Performance Study for Jet Energy Resolution of the Dual-Readout Calorimeter with GEANT4 Simulation

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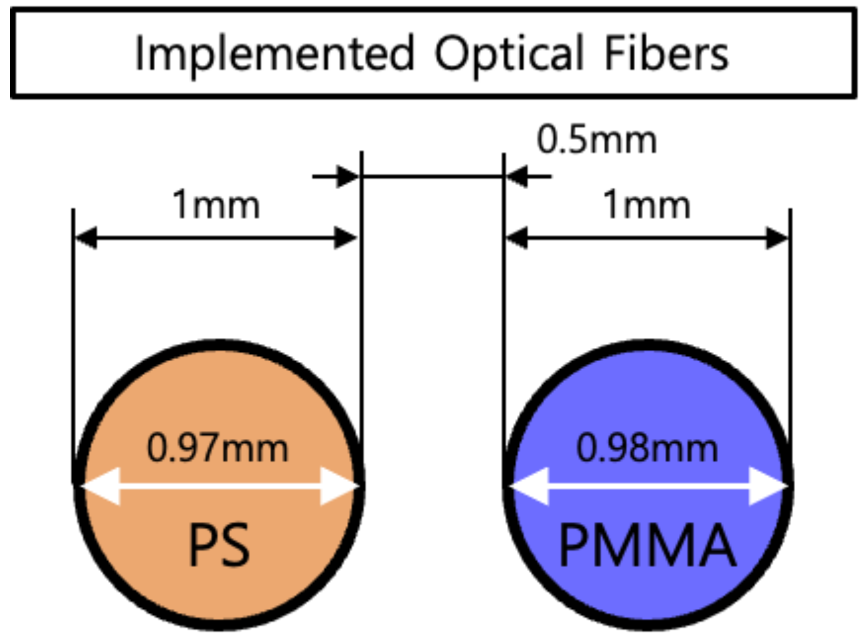
Dual-Readout Calorimeter

◉ IDEA detector concept

- **IDEA detector concept:** proposed in conceptual design report of **FCC-ee and CEPC**
- **Dual-Readout Calorimeter** is included in the **IDEA detector concept** which can **detect** both **EM & hadronic particles simultaneously**

◉ What is the Dual-Readout Calorimeter (DRC)

- **Precise hadronic energy measurement** is **difficult** due to
  - **Non-gaussian fluctuation from EM shower component**
  - **Invisible energy** induced during shower development
- **DRC** can achieve **outstanding energy resolution**
  - by measuring the EM component and correcting hadron energy



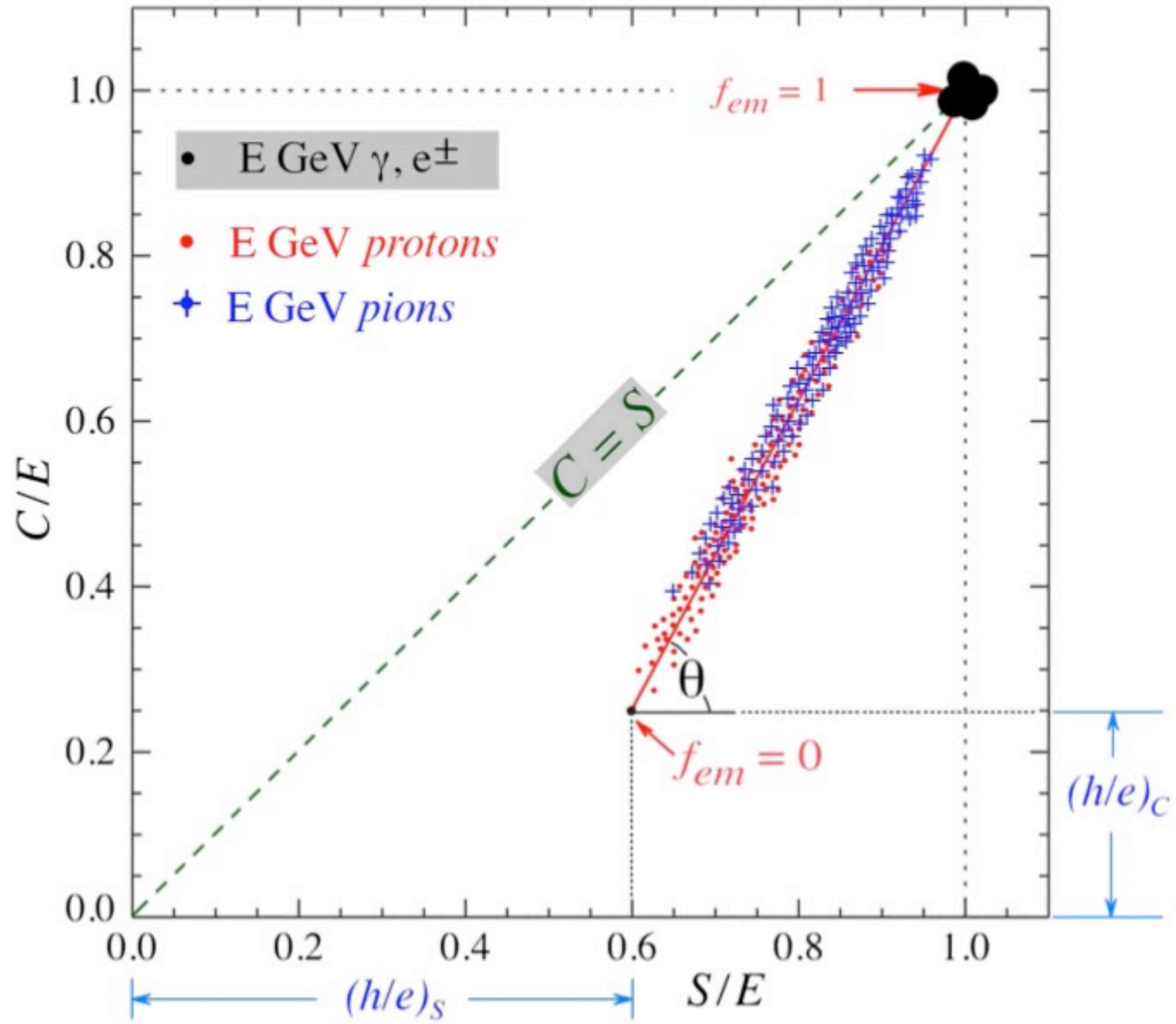
1. $C = E\left[f_{EM} + \frac{1}{(e/h)_C}(1 - f_{EM})\right]$

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

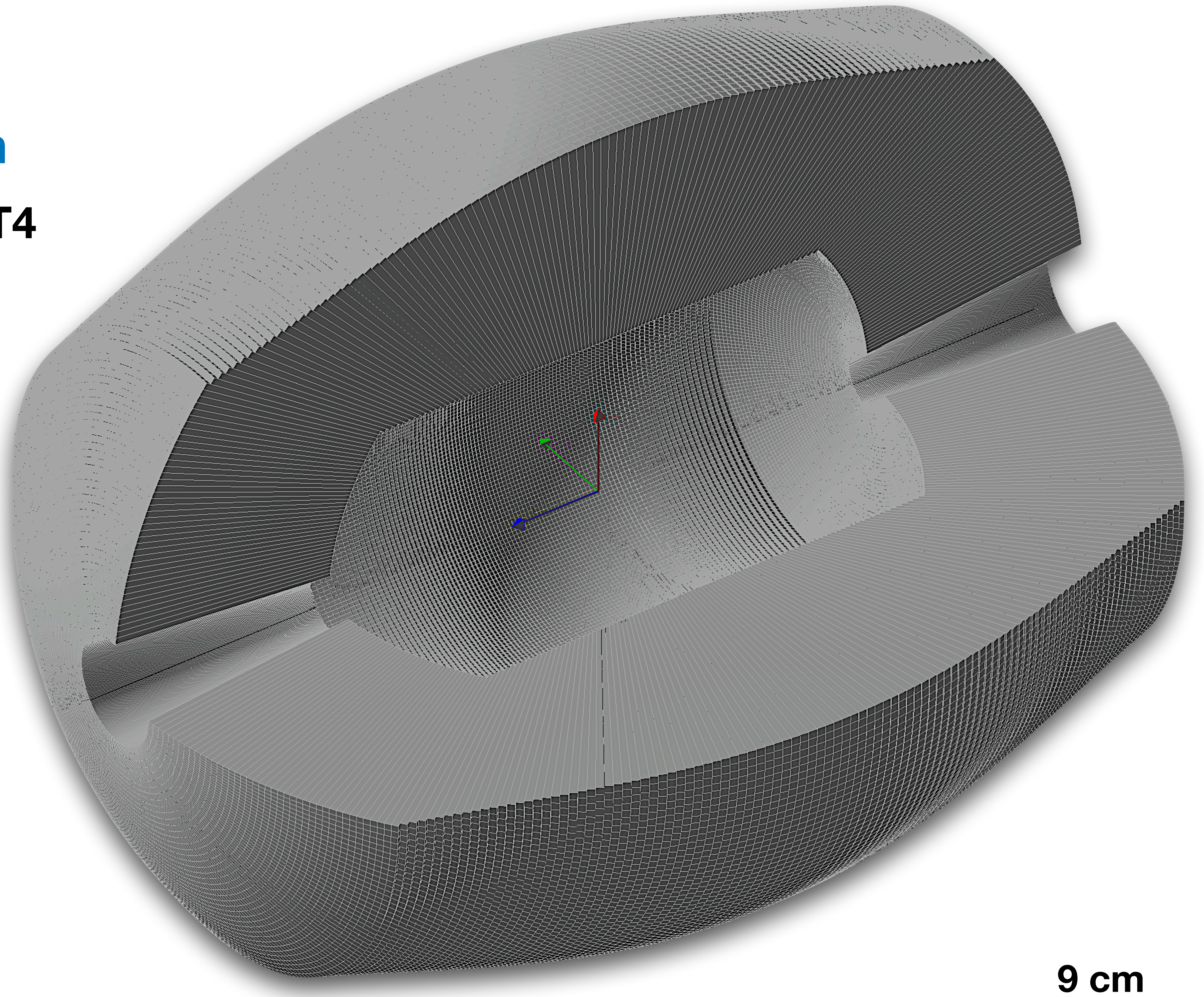
5. $E = \frac{S - \chi C}{1 - \chi}$

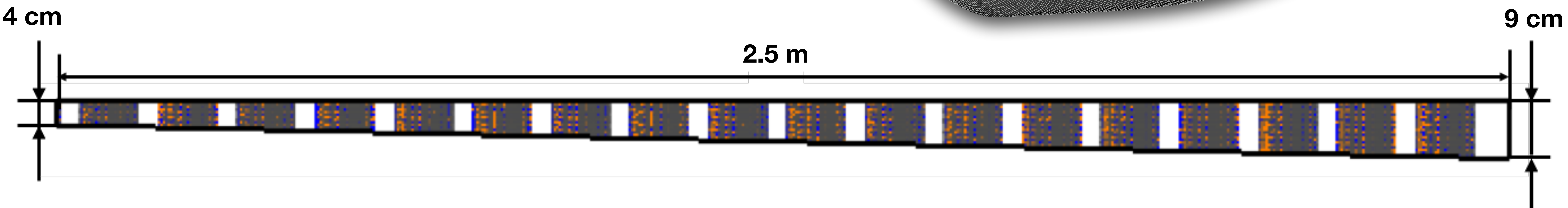


Simulation Setup

◉ Detector geometry in the GEANT4 simulation

- **4pi full projective DRC** implemented in the **GEANT4**
  - composed with **~ 52000 individual towers**
- **Each tower has 2.5 m length**
  - which corresponds to **~ 10 nuclear interaction length**
  - allowing us to get **~ 99% energy deposit for EW window**
  - **implemented by ~O(1000) fibers in copper absorber**



