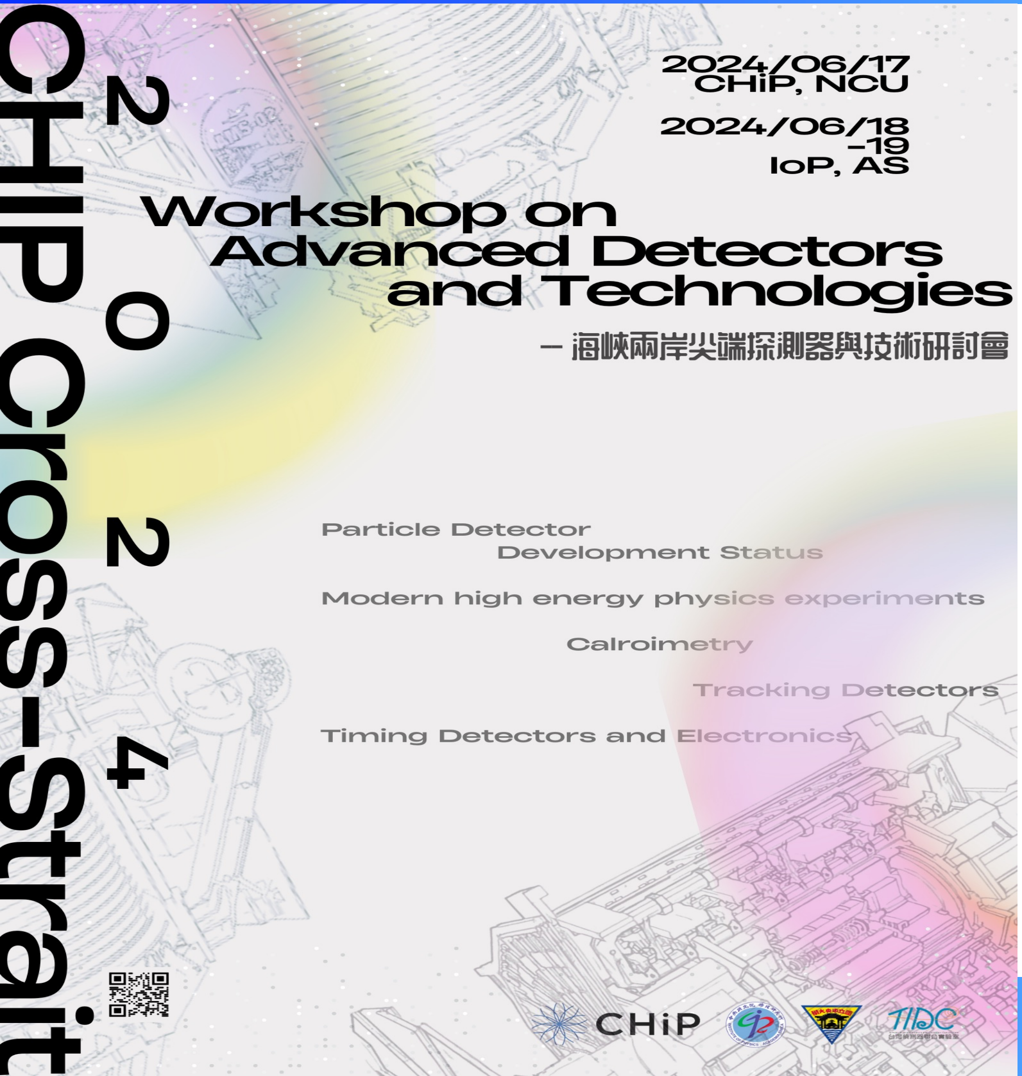
Stereo crystal ECAL design and simulation studies



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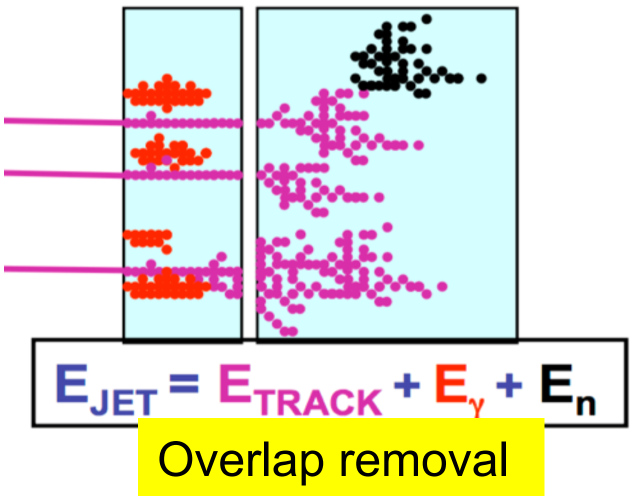
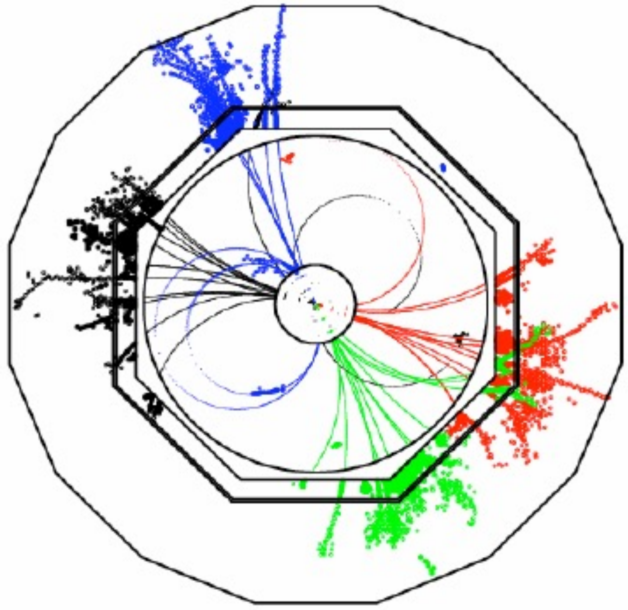
Jun. 17, 2024

Requirement of a CEPC PFA calorimeter

- CEPC Physics requirements
  - Precision measurements with Higgs and Z/W
  - Jet energy resolution (dEjet/Ejet- 3~4%)

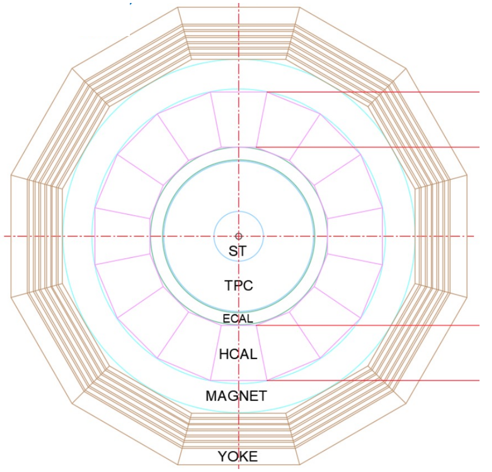


- PFA based Calorimeter (CEPC)
  - Good Shower separation
    - Small Moliere radius (Dense detector)
    - High lateral granularity (~Moliere radius)
  - Good Energy resolution
    - Critical in some special process
  - Sophisticate algorithm
    - Multi-million channels(energy and timing)
    - Multi-Dimensional information

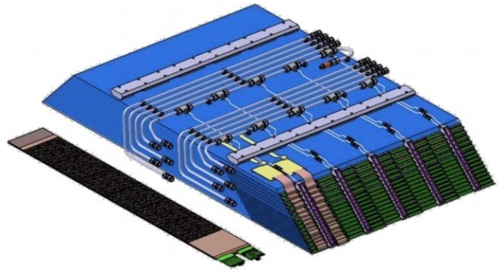


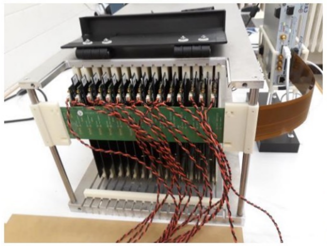
Available options for CEPC ECal

- Silicon tungsten ECal
- Scintillator sampling ECal
- Dual readout calorimeter
- Homogenous Crystal ECal: long bar, Stereo

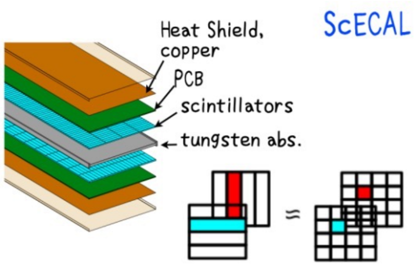


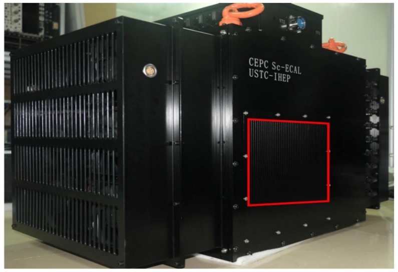
SiW ECal



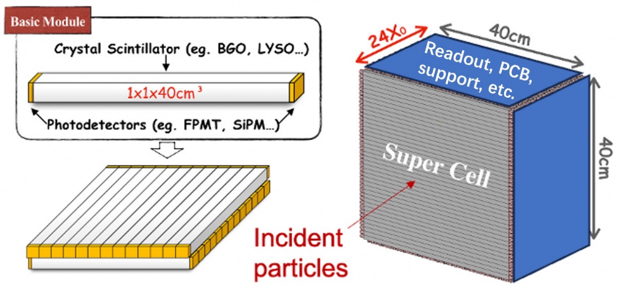


Sc ECal





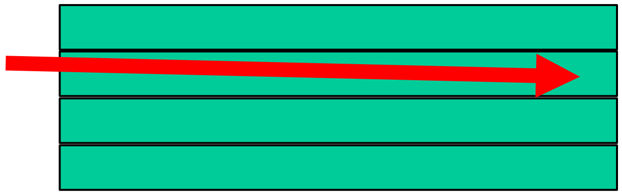
Long bar Crystal ECal



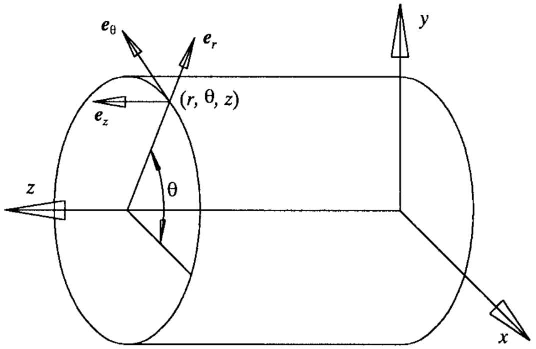
Stereo Crystal ECal: Try to get 3D shower with 2D readout

