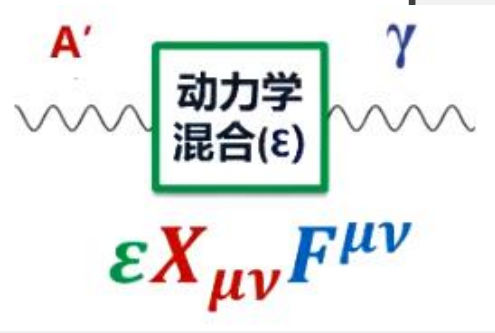
ECAL Simulation & Reconstruction

Qibin LIU o.b.o ECAL team

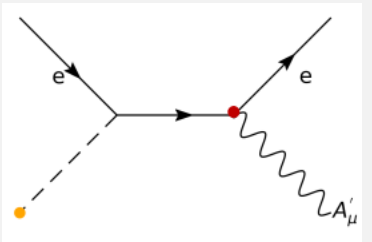
Contributions from Zhiyu ZHAO, Xuliang ZHU, and Jiyuan CHEN

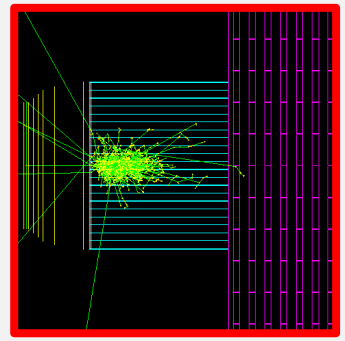
SJTU/TDLI

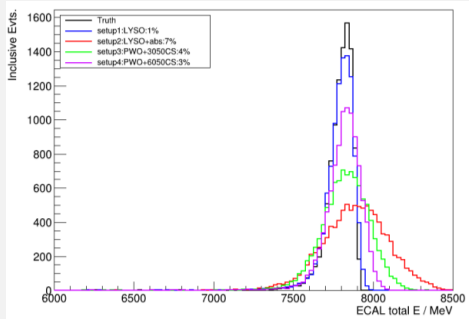
Introduction



- DarkShine experiment: fixed target experiment searching for dark photon
  - Electron beam with energy at GeV: high frequency single electron/bunch
  - W target where the dark photon would produce from electron/photon with the existence of nuclear
- As important part of detector system, EM calorimeter(ECAL) plays an important role
  - Measured all the EM energy with full-crystal design – good resolution and linearity
  - Efficiently separate the invisible signal (low EM energy) and SM background (high EM energy)
  - High gratuity information enables advance analysis method such as shower feature and particle reconstruction
- ECAL simulation and reconstruction successfully supports the first release of DarkShine paper
  - Geant4 based simulation with parametric smearing (considering optical effect and digitization)
  - High EM energy veto analysis method which use total energy of ECAL to reduce background
- Moving forward to reconstruction-based analysis
  - Targeting reconstruction of particles (combined all the detector parts) → single particle done and moving to multi-particle
  - ECAL design become vital for the reconstruction and some new study → work in progress
- Prospective ECAL x Machine learning brainstorm

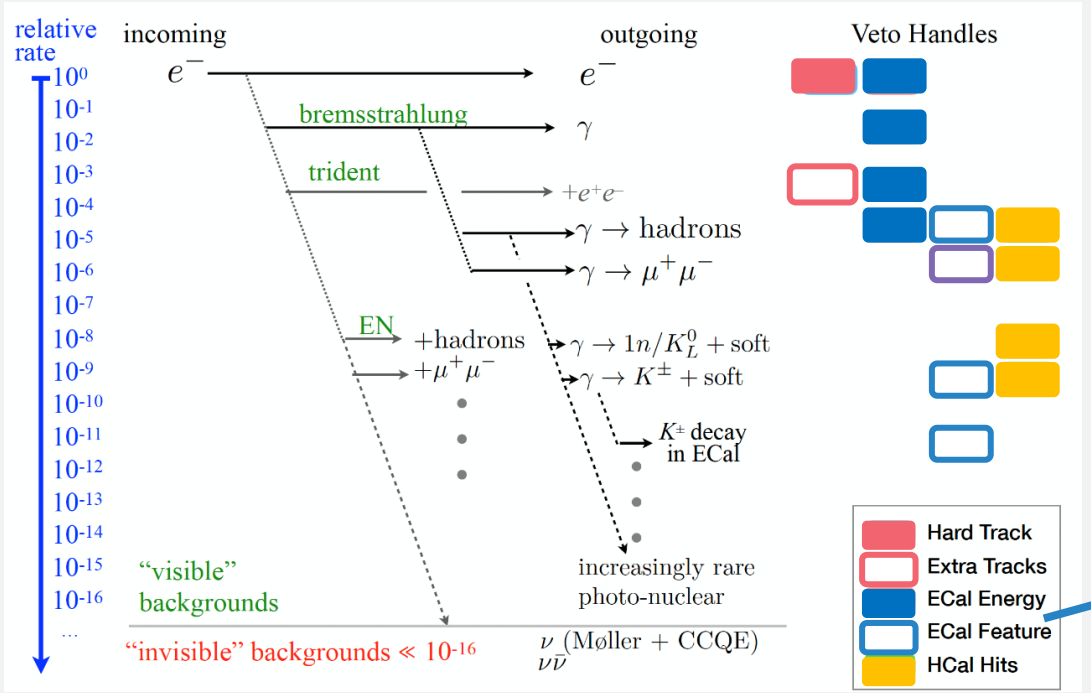


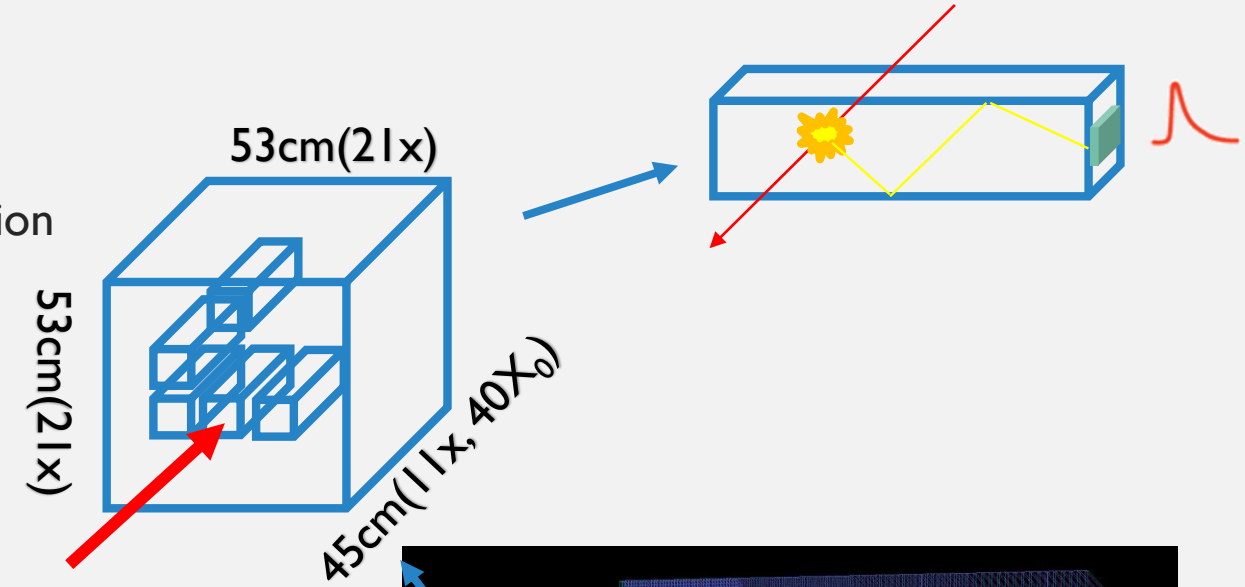


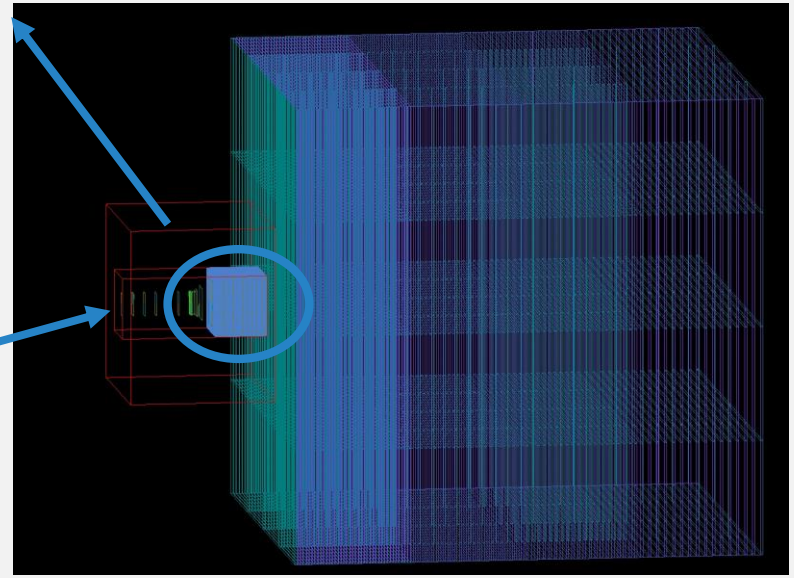


Baseline ECAL design

- Basic goal: detect total energy incident to ECAL
  - Invisible signal usually has low energy deposition
- Advanced goal: shower feature and particle reconstruction
  - Background: separate further with sensitive variable
  - Signal: identify single particle especially hard gamma







