Development and Commissioning of the Highly Granular Scintillator-based Calorimeters of CEPC

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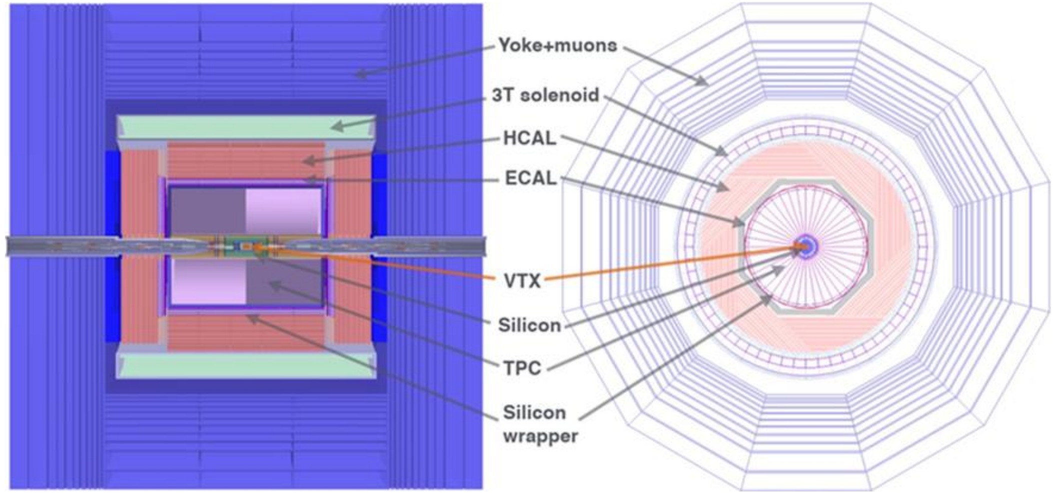
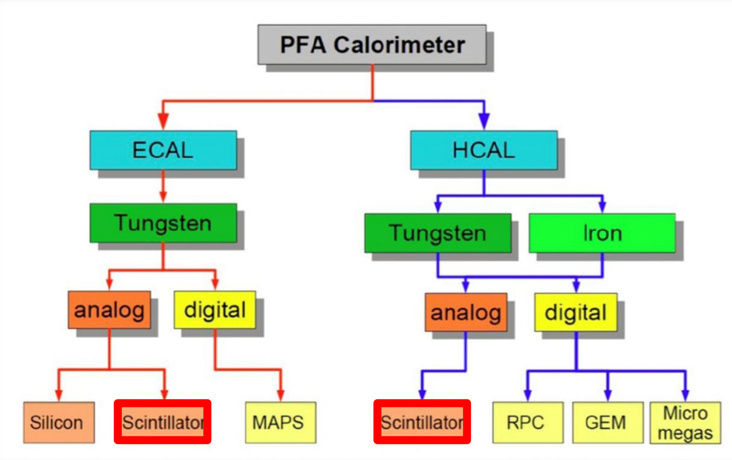
On behalf of CEPC Calorimeter working group

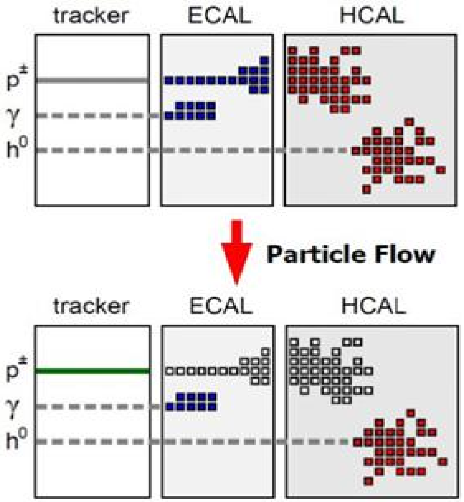
CEPC brief introduction and particle flow algorithm

- Circular Electron Positron Collider(CEPC)
  - ➢ Future lepton collider as Higgs/W/Z factories
  - ➢ Precision measurements of the Higgs/EW/QCD
  - ➢ Calorimetry requirement: 3-4% boson mass resolution for W/Z hadronic decays → 30%/$\sqrt{\mathrm{E}}$ jet resolution



- Particle flow algorithm(PFA)
  - ➢ Use optimal sub-detectors to measure energy/momentum of secondary particles in a jet
    - ☐ ~60% E_{jet} : charged particles measured by tracker
    - ☐ ~30% E_{jet} : photons measured by ECAL
    - ☐ ~10% E_{jet} : neutral hadrons measured by HCAL
  - ➢ Separation of close-by particles in jet → high granularity calorimeters
  - ➢ This talk focus on following high-granularity calorimeters
    - ☐ Scintillator-tungsten ECAL prototype
    - ☐ Scintillator-steel AHCAL prototype





Scintillator-tungsten ECAL prototype(ScW-ECAL)

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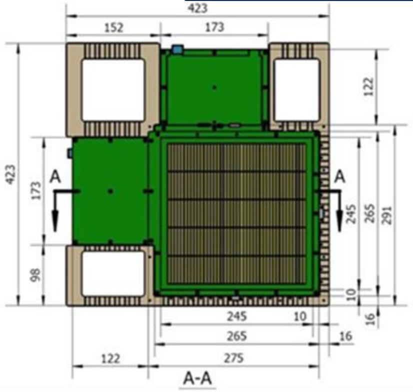
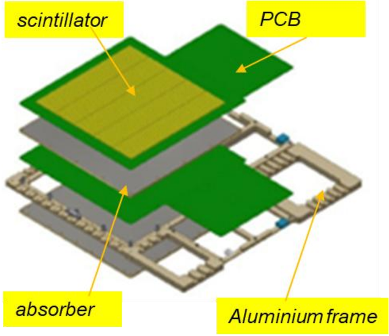
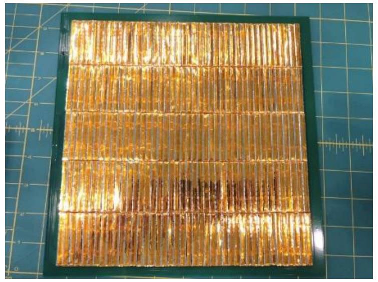
ScW-ECAL technological prototype

ScW-ECAL "Superlayer" design

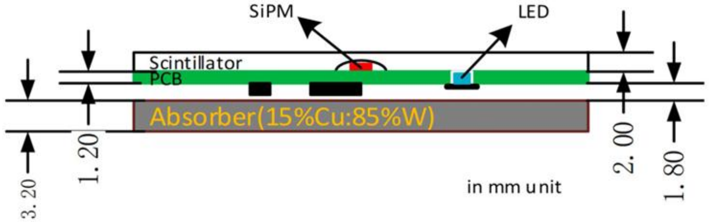




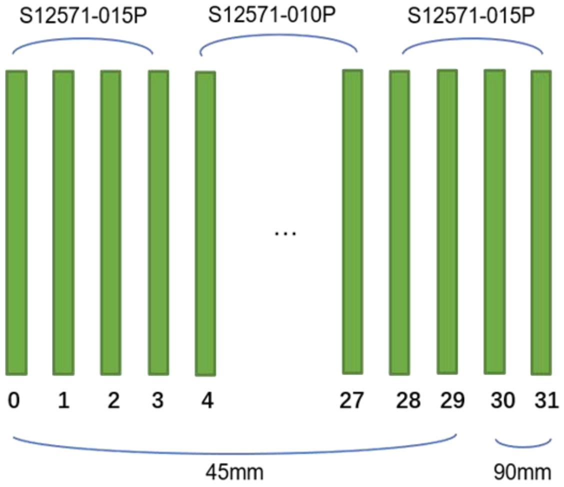


Plastic scintillator strips with ESR film on PCB board

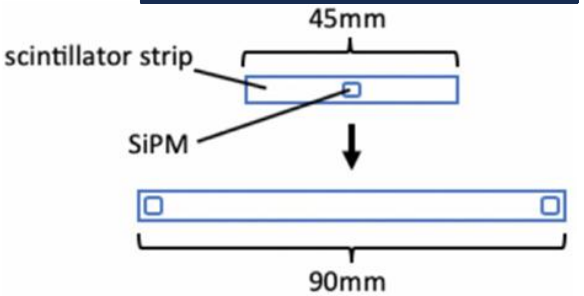
ScW-ECAL basic unit design



ScW-ECAL layer arrangement



SiPM coupled with scintillator



- ScW-ECAL technological prototype
  - Plastic scintillator strips($45\times5\times2\ mm^3$) + WCu(85:15) absorber + Hamamatsu S12571-010, S12571-015 SiPMs
  - Sensitive area : 22x22 cm^2, 32 layers in longitudinal dimension(~22.4X_0)
  - Orthogonal placement of two adjacent layers for almost 5x5 mm^2 granularity
  - 6920 channels, 192 SPIROC2E electronics chips, ~350kg

Scintillator-steel AHCAL prototype

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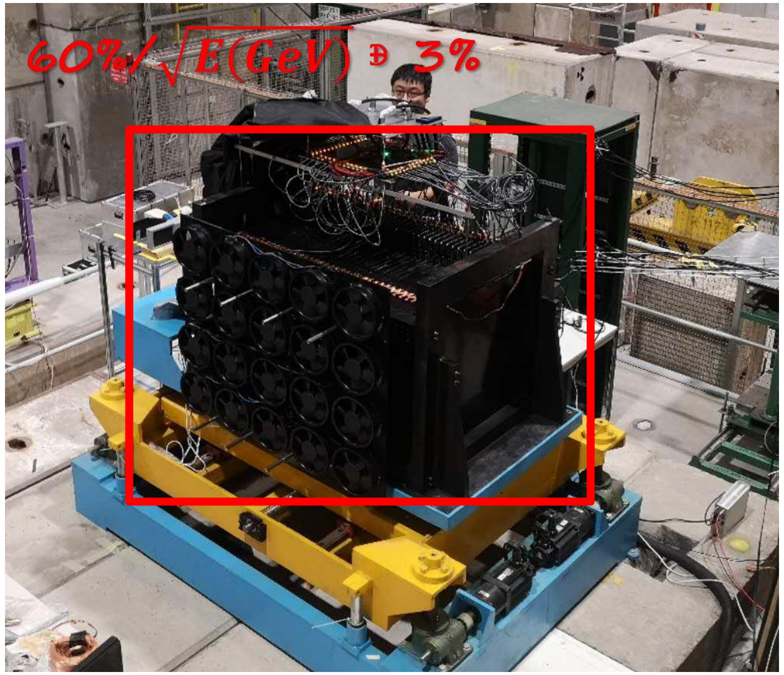
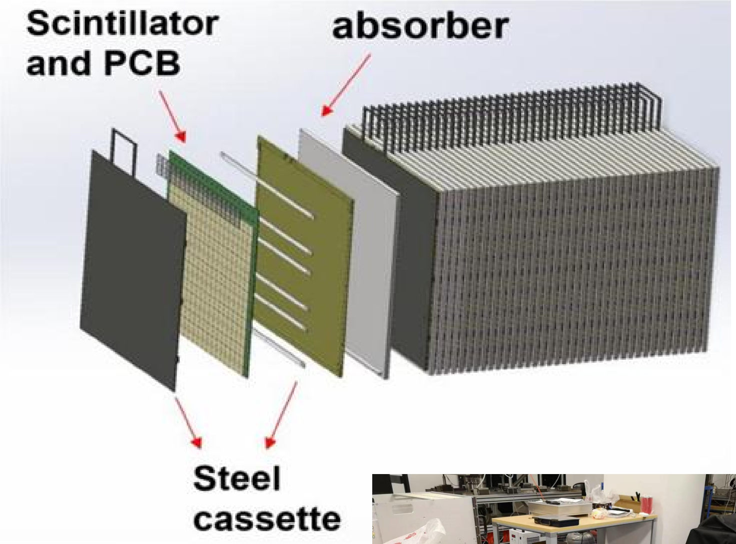
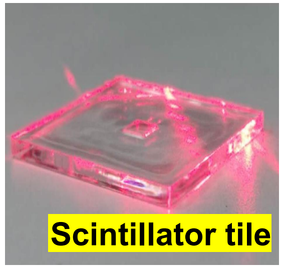
AHCAL technological prototype

