Detailed performance studies of SiPM-on-tile ZDC HCAL

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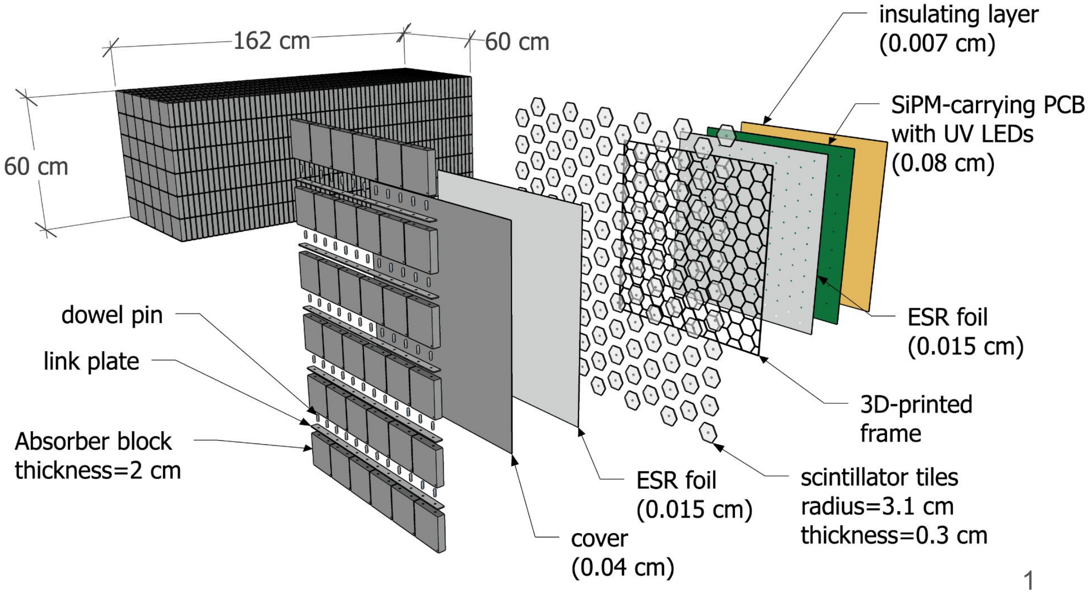
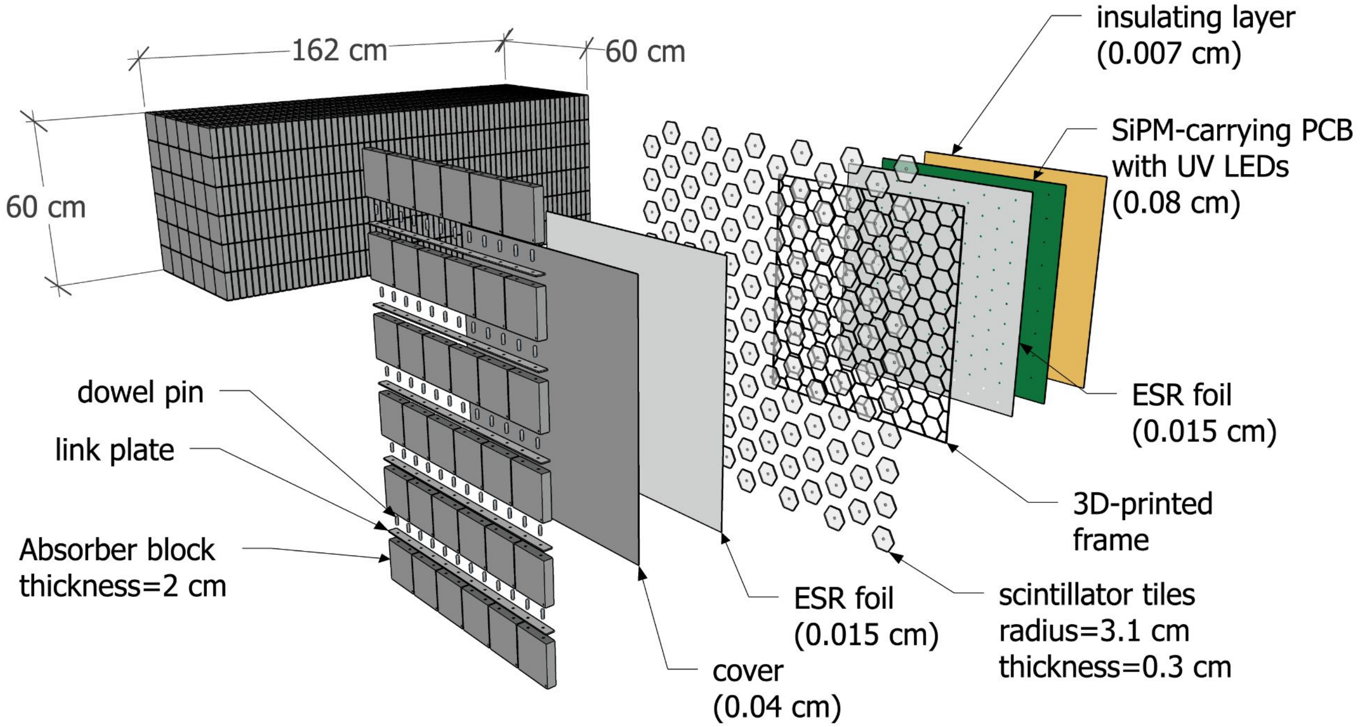


Reminder: a possible SiPM-on-tile ZDC HCAL design

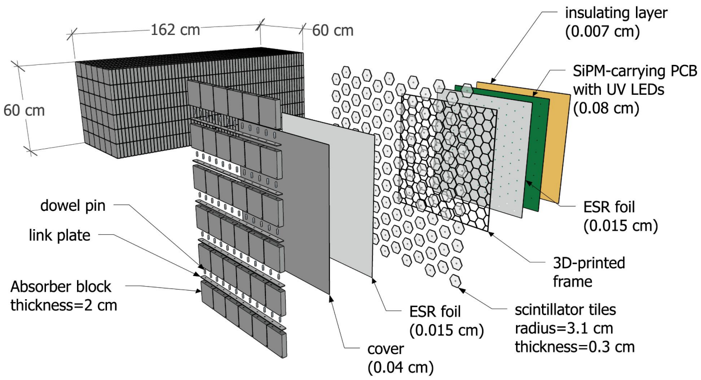
(more details in https://indico.bnl.gov/event/20029/)

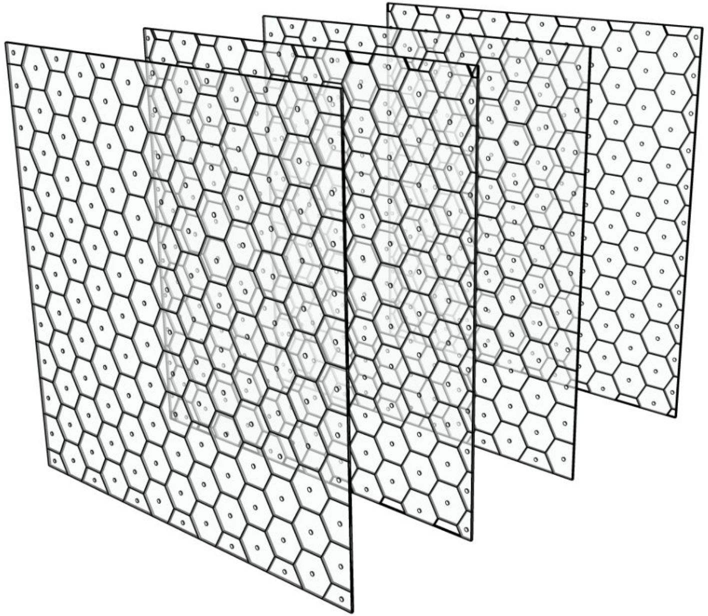


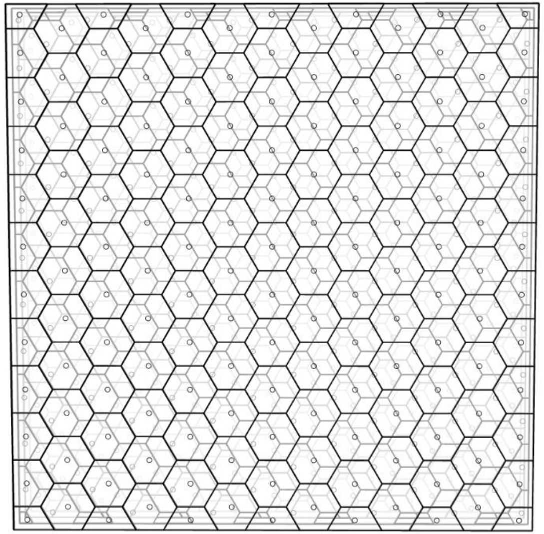
- SiPMs and bias & readout (HGROC) and scintillator cells (injection molding) relatively inexpensive.
- Could work with either Fe or Pb, but if we use Fe it could be very inexpensive by reusing STAR HCAL blocks