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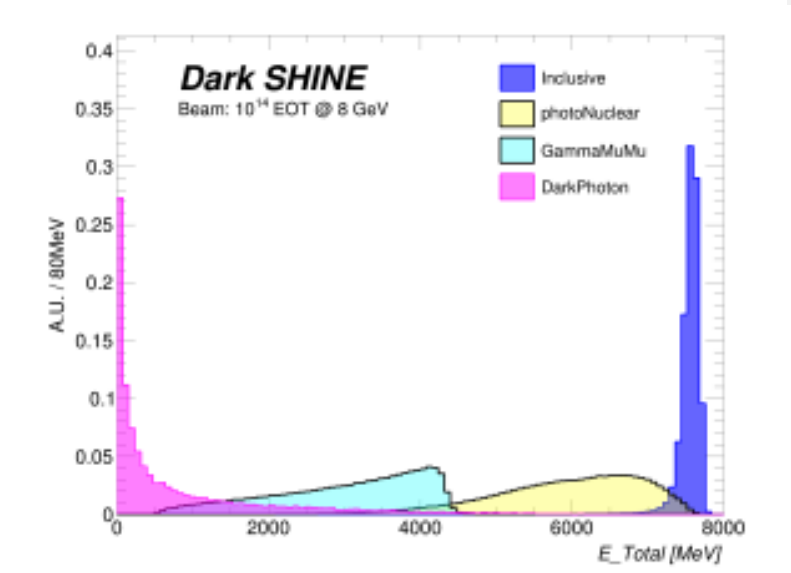
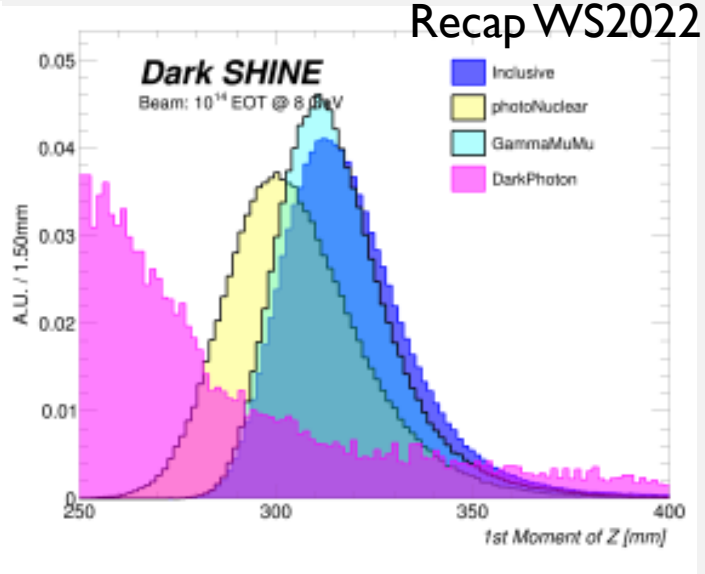
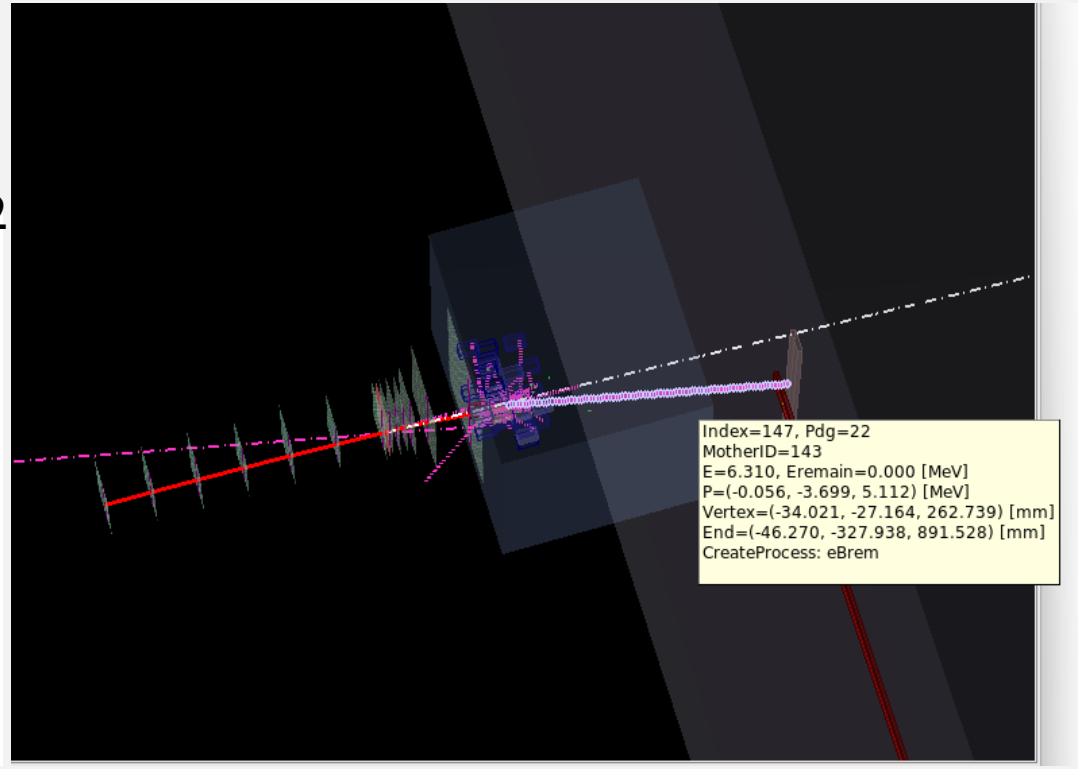
Recap WS2022

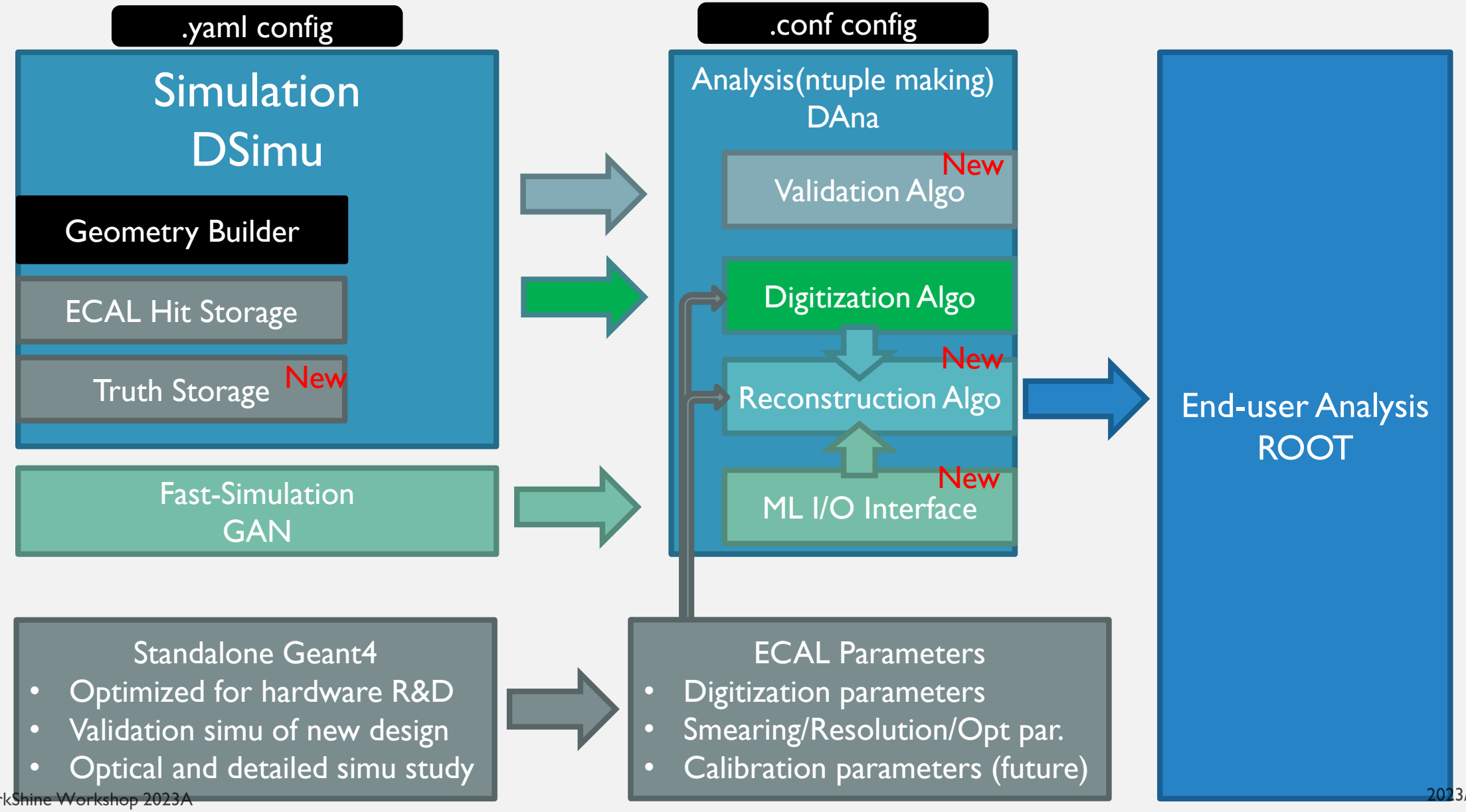




New



ECAL Software Architecture



real ECAL effect is now all simulated in analysis level

ECAL "Simulation"

Digitization Algo

Parametric Smearing (Recap)

Noise cut (New)

Digitizer Algorithm

- Support 2 modes:
  - Detailed optical simulation enabled in DSimu → ADC Digitizer
    - Convert the photon hit to energy, consider noise, dynamic range, pedestal effect so on
  - ➢ Detailed optical simulation enabled in DSimu → FastSmear
    - ➢ Mimic the optical and digitizer effect: parametric smearing, noise cut, so on
- Currently the smearing mode are used for batch production

```
###
Algorithm.List = Digitizer MCTruthAnalysis Tracking RecECAL  CutFlowAnalysis

### Algorithm Configuration


Digitizer.ApplytoECAL = 1  # Smearing on ECAL
Digitizer.ApplytoHCAL = 1  # Smearing on HCAL
Digitizer.RandomSeed = 0  # Random seed for smearing
Digitizer.pedestal = 0  # pedestal
Digitizer.rangeMax = 2048  # rangeMax
Digitizer.rangeMin = -2047  # rangeMin
Digitizer.Calibration_Factor = 1  # Calibration Factor
Digitizer.Nominal_Yield = 20000  # Nominal Yield of material, like 20000/MeV for LYSO
Digitizer.voltageToADC = 1.2207  # voltageToADC: fullRangeMV/ADCbits
Digitizer.CalibrationFile =   # YAML file for reference
```

```
void FastSmear::ReadConfigFile() {
    if (config_file.empty()) {
        Calibration_Table ct;
        ct.E = vector<double>({0});
        ct.A = vector<double>({0});
        ct.B = vector<double>({0});
        ct.C = vector<double>({0});

        Calibration_Table ct1;
        ct1.E = vector<double>({8000});
        ct1.A = vector<double>({31.62e-02});
        ct1.B = vector<double>({0});
        ct1.C = vector<double>({0});

        Calibration_Table ct2;
        ct2.E = vector<double>({8000});
        ct2.A = vector<double>({211.69e-02});
        ct2.B = vector<double>({0});
        ct2.C = vector<double>({0.0851});

        Calibration_Table ct3;
```

Recap of ECAL Smearing Scheme (WS2022)

- ECAL cell energy parametric smearing: parameter (A) obtained from optical simulation of single crystal
- LYSO setup in simulation (1% smearing) validated with real measurement (0.1%~0.6%)

	cube	Wrapper	SiPM Size	coupling*QE	Yield/MeV
R90_LYSO	2.5*2.5*4cm	Ref=90% (ref.)	$9mm^2$	20%	30000(LYSO)
R10_LYSO	2.5*2.5*4cm	Ref=10% (abs.)	$9mm^2$	20%	30000(LYSO)
R90_S9_PWO4	2.5*2.5*4cm	Ref=90% (ref.)	$9mm^2$	20%	200(PWO)
R90_S36_PWO4	2.5*2.5*4cm	Ref=90% (ref.)	$36mm^2$	20%	200(PWO)

