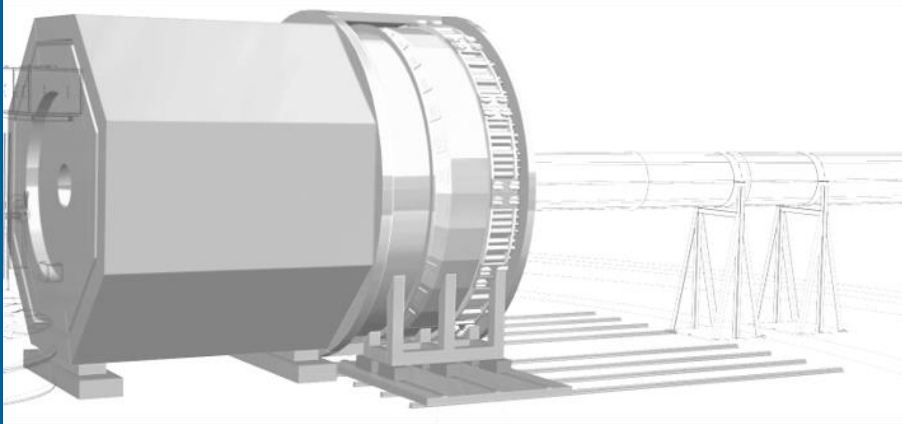
Imaging Calorimetry



CHAO PENG
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ANL EIC Calorimetry Team
W. Armstrong, S. Joosten, J. Kim, J. Metcalfe, Z.E. Meziani, C. Peng, M. Żurek

06/10/2021

Imaging calorimeter based on monolithic silicon sensors

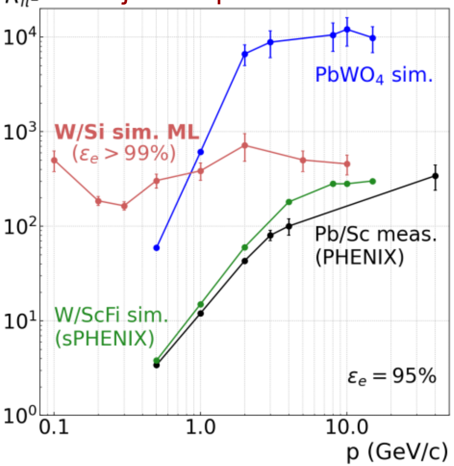
AstroPix (developed for NASA, off-the-shelf)

- Have no stringent power and cooling requirements (used in space)
- Energy resolution: 2% within dynamic range (20 keV ~ a few MeV)
- Time resolution: 50 ns

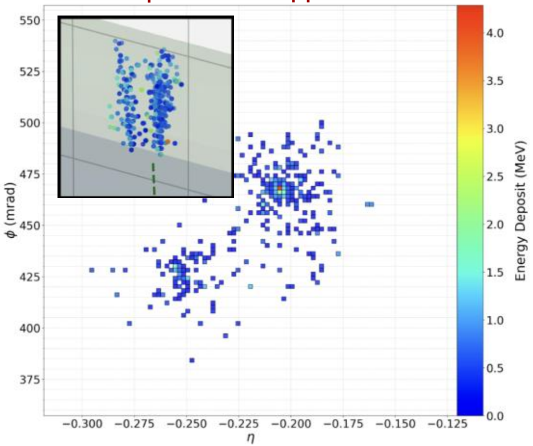
Ongoing design optimization using the simulation with IP6@EIC software framework with **AstroPix digitization, 3D clustering, ML algorithms,** …

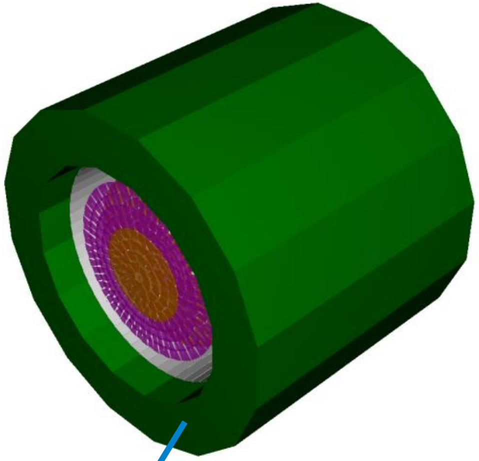
Tests against YR benchmarks: separation, shower separation, spatial and energy resolutions

