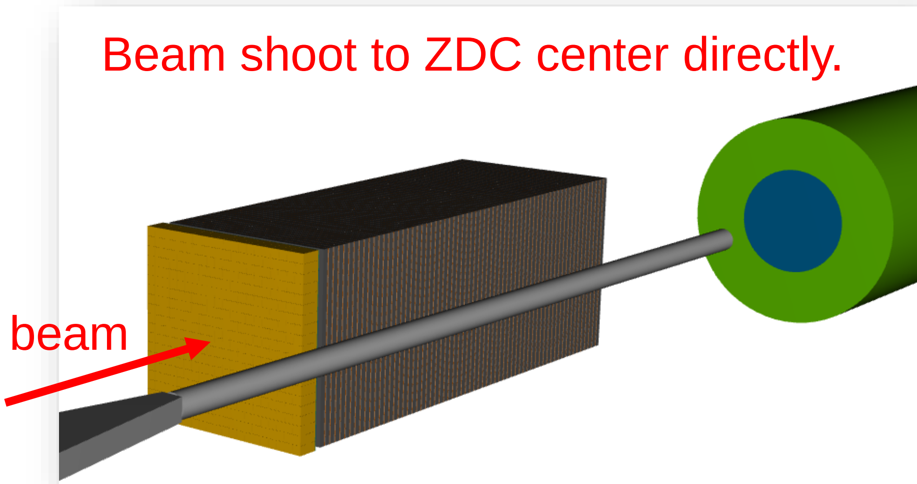
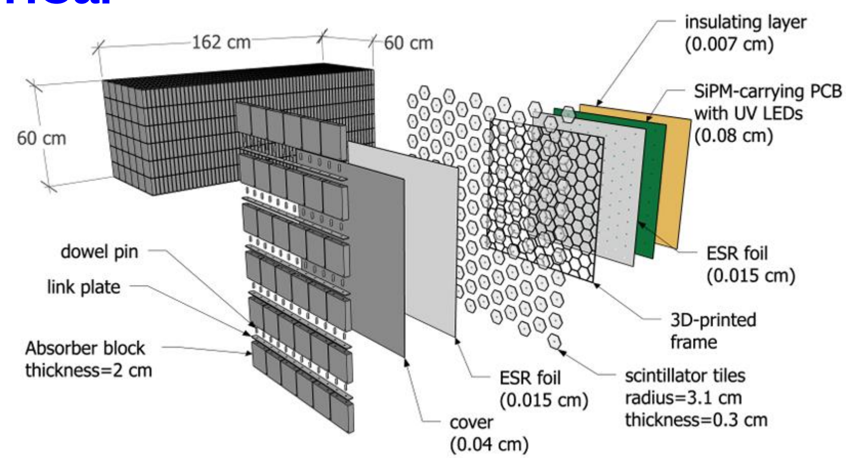
ePIC ZDC MC
20250408

Current Design of ZDC

LYSO Crysal
60cm*60cm
3cm*3cm*7cm / cell
20*20 cells
7cm ~ 6X0 in Z

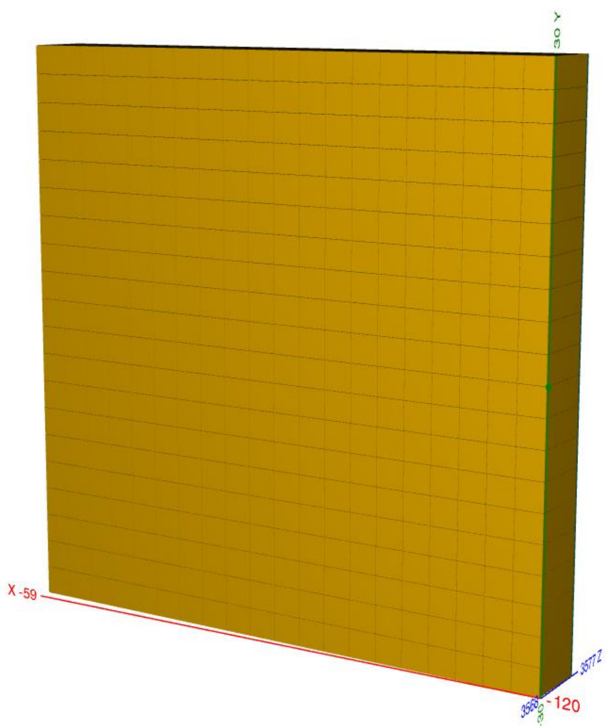


HCal



1 layer = steel + scintillator tile + SiPM
64 layers, 8 slice/layer
65cm in X, 60cm in Y, 163cm in Z

ECal



60cm in X, 60cm in Y, 7cm~6X0 in Z
400 cells, 3cm*3cm*7cm / cell

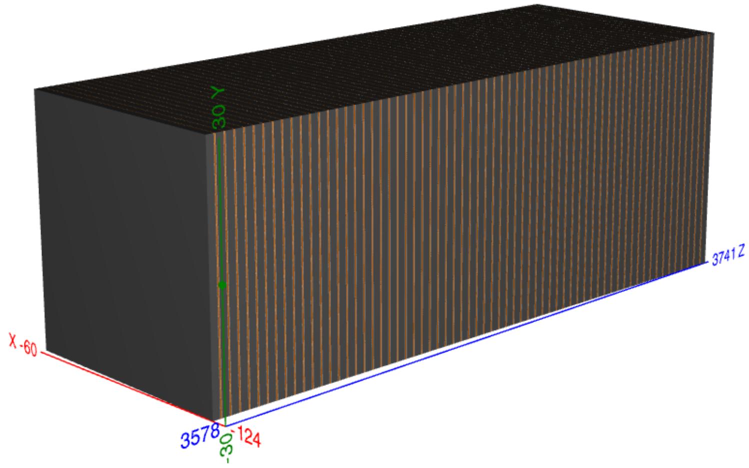
```
<define>
  <constant name="ZDC_width"           value="60.0 * cm"/>
  <constant name="ZDC_r_pos"           value="3550.0 * cm"/>
  <constant name="ZDC_y_pos"           value="0.0 * cm"/>
  <constant name="ZDC_Crystal_r_pos"           value="ZDC_r_pos + 5.9 *cm +19.2*cm"/>
  <constant name="ZDC_Crystal_z_pos"           value="ZDC_Crystal_r_pos * cos(ionCrossingAngle)"/>
  <constant name="ZDC_Crystal_x_pos"           value="ZDC_Crystal_r_pos * sin(ionCrossingAngle)"/>
  <constant name="ZDC_Crystal_y_pos"           value="ZDC_y_pos"/>
  <constant name="ZDC_Crystal_rotateX_angle"   value="0"/>
  <constant name="ZDC_Crystal_rotateY_angle"   value="ionCrossingAngle"/>
  <constant name="ZDC_Crystal_rotateZ_angle"   value="0"/>
  <constant name="ZDC_Crystal_width"           value="ZDC_width"/>


  <constant name="ZDC_Crystal_cell_width"      value="3.*cm"/>
  <constant name="ZDC_Crystal_cell_length"     value="7.*cm"/>
  <constant name="ZDC_Crystal_frame_thickness"  value="0.3*mm"/>
  <constant name="ZDC_Crystal_active_x"        value="ZDC_width"/>
  <constant name="ZDC_Crystal_active_y"        value="ZDC_width"/>
  <constant name="ZDC_Crystal_nx"              value="ZDC_Crystal_active_x/ZDC_Crystal_cell_width"/>
  <constant name="ZDC_Crystal_ny"              value="ZDC_Crystal_active_y/ZDC_Crystal_cell_width"/>
  <constant name="ZDC_Crystal_APD_socket_z"    value="2.5*mm"/>
  <constant name="ZDC_Crystal_space"           value="2.8*cm"/>
</define>
```

~6X0 (1X0 = 1.1 cm)

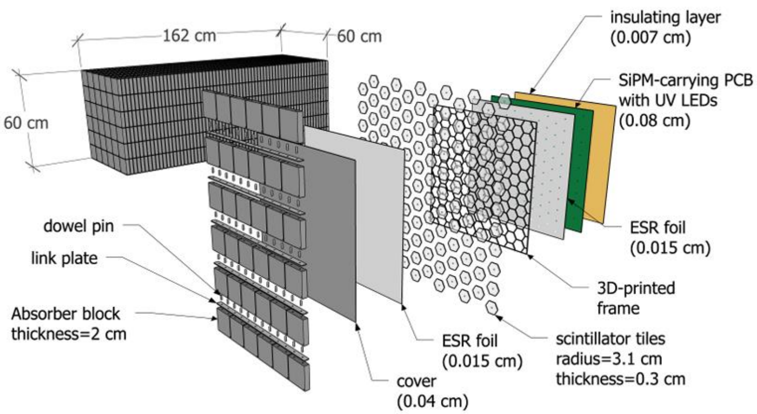
/usrX/cyhsieh/2024ZDC/eic/epic/install/share/epic/epic.xml
/usrX/cyhsieh/2024ZDC/eic/epic/install/share/epic/compact/far_forward/default.xml
/usrX/cyhsieh/2024ZDC/eic/epic/install/share/epic/compact/far_forward/ZDC_Crystal_LYSO.xml
/usrX/cyhsieh/2024ZDC/eic/epic/install/share/epic/compact/far_forward/ZDC_SiPMonTile.xml

Change setting : modify xml file and recompile.

