# Design of the EIC Zero Degree Calorimeter

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26/Oct./2021  RBRC exp. meeting

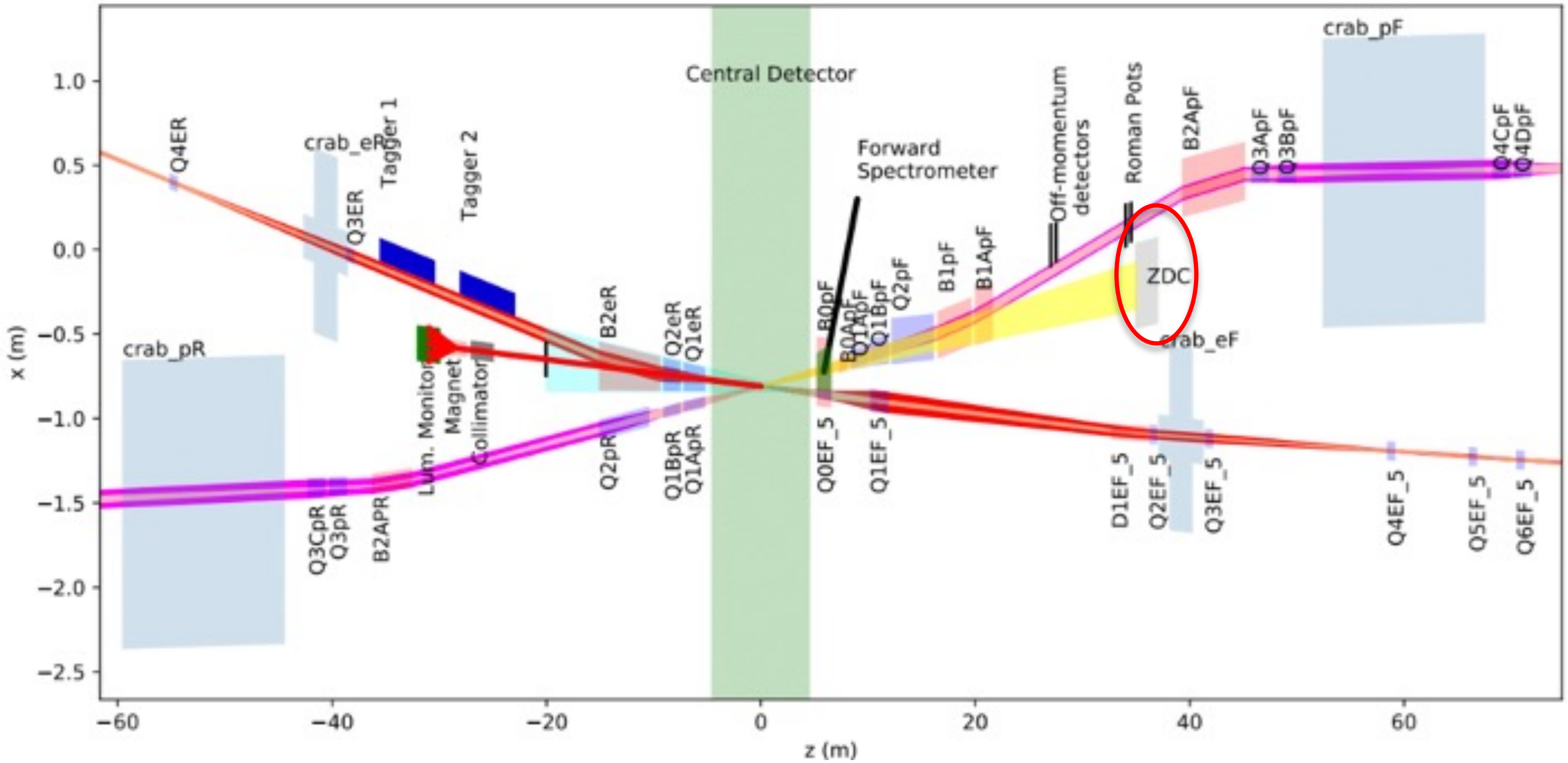
# My activities in ECCE EIC

- **EIC ZDC design → Today**
  - First design implemented in the ECCE software in May.
  - Performance study against single particles
    - Using energy deposits ( = no readout) in Geant simulation.
    - 1 particle per event. (Neutron or photon)
  - → Estimation of energy and position resolution.
  - → Optimization of the ZDC design

- **Inclusive DIS cross section measurements**
  - Preparation of MC samples
  - Simulation study for Charged Current measurement
    - Using fully simulated sample.
  - → Check if the measurement is doable.

# EIC Zero Degree Calorimeter

- A calorimeter to tag photons and neutrons in the proton beam forward direction.
  - 37.5 m (33.5 m) away from the interaction point of IP6 (IP8).

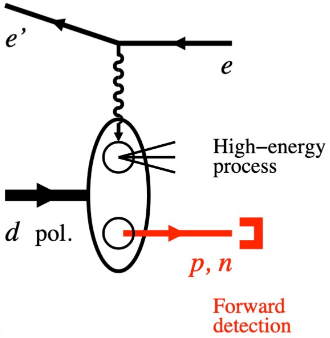



Yellow Report Fig. 11.85 (arXiv:2103.05419)

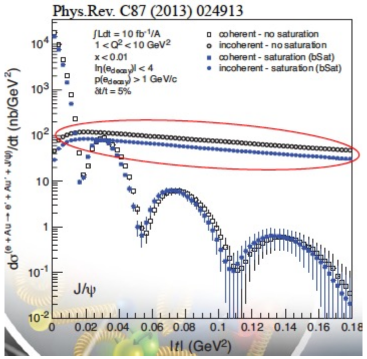
IP6, but x direction is flipped upside down

# Relevant Physics

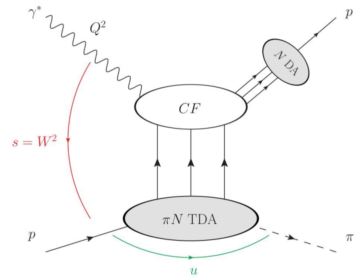
*Please see YR (arXiv:2103.05419) for details (sec. 8.4, 8.5)*



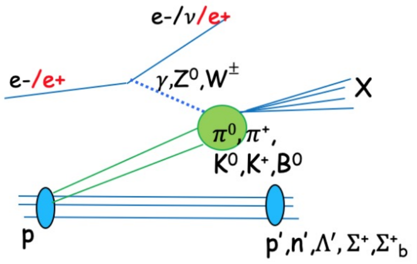

- Spectator neutron tagging in e+d DIS (e + d → e' + X + n)
  - → Nuclear modifications of p and n structure, such as EMC effect.
  - Diffractive J/Ψ in e+d scattering (arXiv: 2005.14706)
    - → Short range correlation (SRC)




- Exclusive vector meson production in e+A
  - → Sensitive to saturation
  - Separation of coherent vs incoherent processes
    - $^{208}$Pb de-excitation




- u-channel exclusive electroproduction of $\pi^0$ (e + p → e' + p' + $\pi^0$)
  - → Nucleon-to-meson Transition Distribution Amplitudes




- Meson structure (Sullivan process)
  - e+p->(π) -> e'+X+n
  - Λ decay
- Cross section and asymmetry measurement of leading neutrons

# 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 <-> $p_T$~ 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 $\pi^0$

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

      Position resolution: 0.5-1mm

# The first ZDC design (May 2021)

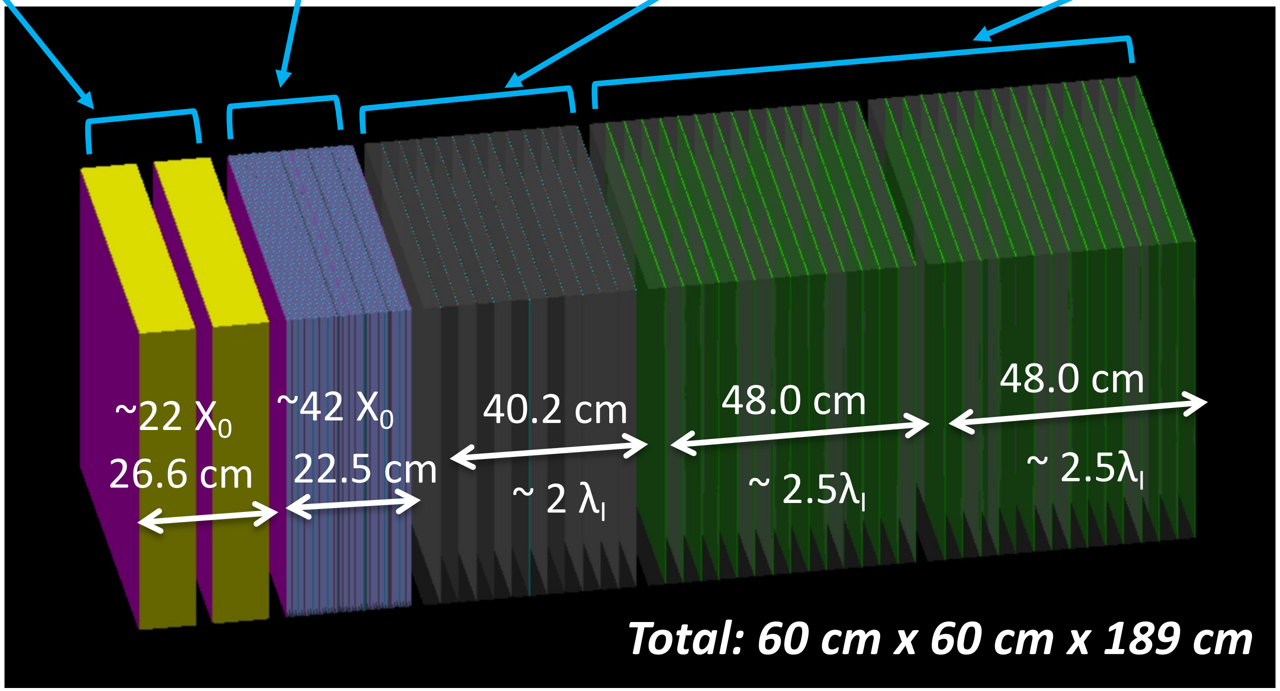
- Concept: **Crystal** + **FoCal style EM calorimeter** + **Hadron Calorimeter**

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

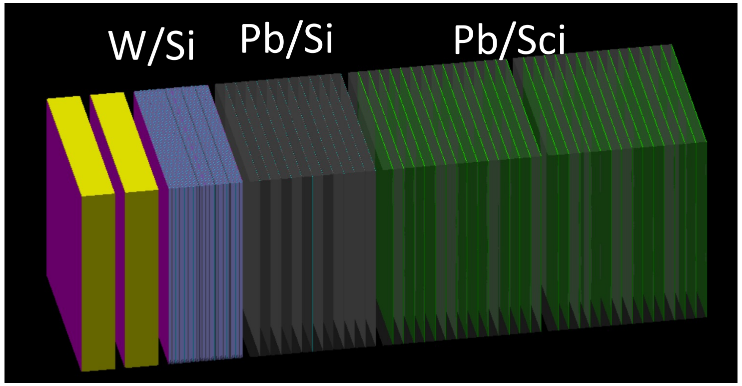
**Tungsten**
**Silicon** (1 cm x 1 cm)
with a few **Si** (3mm x 3mm) layers
- Measure EM shower
- Identify photon/neutron

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

**Pb**
**Scintillator**
- Measure hadron energy



# Neutron energy reconstruction:
# Quick estimation of neutron reconstruction factors




The designed ZDC consists of (crystal and) 3 types of sampling calorimeters.

