A Digital Calorimeter for Dark Matter Search in Space

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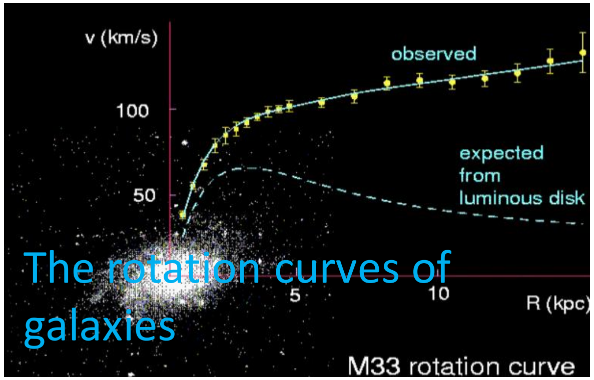
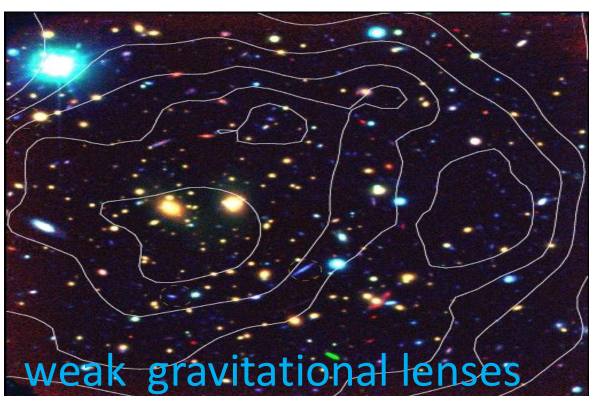
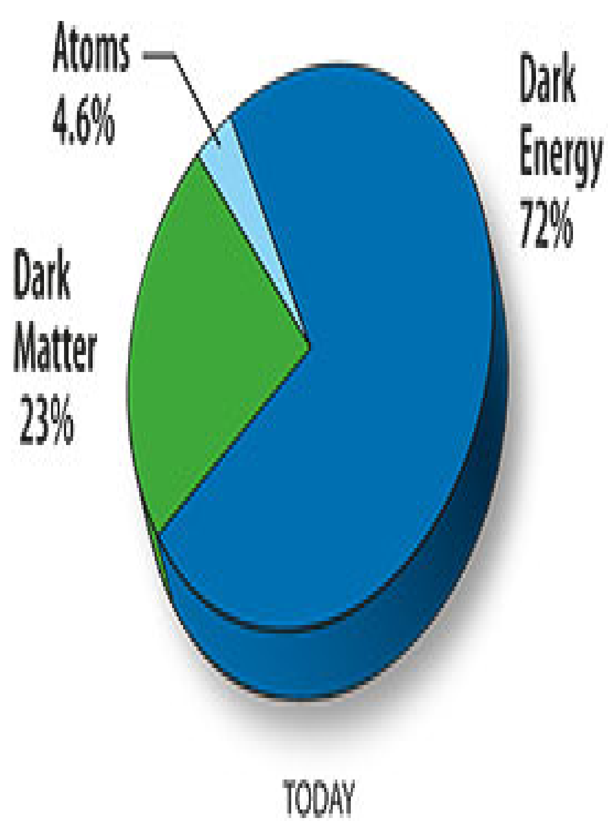
Some of the evidences for Dark Matter





