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Progress of the CEPC AHCAL

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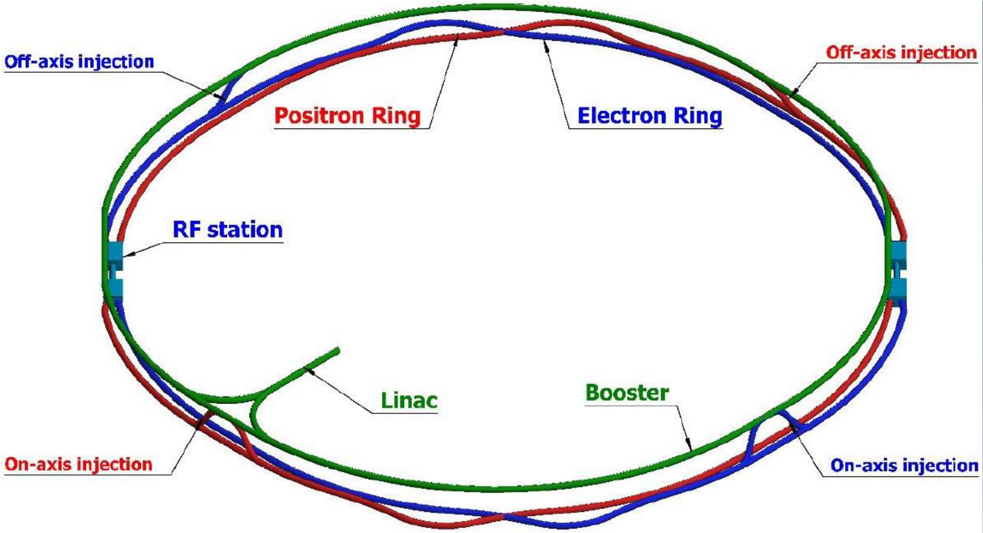
On behalf of the CEPC Calorimeter Group
Joint Workshop of the CEPC 2021.4

OutLine

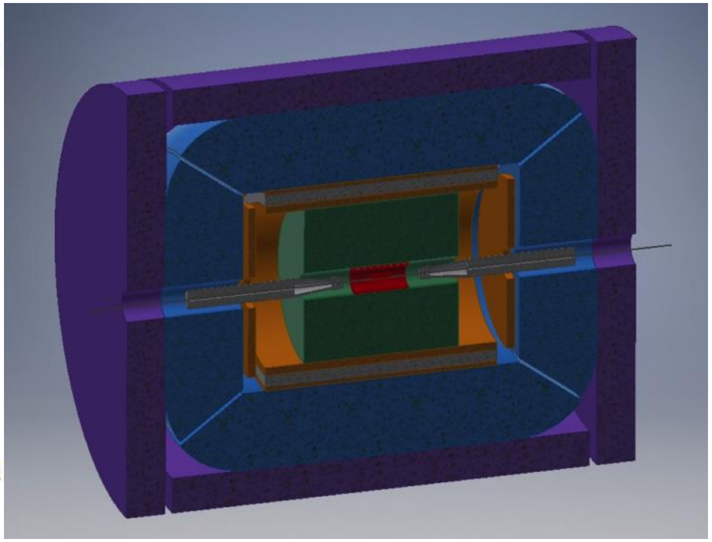
- Background
- AHCAL optimization
- Scintillator and SiPM
- HCAL Board Unit
- Summary and outlook

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)



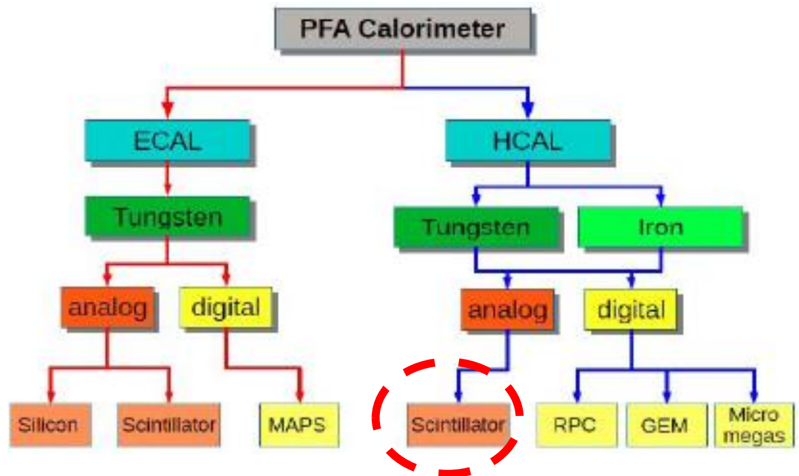
Design of the CEPC Accelerator



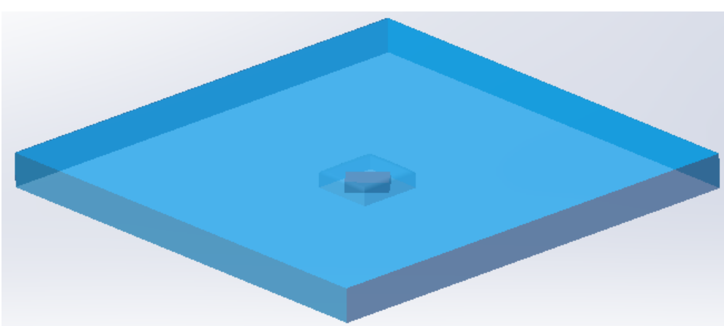
CEPC baseline detector

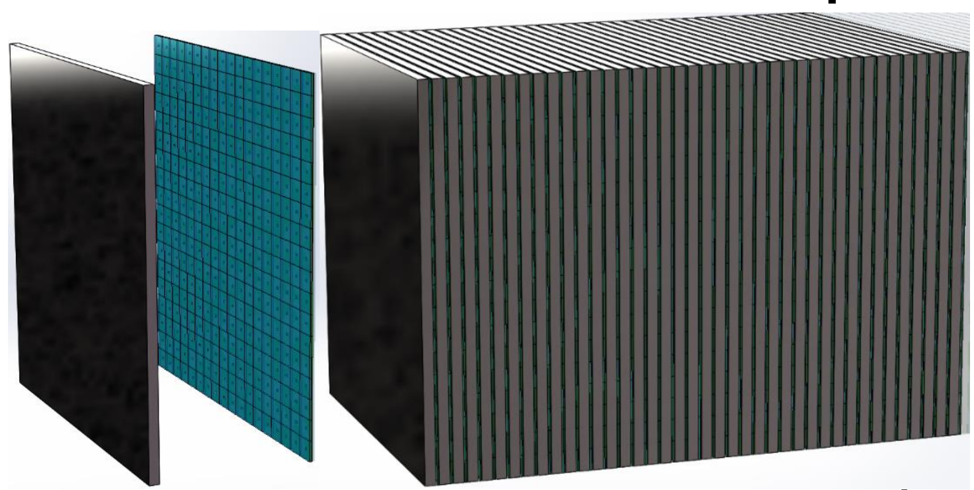
Background

- The Scintillator-Steel AHCAL
  - PFA oriented: high granularity
    - 40mm cell size
  - 40 sampling layers
    - 20mm steel
    - 3mm scintillator
    - 2mm PCB
  - Analog readout: SiPM+SPIROC



CEPC baseline calorimeter options





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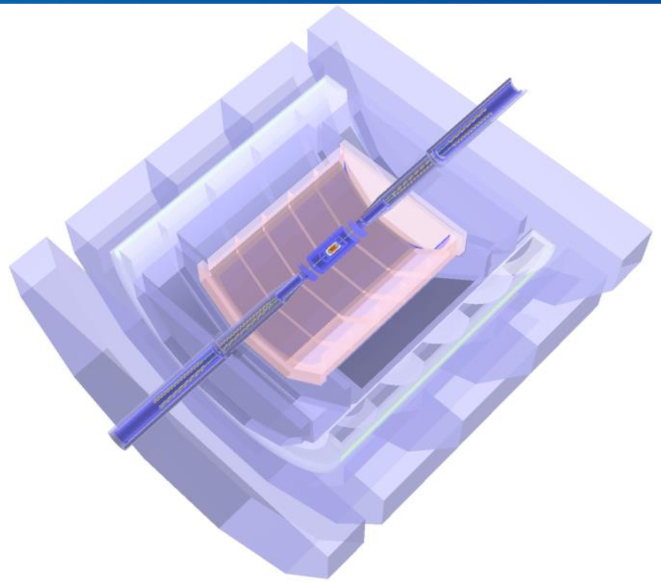
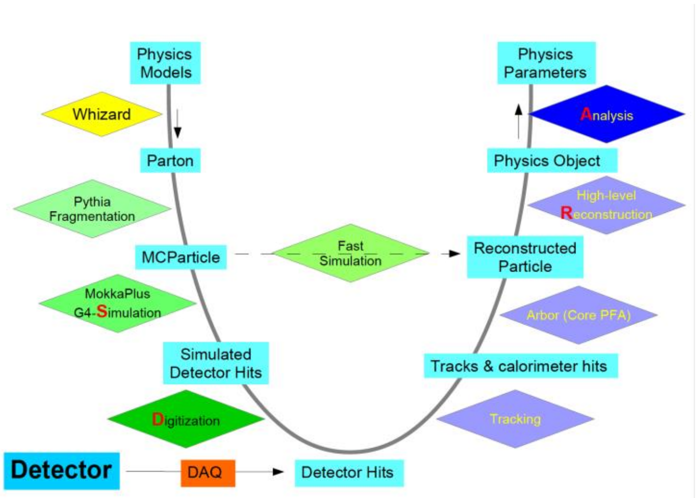
AHCAL optimization

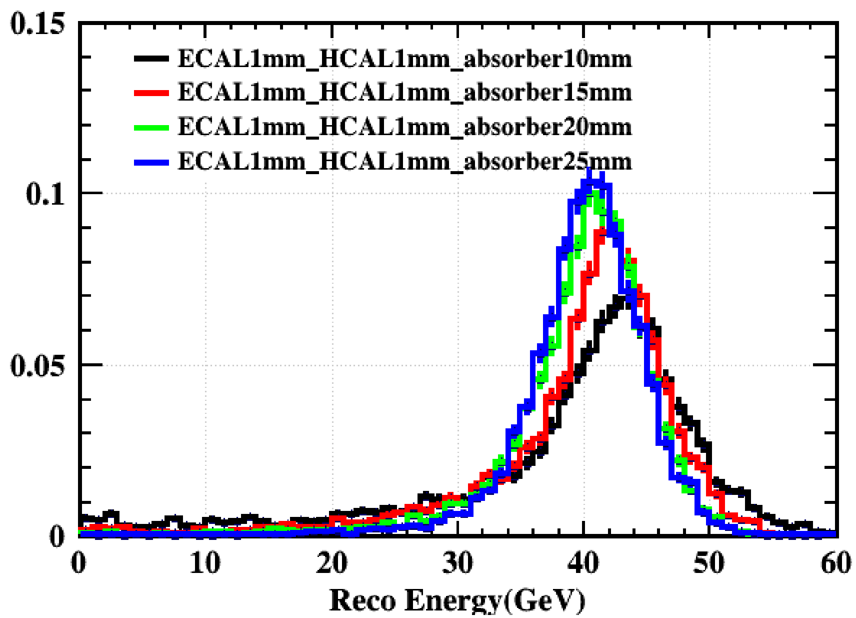
- CEPC software environment
  - CEPC V4 geometry
    - Tracker and magnet field
    - ECAL and HCAL
    - Muon detector
  - PFA reconstruction
    - Detect particles with optimal detector
    - Higgs boson mass could be reconstructed with the recoil mass method
  - Physics benchmarks
    - $\nu\nu H - gg$: 4% BMR
    - Zuds: $e^{+}e^{-} - q\bar{q}(q = uds)\ via\ Z$

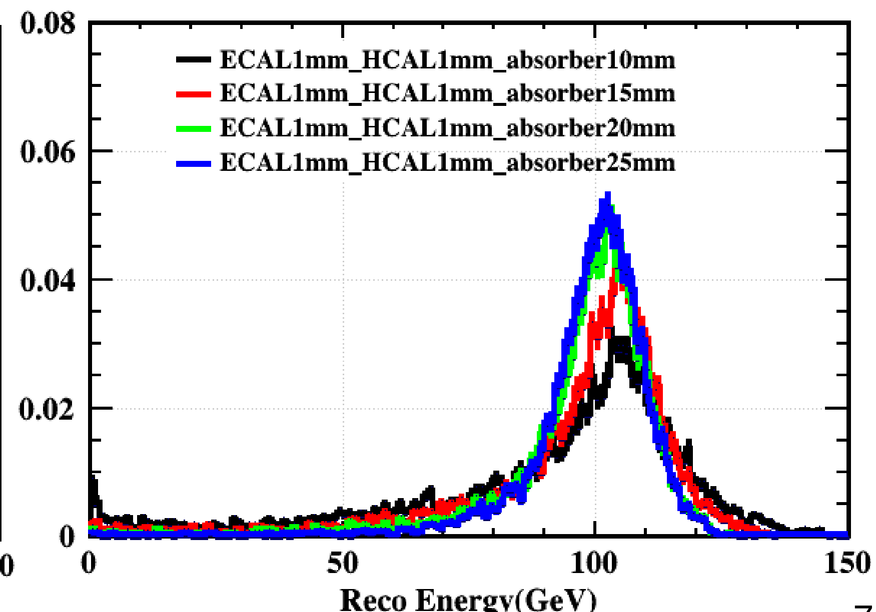




CEPC AHCAL optimization

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





KL reconstructed energy at different absorber thickness

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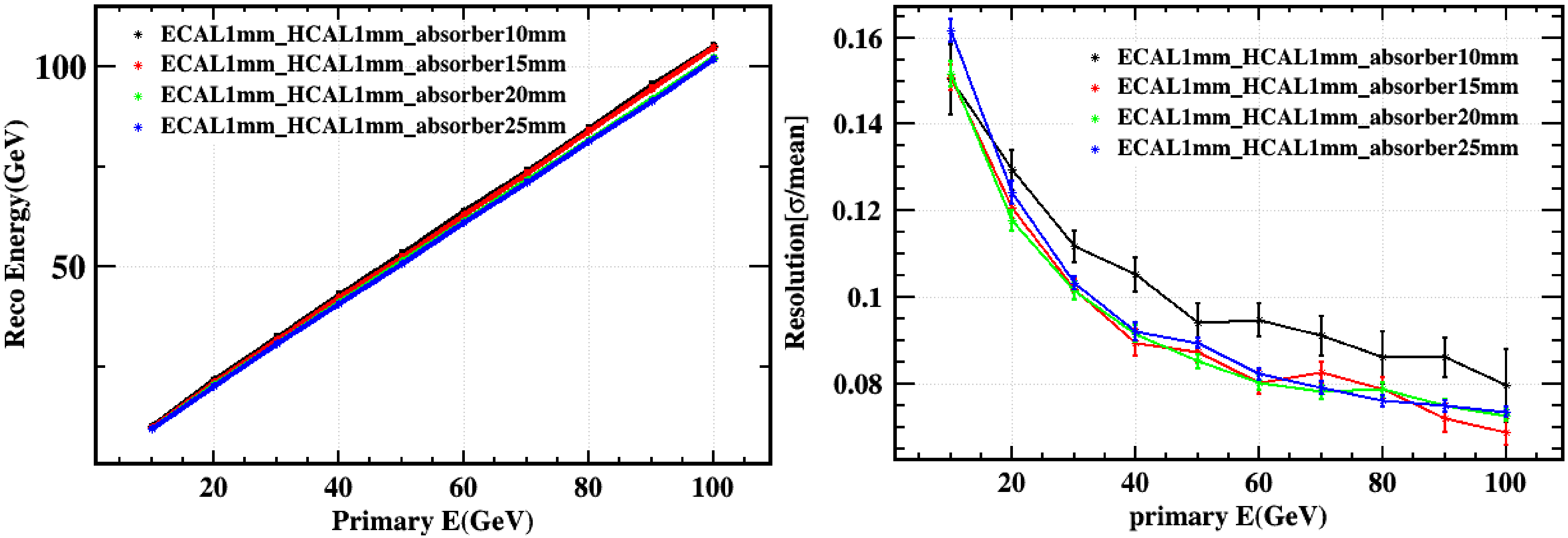
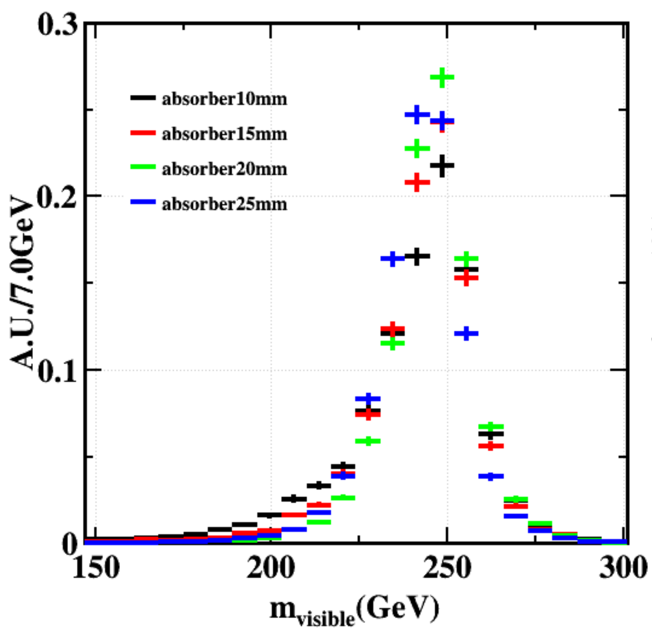
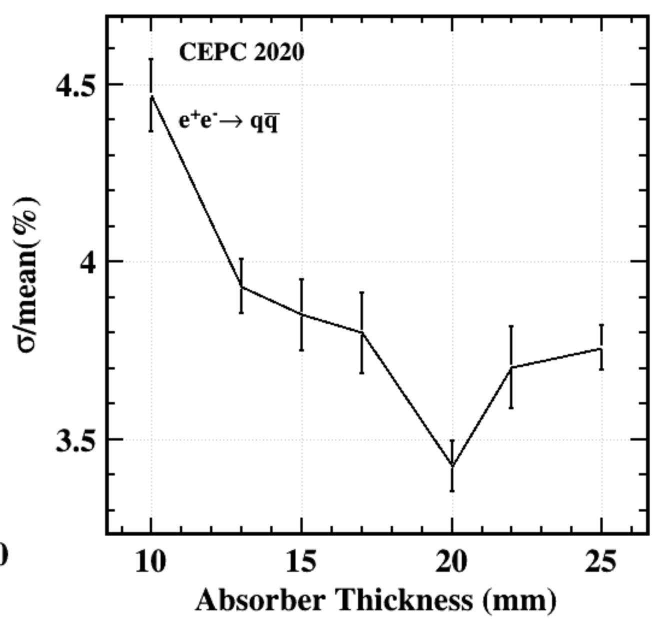
- KL events
  - Use crystal ball function as fitting function
  - The linearities are all within $\pm 3\%$ for different absorber thickness
  - Resolutions are similar except 10mm absorber



KL linearity and resolution at different absorber thickness

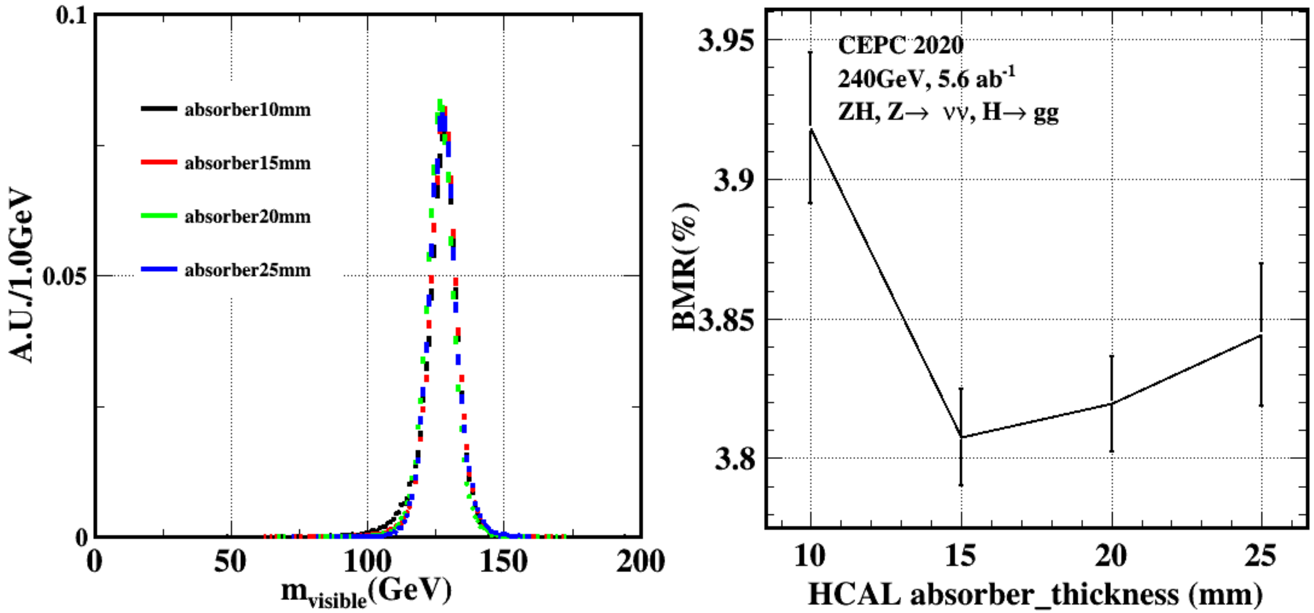
- Zuds events
  - The $m_{visible}$ is reconstructed from all “visible” particles
  - The resolution of $m_{visible}$ as a function of absorber thickness shows that 20mm is a turning point





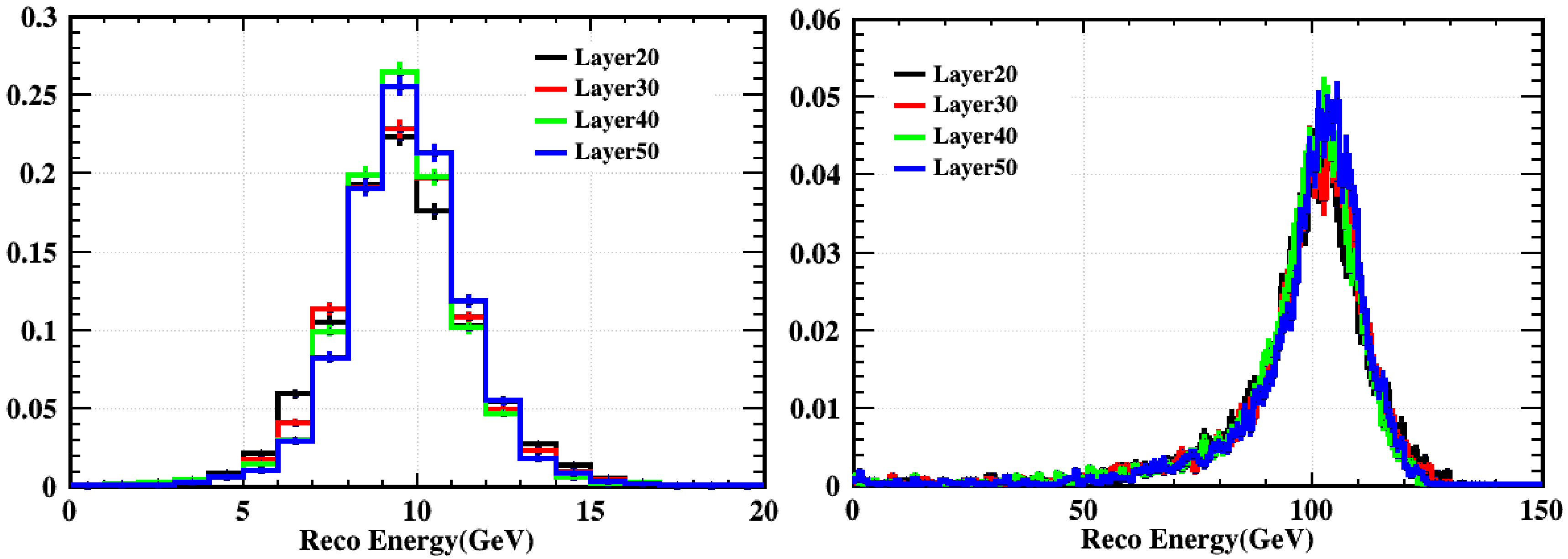
Zuds events for different absorber thickness