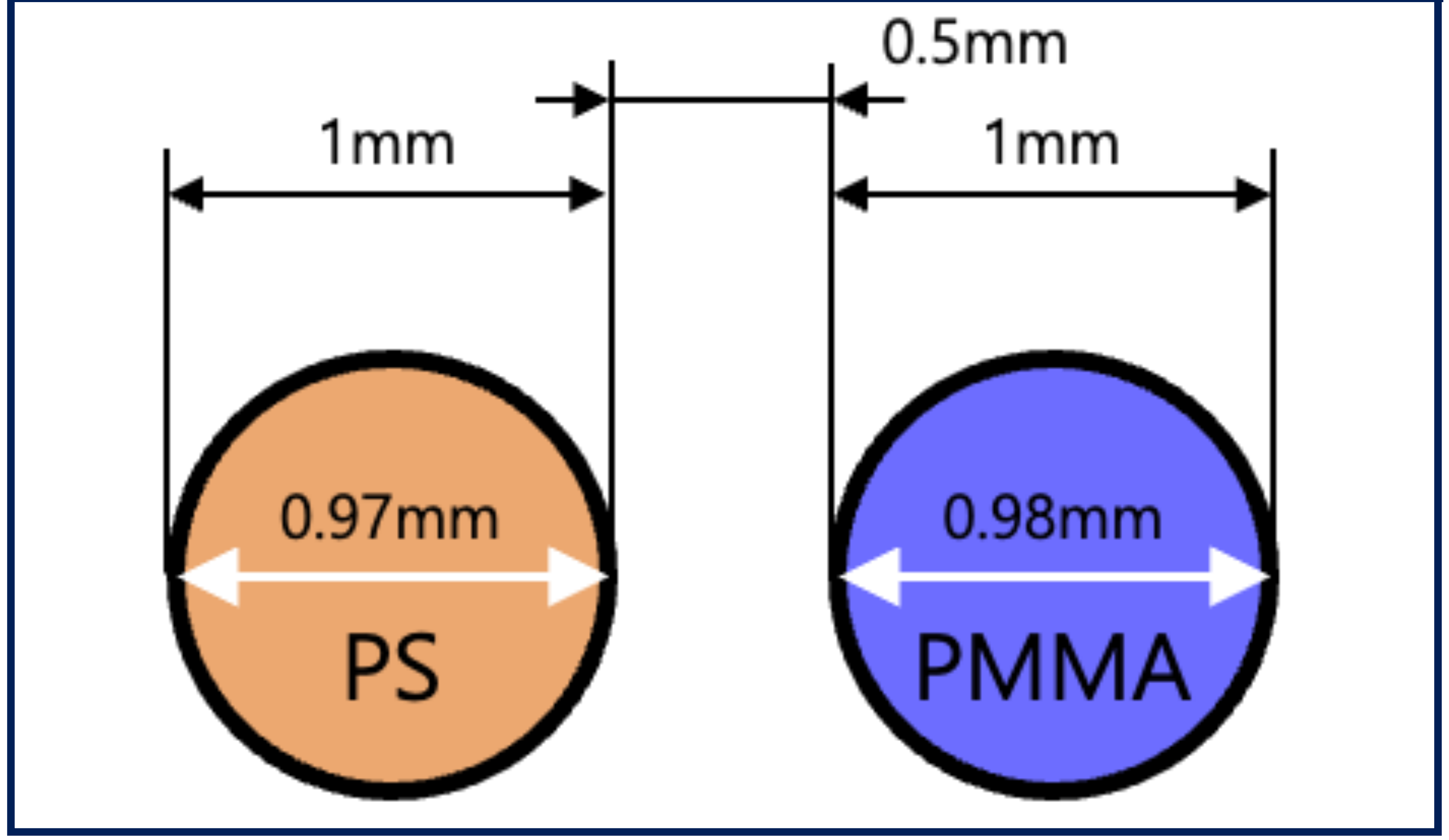


Simulation Setup

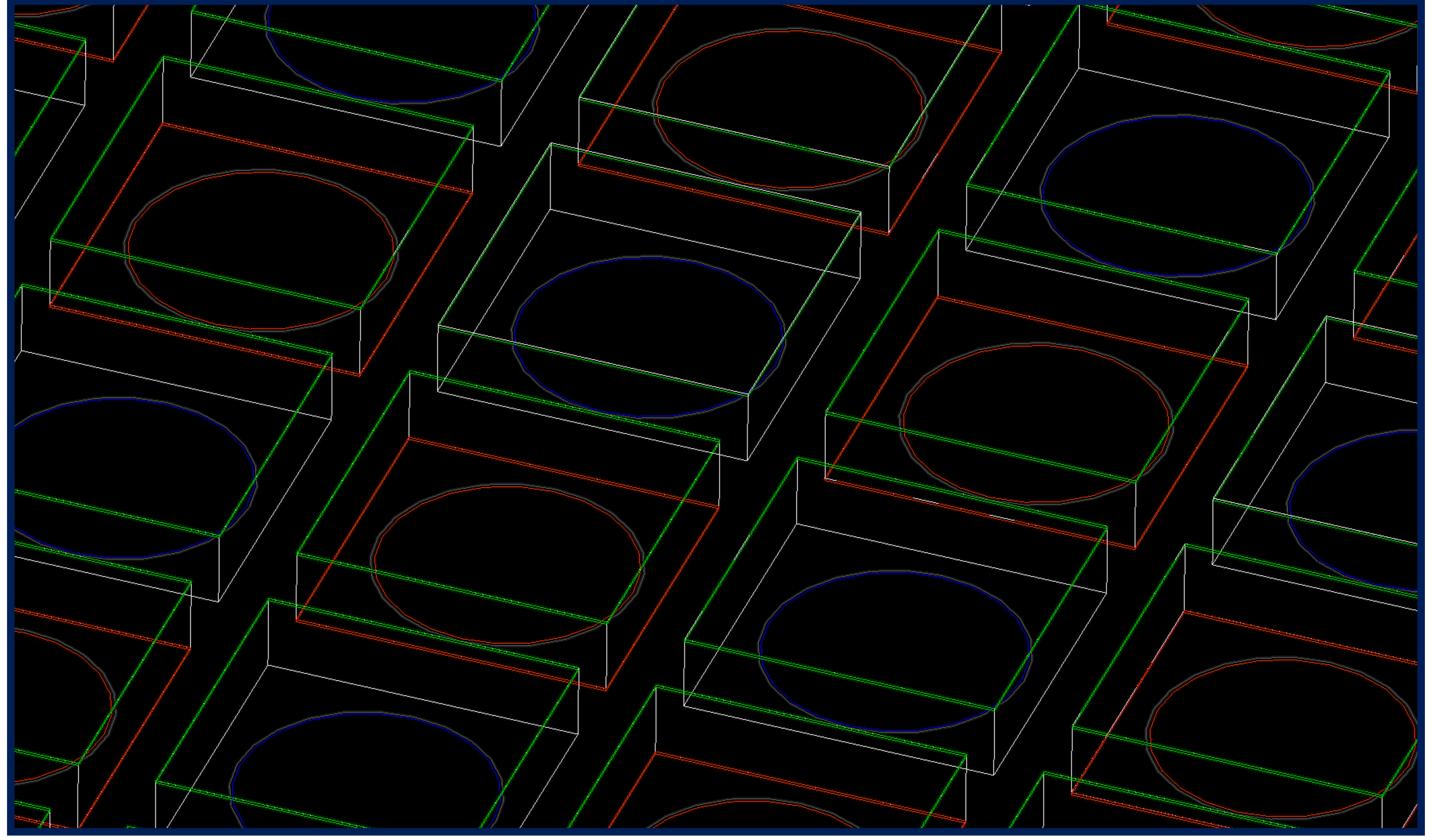
◉ Detector geometry in the GEANT4 simulation

- **High granularity SiPM layers** as a readout system
  - **Scintillation (PS) and Cerenkov (PMMA) fibers** are implemented **alternatively** with 0.5 mm spacing
- **Full optical photon simulation in GEANT4**
  - **Huge time consumption** for simulation (**~ 1 hour /GeV /Event /CPU**)
  - First result with full optical photon simulation

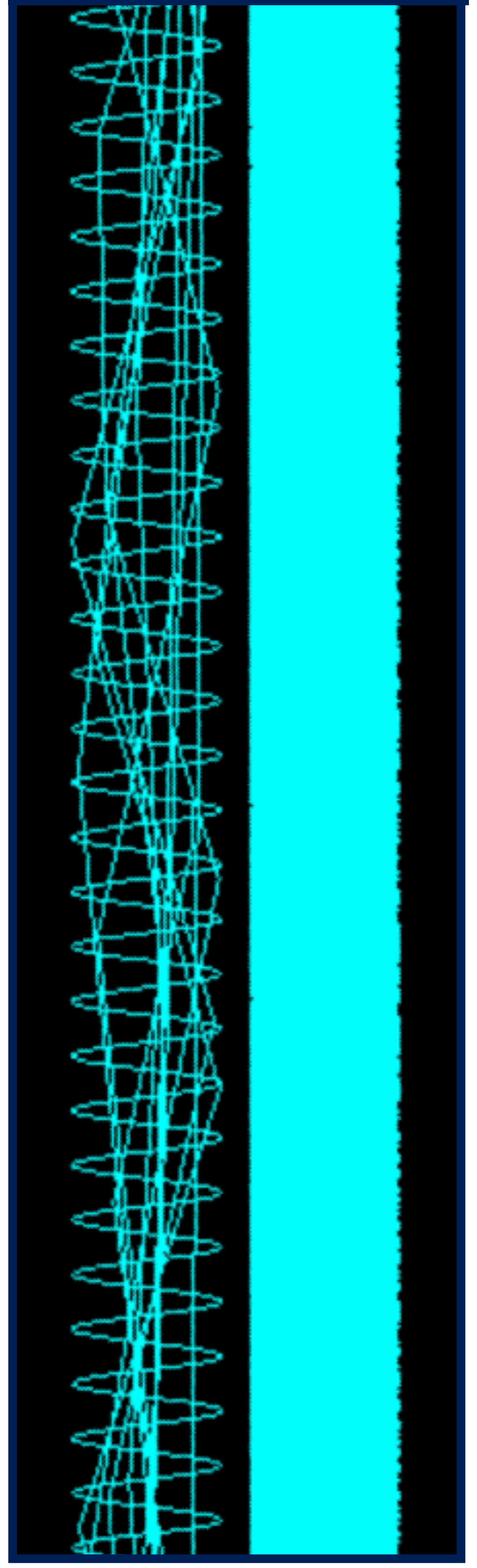
2 different types of implemented fiber



Read side of the tower



Optical Photon in GEANT4



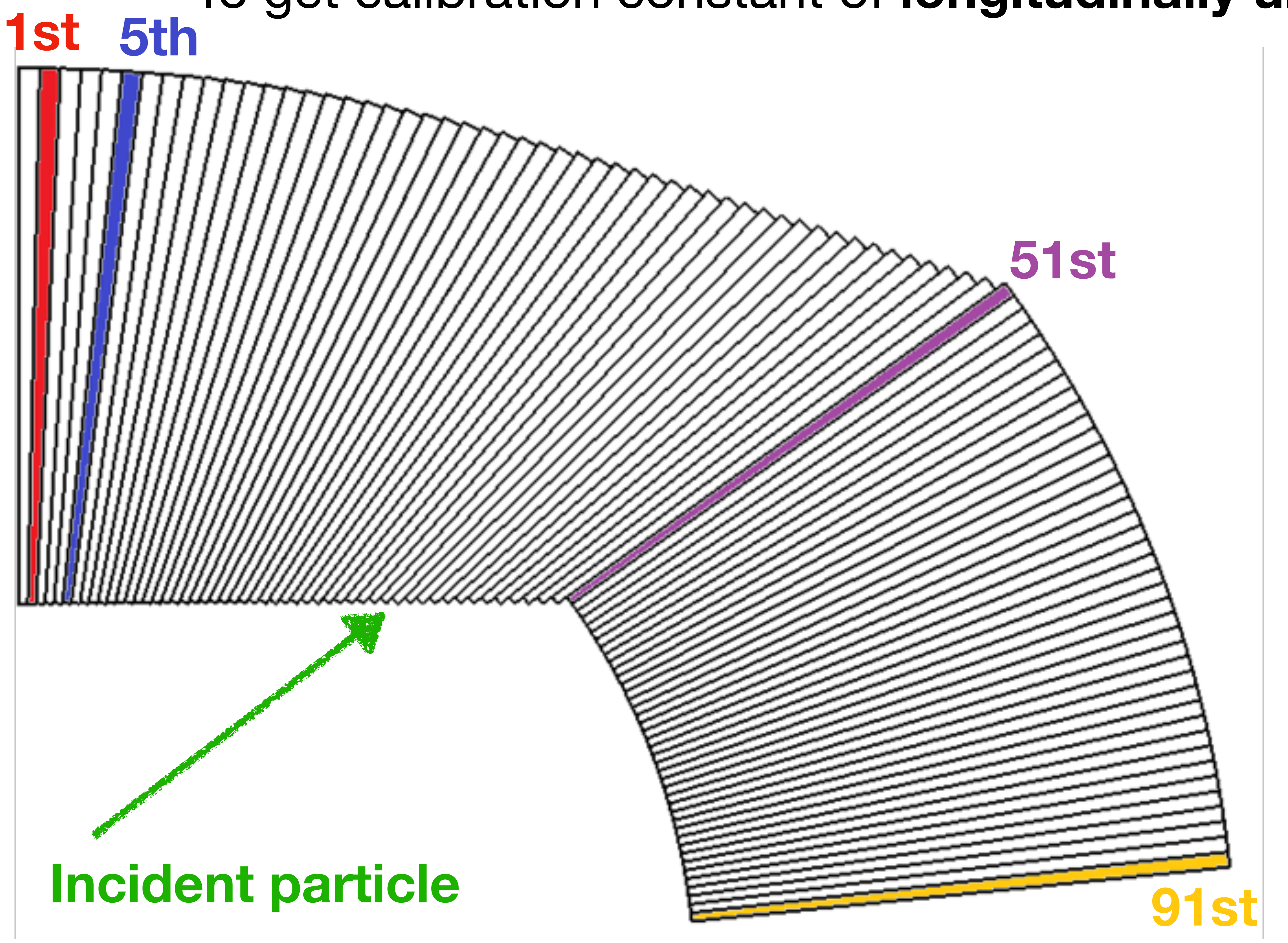
Calibration

For calibration, 20 GeV e- simulation is utilized

- **EM particles** has **same response** between two independent channels, **Cerenkov and scintillation channels**

Calibration procedure

- With **geometrical feature**, modules composing the DRC could be **categorized into 92 components**, towers from 0 to 91
  - in Phi direction, towers are having same geometry
- Simulation for those towers is done with **20 GeV e- beams**, getting **# of photoelectrons**
- To get calibration constant of **longitudinally un-segmented calorimeter**, **minimizing process is introduced**



Minimizing

1. **Energy measurement** defined as

$$\mathrm{E} = N_{pe}^{0}CC^{0} + N_{pe}^{1}CC^{1} + \cdots + N_{pe}^{51}CC^{51} + \cdots + N_{pe}^{91}CC^{91}$$

2. **With 20 GeV e- simulation**, measured **energy should be 20 GeV**

   Define **chi-square** with the **residual between 20 GeV and measured one**

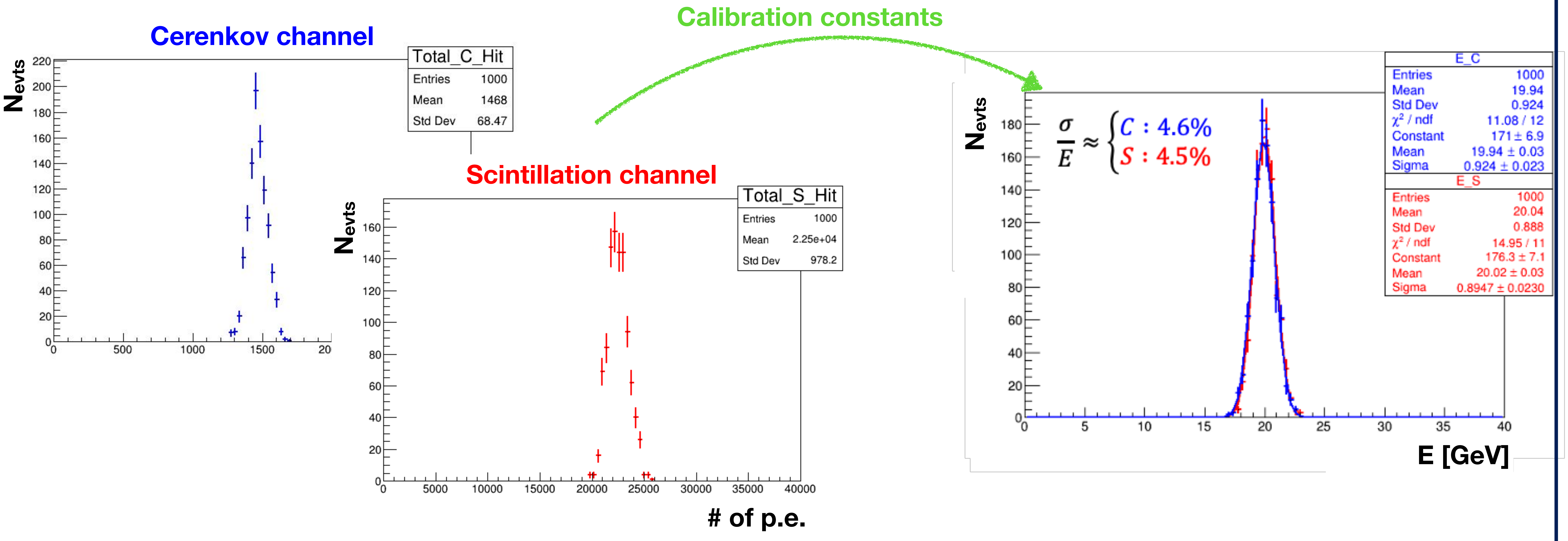
$$\chi^2 = \sum [20\ \mathrm{GeV} - E]^2$$

