Simulation study on dual-readout calorimeter for future e^+e^- colliders

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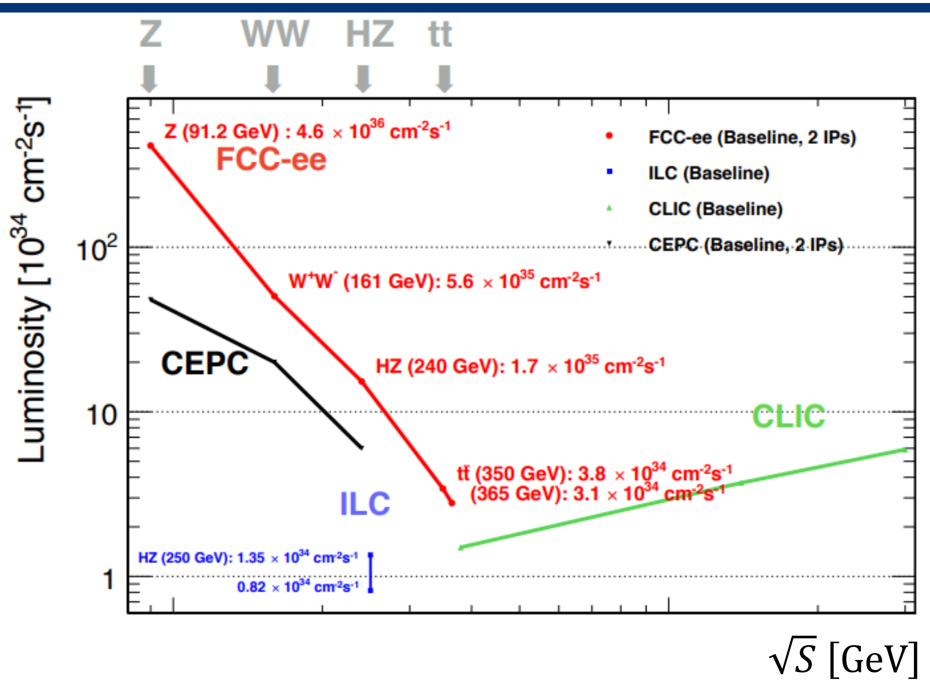
① Introduction

Future e^+e^- Collider

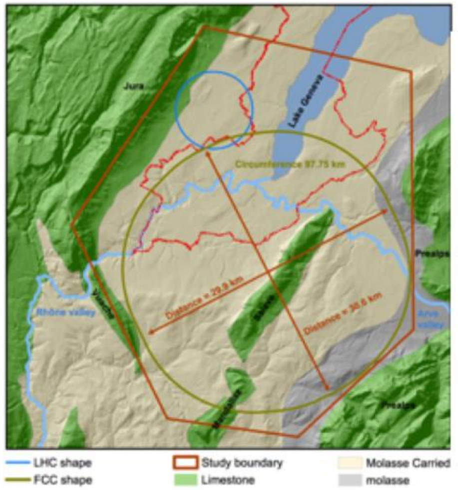
Motivation of future collider

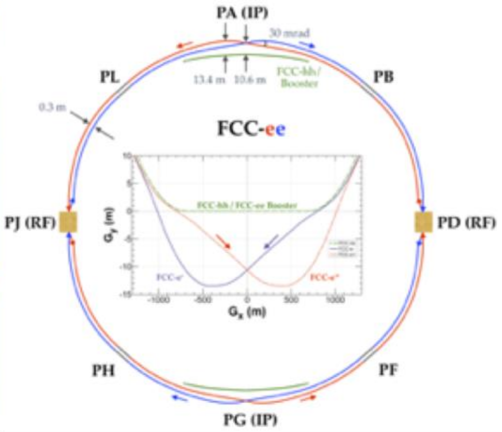
- Currently, detector experiment achieved high precision measurements.
- With this precision, observing higgs physics and BSM which is on priority.
  - Higgs factory (HZ) : 10^6
  - EW & Top factory : 5×10^{12} (Z), 10^8 (WW), 10^6 (tt)
  - Flavour factory : 5×10^{12} (Z->bb, cc, tautau)
  - QED, QCD, BSM, etc

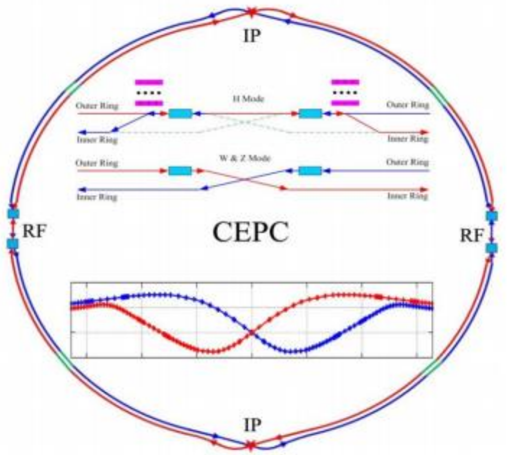


Programs in two phases

- Phase 1: FCC-ee (Z, W, H, tt) as Higgs, EW and top factory ↔ CEPC
- Phase 2: FCC-hh (~100 TeV) as natural continuation at energy frontier (ion and eh options) ↔ SPPC

