Energy Digitization for CEPC Crystal ECAL

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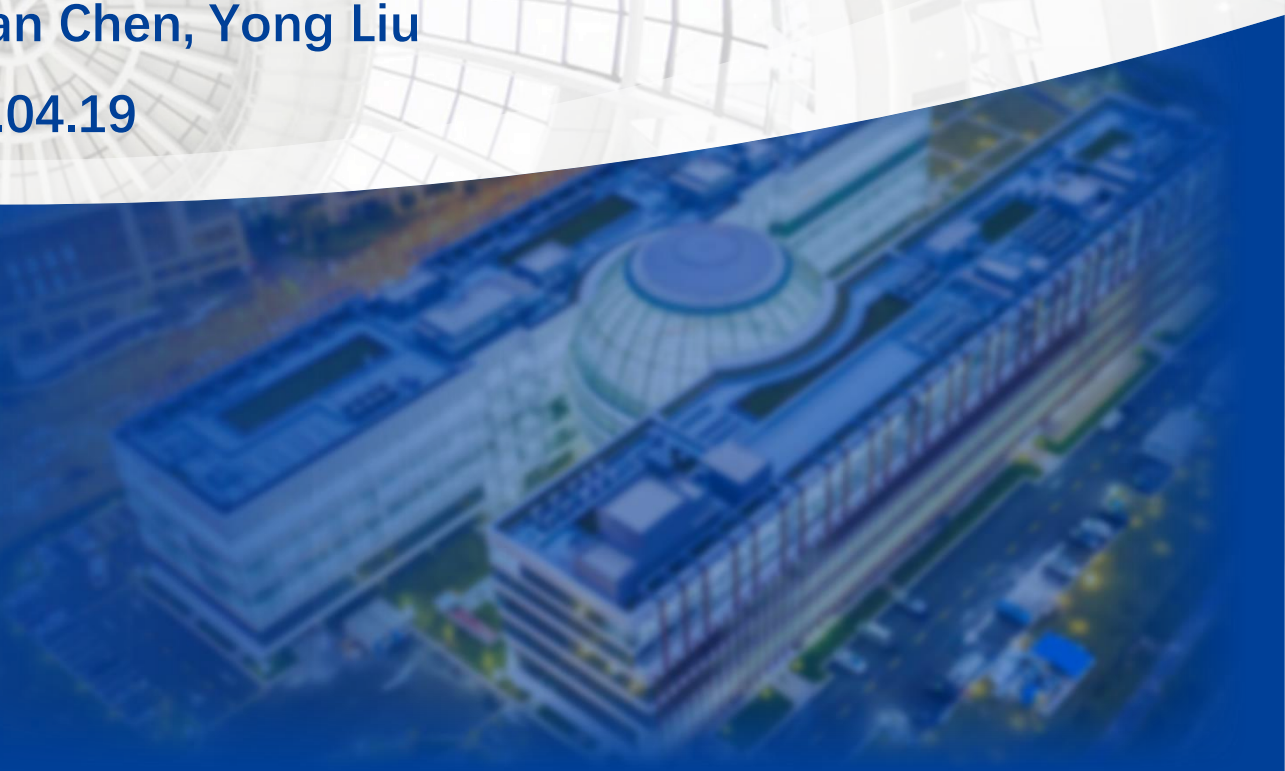

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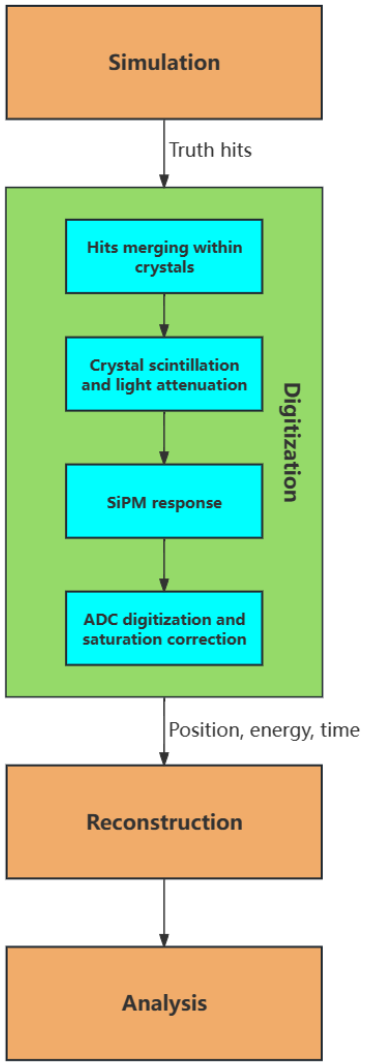
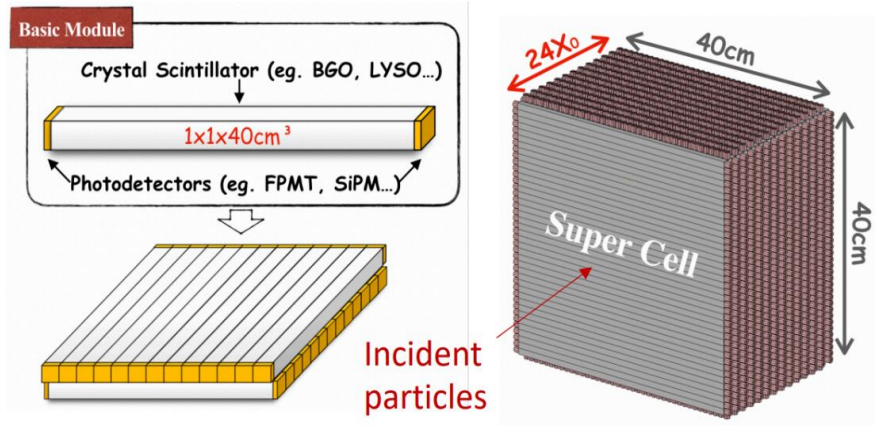
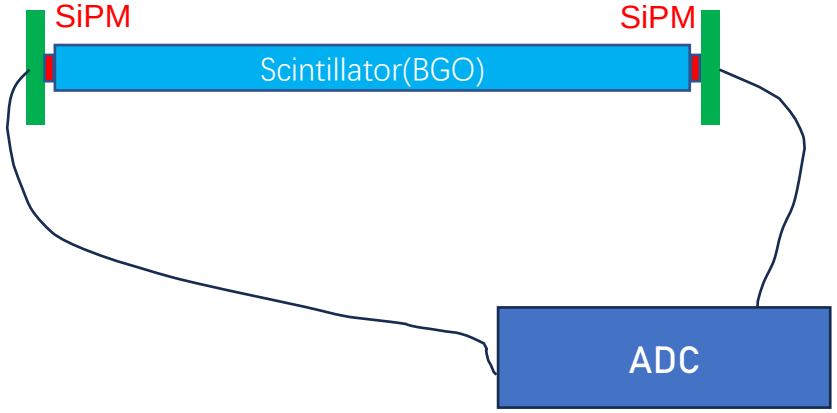
Introduction







