中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

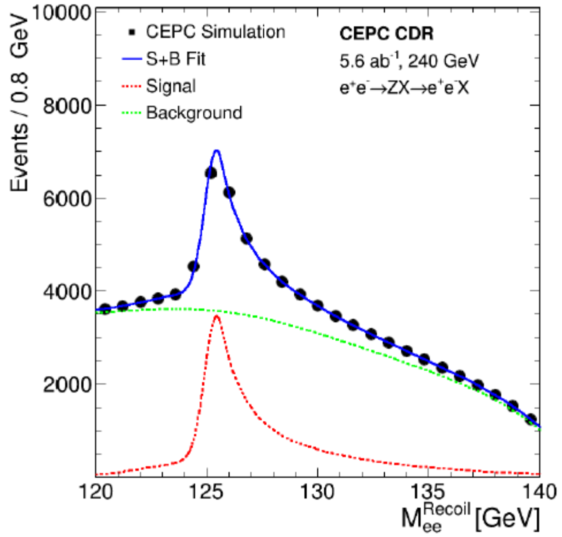
High-granularity Crystal Calorimeter: R&D status

Yong Liu (Institute of High Energy Physics, CAS),
on behalf of the CEPC Calorimetry Working Group

CEPC Day, May 8, 2020

Motivations

- Background: future lepton colliders (e.g. CEPC)
  - Precision measurements with Higgs and Z/W
- Why crystal calorimeter?
  - Homogeneous structure
    - Optimal intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Energy recovery of electrons: to improve Higgs recoil mass
    - Corrections to the Bremsstrahlung of electrons
  - Capability to trigger with a single photon
    - Flavour physics at Z-pole
    - Potentials in search of new physics, …
- Fine segmentation
  - PFA capability for precision measurements of jets



High-granularity crystal ECAL

- Plenty of room for broad collaborations
  - New ideas proposed and discussed in a dedicated CEPC calorimetry workshop in March 2019
  - Key issues and technical challenges: listed and needs further iterations
- R&D activities: recent progress since previous CEPC Day
  - Crystal granularity optimisation: longitudinal depth, lateral segmentation
  - Dynamic range studies
  - Readout electronics: tests with KLauS ASIC

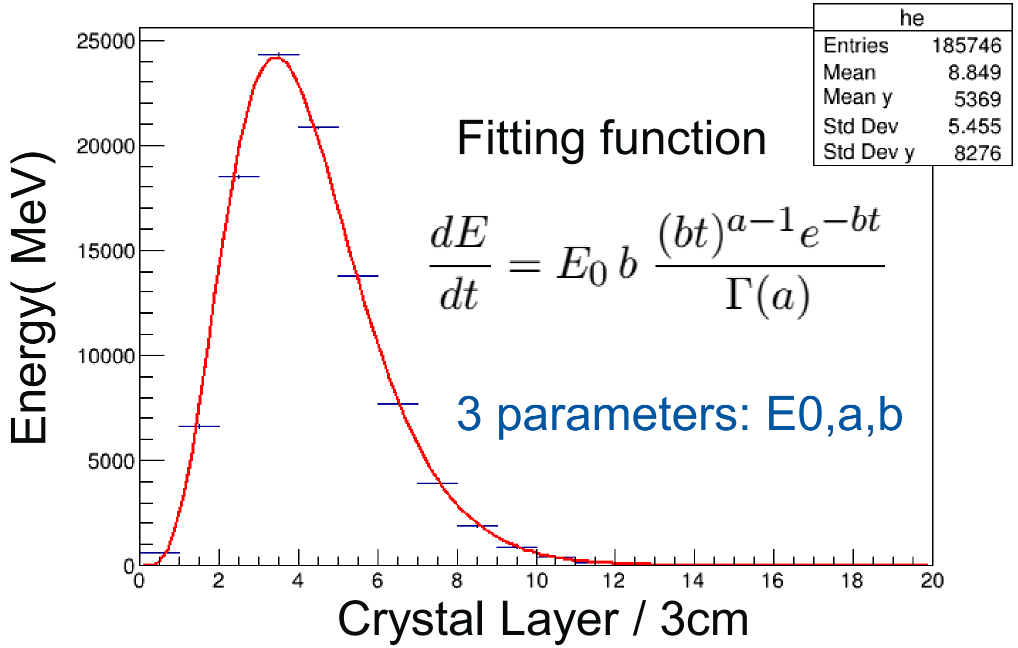
Key issues and technical challenges (reminder)

- Key issues: optimization
  - Crystal options: BGO, PWO, etc.
  - Segmentation: in longitudinal and lateral directions
  - Performance: single particles and jets with PFA
  - Impacts from dead materials: upstream, services (cabling, cooling)
  - Fine timing information, dual-gated readout, etc.
  - …
- Key issues: technical challenges
  - Front-end electronics
  - Power consumption and cooling options
  - Calibration and monitoring systems
  - Scalable detector design: modules and mass assembly
  - Mechanics
  - …
- Need further iterations and discussions

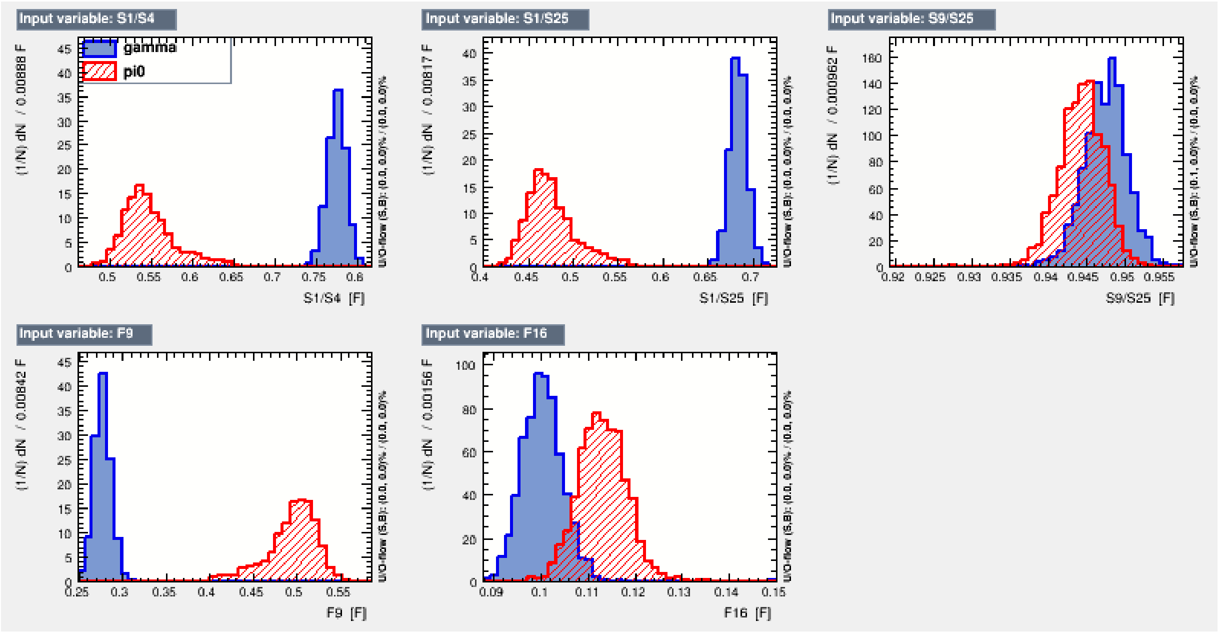
Crystal cell optimisations

Chunxiu Liu (IHEP)

- Crystal longitudinal depth
  - Use shower profiles in segmented layers to correct for tails (energy leakage)
  - Aim for shorter crystal depth (cost), balance with performance (correction precision)
- Crystal transverse segmentation
  - Crystal transverse size: separation of neutral pions and photons



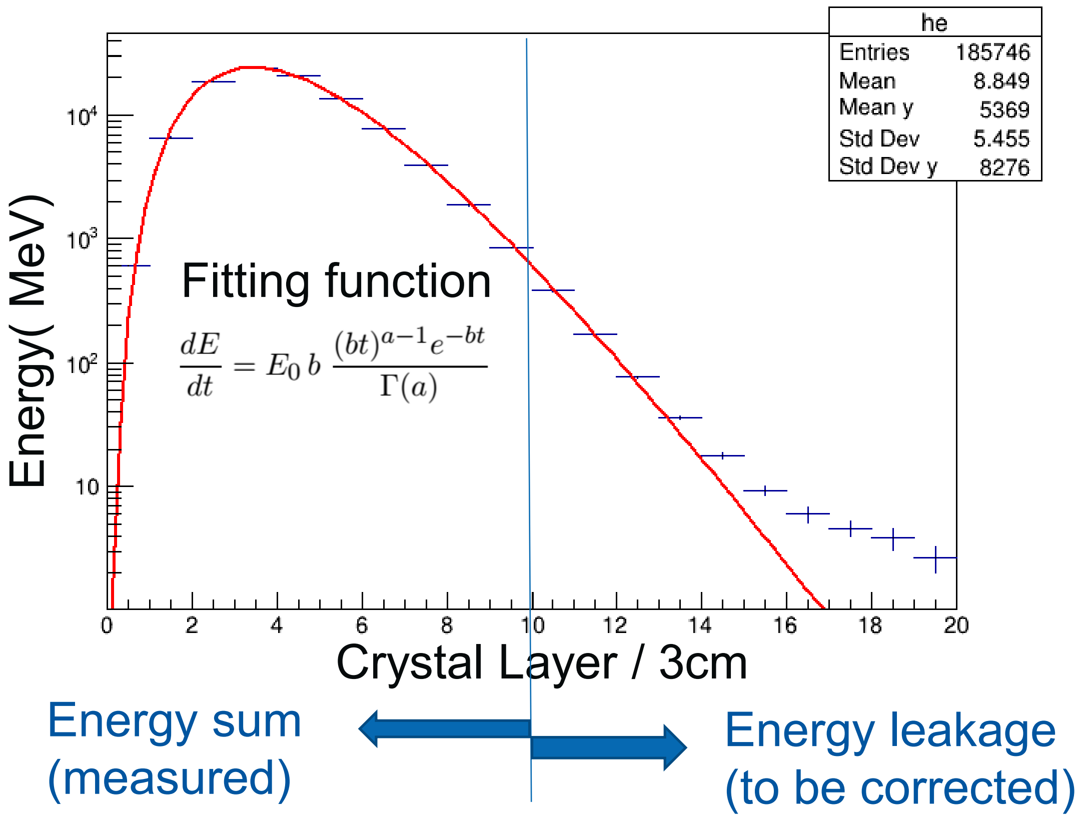
$$\frac{dE}{dt} = E_0\, b\, \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