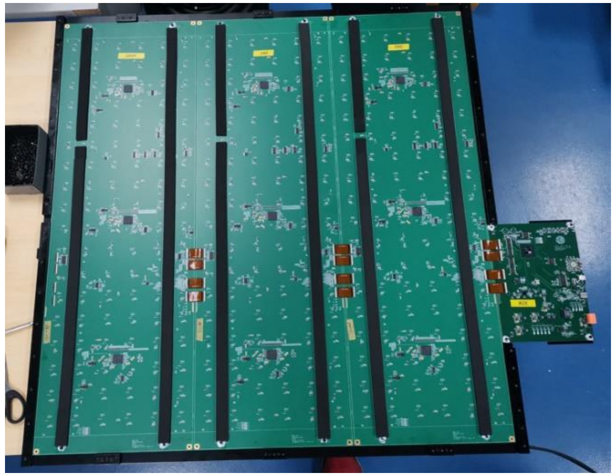


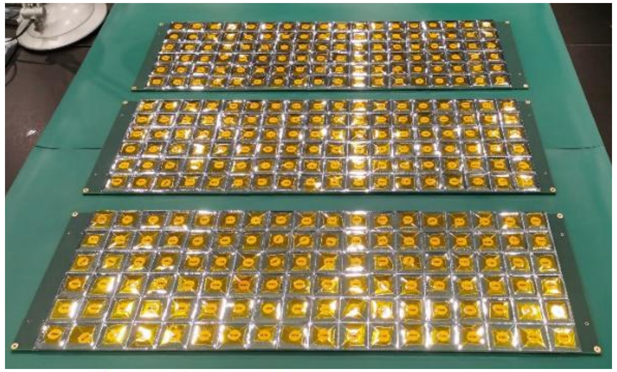
AHCAL layer design

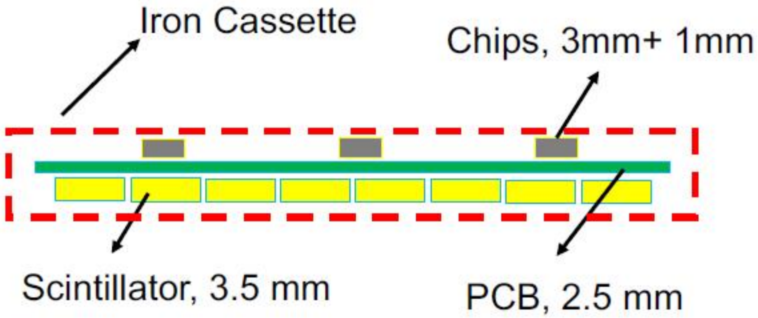




AHCAL basic unit design







- AHCAL technological prototype
  - Plastic scintillator tiles ($40\times40\times3\ mm^3$) + steel absorber plates + Hamamatsu S14160-1315PS and NDL 22-15 SiPMs
  - Sensitive area : 72x72 cm^2, 40 layers in longitudinal dimension (~4.6λ_I)
  - 12960 channels, 360 SPIROC2E chips, ~5 ton

CERN beamtests in 2022-2023

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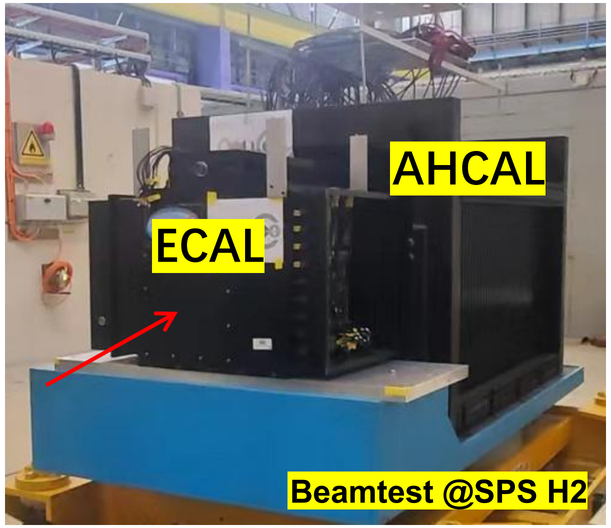
Oct 19 – Nov 2, 2022	Apr 26 – May 10, 2023	May 17 – 31, 2023
SPS H8 beamline	SPS H2 beamline	PS T9 beamline

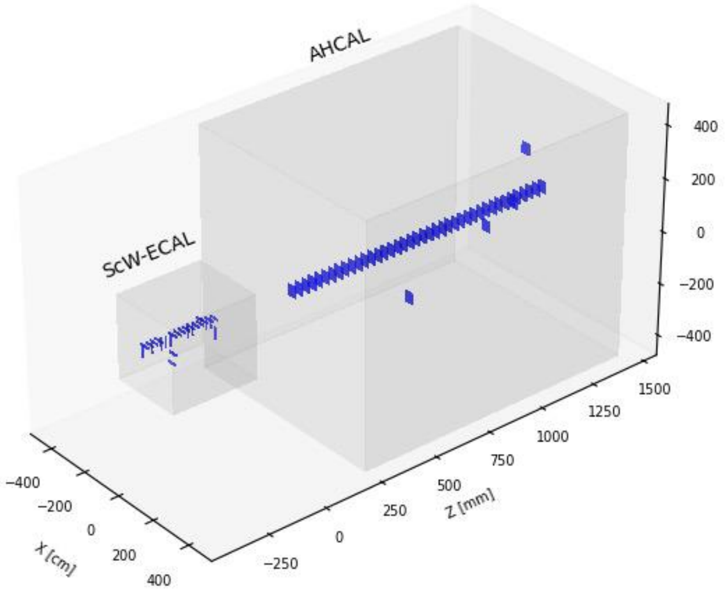


- Three beamtest campaigns at CERN SPS-H8(2022), SPS-H2(2023) and PS-T9(2023)
  - ➢ Data acquisition: combined mode, AHCAL standalone mode
  - ➢ Supporting table for alignment of ECAL and AHCAL transverse sensitive area and adjustment of beam position

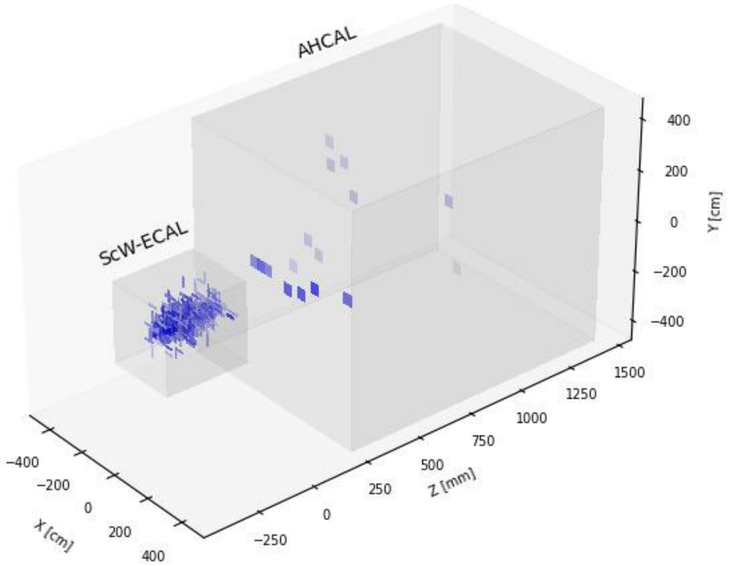
Data taking overview

- Decent statistics of beamtest data samples (~63M events in total)
  - ➢ Muons: 10 GeV (PS-T9), 108/160 GeV (H8), 100/120 GeV (H2);
  - ➢ Electrons/positrons: 0.5 – 5 GeV at PS; 10 – 250 GeV at SPS;
  - ➢ Pions: 1 – 15 GeV at PS, 10 – 120 GeV (also 150 – 350 GeV) at SPS