- Realistic digitization model dedicated to CEPC Crystal ECAL
  - Position(x, y, z): determined by crystal alignment
  - Energy(hit energy → detected energy): parameterized behaviors of scintillator & SiPM & ADC
    - Scintillation digitization: Crystal light yield and uniformity
    - SiPM digitization: SiPM response and saturation correction
    - ADC digitization: ADC precision, noise and dynamic range
  - Time: depends on TDC and time resolution of crystal unit

Digitization: Scintillation

- Energy deposit and scintillation
  - A fluctuation of 1% in crystals' light yield: Gaussian sampling

$$LY = Gaus(LY_{MIP}, 0.01 \cdot LY_{MIP})$$

  - Fluctuation in scintillation(energy → photons): Poisson sampling

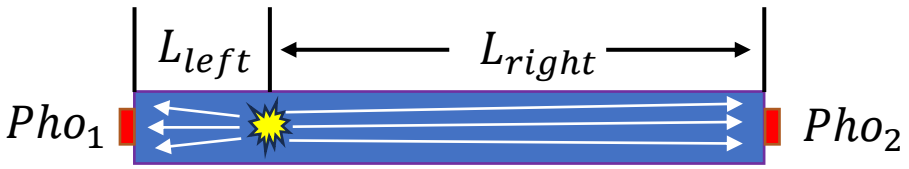
$$N_{ph} = Poisson(E_{dep}/E_{MIP} \cdot LY)$$

  - Light propagates to both ends: ratio of exponential decay

$$\epsilon N_{In,l/r} = R_{l/r} \cdot N_{ph}$$

MIP light yield (p.e./MIP)	200
MIP energy (MeV/MIP)	8.9
LY calibration precision	1%
L_A (mm)	8000

Assume the light measured at both ends follows exponential decay.



$L_A = 8000\ mm$, max response non-uniformity along crystal bar is ~5%

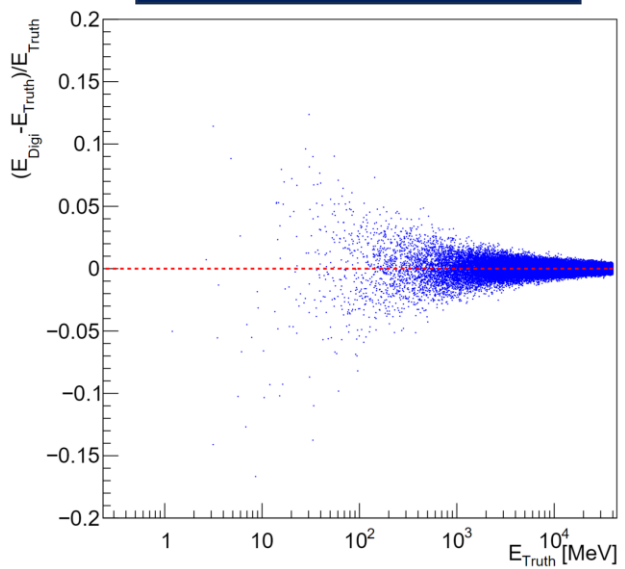
$$N_{ph1} = \frac{e^{\frac{-L_{left}}{L_A}}}{e^{\frac{-L_{left}}{L_A}} + e^{\frac{-L_{right}}{L_A}}} \cdot N_{ph}$$