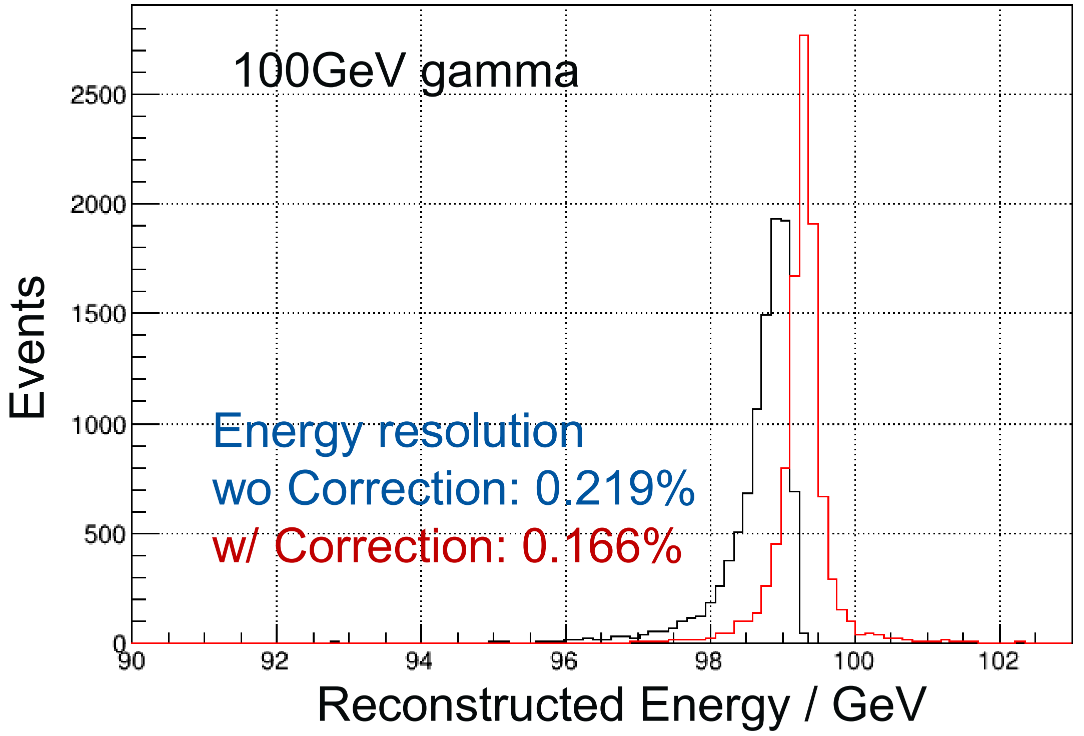


Crystal longitudinal depth optimisation

Chunxiu Liu (IHEP)

- Energy leakage correction using longitudinal shower profile
  - Based on the fine segmentation in crystal length
  - Shower profile function can not well describe the shower tails; needs fine tuning





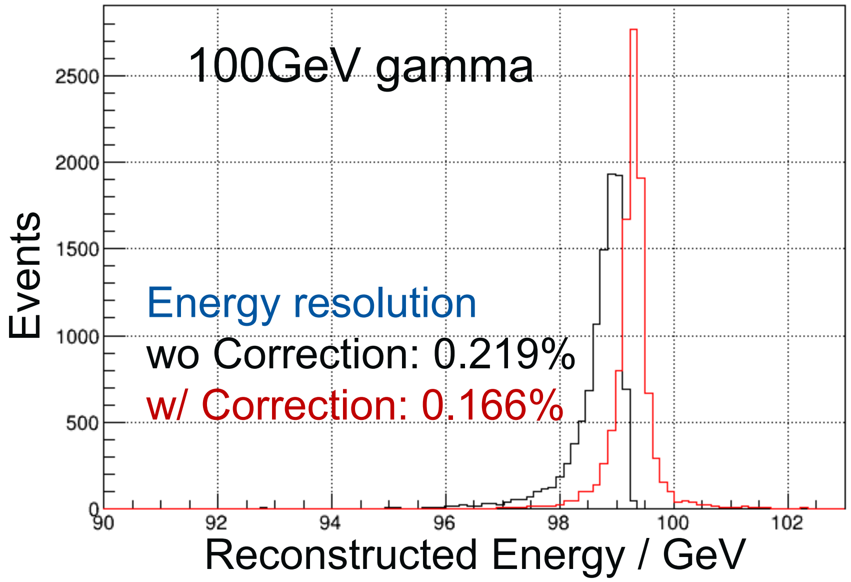
30cm long BGO (~27X0), 10 layers, 3cm per layer

Crystal longitudinal depth optimisation

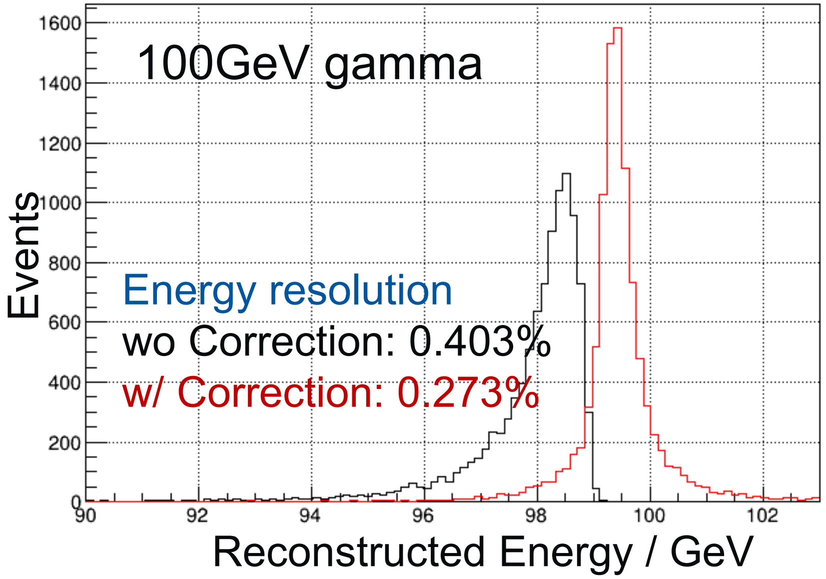
Chunxiu Liu (IHEP)

- Merits
  - Cost saving with shorter crystal depth
  - Potentials for energy loss corrections in solenoid magnet between ECAL and HCAL

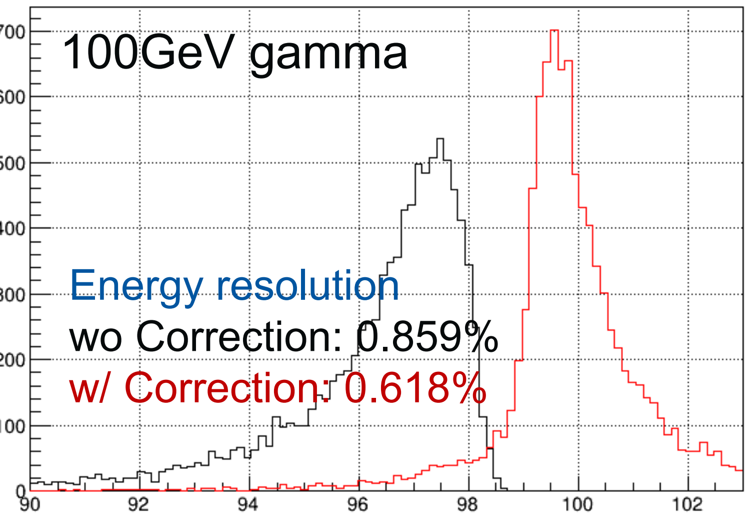
(as an alternative detector option being investigated)



30cm long BGO (~27X0),
10 layers, 3cm per layer



27cm long BGO (~27X0),
9 layers, 3cm per layer

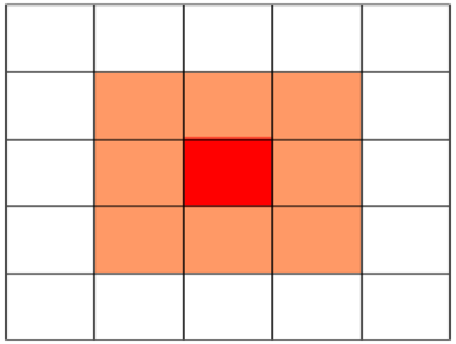


24cm long BGO (~21X0),
8 layers, 3cm per layer

Crystal transverse size optimisation

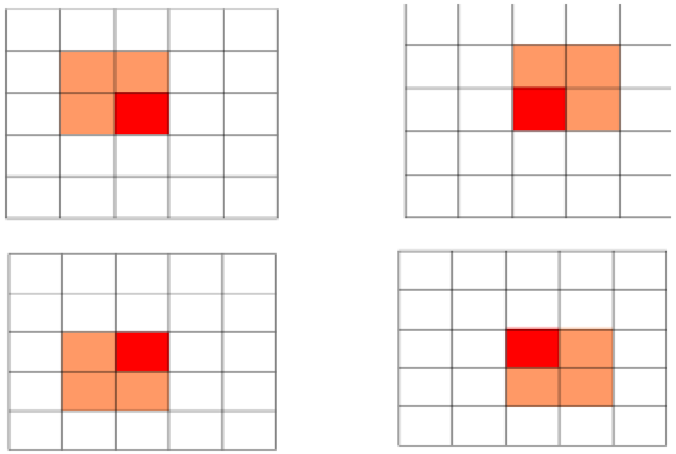
Chunxiu Liu (IHEP)

- Study of the separation performance of γ and merged π^0
  - Can not be distinguished in transverse shower profiles
- Energy-related variables defined for TMVA
  - S1/S4, S1/S9, S1/S25, S9/S25, S4/S9, F9, F16

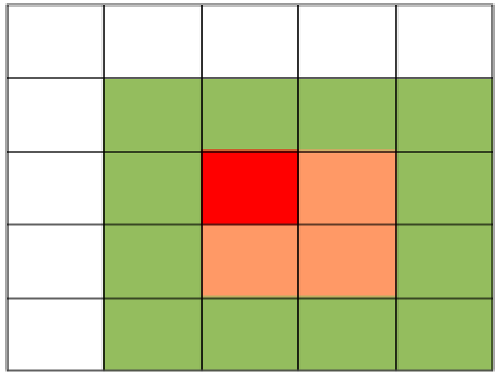


S1,S9,S25

$$F_9 = \frac{S9 - S1}{S9}$$



S4 the energy maximum in the four 2x2 arrays



S16

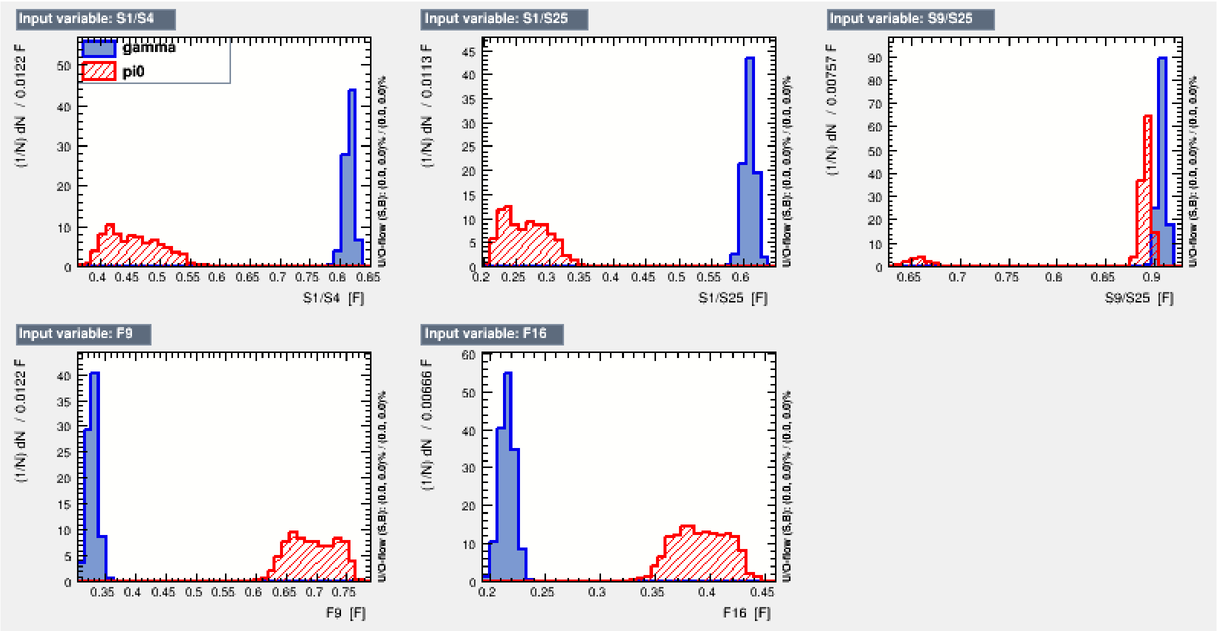
$$F_{16} = \frac{S16 - S4}{S16}$$

Crystal transverse size optimisation

Chunxiu Liu (IHEP)