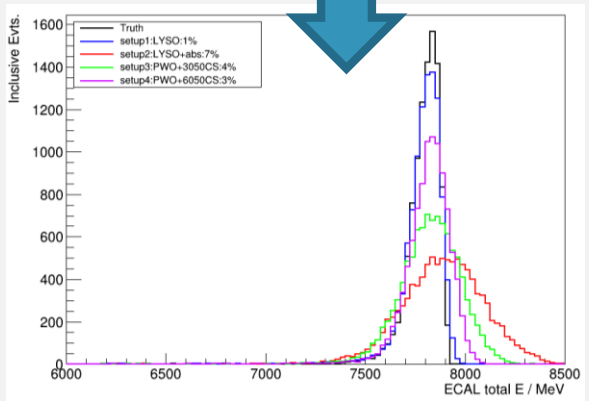
Optical Simu(single crystal)

$$P(E) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(E-E_{truth})^2}{2\sigma^2}}$$
$$\sigma = A\sqrt{E_{truth}}$$
$$A = \frac{1}{\sqrt{N}}$$

	$A/\sqrt{MeV}$	$A/\sqrt{GeV}$
R90_LYSO	31.62%	1.00%
R10_LYSO	211.69%	6.69%
R90_S9_PWO4	134.56%	4.26%
R90_S36_PWO4	73.32%	2.32%

Real measurement

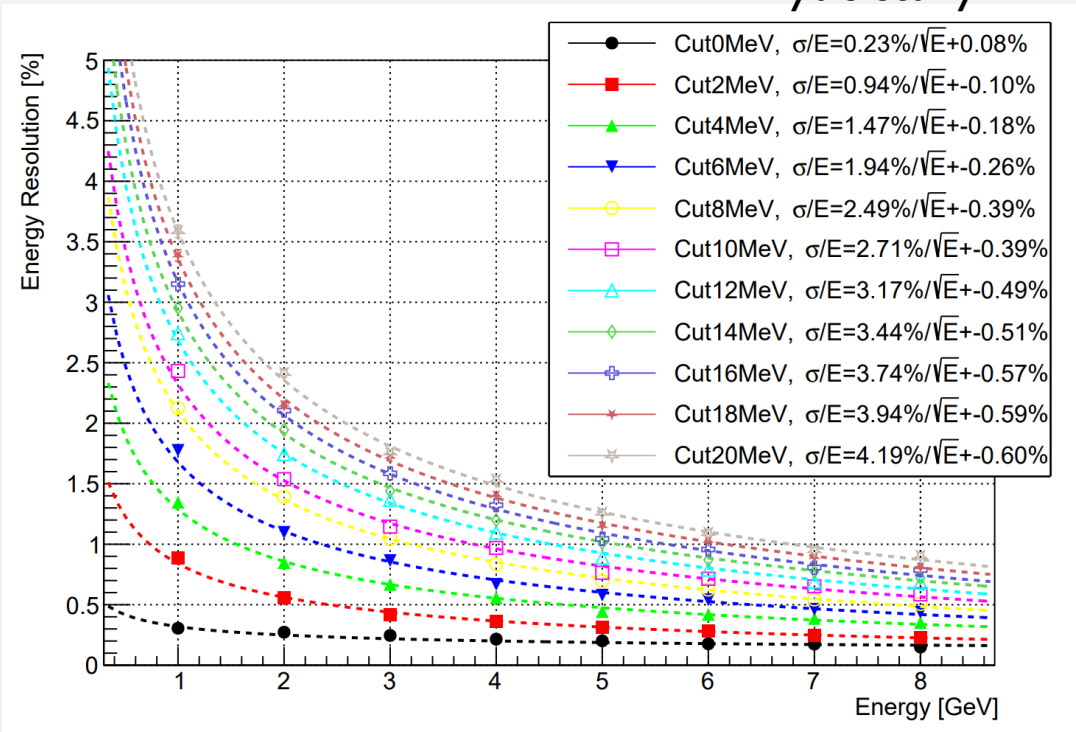
SiPM model ~3500 pixels	ph/MeV 10cm~2cm	$A/\sqrt{GeV}$ no atten max E~100MeV
S13360-1325CS	30~60	0.4%~0.6%
S13360-3050CS	250~600	0.1%~0.2%



Noise Cut Implementation

- Another important factor which will impact the ECAL analysis: **noise cut**
  - Impact up to 3.5%@1GeV when 20 MeV noise cut applied
- Supported the DAna algorithm (digitizer algo) and end-user no need to worry
- Default value:0 could be change in the future when the cut value determined with measurement

Zhiyu's study




```
Digitizer.ApplytoECAL = 1   # Smear
Digitizer.ApplytoHCAL = 1   # Smear
Digitizer.RandomSeed = 0   # Random
Digitizer.pedestal = 0   # pedesta
Digitizer.rangeMax = 2048   # range
Digitizer.rangeMin = -2047   # rang
Digitizer.Calibration_Factor = 1
Digitizer.Nominal_Yiel = 20000   #
Digitizer.noiseCutMeV = 0   # noise
Digitizer.voltageToADC = 1.2207   #
Digitizer.CalibrationFile =    # YA
```

ECAL Reconstruction

Reconstruction Algo

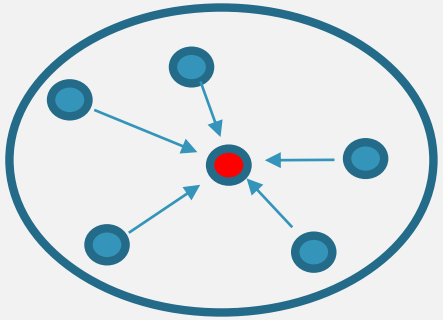
Recap of baseline1 analysis

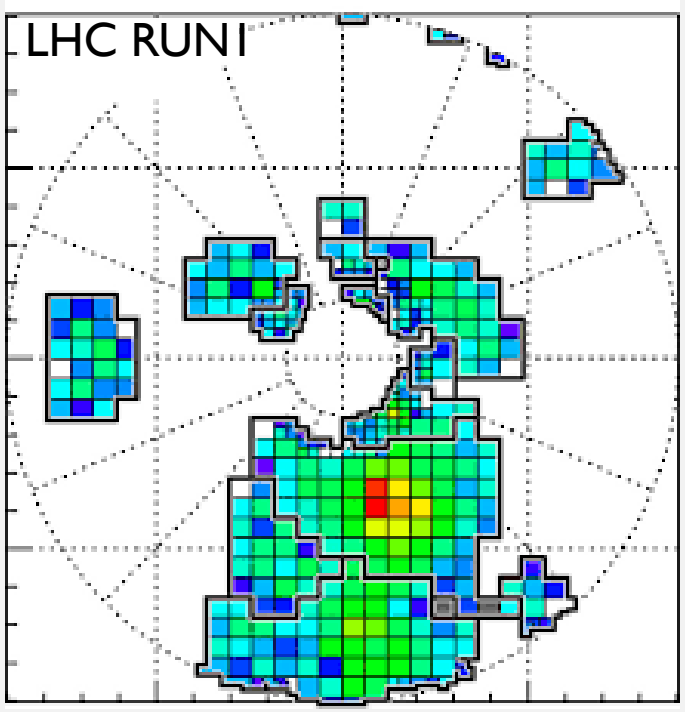
Topo clustering Method

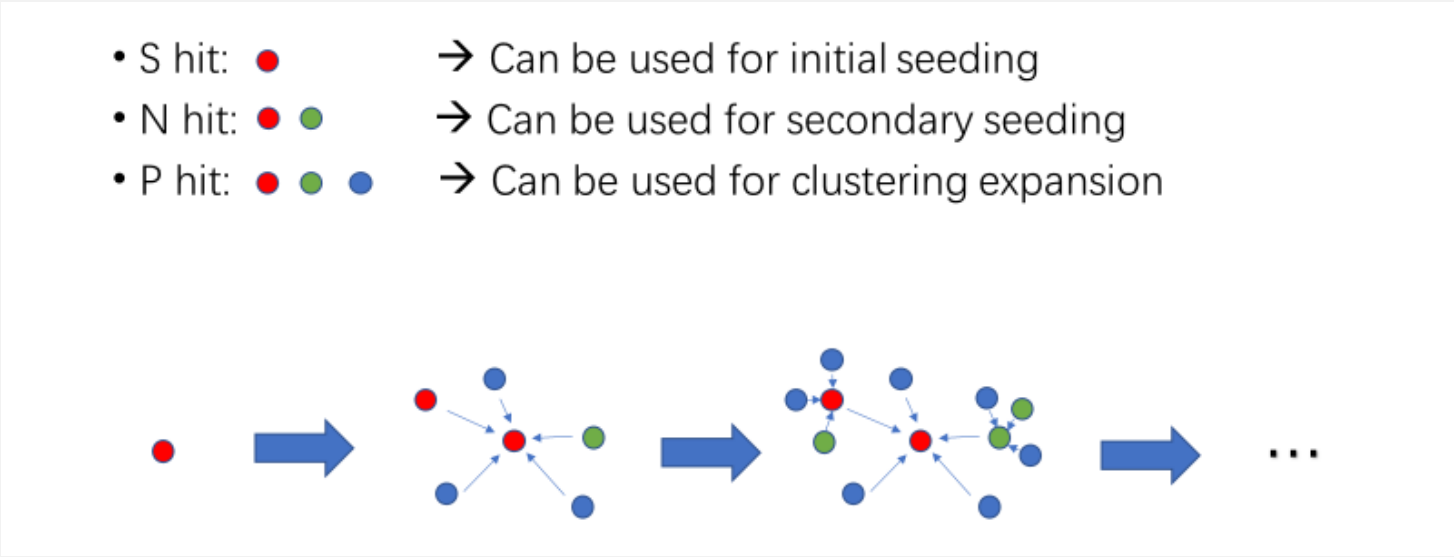
Track-ECAL combined reconstruction (WIP)

ECAL Reconstruction Algorithm

- ECAL cluster reconstructed using topo-clustering algorithm
- Formation & Splitting with the consideration of noise and calibration
- Key parameters: 4-2-0 scheme
- Output: cluster(for most analyses) and sub_cluster(for detailed shower structure)
  - ECAL_Cluster_xxx, (ECAL_ClusterSub_xxx)
- Fully implemented in the DAna and enabled by default