Staggered design

3D printed frames define layers
Identical cells are just placed in patterns







Can the SiPM-on-tile approach meet the YR requirements for ZDC HCAL?

$$\Delta E/E < 50\%/\sqrt{E}$$

$$\Delta\theta < 3\,\mathrm{mrad}/\sqrt{E}$$

ZDC simulation in DD4HEP

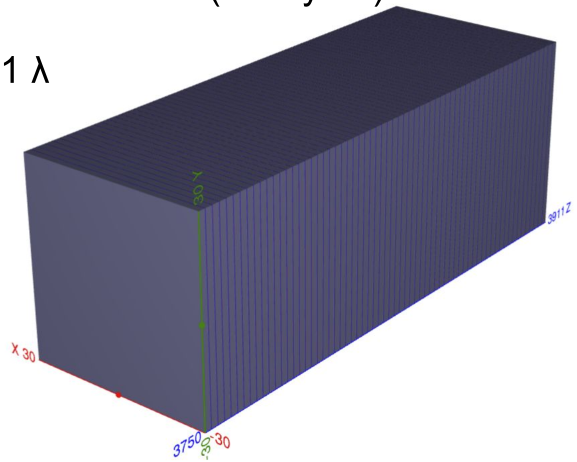
- Two geometries are simulated: Fe/Sc and another Pb/Sc.

- Same digitization and hit-level cuts as applied to HCAL Insert studies (which are based on CALICE studies: E>0.5 MIP, t<150 ns).

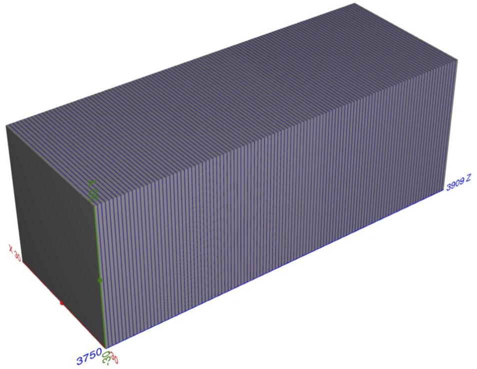
- Neutrons generated over range θ<5.5 mrad and full azimuth

Fe 20 mm/ Sc 3.0 mm (64 layers)

75 X0, 8.1 λ



Pb 10 mm/ Sc 2.5 mm (110 layers)
200 X0, 6.8 λ



ZDC simulation in DD4HEP

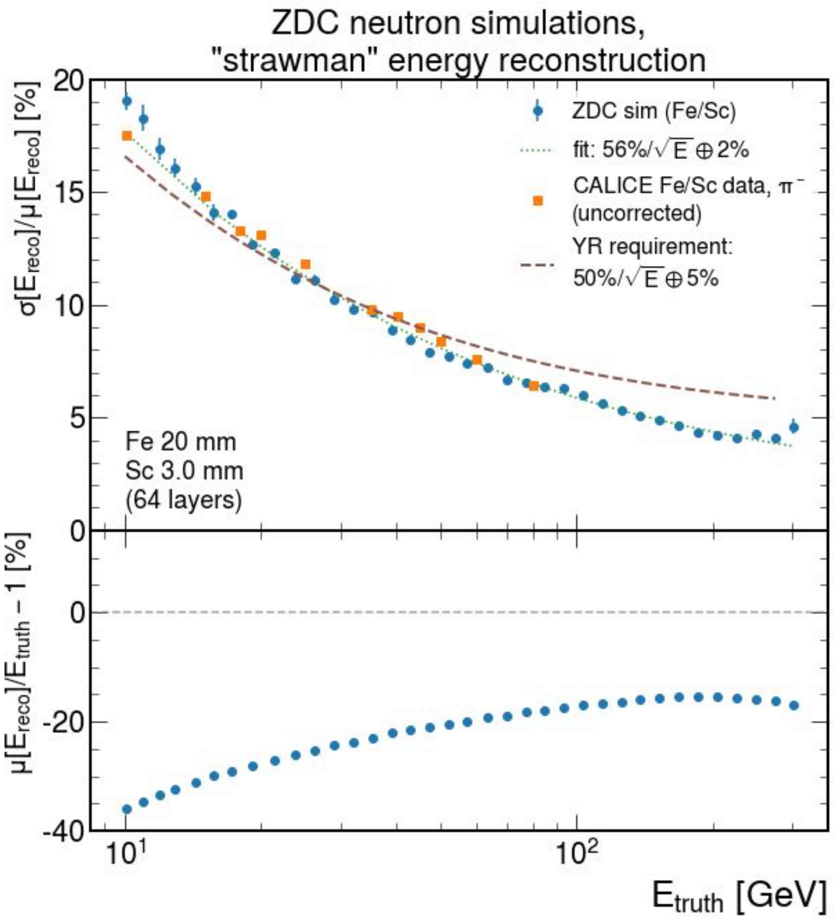
- DD4hep plugin for hexagonal segmentation and staggering in official DD4HEP core software
    - https://github.com/AIDASoft/DD4hep/pull/1161
- ZDC Fe/SiPM-on-tile is in official ePIC sim:
    - https://github.com/eic/epic/pull/534

Link to HEXPLIT example code:
https://zenodo.org/record/8245245

Fe 20 mm/ Sc 3.0 mm (64 layers)

Energy resolution

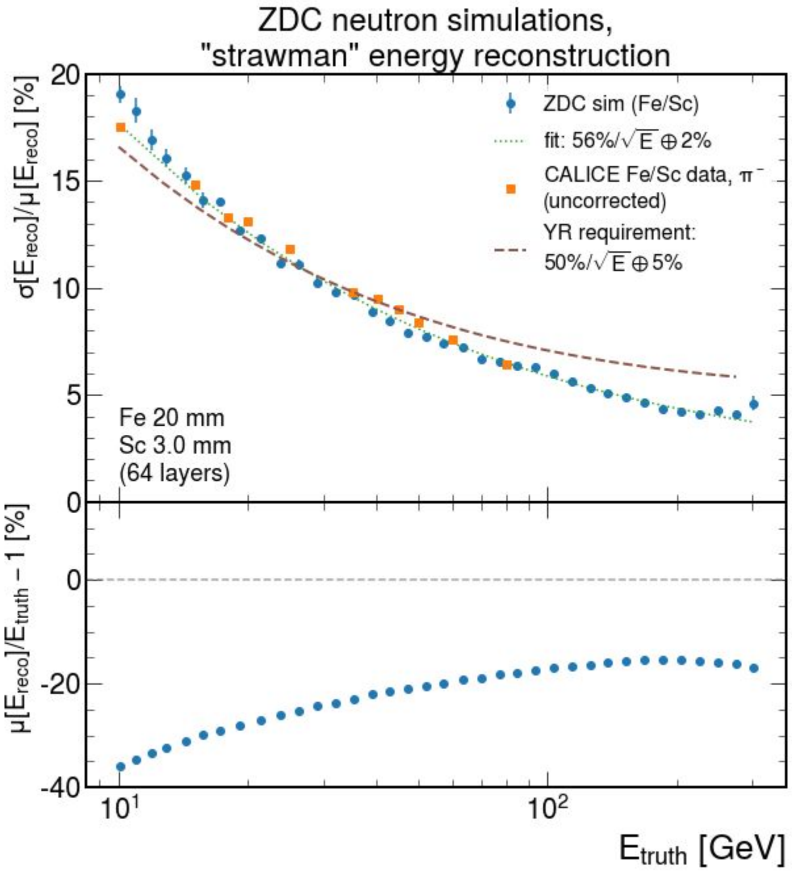
Energy resolution: Strawman reconstruction