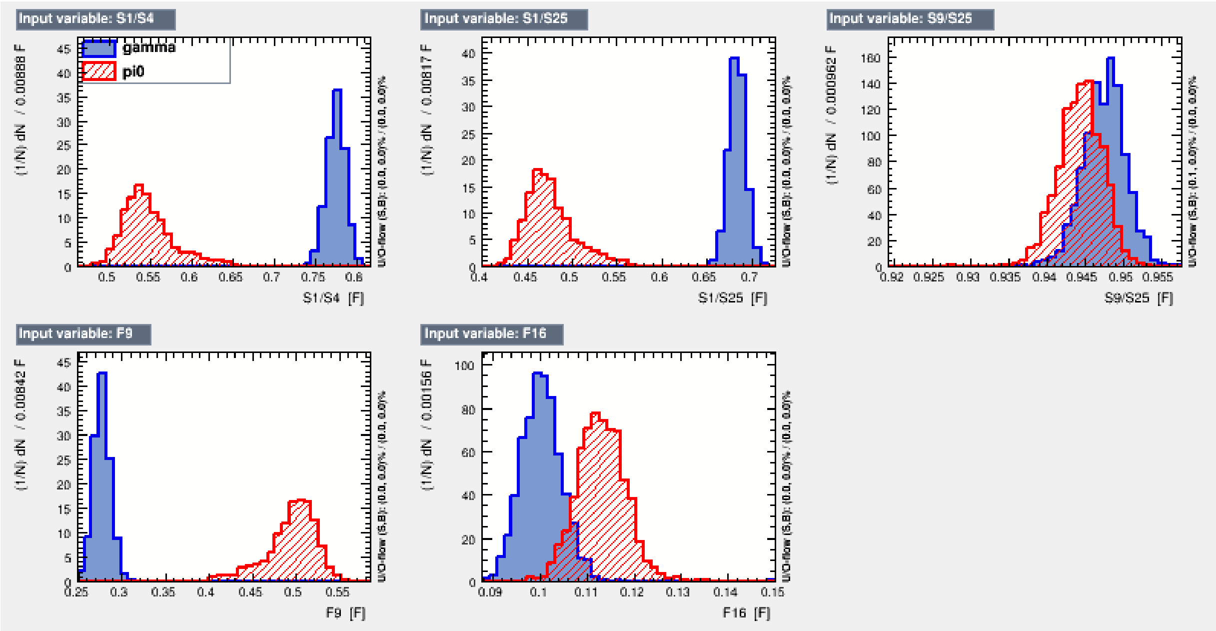
- Separation performance of the 40GeV γ and merged π^0

Transverse size 1x1cm2



100% separation with most variables

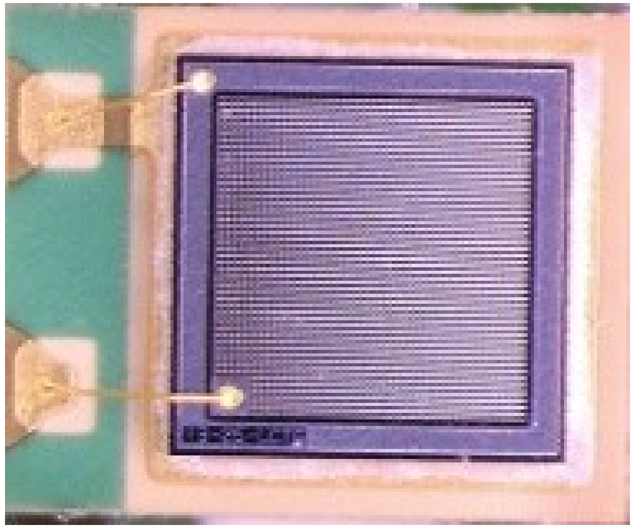
Transverse size 2x2cm2

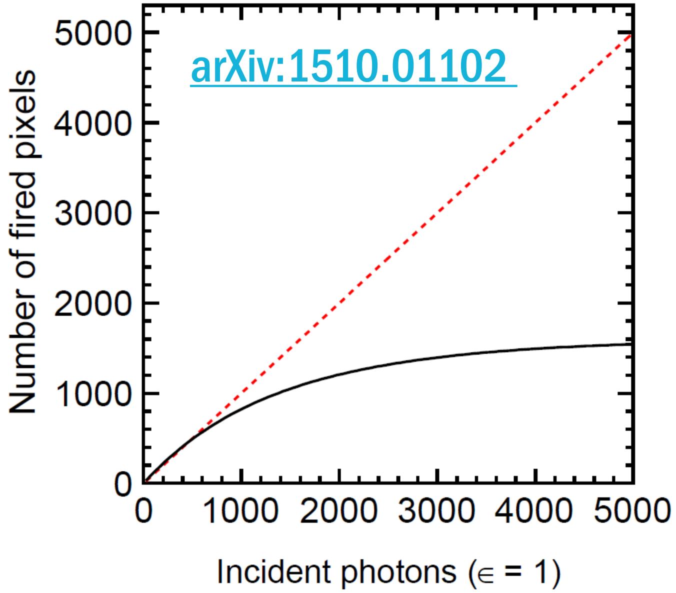


100% separation with S1/S4, S1/S25 and F9

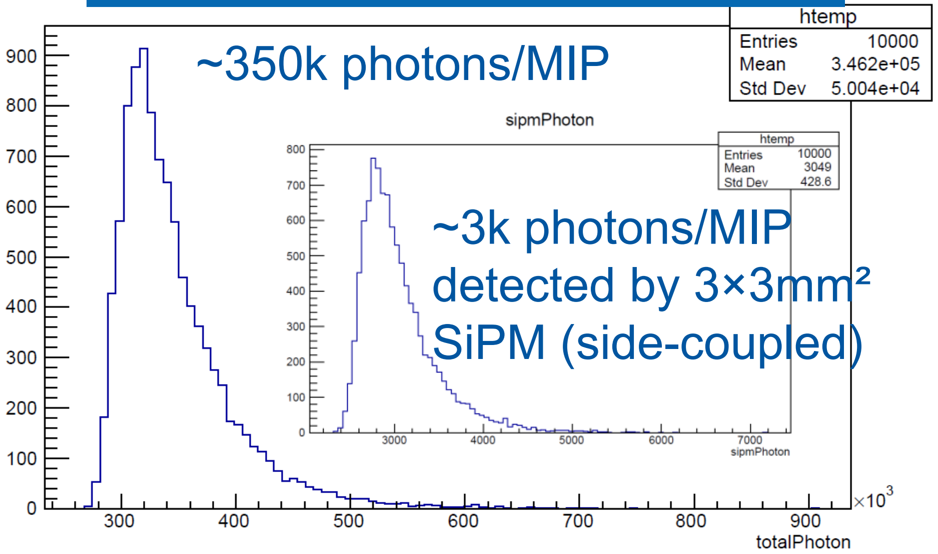
Crystal cells: dynamic range (reminder)

- Silicon Photomultiplier (SiPM)
  - Non-linear response due to finite #pixels (each as a binary counter)
- Crystal such as BGO produces (too) many photons
  - Stringent requirement on the readout: response linearity





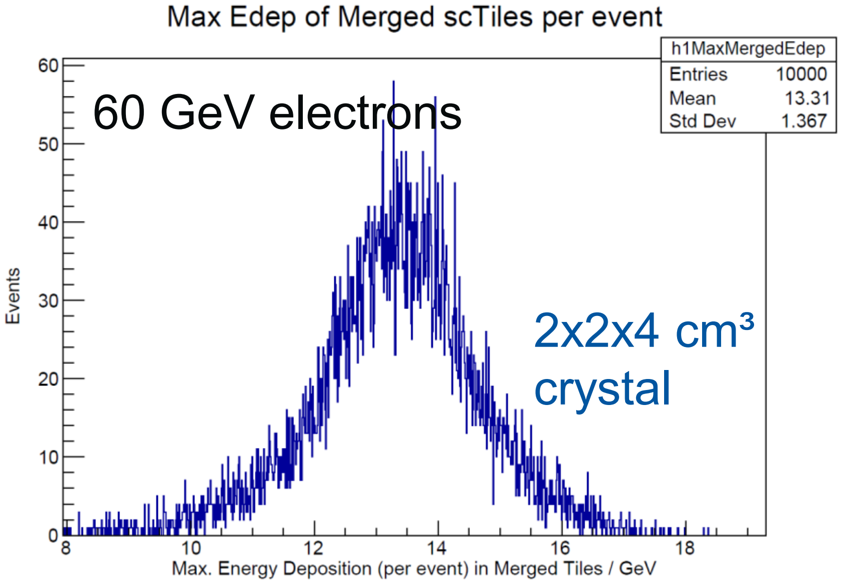
Geant4 simulation of BGO crystal



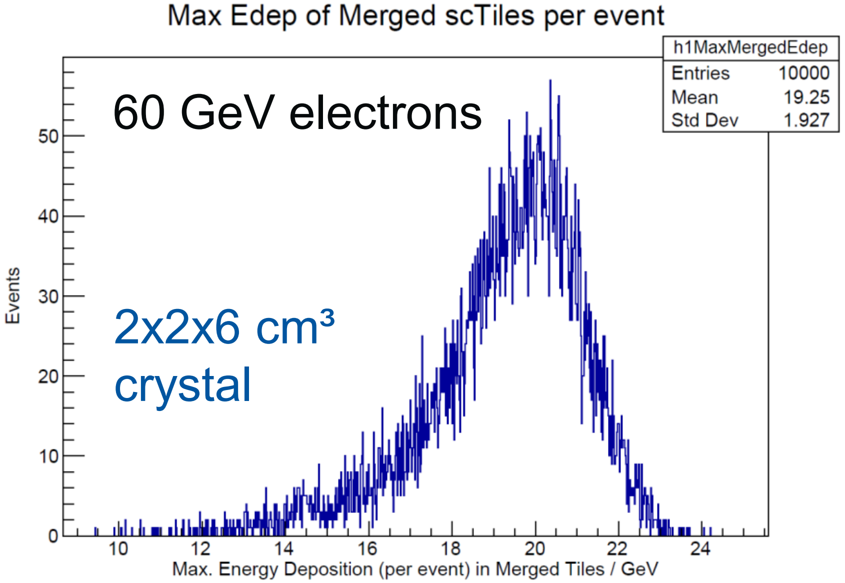
~40 MeV energy deposition for 1 GeV muons passing through a 45 mm crystal bar (BGO)

