Status of the ePIC ZDC

22 January 2024

Japan: RIKEN, Universities of Kobe, Shinshu, Tsukuba
Taiwan: NCU, Academia Sinica
Korea: Sejong Univ.
USA: Kansas, UC Riverside, Pacific Northwest Lab.

ZDC requirements

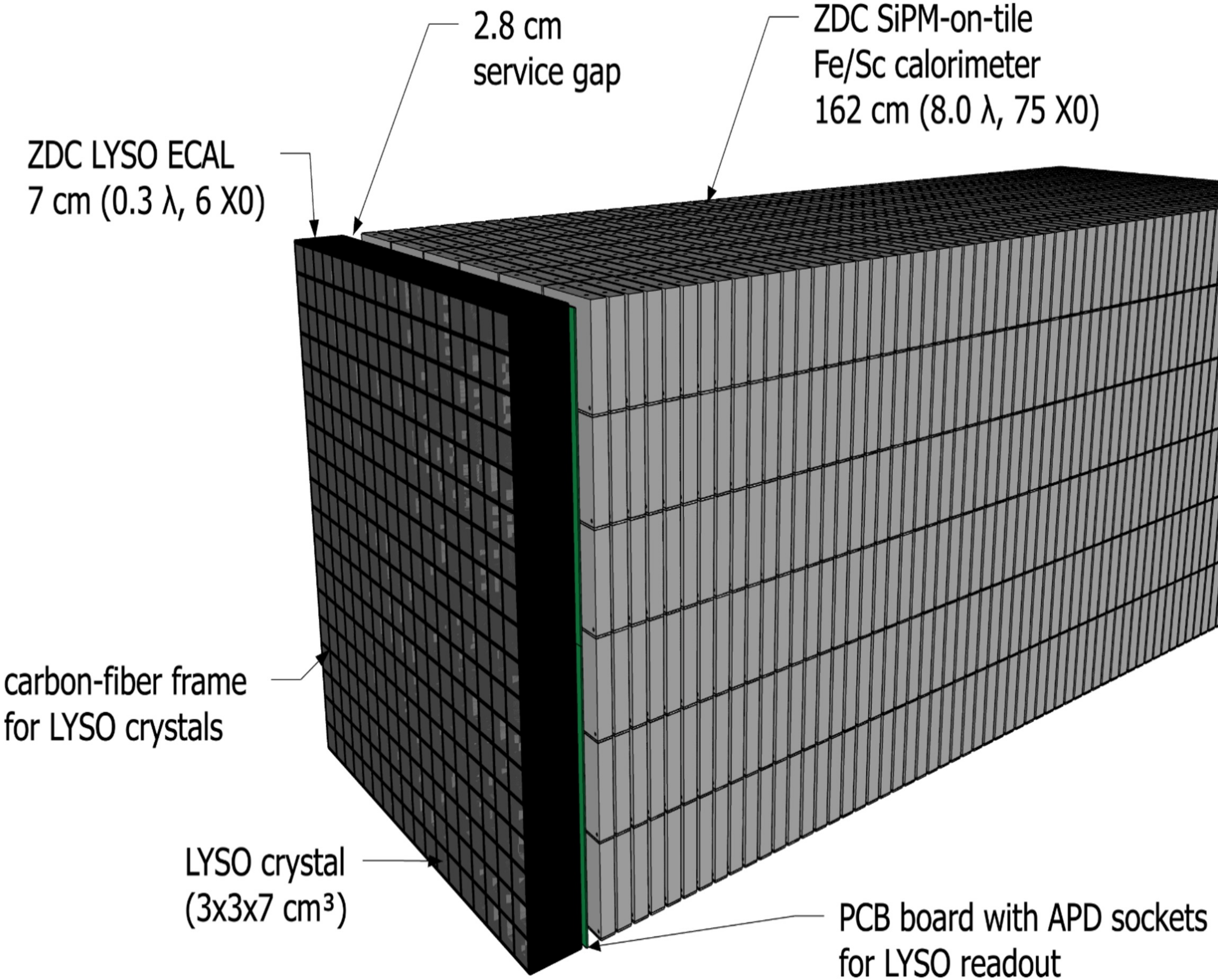
<table>
<tr><th></th><th>Energy range</th><th>Energy resolution</th><th>Position resolution</th><th>Others</th></tr>
<tr><td rowspan="2">Neutron</td><td rowspan="2">up to the beam energy</td><td>$\frac{50\%}{\sqrt{E}} + 5\%$, ideally $\frac{35\%}{\sqrt{E}} + 2\%$</td><td>$\frac{3\text{mrad}}{\sqrt{E}}$</td><td>Acceptance: 60 cm × 60 cm</td></tr>
<tr><td colspan="3">Note:
The acceptance is required from meson structure measurement.
Pion structure measurement may require a position resoultion of 1 mm.</td></tr>
<tr><td rowspan="4">Photon</td><td rowspan="2">0.1 – 1 GeV</td><td>20 – 30%</td><td></td><td>Efficiency: 90 – 99%</td></tr>
<tr><td colspan="3">Note:
Used as a veto in e+Pb exclusive J/ψ production</td></tr>
<tr><td rowspan="2">20 – 40 GeV</td><td>$\frac{35\%}{\sqrt{E}}$</td><td>0.5–1 mm</td><td></td></tr>
<tr><td colspan="3">Note:
u-channel exclusive electromagnetic π^0 production has a milder requirement of $\frac{45\%}{\sqrt{E}} + 7\%$ and 2 cm, respectively. Events will have two photons, but a single-photon tagging is also useful.
Kaon structure measurement requires to tag a neutron and 2 or 3 photons, as decay products of Λ or Σ.</td></tr>
</table>

Table 2: Physics requirement for ZDC

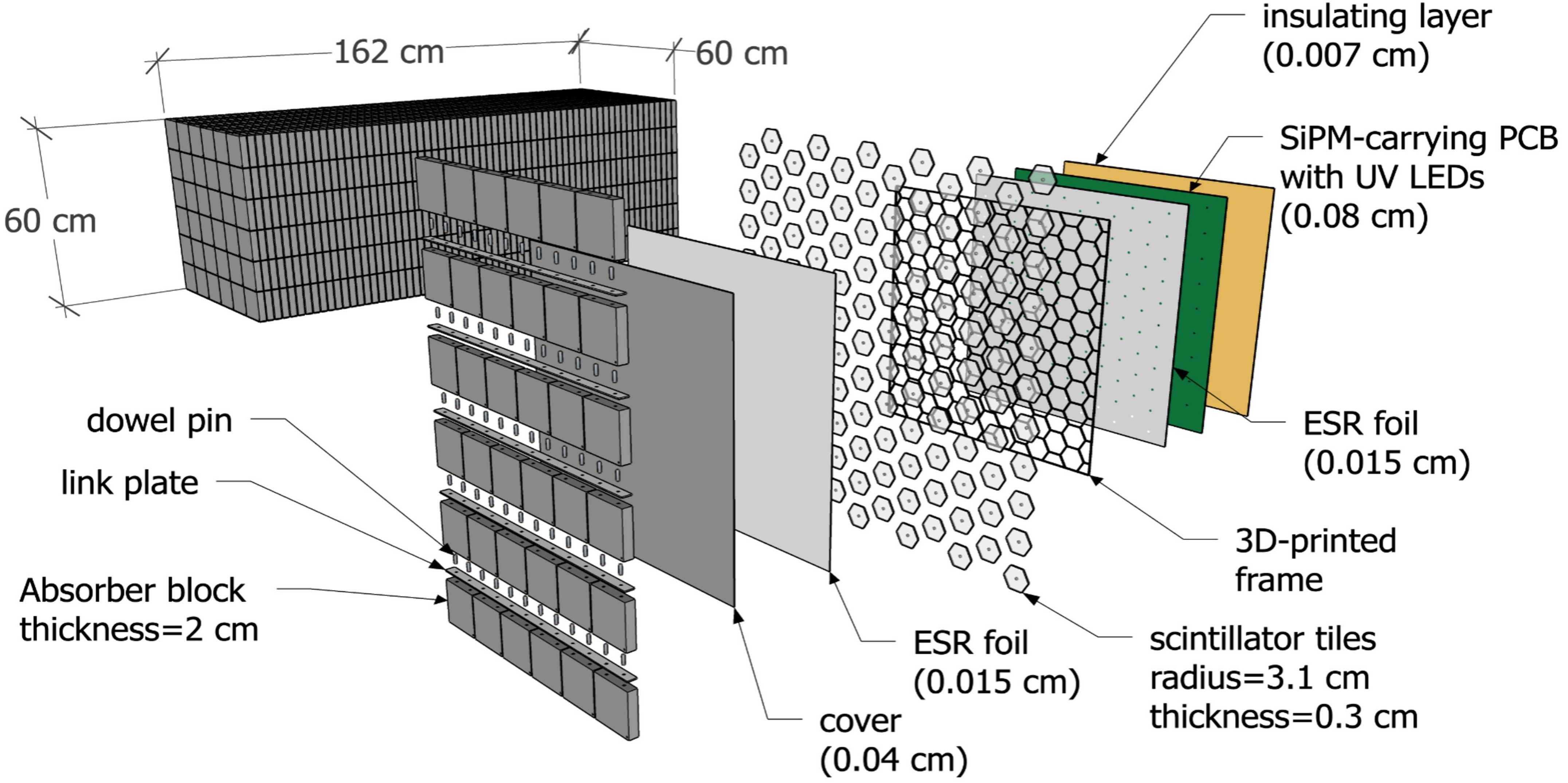
Changes since last year

- Major effort to reduce cost of hadronic calorimeter
- Moving to Fe/Scintillator with SiPMs on each tile gives major reduction in cost
- Also has significant synergies with Forward Hadron Calorimeter
- New radiation estimates, ~ 2 10^{11} N equivalent, suggest design OK
- For EM section looking to LYSO crystals ~ 20cm in order to get sufficient light for very low energy photons.
  - Working to find synergies with B0 calorimeter