- $\nu\nu H - gg$ events
  - 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

- 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

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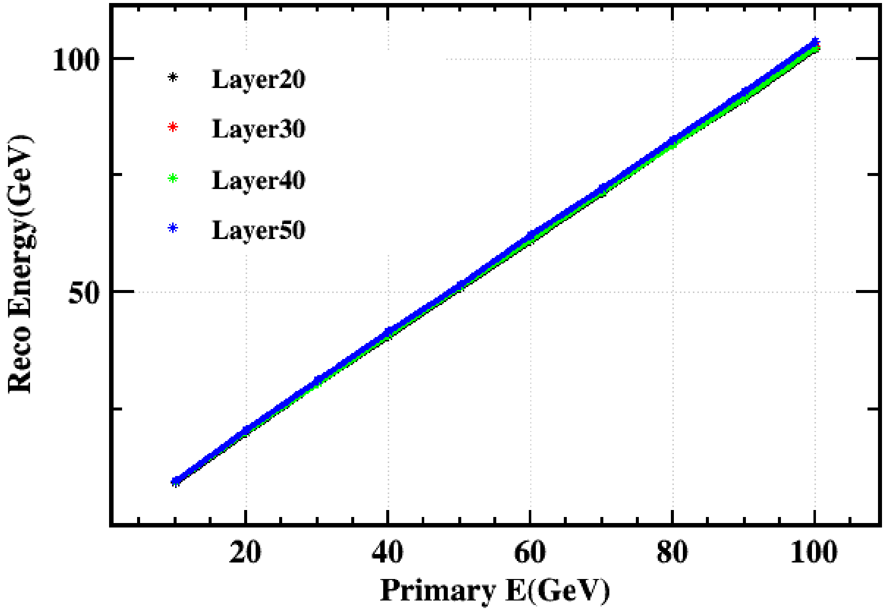
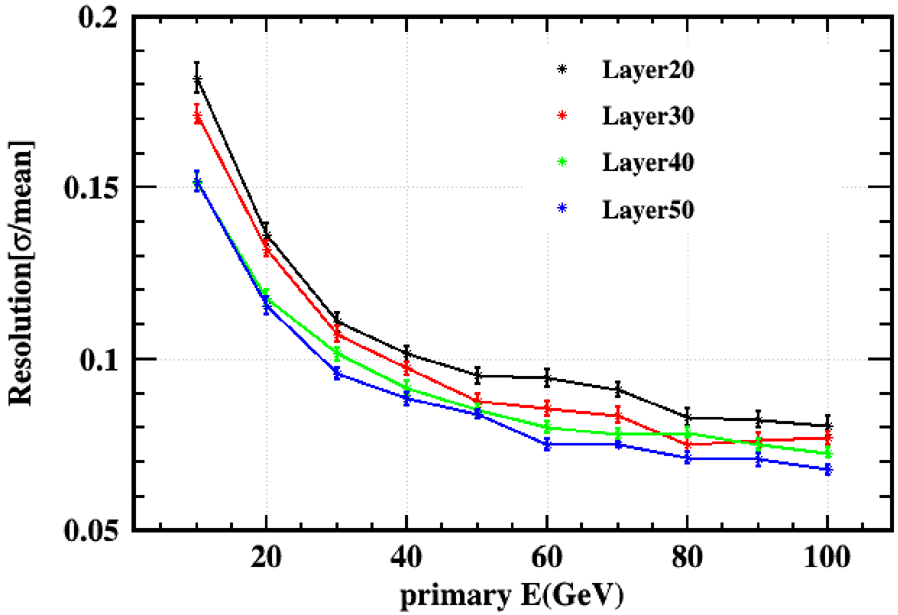
- KL events
  - The linearities are almost the same for different sampling layers
  - More sampling layers have better resolution but means more cost

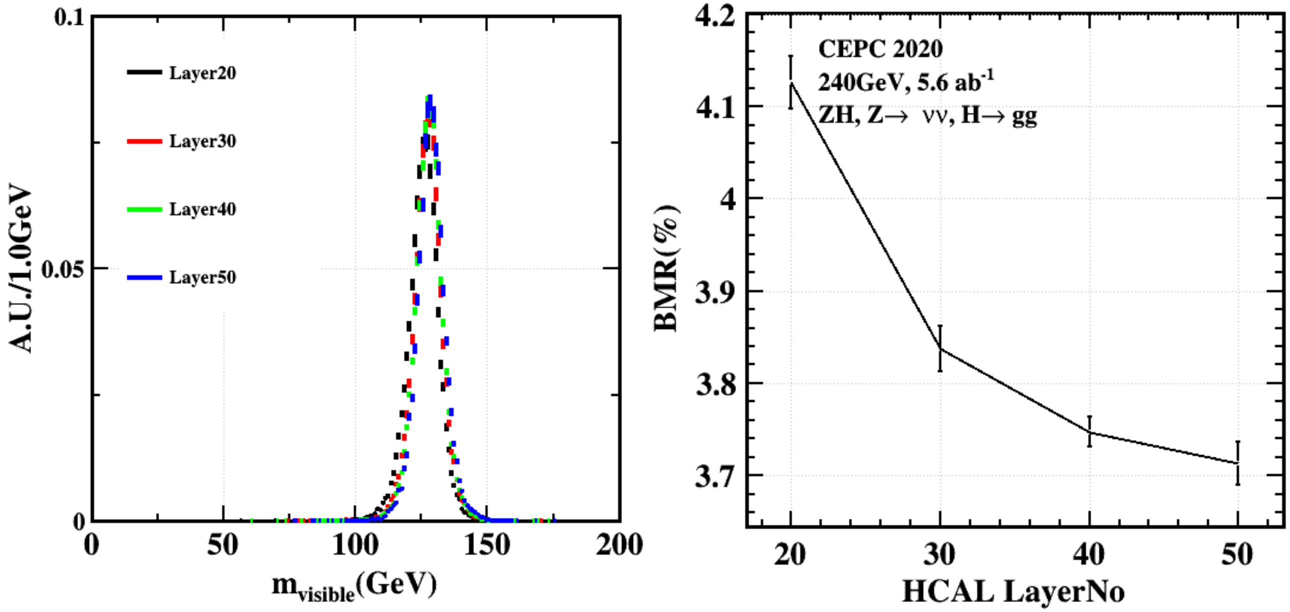




KL linearity and resolution at different sampling layers

CEPC AHCAL optimization

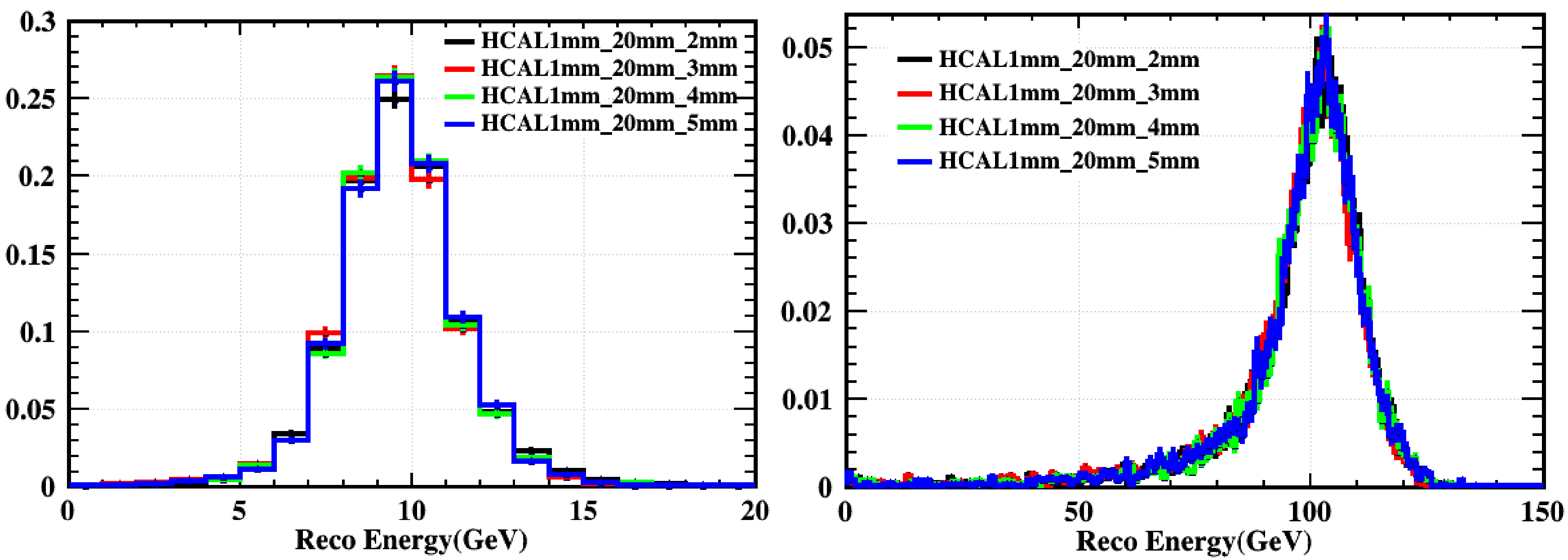
- $\nu\nu H - gg$ events
  - $\nu\nu H - gg$ events are reconstructed for different sampling layers
  - 30 sampling layers already reach the 4% BMR



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

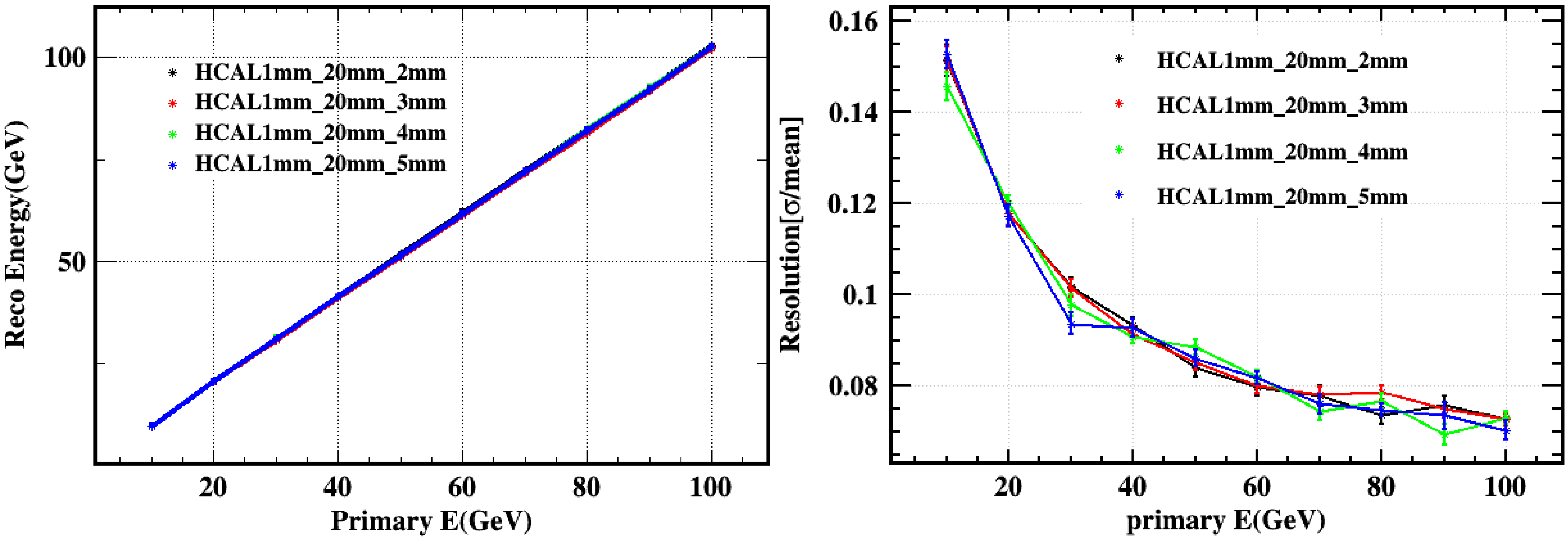
CEPC AHCAL optimization

- 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

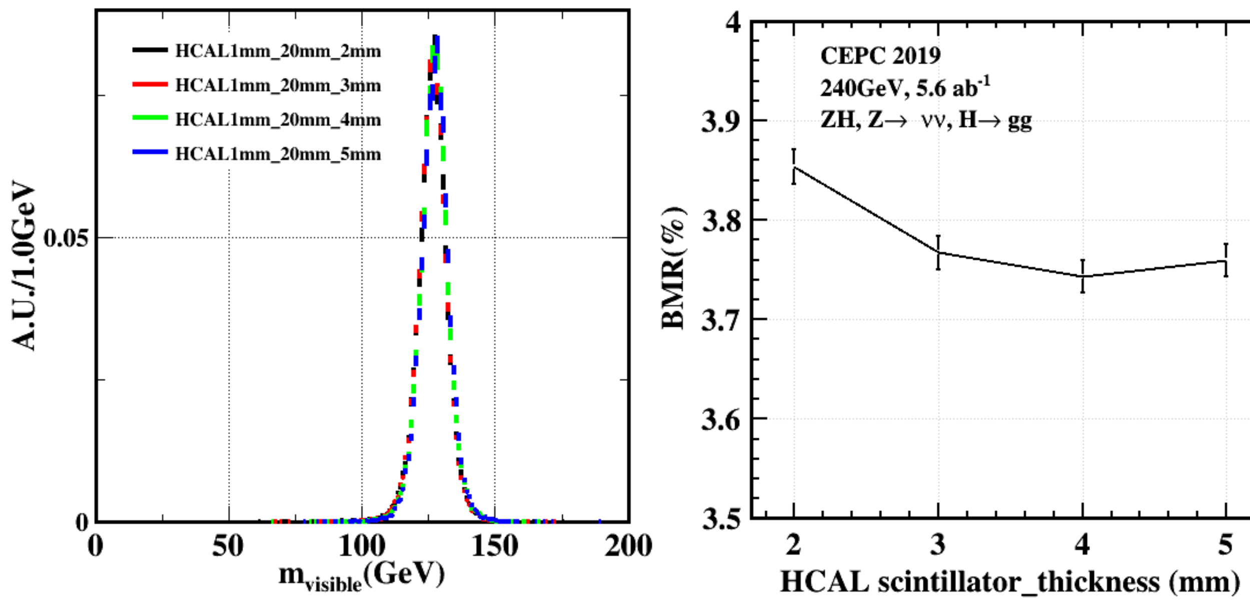
- KL events
  - The linearities are almost the same for different scintillator thickness
  - The linearities are all within ±3% for different scintillator thickness
  - The resolutions are almost the same



KL linearity and resolution at different scintillator thickness

CEPC AHCAL optimization

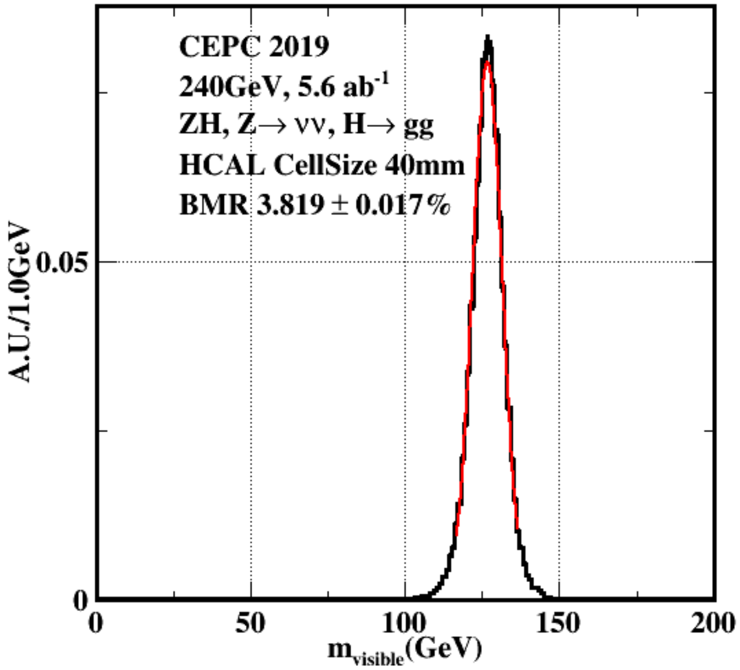
- $\nu\nu H - gg$ events
  - $\nu\nu H - gg$ events are reconstructed for different scintillator thickness
  - The difference of BMR is within 0.1%
  - The 3mm scintillator is a reasonable choice



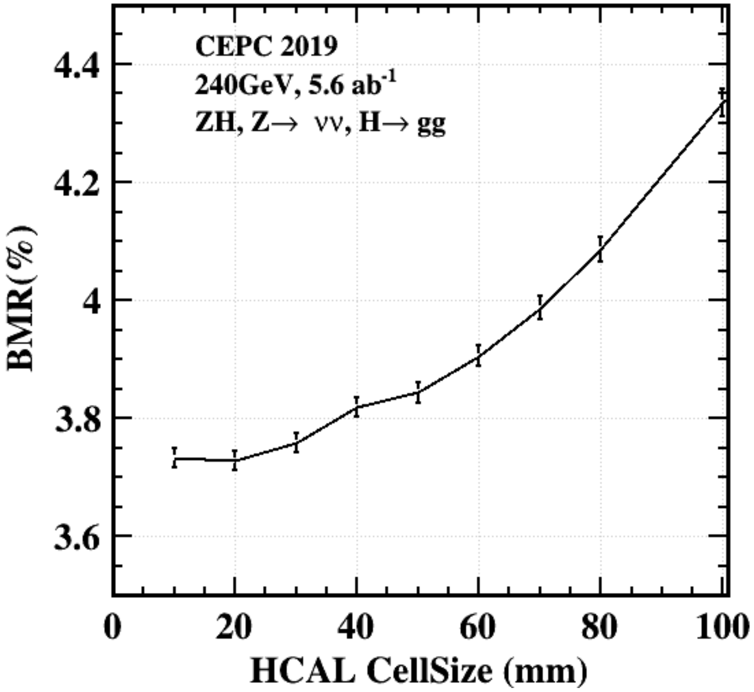
$\nu\nu H - gg$ events for different scintillator thickness

CEPC AHCAL optimization

- Cell size optimization
  - 40mm cell size can satisfy the BMR requirement while reducing about half of the readout channels comparing to 30mm



cell size 40mm: BMR

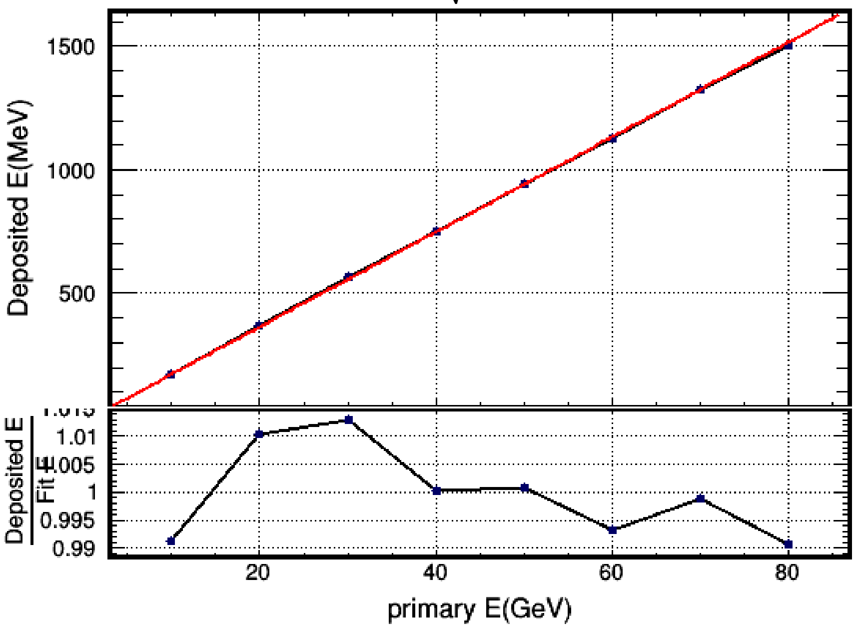


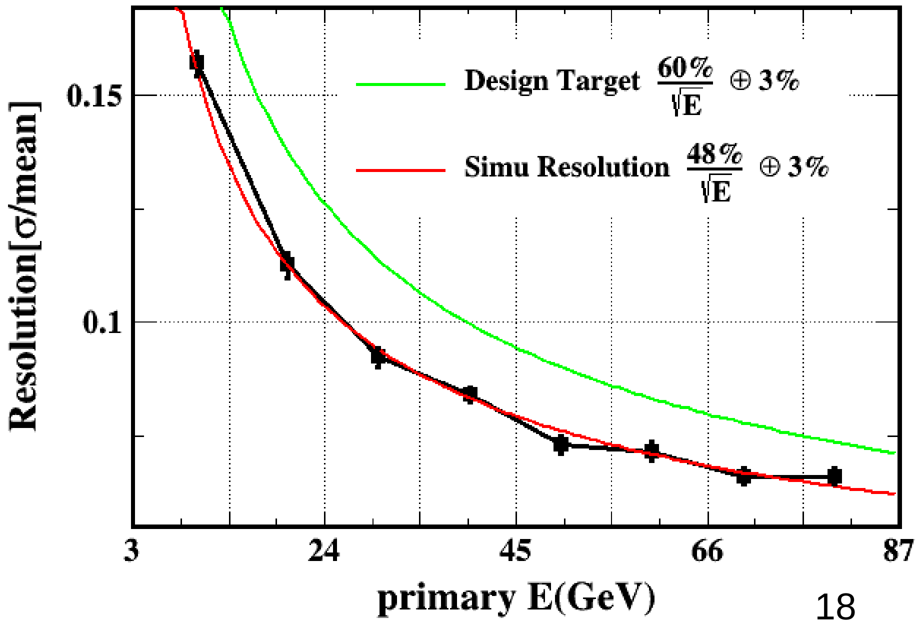
CEPC ACHAL cell size vs BMR

Optimization results

– Prototype design and performance

- Transverse size: $72 \times 72\text{cm}^2$
- 40 layers: each layer has 20mm steel,3mm scintillator and 2mm PCB
- Cell size:40mm
- Linearity:$\sim \pm 1\%$
- Resolution:$\frac{48\%}{\sqrt{E(GeV)}} \oplus 3\%$





Linearity and resolution for HCAL prototype

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Production of scintillators

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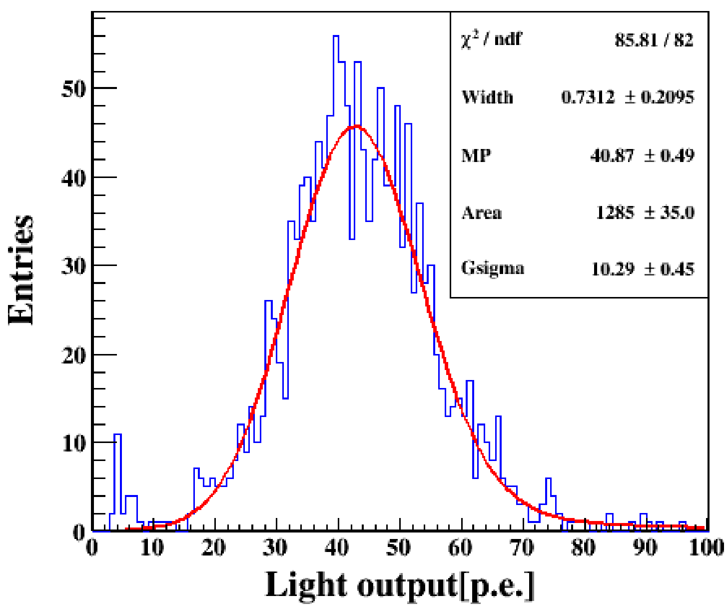
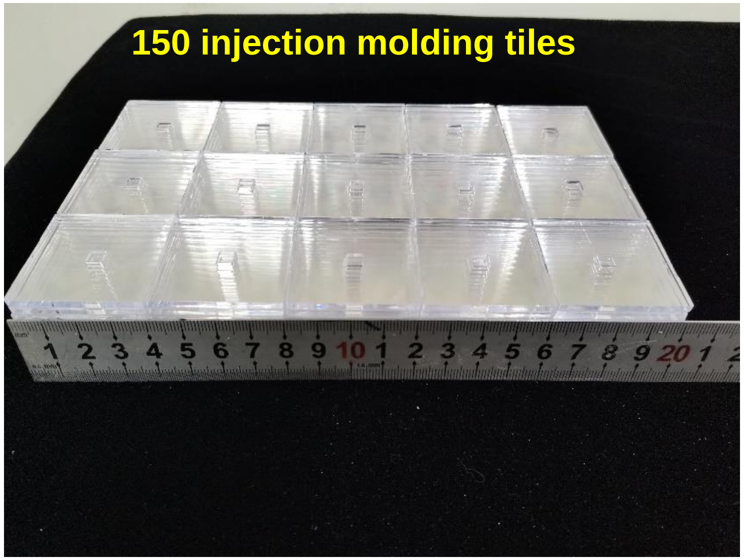
- 11000 scintillators have been produced using the injection molding technique
- The light yield of one scintillator is about 40 p.e. test by NDL-22-1313-15S

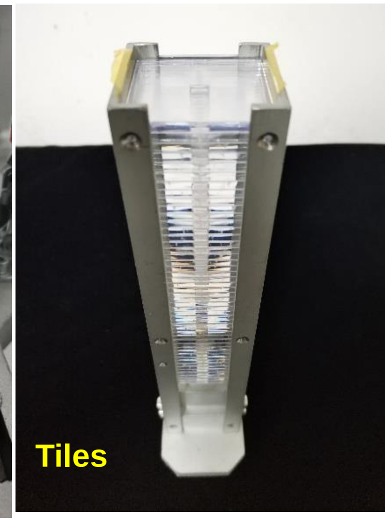
Light output:41p.e.