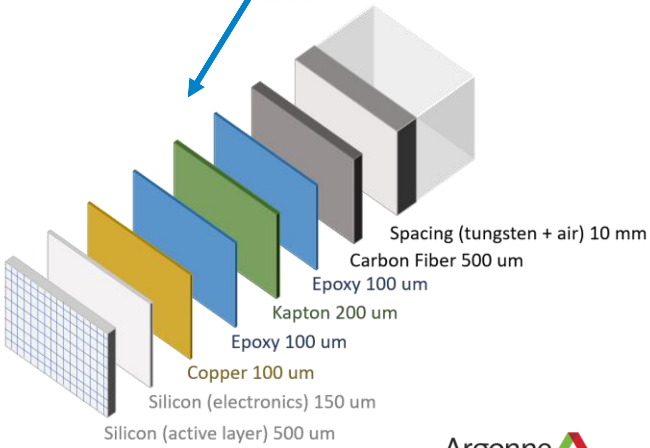
Rejection power for e/π



Example of $\pi^0 \to \gamma\gamma$ at 5 GeV

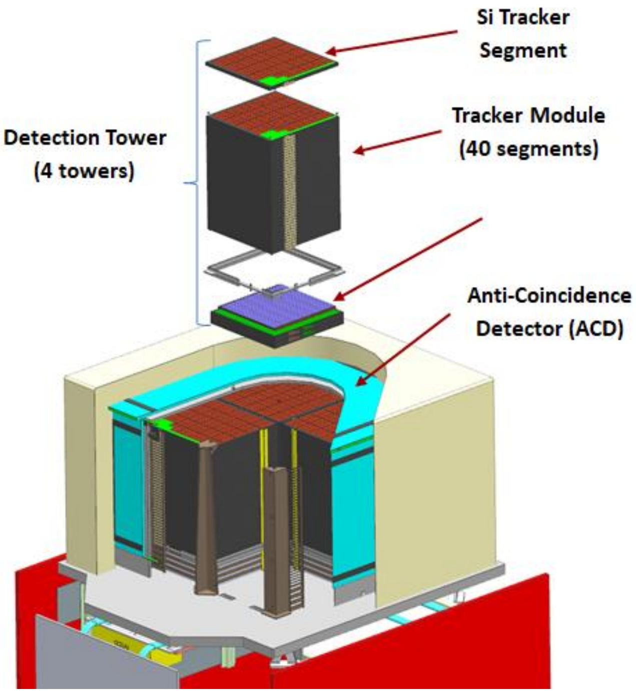


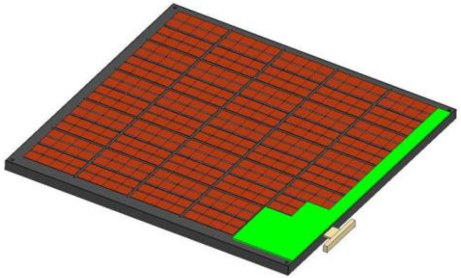




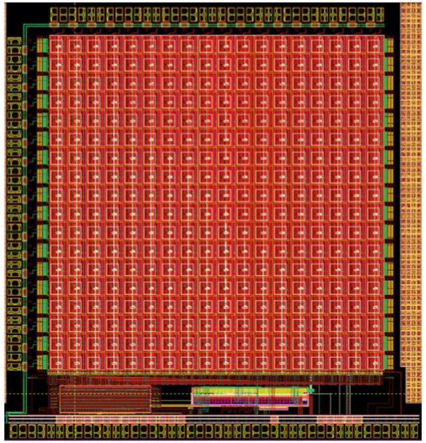
AstroPix

Ongoing Development by AMEGO-X collaboration
Descendant of AtlasPix
AstroPix_v2 beging designed, AstroPix_v3 funded





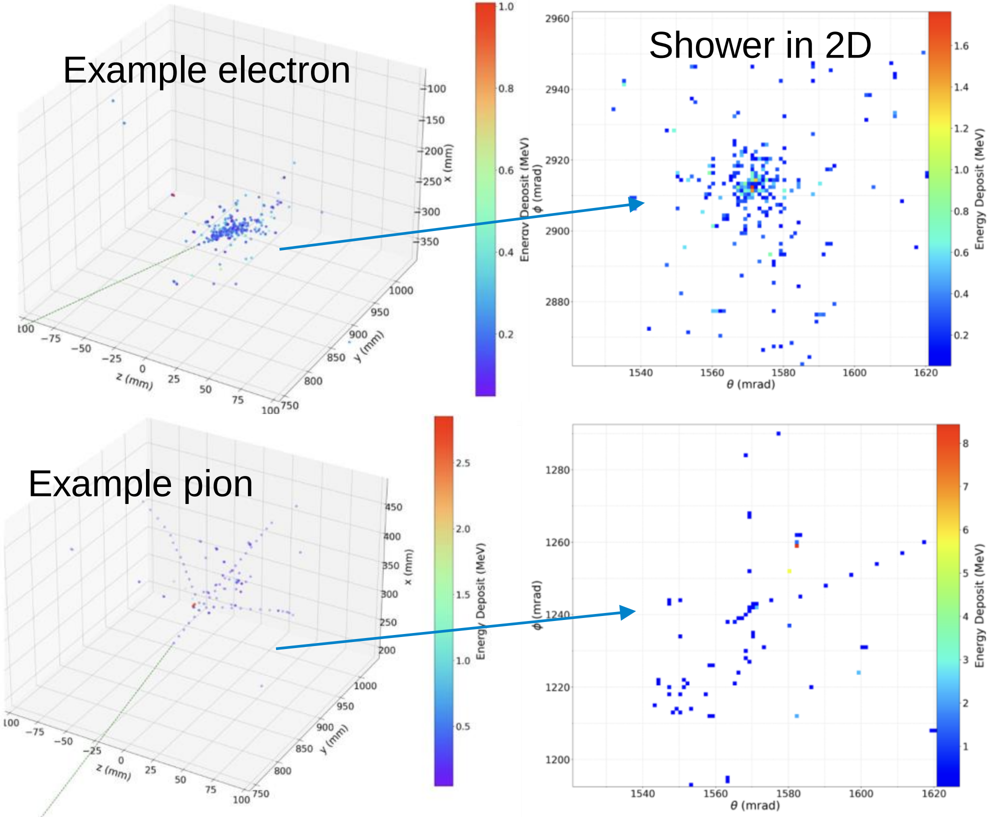
AMEGO-X Tracker Segment with 95 Quad Chips