HCal



65cm in X, 60cm in Y, 163cm in Z
64 layers, 8 slice/layer




```
<comment> Slices will be ordered according to the slice order listed h
<comment> Steel/Sc layers </comment>
<layer repeat="HcalFarForwardZDC_SiPMonTile_Layer_NSteelRepeat" thickn
  <slice name="Absorber_slice" material="Steel235" thickness="HcalFarF
  <slice name="Air_slice" material="Air" thickness="HcalFarForwardZDC_
  <slice name="ScintCover_slice" material="Aluminum" thickness="HcalFa
  <slice name="ESRFoil_slice" material="Polystyrene" thickness="HcalFa
  <slice name="Scintillator_slice" material="Polystyrene" thickness="H
  <slice name="ESRFoil_slice" material="Polystyrene" thickness="HcalFa
  <slice name="PCB_slice" material="Fr4" thickness="HcalFarForwardZDC_
  <slice name="Air_slice" material="Air" thickness="HcalFarForwardZDC_
</layer>
<comment> Final layer of steel </comment>
```

```
<documentation>
  #### Material Thicknesses
</documentation>
<constant name="HcalFarForwardZDC_SiPMonTile_AirThickness"                 value="0.02*cm"/>
<constant name="HcalFarForwardZDC_SiPMonTile_AbsorberThickness"            value="2*cm"/>
<constant name="HcalFarForwardZDC_SiPMonTile_ScintillatorCoverThickness"   value="0.04*cm"/>
<constant name="HcalFarForwardZDC_SiPMonTile_PolystyreneThickness"         value="0.30*cm"/>
<constant name="HcalFarForwardZDC_SiPMonTile_PCBThickness"                 value="0.08*cm"/>
<constant name="HcalFarForwardZDC_SiPMonTile_ESRFoilThickness"             value="0.015*cm"/>
```

Beam Condition

Steering.py

```
energyMin = "10*GeV"
energyMax = "10*GeV"
particle = "neutron" #e+, don't use positron
```

beam type and energy
Gamma : 0-40GeV
Neutron : 0-350 GeV

```
ionCrossingAngle = -0.025 * radian
ZDC_r_pos = 35500
ZDC_x_pos = ZDC_r_pos * math.sin(-0.025)
ZDC_y_pos = 0
ZDC_z_pos = ZDC_r_pos * math.cos(-0.025)
shift = 15
```

beam starting point
➔ In front of ZDC surface

```
SIM.numberOfEvents = 1000
SIM.enableGun = True
SIM.gun.particle = particle
SIM.gun.momentumMin = eval(energyMin)
SIM.gun.momentumMax = eval(energyMax)
SIM.gun.distribution = "uniform"
SIM.gun.multiplicity = 1
```

```
SIM.gun.position = (ZDC_x_pos-shift, ZDC_y_pos-shift, ZDC_z_pos)
SIM.gun.thetaMin = ionCrossingAngle #- 70* degree
SIM.gun.thetaMax = ionCrossingAngle #+ 70* degree
SIM.gun.phiMin = 0* degree
SIM.gun.phiMax = 0* degree
```

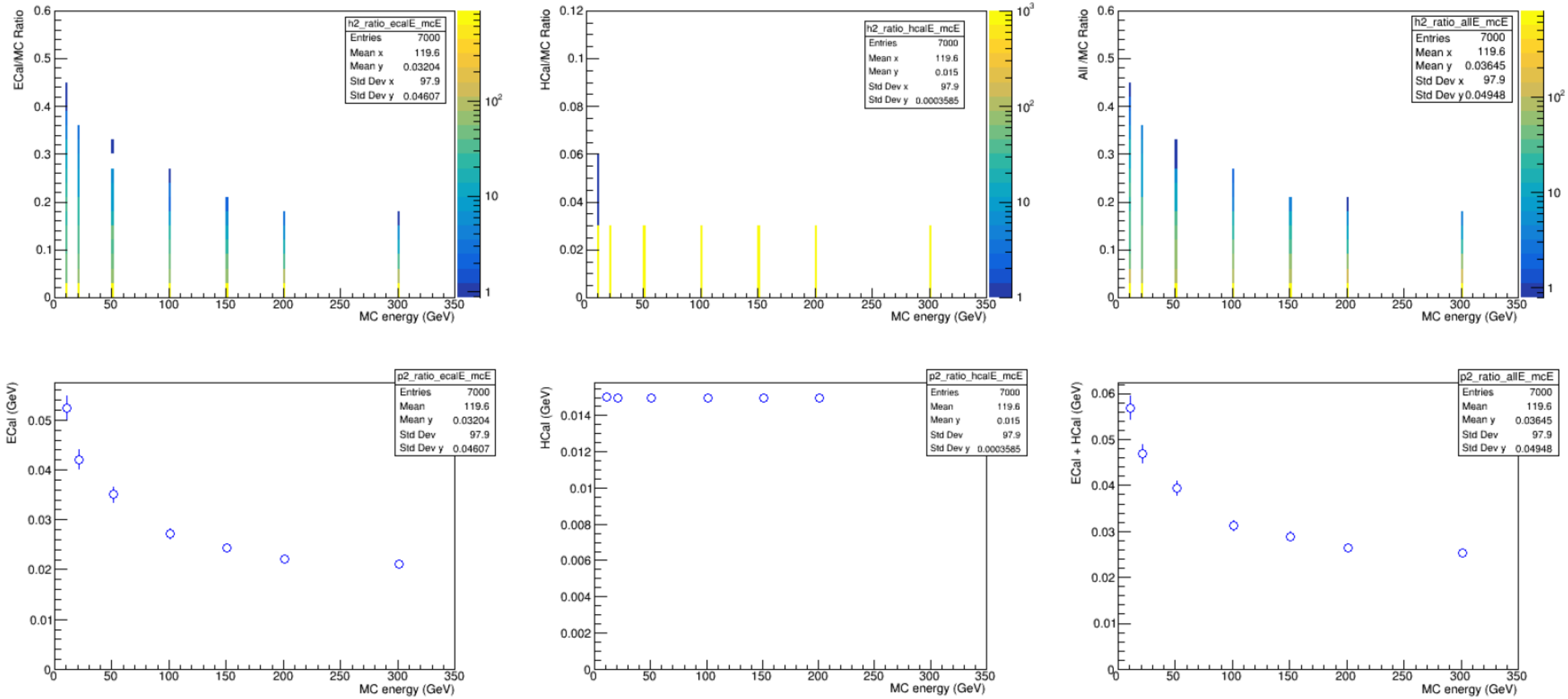
beam angle
➔ Straight beam

0-350GeV Neutron LYSO Crystal

Ebeam = {10., 20., 50., 100, 150., 200., 300.} (GeV)

Neutron + LYSO : Energy Dump

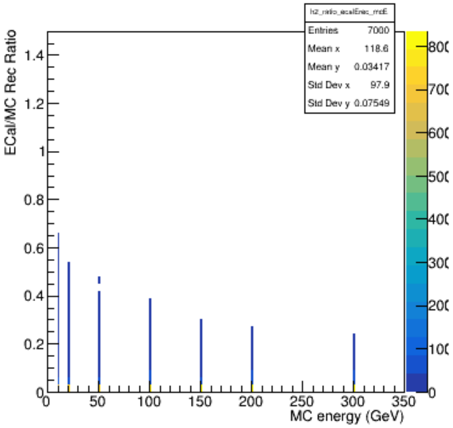
ECal / Ebeam   HCal / Ebeam   "ECal + Hcal" / Ebeam

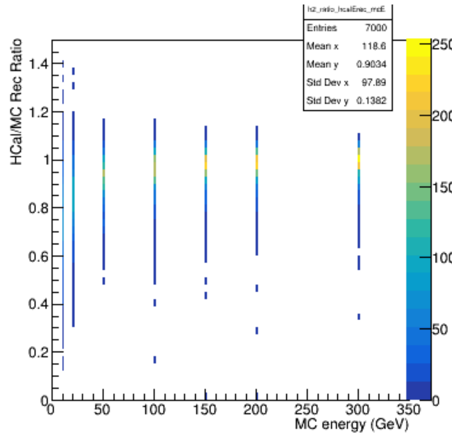


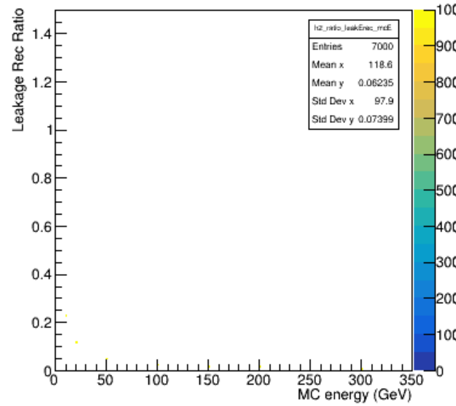
- < 6% energy dumped in ZDC.
- More energy dumped in ECal than Hcal (?)

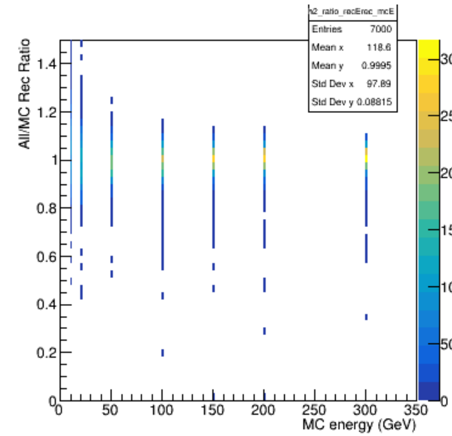
Neutron + LYSO : Energy Rec.