Stereo Crystal Electromagnetic Calorimeter: Basic idea

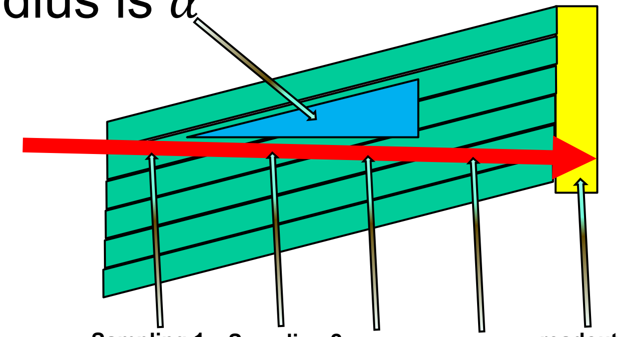
- Traditional Crystal Ecal（CMS/BES…):
  - Crystal long bar pointing to interaction point (IP)
  - Slight twist to avoid escape of particles



Cylindrical coordinate

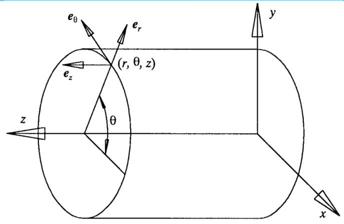


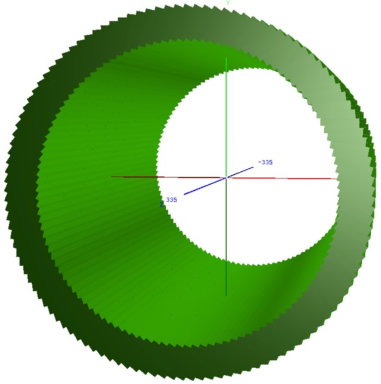
- Stereo Crystal ECal:
  - Crystal long bar not pointing to IP
    - Angle between Crystal long bar and det. radius is α
      - -90 <= α <= 90 degrees
      - α = 0; pointing to Z axis ➔ traditional
      - α != 0: obtain sampling on R
  - Number of sampling can be optimized
  - Single-end readout on the outer surface w.r.t. IP
  - Form circular structure with trapezoid crystal

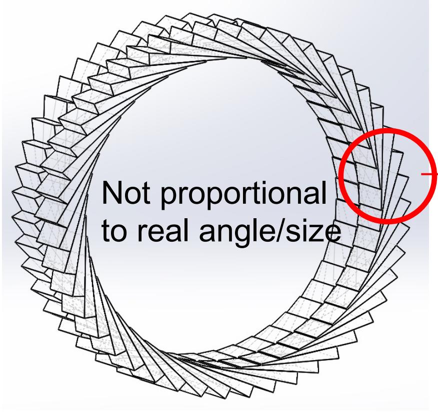


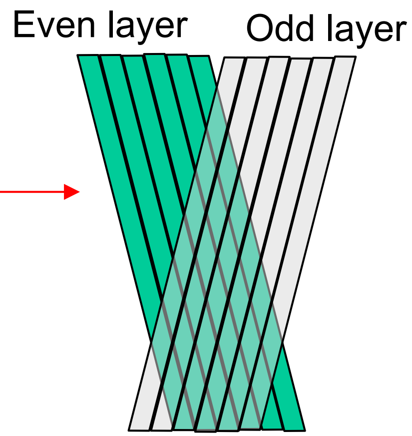
Stereo Crystal Electromagnetic Calorimeter: Design

- To improve the 3D position resolution
  - Pointing angle of even layers alone Z: α
  - Pointing angle of odd layers alone Z: $\alpha' = -\alpha$

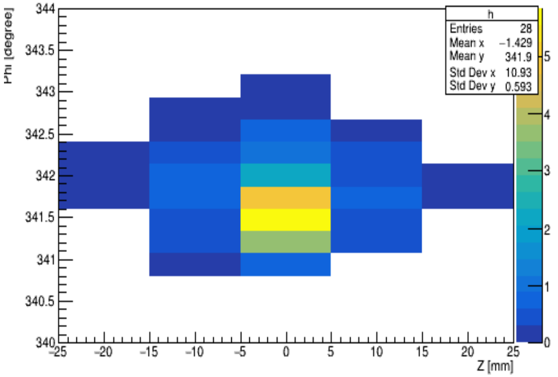




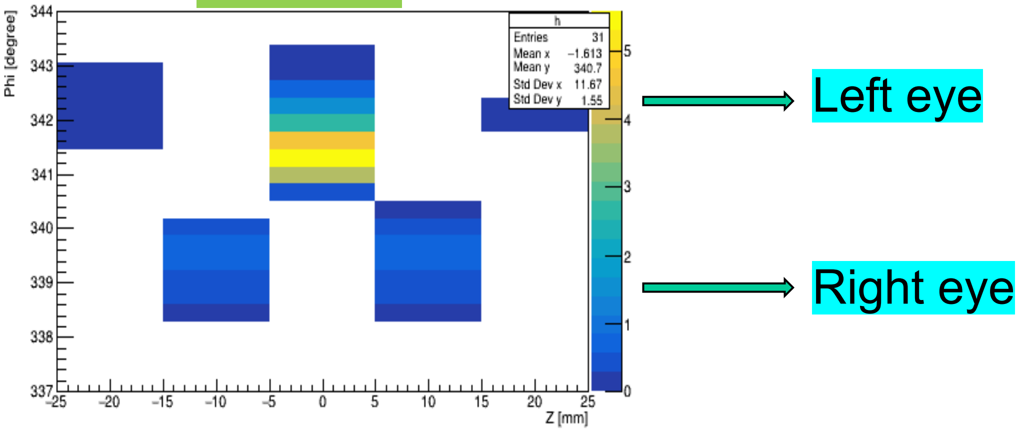




Traditional Crystal Ecal

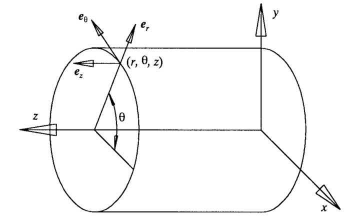


SCEcal

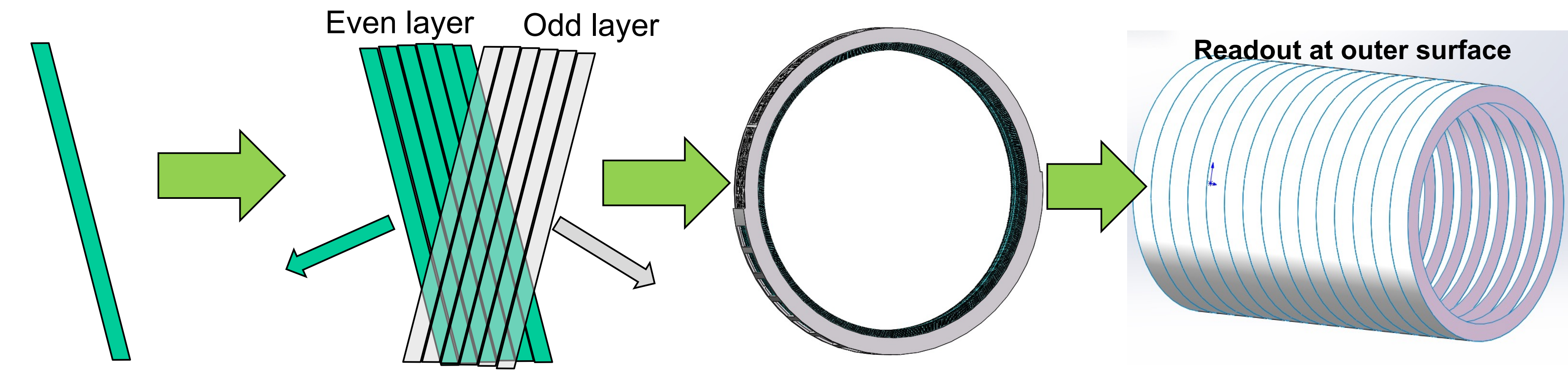


Analytical optimization of SCECal geometry

- 3 degree of freedom for a given inner and outer radius of barrel
  - Pointing angle: $\alpha = [\frac{\pi}{2}, \frac{\pi}{2}]$
    - Correlated with the crystal length: L_R
  - Number of sampling along R: $N_R = [0,1,2,3 \ldots]$
    - *Correlate with the crystal size(typically ~1cm) along* ϕ: L_ϕ
  - Crystal size along Z : L_z (typically 1 cm)