4.5 x 4.5 mm^2 sensor
100 um thick
200 x 200 um^2 pixels

Electron/Pion separation

Shower profile analysis



ML Classification

Utilize hit information from every layer (3D)

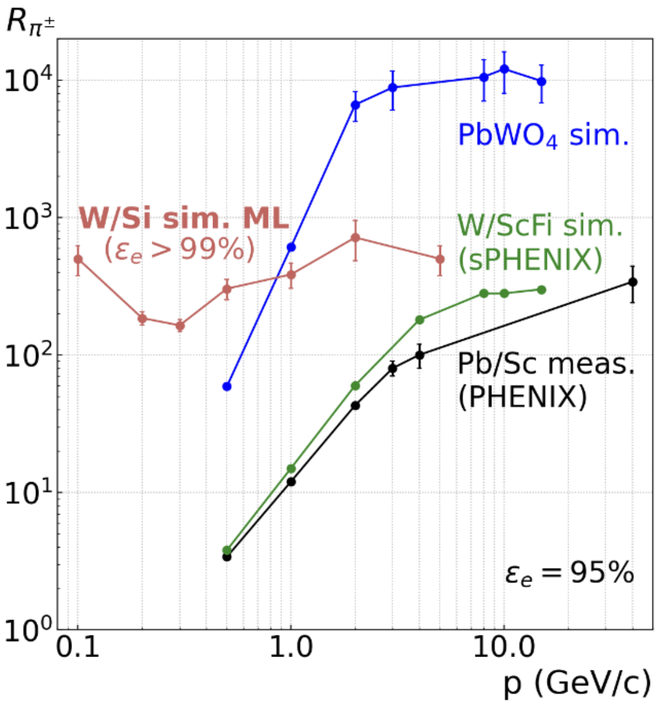
$20 \times 20 \times 3$

Layers Hits Features (E, η, ϕ)

- Grid size for hits is [η:0.001, ϕ:0.001rad]
  - Raw hits grouped if within the same grid (energy sum)
- Sorted by energy
  - Drop lowest energies ones if there were more than 20 hits
  - Feature values normalized to [0, 1]
- Padded with zero
  - Fill (0,0,0) if less than 20 hits

Electron/Pion separation

Shower profile analysis



ML Classification

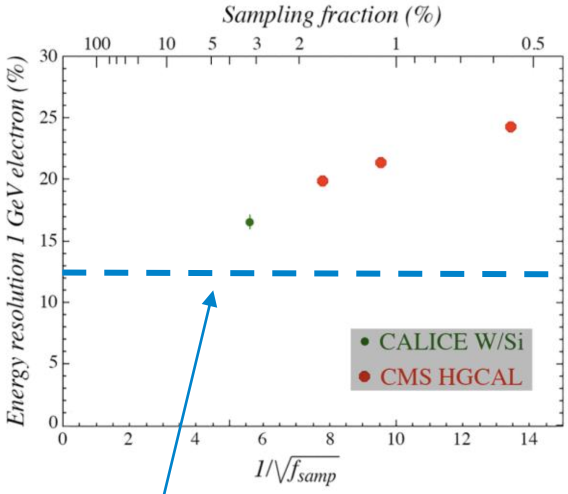
- Convolutional Neural Network (CNN) + Multi-Layer Perceptron (MLP)
  - Implemented with tensorflow
- Trained with 100k events
  - Mixture of electrons and pions
- Test results are shown
  - 100k electrons
  - 100k pions
  - Statistical uncertainty (binary distribution) is shown

Energy Resolution for Si Calorimetry

$$\sigma / E = \alpha \oplus \beta / \sqrt{E} \oplus \gamma / E$$

- **Pathlength fluctuations** - important contribution to sampling fluctuations for scintillators with thin layers
- **Soft electrons** are an important component of the developing EM showers
- For **500 µm Si** the signal from shower electrons with energies larger than **330 keV** produced in Compton scattering or photoelectric effect **depends on the angle at which they traverse an active layer**
- **The larger the angle** with the shower axis, **the larger the contribution** of these particles to the signal