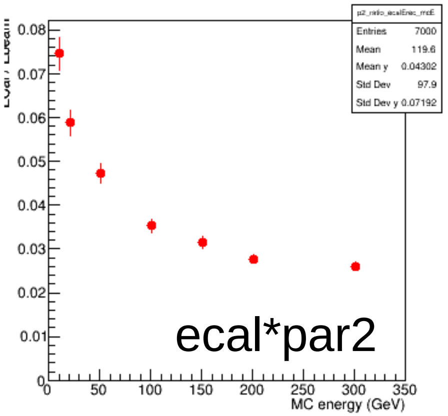
ECal / Ebeam	HCal / Ebeam	Leakage / Ebeam	All / Ebeam

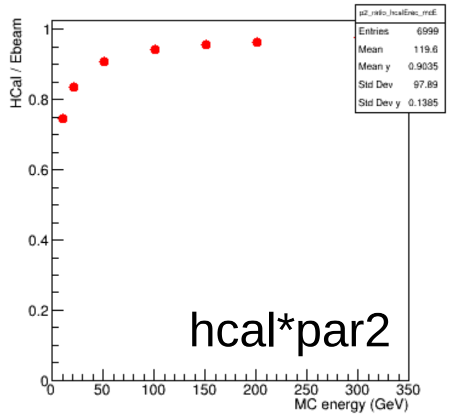


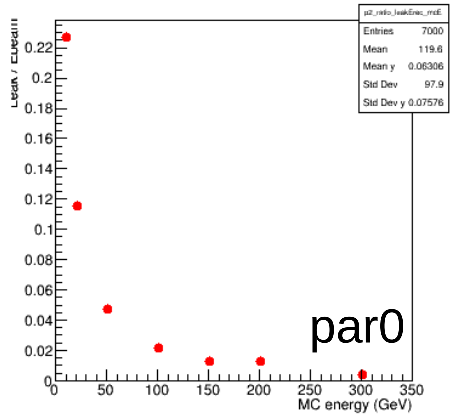


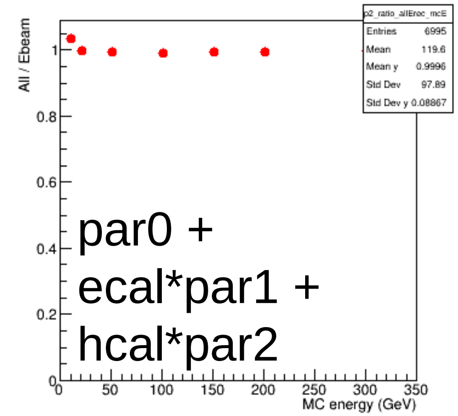












After reconstruction, energy dump in HCal dominates.

```
par[0]=2.238282+-0.085743
par[1]=1.518254+-0.034480
par[2]=54.494963+-0.074631
```

Energy Reconstruction

Loop over all events

```
// --- Assign data for liner fitter
data[0 + ev_tot*npar] = ecal_e;
data[1 + ev_tot*npar] = hcal_e;
e[ev_tot] = sqrt( eList_num[ifl] );
y[ev_tot] = eList_num[ifl];
```

Reconstructed energy

params(0) : leakage
Params(1) : scaling for ecal
Params(2) : scaling for hcal

```
//- ZDC rec energy
all_e = params(0)
  + ( ecal_e*params(1) )
  + ( hcal_e*params(2) );
```

Linear fit

```
// ------------ Linear fitter ------------
// hyp2  = p0 + p1 * ecalData + p2 * hcalData = Etoal
//-> p0 , p1*ecalData, p2*hcalData
TLinearFitter *lf = new TLinearFitter(npar, "hyp2");
lf->AssignData(ev_tot, npar, data, y, e);
lf->Eval();

TVectorD params;
TVectorD errors;
lf->GetParameters(params);
lf->GetErrors(errors);
for (Int_t i=0; i<npar+1; i++)
  printf("par[%d]=%f+-%f\n", i, params(i), errors(i));
Double_t chisquare=lf->GetChisquare();
printf("chisquare=%f\n", chisquare);
```

```
2.2.3 The fastest functions to compute are polynomials and hyperplanes.
      --Polynomials are set the usual way: "pol1", "pol2",...
      --Hyperplanes are set by expression "hyp3", "hyp4", ...
      ---The "hypN" expressions only work when the linear fitter
         is used directly, not through TH1::Fit or TGraph::Fit.
         To fit a graph or a histogram with a hyperplane, define
         the function as "1++x++y".
      ---A constant term is assumed for a hyperplane, when using
         the "hypN" expression, so "hyp3" is in fact fitting with
         "1++x++y++z" function.
```

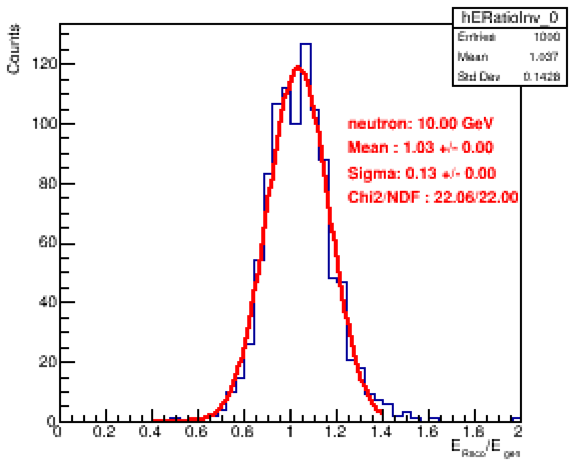
https://root.cern.ch/doc/master/TLinearFitter_8h_source.html

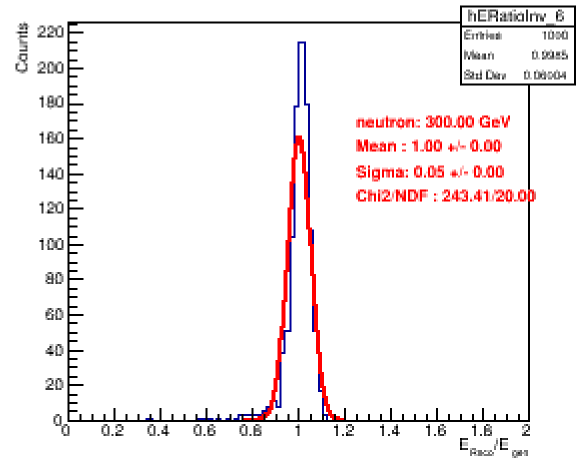
Fitting of Erec/Ebeam

10GeV

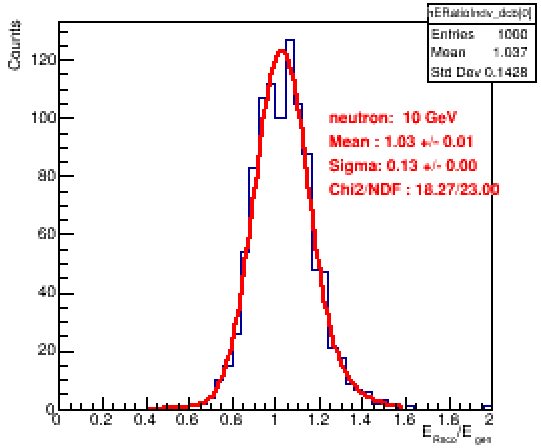
300 GeV

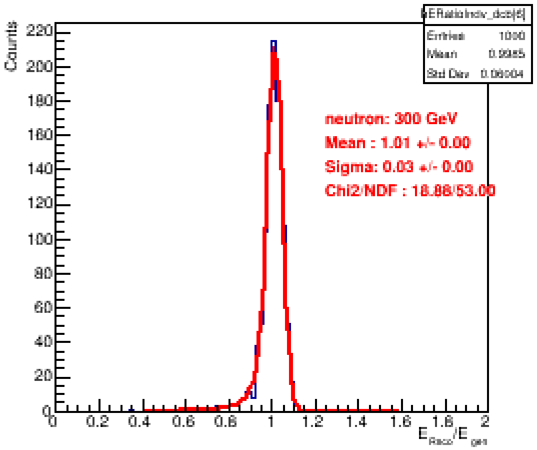
Gaus Fit



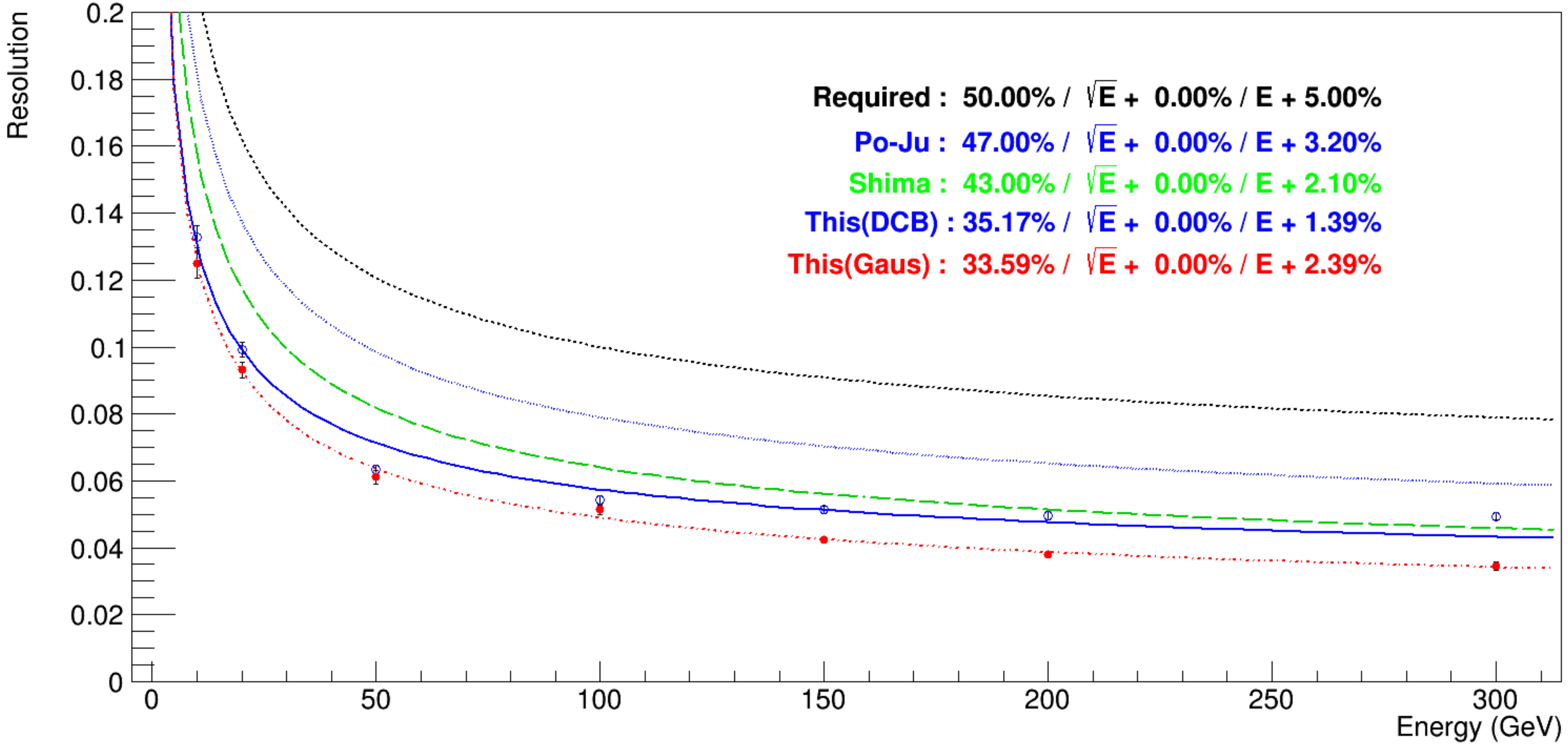


DCB Fit





Energy Resolution (Neutron)



New design of ZDC is better than the previous design (Shima , Po-Ju).