Only one freedom left, α or longitudinal sampling N_R



One trapezoid shape

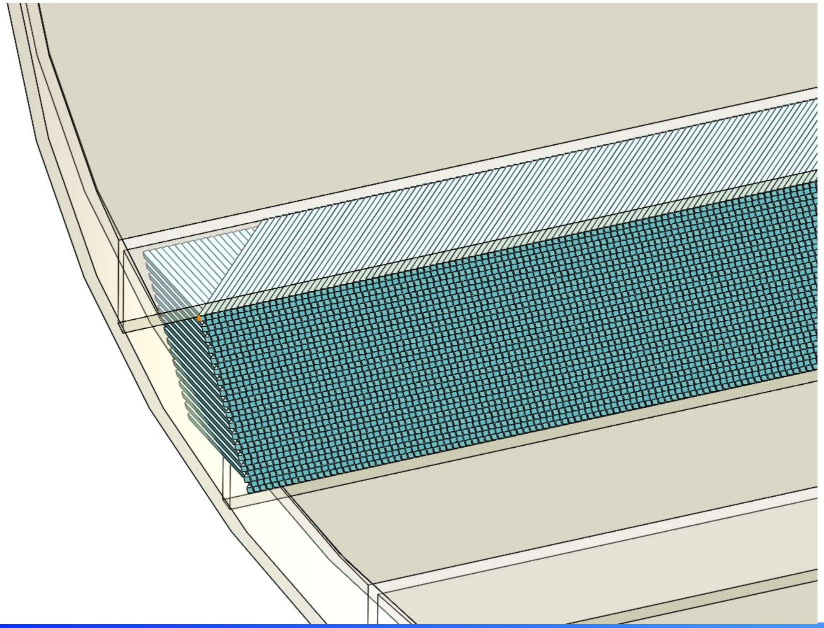
Form stereo structure

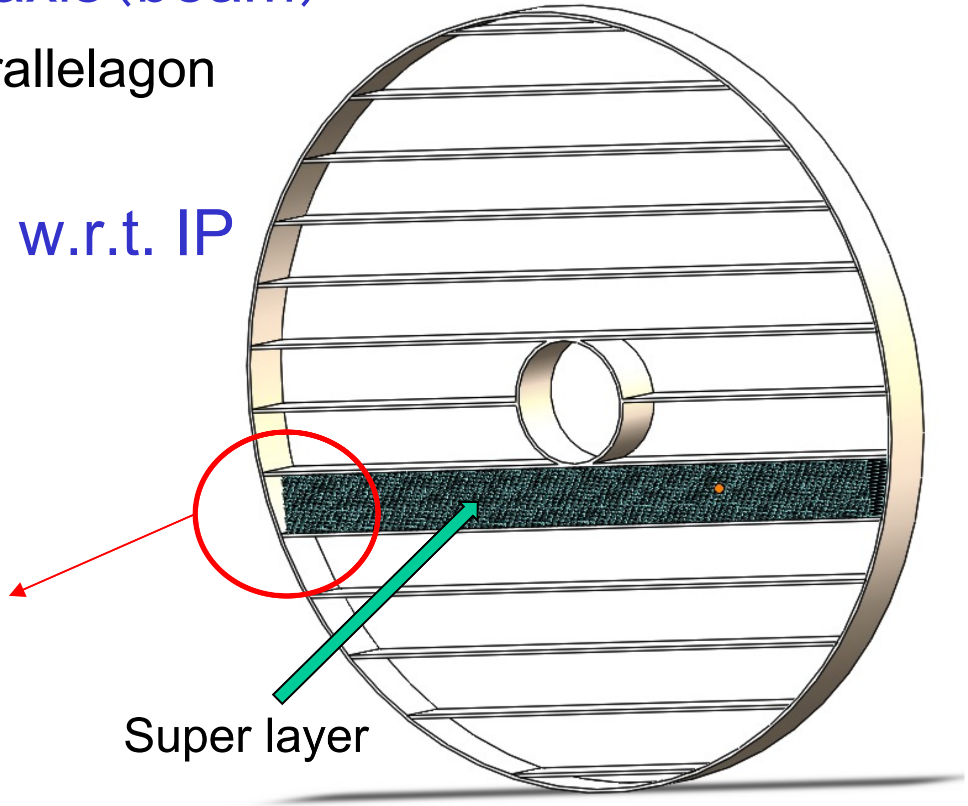
Form a super layer of 30 cm thick along Z

Super layer form the full barrel

Design of Endcap SCECal

- Shelf like structure
- Each Super layer consistent of 30 layers of crystals
- Crystal pointing angle w.r.t. Z axis（beam）
  - One variant of crystal shape: Parallelagon
  - Even layers: α; Odd layers: $-\alpha$
- Readout electronics at outer Z w.r.t. IP





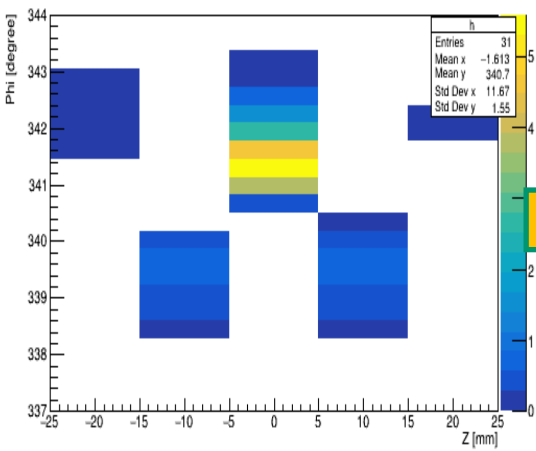
SCECal simulation using BGO crystal

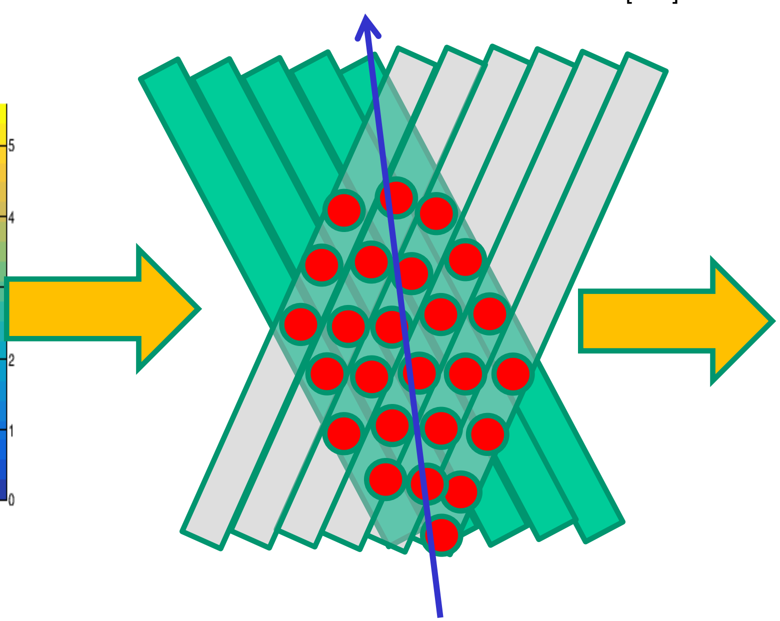
- Simulation and reconstruction done using CEPCSW
  - Ideal Geometry implemented
  - Crystals（BGO）without wrapper/gap etc. (ideal situation)
  - Simulation readout using carloStep info (no digitization)
    - Threshold of readout energy is applied
- Energy, position resolution and separation of photon/pion:
  - Different R segmentations tested: 5/10/14 layers
    - 10 layers turn out to be the best
  - Different recontruction method:
    - Simplified reconstruction
    - End-to-End Machine learning
- The following study based on 10 layers segmentation on R
  - r_1=1.9 m, r_2=2.2m, Z=6.7 m; endcap not included yet. 26.7 X0 BGO
  - Crystal size: L_ϕ = [8.8-8.9]mm; L_Z =10mm; L_R =316 mm
  - Pointing angle: α=20°

Simplified Reco method for isolated particle

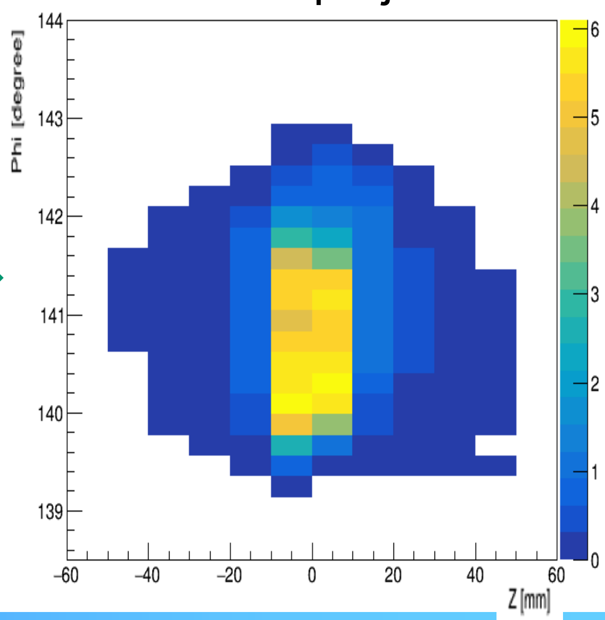
- Find a 2D Cluster, energy is the sum of crystals about 2 MeV
- Hit (red points): The cross point of two nearby cluster crystal
  - Geometric center of hit define its z, phi, R
  - Assign hit energy as sum of the two crossed crystals
  - Renormalize the total energy to the Energy of 2D cluster
- Cluster Phi/Z/R: energy weighted phi/Z/R of all hits

