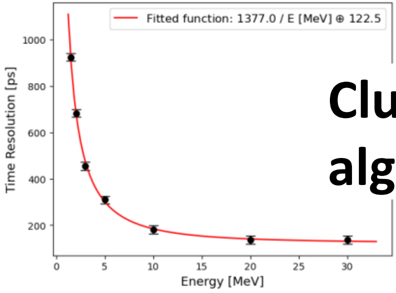
1. Radioactivity appears as a flat background in time – we can count hits in regions of time not coincident with the positron hit.
2. This number of radioactive events is then normalized to the total number of events to determine the radioactive rate in the LYSO array: 150 kHz
3. This number is then multiplied by 135 (the relative LYSO volume in the PIONEER calorimeter to the volume of the test beam array). **The intrinsic rate in the PIONEER calo is then 20 MHz.**



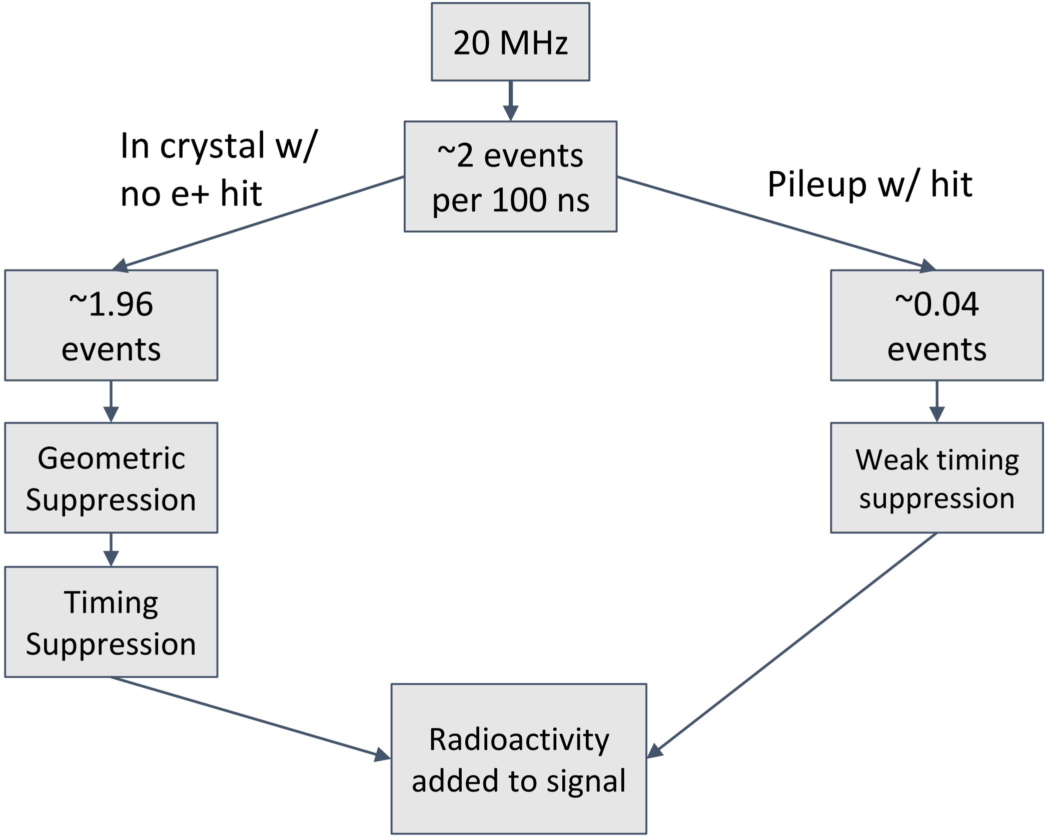


Reconstruction of intrinsic radioactivity





Clustering algorithm



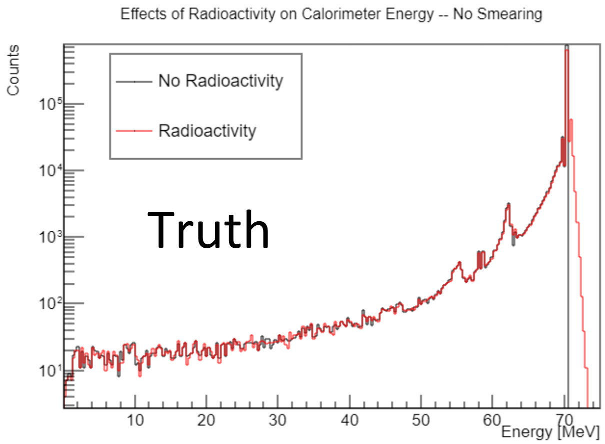
1. ***Within 3.5 sigma time and 2.5 M_R***
2. ***Within 2.5 sigma time and 4 M_R***