Fitting : Resolution VS Energy

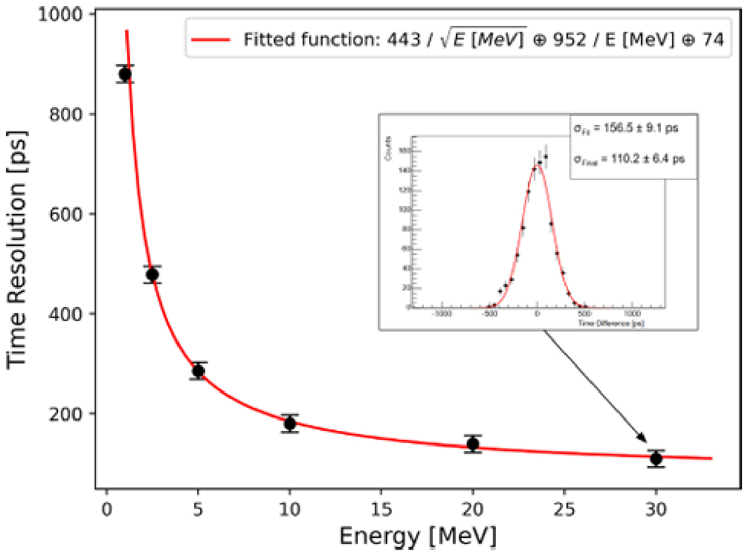


Fig. 13. Dependence of time resolution of a LYSO crystal in the array on the energy deposition in the LYSO crystal for energy deposition between 1–30 MeV. A 110 ps time resolution is measured for 30 MeV energy deposits after the resolution of the reference time is removed via quadrature from σ_{Fit}.

Energy resolution measurements were performed using all three radioactive sources, which provided nine different energies in total. The resulting energy resolution of a LYSO crystal as a function of γ-ray energy is shown in Fig. 5. An electromagnetic calorimeter energy resolution is typically represented with the following functional dependence:

$$\frac{\sigma_{E_\mu}}{E_\mu}(\%) = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c, \quad (2)$$

where a, b, c are constants and E_μ is the incident particle energy in MeV. Here, $a/\sqrt{E}$ is a statistical term used to express the contribution from Poisson processes, such as photostatistics, to energy resolution. The b/E term parameterizes noise contributions to energy resolution from electronics and PMTs, and the constant c parameterizes contributions from shower leakage, crystal non-uniformity, and intra-crystal miscalibrations to energy resolution. In single crystal testing, the photosensor used to read out the crystal is operated at a high voltage where noise is minimized, thereby resulting in $b \to 0$ in the fit to Eq. (2). The constant term c is also assumed to be dominated by crystal non-uniformity for single crystal tests. We find $a = (3.84 \pm 0.19)\ \sqrt{\text{MeV}}$ and $c = (0.64 \pm 0.57)$. Because the PIONEER experiment operates at a higher energy range than radioactive sources ($\mathcal{O}(10) - \mathcal{O}(100)$ MeV), the stochastic term will be greatly suppressed in the PIONEER energy regime.

Previous Design of ZDC (Shima)

The first ZDC design (May 2021)

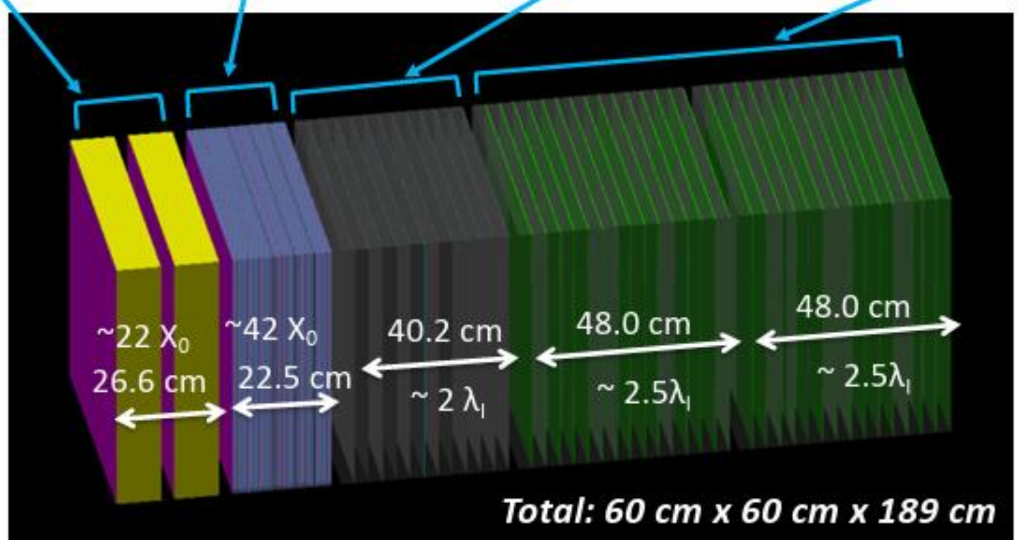
- Concept: **Crystal + FoCal style EM calorimeter + Hadron Calorimeter**

Silicon
(3 mm x 3mm)
Crystal (PbWO4)
- Tag low energy photon

Tungsten
Silicon (1 cm x 1 cm)
with a few **Si** (3mm x 3mm) layers
- Measure EM shower
- Identify photon/neutron

Pb
Silicon (1 cm x 1 cm)
- Measure starting of hadron shower (position)
- Radiation hardness

Pb
Scintillator
- Measure hadron energy



6

Previous Requiems

Physics requirements

- **Neutrons**
  - Need to measure neutrons with **$E \sim E_p^{beam}$**
  - Energy resolution: acceptable **50%/√E + 5%**, ideally **35%/√E + 2%**
  - Angular resolution: **3mrad/√E**

    300 μrad <-> 1 cm on ZDC <-> $p_T \sim$ 30 MeV for 100 GeV neutron
  - Large acceptance of 60cm x 60 cm.
- **Photons**
  - Detect soft photons of **O(100) MeV**
    - Efficiency **> 90%**
    - Energy resolution: **20 – 30%**
  - Detect photons of **20-40 GeV**
    - Energy resolution: **35%/√E**
    - 2 photons from π^0

      Nominal distance of 2 photons: 14 cm
    - neutron + 2 photons (Λ decay) , neutron + 3 photons (Σ^0 decay)

      Position resolution: 0.5-1mm

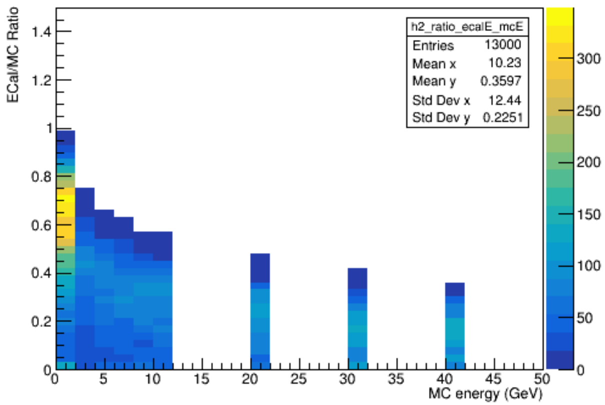
5

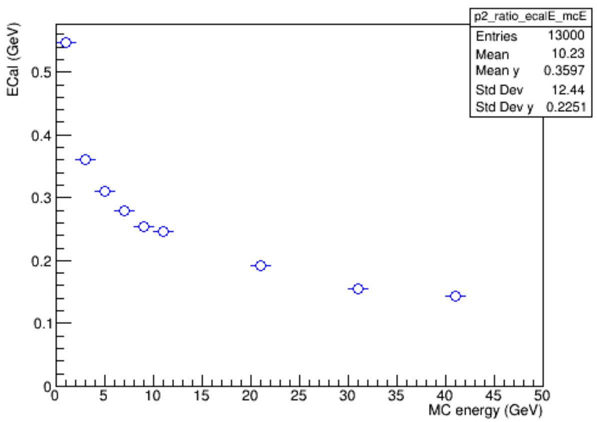
0-40GeV Gamma
LYSO crystal

Ebeam = {0.3, 0.5, 0.7, 0.9, 1.0, 3.0, 5.0, 7.0, 9.0, 10.0, 20.0, 30.0, 40.0} GeV