2D cluster



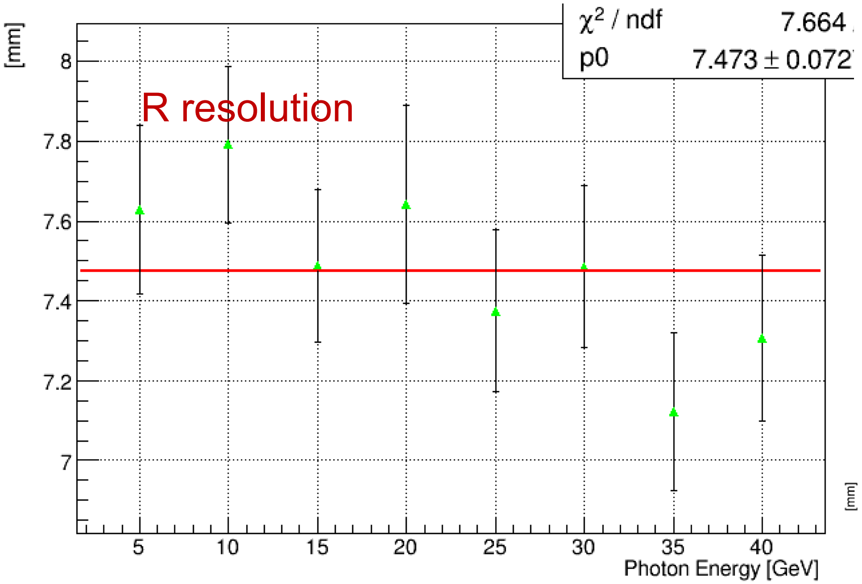


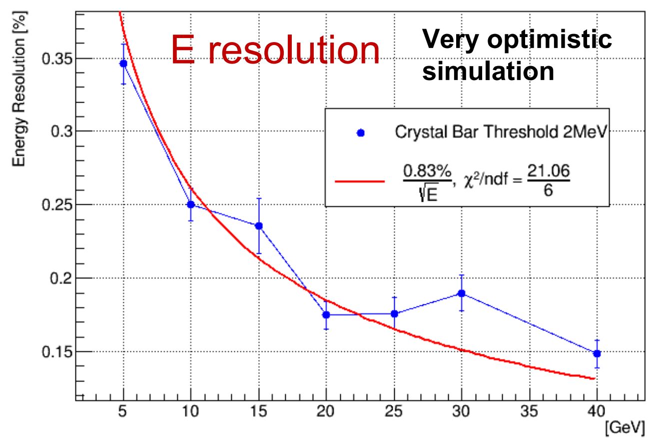
3D hits projection

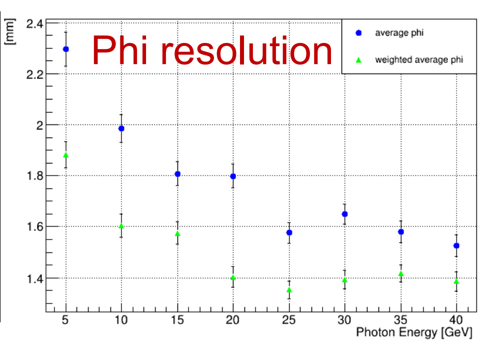


Performance of Energy and 3D positioning resolution

- **Particle gun used: check resolutions as function of γ energy**
- **For 5GeV γ, phi: 0~360°, theta: 90°**
  - Z resolution ~ 0.84 mm; Phi resolution ~ 1.9 mm
  - R resolution ~ 7.6 mm; Energy resolution 0.35%



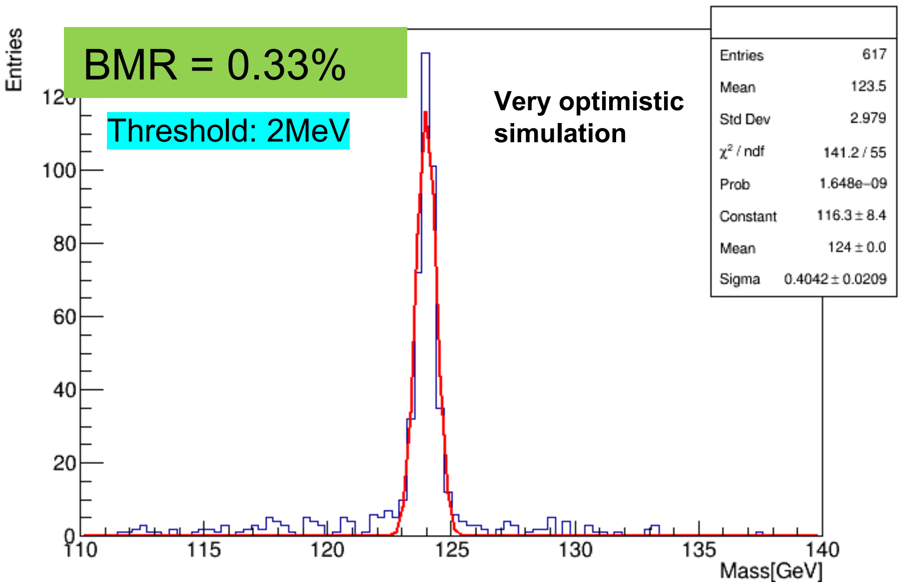


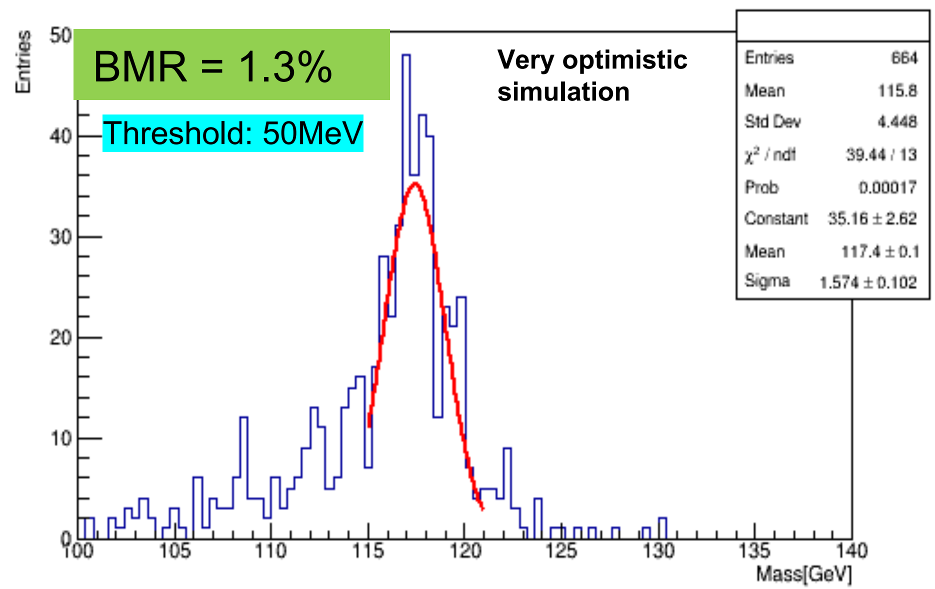


Good energy resolution ☺
Gain resolution along R ☺
Good Z/phi resolution

Boson mass resolution in H→ γγ

- Sample: ZH->2neutrinos + γγ at 240 GeV
- Energy, position reconstruction and separation using simplified reconstruction method described above
- Crystal energy threshold: 2 MeV/50MeV

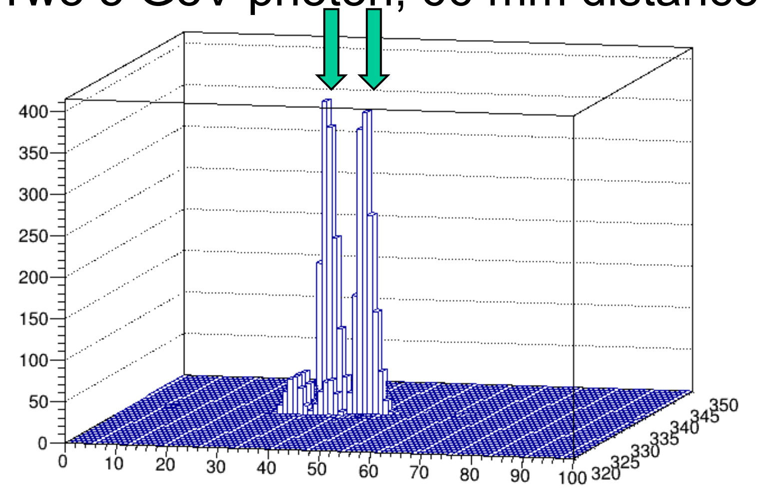




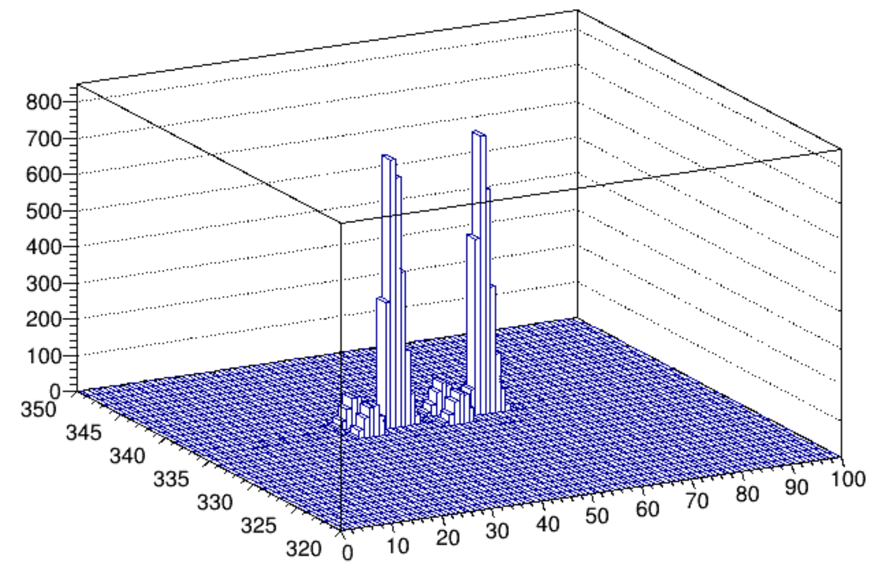
Good BMR, more realistic simulation will give more reliable results