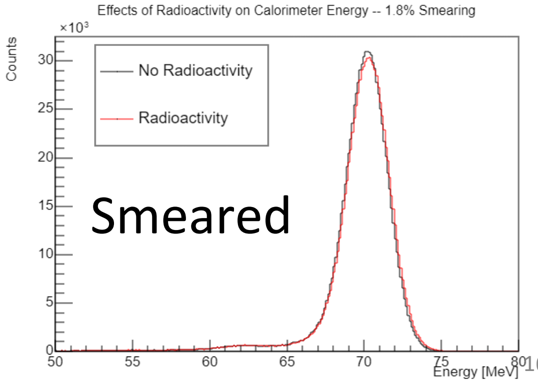
Effects of intrinsic radioactivity are minimal

Intrinsic energy deposits will be added to real energy deposits **<u>BUT</u>**

- Most radioactivity is not time/spatially coincident with real hits
- Intrinsic radioactivity is peaked at 0.6 MeV – a 1.8% resolution gives a σ=1.3 MeV @ 70 MeV
- **<u>Resolution goes from 1.85% → 1.89%</u>**

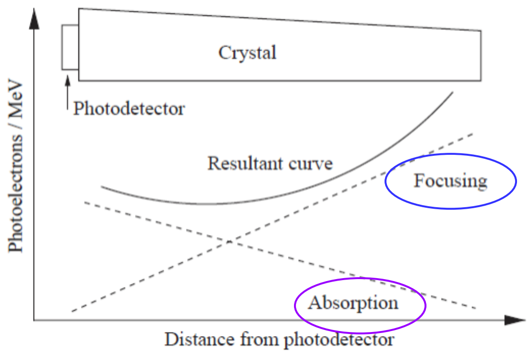
<u>Takeaway</u>: **LYSO intrinsic radioactivity will have a very minor effect on calorimeter performance. This radioactivity is low energy, and timing/segmentation provide additional rejection of radioactive pulses in reconstruction.**

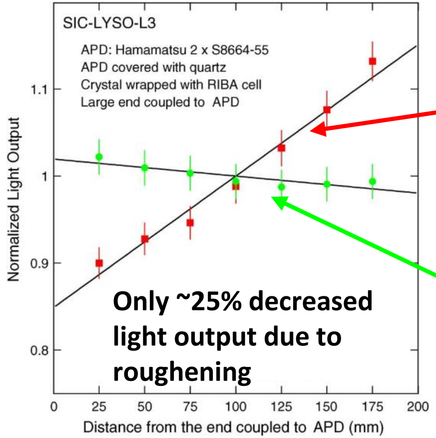




Effects of tapered crystals on response uniformity

Previous experiments (L3, SuperB, CMS, PEN, + more) have developed methods to counteract the focusing effect through roughening of crystal surfaces. SICCAS can use analogous methods to those developed previously to ensure uniform crystal response for PIONEER.

