Comparison of the Performance of the Dual-Readout Calorimeter for different absorbers

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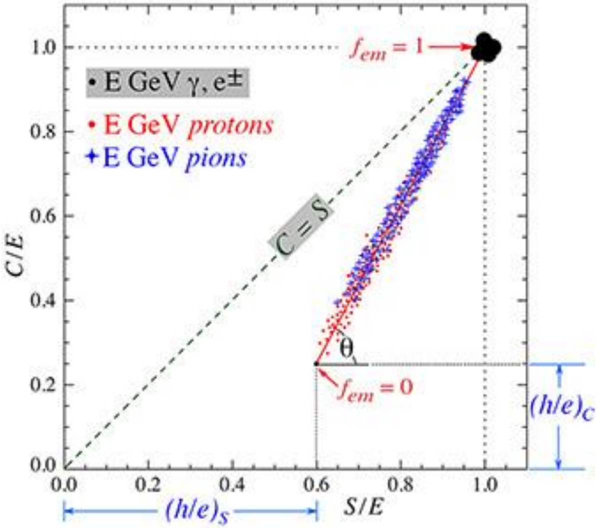
On behalf of the Korea Dual-Readout Calorimeter Team

Supported by

Introduction

Dual-Readout Calorimeter

- A major factor which makes hard to measure energy of hadronic particles is event-to-event fluctuations in fraction of EM shower components (f_{em}).
- The dual-readout method **allows to measure f_{em} of single event**, by using complementary information from scintillation and Cherenkov light – different response ratio to EM and non-EM shower components (e/h)

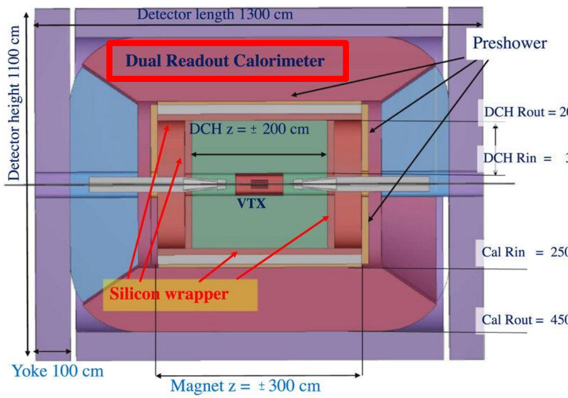


Nucl. Instrum. Meth. A 882 (2018)

1. $S, C = E[f_{em} + \frac{1}{(e/h)_{S,C}}(1 - f_{em})]$
2. $f_{em} = \frac{(h/e)_C - (C/S)(h/e)_S}{(C/S)[1-(h/e)_S] - [1-(h/e)_C]}$
3. $\chi \equiv cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C}$
4. $E = \frac{S - \chi C}{1 - \chi}$

$S, C :$ *Signals from scintillation | Cherenkov channel*

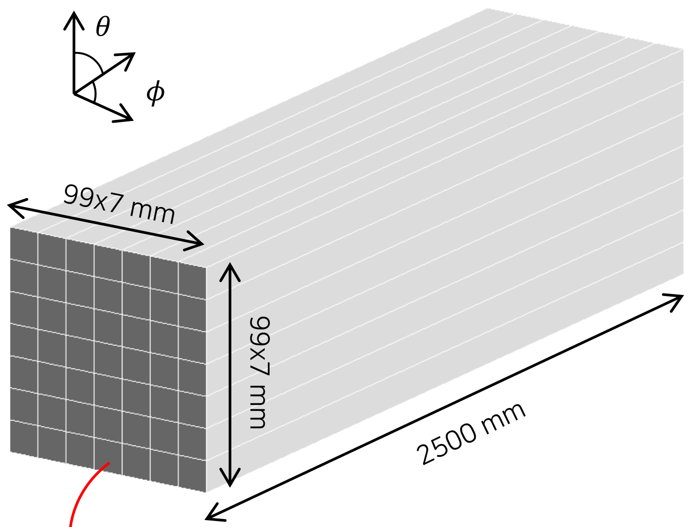
- Dual-Readout Calorimeter (DRC) can offer **excellent energy resolution for hadron showers, even for EM showers** – in single detector.
- DRC has been included in IDEA detector concept, which is proposed in conceptual design report (CDR) of FCC-ee & CEPC.
- On this talk, the comparison of absorbers for DRC, based on GEANT4 simulation will be presented.



Scehmatic figure of IDEA detetctor
Eur. Phys. J. Spec. Top. 228 (2019)

Simulation Setup

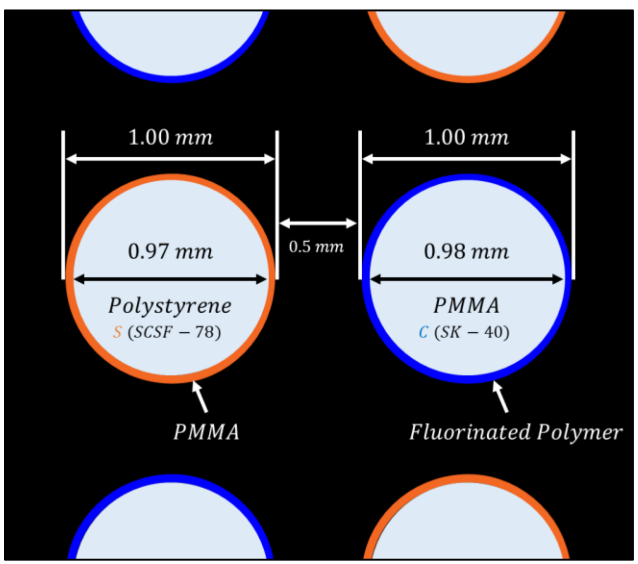
Geometry, physics setup

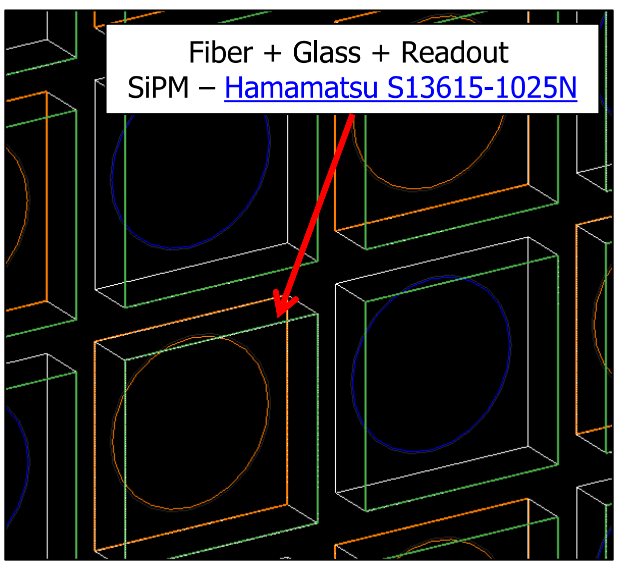


- Simulation setup is based on Geant4 toolkit, 10.5.p01, physics list FTFP-BERT.
- The geometry is **longitudinally unsegmented**, box shape, 7x7 modules.
- 5 different absorbers were used –

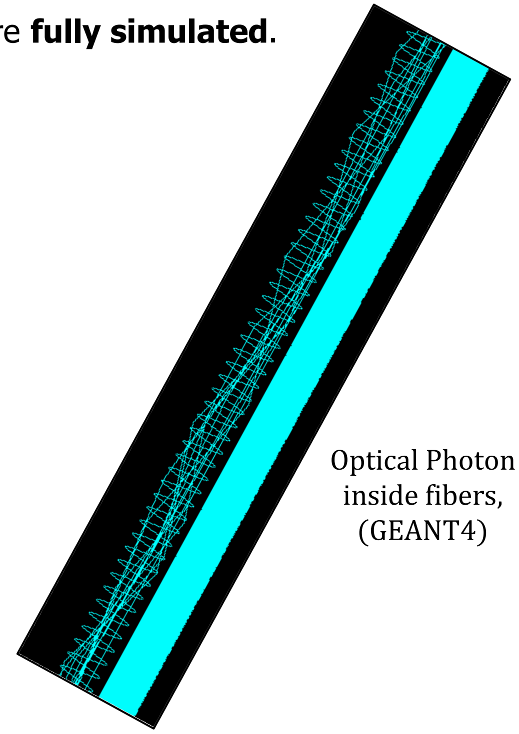
  Copper, Brass (Cu:Zn=7:3), Iron, Lead, Tungsten

- 1mm diameter scintillating & Cherenkov (Clear) optical fibers are implemented.
- **Optical physics process** inside fibers are **fully simulated**.
- SiPM is attached for each single fibers.





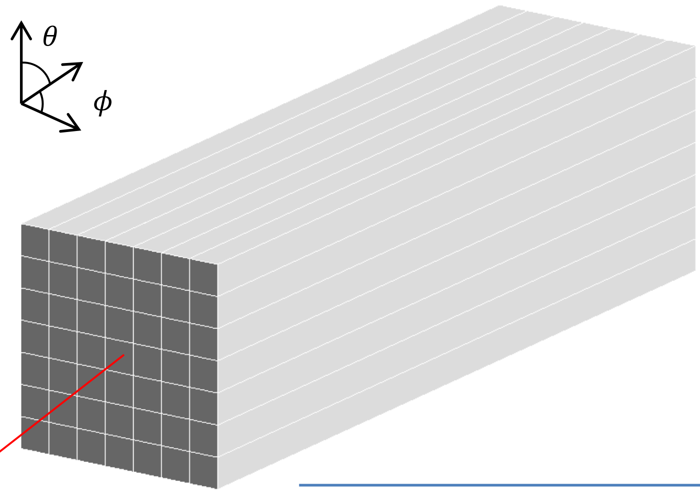
Rearside of module (GEANT4)



Optical Photon inside fibers, (GEANT4)

Simulation Setup

Calibration

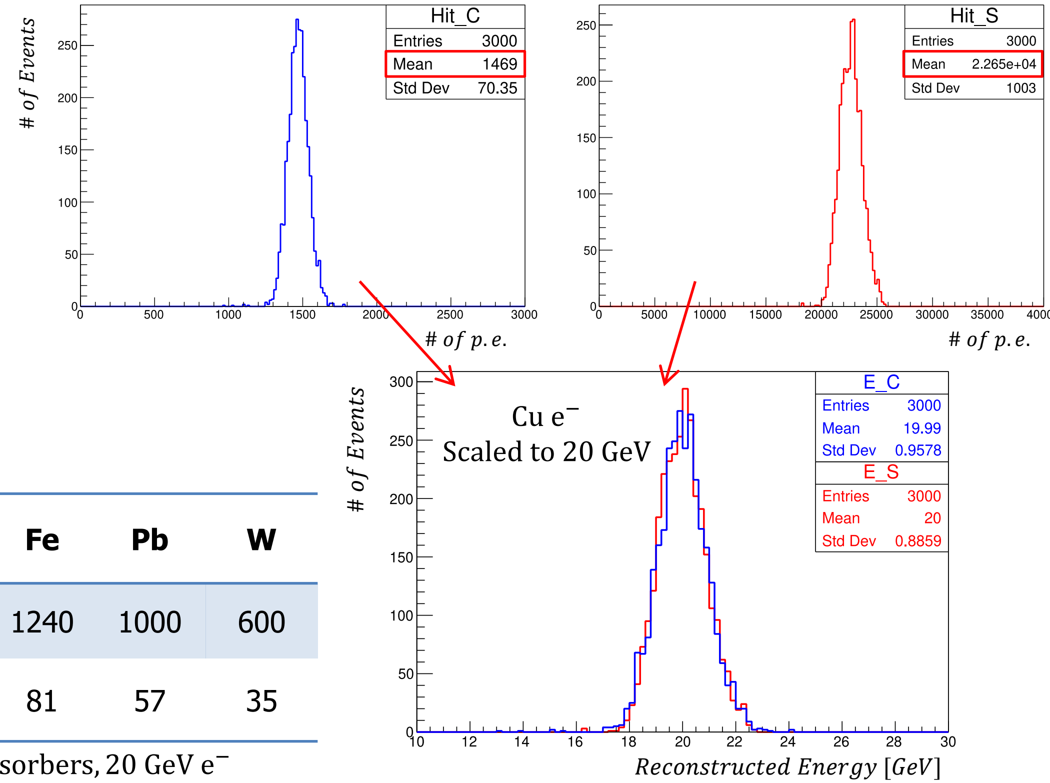


$(\theta, \phi) = (1.5°, 1.0°)$,
$10 \times 10\ \mathrm{mm}^2$ Beam Size

Light Yield	Cu	Brass	Fe	Pb	W
$S\ (\frac{\#of\ p.e.}{GeV})$	1130	1180	1240	1000	600
$C\ (\frac{\#of\ p.e.}{GeV})$	73	77	81	57	35