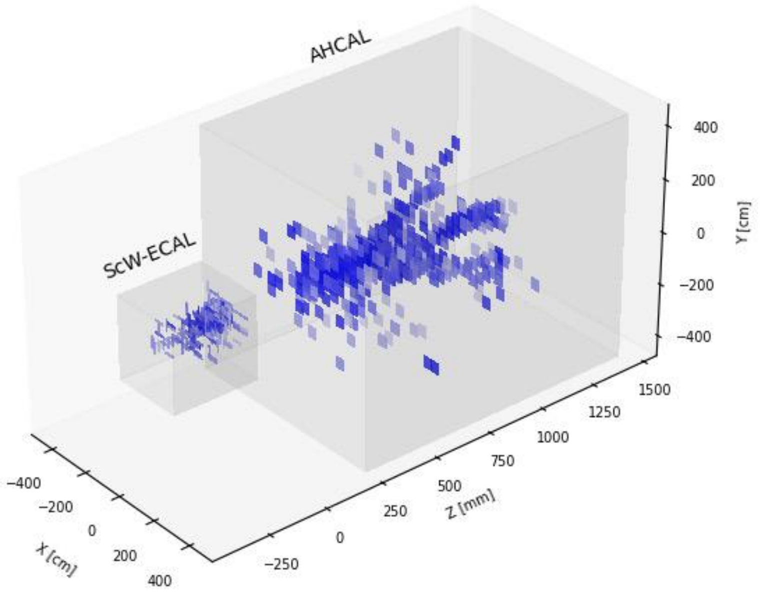
100GeV mu-@SPS



60GeV e-@SPS

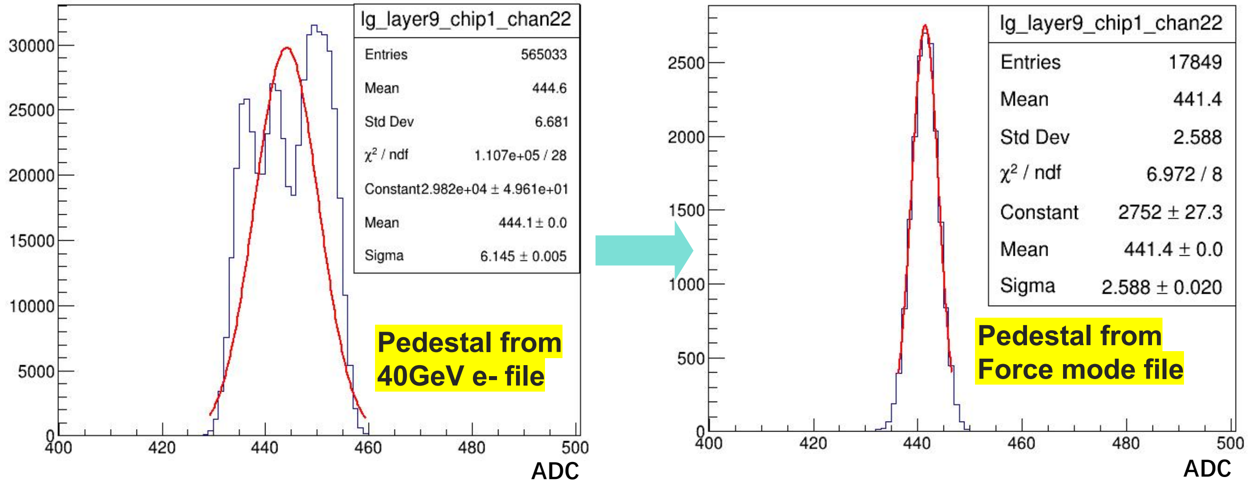


60GeV π-@SPS

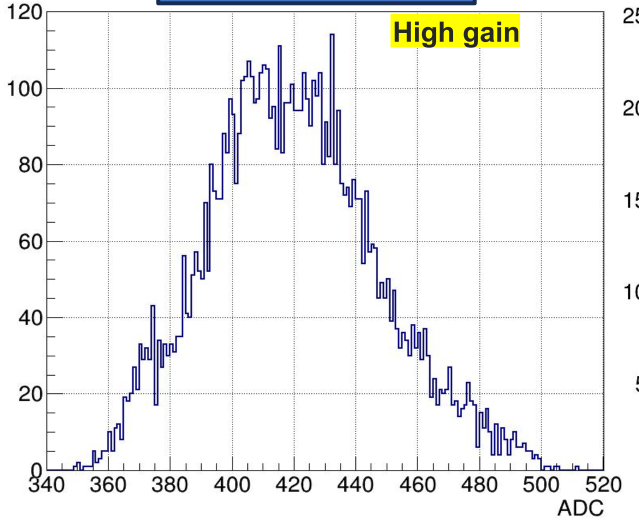


Pedestal calibration

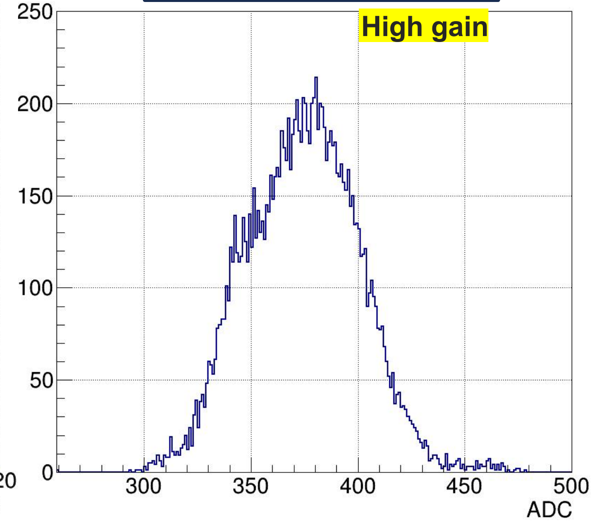
- Pedestal acquisition
  - ➢ Multi-peaks pedestal distribution due to crosstalk
  - ➢ Channel-level pedestal from force-trigger mode file
- Stable pedestal during beamtest
  - ➢ Pedestal mean : 280~550 ADC for both ECAL and AHCAL pedestal sigma : 1~6 ADC for both ECAL and AHCAL
  - ➢ 0~2 ADC fluctuation in both SPS and PS TB
  - ➢ Pedestal changes when beamtest condition changes



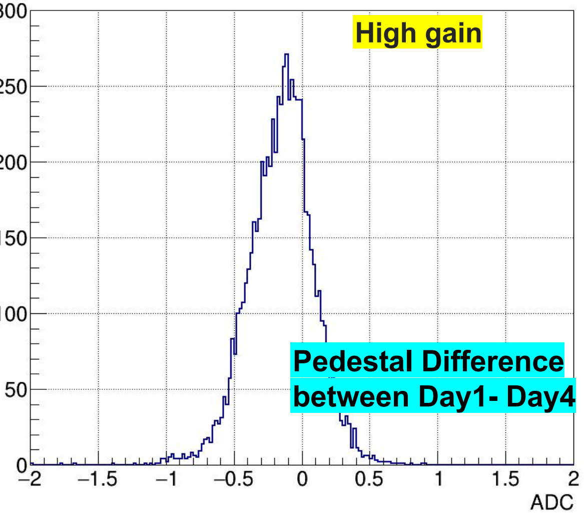
ECAL: pedestal mean



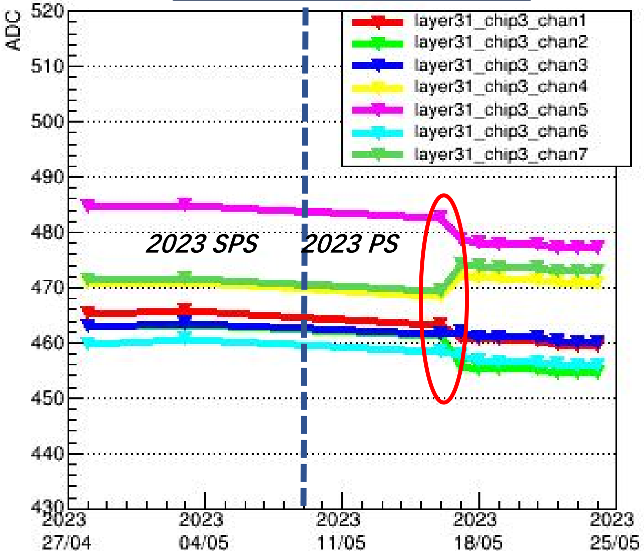
AHCAL: pedestal mean



ECAL: pedestal difference of two days during TB

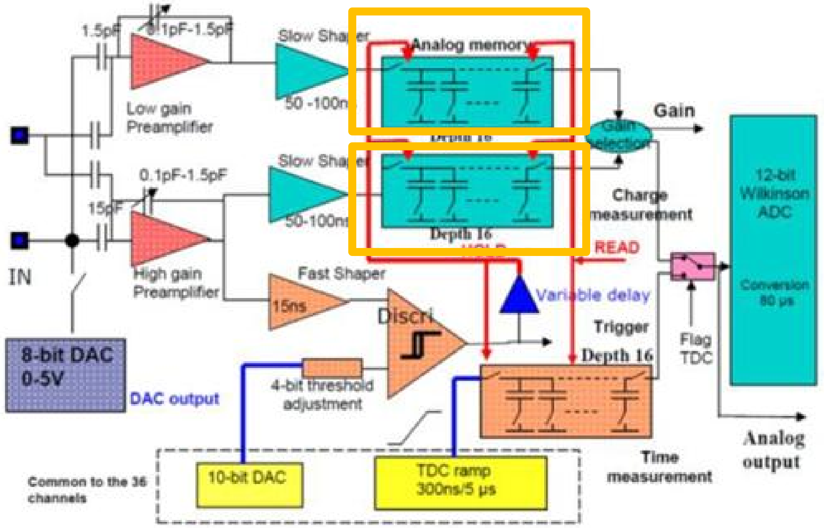


ECAL: pedestal stability

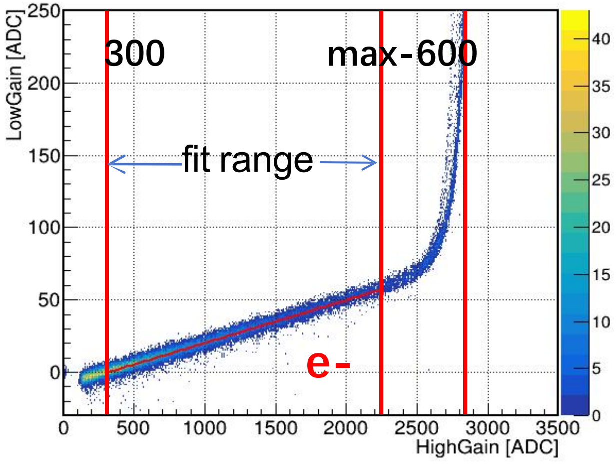


ASIC chip gain calibration

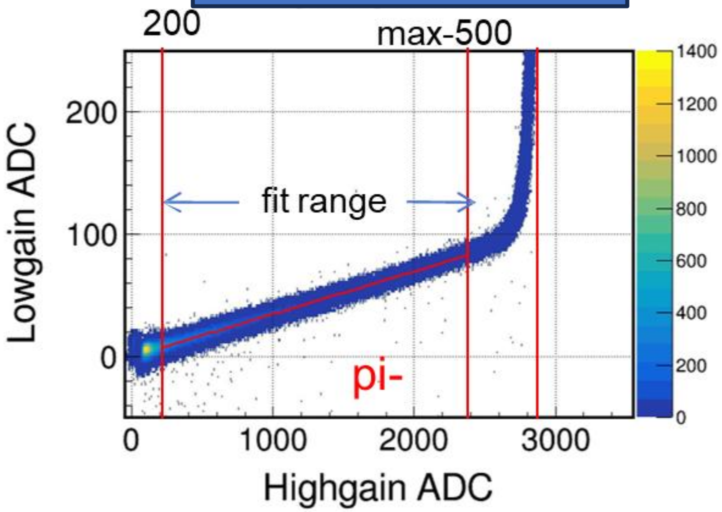
- Large dynamic range: high-gain/low-gain mode on SPIROC2E
- SPIROC2E chip gain: high-gain/low-gain ratio calibration
  - ➢ Datasets selection: e- for ECAL, pi- for AHCAL
  - ➢ Linear fit range limits: ECAL(300, max-600), HCAL(200, max-500)
  - ➢ SPIROC2E chip gain: high-low gain ratio 30~40
- Dead channel monitor
  - ➢ ECAL: 64 dead channels, less than 3%
  - ➢ AHCAL: less than 10 dead channels



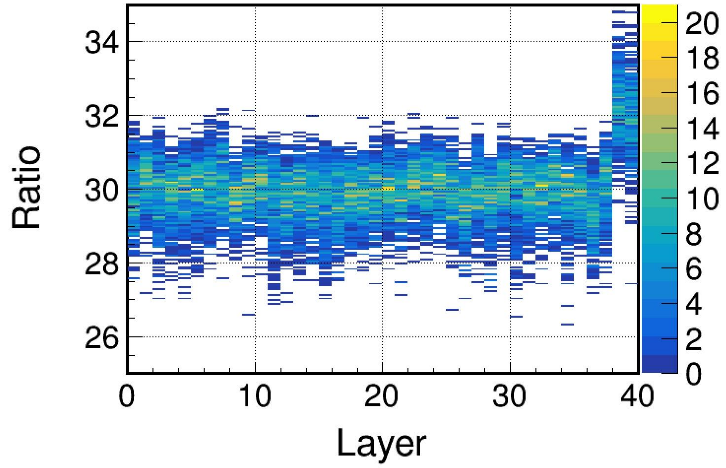
ECAL: single channel ASIC gain calibration