- Energy reconstruction for neutrons is not simple.

➔ Estimation of factors to convert
**deposited energy [MeV] → reconstruction energy [GeV]**

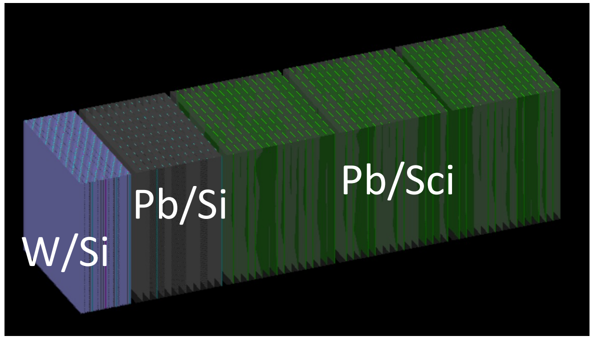
- Estimation is done by two methods:
  - (Step-by-step estimation) ← not shown today.
  - Fit
- Check energy resolution and energy leakage.

Note:
We are still at designing of the ZDC

- Aim is to obtain reasonable factors but not the best factors.
- This is to understand any feature of the designed ZDC.

estimation by fit

# Neutron energy reconstruction: Parameters from fit

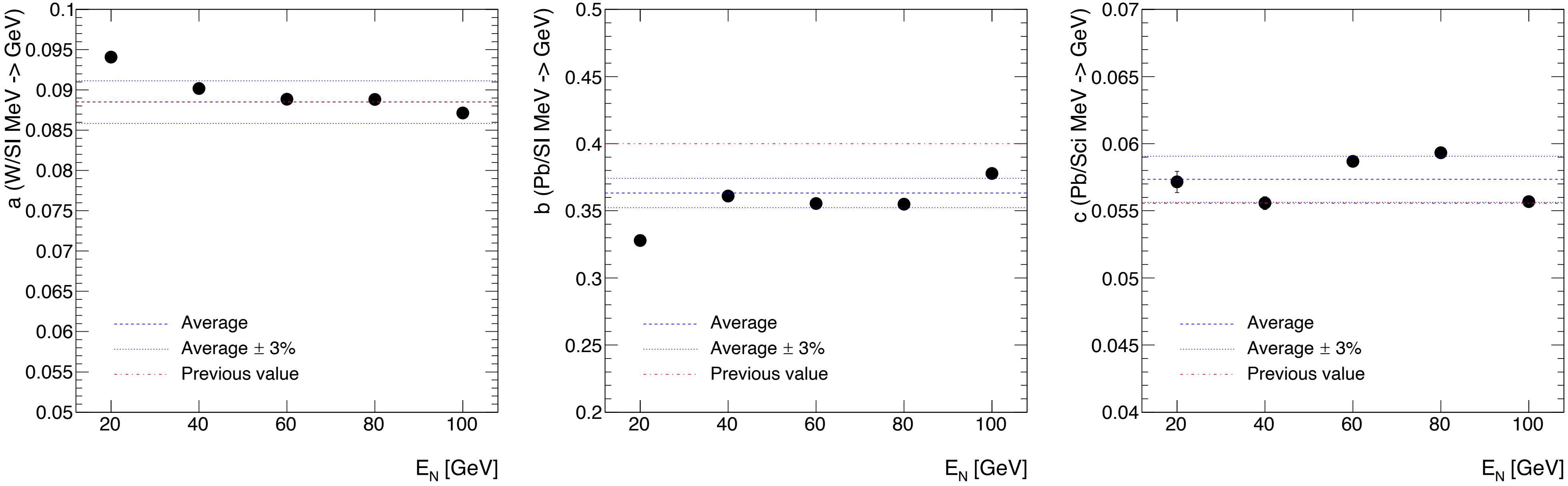



- The energy response in each detector looks quite linear.
- Extract parameters from fits:

$$a \cdot E_{\mathrm{SI\ (W/SI)}} + b \cdot E_{\mathrm{SI\ (Pb/SI)}} + c \cdot E_{\mathrm{Sci}} = E_{\mathrm{N}}$$ ($E_N$ = Neutron energy)

Fit is done for each energy sample ($E_N$= 20, 40, 60, 80, 100 GeV)

- A Pb/Sci box is further added. Events analysed have no energy deposits in the last 5 layers.




- Five fits give more-or-less consistent results.
- Parameter for Pb/SI has large correction from the previous step-by-step estimation.
- Parameters for silicon shows a small sample-energy dependence.

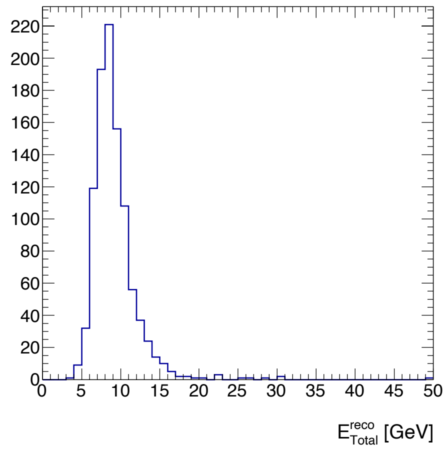
estimation by fit

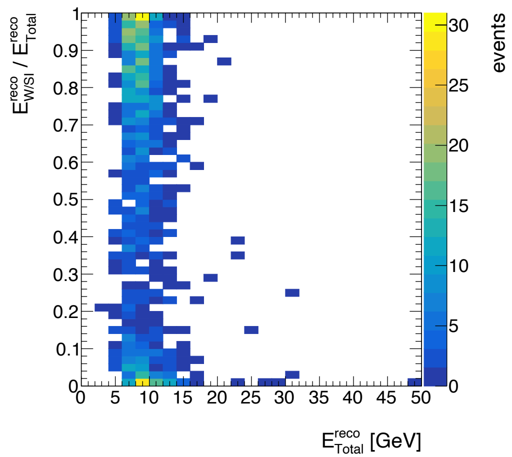
# Check of reconstruction

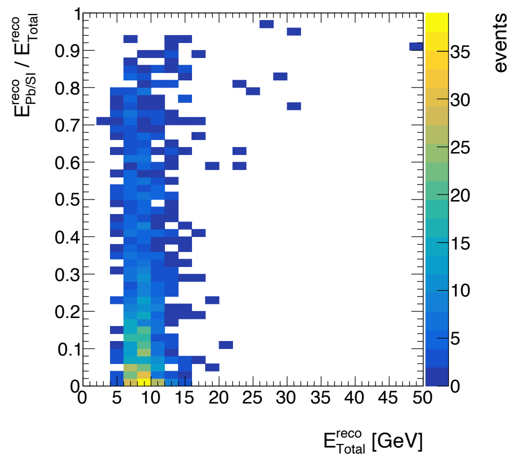
- Energy dependence is introduced in the factors, based on made-up slopes by eye.
- Reconstruction bias is very little for both of 10 GeV and 200 GeV photons

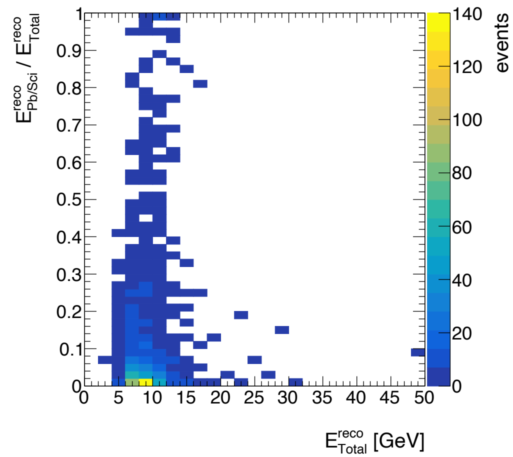
**Total Reco. Energy** | **Fraction of W/SI to total vs. total energy** | **Fraction of Pb/SI** | **Fraction of Pb/Sci**