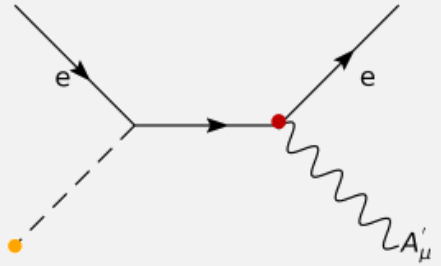






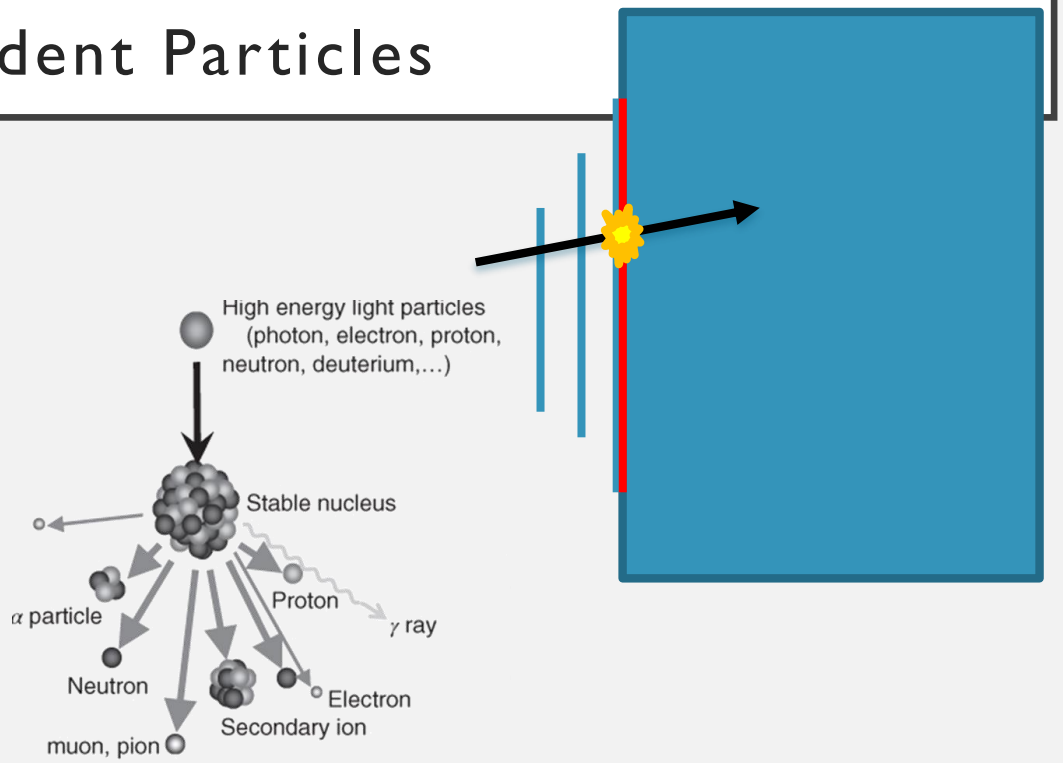
Dominant ECAL Incident Particles

- Most signal with only one electron or gamma
  - Low energy and electron usually well reconstructed in tracker
- Background usually has more particles
  - Complex final states and not helpful to reconstruct each particle

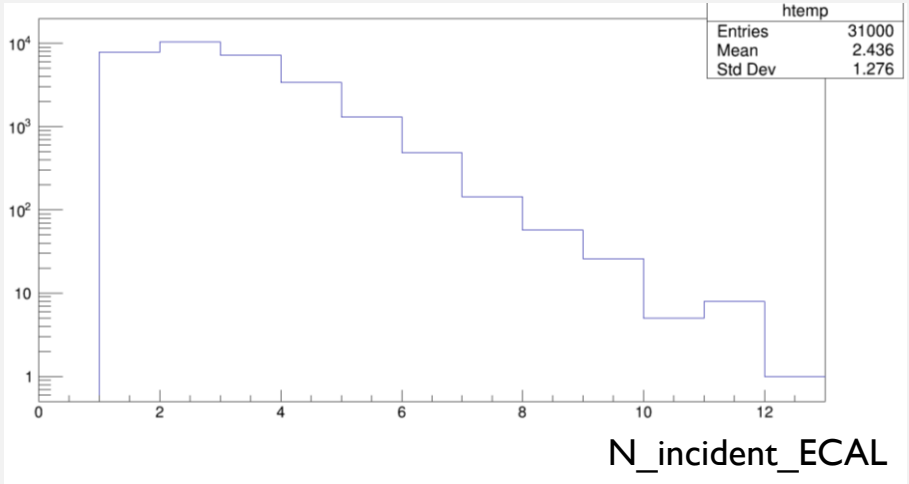


Invisible Signal

mass/MeV	DM+e	DM+γ	e+DM	None	Others
1	67.0%	8.2%	21.3%	0.9%	2.60%
10	65.2%	18.6%	7.4%	7.7%	1.10%
20	58.0%	23.1%	5.9%	12.2%	0.80%
50	56.5%	24.2%	3.8%	14.9%	0.60%
100	55.0%	23.8%	4.7%	15.9%	0.60%
500	57.9%	24.5%	0.6%	16.7%	0.30%
1000	60.0%	22.0%	0.1%	17.5%	0.40%
2000	59.2%	18.2%	0.1%	22.0%	0.50%

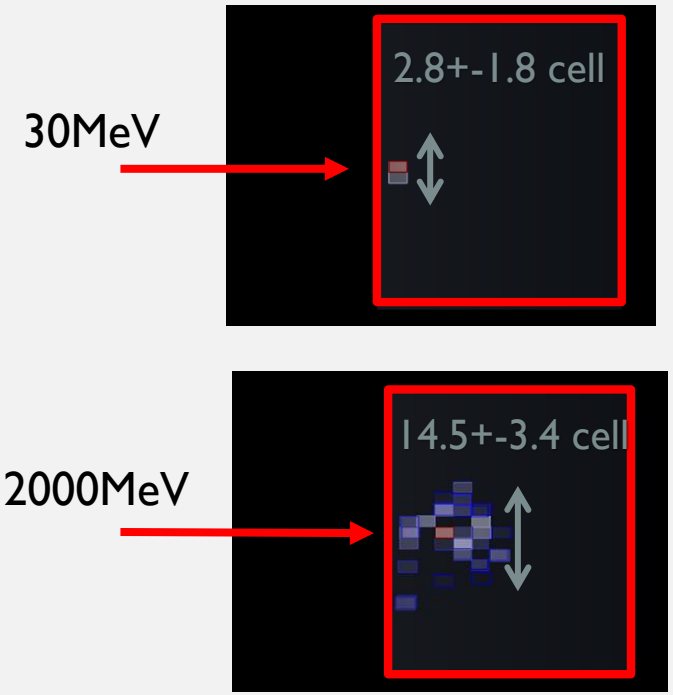


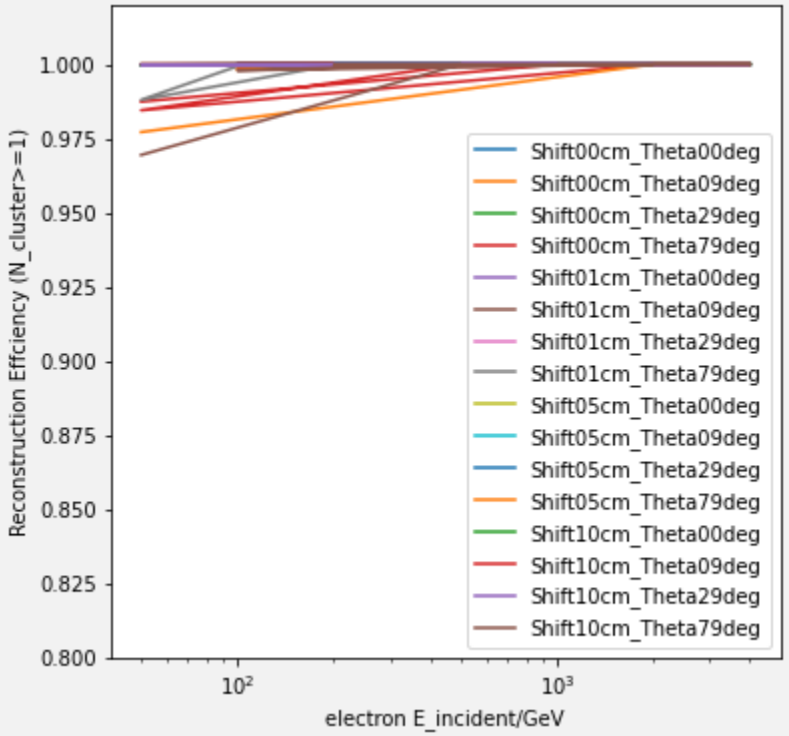
Inclusive Background

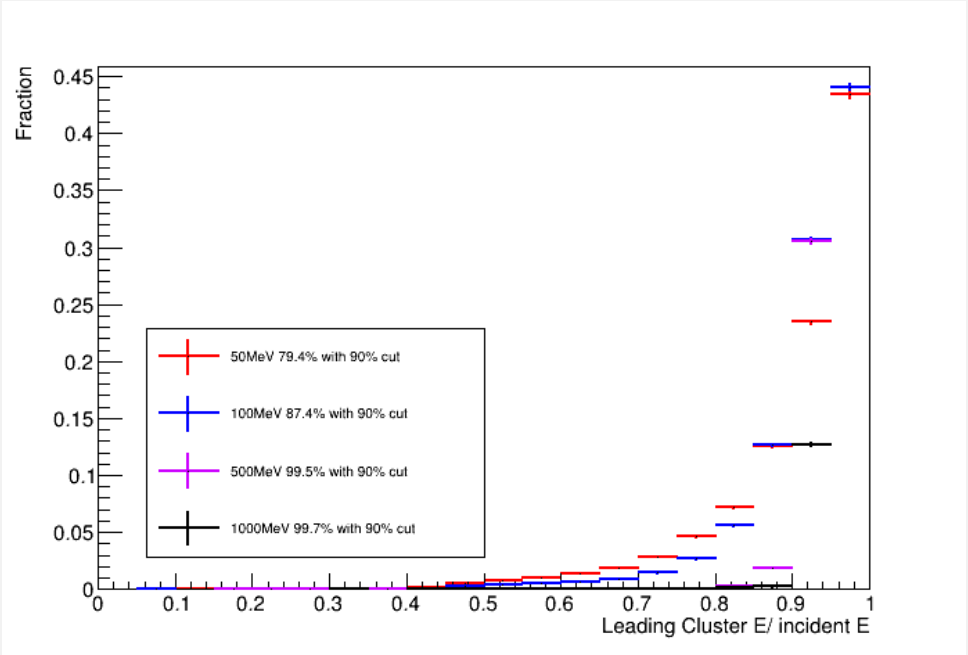


ECAL Reconstruction Performance (single e)

- For single electron around central point, angle from 0~80 the inclusive efficiency (N_Cluster>=1) > 95%
- With energy increase, fraction of "90% E reconstructed in leading cluster" increase and near 100%
- 50MeV electron with 90% E reconstructed requirement: efficiency around 80%