Light Yield of different absorbers, 20 GeV e^-

# of photoelectrons on S, C channels | Cu , 20 GeV e-

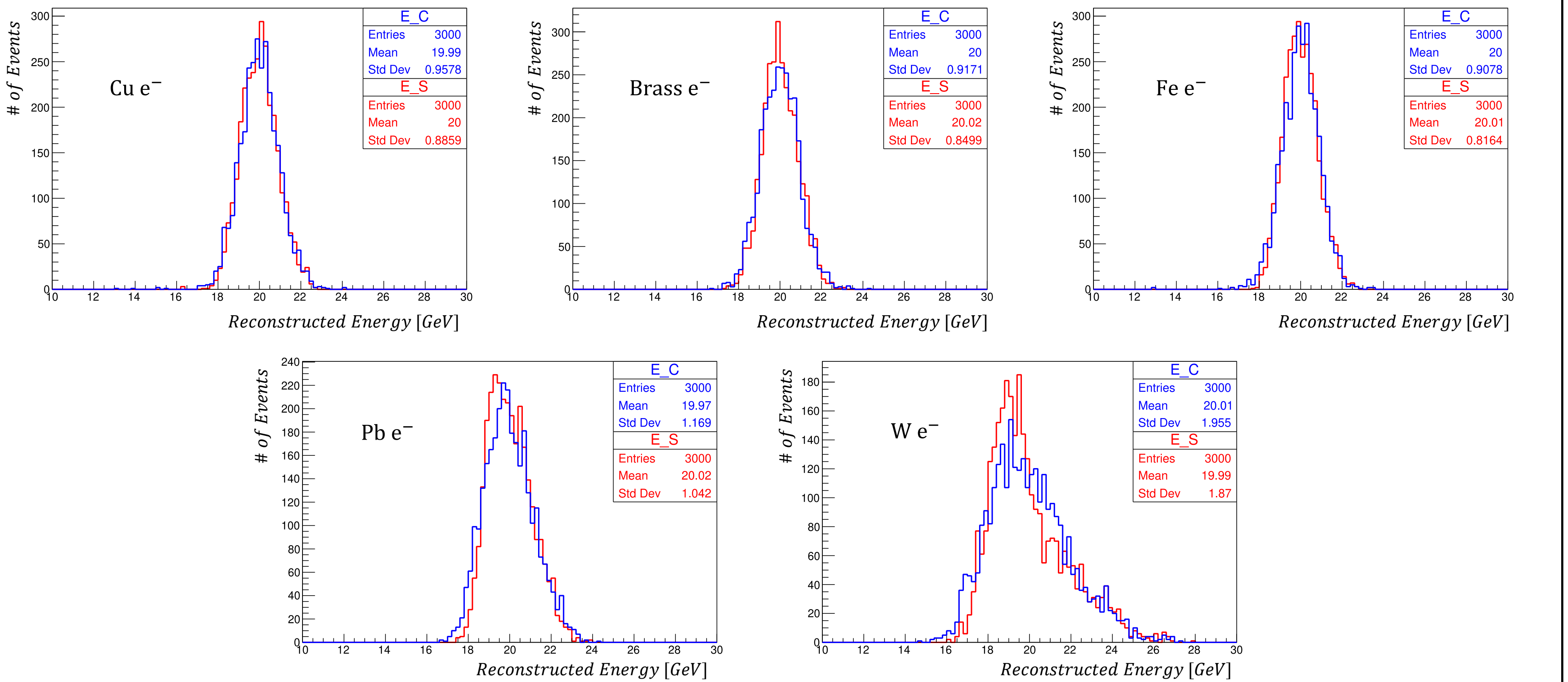


- Matched total energy deposit of **20 GeV electron** in entire module to signal of the scintillation and Cherenkov light. (# of p.e.)
- This obtained calibration constant was **applied to events of any particles**, including hadrons.
- Light yield of different absorbers show dependency generally on their Z value.
- For hadronic events, attenuation correction is applied.

Simulation Result

Single electron – Energy Distribution

Reconstructed Energy of 20GeV e- $(\theta, \phi) = (1.5°, 1.0°)$



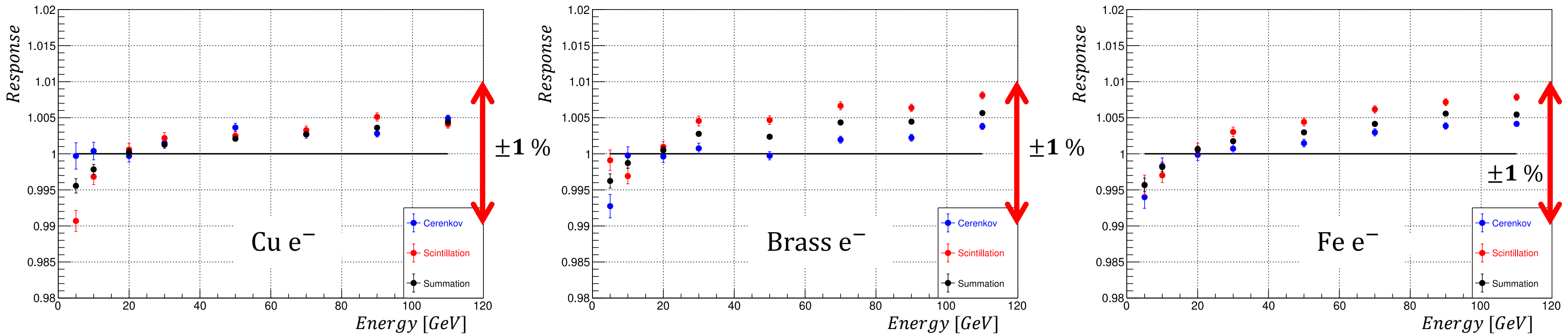
- The signal gets highly **dependent on impact point** as the Z value (~radiation length) of absorber gets bigger.
- This affects directly on energy resolution.

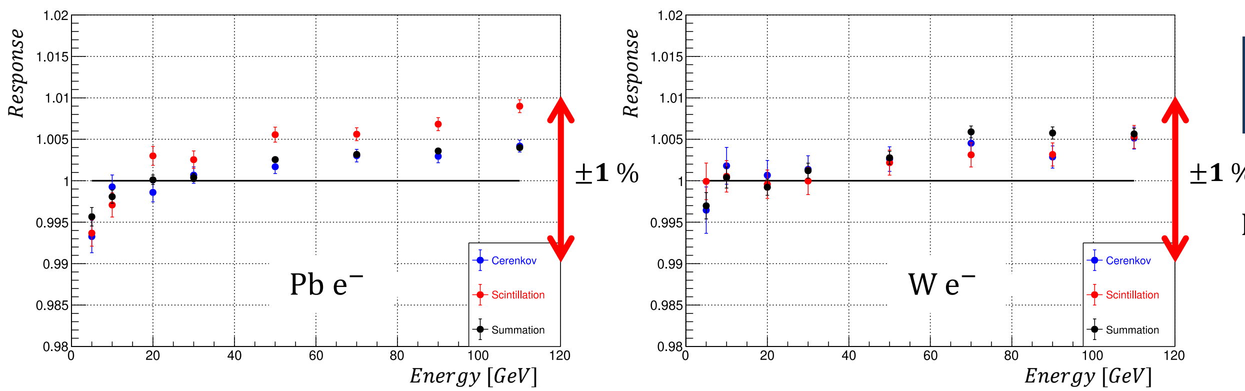
Abosrber	Cu	Brass	Fe	Pb	W
Radiation Length (cm)	1.436	1.528	1.757	0.561	0.350

Radiation length of absorbers (pdg)

Simulation Result

Single electron – Energy Linearity





Energy linearity of electron, 5~110 GeV, $(\theta, \phi) = (1.5°, 1.0°)$

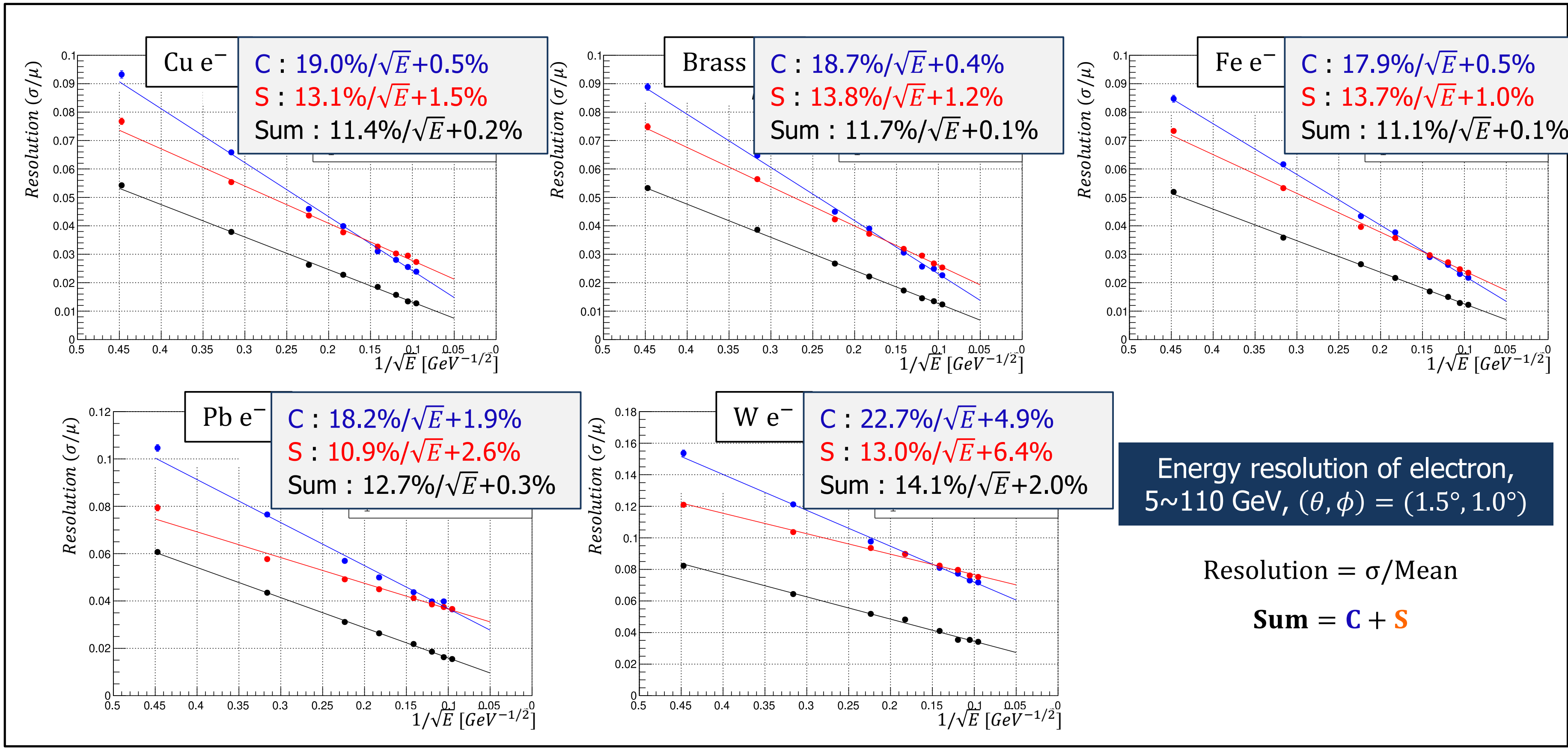
$\text{Response} = \text{Reco. E/Incident Energy}$

$\textbf{Summation} = \textbf{C} + \textbf{S}$

- Used mean & RMS of guassian fit function of reconstructed energy – Scintillation, Cherenkov, and Summation channel.
- Energy linearity of electrons, 5, 10, 20, 30, 50, 70, 90, 110 GeV.
- Regardless of energy or absorber, **energy linearity matches in $\pm 1\%$**

Simulation Result

Single electron – Energy Resolution



Energy resolution of electron, 5~110 GeV, $(\theta, \phi) = (1.5°, 1.0°)$

$\text{Resolution} = \sigma/\text{Mean}$

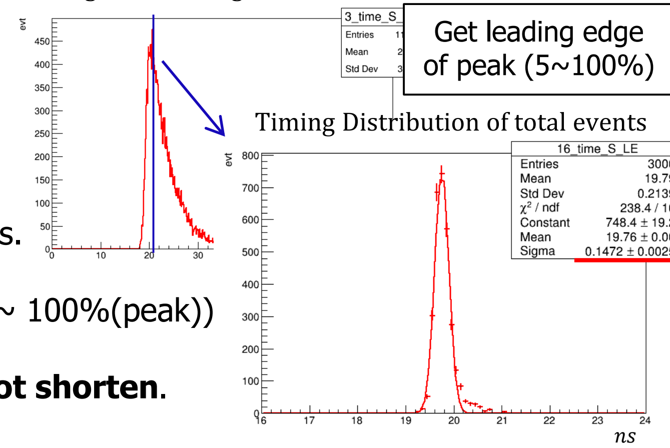
$\textbf{Sum} = \textbf{C} + \textbf{S}$

- Used mean & RMS of guassian fit function of reconstructed energy – Scintillation Cherenkov, and Summation channel.
- Energy resolution of electrons, 5, 10, 20, 30, 50, 70, 90, 110 GeV.
- **Low Z absorbers show relatively better resolution than Pb, W – 11~12% of stochastic term.**

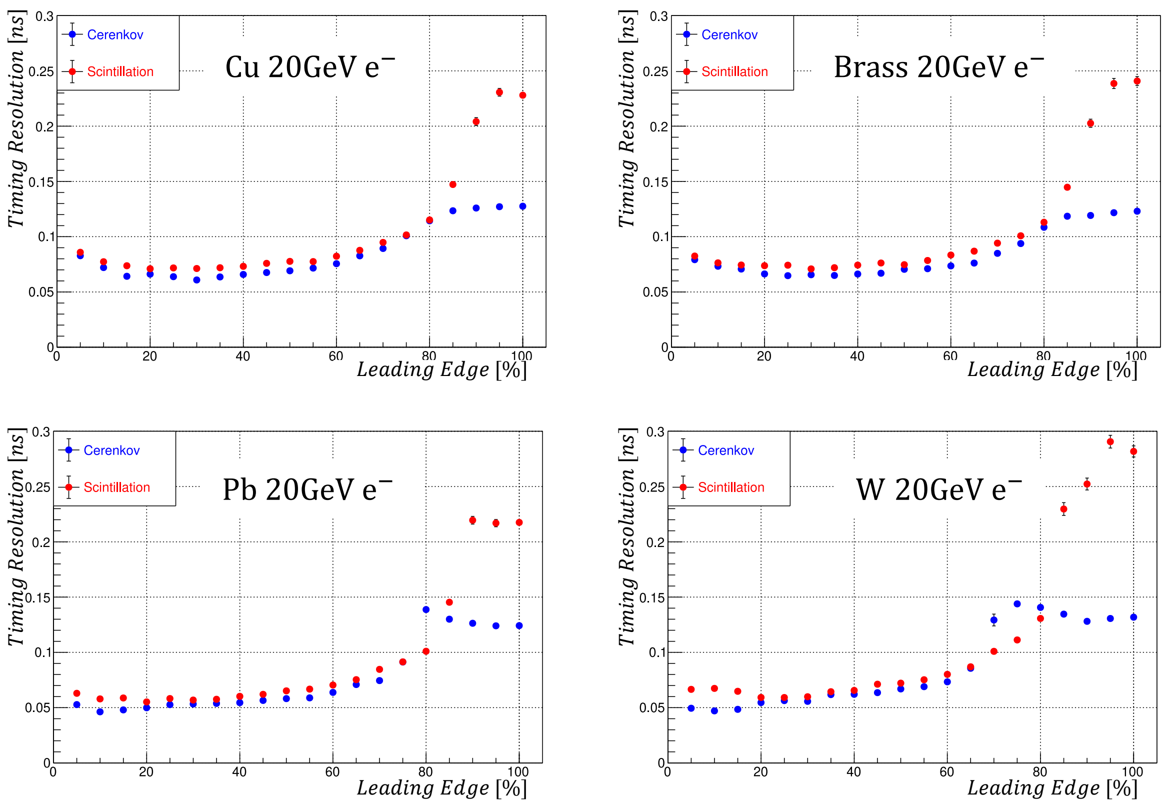
Simulation Result

Single electron – Timing Resolution

Timing of S ch., single event



- Timing resolution could be calculated using timing distribution of each single events.
- Used 20 GeV electron events, took sigma of distribution of timing leading edge (5 ~ 100%(peak))
- Comparing 30% leading edge results, the **timing resolution got better as X_0 got shorten**.