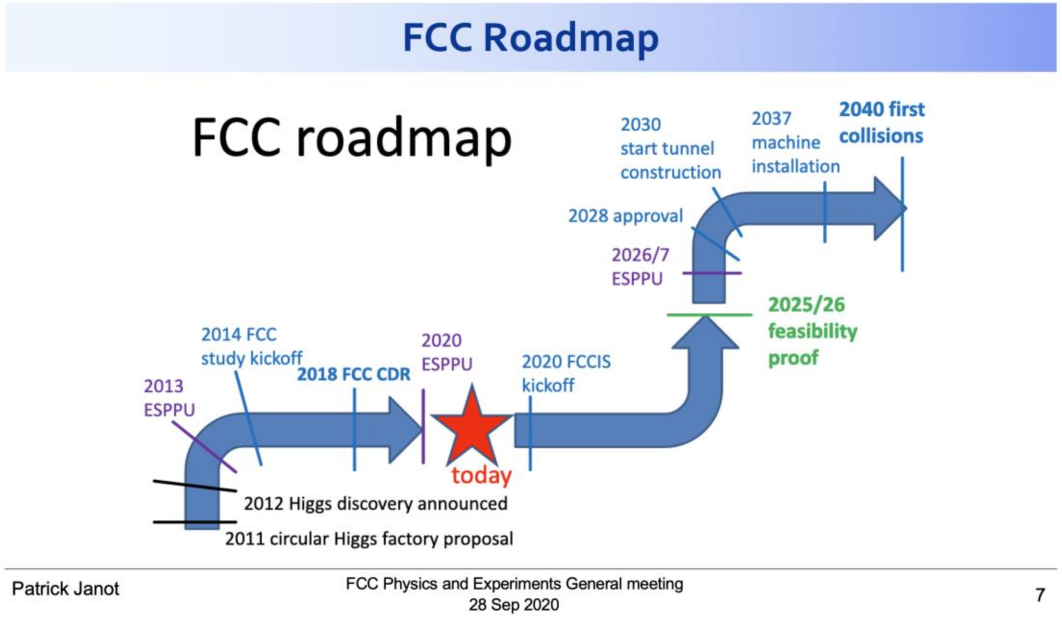


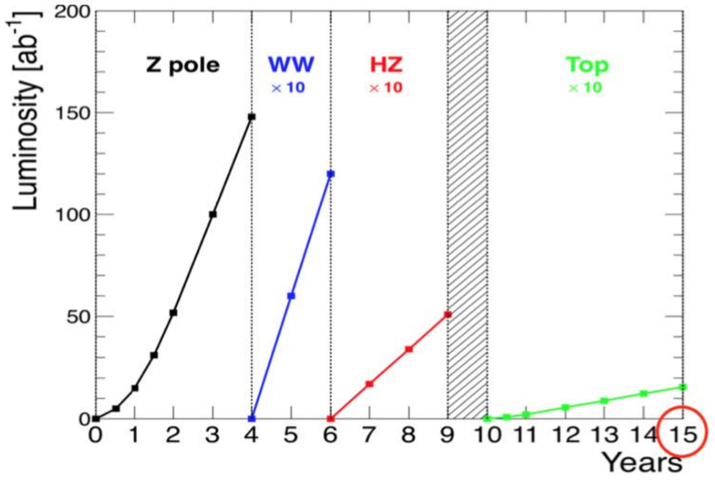




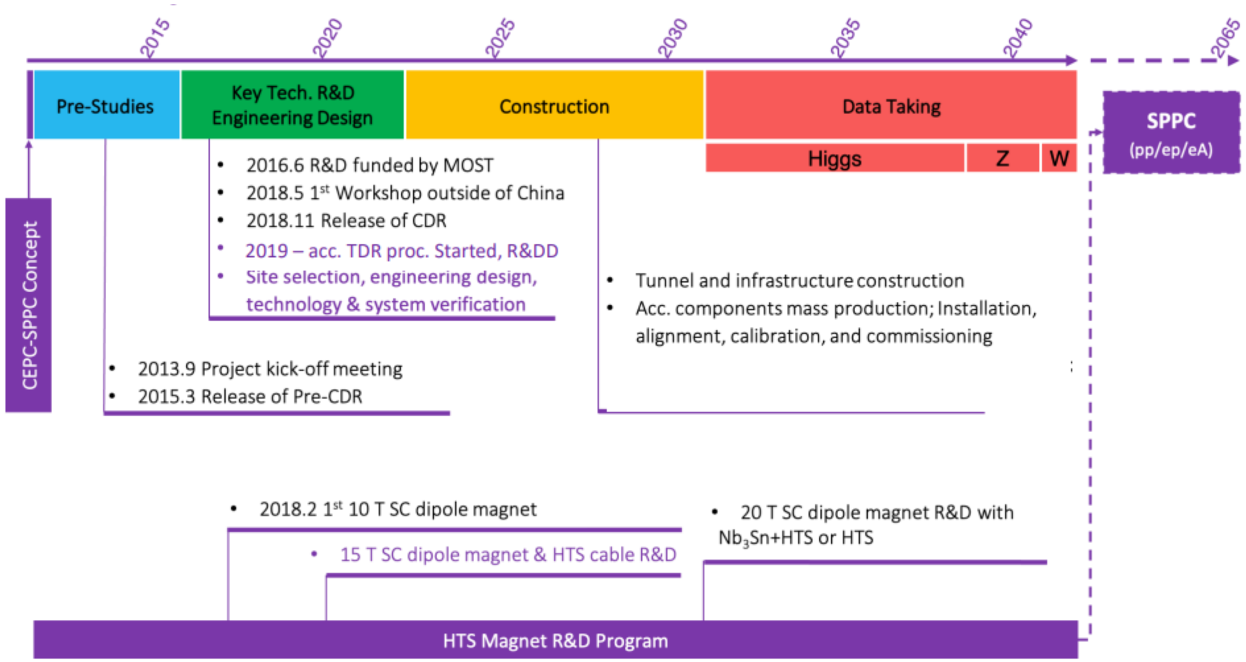
Future e⁺e⁻ Collider

FCC-ee





CEPC



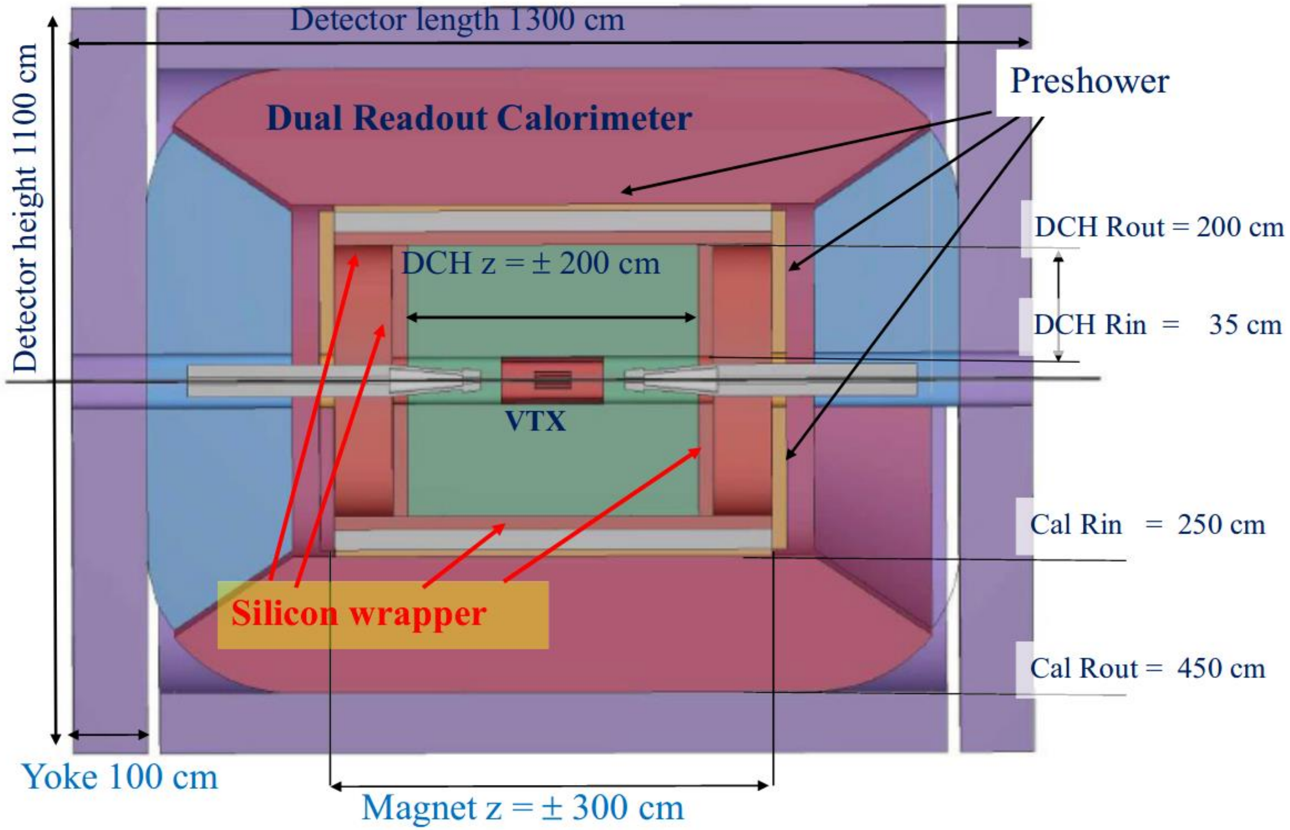
The international workshop on the high energy Circular Electron Positron Collider
26-28 Oct 2020 XinChou Lou

Operation mode	$\sqrt{s}$ (GeV)	L per IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^6
Z	91.2	32 (*)	2	16	7×10^{11}
W^+W^-	158–172	10	1	2.6	2×10^7 (†)

IDEA Detector

Conceptual design of IDEA detector

- IDEA detector has been proposed in conceptual design report(CDR) of both FCC-ee & CEPC.
- Dual-Readout calorimeter is included in the IDEA detector concept which can detect both EM & hadronic particles.

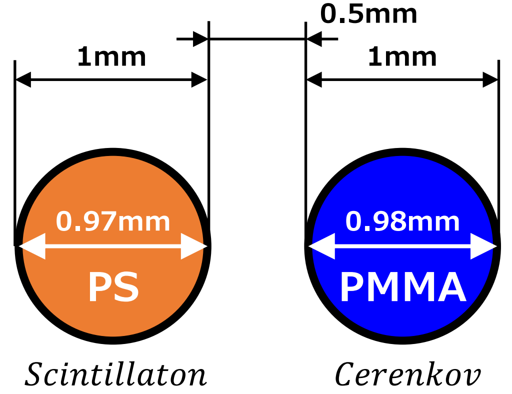


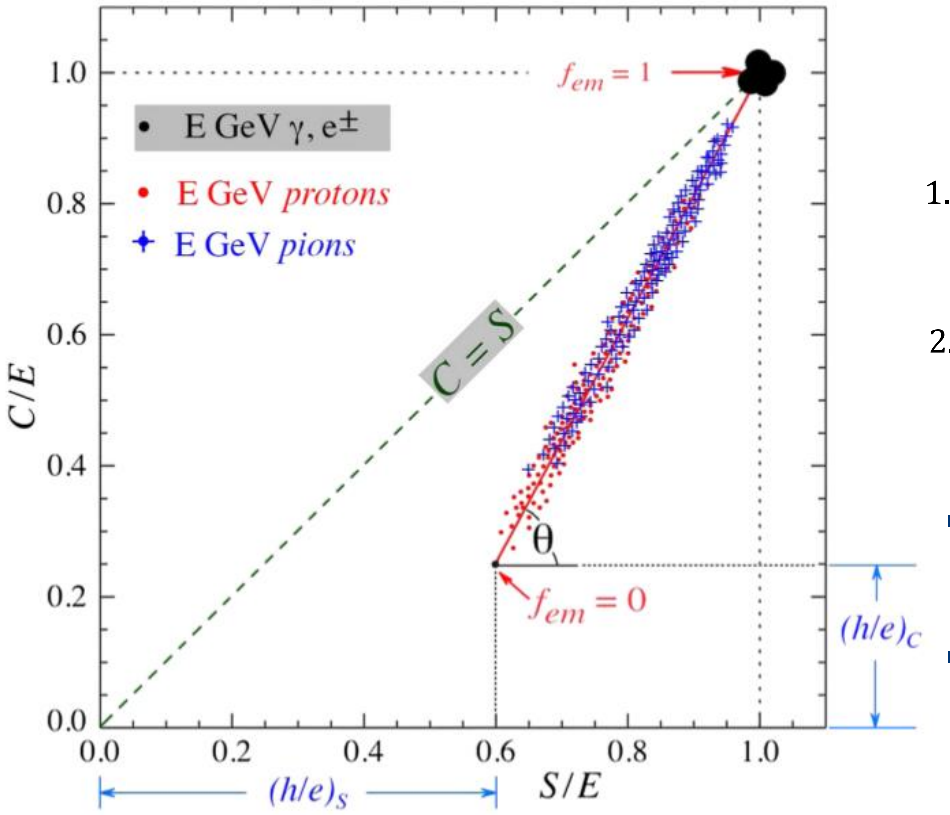
IDEA detector (FCC-ee & CEPC)
Silicon pixel vertex detector
Drift chamber tracker
Passive material radiator with MPGD layer
2 T solenoid
Dual-readout calorimeter **(Korea Dual-Readout team contributed)**
Muon chambers embedded in the magnet yoke

What Is The Dual-Readout Calorimeter

- Non-gaussian EM fluctuations are a major factor that makes it difficult to measure energy of hadron shower.
- f_{EM} can be measured by implemented two different type of fibers with different h/e responses in a calorimeter.

Implemented Optical Fibers





1. $C = E\left[f_{EM} + \frac{1}{(e/h)_C}(1 - f_{EM})\right]$

2. $S = E\left[f_{EM} + \frac{1}{(e/h)_S}(1 - f_{EM})\right]$

3. $f_{EM} = \frac{(h/e)_C - (C/S)(h/e)_S}{(C/S)[1 - (h/e)_S] - [1 - (h/e)_C]}$

4. $\chi \equiv \cot\theta = \frac{1 - (h/e)_S}{1 - (h/e)_C}$

5. $E = \frac{S - \chi C}{1 - \chi}$

- Dual-readout calorimeter offers high-quality energy measurement for both EM particles and hadronic particles.
- Outstanding energy resolution can be achieved by measuring EM component and correcting hadron energy event by event.

GEANT4 Simulation Set-up

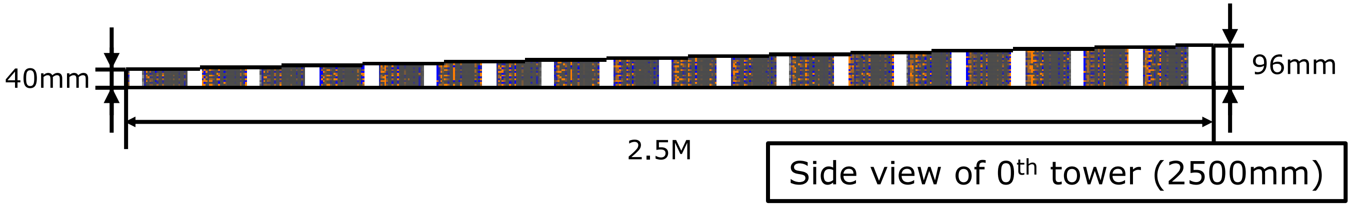
Geometry Setup

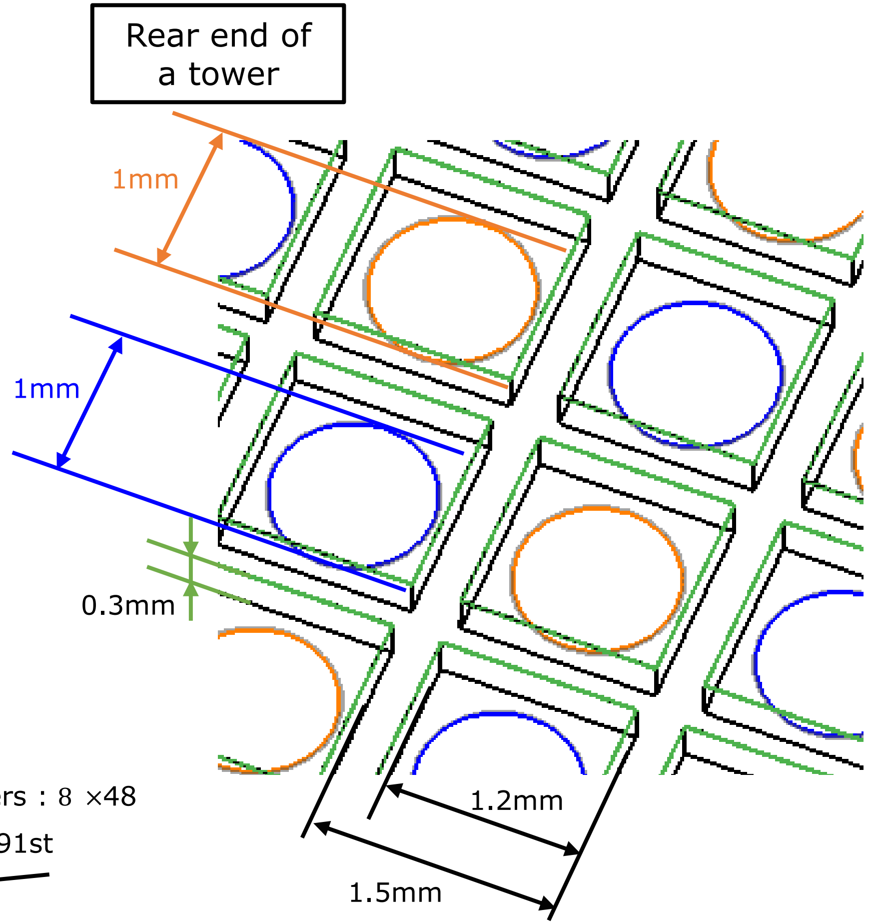
- Cover up to $|\cos\theta| < 0.996(|\eta| < 3.0)$
- All Cu tower with a depth of 2500mm($\sim 10\lambda_{int}$).
- $O(1000)$ Fibers implemented per a tower.

