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CEPC AHCAL Optimization

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OutLine

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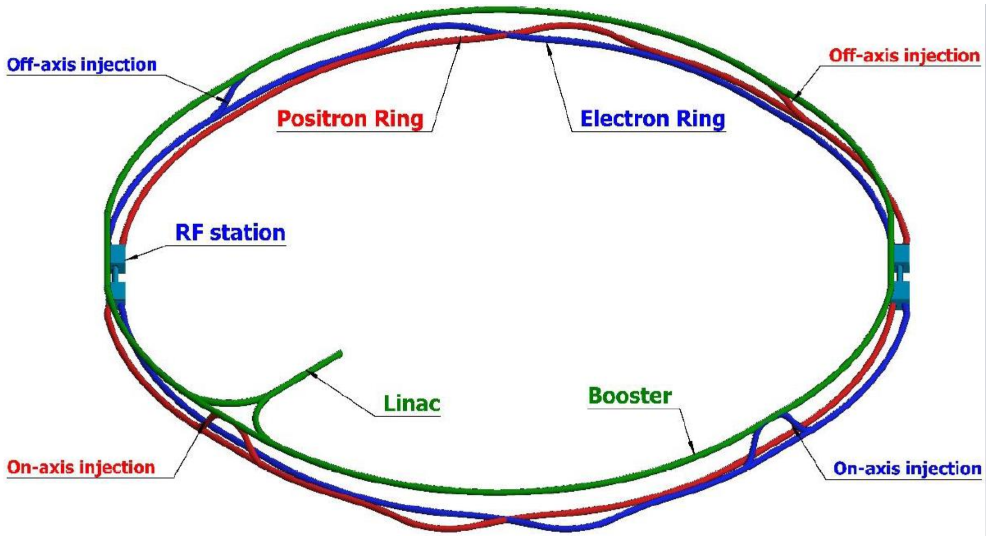
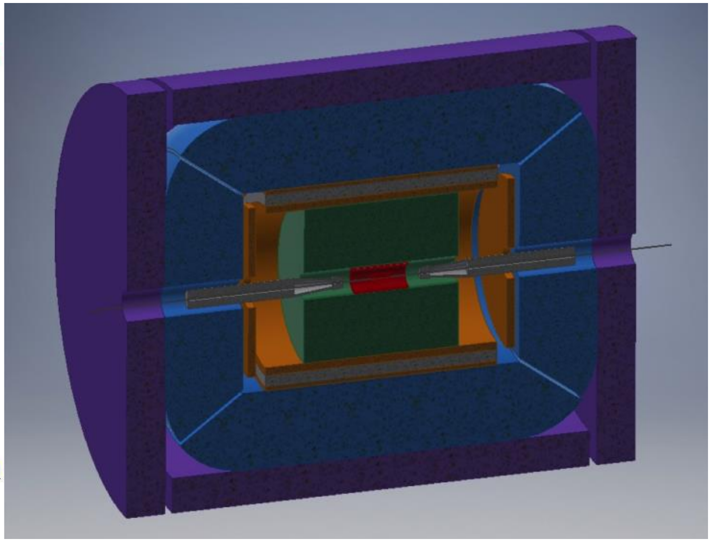
- Prototype optimization
  - Prototype transverse size
  - Absorber thickness
  - Sampling layers
  - Scintillator thickness
  - Prototype design and performance
- CEPC AHCAL optimization
  - Absorber thickness
  - Sampling layers
  - Scintillator thickness
  - Cell size
- Summary and outlook

Background

- CEPC
  - The CEPC is designed as the Higgs factory
  - The baseline detector option for the CEPC is guided by the particle flow algorithm(PFA)



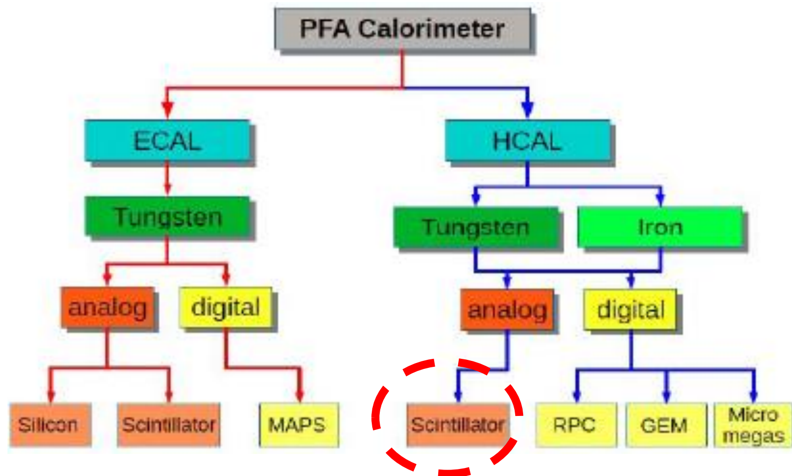
Design of the CEPC Accelerator



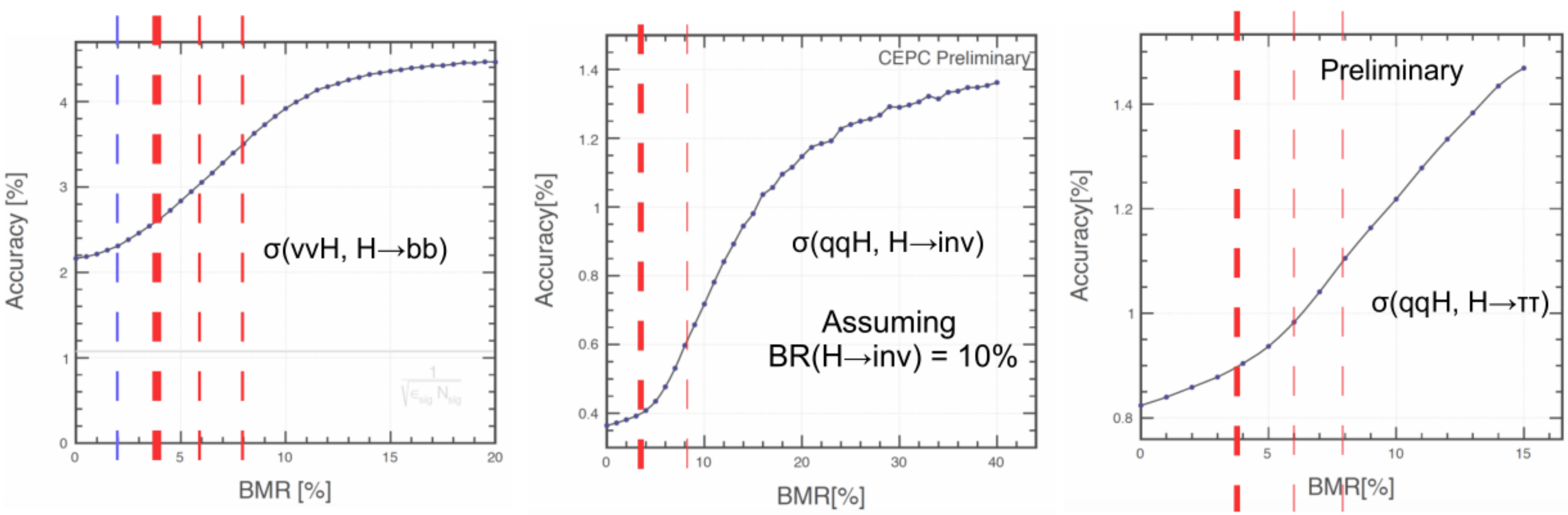
CEPC baseline detector

Background

- Physics requirement for calorimeter
  - Prototype
    - Linearity: $\pm 3\%$
    - Resolution: $\frac{60\%}{\sqrt{E(GeV)}} \oplus 3\,\%$
  - CEPC AHCAL
    - Boson Mass Resolution :4%



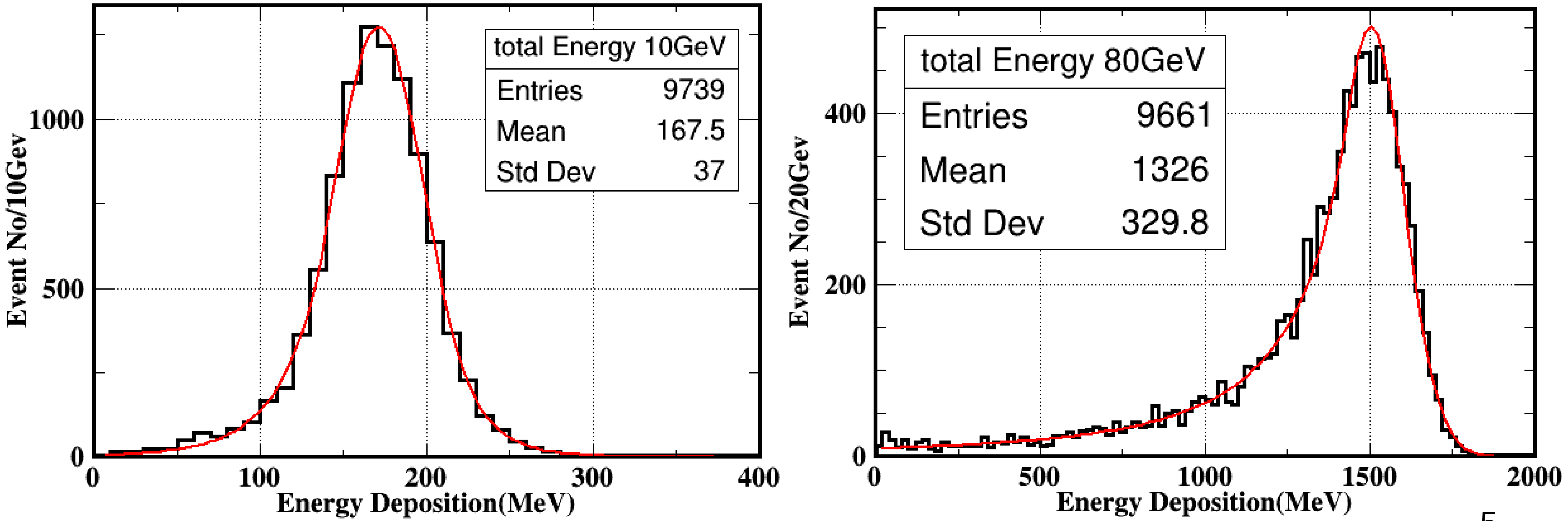
CEPC baseline calorimeter options



BMR requirement from Manqi Ruan's report

Prototype optimization

- Simulation Setup
  - CEPC Simplified Geometry
  - Prototype Transverse size: $72 \times 72\mathrm{cm}^2$
  - 40 layers: each layer has 20mm steel,3mm scintillator and 2mm PCB
  - Incident particle: Klong with energy from 10GeV to 80GeV



Energy deposition for 10GeV and 80GeV KL

Prototype optimization

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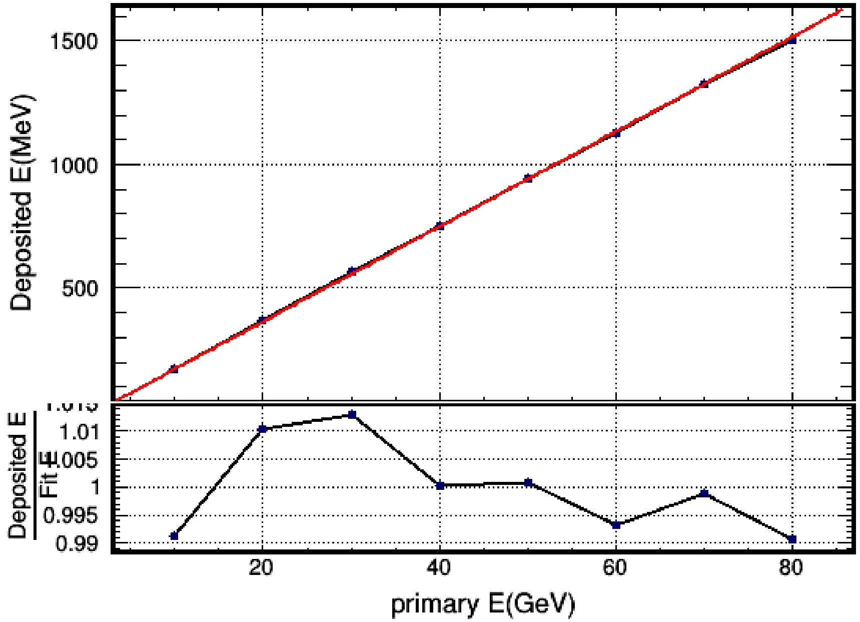
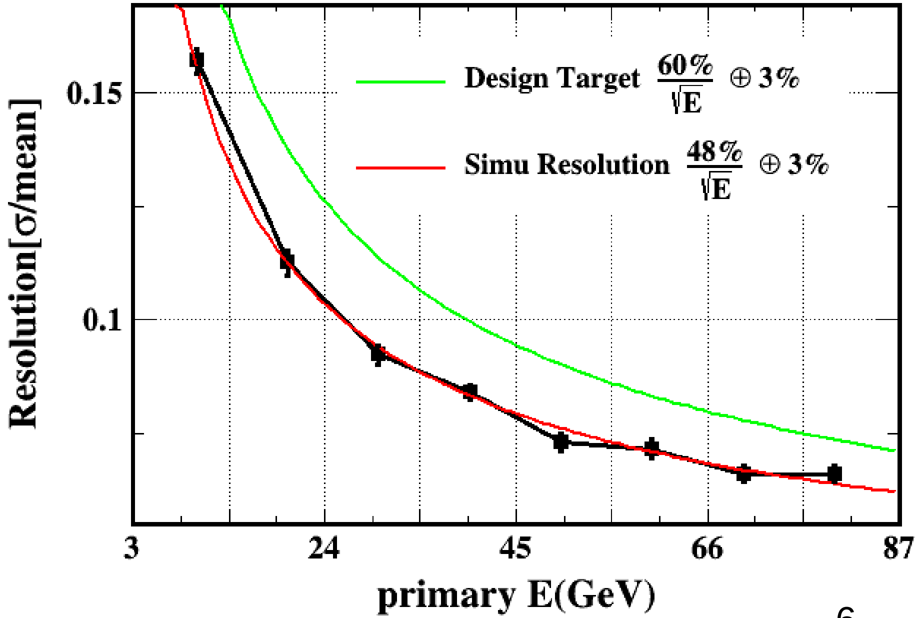
- Analysis
  - Fit by double side crystal ball function
  - Energy resolution as a function of incident particle's energy is described by $\frac{a}{\sqrt{E}} \oplus b$





Linearity and resolution for HCAL prototype

Prototype optimization

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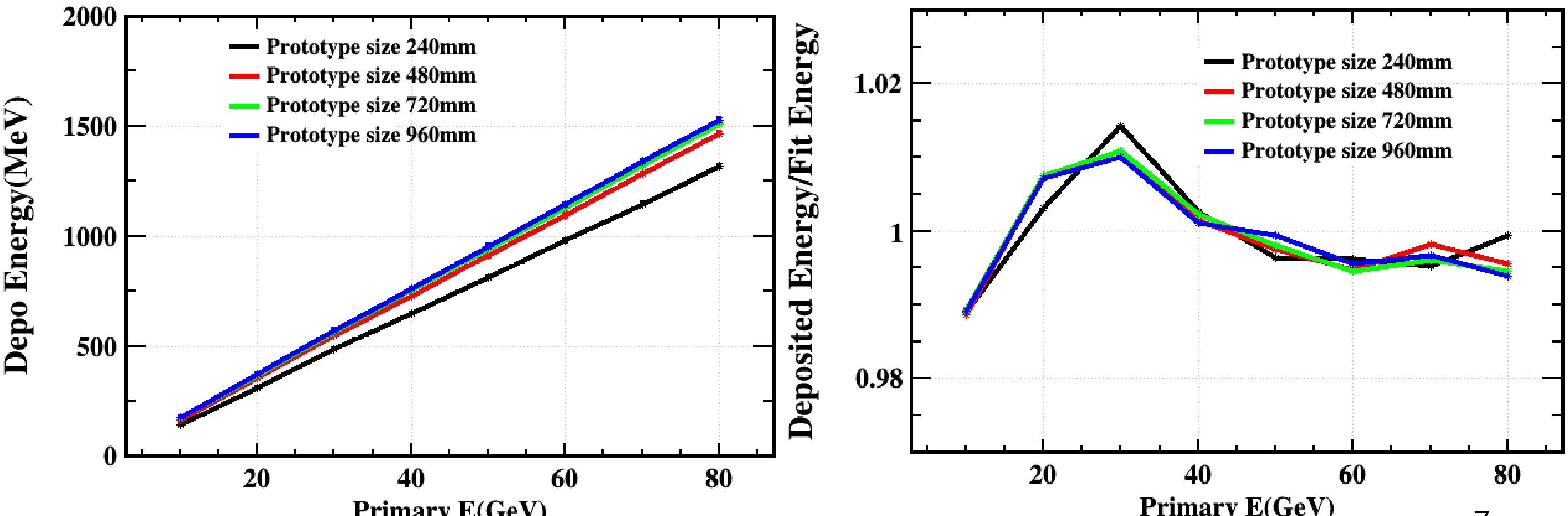
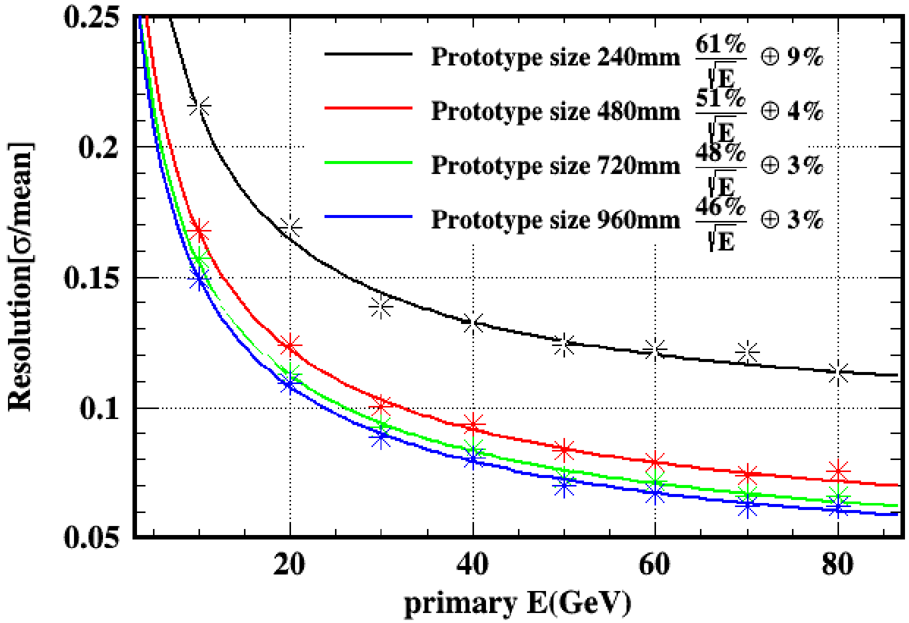
- Prototype size optimization
  - 40 sampling layer, each layer has 20mm steel, 3mm scintillator and 2mm PCB
  - The transverse prototype size ranges from 240mm to 960mm
  - All have a linearity < $\pm 3\%$