R_l

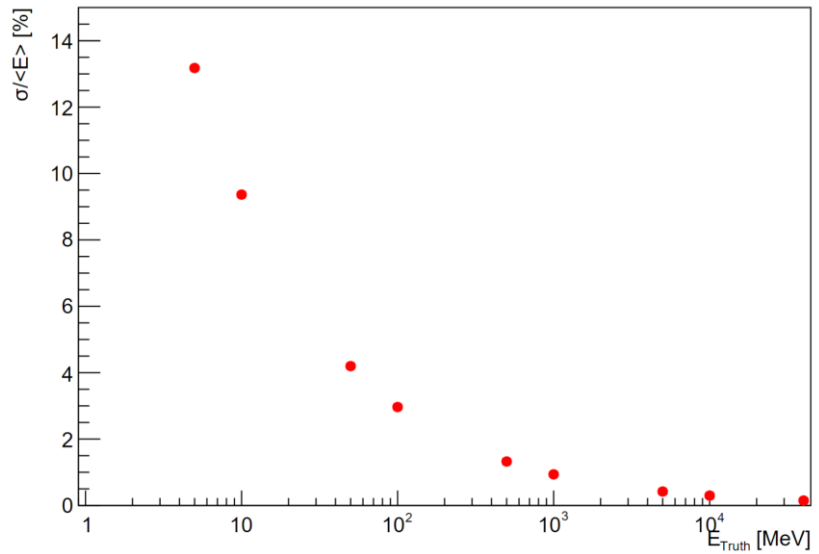
Performance Check: Scintillation

- Only check for the algorithm for single-end readout(LY=100p.e./MeV). No detector simulation and attenuation here
- Linearity of scintillation digitization is no problem
- ~1% resolution at 1GeV

Linearity



Resolution introduced by Scintillation Digi



Digitization: SiPM

- SiPM response and its fluctuation were obtained from simulation, which is based on 40cm BGO and SiPM with 6μm pixel
  - SiPM response: response function and Gaussian sampling

$$\langle N_{Det} \rangle = f(\epsilon N_{In})$$

$$\sigma_{Det} = g(\epsilon N_{In})$$

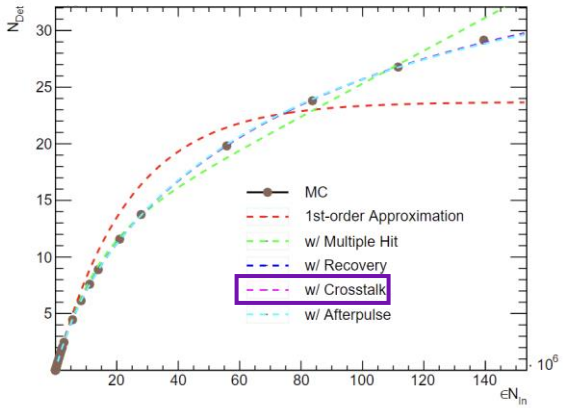
  - Saturation correction **(after ADC Digi)**: inverse form of response function

$$\langle N_{Rec} \rangle = f^{-1}(N_{Det})$$

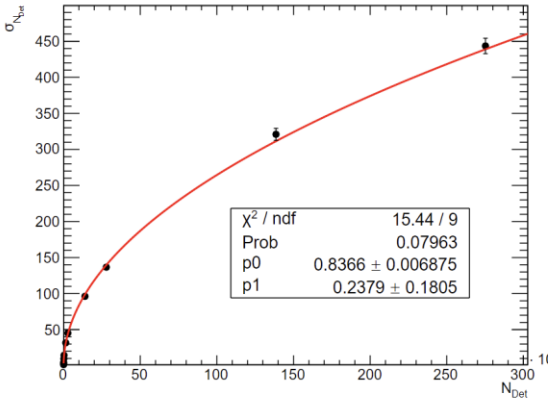
$$\sigma_{Rec} = \left| a^{-1}/b^{-1}(N_{Det}) - N_{Rec} \right|$$