3. **Calibration constant** estimated by **minimizing the chi-square**

Calibration

- **With calibration constant, # of p.e. from simulation could be converted to the energy**
  - With **20 GeV e$^-$ simulation, energy of Cerenkov and scintillation channel are well reconstructed with 20 GeV**
  - **Linear relationship** of beam energy and reconstructed energy is **validated** in later slide

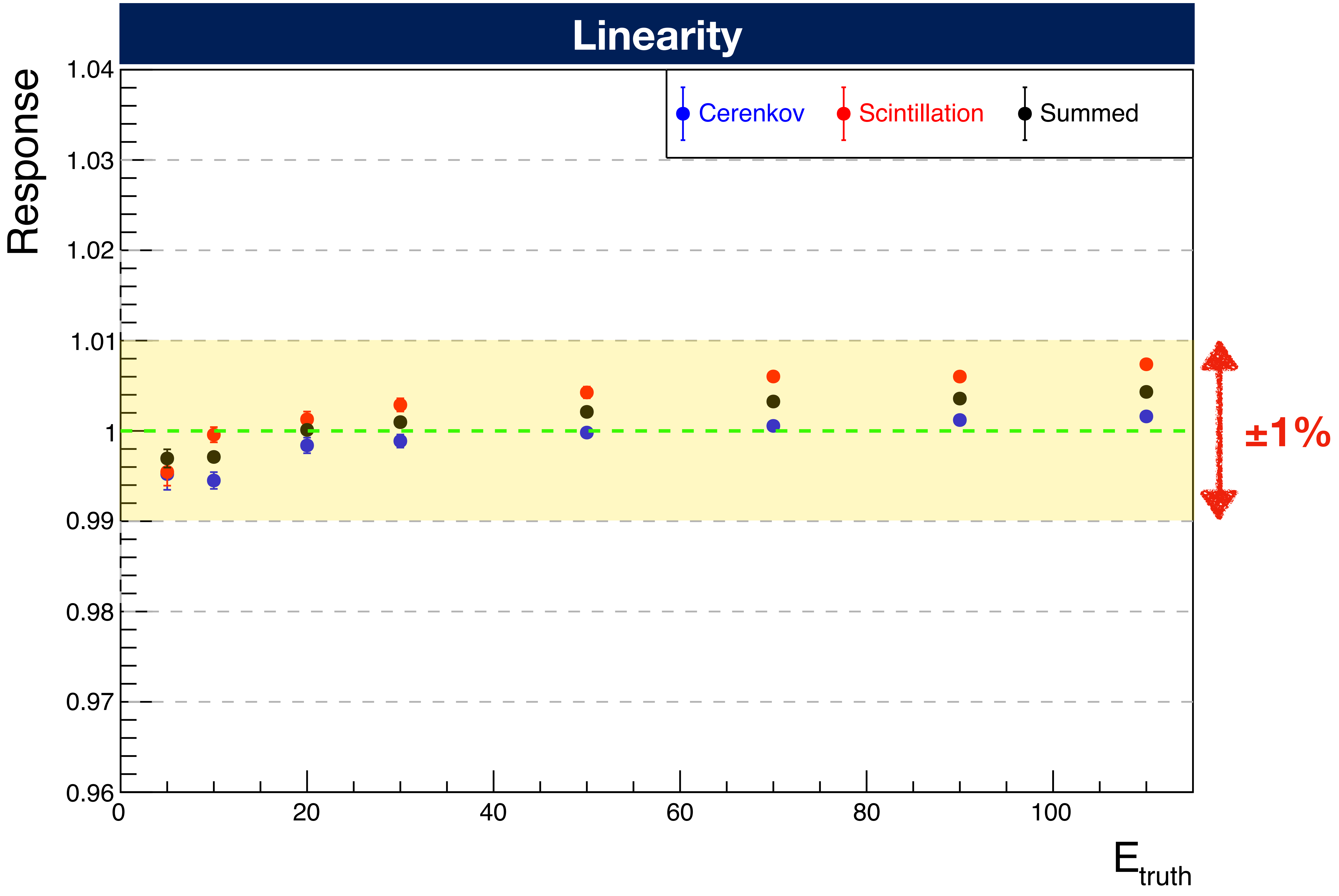
20 GeV e- example

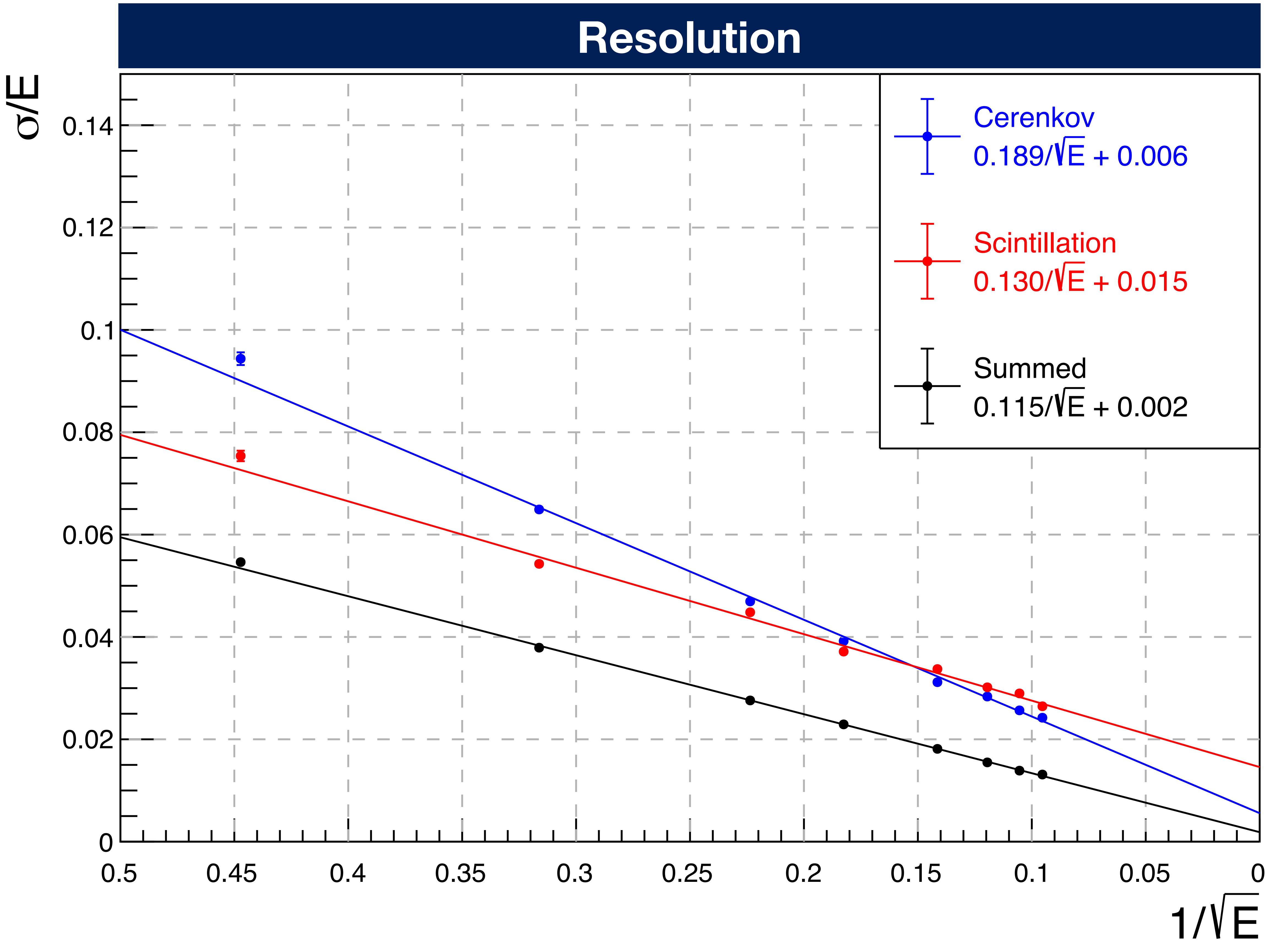


Electromagnetic Energy Resolution

◉ EM energy resolution with 5 ~ 110 GeV e^- simulation

- Resolution result for each energy is **scaled to 1 / √E**
- **Linearity** is satisfied **within 1% level**
- **Stochastic term** of the resolution is estimated **~11.5%**