AHCAL: single channel ASIC gain calibration



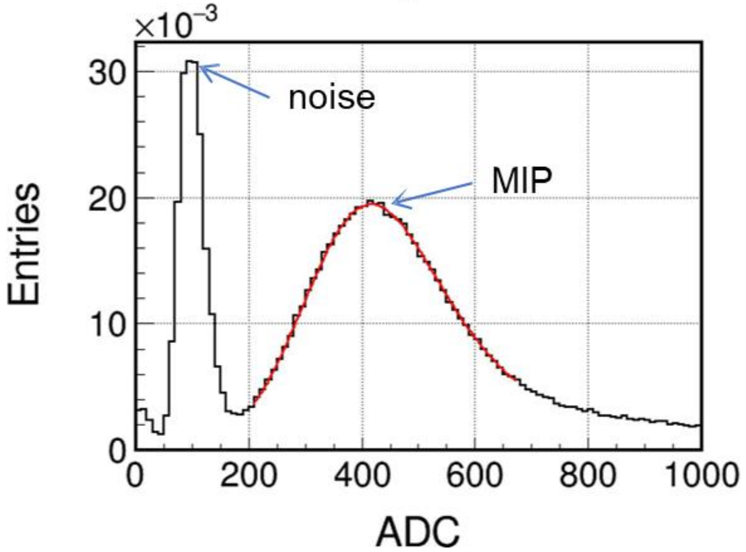
AHCAL: ASIC gain overview



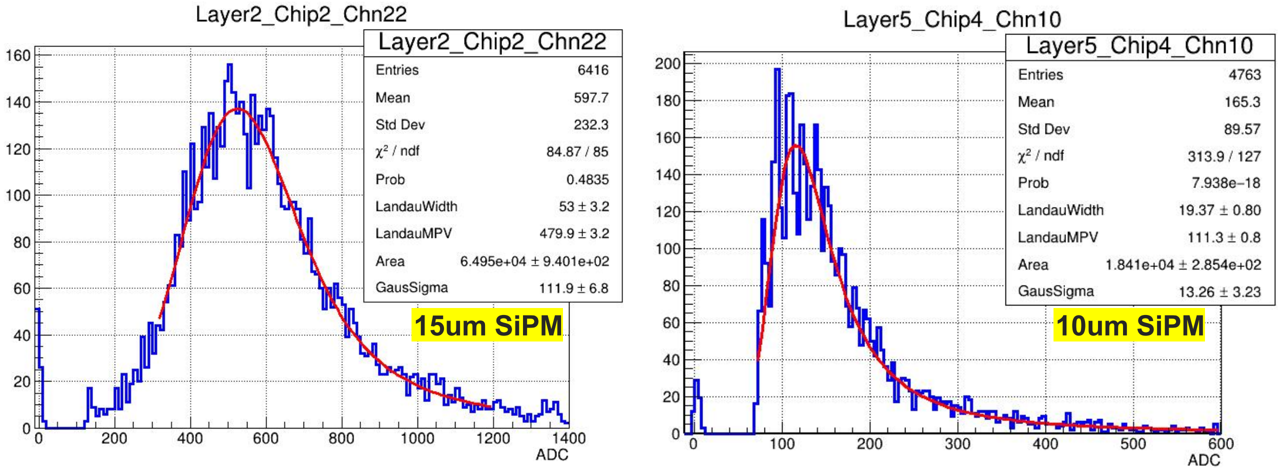
MIP calibration

- 100GeV muon file as datasets with position scan
- Track fit to exclude the dark noise
- Landau convoluted gaussian function
- MIP calibration monitor
  - ➢ ECAL: 68.9% channels calibrated successfully
  - ➢ AHCAL: 93.3% channels calibrated successfully

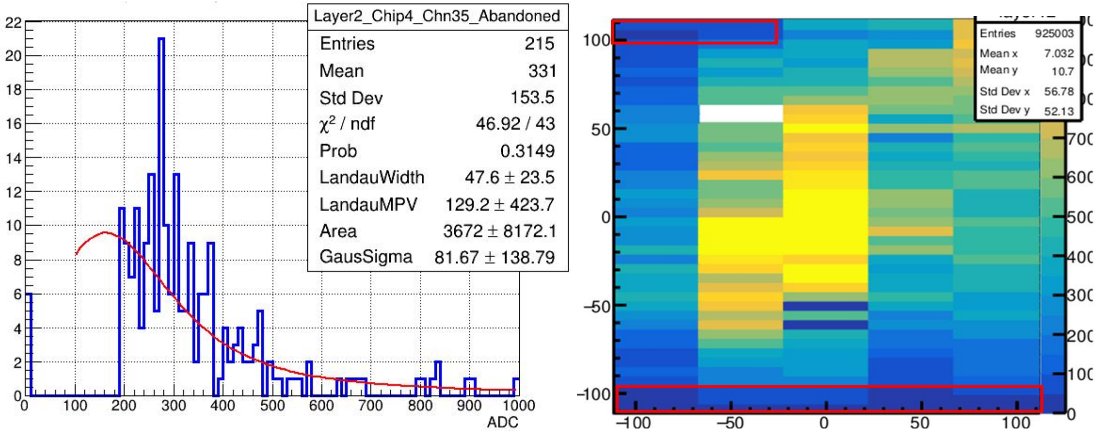
AHCAL: MIP spectrum of 15um-SiPM Hamamatsu channel



ECAL: MIP spectrum of 15um-SiPM and 10um-SiPM channel



Inadequate statistics on edge channels



SiPM gain calibration

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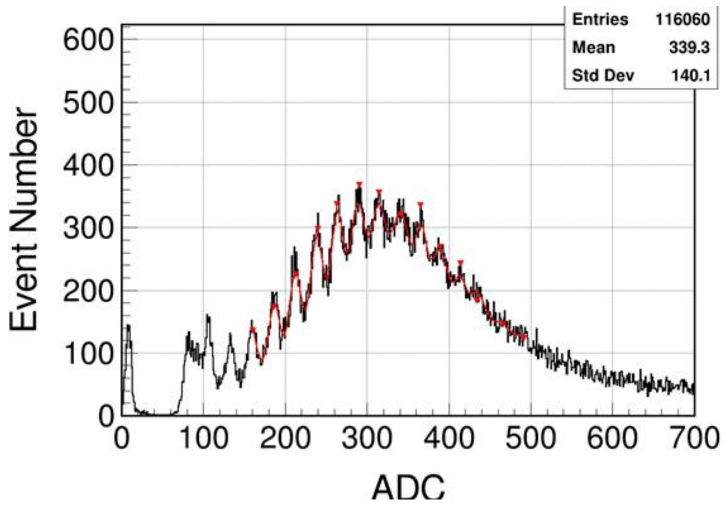
- SiPM gain calibration for MC digitization
  - ➢ Multiple APD pixels operating in Geiger mode
  - ➢ SiPM response non-linearity correction

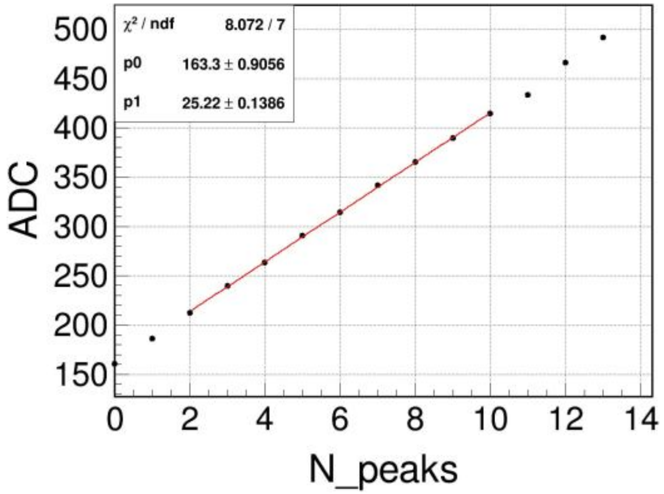
$$N_{fired} = N_{pixel} \cdot (1 - e^{-\frac{N_{seed}}{N_{pixel}}}) \quad , N_{seed} = N_{photon} \times PDE$$

- SiPM gain calibration: LED data during TB
  - ➢ Single photoelectron spectrum with multi-gaussian peaks
    - ☐ Peak number → photoelectron number
    - ☐ Peak interval → SiPM gain
  - ➢ Linear fit of the peak position: SiPM gain determined by slope