Dynamic range: simulation with high-energy electrons

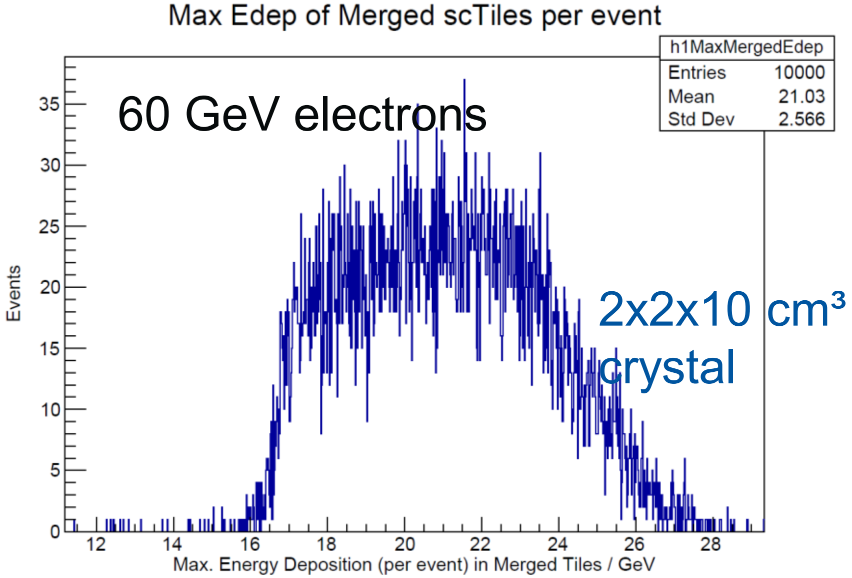
- Maximum energy deposition per cell
  - Depends on the crystal segmentation configurations
  - Provide inputs for the SiPM and its readout electronics



~13 GeV/cell



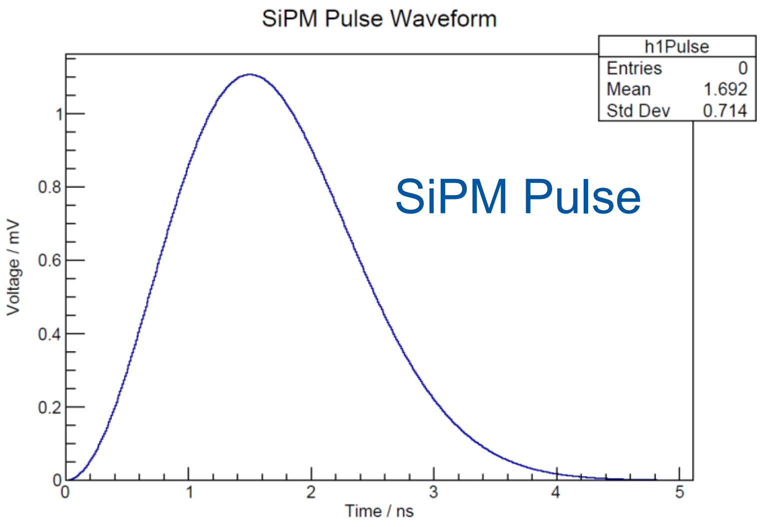
~19 GeV/cell



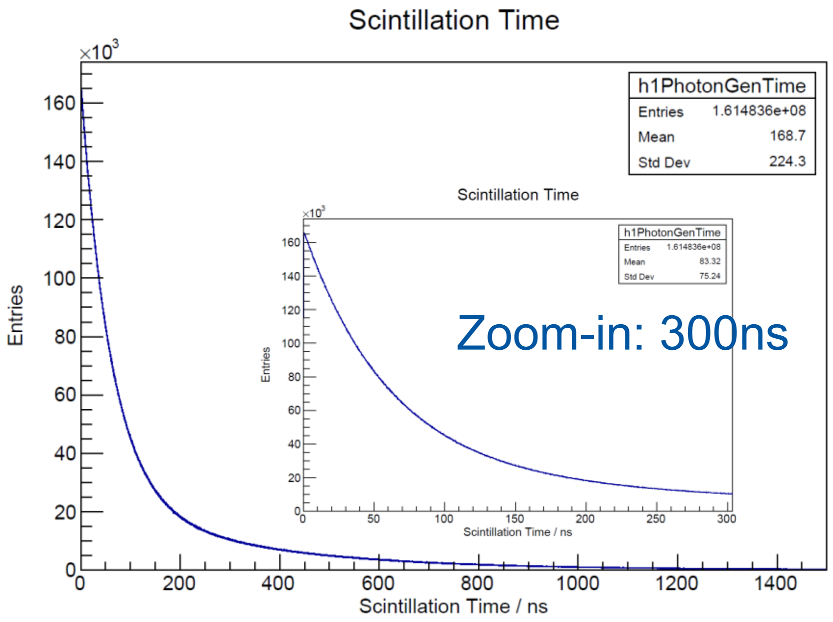
~21 GeV/cell

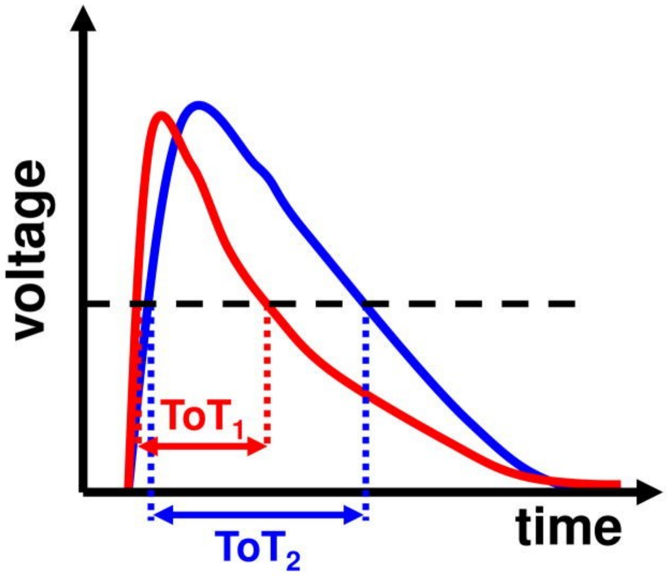
Crystal cells: dynamic range

- Geant4 full simulation of TOT with BGO crystals
  - Realistic simulation of BGO scintillation: detailed properties
    - 8200 photons/MeV, time constants tau1=60ns, tau2=300ns
  - TOT: time duration of the rising and trailing edges at a fixed threshold



SiPM Single-Photon Pulse Waveform

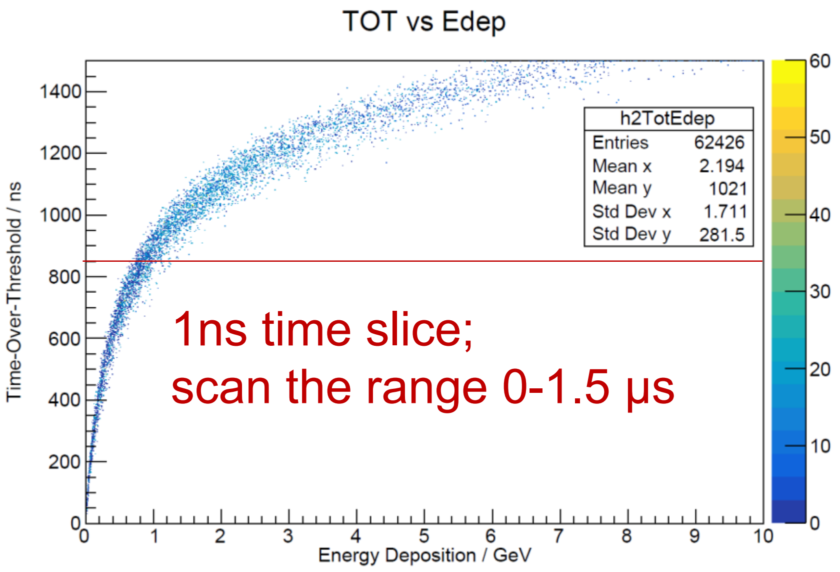


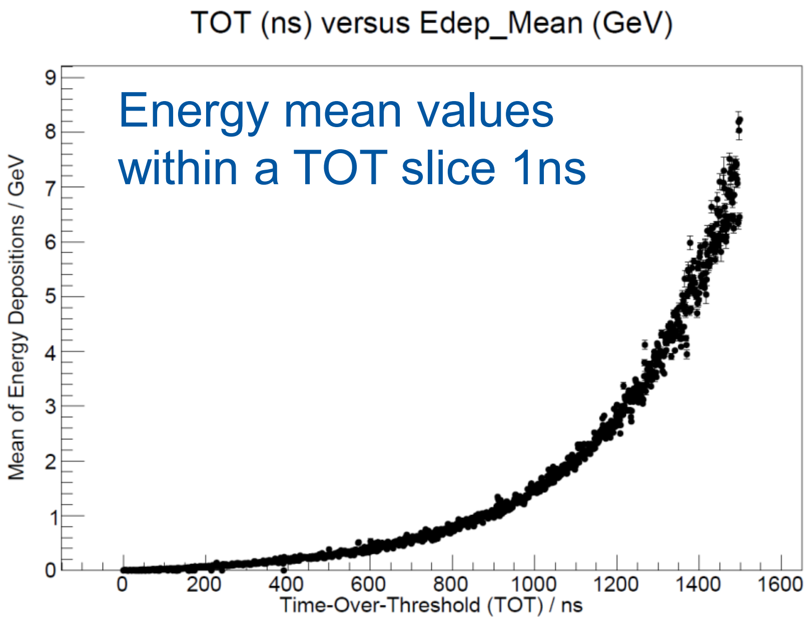


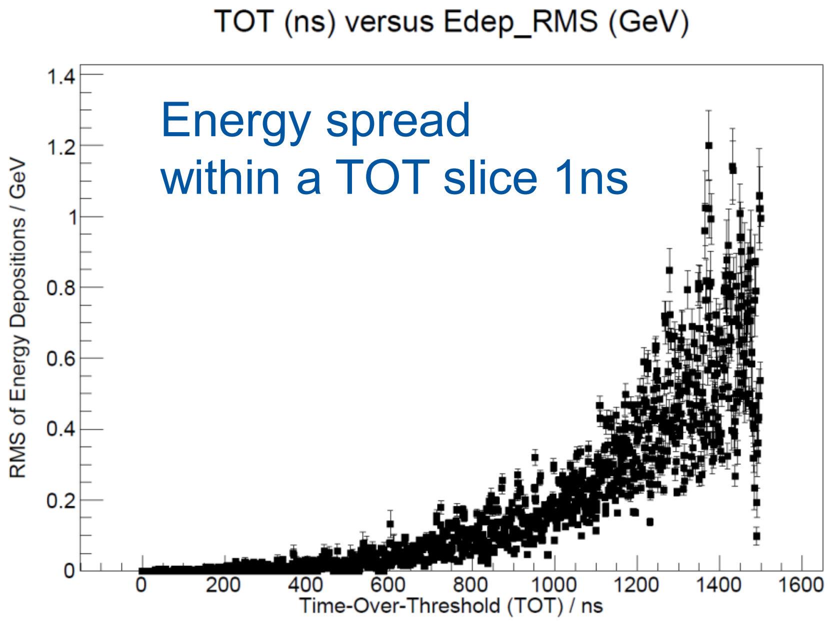
Computing intensive for the simulation (>1M photons); techniques developed to fasten the procedure