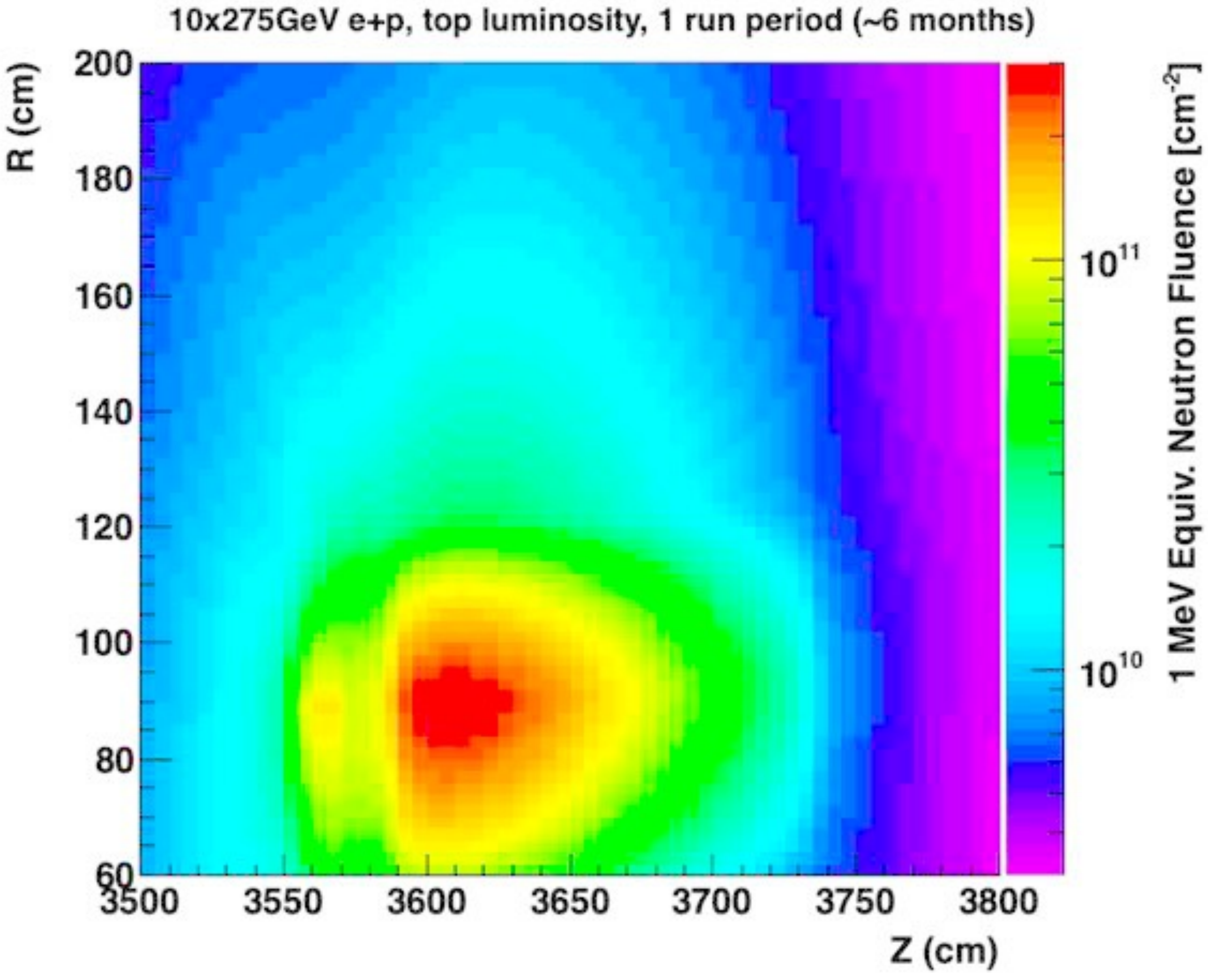
Current Design



Hadronic Section

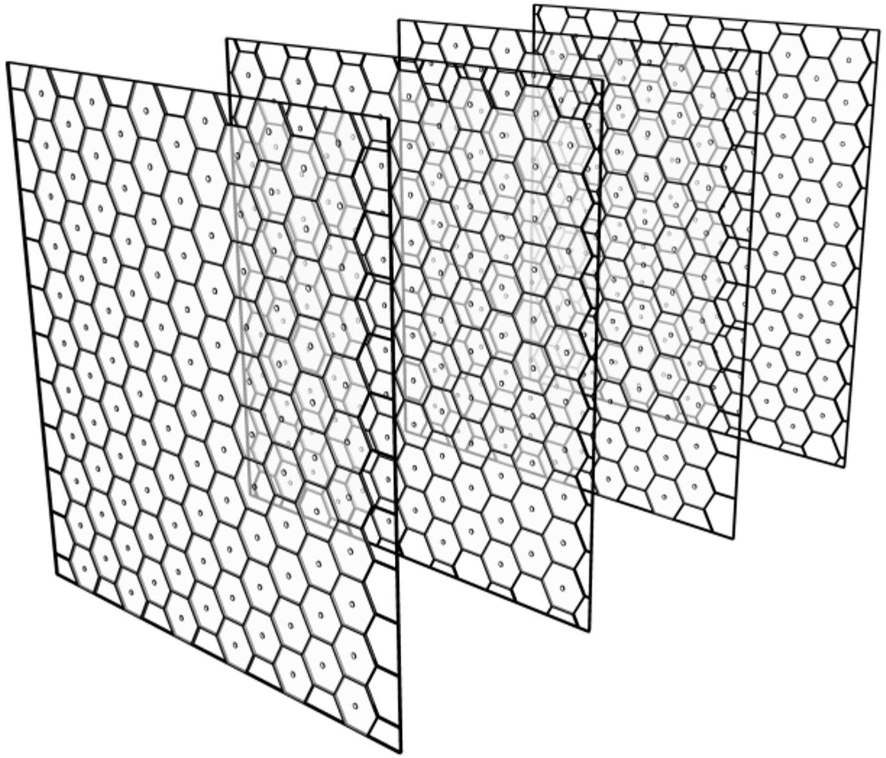


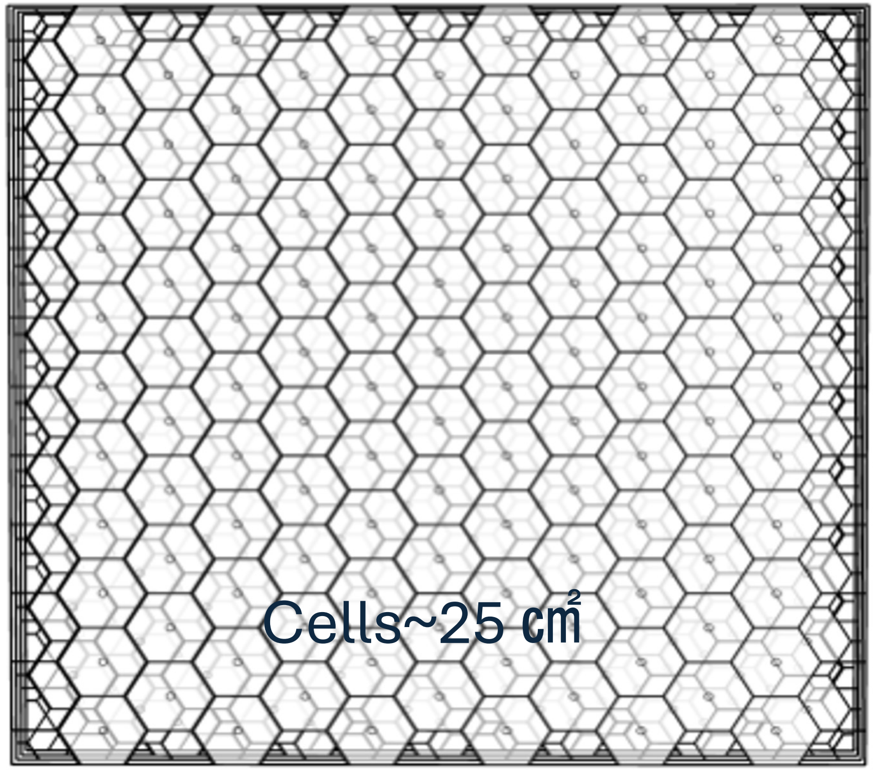
Radiation Load ~ 2 10^{11} N equivilent/running year