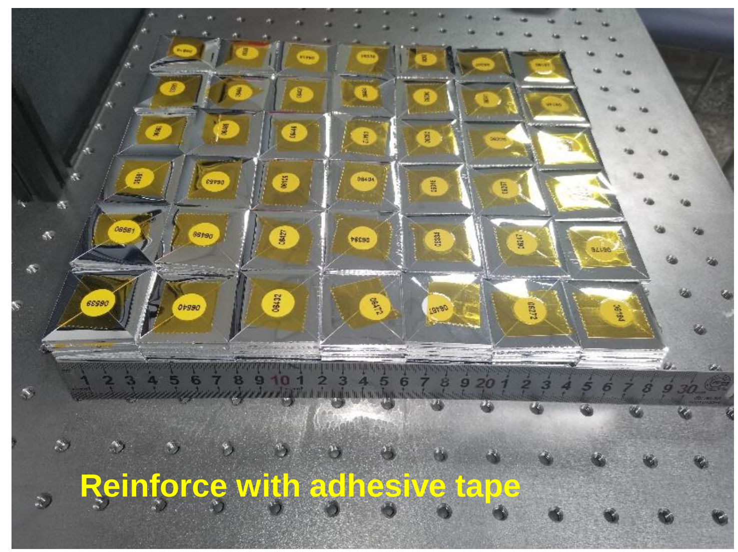




Wrapping of scintillators

- The material of the wrapper is ESR
- The whole wrapping and labelling procedure is automatic
- 100 scintillators cost 75min once

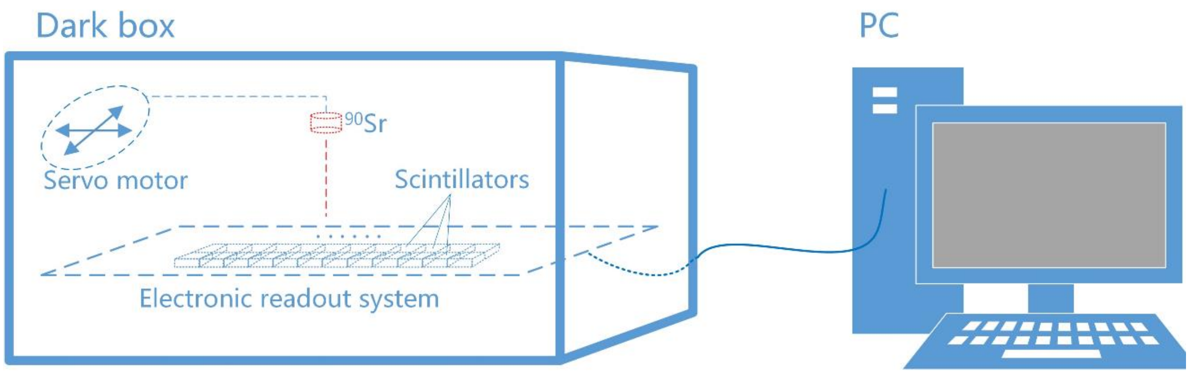


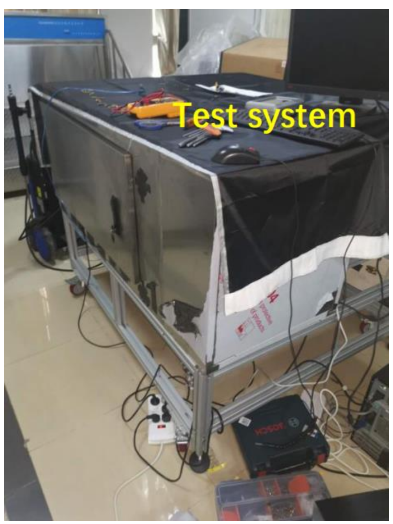


Batch test of scintillators

Batch Testing Platform

- Test the uniformity of all scintillators
- 144 channels one platform
- Auto-moving
- 3 batch testing platforms





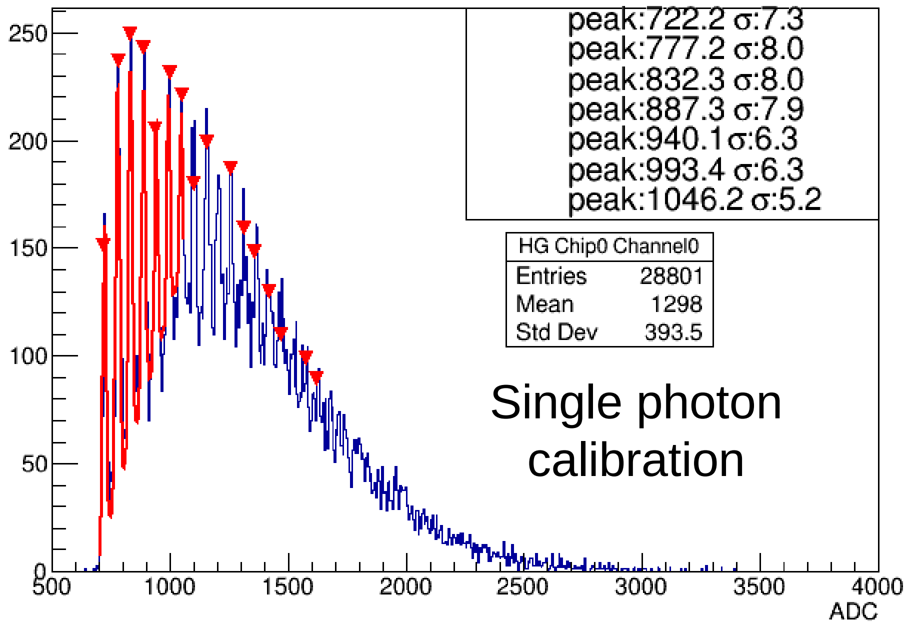
USTC

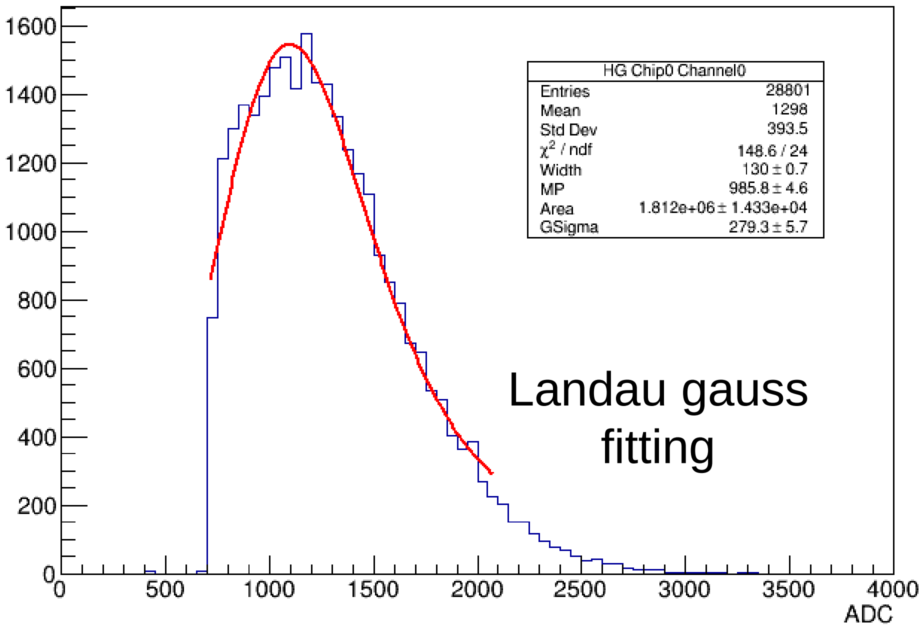
SJTU

IHEP

Batch test of scintillators

- MIP source : Sr 90
- The scintillator light is detected by the SiPM 13360-1325PE working at the 5V overvoltage
- The SiPM signal is read by the SPIROC2E chip





The MIP Spectrum

Batch test of scintillators

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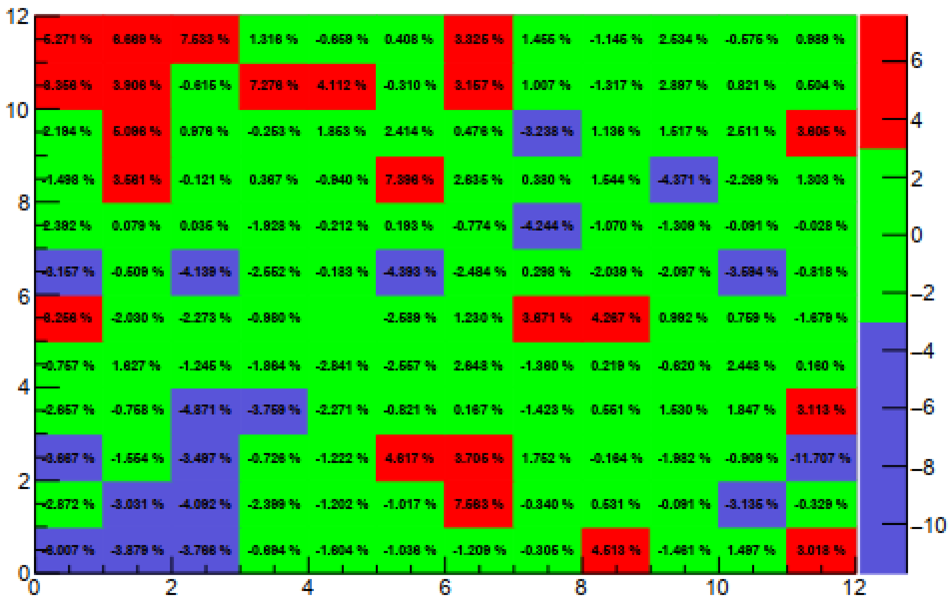
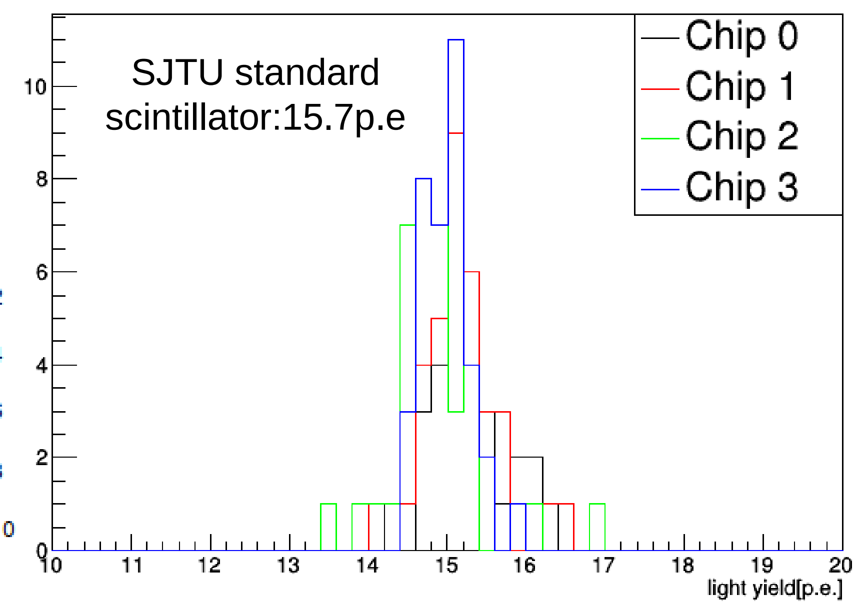
- Calibration
  - Self calibration of SJTU
  - Inter calibration between USTC and SJTU



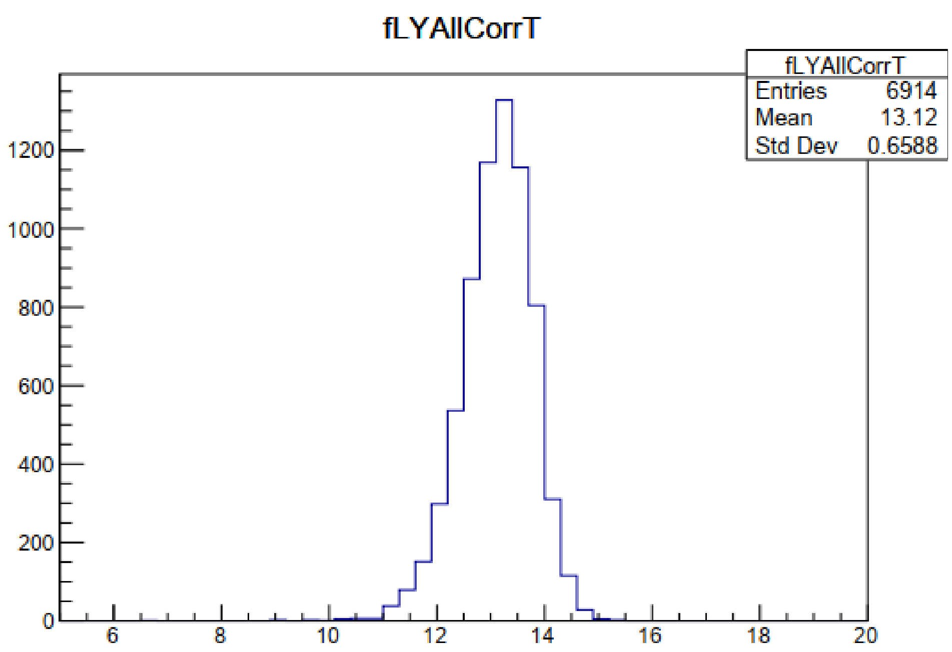
SJTU self calibration

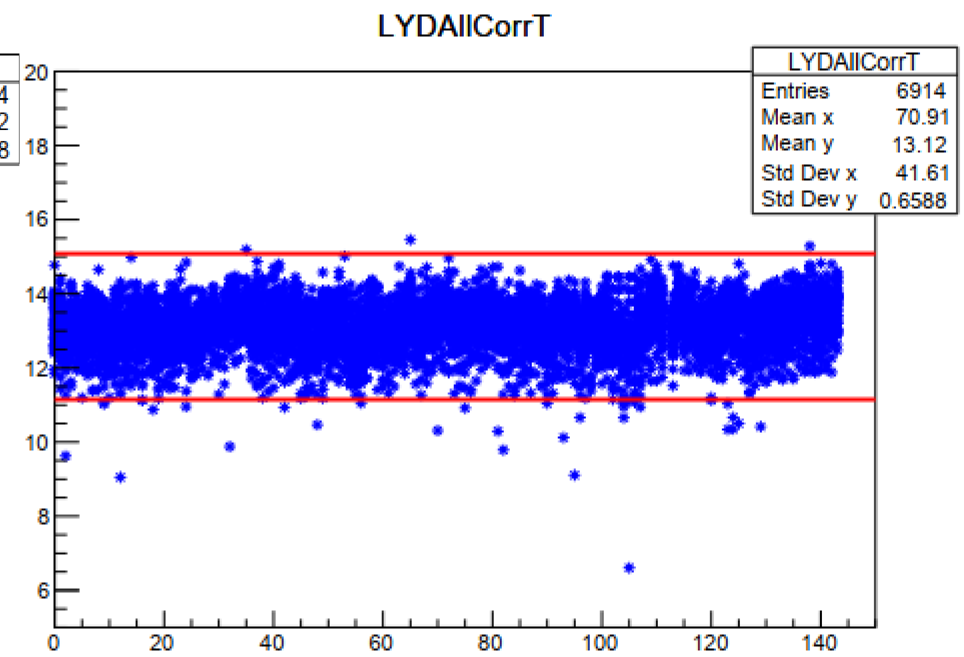


SJTU and USTC inter calibration

Batch test of scintillators

- SJTU results
  - 6914 scintillators have been test
  - 95% scintillators's light yield are within mean ±15%

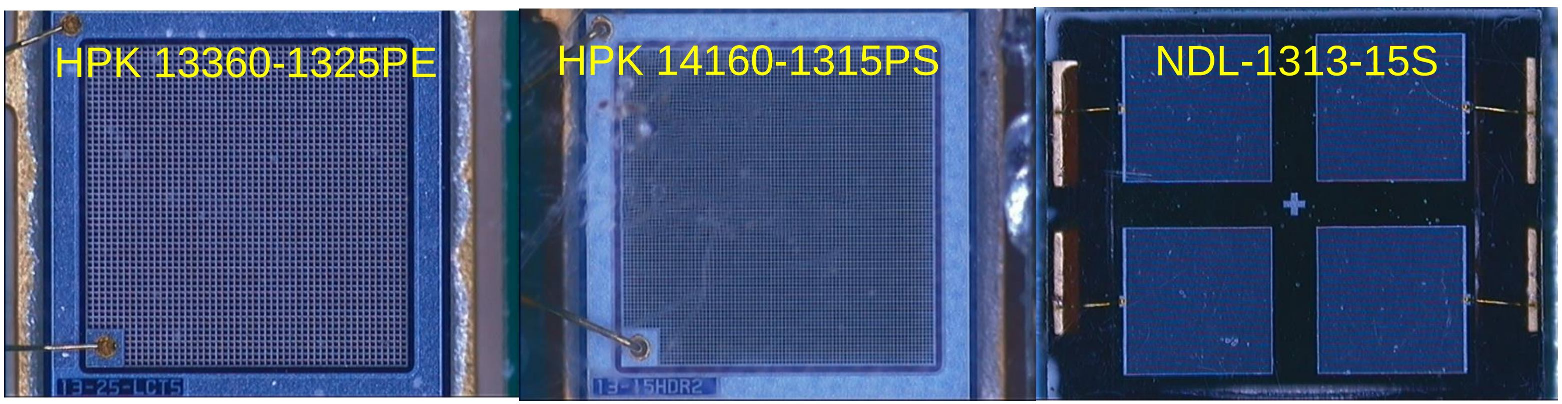




The SiPM comparison

- **HPK-SiPM**
  - Low light yield, dark rate and crosstalk
  - High breakdown
  - High price

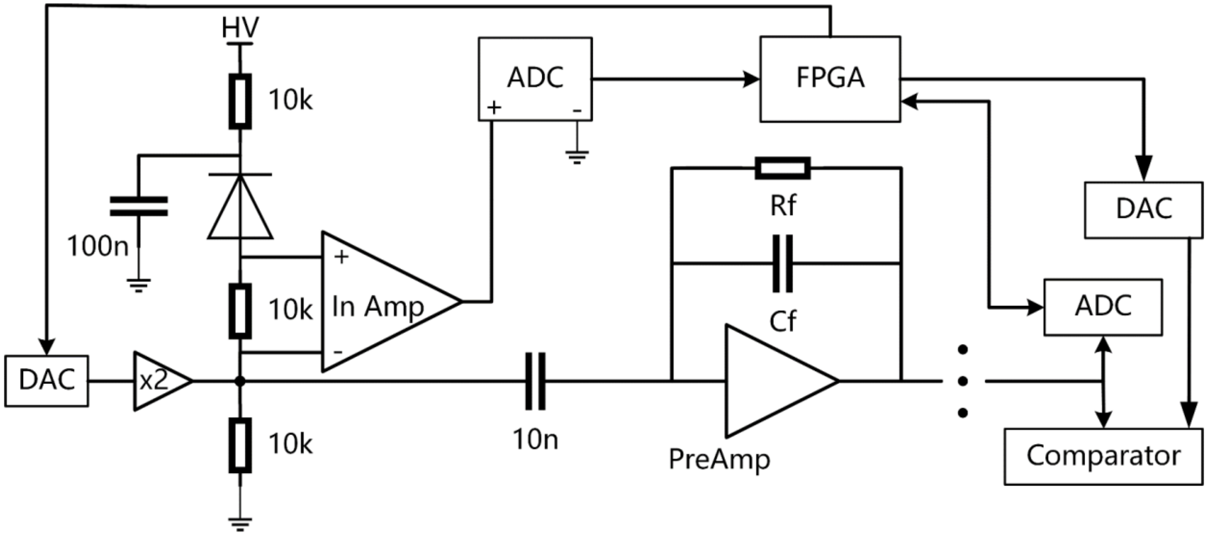
- **NDL-SiPM:**
  - High light yield, dark rate and crosstalk
  - Low breakdown
  - Low price



Company	HPK		NDL
Type	13360-1325PE	14160-1315PS	22-1313-15S
Light output [p.e.]	13	17	40
Crosstalk[%]	1.59	1.17	4.4
Dark Counts [kHz]	120	290	550
Breakdown[V]	53	38	27.5

Batch test of SiPM

- The design of the SiPM test platform
  - Assure the uniformity of SiPMs
  - A SiPM detachable fixer
  - SKIROC2a readout or discrete-circuit readout
  - Test quality : break down voltage, dark count, gain



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HBU(HCAL Basic Unit)