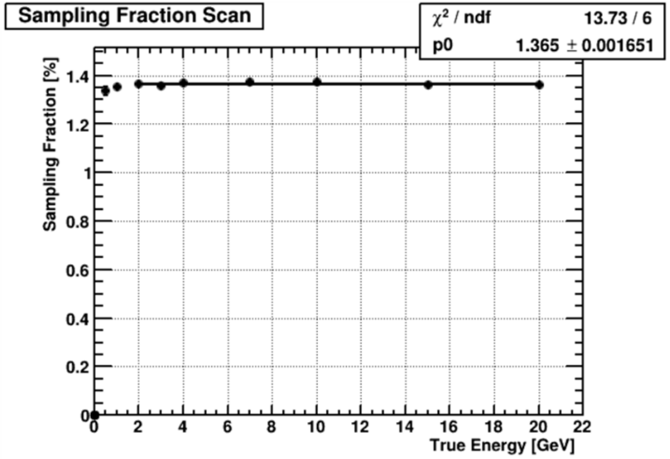
New Developments in Calorimetric Particle Detection, R. Wigmans, https://arxiv.org/abs/1807.03853



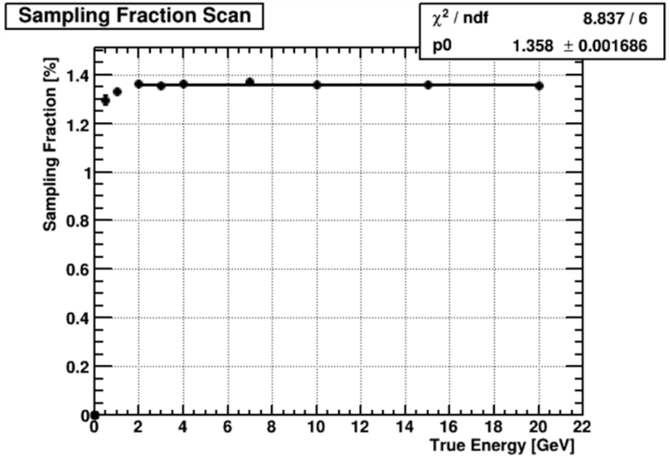
~12% from the $0.027\sqrt{(d/f_{sam})}$ dependence

Sampling Fraction and Energy Resolution

20 layers with 4 mm tungsten (~ 20 X_0)



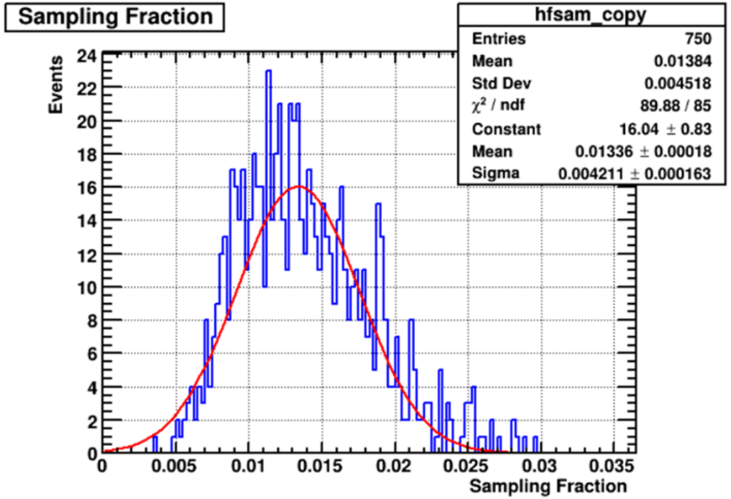
Electrons

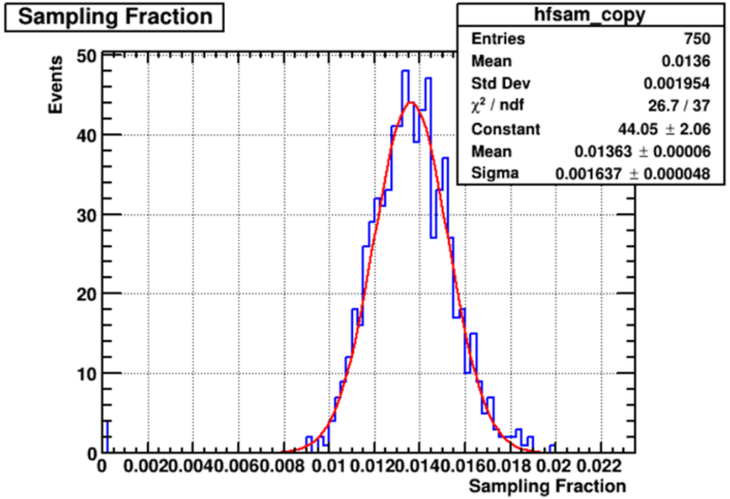


Photons

Sampling Fraction and Energy Resolution

20 layers with 4 mm tungsten (~ 20 X_0)