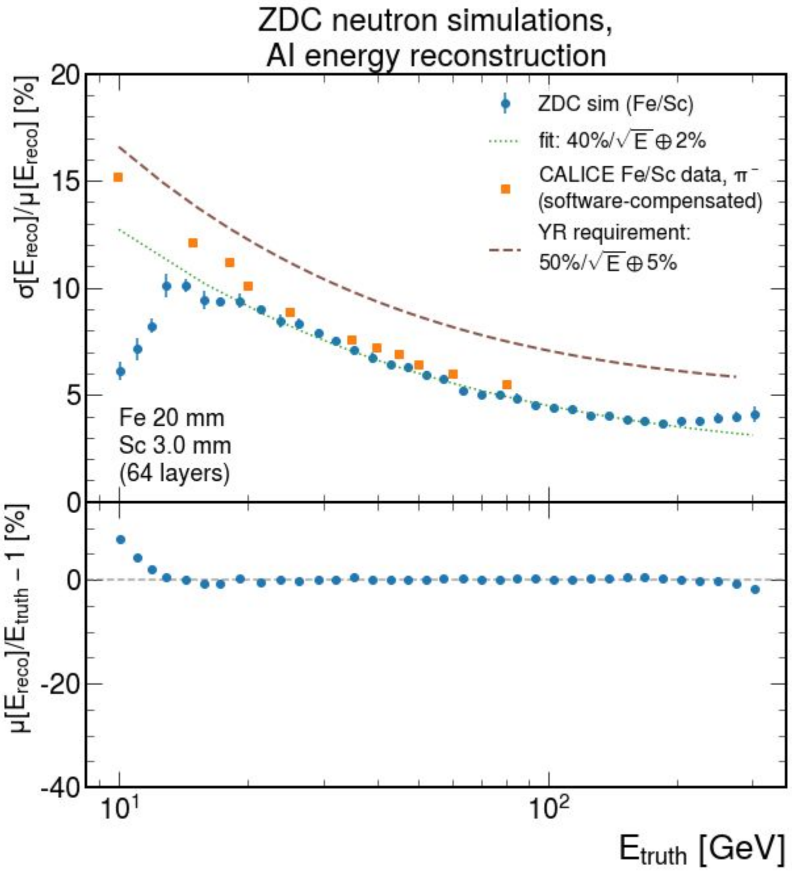


- Strawman= add all hits above 0.5 MIP, multiply by sampling fraction of electrons.
- Simulation matches CALICE AHCAL data.
- Non-compensated response, non-linear at low energies.
- Strawman approach close to YR requirement

Energy resolution: Strawman & AI (DeepSets)

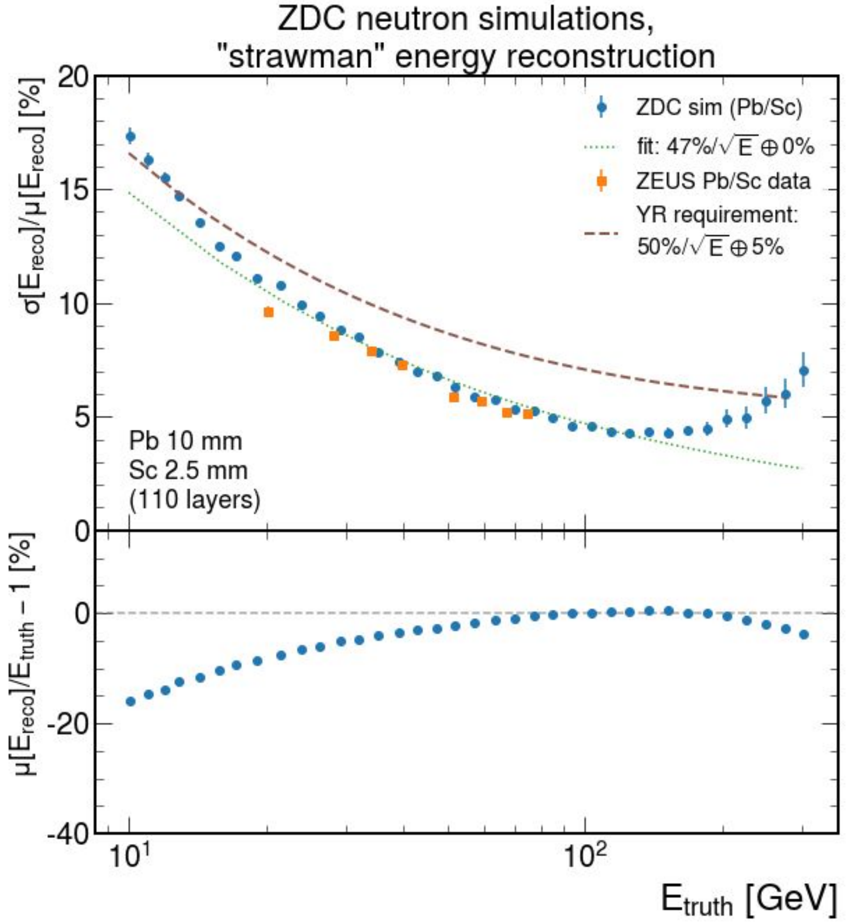
More details in Bishnu's presentation
https://indico.bnl.gov/event/19383/





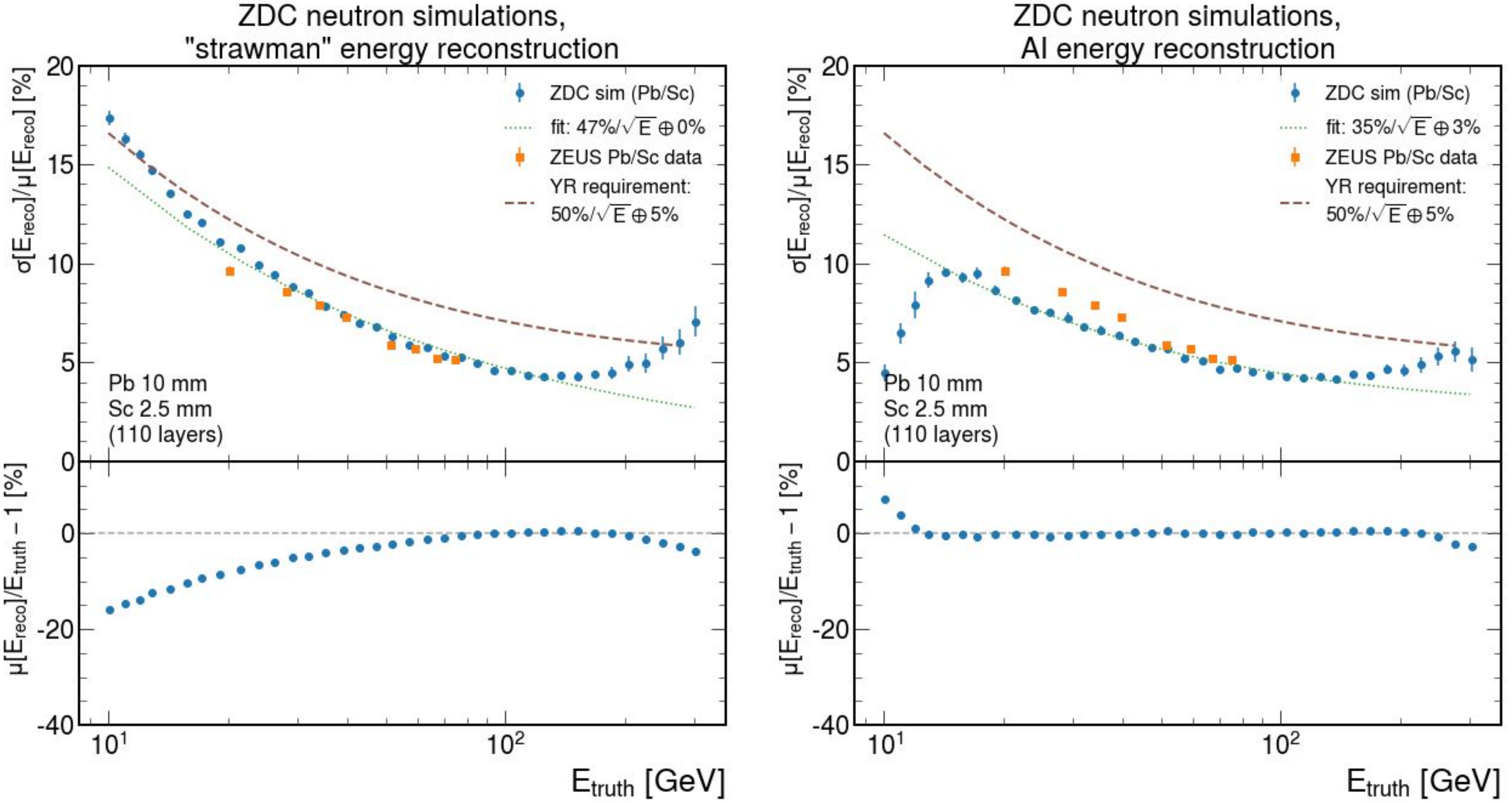
Matches YR requirement and matches CALICE