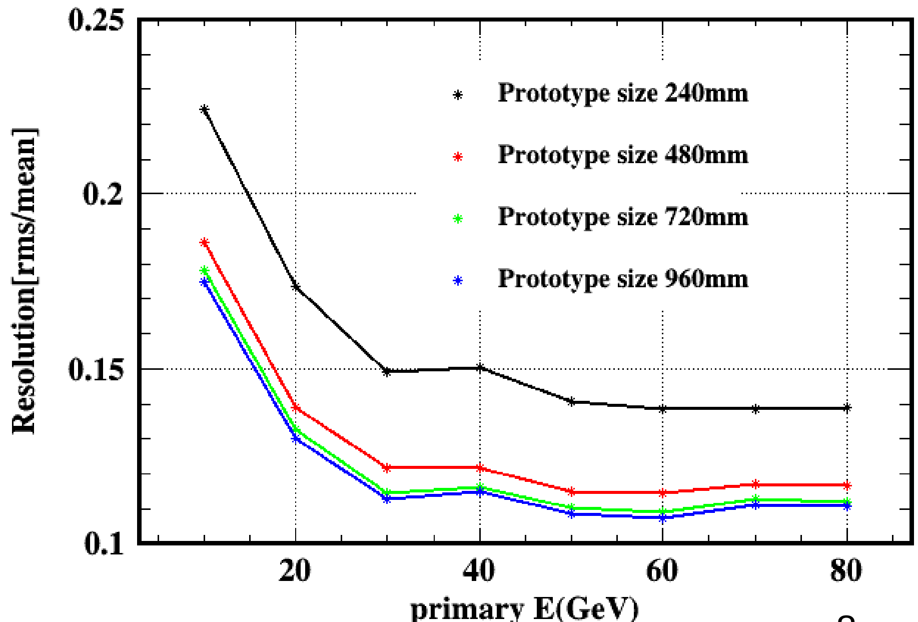


Linearity for different prototype transverse size

Prototype optimization

- Prototype size optimization
  - Larger prototype size has less energy leakage and better resolution
  - Prototype size has a strong impact on the cost and power consumption of the prototype
  - 720mm is chosen to be the prototype transverse size





resolution for different Prototype size

Prototype optimization

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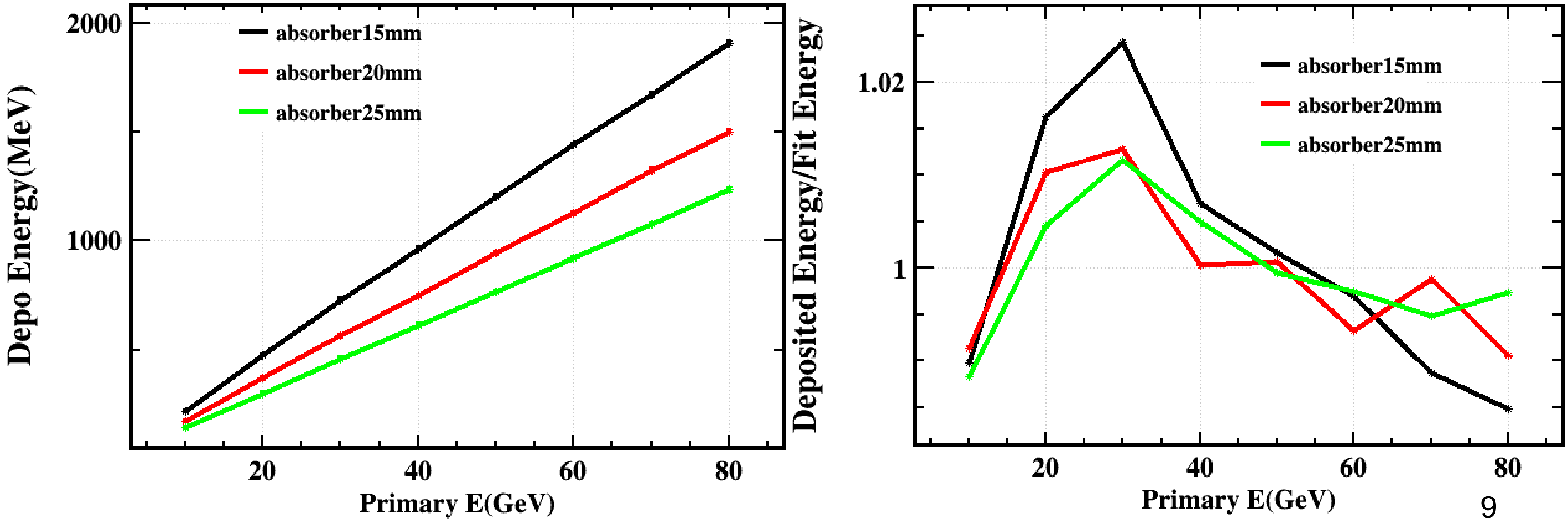
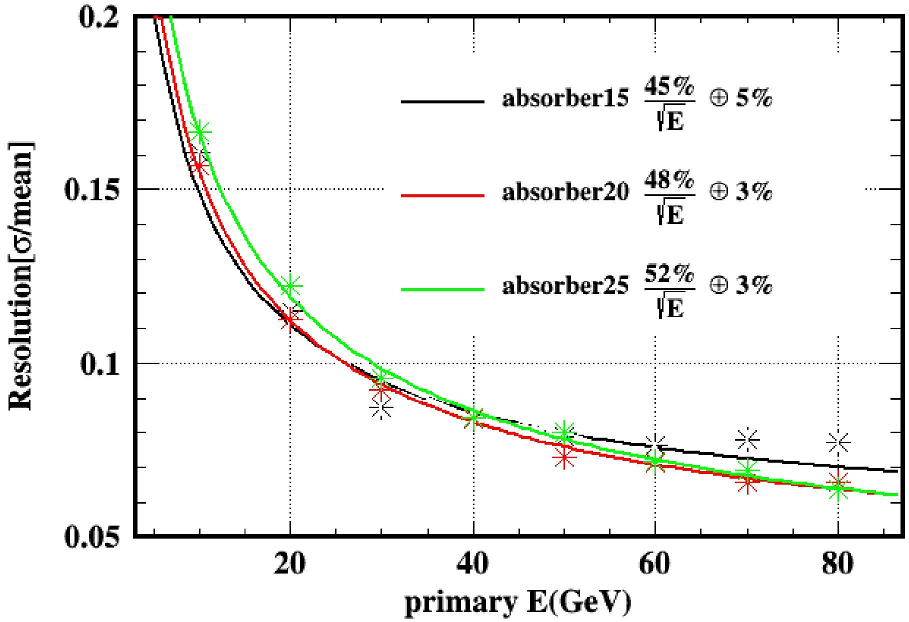
- Absorber thickness optimization
  - Prototype Transverse size: $72 \times 72\text{cm}^2$
  - 40 sampling layer, each layer has 3mm scintillator and 2mm PCB
  - Absorber thickness for each layer ranges from15mm to 25mm
  - Total absorber thickness ranges from 3.8λ to 6.3λ
  - All have a linearity < $\pm 3\%$

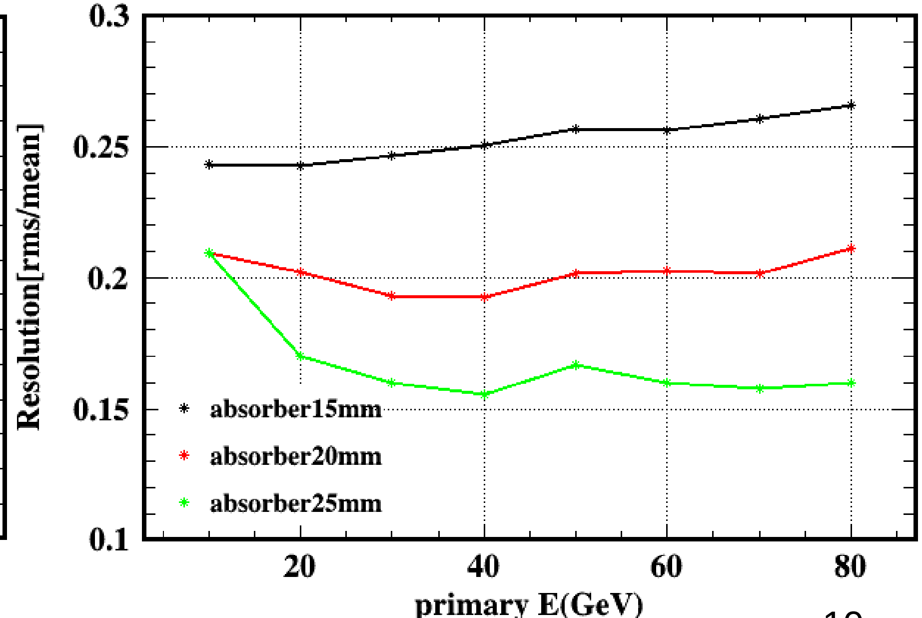


Linearity for different absorber thickness

Prototype optimization

- Absorber thickness optimization
  - Thinner absorber has a better sampling ratio resulting a smaller statistical term
  - Thinner absorber has larger leakage resulting a bigger constant term
  - The 20mm absorber can satisfy our need





resolution for different absorber thickness

Prototype optimization

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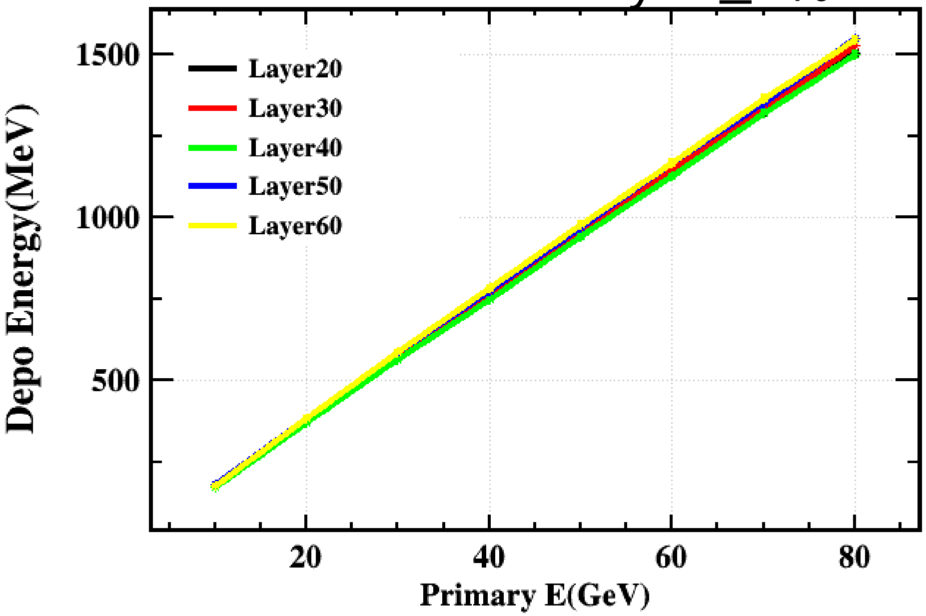
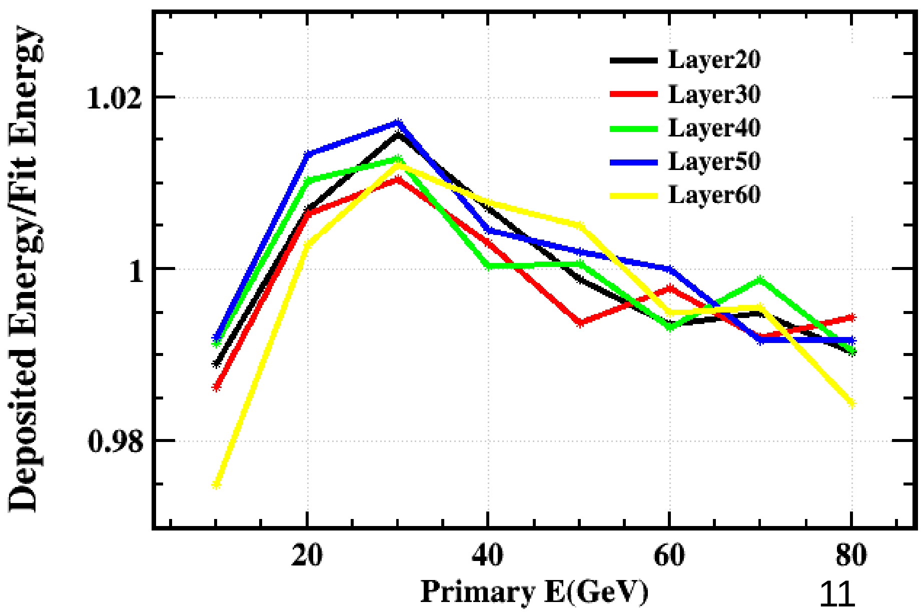
- Sampling Layer optimization
  - Prototype Transverse size: $72 \times 72\mathrm{cm}^2$
  - Total absorber thickness is fixed as 800mm and total scintillator thickness is fixed as 120mm
  - The thickness of PCB for each layer is 2mm
  - The number of sampling layers ranges from 20 to 60
  - All have a linearity < $\pm 3\%$





Linearity for different sampling layers

Prototype optimization

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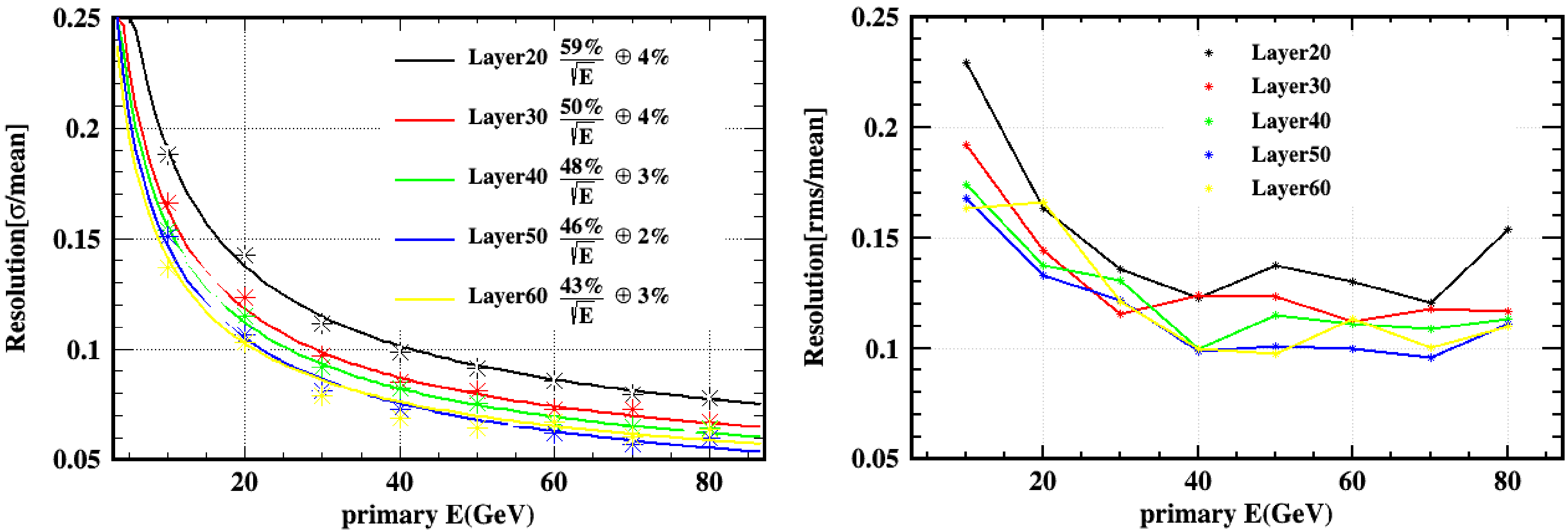
- Sampling Layer optimization
  - More sampling layers have less statistical fluctuation
  - Since PCB thickness for each layer is fixed, it could be a problem for more sampling layers in the prototype
  - 40 layers is reasonable for the prototype



Resolution for different sampling layers

Prototype optimization

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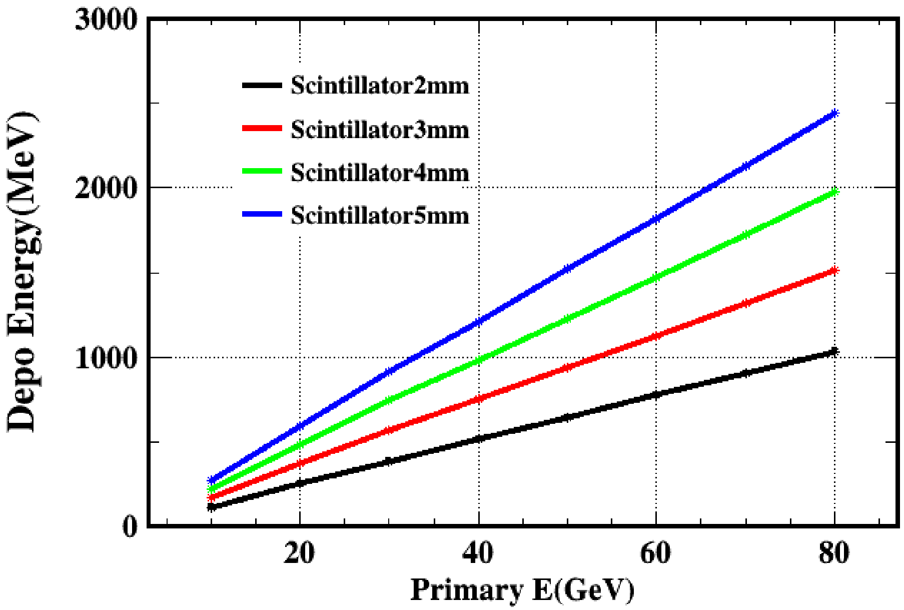
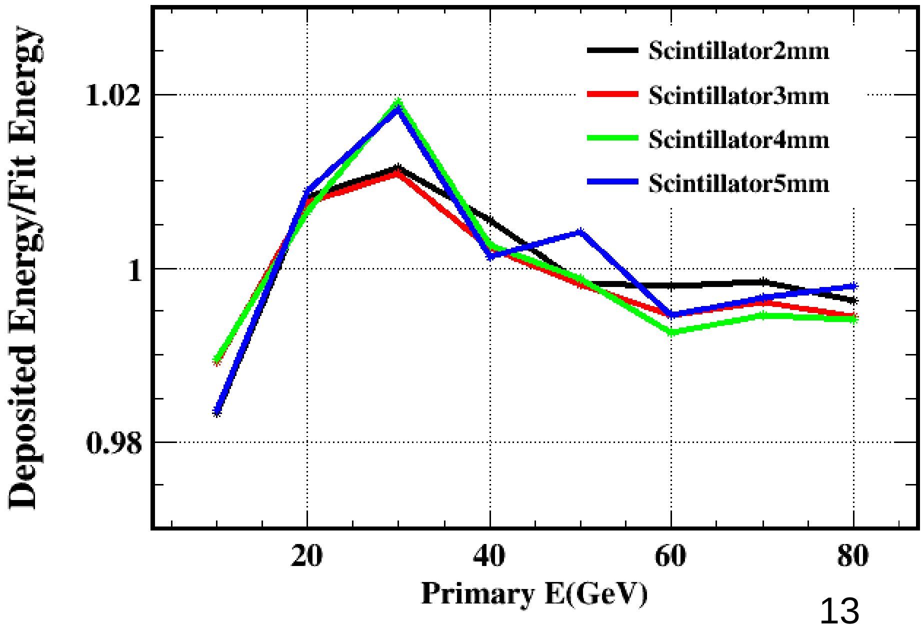
- Scintillator thickness optimization
  - Prototype Transverse size: $72 \times 72\text{cm}^2$
  - 40 sampling layer, each layer has 20mm steel and 2mm PCB
  - The scintillator thickness for each layer ranges from 2mm to 5mm
  - All have a linearity < $\pm 3\%$