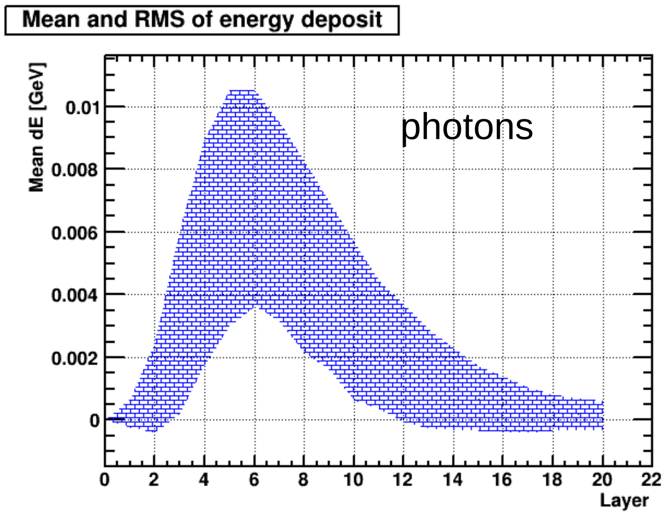


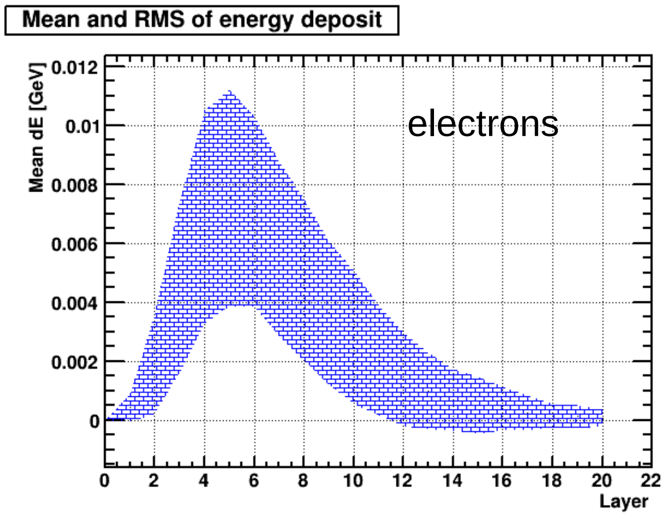


Electrons: Energy deposit for 0.5 GeV and 5 GeV electrons

Sampling Fraction and Energy Resolution

20 layers with 4 mm tungsten (~ 20 X_0)