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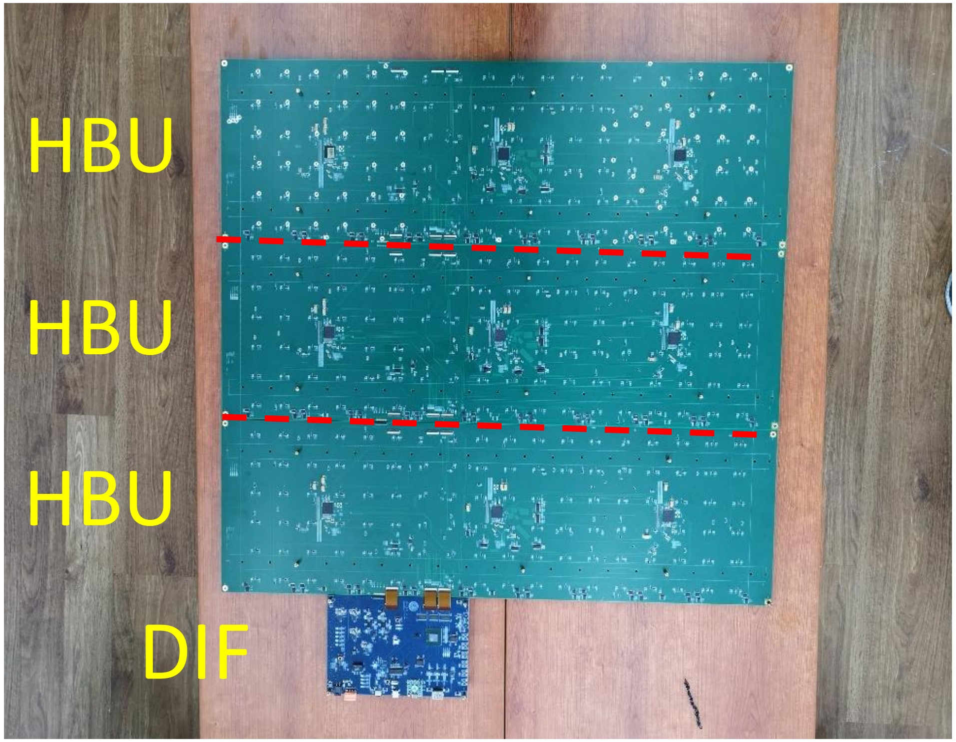
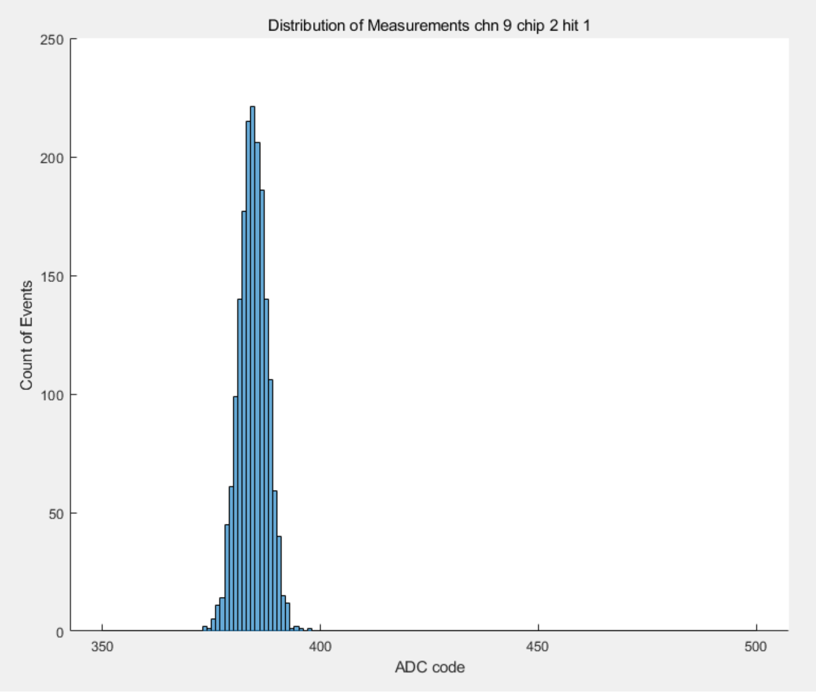
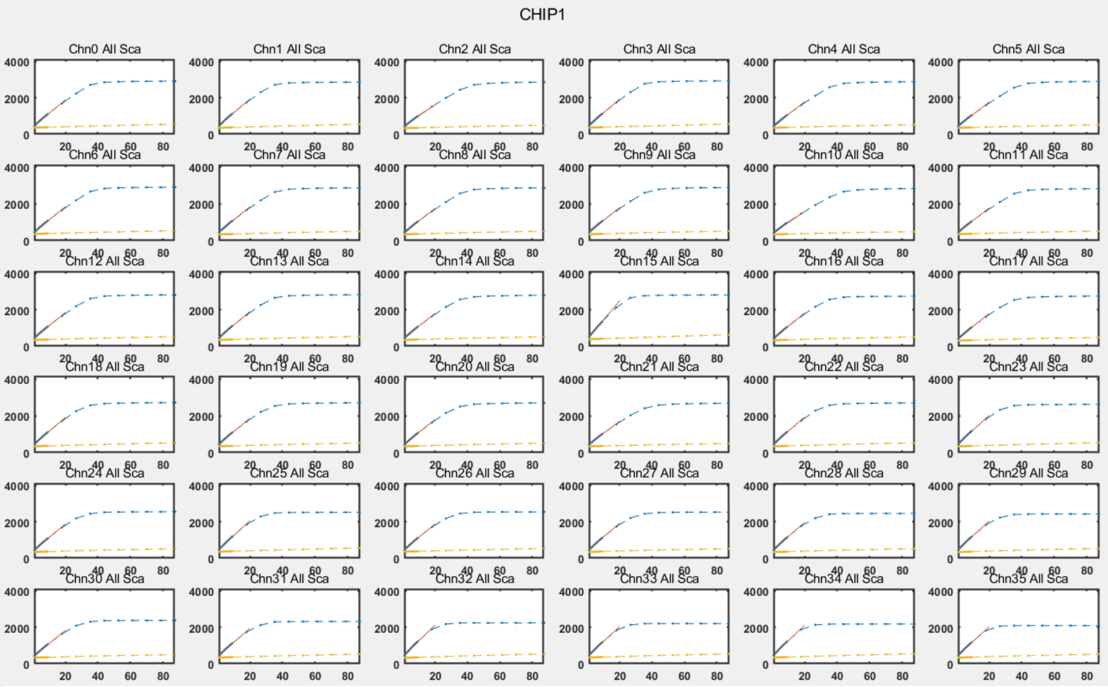
- The sensitive size of one layer is designed as $72 \times 72\text{cm}^2$
- A single layer is equally divided into 3 boards
- each HBU is $78.5 \times 24\text{cm}^2$ and has 108 channels
- Every layer is controlled by one DIF board



- Electronic test
  - The pedestal and charge calibration results mean that the chips are working normally



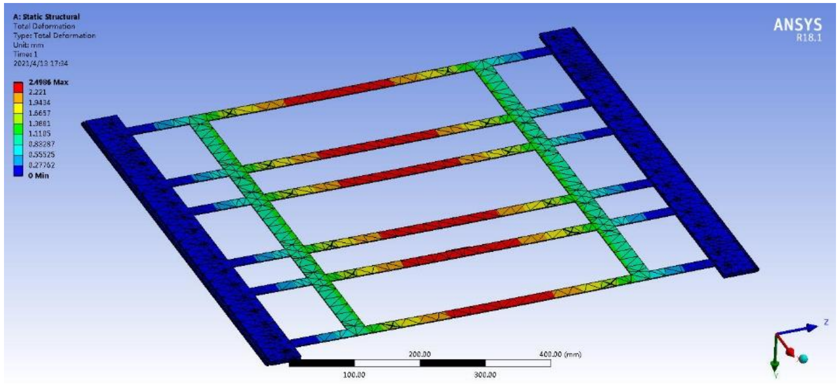


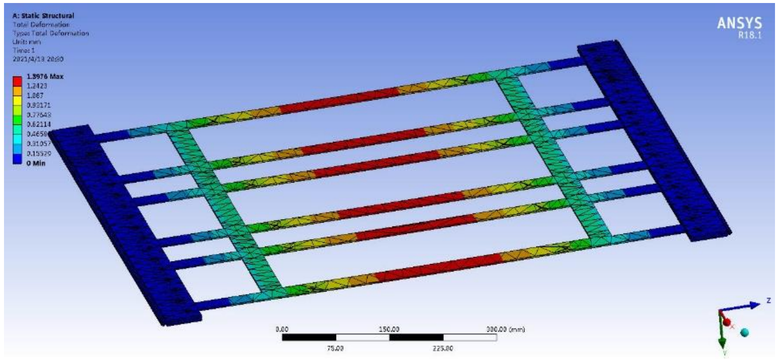
pedestal

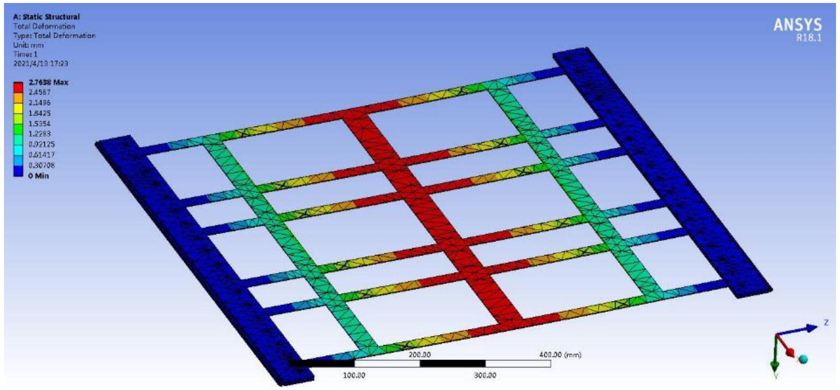
Charge calibration

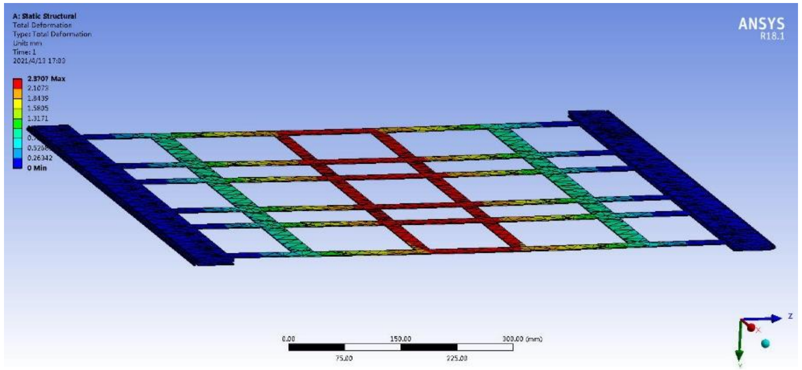
HBU

- Mechanics
  - The design for HBU has just started
  - Simulation focuses on how to support such a large PCB



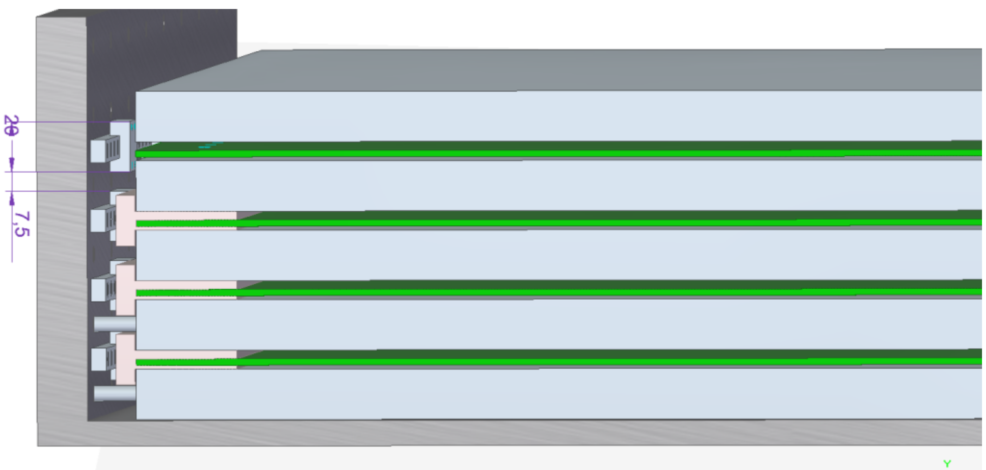




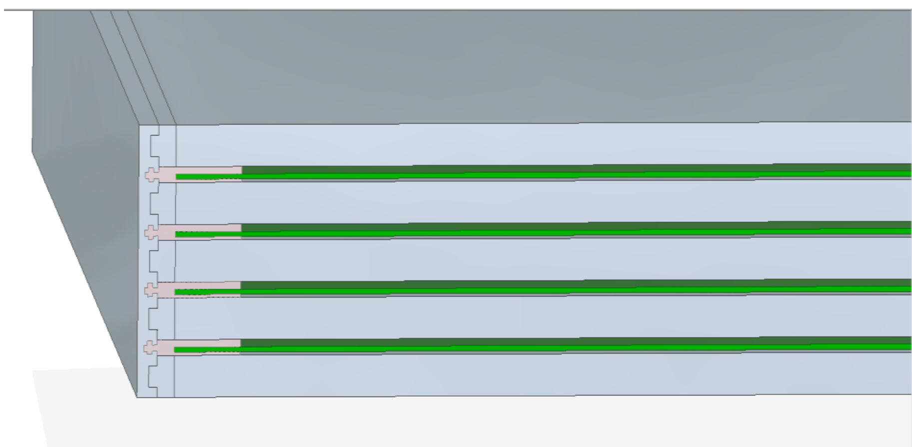


HBU

- Slideway options
  - Commercial: reliable and time saving
  - Self designed: compact and flexible



commercial



Self designed

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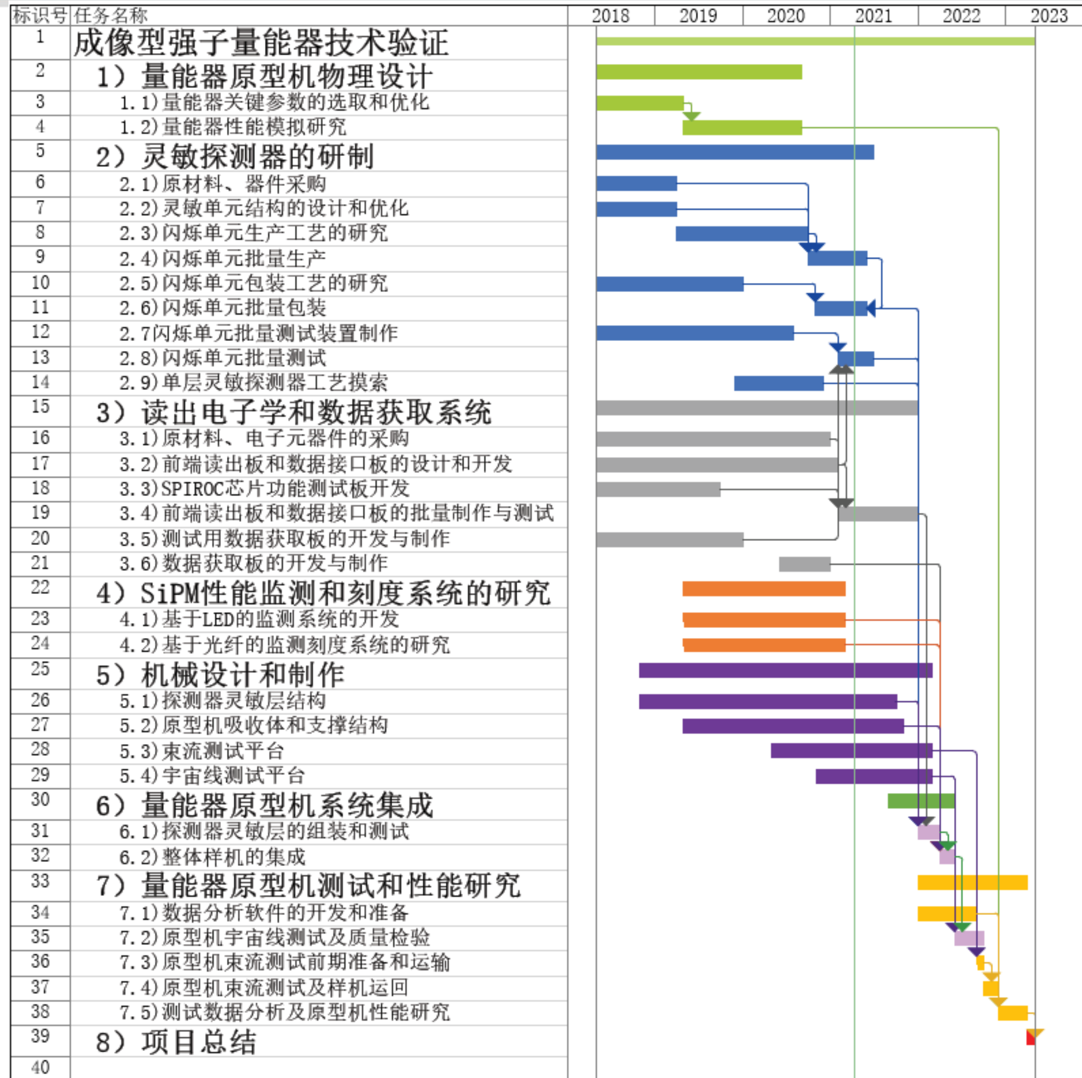
Time line

- We are late on HBU production, mechanics and prototype construction
- We are trying to produce 40 layers of HBU by the end of this year and start prototype construction next year
- Cosmic and beam test are still expected next year



Summary and outlook

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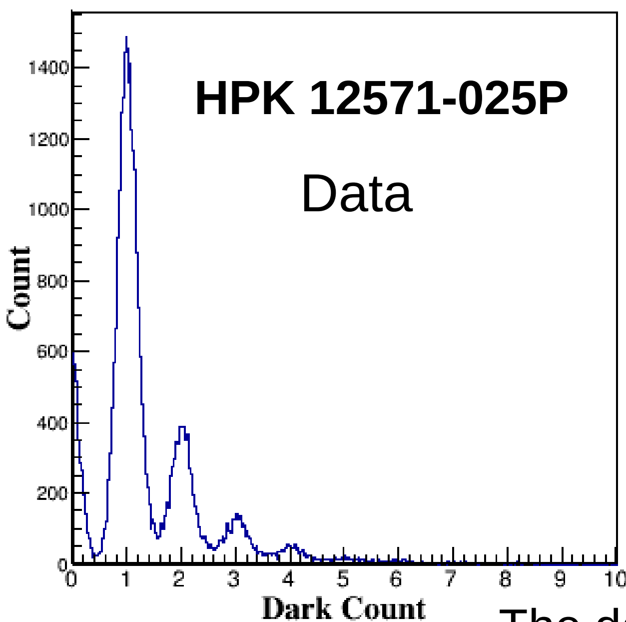
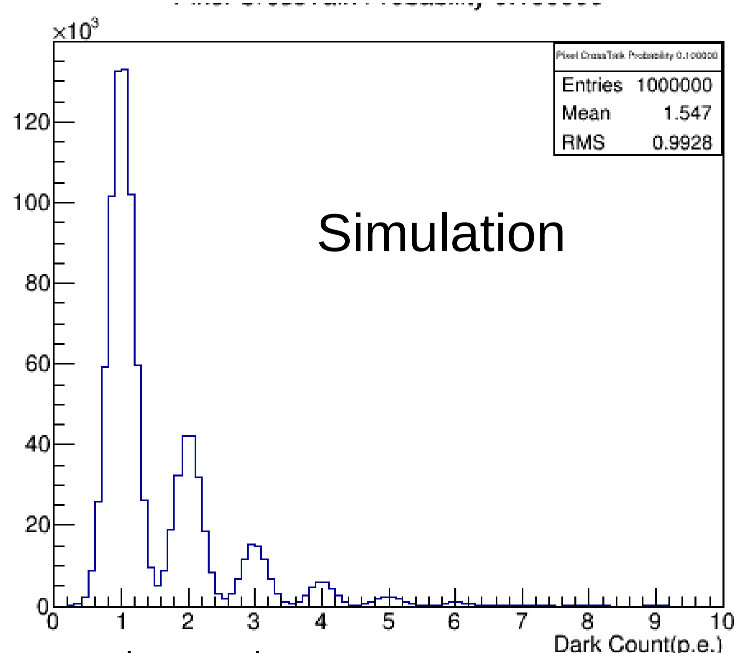
- Summary
  - the optimization for AHCAL has been done, the prototype design has been settled
  - 11000 scintillators have been produced and test, the light yield and uniformity reach our expectation
  - The BNU SiPM is chosen for this prototype
  - The HBU electronics works normally
- Outlook
  - The test platform for SiPMs will be completed before summer
  - Production of all 40 prototype layers will be finished this year
  - The next step, the whole prototype construction, will start before the end of this year, and the cosmic and beam test is expected next year

Back up

The SiPM simulation

- The dark count and threshold
  - The dark count spectrum has been simulated
  - The SiPM is S12571-025P
  - Crosstalk probability is 22.6%





The dark count spectrum

The SiPM simulation

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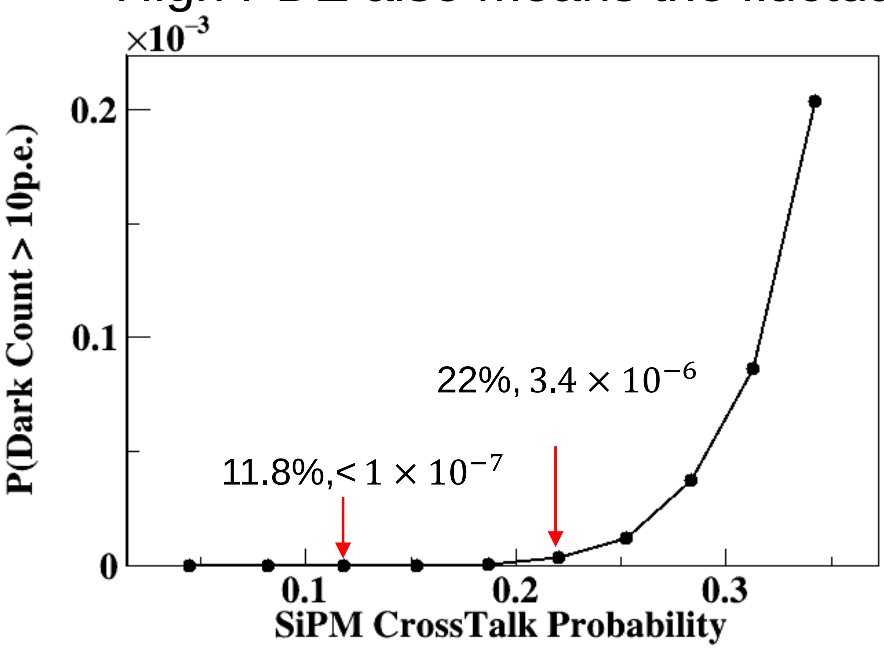
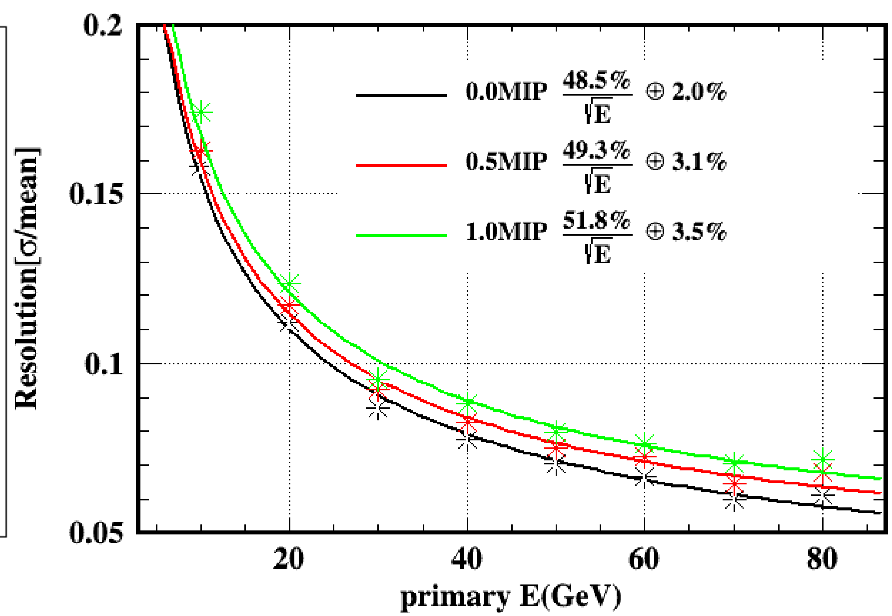
- For the BNU SiPM, the 0.5MIP equals 20p.e. while for the HPK SiPM, the 0.5MIP equals 10p.e.
- The probability that a Dark count is over 10p.e. is quite low, not to mention the 20p.e.
- From this point of view, PDE is dominant in the threshold issue
- High PDE also means the fluctuation is lower