Timing resolution of electron, 20 GeV, $(\theta, \phi) = (1.5°, 1.0°)$

$Resolution = \sigma \; of \; timing \; distribution$

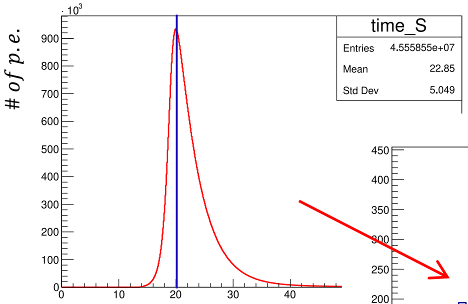
30% L.E.	Cu	Brass	Fe	Pb	W
S (ps)	71.2	70.9	78.5	56.9	59.9
C (ps)	60.9	65.6	71.2	53.3	55.7

$\sim \pm\; 1\; ps\; uncertainty$

Simulation Result

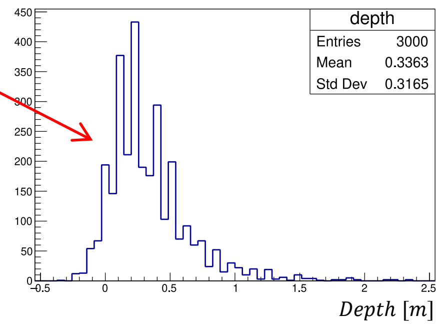
Hadronic particle – Attenuation correction

- For hadrons, they deposit energy in deeper inside than EM particles, which is used to calibrate energy.
- Since the distance between shower maximum and readout differ event by event, **attenuation correction** for light inside optical fiber is needed – **only for scintillation**, since attenuation length of scintillation fiber is far more shorter than Cherenkov fiber.

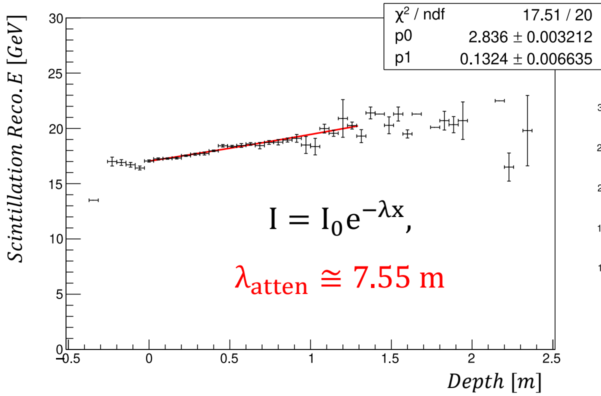


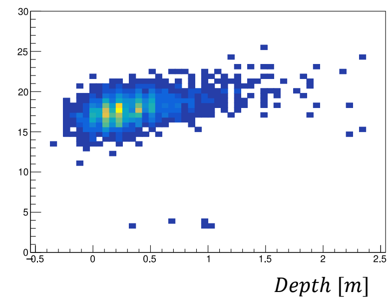
Get peak of timing event by event

Calculate depth (TOF method)

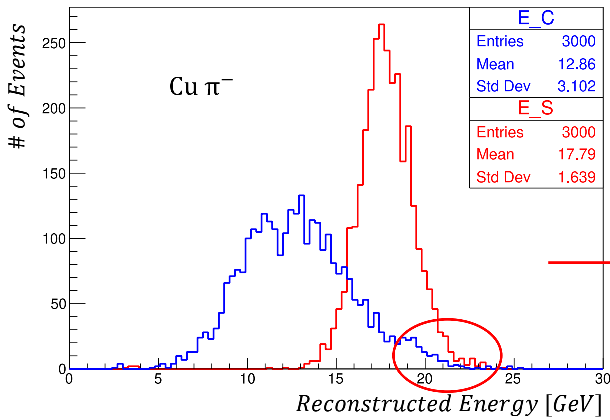


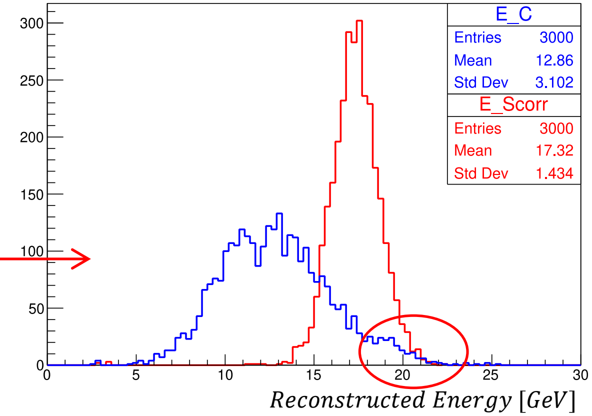
Reco S ch. Energy / Depth | 20 GeV π^-, Cu





Reco Energy, Before / After Attenuation Correction



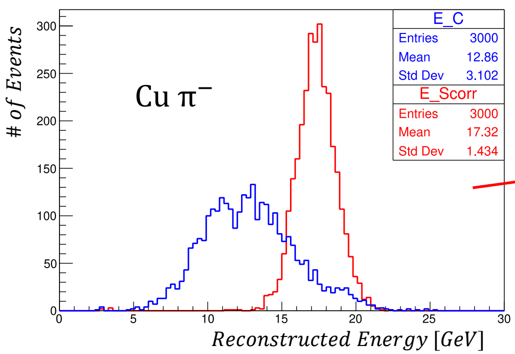


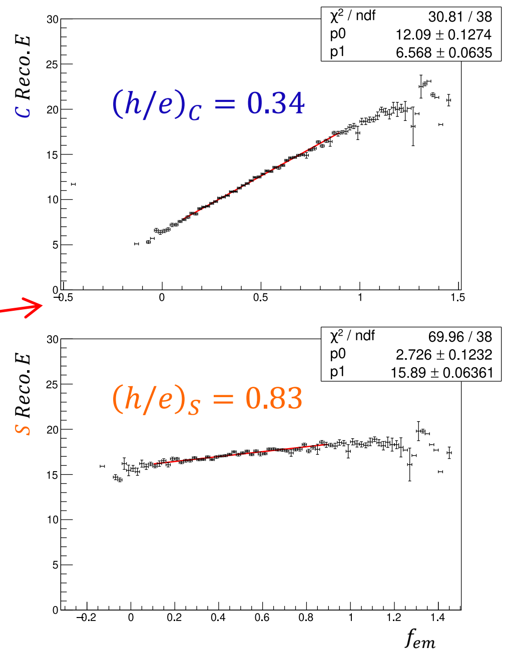
Simulation Result

Hadronic particle – h/e calculation

DREAM FOR FUTURE

- To apply dual-readout correction on hadronic events, **h/e (response to hadronic / EM) ratio should be calculated** for each absorbers.
- h/e ratio can calculated by scanning their values from 0~1.0, finding the value where the reconstructed energy best matches to the initial beam energy at $f_{em} = 1$.

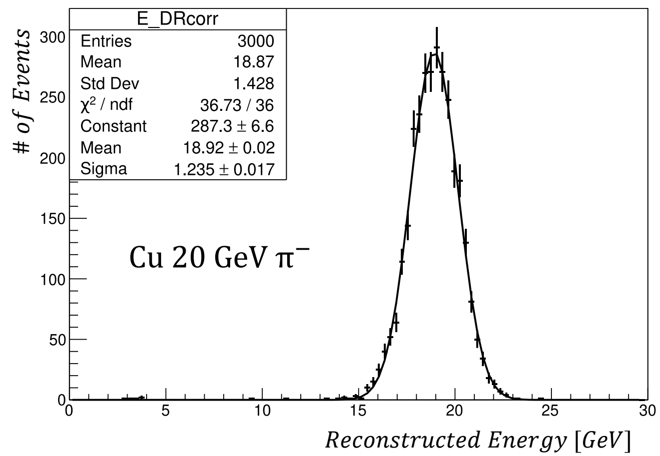




Using equations

1. $S, C = E[f_{em} + \frac{1}{(e/h)_{S,C}}(1 - f_{em})]$
2. $f_{em} = \frac{(h/e)_C - (C/S)(h/e)_S}{(C/S)[1-(h/e)_S] - [1-(h/e)_C]}$
3. $\chi = \frac{1-(h/e)_S}{1-(h/e)_C}$
4. $E = \frac{S - \chi C}{1 - \chi}$

Dual Readout Corrected Energy



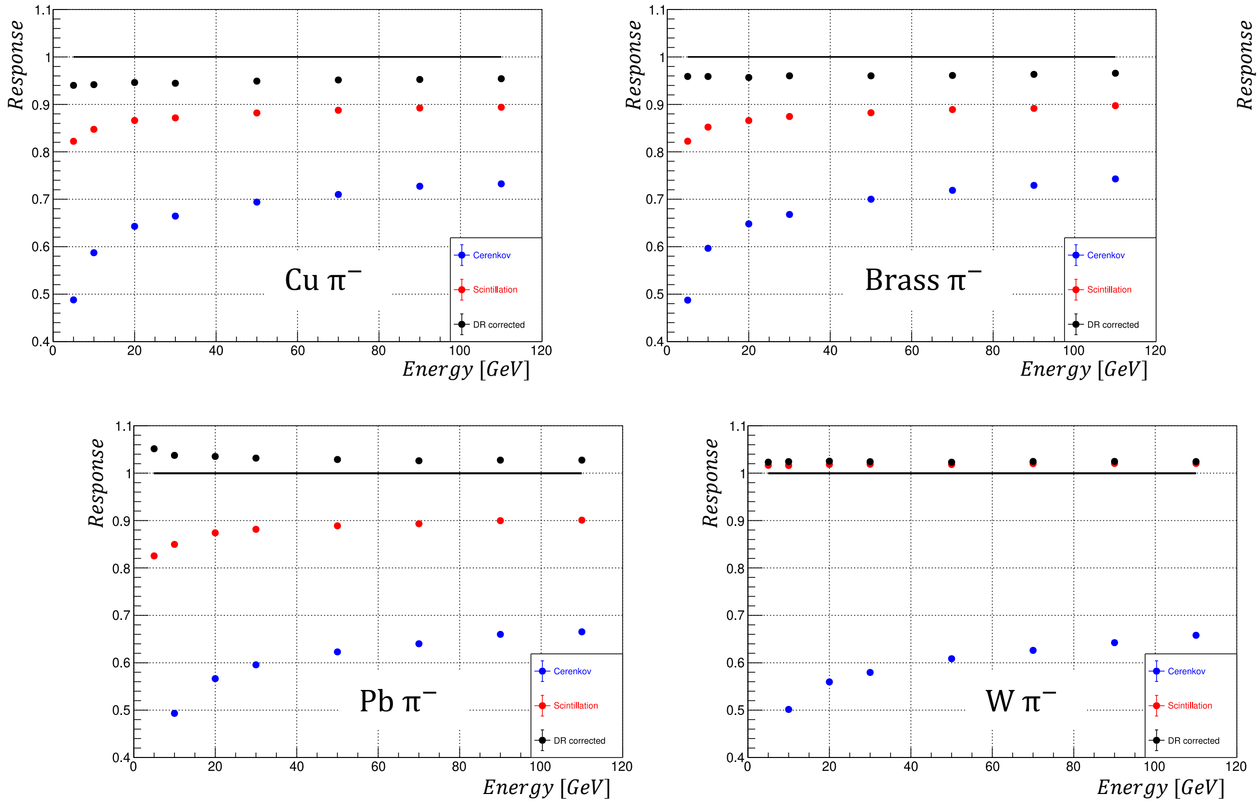
	Cu	Brass	Fe	Pb	W
χ	0.258	0.288	0.333	0.341	0.012

Calculated χ value of different absorbers

Simulation Result

Single charged pion – Energy Linearity

DREAM FOR FUTURE



Energy linearity of pion, 5~110 GeV, $(\theta, \phi) = (1.5°, 1.0°)$

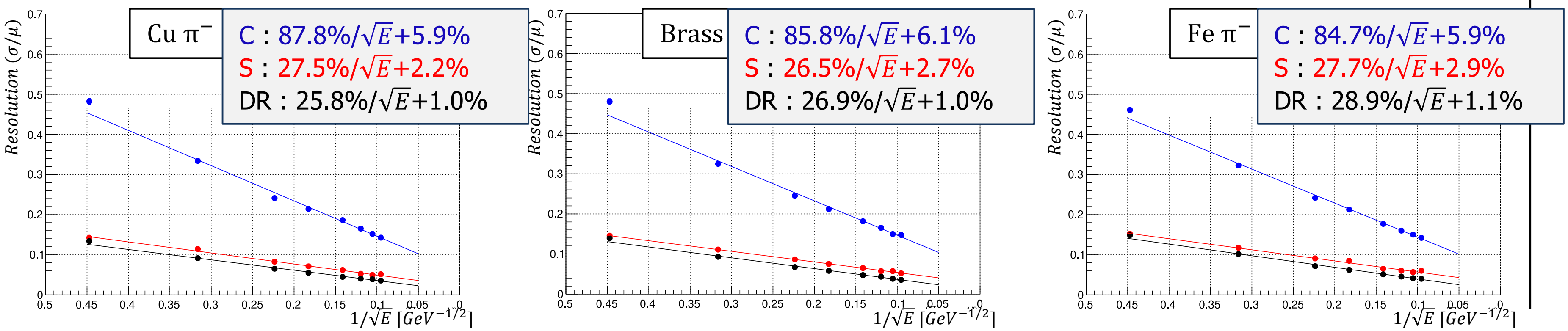
$\text{Response} = \text{Reco. E}/\text{Incident Energy}$