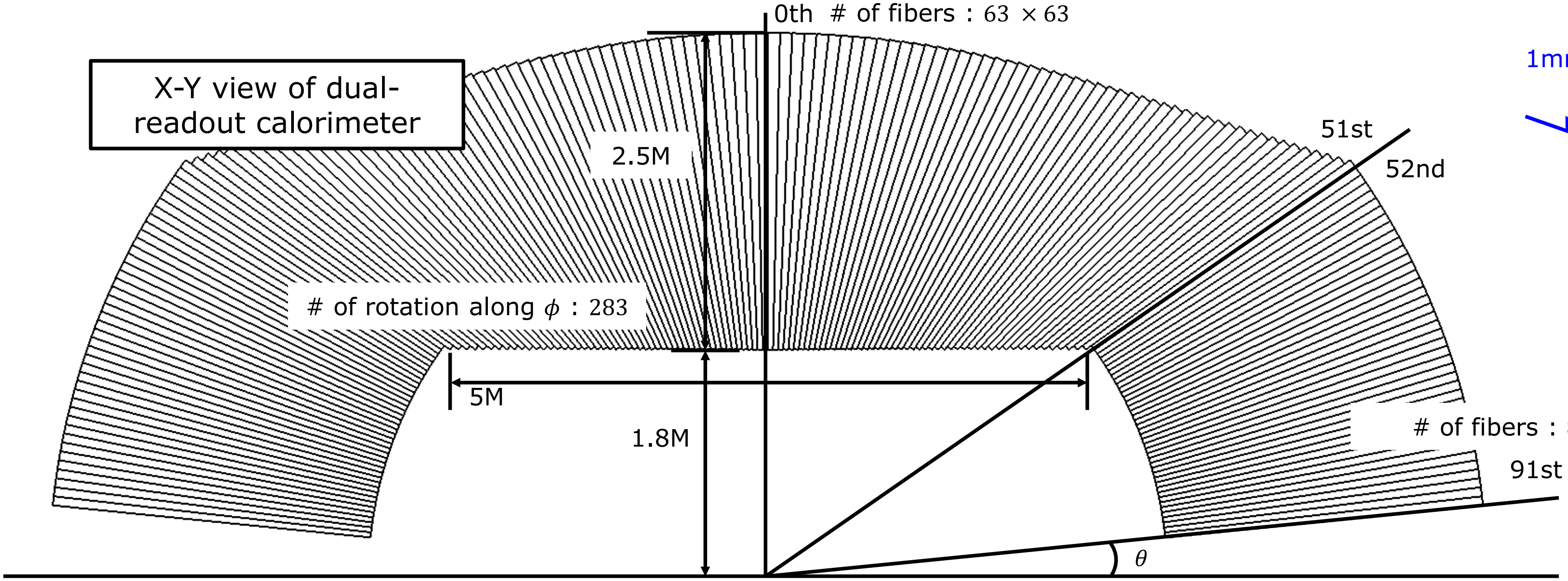
  Scintillation(S) fiber : Polystyrene(PS) (Kuraray SCSF-78)

  Cerenkov(C) fiber : PMMA (Eska SK40)
- High granularity SiPM array (Hamamatsu S13615-1025N)

  →This high-granularity design allows good position resolution.

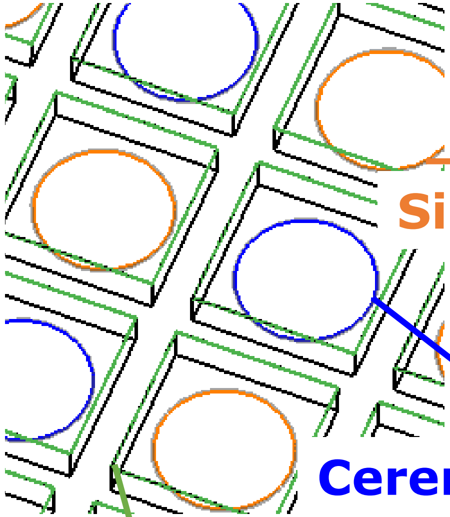






GEANT4 Simulation Set-up

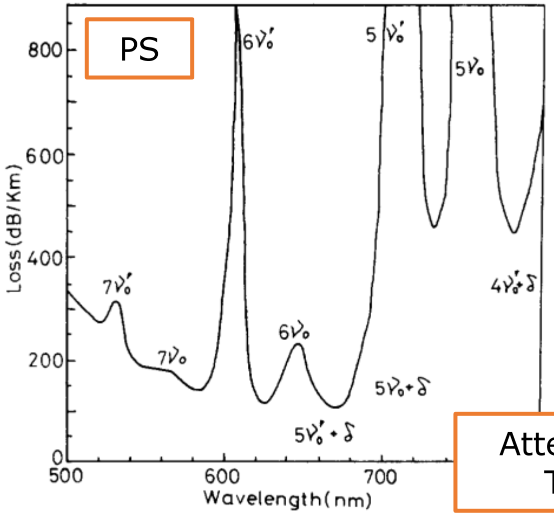
Optical physics set-up

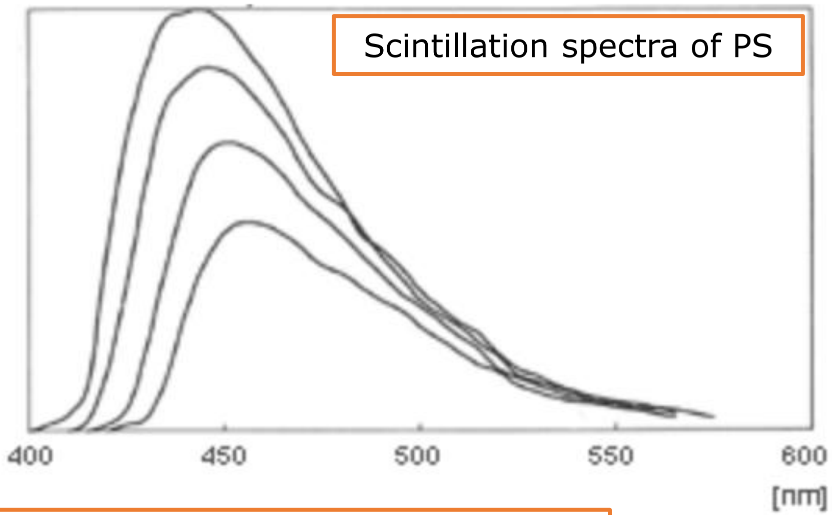


Sintillation

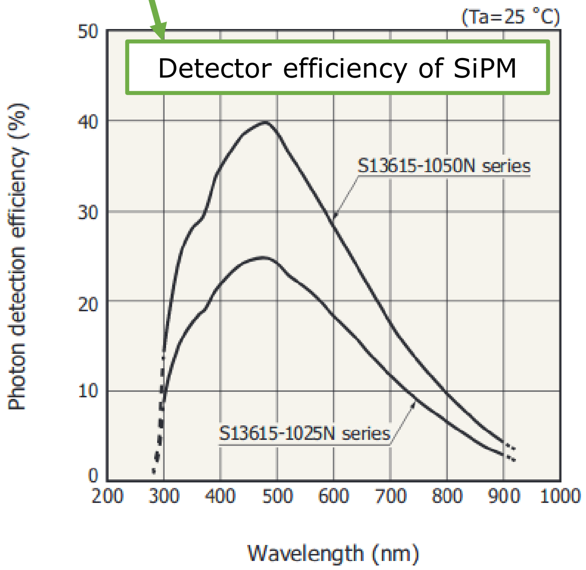
Cerenkov

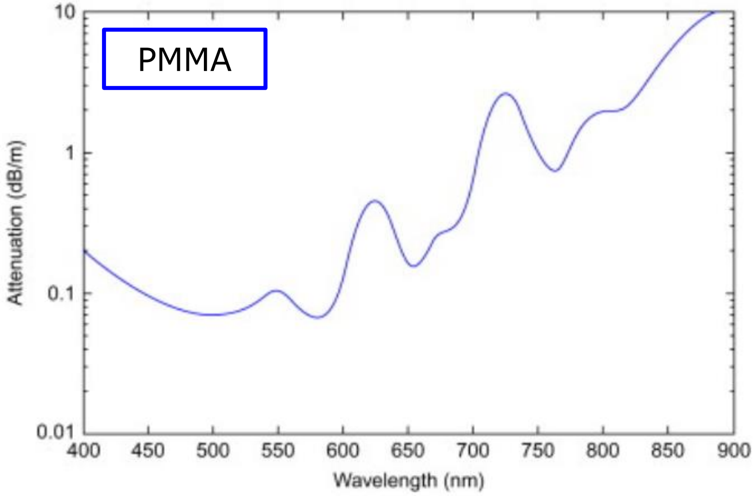
Attenuation loss



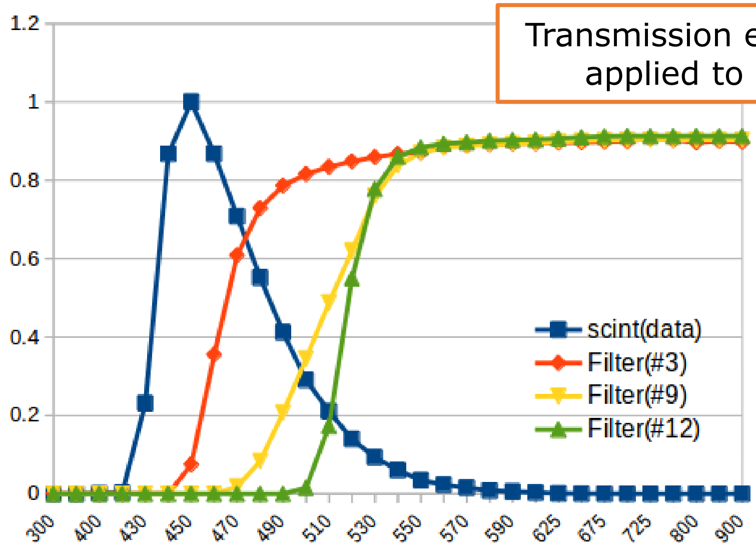


Attenuation loss of PS diverges at 400nm.
Thus, filter is applied to moderate it.





Transmission efficiency of the filter
applied to Scintillation fiber



② Calibration

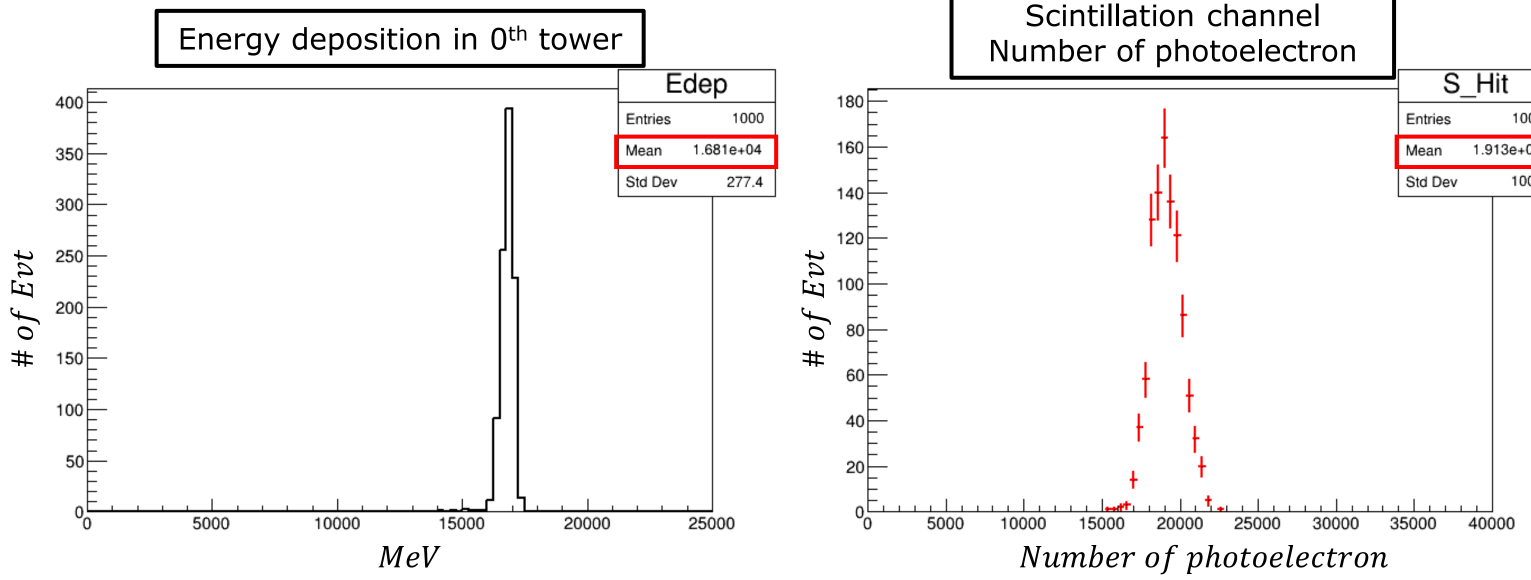
Calibration

- 20 GeV electron beams are used for calibration to each tower from 0th to 91st.