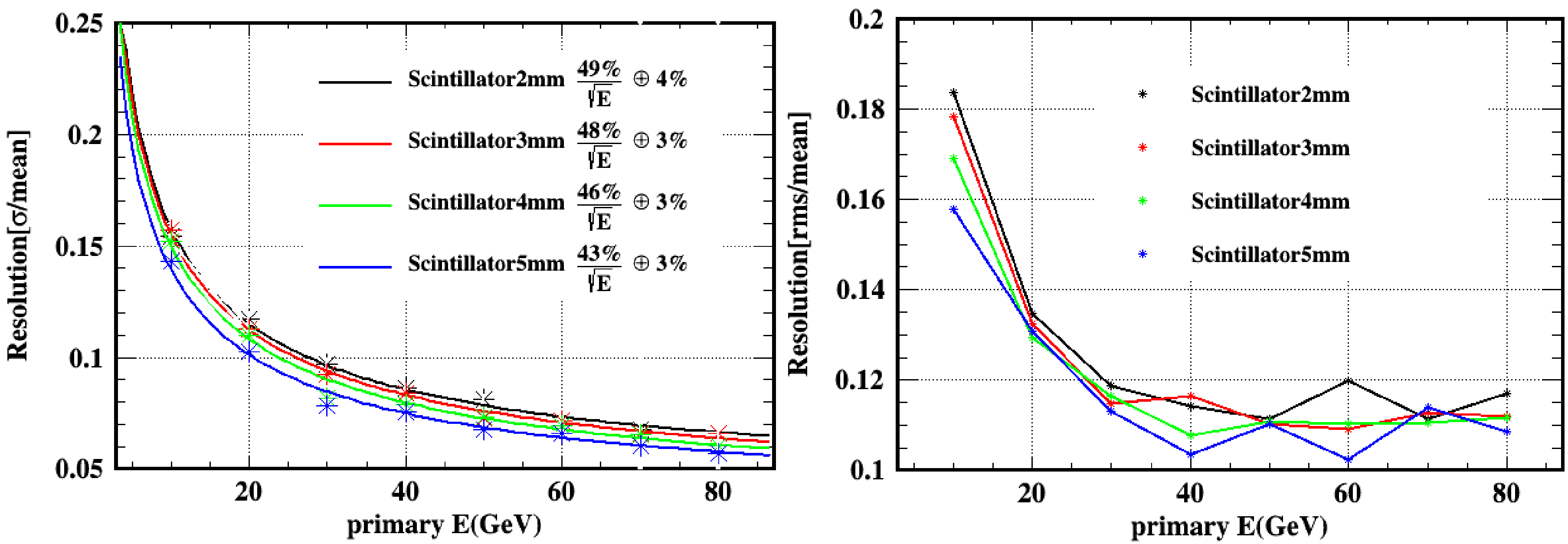




Linearity for different scintillator thickness

Prototype optimization

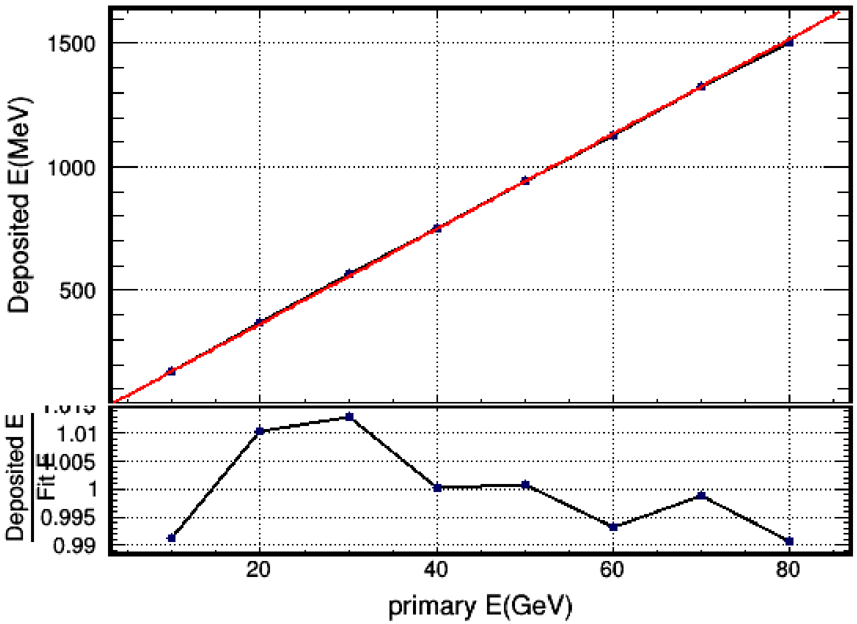
- Scintillator thickness optimization
  - Thicker scintillator has better resolution but the improvement isn't obvious
  - Thicker scintillator will increase total thickness and manufacture cost
  - 3mm scintillator is chosen for the prototype

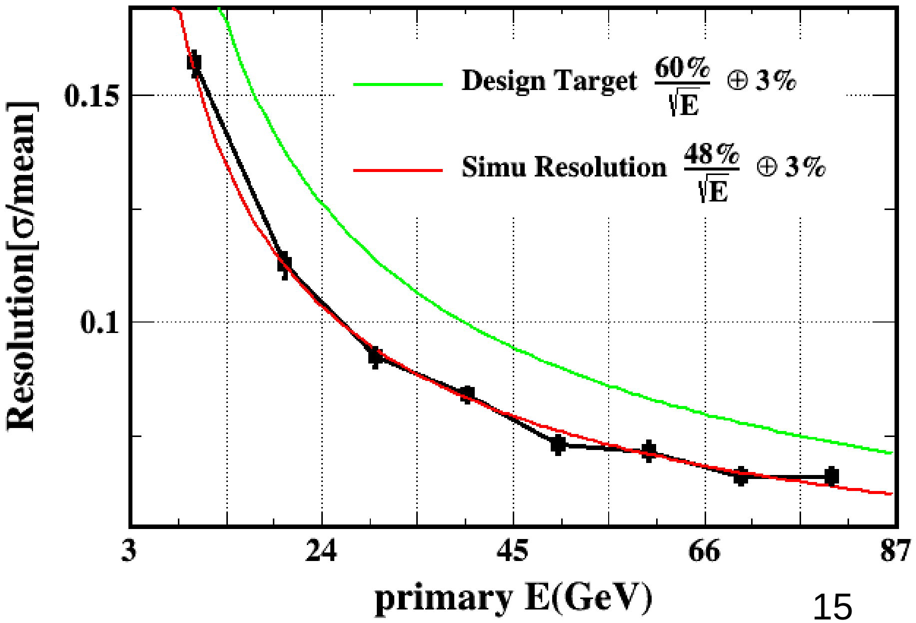


Resolution for different scintillator thickness

Prototype optimization

– Prototype design and performance
- Transverse size: $72 \times 72\mathrm{cm}^2$
- 40 layers: each layer has 20mm steel,3mm scintillator and 2mm PCB
- Linearity:$< \pm 3\%$
- Resolution:$< \frac{60\%}{\sqrt{E(GeV)}} \oplus 3\ \%$





Linearity and resolution for HCAL prototype

CEPC AHCAL optimization

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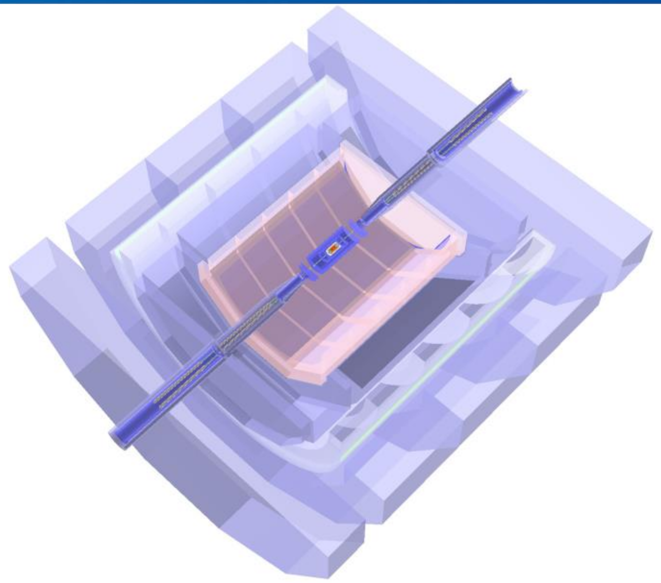
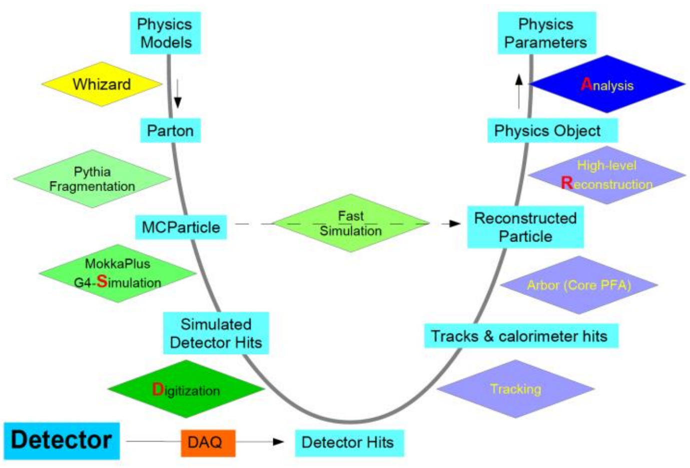
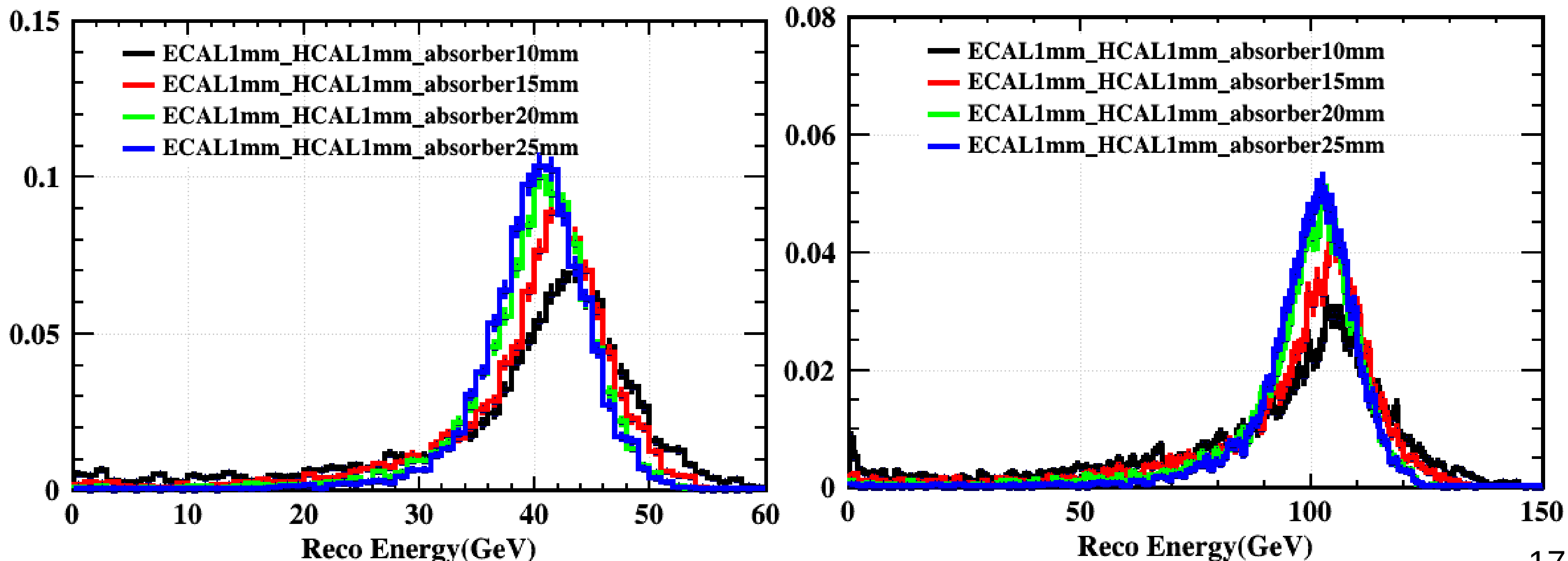
- CEPC software environment
  - CEPC V4 geometry
    - Tracker and magnet field
    - ECAL and HCAL
    - Muon detector
  - PFA reconstruction
    - Detect particles with optimal detector
    - Higgs boson mass could be reconstructed with the recoil mass method
  - Physics benchmarks
    - $\nu\nu H - gg$
    - Zuds: $e^{+}e^{-} - q\bar{q}(q = uds)\ via\ Z$





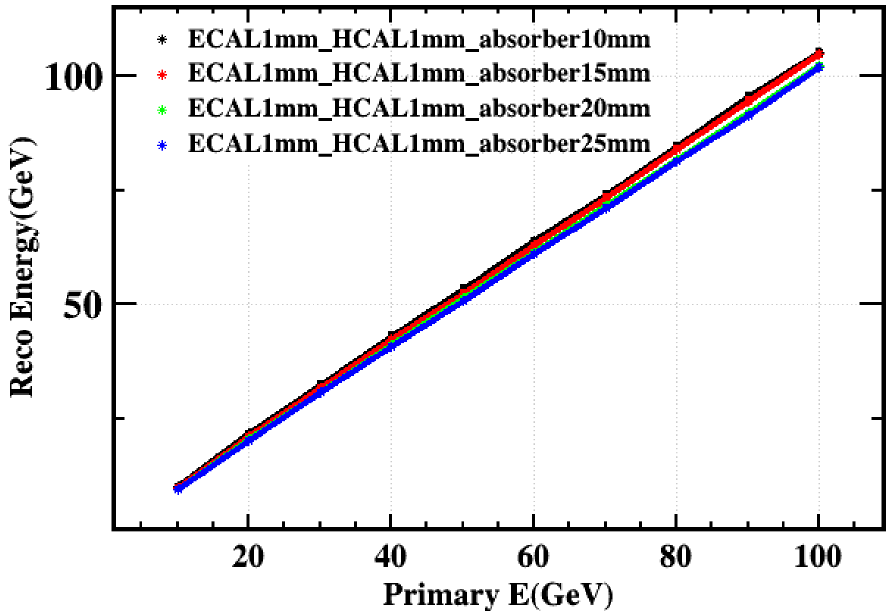
CEPC AHCAL optimization

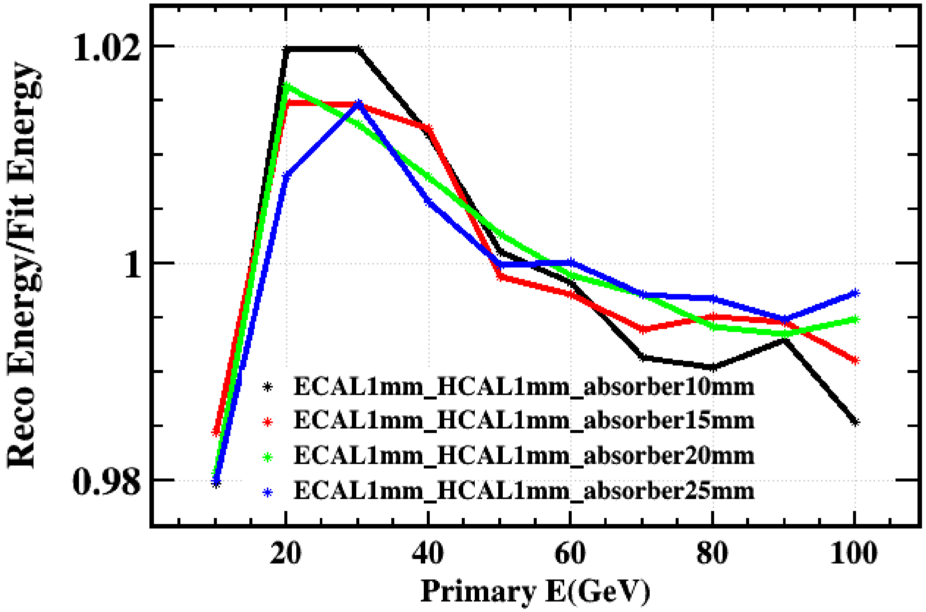
- Absorber thickness optimization
  - Klong with energy from 10 to 100GeV
  - Absorber thickness ranges from 10mm to 25mm
  - KL energy is reconstructed from ECAL and HCAL energy



KL reconstructed energy at different absorber thickness

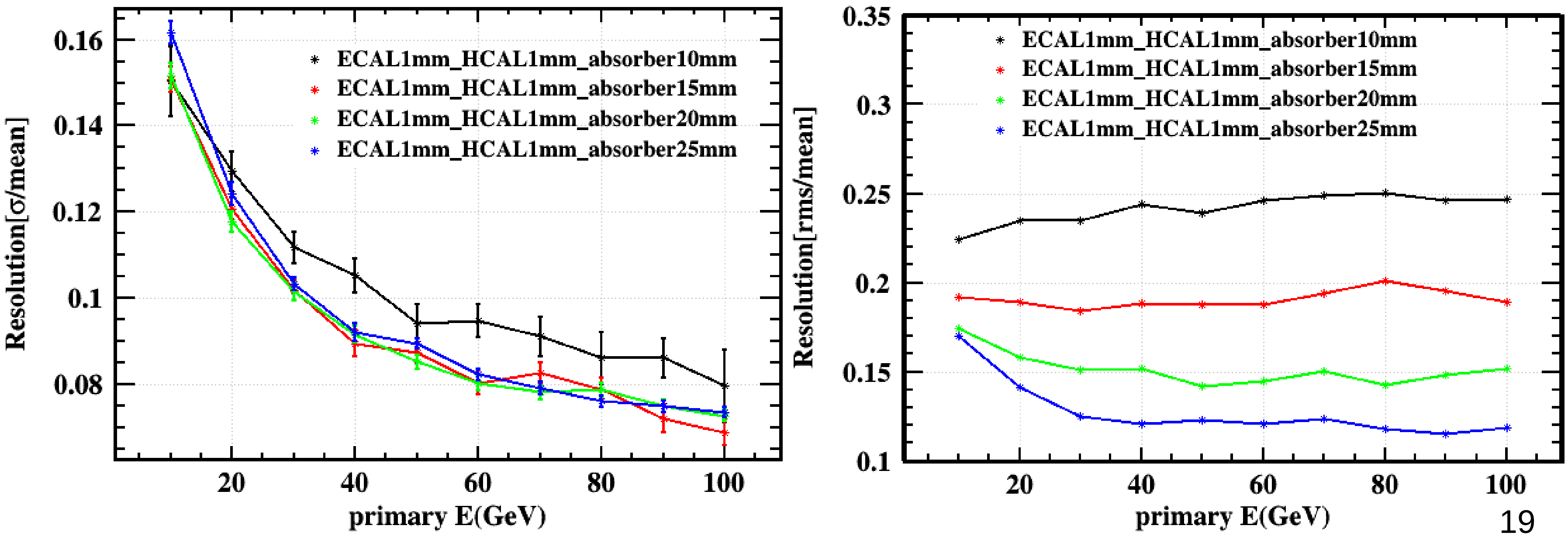
- Absorber thickness optimization
  - Use crystal ball function as fitting function
  - The linearities are all within $\pm 3\%$ for different absorber thickness