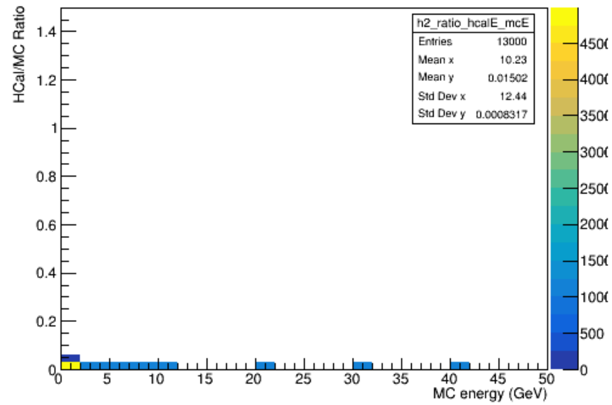
Gamma + LYSO : Energy Dump

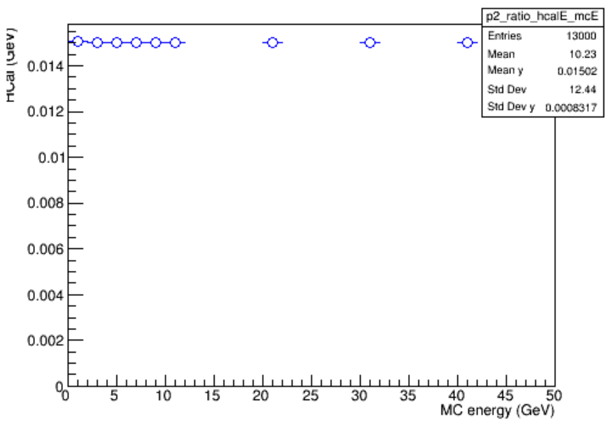
ECal / Ebeam



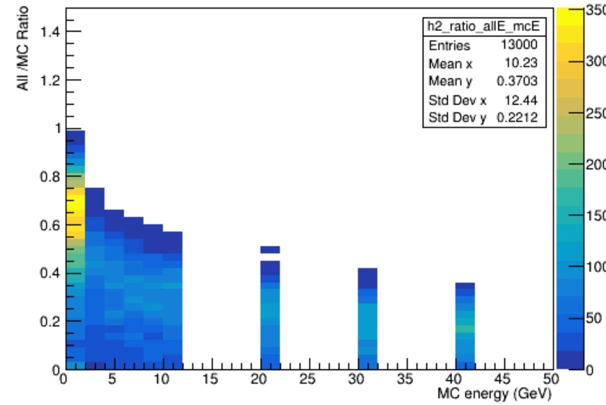


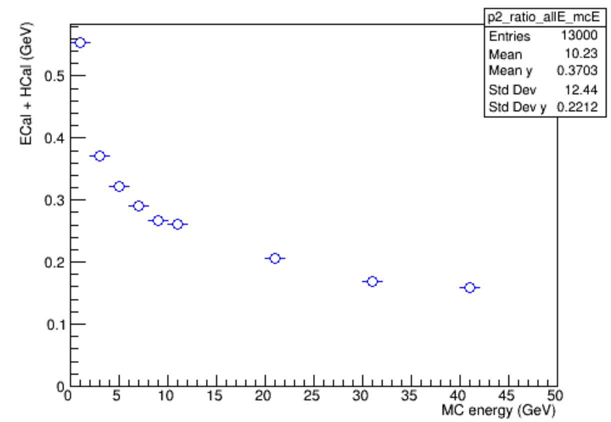
HCal / Ebeam





“ECal + Hcal” / Ebeam

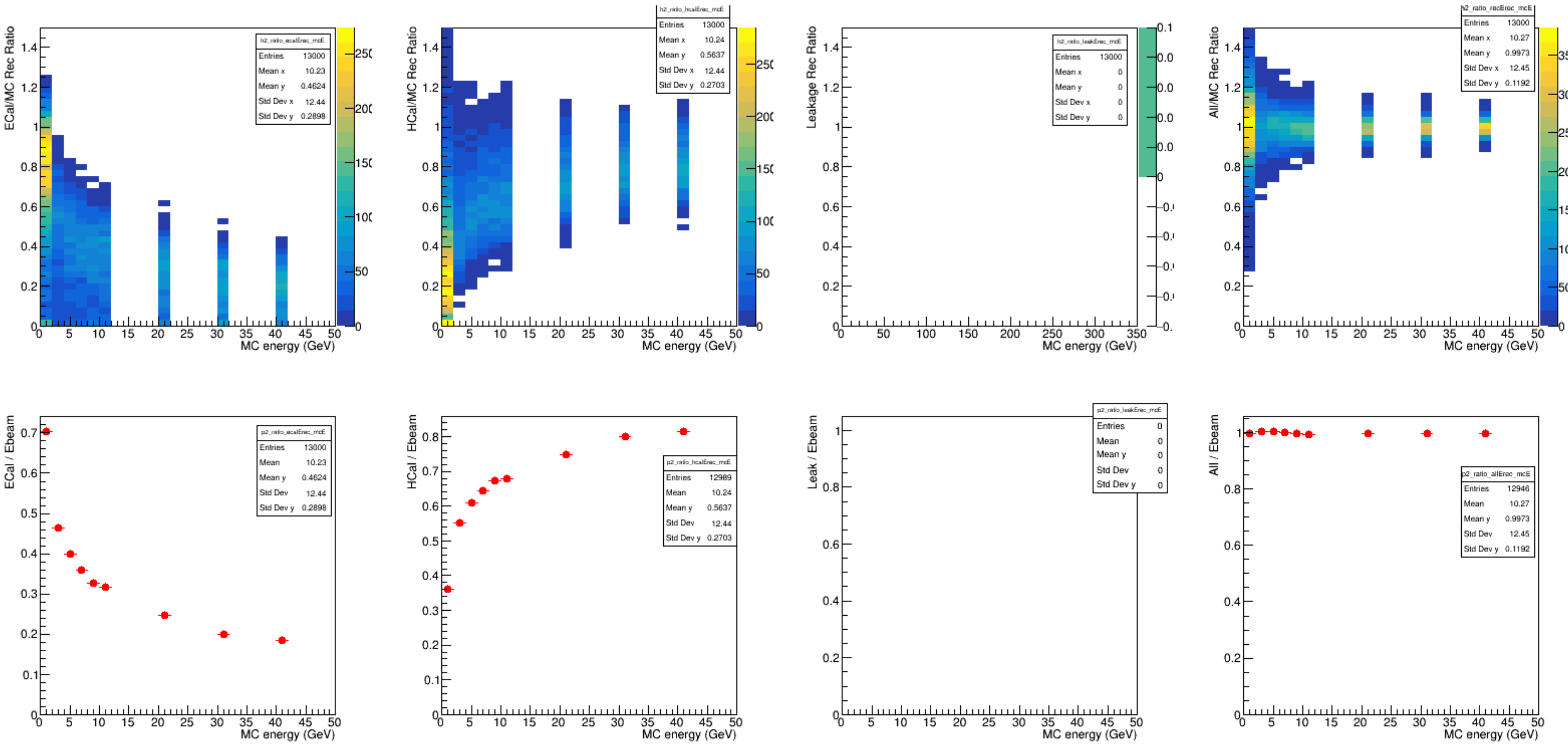




Most energy dumped in Ecal ➔ Normal

Gamma + LYSO : Energy Rec.

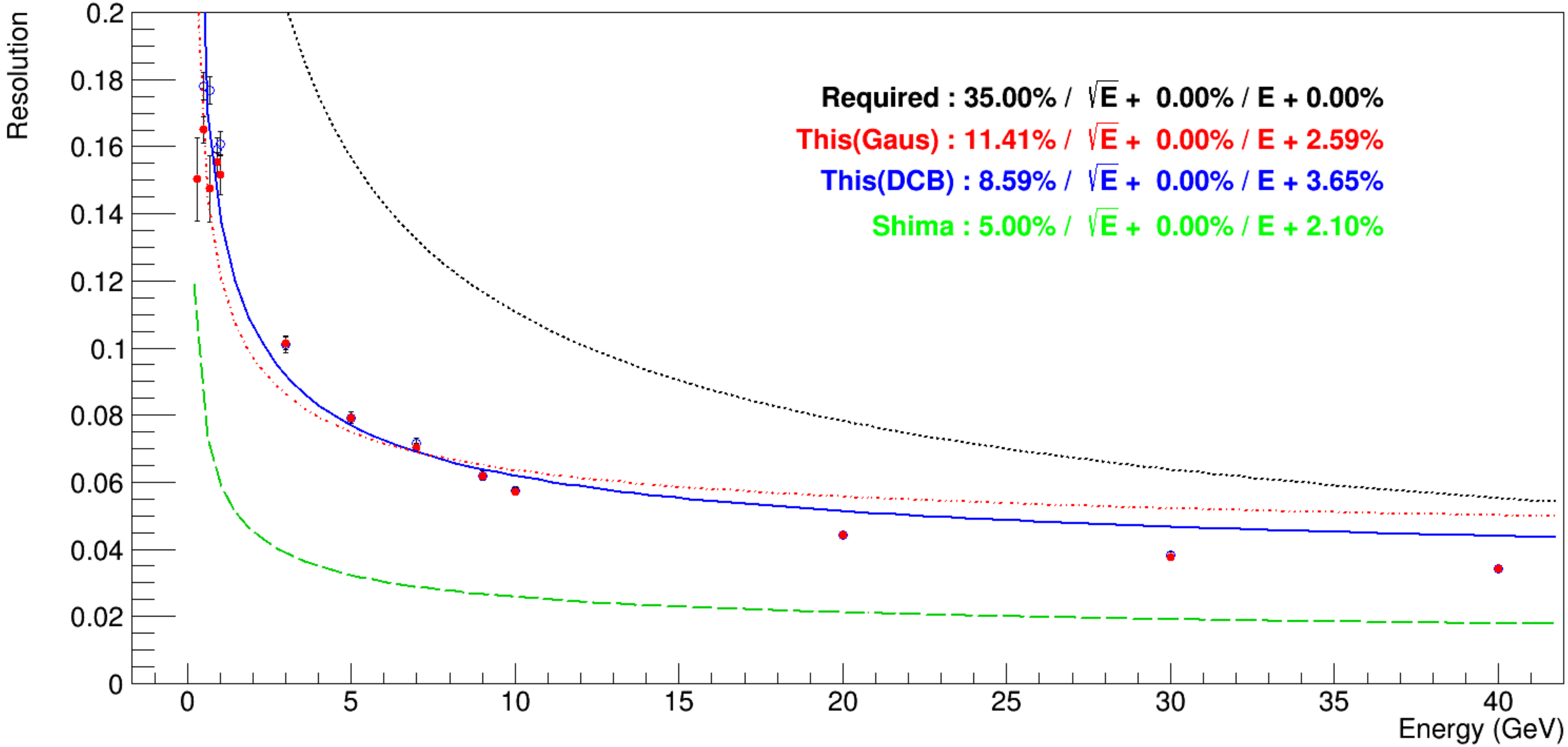
ECal / Ebeam | HCal / Ebeam | Leakage / Ebeam | All / Ebeam