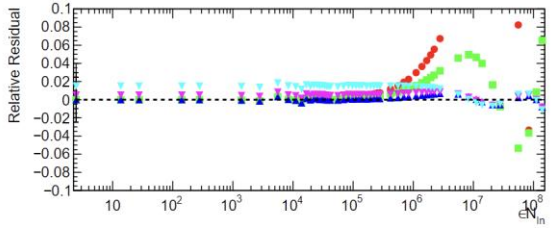
$$a/b = f +/- g$$

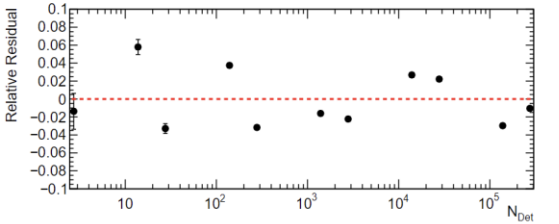
$N_{Det} = f(\epsilon N_{In})$



$\sigma_{Det} = g(N_{Det})$

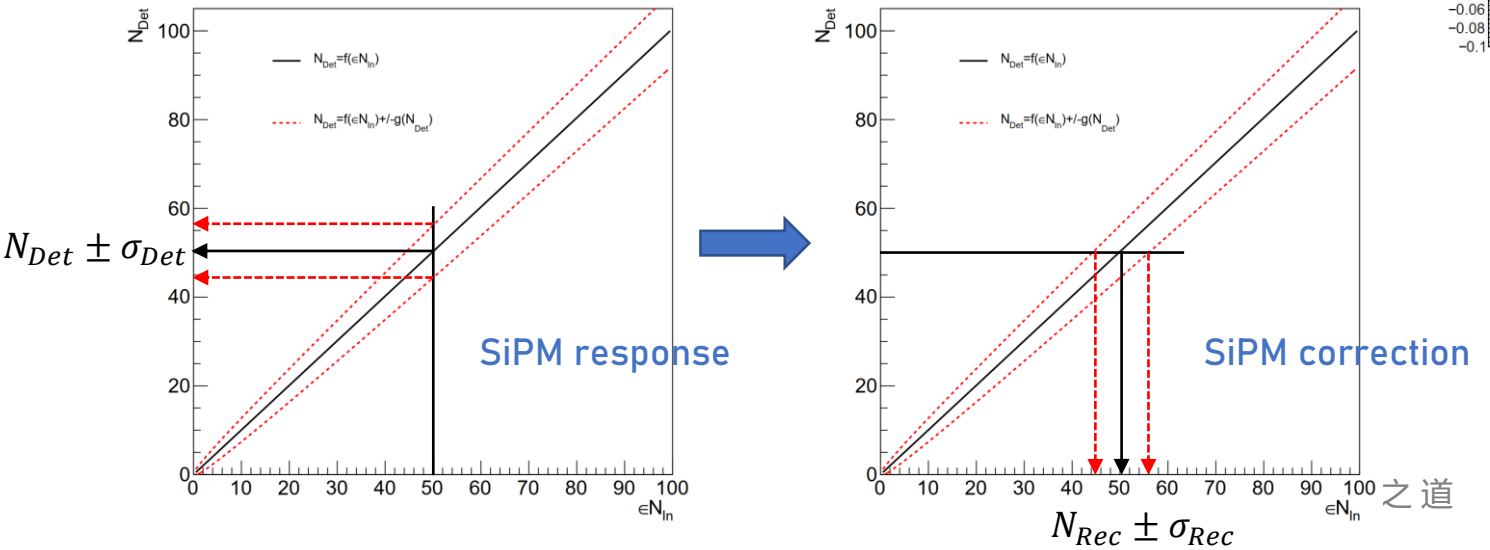






$$f(x) = a\frac{(x+b\varphi)\varphi^2}{x+c\varphi},\ \varphi = (1-e^{-\frac{x}{d}})$$

$$g(x) = p_0\sqrt{x+p_1}$$



arxiv.1510.01102

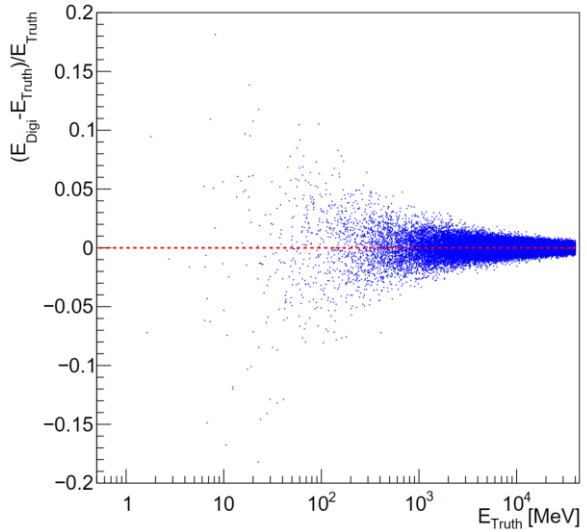
Performance Check: SiPM

0.5% crosstalk

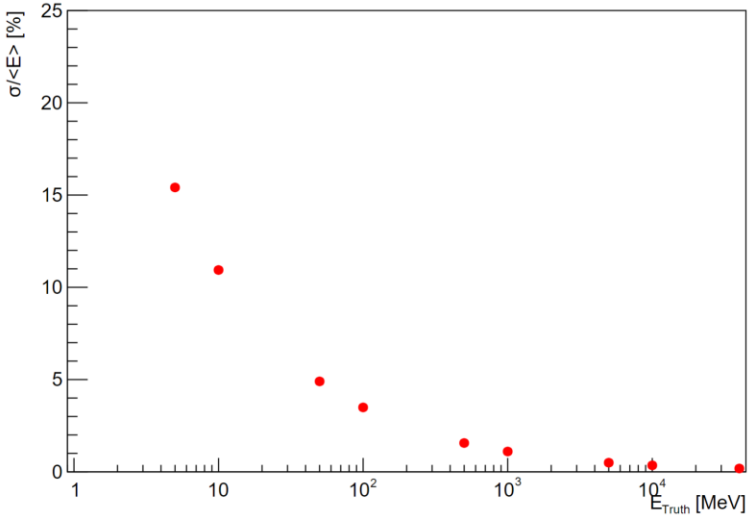
N_{Rec} follows an asymmetric Gaussian distribution

	ϵN_{In}	10	100	1,000	10,000	100,000	500,000
Response	$\langle N_{Det} \rangle$	10.05	100.5	1,005	10,045.3	100,037	491,159
	σ_{Det}	2.66	8.33	26.3	83.14	262.3	581.02
Correction	$\langle N_{Rec} \rangle$	10	100	1,000	10,000	100,000	500,000
	$\sigma_{Rec,-/+}$	2.32/3.00	7.96/8.65	25.89/26.58	82.68/83.37	264.38/265.08	613.48/614.27

SiPM Linearity (after correction)



Resolution introduced by SiPM Digitization



σ_{Rec} is very close to σ_{Det} when $\epsilon N_{In} < 100{,}000$, and the asymmetry can almost be ignored