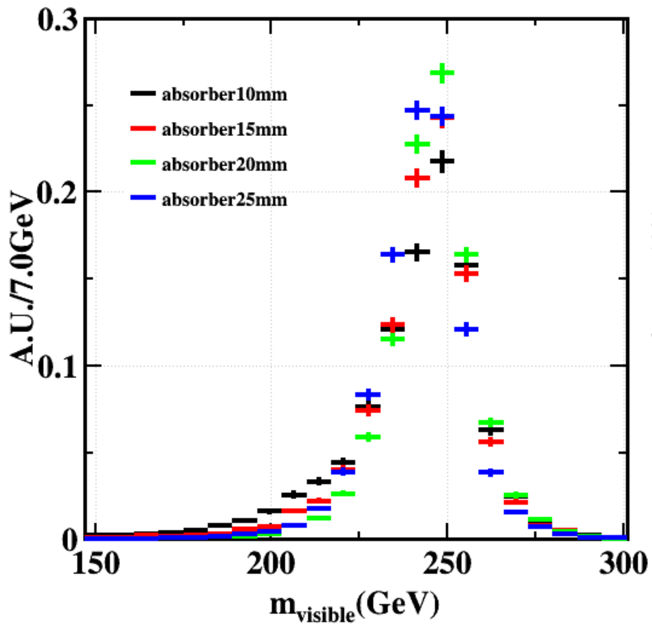
KL Linearity at different absorber thickness

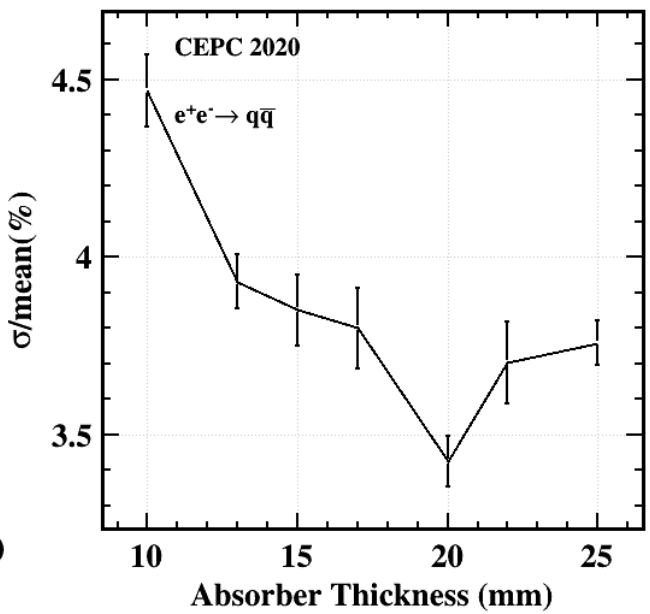
- Absorber thickness optimization
  - ECAL introduce more material comparing to Simplified geometry
  - The 10mm absorber has a worse resolution than others
  - The rms/mean reflects the leakage for different absorber



KL resolution at different absorber thickness

- Absorber thickness optimization
  - The $m_{visible}$ is reconstructed for each Zuds event
  - The resolution of $m_{visible}$ as a function of absorber thickness shows that 20mm is a turning point





Zuds events for different absorber thickness

CEPC AHCAL optimization

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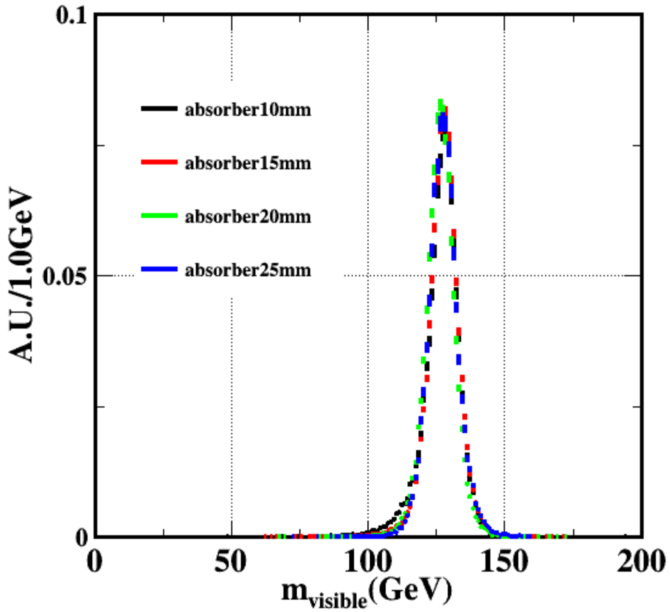
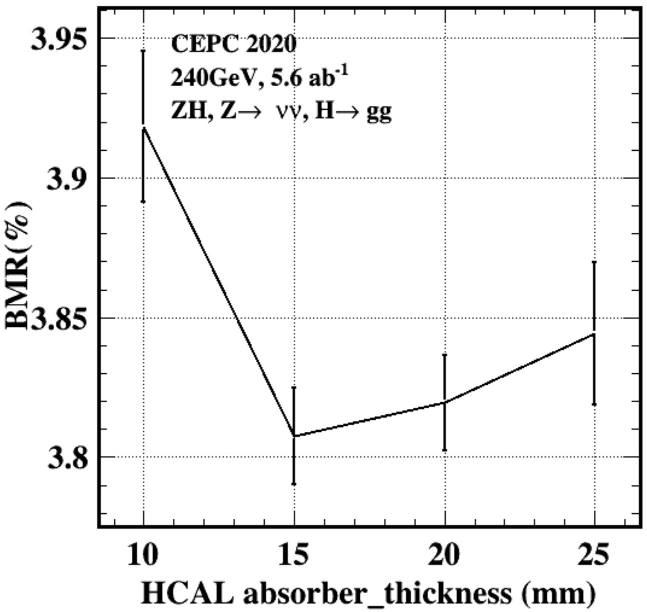
- Absorber thickness optimization
  - The jets in $\nu\nu H - gg$ events have lower energy comparing to the jets in Zuds events
  - The Higgs mass is reconstructed as $m_{visible}$ in $\nu\nu H - gg$ events
  - The boson mass resolution(BMR) as a function of absorber thickness shows 15mm is the turning point

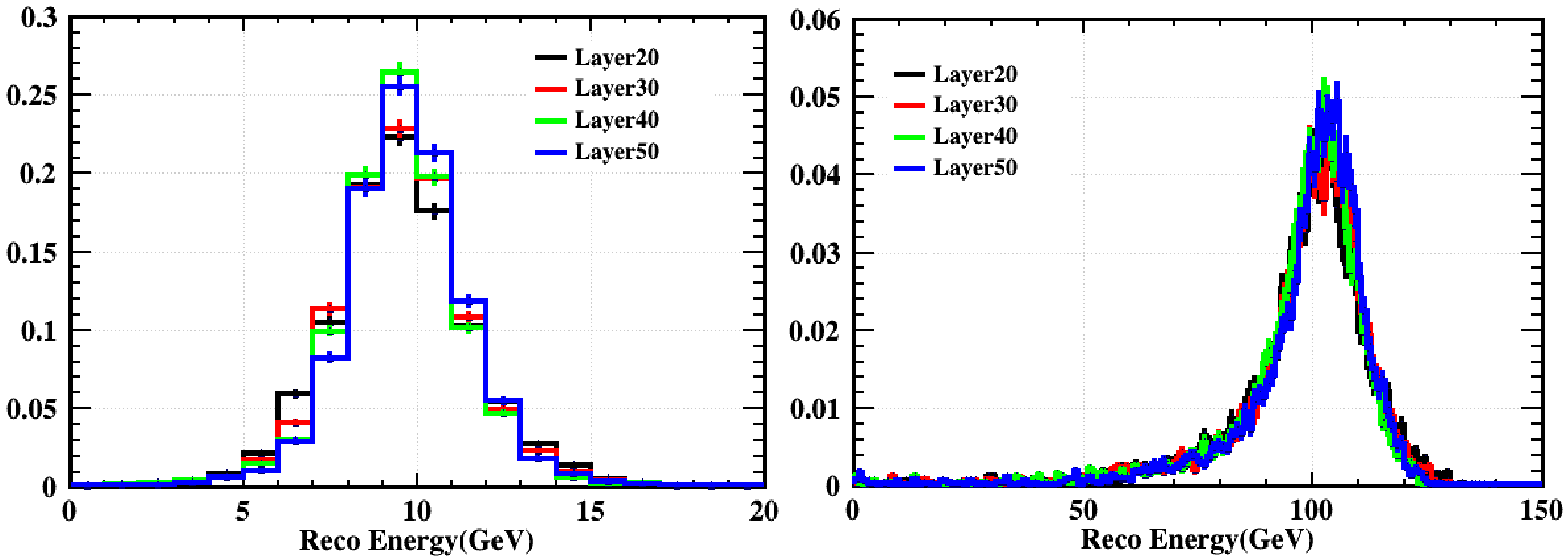




$\nu\nu H - gg$ events for different absorber thickness

CEPC AHCAL optimization

- Sampling Layer optimization
  - Total absorber thickness is fixed as 800mm and total scintillator thickness is fixed as 120mm
  - The thickness of PCB for each layer is 2mm
  - The number of sampling layers ranges from 20 to 50



KL reconstructed energy at different sampling layers

CEPC AHCAL optimization

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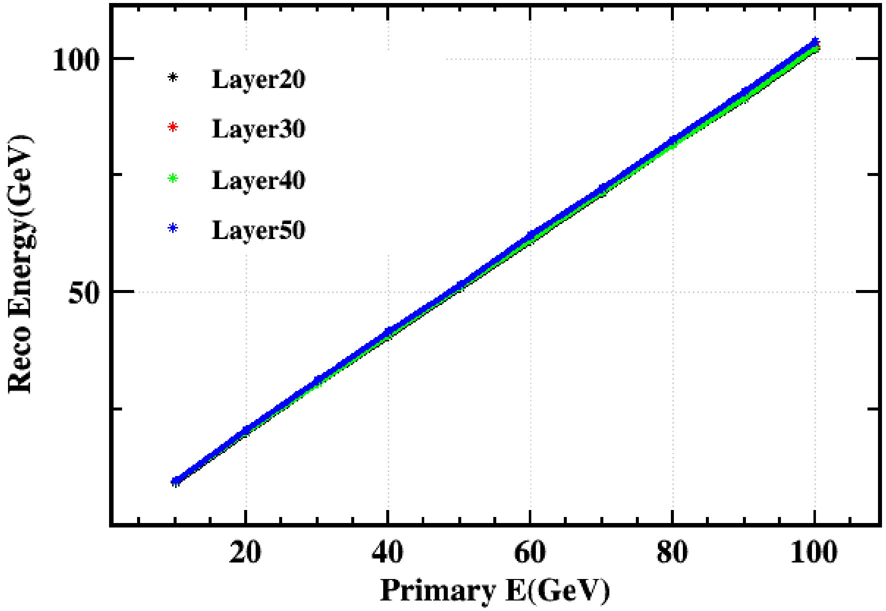
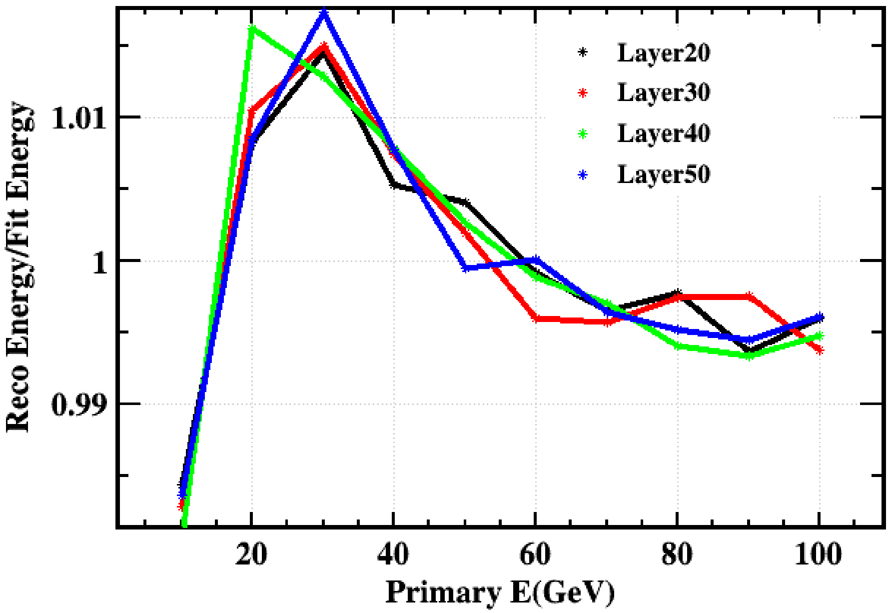
- Sampling layer optimization
  - The linearities are almost the same for different sampling layers
  - The linearities are all within ±2% for different sampling layers





KL Linearity at different sampling layers

CEPC AHCAL optimization

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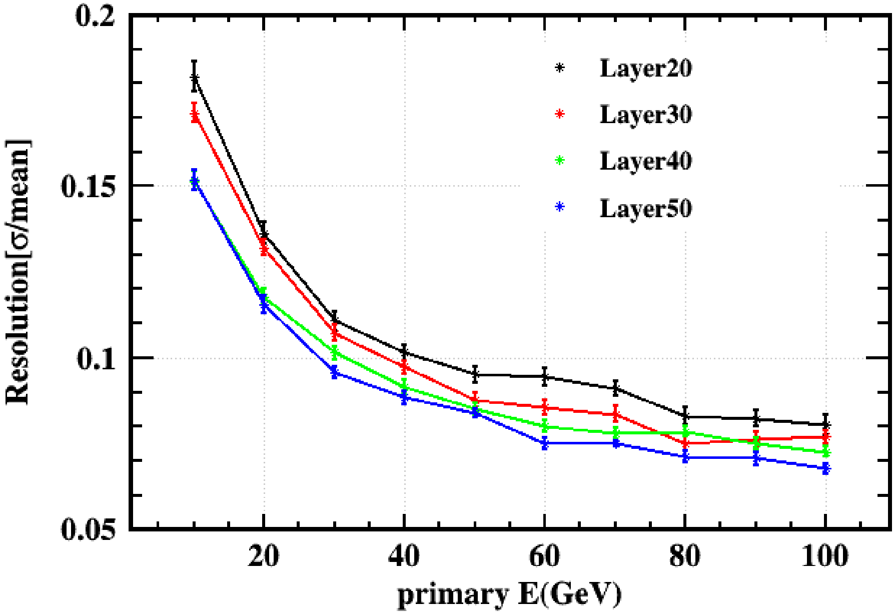
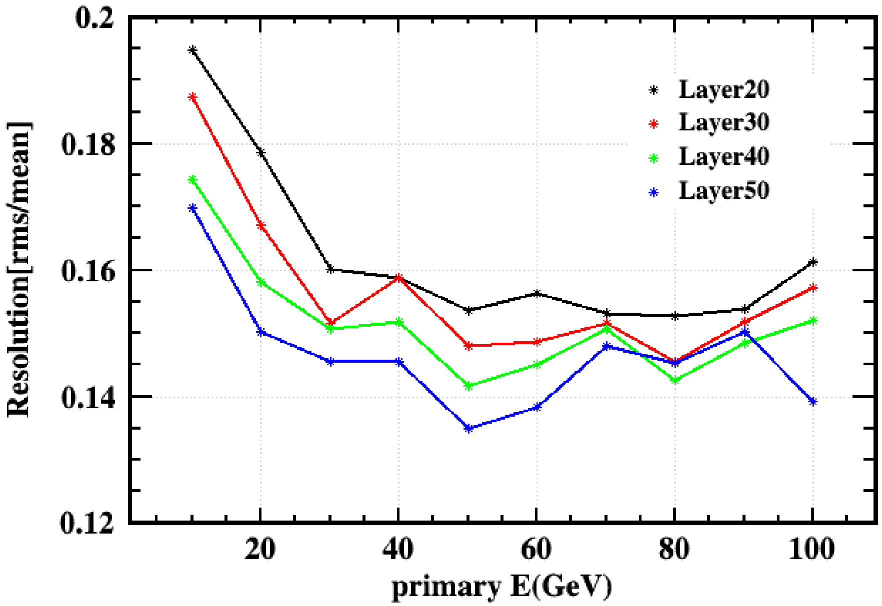
- Sampling layer optimization
  - More sampling layers have better energy resolution