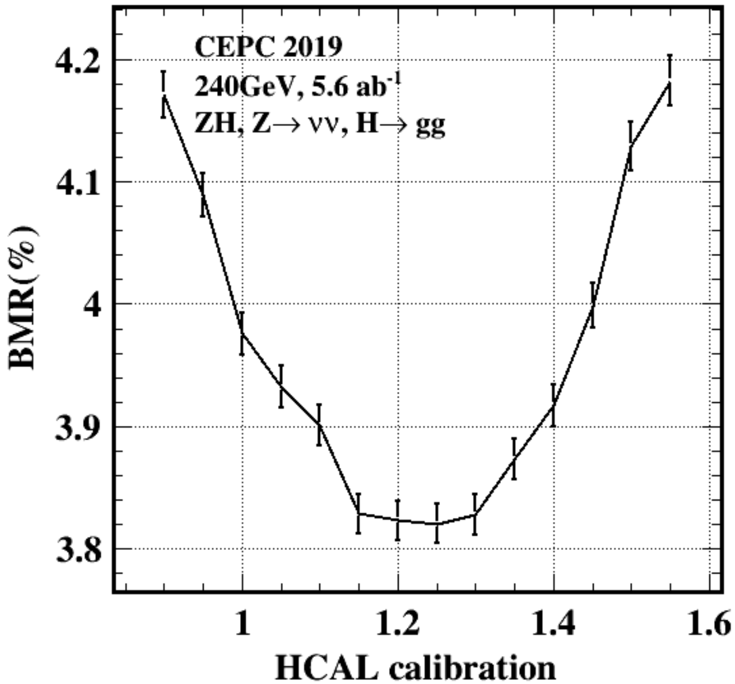


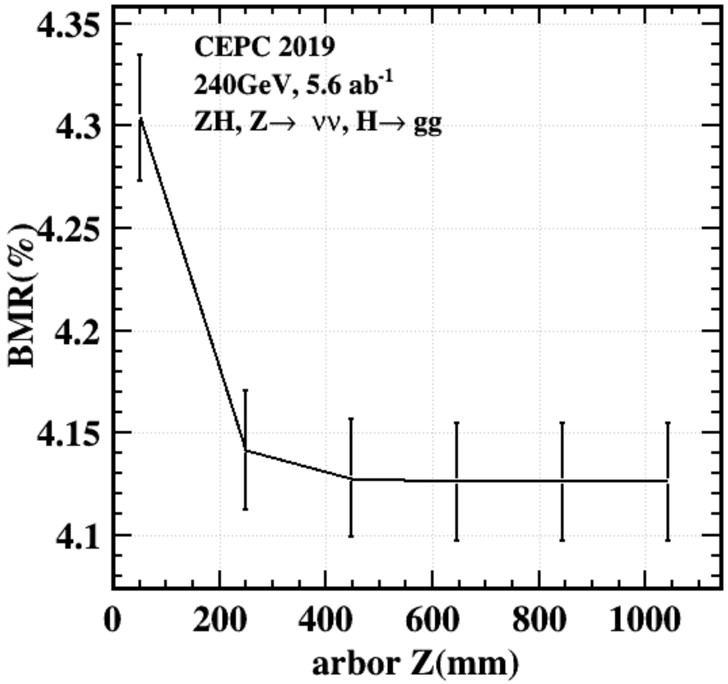
The cross talk probability and threshold efficiency



The threshold and energy resolution

- 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

Prototype optimization

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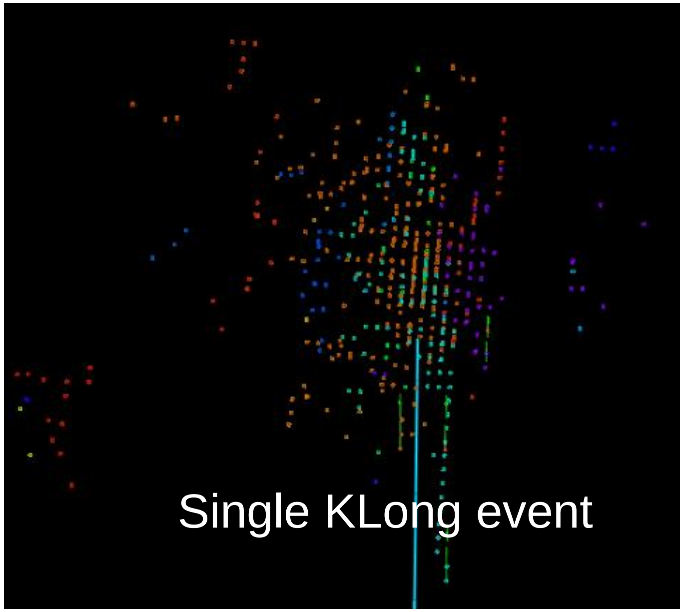
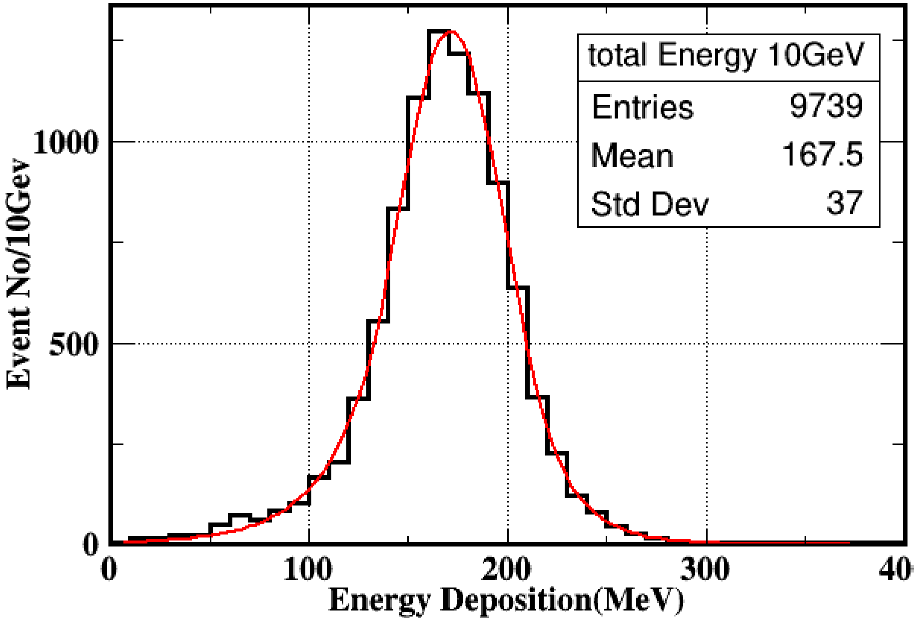
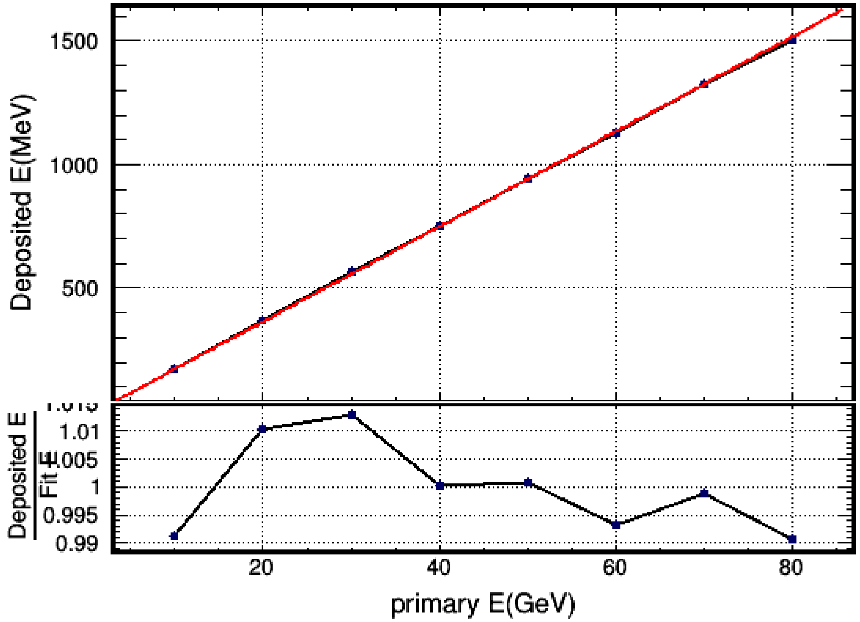
- Simulation Setup
  - CEPC Simplified Geometry: only AHCAL is implemented
  - Prototype Transverse size: $72 \times 72\mathrm{cm}^2$
  - 40 layers: each layer has 20mm steel,3mm scintillator and 2mm PCB
  - Incident particle: Klong which's energy ranges from 10GeV to 80GeV

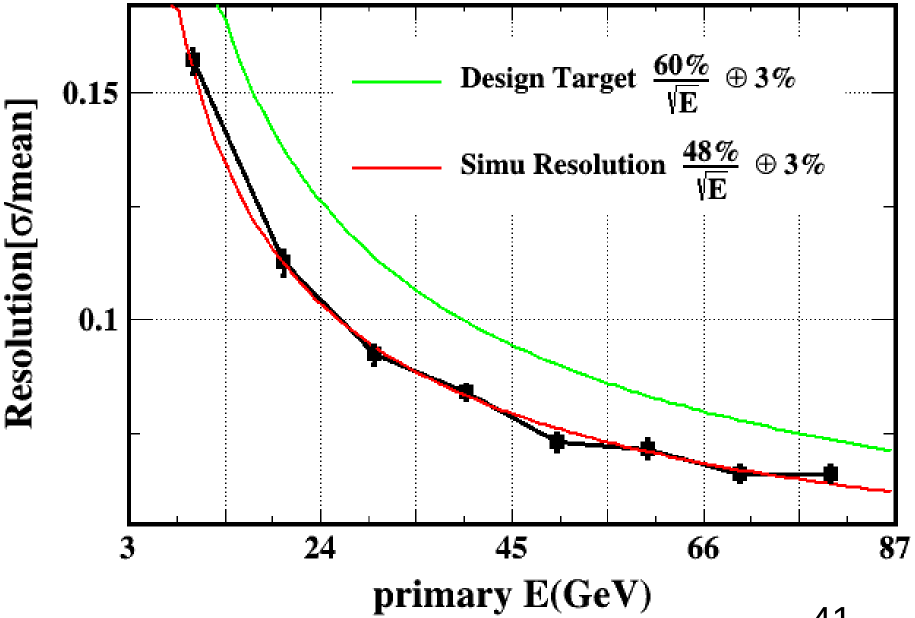




Event Display and Energy deposition for 10GeV KL

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

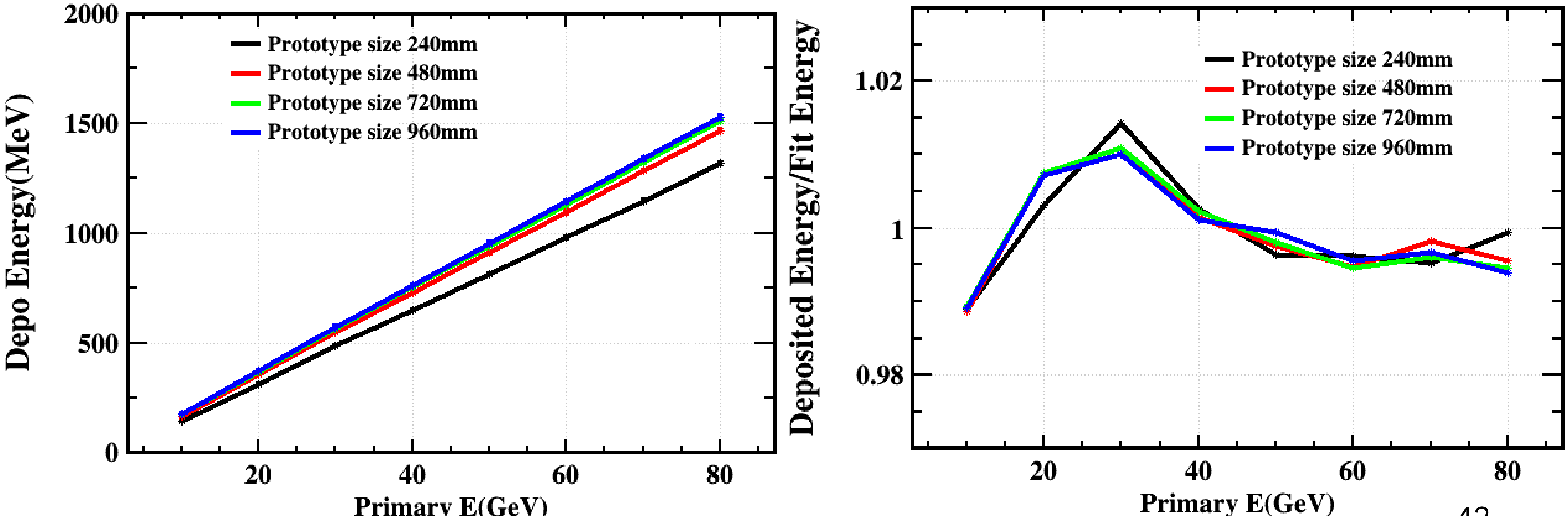




Linearity and resolution for HCAL prototype

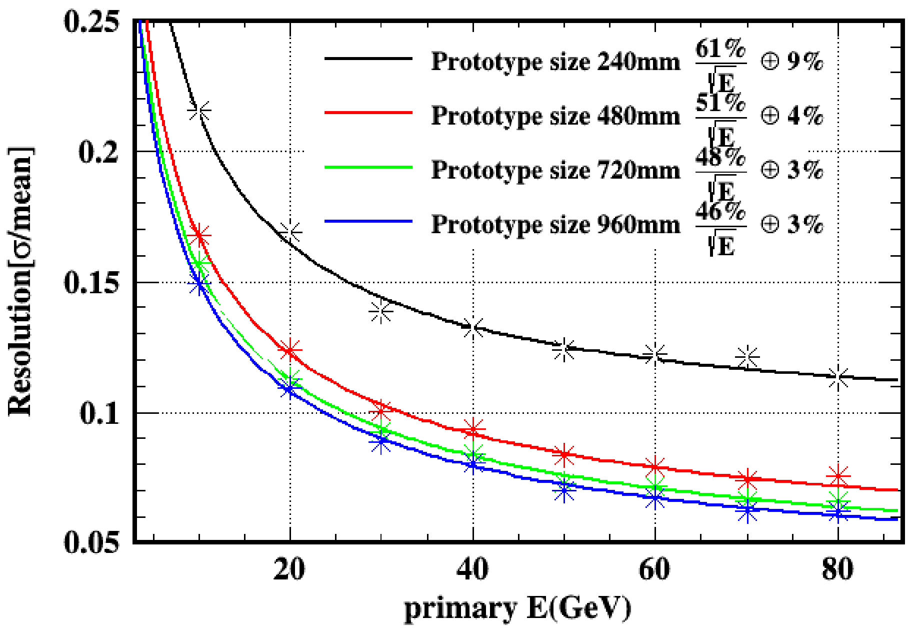
Prototype optimization

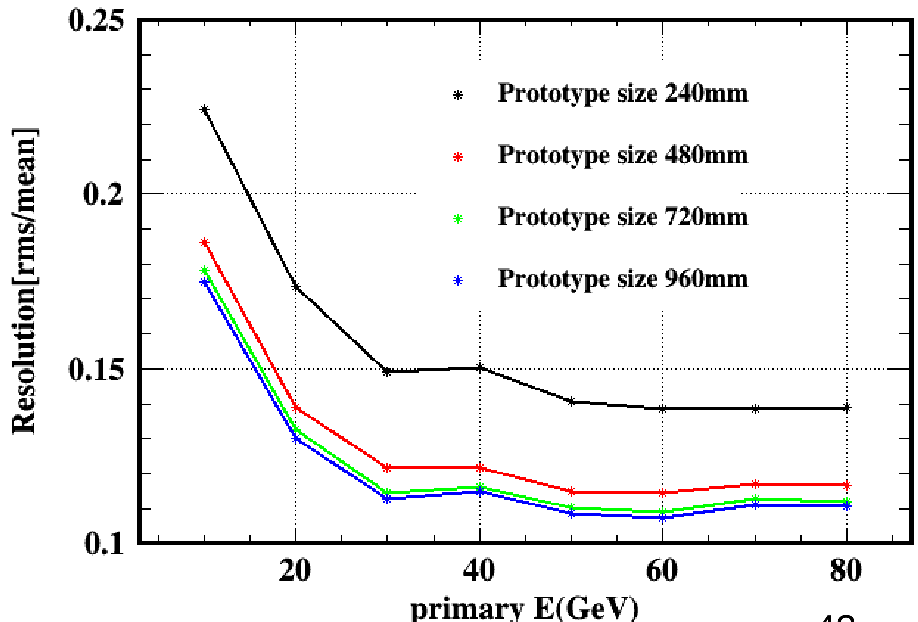
- Prototype size optimization
  - 40 sampling layer, each layer has 20mm steel, 3mm scintillator and 2mm PCB
  - The transverse prototype size ranges from 240mm to 960mm
  - All have a linearity < $\pm 3\%$



Linearity for different prototype transverse size

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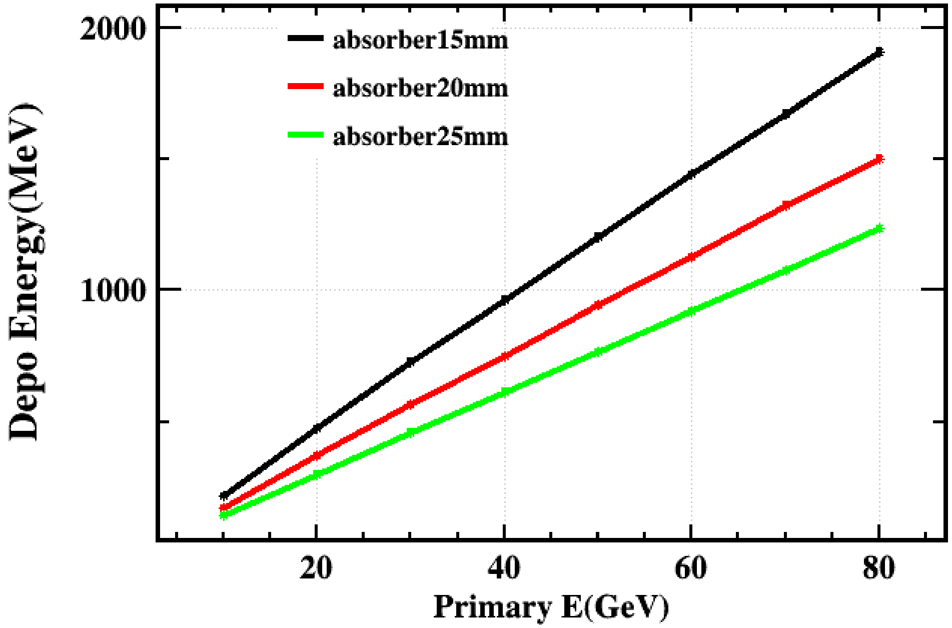
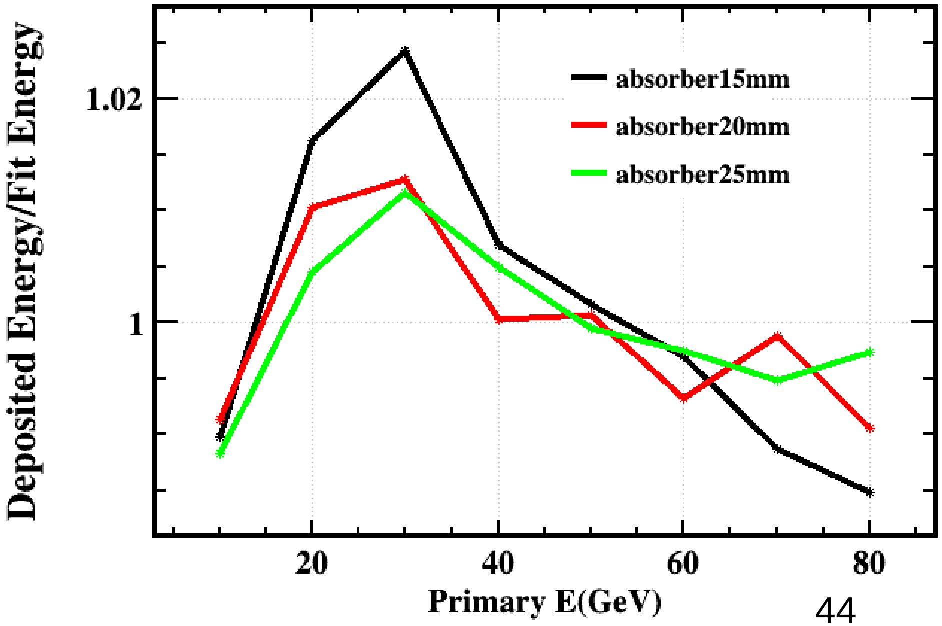
- Absorber thickness optimization
  - Prototype Transverse size: $72 \times 72\mathrm{cm}^2$
  - 40 sampling layer, each layer has 3mm scintillator and 2mm PCB
  - Absorber thickness for each layer ranges from15mm to 25mm
  - Total absorber thickness ranges from 3.8λ to 6.3λ
  - All have a linearity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