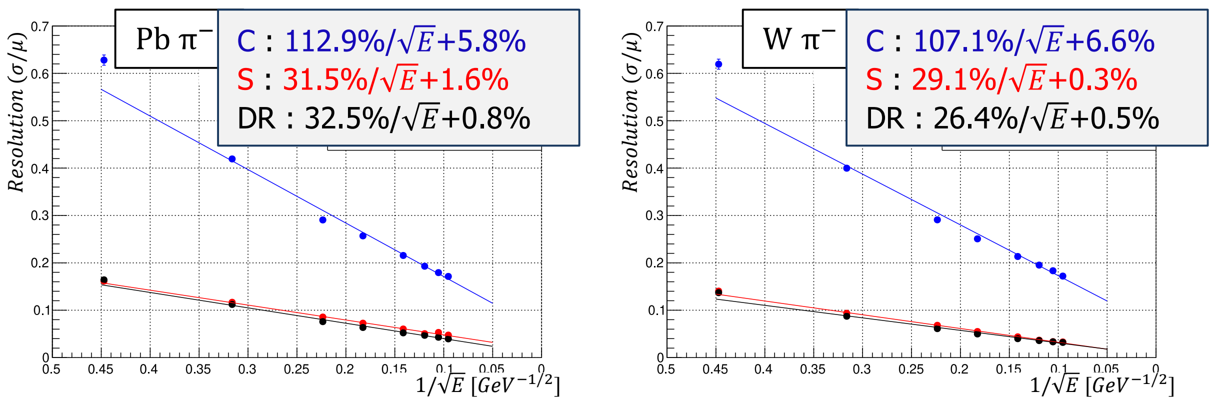
S, C, Dual Readout corrected

- Used mean & RMS of distribution of reconstructed energy – Scintillation Cherenkov, and gaussain fit for DR corrected ch.
- Energy linearity of pions, 5, 10, 20, 30, 50, 70, 90, 110 GeV.
- Regardless of energy or absorber, **energy linearity of dual-readout corrected energy is constant within few %.**

Simulation Result

Single charged pion – Energy Resolution





Energy resolution of pion, 5~110 GeV, $(\theta, \phi) = (1.5°, 1.0°)$

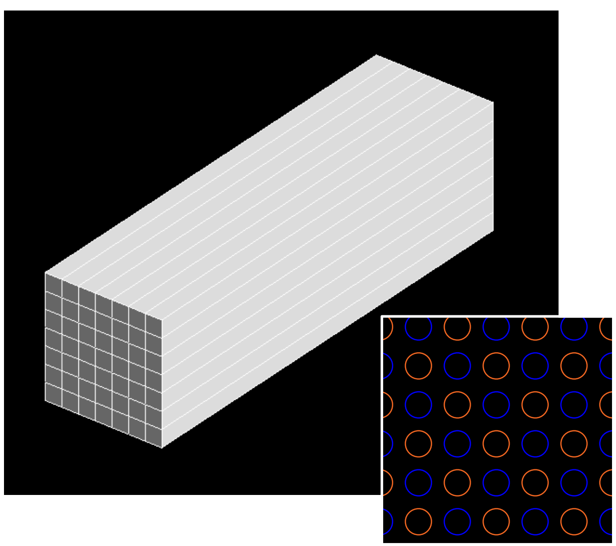
Resolution = σ/Mean

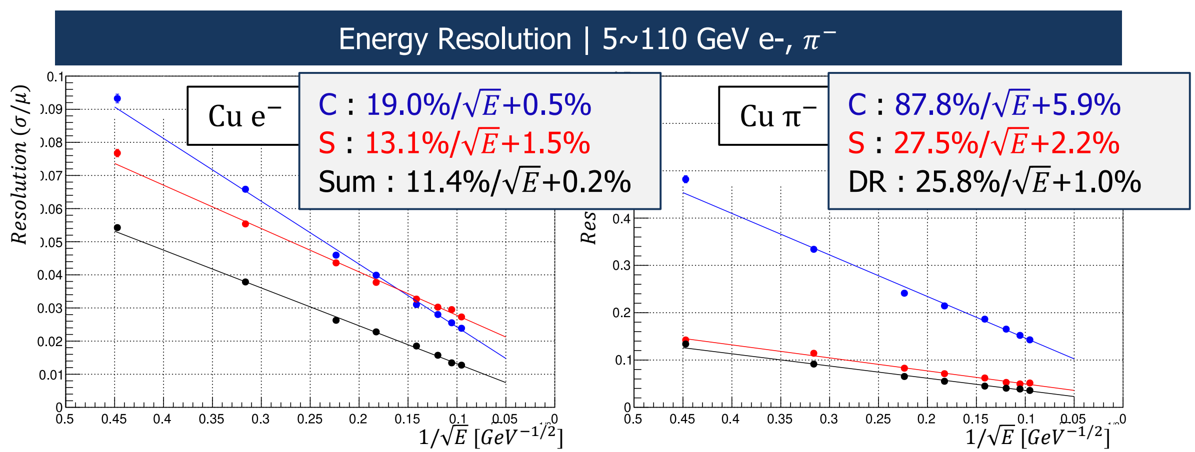
S, C, Dual Readout corrected

- Used mean & RMS of distribution of reconstructed energy – Scintillation Cherenkov, and gaussain fit for DR corrected ch.
- Energy resolution of pions, 5, 10, 20, 30, 50, 70, 90, 110 GeV.
- **Low Z absorbers show stochastic term of corrected channel under 30%,** for **copper – 25.8%**/$\sqrt{E}$

Summary

- **Compared performance of Dual-Readout Calorimeter** (DRC) between different absorbers.
- Simulation was done in 7x7 box geometry, 10< nuclear interaction length, fully simulated optical physics process.
- For electromagnetic particles, **linearity matched in $\pm 1\%$ range** regardless of energy or absorber type.
- Energy resolution for EM particles, showed different tendency for relatively low Z (Cu, Brass, Fe) and high Z (Fe, W) absorbers.
- **Timing resolution showed better as radiation length of absorber material increase**.
- By measuring (e/h) value for each absorbers, dual-readout corrected energy was calculated for all absorber types.
- For hadronic particle (pion), **low Z absorbers gave stochastic term of corrected energy under 30%.**





Backup

Material Specification

Optical Fibers, SiPM

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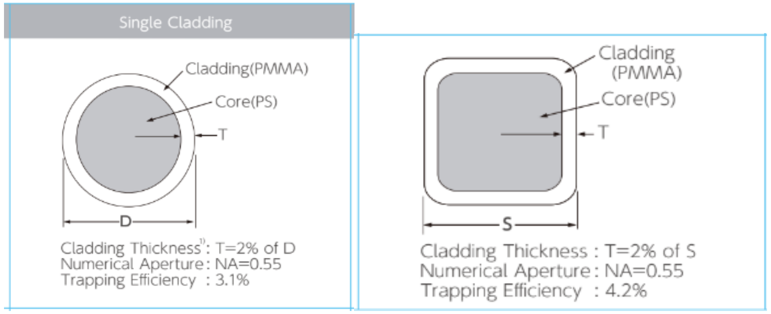
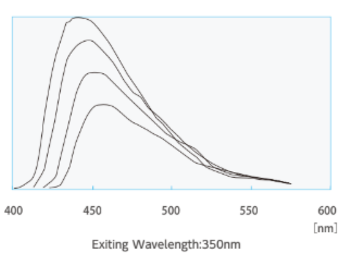
Scintillating Fiber (SCSF-78)



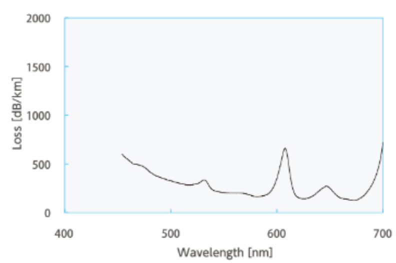
Core		Polystylene(PS)	n_D=1.59	1.05	C: 4.9x10^{22} H: 4.9x10^{22}
Cladding	for single cladding inner for multi-cladding	Polymethylmethacrylate (PMMA)	n_D=1.49	1.19	C: 3.6x10^{22} H: 5.7x10^{22} O: 1.4x10^{22}

Description	Emission			Decay Time [ns]	Att.Leng.[2] [m]
	Color	Spectra	Peak[nm]		
SCSF-78	blue	See the	450	2.8	>4.0

Emission Spectra



Transmission Loss



[Manufacture Specification Sheet](#) (Kuraray)

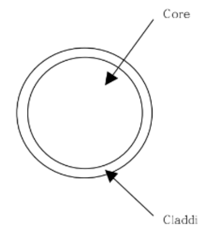
[Attenuation Length](#) (LHCb SciFi Project)

Cerenkov Fiber (SK-40)

Table 1

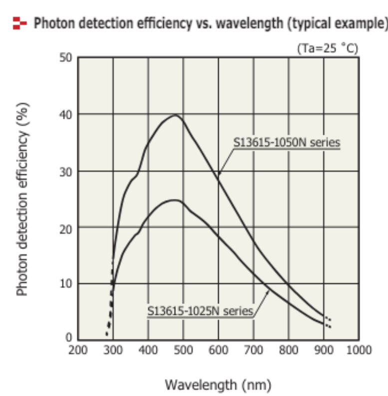
Item		SK-40 Specification			
		Unit	Min.	Typ.	Max.
Optical Fiber 1	Core Material	–	Polymethyl-Methacrylate Resin		
	Cladding Material	–	Fluorinated Polymer		
	Core Refractive Index	–	1.49		
	Refractive Index Profile	–	Step Index		
	Numerical Aperture	–	0.5		
	Core Diameter	μm	920	980	1,040
	Cladding Diameter	μm	940	1,000	1,060
Approximate Weight		g/m	1		

Sectional View



[Attenuation Length](#)

(Handbook of Fiber Optic Data Communication, 4th edtiion)

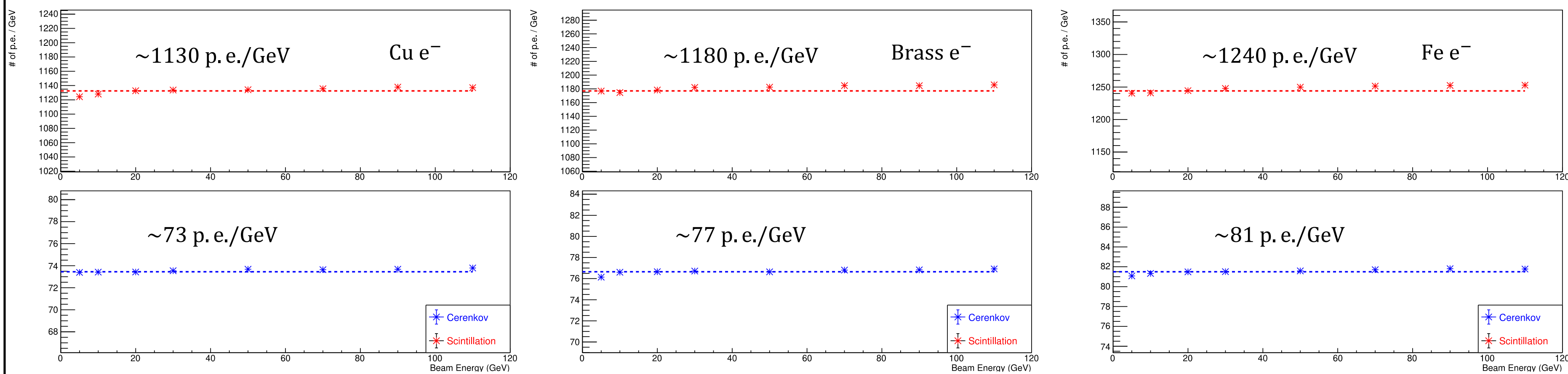


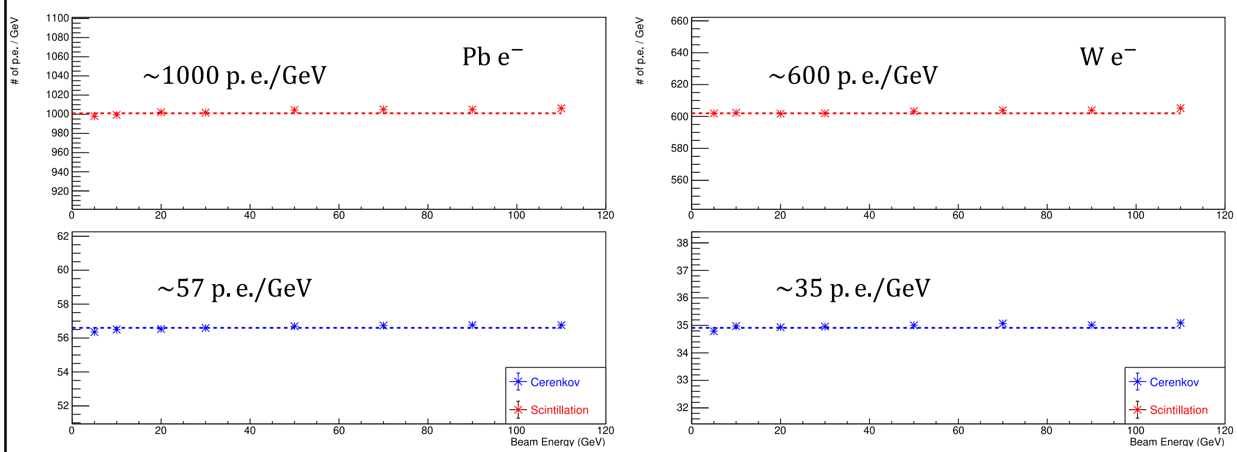
SiPM – Hamamatsu S13615-1025N

[Manufacture Specification Sheet](#)

Simulation Result

Light Yield / GeV





Light yield of electron, 20 GeV, $(\theta, \phi) = (1.5°, 1.0°)$

$$Light\ Yield = \frac{Mean\ \#\ of\ p.e.}{Beam\ Energy}$$

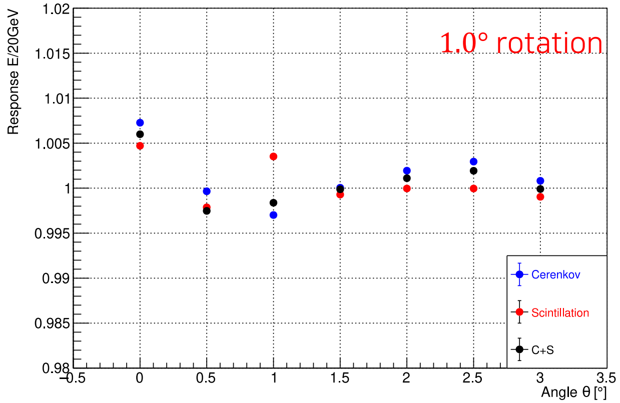
Light Yield	Cu	Brass	Fe	Pb	W
$S\ (\frac{\#of\ p.e.}{GeV})$	1130	1180	1240	1000	600
$C\ (\frac{\#of\ p.e.}{GeV})$	73	77	81	57	35

- Light yield surely shows dependency on absorber material's radiation length (~ Z value) affects energy resolution.

