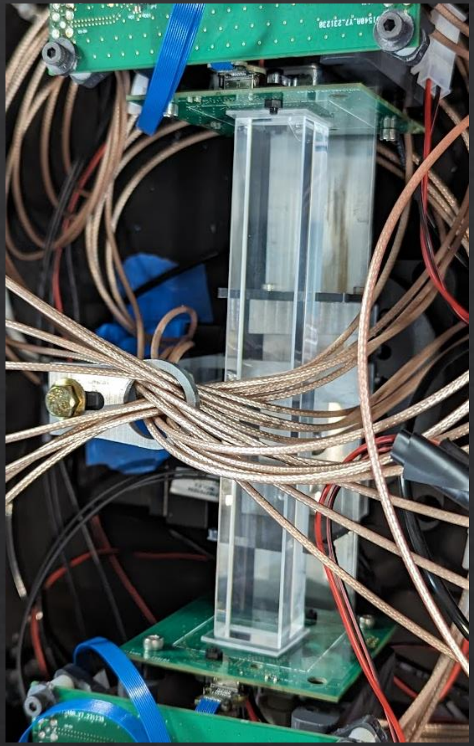   

Dual Readout Calorimetry for FCC Recent News

FUTURE CIRCULAR COLLIDER

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U. Maryland

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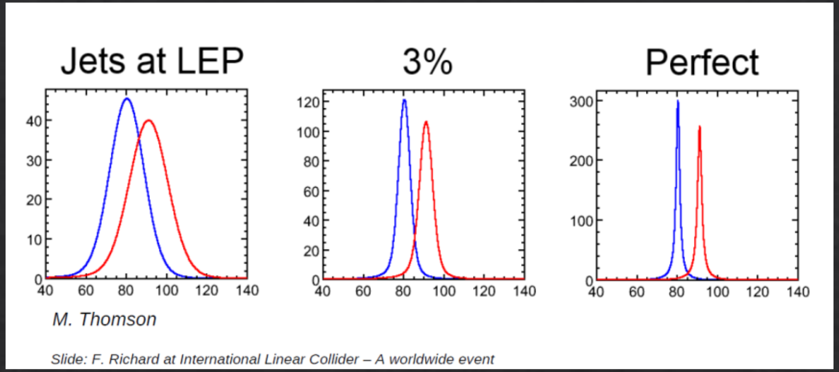
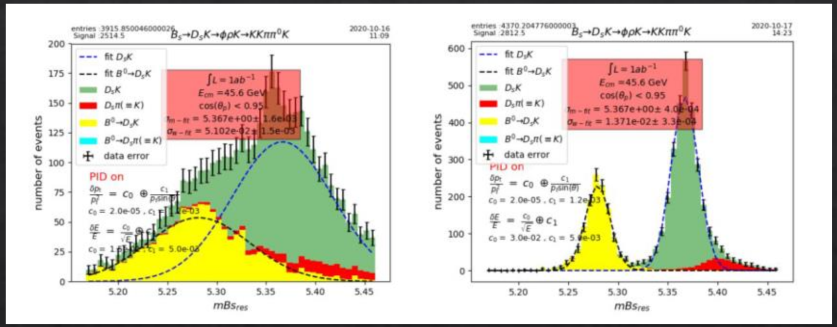
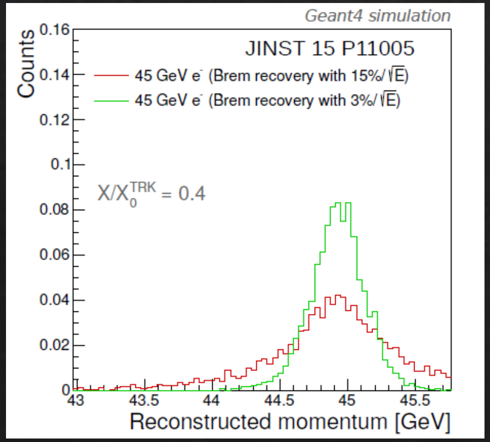
Calorimetry and the physics goals of the FCC-ee program

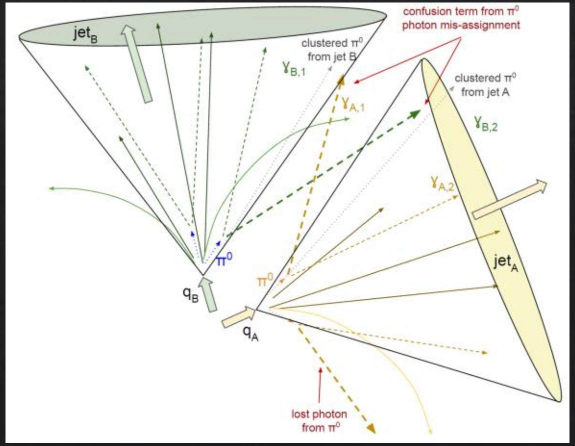
The physics goals of the FCC-ee program put stringent demands on calorimetry; e.g.:

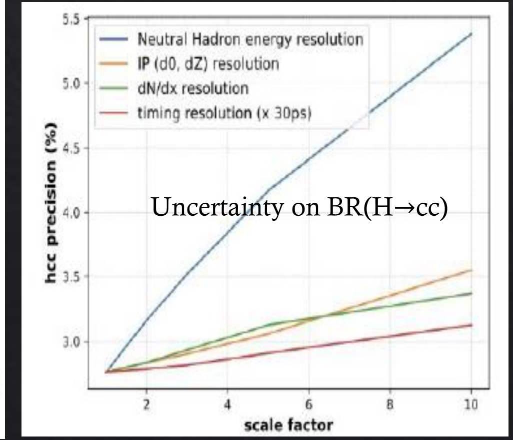
- Distinguish hadronic decays of W,Z,H
- Precision reconstruction of exclusive b and tau final state to reduce backgrounds
- Reduce effect of bremsstrahlung on electron resolution
- Correct association of particles to jets
- 4 pi coverage

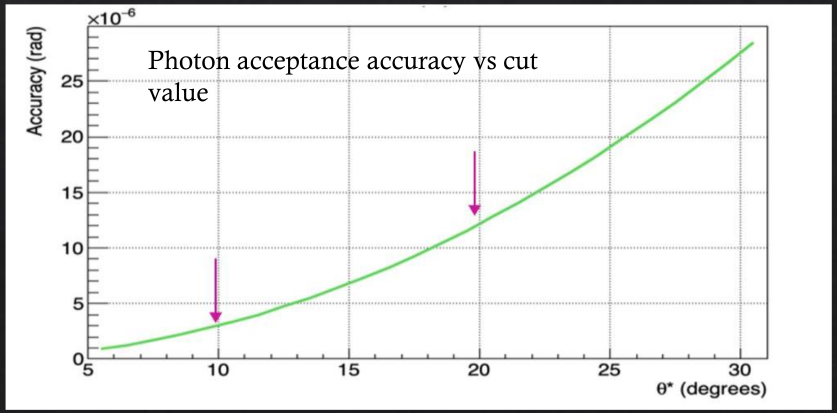






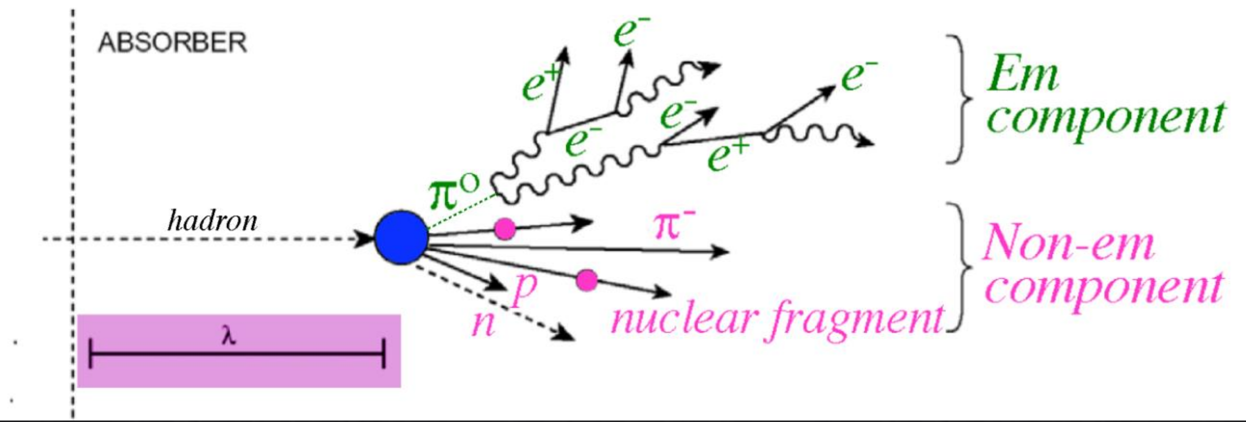


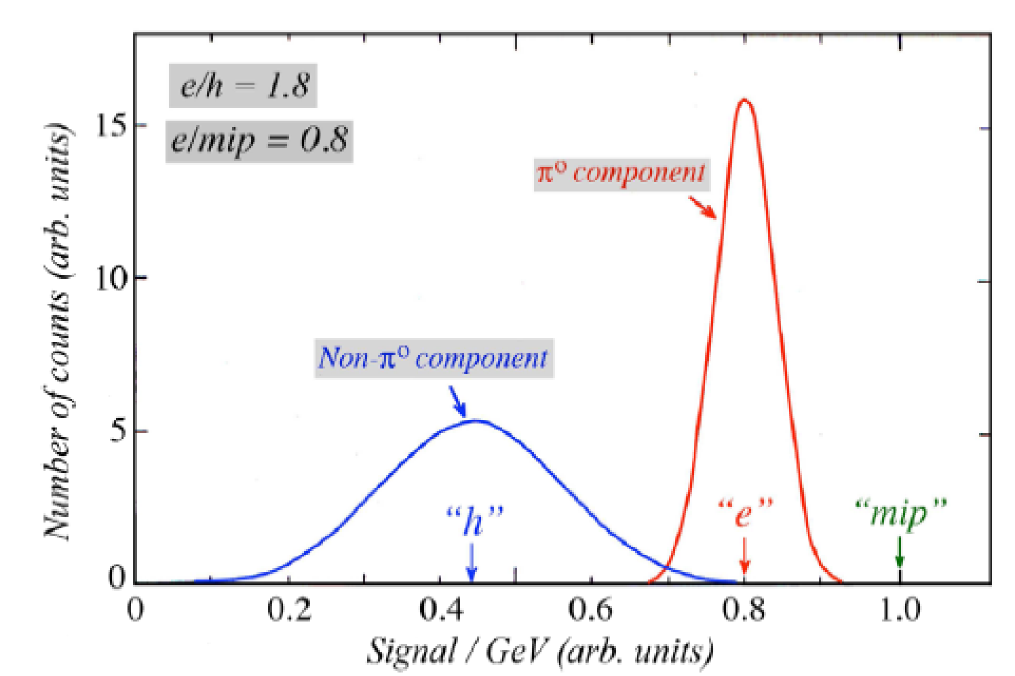




Challenges of hadronic calorimetry

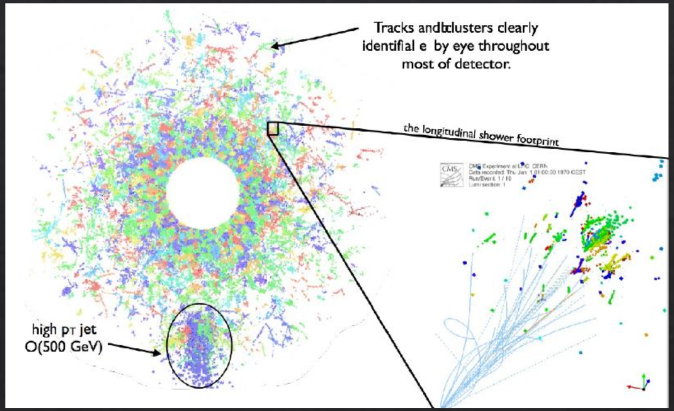
Hadronic Calorimetry is hard

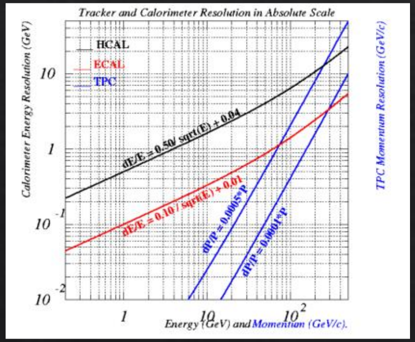




Two complementary solutions

High Granularity calorimetry minimizes reliance on hadronic calorimeter, used mostly for neutral hadron measurement.





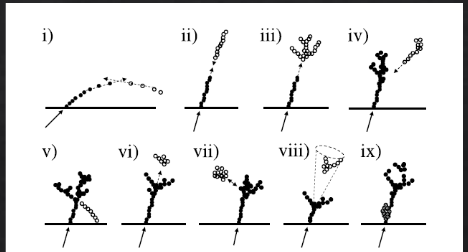
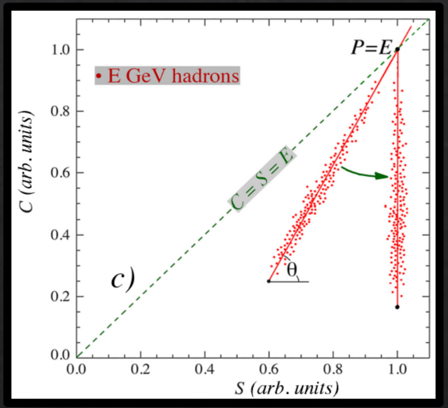


Figure 4: The main topological rules for cluster merging: i) looping track segments; ii) track segments with gaps; iii) track segments pointing to hadronic showers; iv) track-like neutral clusters pointing back to a hadronic shower; v) back-scattered tracks from hadronic showers; vi) neutral clusters which are close to a charged cluster; vii) a neutral cluster near to a charged cluster; viii) cone association; and ix) recovery of photons which overlap with a track segment. In each case the arrow indicates the track, the filled points represent the hits in the associated cluster and the open points represent the hits in the neutral cluster.

Dual readout reduces contribution to resolution from fluctuations in the number of nuclear breakups by using proxies to estimate their number.

Most commonly done by comparing scintillator (sensitive to all charge particles) to Cherenkov light (mostly e^+ e^-) t

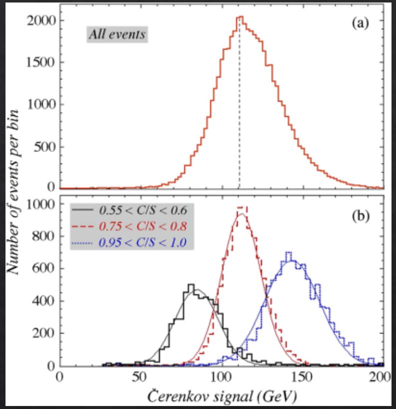


$$S = E[f_{em} + (h/e)_S(1 - f_{em})]$$

$$C = E[f_{em} + (h/e)_C(1 - f_{em})]$$

$$E = \frac{S - \chi C}{1 - \chi}$$

$$\chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$



For an excellent review, see New Developments in Calorimetric Particle Detection
arXiv: 1807.03853

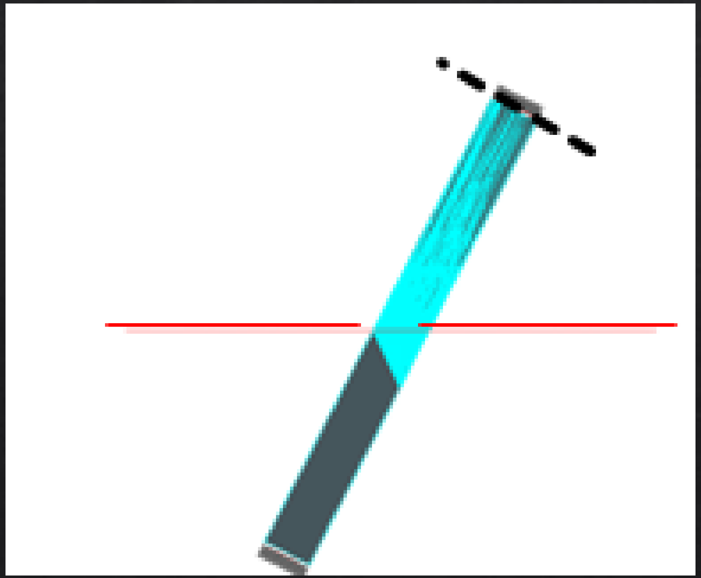
Since FCC-ee will have multiple detectors, solutions with very different systematics are possible.