**10 GeV**

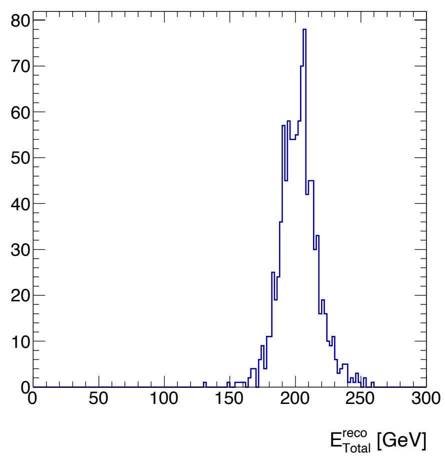


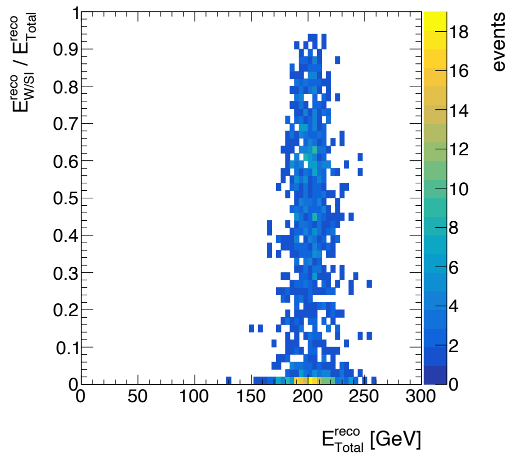



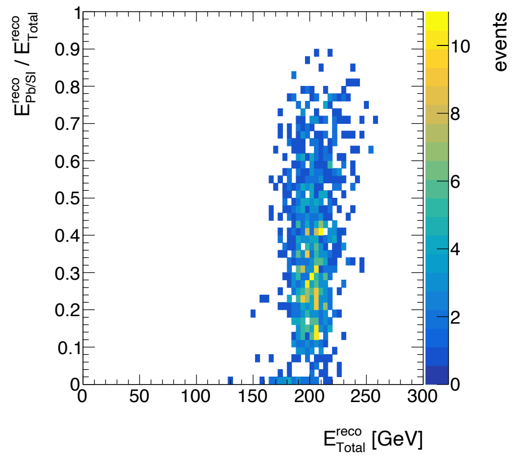



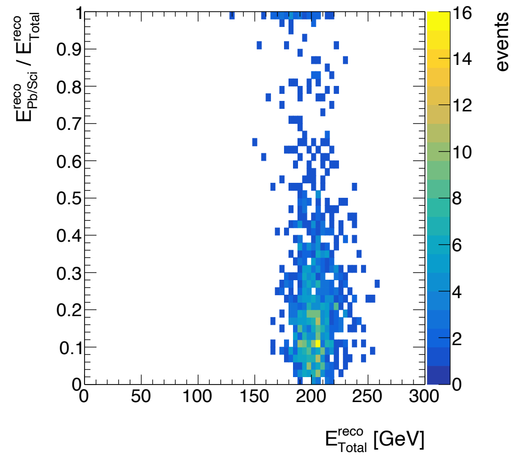




**200 GeV**



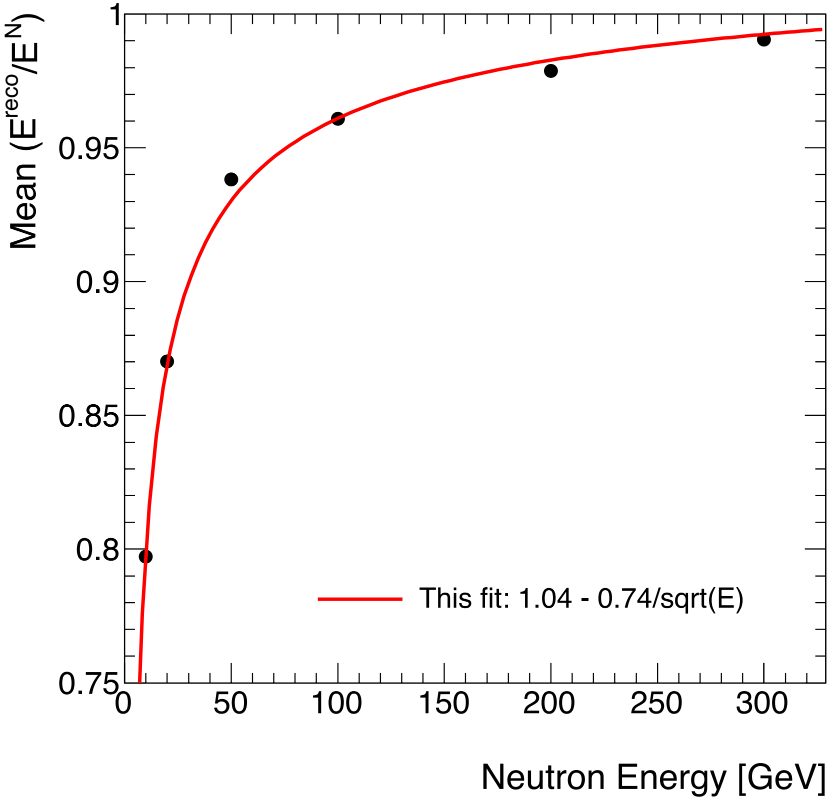



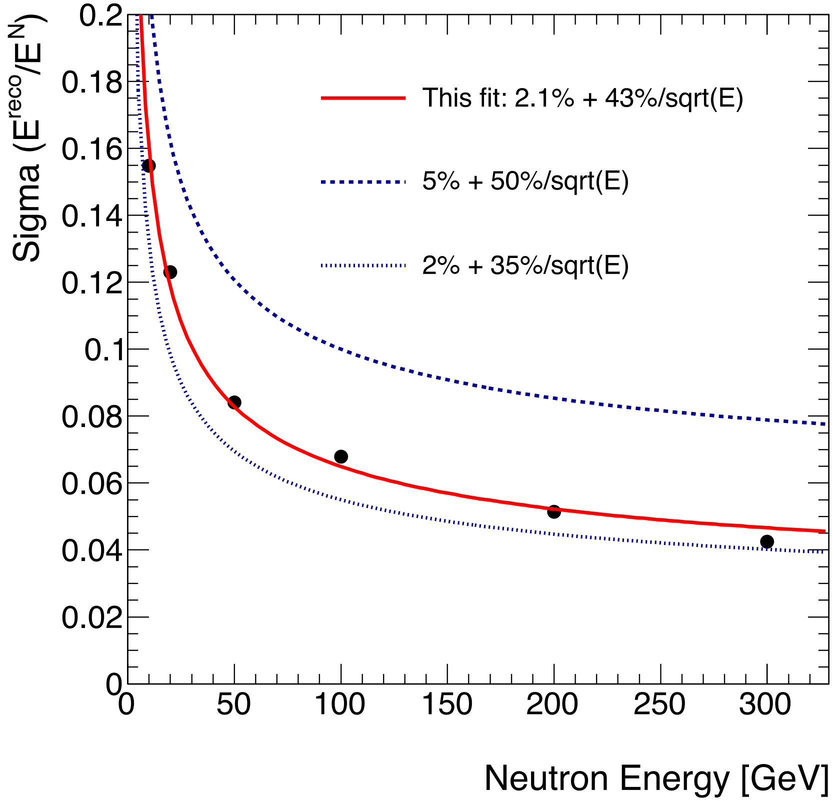



estimation by fit

# Neutron Energy Reconstruction with Full Detector + additional Pb/Sci box

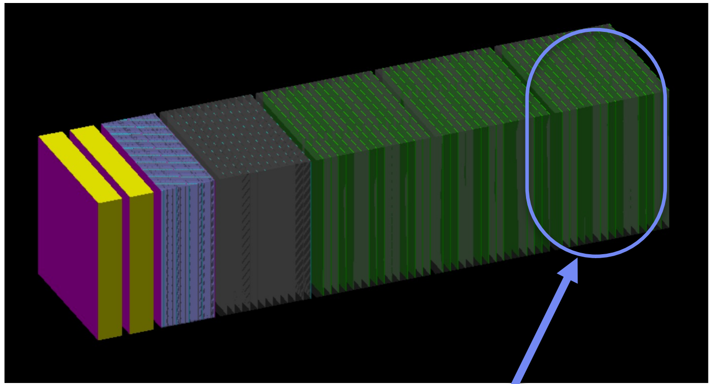
- Large bias is seen for lower energy neutrons.
- Resolution is already larger than the ideal value (35%/√E + 2%) in YR but smaller than the required value (50%/√E + 5%).
  - Estimation is based on the energy in active materials. Readout etc. will increase the resolution.



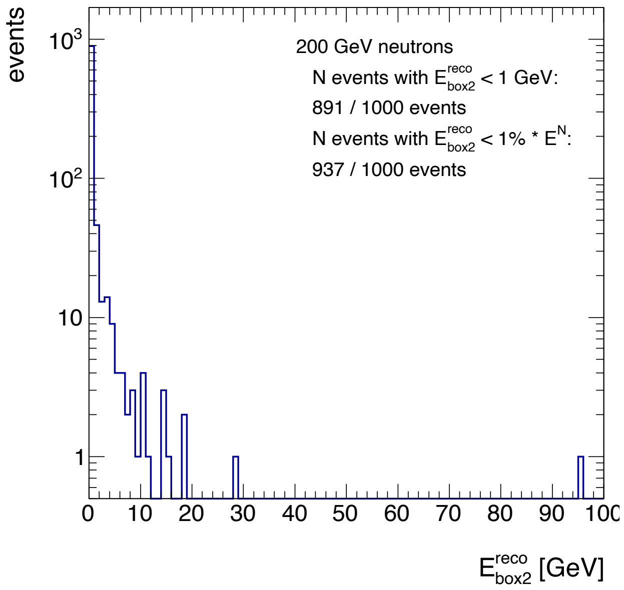



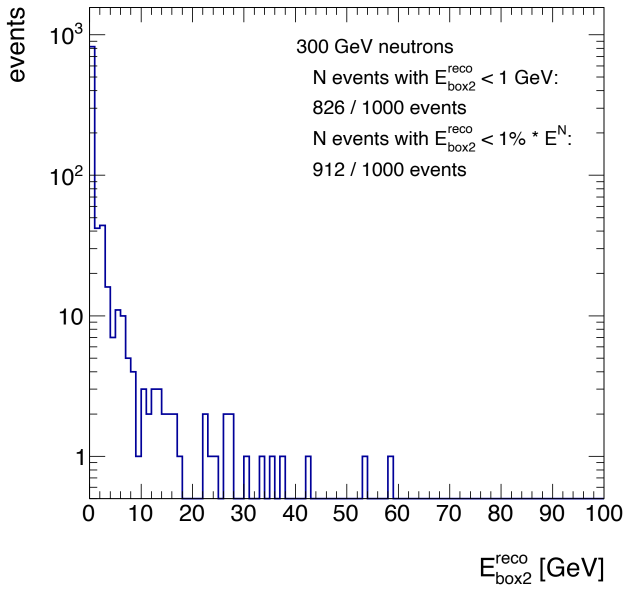
# Energy leak for neutrons

- The first design has two box of Pb/Sci instead of three.



Energy in the last box can be considered as energy leak.

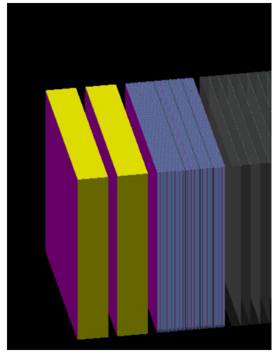



> 1 % of energy leak for 5-10 % of events.

**Conclusion:**
**The first ZDC design would give reasonable performance for neutrons.**

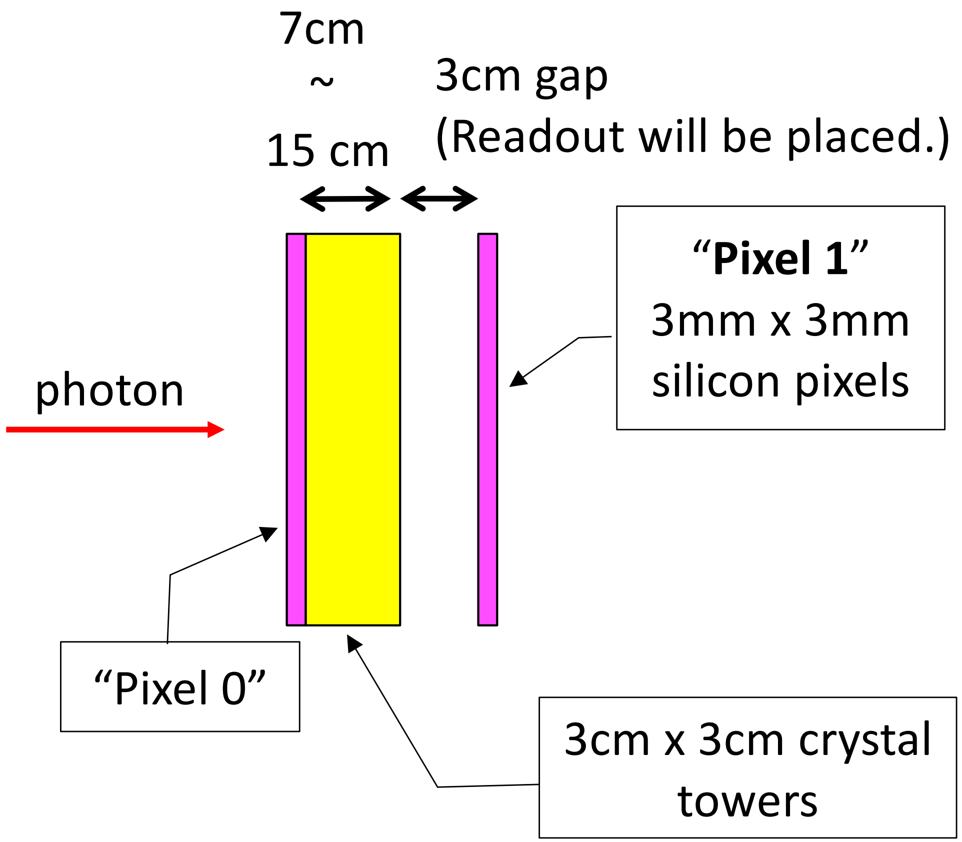
# Photon position reconstruction



- Physics requirement:

  Position resolution of (0.5~) 1 mm

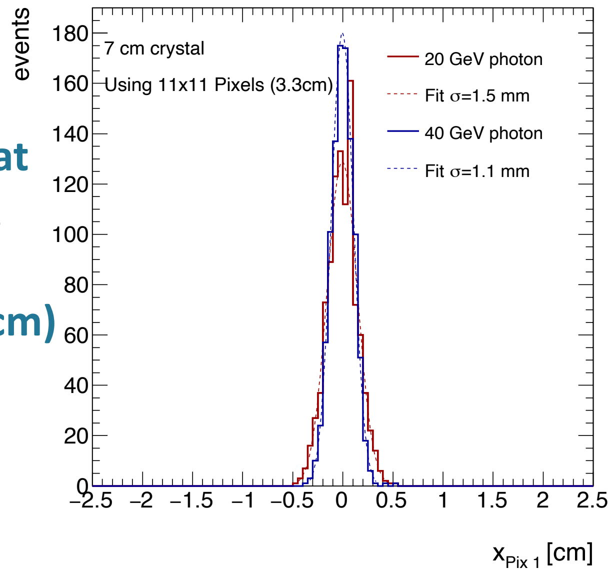
- Checked with three setups:
  - 7 cm ($7.9X_0$) thickness of Crystal
  - 10 cm ($11\ X_0$) thickness of Crystal
  - 15 cm ($16\ X_0$) thickness of Crystal
- Analysis:
  1. Photons are shot at the center of the plane (0,0).
  2. Reconstruct the photon position using the 1st crystal layers. Energy weighted mean of 3 x 3 towers → $(x_{Crystal}, y_{Crystal})$
  3. Look into the pixel cells on the next layer, around $(x_{Crystal}, y_{Crystal})$.

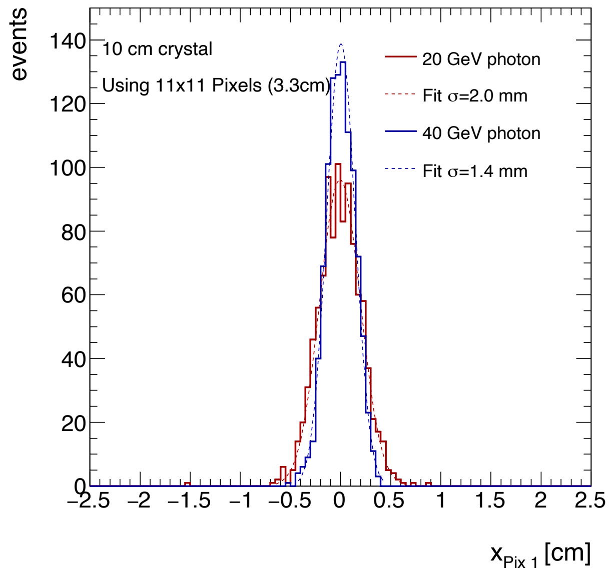


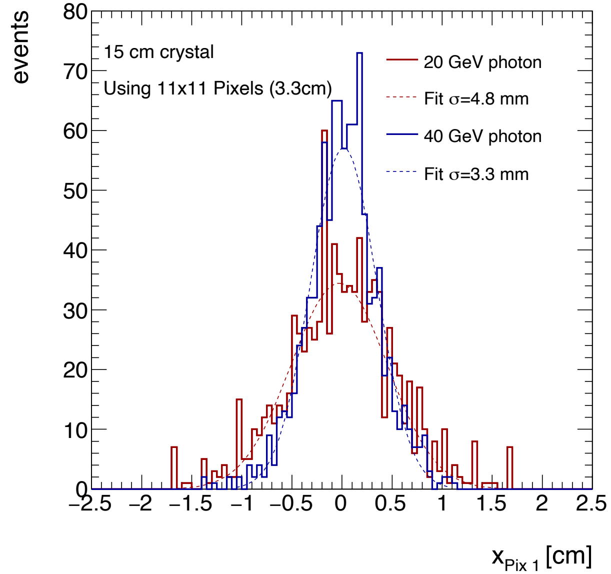
# Photon position reconstruction on Pixel 1

**7 cm crystal** | **10 cm crystal** | **15 cm crystal**

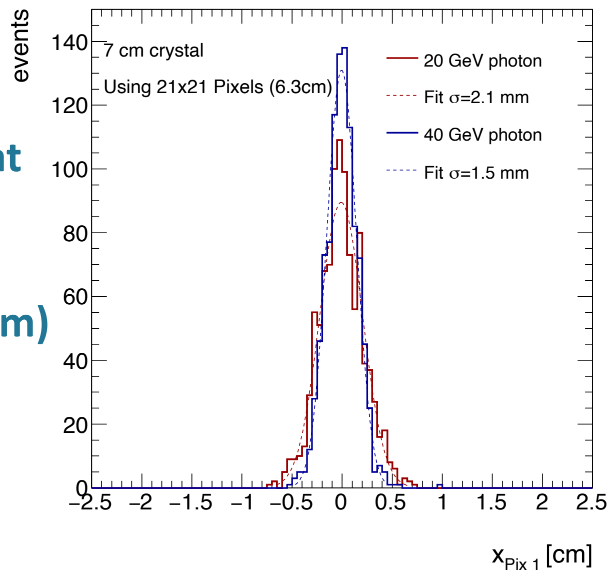
**looking at 11 x 11 pixels (11 =3.3 cm)**




**looking at 21 x 21 pixels (21 =6.3 cm)**




**Best resolution: 1.1 mm**

from:

- 40 GeV photon.
- 7 cm thickness.
- in 3.3 cm square. (11 x 11 chns)

- 20 GeV → 1.5 mm
- 10 cm thickness → 1.4 mm
- 6.3 cm square → 1.5 mm (21 x 21 chns)

➔ **Thinner crystal is preferred.**

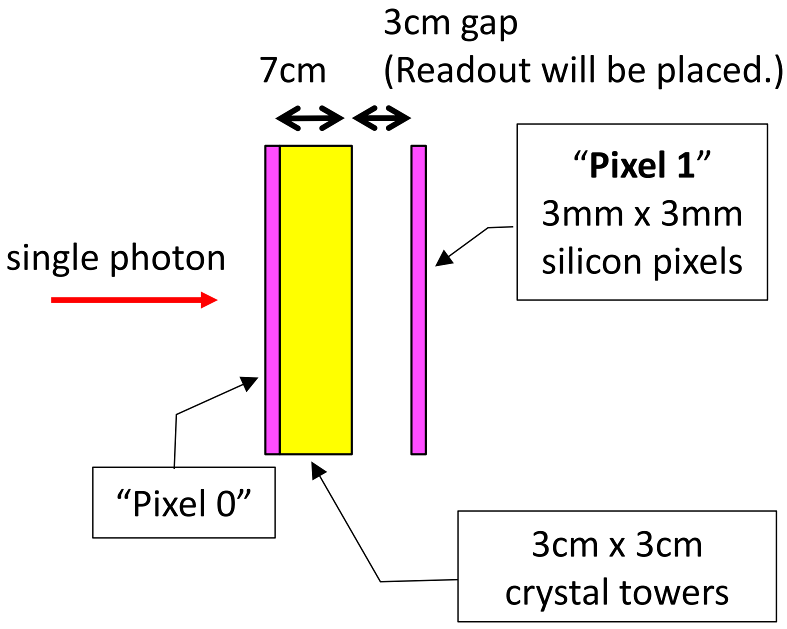
# Photon energy reconstruction

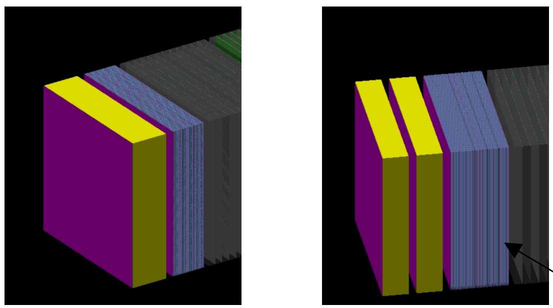
- Physics requirement:
  - 20 – 30 % energy resolution for O(100) MeV photons
  - 35%/√E energy resolution for O(10) GeV photons

- Setup

  EM calorimeter:
  - 1 or 2 layers of 7 cm crystal
  - 22 layers of W/SI

  with Silicon Pixel layers inserted.



**W/SI layers**
- 3.5 mm Tungsten plate
- Silicon
  - Pad layer: 1 cm x 1 cm x 320 μm (20 layers)
  - Pixel layer: 3mm x 3mm x 300 μm

# Photon energy reconstruction

$E_{\text{Reco, total}} = E_{\text{Reco, crys.0}} + E_{\text{Reco, crys.1}} + E_{\text{Pix1}} + E_{\text{reco, W/SI}}$

**Crystal**

- Clustering of EM crystal towers
  - Take a tower with $E_{tower}$> 15 MeV as a seed tower.
  - 3x3 towers with a seed as the center → cluster
  - Cluster raw energy is $\sum_{3\times3} E_{\text{tower}}$
  - Cluster raw energy is smeared based on $\frac{2.5\%}{\sqrt{E}} + 1\%$ → "Reco." cluster energy
- On the 1st crystal layer (Crystal 0), a cluster with the highest energy is taken.
- On the 2nd crystal layer (Crystal 1), a cluster close to the cluster on the Crystal 0 is taken.

Based on CMS and PANDA:
~20 cm crystals
Also tried $\frac{5\%}{\sqrt{E}} + 1\%$

**Pixel 1**

- 11x11 cells RoI is formed around (x, y) of Crystal 0 cluster. Energy deposit in RoI is taken.

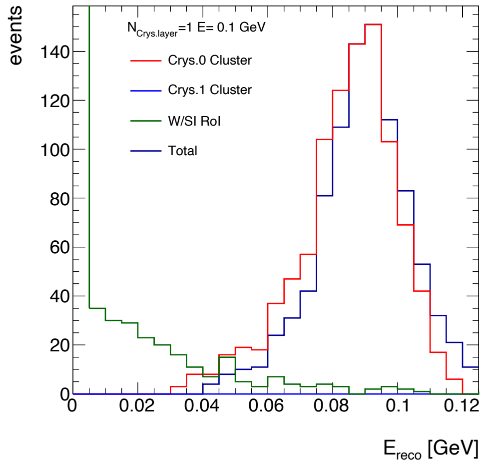
**W/SI**

- 9cm x 9cm RoI is formed around (x, y) of Crystal 0 cluster.
  - "Reco." energy = 82.7 * Energy sum in RoI.