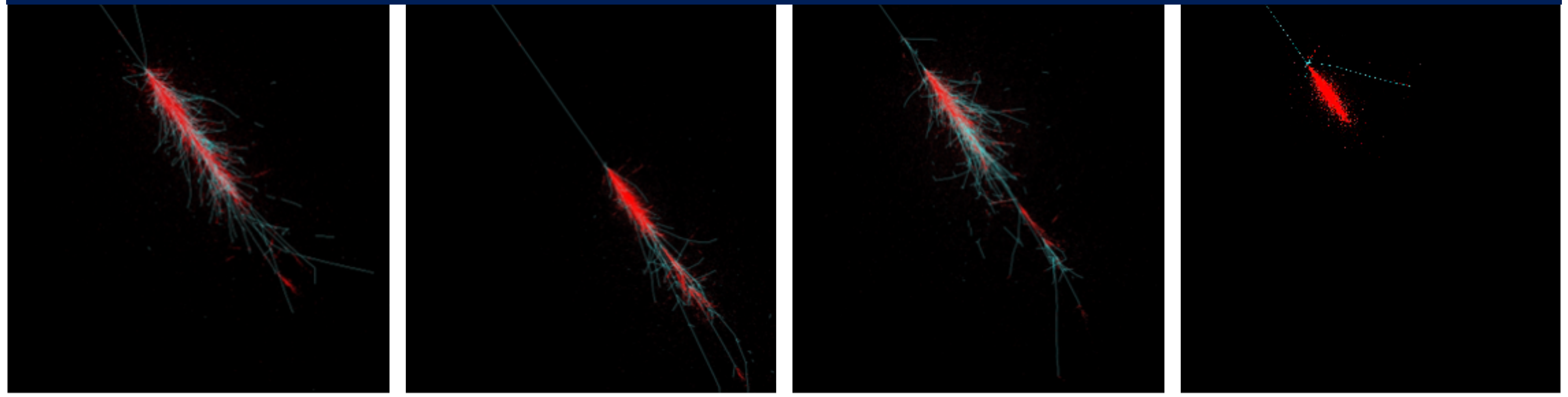


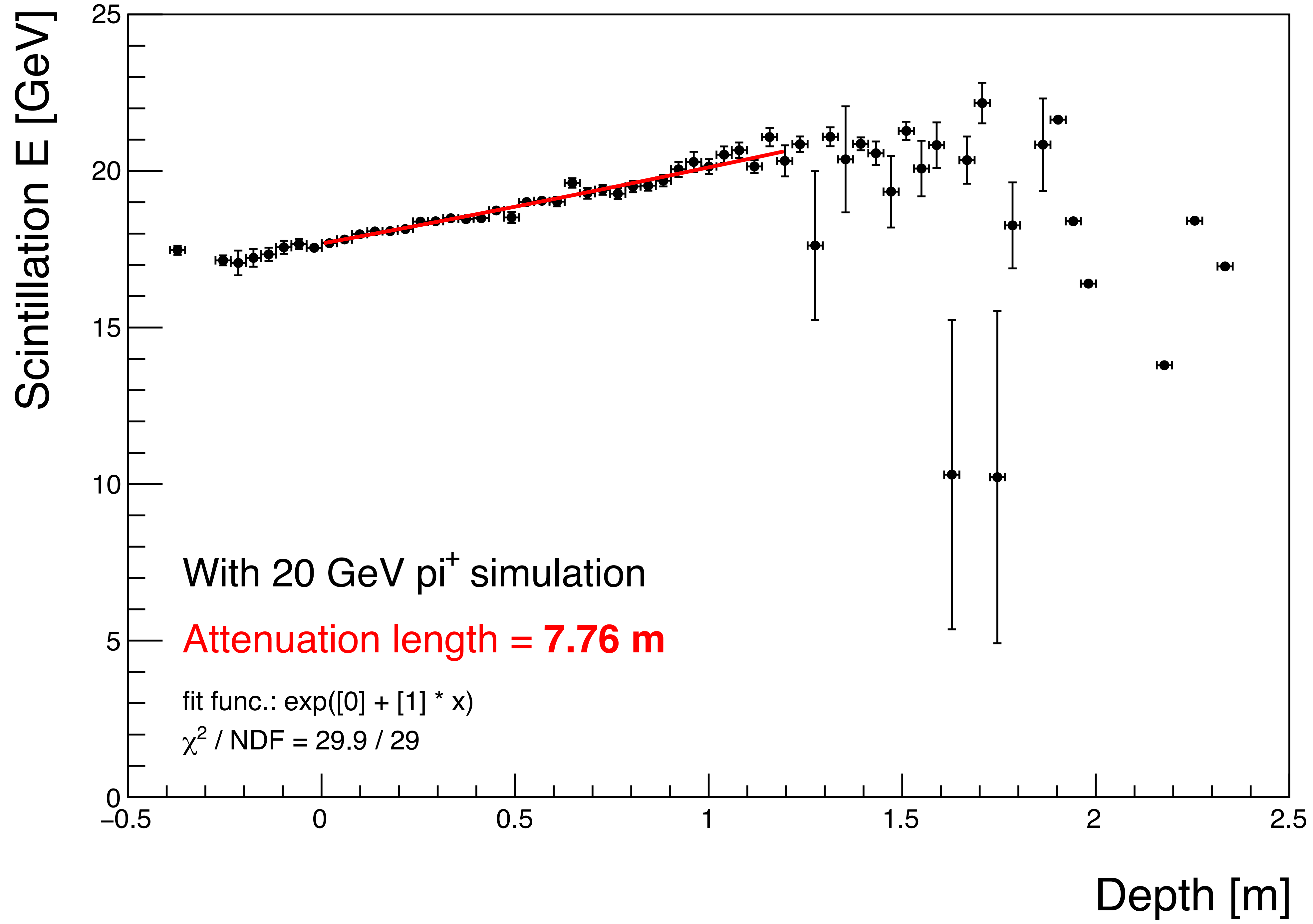


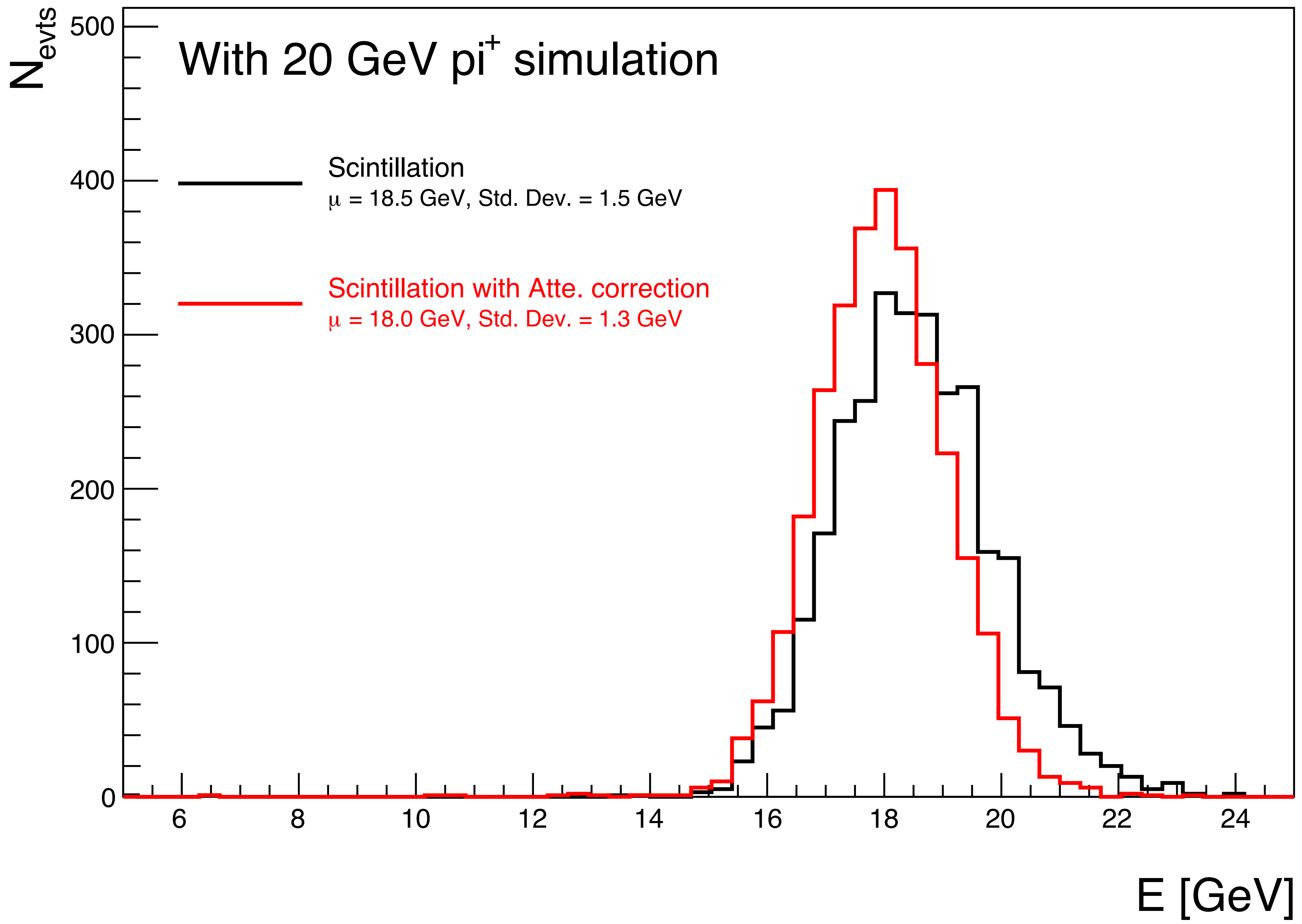
Attenuation

- ◉ **Hadronic particle's behavior in the calorimeter**
  - **Hadronic shower**
    - developed relatively **deeper than EM shower**
    - has **large depth fluctuation**
  - **Longitudinally unsegmented** fiber calorimeter
    - shower affected **different amount of attenuation w.r.t the depth** of shower development
  - **To moderate this effect**, **attenuation length** for the scintillation fiber is estimated and **utilized to the correction**

Shower shape developed from hadronic particle



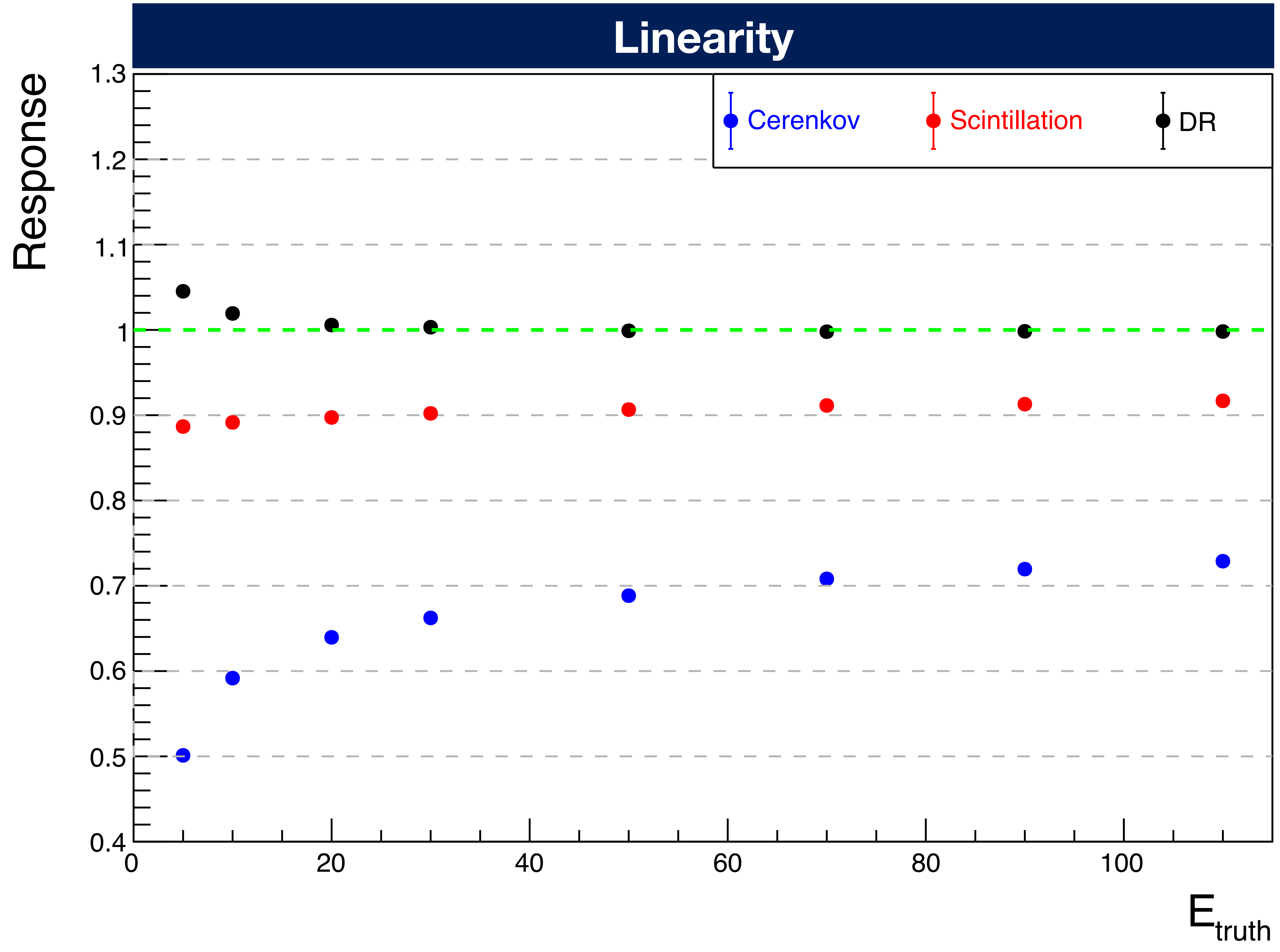


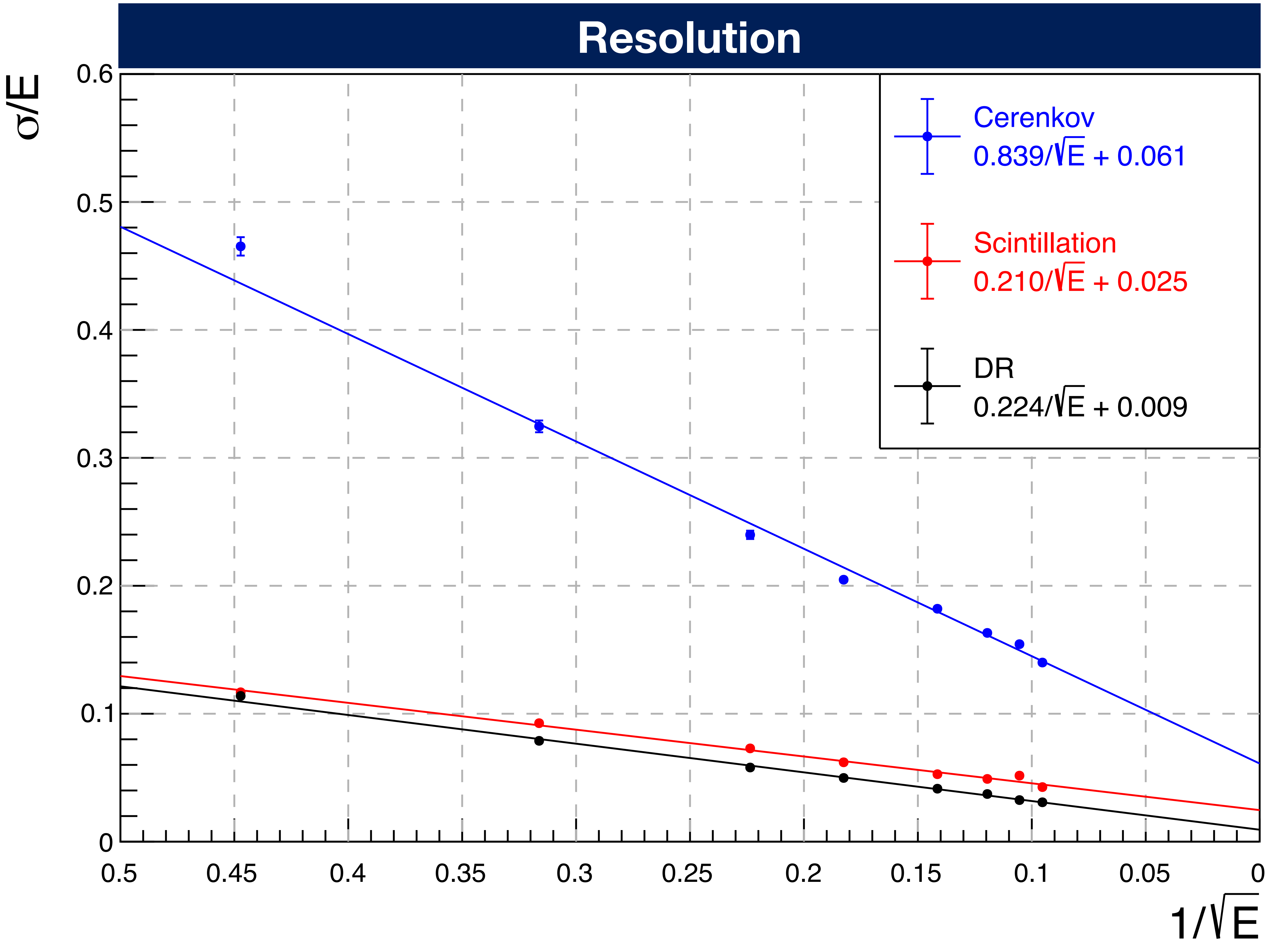


Hadronic Energy Resolution

◉ Hadronic energy resolution with 5 ~ 110 GeV pi+ simulation

- Resolution result for each energy is **scaled to 1 / √E**
- **Attenuation correction** is applied to scintillation channel
- Dual-Readout correction shows **~ 22.4% stochastic term for the hadronic energy resolution**





Jet Events

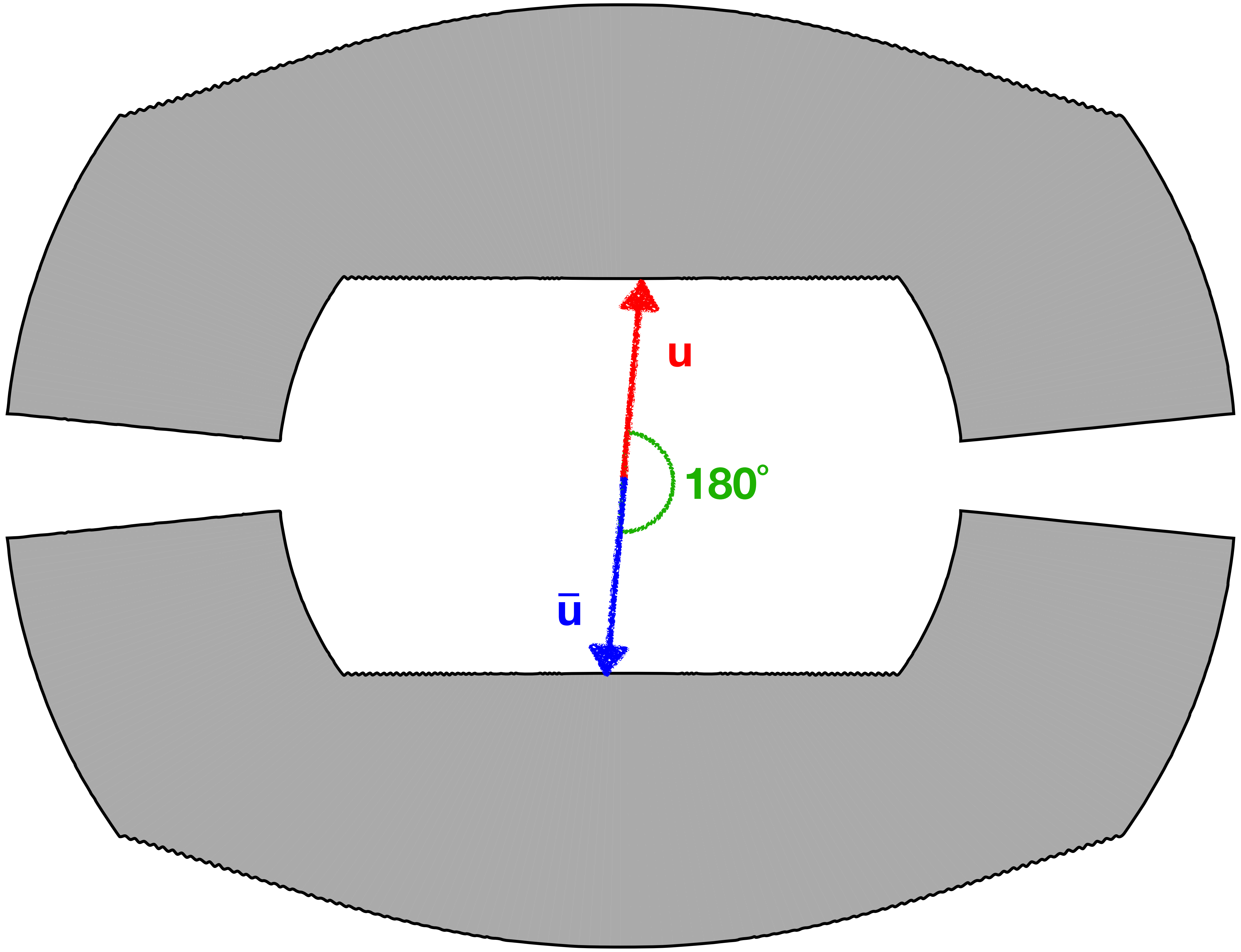
◉ Jet events for the simulation

- **To get a quark have being hadronized,** satisfaction of the **color confinement** is mandatory
  - **u and ubar quarks are generated simultaneously**
- **To make CoM energy zero**, generated quarks having **same energy with back-to-back direction**
- Events are **generated** and jets are **hadronized** with **Pythia8**