Dynamic range: TOT simulations

- Energy depositions in a crystal cell: 10MeV – 8 GeV
  - TOT values will go beyond 1.5 μs for energy deposition larger than 8 GeV
  - Energy spread: fluctuations due to BGO scintillation long slow slope
  - Impact from TOT threshold will be studied



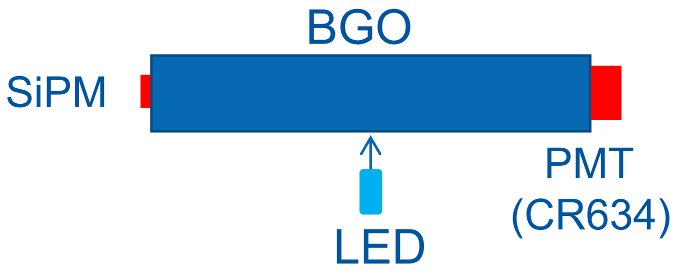


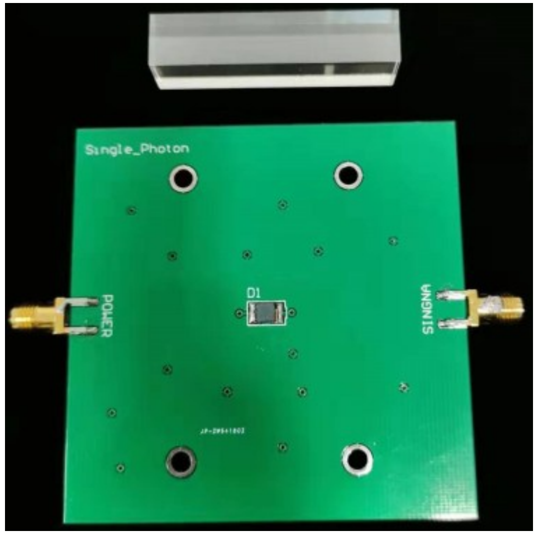


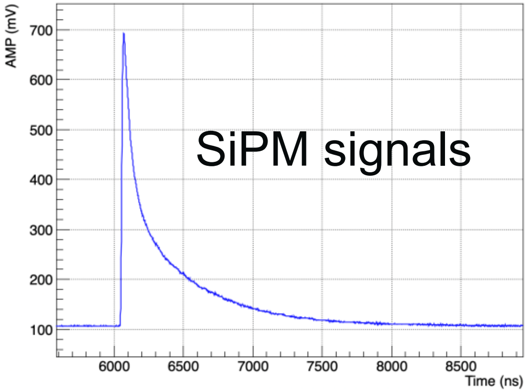
Dynamic range: TOT measurements

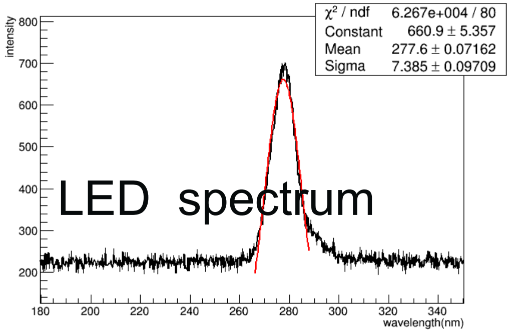
Zhigang Wang (IHEP)

- First TOT tests with UV-LED for BGO-SiPM readout
  - Preliminary: a few percent resolution achieved in the range 1-350 MIPs



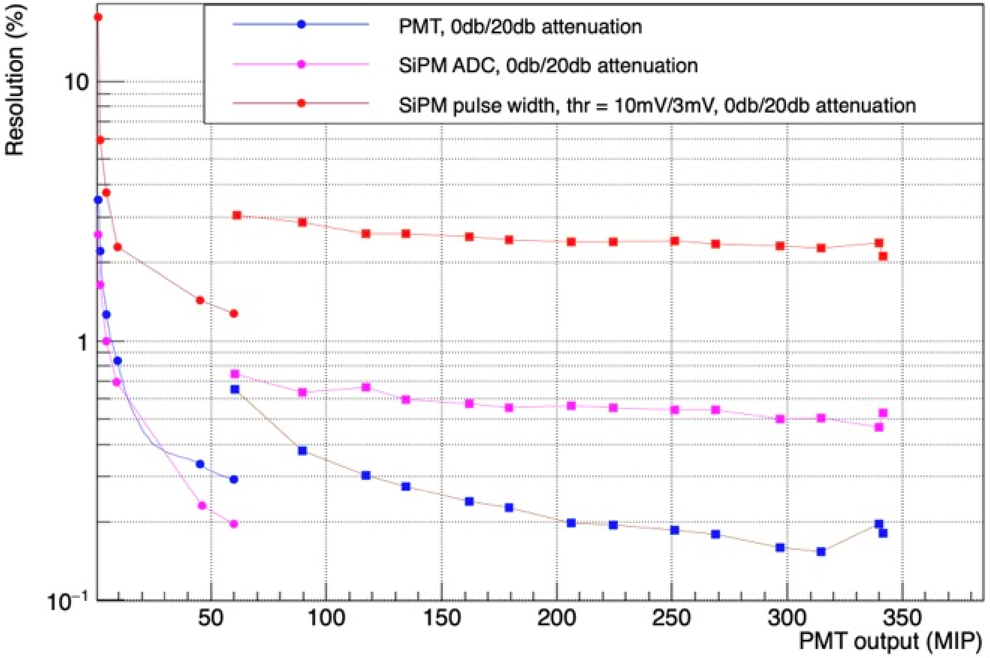






Use UV light to excite BGO

Further detailed analysis and upgrade of the setup will be performed in the future.

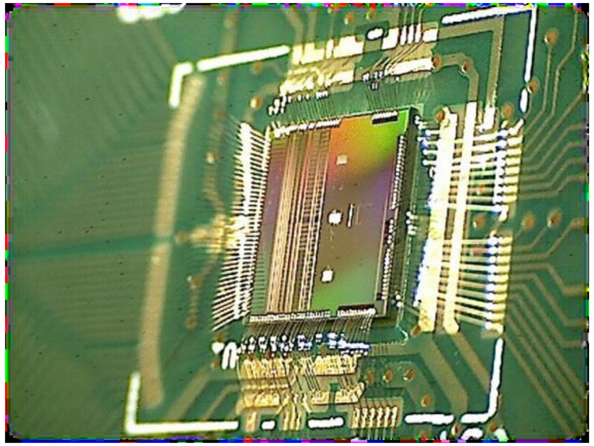


Front-end electronics for SiPM readout

U. Heidelberg, IHEP

- ASIC "KLauS", developed within CALICE
  - Designed by U. Heidelberg (KIP)
  - Originally for CALICE scintillator-SiPM HCAL (AHCAL)
  - Promising candidate: 36-channel, low-power chip
    - Excellent S/N ratio: stringently required by high-dynamic SiPMs (small pixels)
    - **Continuous** working mode: crucial for circular colliders (no power pulsing)
  - Need to quantitatively verify its performance and power consumption

Wire-bonded Klaus5 chip

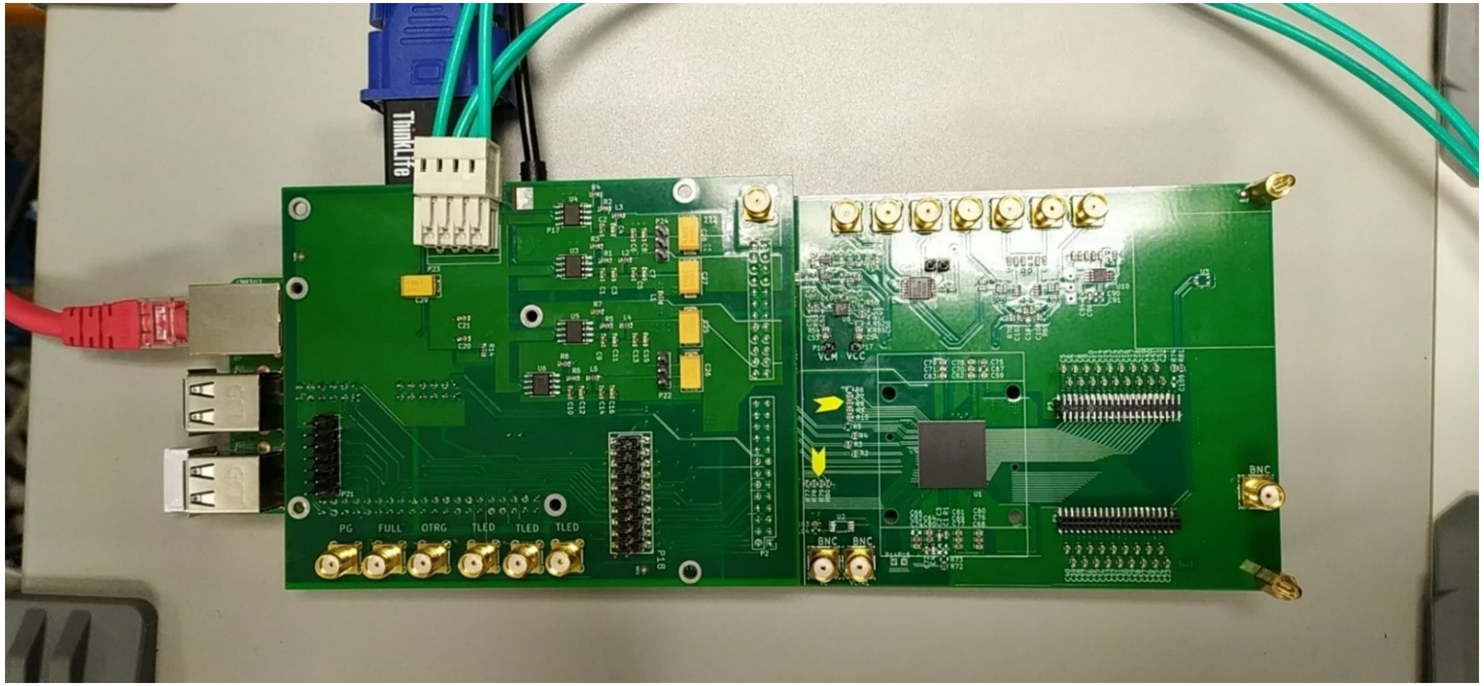


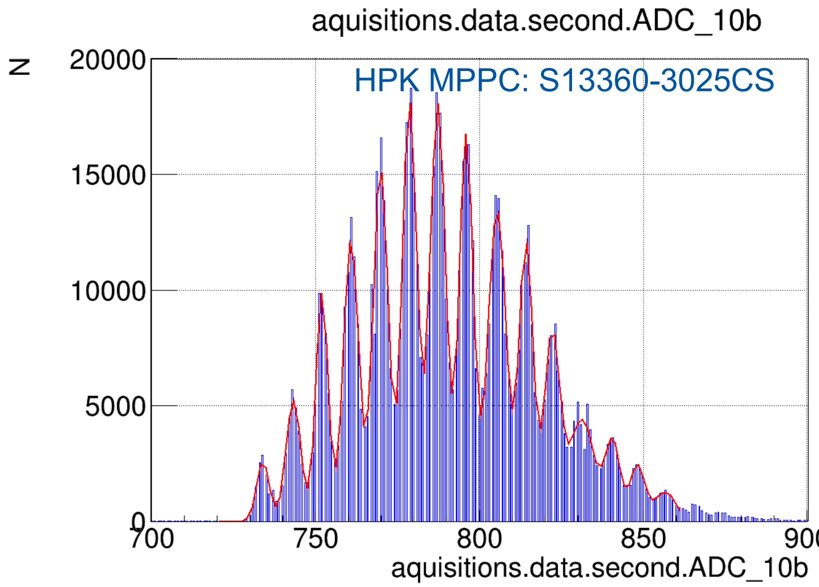
Klaus5 in BGA

Front-end electronics for SiPM readout

U. Heidelberg, IHEP

- Test boards for KLauS-5 in BGA
  - Boards produced after several iterations of designs/debugging
  - Boards tested first at Heidelberg and later at IHEP
  - Synergies with the JUNO-TAO