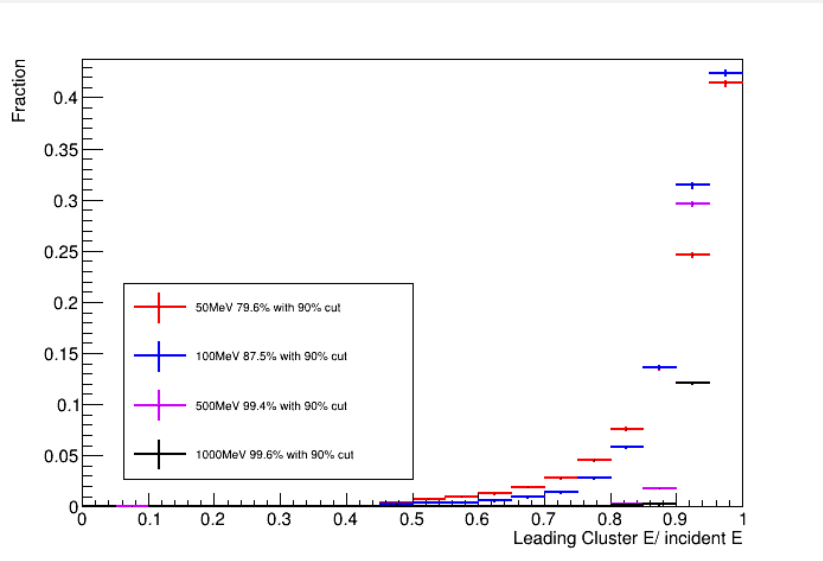


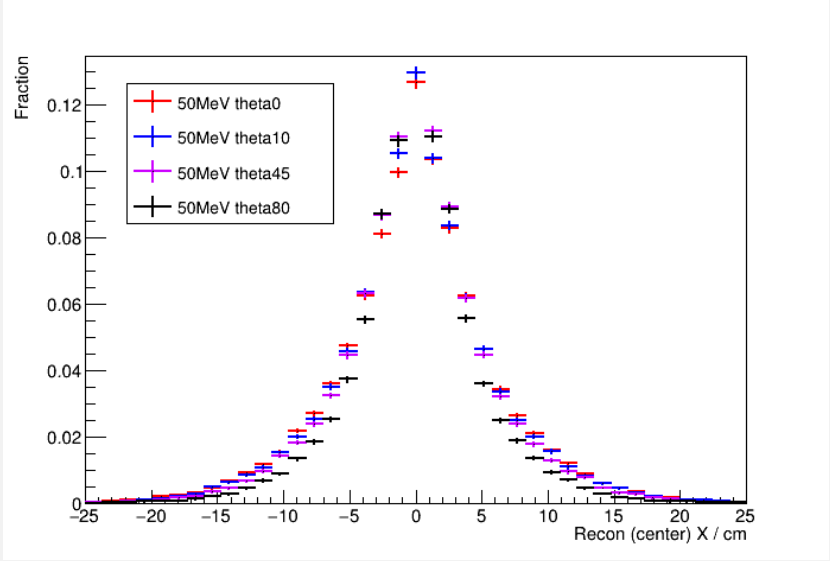


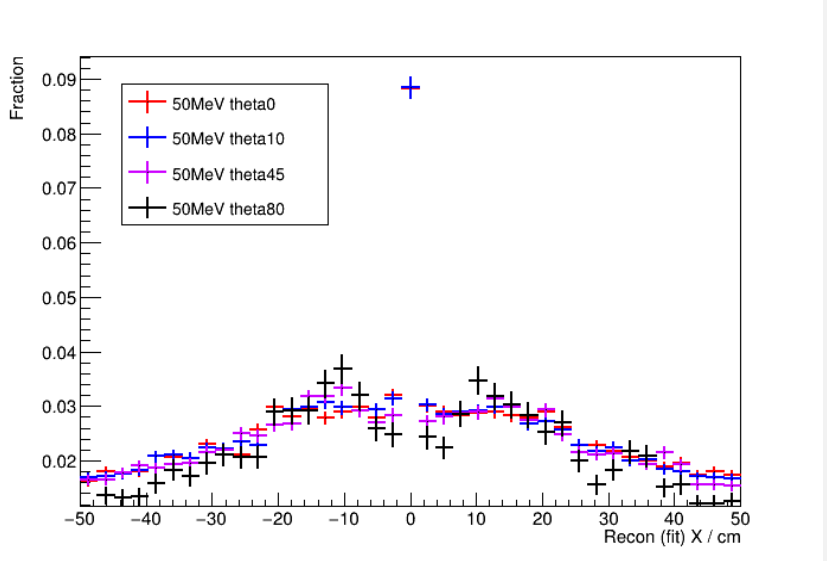


ECAL Reconstruction Performance (single gamma)

- Gamma as common EM particle takes up to 20% in signal events: ECAL could play an role!
- Very similar reconstruction performance as single electron and rven higher inclusive efficiency >> 95%
  - Center method gives unbias location identification – though large width
  - Fit method (fit the principal axis of cluster) gives precise location but not all could be reconstructed



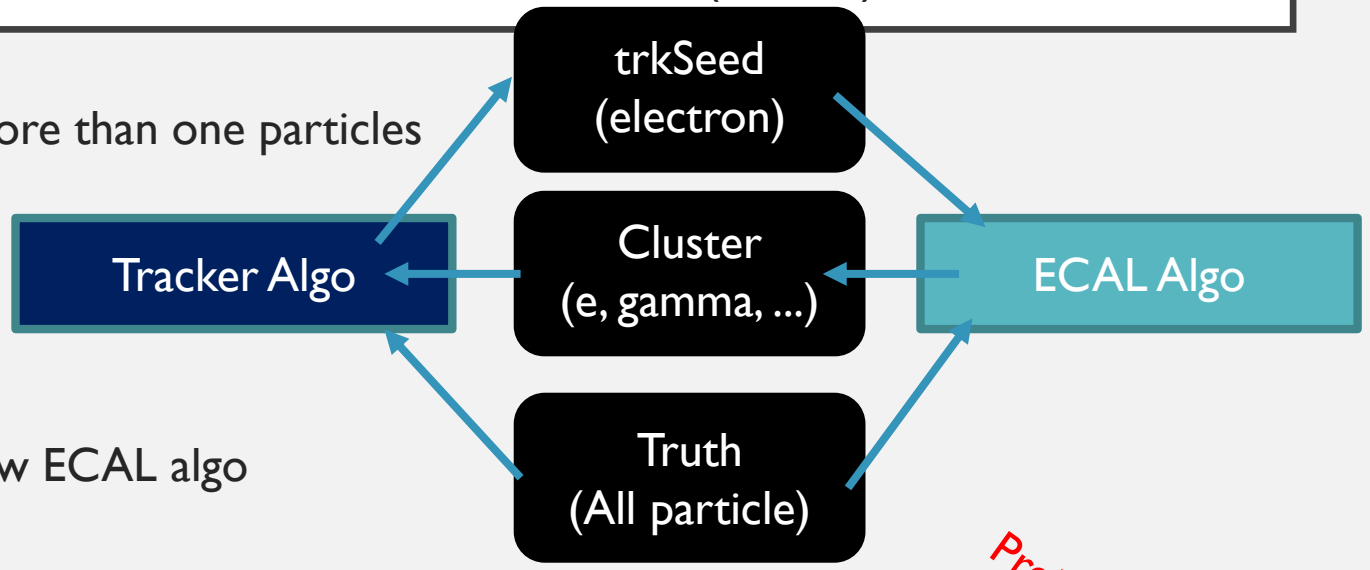




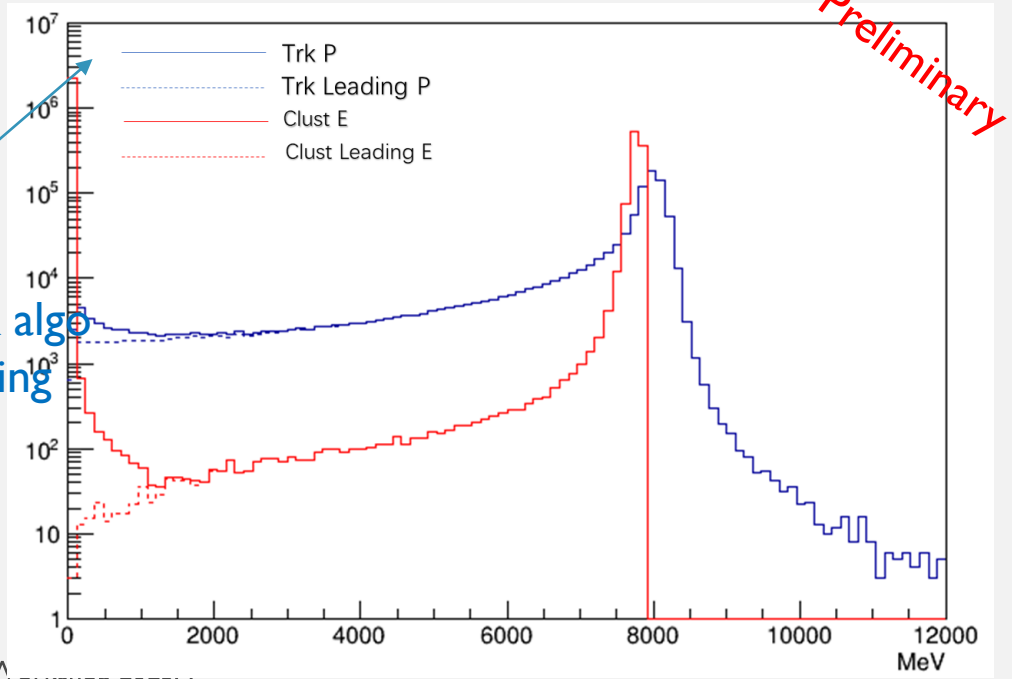
Thanks for Yifan's cooperation

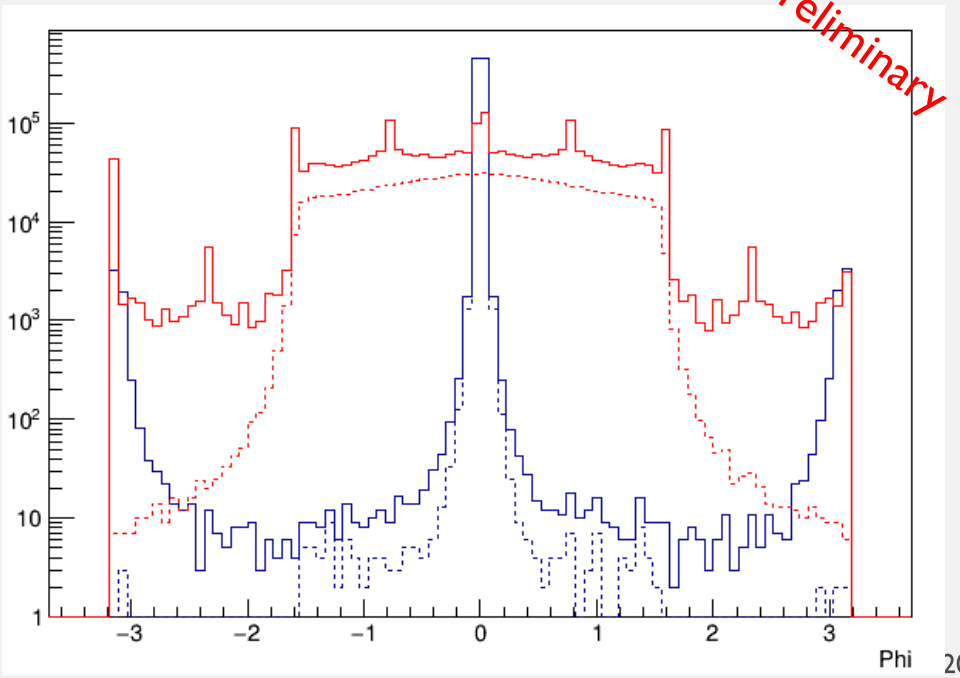
Tracker-ECAL Combined Reconstruction (WIP)