Linearity for different absorber thickness

Prototype optimization

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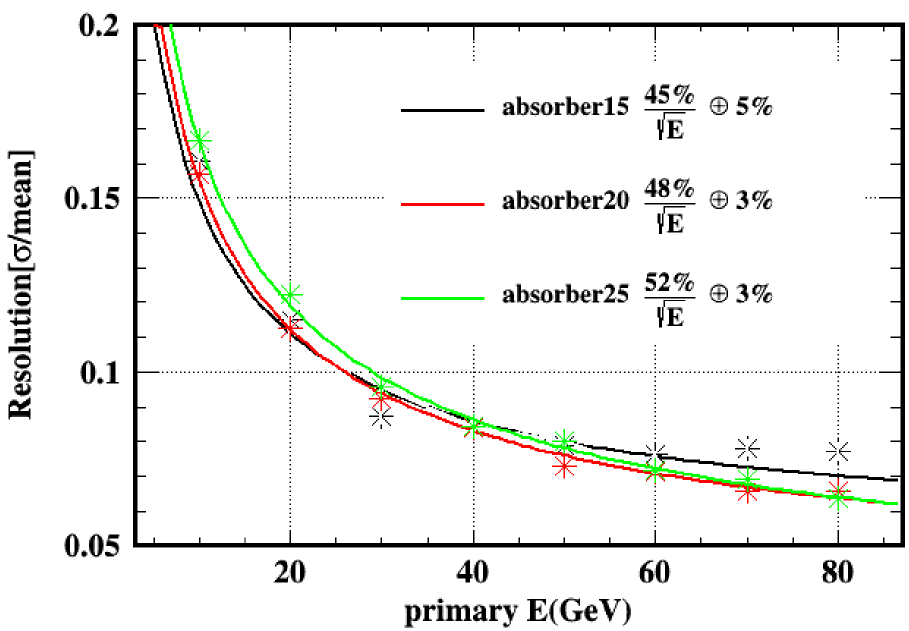
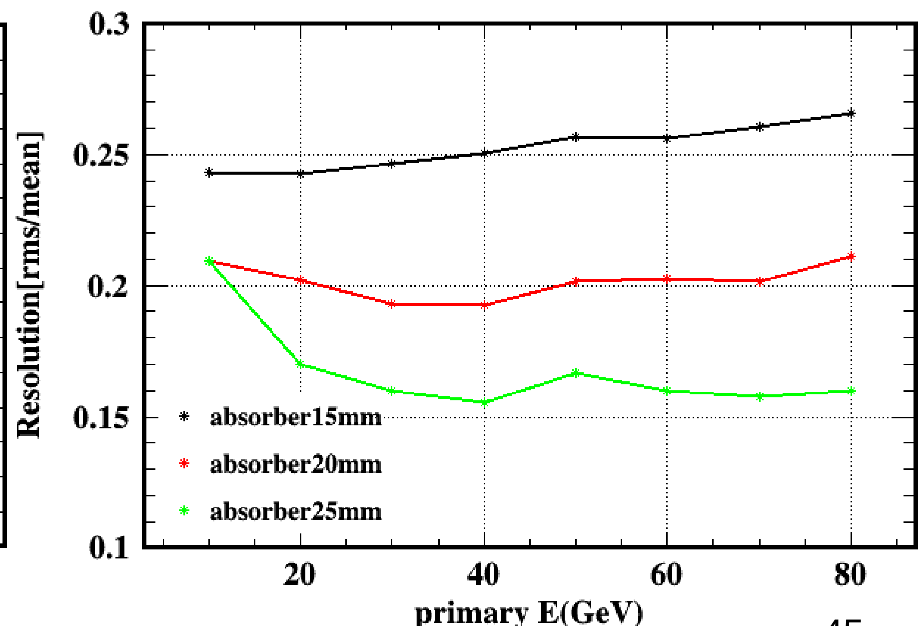
- Absorber thickness optimization
  - Thinner absorber has a better sampling ratio resulting a smaller statistical term
  - Thinner absorber has larger leakage resulting a bigger constant term
  - The 20mm absorber can satisfy our need





resolution for different absorber thickness

Prototype optimization

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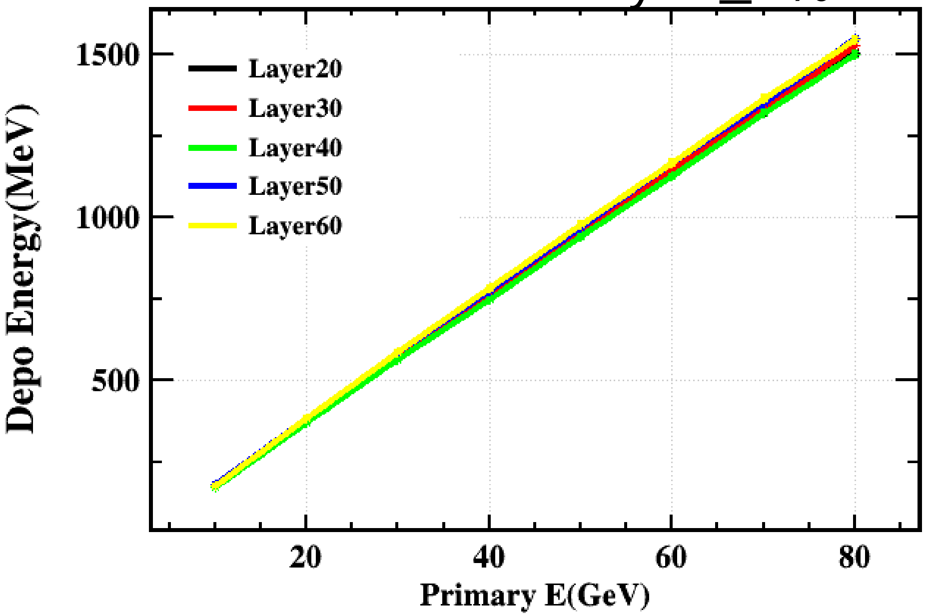
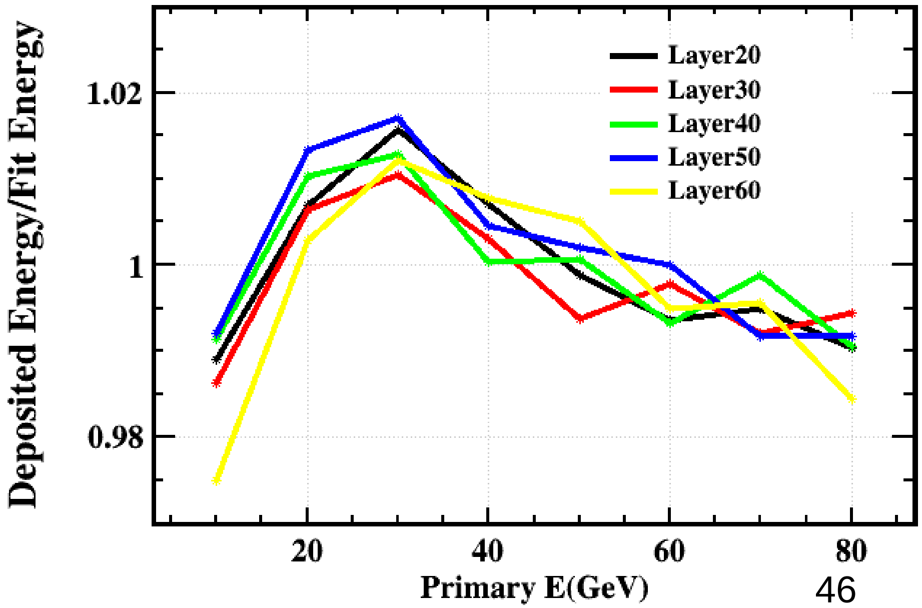
- Sampling Layer optimization
  - Prototype Transverse size: $72 \times 72\text{cm}^2$
  - Total absorber thickness is fixed as 800mm and total scintillator thickness is fixed as 120mm
  - The thickness of PCB for each layer is 2mm
  - The number of sampling layers ranges from 20 to 60
  - All have a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





Linearity for different sampling layers

Prototype optimization

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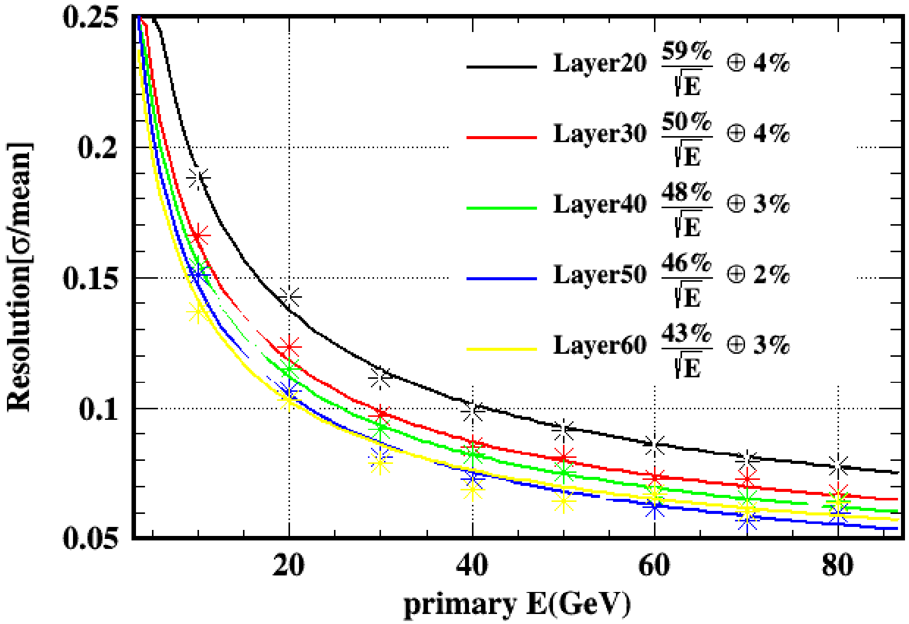
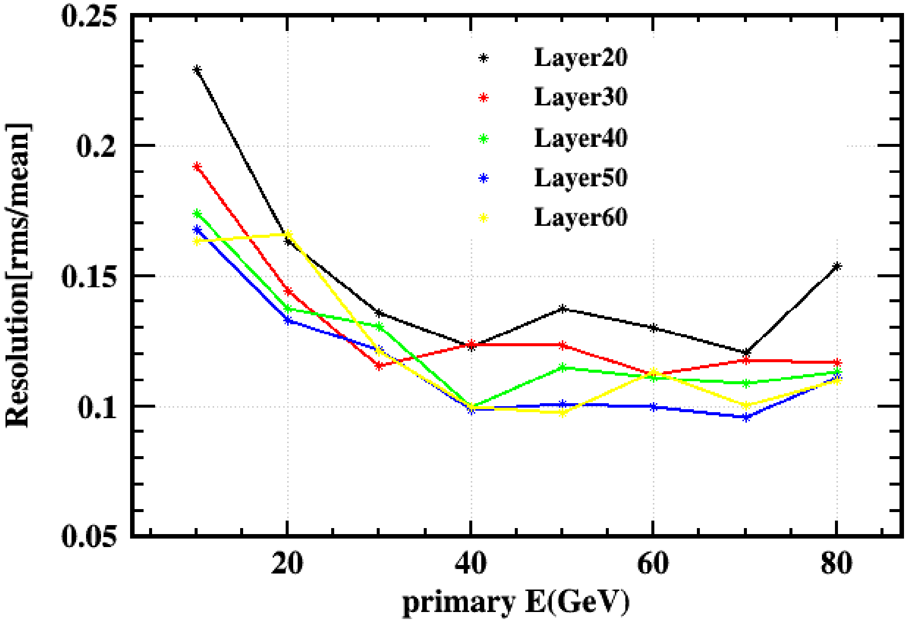
- Sampling Layer optimization
  - More sampling layers have less statistical fluctuation
  - Since PCB thickness for each layer is fixed, it could be a problem for more sampling layers in the prototype
  - 40 layers is reasonable for the prototype





Resolution for different sampling layers

Prototype optimization

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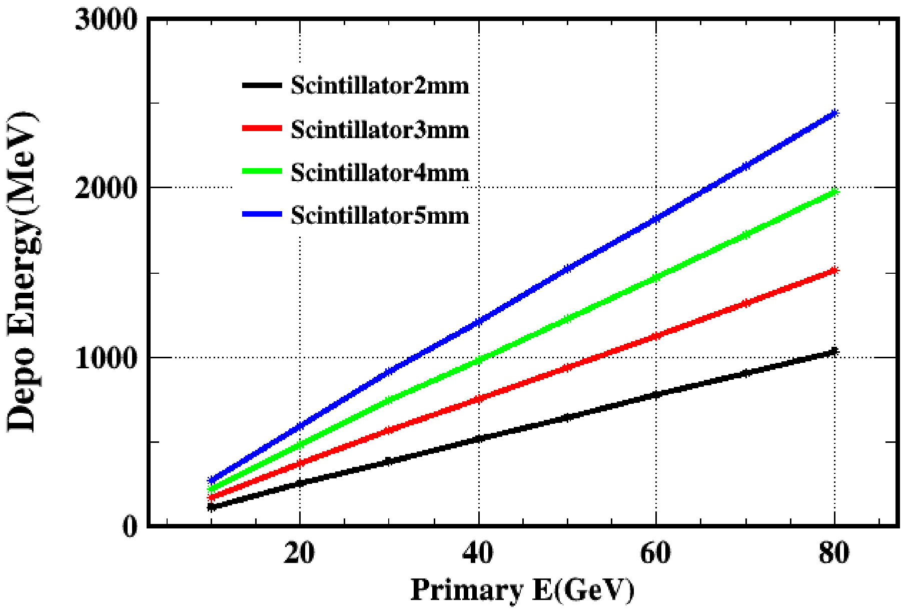
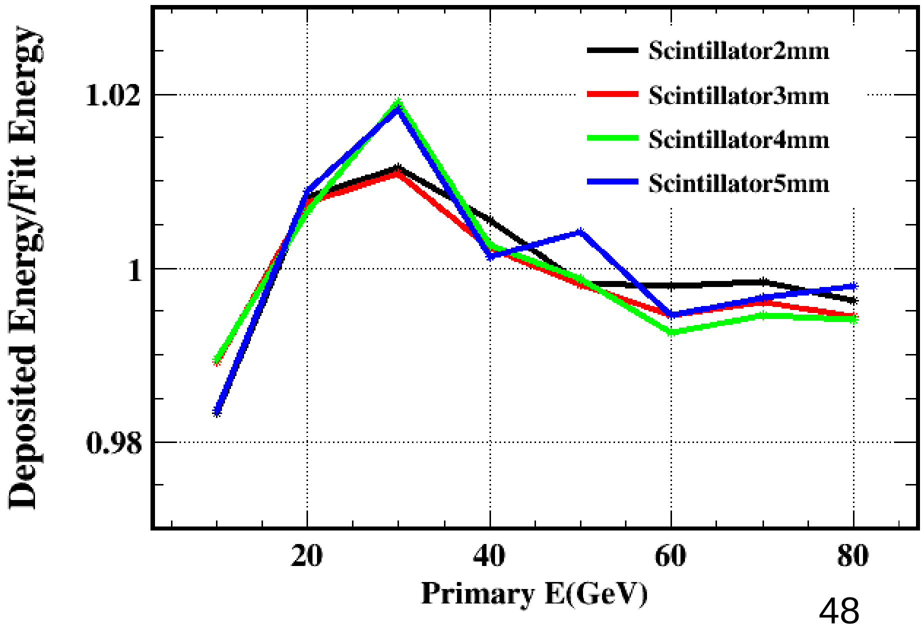
- Scintillator thickness optimization
  - Prototype Transverse size: $72 \times 72 \text{cm}^2$
  - 40 sampling layer, each layer has 20mm steel and 2mm PCB
  - The scintillator thickness for each layer ranges from 2mm to 5mm
  - All have a linearity < $\pm 3\%$





Linearity for different scintillator thickness

Prototype optimization

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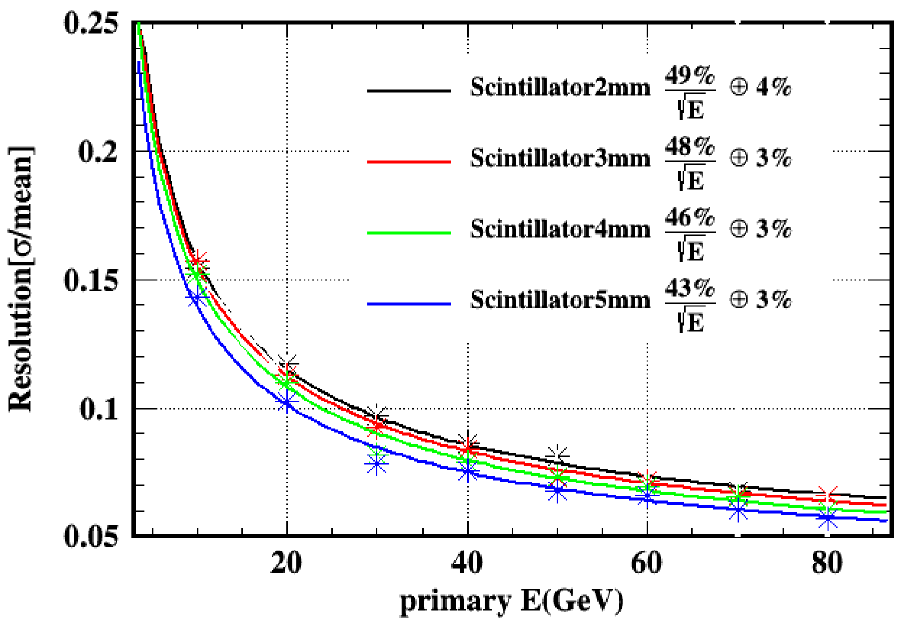
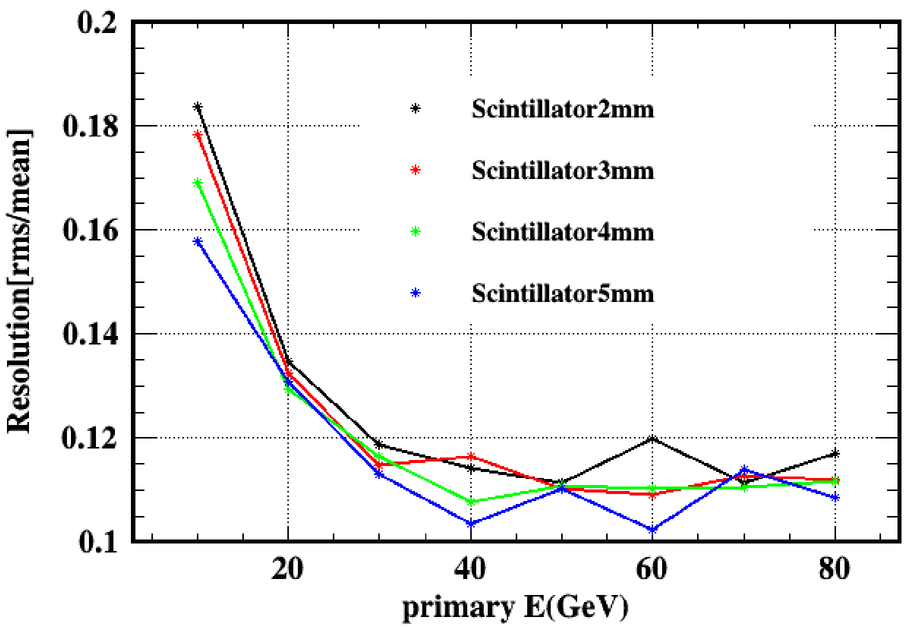
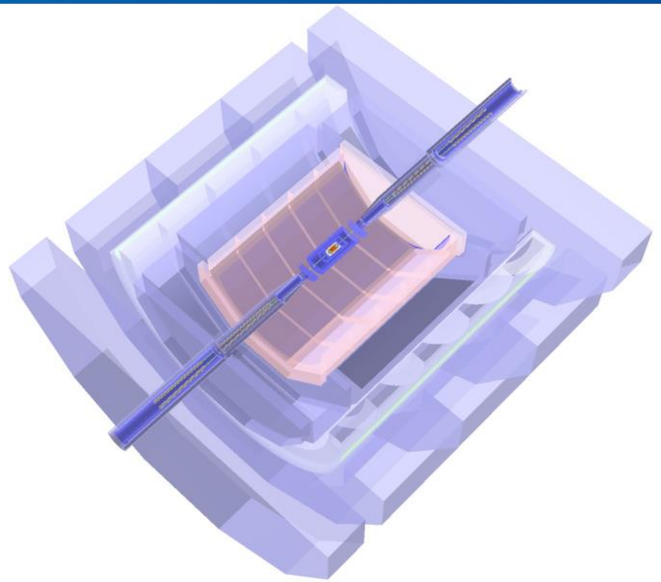
- Scintillator thickness optimization
  - Thicker scintillator has better resolution but the improvement isn't obvious
  - Thicker scintillator will increase total thickness and manufacture cost
  - 3mm scintillator is chosen for the prototype

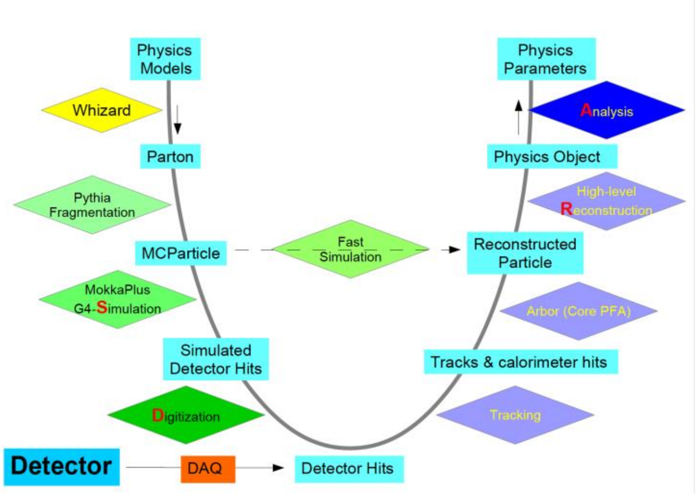




Resolution for different scintillator thickness

- 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: $e^{+}e^{-} - q\bar{q}(q = uds)\ via\ Z$





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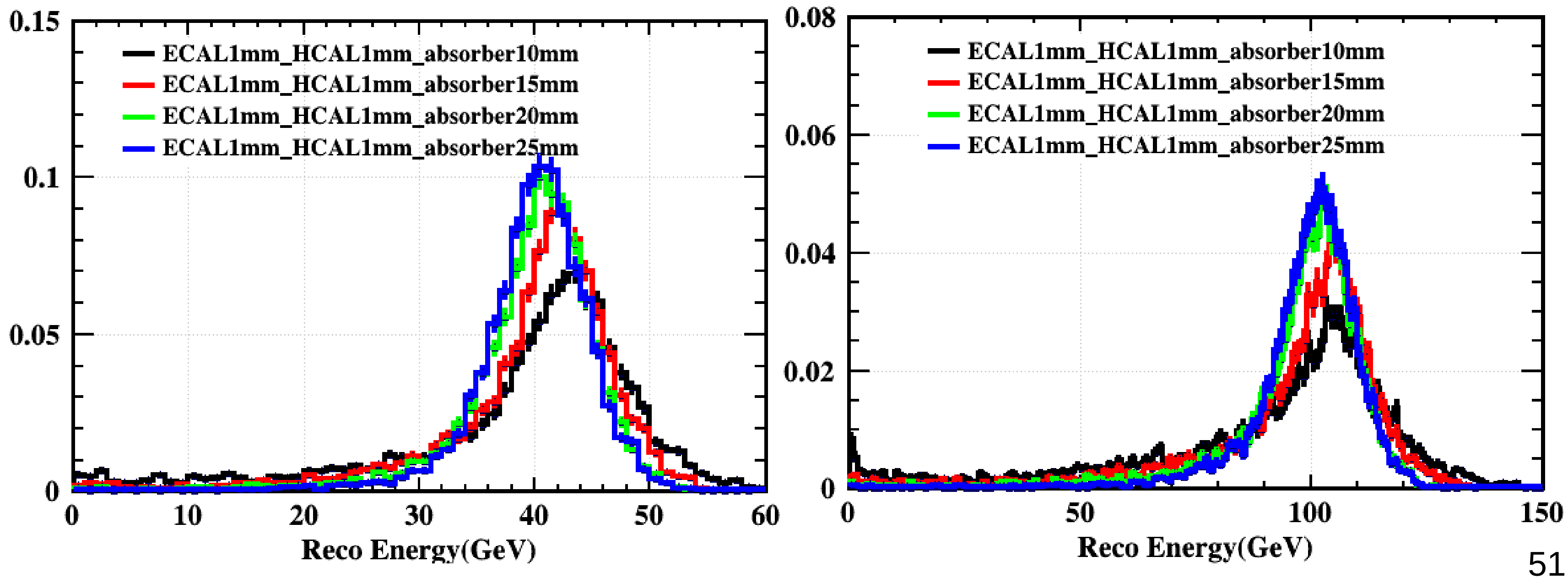
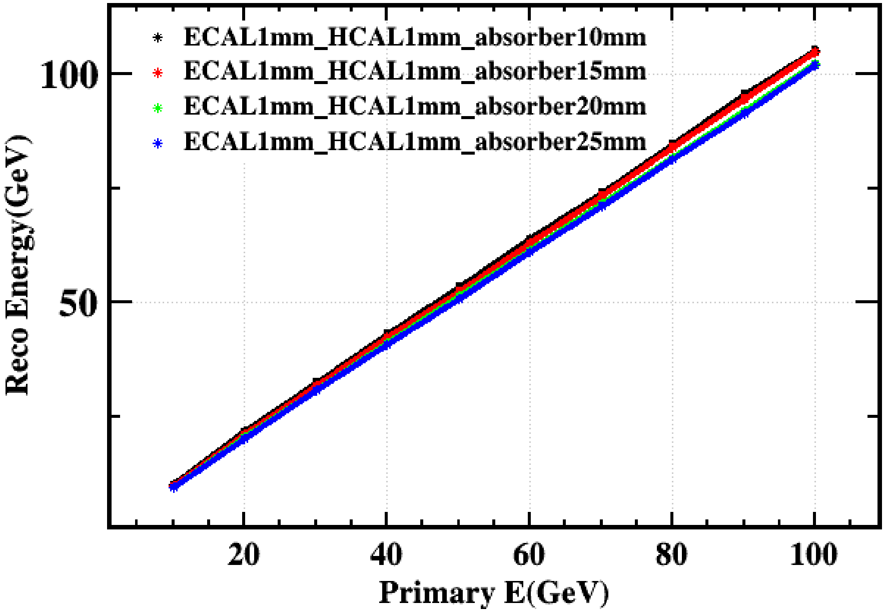
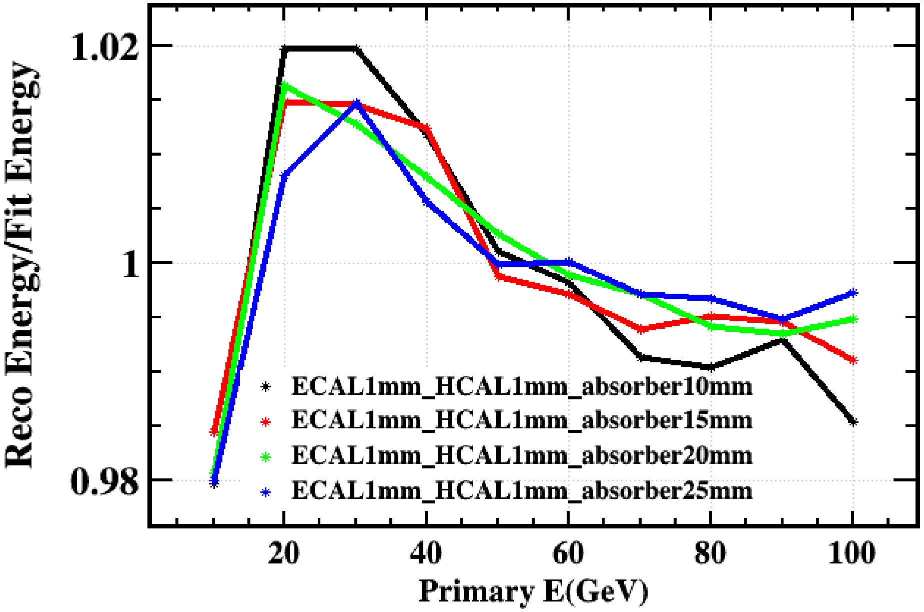
- Absorber thickness optimization
  - Klong with energy from 10 to 100GeV
  - Absorber thickness ranges from 10mm to 25mm
  - KL energy is reconstructed from ECAL and HCAL energy