Energy resolution for Pb version:



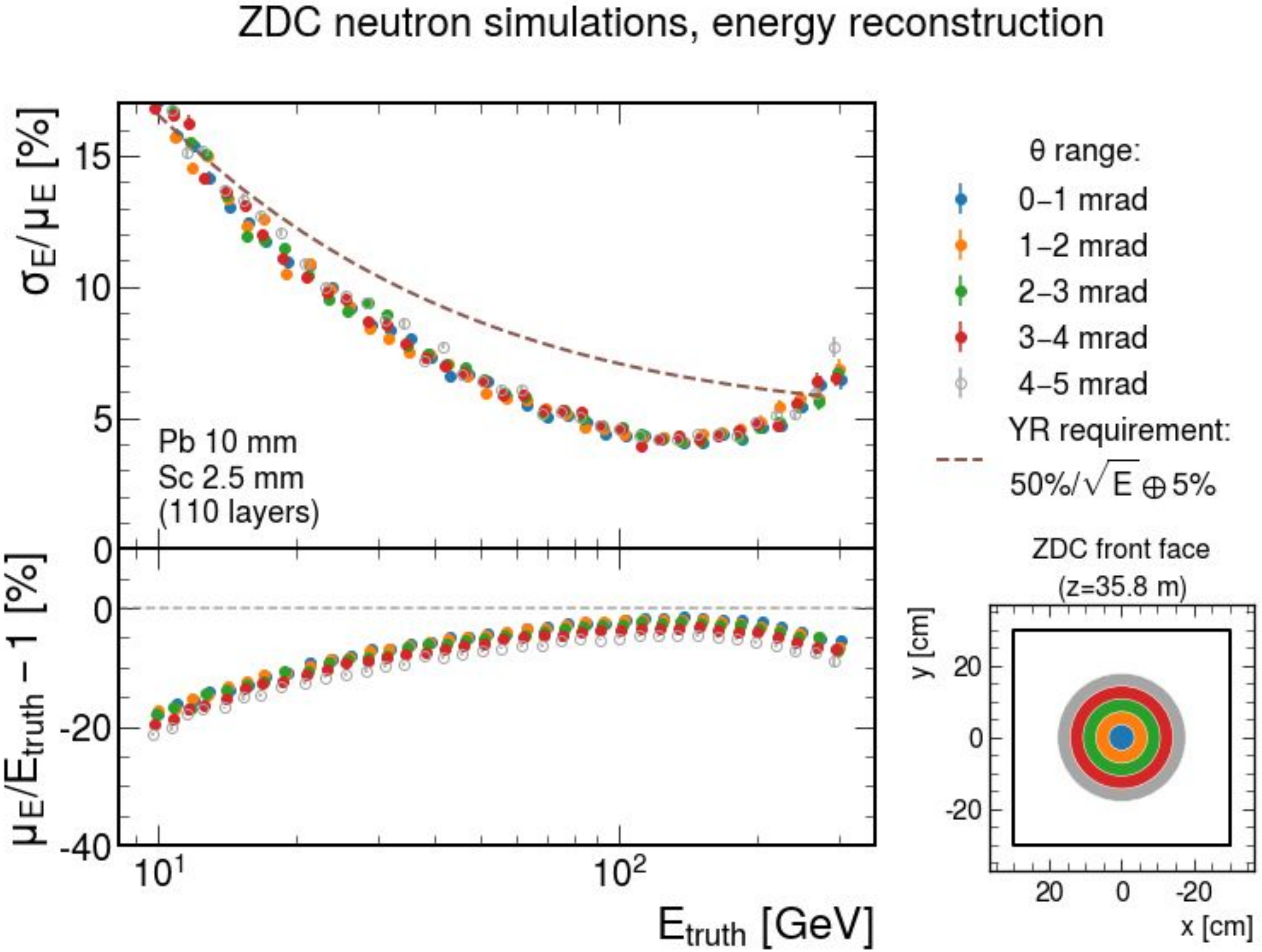
- Approximately compensating by hardware (4:1 Pb/Sc ratio)
- Consistent with ZEUS Pb/Sc prototype (thanks Alex for references and info)

Energy resolution for Pb version:

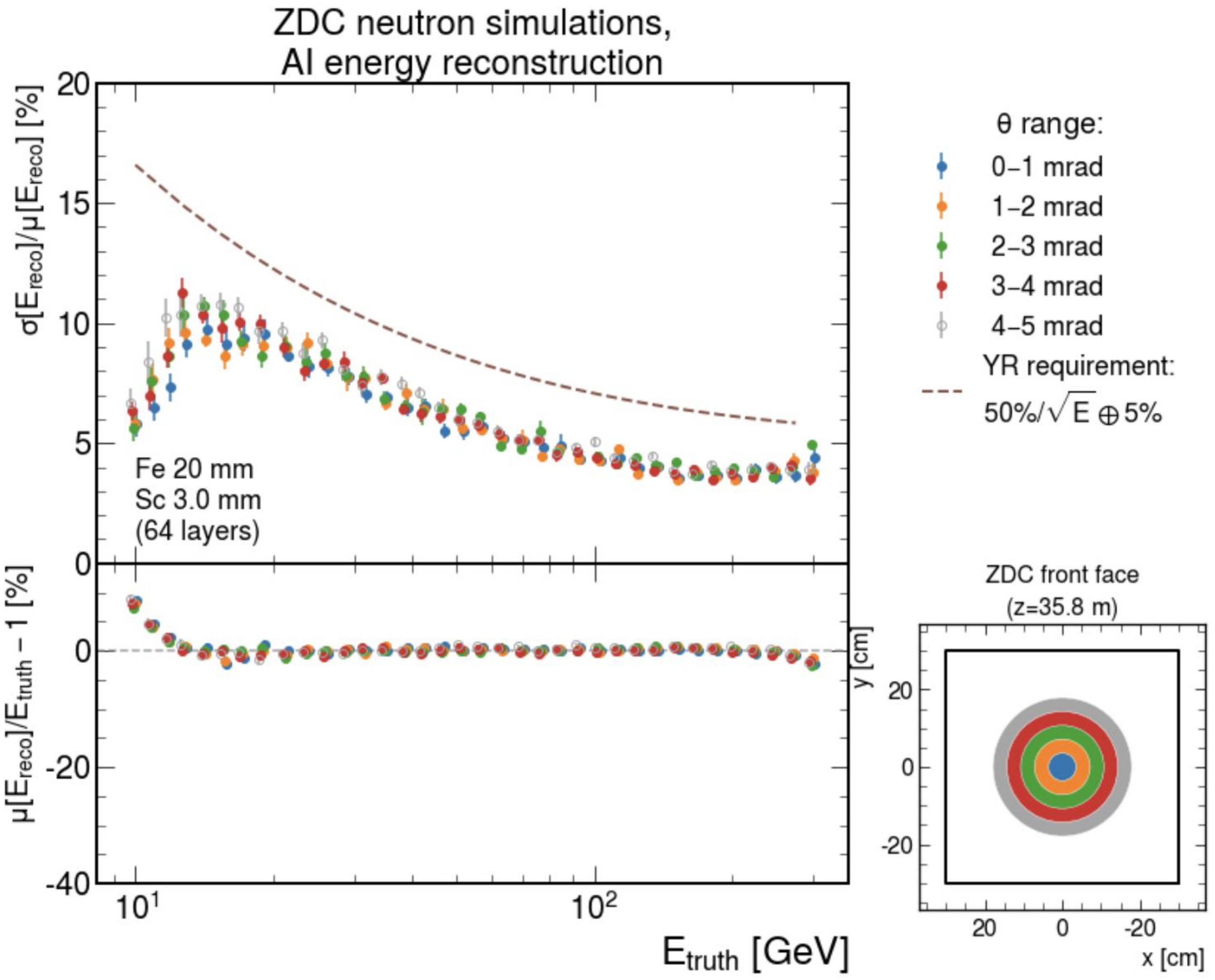


Software compensation improves resolution at low energies

Angular Dependence (practically no effect)