Event display for shower seperation

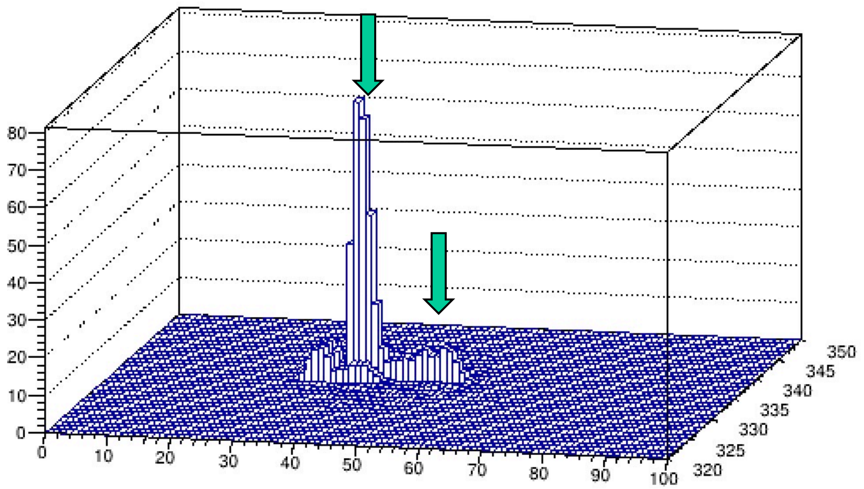
Two 5 GeV photon, 66 mm distance



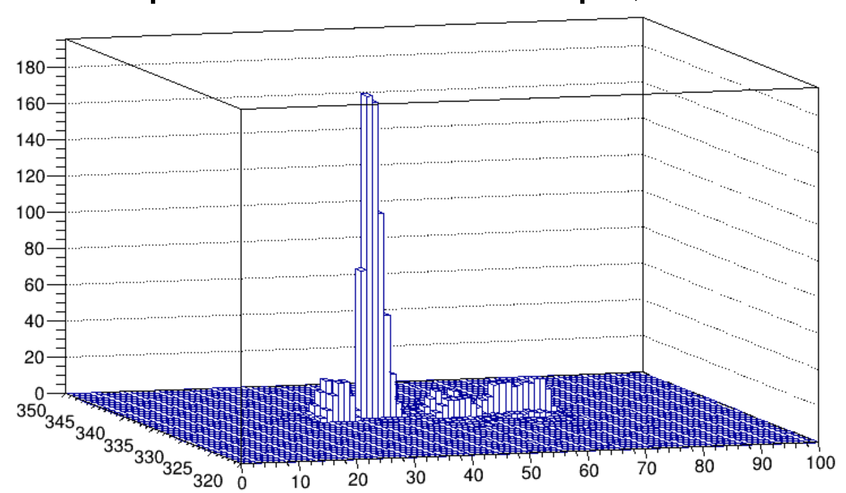
Two 5 GeV photon, 165 mm distance



5 GeV photon and 10 GeV pi-, 66mm

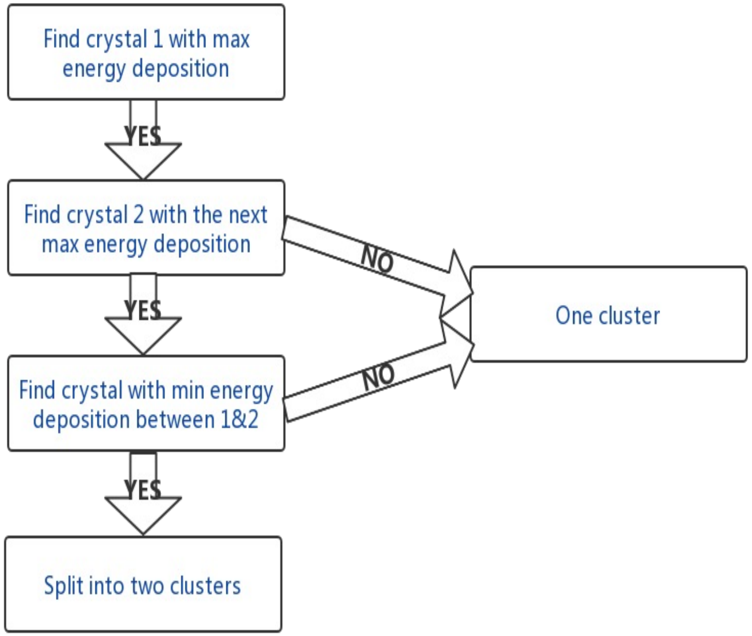


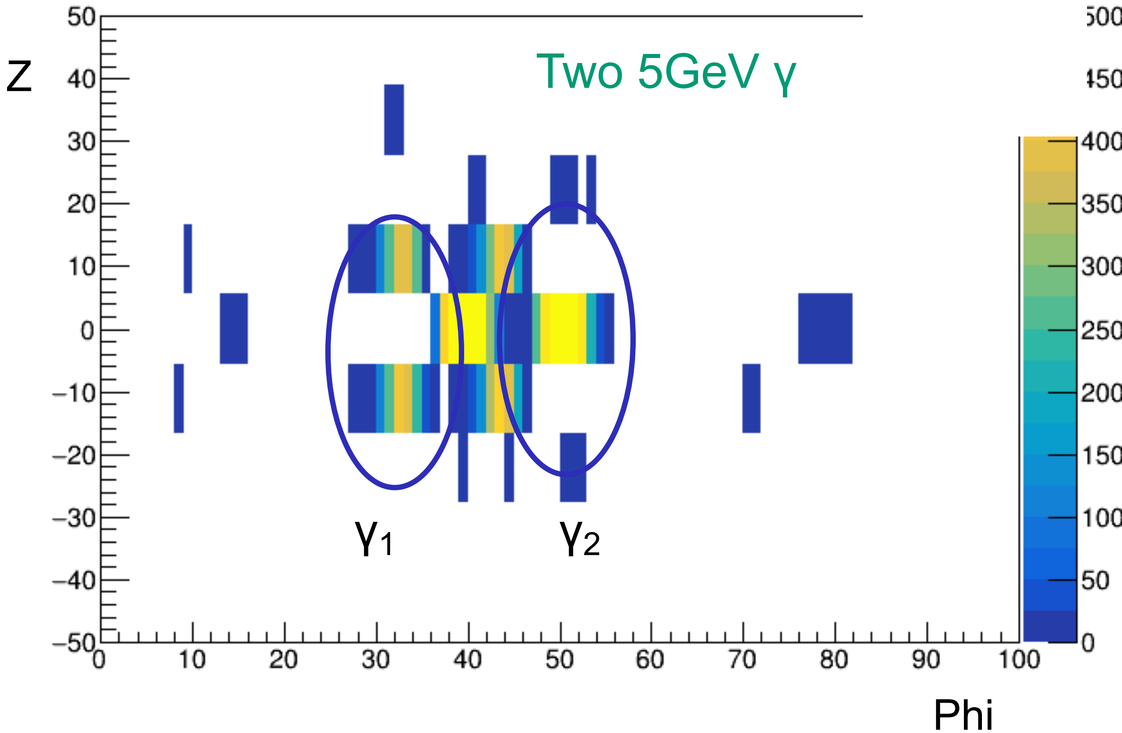
5 GeV photon and 10 GeV pi-, 195mm



Simplified Reco method for 2 particle separation

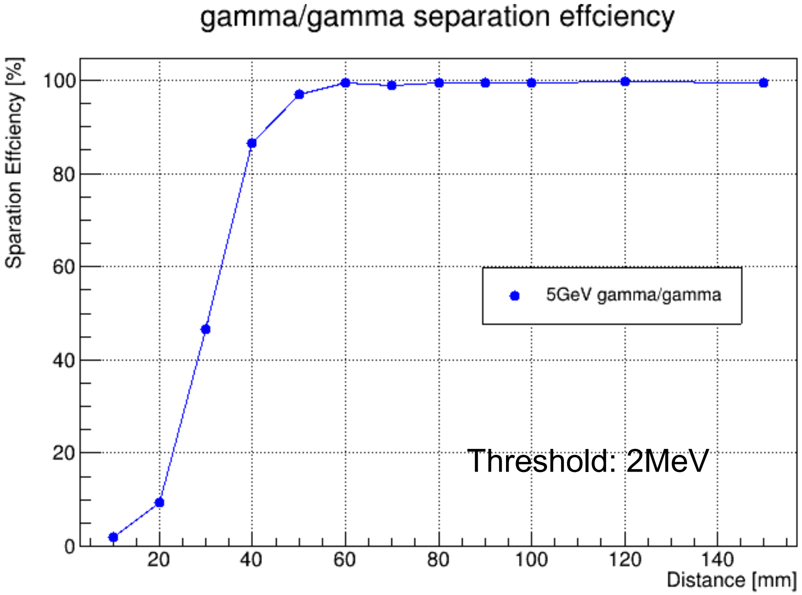
- Cluster splitting
  - For each layer (along Z): Find two locations with maximum energy deposition and separate them by the min. value between them
  - Merge clusters in individual layers use layer matching alg.
    - Criteria on delta phi according to its point angle direction