Performance Check: SiPM Verbose

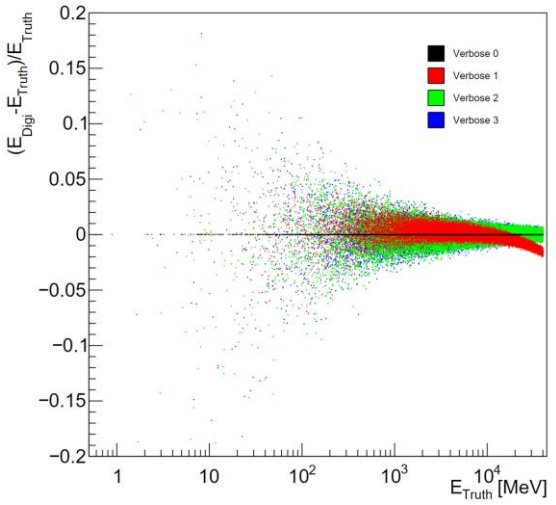
SiPM Digitization Verbose in CEPCSW

fast → slow

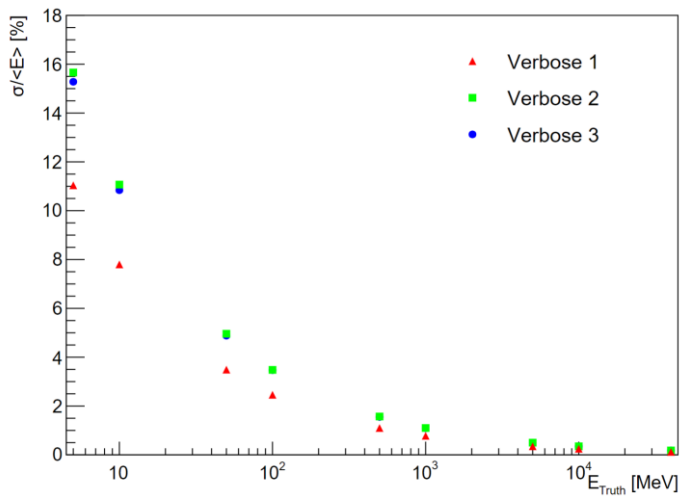
Verbose	0	1	2	3
Description	☒response ☒correction	☑response ☒correction	☑response ☑simple correction	☑response ☑full correction

- Verbose 0: no SiPM related effect in digitization
- Verbose 1: SiPM response follows the function $f(x)$, while no correction on saturation
- Verbose 2: SiPM response follows the function $f(x)$, and a simple correction on saturation with $\boldsymbol{\sigma_{Rec} = \sigma_{Det}}$
- Verbose 3: SiPM response follows the function $f(x)$, and a full correction on saturation

SiPM Linearity



Resolution introduced by SiPM Digitization



Verbose-1 without saturation correction has better resolution but a 2% non-linearity at 40GeV.

Digitization: ADC

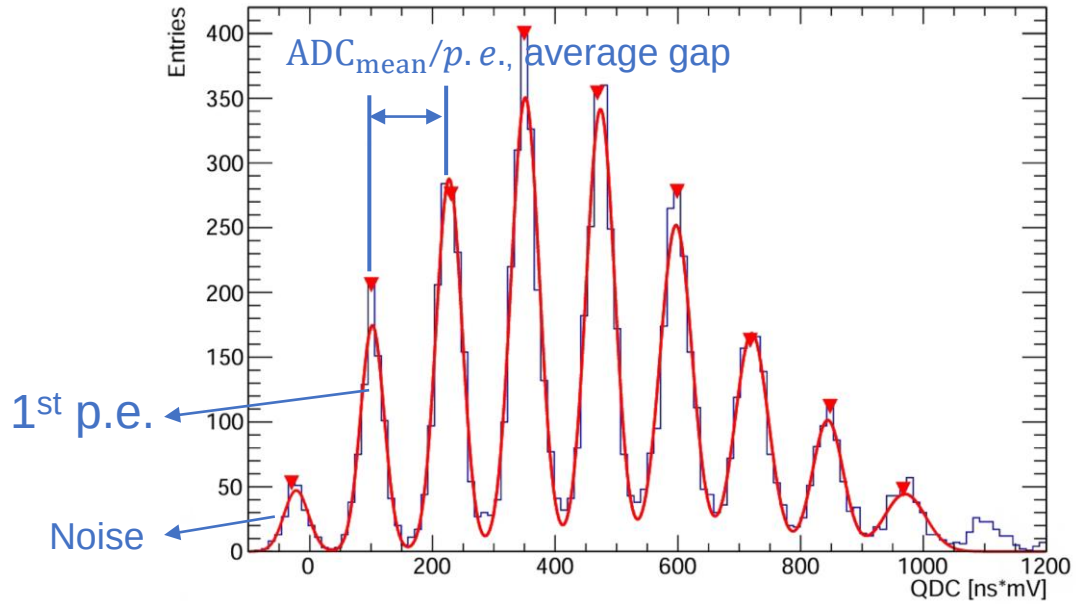
- ADC digitization: multi-gains to expand dynamic range
  - 4096 ADC counts, 3 gains
  - $NPE \rightarrow$ ADC: Gaussian sampling

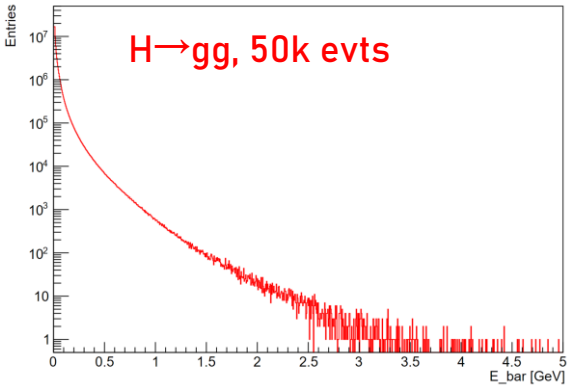
$$\langle ADC \rangle = NPE \cdot \langle ADC \rangle_{SPE}$$