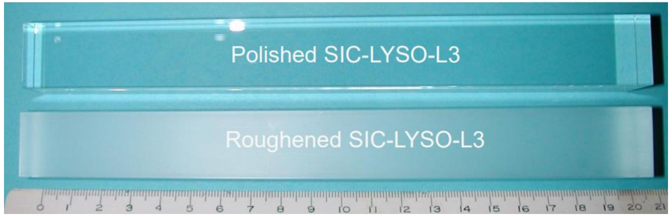




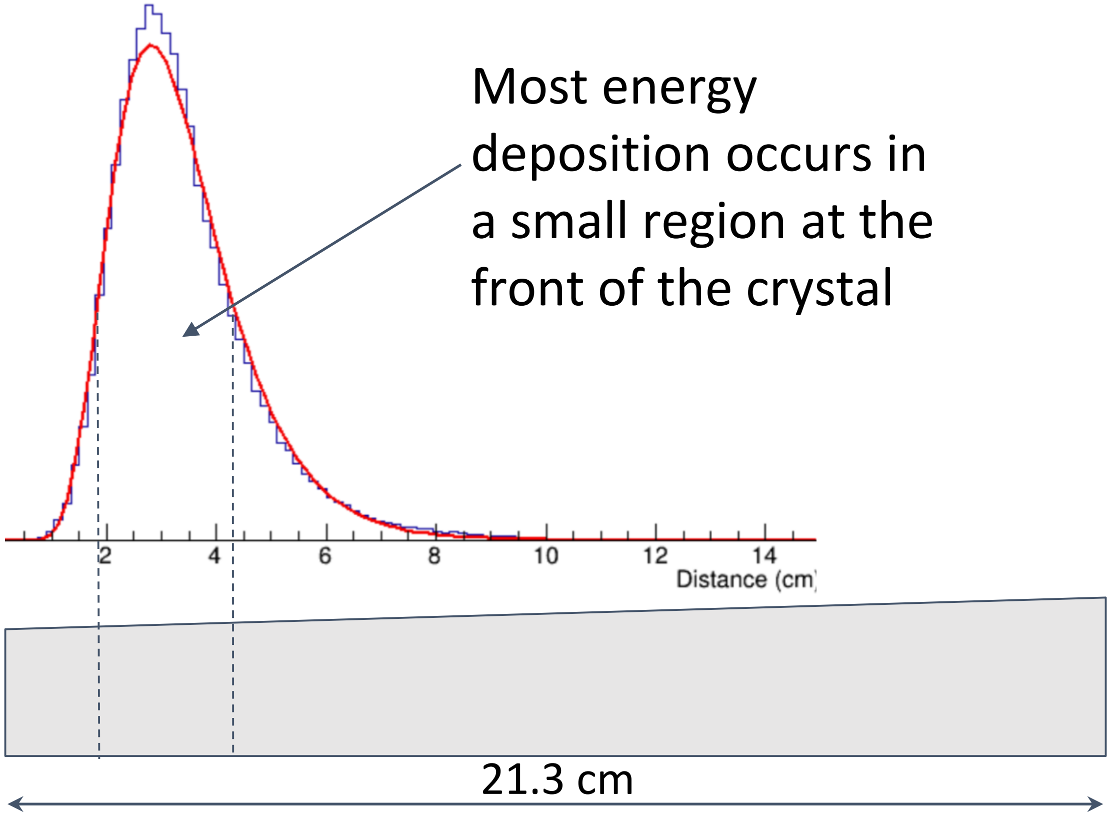
Before: 22% non-uniformity

After: 3% non-uniformity

- Competing ***absorption*** and ***focusing*** effects determine the crystal response uniformity
- ***Roughening*** crystal sides counteracts the focusing effect. We can tune roughening to achieve a uniform crystal response.



Longitudinal response uniformity in PIONEER



Due to shower concentration at the front of the LYSO crystal, PIONEER has a looser specification on uniformity than high energy experiments with large dynamic ranges spanning many orders of magnitude in energy.

To maintain an energy resolution <2%, PIONEER response uniformity must be only 1.0%/cm or better. (~20% along crystal length)

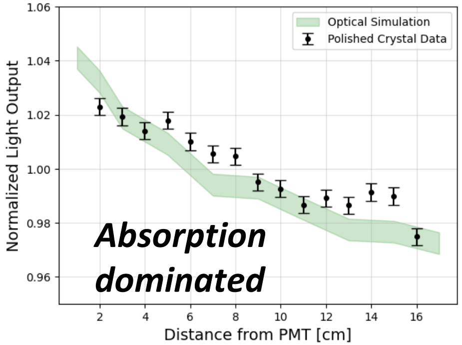
Optical simulation reproduces focusing effect

Optical simulation includes:

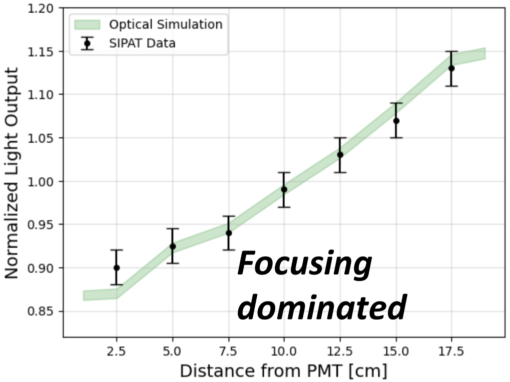
- Crystals with accurate shapes
- Optical properties of LYSO measured using a spectrometer
- Wrappings and optical grease
- Photodetector QE

Optical photons are started from cross sections in the crystal longitude and counted at the photosensor. <u>Simulation matches data for rectilinear and SIPAT tapered crystals with polished sides.</u>