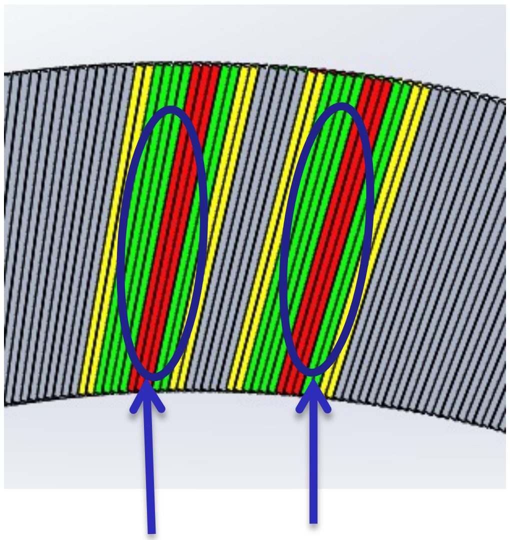




Separation between two 5 GeV photons

- Two 5 GeV photons, vary distance along phi between them
- Success reconstruction: 2 neutral particles, 3.3GeV<Eγ<6.6GeV for each photon

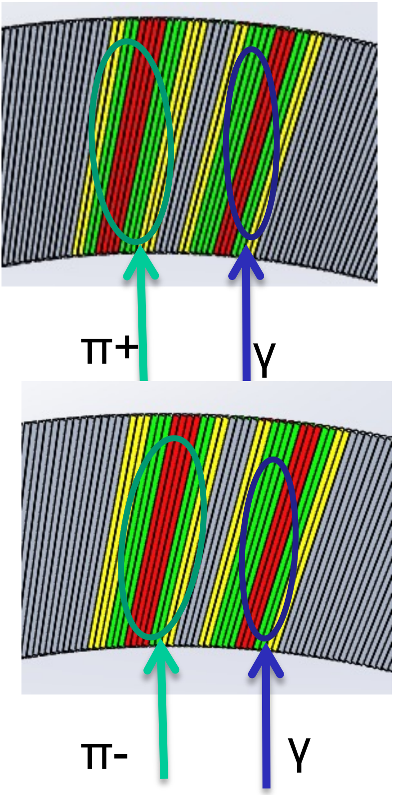


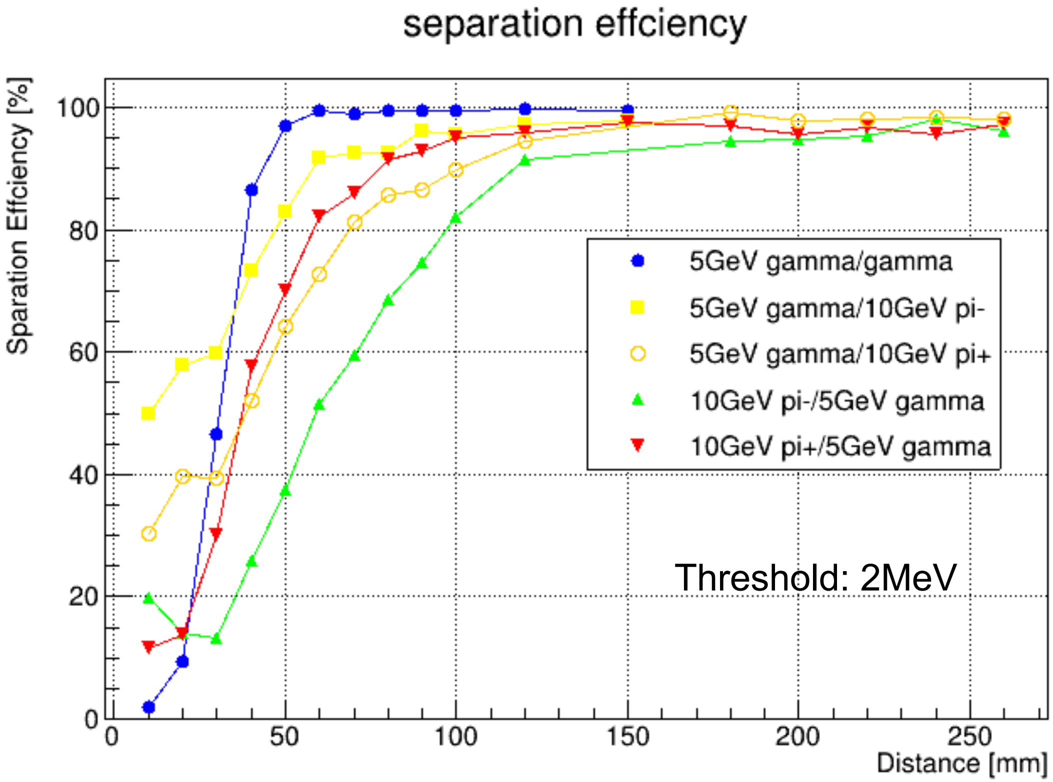


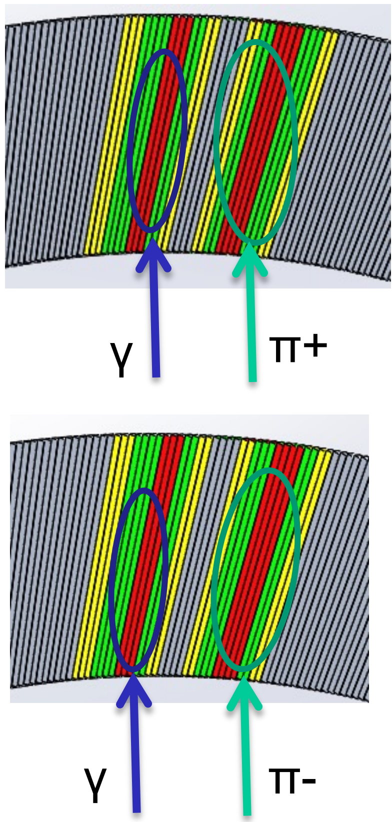
two γ from IP

Separation between γ/π

- 5 GeV γ/10GeV π, vary distance along phi between them
- Success reconstruction: $3.3\text{GeV}<E_\gamma<6.6\text{GeV}$
- Different π/γ separation power: pointing angle / magnetic field

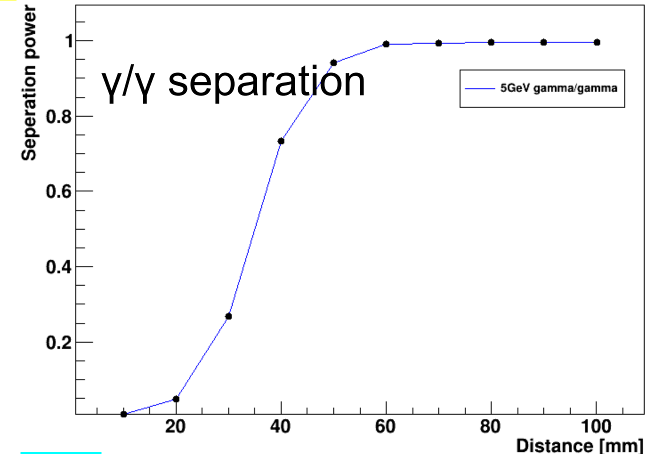




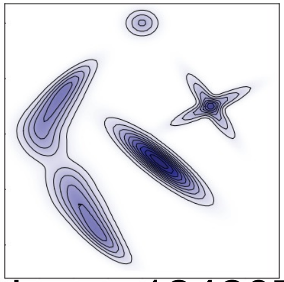


γ/γ performance using CLUE algorithm

- **CLUE (CLUstering of Energy):** Current CMS HGCal reco. alg.
  - Input parameters to determine cluster seeds, outliers and follower hits
  - the cut-off distance in the calculation of local energy density (dc);
  - the minimum density to promote a hit as a seed or the maximum density to demote a hit as an outlier (ρc);
  - the maximum distance for a hit to be linked to a nearest higher point (δo);
  - the minimum distance for a local high density hit to be promoted as a seed (δc).