KL resolution at different sampling layers

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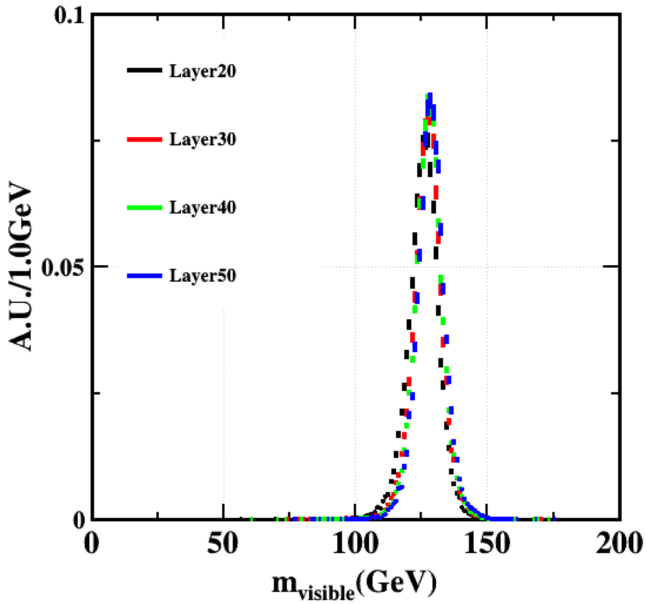
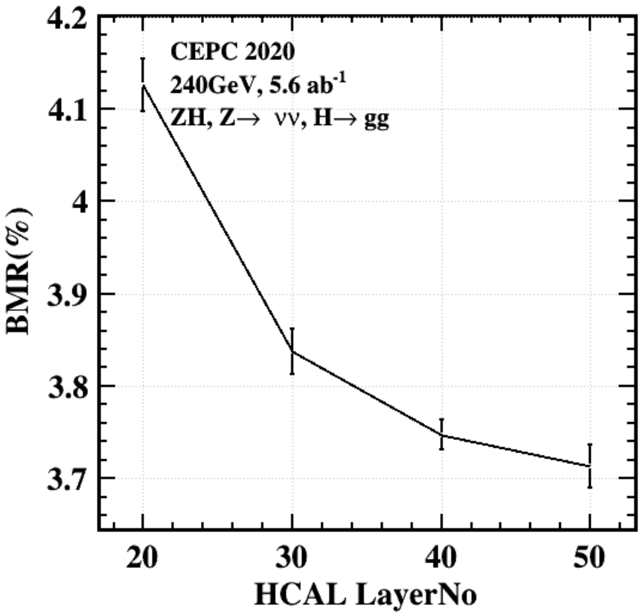
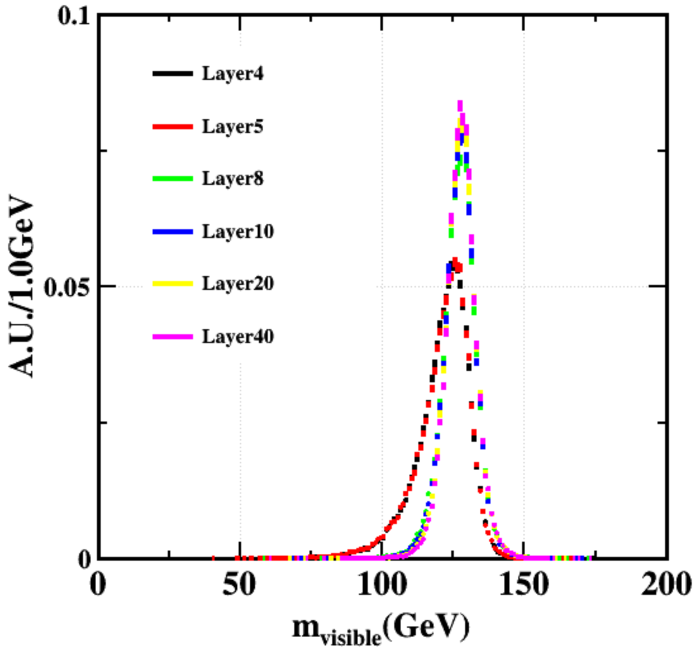
- Sampling layer optimization
  - $\nu\nu H - gg$ events are reconstructed for different sampling layers
  - 30 sampling layers can satisfy the 4% BMR requirement but prototype needs 40 sampling layers to fulfill the design target

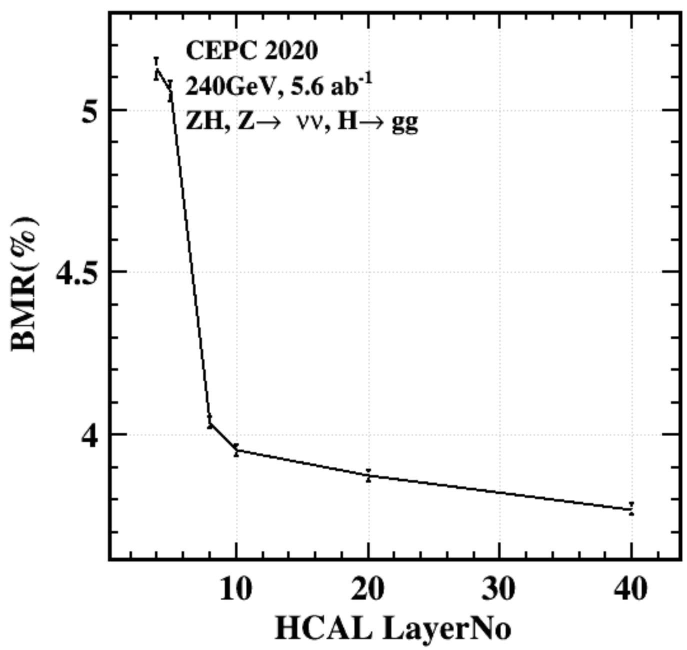




$\nu\nu H - gg$ events for different sampling layers

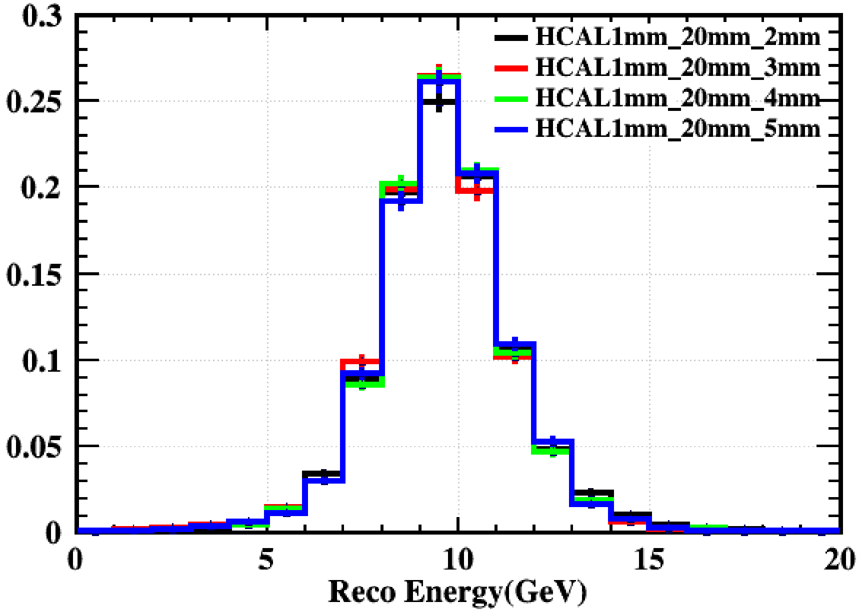
- Merge layer optimization
  - The number of sampling layers is fixed as 40
  - Combine the hits from adjacent layers to change the longitudinal segmentation without affecting the energy resolution

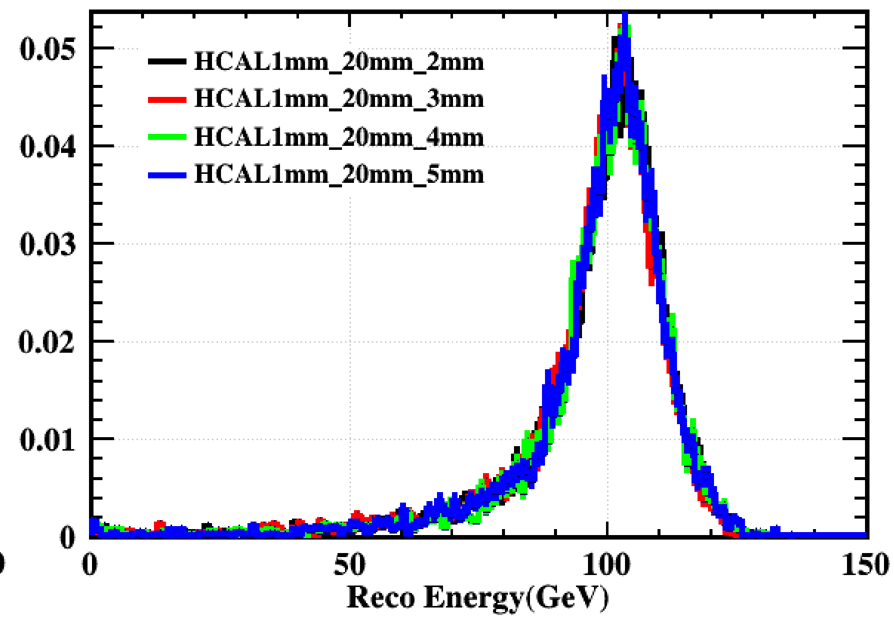




$\nu\nu H - gg$ events for different readout layers

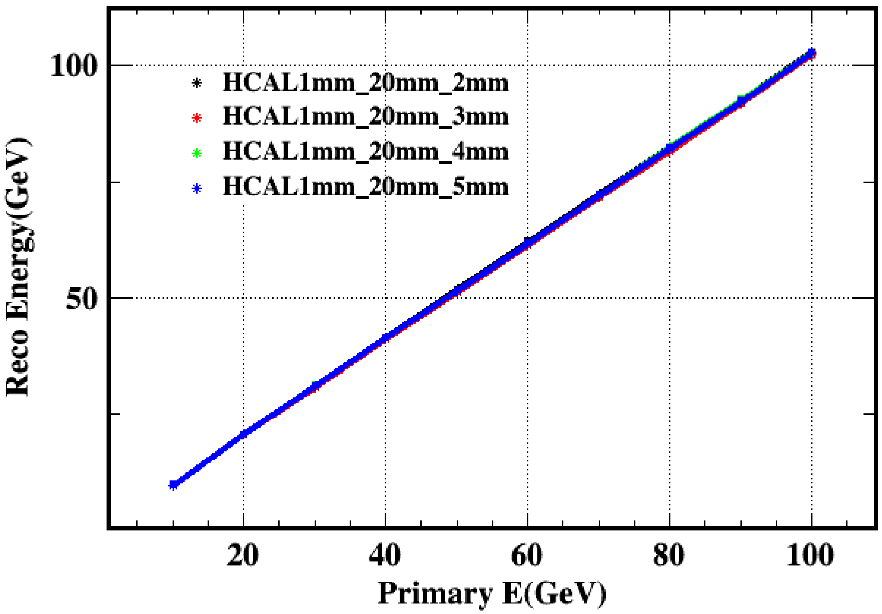
- Scintillator thickness optimization
  - 40 layers: each layer has 20mm Steel and 2mm PCB
  - Scintillator thickness for each layer ranges from 2 to 5mm

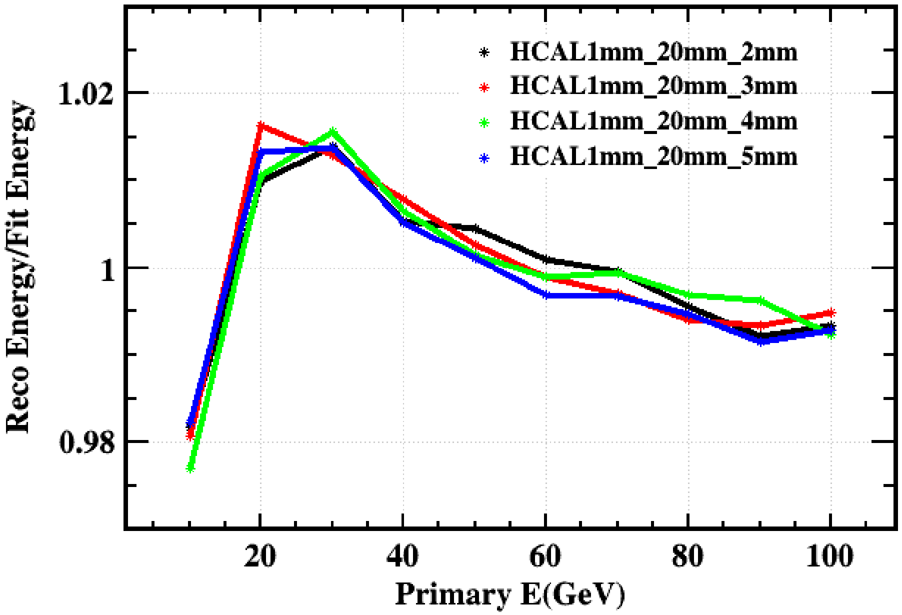




KL reconstructed energy at different scintillator thickness

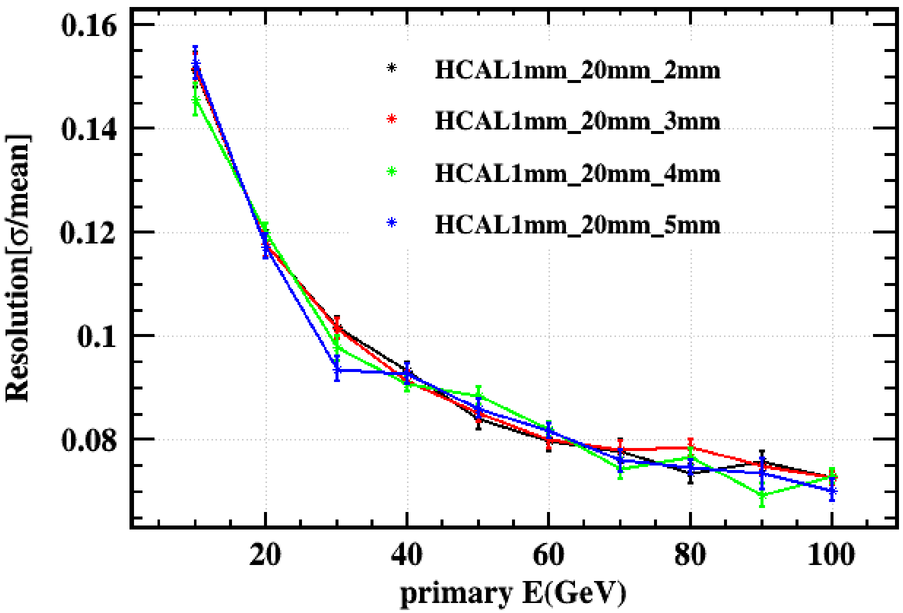
- Scintillator thickness optimization
  - The linearities are almost the same for different scintillator thickness
  - The linearities are all within ±3% for different scintillator thickness

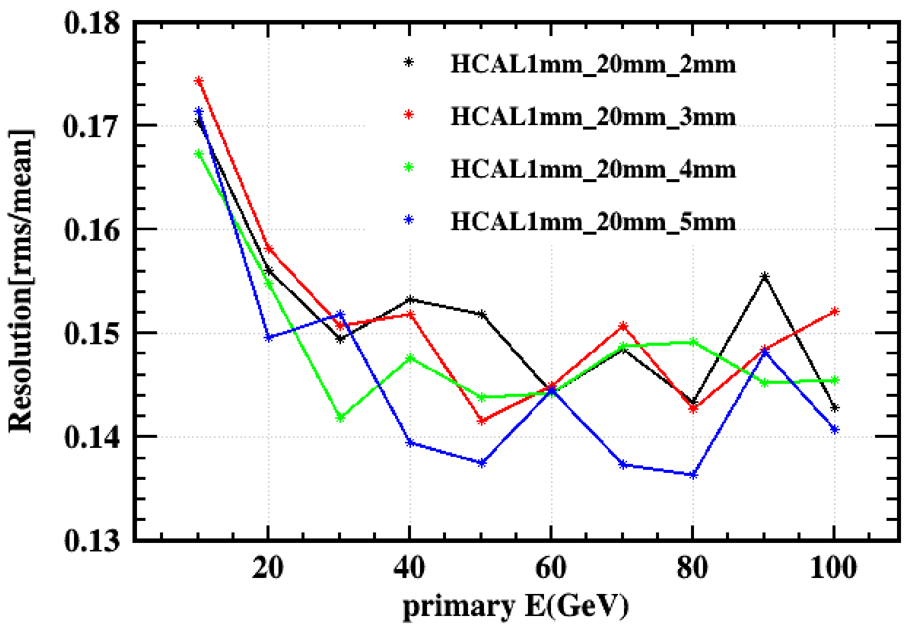




KL Linearity at different scintillator thickness

- Scintillator thickness optimization
  - Different scintillator thickness doesn't have much difference on resolution

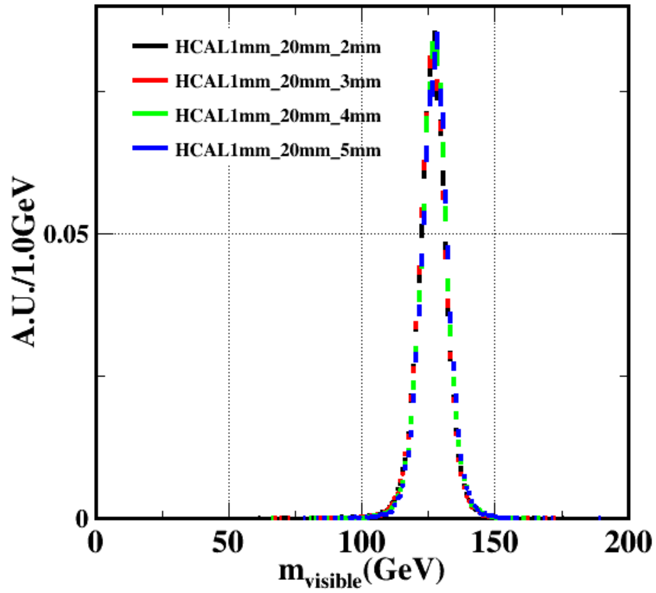


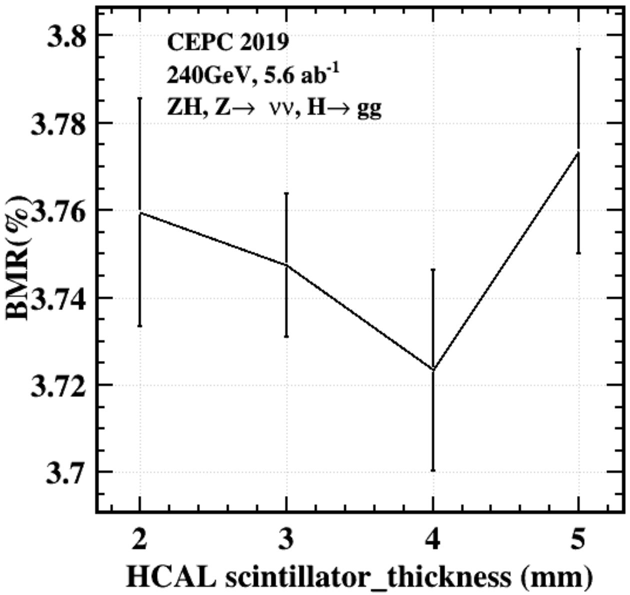


KL resolution at different scintillator thickness

CEPC AHCAL optimization

- Scintillator thickness optimization
  - $\nu\nu H - gg$ events are reconstructed for different scintillator thickness
  - The difference of BMR is within 0.1%
  - The 3mm scintillator is a reasonable choice