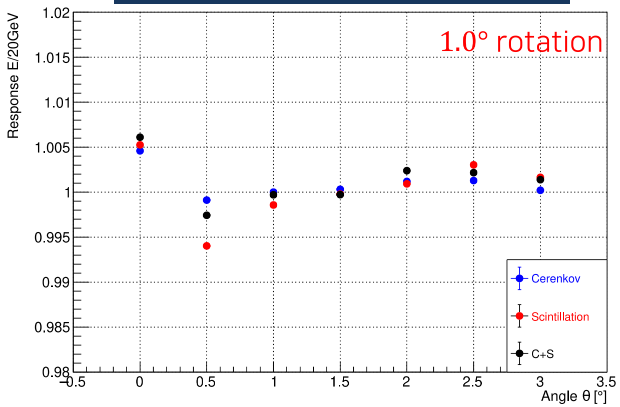
Simulation Result

Angular Dependency, Linearity e-

0~3.0° EM response | Cu



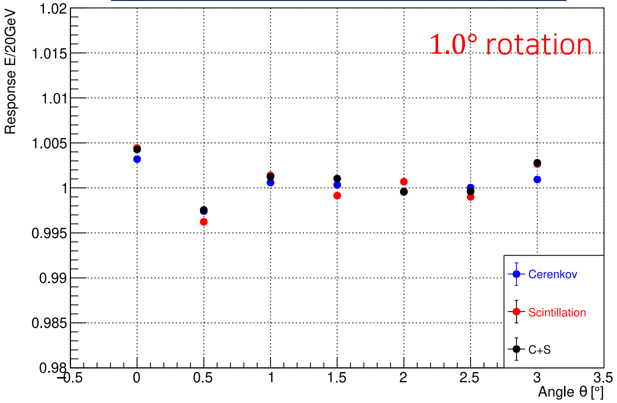
0~3.0° EM response | Brass



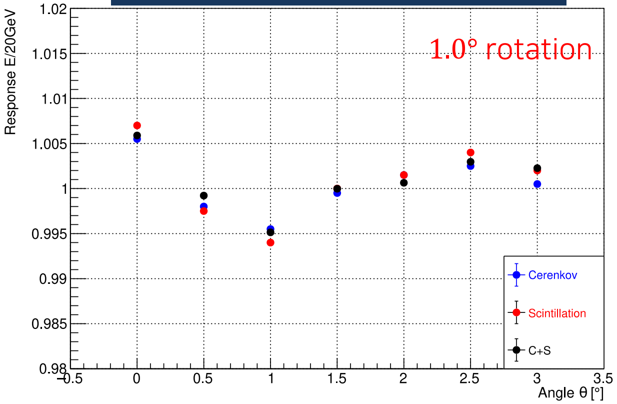
$20\ GeV\ e^{-}\ (\theta, \phi) = (0 \sim 3.0^{\circ}\ (0.5^{\circ}\ unit), 1.0^{\circ})$, 1000evts / point

Used Std & Mean value for Pb & W, not of gaussian fitting function.

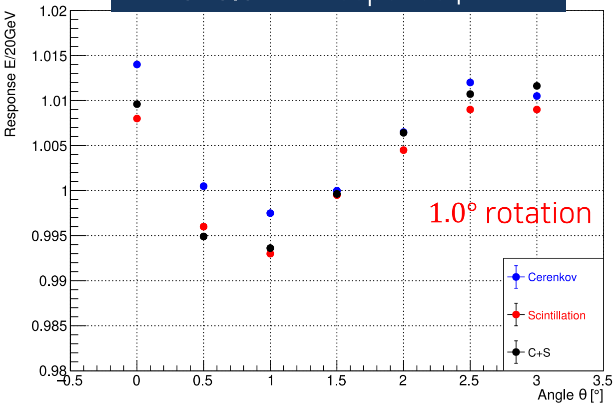
0~3.0° EM response | Fe



0~3.0° EM response | Pb



0~3.0° EM response | W



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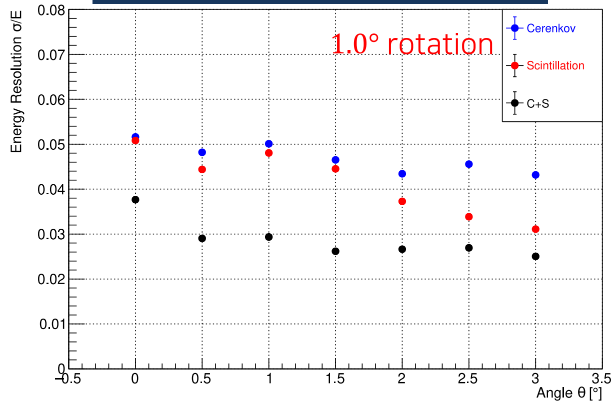
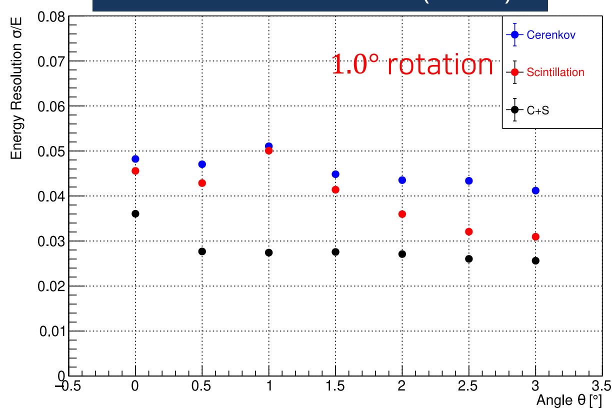
Simulation Result

Angular Dependency, Resolution e-

0~3.0° EM Resolution (Cu)



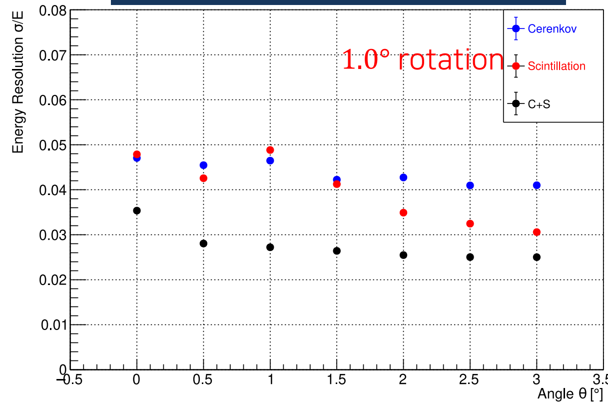
0~3.0° EM Resolution (Brass)



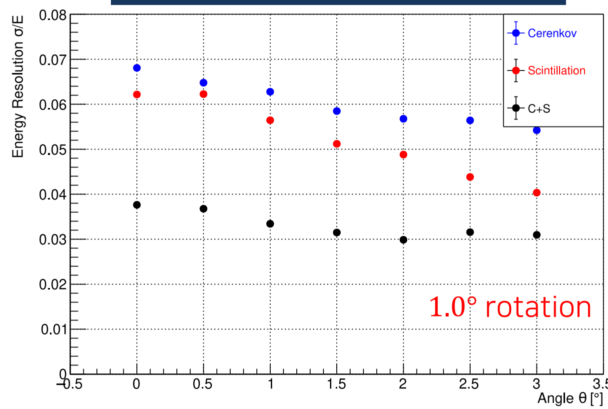
$20\ GeV\ e^{-}\ (\theta, \phi) = (0 \sim 3.0°\ (0.5°\ unit)\ , 1.0°)$, 1000evts / point

Used Std & Mean value for Pb & W, not of gaussian fitting function.

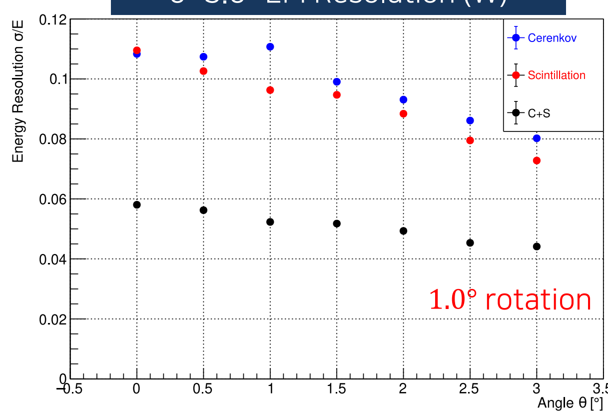
0~3.0° EM Resolution (Fe)



0~3.0° EM Resolution (Pb)



0~3.0° EM Resolution (W)

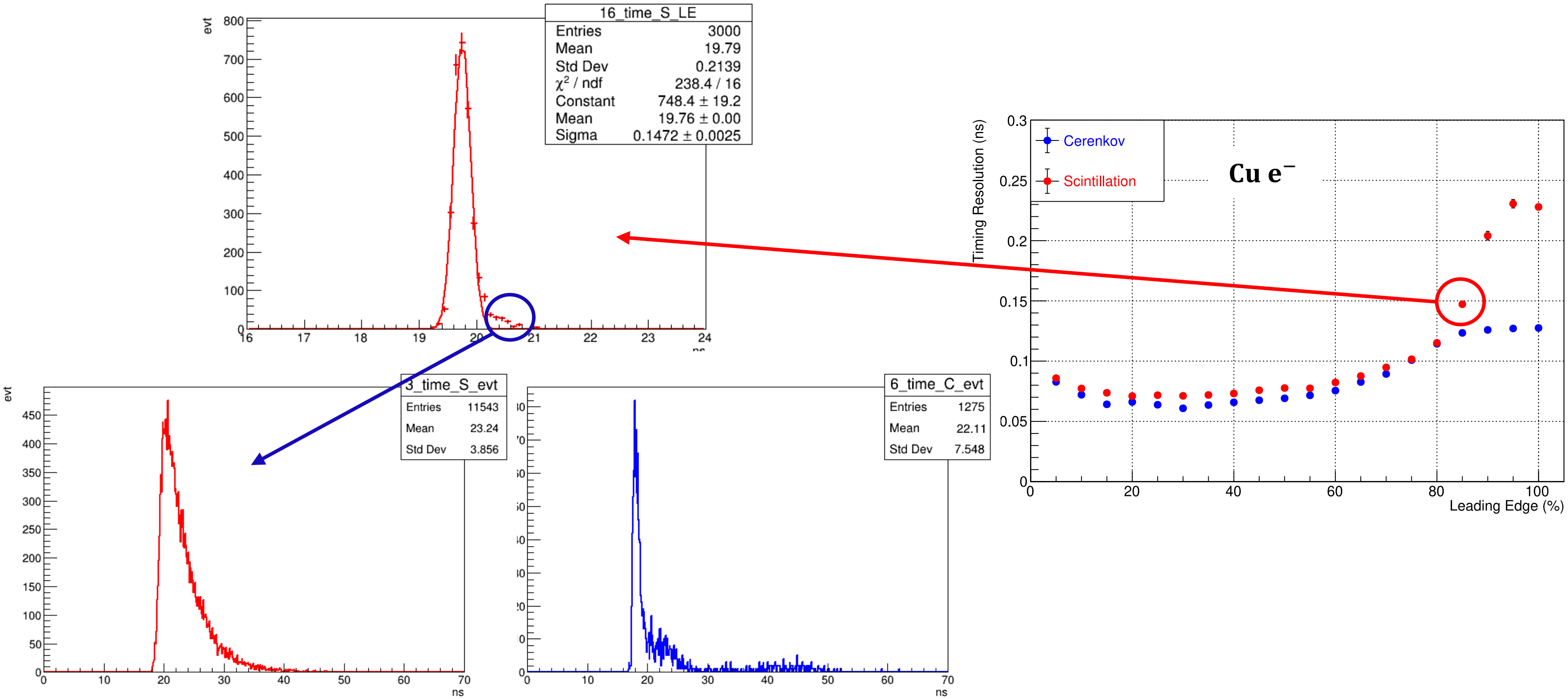


DREAM FOR FUTURE

Simulation Result

Single electron – Timing Resolution

L.E. 85% S timing



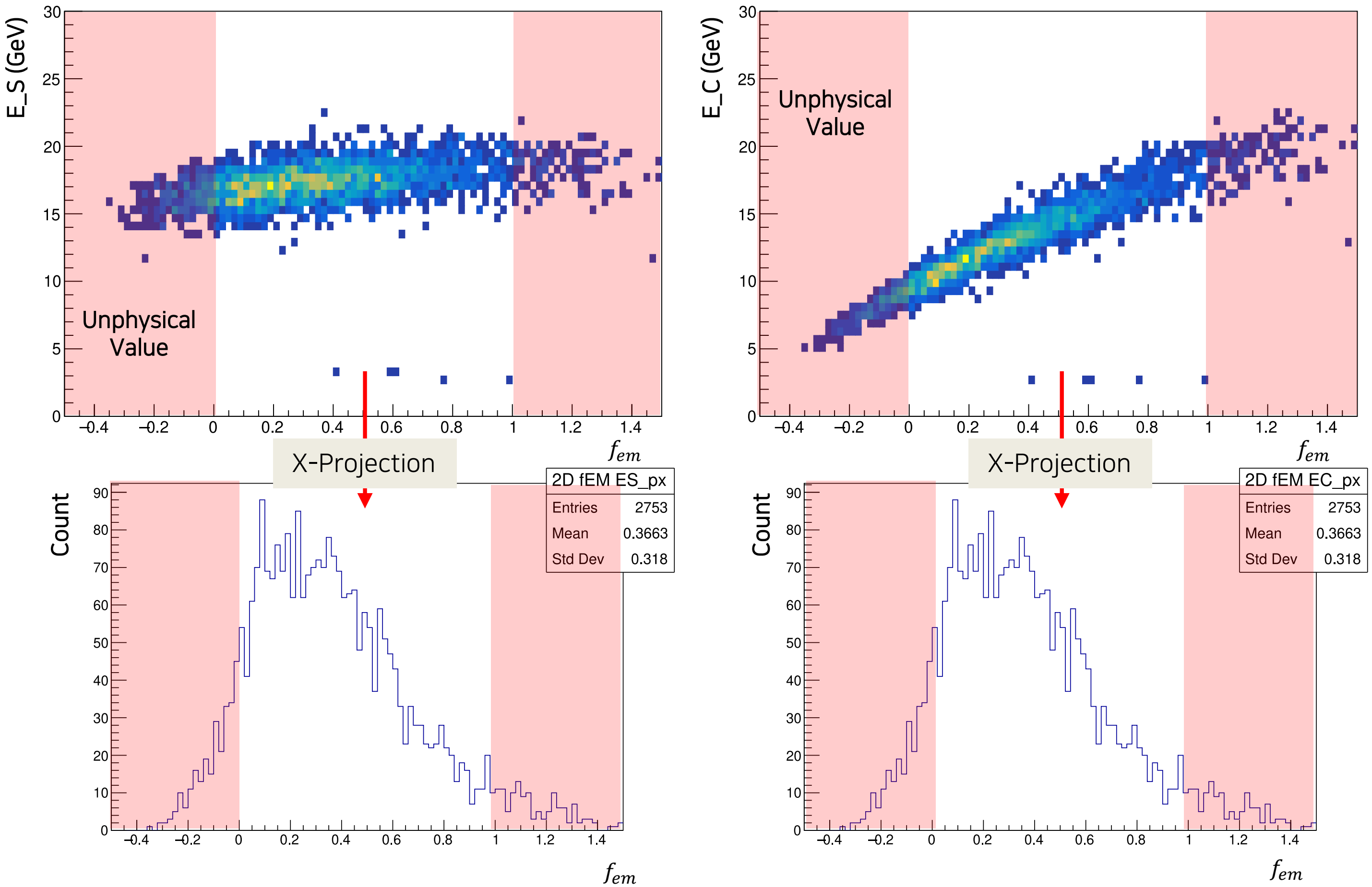
- Calculated timing resolution, by getting leading edge of peak timing, **event by event.**

- Taking **sigma of leading edge distribution as timing resolution**, compared these in different leading edge %.