- ECAL only reconstruction shows limitation for more than one particles
- Tracker information comes into the play
  - High energy and gamma: **ECAL**
  - Low energy electron: **Tracker**
  - Ongoing study review with new tracker algo + new ECAL algo



based on last version of trk algo updates ongoing





ECAL Design Review

Validation Algo

Geometry Builder

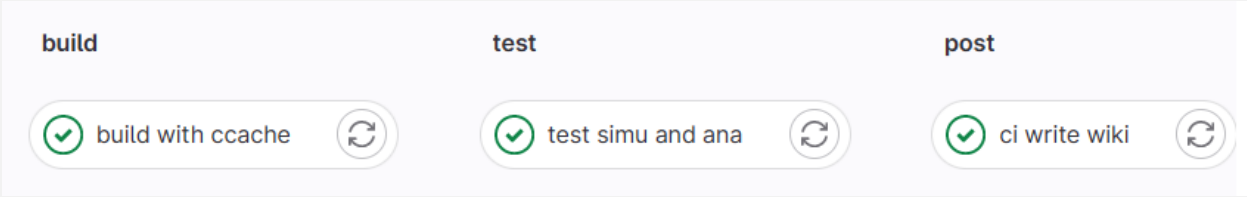
ECAL auto-validation

Staggered ECAL simulation (WIP) ← More on Zhiyu's talk

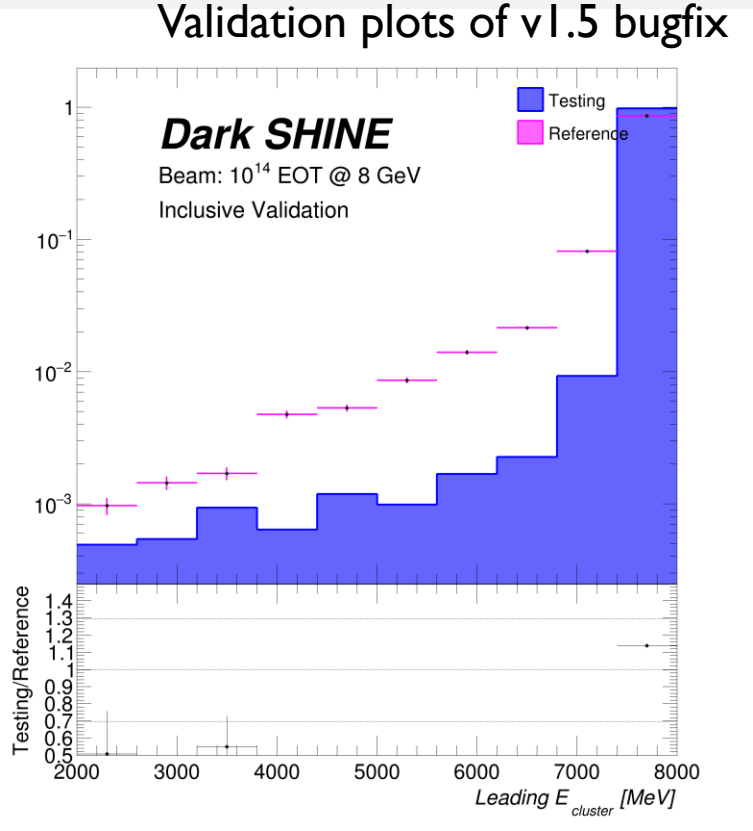
PWO4 ECAL module (WIP) ← On Zhiyu's talk

ECAL Validation

- Automatic validation of simulation and reconstruction
- Record the key plots in the wiki
- Useful tool for RCAL R&D



Validation plots of v1.5 bugfix



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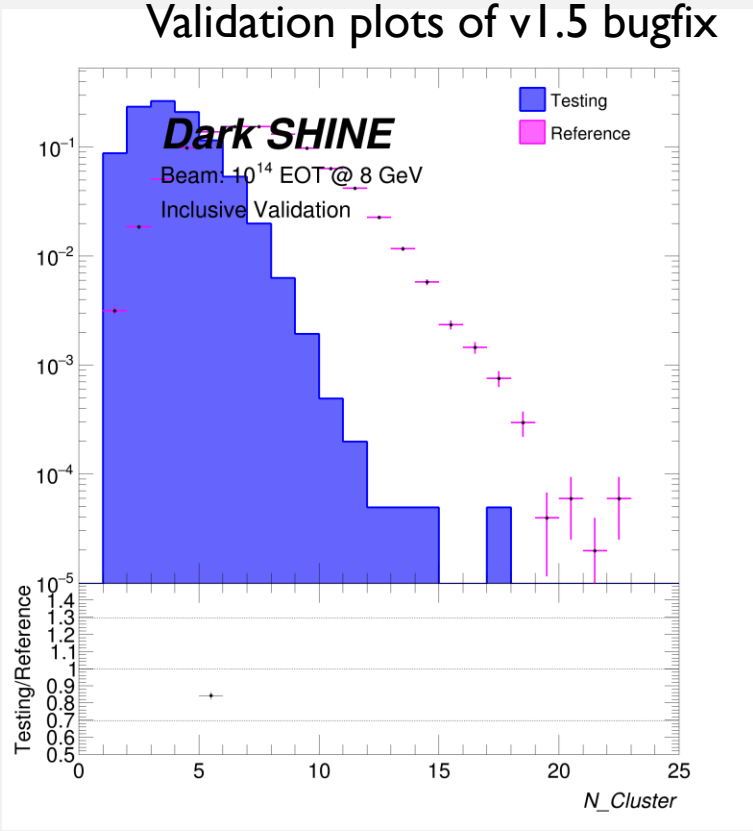
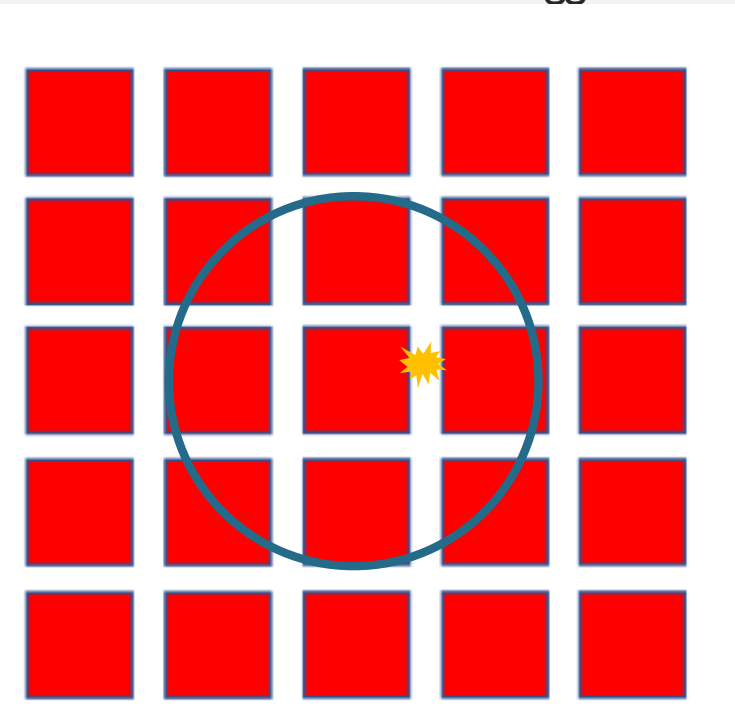
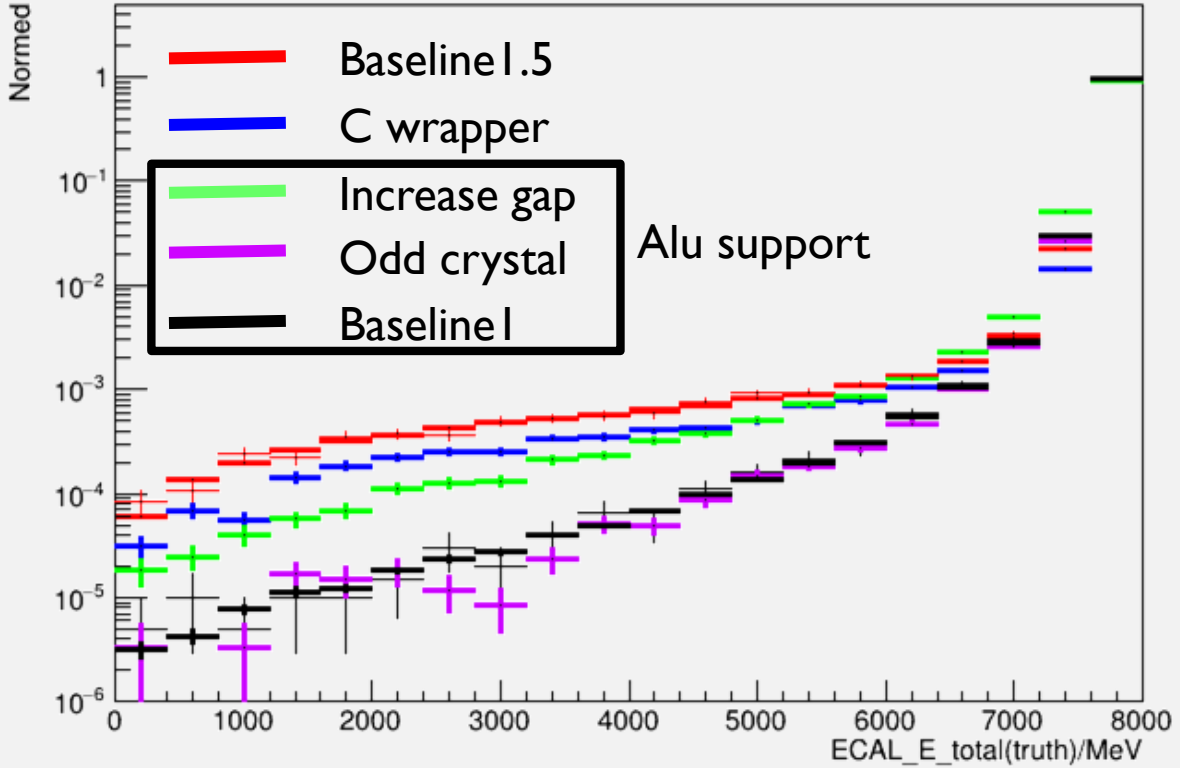