Radiation load comparable to peak of forward hadron calorimeter

Tessellation of hexagons improves position resolution

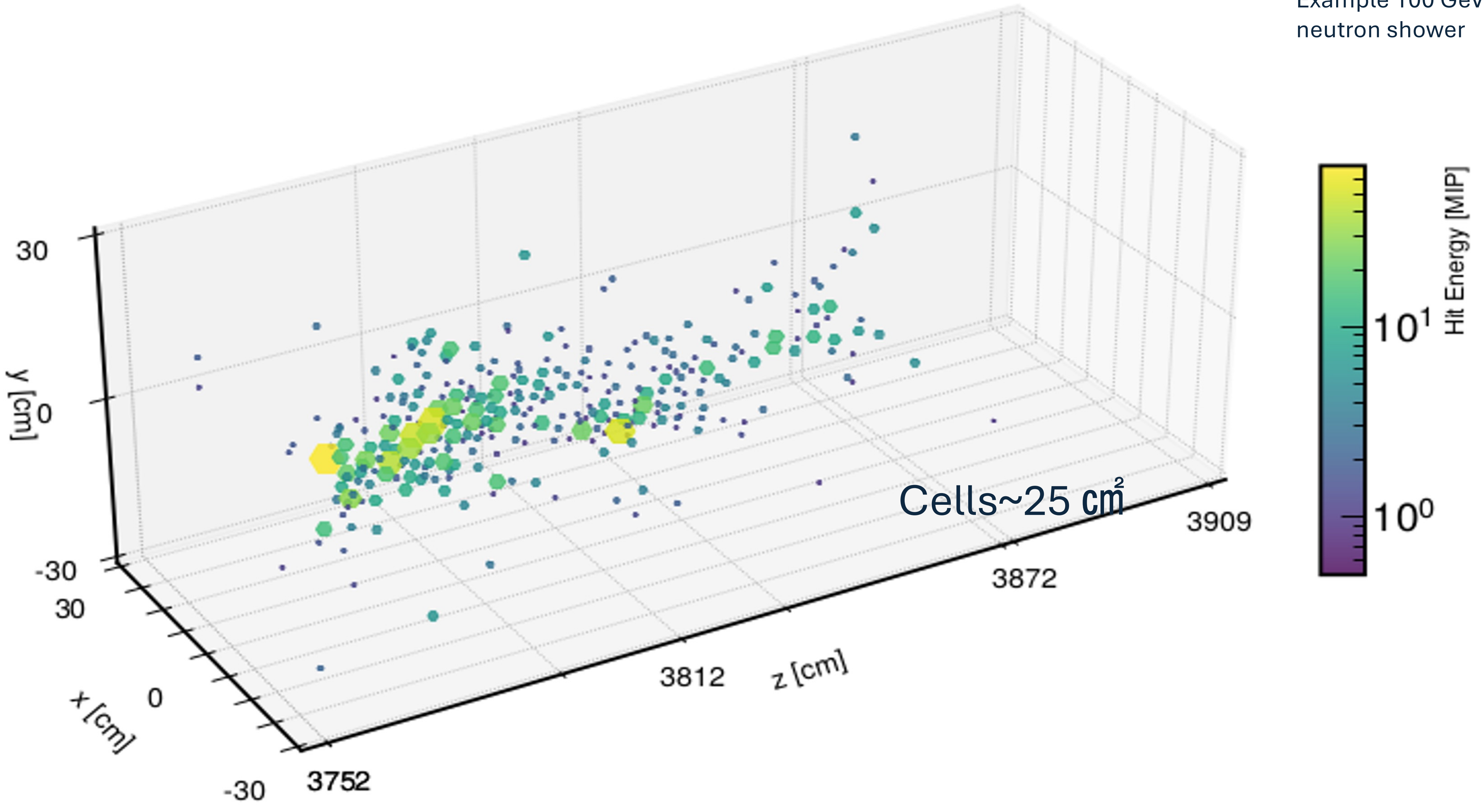




Fe blocks from STAR

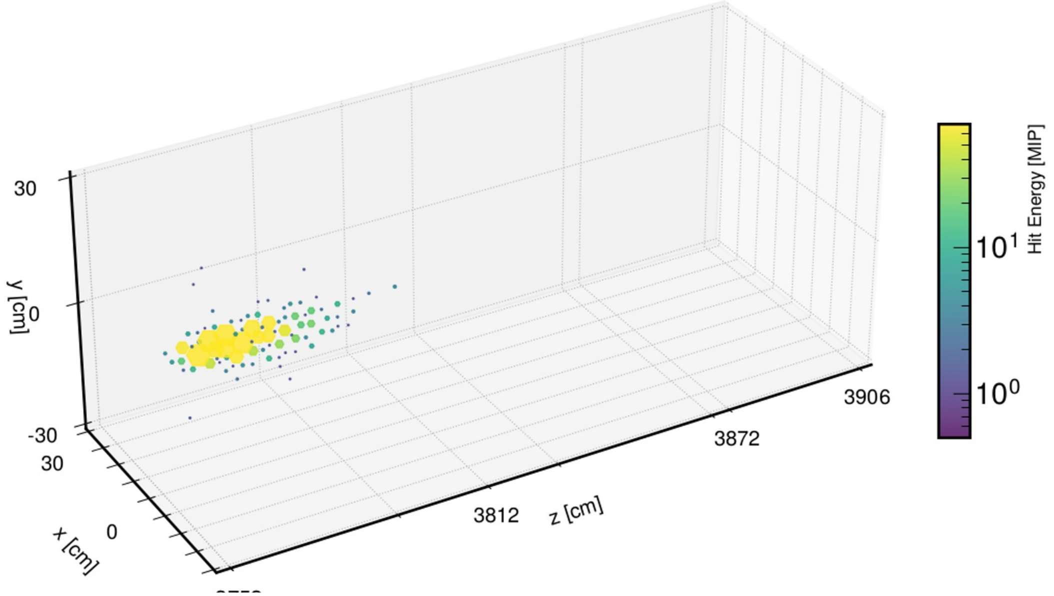
arXiv:2308.06939

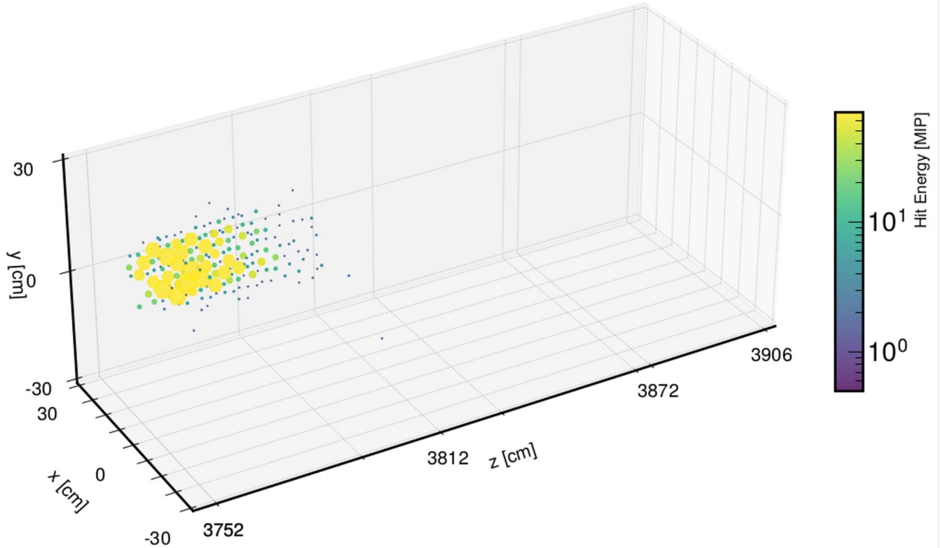
Example of 100 GeV neutron shower

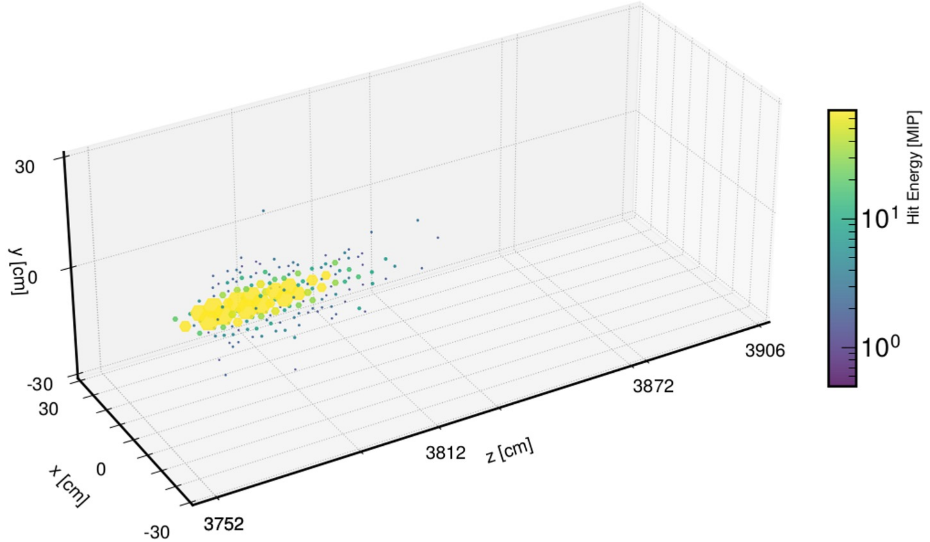


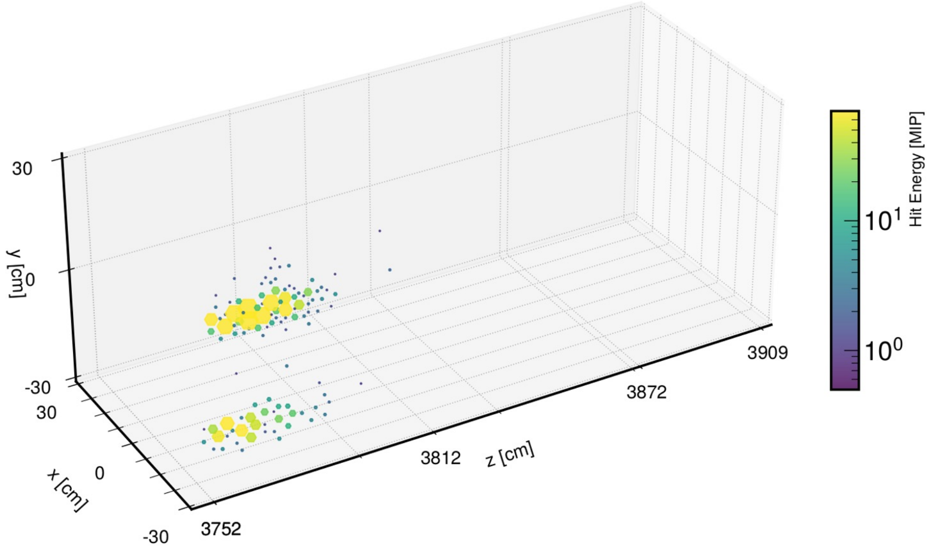
Example 100 GeV neutron shower

Example one and two photon showers

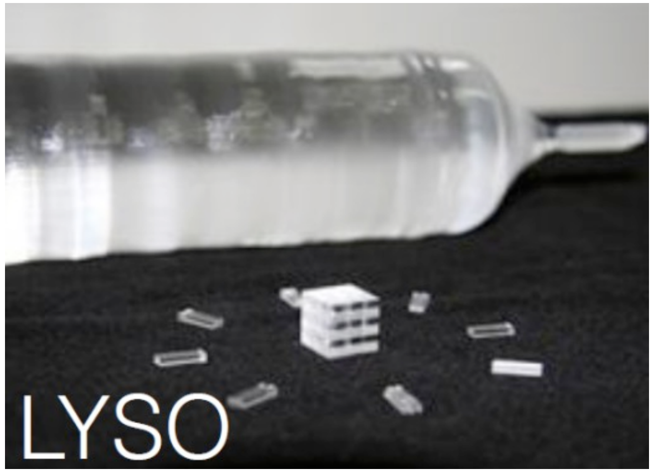


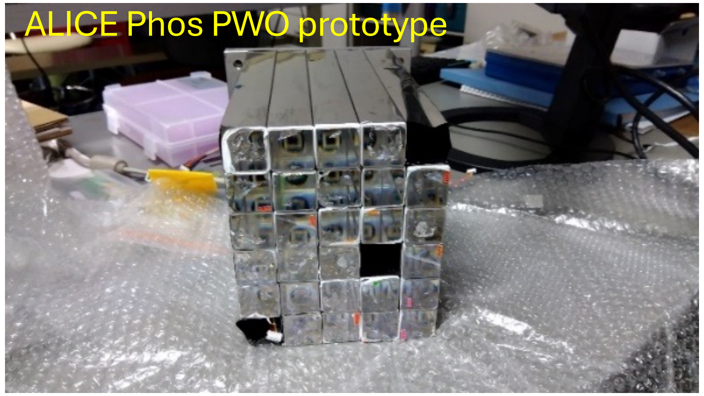






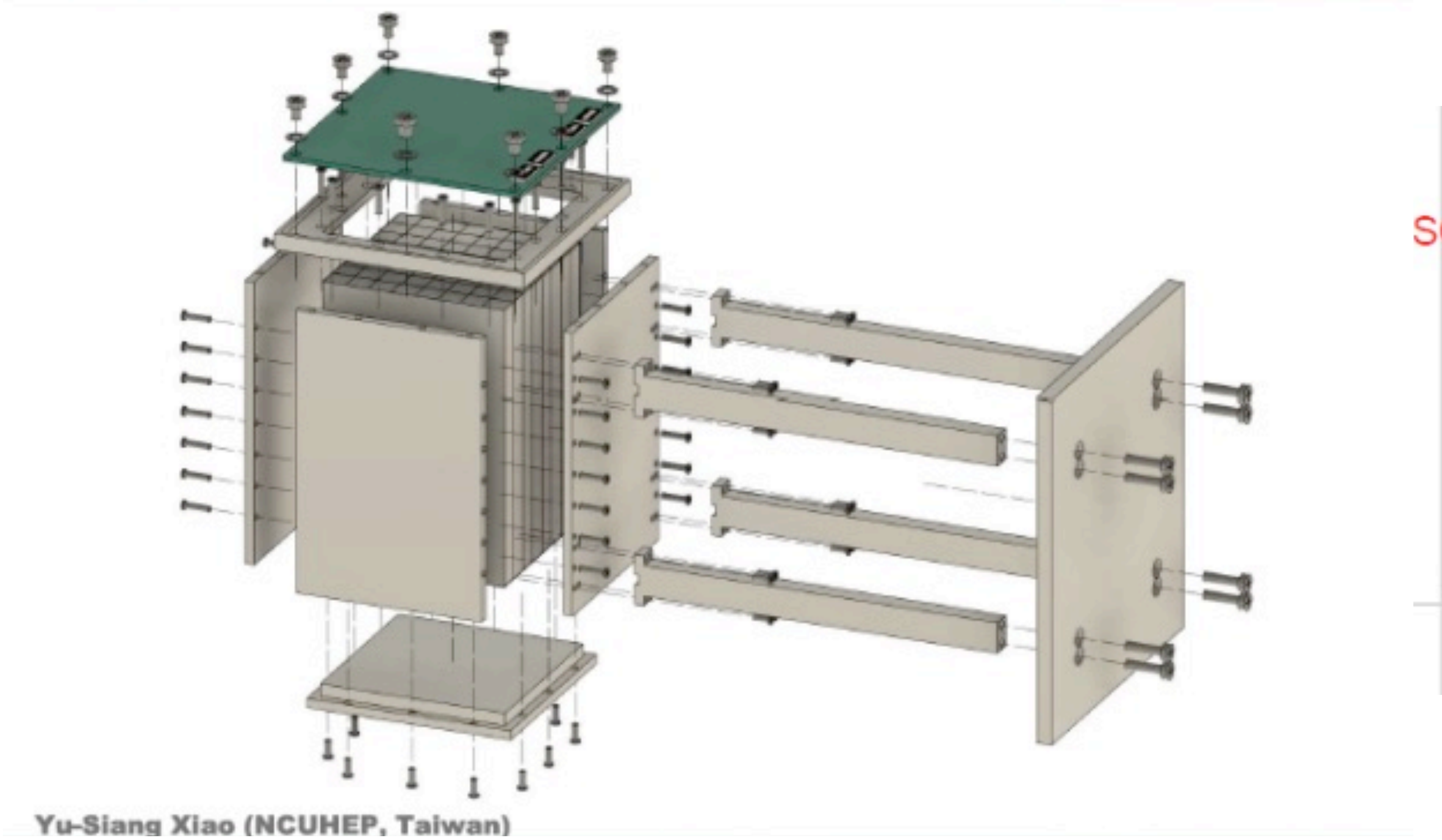
We prefer LYSO because of higher light yield.