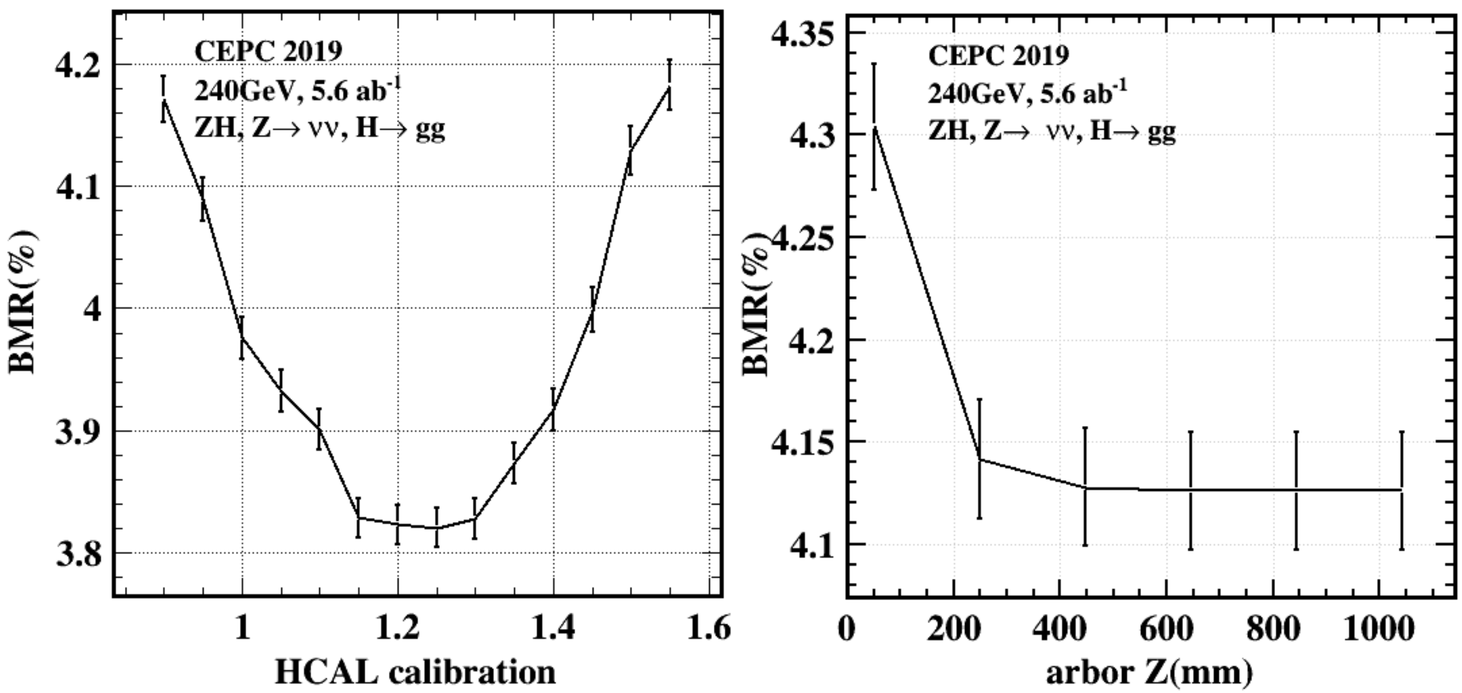




$\nu\nu H - gg$ events for different scintillator thickness

CEPC AHCAL optimization

- Cell size optimization
  - Cell size is the key parameter for PFA oriented HCAL
  - Cell size has a strong impact on both detector performance and cost
  - Careful optimization has been done to reconstruction parameter



Parameter optimization in terms of BMR

CEPC AHCAL optimization

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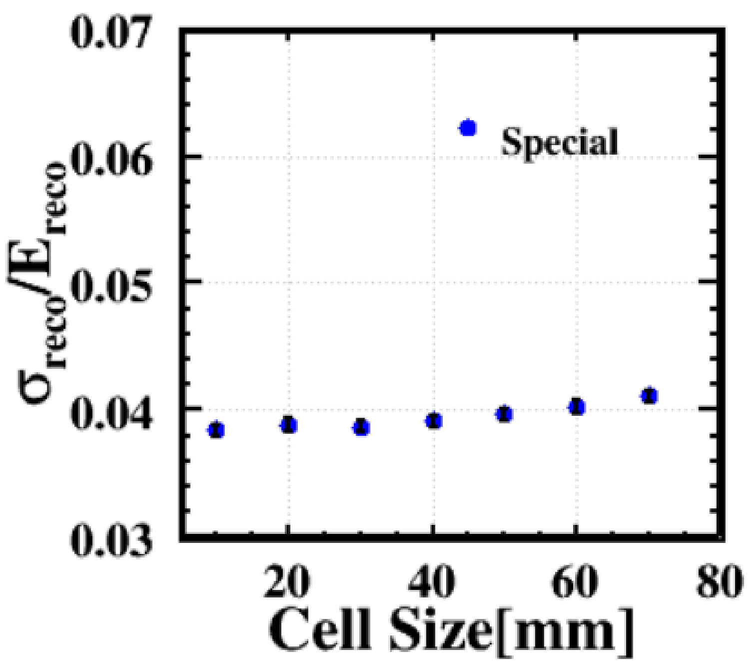
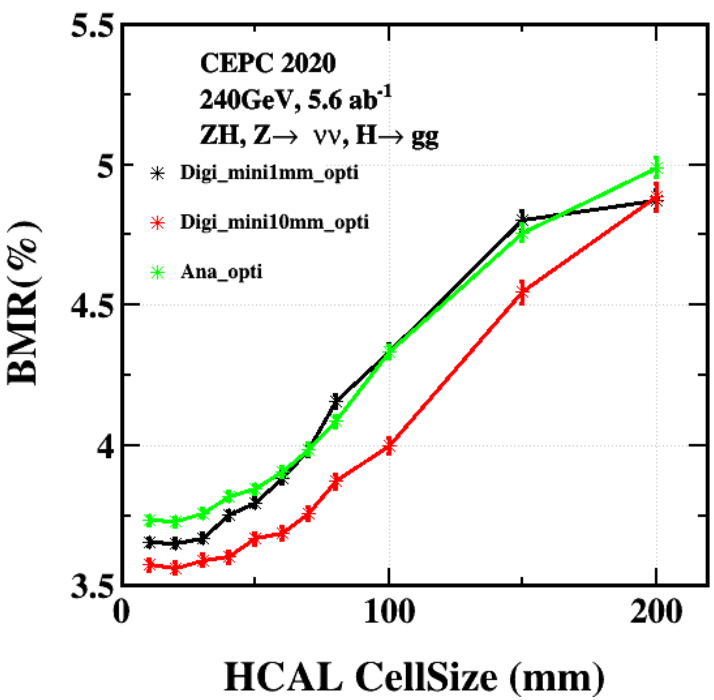
- Cell size optimization
  - The relation between cell size and BMR has been studied
  - Similar study has been done to CEPC DHCAL as comparison
  - 40mm is the final choice for AHCAL prototype



CEPC DCHAL(from Jiechen Jiang)



CEPC ACHAL cell size vs BMR

Summary and outlook

- Summary
  - The final design for the AHCAL prototype
    - Prototype Transverse size: $72 \times 72\text{cm}^2$
    - 40 sampling layers
    - Each layer: 20mm absorber, 3mm scintillator and 2mm PCB
    - Cell size: 40mm
  - The performance for the AHCAL prototype
    - Linearity: $\pm 1.5\%$
    - Resolution: $\frac{48\%}{\sqrt{E(GeV)}} \oplus 3\,\%$
- Outlook
  - The prototype will be constructed and tested to verify the design before the end of 2023
  - Software work will be going on to improve the detector performance

Back up

Prototype optimization

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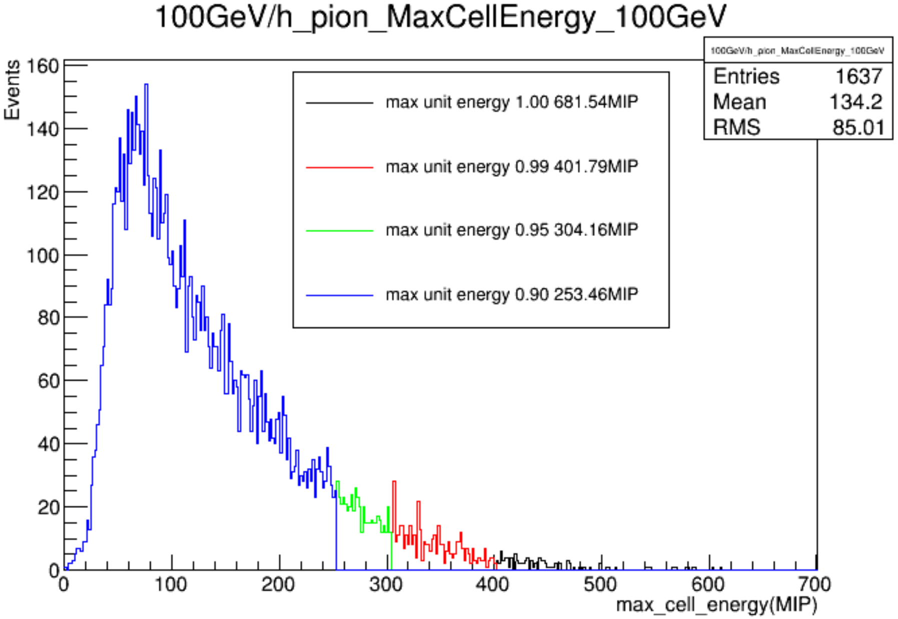
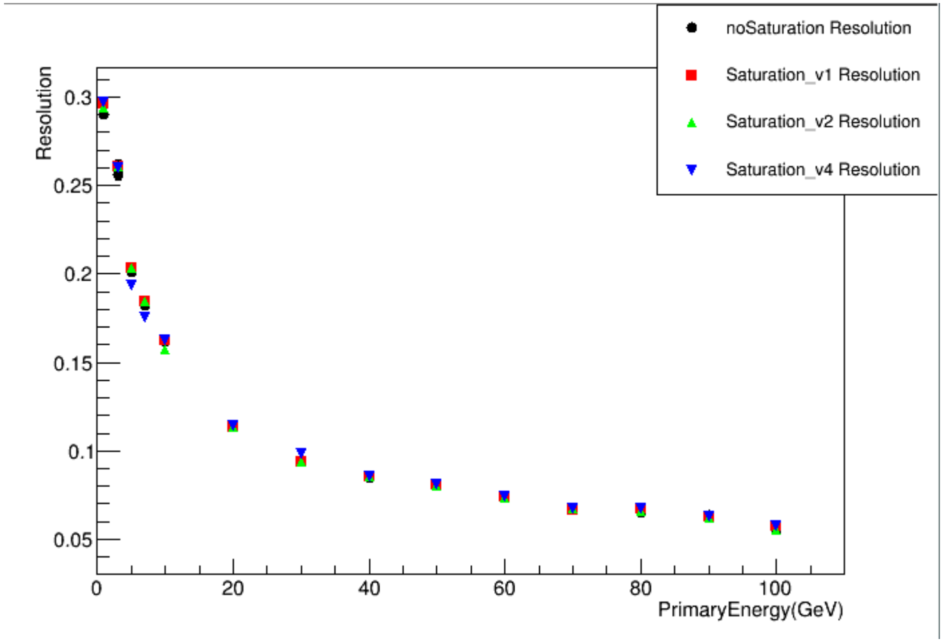
- Dynamic Range
  - the SiPM saturation effect could be corrected
  - The dynamic Range wouldn't be a problem



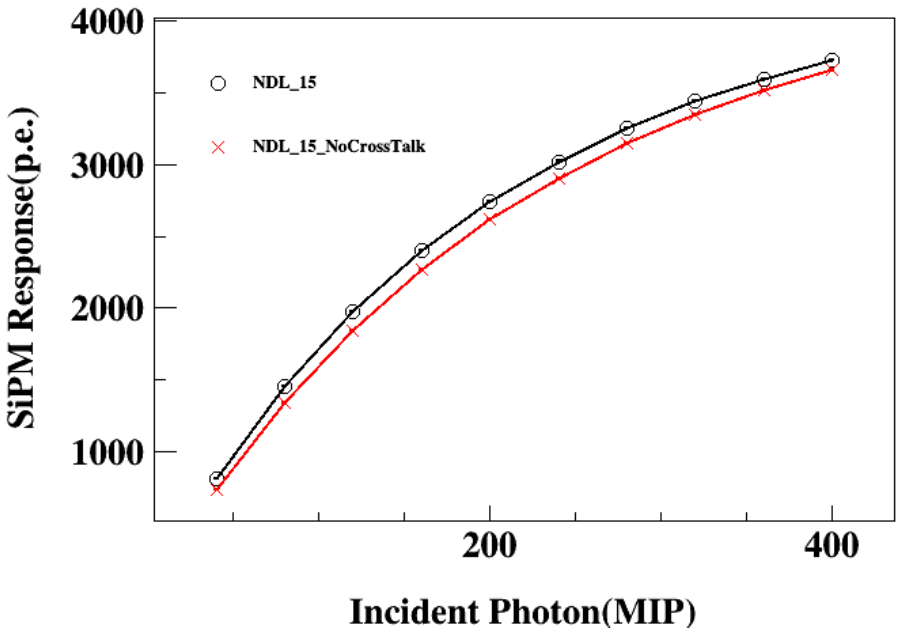
max energy deposition in cells for 100GeV pion

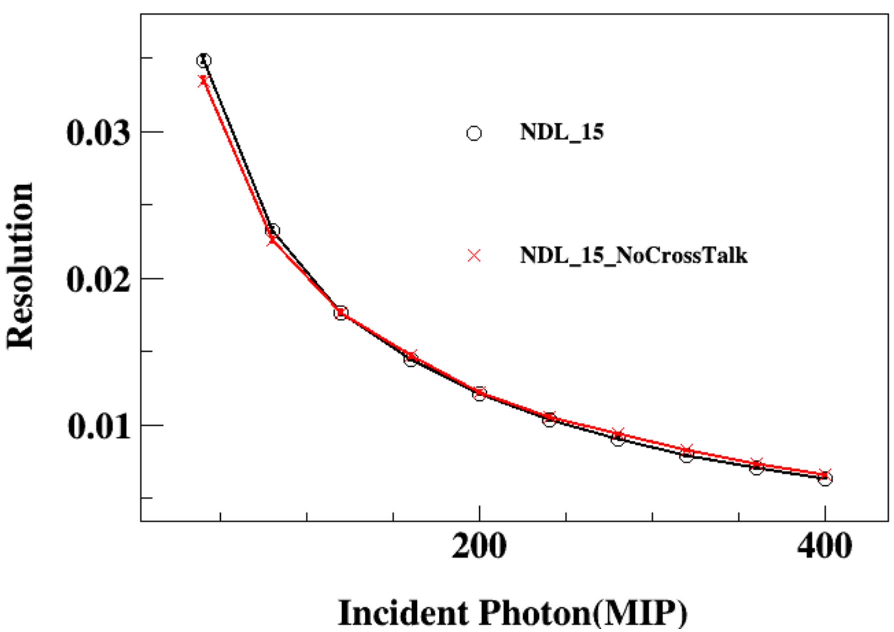


energy resolution using different SiPM after saturation correction

Prototype optimization

- SiPM Simulation
  - NDL 15um SiPM is simulated
  - Cross talk has limited influence on SIPM performance

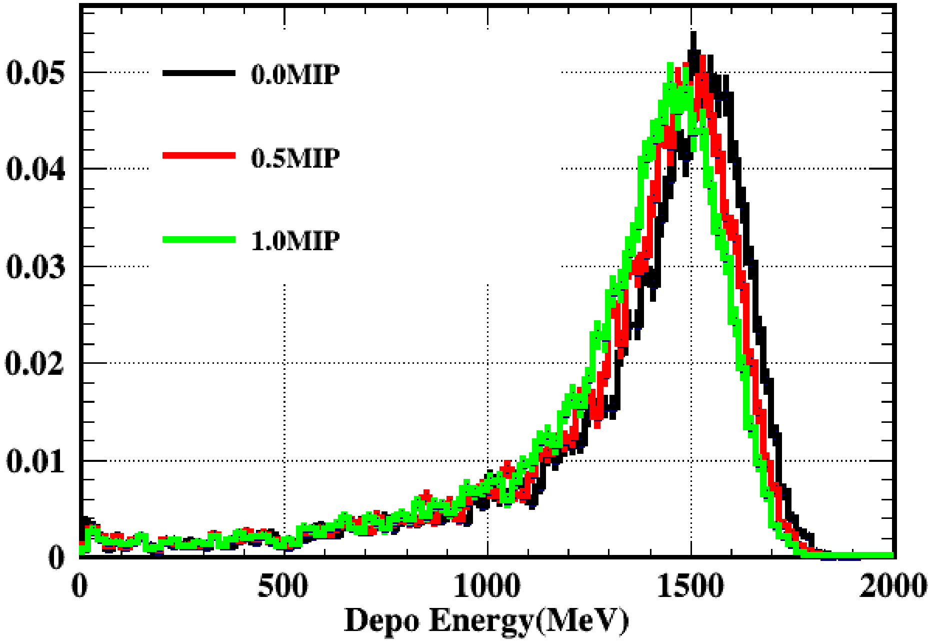




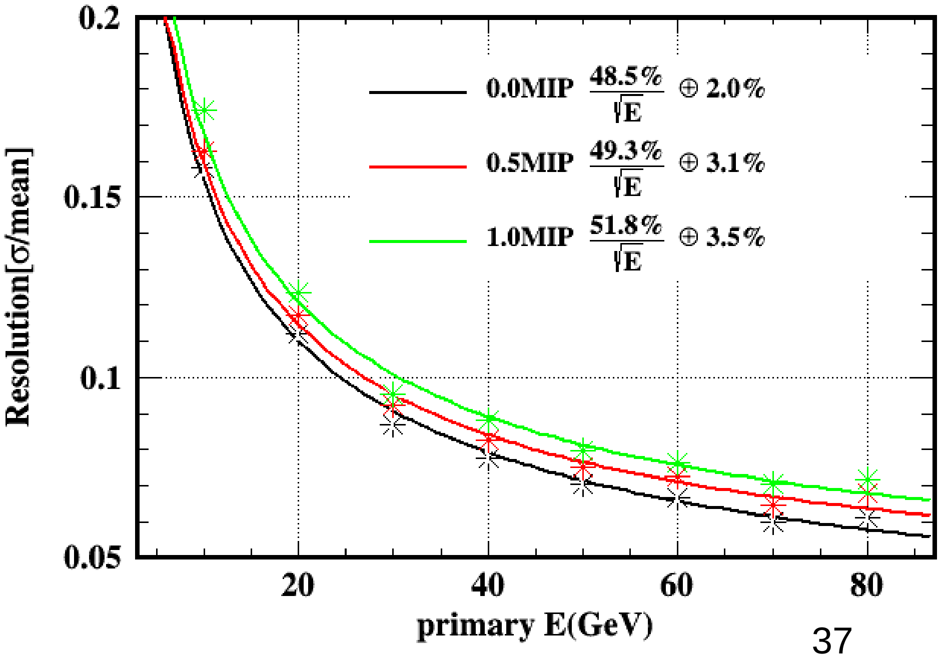
Linearity and resolution w/wo crosstalk

HCAL prototype

- Threshold for cells
  - 20mm absorber geometry with different threshold for cells
  - It's a nonnegligible parameter in terms of resolution
  - It has a strong correlation with scintillator and SiPM
  - 0.5MIP threshold is applied in the following simulation