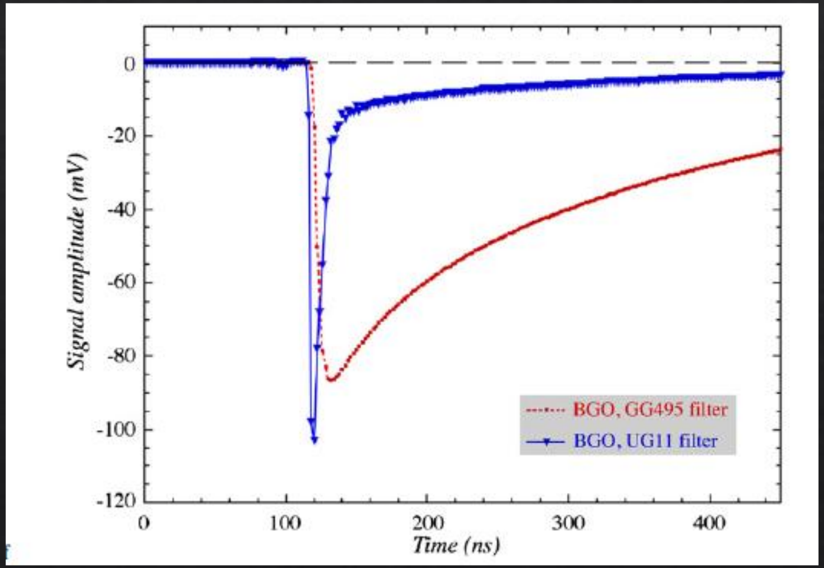
Scintillation versus Cherenkov

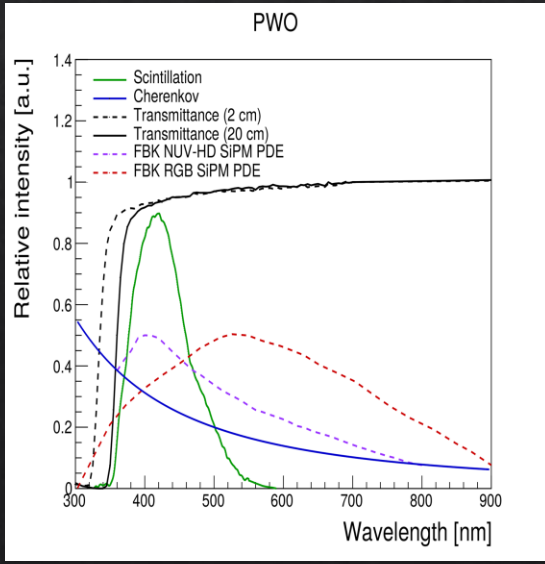
Can use two media, with and without scintillation

Or can be identified by its

- Angle
- Timing
- Wavelength
- polarization

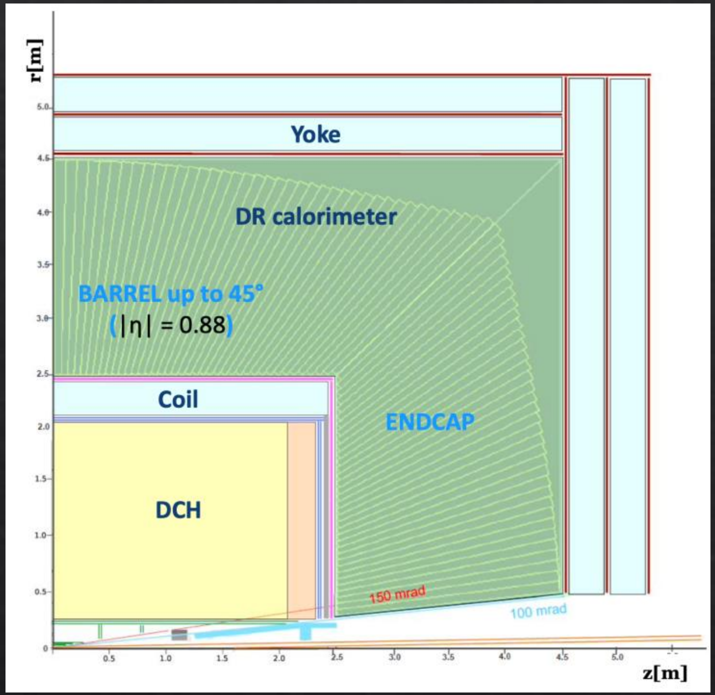


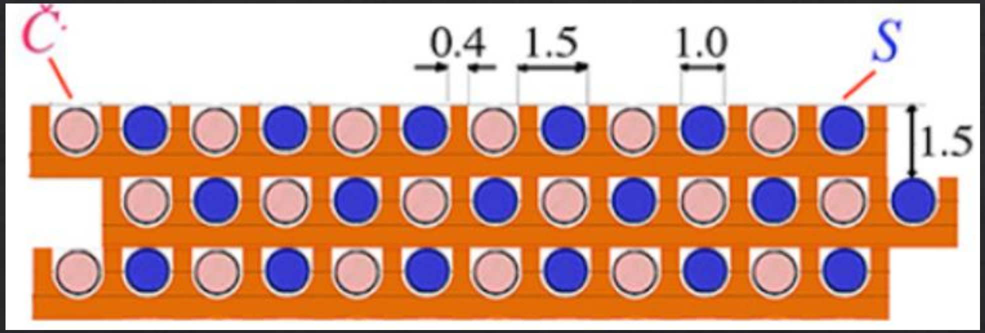


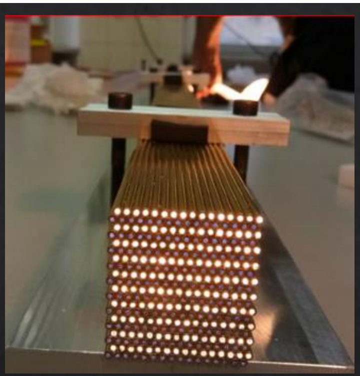


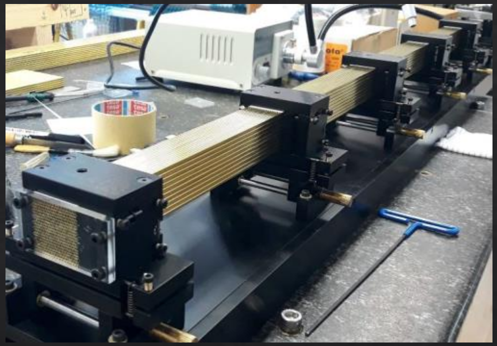
FCCee – flavor 1: the fiber solution

A brass-fiber calorimeter proposed as part of the IDEA detector concept







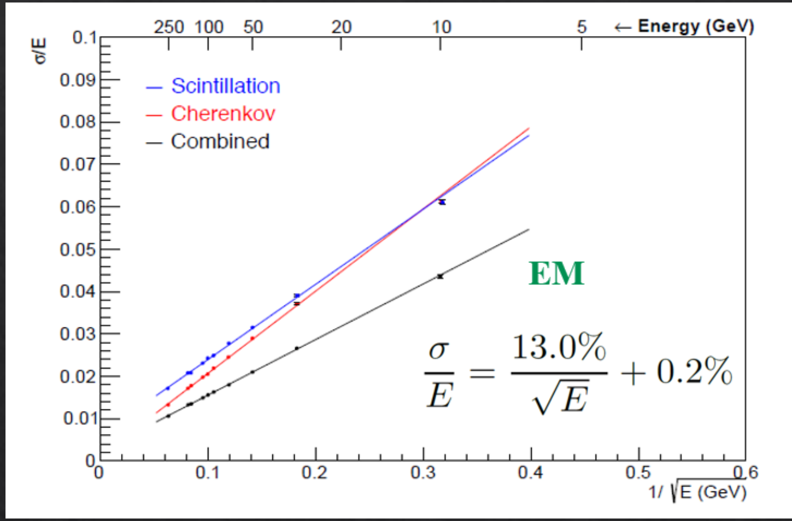


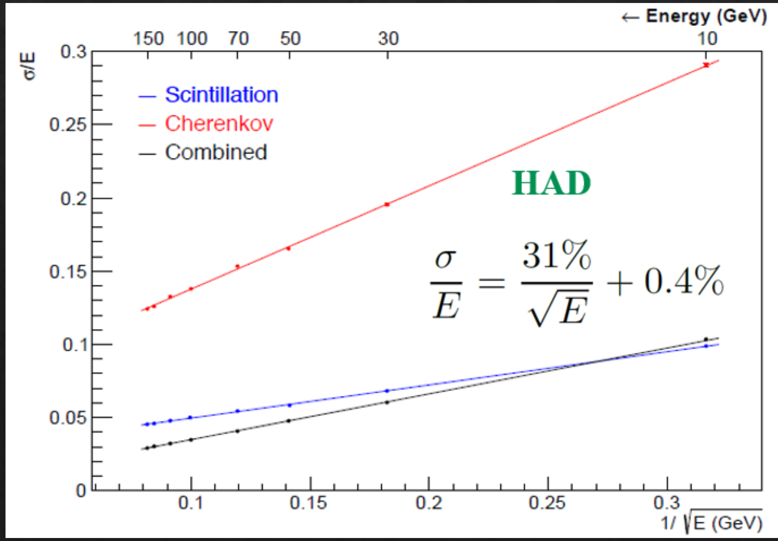
Collaborators from Italy, S. Korea, USA, UK, Chile

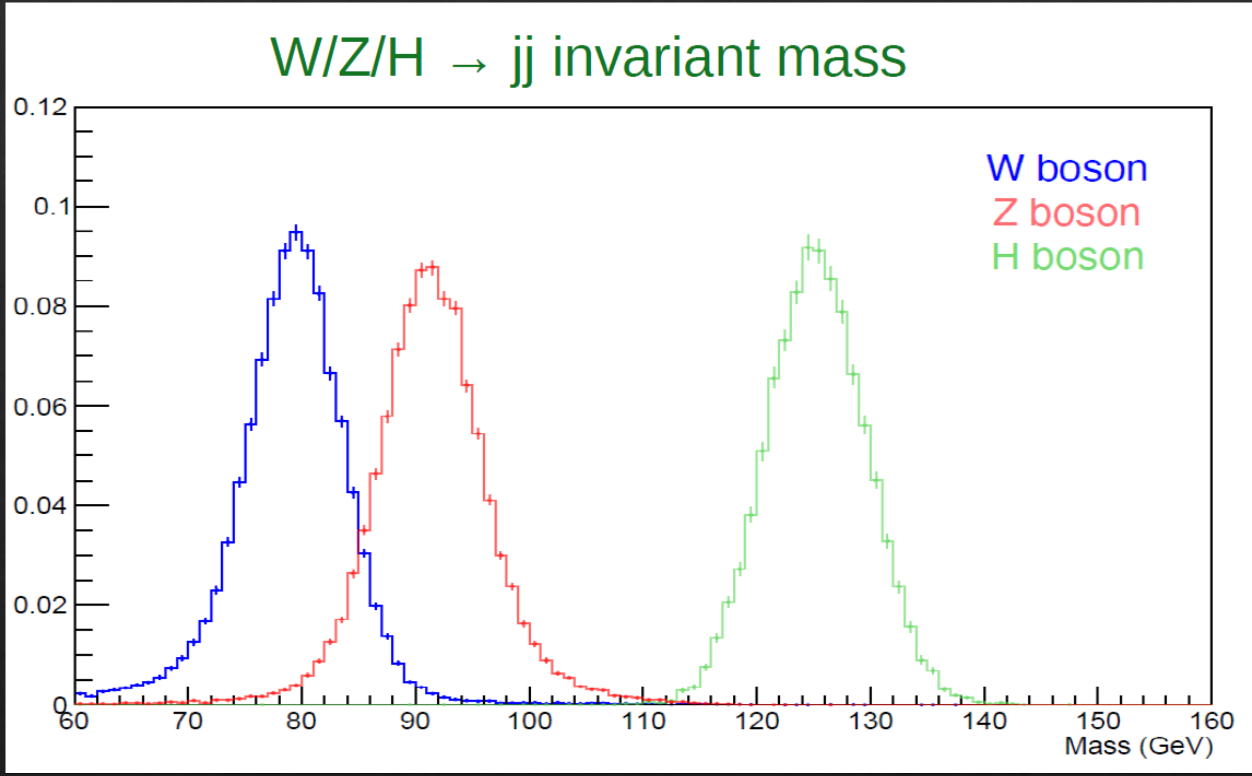
130M SiPMs. 16.3M channels (can reduce by x3 if crystal ECAL in front)