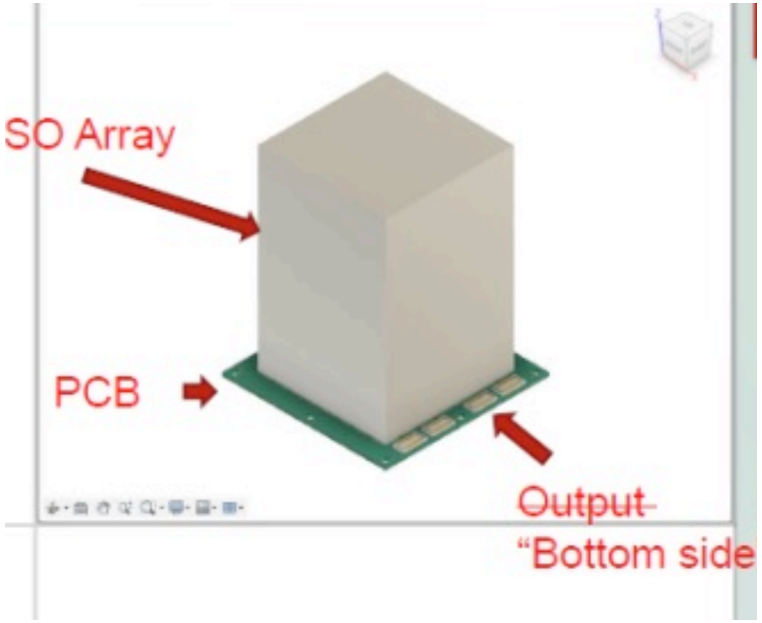




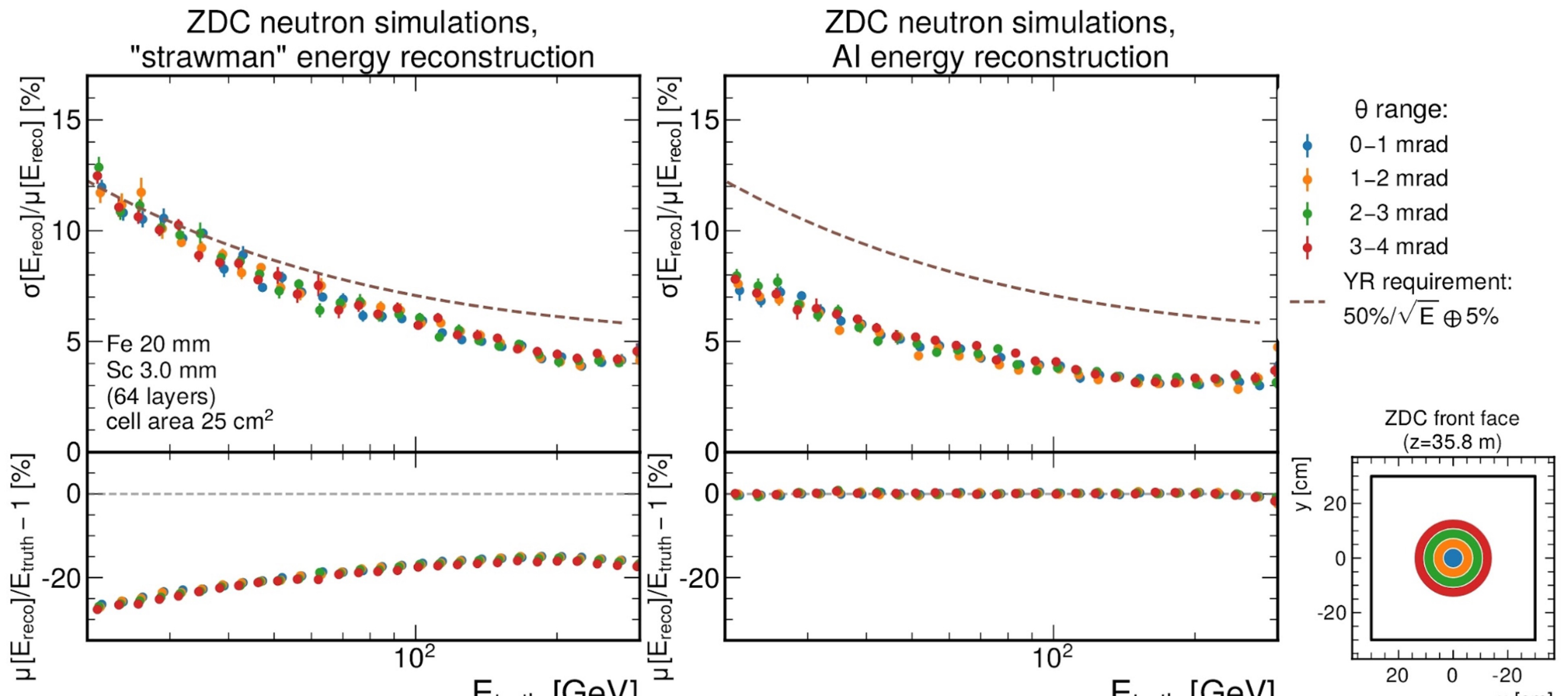
	X_0	LY (ph/MeV)	T dep. of LY (%/K)	Decay time (ns)	λ_{em} nm
$PbWO_4$ (CMS)	0.89 cm	200	-1.98	5 (73%) 14 (23%) 110 (4%)	420
LYSO	1.14 cm	30,000 (market standard)	-0.28	36	420
SciGlass	2.4-2.8 cm	>100		22-400	440-460

LYSO Test module built by Taiwan Group

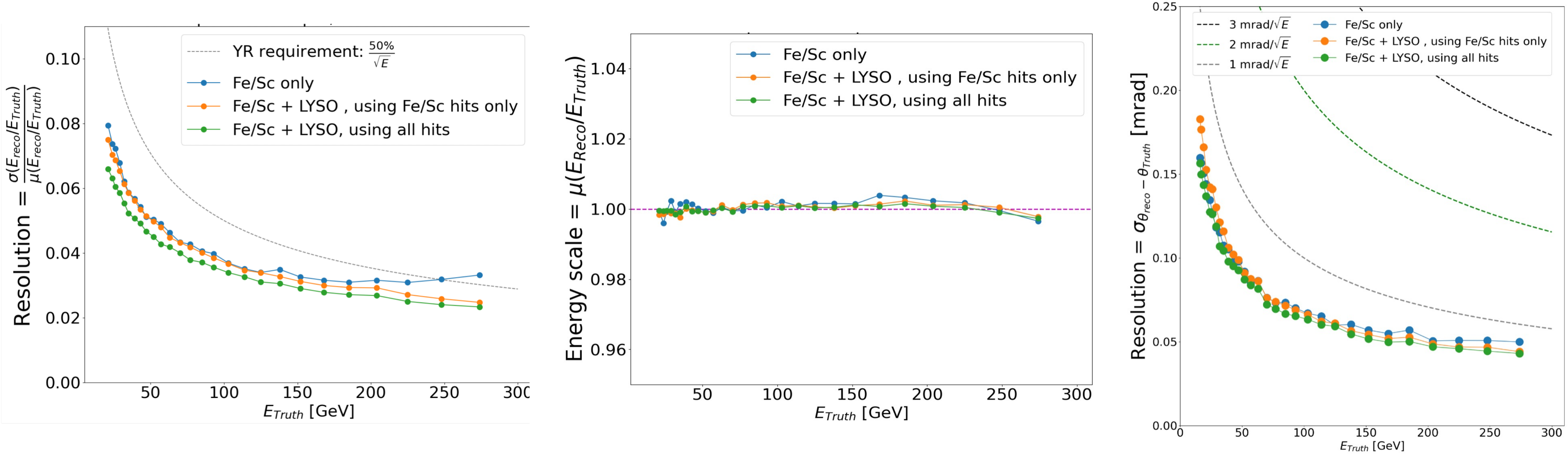




AI shower reconstruction improves resolution



Resolution of combined EM and Hadronic sections.



- Layer by layer information allows software compensation
- Adding LYSO slightly improves energy resolution.
- No significant impact on the angular resolution

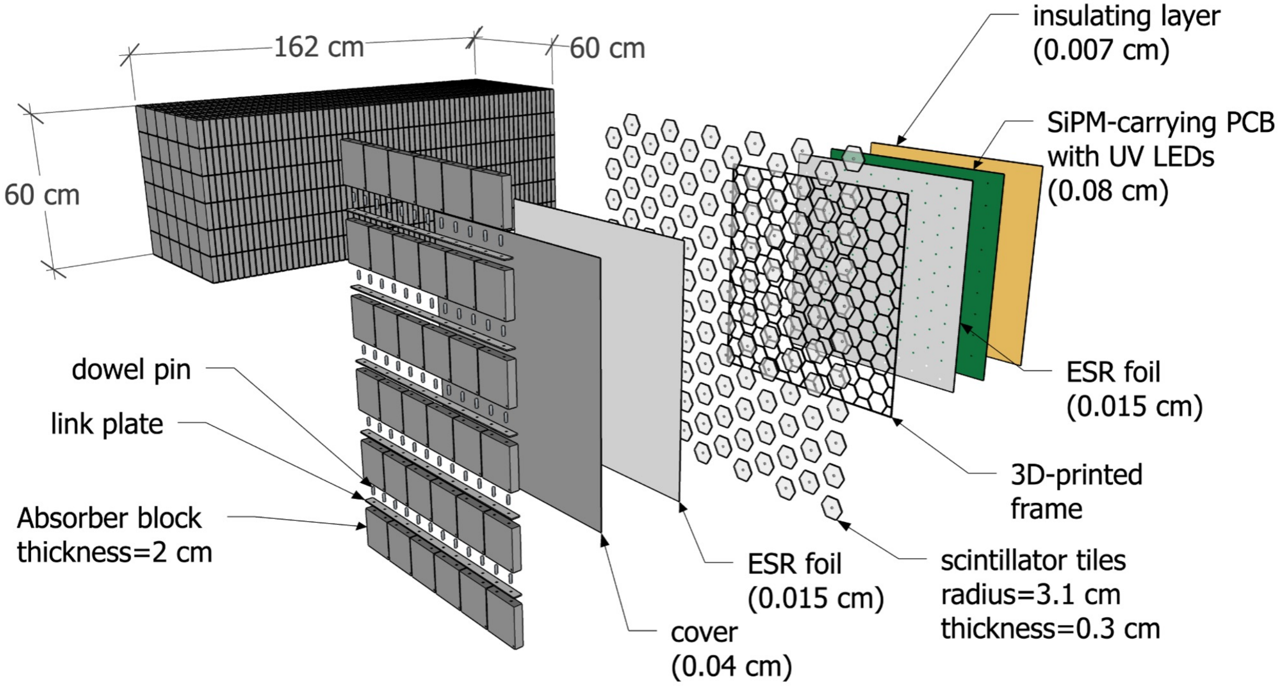
Summary: Current design meets physics requirements

	Energy resolution	Angular resolution [mrad]	π^0 rejection
Neutron	$54\%/\sqrt{E} \oplus 2\%$ (strawman)	$0.79/\sqrt{E} \oplus 0.02$ (HEXPLIT)	—
	$35\%/\sqrt{E} \oplus 2\%$ (GNN)	$0.66/\sqrt{E} \oplus 0.02$ (GNN)	—
Photon	$20\%/\sqrt{E} \oplus 1\%$ (strawman)	$0.19/\sqrt{E} \oplus 0.01$ (baselin)	$> 97\%$ for $E > 150$ GeV (σ cut)
			$> 98\%$ for $E > 150$ GeV (GNN)

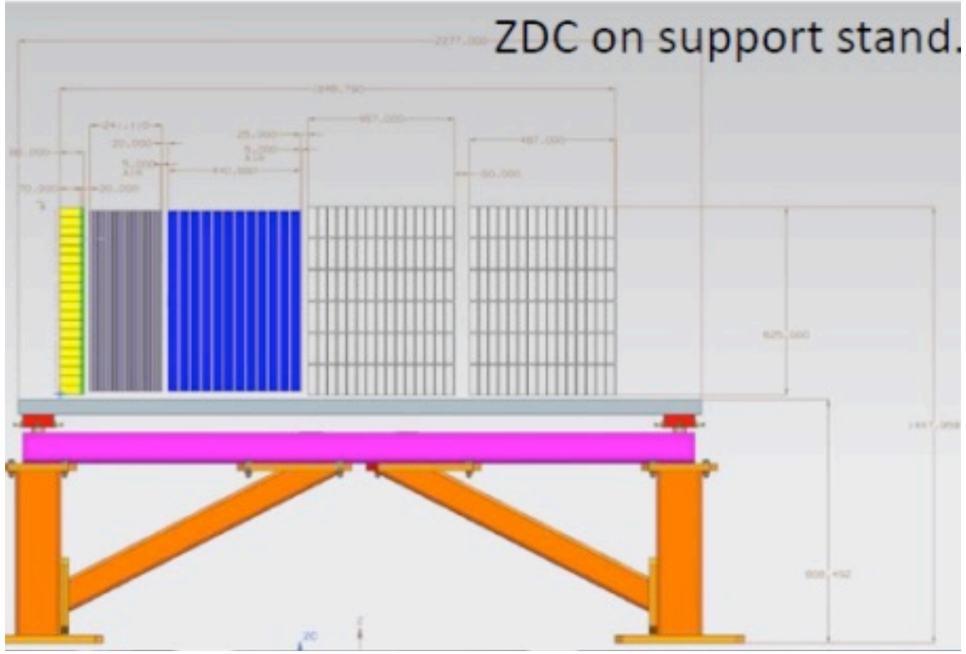
- At 100 GeV, the neutron angular resolution is 2.5 mm or 80 μrad, which added in quadrature with beam divergence in the high-acceptance configuration (56 μrad) yields a pT resolution of 10 MeV
- At 100 GeV, the position resolution for photons is 0.6 mm.

Safety and operational considerations.