Same thing for AI
(no edge effect)



Energy resolution summary:

Fe version:

- 40% stochastic term after software compensation with AI.
(56% strawman)

- 2% constant term

- Strawman and software-compensated result validated with CALICE Fe/Sc data

- No edge effects within fiducial volume

Pb version:

- 35% stochastic term after software compensation with AI.
(47% strawman)

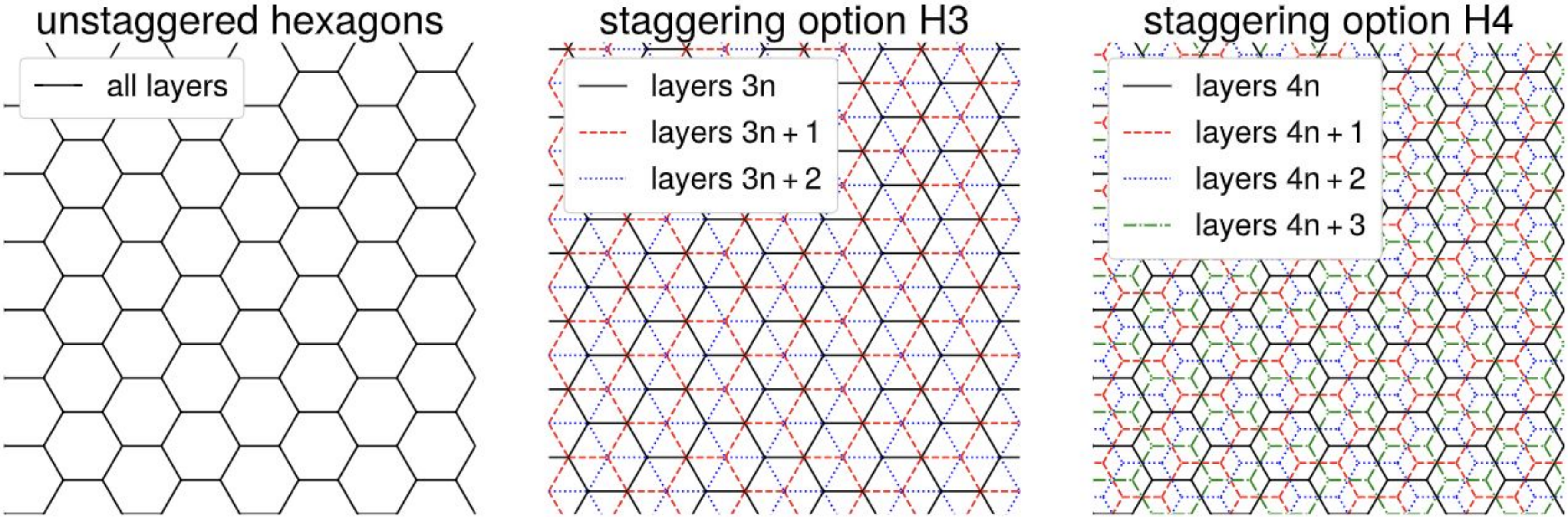
- 3% constant term

- Strawman validated with ZEUS Pb/Sc data

- No edge effects within fiducial volume

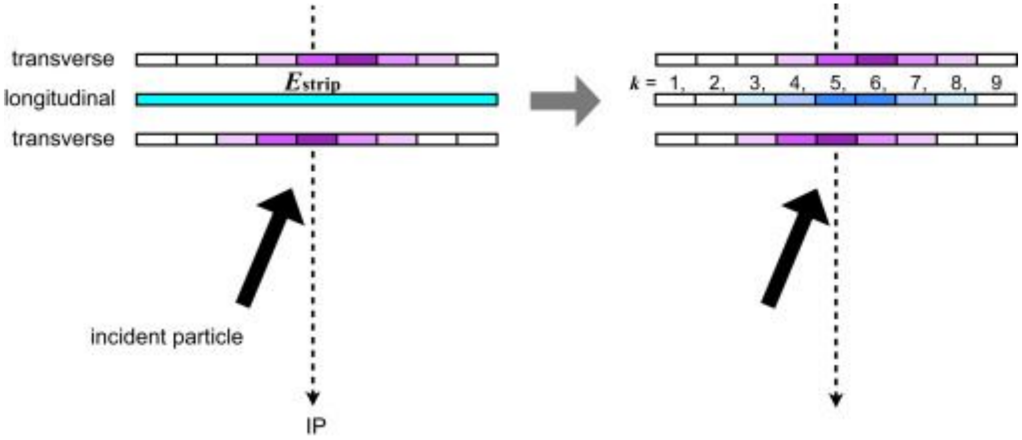
Position resolution

Position resolution improved through staggering



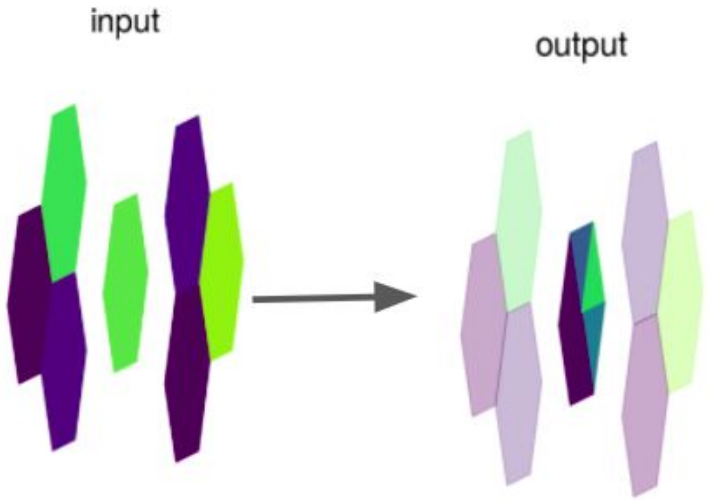
Staggering leads to partial overlap that can be used to define “subcells”. Algorithms can estimate subcell energy according to neighbour info

Strip-Split Algorithm



[Kotera et al. NIMA 789 (2015) 158-164,](#)

HEXPLIT Algorithm



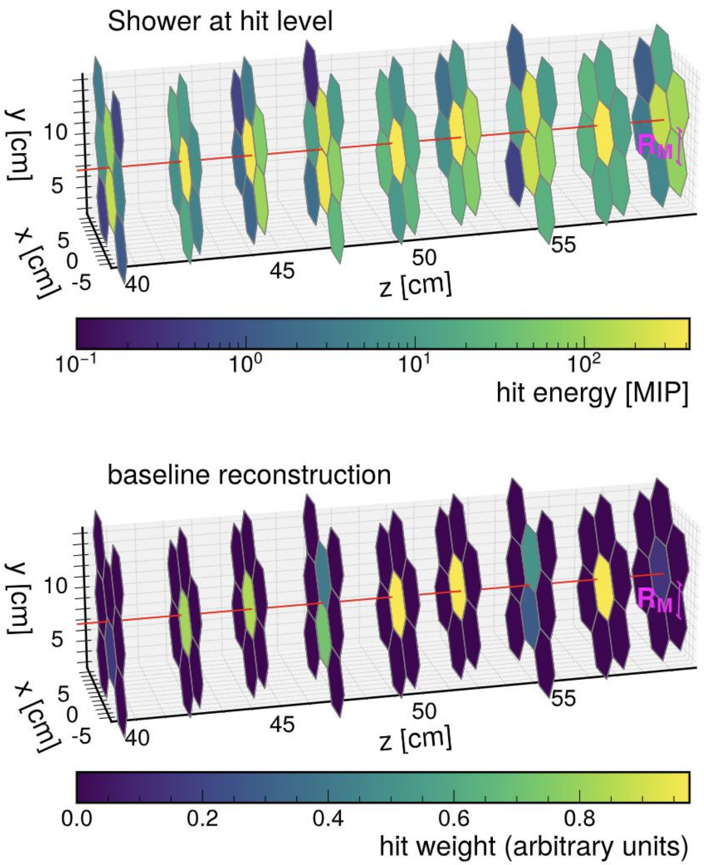
[S. Paul, M. Arratia arXiv:2308.06939](#)