Resolutions

Simulation predicts excellent resolutions

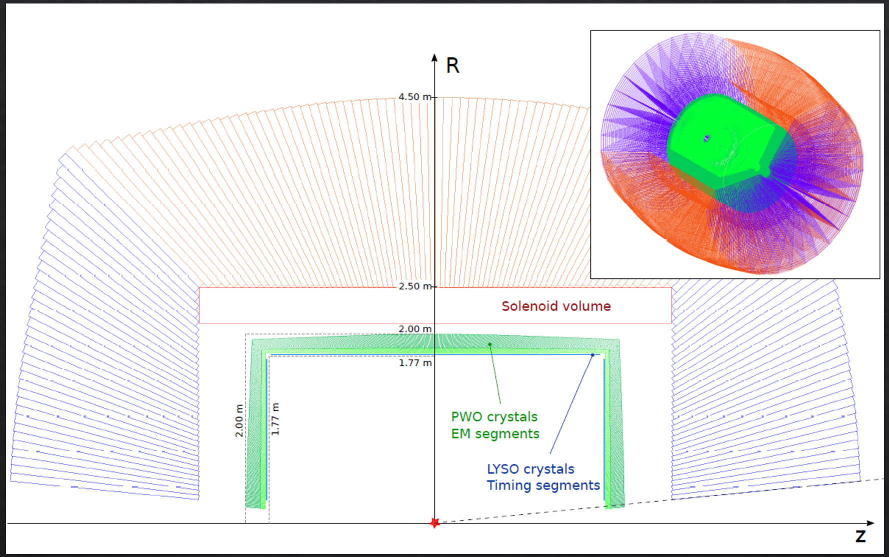


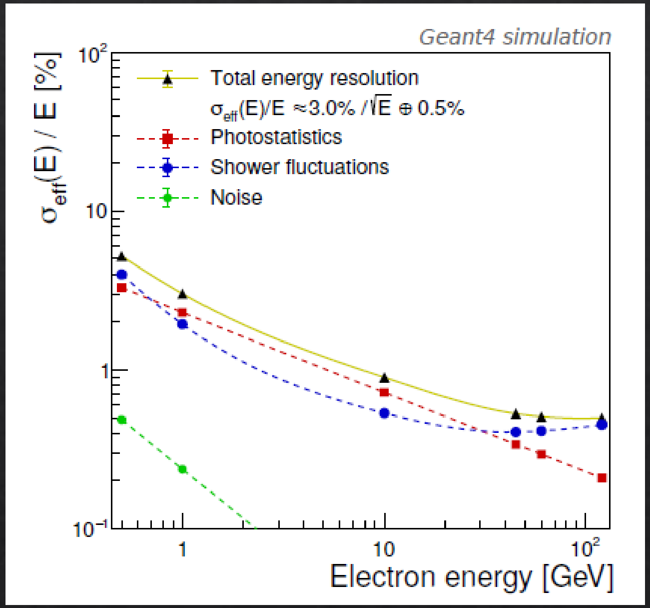


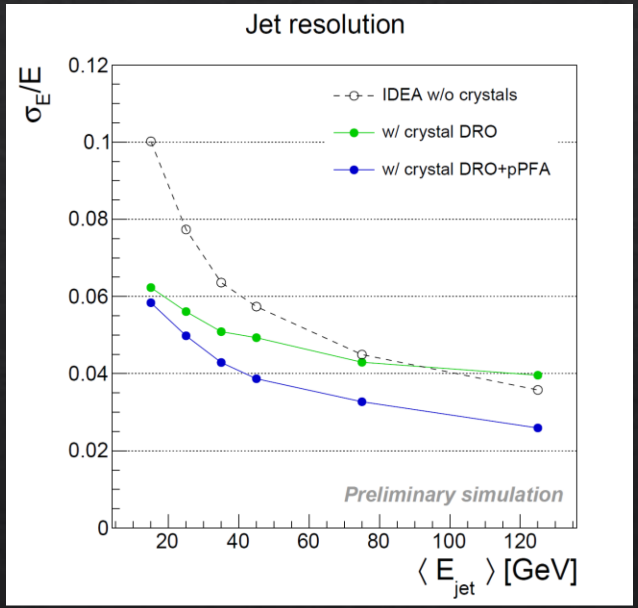


FCC-ee: flavor 2

Option with crystal dual-readout electromagnetic calorimeter gives state of the art electromagnetic resolution with just slightly degraded hadronic resolution



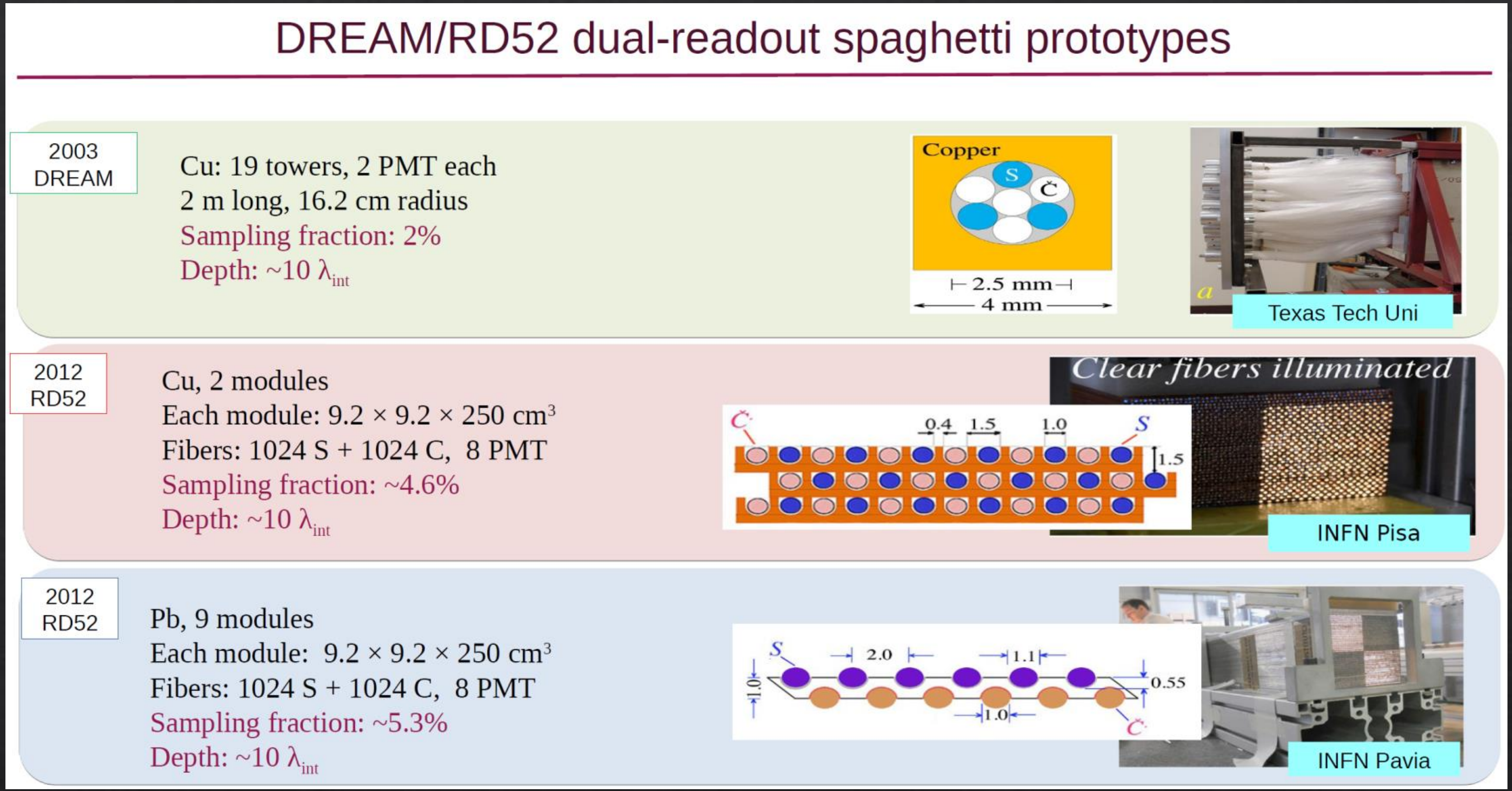




Collaborators from USA, Italy, France, CERN

Status: fiber-based dual readout

Builds on a long history of work

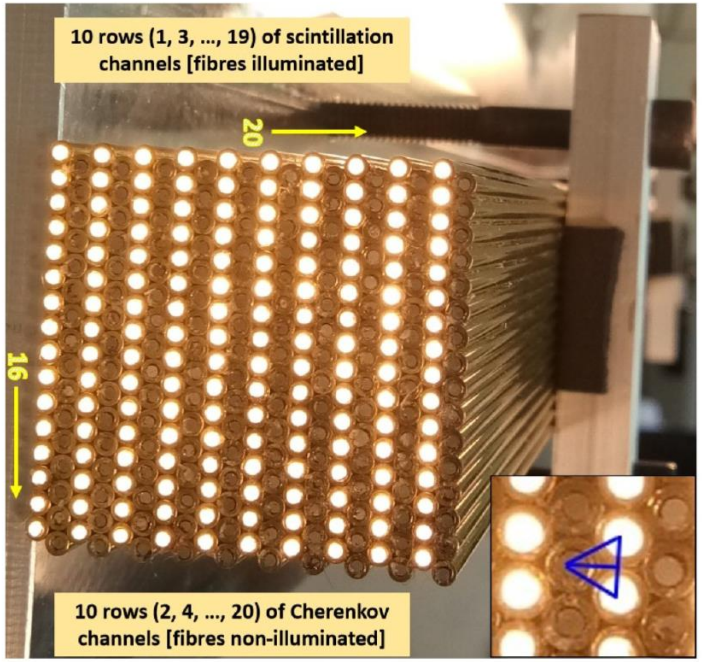


Recent Milestones:

- Prototype of size suitable for electrons tested at DESY/CERN
- Construction in full swing of a full scale prototype (Hidra2)

Positron results

Nine ~3.5×3.3 cm² towers made of capillary brass tubes

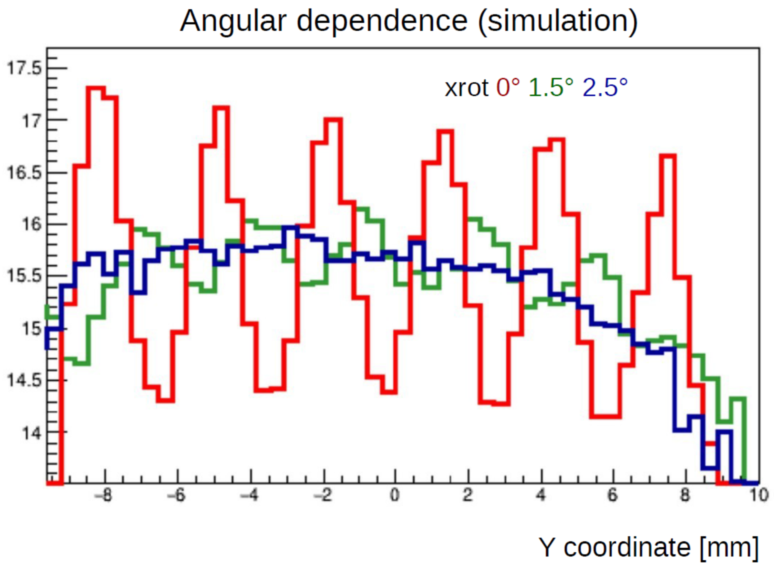


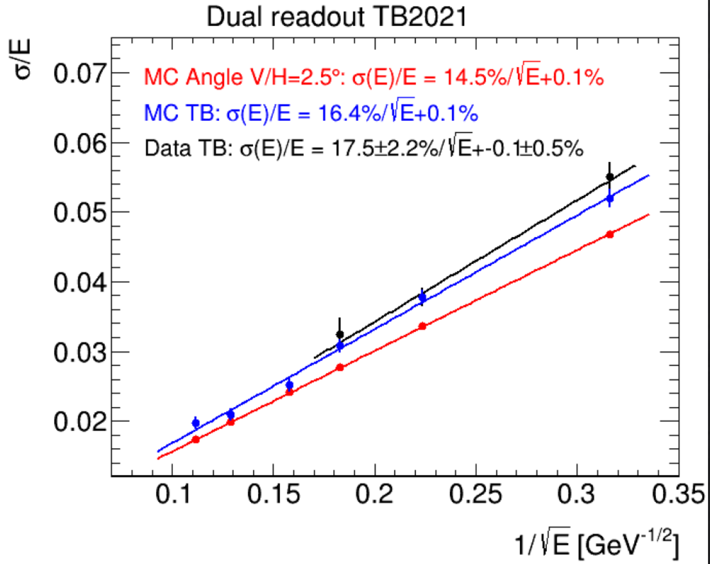
Test 2021 (CERN+DESY):

Verified strong dependence of response on impact angle

Very poor positron-beam purity in SPS H8 line only allowed limited testing

Electron resolution from JINST 18 (2023) 09, P09021

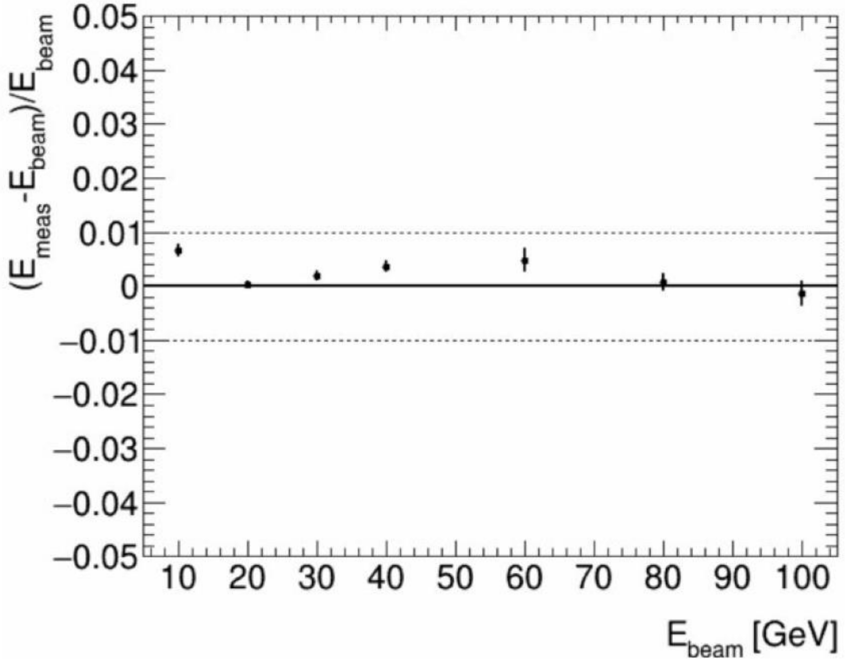




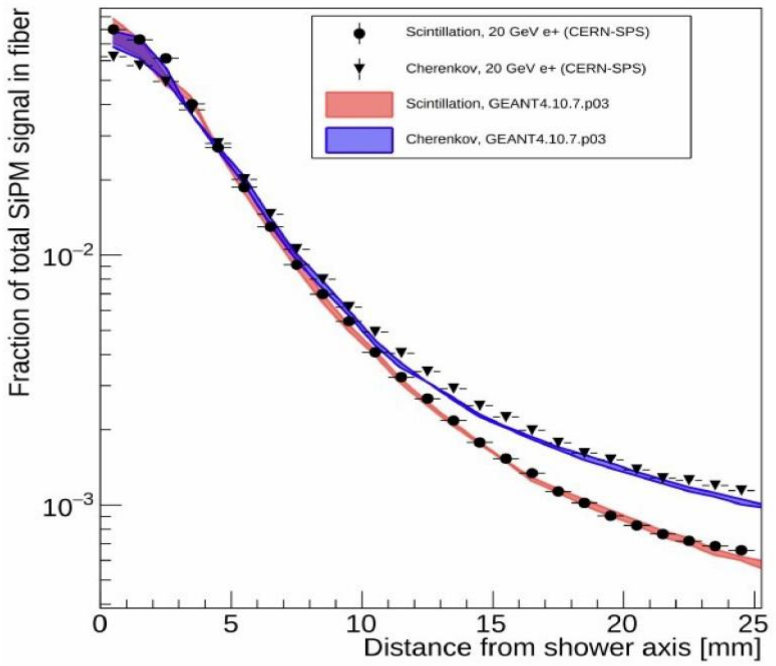
Positron results

JINST 18 (2023) 09, P09021

Energy well reconstructed within 1%



Lateral shower profile compared to G4 simulation
→ **unprecedented resolution** ←

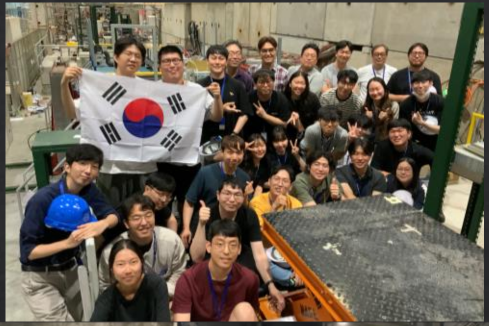


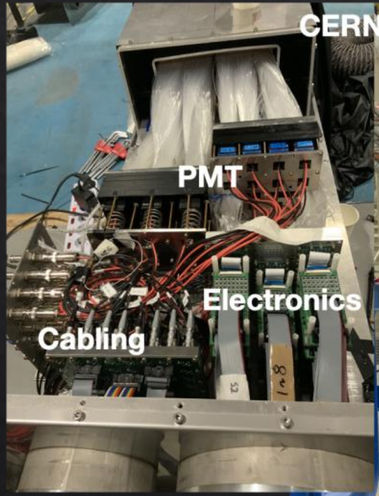
Additional data taken in 2023: analysis ongoing