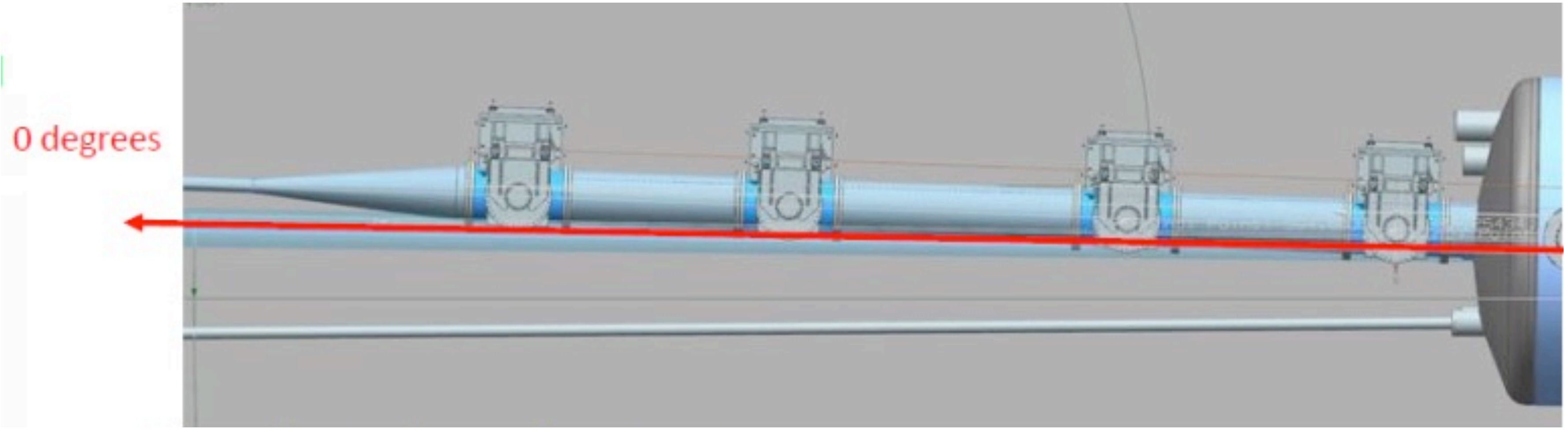
- Current design envisions whole of calorimeter as one piece
- Will need strong internal structure to give rigidity to frame while maximizing active area.
- It may be possible to go to stackable design for mechanical reasons.
- There is space around the ZDC for cooling, power and other services.



Need to stay clear of cryostats, hadronic beam pipe and electron crab cavity



Current hadron beam pipe cuts acceptance for photons. Machine is aware of this.

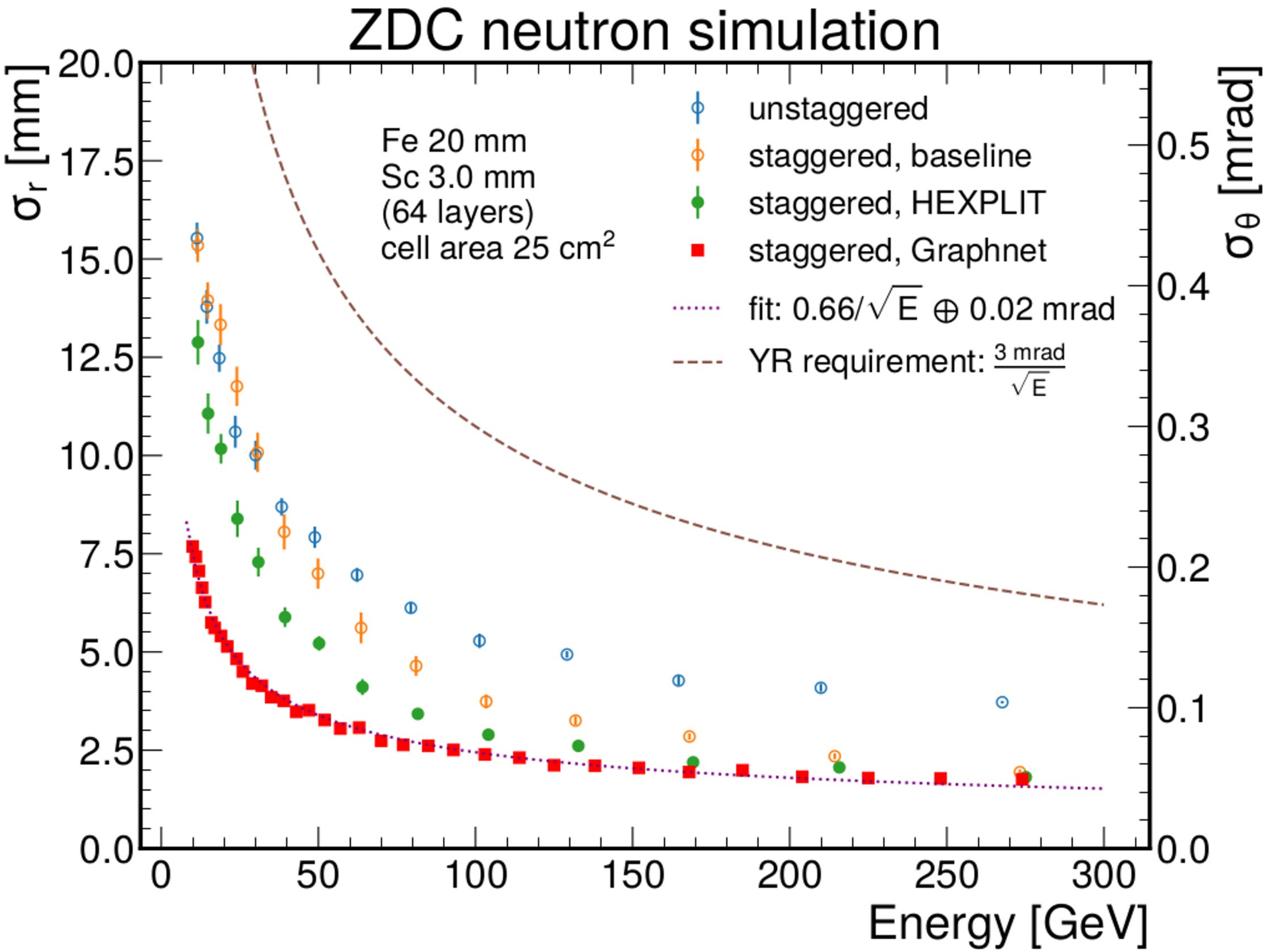


Plan for 2024: Getting to final design

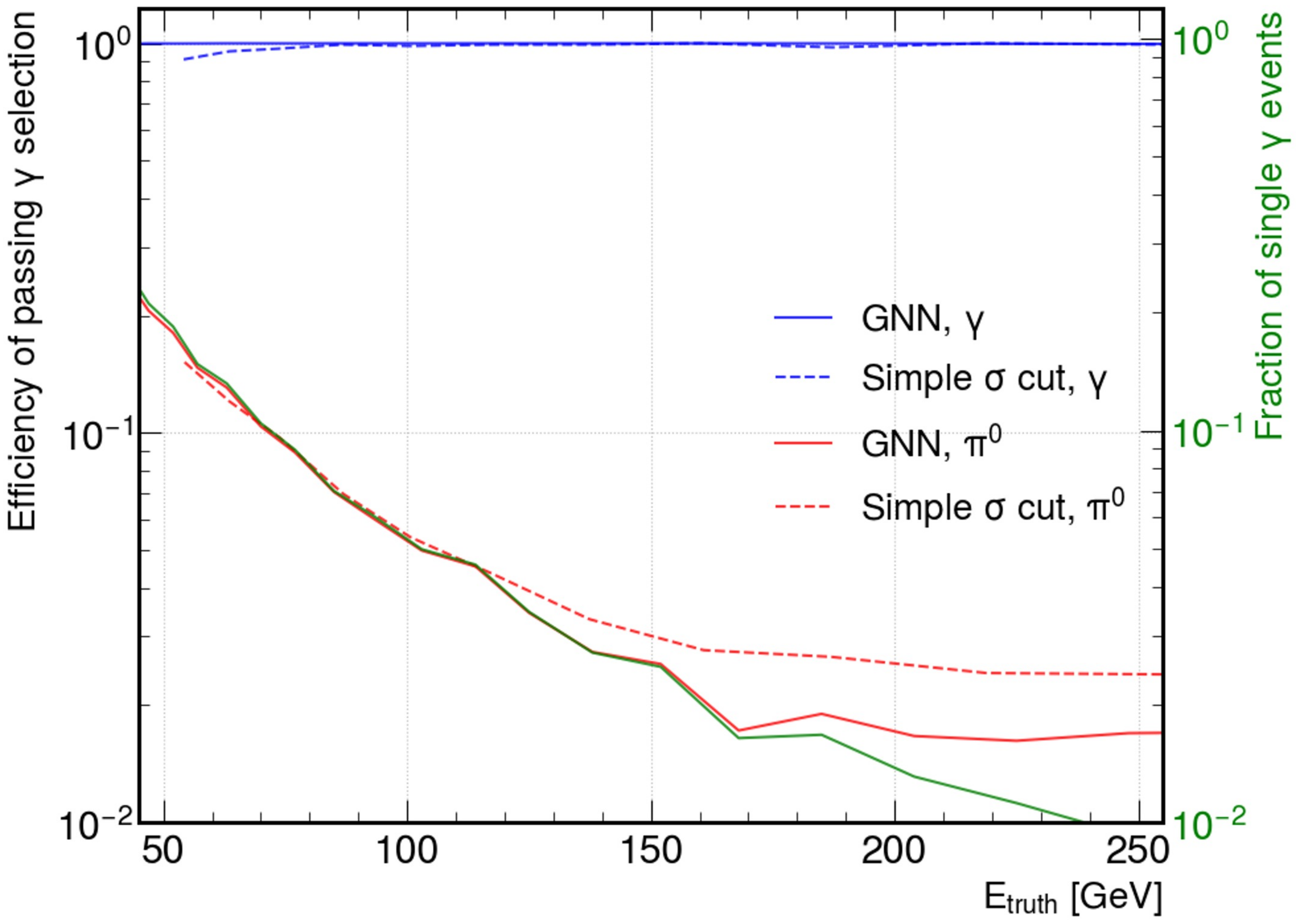
- Need to finalize length of LYSO crystals: Ideally the same length as other detectors.
- Realistic mechanical design that is sufficiently rigid to pass safety review.
- Include realistic distribution of services.
- Get full simulation and physics benchmarks into ePIC framework
  - This is vital for integration with detector elements such as beam pipe.
- Work to strengthen group by working for all possible funding options.

BACKUP

Reminder: standalone neutron performance



SiPM-on-tile standalone performance on π0/ɣ separation



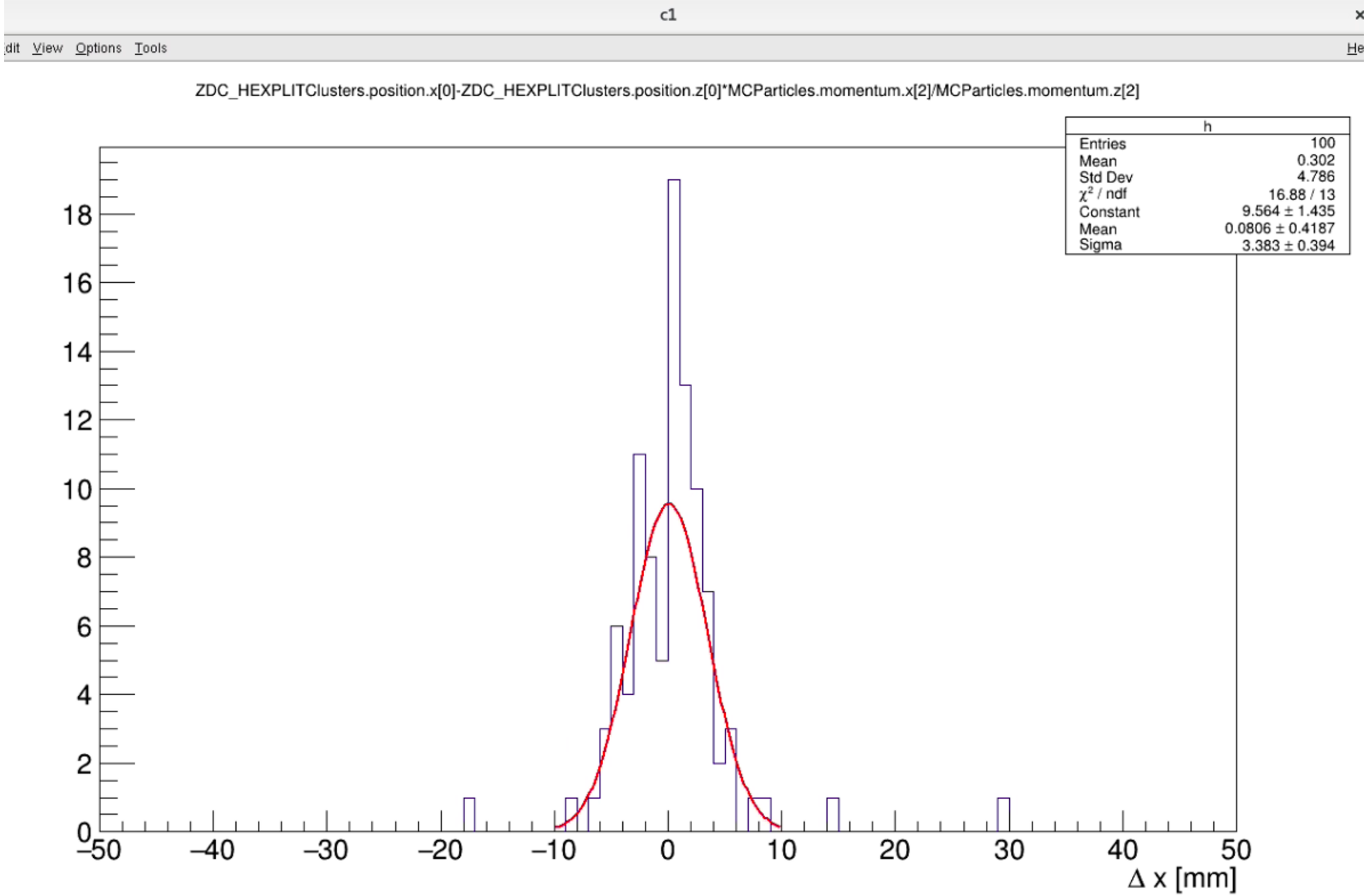
- GNN (solid red) improves simple shower-shape cut above ~120 GeV
- GNN reaches ~2% misclassification rate above 150 GeV
- For reference, a perfect detector would yield a performance shown in green (true fraction of π0 that yield only on photon in acceptance).
- Simple shower shape close to perfect case until ~120 GeV, GNN close to perfect until ~170 GeV.