- With the increase of Ebeam, more reconstructed energy in HCal than ECal.
- No leakage.

```
par[0]=-0.035431+-0.012318
par[1]=1.286562+-0.019381
par[2]=50.198061+-0.262423
```

Energy Resolution (Gamma + LYSO)



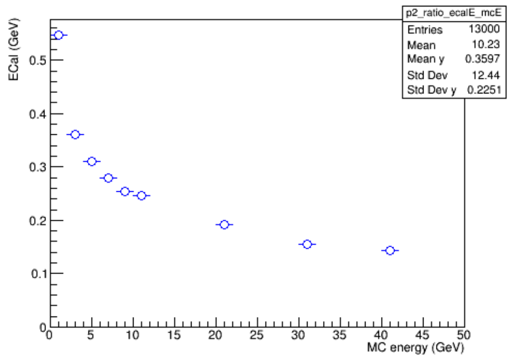
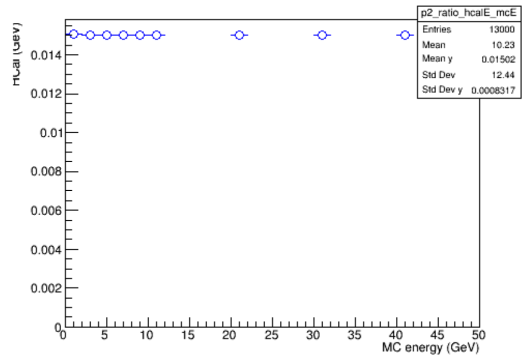
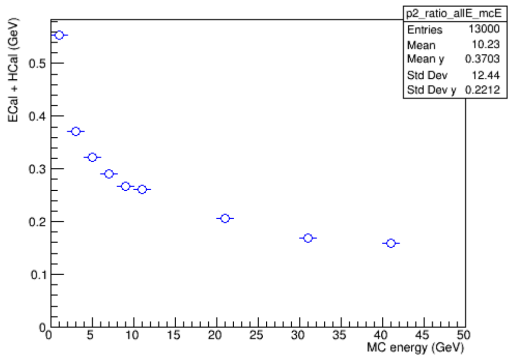
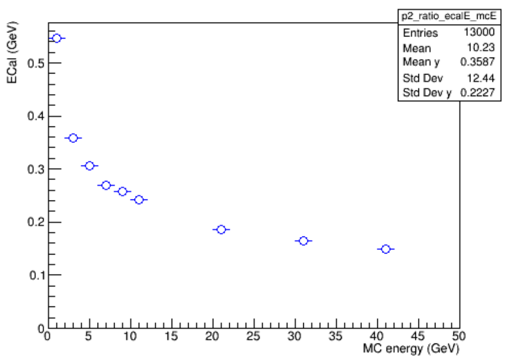
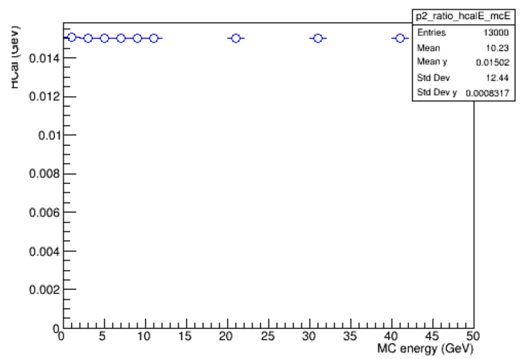
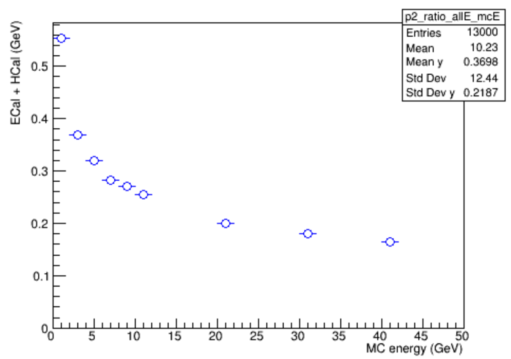
New design of ZDC is worse than the previous design (Shima , Po-Ju).

Change Crystal

Gamma, Pencil beam

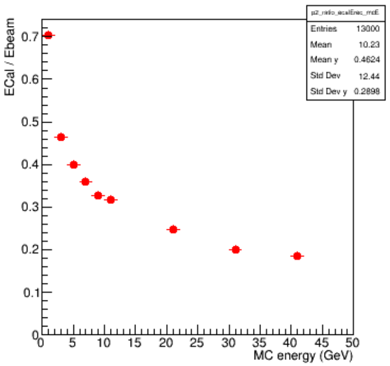
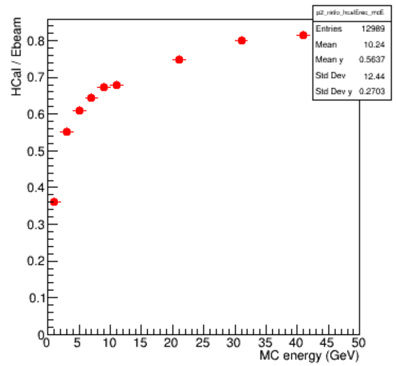
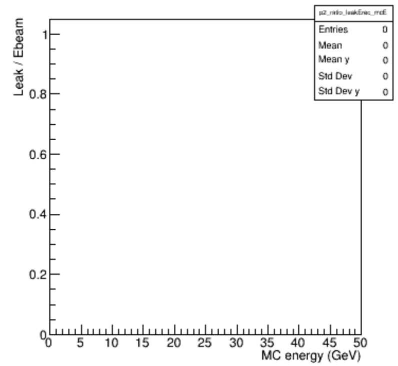
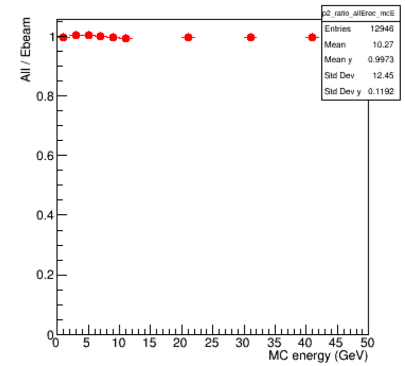
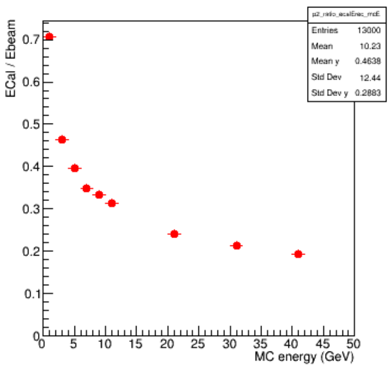
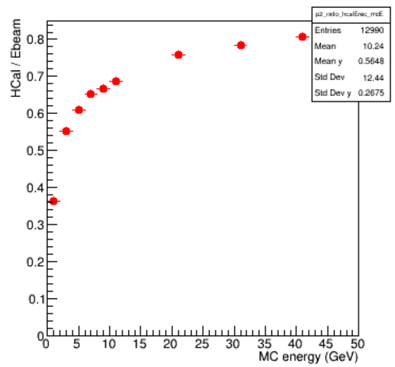
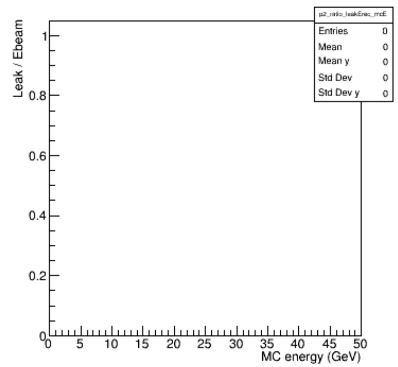
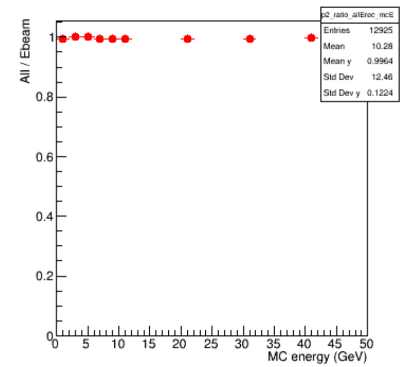
1. LYSO (org)
2. PbWO4 (tested)

Energy Dump

	ECal / Ebeam	HCal / Ebeam	"ECal + Hcal" / Ebeam
LYSO			
PbWO4			

No difference between two kinds of crystal.