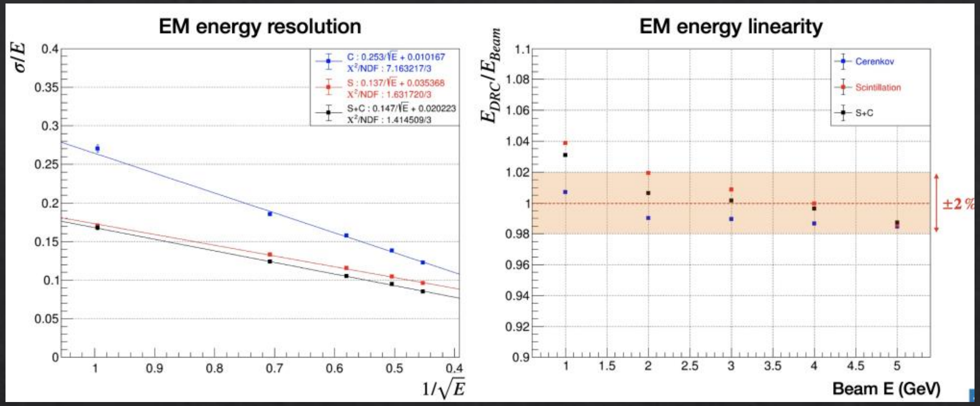
Test beam: S. Korea

- Full-size (2.5 m length) modules are newly built by Korean group
- Various R&D tests: optical fibers, high granularity (SiPM, MCP-PMT), fast timing resolution

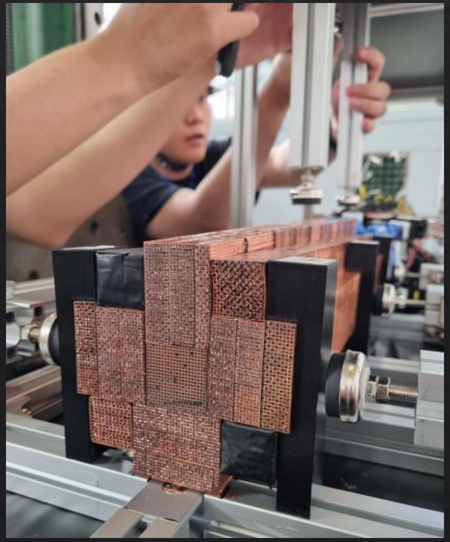
2022 at CERN SPS





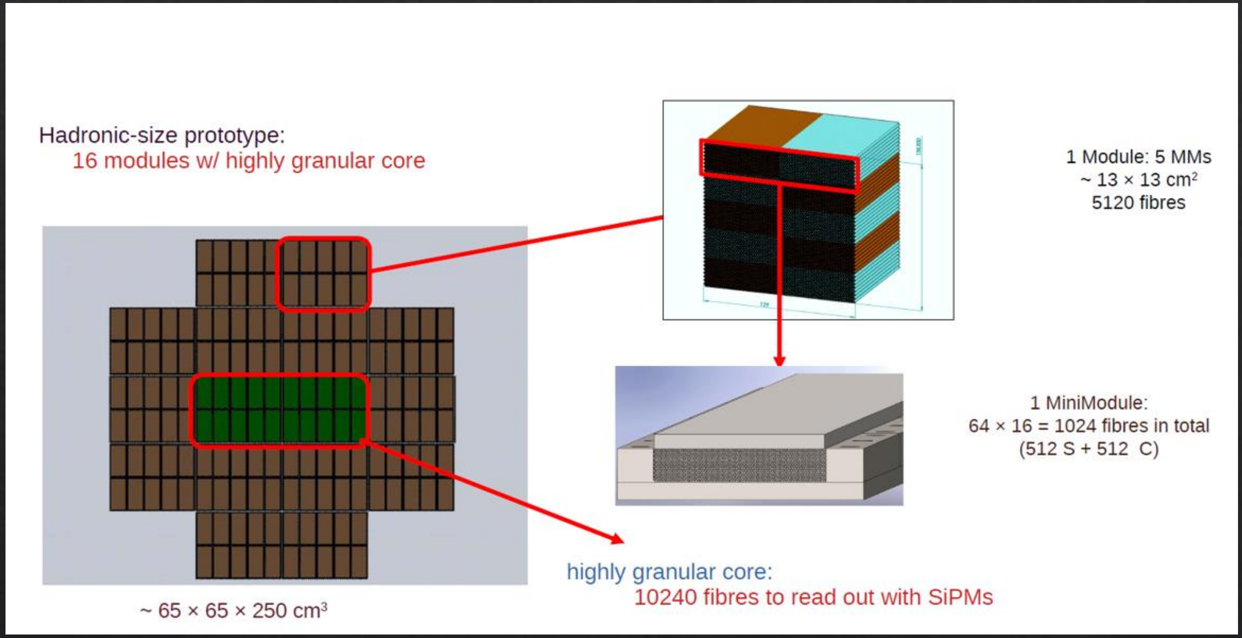


2023 at CERN PS



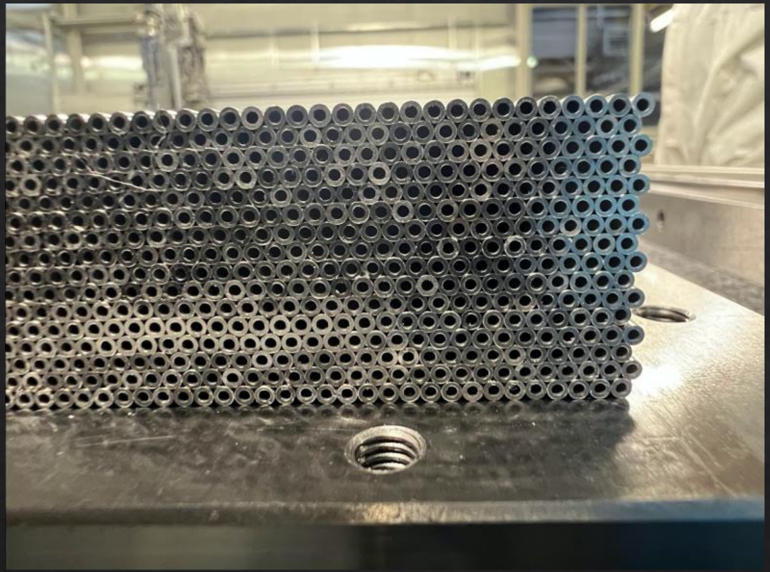
Large prototype

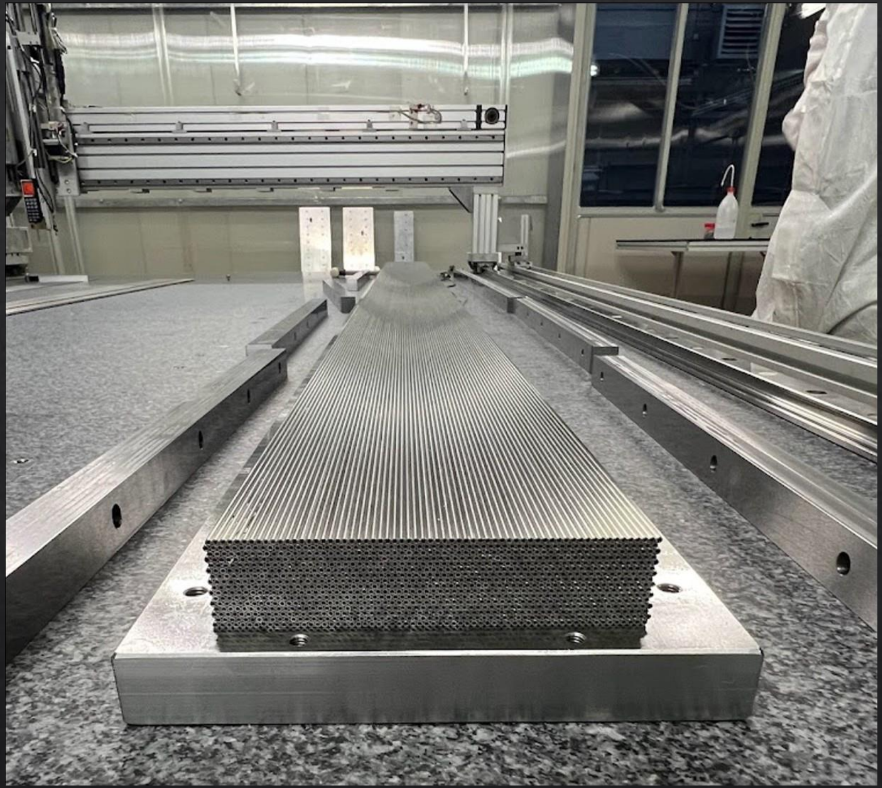
2022: construction of a prototype large enough for hadron studies

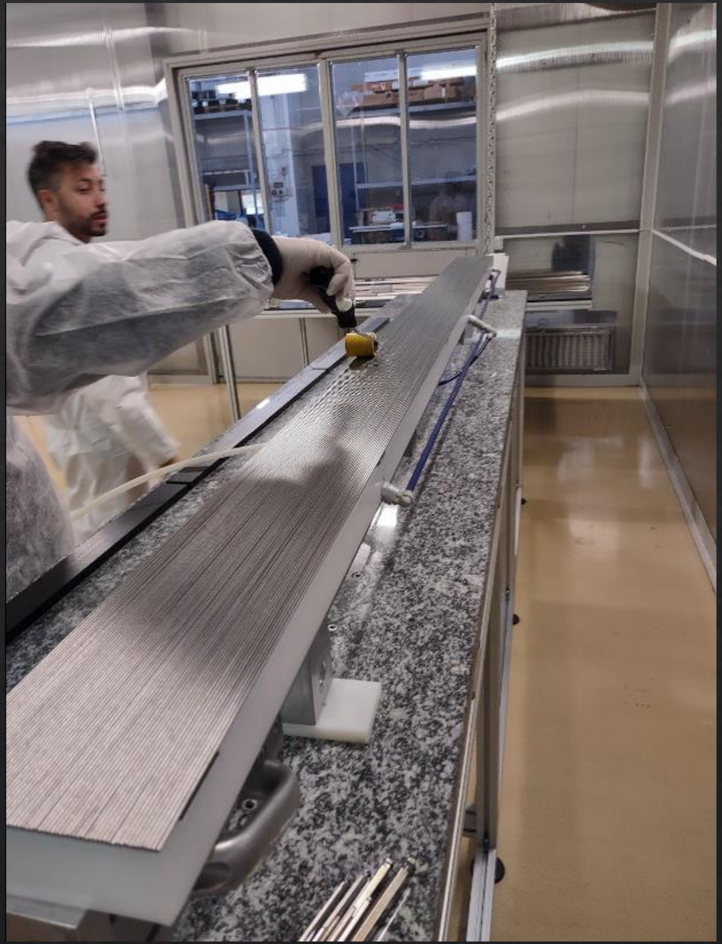


Status: fiber-based dual readout

Construction on full size hadronic prototype in progress





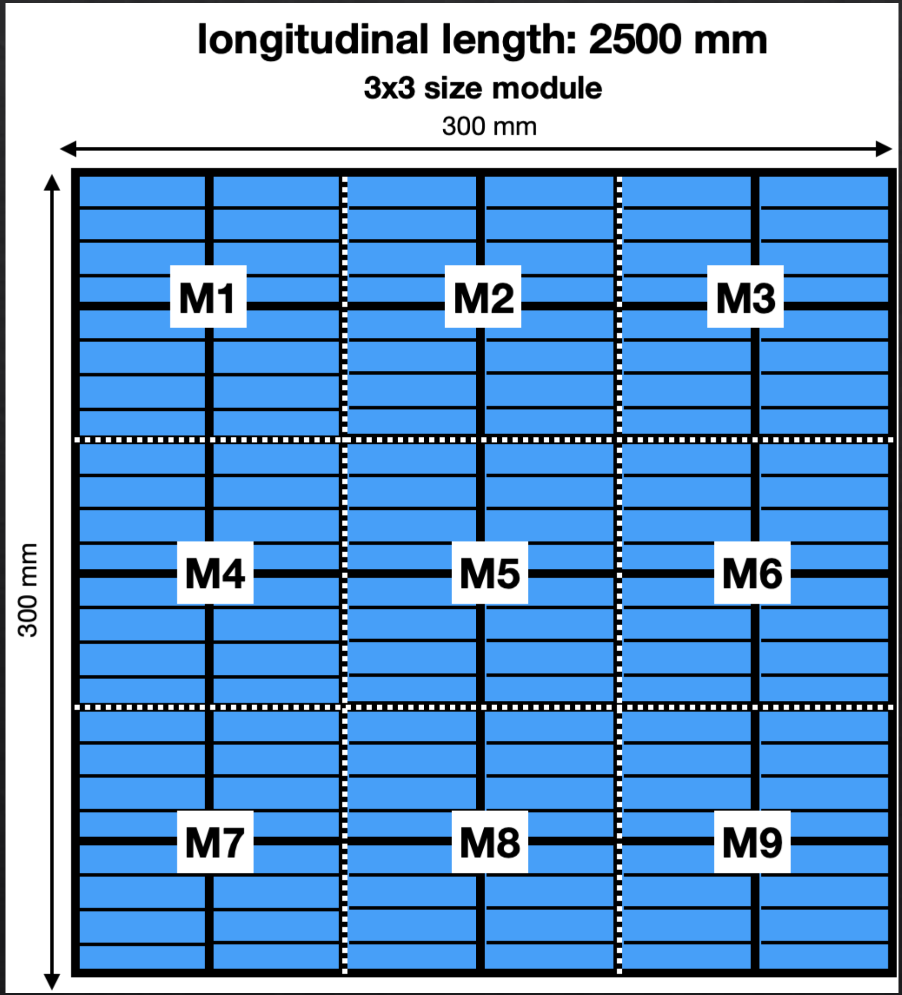


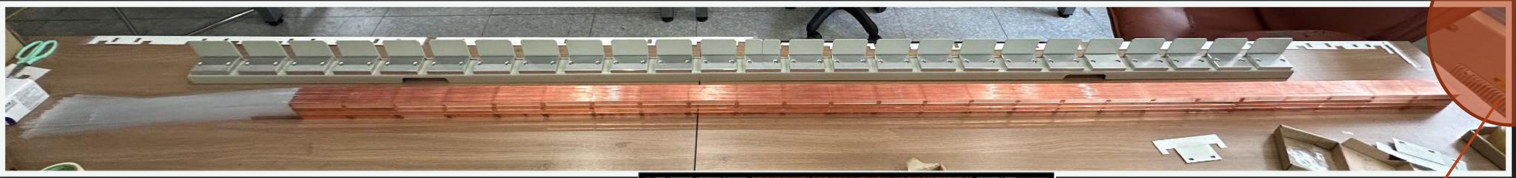
S. Korea: Test-beam 2024 at CERN (SPS H8)

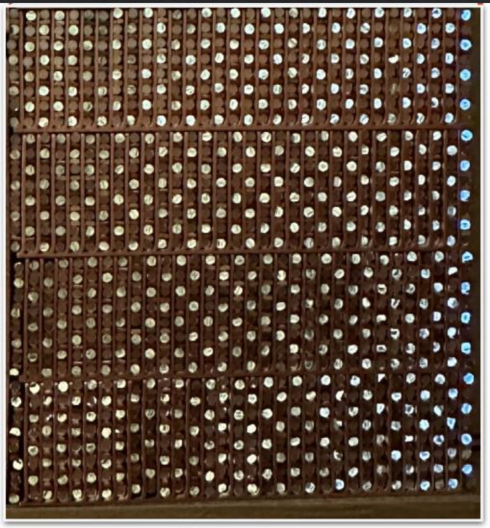
Aim to build big-size protype detector to measure the hadronic energy resolution