KL reconstructed energy at different absorber thickness

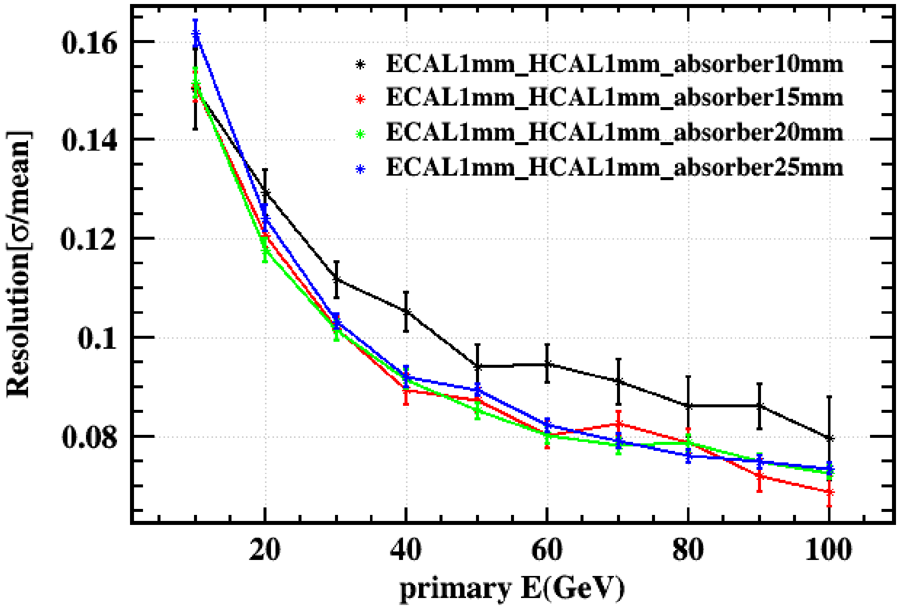
- Absorber thickness optimization
  - Use crystal ball function as fitting function
  - The linearities are all within ±3% for different absorber thickness

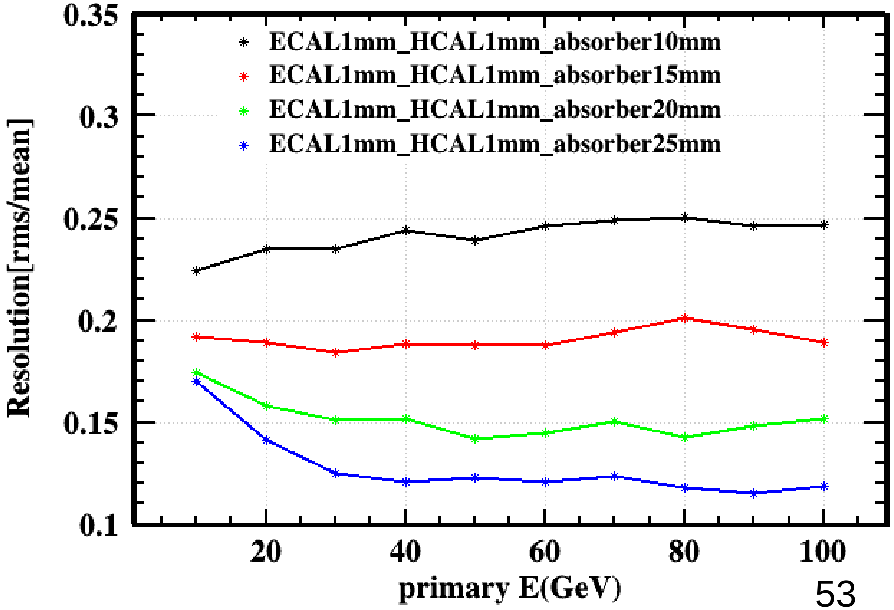




KL Linearity at different absorber thickness

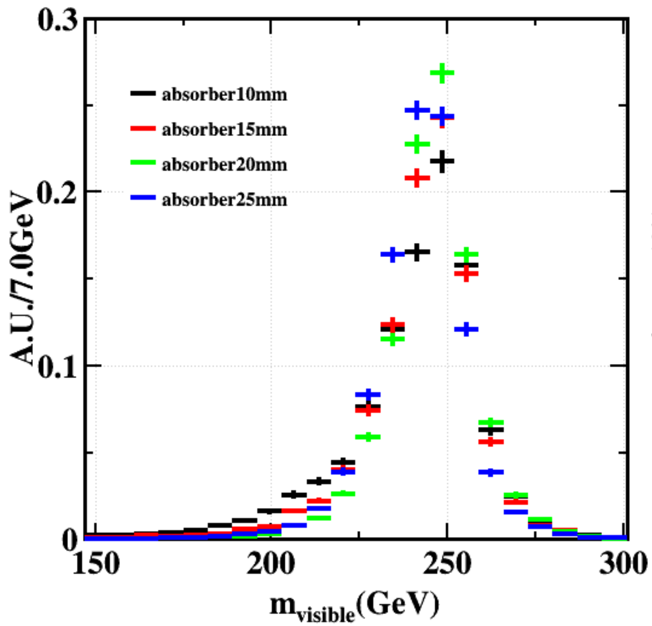
- Absorber thickness optimization
  - ECAL introduce more material comparing to Simplified geometry
  - The 10mm absorber has a worse resolution than others
  - The rms/mean reflects the leakage for different absorber

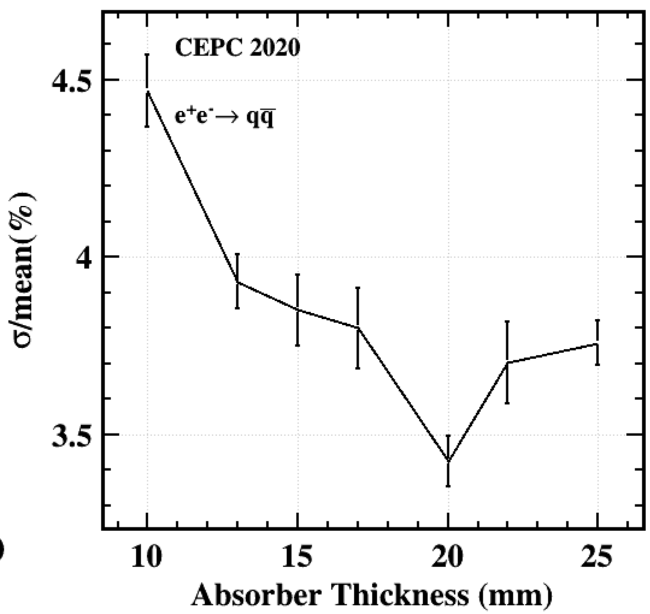




KL resolution at different absorber thickness

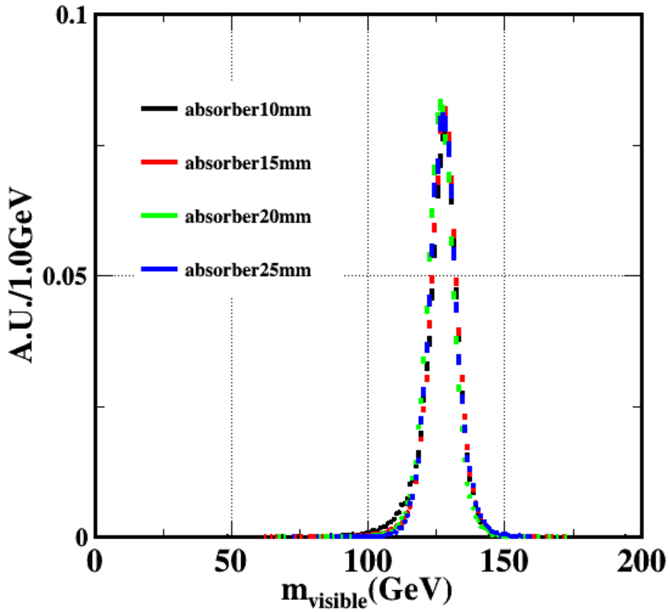
- Absorber thickness optimization
  - The $m_{visible}$ is reconstructed for each Zuds event
  - The resolution of $m_{visible}$ as a function of absorber thickness shows that 20mm is a turning point

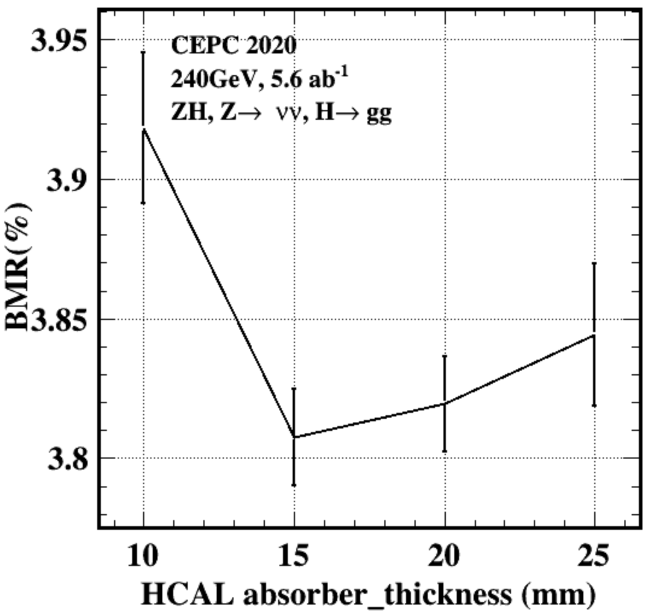




Zuds events for different absorber thickness

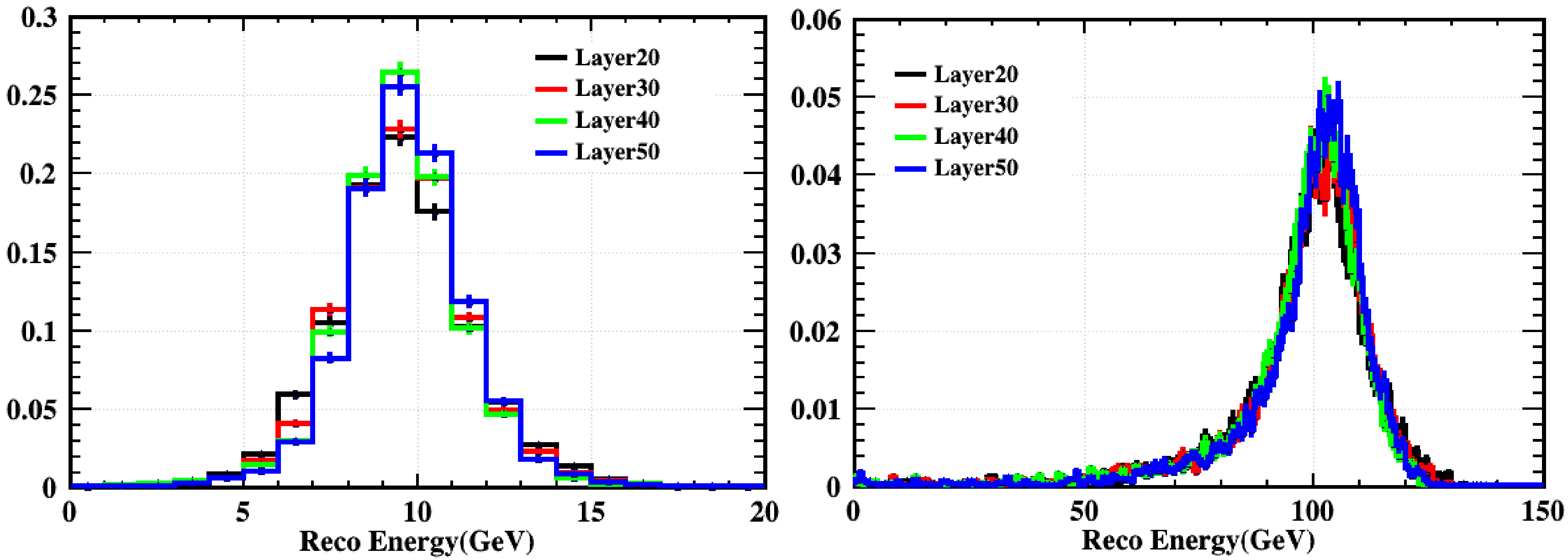
- Absorber thickness optimization
  - The jets in $\nu\nu H - gg$ events have lower energy comparing to the jets in Zuds events
  - The Higgs mass is reconstructed as $m_{visible}$ in $\nu\nu H - gg$ events
  - The boson mass resolution(BMR) as a function of absorber thickness shows 15mm is the turning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





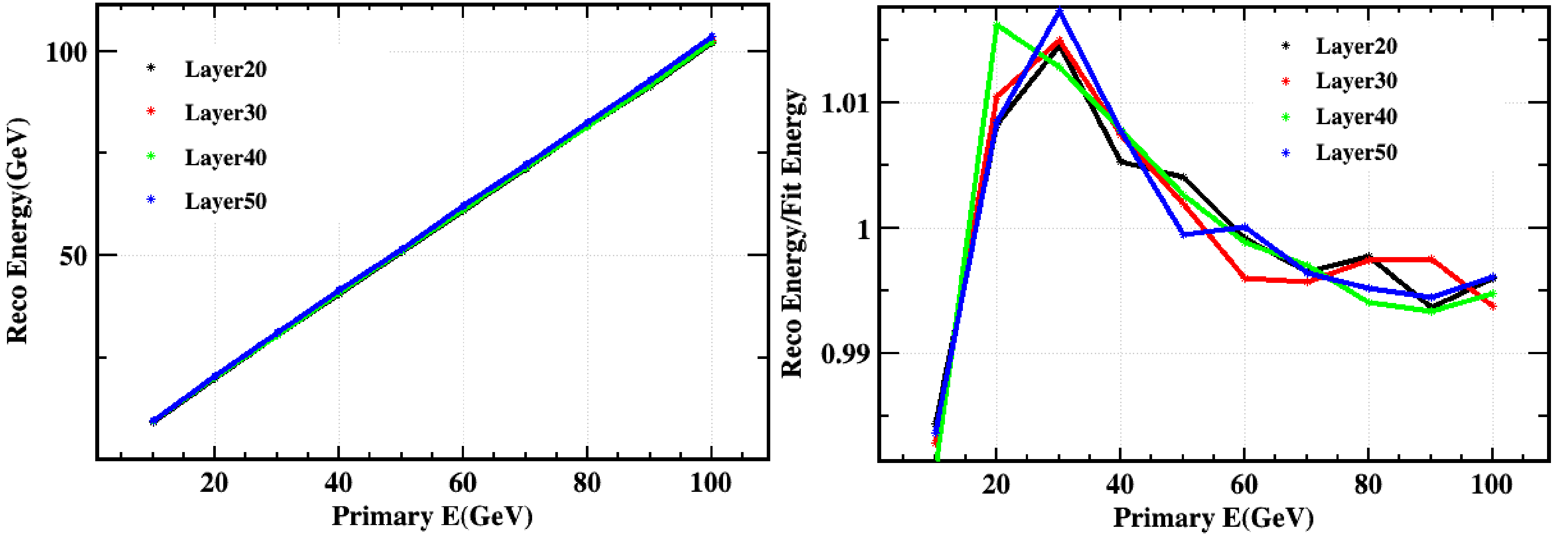
$\nu\nu H - gg$ events for different absorber thickness

- 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



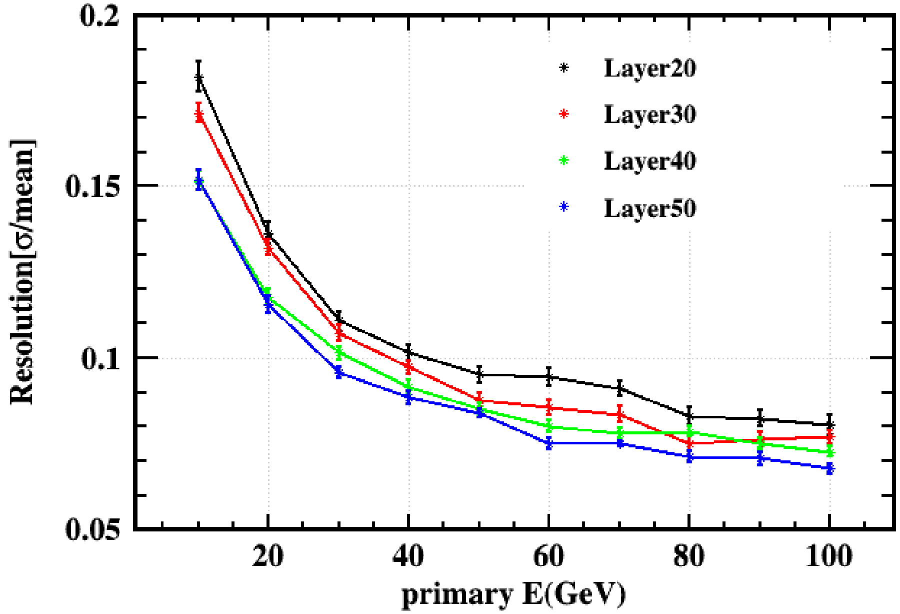
KL reconstructed energy at different sampling layers

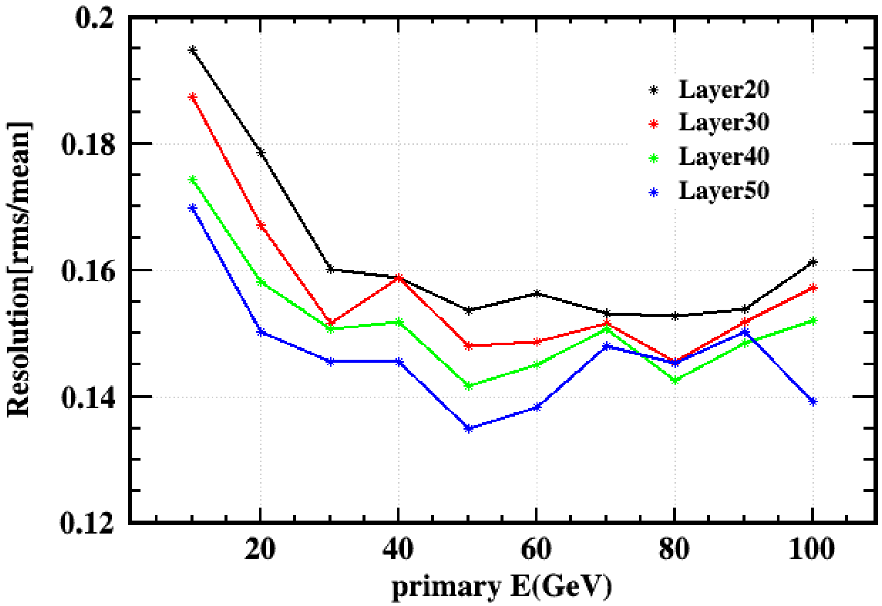
- Sampling layer optimization
  - The linearities are almost the same for different sampling layers
  - The linearities are all within ±2% for different sampling layers



KL Linearity at different sampling layers

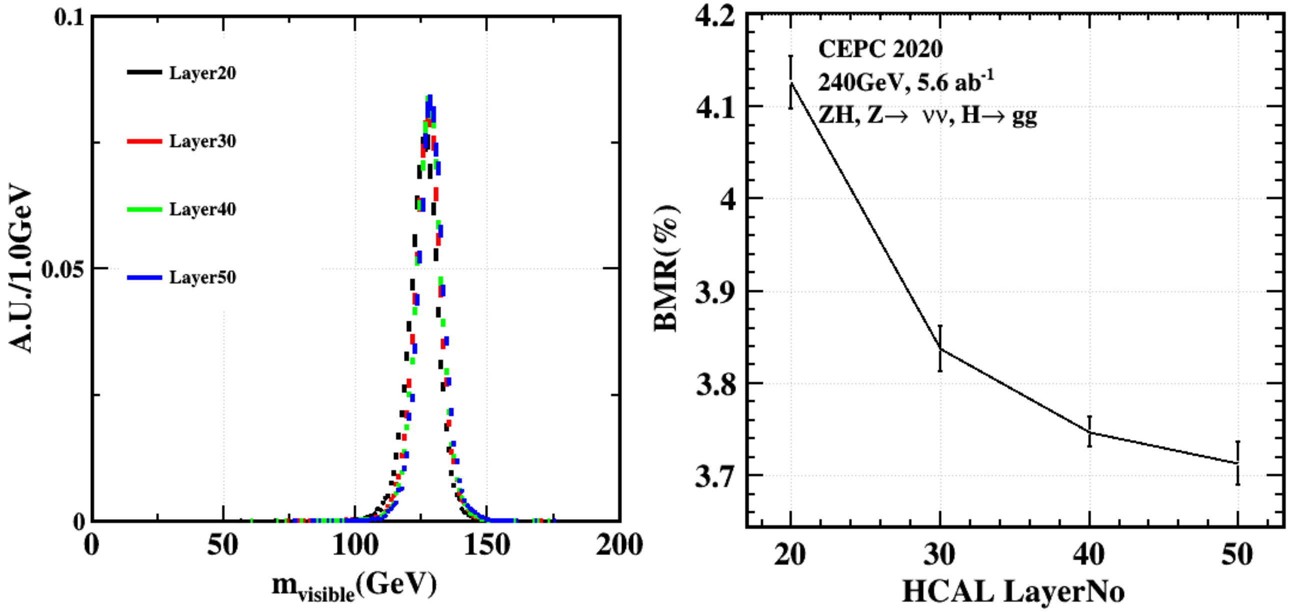
- Sampling layer optimization
  - More sampling layers have better energy resolution