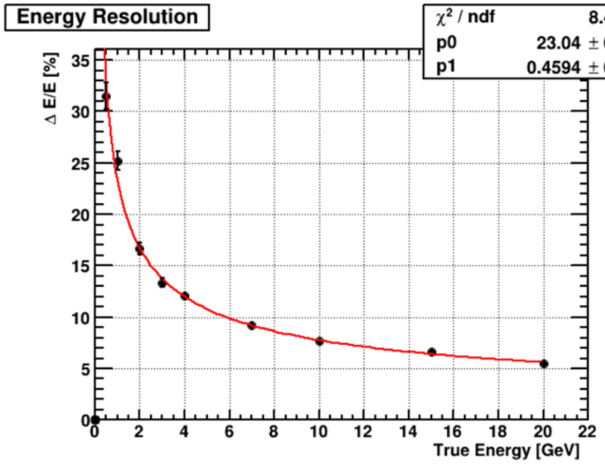


4 GeV photons (left) electrons (right) energy loss in active layers

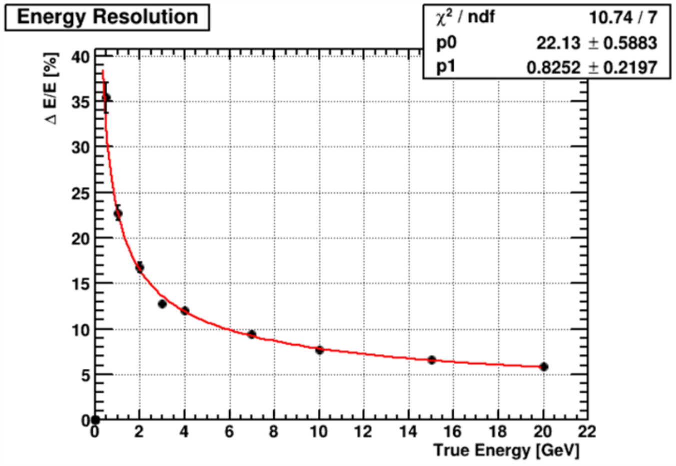
Sampling Fraction and Energy Resolution

20 layers with 4 mm tungsten

$$\sigma_E/E = 23.04/\sqrt{E} \oplus 0.46\,\%$$



Electrons

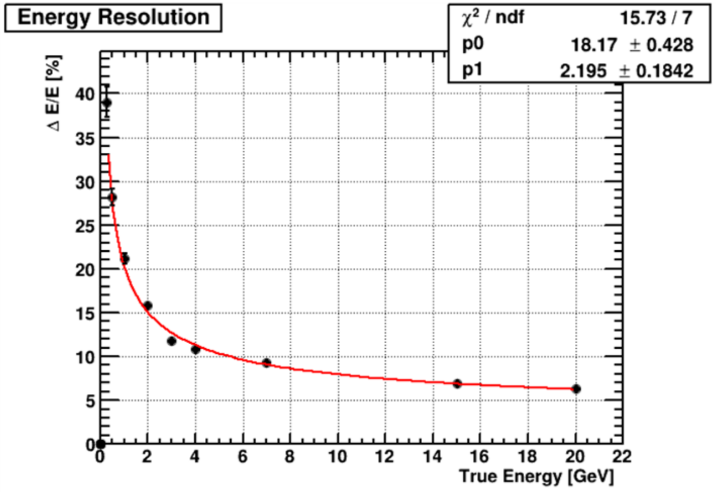


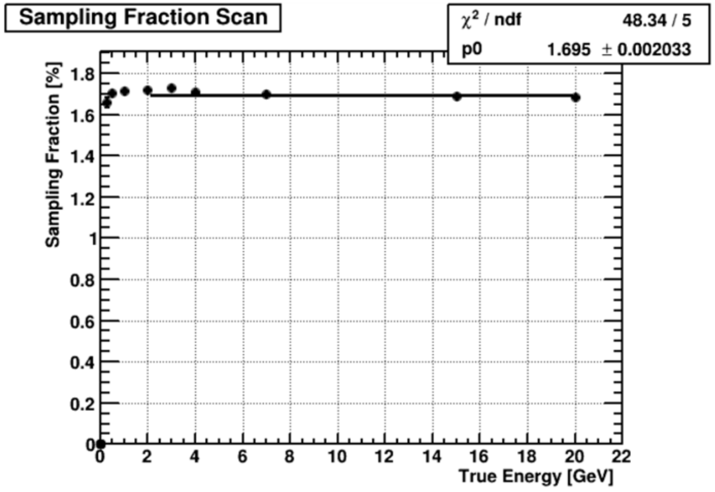
Photons

Sampling Fraction and Energy Resolution

20 layers with 3 mm tungsten (~ 17.5 X0)

$$\sigma_E/E = 18.17/\sqrt{E} \oplus 2.20\,\%$$





Hybrid Calorimeter (ImagingCal + Ecal)

Use ScFi/W layers instead of W layers

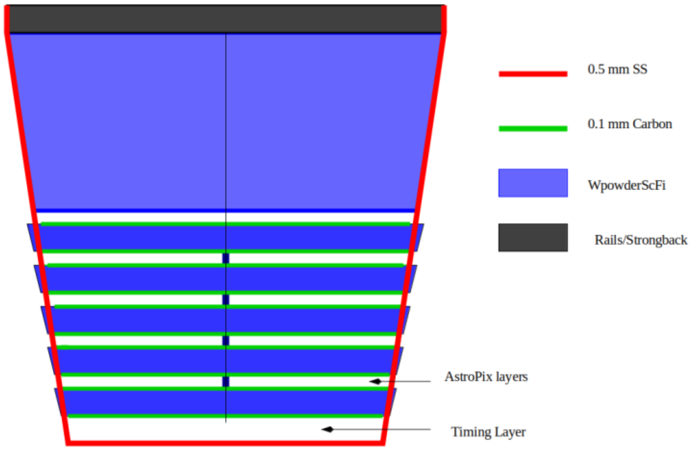
05/27/21 Concept for BEcal ATHENA. O.Tsai

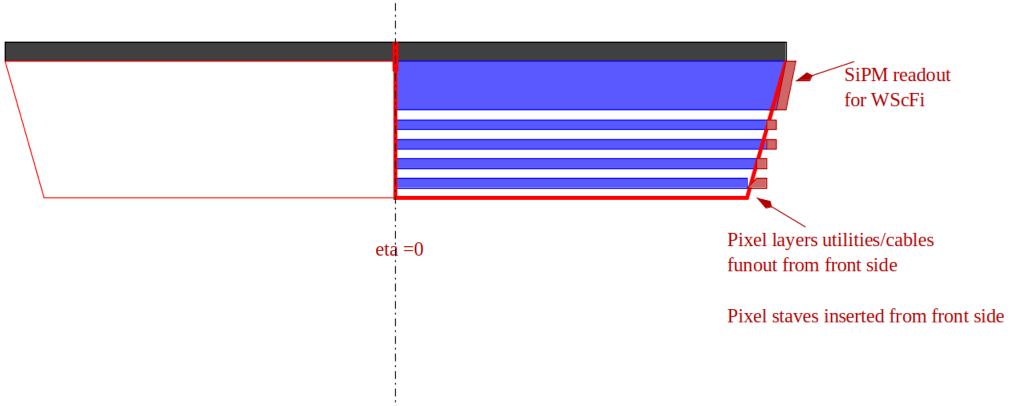
- Replace solid tungsten layers with W-powder/ScFi ‘active’ layers – that will allow to tune energy resolution to desired value by choosing sampling fraction/frequency

- Technology vise making encapsulated W/ScFi with carbon skin should be very easy
- Thickness of WScFi layers can be as desired, i.e. may be thicker than $1X_0$
- Outer shell 0.5 mm SS, W/ScFi layers glued to shell creating compartments for sensor layers
- Sensor layers inserted from front side
- SiPM readout on the front side, cables utilities from sensor layers fanout from front side
- Support structure similar to STAR/sPHENIX, i.e. rails/bearings
- EM Modules inserted into solenoid from both sides. (like it was done in STAR barrel ecal)
- Number of pixels layers, thickness of WScFi layers had to be optimized
- Granularity in W/ScFi readout has to be optimized (phi and X/Y)