- 3x3 modules (totally 9 modules) based on skiving fin heatsink Cu forming

Module assembly has been almost done







Front view

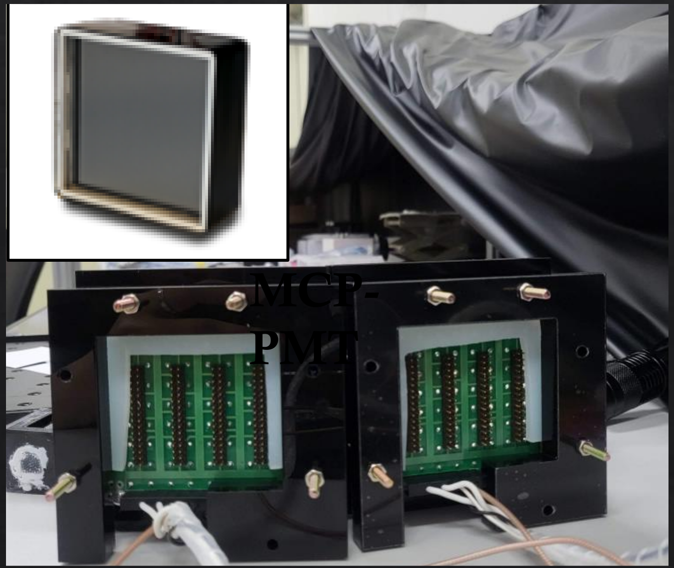
Status: fiber-based dual readout

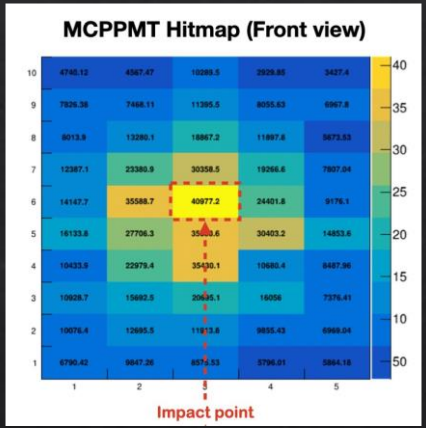
Future:

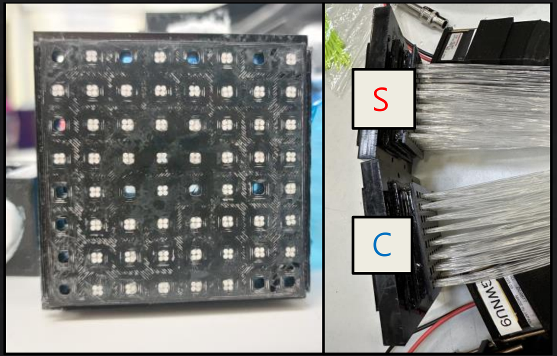
- Complete construction/test of full scale prototype
- Develop scalable readout electronics
- Optimize metal matrix mechanics for large production
- Develop mechanical model of full system with services

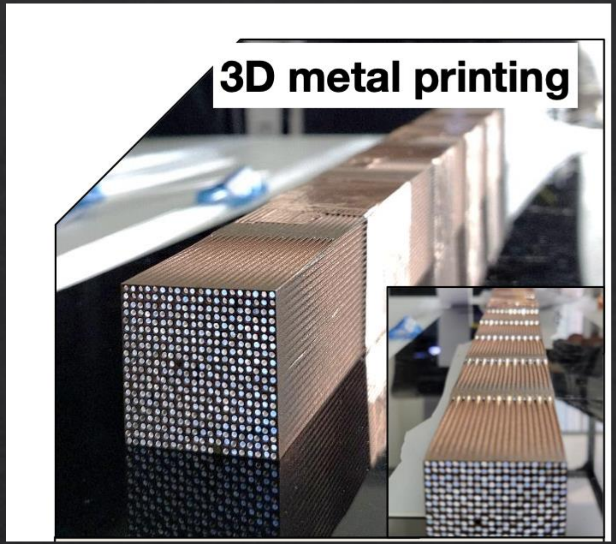
Future: S. Korea

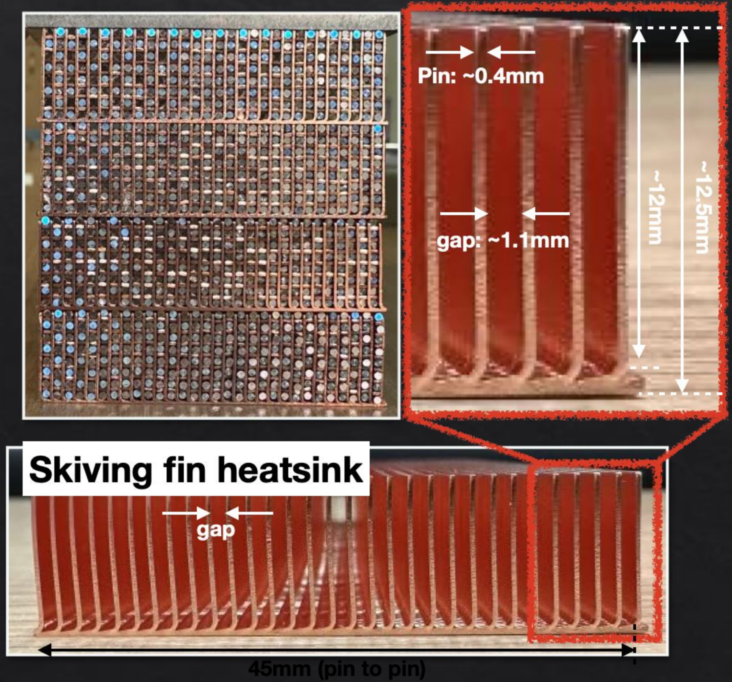
- Finding the solutions toward FCC TDR

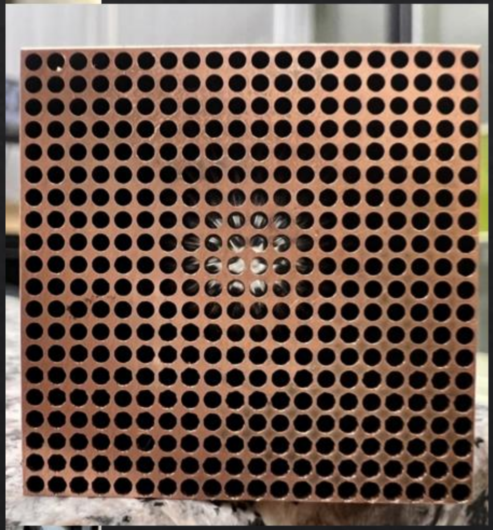








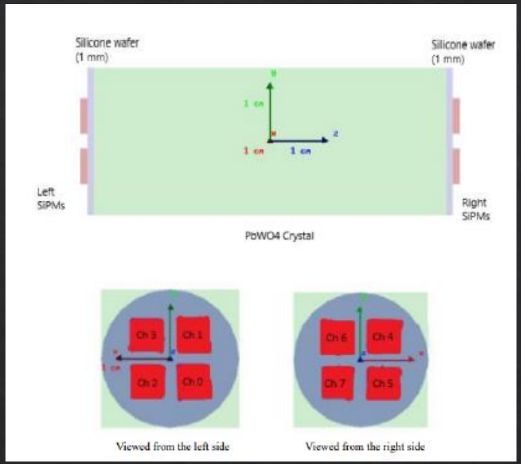




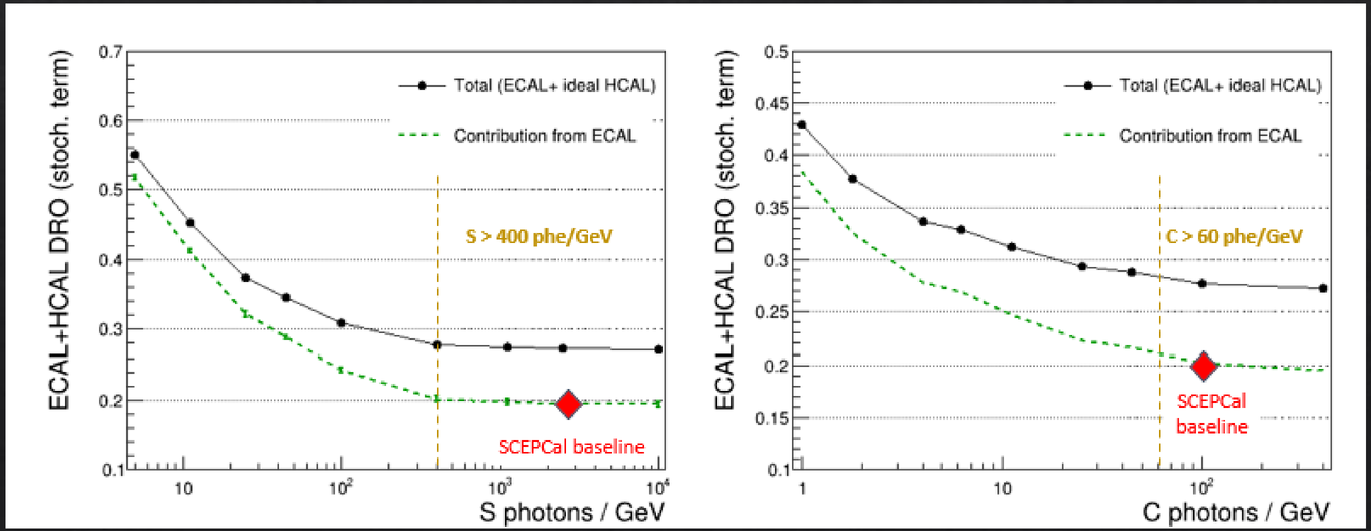
Status: crystal dual readout

Have completed four test beams studying single crystals PbWO4, PbF2, BGO, new heavy glasses

- •Notre Dame radiation lab 8 MeV electrons
- •FNAL1 120 GeV protons
- •FNAL2 120 GeV protons
- •DESY 2 GeV electrons April 2024

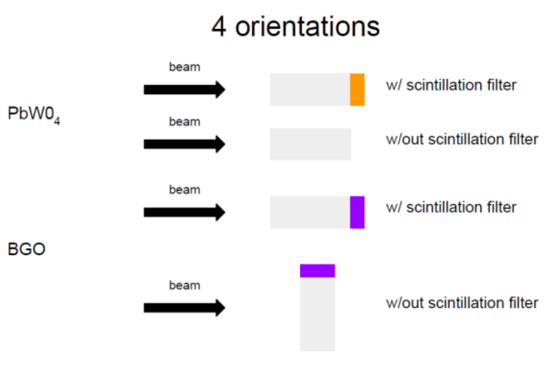


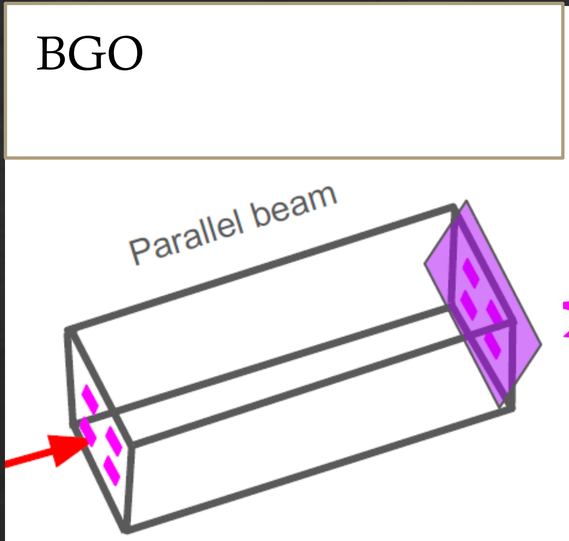
Goal: demonstrate about 60 well-identified Cherenkov photons / GeV without compromising scintillation signal (400/GeV)

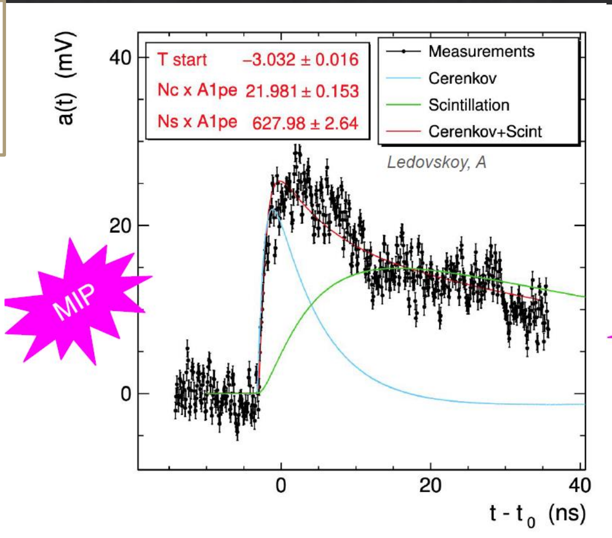


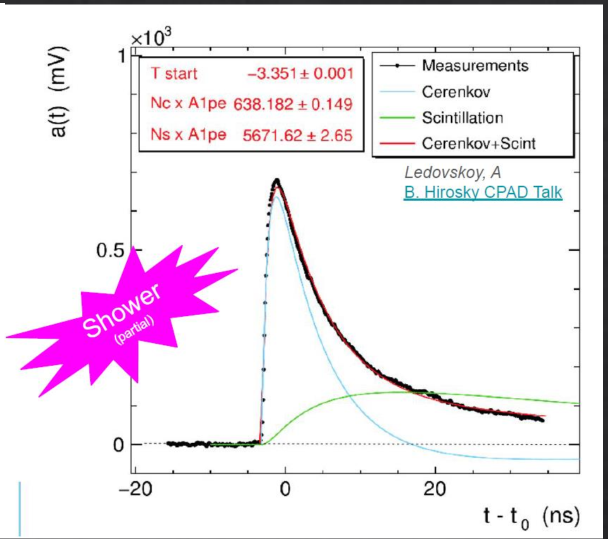
Status: crystal dual readout

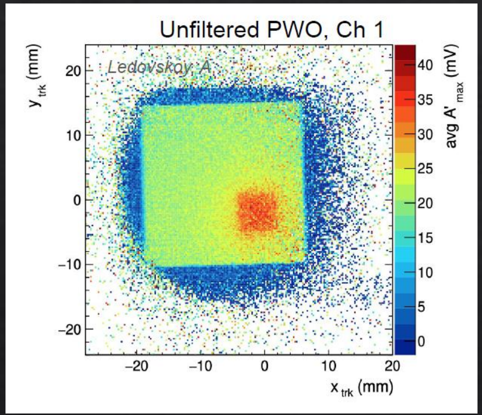
FNAL test beam: Cherenkov/scintillation separation using timing and filters BGO