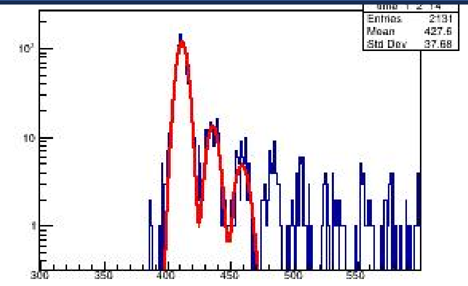
AHCAL: Single photoelectron Spectrum



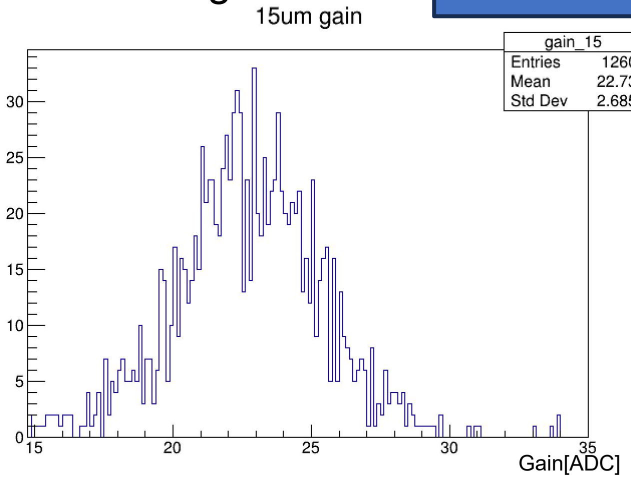
AHCAL: Peak position linear fit

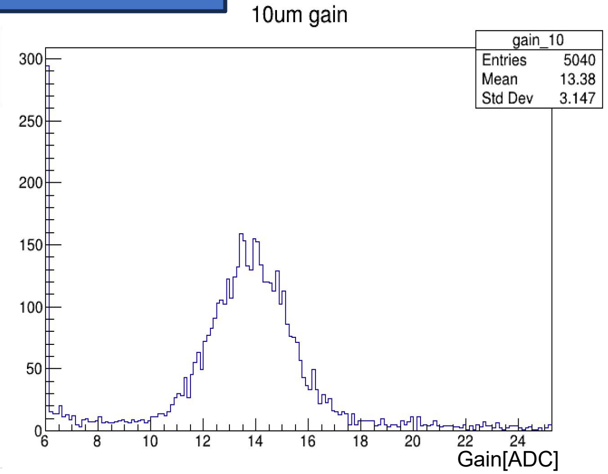


ECAL: Single photoelectron Spectrum

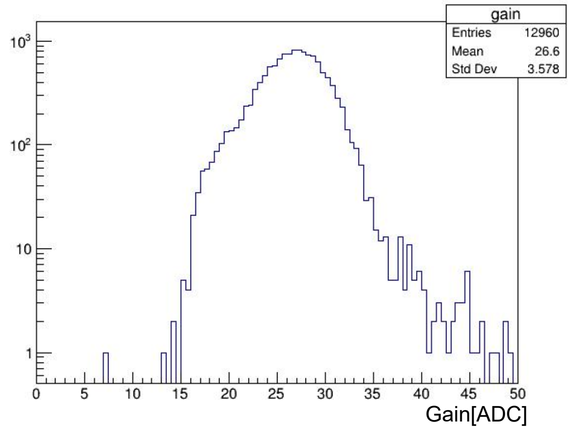


ECAL: SiPM gain overview





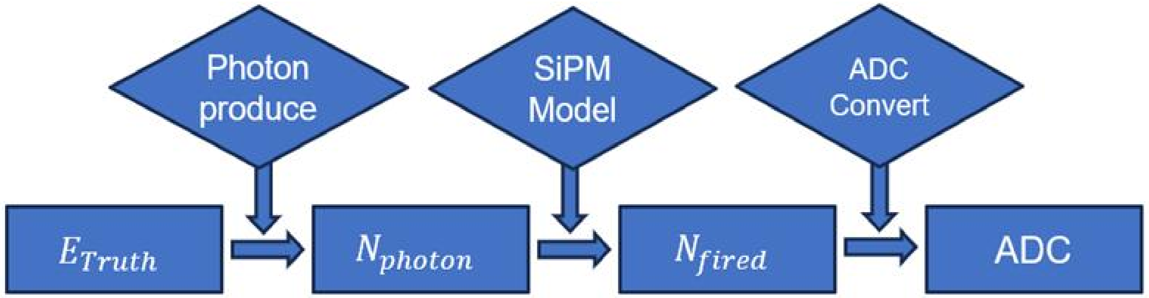
AHCAL: SiPM gain overview



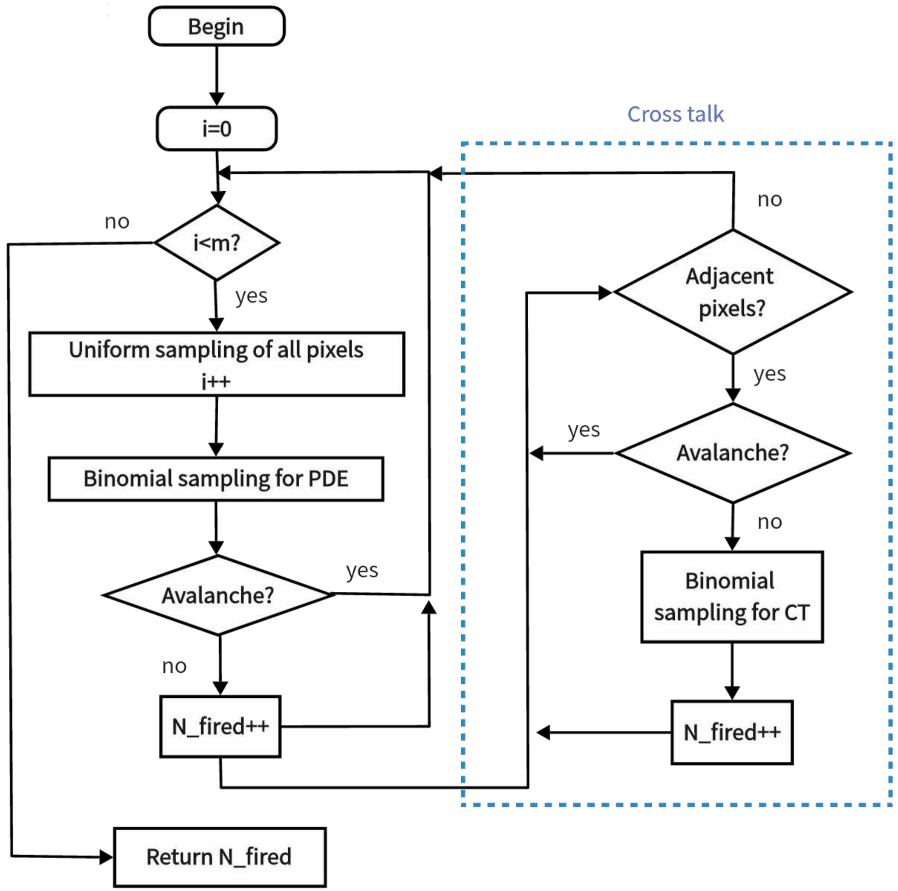
15um-SiPM channel has higher gain

Simulation and digitization

- Geant4 simulation: standalone ScW-ECAL and AHCAL prototypes' geometry
- Digitization: Improvement on consistency of MC/data
  - Energy deposition in Geant4 → ADC counts in electronics
    - Scintillation process: Energy deposition → photon number (SiPM gain, MIP MPV)
    - SiPM response: Photon number → fired pixel number (sampling model to do SiPM saturation correction)
    - Electronics: fired pixel number → ADC counts (Pedestal , ASIC chip gain)



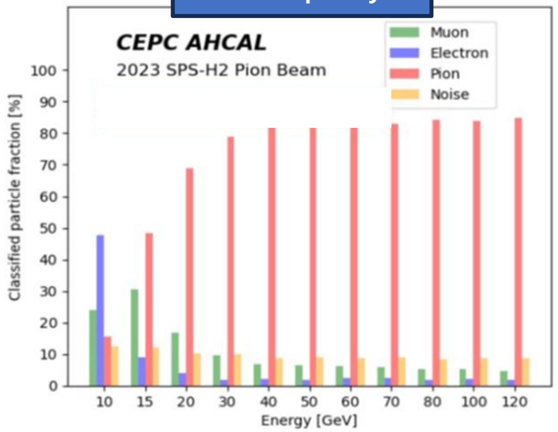
SiPM response MC sampling model diagram



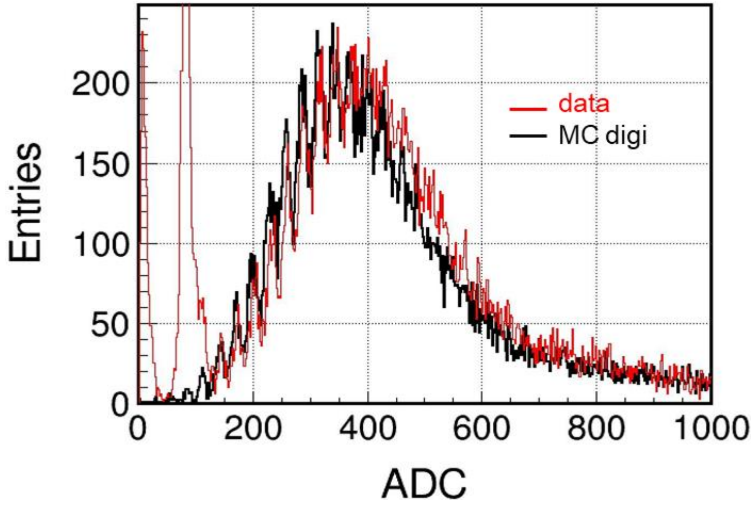
AHCAL response data/MC comparison

- Beam purity study: fractal dimension(FD) and Artificial Neural Network (ANN)
- AHCAL prototype data/MC comparison
  - ➢ Event selection applied on data file analysis
  - ➢ MIP spectrum data/MC crosscheck: slight difference
  - ➢ Electron datasets (1-50GeV) :~10% discrepancy