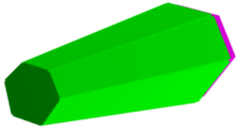
Rectilinear
2.5x2.5x18 cm^3



SIPAT – front: 2x2 cm^2 back: 2.3x2.3 cm^2 length: 20 cm



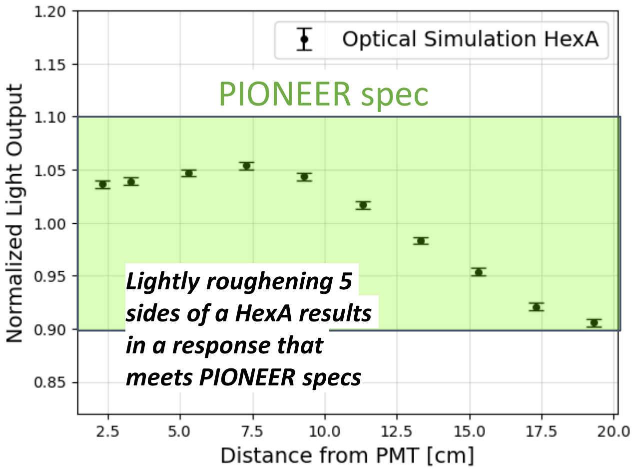
Optical simulation predicts roughening procedure that meets PIONEER specs



Roughening all sides of a PENT/HexA results in a dominant contribution from absorption

→ There exist roughening recipes (num sides roughened, roughness of sides) that will produce uniform crystal responses

A quick probe of roughening parameter spaces finds recipes that **<u>meet the PIONEER specs for PENT/HexA</u>**



Dear David,

After inspection, it is confirmed that the surface roughness range of the crystal roughened by the method developed in this laboratory covers the roughness value you mentioned (Ra = 0.3 um), which means that according to actual needs, we can use this method to roughen the crystal (Pent and Hex) to be delivered to you until we get the result you need.

Cheers,
Dongzhou

<u>SICCAS confirmed there is a roughening procedure already developed</u>

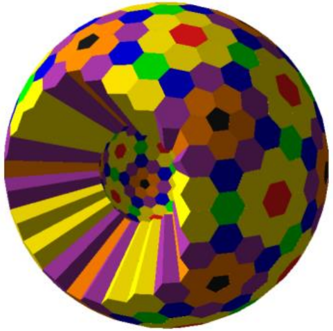
Takeaway: **Previous experiments with tapered crystals have met their specifications for uniformity and PIONEER has looser constraints on uniformity than these experiments. Optical simulation predicts that roughening methods already developed by SICCAS can be used to achieve PIONEER's specs.**

Draft of the next 3+ years we are proposing to DOE for CENPA related to LYSO [this is private and shared in the spirit of collaboration]

Calo detailed *draft* program

year	project	main activities	milestones	deliverables
0	Crystals	Establish tapered crystal uniformity in simulation and samples measured	Acquire 3 samples	Measurements of uniformity for various treatments of surfaces
1	Crystals	Build and measure 6-element tapered array Test production of large HexG module Seek funding for expansion of array	PSI run with 6-array CENPA run with 6-array Grant preparation	Energy, Timing resolution in realistic situation; library of real waveforms for Simulation and reconstruction Submitted grant
2	Crystals	Prepare PIONEER Demonstrator calorimeter components Analyze data and prepare final funding requests Build laser calibration system	PSI Run with all PIONEER Demonstrator components Analyze Calo-specific results	Calo array as part of the full Demonstrator
3	Crystals	UW Builds lightguides, mechanical supports, and calibration system for full array; Participate in assembly at PSI of crystals as they arrive	This is an assembly year with a continuous activity of assembly and testing	As many modules as the company can produce of the 311 needed

Summary



- Meets Pioneer specs
- Practical factors that lower cost and complexity
  - Blue light out → conventional PMT;   UV laser/LEDs can be used to excite scint for calibrations
  - Can be craned in/out easily, rotated for calibration, serviced to change any faulty sensors;
  - No significant safety concerns, not temp sensitive
- Segmentation is a significant advantage
  - Much lower pileup, lower data rate, position coordinate, calibration plan
  - The important PiBeta physics case is enabled
- High density
  - Compact showers, smaller volume, closer to Quads, fiducial volume greater vs polar angle
- It's *Simpler* in every aspect
  - Easy to maintain, Easy to calibrate, Easy to analyze, Easy to trigger, …
  - Reconstruction of events is much easier
  - Allows systematic confirmation of radiative decays, Bhabha scattering, mixed events, and so on..
- Progress does not depend on the completion and availability of resources from MEG II