- Increase of time resolution on high leading edge % region is due to different process between S & C.

Simulation Result

h/e calculation – matching energy



$$f_{em} = \frac{\left(\frac{h}{e}\right)_C - \left(\frac{C}{S}\right)\left(\frac{h}{e}\right)_S}{\left(\frac{C}{S}\right)\left[1-\left(\frac{h}{e}\right)_S\right] - \left[1-\left(\frac{h}{e}\right)_C\right]}$$

- Only matching reco. energy near to beam energy has problem.

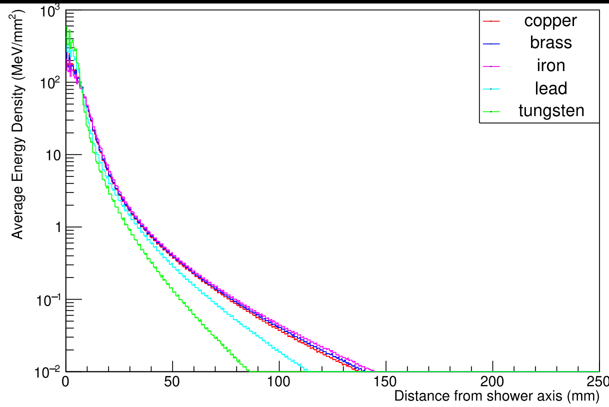
- Most events have reconstructed energy at $f_{em} < 0$, which is unphysical.

- So gave also condition that **most of events should have $f_{em} > 0$** => $(\bar{X} - 2\sigma) > 0$ (of X-Projection)

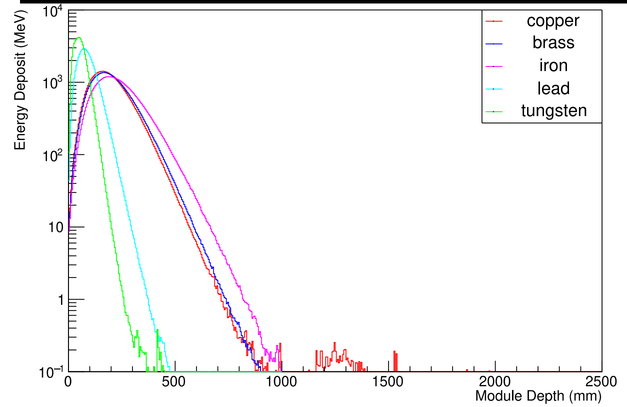
DR Absorber Material Simulation

Shower Profile

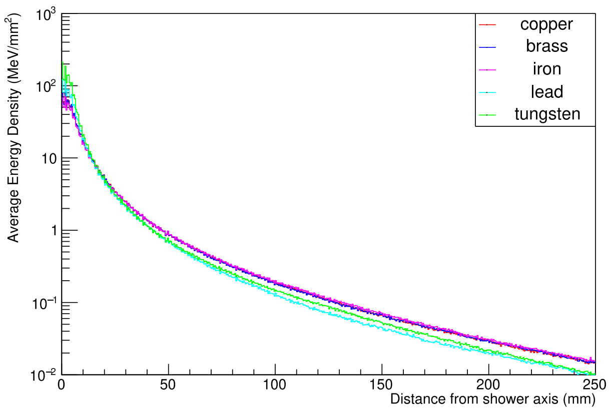
Radial Energy Deposit | 60GeV e- $(\theta, \phi) = (1.5°, 1.0°)$



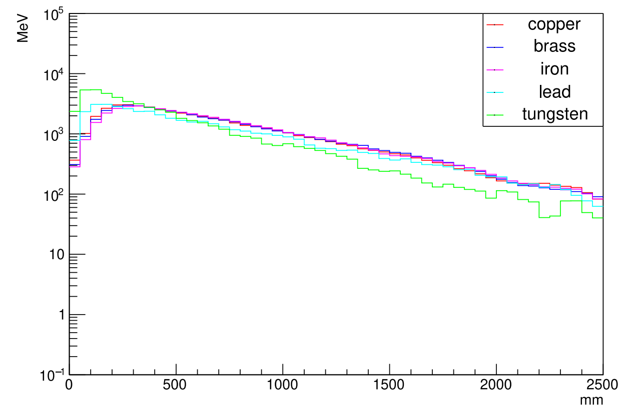
Longitudinal Energy Deposit | 60GeV e- $(\theta, \phi) = (1.5°, 1.0°)$



Radial Energy Deposit | 60GeV pi- $(\theta, \phi) = (0°, 0°)$



Longitudinal Energy Deposit | 60GeV pi- $(\theta, \phi) = (0°, 0°)$



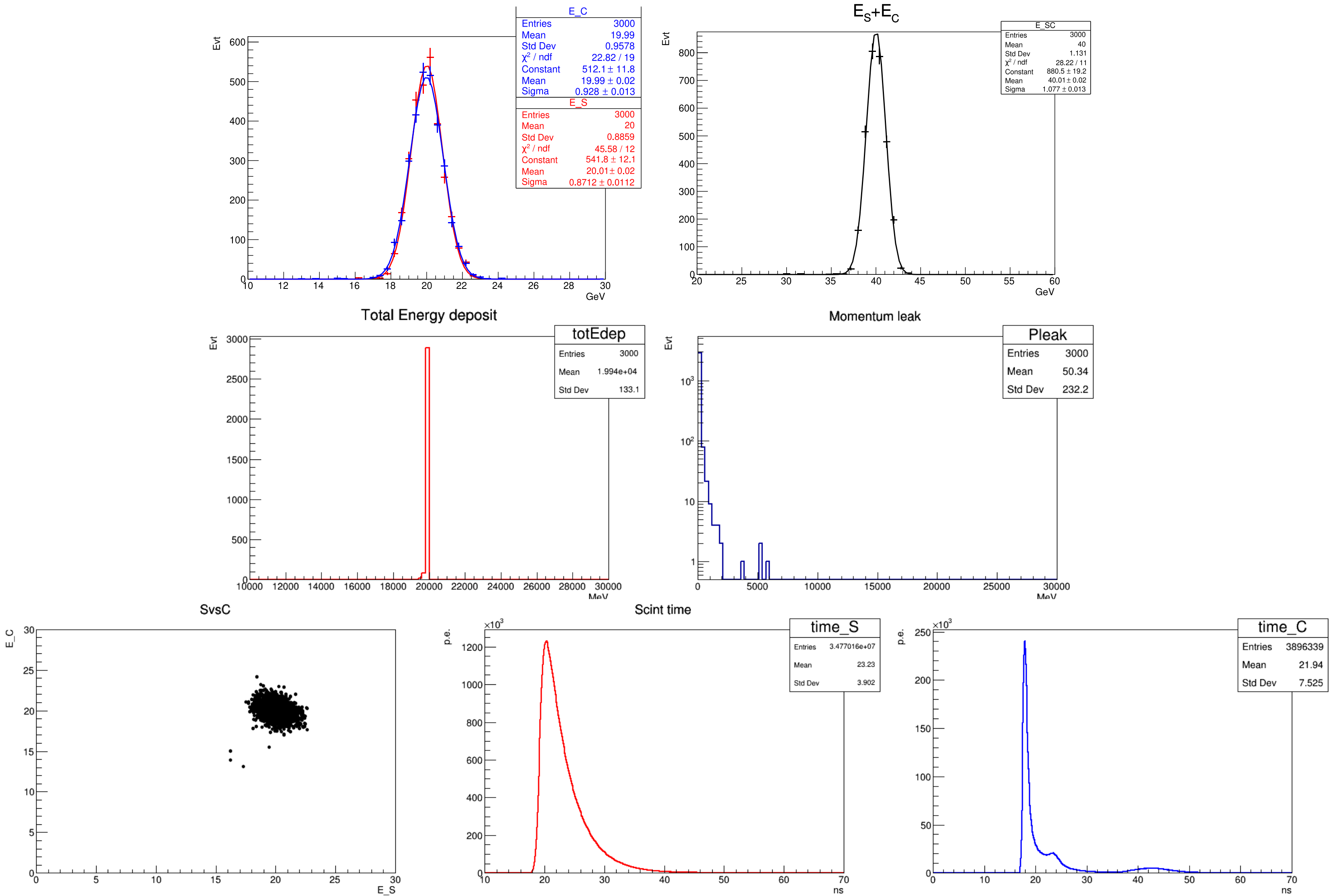
- Compared radial & longitudinal energy deposit on different absorbers.