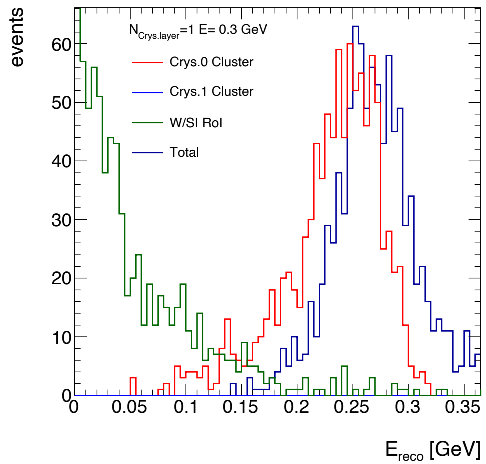
# Reconstructed photon energy

## Setup: 1 Crystal layer

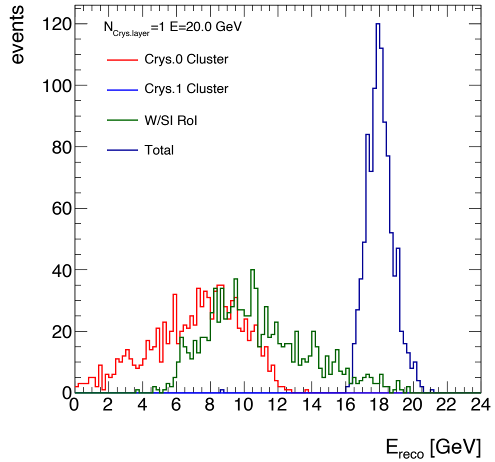
### 100 MeV



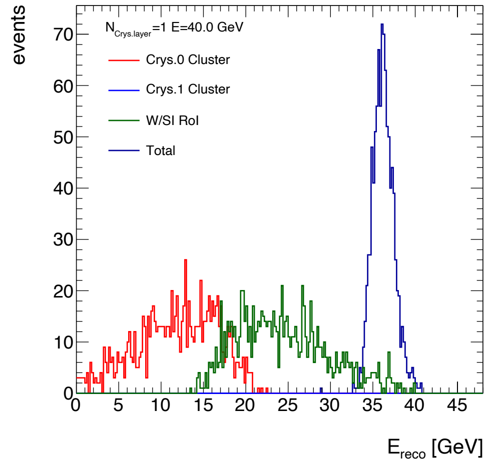

### 300 MeV



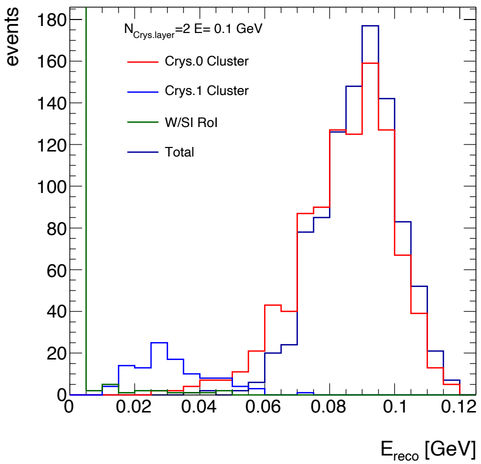

### 20 GeV

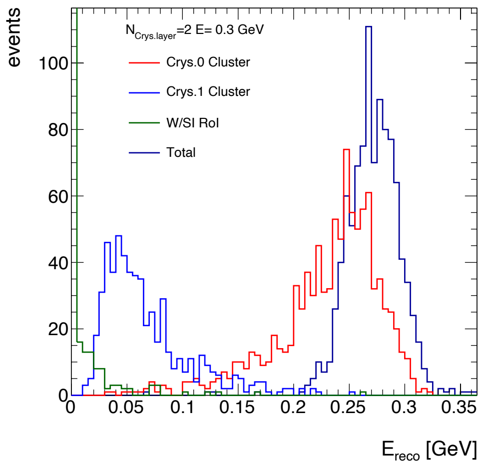


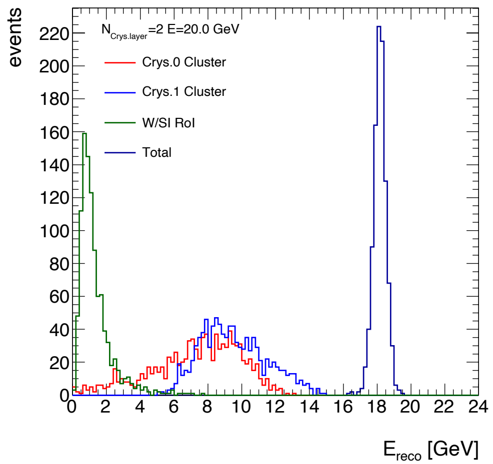

### 40 GeV

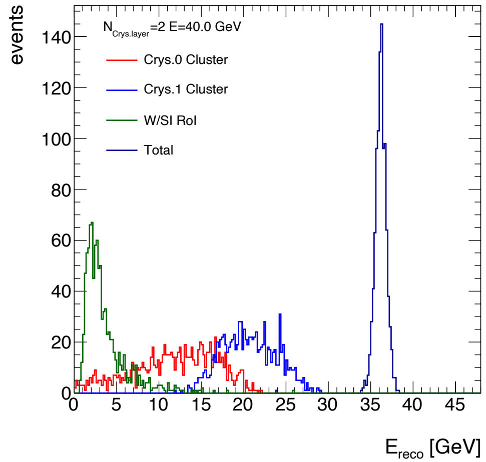



## Setup: 2 Crystal layers



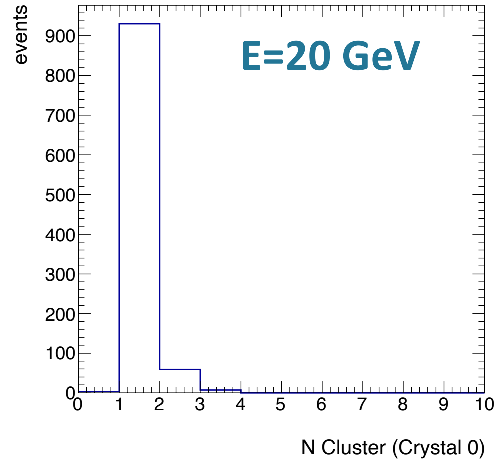

O(100) MeV photons: Most of the energy measured in the 1st Crystal layer.

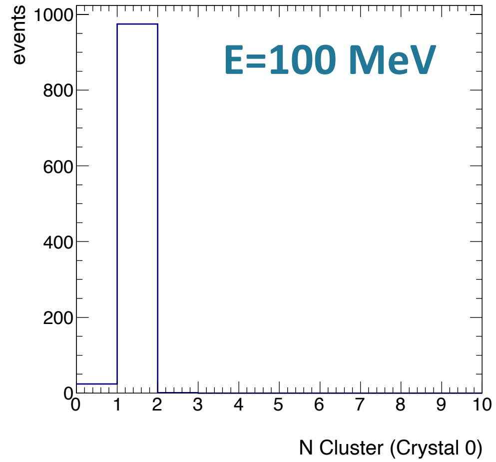
O(10) GeV photons: All of the Crys.0, Crys.1, and W/SI contribute to the reconstruction.

# Some details…

- Clustering of Crystal tower
  - 15 MeV seed gives reasonable reconstruction efficiency for both 20 GeV and 100 MeV photons

**Number or clusters on the 1st Crystal layer (Crystal 0)**



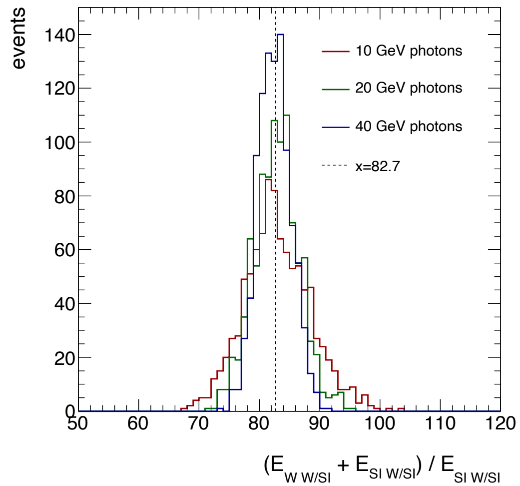




- W/SI energy reconstruction

  $E_{W/SI\ Reco} = E_{W/SI\ RoI,\ raw} \times \underline{82.7}$

  - Scale factor 82.7 is obtained from direct shots of photons on W/SI layers (No crystal)

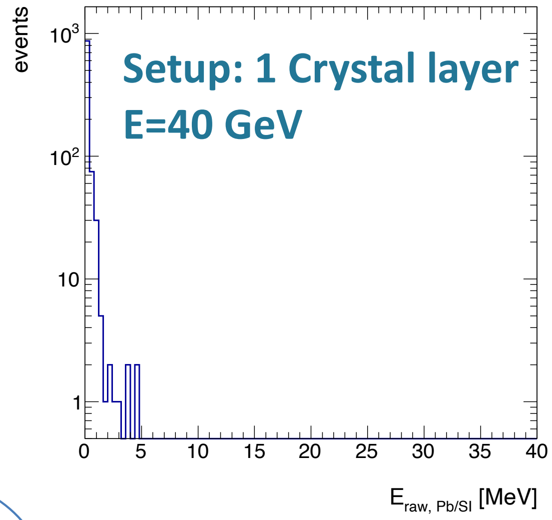
  Events with $E_{Abs.\ (W+PET)} + E_{SI} > 99\%$ of beam energy are analysed.



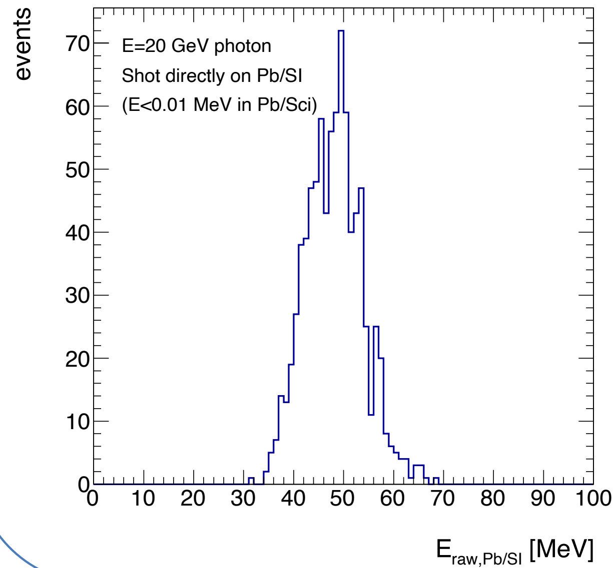

➔ SF = 82.7

# Photon energy leakage to hadron calorimeter

- Energy in Pb/SI layer (HC part)
  - Not significant for most of the events, even for 40 GeV photons on 1 Crystal-layer setup.
  - Maximum 5 MeV in SI
    