Energy deposition for 100GeV KL



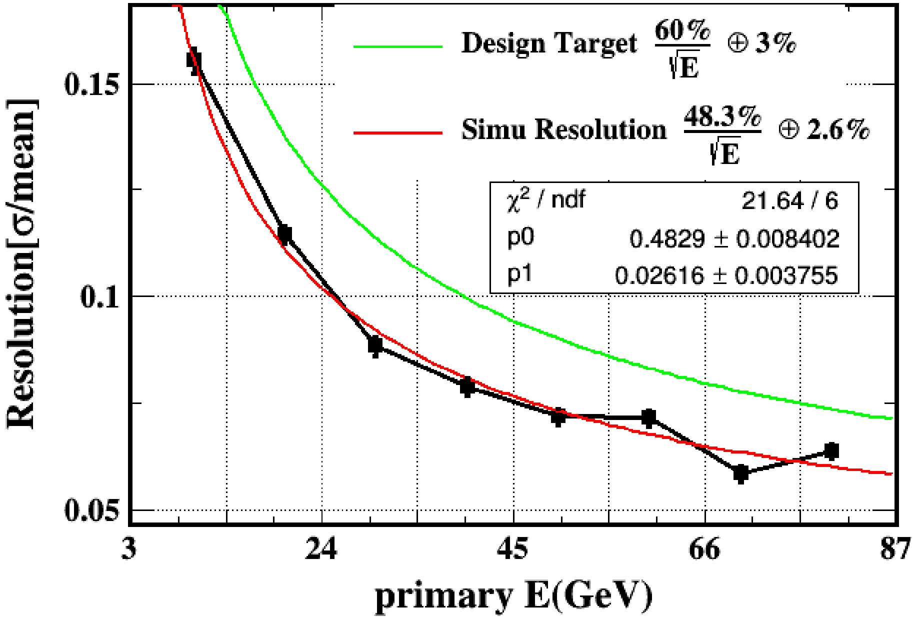
Resolution for different threshold

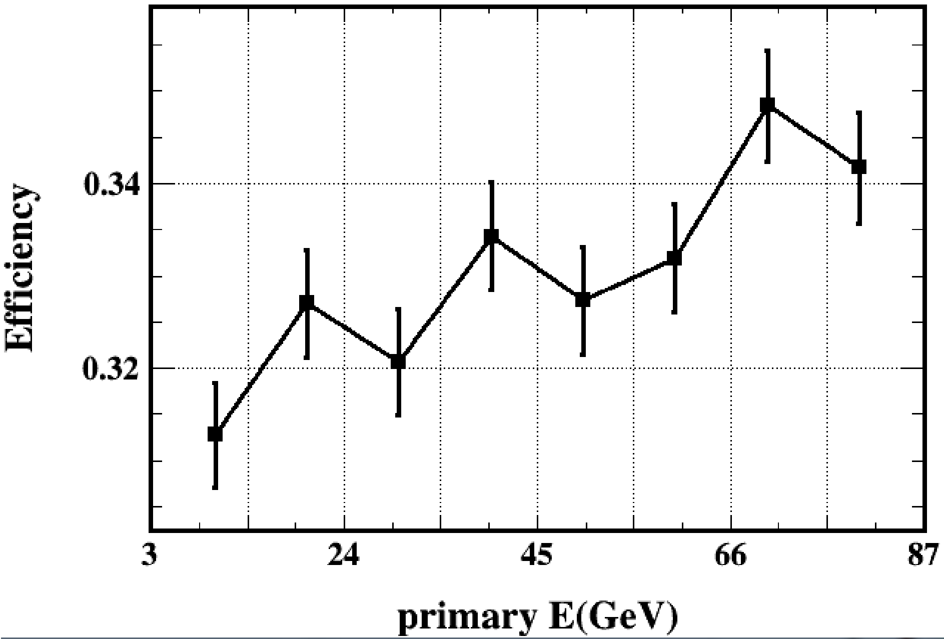
HCAL prototype

- Threshold for cells
  - This parameter is a bridge between software and hardware
  - 0.5MIP isn’t a perfect value but it’s acceptable for present hardware and software settings

HCAL prototype

- Comparison with different absorber thickness
  - With leakage cut
  - So what should be the principle for leakage cut

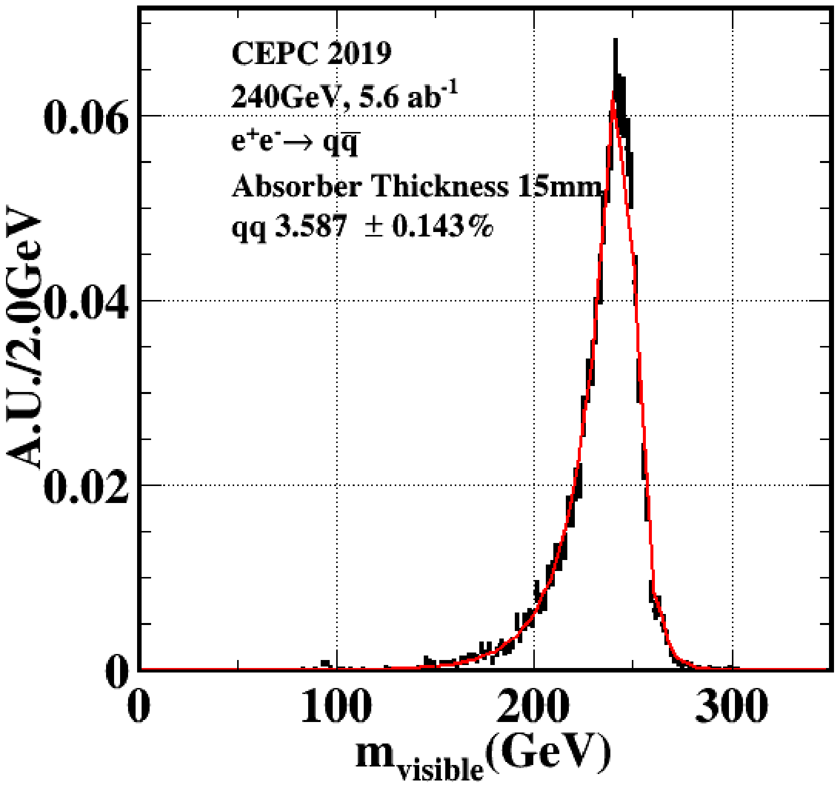


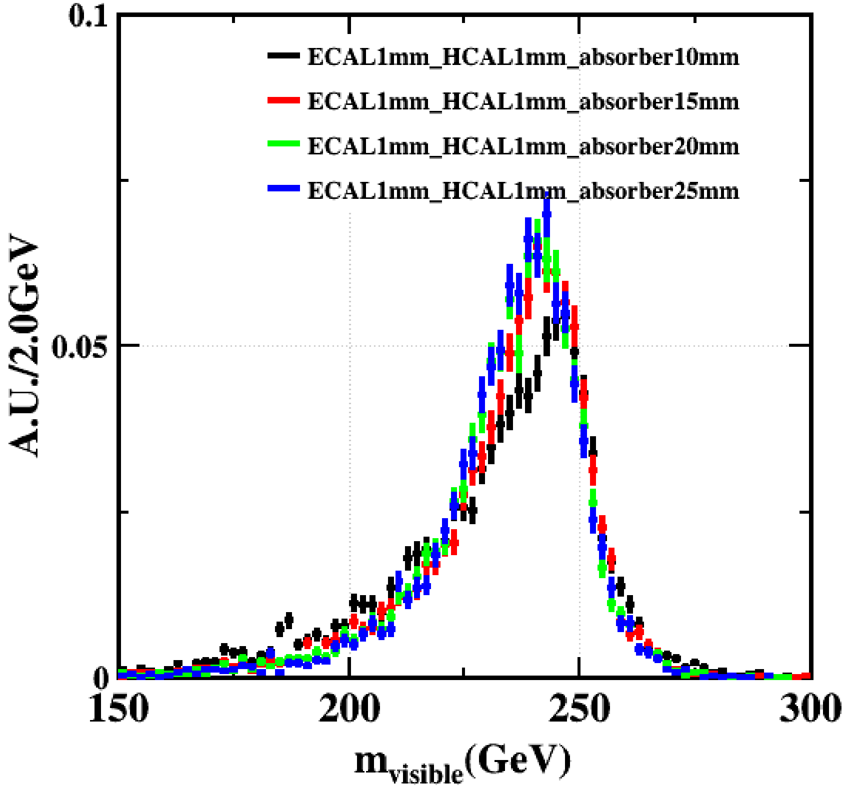


Resolution for different absorber(40 Layer) after leakage cut

ee-$q\bar{q}$ events

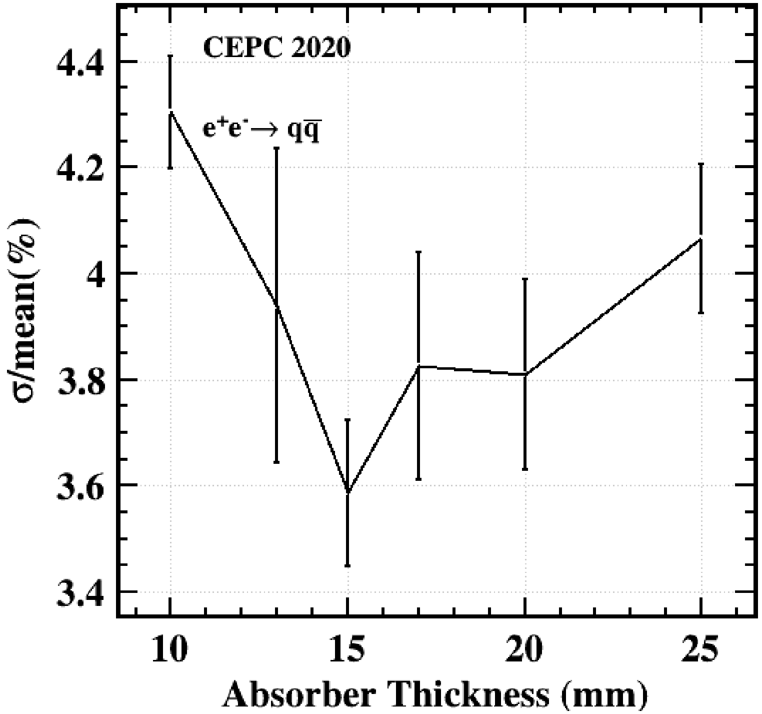
- $m_{visible}$ reconstructed by the $q\bar{q}$ jets
- Crystal ball function is used for fitting

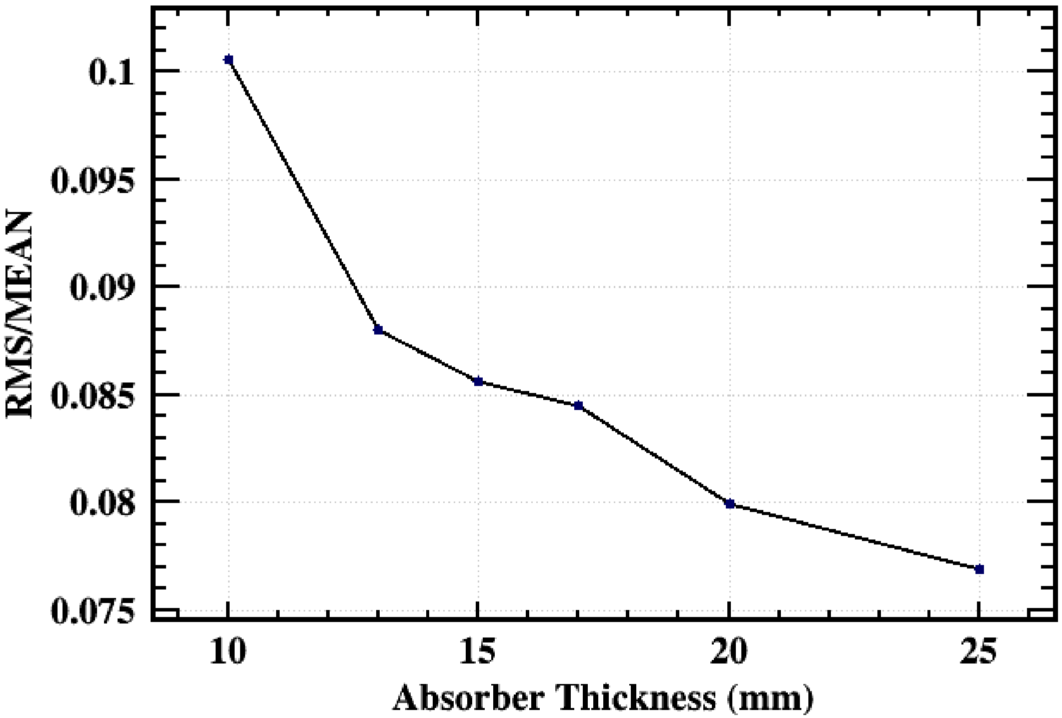




ee-$q\bar{q}$ events

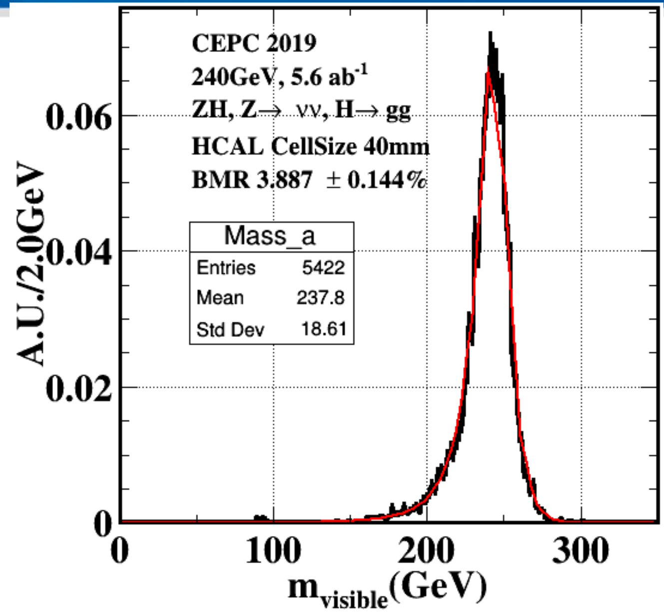
- Resolution for $m_{visible}$
  - Resolution1: fit sigma/peak
  - Resolution2: histogram rms/peak

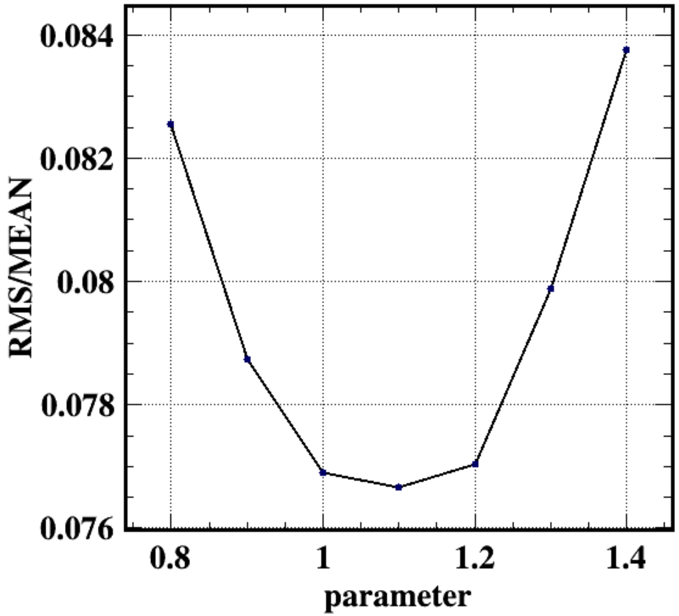


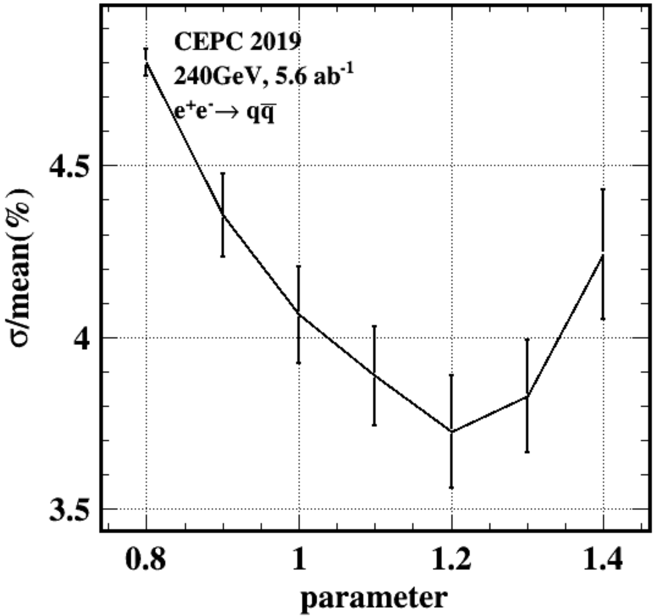


Parameter optimization

- Absorber is 25mm for each layer
- KL determines HCAL calibration constant
  - KL energy ranges from 10 – 100GeV
  - Minimum χ^2 method
  - This constant doesn't suit all kinds of hadrons
- Scan HCAL constant in ee-$q\bar{q}$ events
  - hadron response is more than KL response
  - Optimize HCAL constant to correct this effect







ee-$q\bar{q}$ events

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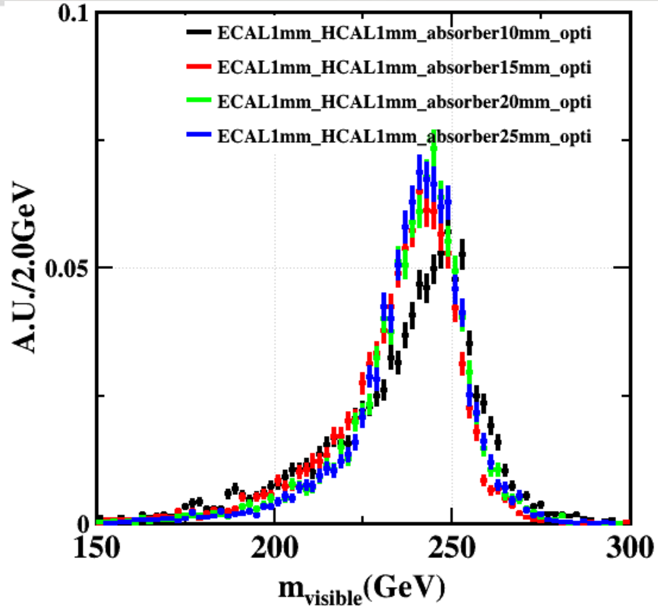
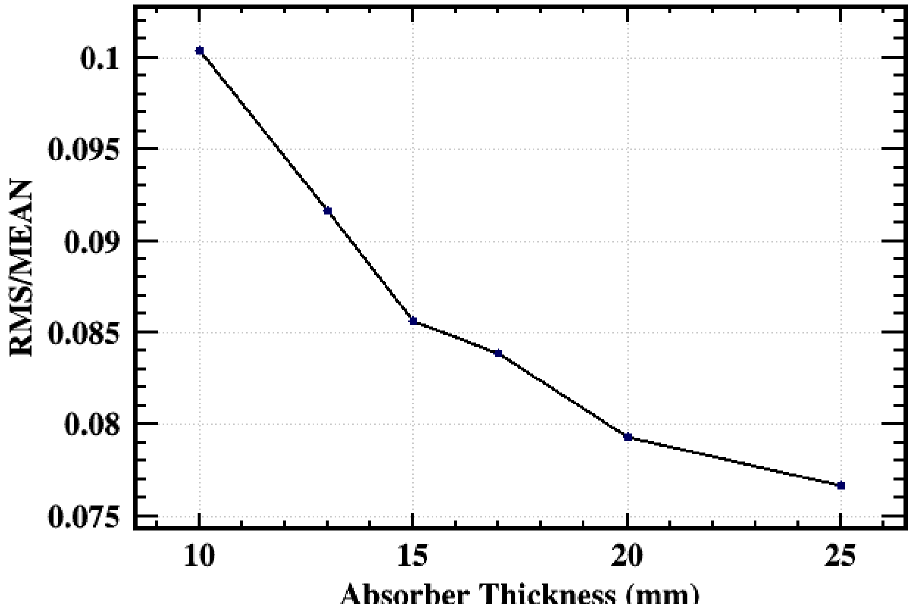
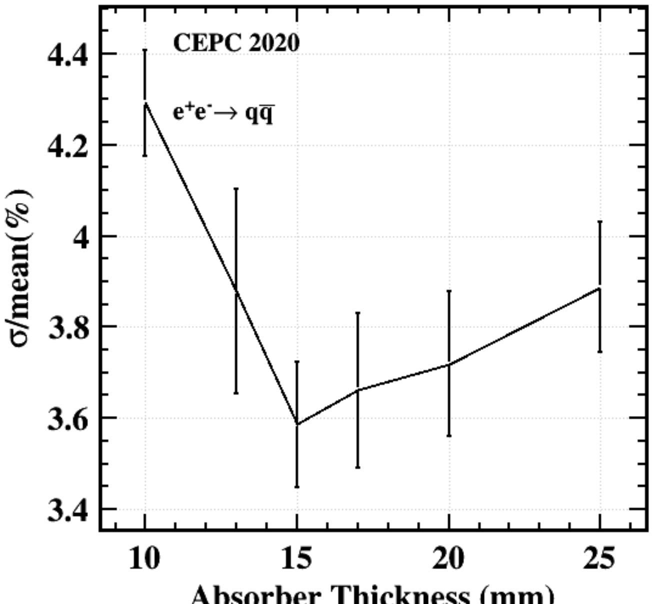
- Resolution for $m_{visible}$
  - After HCAL constant optimization
  - Resolution1: fit sigma/peak
  - Resolution2: histogram rms/peak