◉ Energy reconstruction with Jet events

- **Obtain energy response from whole detector**
  - e.g) **40 GeV** u and ubar quark event

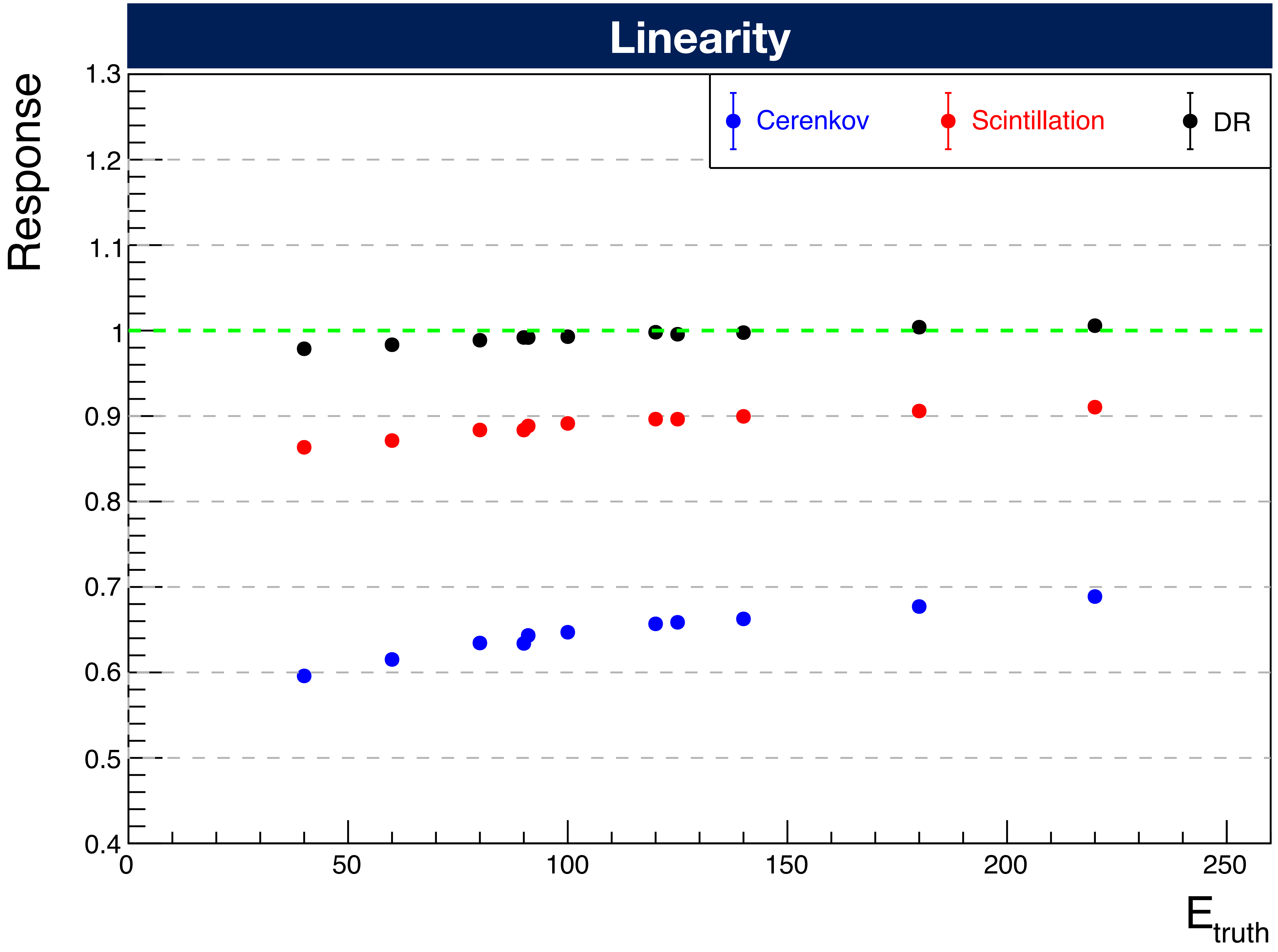
    ➡ corresponding energy is **80 GeV**

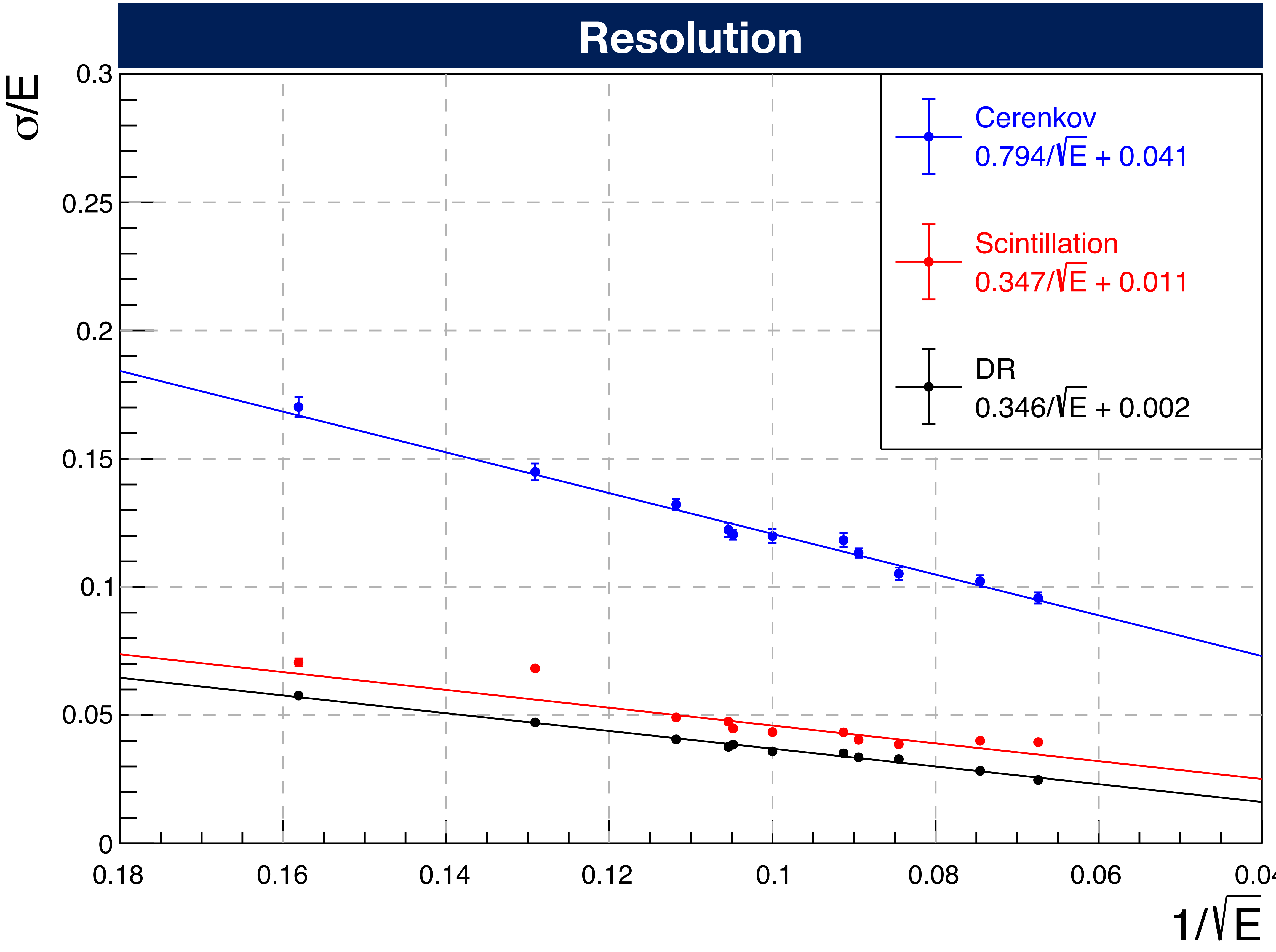


Jet Energy Resolution

◉ Estimation of Jet energy resolution with u quark jet simulation

- Generated u and ubar quarks have the energy from 20 GeV to 110 GeV
- Resolution result for each energy is **scaled to 1 / √E**
- Stochastic term of resolution: **34.6% stochastic term** → **with 100 GeV: 3.7% resolution**



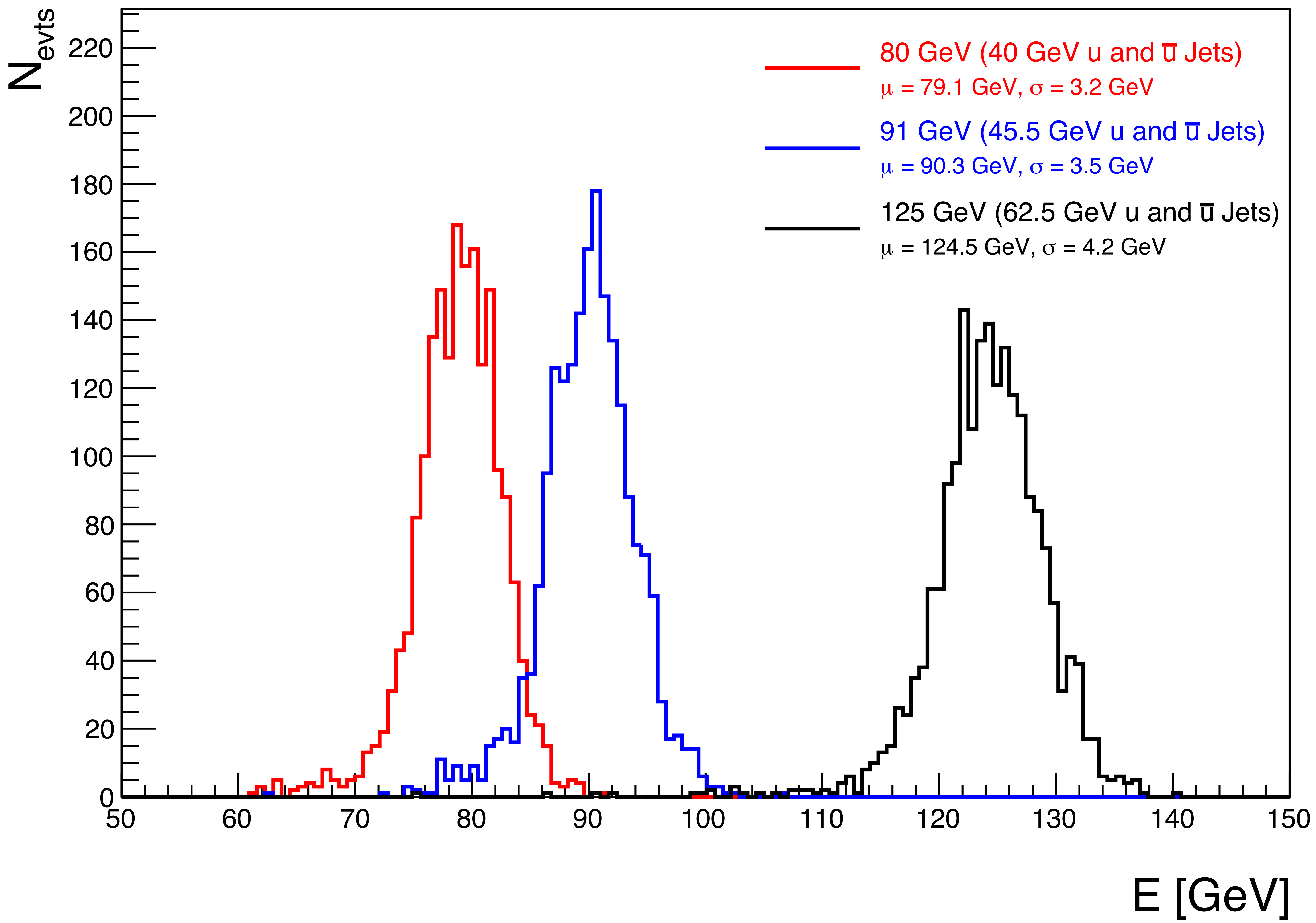


Energy Separation

Energy separation between the events with 80, 91 and 125 GeV u and ubar quark jets simulation

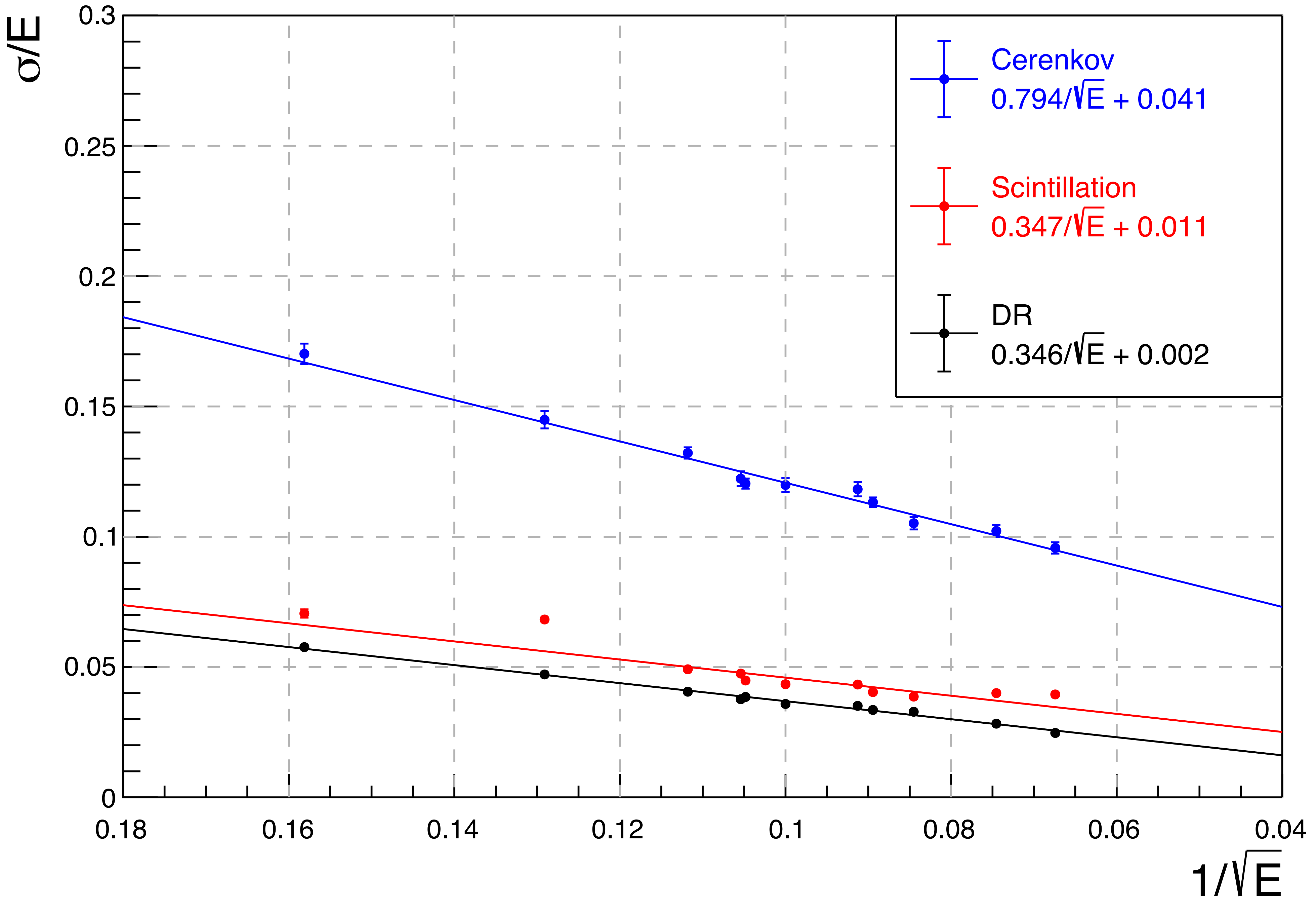
- As future collider experiment aiming to see Higgs, **mass separation between bosons is the most important aspect**
- The **DRC** shows **good separation** between the energies that correspond **the mass of bosons**