Take home message: SiPM-on-tile granularity good enough for this application.
Higher granularity would yield insignificant gains, which are neither required nor justified by physics.

ZDC SiPM-on-tile software in DD4HEP and ePIC

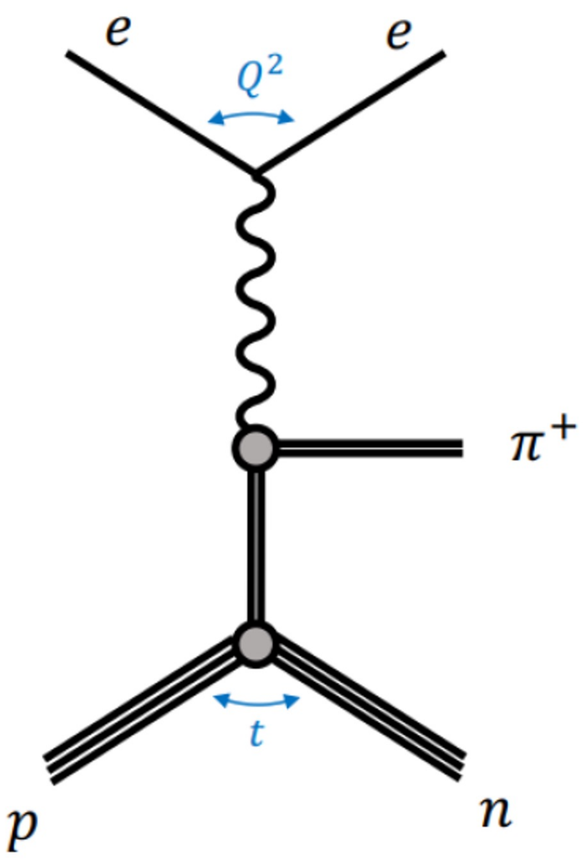
- DD4hep plugin for hexagonal segmentation and staggering was added to official DD4HEP core software
  https://github.com/AIDASoft/DD4hep/pull/1161
- ZDC Fe/SiPM-on-tile was added to official ePIC sim DD4HEP geometry model
- **New:** Digitization parameters tuned and added to EICrecon:
  https://github.com/eic/EICrecon/blob/sipmzdc/src/detectors/ZDC/ZDC.cc
- **New:** Fe/Sc + LYSO configuration added to dedicated branch of ePIC sim: https://github.com/eic/epic/tree/ZDC_LYSO
- **New:** new branch of EICRecon for ZDC SiPM-on-tile algorithms:
  https://github.com/eic/EICrecon/tree/sipmzdc
- **New:** HEXPLIT algorithm C++ version is on EICrecon:
  https://github.com/eic/EICrecon/blob/sipmzdc/src/algorithms/calorimetry/HEXPLIT.cc
- **New:** LogWeighting 3D position reco algorithm is on EICrecon:
  https://github.com/eic/EICrecon/blob/sipmzdc/src/algorithms/calorimetry/LogWeightReco.cc
- **New:** ZDC Physics Benchmark with Deeply-exclusive meson events created
  https://github.com/eic/physics_benchmarks/tree/demp_zdc/benchmarks/demp/analysis
- **New:** 3D Topological clustering algorithm deployed for ZDC benchmark:
  https://github.com/eic/EICrecon/blob/sipmzdc/src/algorithms/calorimetry/ImagingTopoClusterConfig.h

Complete neutron reconstruction is now built in (part of EICrecon output)