Baseline shower-position reconstruction

$$\vec{x}_{\text{recon}} = \frac{\sum_{i \in \text{hits}} \vec{x}_i w_i}{\sum_{i \in \text{hits}} w_i}$$

$$w_i = \max\left(0, w_0 + \ln \frac{E_i}{E_{\text{tot}}}\right)$$

Core Portion of Neutron Shower



The HEXPLIT algorithm

arXiv:2308.06939

Subcell reweighting

$$W_i = \prod_{j=1}^{N-1} \max(E_j, \delta),$$

Product over overlapping cells, *j*, in neighboring layers

$$E_i = E_{\text{tile}} W_i / \sum_j W_j .$$

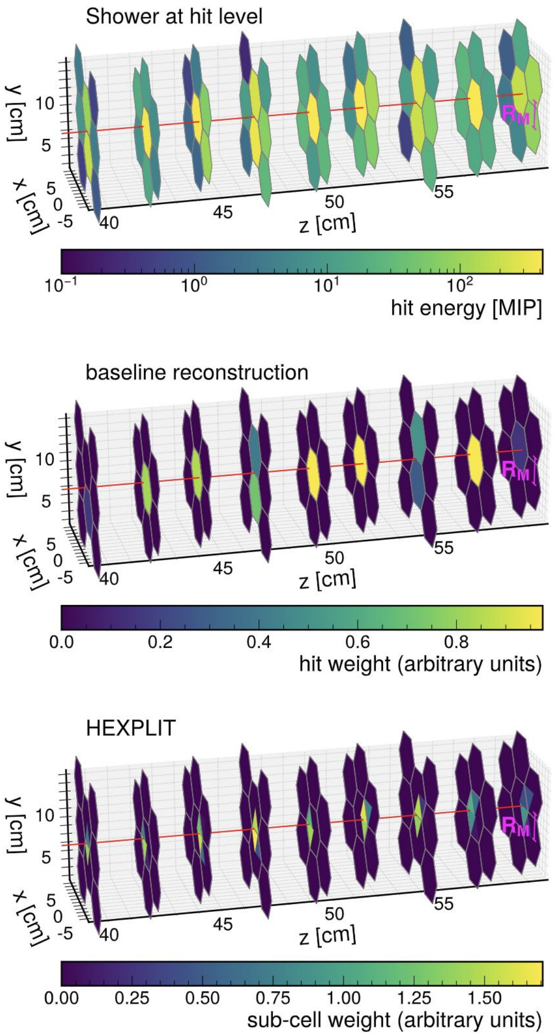
Energy in a given subcell, *i*

Reconstruct shower from subcells

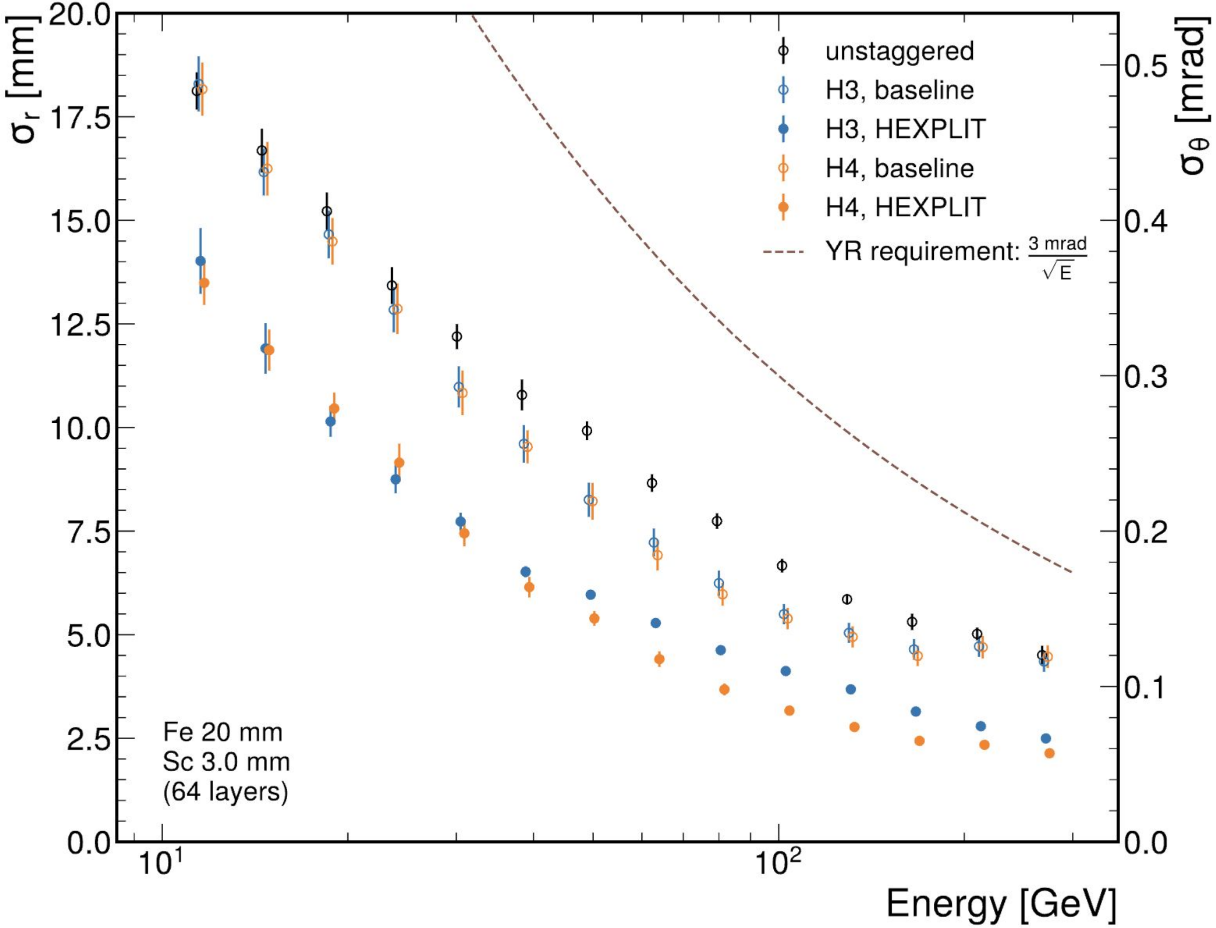
$$\vec{x}_{\text{recon}} = \frac{\sum_{i \in \text{subcells}} \vec{x}_i w_i}{\sum_{i \in \text{subcells}} w_i}$$