    → corresponds to ~ 2 GeV * = 5% of $E_\gamma$




*Quick estimation of SF for Pb/SI




20 GeV photons are directly shot on Pb/SI

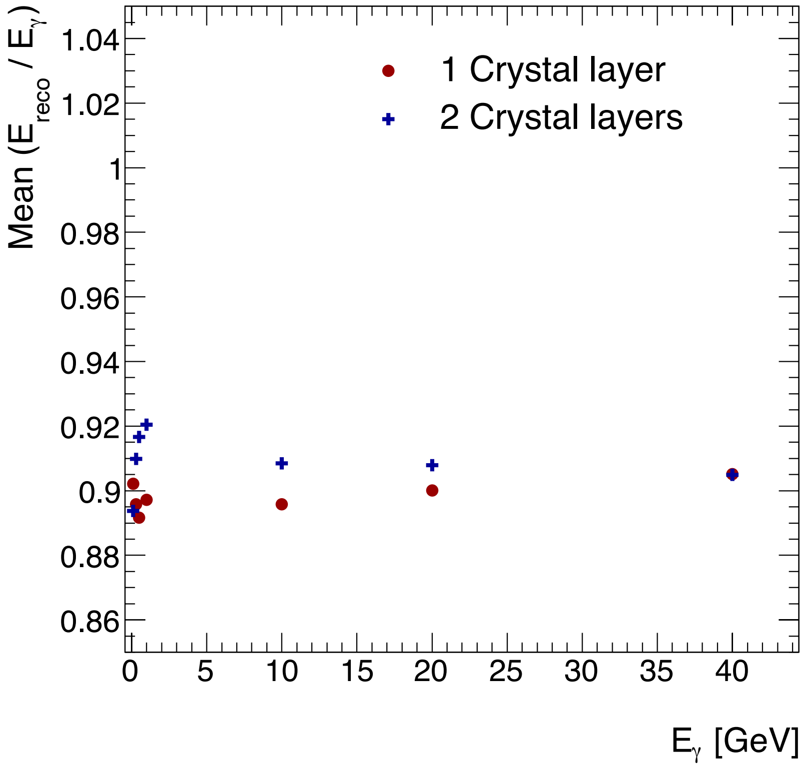
$E_\gamma$ = 20 GeV <-> $E_{SI\ (Pb/SI)}$ ~ 50 MeV

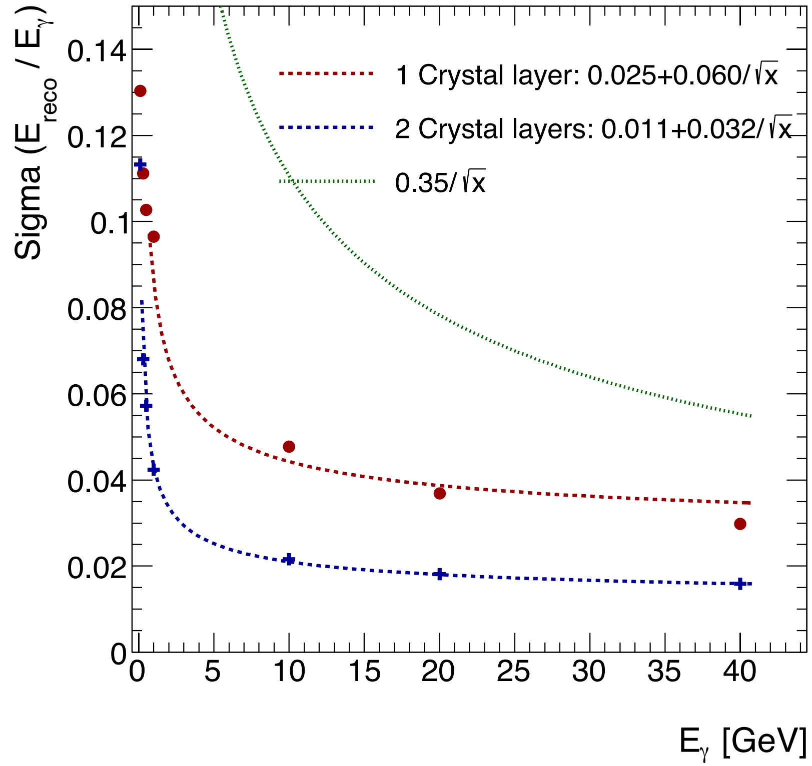
➔ SF ~ 400

# Summary of photon energy reconstruction

$E_{Reco,\ total}$ / $E_{\gamma}$ distributions are fitted.

(Note: No energy correction for RoI use (Crystal, Pix1, W/SI) and for energy leakage)




Both 1 Crystal and 2Crystals setups have better resolution than required.

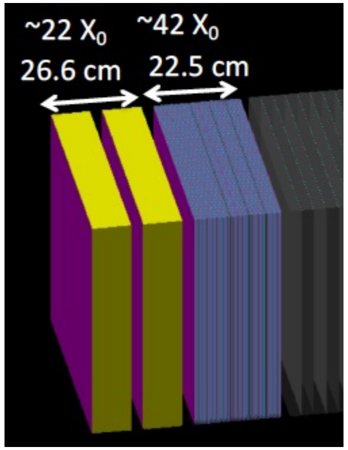
- **1 Crystal layer will double the size of resolution, but still better than required.**

# Update of the design

- The first ZDC design is:
  - Good for photon and neutron energy measurements,

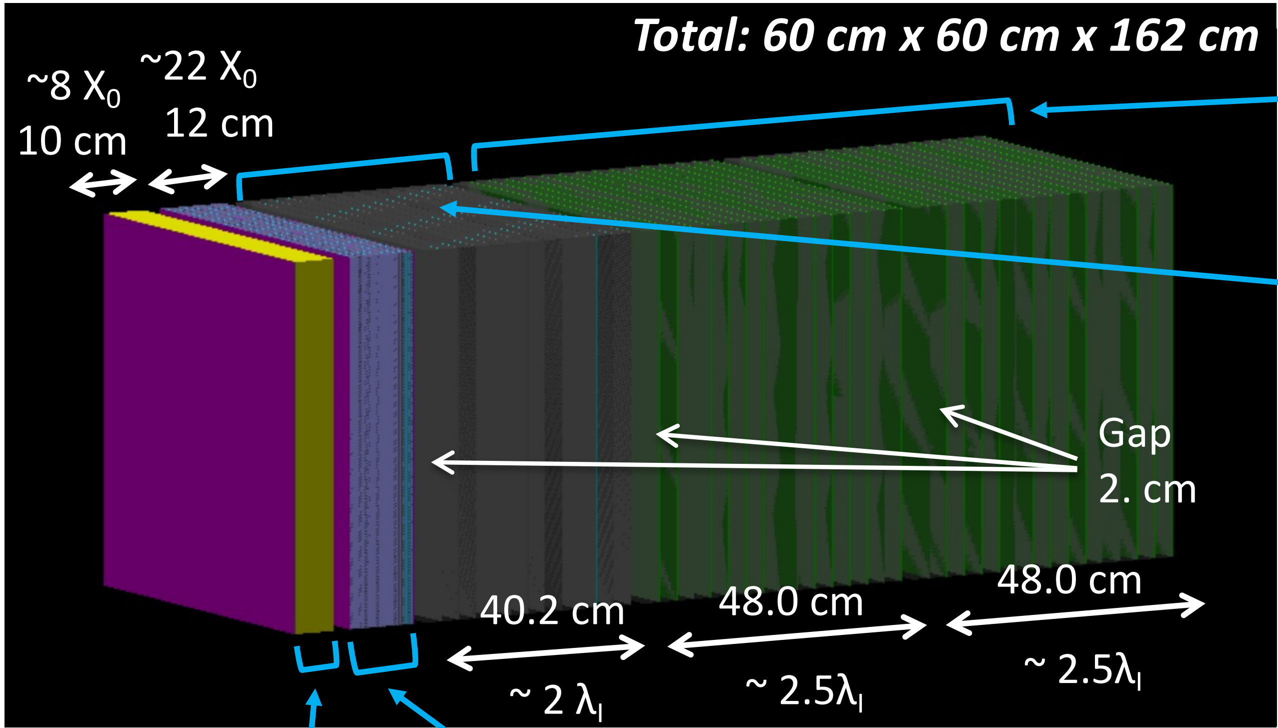
  but
  - Too expensive
  - Not optimal for photon position measurement

<u>Design update</u>




- **7 cm crystal** is preferred to 10 cm.
- W/SI layers can be reduced to **22 layers** from 42 layers.
- Crystal layer can be **a single layer**.

# The Second ZDC design (Oct. 2021)




**30 layers (15 layers x 2)**

**Pb** 3cm Thickness
**Scintilator**
10 cm x 10 cm x 2 mm
Gap 0.0013 mm

**12 layers**

**Pb** 3cm Thickness
PET (Glue) 0.11 mm
**Silicon**
1 cm x 1 cm x 320 μm
PET (Glue, FPC) 0.41 mm
Gap 1. mm

**1 layer**

**Silicon**
3 mm x 3mm x 300 μm
PET (Glue, FPC) 0.39 mm
Gap 1.2mm
**Crystal** (PbWO4)
3cm x 3cm x 7 cm
Gap 3 cm

**Si: 3 layers,**
**Si: 20 layers,**
**W: 22 layers**

**= Si + 2 x** (**10 layers** + **1 layer**)

**10 layers**

**Tungsten** 3.5 mm Thickness
PET (Glue) 0.11 mm
**Silicon** 1 cm x 1 cm x 320 μm
PET (Glue, FPC) 0.41 mm, Gap 1.mm

**+**

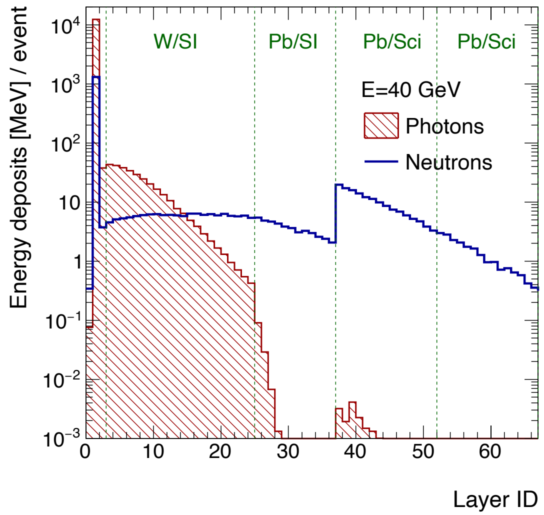
**1 layer**

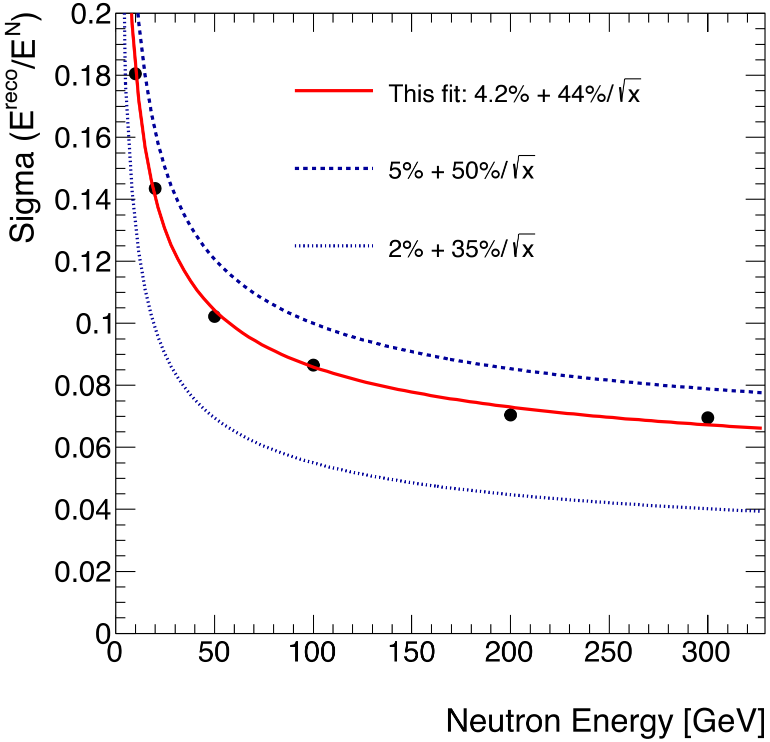
**Tungsten** 3.5 mm Thickness
PET (Glue) 0.11 mm
**Silicon** 3 mm x 3mm x 300 μm
PET (Glue, FPC) 0.39 mm, Gap 1.2mm