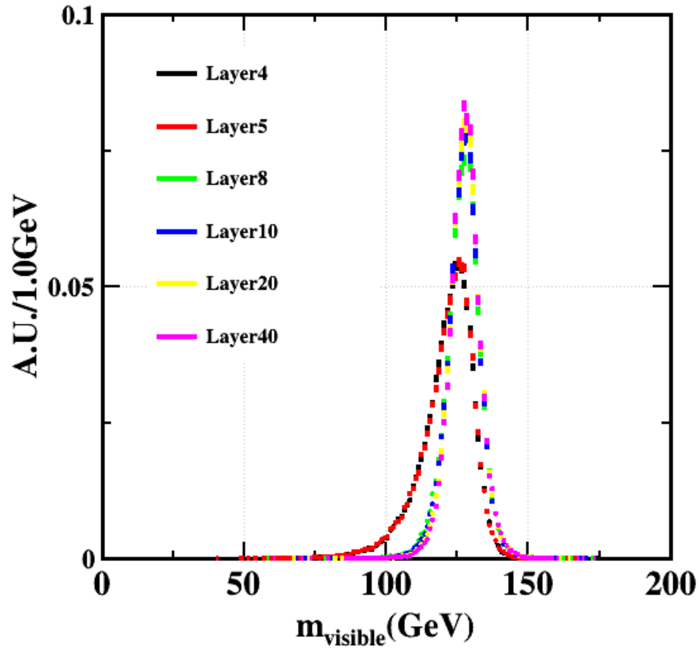
KL resolution at different sampling layers

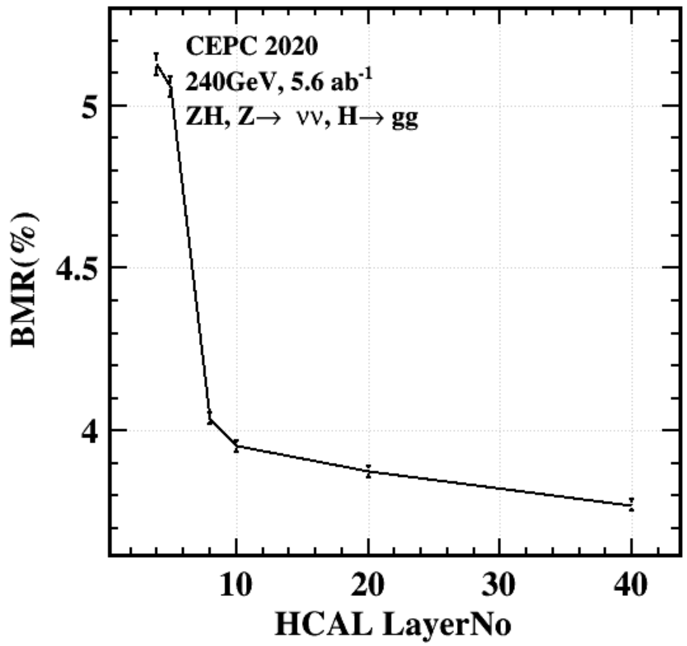
- Sampling layer optimization
  - $\nu\nu H - gg$ events are reconstructed for different sampling layers
  - 30 sampling layers can satisfy the 4% BMR requirement but prototype needs 40 sampling layers to fulfill the design target



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

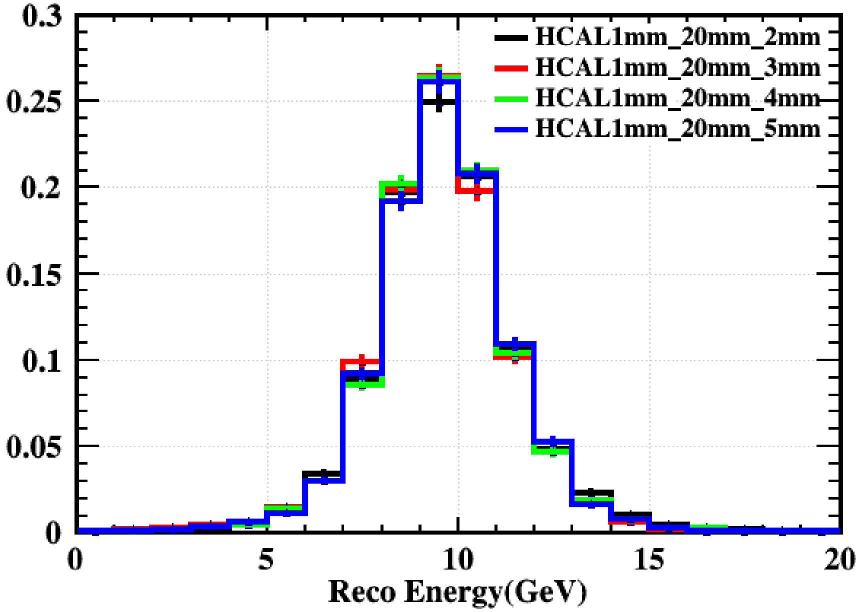
- Merge layer optimization
  - The number of sampling layers is fixed as 40
  - Combine the hits from adjacent layers to change the longitudinal segmentation without affecting the energy resolution

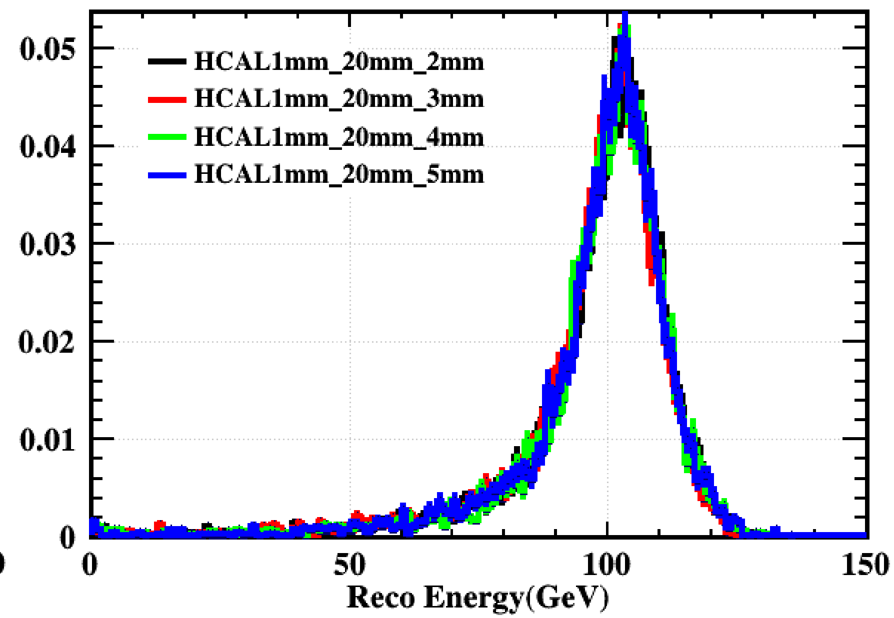




$\nu\nu H - gg$ events for different readout layers

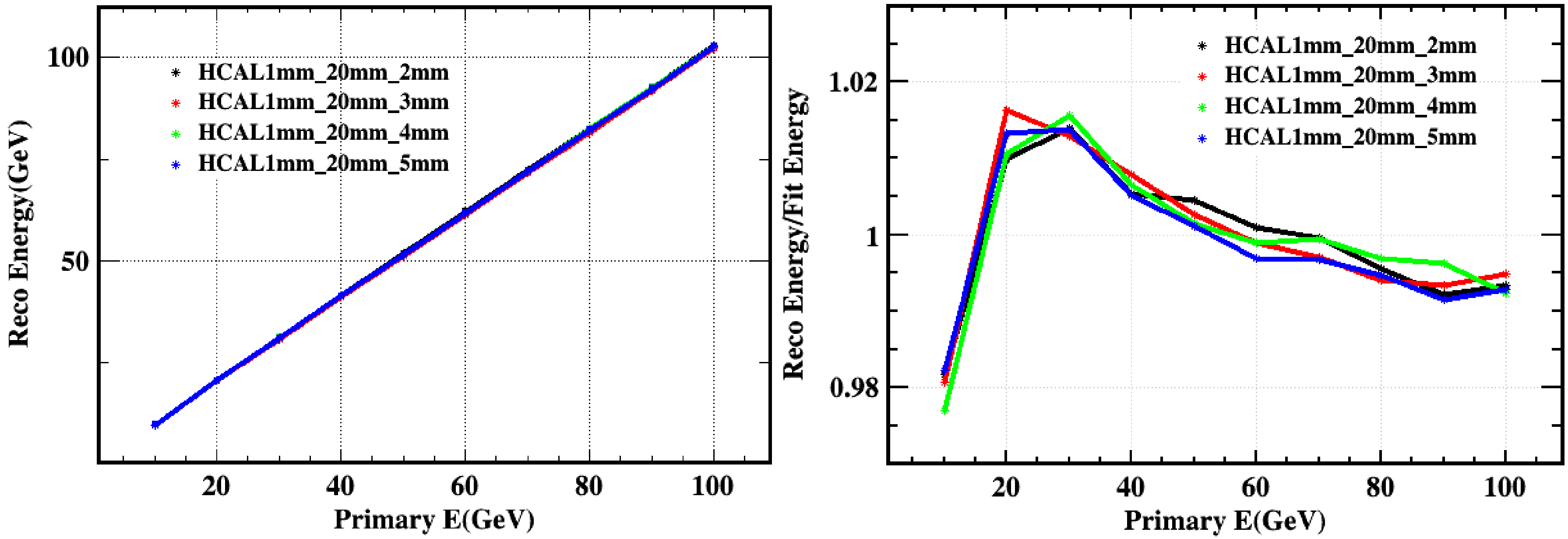
- Scintillator thickness optimization
  - 40 layers: each layer has 20mm Steel and 2mm PCB
  - Scintillator thickness for each layer ranges from 2 to 5mm





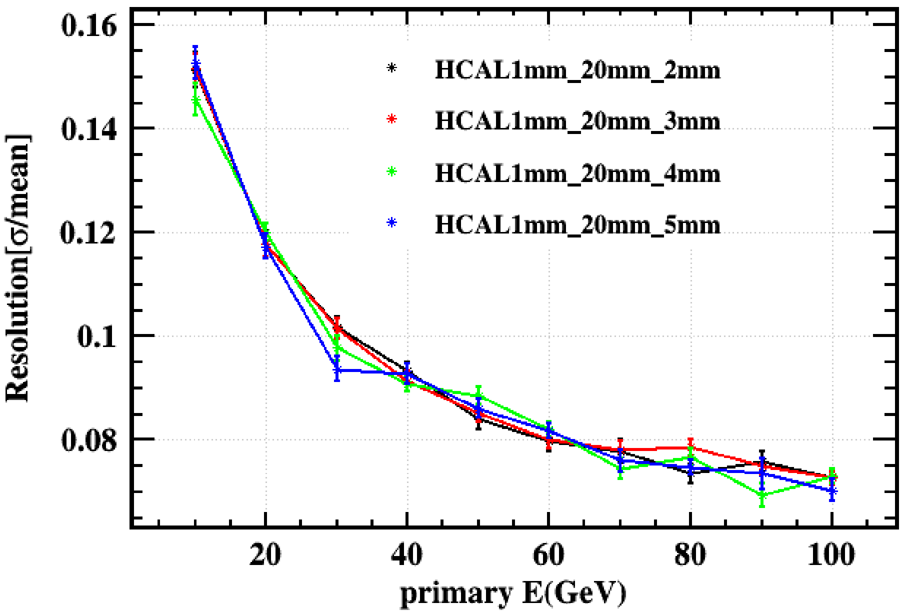
KL reconstructed energy at different scintillator thickness

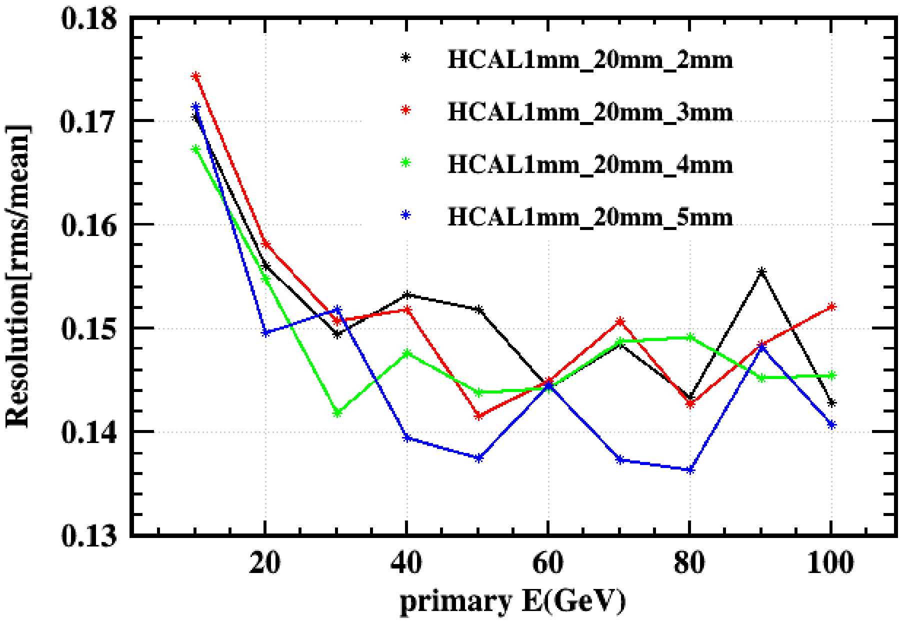
- Scintillator thickness optimization
  - The linearities are almost the same for different scintillator thickness
  - The linearities are all within ±3% for different scintillator thickness



KL Linearity at different scintillator thickness

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

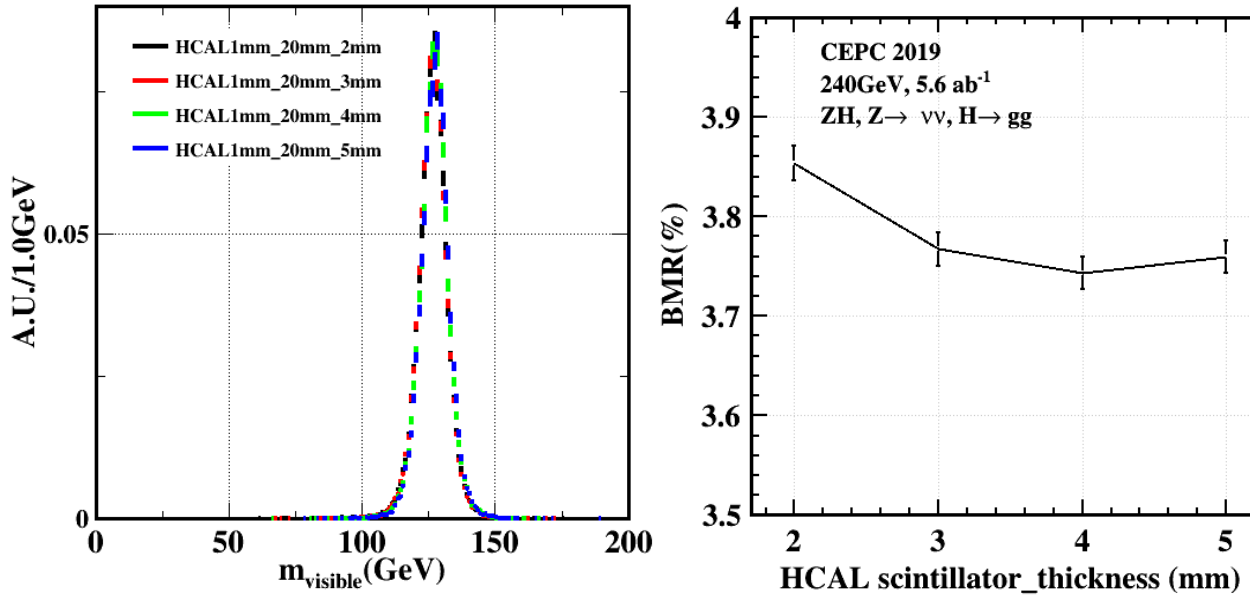




KL resolution at different scintillator thickness

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

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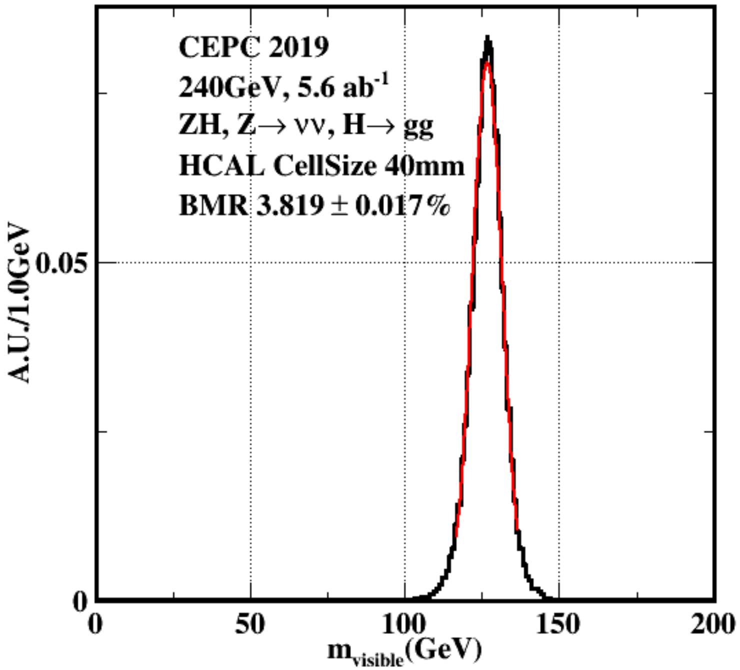
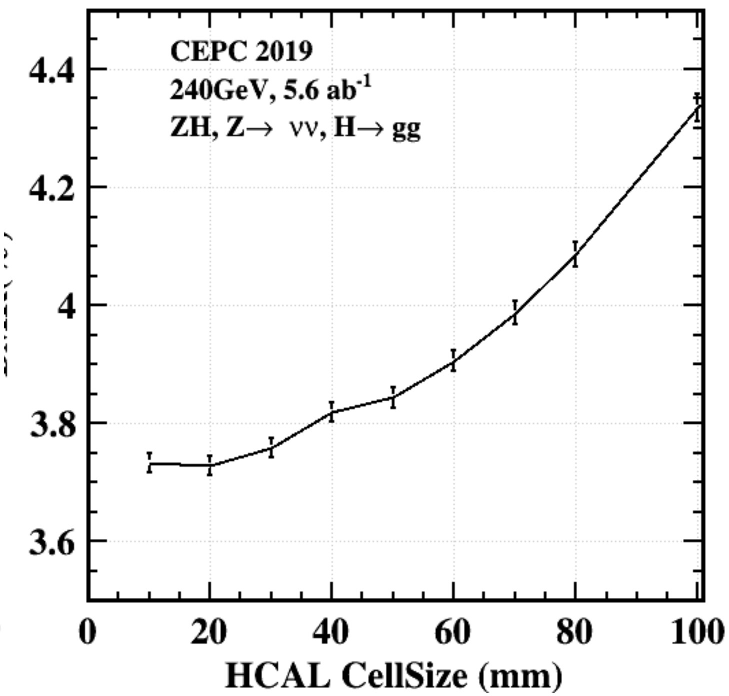
- Cell size optimization
  - The boson mass resolution(BMR) is reconstructed by arbor under CEPC V4 environment
  - 40mm cell size can satisfy the BMR requirement while reducing about half of the readout channels comparing to 30mm



cell size 40mm: BMR

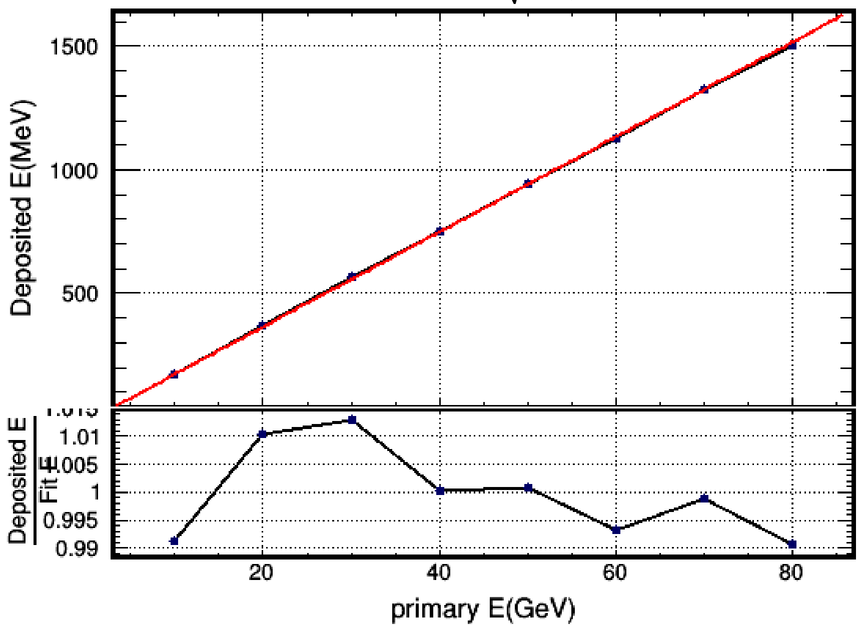


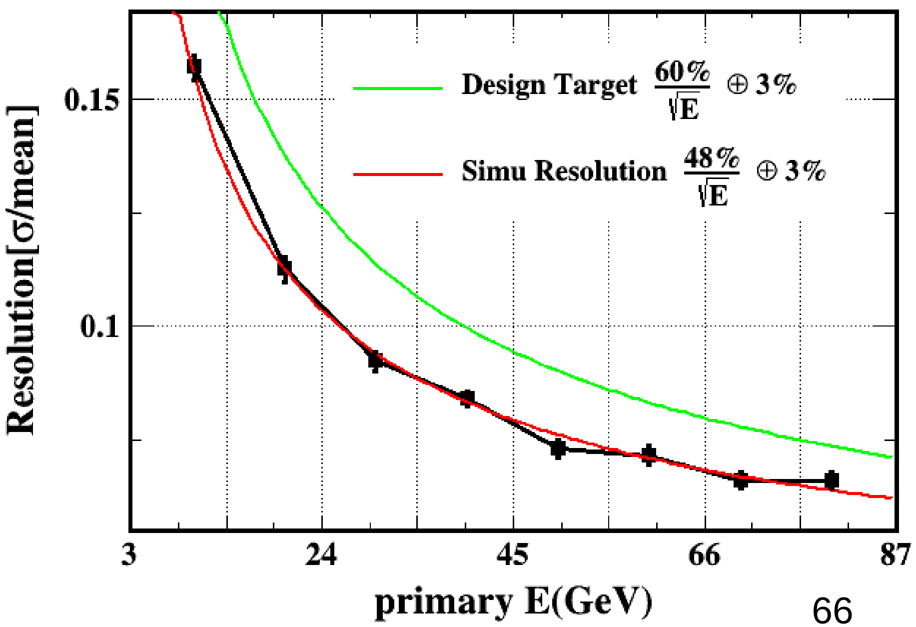
CEPC ACHAL cell size vs BMR

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
- Cell size:40mm
- Linearity:$< \pm 3\%$
- Resolution:$< \frac{60\%}{\sqrt{E(GeV)}} \oplus 3\,\%$





Linearity and resolution for HCAL prototype