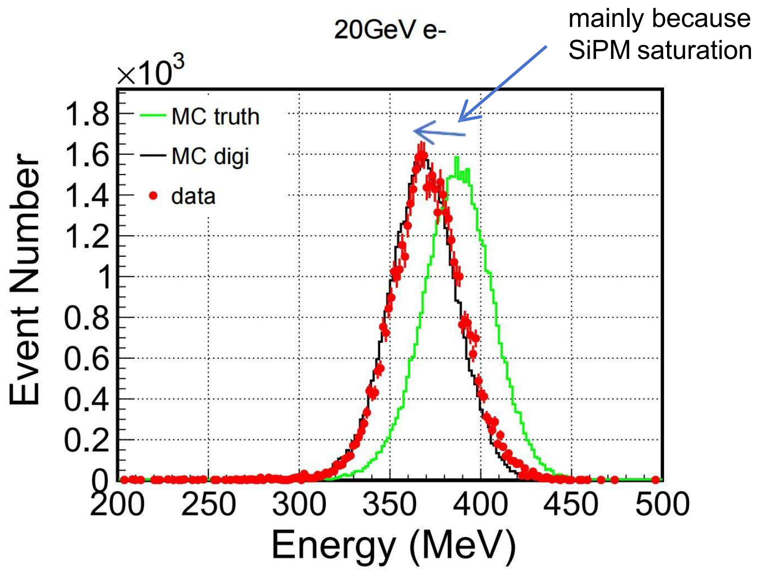
Beam purity



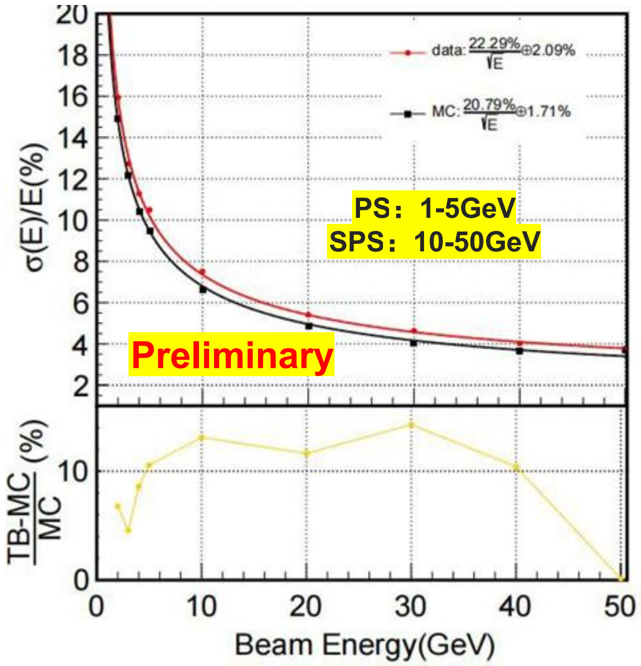
AHCAL data/MC comparison: MIP spectrum



AHCAL data/MC comparison: 20GeVe- energy response



AHCAL data/MC comparison: e- energy response

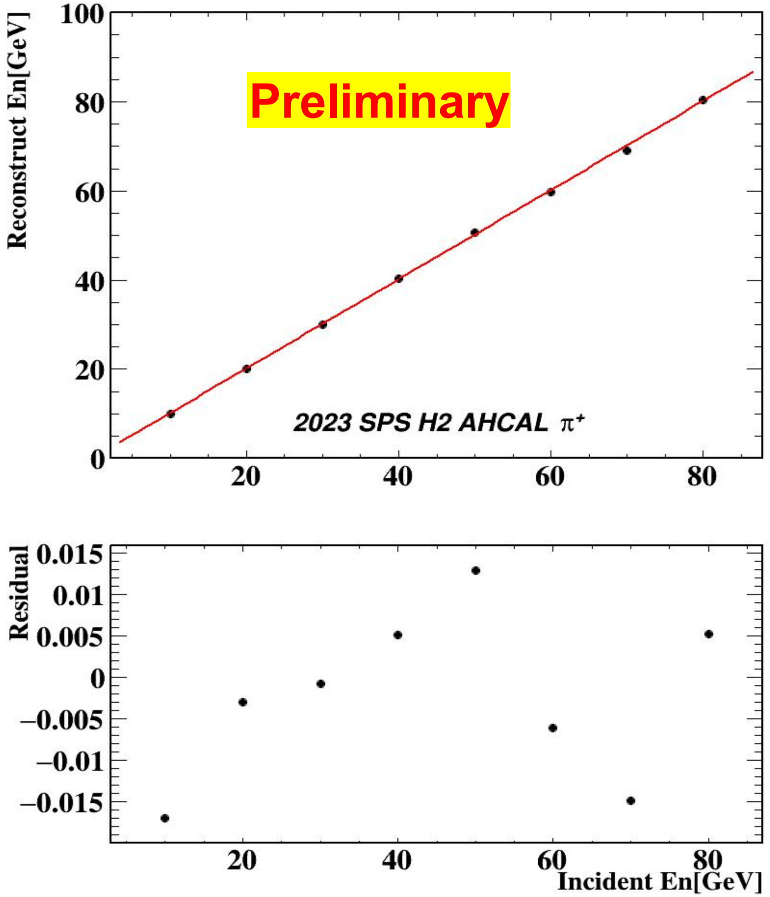


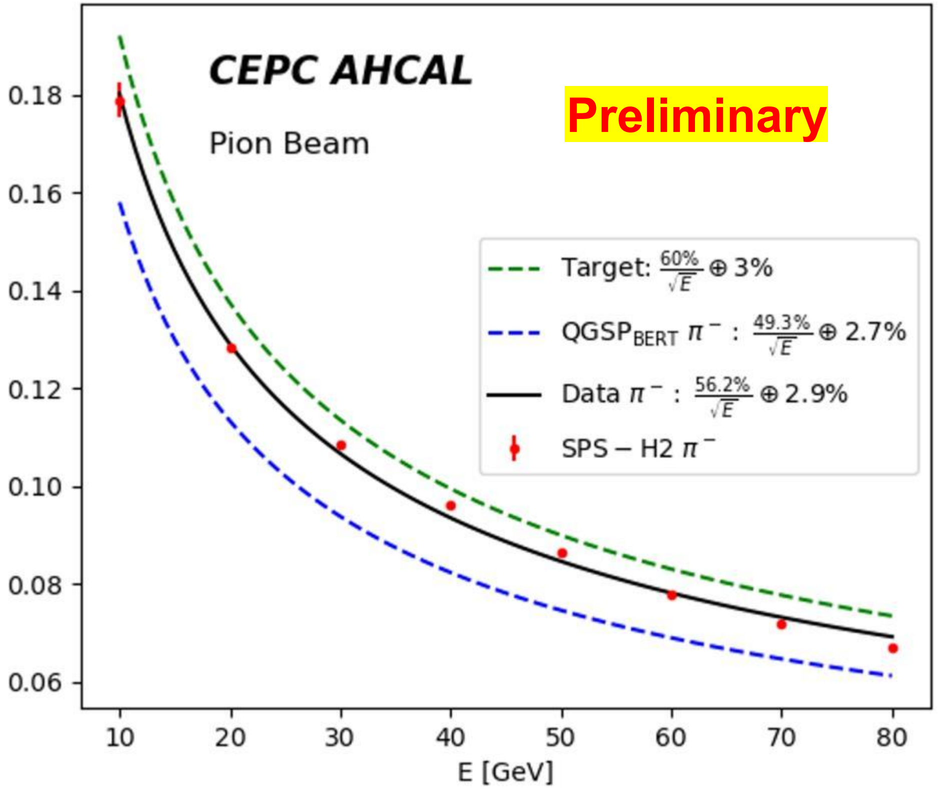
AHCAL performance preliminary results

- Pion datasets: 10-80GeV with event selection
  - Energy linearity is within ±1.5% (expected 3%)
  - Energy resolution: $56.2\%/\sqrt{E(GeV)} \oplus 2.9\%$ (expected $60\%/\sqrt{E(GeV)} \oplus 3\%$)

$$E_{reco}[GeV] = \sum_{i=1}^{12960} E_i^{Dep} \times C_{particle}^{sampling}$$

$$E_i^{Dep}[\text{MeV}] = \begin{cases} \dfrac{HS_i - HP_i}{C_i^{ADC\rightarrow MIP} \times C^{MIP\rightarrow \text{MeV}}} & HS_i - HP_i < SP_i \\ \dfrac{(LS_i - LP_i) \times C_i^{LG\rightarrow HG}}{C_i^{ADC\rightarrow MIP} \times C^{MIP\rightarrow \text{MeV}}} & HS_i - HP_i > SP_i \end{cases}$$





Summary and prospects

- High granularity calorimeter is the baseline option of CEPC
- Development of Scintillator-based tungsten ECAL and steel AHCAL prototype
- Successful beamtests campaigns at CERN SPS/PS during 2022-2023
  - Huge amount data samples cover wide energy range including various particle species
- Preliminary analysis results of calorimeters
  - Fundamental parameters calibration and stability check
  - Optimization of prototype simulation and digitization for validation between data/MC samples
  - Calorimeters performance analysis: AHCAL performance reach the design requirements
- Future
  - Ongoing analysis activities
    - ScW-ECAL prototype performance study
    - Improvement on data/MC consistency
  - ECAL and AHCAL combined analysis
    - PFA performance study

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  - ECAL and AHCAL combined analysis
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Thanks for your attention!

Backup

SiPM of ECAL and AHCAL

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ECAL SiPM

关键参数	S12571-010P	S12571-015P
灵敏面积	$1\ mm \times 1\ mm$	$1\ mm \times 1\ mm$
封装尺寸	$1.9\ mm \times 2.4\ mm$	$1.9\ mm \times 2.4\ mm$
像素数量	10000	4489
像素尺寸	$10\ um$	$15\ um$
增益	1.35×10^5	2.3×10^5
最灵敏波长	$470\ nm$	$460\ nm$
光探测效率	10 %	25 %
暗计数	$100\ kHz$	$100\ kHz$
串扰率	$\sim 7\%$	$\sim 13\%$
推荐电压	击穿电压 +4.5 V	击穿电压 +4 V

AHCAL SiPM

Company	NDL	HPK
Type	22-15	S14160-1315PS
Sensitive area (mm^2)	1.6*4	1.69
PDE (%)	40	32
Gain (*10^5)	2.4	3.6
Pixel No.	7400*4	7284
Breakdown Voltage (V)	19	38
OverVoltage (V)	4	4
Dark Count (kHz)	330*4	120
Cross Talk (%)	8.5	1.0

Pedestal issue

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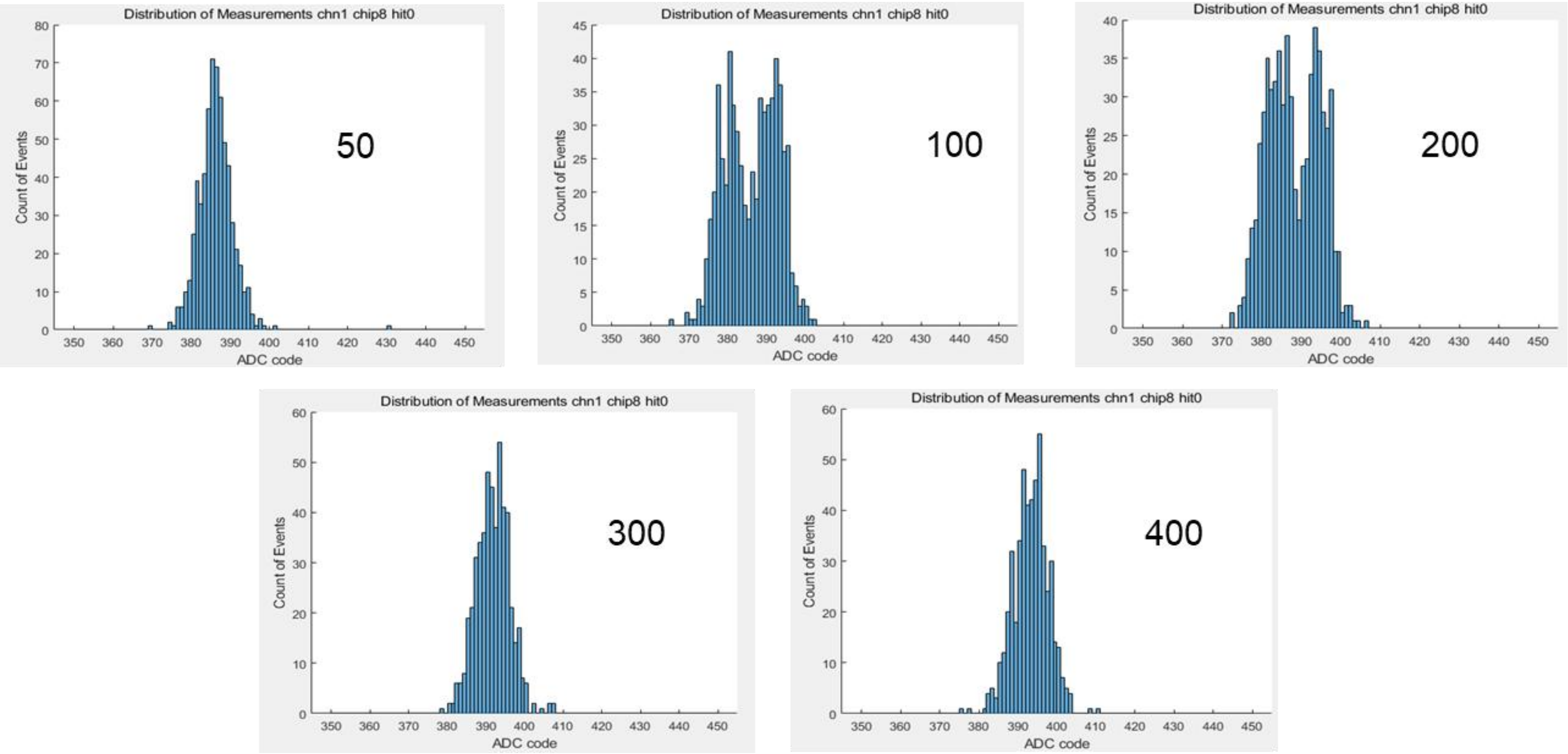
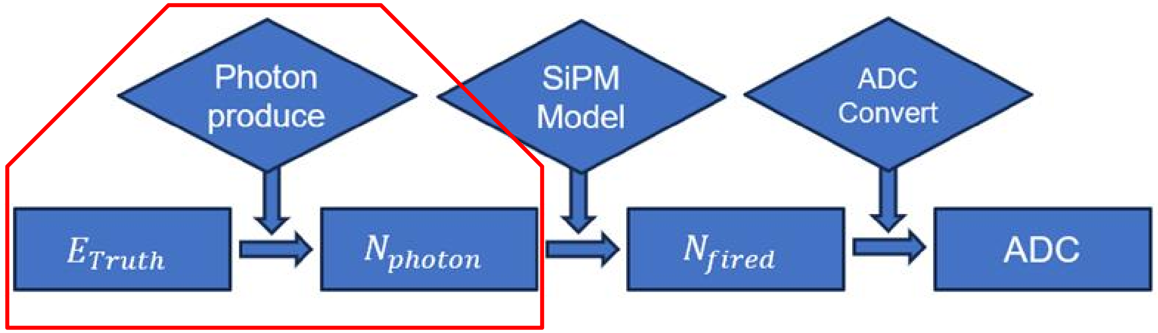
- Self-trigger mode, DAC calibration
- Inject DAC(50, 100, 200, 300, 400) into channel 0, and observe the signal in channel 1