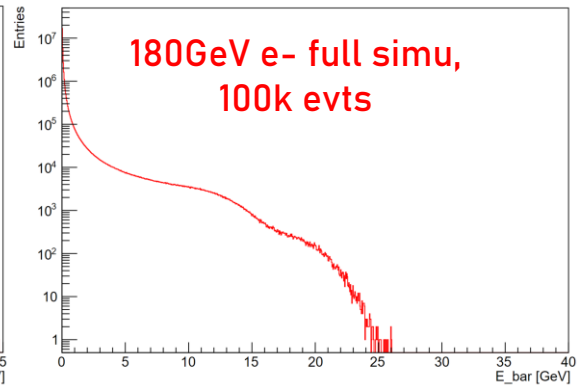
$$\sigma = \sqrt{NPE \cdot \sigma_{SPE}^2 + \sigma_{\mathrm{Noise}}^2},\ \sigma_{SPE} = \sqrt{\sigma_{1\mathrm{st}}^2 - \sigma_{\mathrm{Noise}}^2}$$

  - Precision 0.2%: Gaussian sampling
  - Switch at 4000ADC for Gain-1 and Gain-2
  - ADC(→SiPM correction) → Energy
  - Energy threshold: 0.05MIP

SiPM spectrum







÷ 70 ÷ 40

	Gain-1	Gain-2	Gain-3
$\langle ADC \rangle_{SPE}$	25	0.36	0.009
σ_{SPE} (ADC)	1.5	0.021	0.00052
σ_{Noise} (ADC)	5	5	5
Switching (ADC)	4000	4000	-
Energy range	0~1.6MIP	1.6~112MIP	112~4586MIP
		14MeV	997MeV 40,819MeV

40GeV dynamic range was set

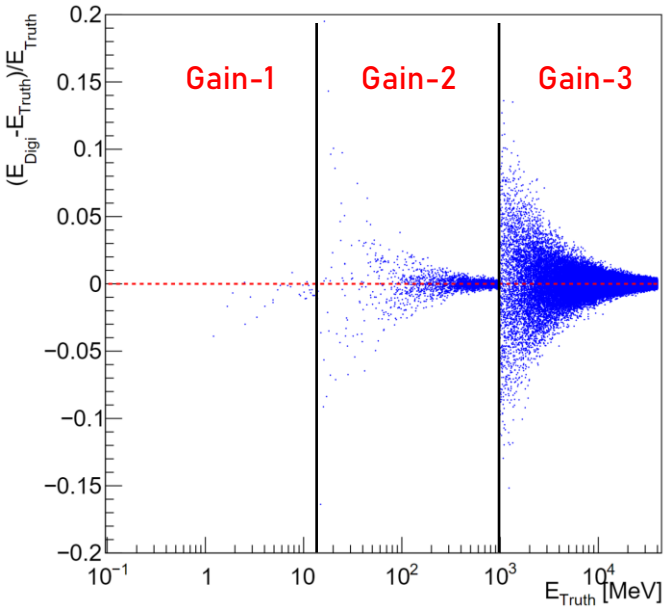
Performance Check: ADC

- Linearity of ADC digitization is no problem
- The resolution has a drop after switching points
  - Need to be careful when setting the range. Since the Gain-2 is designed to cover the energy range that most possibly deposited in crystal bars
- S/N is a ideal, difficult to be achieved for SiPM with 6μm pixel

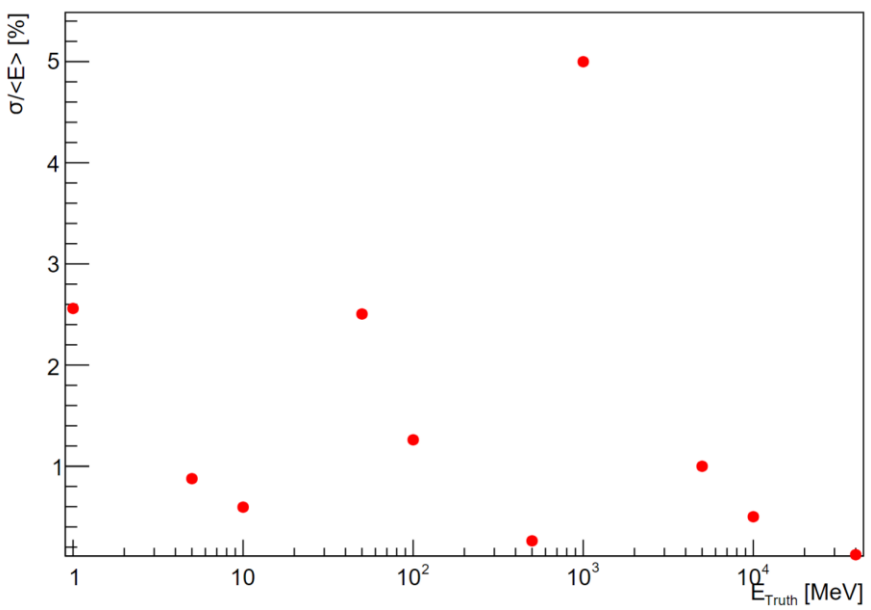
	Gain-1	Gain-2	Gain-3
$\langle ADC \rangle_{SPE}$	25	0.36	0.009
σ_{SPE} (ADC)	1.5	0.021	0.00052
σ_{Noise} (ADC)	5	5	5
Switching (ADC)	4000	4000	-
Energy range	0~1.6MIP	1.6~112MIP	112~4586MIP
		14MeV	997MeV 40,819MeV