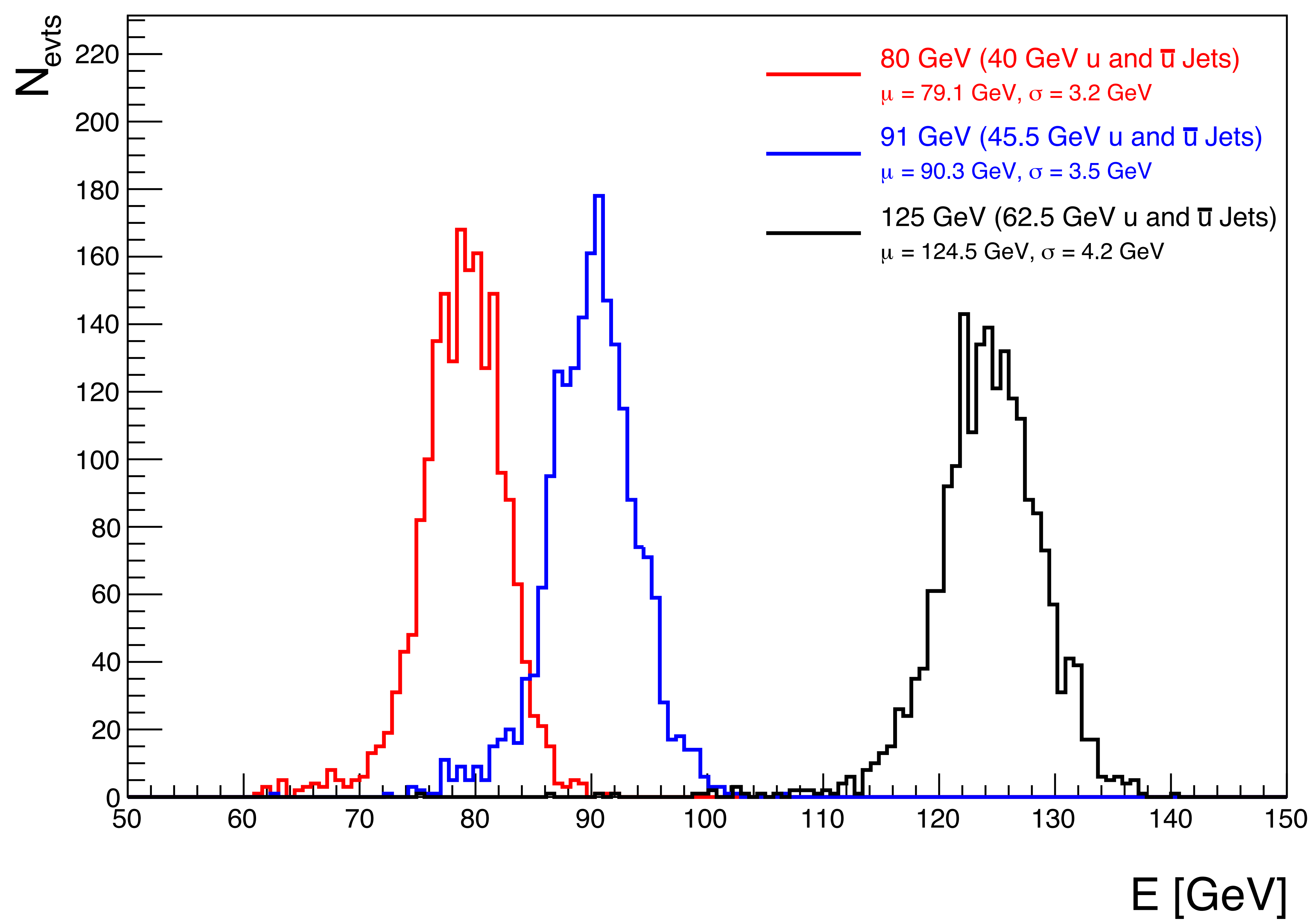
- **Each simulation correspond to the invariant mass of bosons**
  - e.g) 40 GeV u and ubar jet events
    ➡ 80 GeV ~ W inv. mass



Summary

- **Dual-Readout Calorimeter performance estimation with GEANT4 simulation**
  - **4pi full projective detector** with **full optical photon simulation via GEANT4**
  - **Full optical photon simulation was conducted**
  - **Energy Resolution** for EM, hadronic and jet energy resolutions are estimated
    - **Jet**: for 100 GeV jet, DRC has ~ **3.7%** resolution which **satisfies the requirement** of the future collider
  - **Energy separation with respect to bosons**
    - DRC shows that the energy corresponding each boson's mass are well separated