① Calculating equalization constants

- From MC truth energy deposition and # of hit, get equalization constants in dimension of energy per p.e.

0th tower case



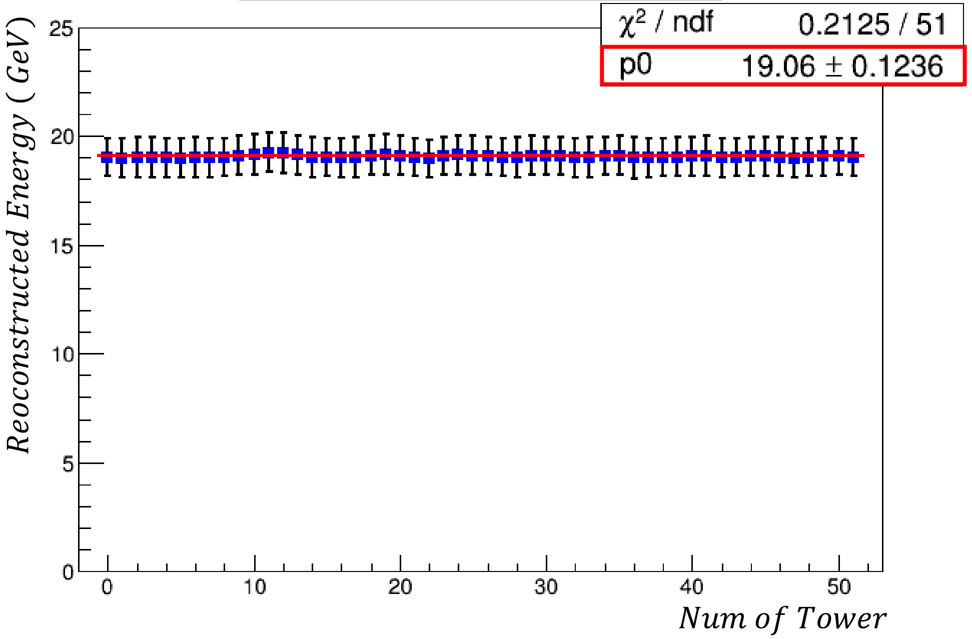
$$equalization\ constant = \begin{cases} scintillation\ channel : 16810/19130 = 0.878\ MeV/p.e. \\ cerenkov\ channel : 16810/1298 = 12.951\ MeV/p.e. \end{cases}$$

Calibration

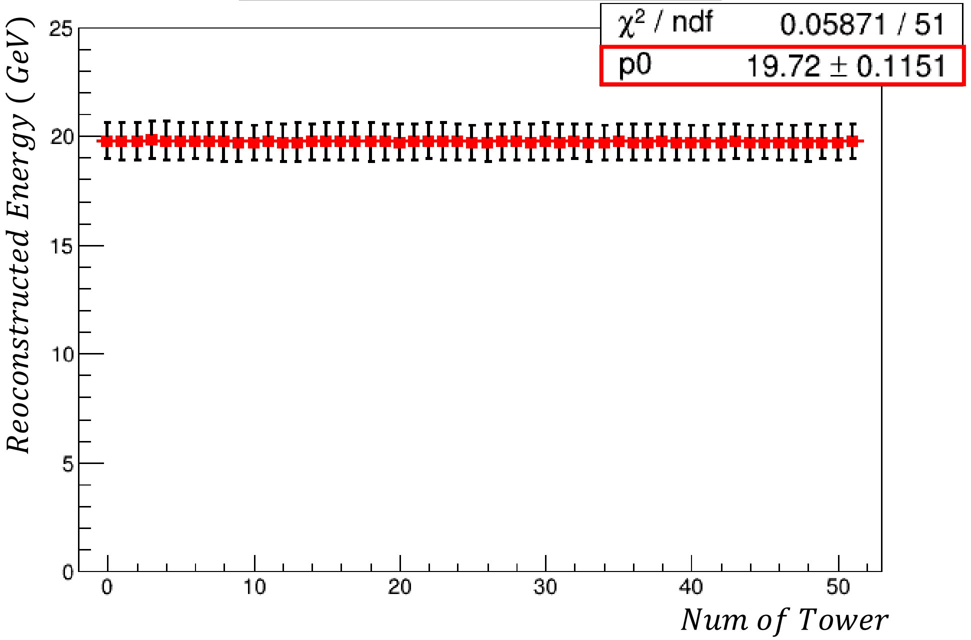
② Reconstructing energy of each event based on equalization constant.

- Reconstructed energy does not match to 20GeV. Scale factor can moderate this inconsistency.

Cerenkov channel
Reconstructed Energy



Scintillation channel
Reconstructed Energy



③ Measuring scale factor.

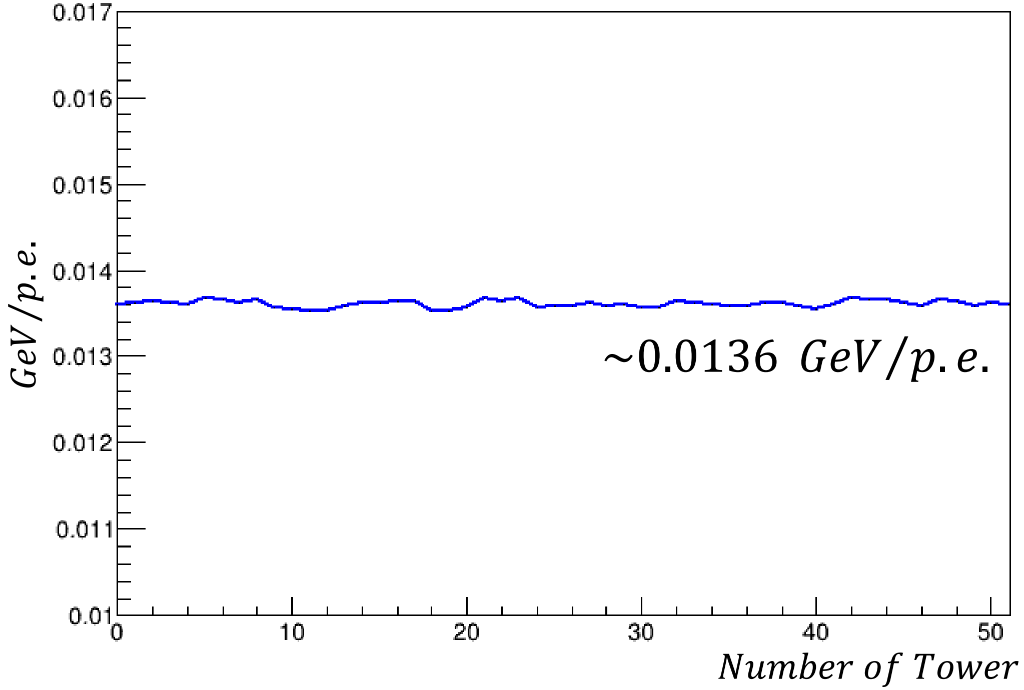
$$Scale\ factor = \begin{cases} Scint: 19.72/20 = 0.986 \\ Ceren: 19.06/20 = 0.953 \end{cases}$$

Calibration

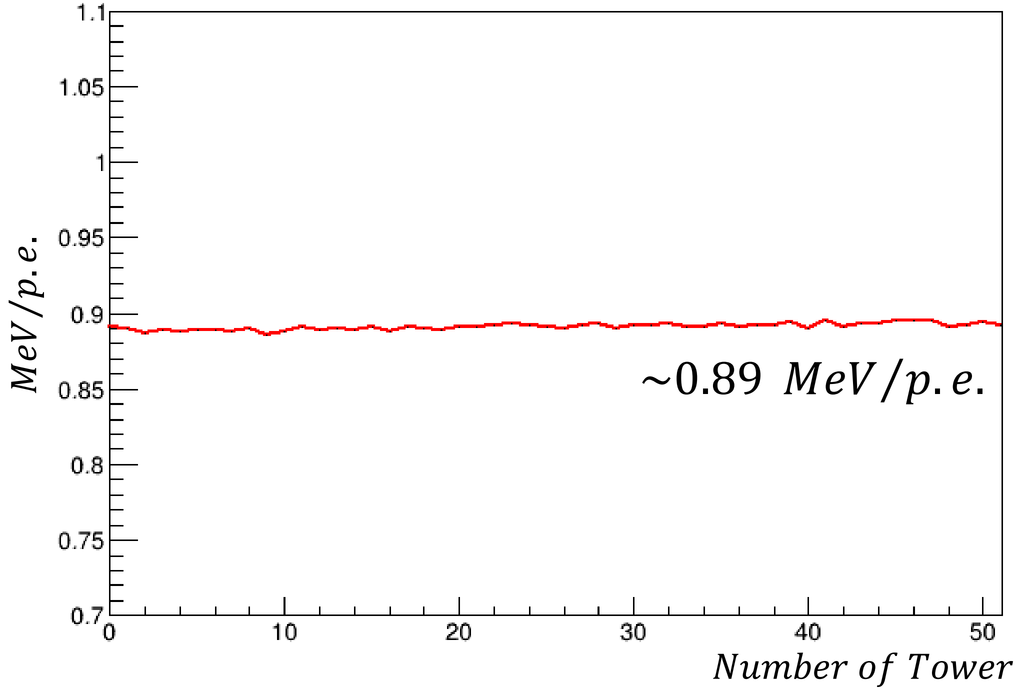
④ Calibration constant can be measured from equalization constants and scale factors.

$$Calibration\ constant = eq.constant/Scale\ Factor$$

Cerenkov Calibration Constant



Scintillation Calibration Constant



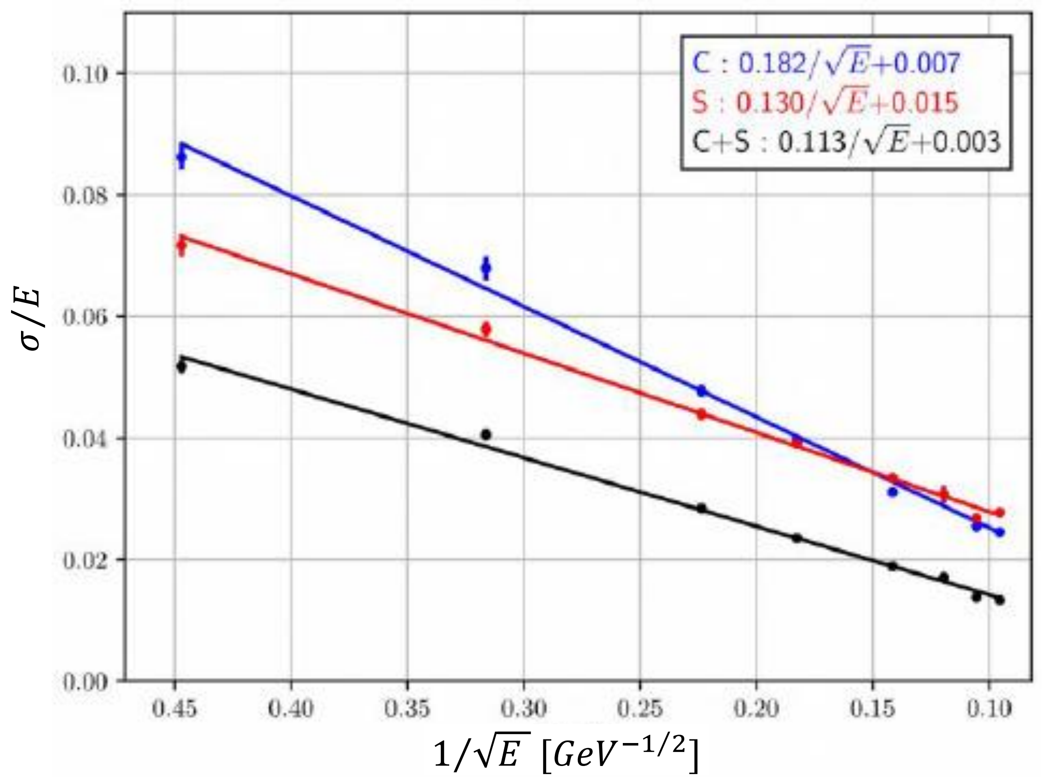
- Result is very stable, which means calibration is done as expected.