Energy Reconstruction

	ECal / Ebeam	HCal / Ebeam	Leakage / Ebeam	All / Ebeam
LYSO				
PbWO4				

LYSO, ECal / Ebeam:

LYSO, HCal / Ebeam:

LYSO, Leakage / Ebeam:

LYSO, All / Ebeam:

PbWO4, ECal / Ebeam:

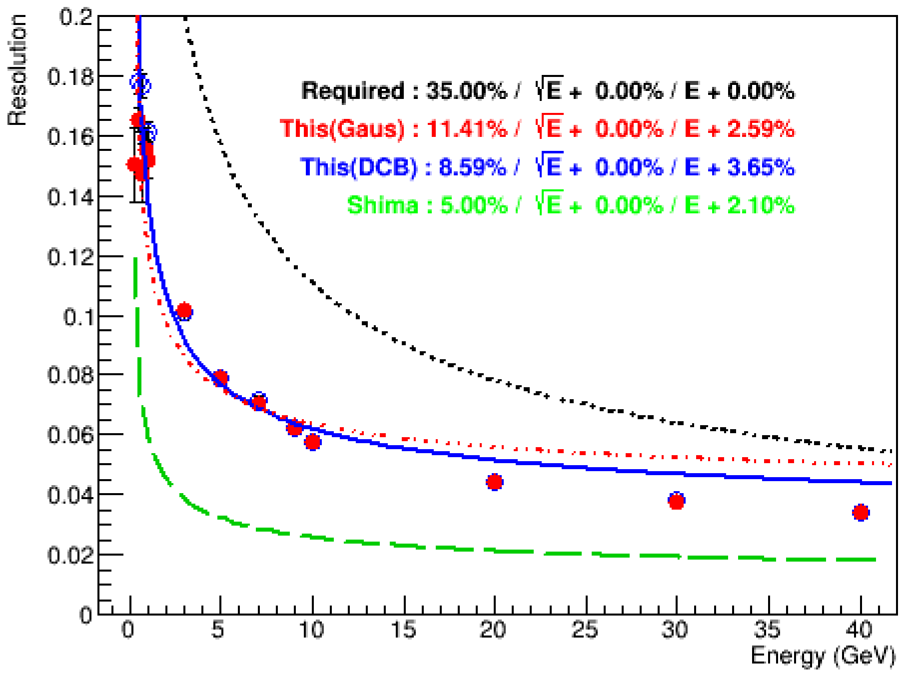
PbWO4, HCal / Ebeam:

PbWO4, Leakage / Ebeam:

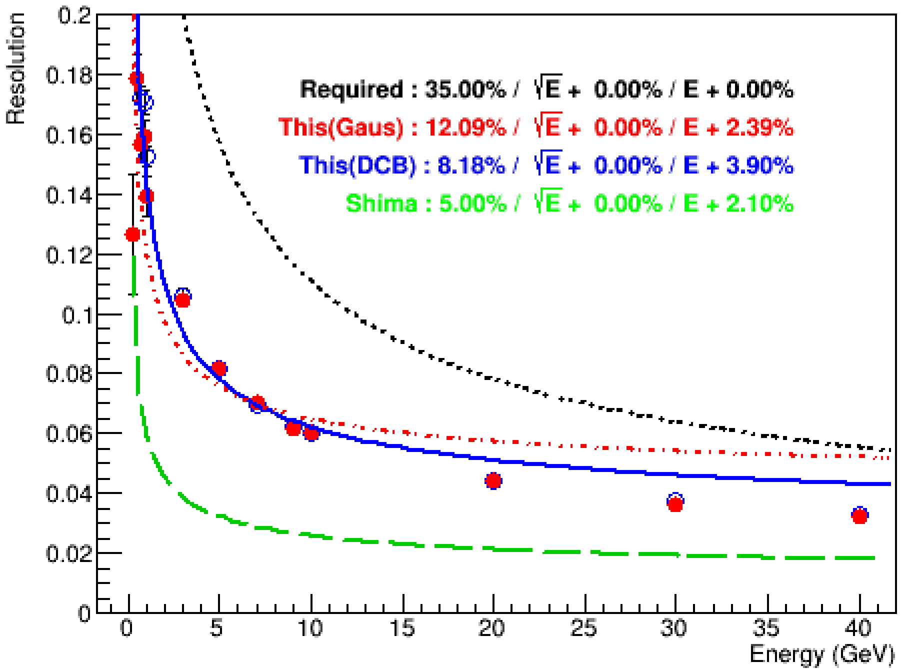
PbWO4, All / Ebeam:

Energy Resolution

LYSO



PbWO4



Same performance.
Optical photon is not on.

Change Beam Angle

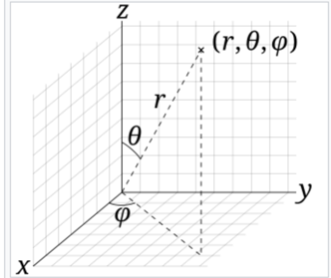
- Gamma + PbWO4 crystal
- 1. Pencil beam

```
SIM.gun.position = (ZDC_x_pos-shift, ZDC_y_pos-shift, ZDC_z_pos)
SIM.gun.thetaMin = ionCrossingAngle
SIM.gun.thetaMax = ionCrossingAngle
SIM.gun.phiMin = 0* degree
SIM.gun.phiMax = 0* degree
```

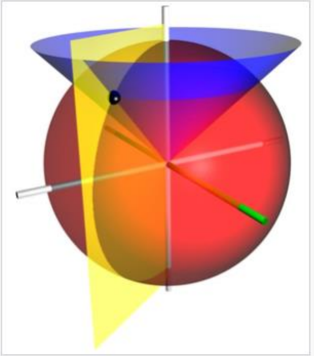
Shift = 15 mm (half cell)

- 2. Spread beam

```
SIM.gun.position = (ZDC_x_pos-shift, ZDC_y_pos-shift, ZDC_z_pos)
SIM.gun.thetaMin =  ionCrossingAngle + 0* degree
SIM.gun.thetaMax =  ionCrossingAngle + 45* degree
SIM.gun.phiMin = 0* degree
SIM.gun.phiMax = 180* degree
```



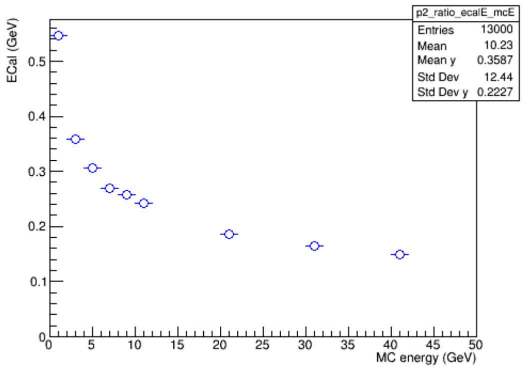
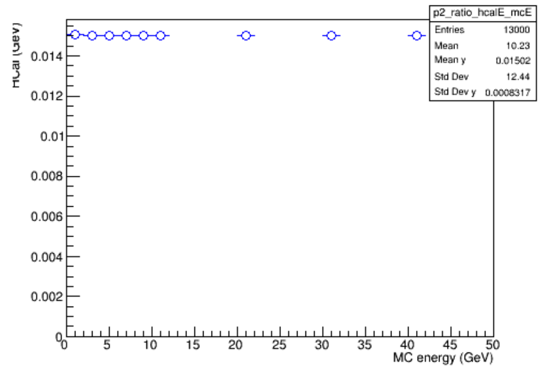
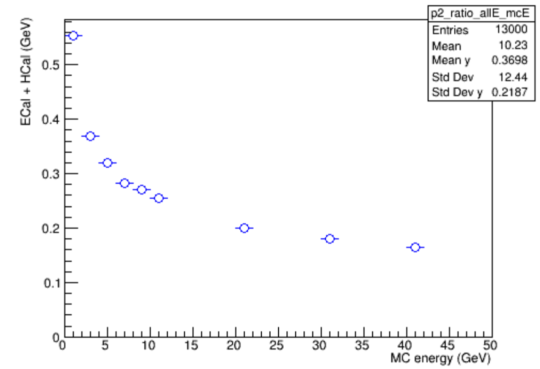
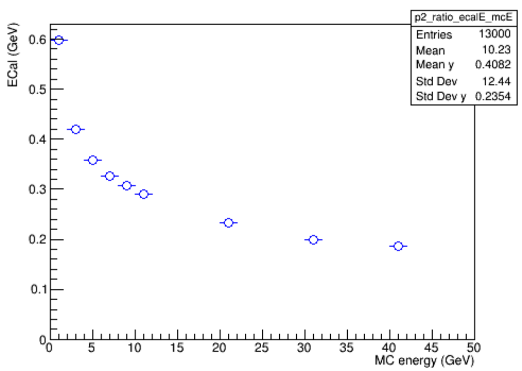
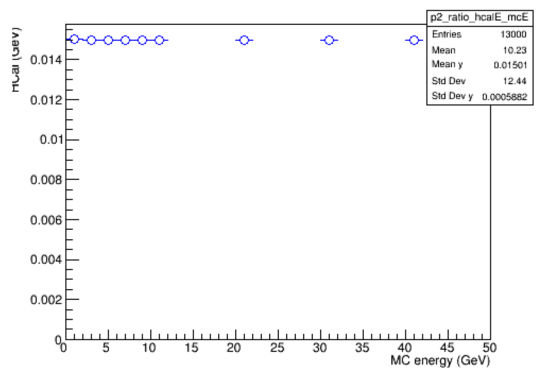
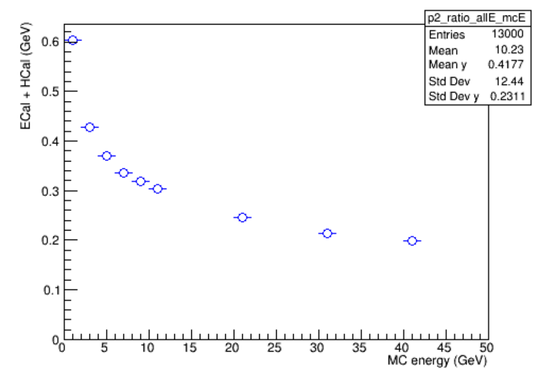
物理學中通常使用的球座標 (r,θ,φ)（ISO 約定）：徑向距離 r，極角 θ（theta）與方位角 φ（phi）。