- The **tendency followed their radiation length & nuclear interaction length**

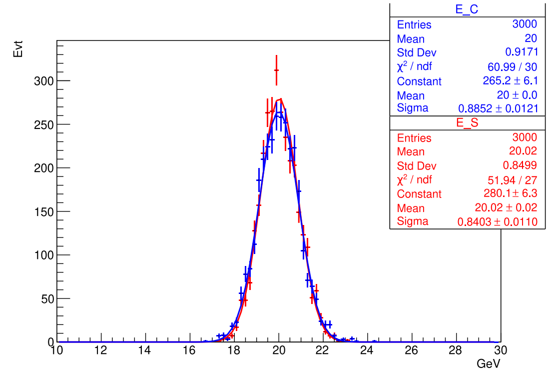
Simulation Result

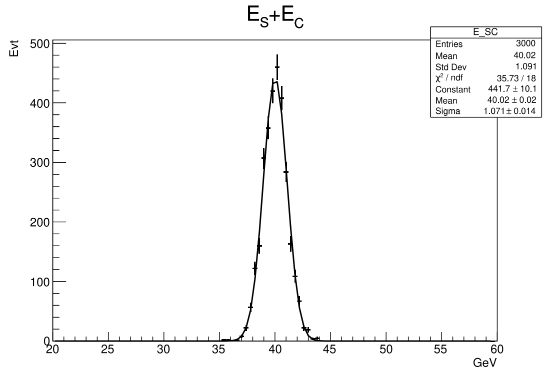
Copper – 20GeV e-

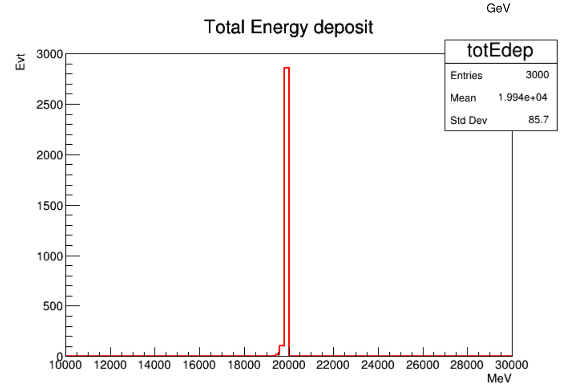
DREAM FOR FUTURE

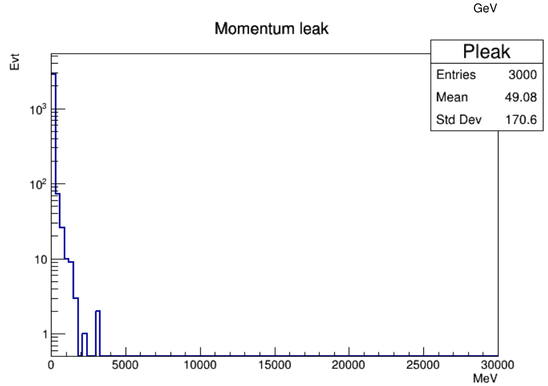


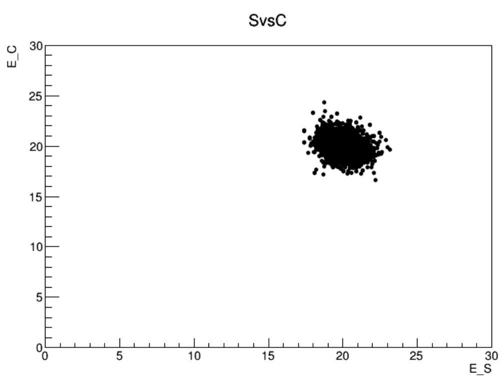
Simulation Result
Brass – 20GeV e-

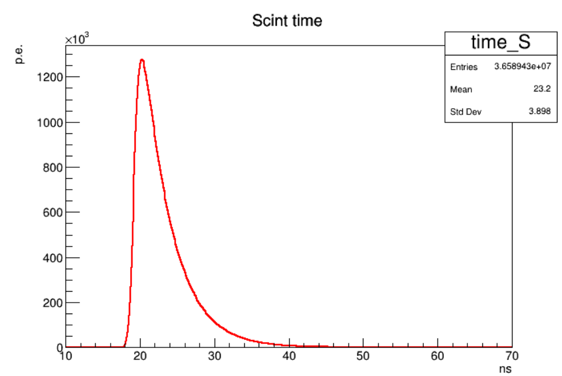


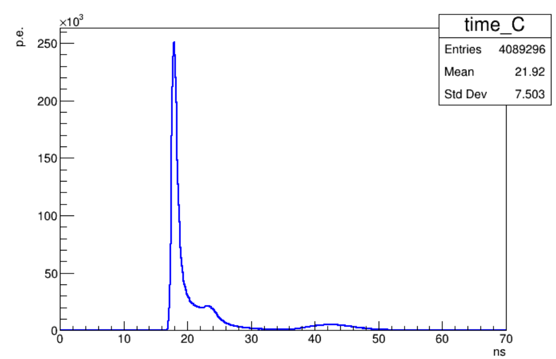






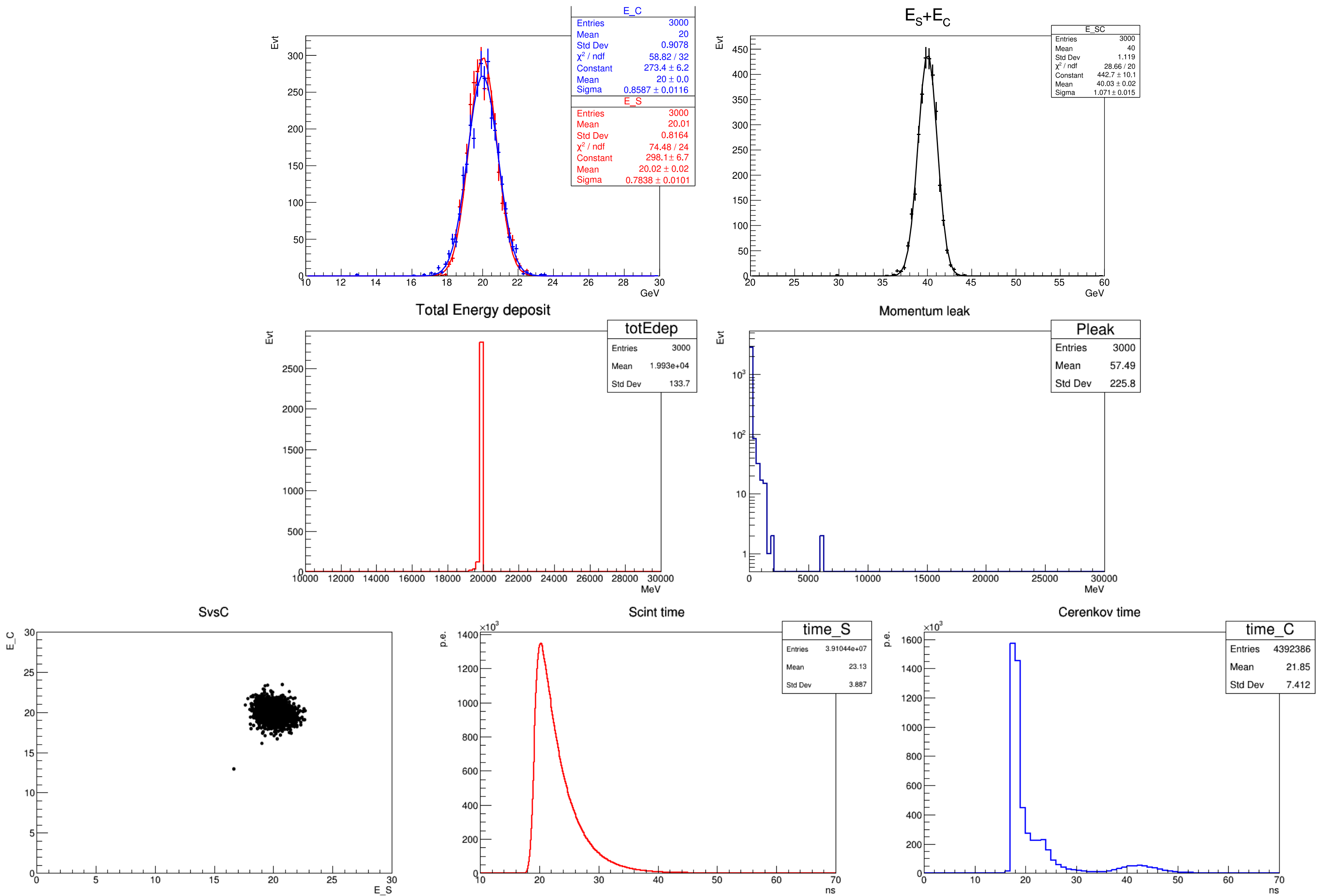






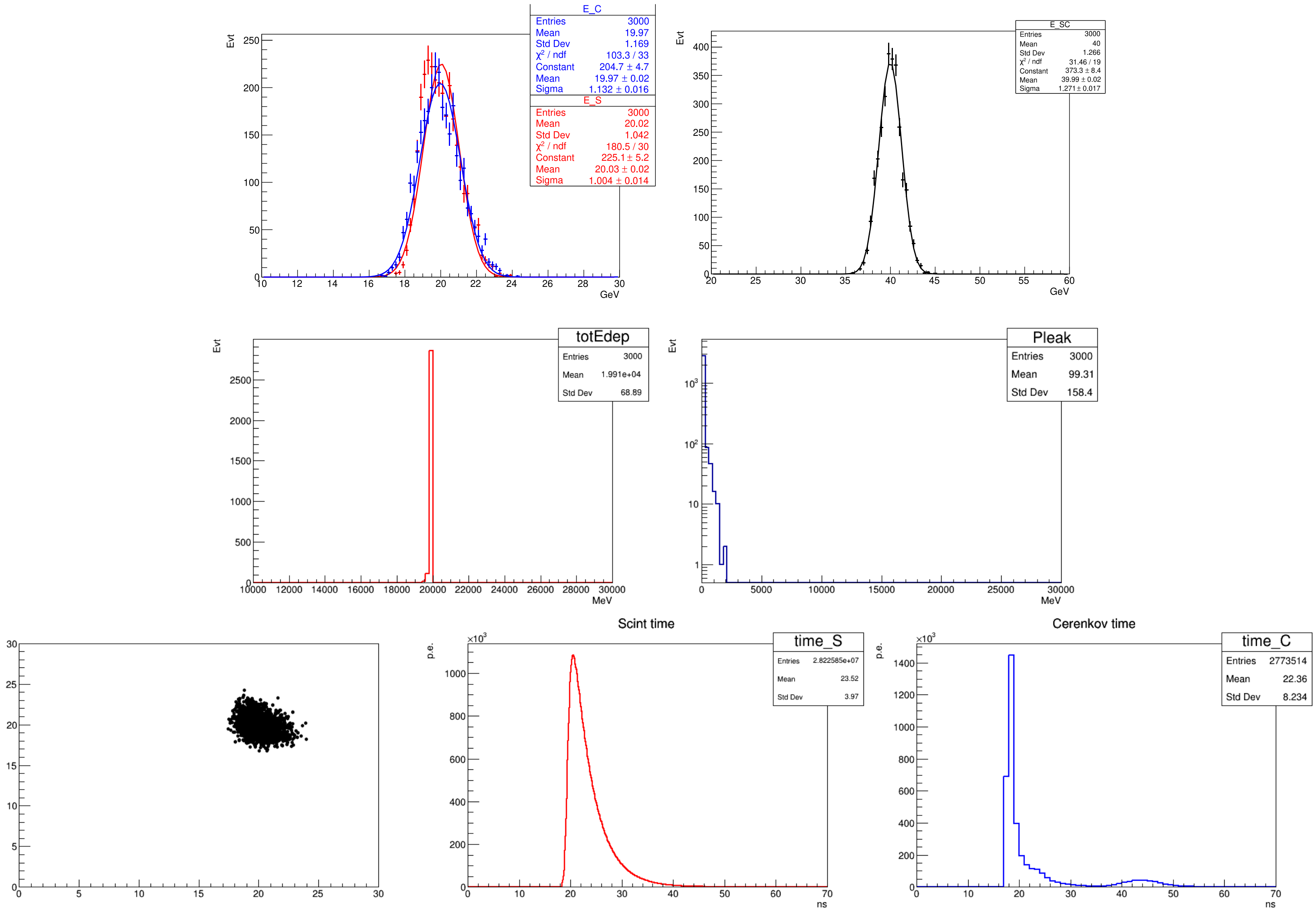
Simulation Result

Iron – 20GeV e-



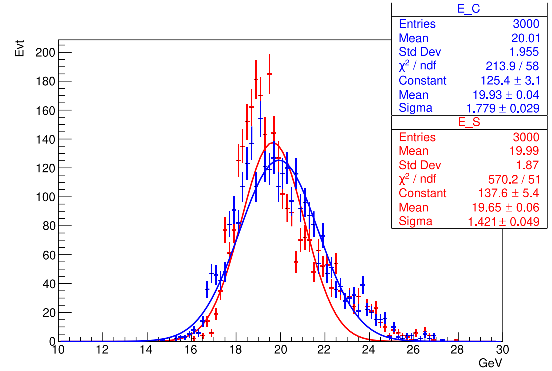
Simulation Result