③ Energy resolution

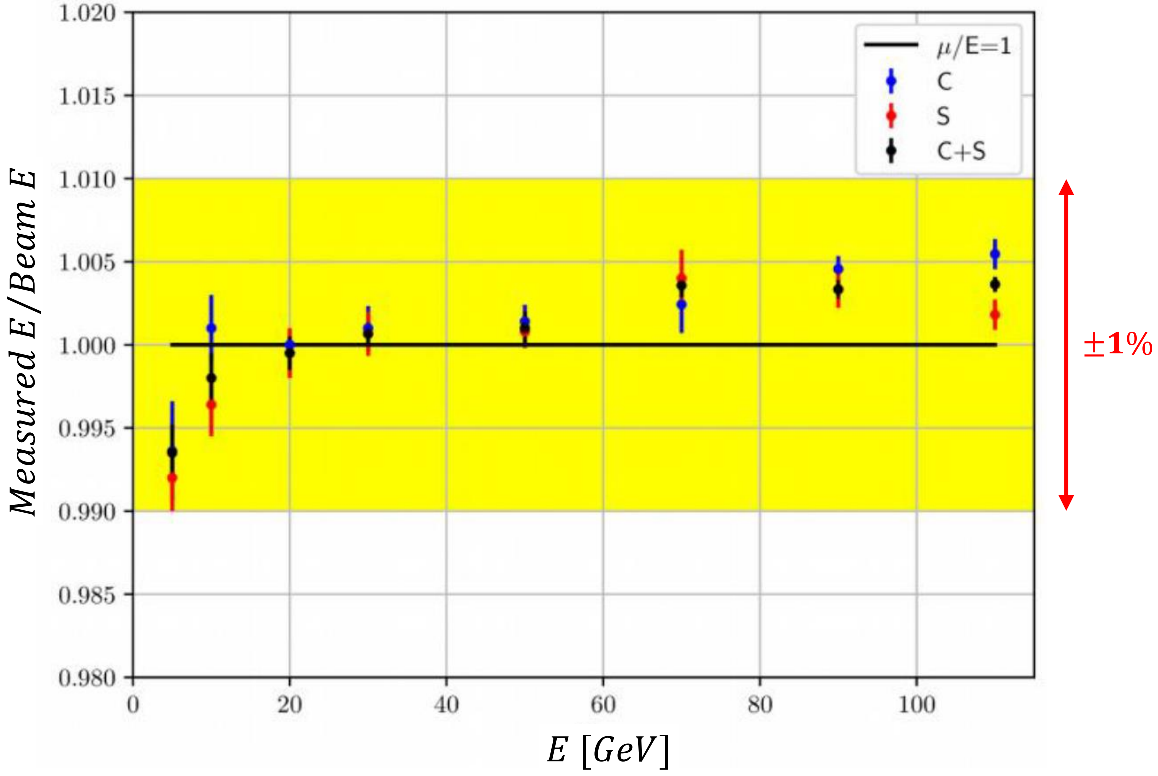
EM Energy Resolution

- EM energy resolution is measured with different 8 energy points electron and scaled with $1/\sqrt{E}$.
- Stochastic & constant term of energy resolution can be obtained by linear fitting.

EM Energy Resolution



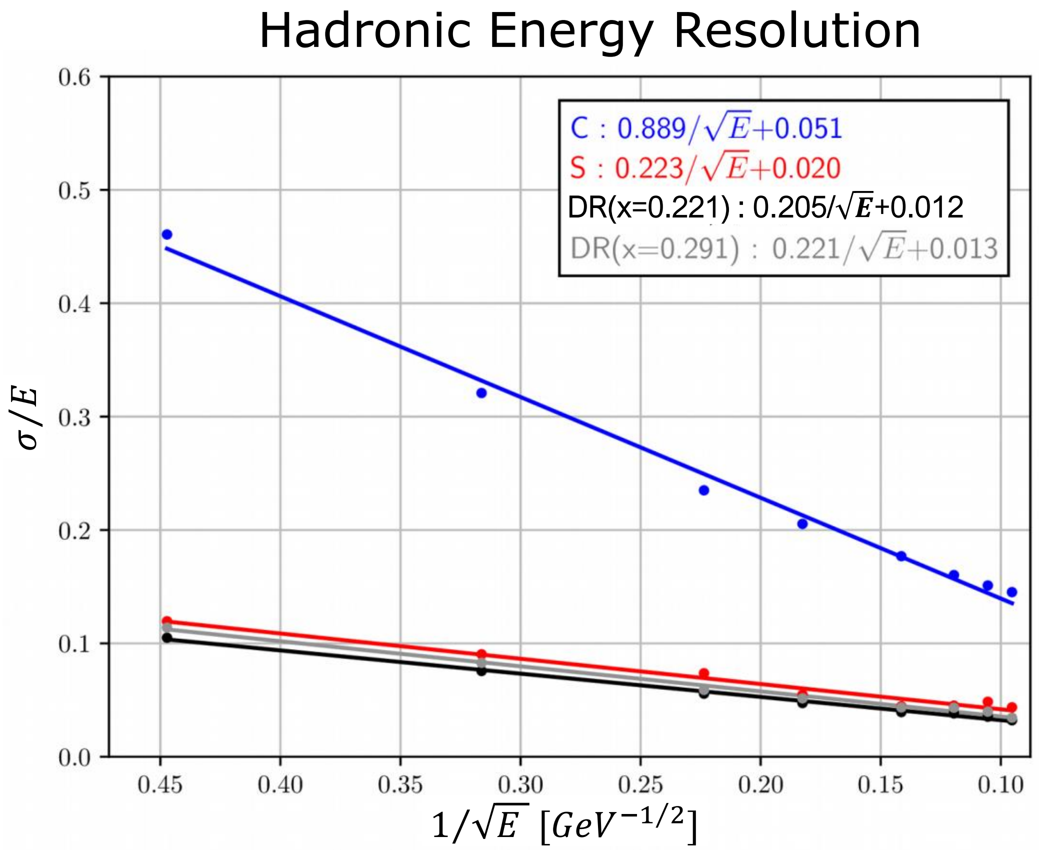
EM Energy Linearity

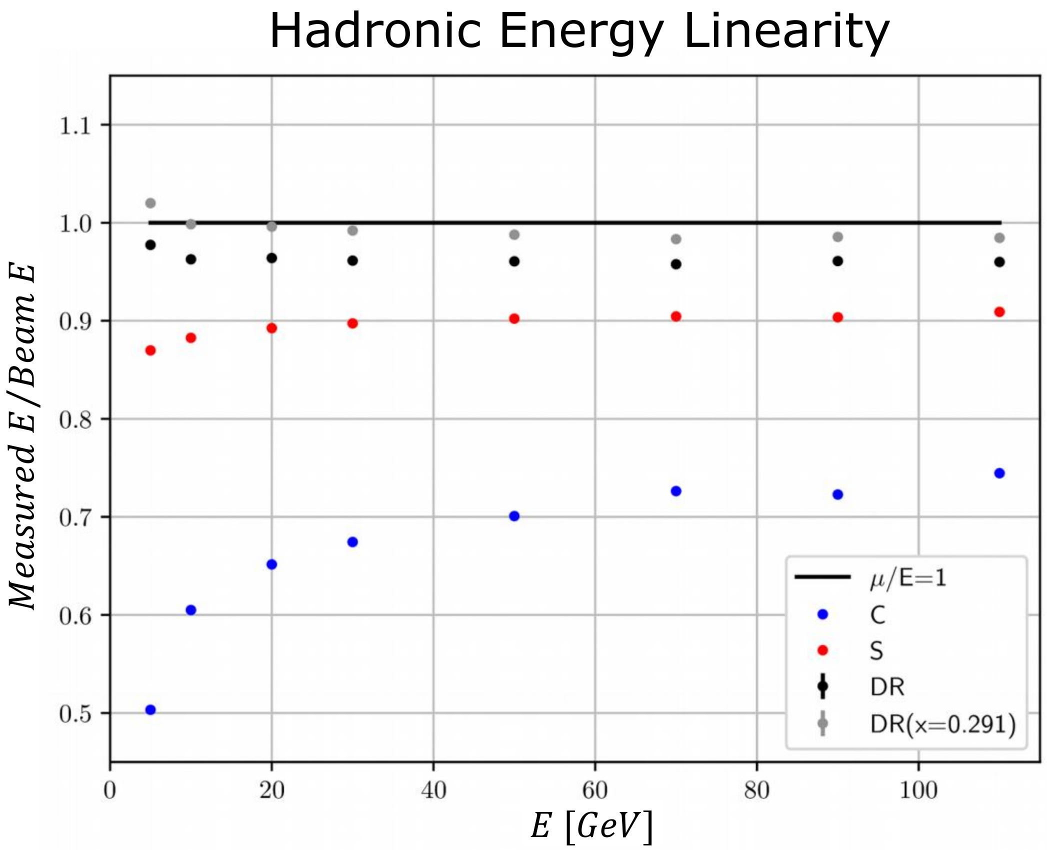


- Stochastic term for EM energy resolution is ~11%.
- Measured EM energy satisfies linearity within 1% level at both scintillation and Cerenkov channels.

Hadronic Energy Resolution

- Hadronic energy resolution is measured with 8 different energy single pion beams.
- Two chi values(0.221 and 0.291) are used for DR correction.

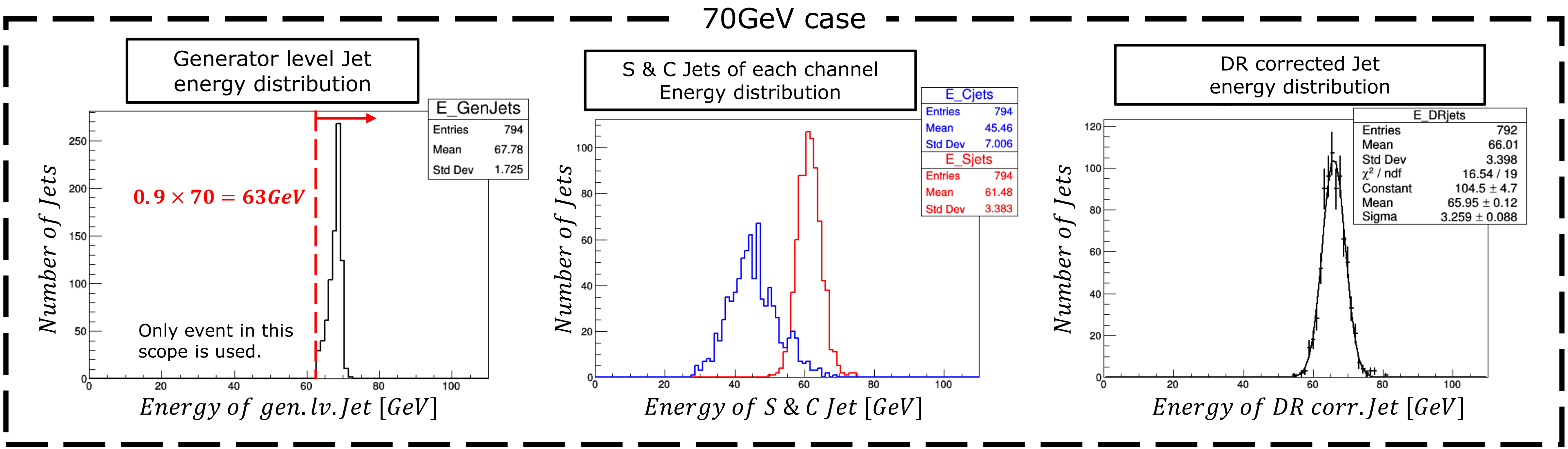




- Stochastic term for hadronic energy resolution is ~21%.
- Energy resolution differs with chi values.