even dc :1 rho: 2 delta_c: 2 delta_o:3
odd dc :1 rho: 0.2 delta_c: 2 delta_o: 2



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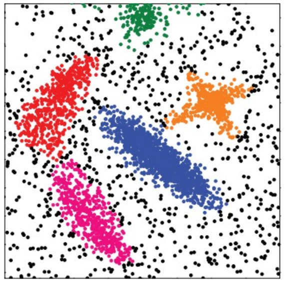
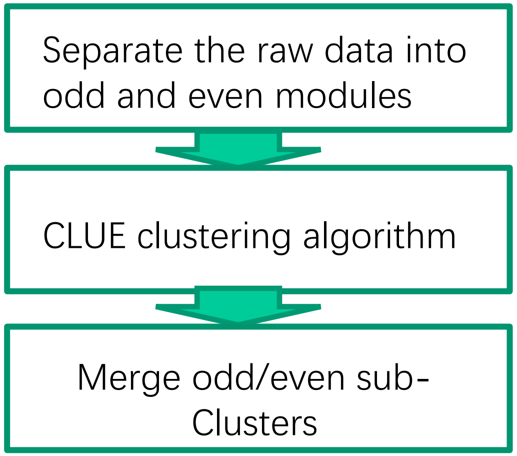
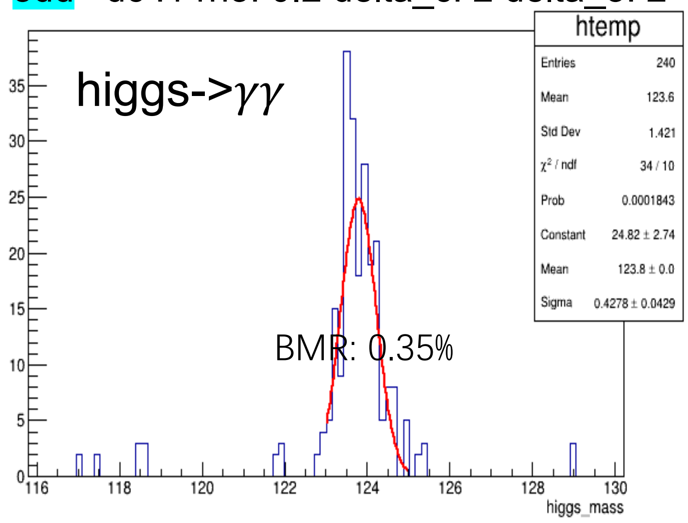






[1] https://cds.cern.ch/record/2802590/files/CR2022_027.pdf

Consistent with simplified method, further tunning possible

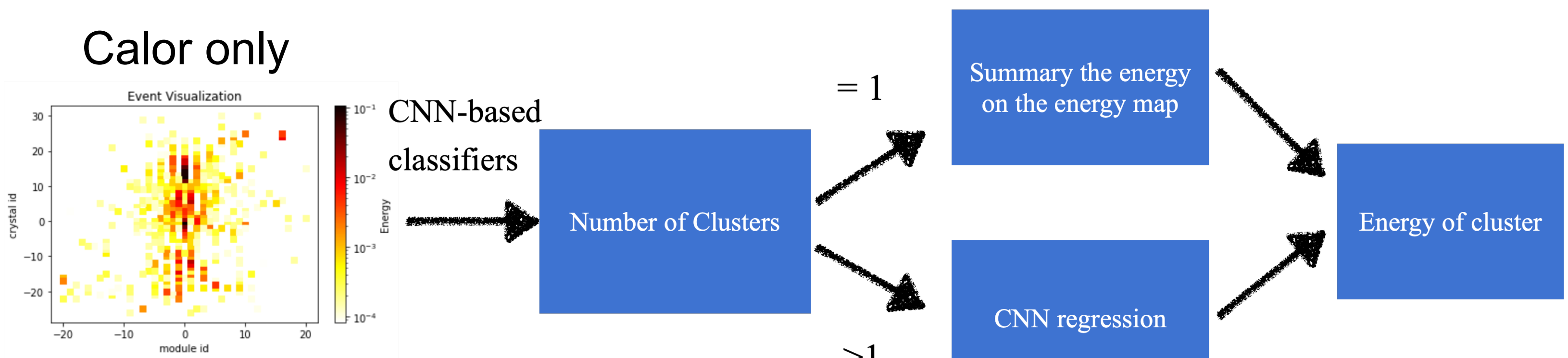
Particle separation using ML

CMS reconstruction of merged photons paper
PRD 108, 052002(2023)

- End-to-End method is used
  - 2 steps, one for classification, one for energy regression(max 2 obj. now)
- More complex NN is under investigation
  - Regression of 2D energy hit map of individual particle
  - Regression of 3D energy hit map of individual particle
  - Clustering
  - PID
  - Jet energy

With information from tracker and helps of PFA

Calor only



Energy map as input

Separation between two 5 GeV photons: ML regression

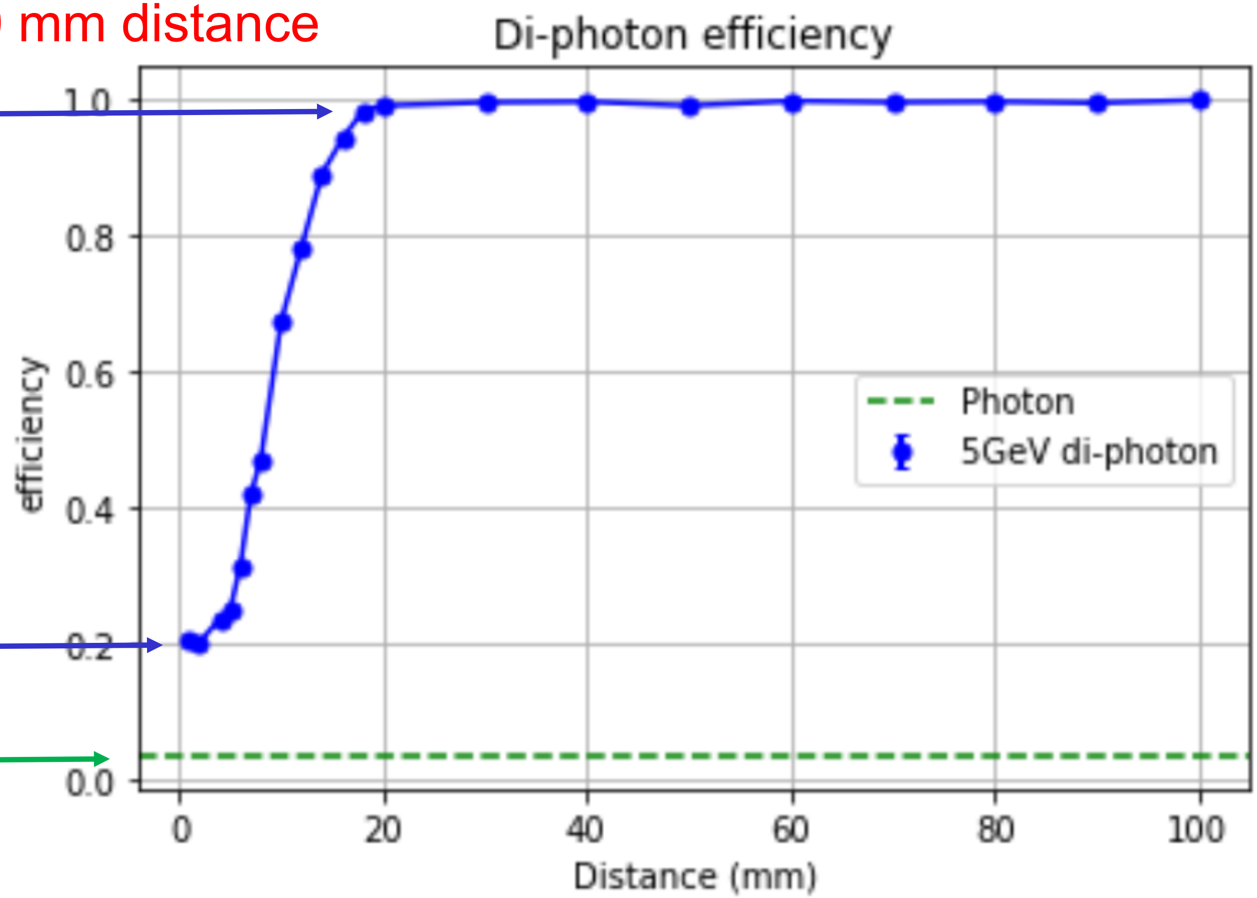
- Trained with 2 γ with energy(0-10] GeV and distances varis
- Significant improvement than simple clustering
  - 100% eff. After 20 mm distance

100% eff when 2 γ distance >20 mm

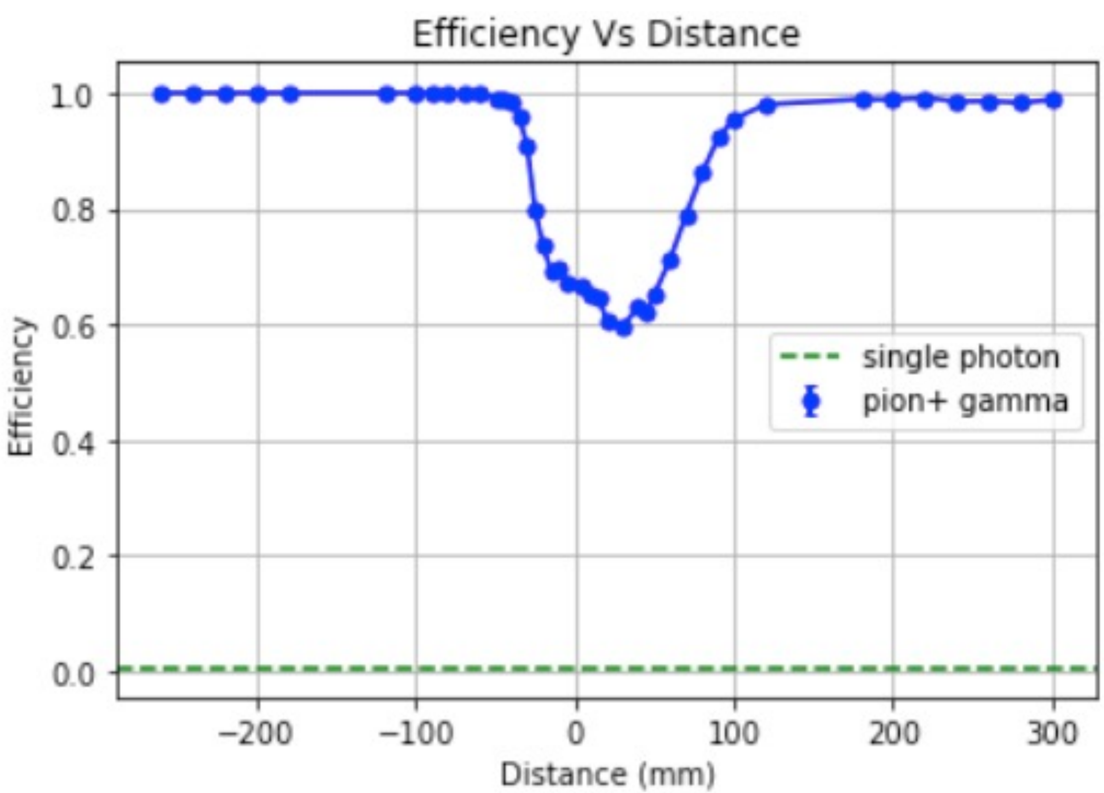
2 γ have diff. shower start

Longitudinal separation, 1->2, conversion

Prob. of 1 γ reco as 2 γs (1->2)