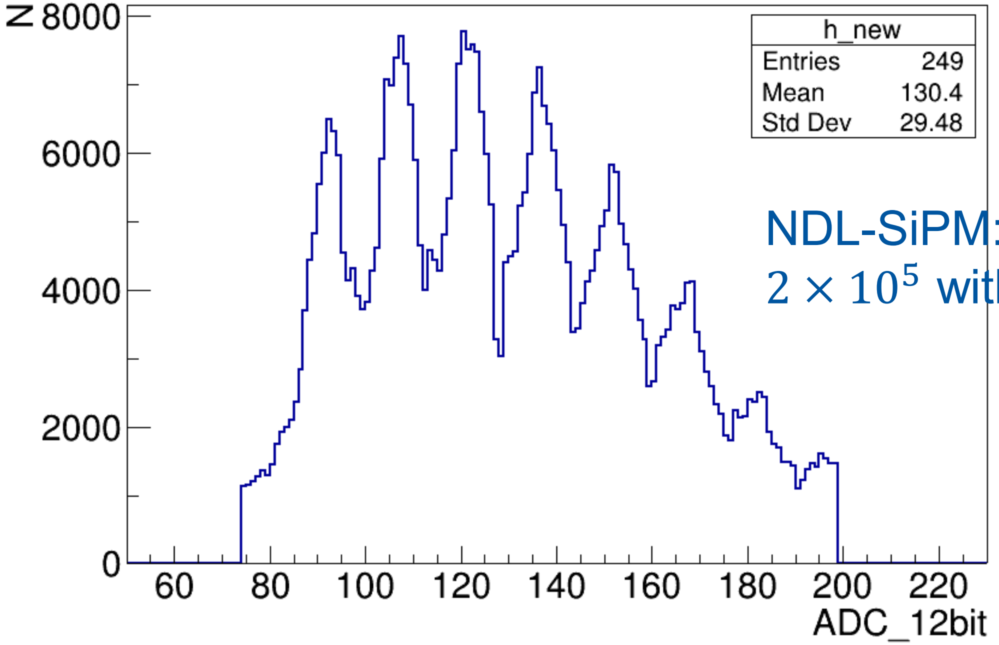


Klaus5: first tests with NDL-SiPM

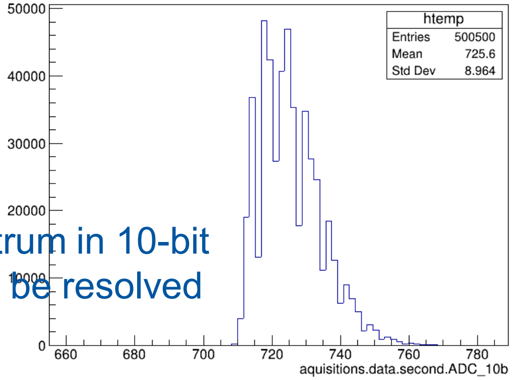
U. Heidelberg, IHEP

- NDL-SiPM: from a Chinese vendor
  - Features: small pixel pitch (10μm or smaller) and high PDE
  - Need high S/N ratio in electronics to resolve single photons (small gain)

Single photon spectrum in 12-bit ADC mode: after corrections



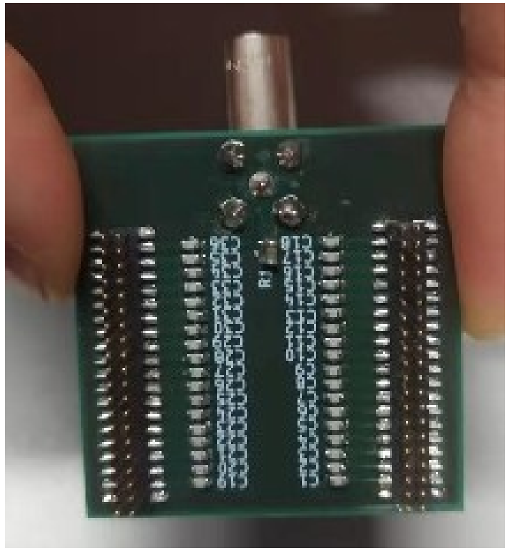
NDL-SiPM: nominal gain 2×10^5 with 10μm pixels



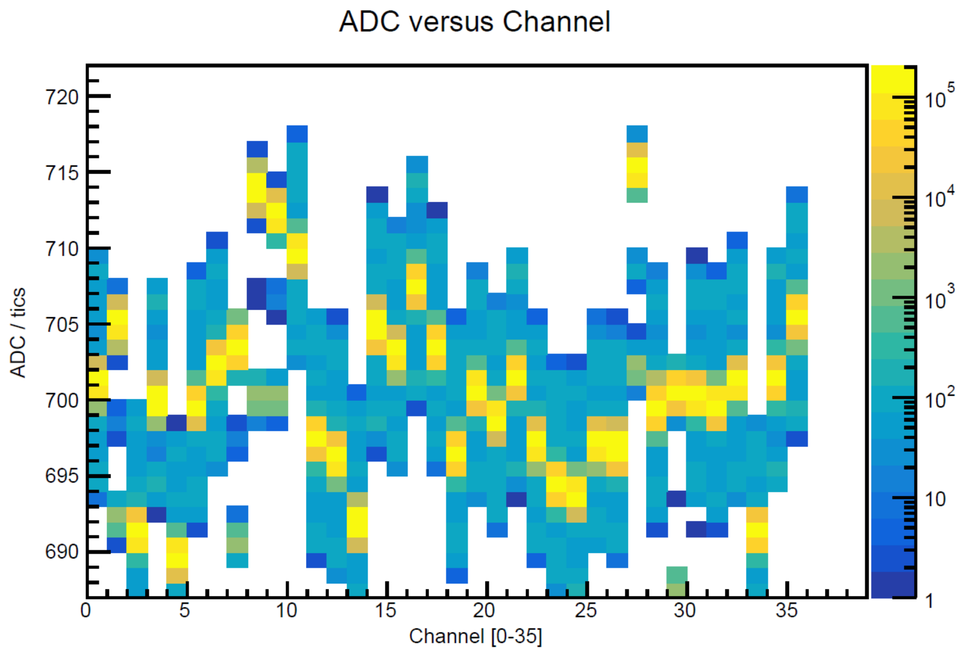
Single photon spectrum in 10-bit ADC mode: can not be resolved

Klaus5: tests with charge injection

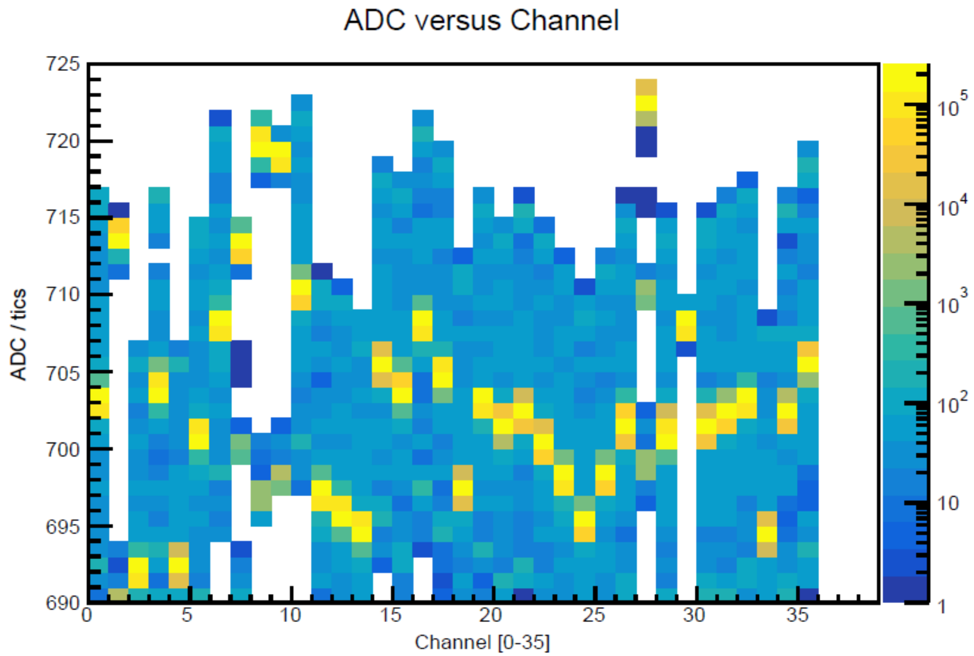
- Pulses injected to all 36 channels
  - Varying input capacitors on adapter PCBs
  - Varying pulse voltages from a pulse generator