- guess : crosstalk may exist in some chips and crosstalk will change

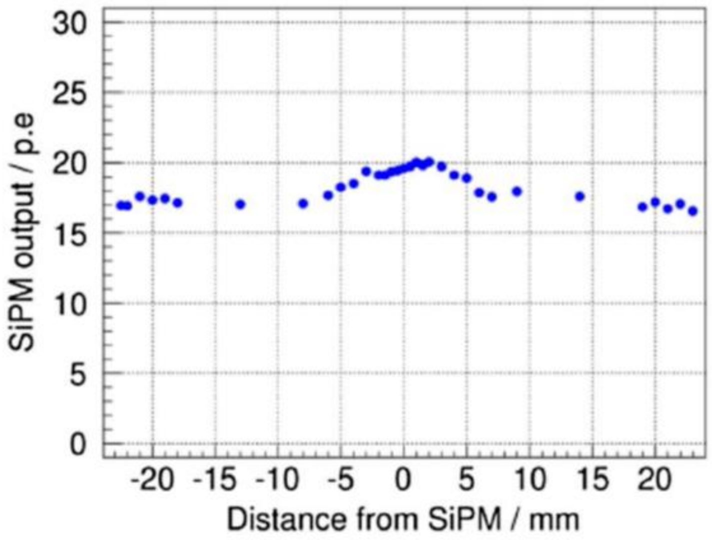
Photon generating process

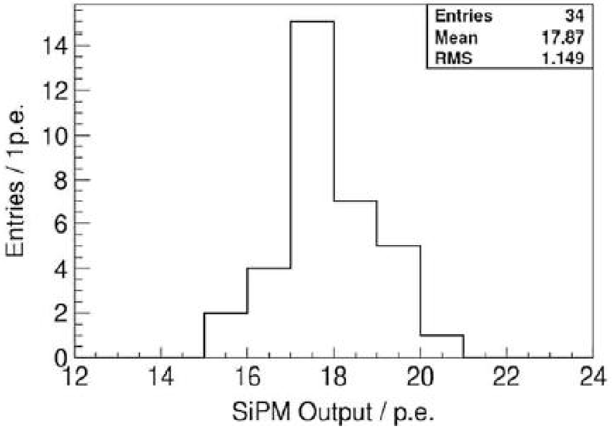
- Photon number
  - ➢ E_{MIP} = E_{Truth} / 0.305 MeV
  - ➢ p.e. = E_{MIP} / light yield(p.e./MIP)
  - ➢ photon = p.e./PDE
- Poisson smear
- Non-uniformity of light output(~4.2%)

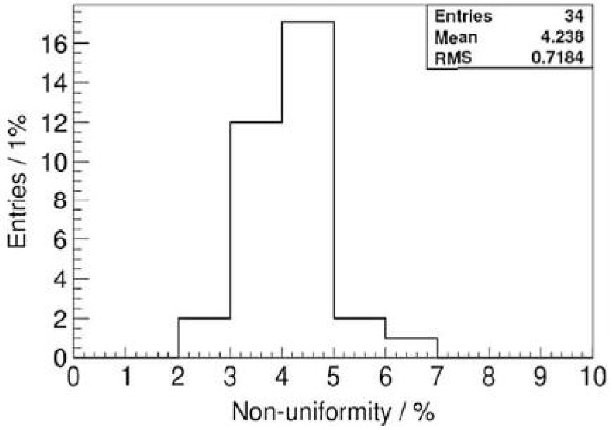


Parameter		Symbol	S12571-010P	S12571-015P	Unit
Spectral response range		λ	320 to 900	320 to 900	nm
Peak sensitivity wavelength		λp	470	460	nm
Photon detection efficiency (λ=λp)*4		PDE	10	25	%
Dark count*5	Typ.	-	100	100	kcps
	Max.		200	200	
Time resolution (FWHM)*6		-	300	250	ps
Terminal capacitance		Ct	35	35	pF
Gain		M	1.35×10^5	2.3×10^5	-
Gain temperature coefficient		ΔTM	1.6×10^3	3.5×10^3	/°C
Breakdown voltage		VBR	65 ± 10	65 ± 10	V
Recommended operating voltage		Vop	VBR + 4.5	VBR + 4.0	V
Temperature coefficient of recommended operating voltage		ΔTVop	60	60	mV/°C

$$N_{photon} = \frac{Hit\_E * MIP\_MPV}{0.305 * SiPM\_Gain * PDE}$$

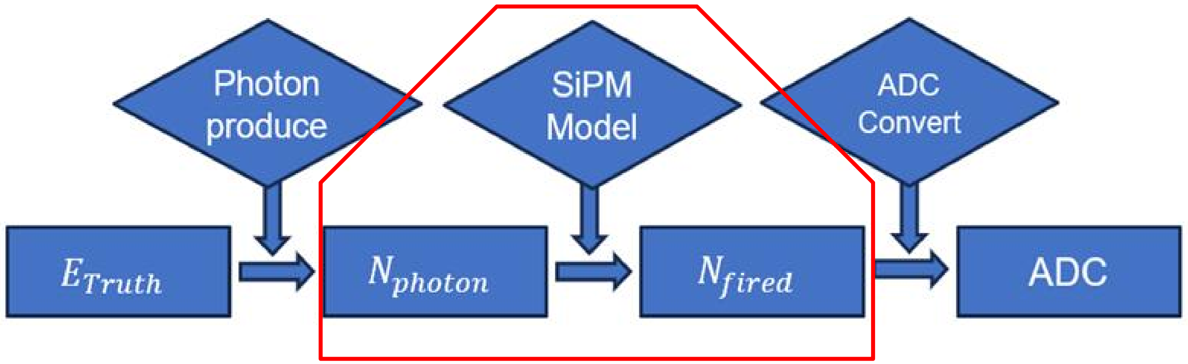


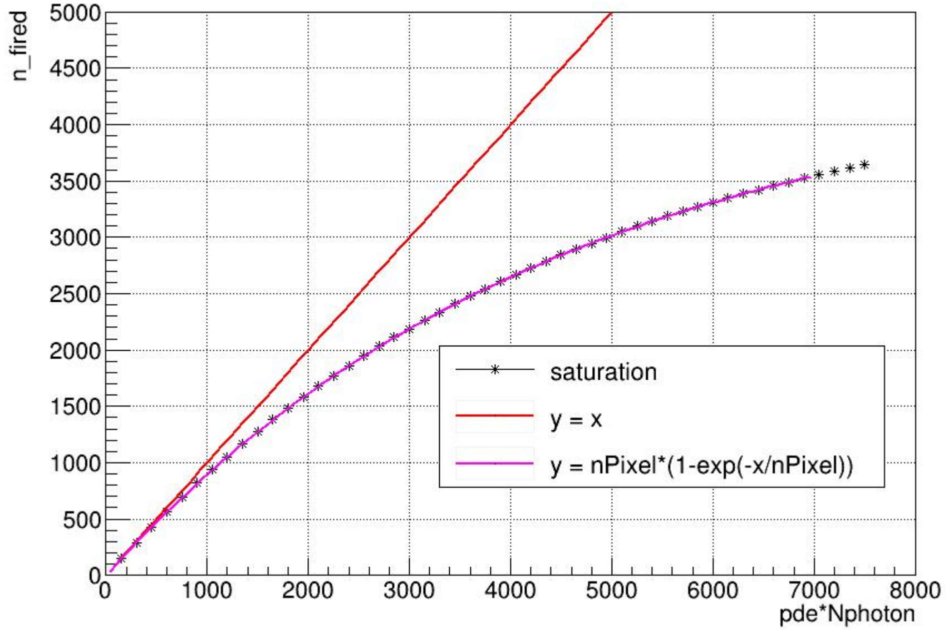




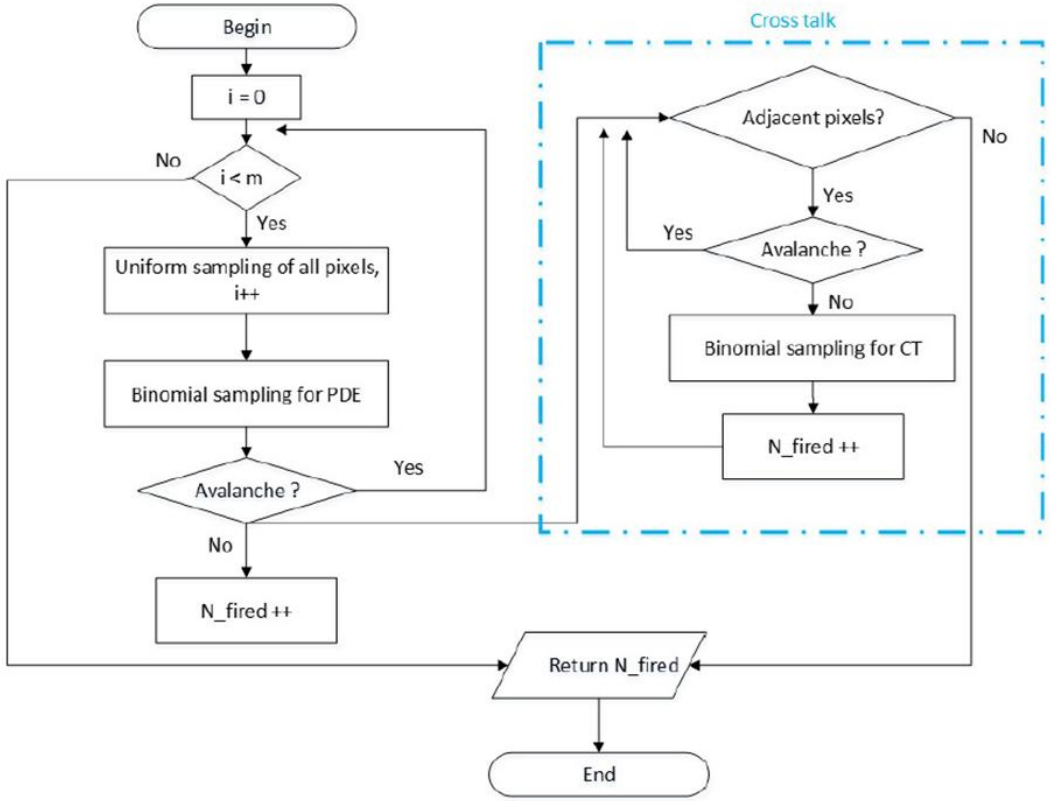
SiPM model: SiPM pixel saturation

- Hamamatsu SiPM S12571-010P, S12571-015P
  - 10000(100*100), 4489(67*67) pixels respectively
  - ~ 8 , 22 p.e./MIP
- SiPM saturation model
  - Uniform sampling a pixel from pixel array
  - Binomial sampling for PDE
  - IF NOT avalanche, then let it avalanche
  - Get total fired pixel number



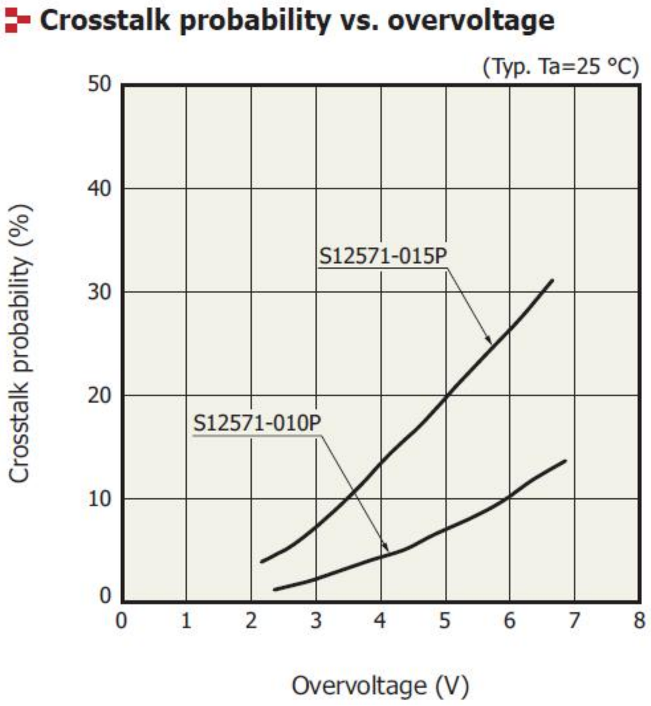


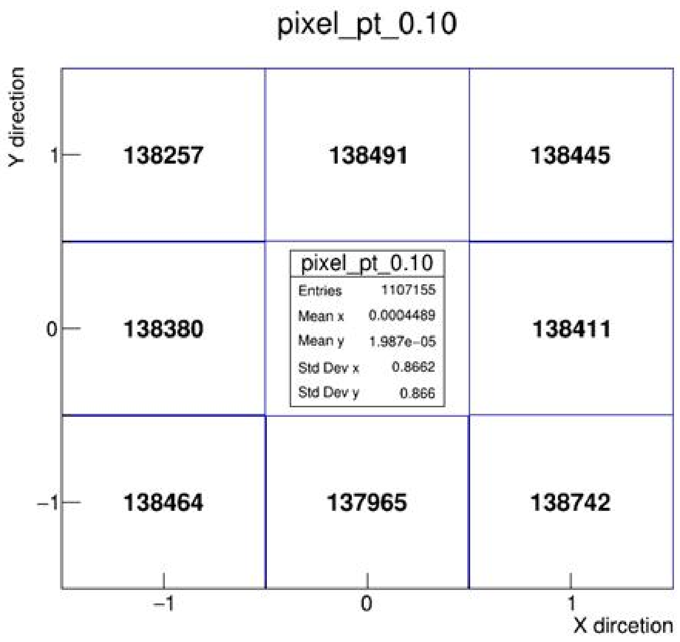
Formula matches the SiPM saturation model very well