球座標系的幾個座標曲面。紅色圓球面的 $r=2$。藍色圓錐面的 $\theta=45^\circ$。黃色半平面的 $\varphi=-60^\circ$（黃色半平面與xz-半平面之間的二面角角度是 $|\varphi|$）。z-軸是垂直的，以白色表示。x-軸以綠色表示。三個座標曲面相交於點P（以黑色的圓球表示）。直角座標大約為 $(0.707,-1.225,1.414)$。

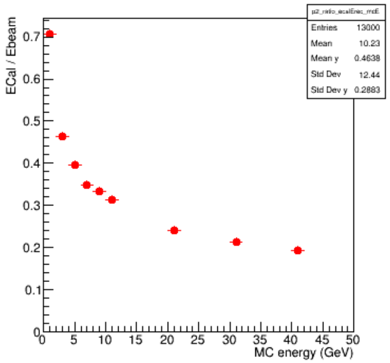
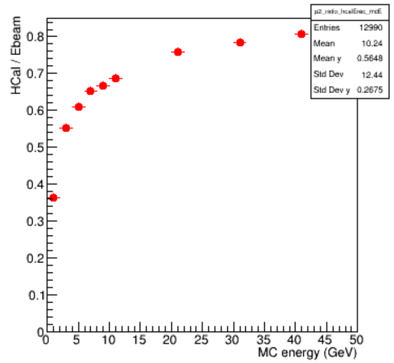
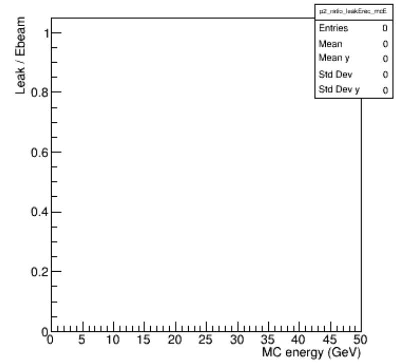
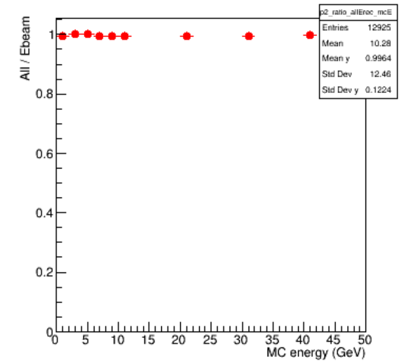
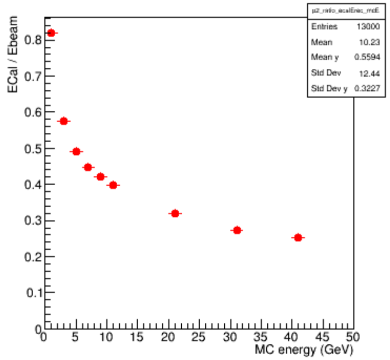
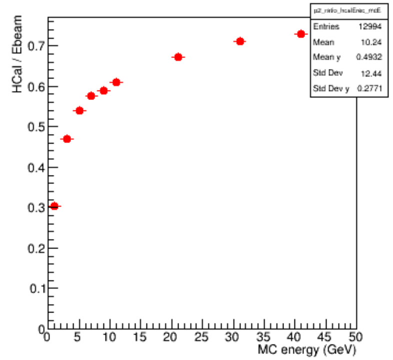
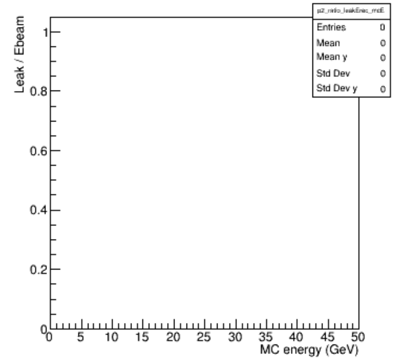
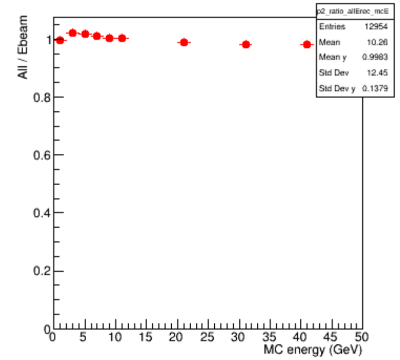
假設P點在三維空間的位置的三個座標是 $(r,\ \theta,\ \varphi)$。那麼，$0\le r$ 是從原點到 P 點的距離，$0\le\theta\le\pi$ 是從原點到 P 點的連線與正z-軸的夾角，$0\le\varphi\le 2\pi$ 是從原點到 P 點的連線在xy-平面的投影線，與正x-軸的夾角。

Energy Dump

	ECal / Ebeam	HCal / Ebeam	"ECal + Hcal" / Ebeam
Pencil beam			
Spread beam			

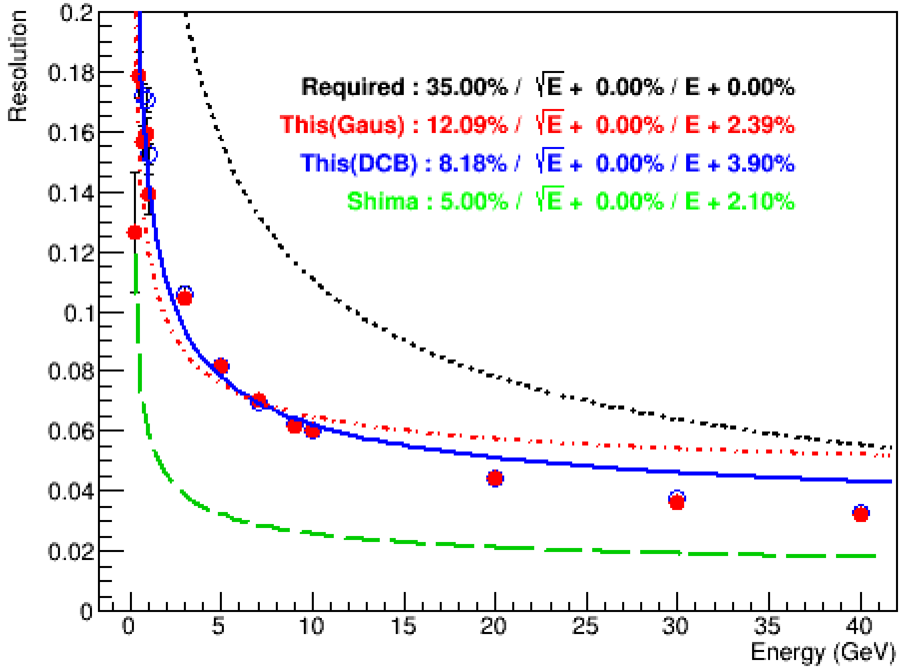
More energy dumped in crystal for spread beam (longer path?)

Energy Reconstruction

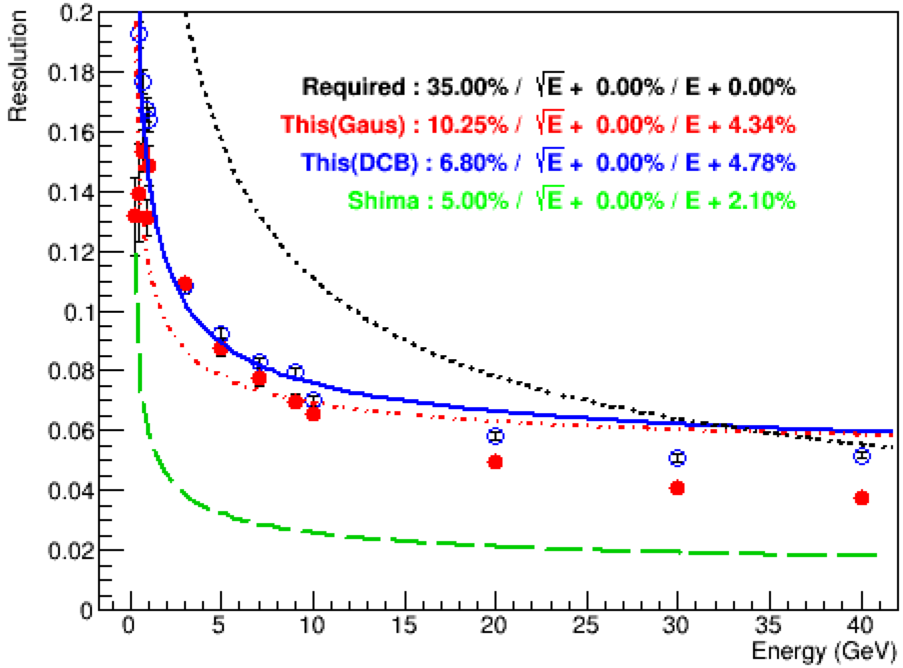
	ECal / Ebeam	HCal / Ebeam	Leakage / Ebeam	All / Ebeam
Pencil beam				
Spread beam				

Energy Resolution

Pencil beam



Spread beam



Slightly better performance for spread beam.

Summary and To do

- Basic framework to simulate the performance of ZDC is ready.

- The current design (LYSO + pencil beam)
- HCal : Better energy res. for neutron beam
- ECal : Worse energy res. for gamma.

- Change crystal material :

No difference between two crystals (optical photon is not on).

- Change pencil beam to spread beam :

Spread beam has slightly better performance.

- To do
- Different crystal length (now 6X0) = [6, 8, 10] X0
- Different crystal coverage (now 60cm* 60cm) = [56^2, 60^2] cm