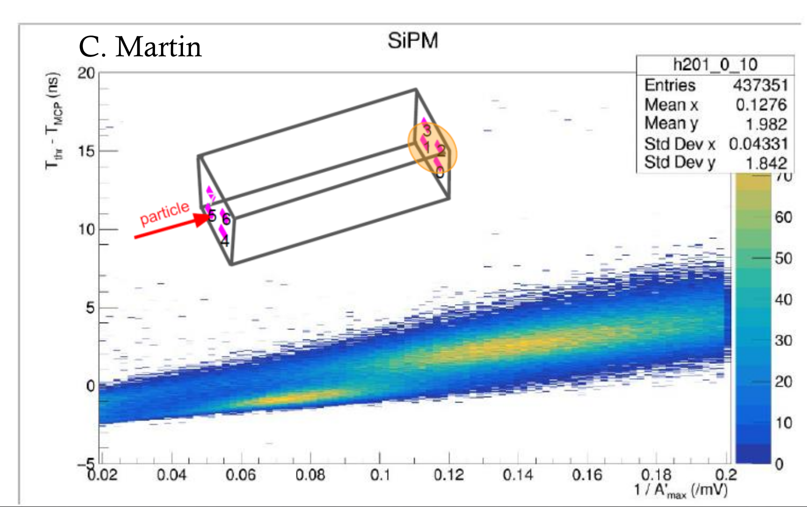






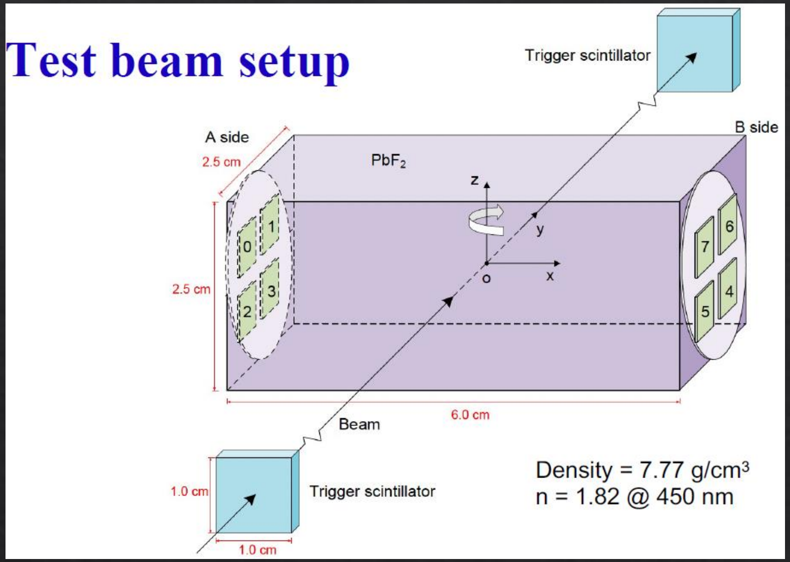
Need to digest effect of particles in sipms, but not expected to be a big effect

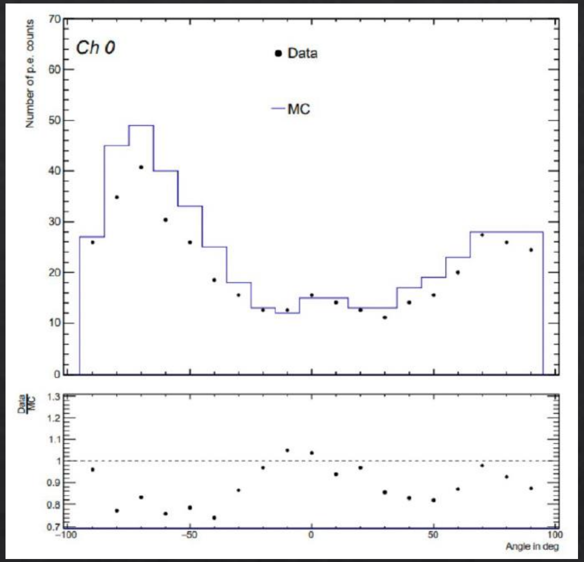
But for PbWO4 (with interference filter) again see challenges related to the directionality of the Cherenkov light and sipmm position.

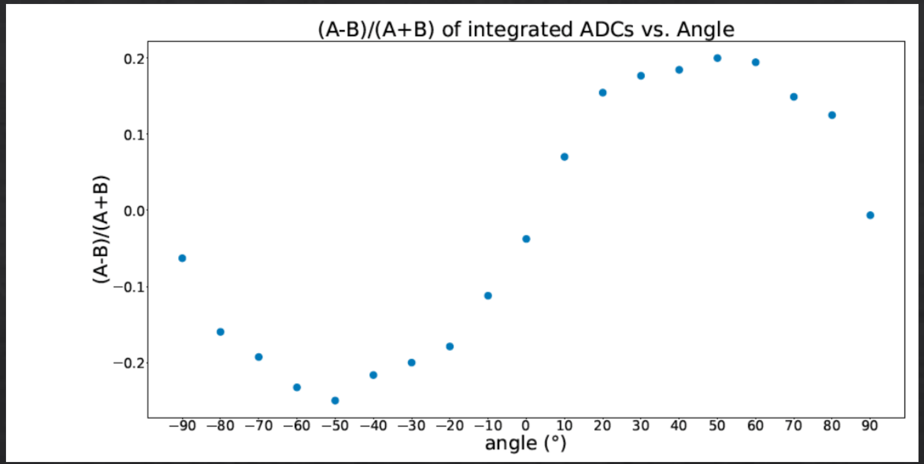


Status: crystal dual readout

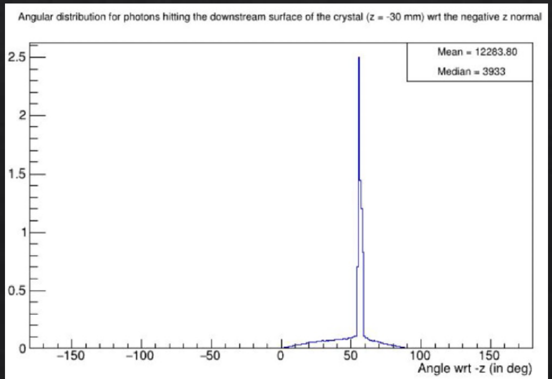
FNAL test beam: study of Cherenkov by itself using PbF2



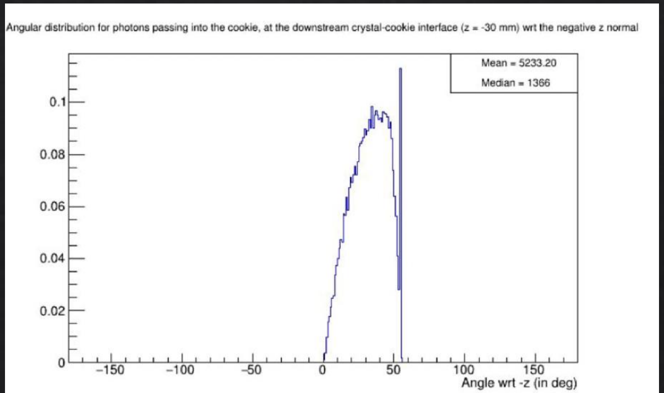




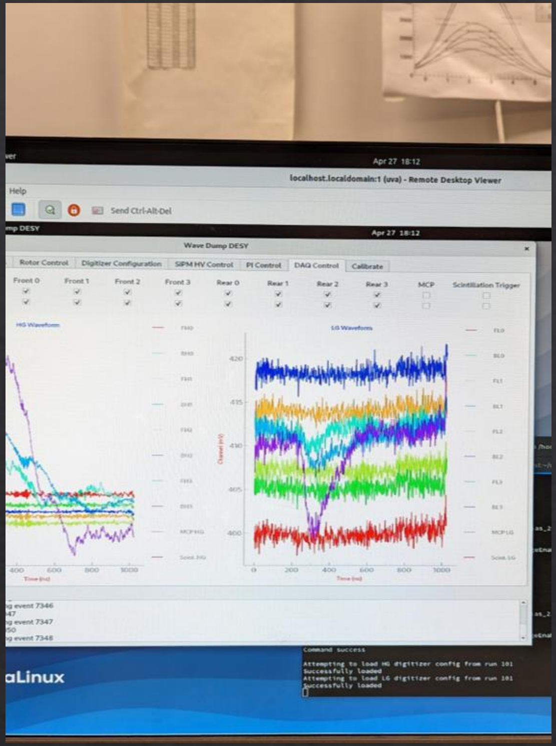
Much of desired light not easily escaping high index crystal into photodetector.

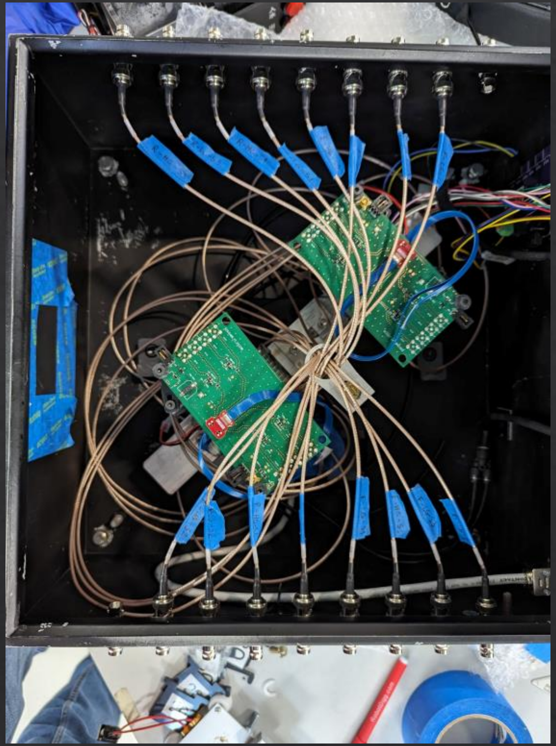


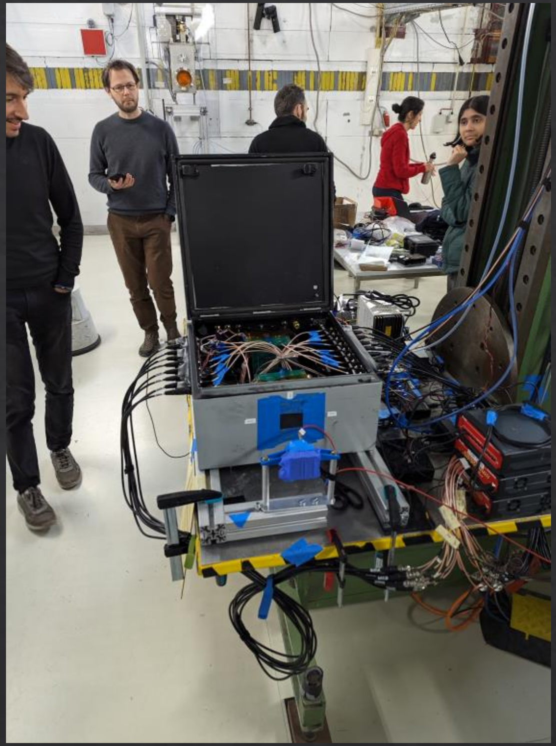
Incident angle reaching crystal side



Incident angle detected by SiPMs

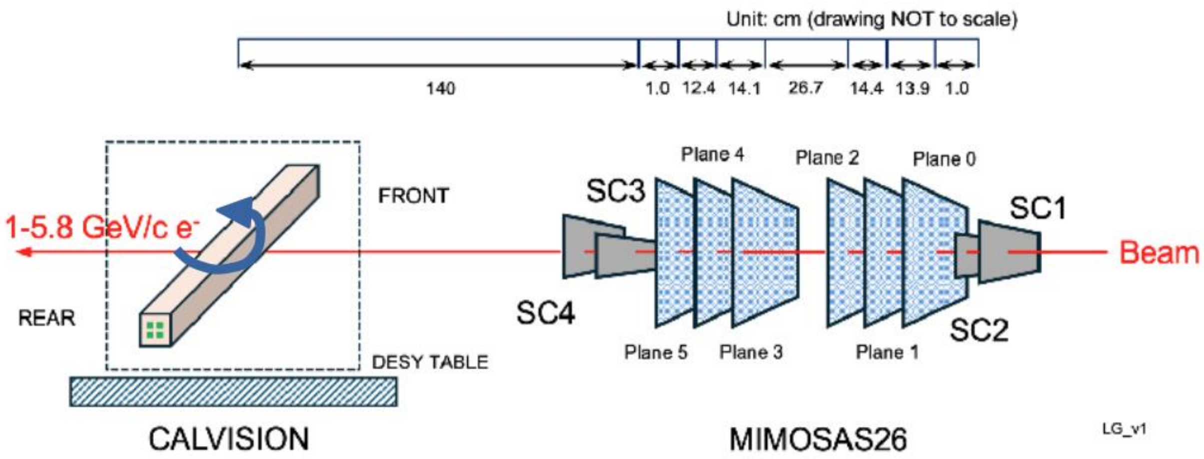




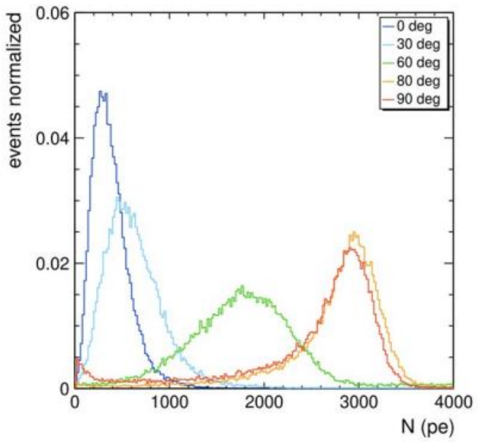


Status: crystal dual readout: DESY test beam March 2024

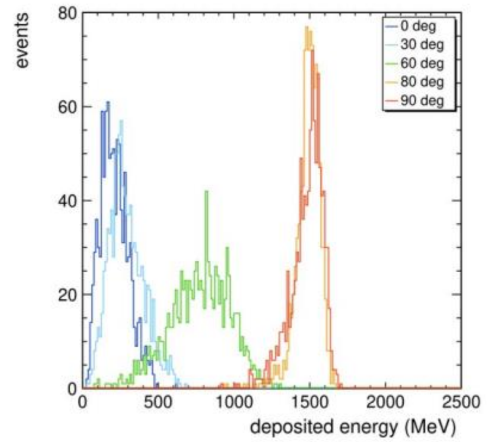
DESY TEST BEAM: Demonstration of Cherenkov light collection in PbF ($25x25x200mm^3$)



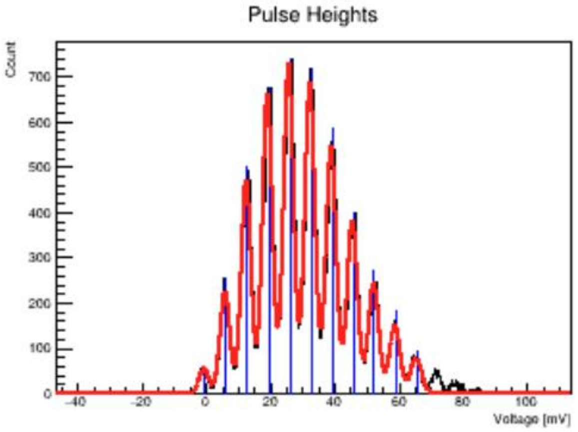
Light collection vs angle



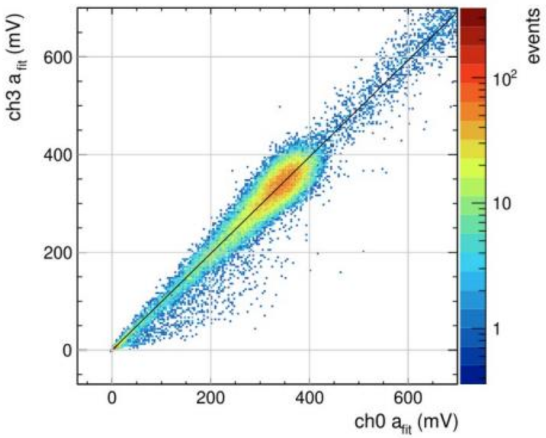
Energy deposited (MC)