ECAL Leakage and Staggered Structure

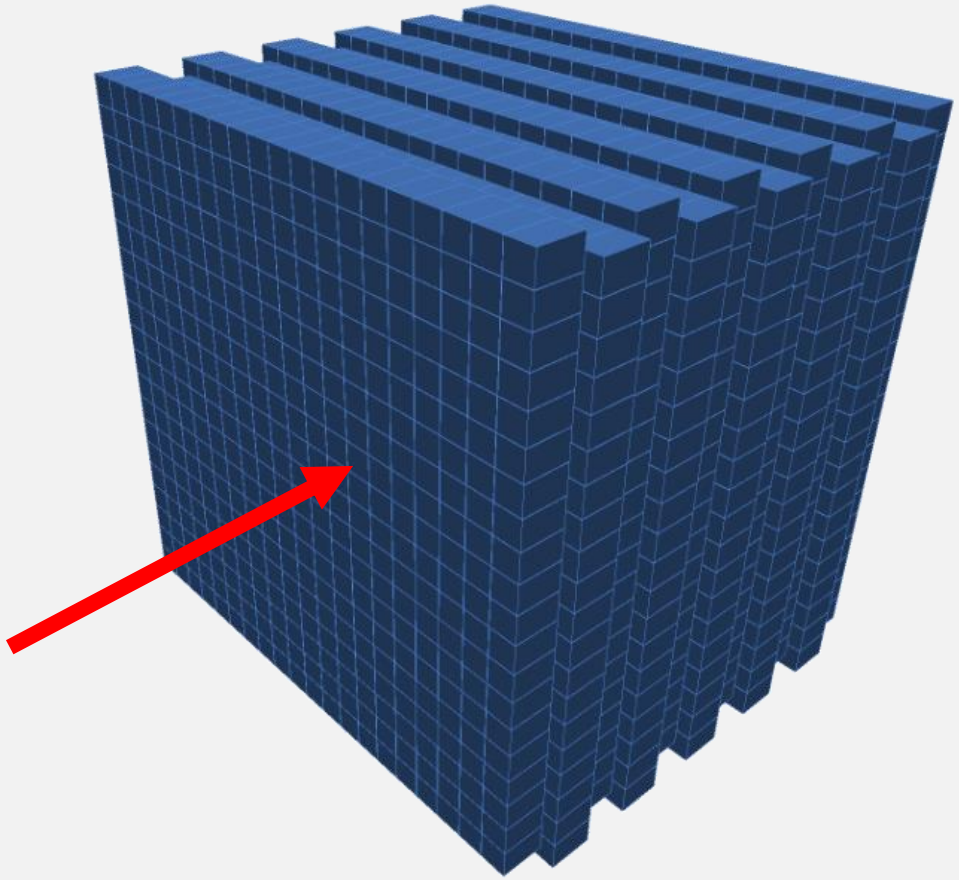
- In the validation the gap effect noticed to be large: usually when beam size larger than one crystal
- Lead to energy leakage in gap:
  - Metal in gap could reduce leakage (e.g. support structure) but huge weight and not possible
  - Carbon in gap is practical but would cause large leakage (especially for low energy particle)
- Reduce the beam size or staggered design needed!



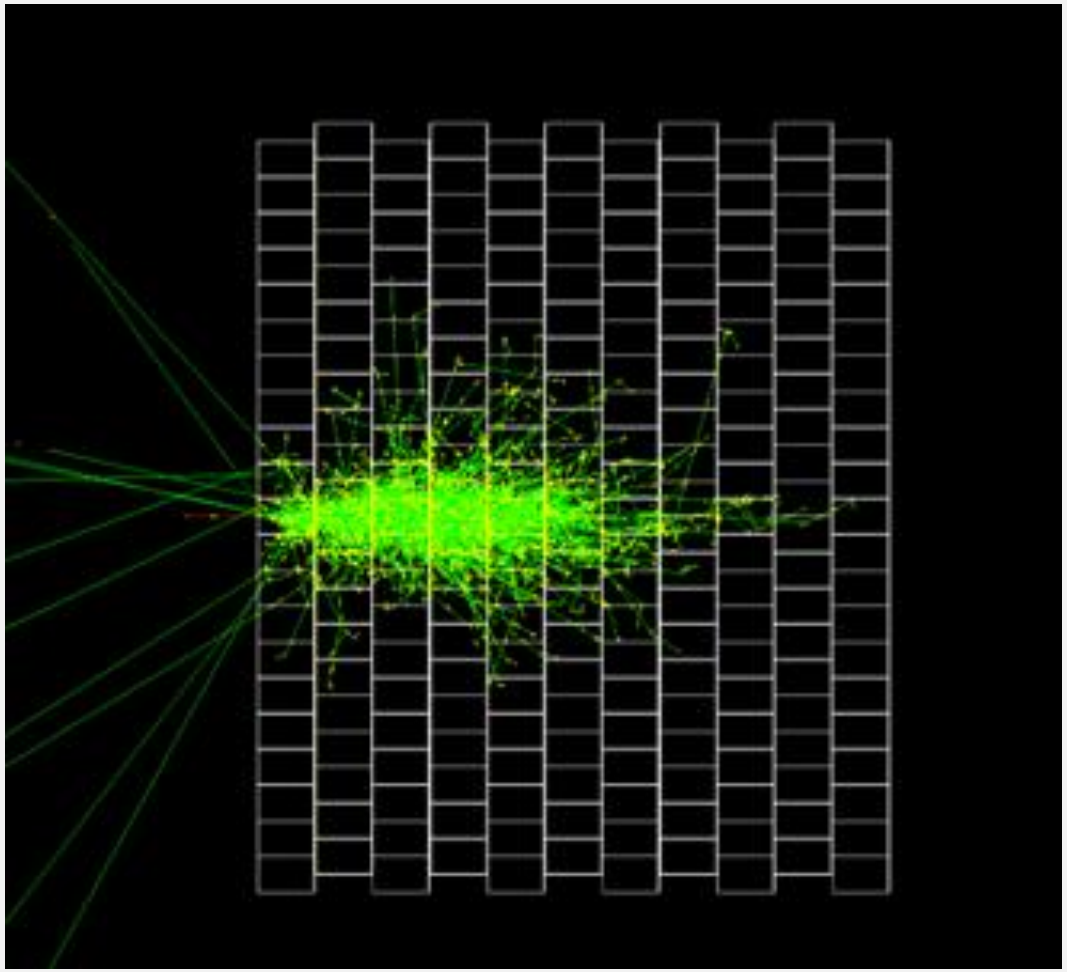


Glance of Staggered ECAL

Xuliang
DSimu

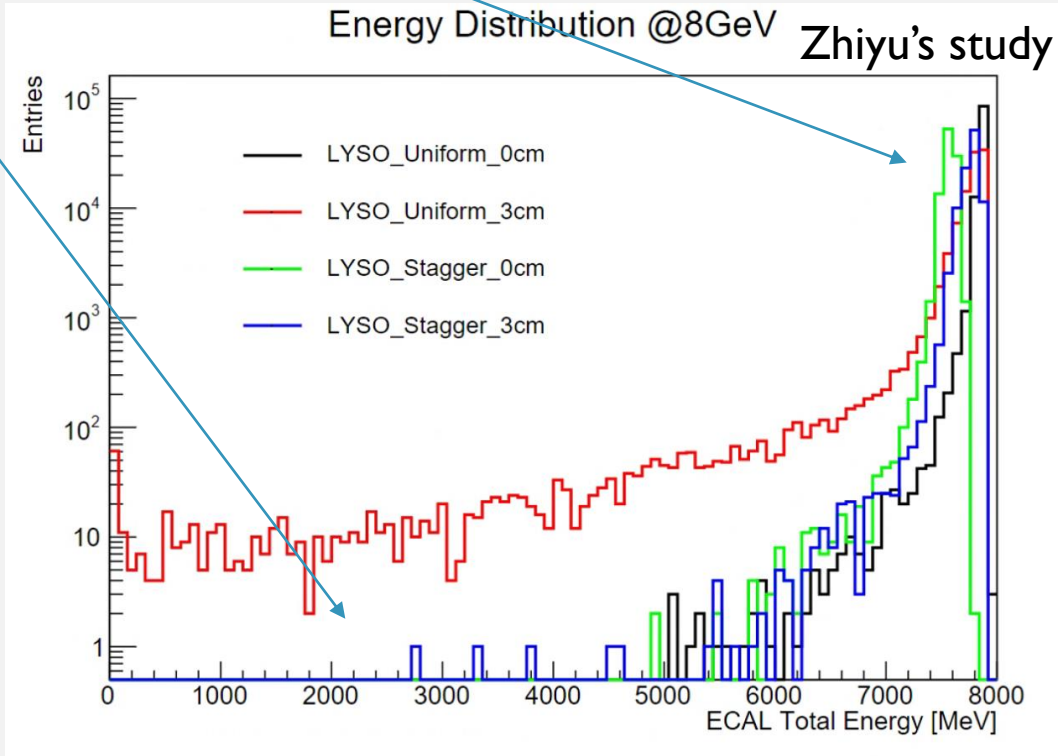


Zhiyu
Standalone



Performance of Staggered ECAL (WIP)

- Staggered structure tested in the standalone FW
- Expected drop the low energy tail → energy leakage in the gap highly reduced
- More obvious leakage in high energy when zero beam size → under investigation
- Now integrated into the DSimu and production recently finished (v1.6) and being studied



Prospective of ECAL

ML I/O Interface

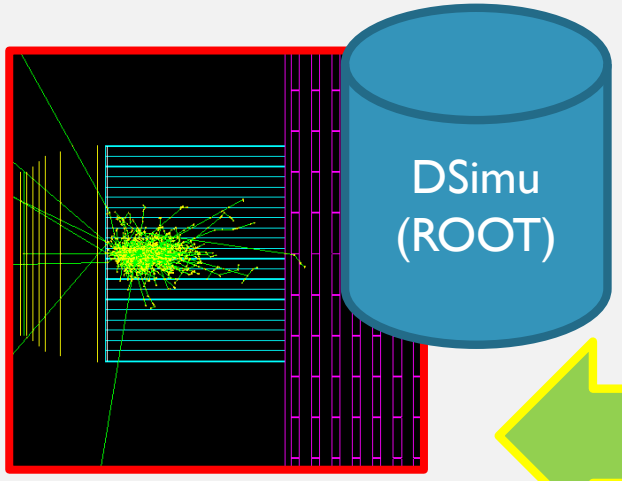
Machine Learning x ECAL

↑ Focus on ML interface with DSimu/DAna
More on Siyuan's talk

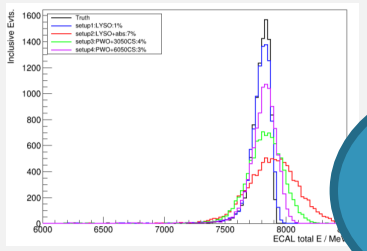
ECAL x Machine Learning: Interface

- Expensive full simulation of ECAL and complex tasks of ECAL reconstruction quests new techniques
- Machine learning enter the stage → unlimited possibility to power up
- ML interface implemented in the DSimu/DAna framework: import/export the ECAL showering info as hdf5 file
  - TB level data deriving in hours