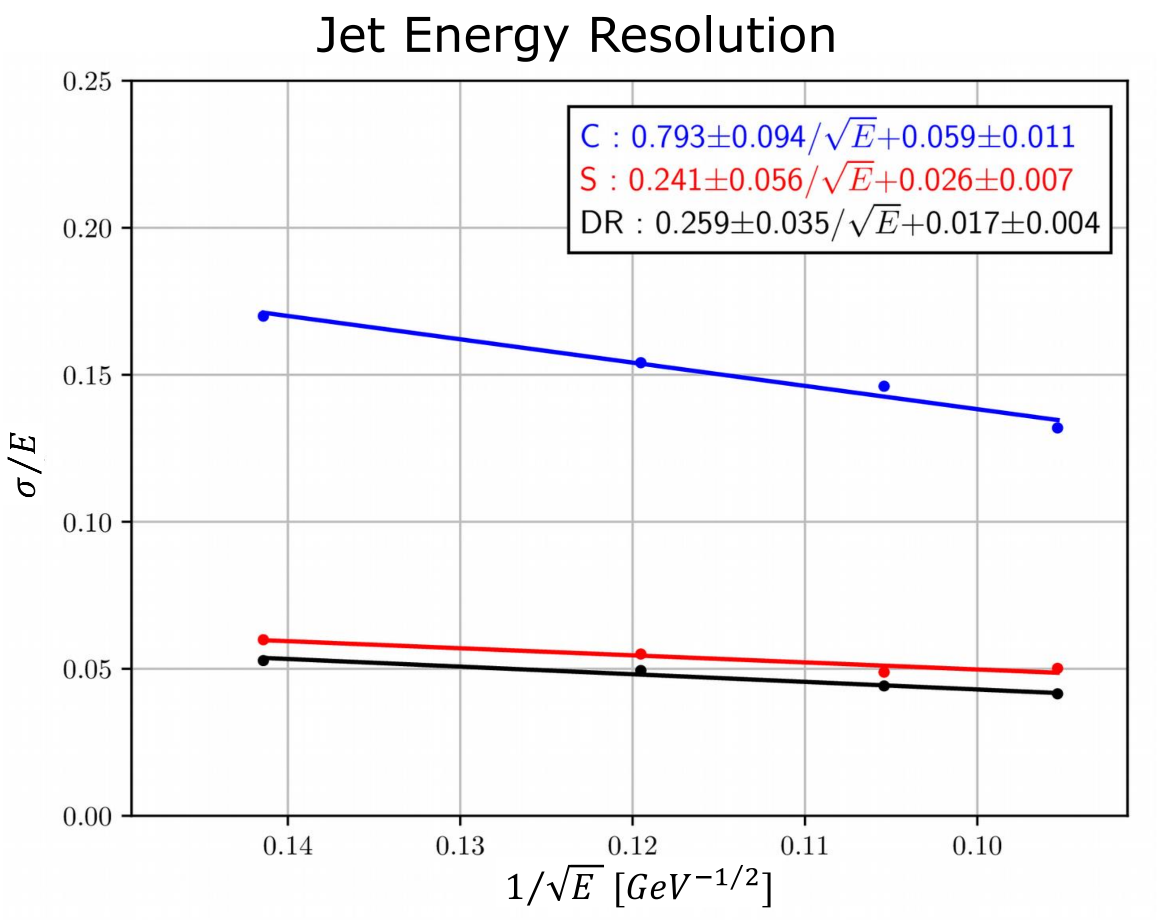
Jet Energy Resolution

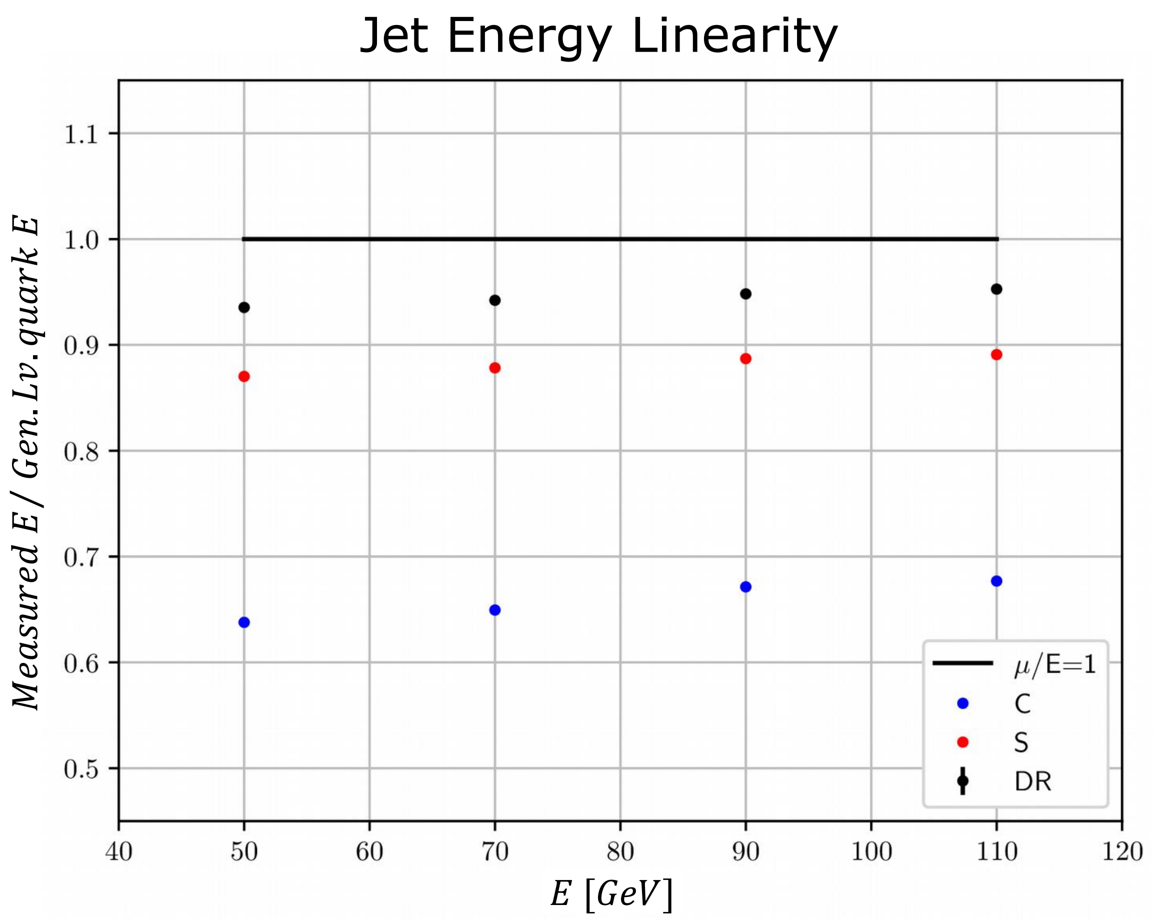
- Jet energy resolution is measured with 4 different energy u quar. (50, 70, 90, 110 GeV)
- Jet is reconstructed with anti-kt algorithm(R=0.8) and chi value for DR correction is 0.221.



- Missing energy from neutrino and neutron during simulatation makes resolution worse.
- Only events are used for jet energy resolution measurement whose Gen. lv. Jet has an energy over 90% of generated jet.

Jet Energy Resolution



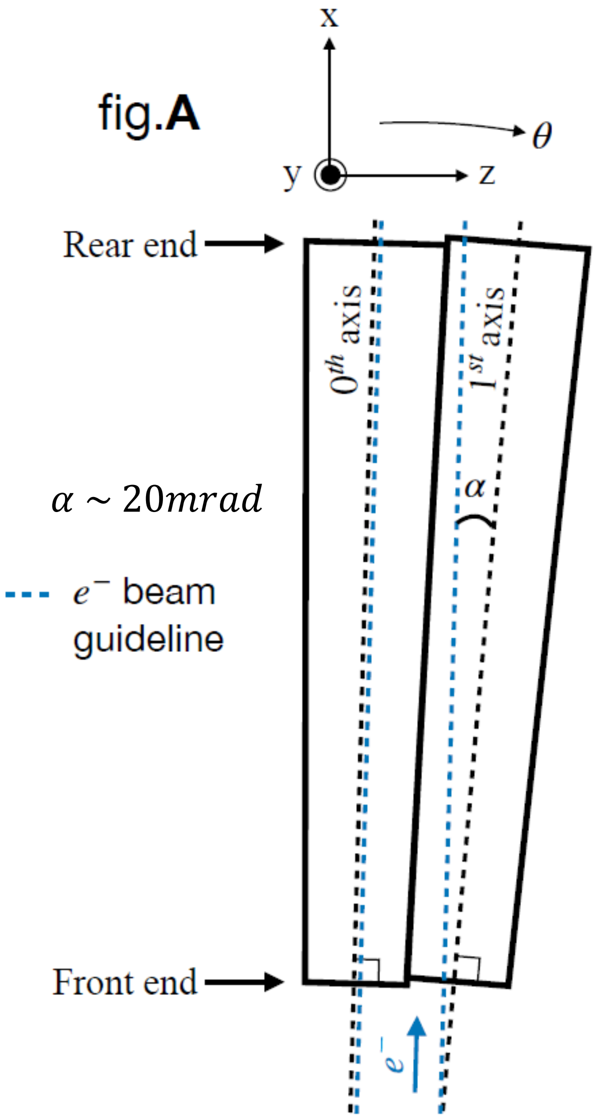


- Stochastic term for jet energy resolution is **~26%**.
- Measured jet energies follow linearity well.

④ Position resolution

Position Resolution

Beam setup & position reconstruction method



- 10, 20, 40, 60, 80, 100 GeV electron events are used.
- Beam is parallel to the 0th tower axis and has about 20mrad angle respect to the 1st tower
- 4cm(z) by 1cm(y) beam spot, covers from the center of 0th tower to the center of 1st tower with 1cm width.
- Position reconstruction
  - Center-of-gravity method is used. $\vec{x}_{reco} = \frac{\sum_i E_i \times \vec{x}_i}{\sum_i E_i}$, $i = \#\ of\ SiPM$
  - Reconstructs the center of gravity of the energies E_i measured by numerous SiPMs.