SiFi/W Calorimeter

Alternative to use instead of W layers





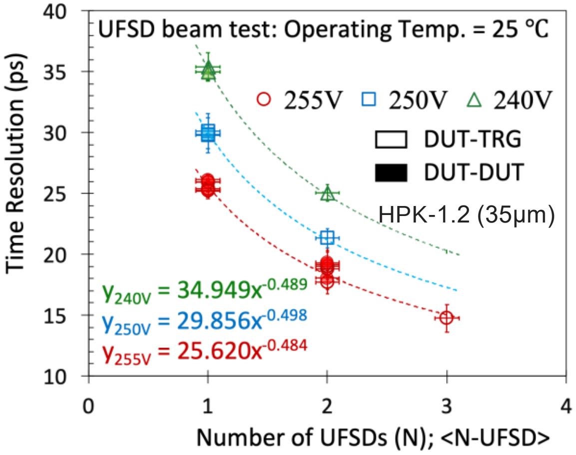
Ultra-fast Silicon Sensors (LGAD)

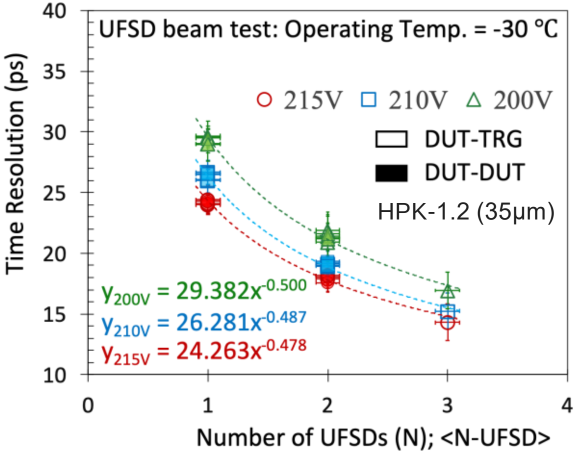
Timing Layer for Imaging Cal

- LGAD (Low Gain Avalanche Diodes) Consortium: ANL, BNL, and UC Santa Cruz
- Achieved timing resolution of **25 ps** from recent beam test at Fermilab

  M. Jadhav *et al.*, Arxiv:2010.02499

- Implementing a timing layer in EIC simulation, and reconstruction with trackers input





sPHENIX SiFi/W Calorimeter

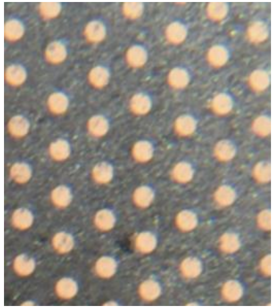
sPHENIX Calorimeter Parameters https://arxiv.org/pdf/1704.01461.pdf

Scintillating Fiber (Kuraray SCSF78) Diameter **0.47 mm**, spacing **1 mm** http://kuraraypsf.jp/psf/sf.html
Absorber Matrix of Tungsten powder and epoxy w/embedded scintillating fibers

- Whole SPACAL block ~10 g/cm^3
  (~ half density of metallic tungsten)
- Tungsten powder: **11.25 g/cm^3**
- Sampling fraction for EM-showers ~ 2.3%
- Radiation length **X_0 ≈ 0.7-0.8 cm**
- **Energy resolution ~12%/$\sqrt{E}$**

TABLE I
EMCAL BLOCK COMPONENT MATERIALS

Material	Property	Value
Tungsten powder	THP Technon 100 mesh	
	particle size	25-150 μm
	bulk density (solid)	$\geq$ 18.50 g/cm^3
	tap density (powder)	$\geq$ 11.25 g/cm^3
	purity	$\geq$ 95.4% W
	impurities ($\leq$ 5 percent)	Fe, Ni, O2, Co, Cr, Cu, Mo
Scintillating fiber	Kuraray SCSF78 (single cladding, blue)	
Epoxy	EPO-TEK 301	



Approximation in simulation:

- W radiation length: 6.76 g/cm^2 (**~0.6 cm** for Tungsten powder: 11.25 g/cm^3)
- Approximation with layers: W - SiFi - W - SiFi - W - SiFi - W   1 - 0.45 - 2 - 0.45 - 2 - 0.45 - 1 [mm]
- This gives radiation length **X_0 ~ 0.735 cm per layer**