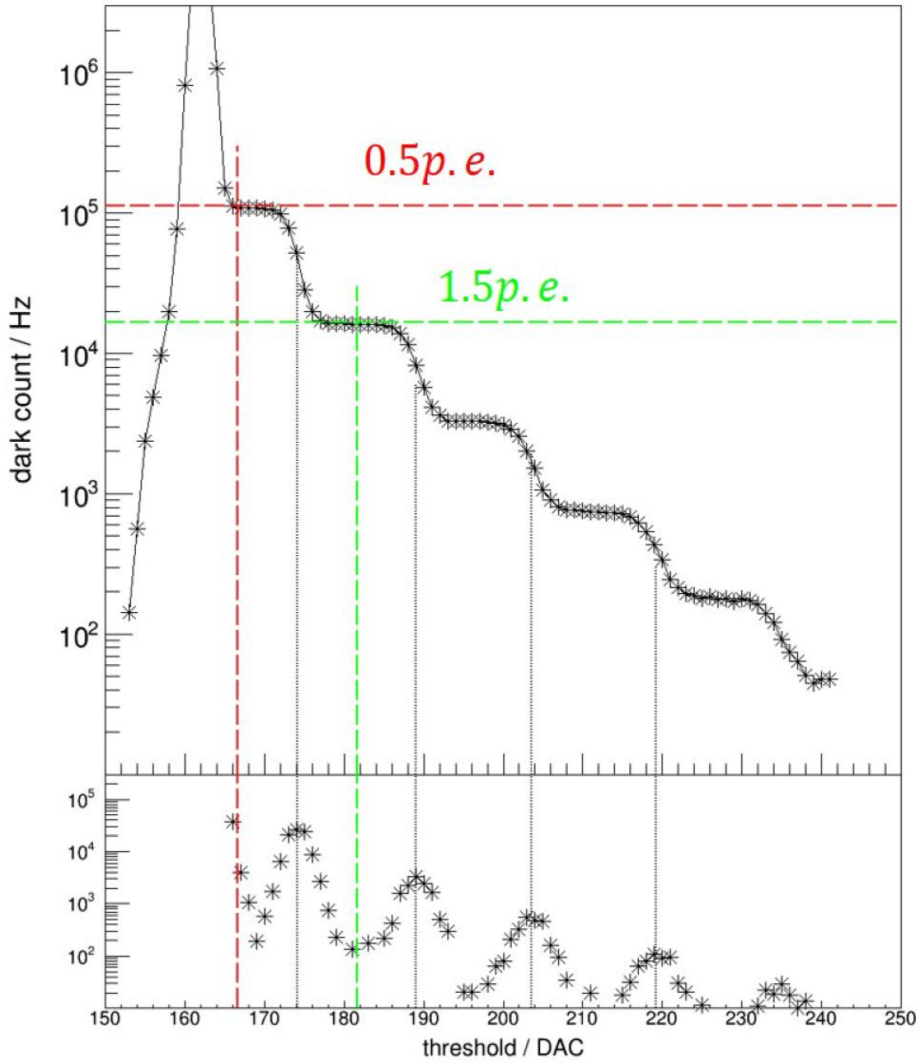


SiPM model: SiPM crosstalk

- Hamamatsu SiPM S12571-010P, S12571-015P
  - ➢ Optical crosstalk may not be ignored
  - ➢ $P_{CT} = (N_{2p.e.} + N_{3p.e.} + N_{4p.e.} + \ldots)/(N_{1p.e.} + N_{2p.e.} + N_{3p.e.} + \ldots)$
- Crosstalk Model
  - ➢ 100*100， 67*67 pixel placement
  - ➢ Uniform sampling a neighboring pixel from eight directions
  - ➢ Set P_{CT} as probability of optical crosstalk occurs in one of neighboring pixel







SiPM model: SiPM crosstalk

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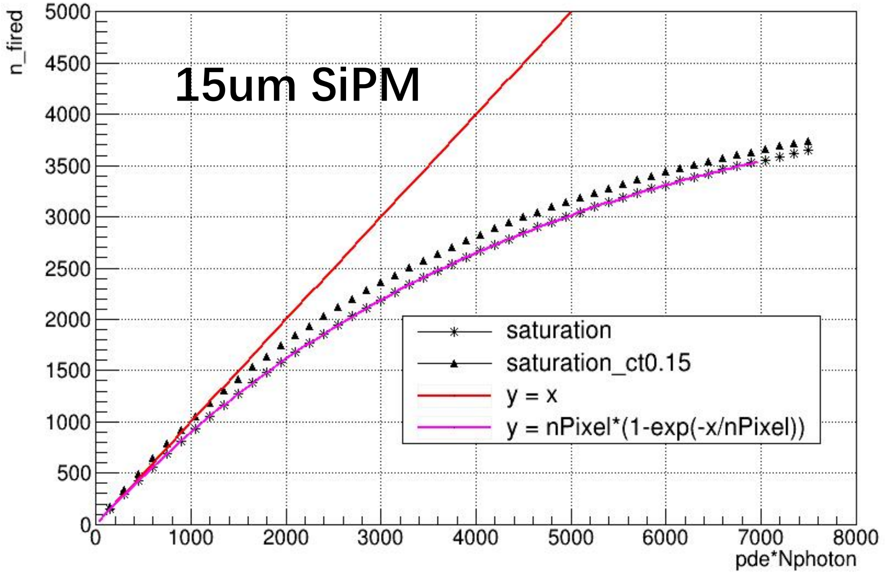
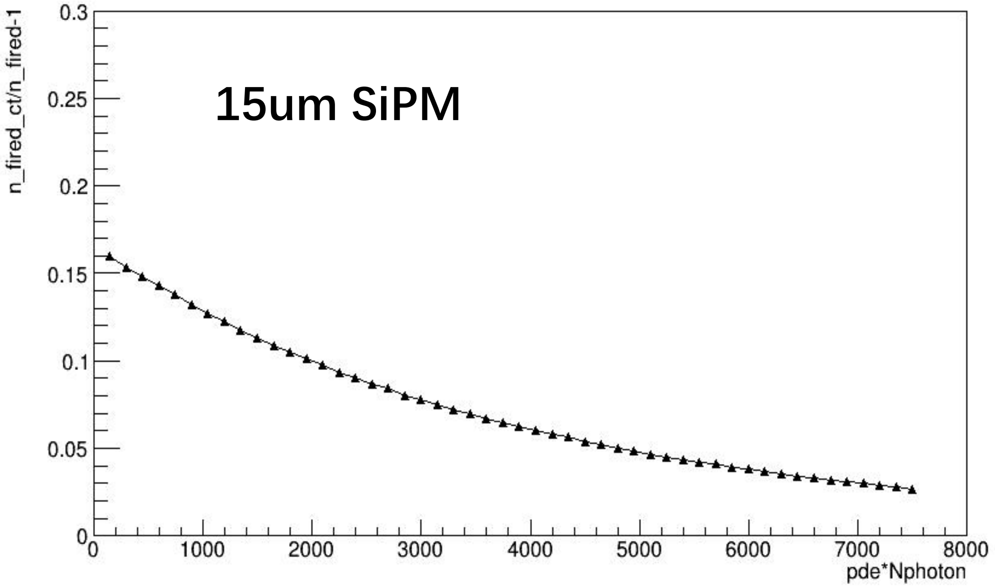
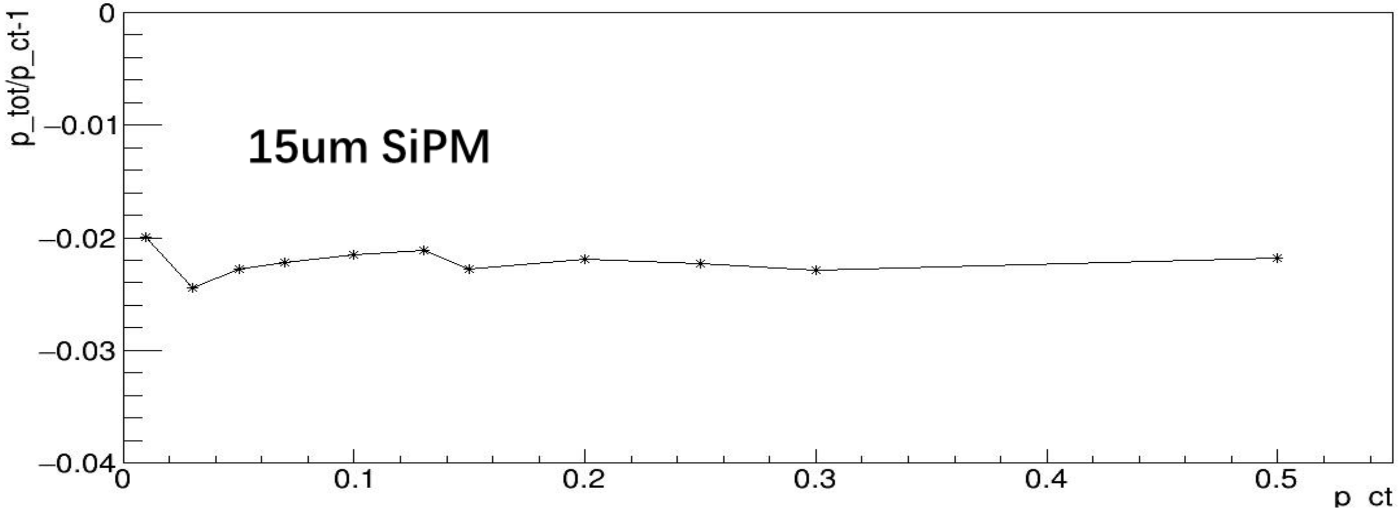




- Formula match SiPM saturation very well
- The discrepancy between with/without crosstalk model will decrease when photon number increases.



P_tot is slightly 2.2% less than P_ct , for 15um SiPM, the SiPM crosstalk model is feasible

P_ct : probability of crosstalk between adjacent pixels

P_tot : probability of crosstalk calculated by $P_{CT} = (N_{2p.e.} + N_{3p.e.} + N_{4p.e.} + \ldots)/(N_{1p.e.} + N_{2p.e.} + N_{3p.e.} + \ldots)$

ADC conversion

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- ADC && gaussian smear
  - ADC Mean = $N_{p.e.}$ * SiPM Gain
  - ADC Sigma = 3 * sqrt($N_{p.e.}$)
- High-low gain mode ADC
- Pedestal fluctuation
- High-low gain saturation
  - High gain saturation: high adc > switch point , let high adc =4000
  - Low gain saturation : low adc > 3000, let low adc = 3000