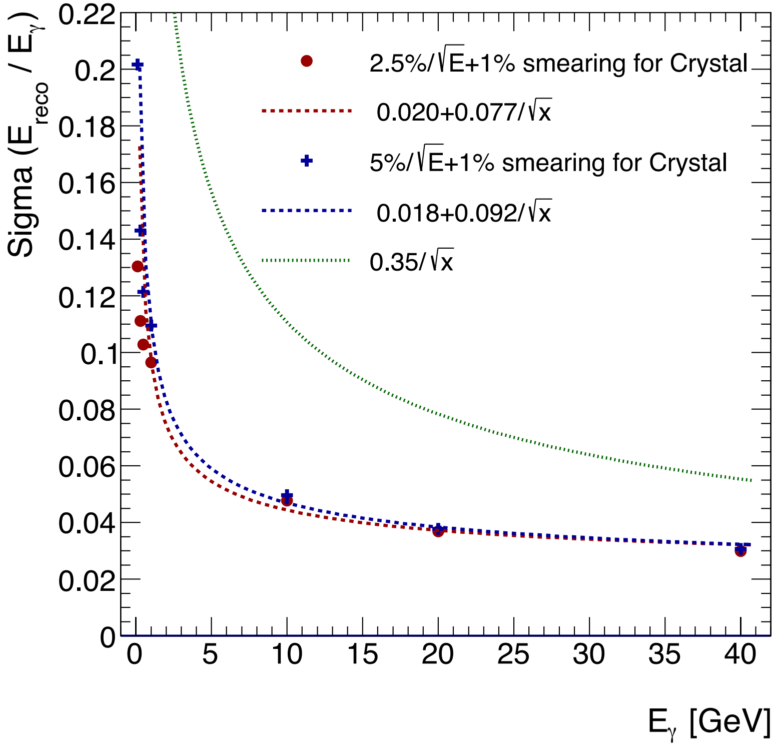
# Performance plots for the second design

- Longitudinal energy response shows clear difference for photons and neutrons.
- Neutron energy resolution is (worse than the 1st design, but) still better than physics requirement.
- Good photon energy resolution.

→ Aiming these plots to be included in the ECCE proposal.



# Summary

- The first design of ZDC was implemented in May.
  - Performance against single neutrons and photons is studied by simulation.
    - Energy resolution is sufficient, but position resolution is not good.
  - Too expensive
- The second design of ZDC is ready.
  - Reduced thickness of EM calorimeter parts.
  - Performance is estimated as still fine.

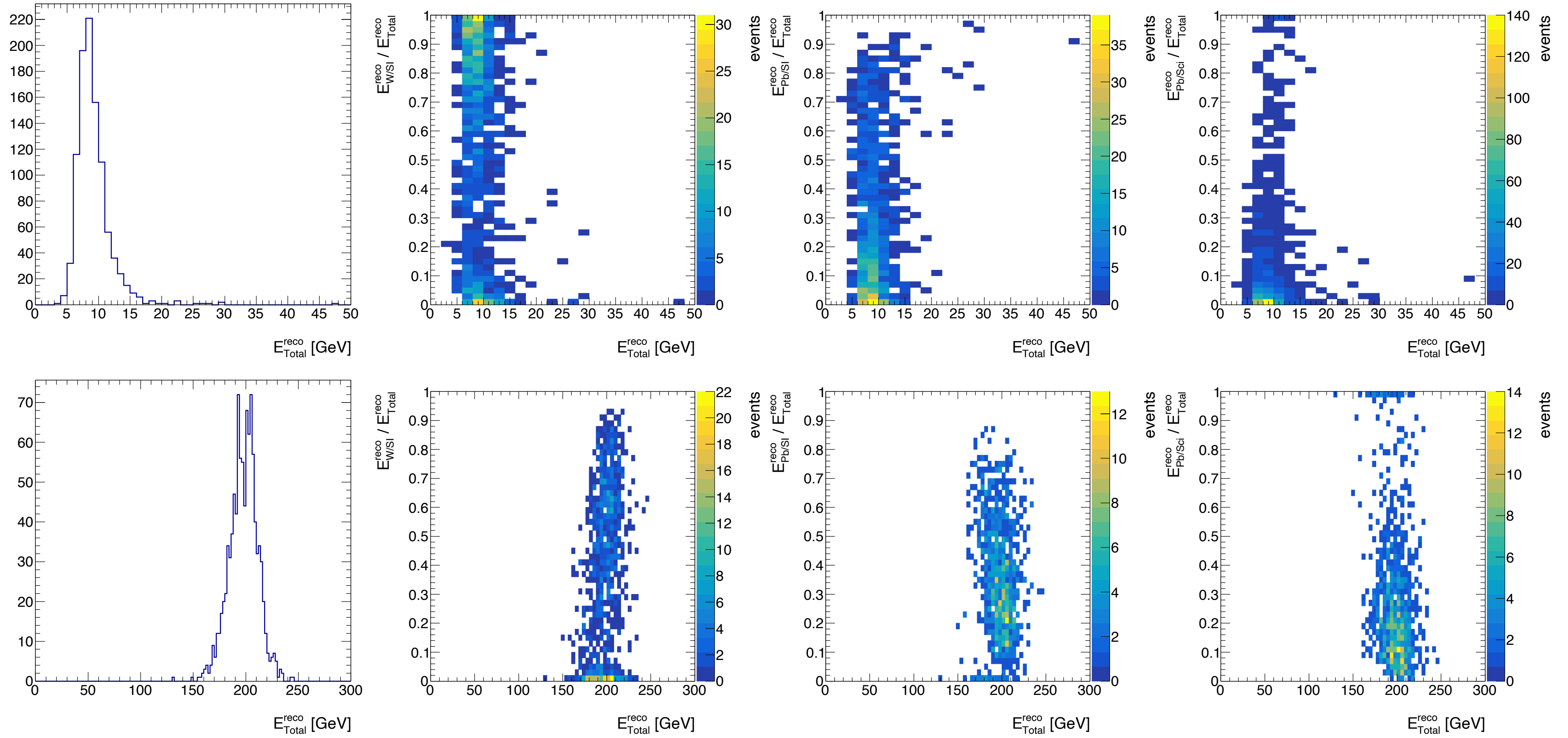
- Next steps for the ZDC design:
  - Further performance study
    - Multiple particles, further optimization for the cost reduction…
  - Check/Study of radiation hardness.
    - Simulation study is done by V. Baturin (ODU)
    - Irradiation test at RANS
  - Readout system

estimation by fit

# Reconstructed Energy

- Energy reconstruction for 10 GeV and 200 GeV neutrons, using the average value from the fits.
  - Still see the double peak, with bias in silicon layers

Total Reco. Energy | Fraction of W/SI | Fraction of Pb/SI | Fraction of Pb/Sci

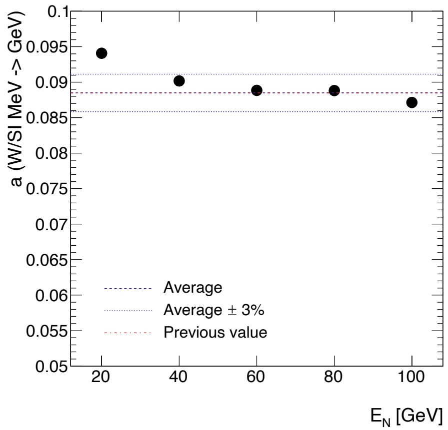


estimation by fit

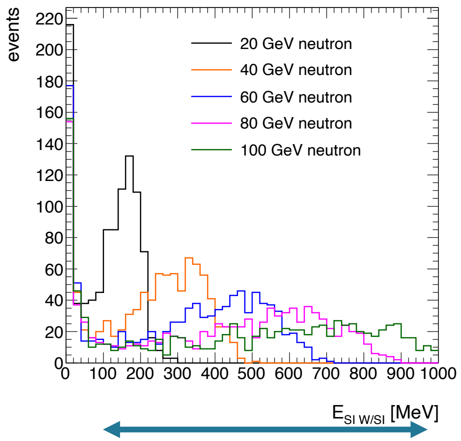
# Energy dependent factors

- Introduce energy dependence to the factors for silicon layers.
  - W/SI: Average * $(1-0.008*(E_{SI}-500)/1000)$
  - Pb/SI: Average * $(1+0.04*(E_{SI}-50)/100)$

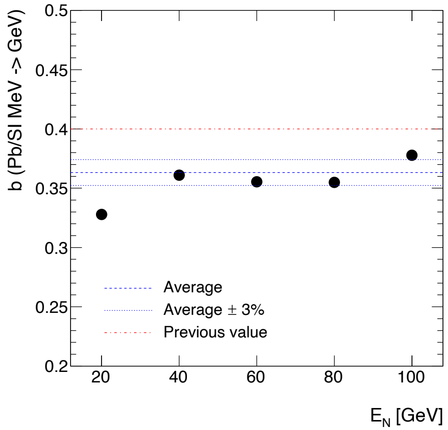
  Made-up slopes by eye. Optimisation is needed in future.

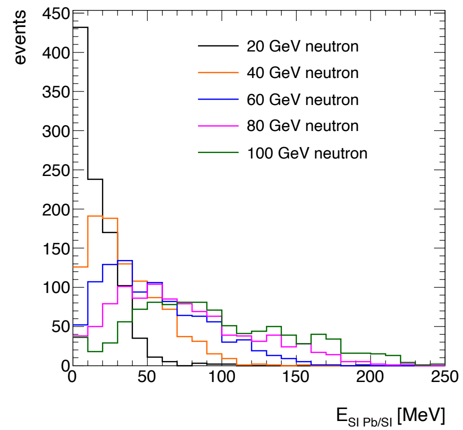



Δ~0.008




Leaver arm ~ 1000



# Some details… (more on backup)

- W/SI energy reconstruction

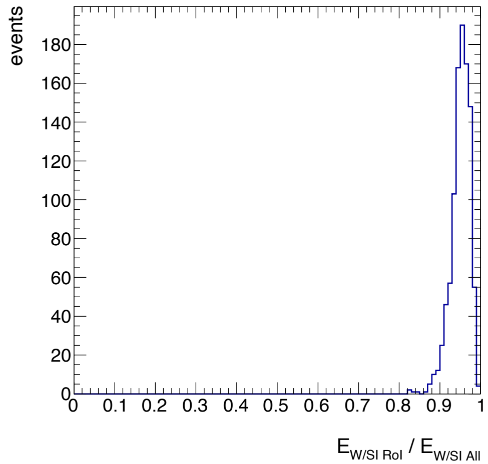
  $E_{W/SI\ Reco} = E_{W/SI\ RoI,\ raw} \times 82.7$

  - Scale factor 82.7 is obtained from direct shots of photons on W/SI layers

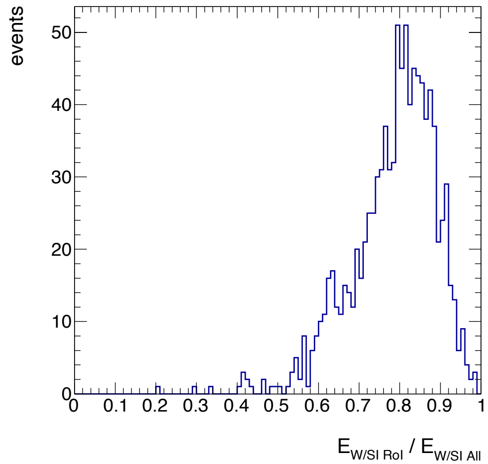
- W/SI RoI
  - RoI (9cm x 9cm) takes ~95% of energy for 1 Crystal setup, but 70~90% for 2 Crystals setup.