Absolute calibration from Npe distribution

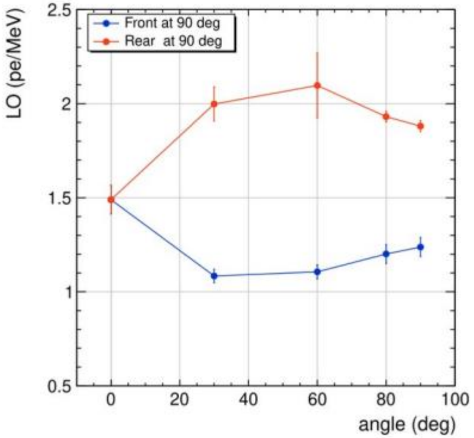


Relative calibration of SiPM outputs

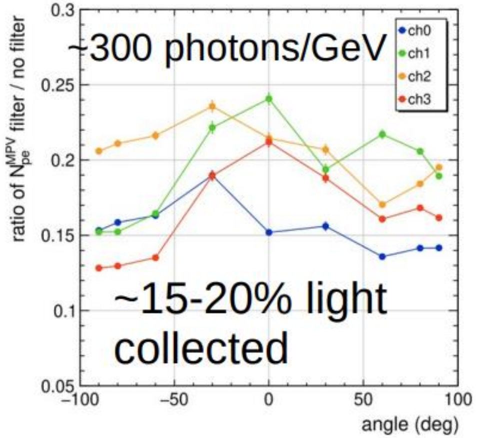


Absolute Ĉ light yield

1800-1900 photons/GeV



Transmittance w/ U330 filter (BGO candidate)



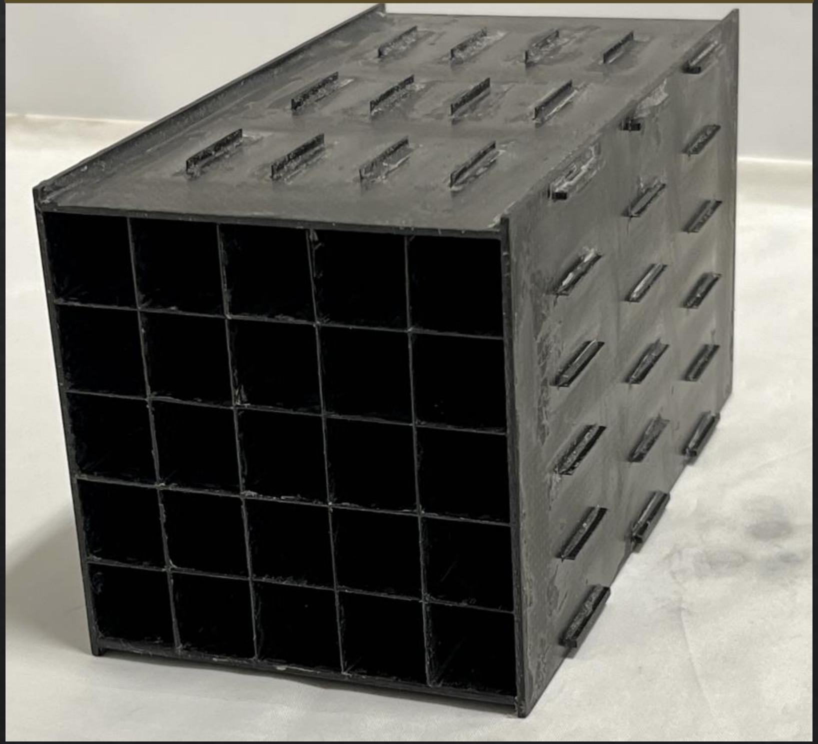
- Strong proof of principle for extracting Ĉ signal needed for DR in homogeneous crystals
- In progess: verify results after S/C component fitting in BGO/BSO/PWO

Status: crystal dual readout

Plans

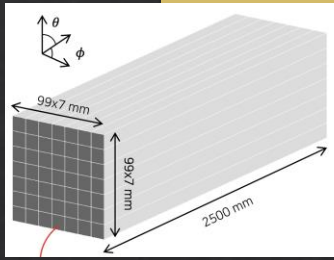
- Finish analysis of DESY data
- Next test beam end of July at CERN (protons)
- Expect to buy crystal array(s) using USA and Italy money this year

Purdue: sarray mechanical design prototype

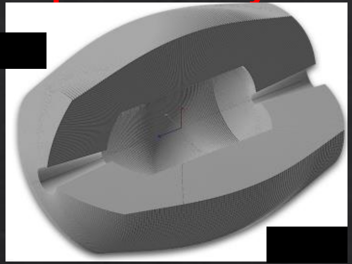


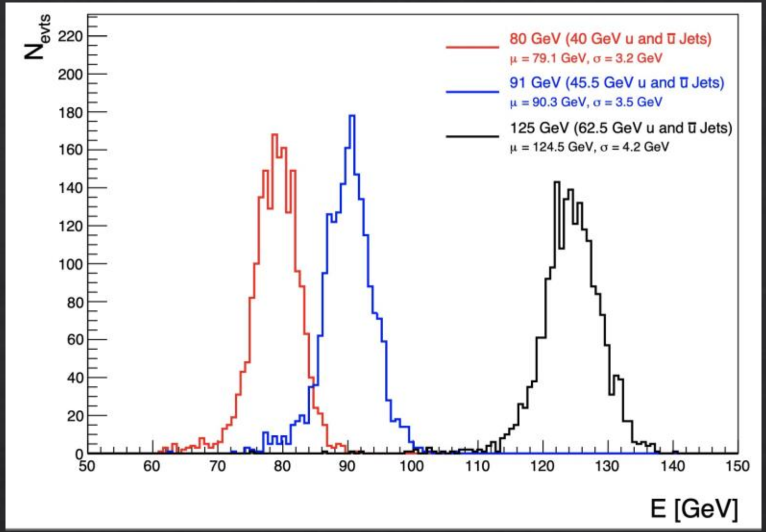
Status Simulation (S. Korea)

Simple Geometry

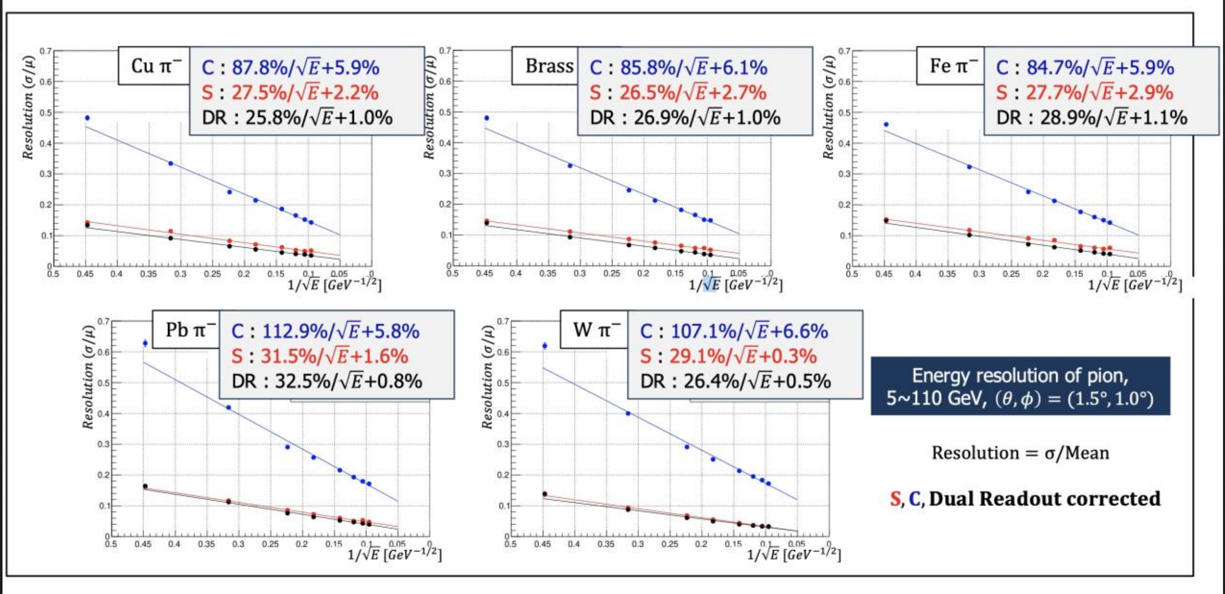


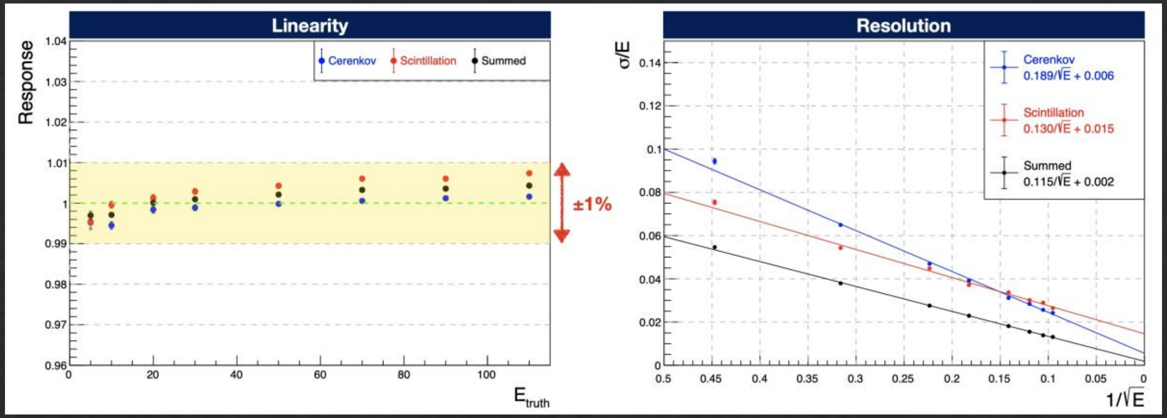
4pi Geometry

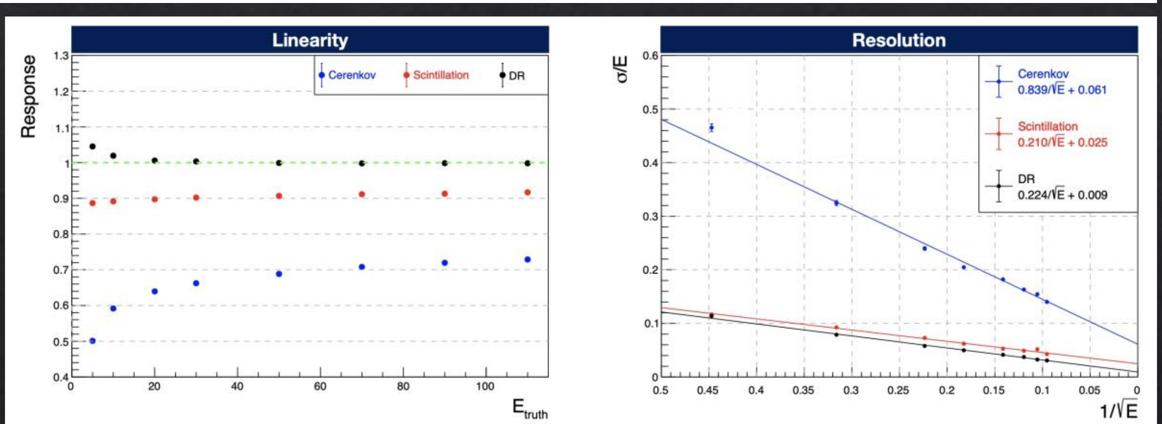




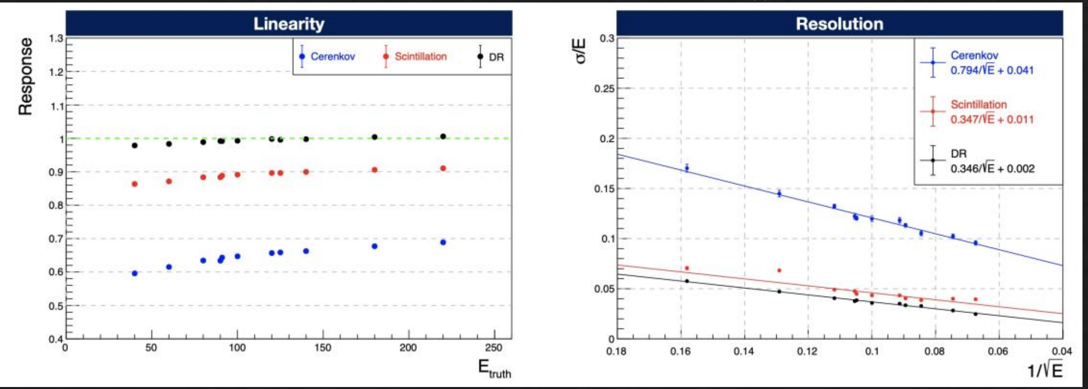
Comparison on absorber types based on simple geometry