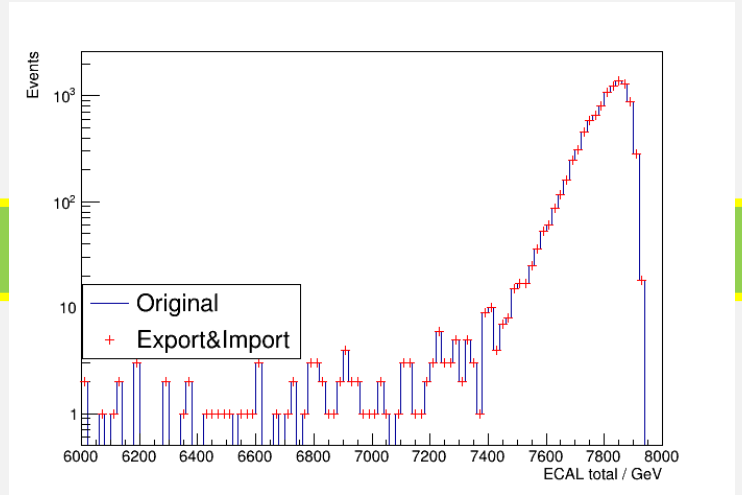
Stat.	Storage	Wall time	N_jobs
1E8	37BG	15min(import) 30min(export)	100



DSimu (ROOT)



Analysis



hdf5

TensorFlow

PyTorch

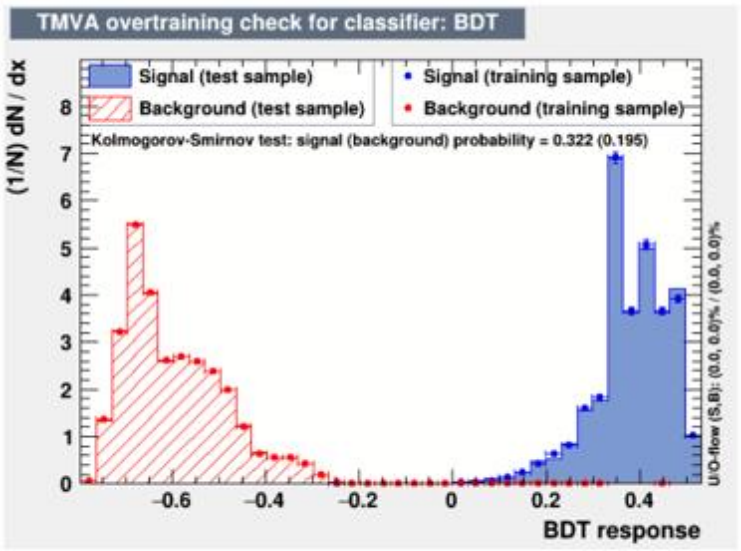
Status and Next Plan

- Simulation of ECAL:
  - Realistic effect now all implemented in post-production level: digitizer, parametric smearing, noise cut
  - Next: implement more realistic effects **when measurement ready and key parameters provided**
- Reconstruction study of ECAL:
  - Topo-clustering algorithm implemented and FW updated – now the truth/reco information ready for ECAL
  - Single particle reconstruction settled down
  - Next: better multiple particles reconstruction/separation: **comb with precise&accurate tracker information**
- Review of ECAL design: (More on Zhiyu's talk)
  - Automatic validation implemented and ready for future R&D
  - Next: **move to staggered ECAL** which found to have better performance on reducing leakage
- Prospective of ECAL: (More on Siyuan's talk)
  - Machine learning interface to DSimu/DAna framework ready: enable mutual info exchange (import from fast simu/export for ML training)
  - Next: **more AI(s) on the way**!
- Next action plan:
  - Validation of **staggered ECAL** structure (v1.6)
  - Finalize reconstruction study to combine the **non-uniform B-field tracker** + **staggered ECAL**
  - Evaluate **ML based fast simulation** results with full analysis chain

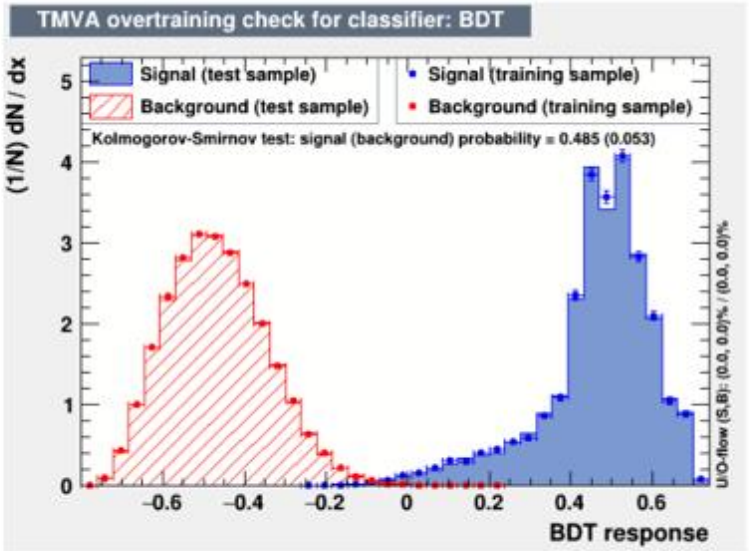
Backups

Recap WS2022 Shower feature analysis

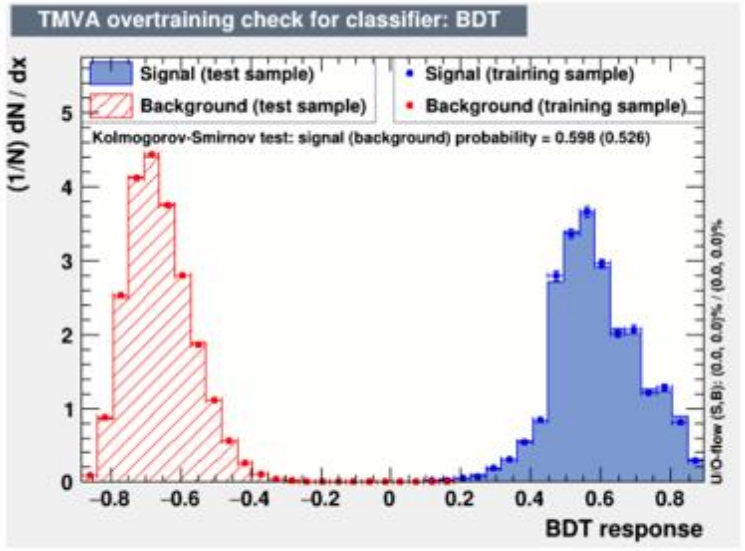
- Promising to separate further the signal v.s. different background
- Limitation: highly affected by the detector effect and hard to estimate the systematics based on simulation only
- Need measurement inputs:
  - Resolution, Linearity, Noise, Calibration ...



Signal to Inclusive



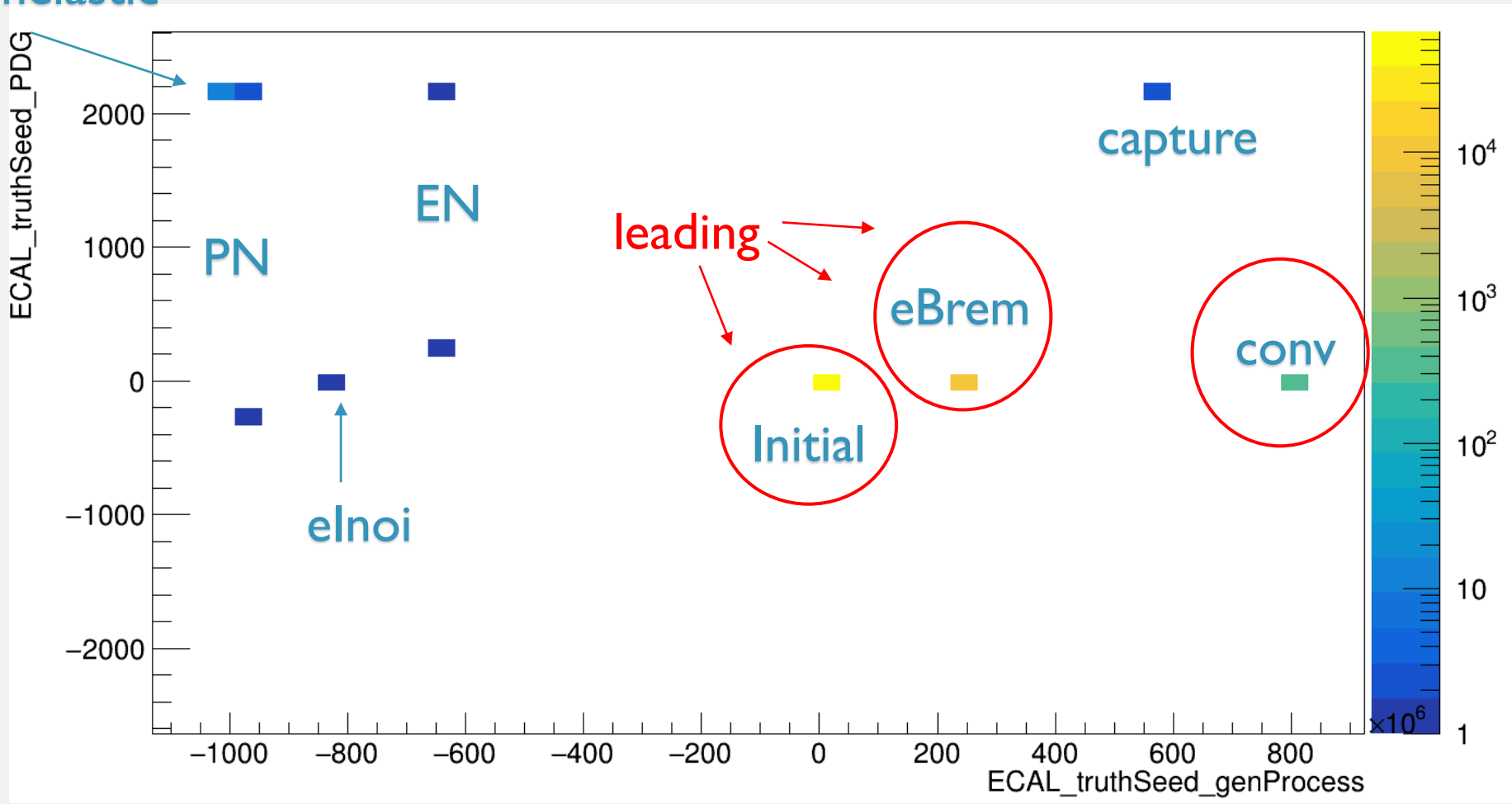
Signal to GMM



Signal to PN

ECAL incident particle of Inclusive Events

neutronInelastic



Reconstruction of 500MeV electron