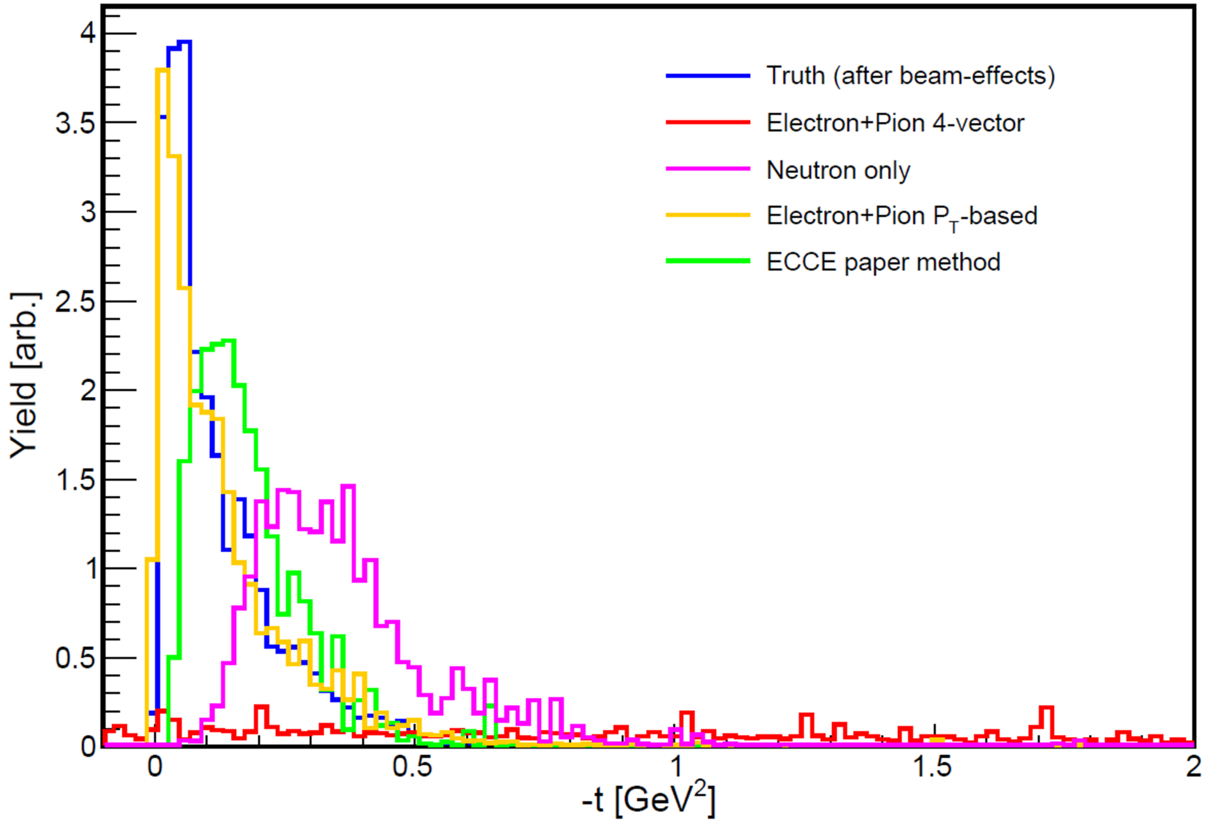


ZDC Physics Benchmark

https://github.com/eic/physics_benchmarks/tree/demp_zdc/benchmarks/demp/



Includes full neutron reconstruction in ZDC

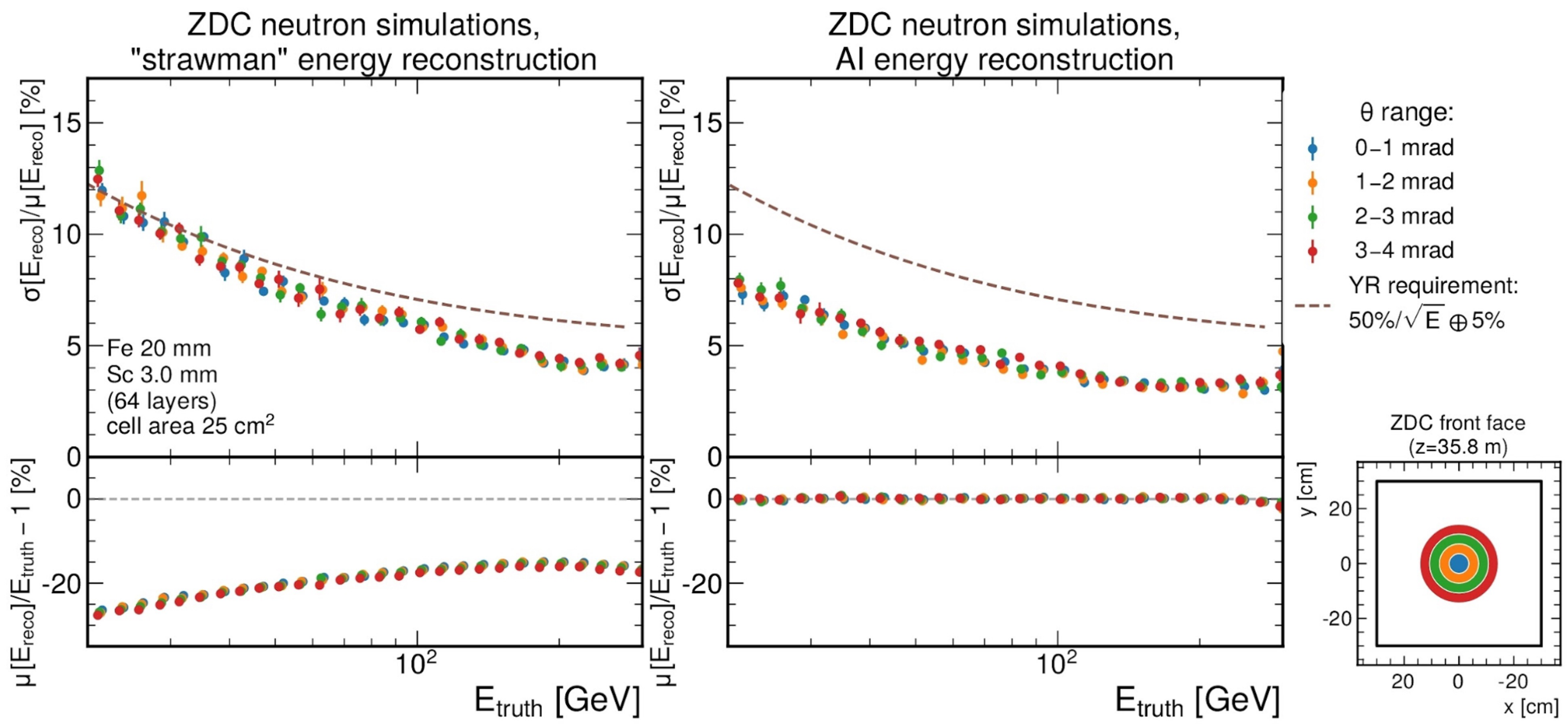


Events from DEMPgen read from S3

Credit, Barak Schmookler, Sebouh Paul

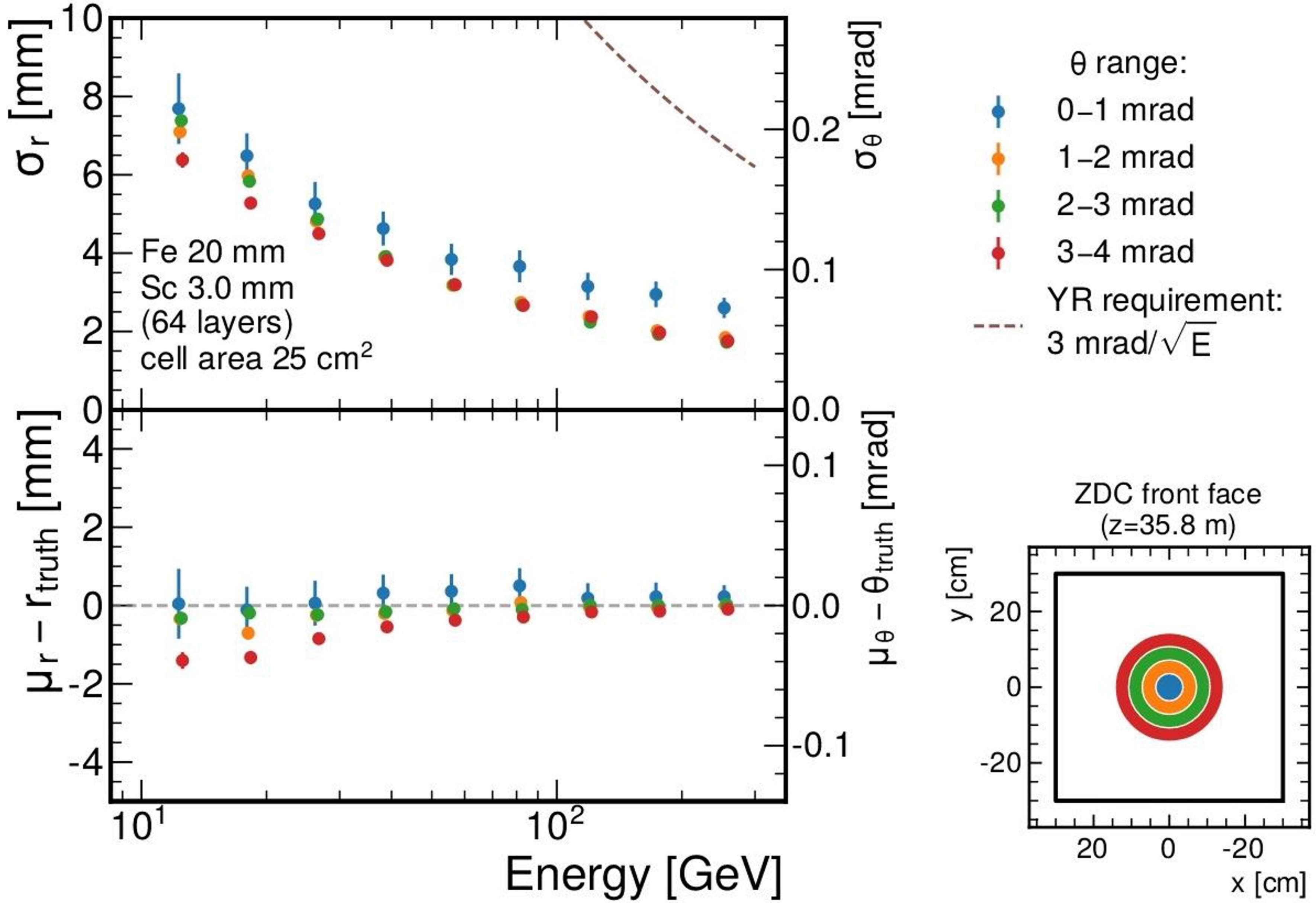
Software status Summary

1) Updates on standalone γ/π0 performance studies
→ Fe/Sc SiPM-on-tile performance is close to be dominated by "irreducible" background of π0 yielding only 1 photon in ZDC acceptance.
2) Updated combined system studies
→ Adding LYSO slightly improves energy resolution and does not impact much the angular resolution for neutron showers.
3) Updates related to software and physics benchmarks
→ Entire chain of algorithms is in ePIC software now
→ Flagship benchmark is in place up and running

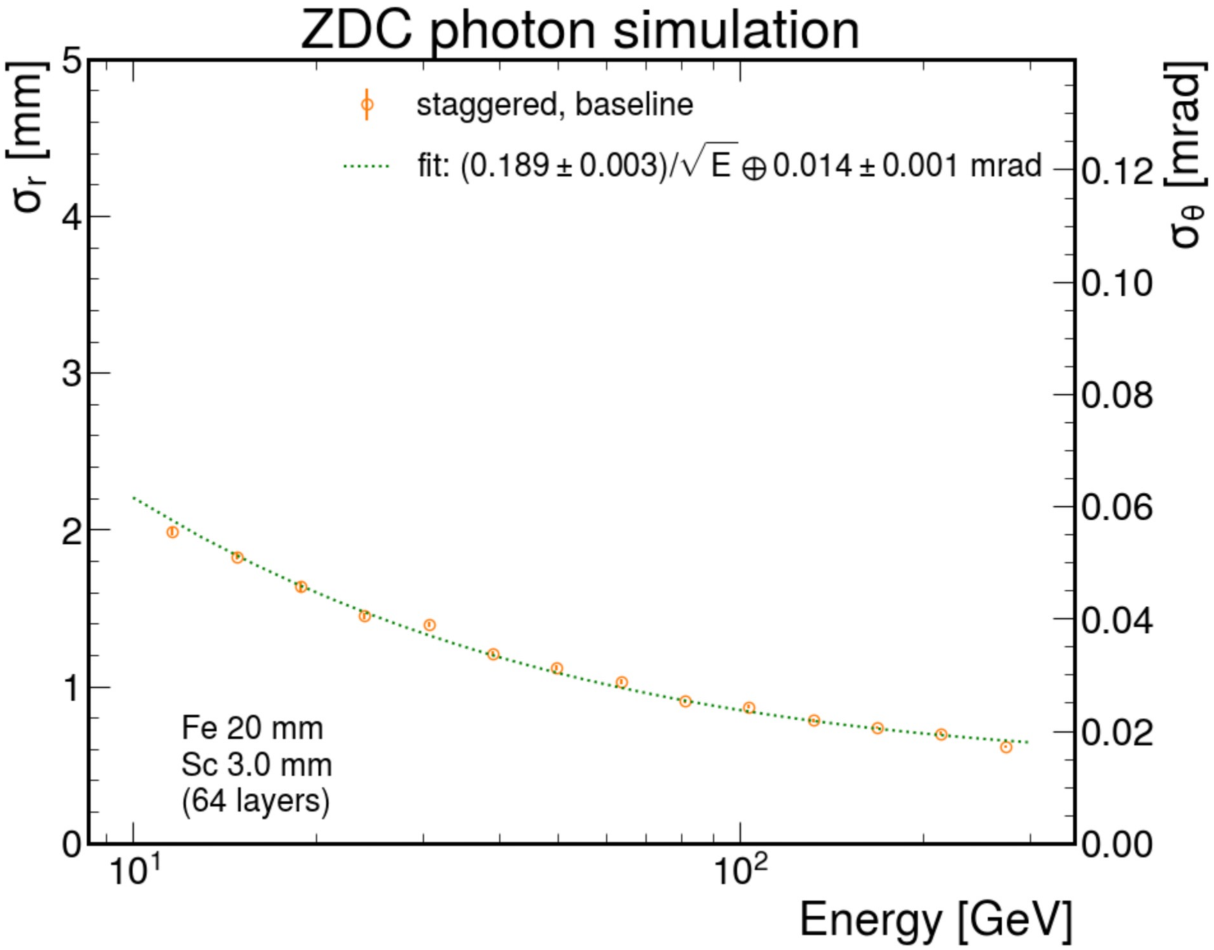


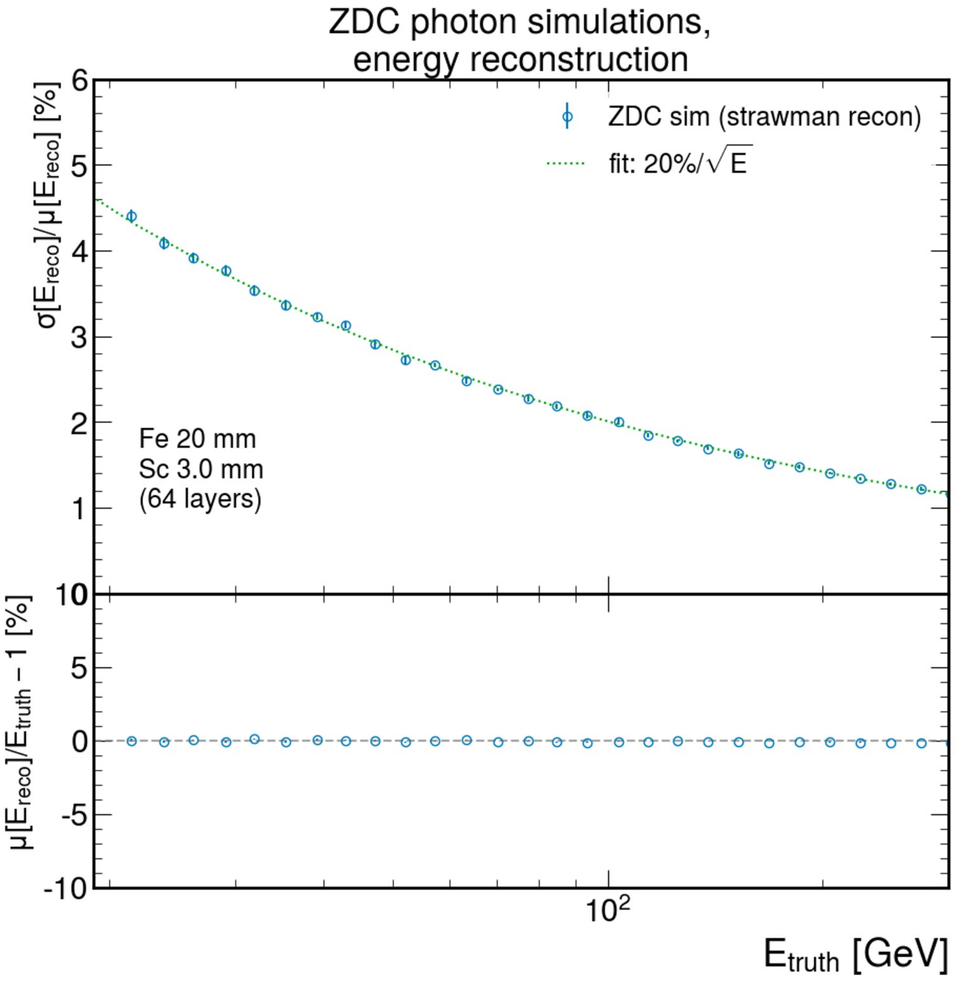
ZDC neutron simulations,
"strawman" energy reconstruction
ZDC neutron simulations,
AI energy reconstruction
σ[E_reco]/μ[E_reco] [%]
μ[E_reco]/E_truth − 1 [%]
Fe 20 mm
Sc 3.0 mm
(64 layers)
cell area 25 cm²
E_truth [GeV]
θ range:
0−1 mrad
1−2 mrad
2−3 mrad
3−4 mrad
YR requirement:
50%/√E ⊕ 5%
ZDC front face
(z=35.8 m)
y [cm]
x [cm]