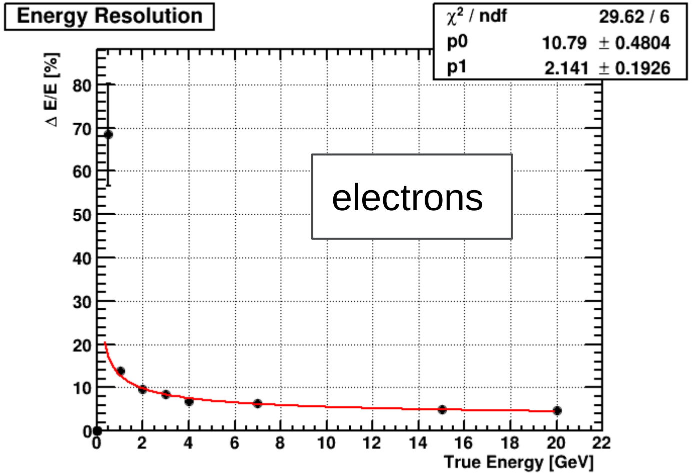
Hybrid Calorimeter

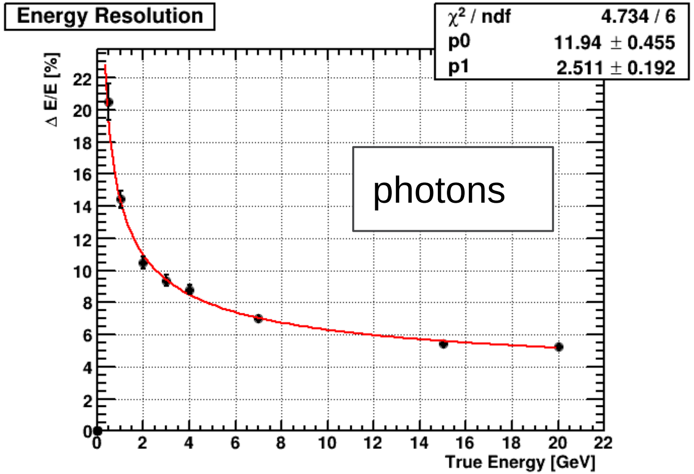
First rough simulations (see previous slide)

- 5 layers AstroPix + SiFi/W (~5 X_0)
- SiFi/W ~15 X_0
  - Only checking total energy losses in active layers (no reconstruction, digitization for SiFi/W layers) - Upper limit of resolution

$$\sigma_E/E = 10.79/\sqrt{E} \oplus 2.14\,\%$$

$$\sigma_E/E = 11.94/\sqrt{E} \oplus 2.51\,\%$$





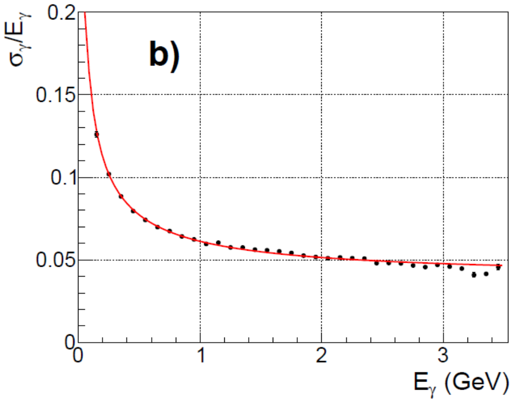
GlueX BCal (ScFi/Pb Calorimeter)

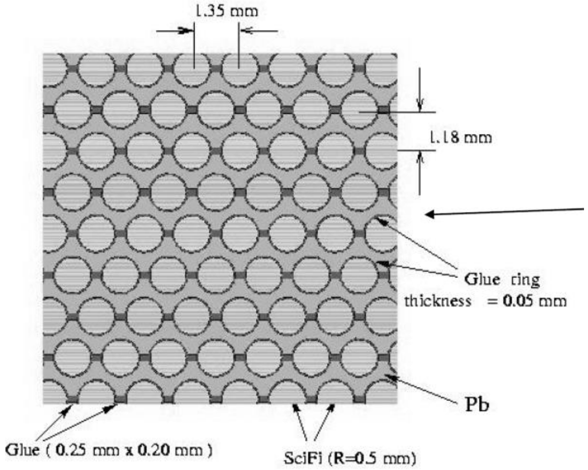
https://arxiv.org/pdf/1801.03088.pdf

Denser scintillating fibers, better energy resolution could be achieved

$$\sigma_E/E = 5.2/\sqrt{E} \oplus 3.6\,\%$$

Effective Radiation Length 1.45 cm, 20 X_0 ~ 29 cm





Cost Estimate

- Material cost
  - < $50k per m^2 per layer (W or ScFi/W not included)
  - $200k per layer for LAEC (radius 0.83 m – 1.4 m)
  - 5 - 10 layers needed for e/pi separation

- Development cost
  - AstroPix is being developed by AMEGO-X
  - Prototyping and test
  - Optional: R&D for hybrid calorimeter

Summary

- 3D shower profiling from Imaging Calorimeter
  - Better e/π separation than sampling calorimetry
  - Possible timing layer before the calorimeter, TOF and connection between Tracking and Calorimetry
  - Energy resolution is limited by the thin active layer, but e/π power does not rely on σ_E

- Hybrid Calorimeter
  - Replacing tungsten layers with ScFi/W or ScFi/Pb layers
  - Synergy between these two types of calorimetry
    - Thin imaging layer (< 0.02 X_0 per layer) does not affect σ_E much
    - ScFi/W or ScFi/Pb serves as absorbers for shower development

Multiple Particles Identification