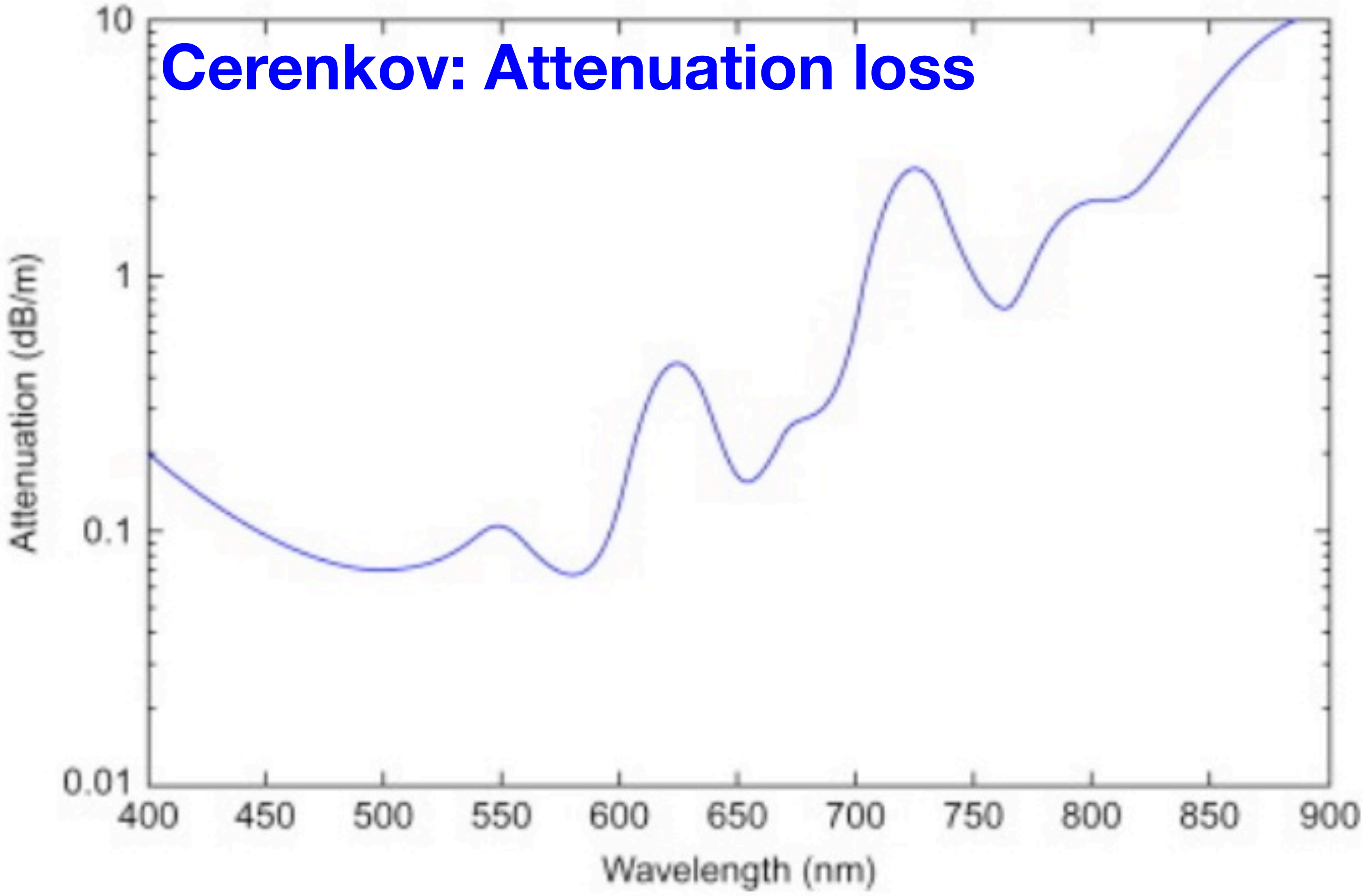


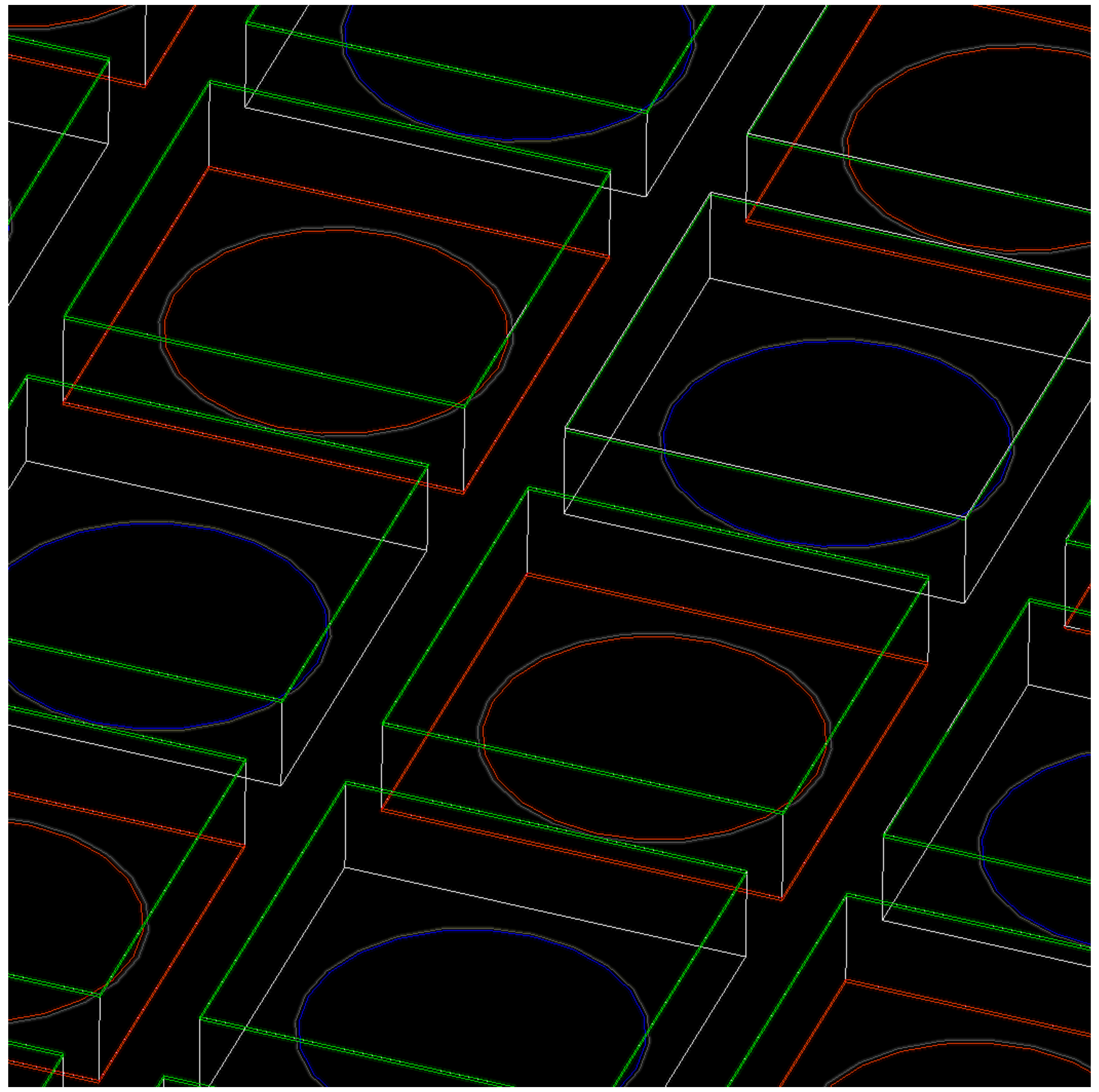
Back up

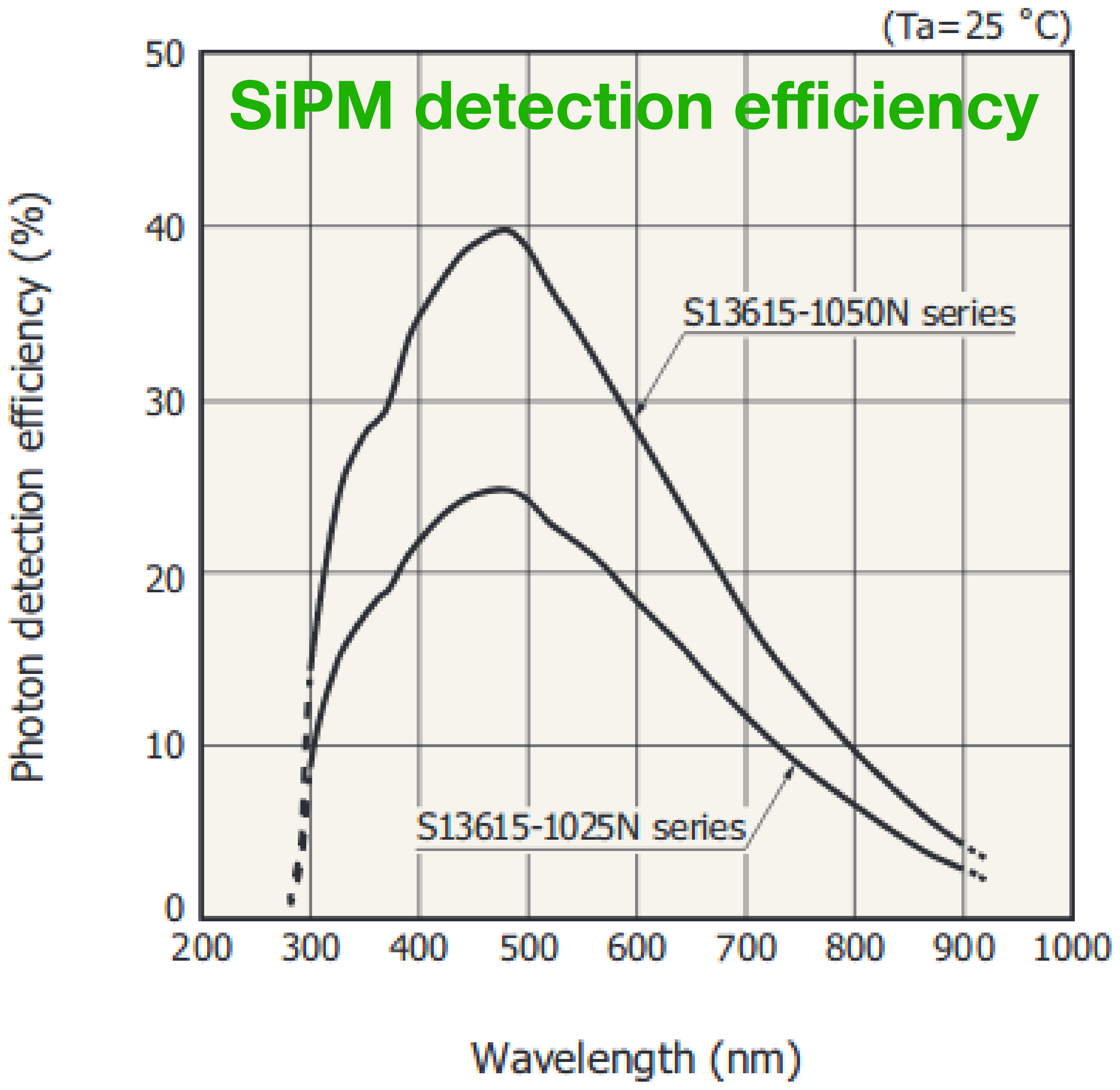
Resolution

1/√E

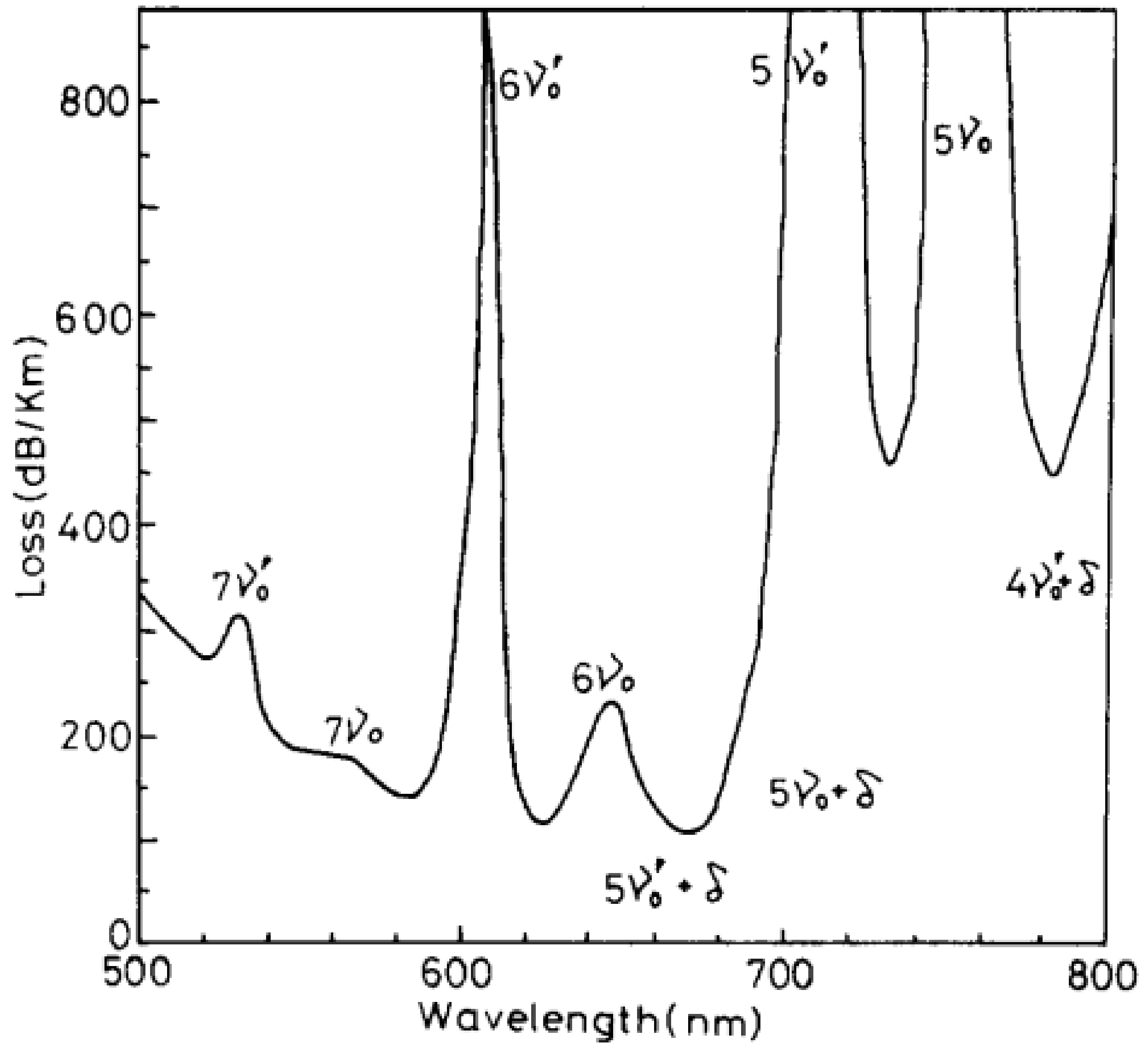
Optical Physics Setup

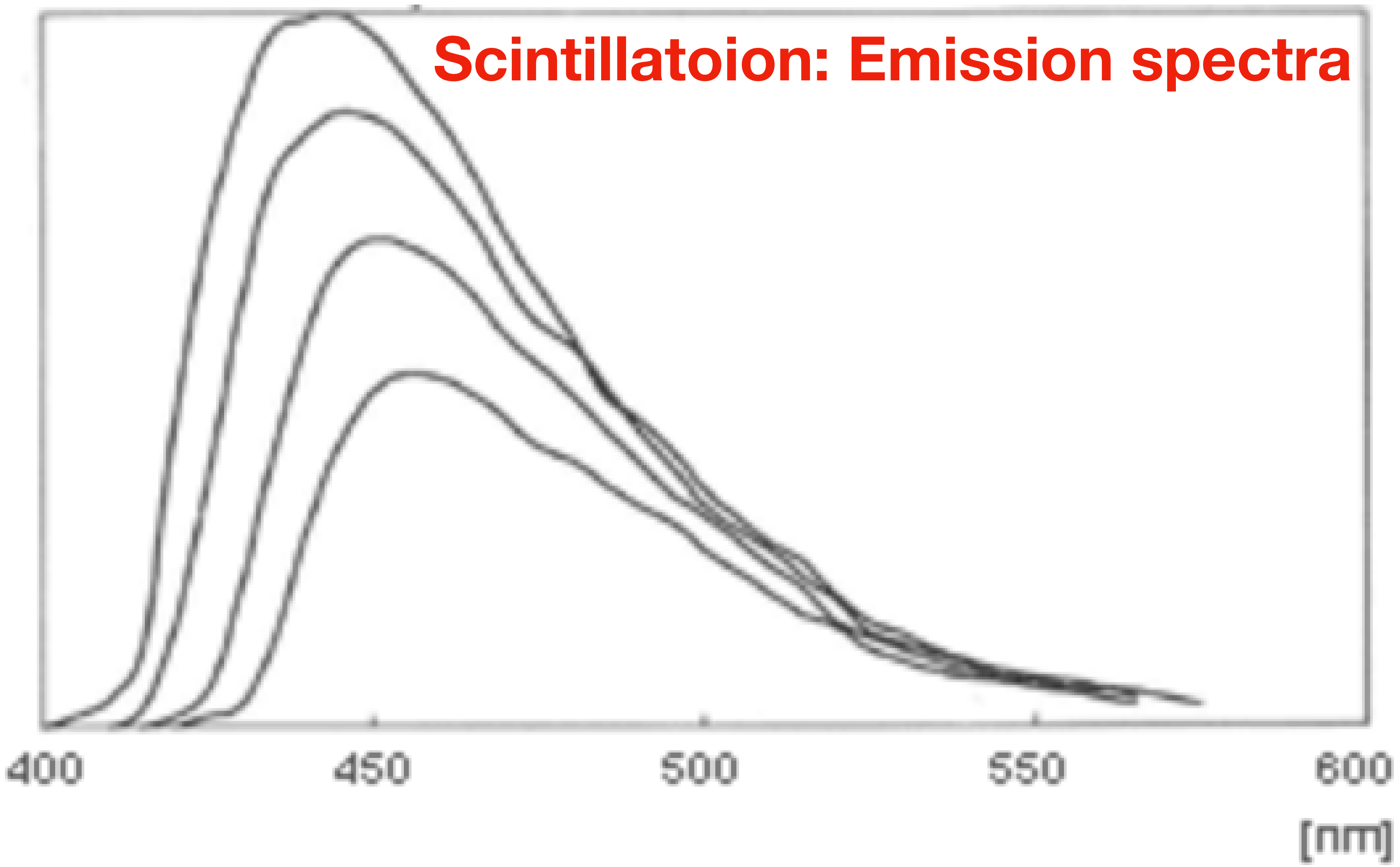


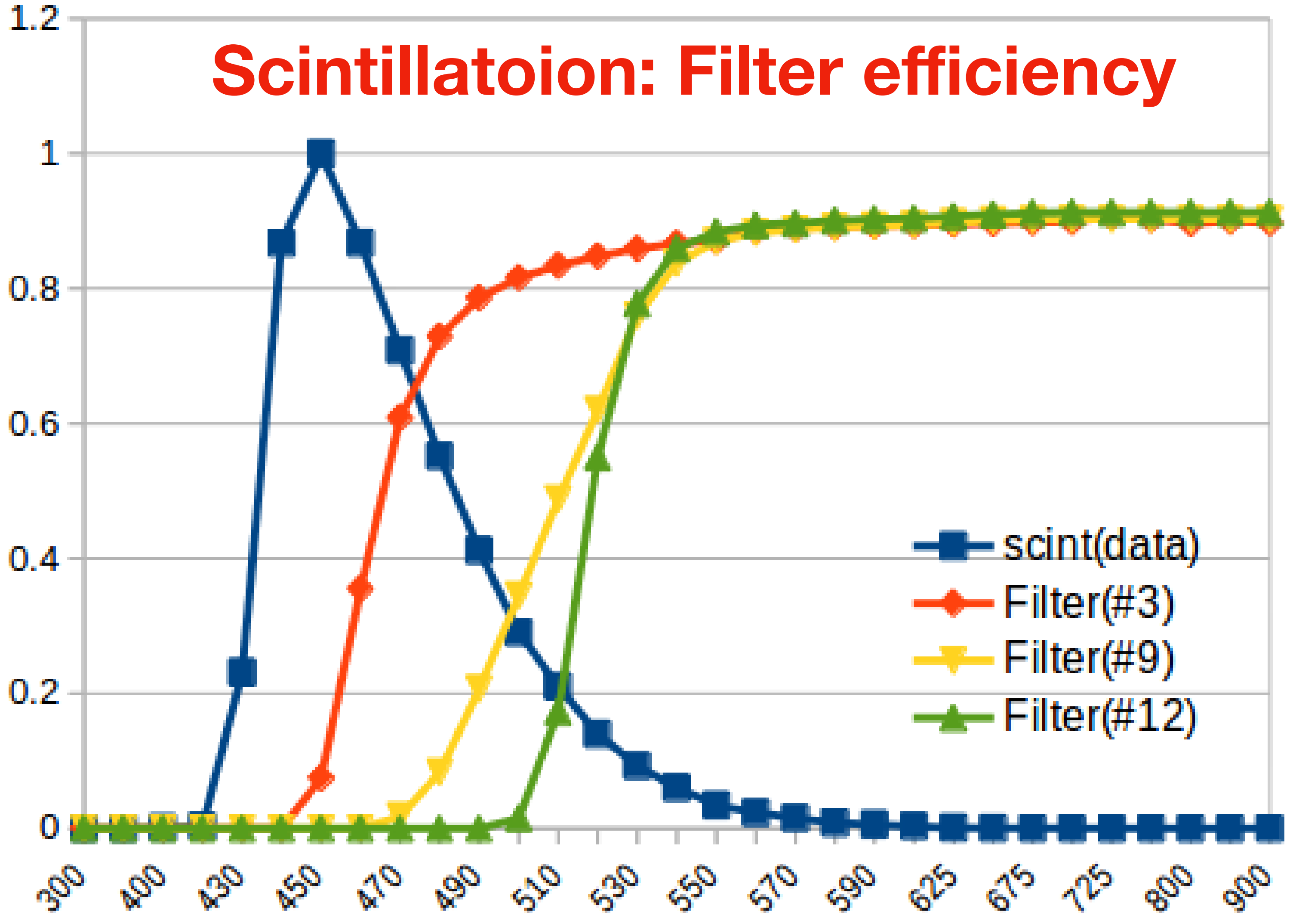




Scintillatoion: Attenuation loss

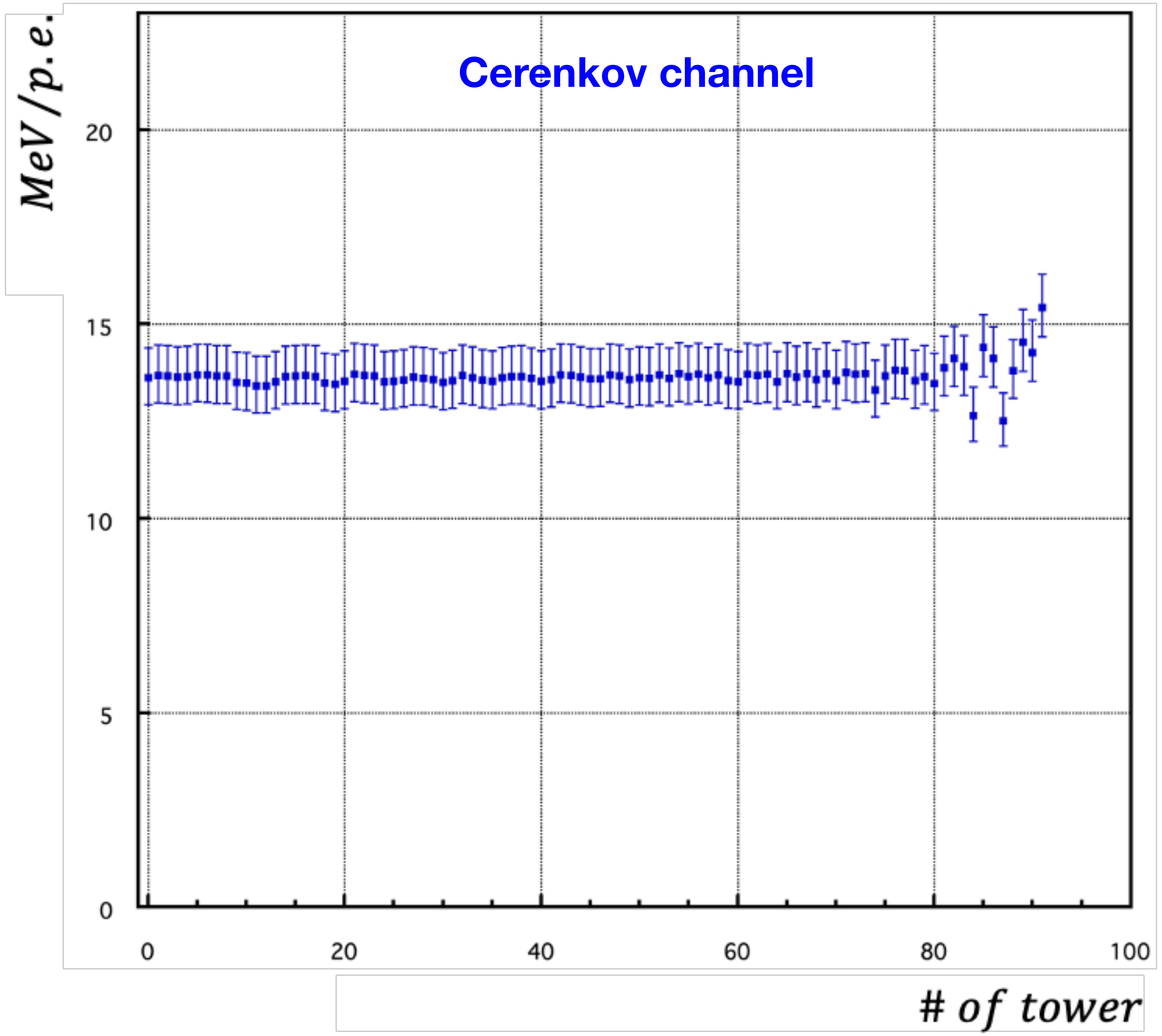


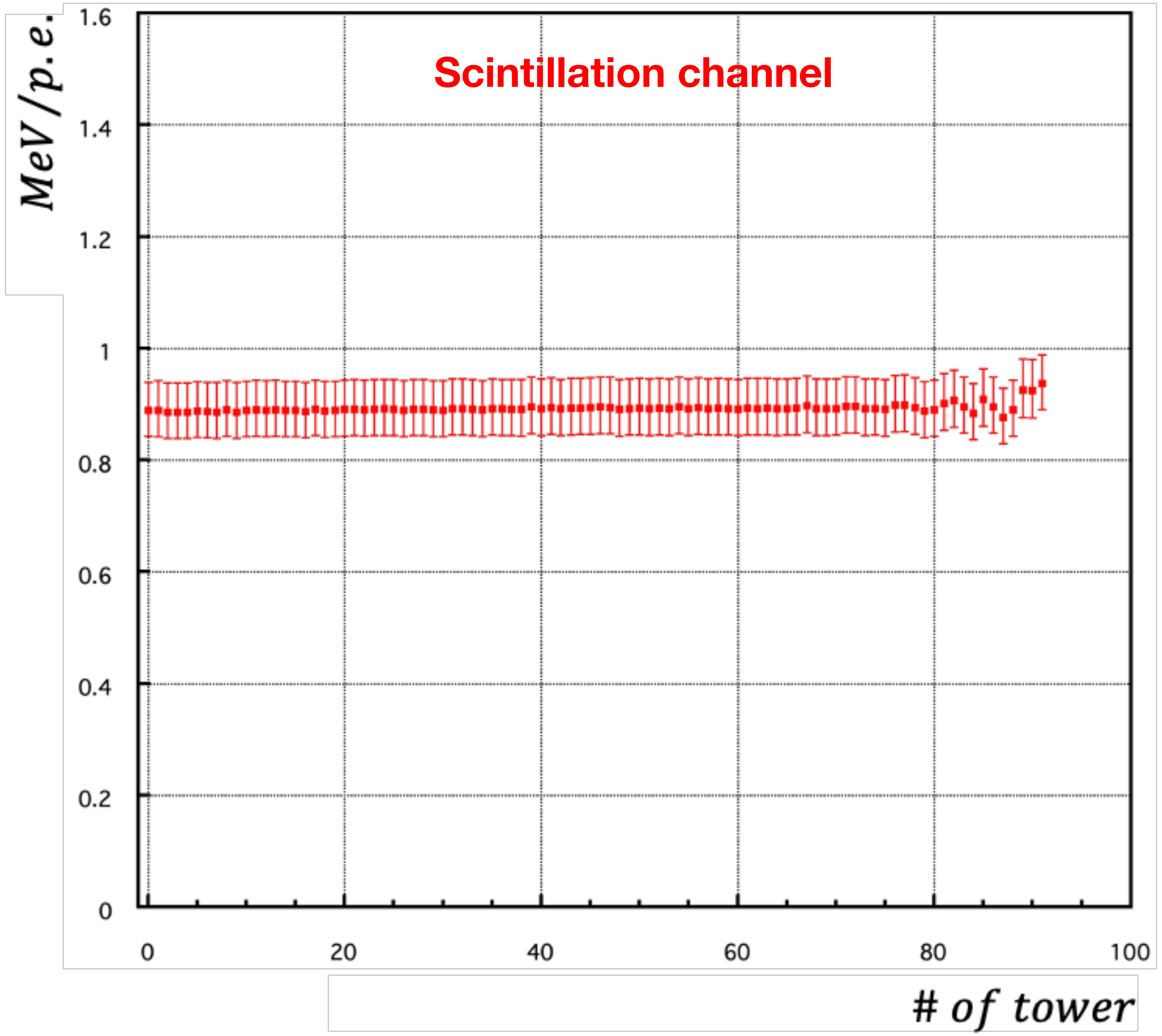




Calibration Constant Result