$$w_i = \max\left(0, w_0 + \ln \frac{E_i}{E_{\text{tot}}}\right)$$

Core Portion of Neutron Shower



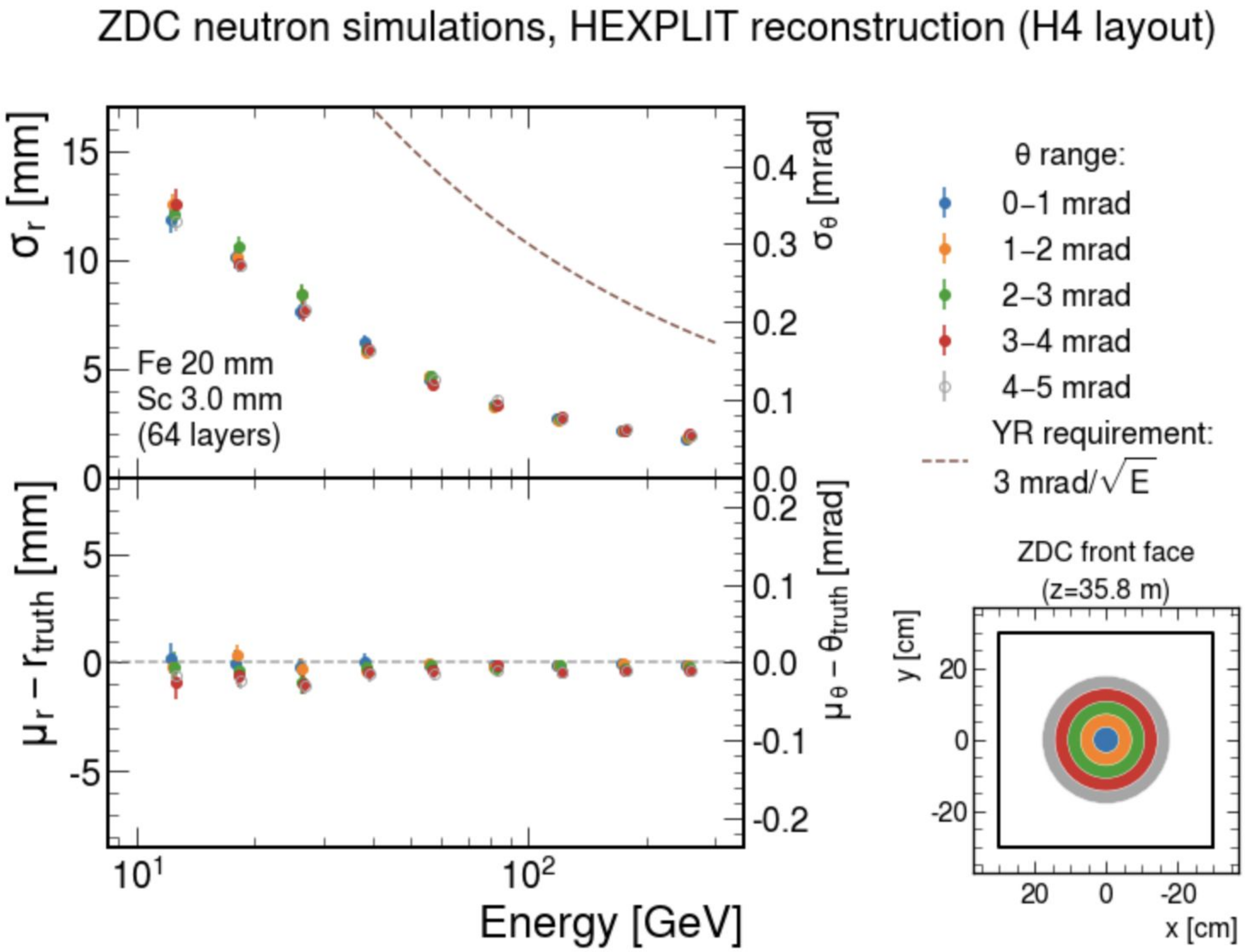
ZDC Neutron position resolution



- Design meets YR requirements with ~25 cm2 cell size, (can be tuned to optimize granularity)
- Meets even ambitious goals relevant for pion structure studies

Edge effects

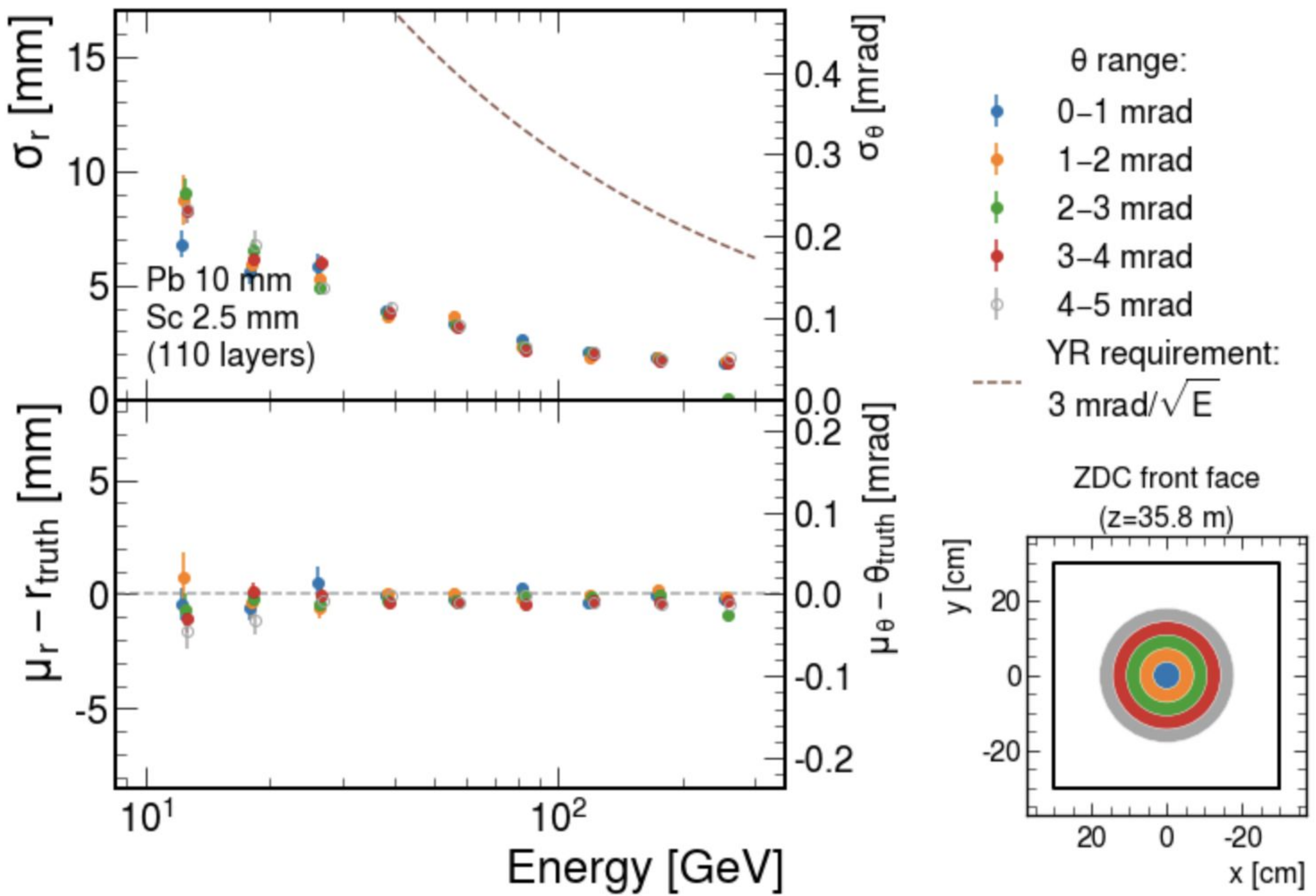
- Fiducial region (colored) far enough away from edge that edge effects are negligible



ZDC neutron simulations, HEXPLIT reconstruction (H4 layout)

Pb version

Even better Resolution (more layers & more hits due to more neutrons)



Position resolution summary:

Fe version:

- Easily meets YR requirements, even more ambitious goals
~3 mm at 100 GeV

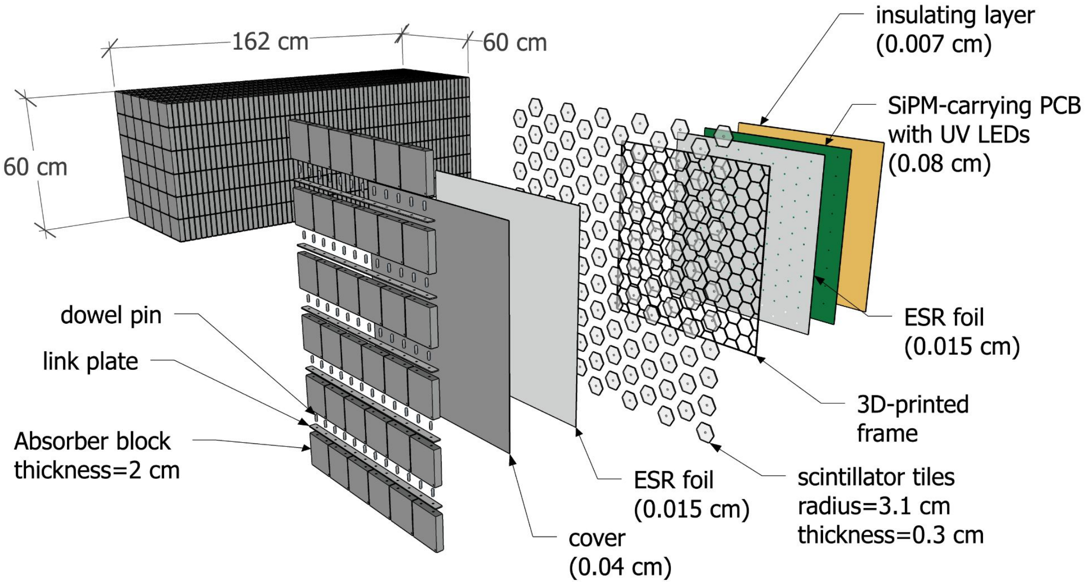
- No edge effects within fiducial volume

Pb version:

- Easily meets YR requirements, even more ambitious goals.
~ 2 mm at 100 GeV

- No edge effects within fiducial volume

Recipe for Fe/SiPM-on-tile option



Blocks: 2304 units of 10x10x2 cm3

Cost: 0$ (reused from STAR)

SiPMs: ~7.5k units of 1.3 mm size.