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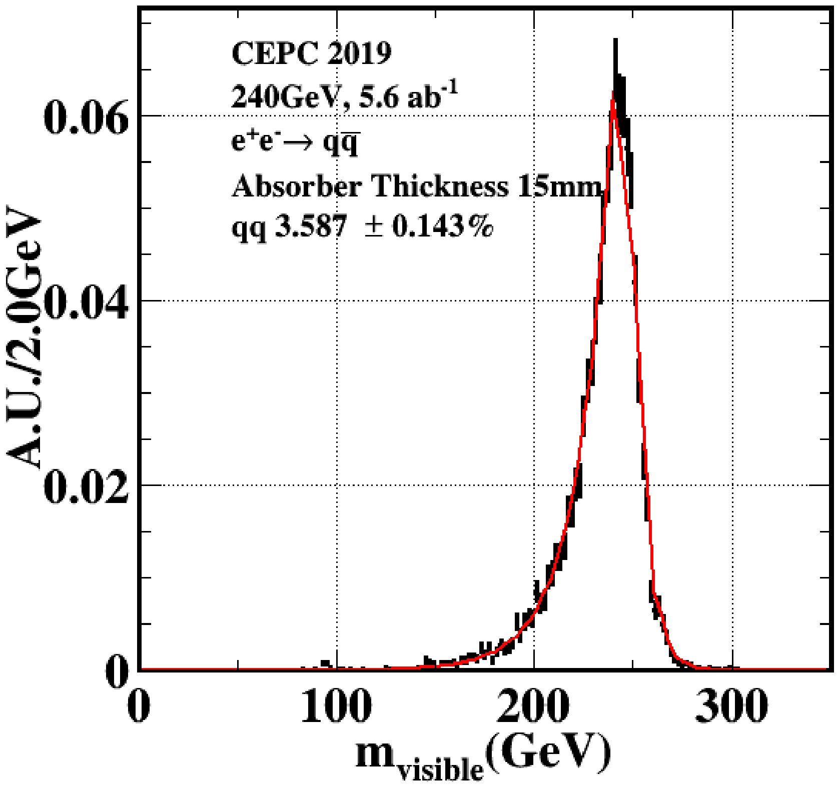

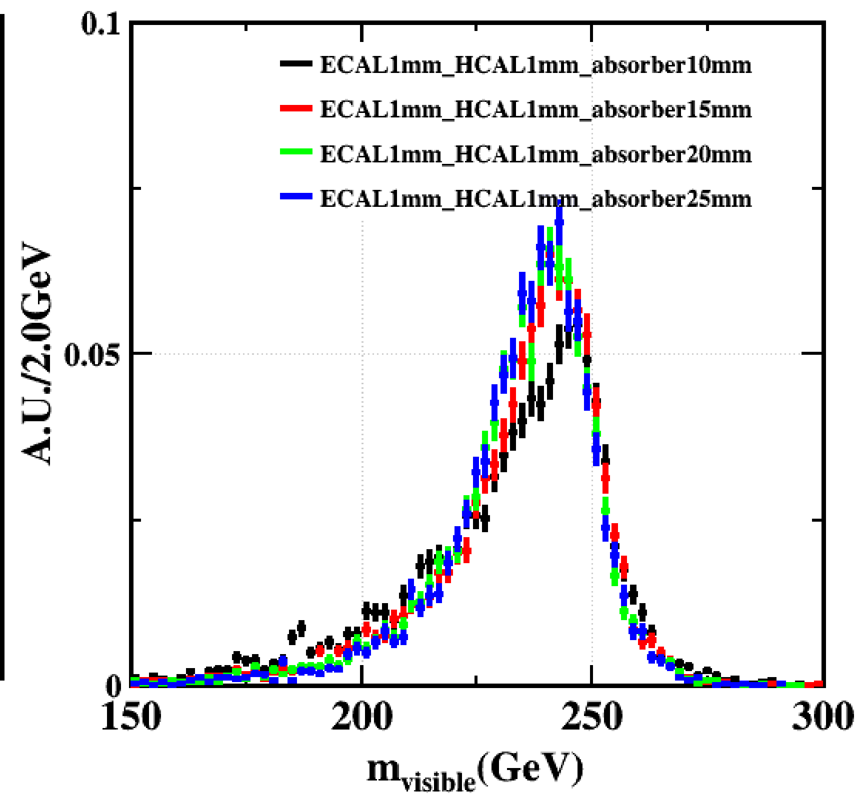

ee-$q\bar{q}$ events

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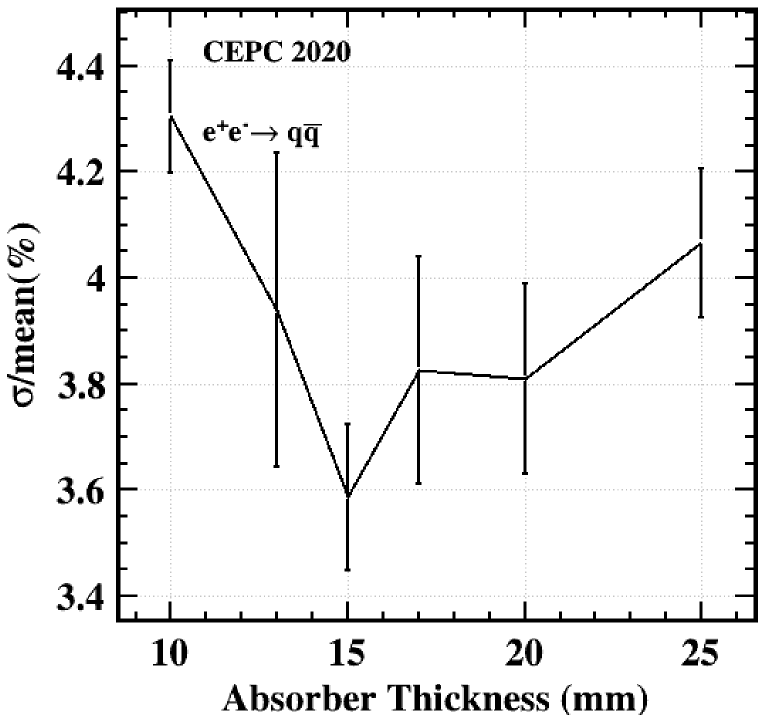
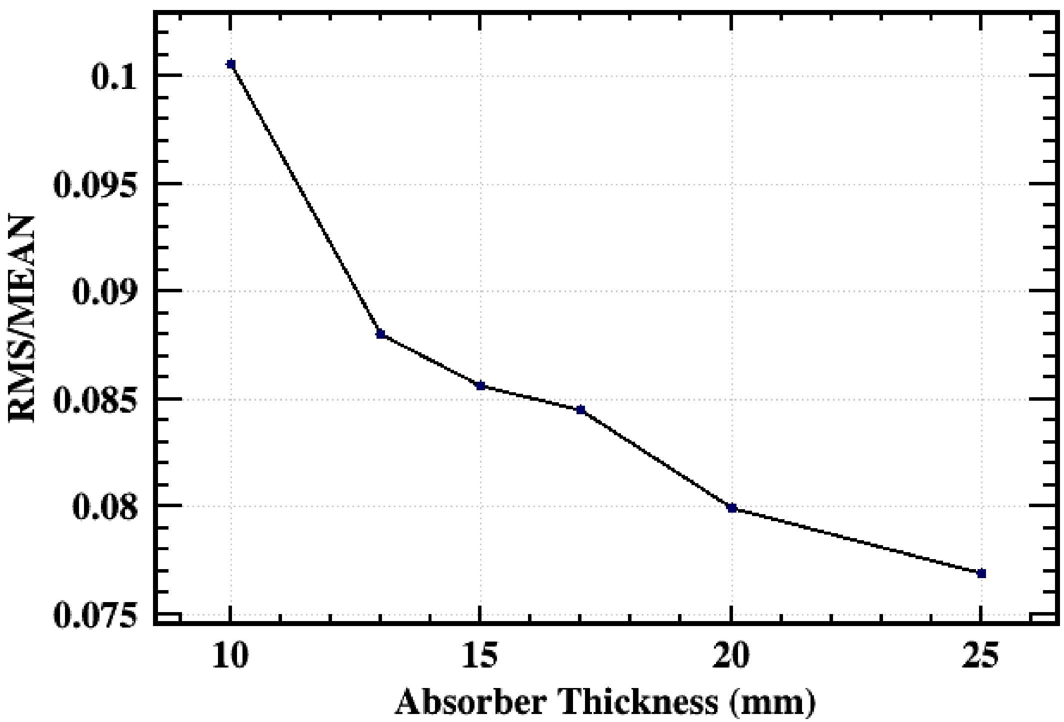
  - Resolution2: histogram rms/peak





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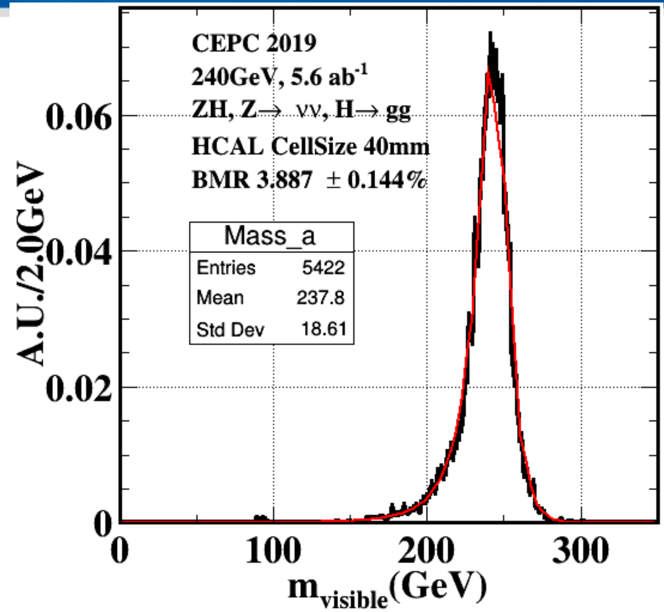
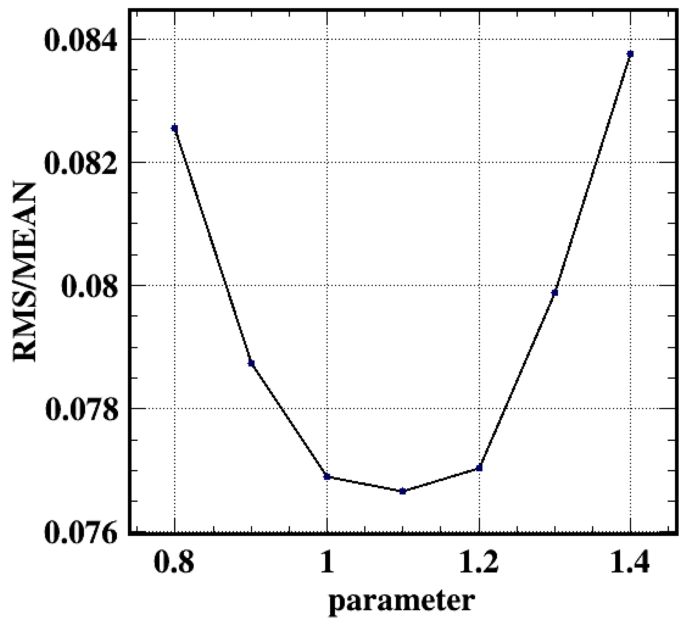
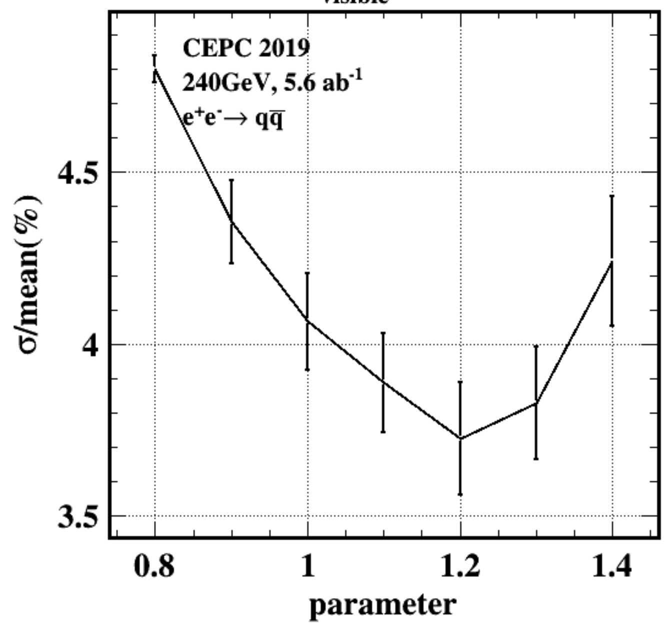
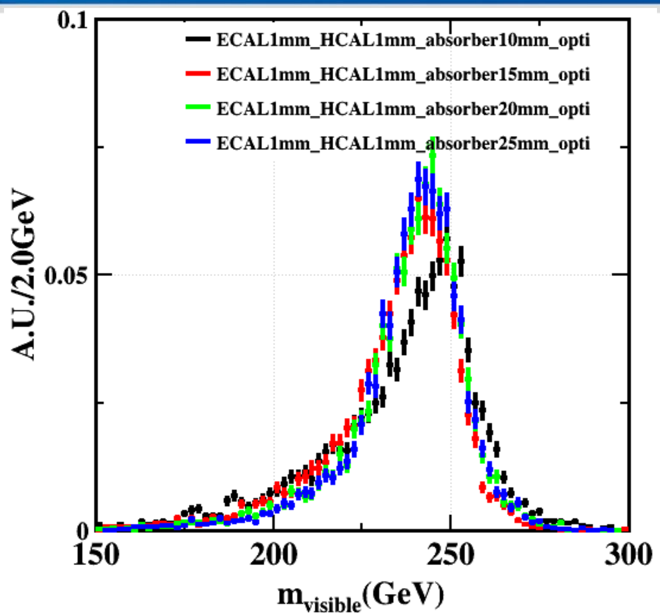


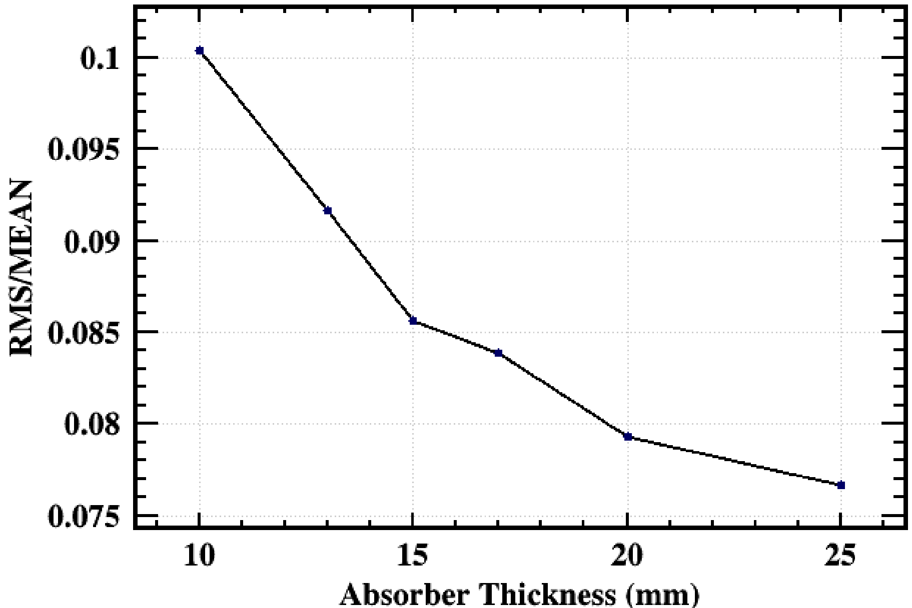


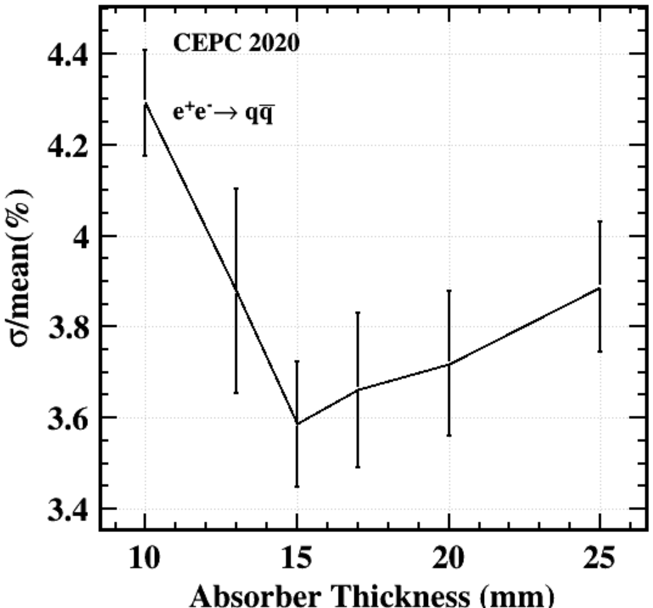


ee-$q\bar{q}$ events

- Resolution for $m_{visible}$
  - After HCAL constant optimization
  - Resolution1: fit sigma/peak
  - Resolution2: histogram rms/peak







Plan for simulation

- Absorber thickness-linearity
  - KL
  - ee-$q\bar{q}$
- Sampling Layer-hadron resolution
  - KL
  - nnH-gg
  - Readout layer for nnH-gg-PFA separation power
- Sensor thickness-hadron resolution
  - KL
  - nnH-gg
- Sensor size-PFA separation power
  - nnH-gg
  - Different kinds of readout mode