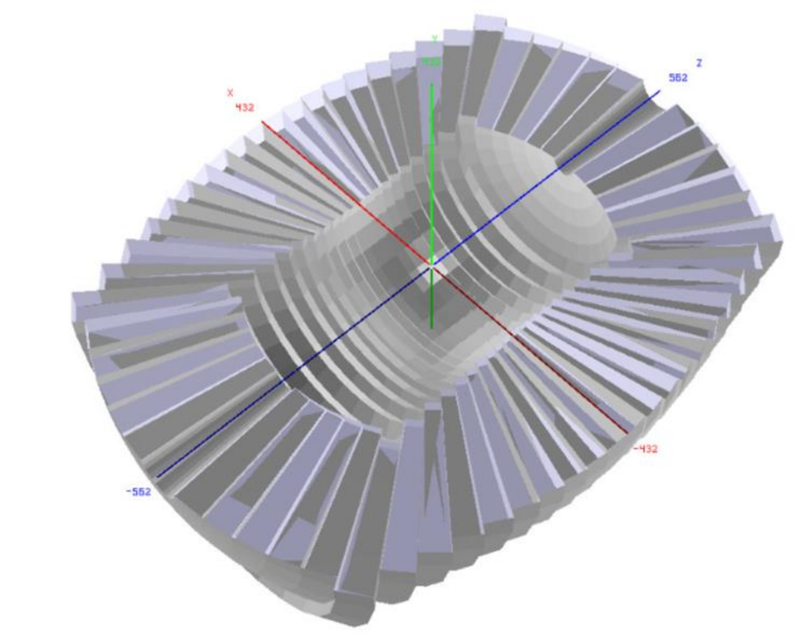
Performance based on 4pi geometry

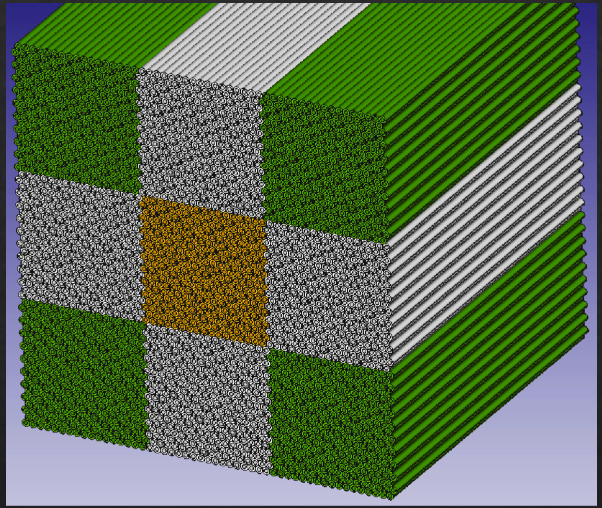


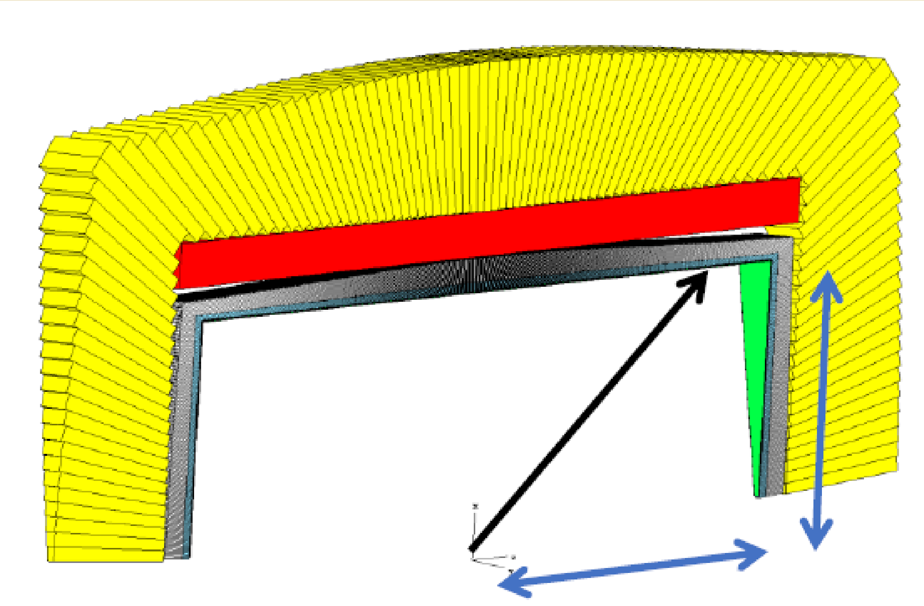
Status: simulation

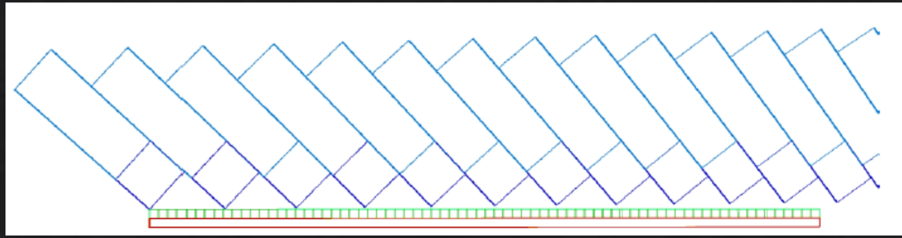
Fiber calorimeter has been in key4hep for some time
First implementation of crystal ECAL occurred this spring.

https://github.com/SCEPCAL/SCEPCAL

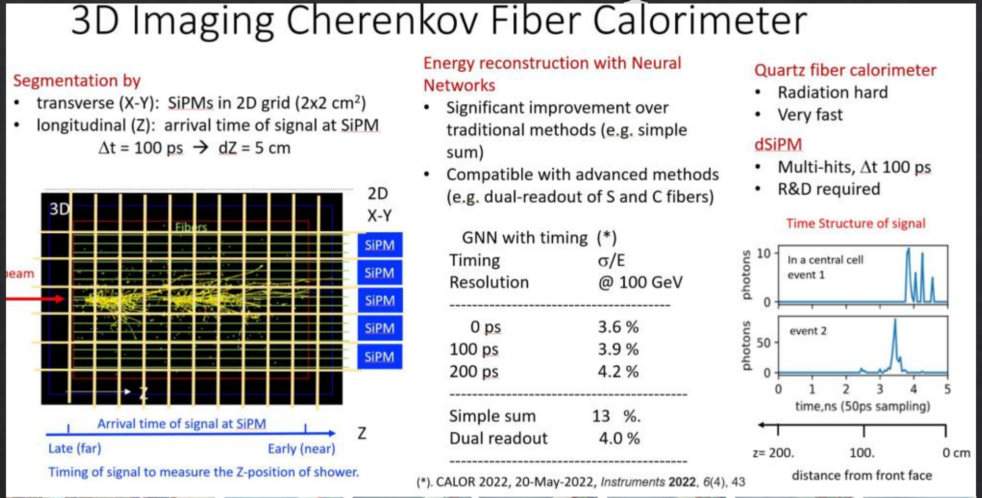


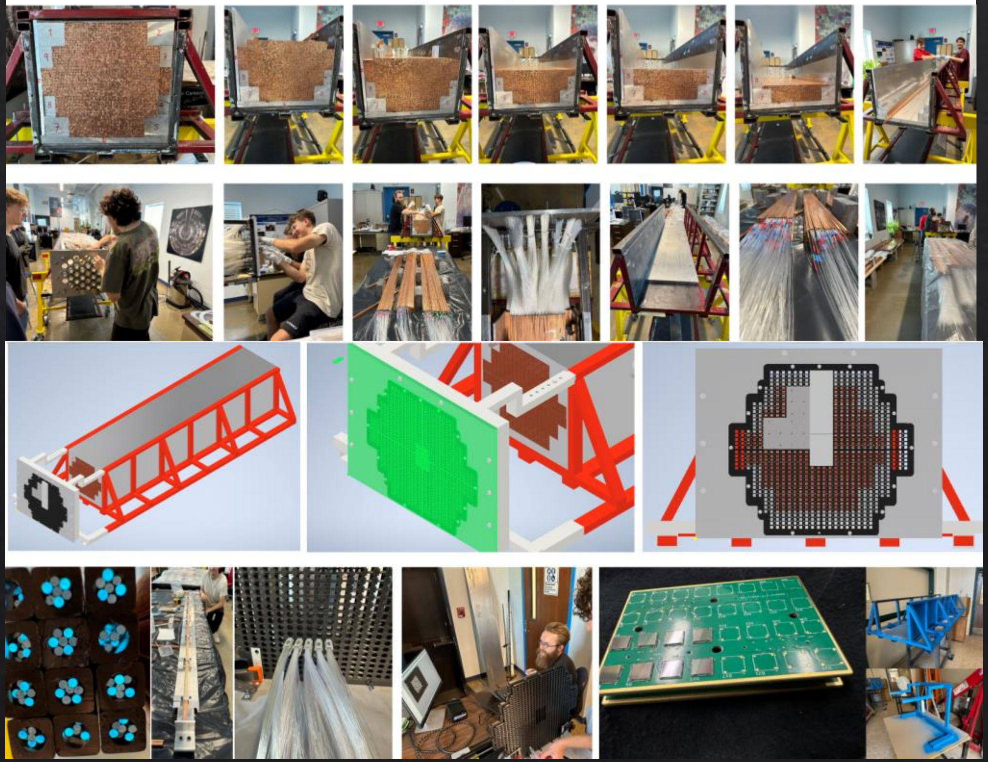




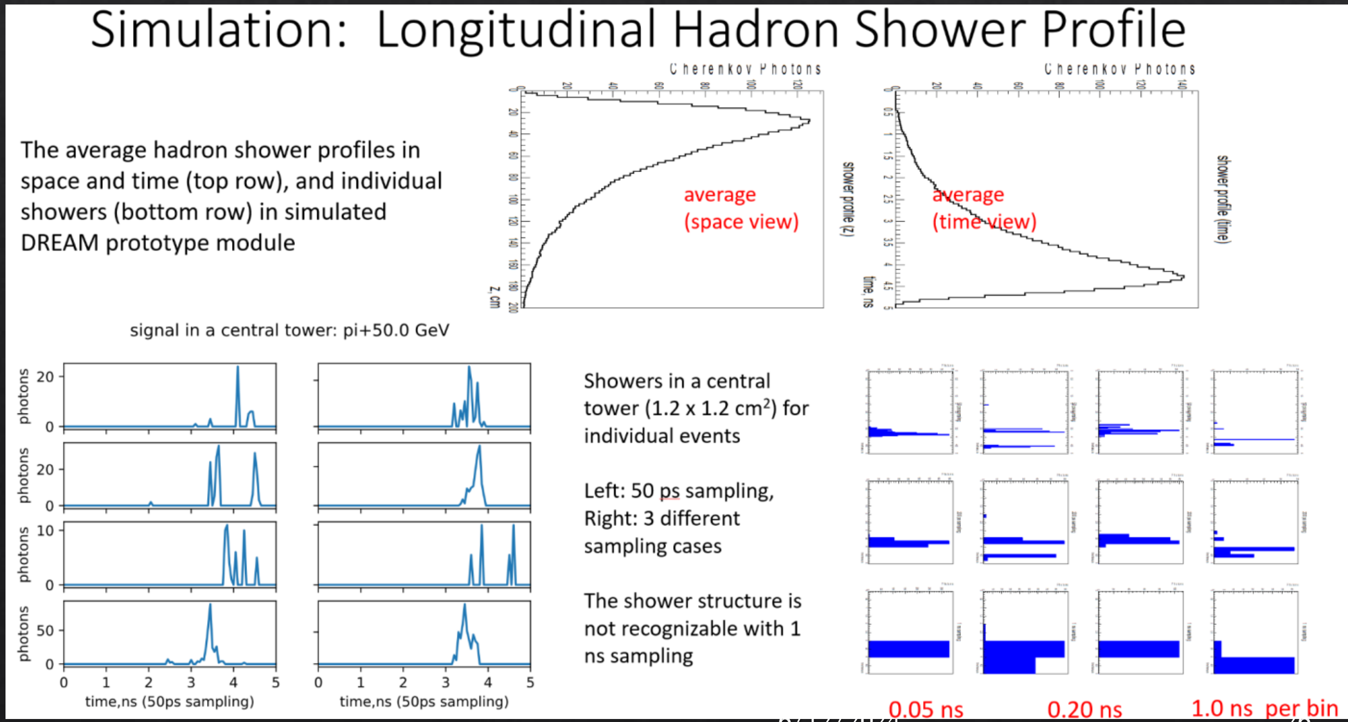


Potential improvements beyond baseline: fiber





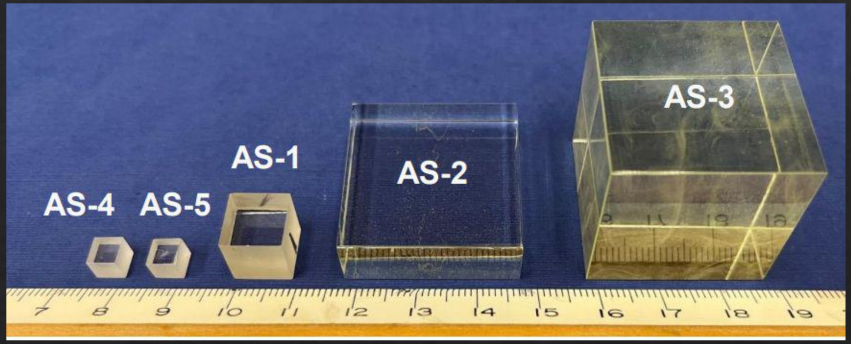
- Could allow precision calorimetry with just Cherenkov photons
- Expect exciting results in test beam this August using fast SiPMs and 5-10 GHz waveform digitizers using refurbished DREAM prototype



Potential improvements beyond baseline: crystal

Goal: a dense (>6 g/cc^3) transparent inorganic scintillators with a cost of < 1$/cc^3.
Have tested promising glass samples obtained from IHEP and Giessen produced in BGRI* and Schott*: aluminoborosilicate (normal "ABS" and Gd-loaded "Z") and barium di-silicate (DSB), respectively.
Expect glass samples from RMD* Inc.

	BGO	BSO	PWO	Z-L	DSB-3
dimensions (mm^3)	17x17x17	17x17x17	13x13x13	25x25x60	20x20x150
density (g/cm^3)	7.1	6.8	8.3	6	4.3
radiation length (cm)	1.12	1.15	0.89	1.55	2.58
interaction length (cm)	22.7	23.4	20.7	24.7	30.9
Decay time (ns)	300	100	30/10	1200	500
emission-weighted PHOTON DETECTION EFFICIENCY S14160-3015PS SiM	31	31	28	29	32
cost ($/cc)	8	8	9	<1	2



http://www.scitlion.com/index.php?m=content&c=index&a=lists&catid=112
https://www.schott.com/en-us/product-selector?productselectormode=truei
https://www.rmdinc.com/

Potential improvements beyond baseline: crystal

Almost everything

- How to support it mechanically?
- What is the jet as opposed to single particle resolution?
- How does upstream material affect the jet reconstruction?
- What is the best tracking system to go with this calorimeter? (current proposal is TPC, but this doesn't work really for high intensity Z running)
- Can cms-style particle flow improve event reconstruction?
- How would segmentation affect tau reconstruction?
- Scintillation/Cherenkov separation can be achieved by wavelength filtering, timing, polarization. The default plan is wavelength separation. But can inexpensive electronics that includes timing help? Can pulse shape measurements in the readout help ()?
- The crystal dual readout hasn't been done with modern photodetectors. But only those (according to simulation) allow this to work. We need to purchase crystals and do test beam measurements.
- Which crystal should we use? PbWO4, BGO, BSO?
- Would the timing layer solve the beam background problems at muon colliders?
- Assembly needs to be understood
- How far can we push timing resolution in crystal readout?

Conclusions

- Dual readout calorimetry is an excellent choice for FCC detectors
- Well advanced prototype program for fiber-based calorimeter
- Strong start of crystal dual readout EM calorimeter
- Expect much progress at the next FCC meeting.

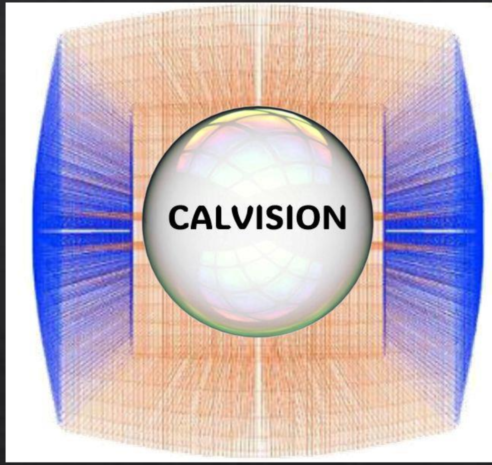
backup

CalVision

Calvision is an international collaboration was formed in 2020. Current members are: FNAL (Cummings, Freeman, Hirschauer, Merkel, Wenzel), Argonne (Sergei Chekanov), Caltech (Newman, Zhu), CERN (Hillemanns), Lyon (Gascon-Shotkin), Maryland (Belloni, Eno), MIchigan (Qian, Zhou, Zhu), Milano-Bicocca (Lucchini), MIT (Harris),Oak Ridge (Demarteau), Perugia (Cecchi), Princeton (Tully), Purdue (Jung), Texas Tech (Akchurin, Kunori), U. Virginia (Hirosky, Ledovskoy). US members are supported by US DOE grant DE-SC0022045. Milano is supported on an Italian grant starting 2023.

Our goals are:

- Develop techniques to improve homogeneous calorimetry for use in hadron measurement
- In concert with the IDEA Calorimeter team, develop techniques to improve fiber-based dual readout calorimetry
- Use simulations to optimize inclusion of a homogeneous calorimeter in a future electron-positron collider
- Develop innovative "Particle Flow" algorithms appropriate for homogeneous calorimeters
- Find new less expensive suitable materials for homogeneous calorimeter
- Develop infrastructure to improve the measurements (asics, photodetectors, structural materials, etc)
- Develop physics cases that benefit from homogeneous calorimeter



We are active members of DRD6 MAXICC, the CPAD Calorimetry RD, and the IDEA detector concept.

More information at: https://detectors.fnal.gov/projects/calvision/