Cost: ~7$/unit

Tile: ~7.5k units of ~25 cm2 size.

Cost: ~2$/unit

(injection molding)

Readout & bias: 100 HGROCs

Cost: ~1$/channel

Materials summary:

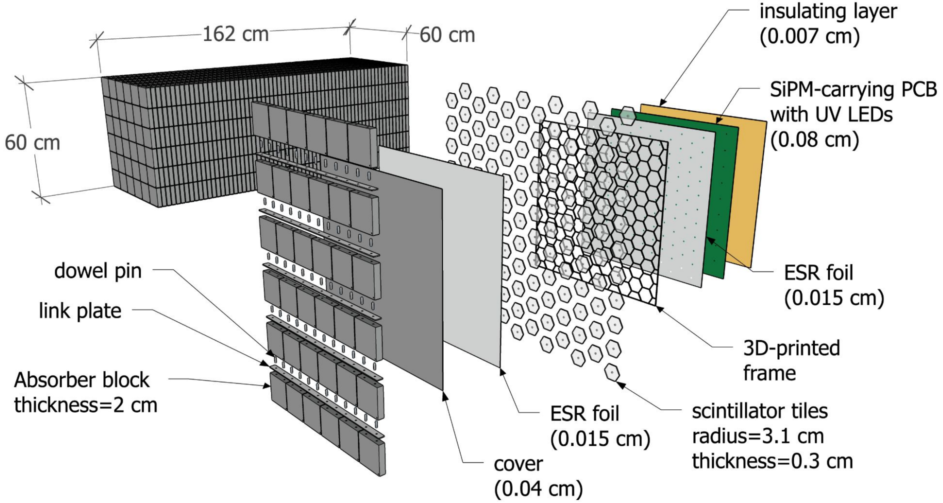
Fe version:

- 64 layers, ~7.5k channels
- SiPM+ tile + readout & bias
  ~ 10$/channel
- Blocks reused from STAR

Pb version:

- 110 layers, ~13k channels
- SiPM+ tile + readout & bias
  ~ 10$/channel
- Pb cost TBD

Summary



- SiPM-on-tile is an attractive option for ZDC HCAL, as it would bring multiple benefits of piggybacking on forward HCAL

- Energy and position studies completed with Fe and Pb options. Both easily meet YR requirements over entire fiducial region.

- Performance alone slightly favours Pb option, but Fe winning card is the option of STAR HCAL reuse and straightforward construction.

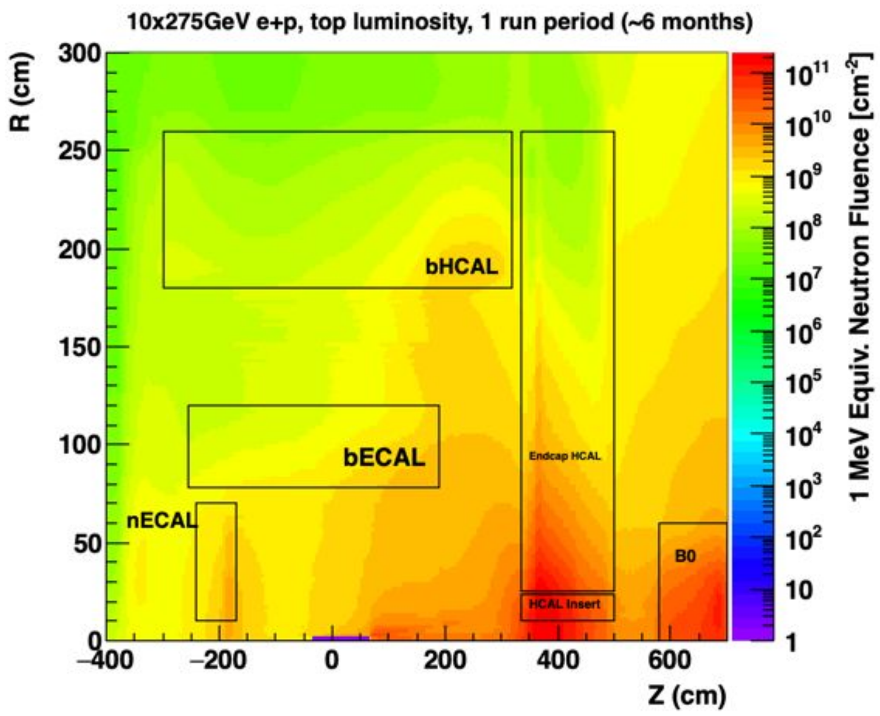
Next steps on simulations

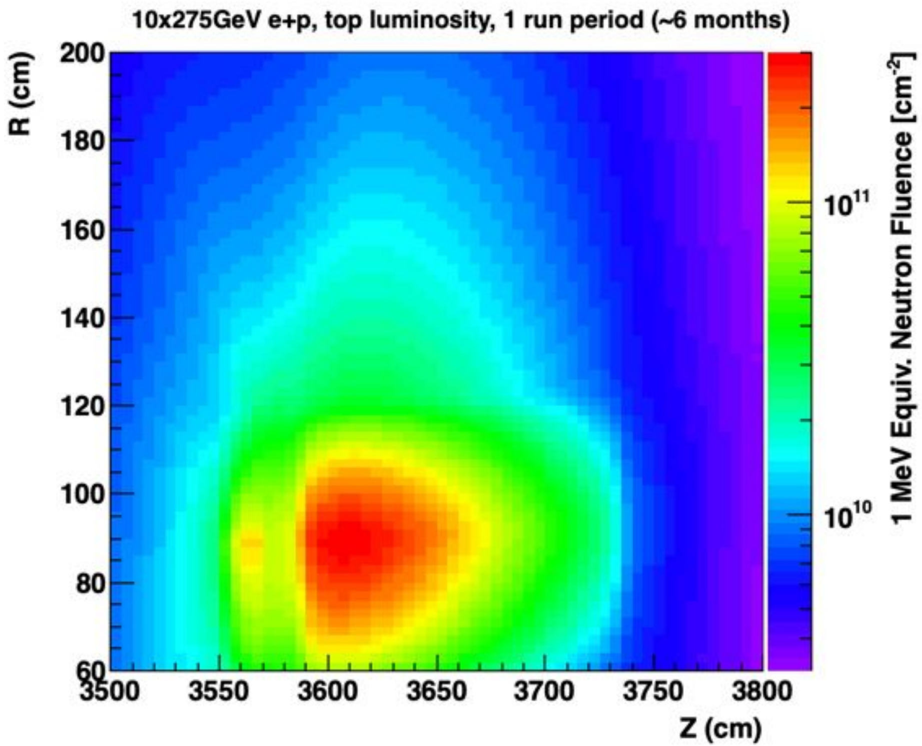
- **Done:** ZDC Fe/Sc HCAL is in DD4HEP
- **Ongoing:** Strawman reconstruction + HEXPLIT is in ePIC software
- **Ongoing**: AI reconstruction is in ePIC software
- **Planned:** Position and transverse area refined to match “final” numbers.
- **Planned:** Cell size studies in simulation (and lab)

backup

Neutron flux in Insert region is similar to that of ZDC

https://wiki.bnl.gov/EPIC/index.php?title=Radiation_Doses





Mitigation strategies discussed for Insert could be used in ZDC