Adapter PCB to inject charge pulses injection to 36 channels



Pedestals in (mid) High Gain mode

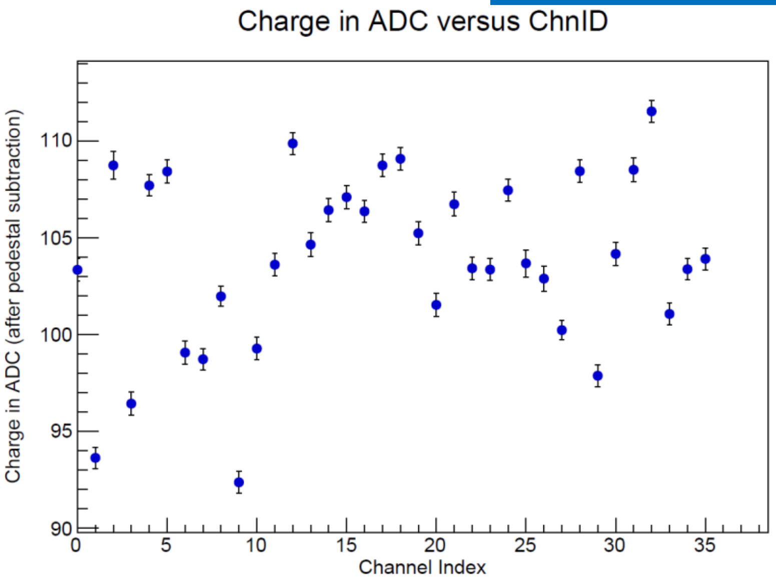


Pedestals in Low Gain mode

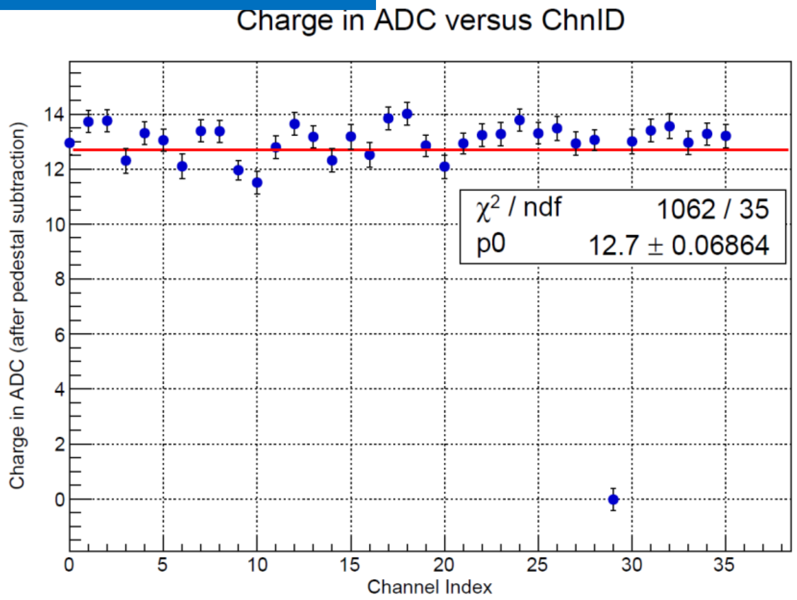
Klaus5: tests with charge injection

- Large amounts of data taken, to be analyzed to evaluate…
  - Dynamic range: different working modes of gains
  - Dead time when all channels are fed with data

Charge Injection to 36 channels

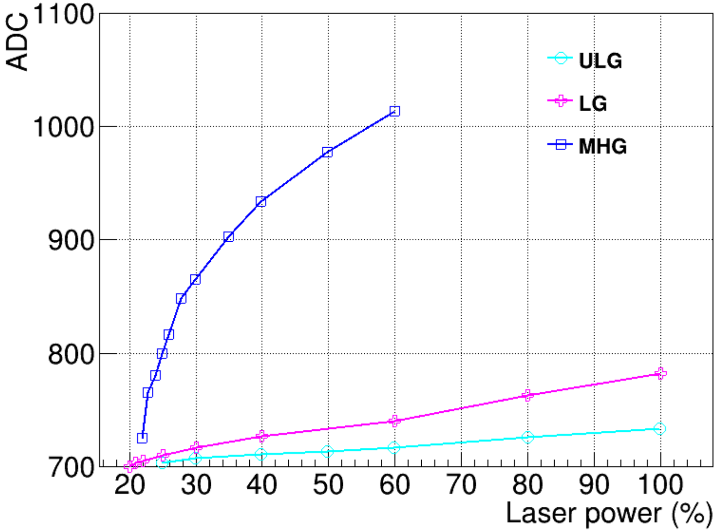


5V pulse input in (mid) High Gain mode



5V pulse input in Low Gain mode

Laser tests for a single channel



Summary

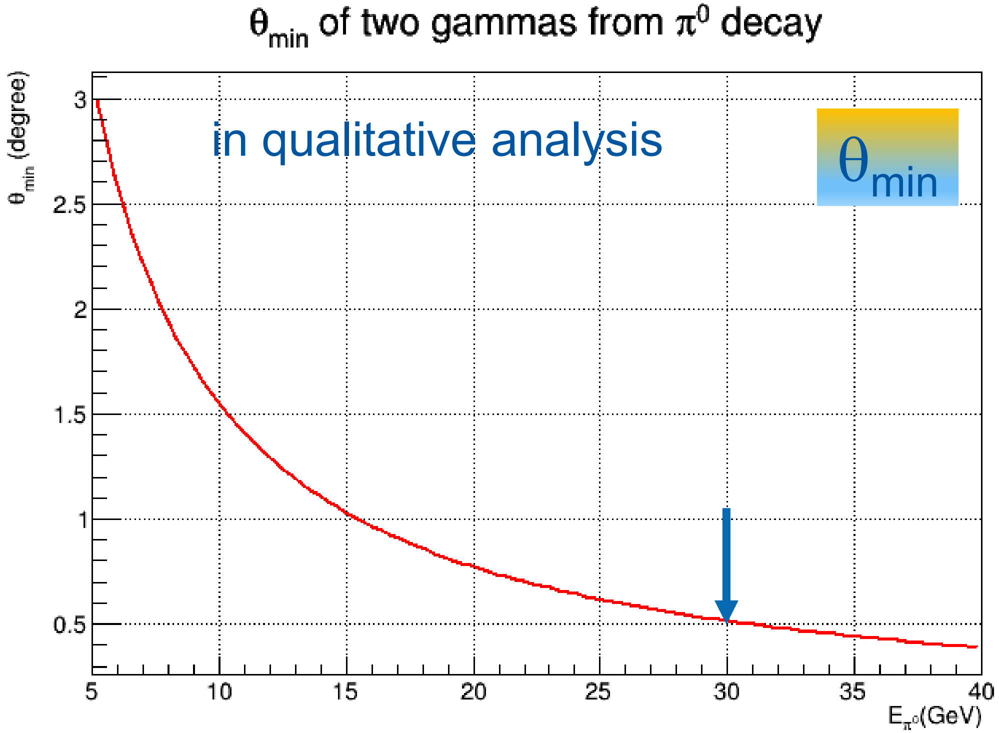
- High-granularity crystal ECAL: steady R&D progress
  - Crystal granularity optimisation
    - Crystal depth, pi0/gamma separation power
  - Dynamic range: requirements and TOT technique studies
  - SiPM readout ASIC within CALICE
    - Characterisations with pulse injection
- Collaborations with US teams
  - Exchanges of ideas, R&D work, plans and technical discussions
  - A separate status talk summarized by Marco Lucchini (Princeton U.)

Thank you!

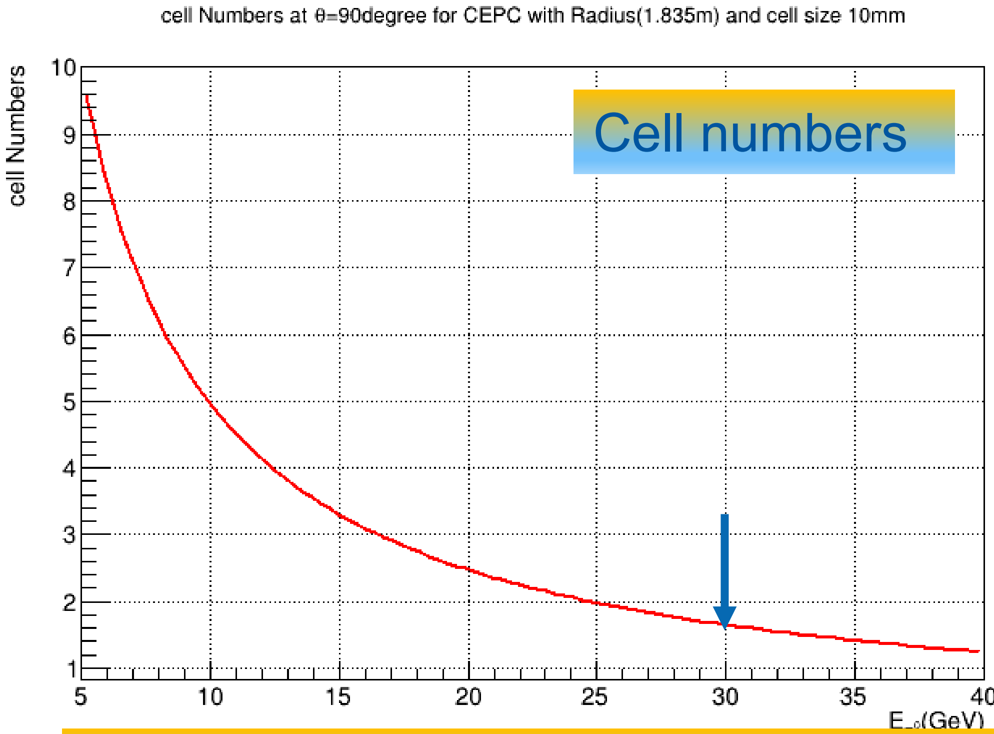
Backup slides

Separation Performance of 2γ's from high energy π^0 decay

- Convert the θ_{min} into the cell numbers at θ=90° for CEPC with R=1.835m and the cell size 10mm
- One crystal has the maximum angle~0.31224° at θ=90° in barrel