÷ 70 ÷ 40

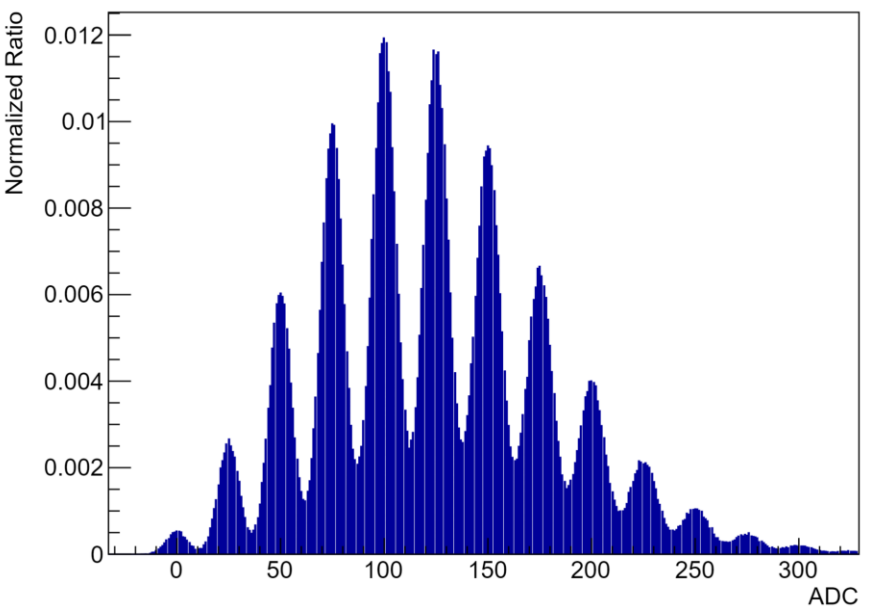
ADC Linearity



Resolution introduced by ADC digitization



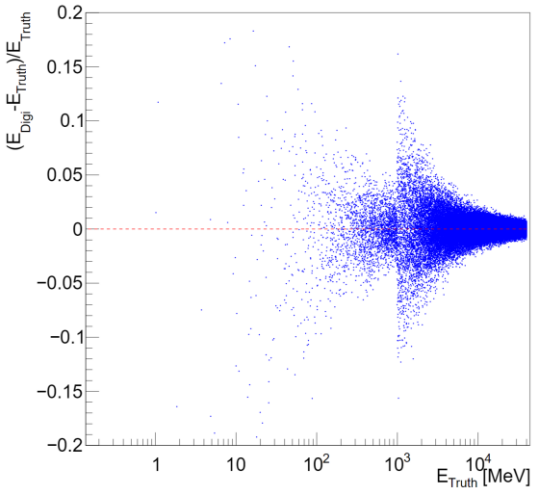
Low energy spectrum in Gain-1



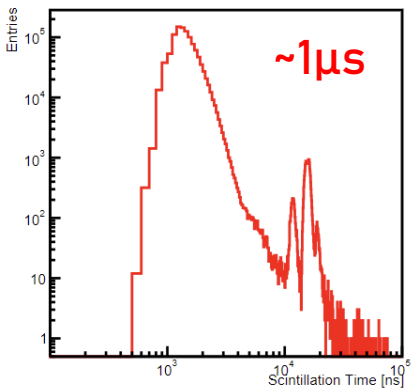
Performance: Total Effects

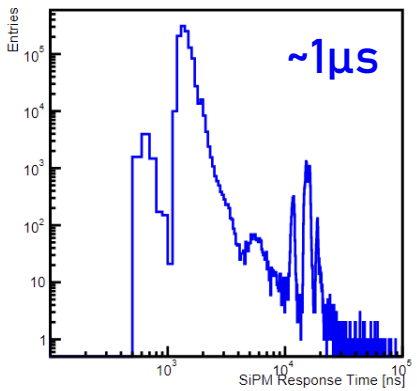
		Gain-1		Gain-2			Gain-3			
		0MeV		14MeV			997MeV			40819MeV
	Energy (MeV)	5	10	50	100	500	1000	5000	10000	40000
Scintillation	σ/<E> (%)	13.18	9.36	4.19	2.96	1.32	0.94	0.42	0.30	0.15
SiPM	σ/<E> (%)	15.28	10.84	4.88	3.47	1.55	1.09	0.49	0.35	0.18
ADC	σ/<E> (%)	0.88	0.60	2.50	1.26	0.26	5.00	1.00	0.50	0.12
1⊕2⊕3	σ/<E> (%)	20.20	14.33	6.90	4.73	2.05	5.20	1.19	0.68	0.26
Total	σ/<E> (%)	19.77	14.20	6.91	4.74	2.05	4.20	1.19	0.68	0.26

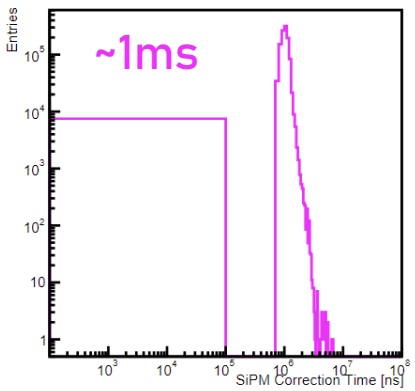
Digitization Linearity

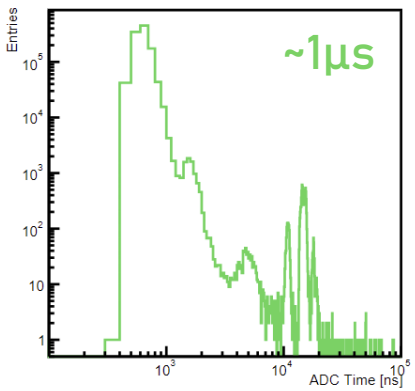


Time consumption: 1~2ms per event, dominated by SiPM correction(Verbose-3)