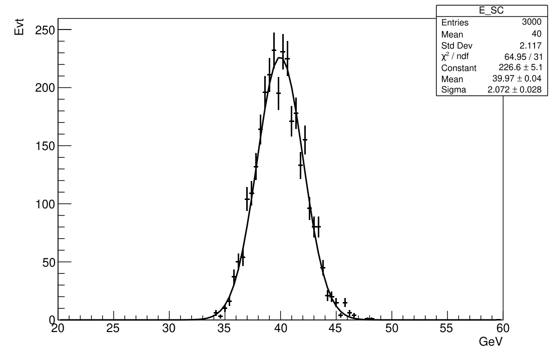
Lead – 20GeV e-

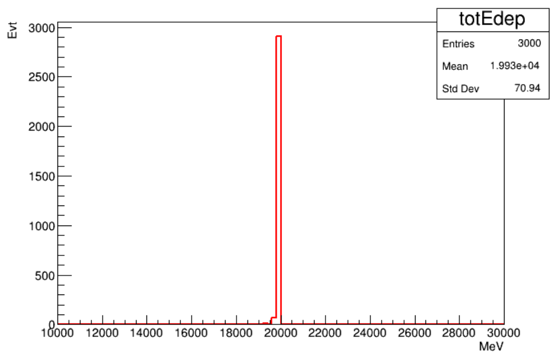


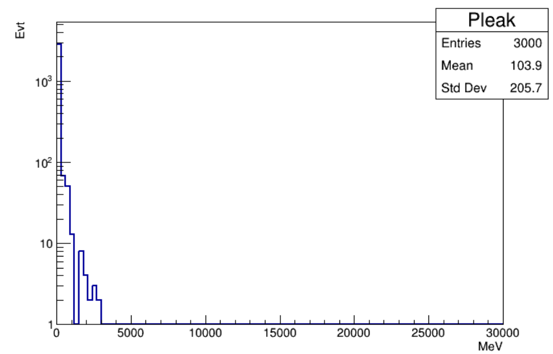
Simulation Result

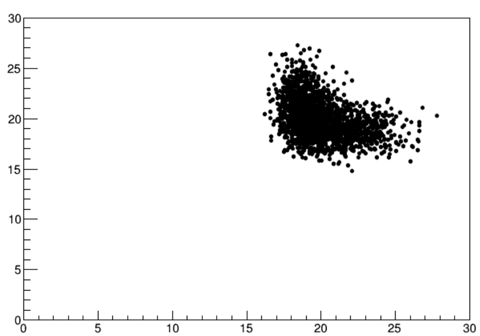
Tungsten – 20GeV e-

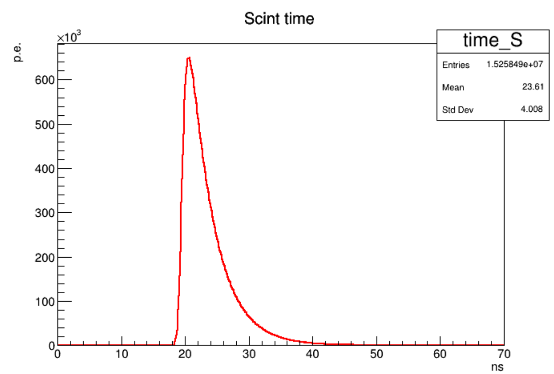


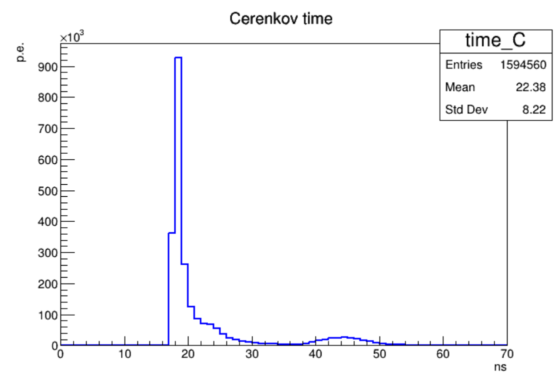






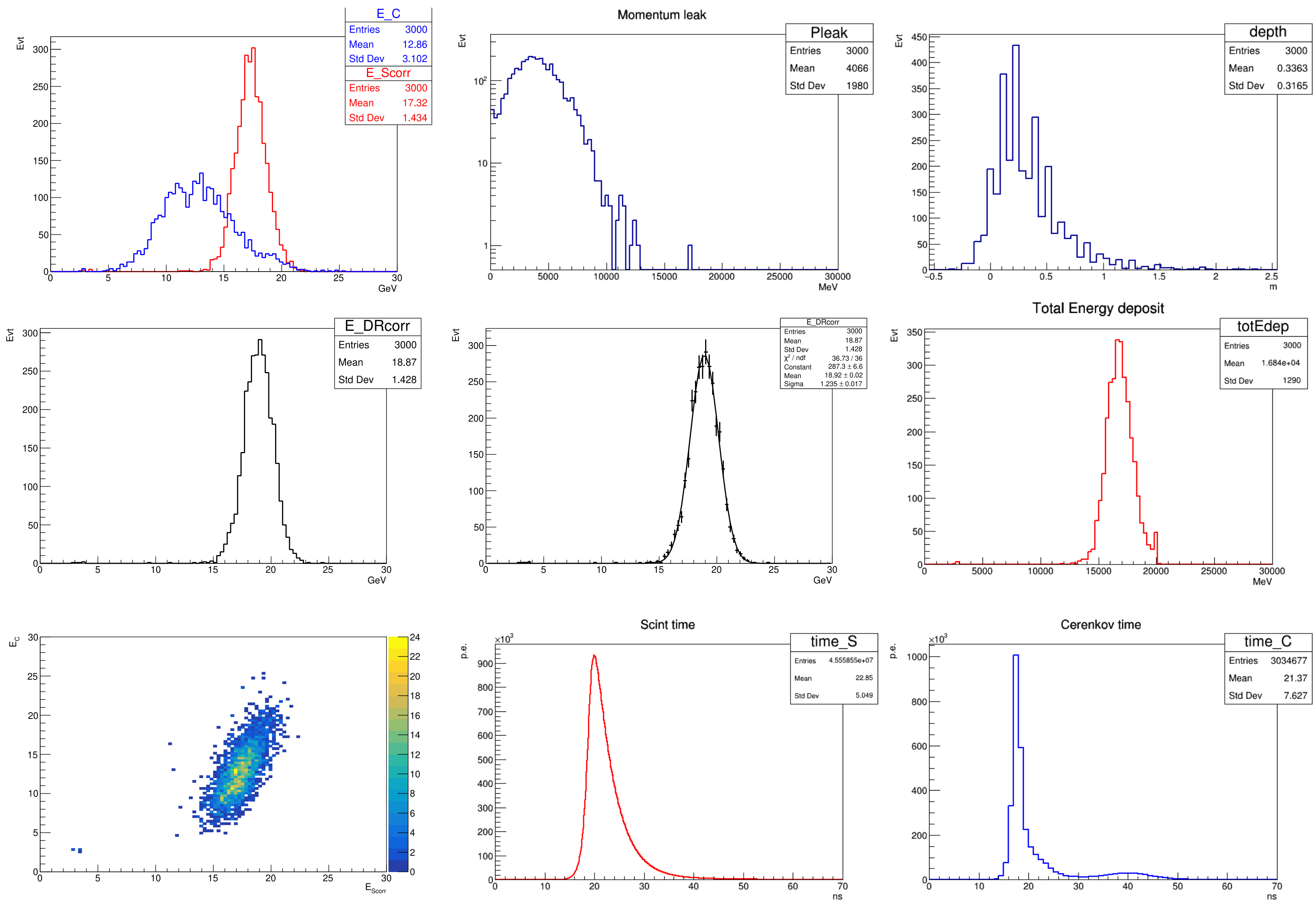






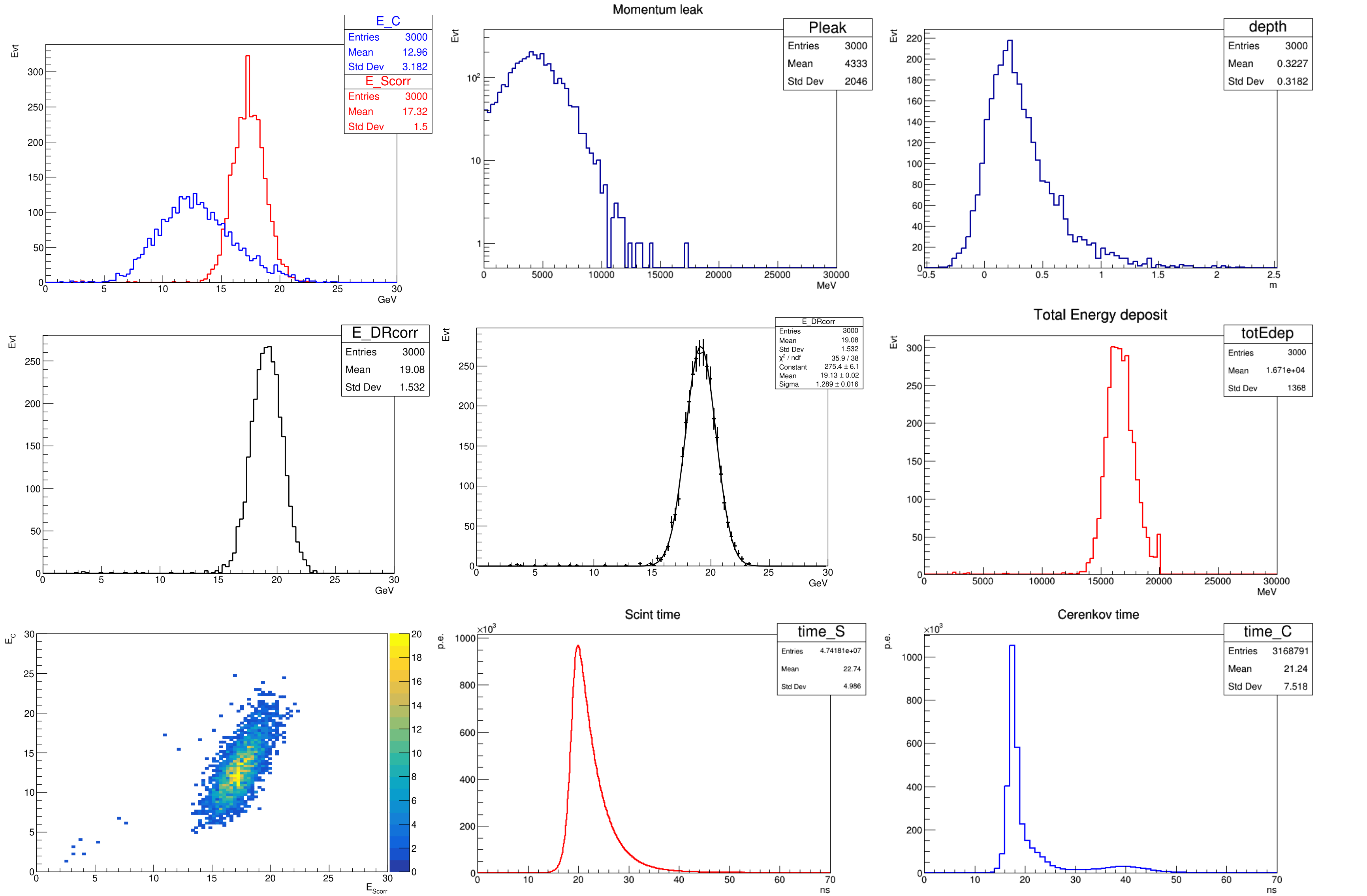
Simulation Result

Copper – 20GeV pi-



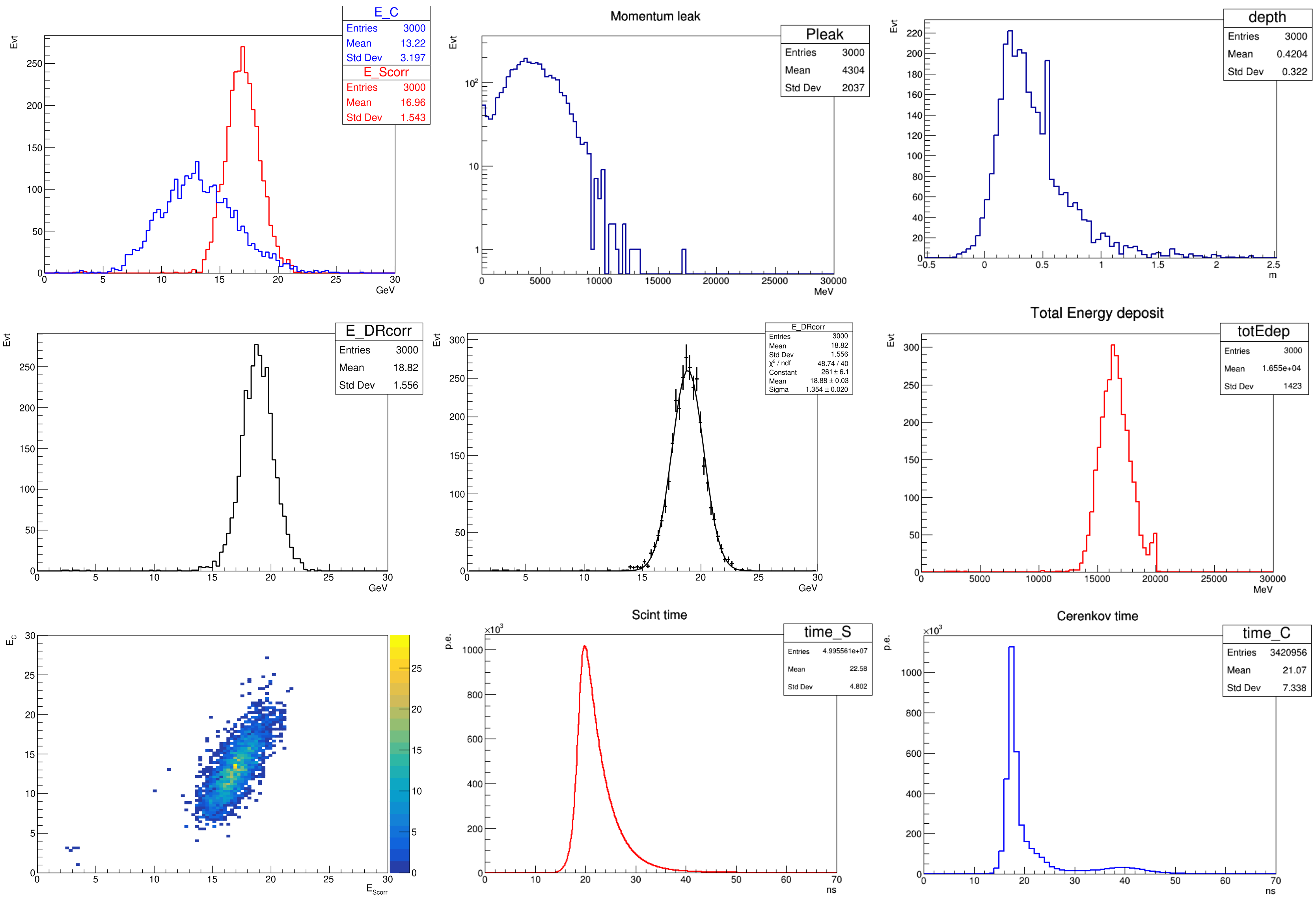
Simulation Result

Brass – 20GeV pi-



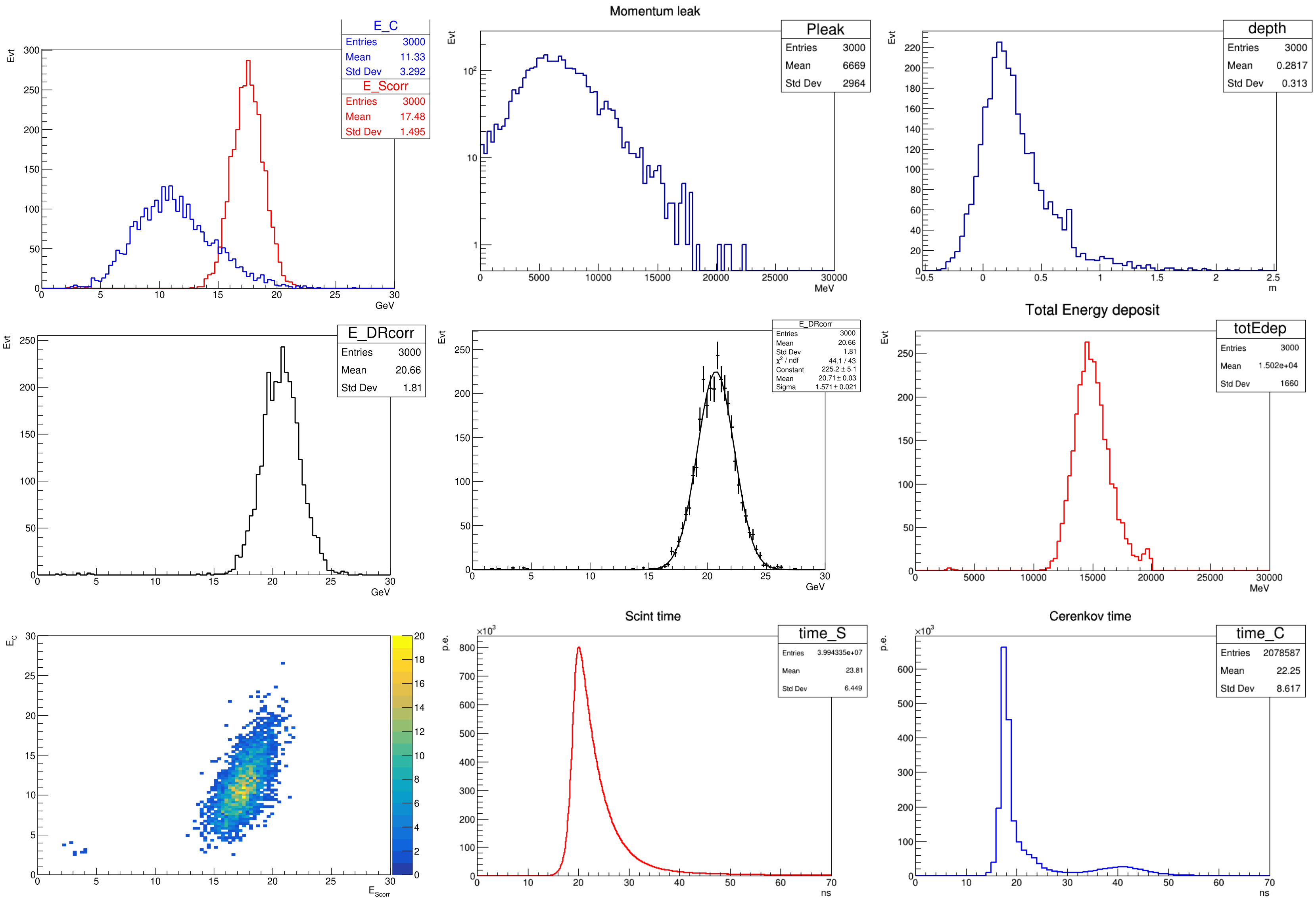
Simulation Result

Iron – 20GeV pi-



Simulation Result

Lead – 20GeV pi-



Simulation Result

Tungsten – 20GeV pi-