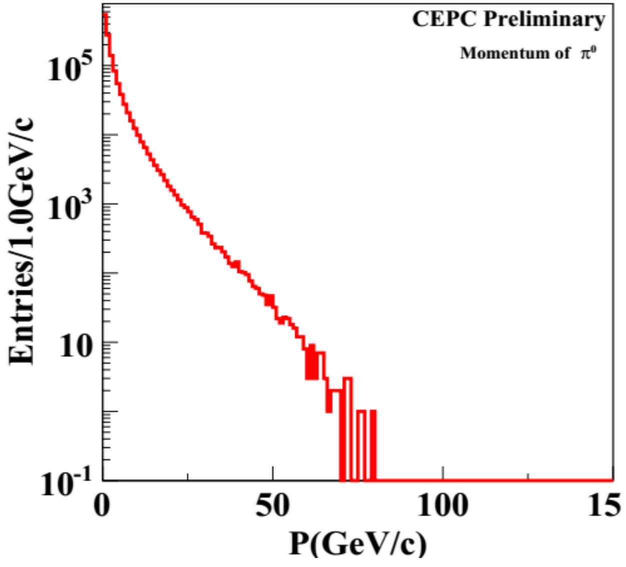


θ_{min} versus π^0 momentum



Cell numbers versus π^0 momentum

Separation Performance of 2γ's from high energy π^0 decay

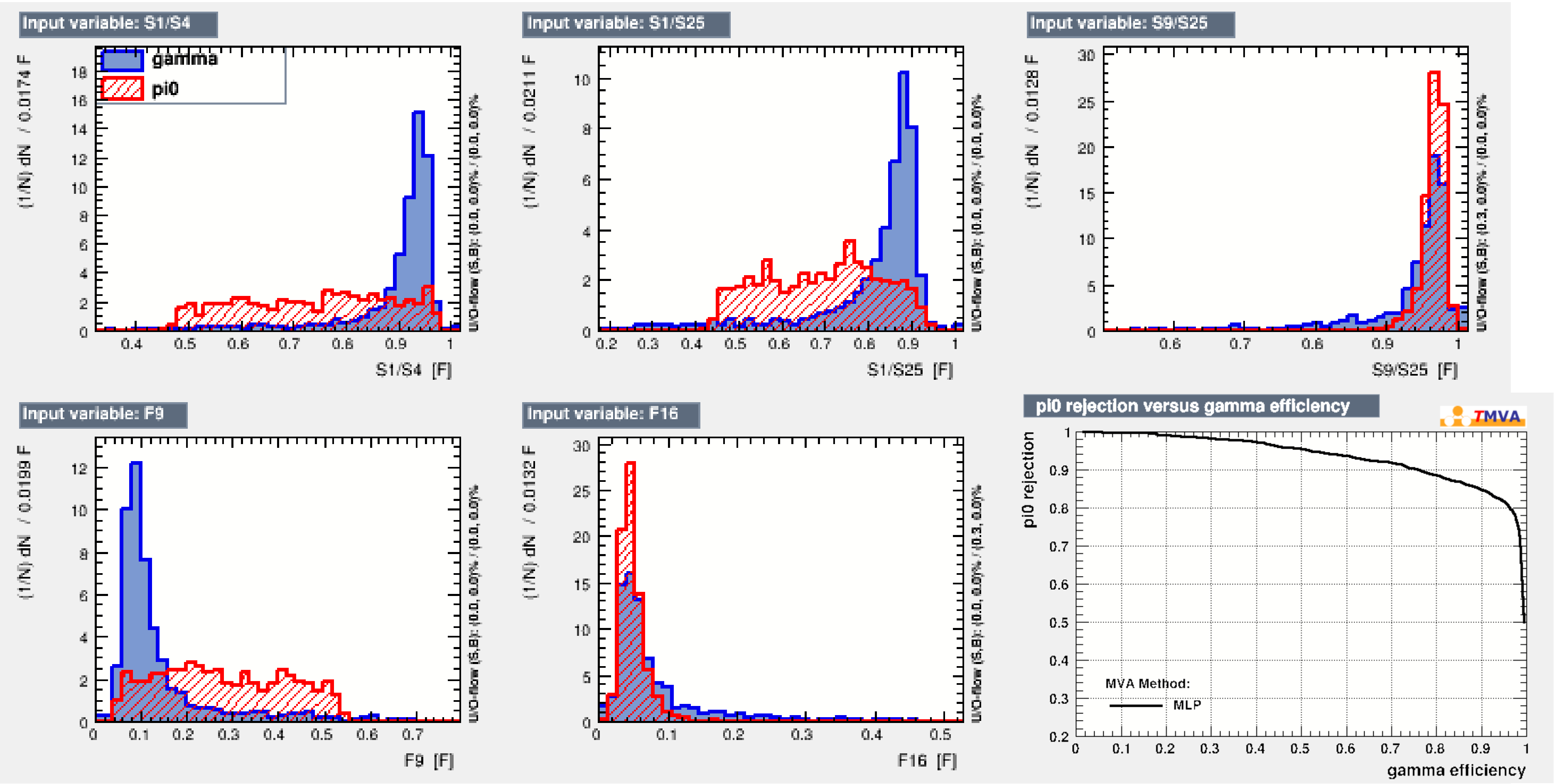


- π^0 decay events with the small opening angle selected
- Two types of π^0 events in ECAL reconstruction
  - "Resolved" π^0 from a pair of photons in two clusters
  - "Merged" π^0 from a single cluster
- Use 40 GeV π^0 samples

	π^0 Momentum	Cell 1x1cm^2	Cell2x2cm^2
Resolved π^0	30GeV	~100%	0%
	40GeV	~60%	0%
Merged π^0	30GeV	0%	100%
	40GeV	~40%	100%

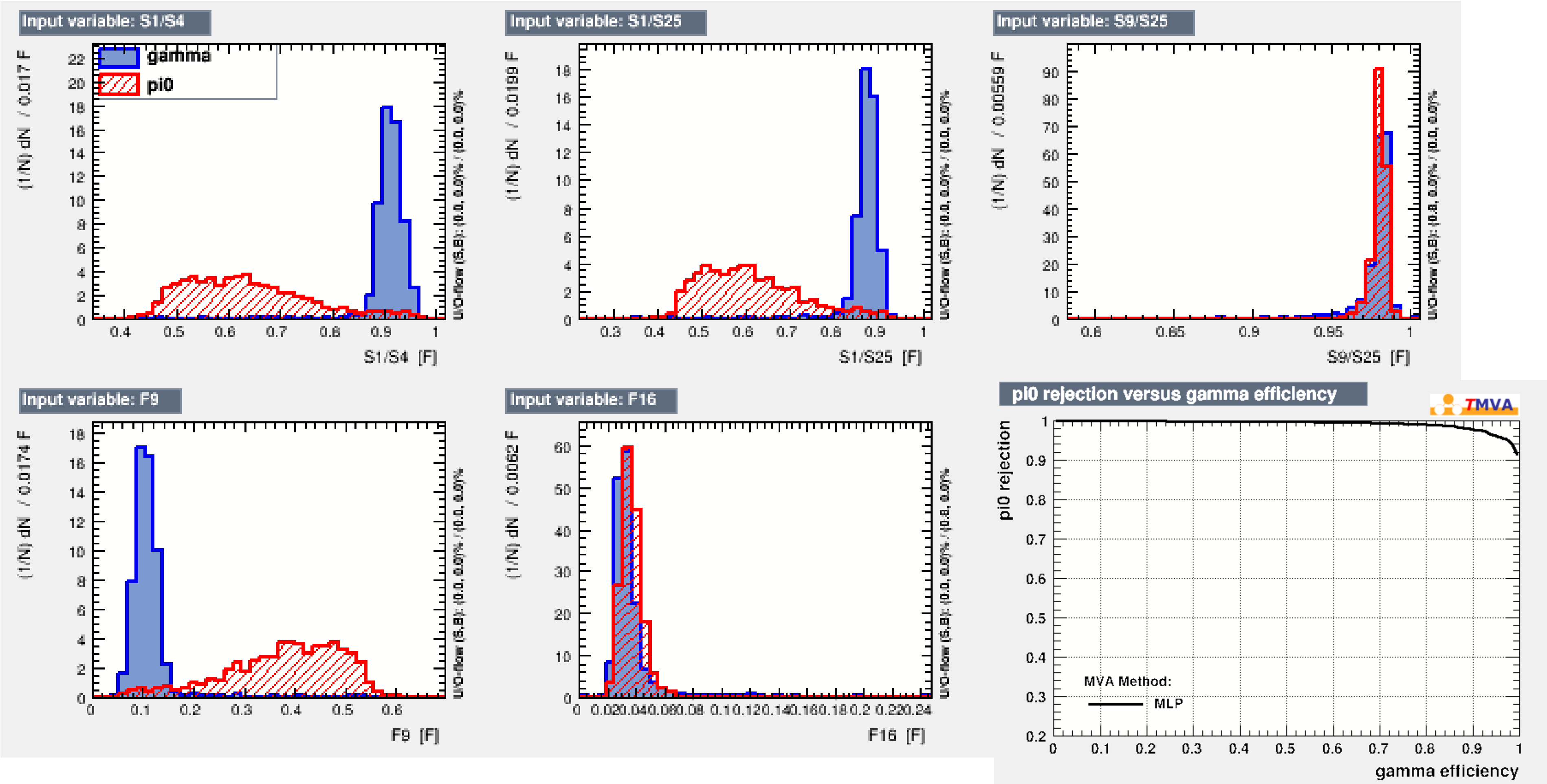
Separation Performance of 2γ's from high energy π^0 decay

- Cell $2x2x3cm^3$ 1^{st} layer



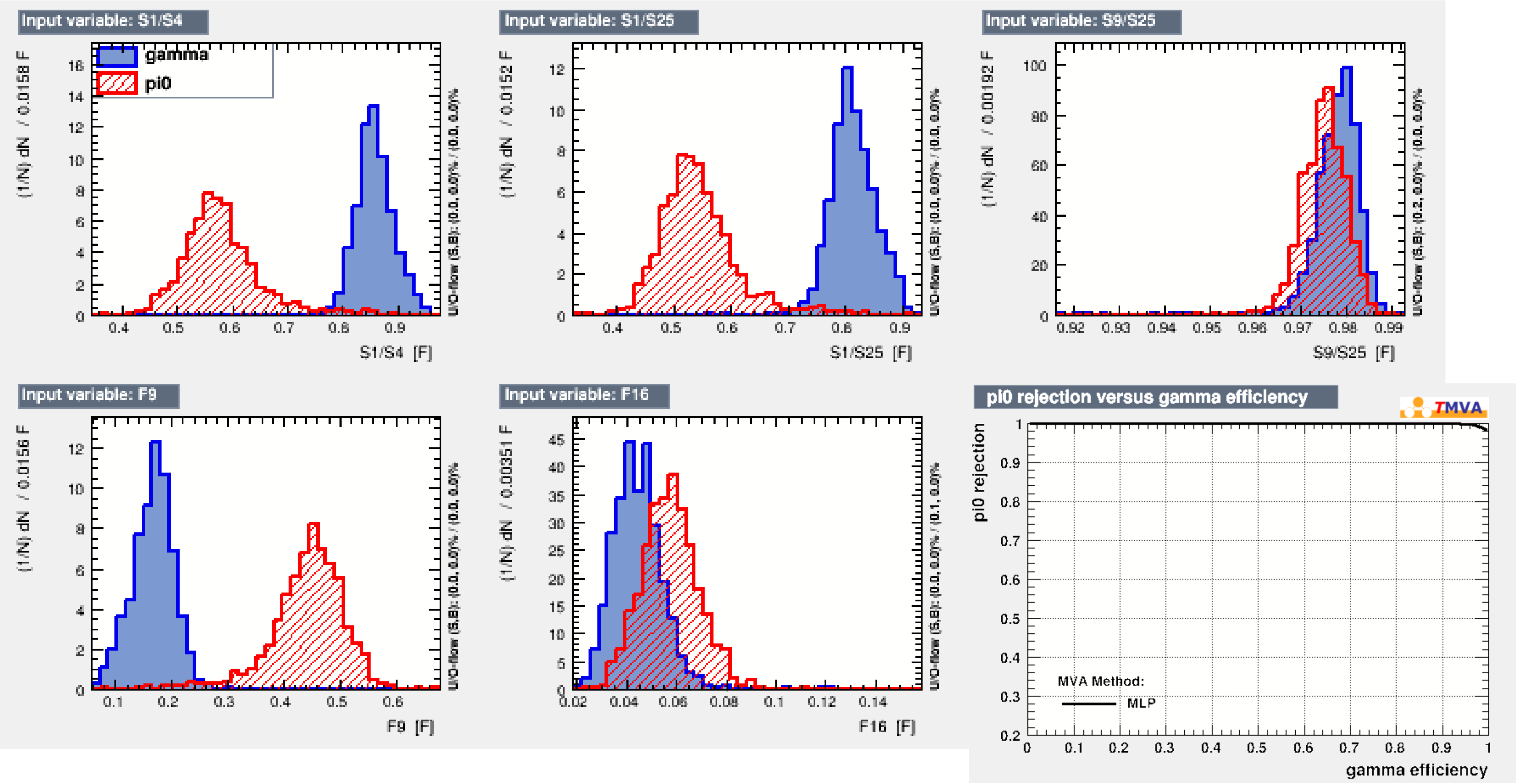
Separation performance of the 40GeV γ and merged π^0

- Cell $2x2x3cm^3$ 2^{nd} layer



Separation performance of the 40GeV γ and merged π^0

- Cell $2x2x3cm^3$ 3^{rd} layer



Separation performance of the 40GeV γ and merged π^0

- Cell 2x2x3cm^3 4th layer