**Fraction of RoI energy wrt all W/SI energy**

**1 Crystal setup**



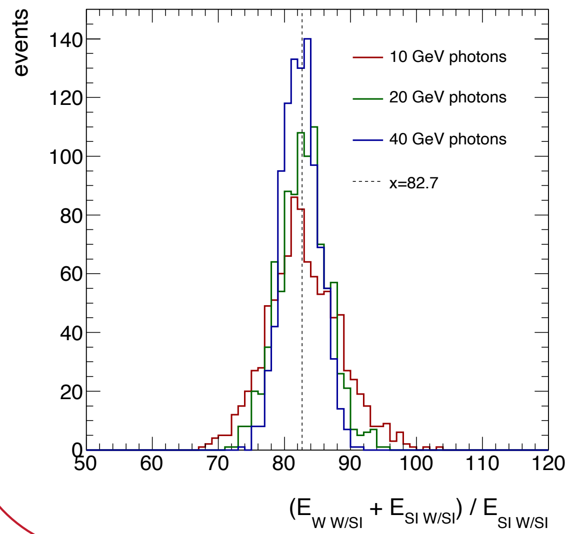

**2 Crystals setup**




**Extraction of the scale factor**

Shot 10 - 40 GeV photons directly on W/SI layers (No crystal)

Events with $E_{Abs.\ (W+PET)} + E_{SI} > 99\%$ of beam energy are analysed.




➔ SF = 82.7

**E=20 GeV photons**

RoI energy correction may be needed in future.

# Impact of resolution of Crystal

- The current setting includes:
  - No readout system
  - **Resolution of crystal is assumed as $\frac{2.5\%}{\sqrt{E}} + 1\%$.** ← Based on CMS and PANDA: ~20 cm crystals

→ Compared to $\frac{5\%}{\sqrt{E}} + 1\%$

Doubled crystal resolution gives:

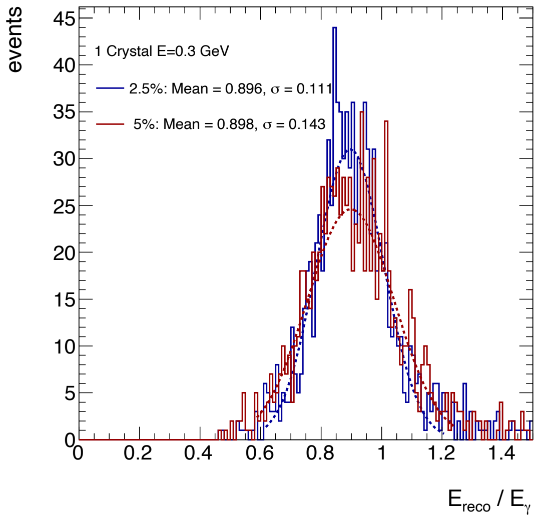
- Less impact on 1 Crystal than 2 Crystals.
- In any case, the impact is not large.
  - 300 MeV: still less than 0.2.
  - 20 GeV: difference is minor.

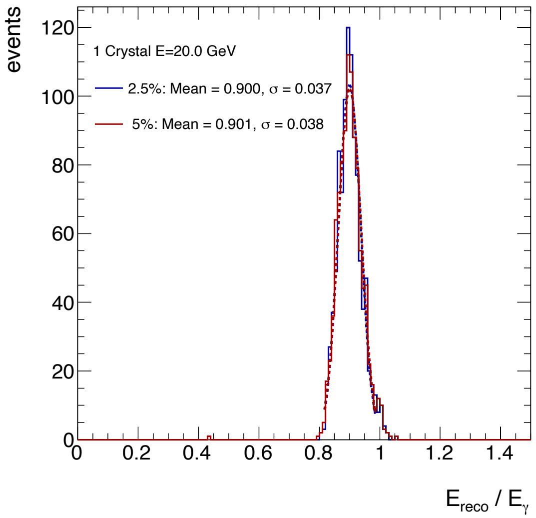
    1 Crystal: 0.037 → 0.038,

    2 Crystals: 0.018 → 0.022

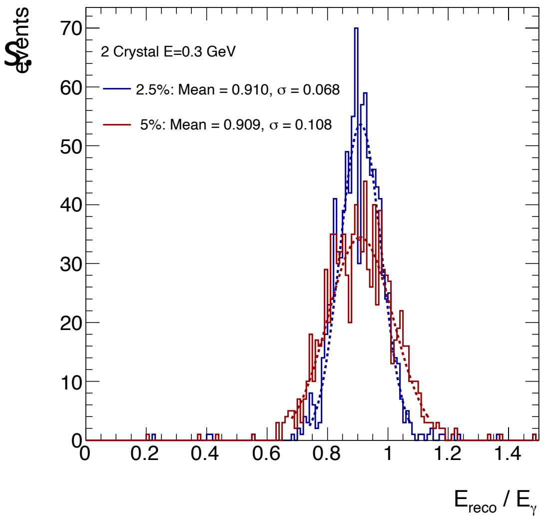
## 1 Crystal setup

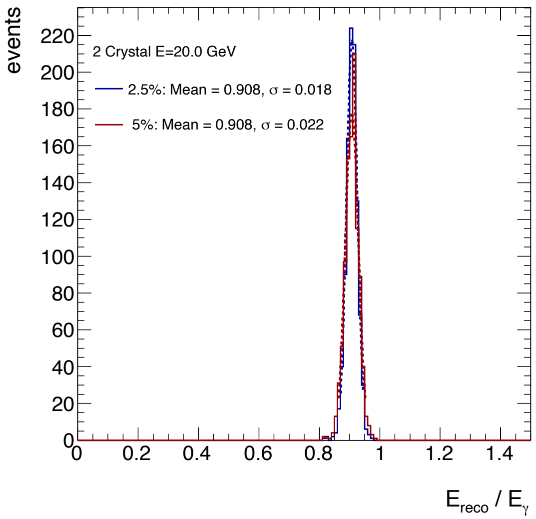
**E = 300 MeV** / **E = 20 GeV**



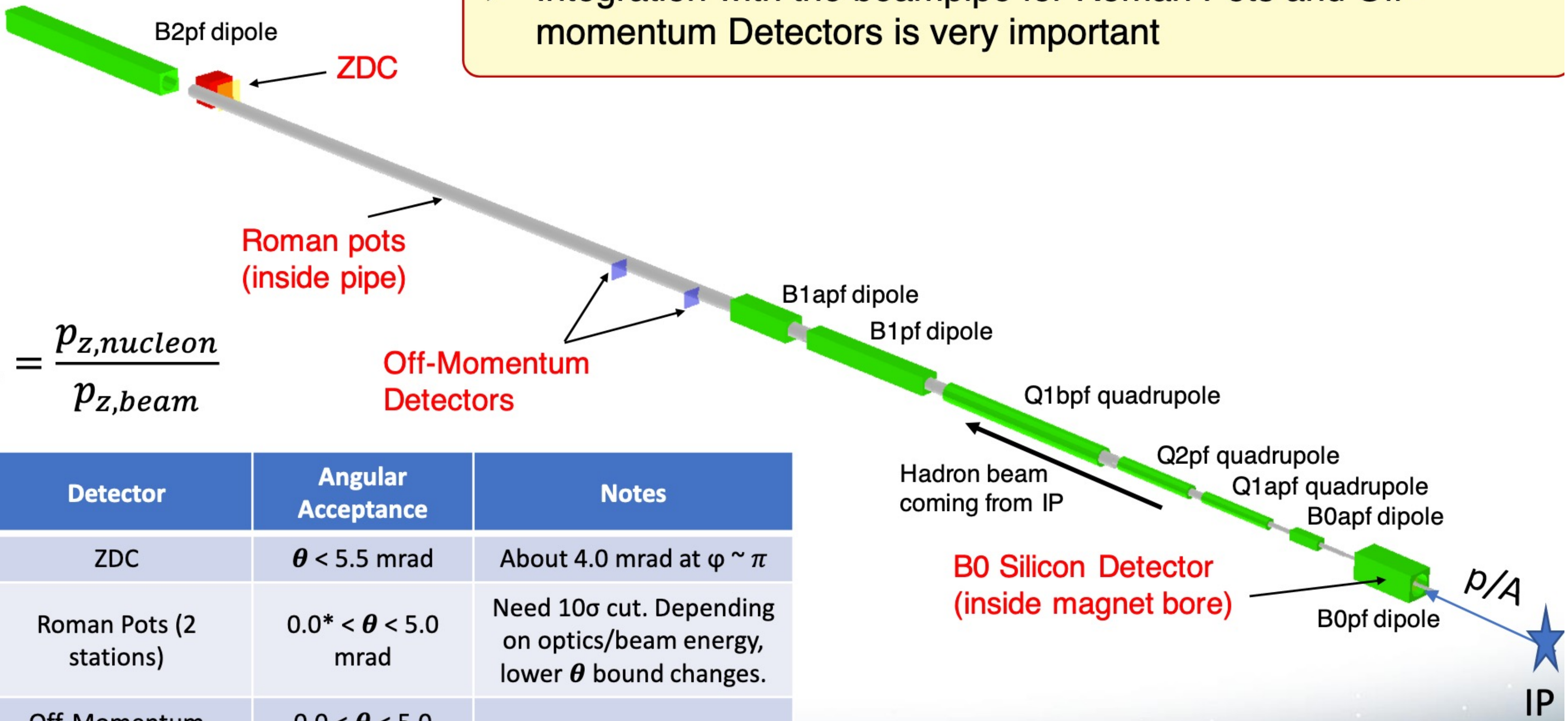

## 2 Crystals setup



# Forward detectors

> ➢ Integration with the beampipe for Roman Pots and Off-momentum Detectors is very important




$$x_L = \frac{p_{z,nucleon}}{p_{z,beam}}$$

| Detector | Angular Acceptance | Notes |
|---|---|---|
| ZDC | $\theta < 5.5$ mrad | About 4.0 mrad at $\varphi \sim \pi$ |
| Roman Pots (2 stations) | $0.0^* < \theta < 5.0$ mrad | Need 10σ cut. Depending on optics/beam energy, lower $\theta$ bound changes. |
| Off-Momentum Detectors | $0.0 < \theta < 5.0$ mrad | Roughly $0.4 < x_L < 0.6$ |
| B0 Sensors (4 layers, evenly spaced) | $5.5 < \theta < 20.0$ mrad | Could change a bit depending on pipe and electron quad |