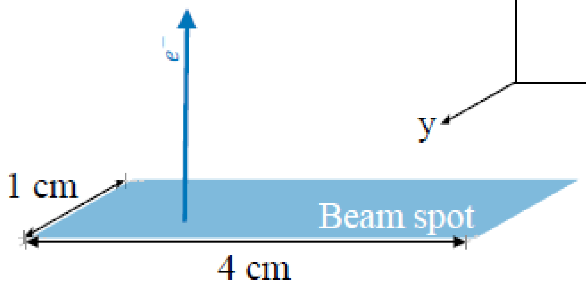


fig.B
Beam spot scheme

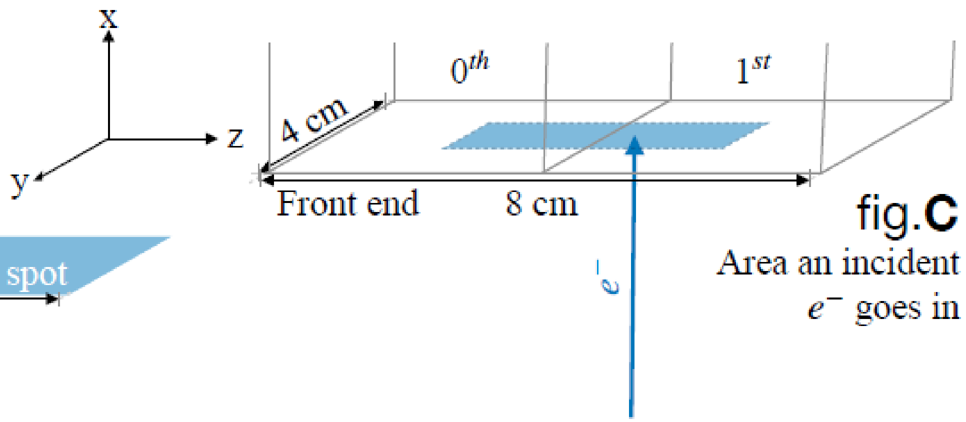
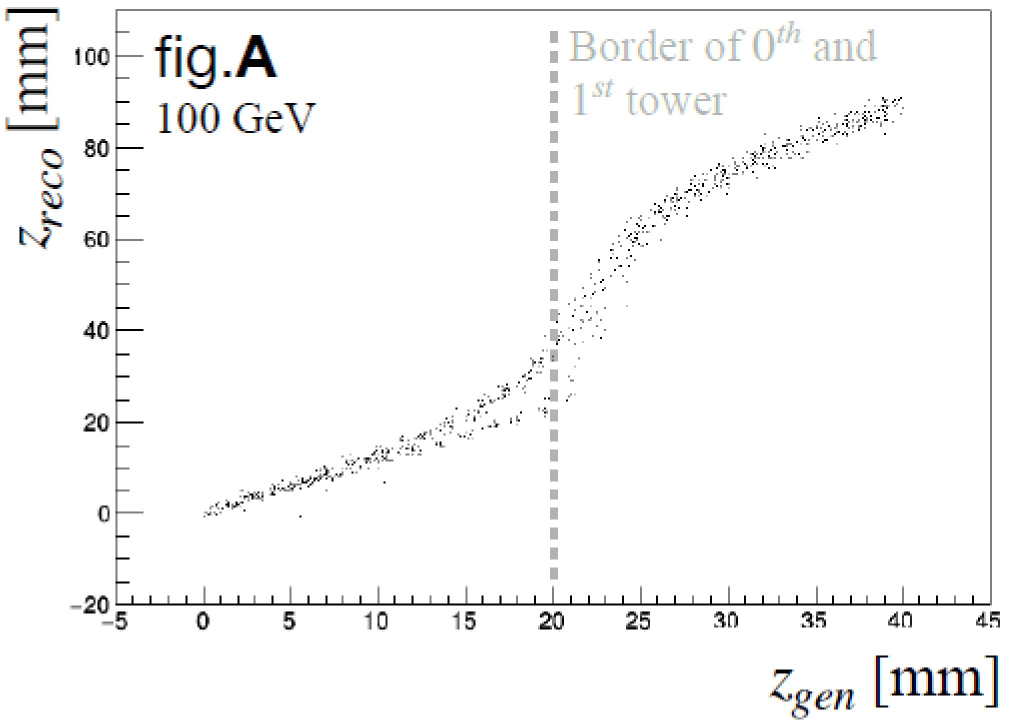
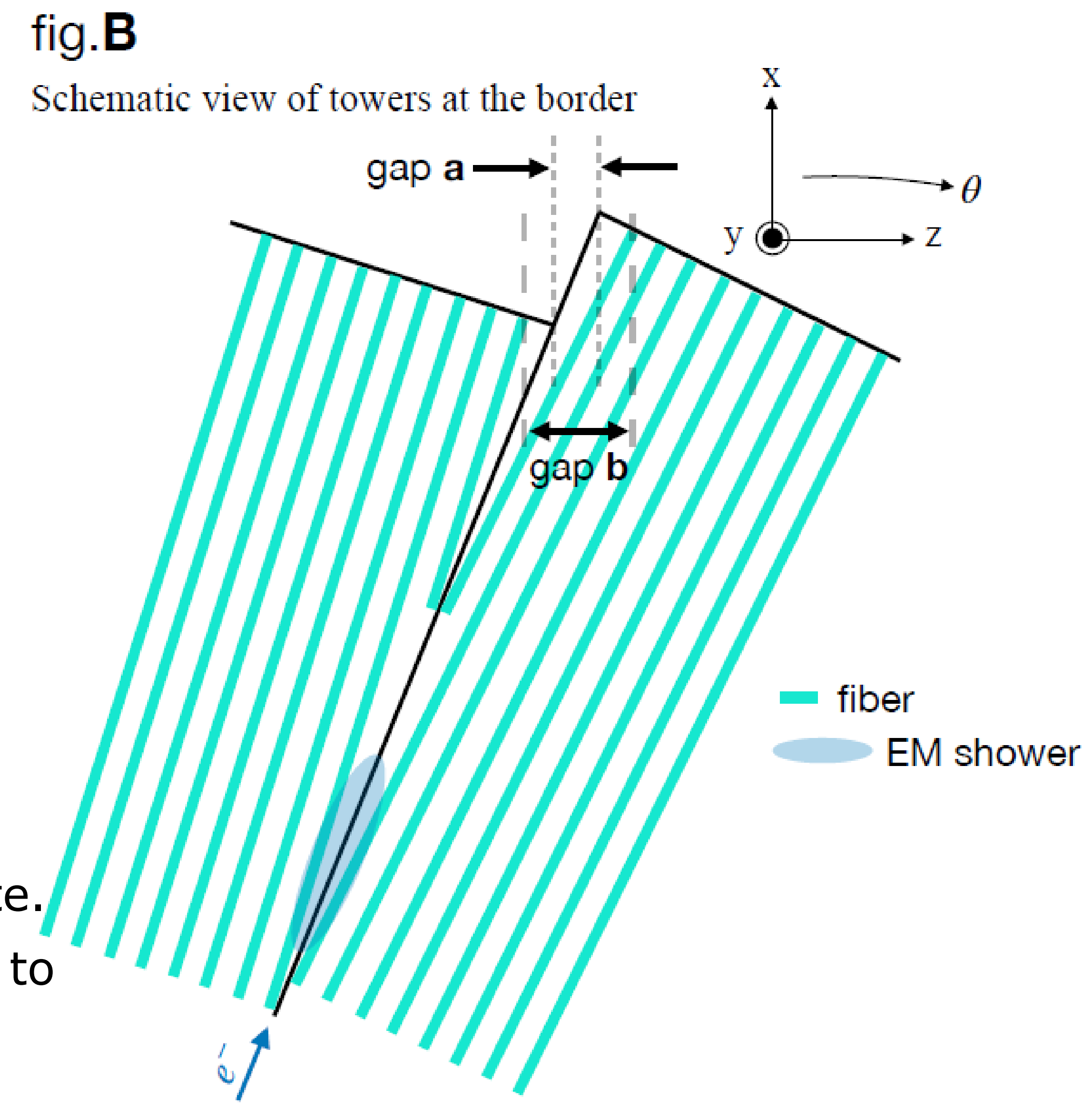


fig.C
Area an incident e^- goes in

Position Resolution

Property of z_{reco} vs z_{gen}

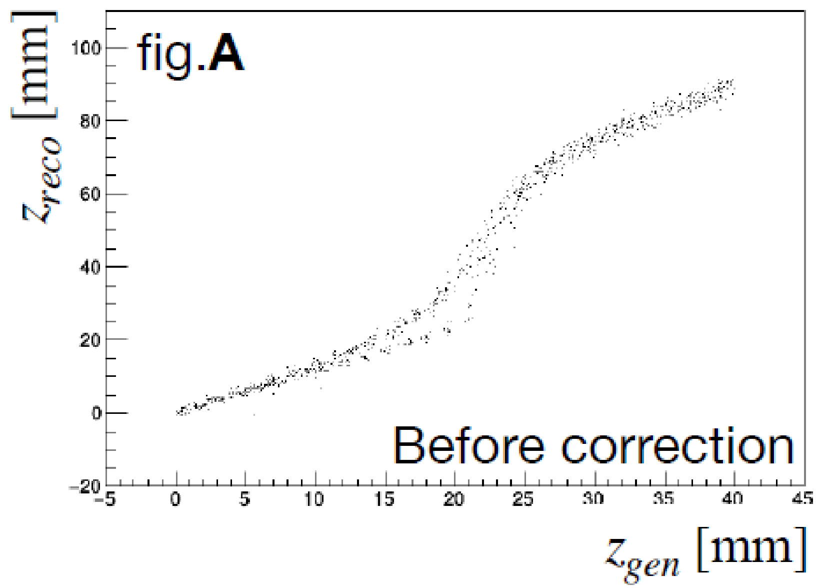


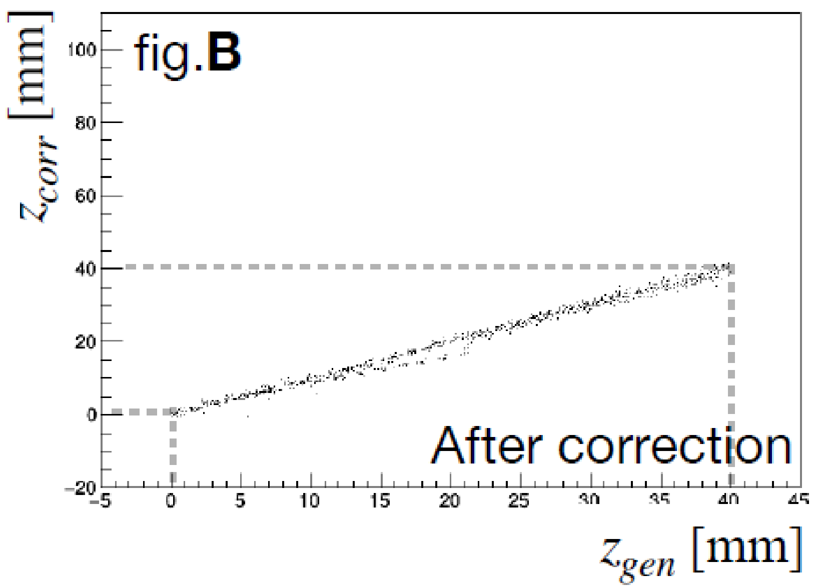


- fig.B
  - gap **A** : Intrinsic structural gap seen in z coordinate.
  - gap **B** : Shower is developed near the depth of 70 to 80 cm, fibers starting beyond shower barely catch signals