ZDC neutron simulations, Graphnet reconstruction



Fe/Sc SiPM-on-tile photon performance

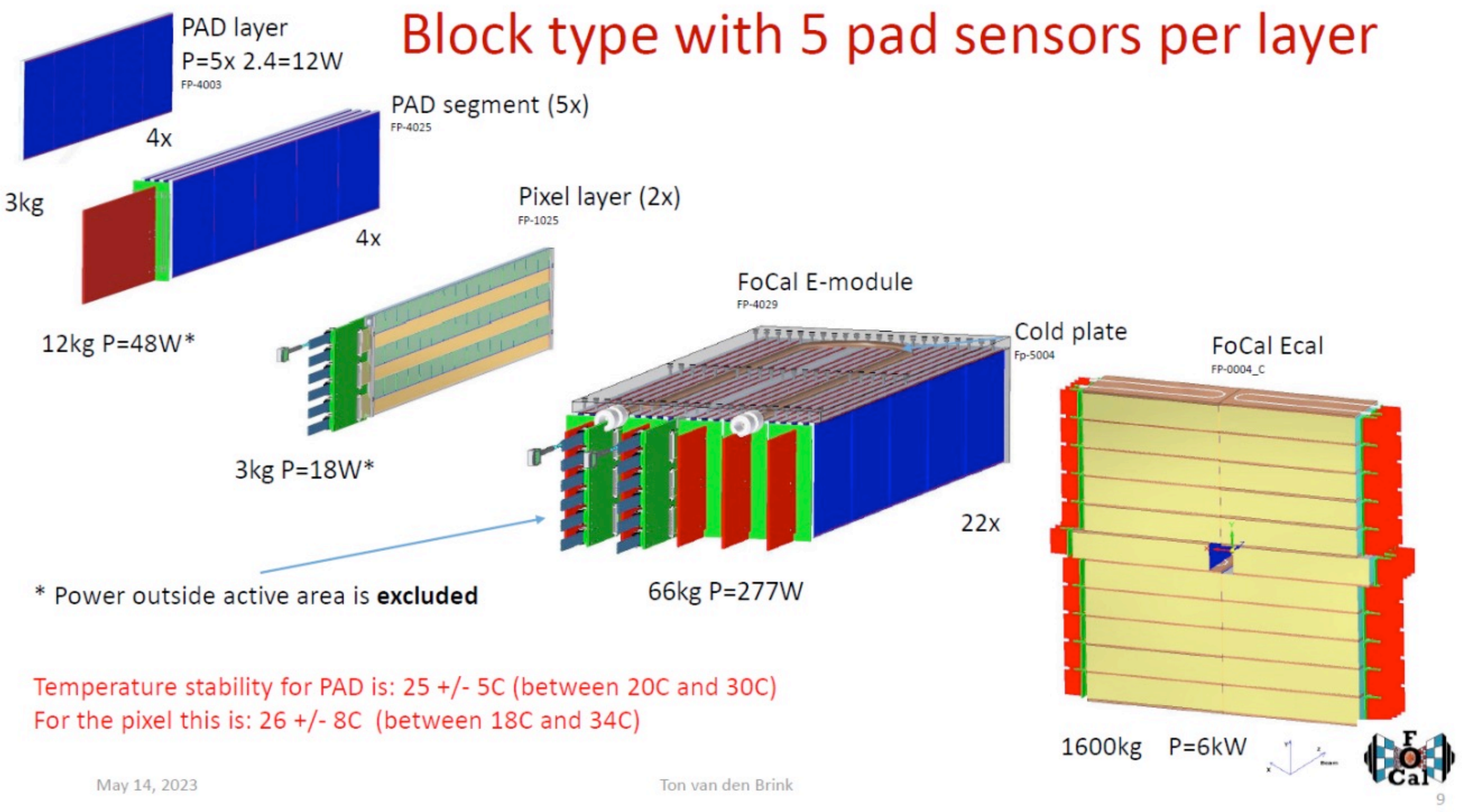




Credit: Sebouh Paul

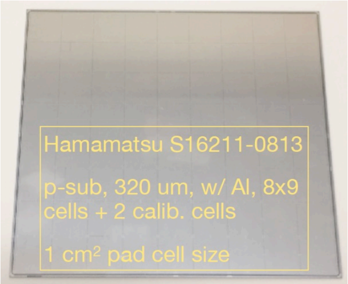
Fe/Sc SiPM is adequate for high-energy photons

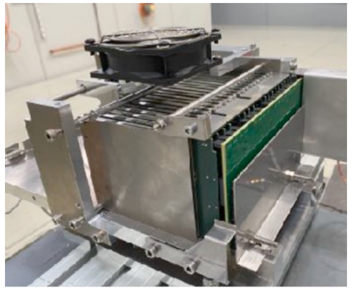
FoCal-E design

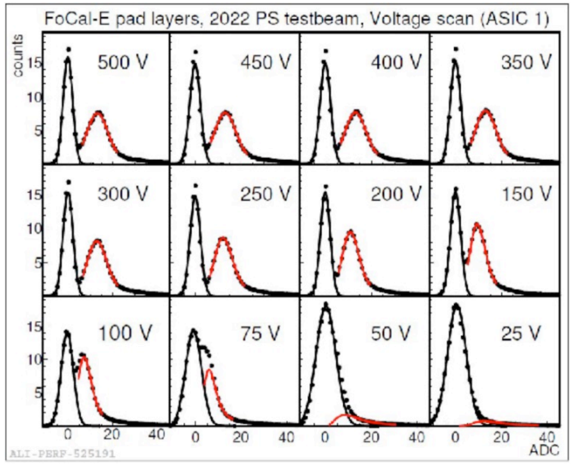


Test-beam studies

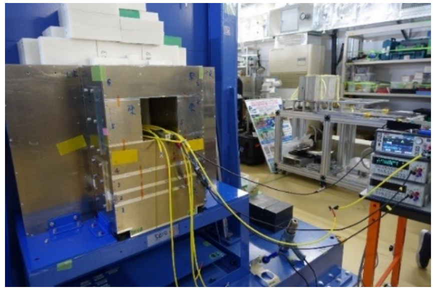
- ALICE FoCal-E test beam @ Tohoku-ELPH & CERN-PS/SPS
  - p-sub sensor, HGCROC v2 for readout
  - Clear MIP peaks observed for almost all channels and layers
  - Reaching full depletion voltage around 300 V

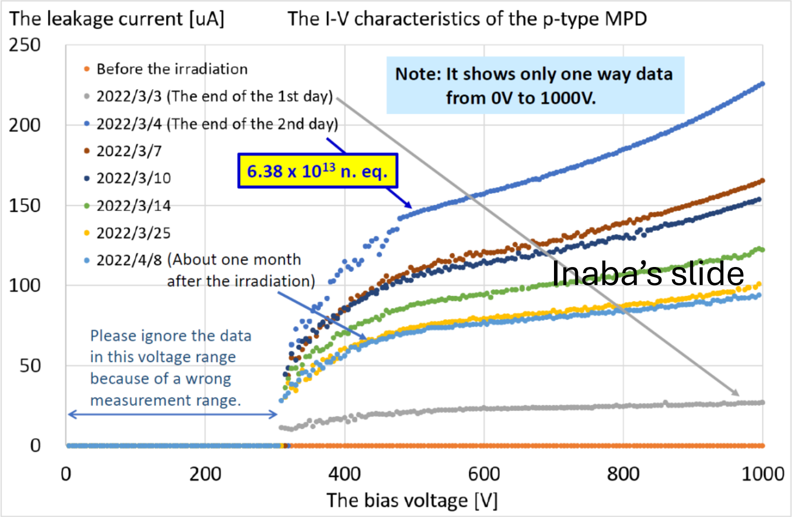






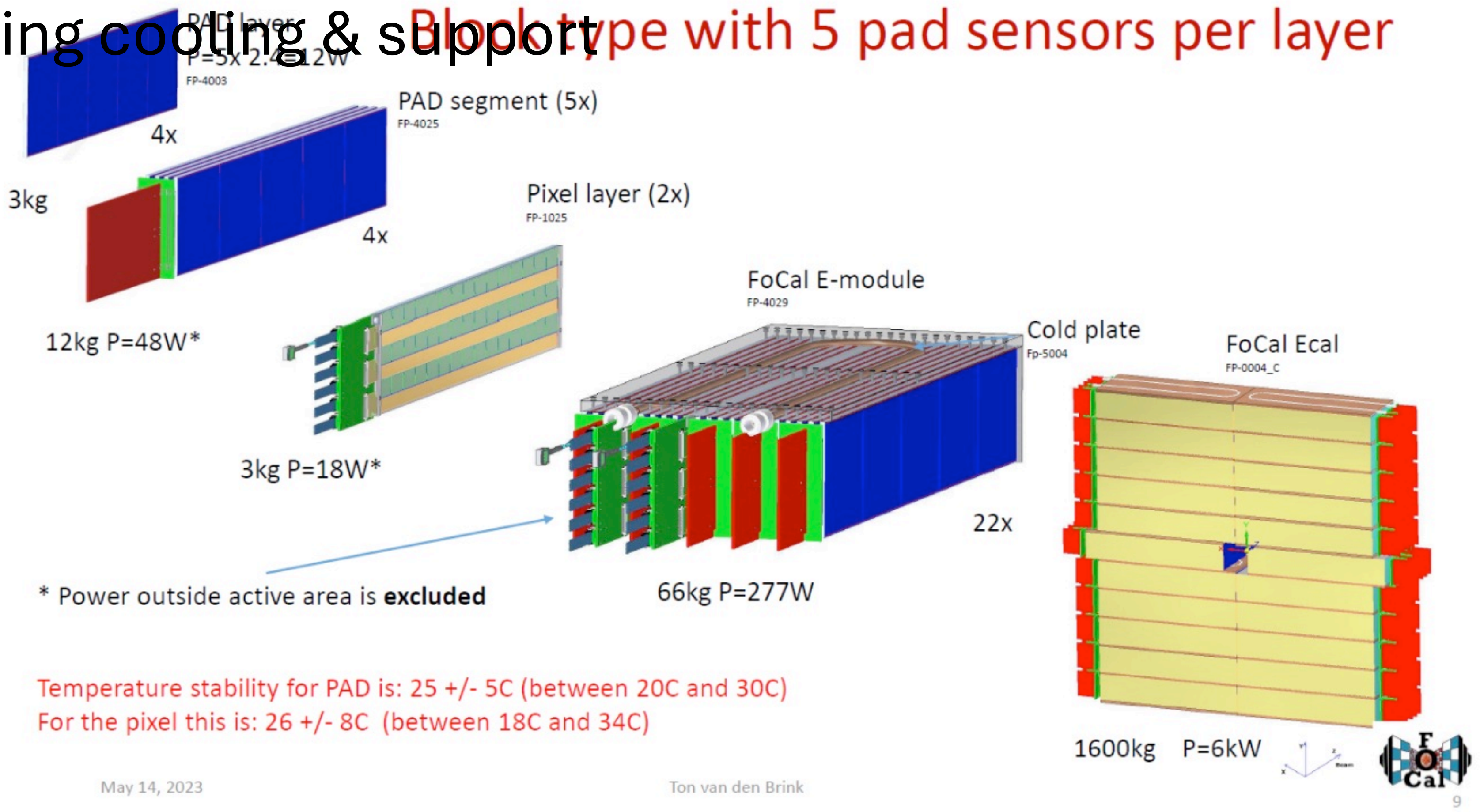
- Neutron irradiation test @ RIKEN-RANS
  - Sensor, photodetectors, chips, cables
  - For FoCal-E, sPHENIX, ePIC-ZDC
  - Up to ~10^{14} neutrons/cm^2



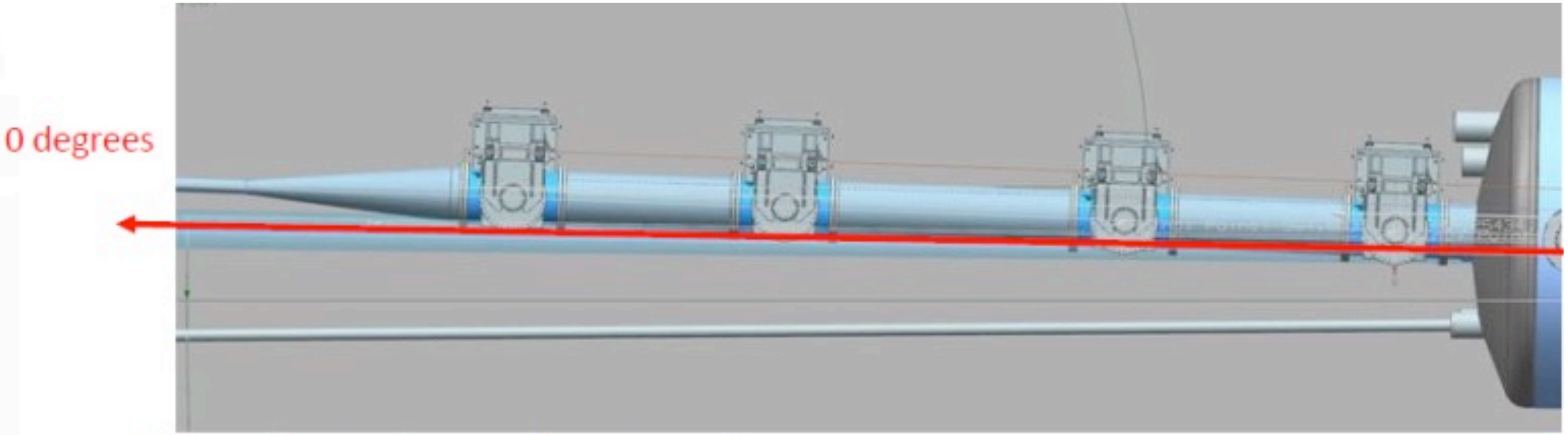


ALICE-FoCal structure

- Including cooling & support



Integration with beam pipe



- Neutral particle cone faces two issues:
    - Exit from beampipe at very shallow angle (~ 22mrad) → effective material length O(10cm) for 2mm thick beam pipe wall!
    - With inclusion of OMD/RP support - interference of zero angle neutrals with flanges/support components!
- **This needs some major optimization (underway).**
    - **The present beampipe design was done by Alex Jentsch as a placeholder back in 2021 - we are in need of an engineer to advance the design and aid in optimization (project is aware – in progress).**

Integration with beam pipe