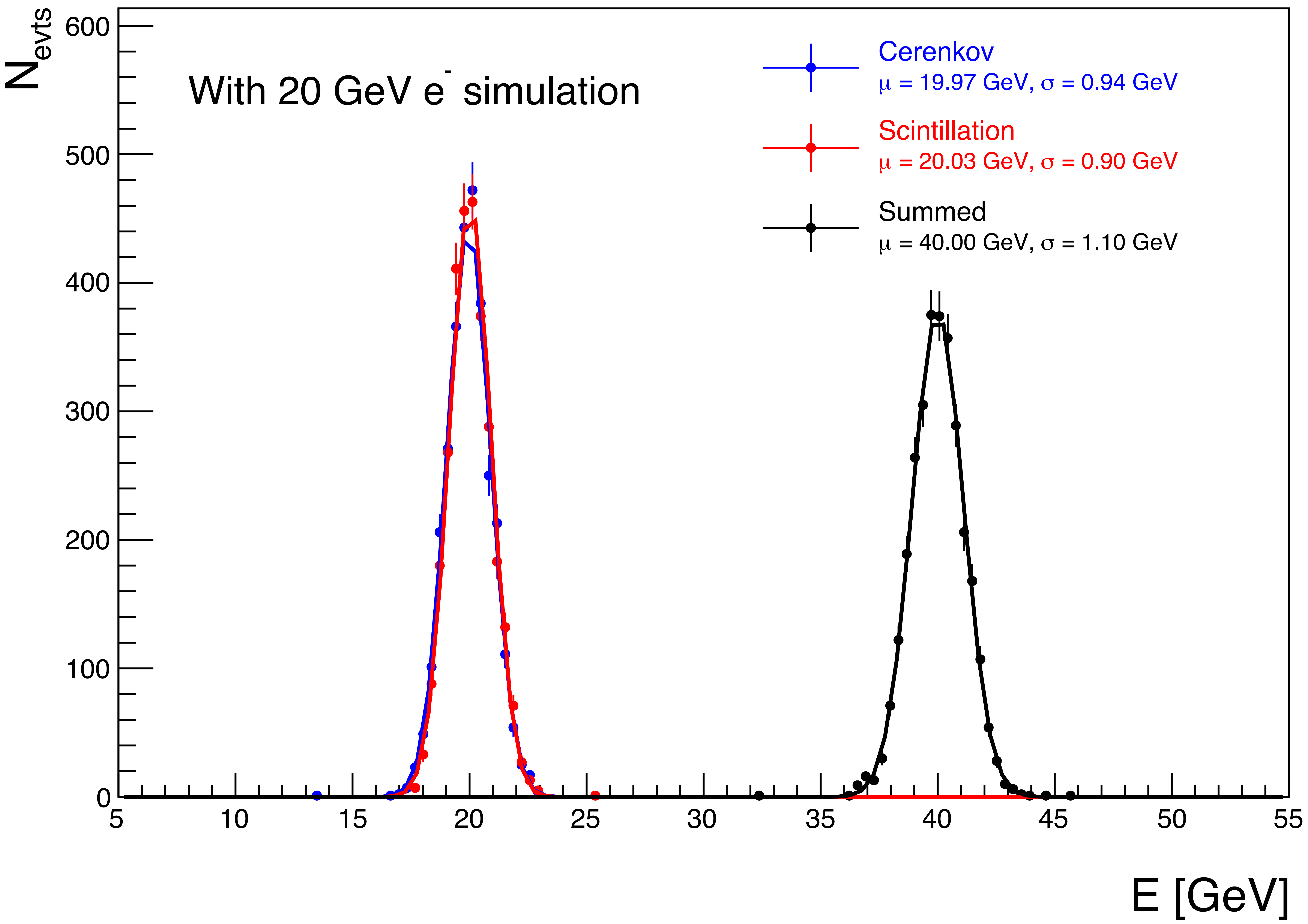
- Calibration constant extraction result shows very stable, which means that calibration is done well
  - Fluctuation from # of tower 80, it is came from the leakage due to no towers at far endcap region





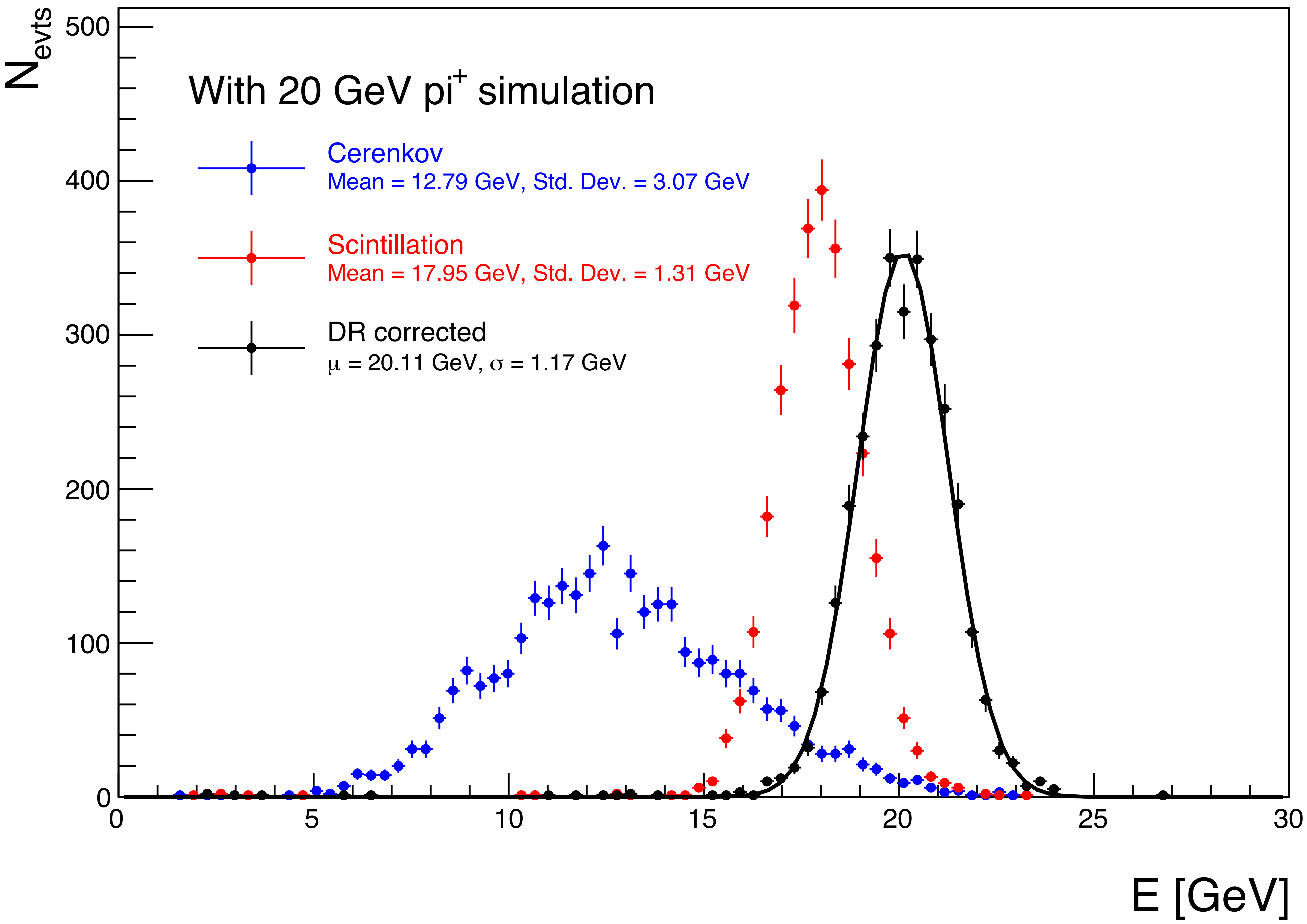
Example Simulation Result

- 20 GeV e- simulation



Example Simulation Result

- 20 GeV pi+ simulation



Example Simulation Result

- 40 GeV u and ubar jets simulation