Position Resolution

Correction to z_{reco}

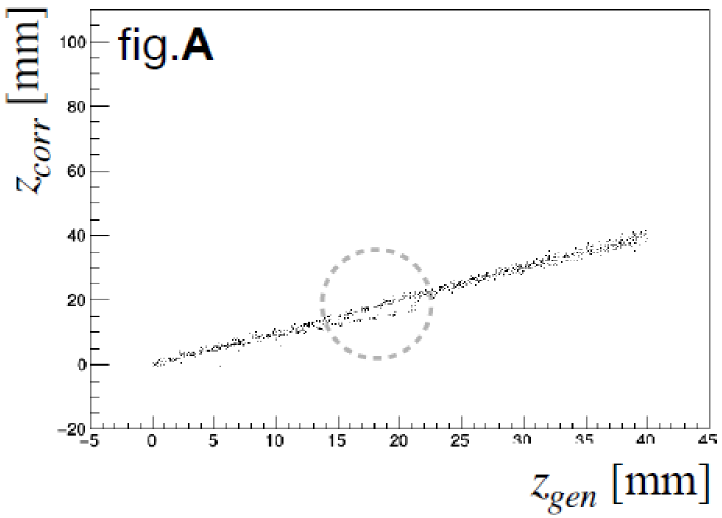


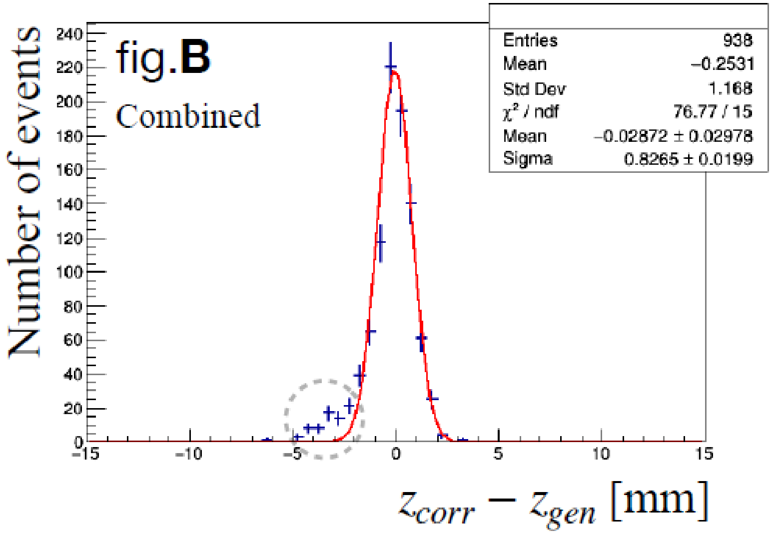


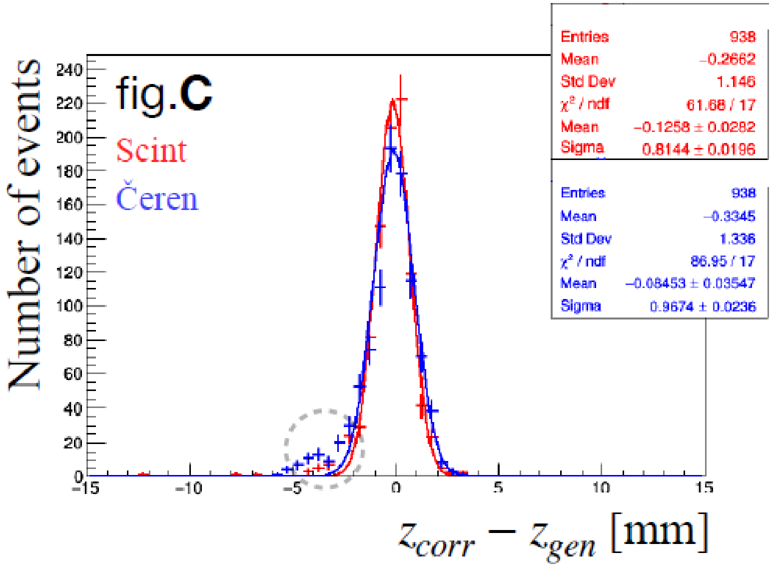
- The position resolution is given by the vertical width of the band in $z_{reco}\ vs\ z_{gen}$ plot.
- In fig.**A**, z_{reco} corresponding to z_{gen}; 15 mm < z_{gen} < 25 mm, shows large increase of its value.
  - Comes from the structural property of the calorimeter
- Applying the correction equation to z_{reco} makes the band in fig.**A** straight
  - $z_{corr} = p_o + p_1 z_{reco} + p_2(z_{reco} - p_3)^2 \tan^{-1}\left(p_4(z_{reco} - p_5)\right)$
- After correction, fig.**B** shows $z_{corr}\ vs\ z_{gen}$ having slope of 45°.

Position Resolution

Obtaining resolution



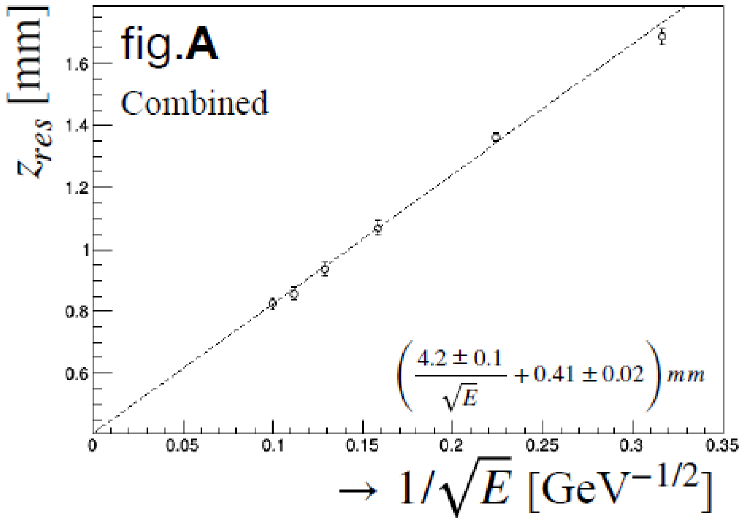


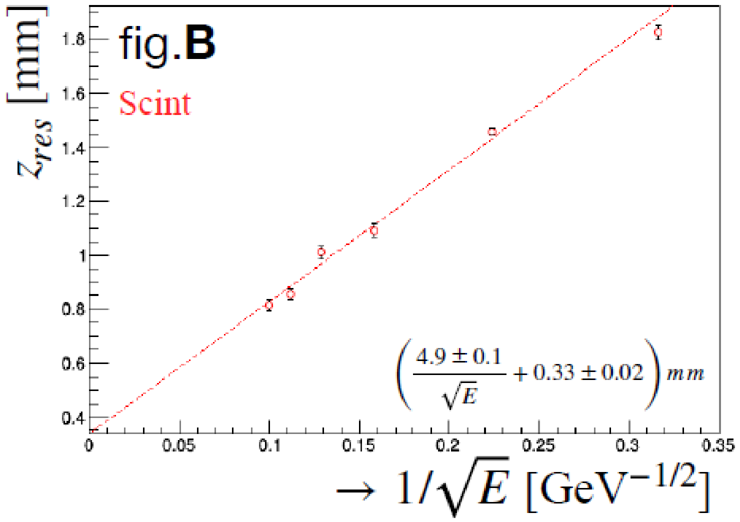


- To obtain resolution
  - [fig.**B**] distribution $z_{corr}\ vs\ z_{gen}$; σ from Gaussian fit is the resolution
  - [fig.**C**] Same are done for each channel S (red)and C (blue)

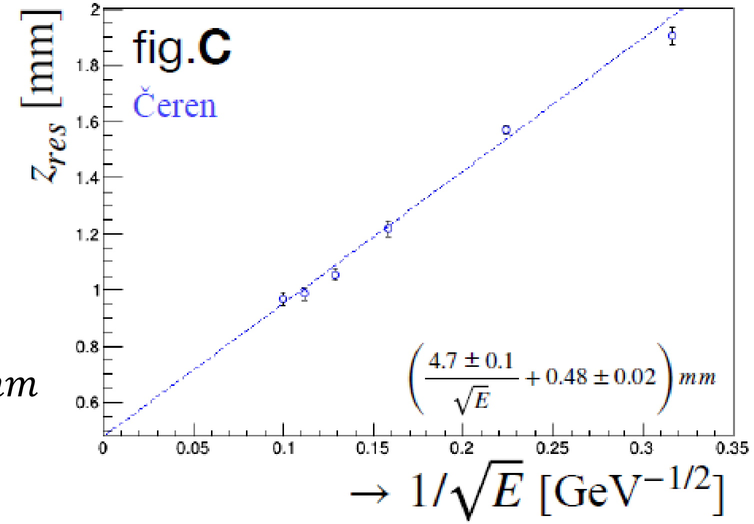
Position Resolution

Resolutions as a function of $1/\sqrt{E}$





- Resolutions for 10, 20, 40, 60, 80 and 100 GeV
  - [fig.**A**] Scintillation and Čerenkov signals combined
  - [fig.**B**] Scintillation only
  - [fig.**C**] Čerenkov only
- It shows the resolution of $\left(\frac{4.2\pm0.1}{\sqrt{E}}+0.41\pm0.02\right)mm$



Summary

Dual-readout calorimeter

- Dual-readout calorimeter is a component of IDEA detector, which is proposed to CDR of FCC-ee and CEPC.
- By measuring EM fraction and correcting energy event by event, high quality energy resolution can be achievable.

Calibration

	Scintillation	Cerenkov
Calibration constant	$0.89\ MeV/p.e.$	$0.0136\ GeV/p.e.$

- Calibration constant is stable for all tower in barrel region.

Study on energy resolution

$$energy\ resolution := \frac{\sigma}{E} = \frac{stocahstic\ term}{\sqrt{E}} \oplus constant\ term$$

	EM (electron)	Hadron (single pion)	Jet (u quark jet)
Stochastic term	~11%	~21%	~26%

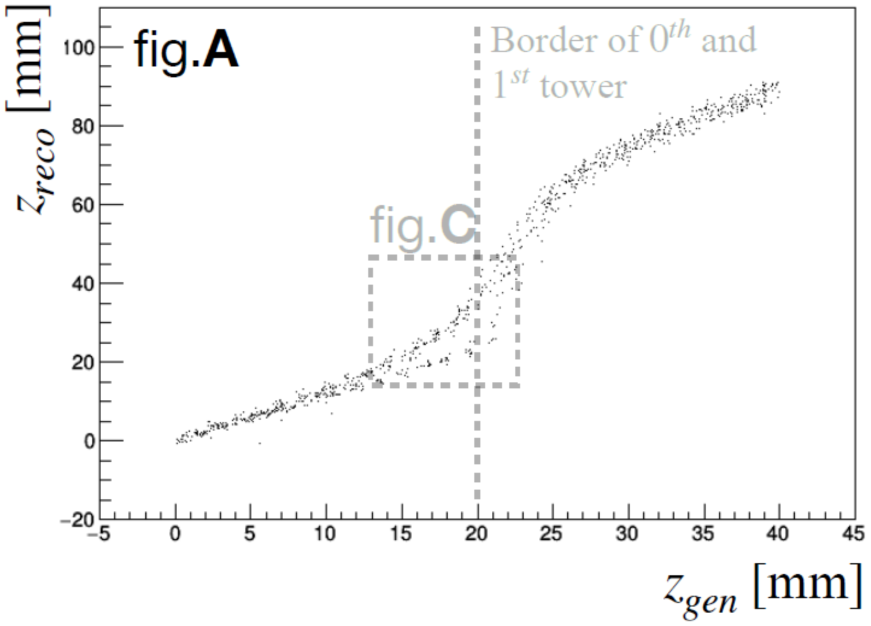
Position resolution

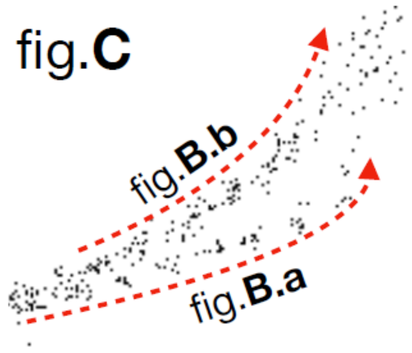
- Position resolution is measured with 4.2mm of stochastic term.

Back up

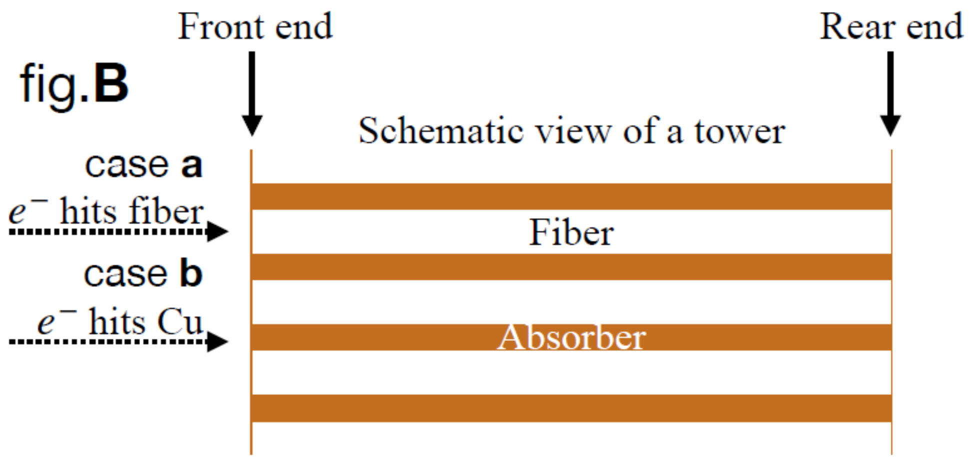
Position Resolution

Peculiarity seen in z_{reco} vs z_{gen}





- fig.**C**
  - Responses of **a** and **b** in fig.**B** are different.
  - Case **a**: signals concentrated near the hit fiber compared to case **b**



- At the border of towers
  - Case **a** shows z_{reco} similar to z_{gen} since the energy is deposited near the hit fiber.
  - Case **b** shows z_{reco} apart from z_{gen} since the neighboring tower has considerable portion of the energy deposit.

Requirements for CEPC

Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) =$ $2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} =$ $5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E =$ $3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E =$ $\frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

Table 3.3: Physics processes and key observables used as benchmarks for setting the requirements and the optimization of the CEPC detector.

CEPC Conceptual Design Report: Volume 2 - Physics & Detector
arXiv:1811.10545