- Trained with a sample of 1-10GeV γ, 2-20GeV π +, distance @calorimeter variated around 20 mm
- Applied to separate 5 GeV photon and 10 GeV π +
  - ~100% efficiency when > 100 mm distance



γ+π

π only

γ only

Summary

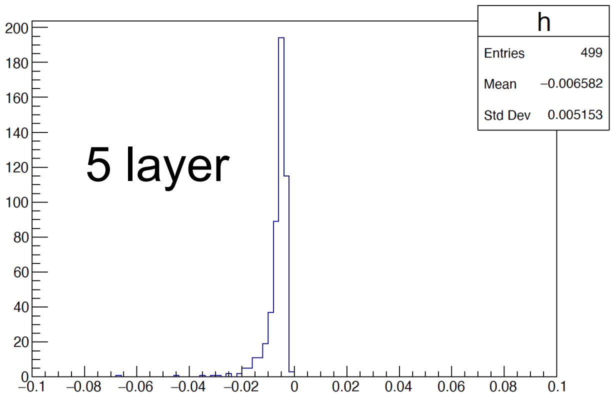
- A new configuration of Homogenous Crystal Ecal is presented
  - Long crystal bar with 2D readout at outer end of ECal
  - Use stereo structure to obtain measurement on the 3rd dimension
    - Only one free parameter: easy to optimize
    - Only one variant of crystal, very uniform in phi, Z, and R
    - minimal dead regions, minimal ghost hits
    - …
- Working principle is demonstrated with preliminary simulation
  - Good energy resolution on EM objects including $H \rightarrow \gamma\gamma$
  - Good separation between γ/γ and γ/π with Machine learning
    - 100% eff. @ 20 mm for γ/γ and @100mm for γ/π
  - PFA/ML jet boson mass resolution study is ongoing
- Optimization of crystal/readout
  - Starting from existing CEPC crystal Ecal R&D: BGO+SiPM
  - Further optimization to consider the large signal size

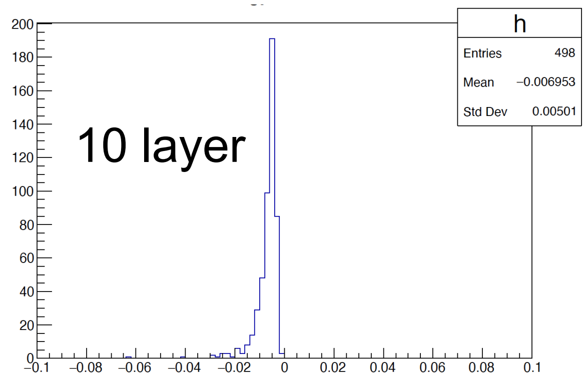
Backup

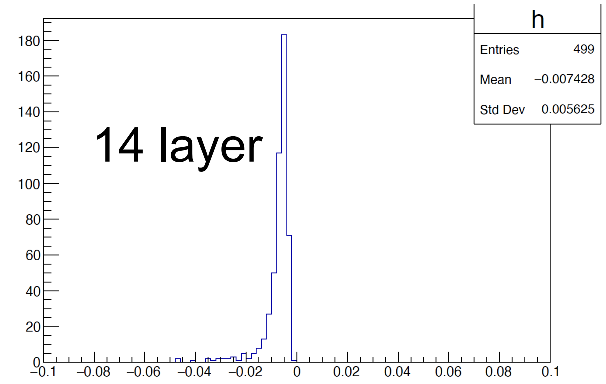
Analytical formular for SCECal geometry

- 3 degree of freedom for a given inner and outer radius of barrel
  - Pointing angle: $\alpha = [0, \frac{\pi}{2}]$
    - Correlated with the crystal length: L_R
  - Number of sampling along R: $N_R = [0,1,2,3 \ldots]$
    - *Correlate with the crystal size(typically ~1cm) along* ϕ: L_ϕ
  - Crystal size along Z : L_z (typically 1 cm)
- $\mathrm{L}_R = \sqrt{r_2^2 - r_1^2 * \sin(\alpha)} - r_1 \cos(\alpha)$
- Crystal bar open angle along ϕ: $\phi_c = acos \frac{r_2^2 + r_1^2 - L_R^2}{2 * r_1 * r_2}$
- Total number of crystals along ϕ: $N_\phi = N_R * \frac{2 * \pi}{\phi_c}$
- Shower depth(S_n) and $crystal\ size\ L_\phi^n$ along R at n^{th} sampling:
  - $S_n = F_{n+1} - F_n; F_n = r_1 * \frac{\sin(\alpha)}{\sin\left(\alpha - n * \frac{\phi_c}{N_R}\right)} - 1; L_\phi^n = S_n * \sin(\alpha - n * \frac{\phi_c}{N_R})$

- Taget: change layers along R, keep similar Z/phi segmentation
  - 5 layers: α=10°; crystal size: [9]*10*304 mm³, n = 1309 * 671;
  - 10 layers: α=20°; crystal size: [8.8-8.9]*10*316 mm³, n = 1276 * 671
  - 14 layers: α=30°; crystal size: [9.1-9.4]*10*339 mm³, n = 1141 * 671
- Simulated 30 GeV photon pointing at theta = 90, phi = [0-360]
- Simpler clustering algorithm with threshold of 1 MeV
- Energy/Z resolution do not change for different layers along R



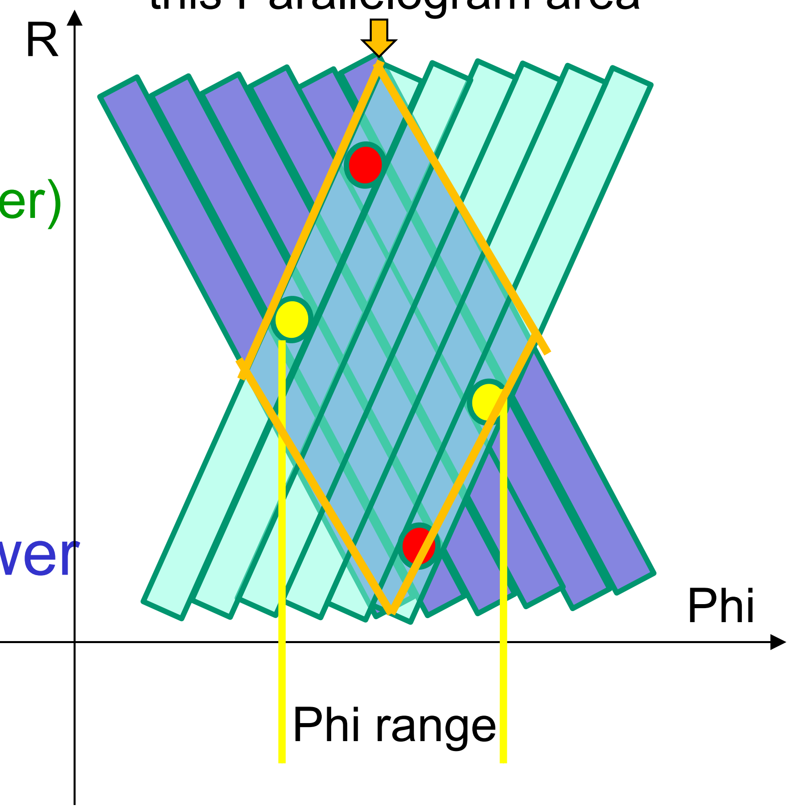




E std. dev. ~0.5%@30GeV

Ghost hits

- Confusion of red hit with yellow ones
  - Happens only in small phi/R range
    - R-range: 0-30CM
    - Phi-range: -4.5 cm - +4.5 cm (10 layer)
- Large probability have hits in middle shower depth, small chance to have hits in small or large shower depth
- Big energy deposited in middle shower depth hit, small in inner/outer depth
- If ghost hits happens
  - largest change of phi: ~4.5 cm,
  - Largest change of R: ~15cm



Ghost hit in Z*phi plane: 1cm * 9cm

Ghost hit in R*phi plane: 30cm * 9cm

SCEcal unit ghost hits area: ～32/2*32/2*sin（2*α）=160cm2;
Long bar Ecal unit ghost hits area: 40*40 = 1600 cm^2