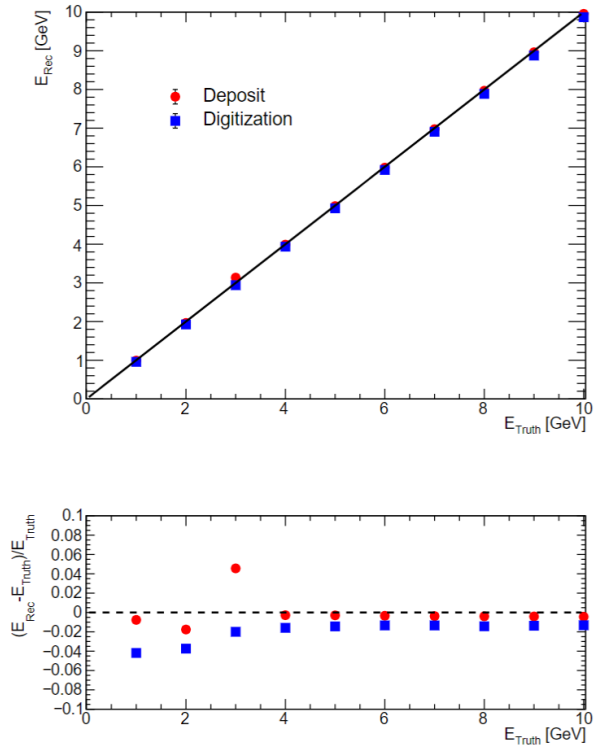




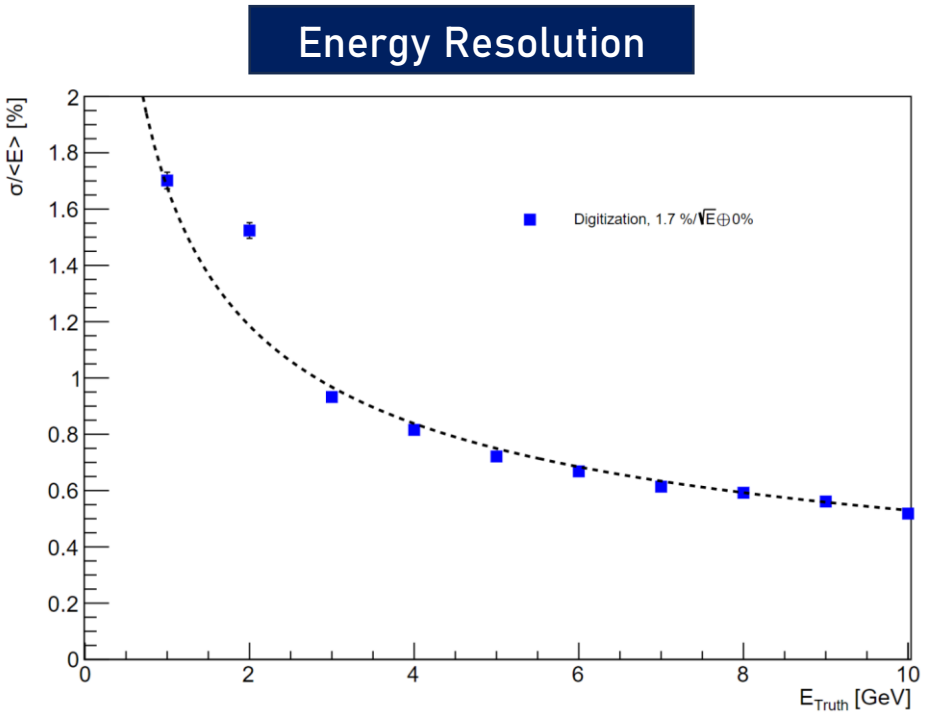
Performance with Detector Simulation in CEPCSW

- <5% energy leakage at low energy region because of 0.05MIP threshold
- ~1.7%/$\sqrt{E}$ energy resolution with 1~10GeV electron after digitization

Energy Linearity



Energy Resolution



Summary & Prospect

- A realistic digitization model combined with behaviors of scintillatior, SiPM and ADC is built. By decoupling the contribution from each process, we conclude that the SiPM resolution dominate in low energy region(<1GeV), while the ADC resolution after the switching points dominate in high energy region(>1GeV).

- The dynamic range still needs to be optimized. To make sure the capability of source calibration at high gain and covering most physical processes in middle gain.

Backup

S/N of ADC

- Digitization only with: scintillation fluc + SPE sigma + ADC noise
- Input: 5 photons with Poisson sampling
- $\langle ADC \rangle_{SPE}$/ σ_{SPE} should be > 10, while $\langle ADC \rangle_{SPE}$/ σ_{Noise} should be > 3

Reference: SiPMs calibrated with oscilloscope and pre-amplifier

	S14160-3010PS	S13360-3025CS
$\langle QDC \rangle_{SPE}$	292	124
σ_{SPE} (QDC)	9.25	7.5
σ_{Noise} (QDC)	67	18.5

$\langle ADC \rangle_{Spe}$	5
σ_{SPE} (ADC)	2.5
σ_{Noise} (ADC)	3

$\langle ADC \rangle_{SPE}$	10
σ_{SPE} (ADC)	1
σ_{Noise} (ADC)	3

$\langle ADC \rangle_{SPE}$	15
σ_{SPE} (ADC)	1
σ_{Noise} (ADC)	3