IMAGES > OTHER IMAGES > CONTENT OF THE UNIVERSE



Content of the Universe - Pie Chart

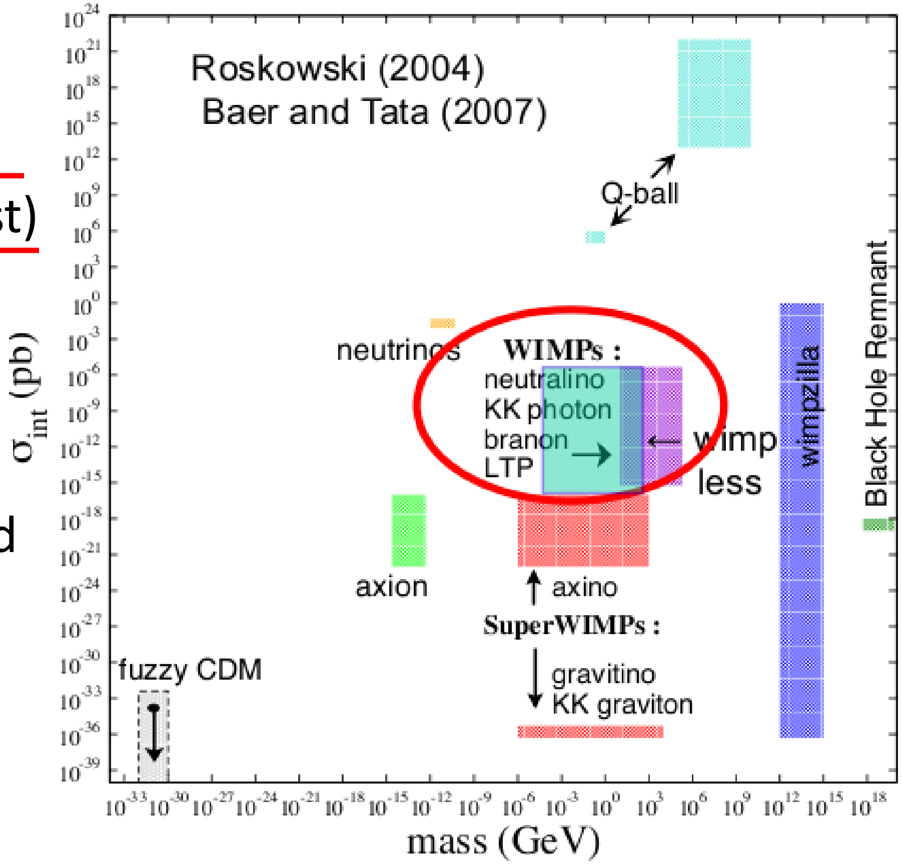
WMAP data reveals that its contents include 4.6% atoms, the building blocks of stars and planets. Dark matter comprises 23% of the universe. This matter, different from atoms, does not emit or absorb light. It has only been detected indirectly by its gravity. 72% of the universe, is composed of "dark energy", that acts as a sort of an anti-gravity. This energy, distinct from dark matter, is responsible for the present-day acceleration of the universal expansion. WMAP data is accurate to two digits, so the total of these numbers is not 100%. This reflects the current limits of WMAP's ability to define Dark Matter and Dark Energy.

DM is a difficult problem of physics

DM candidates from particle physics

Most popular candidates

- Stable weakly interacting massive particles (WIMPs) of mass 10GeV – 10TeV (preferred by most of theorist)
- Massive neutrinos
- Axions
- Kaluza Klein particles



WIMPs occur in several well-motivated theories beyond the Standard Model such as

- Supersymmetry
- Inert Higgs models

etc.

Our detector is focus on WIMPs

Detection mechanisms of WIMPs

- Direct detection:

  detect signal of DM collisions with nuclei

  $$DM + N \to DM + N + e\gamma$$

  until now, No clear signal, only bounds on cross sections and masses of WIMPS

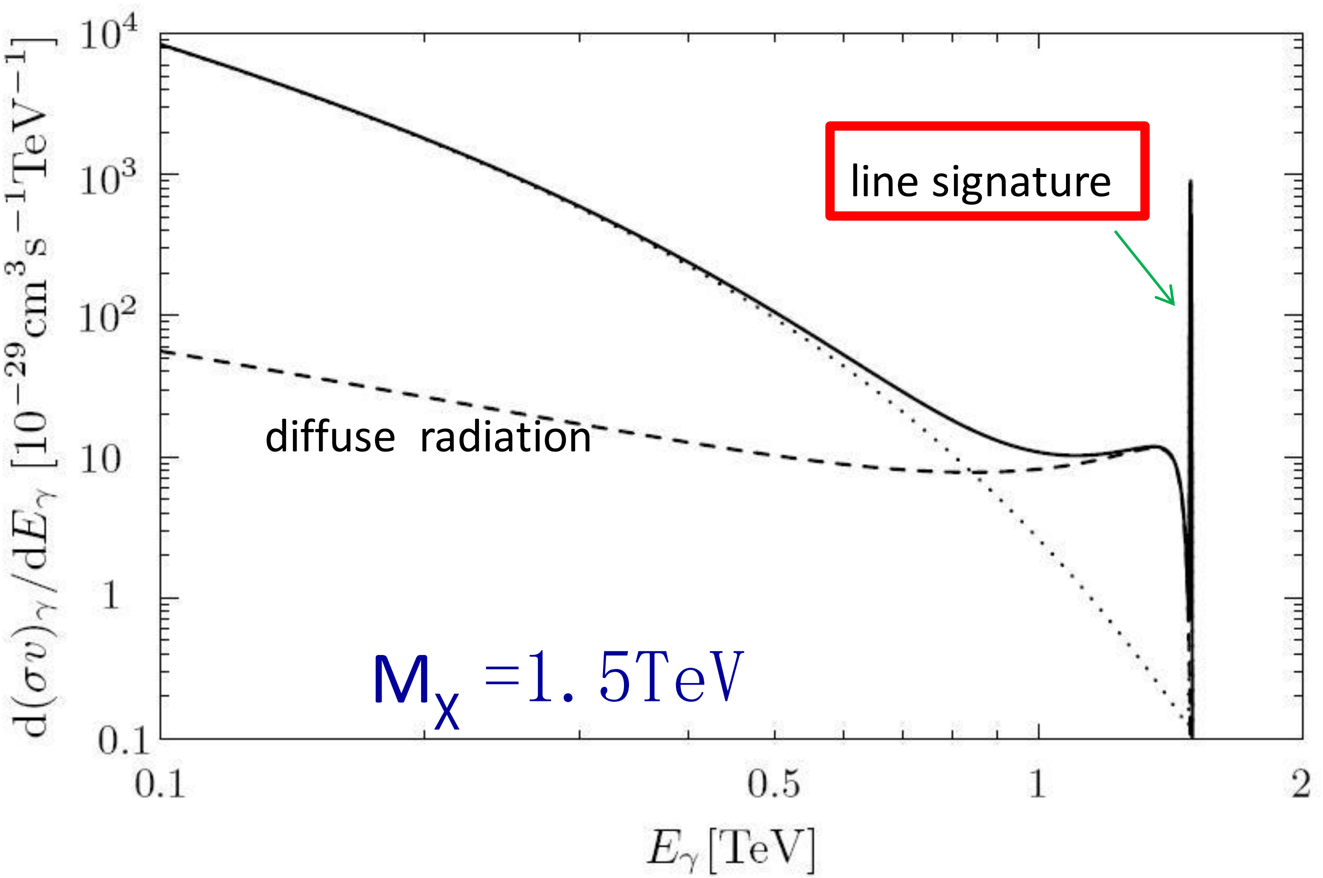
- Indirect detection:

  detect final decay products of DM annihilation

  $$DM + DM \to SM + SM, \quad SM = e, \mu, \tau, \gamma, W, q$$

  $$SM \to e^{\pm}, \gamma, p, \bar{p}, \nu$$

Decisive evidence of DM

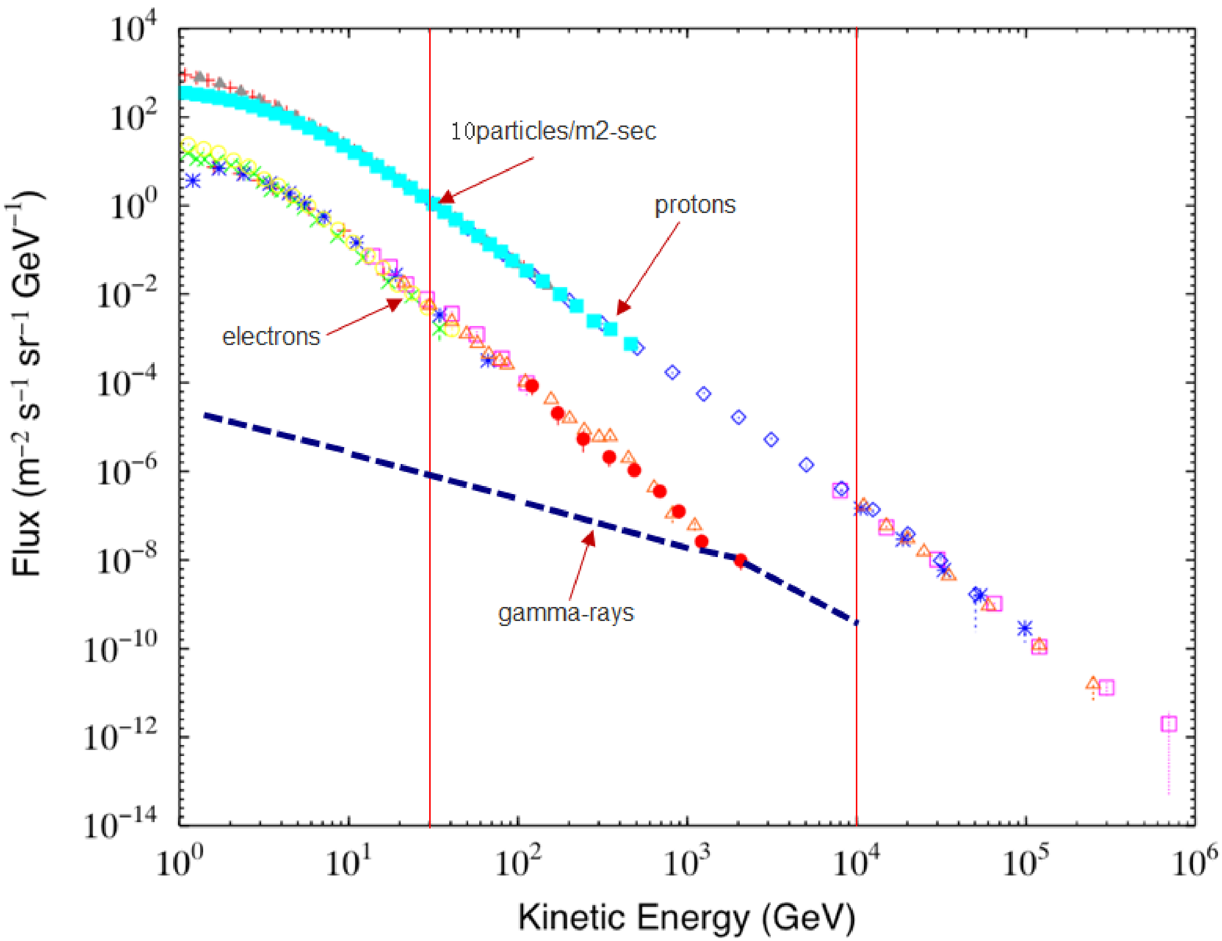


Example for gamma-ray spectrum of DM annihilation

$$\chi + \chi \rightarrow \gamma + \gamma \quad E_\gamma = M_\chi$$

Line signature from DM annihilation to double gamma-ray is the decisive evidence of DM

Flux of cosmic-ray



Range 30GeV—10TeV

Flux of electrons:

~ 10^{-2}—10^{-3} of protons

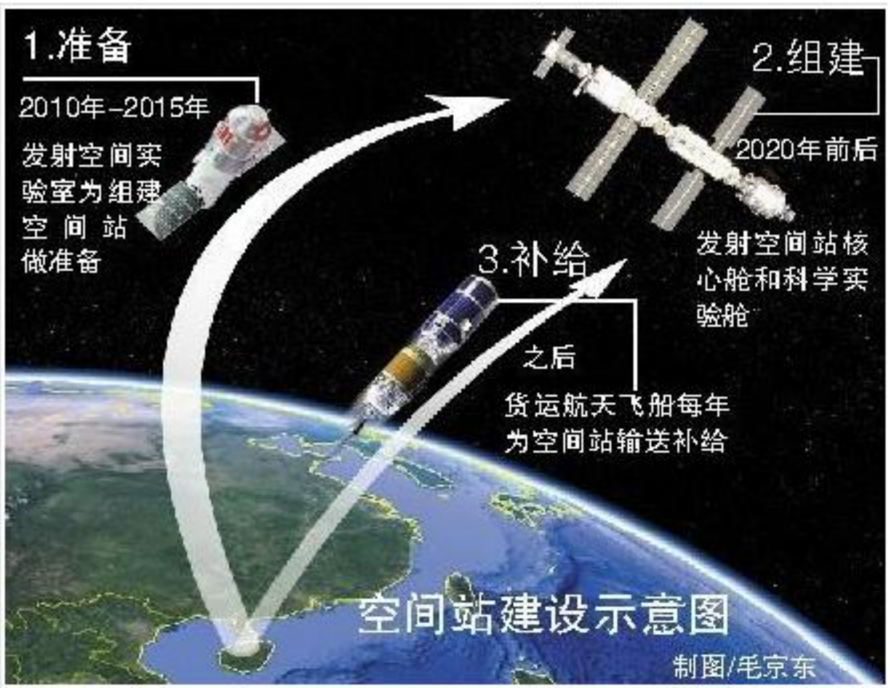
Flux of gamma-rays:

~ 10^{-3}—10^{-6} of protons

To identify electrons and gamma-rays, excellent capability of proton rejection with power ~10^5 is necessary

Space Station of China

A payload for dark matter search is proposed by IHEP



2020 Space Station will be built

the detector should has capabilities :
Energy range
30GeV-5TeV (cover WIMP mass range)
Energy resolution
<5%(detect line signature requirement)
Background rejection power
 > 10^5 (suppress proton background requirement)
Total power
<500 Watts
Total mass
<1.5 Tons

Detector Concept design

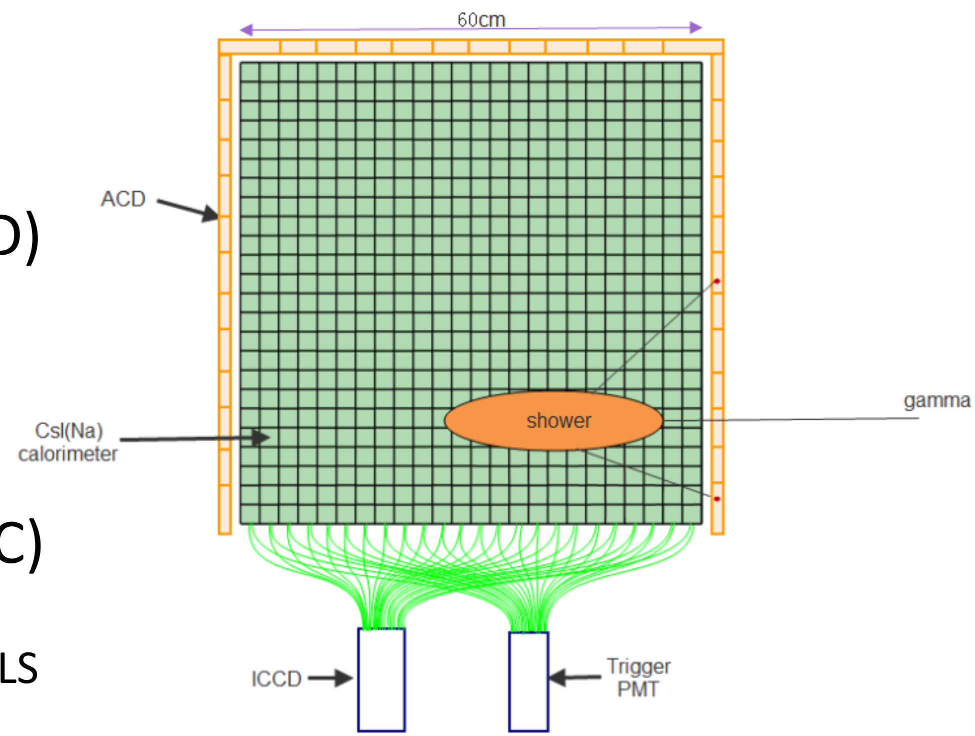
The detector has two chief components:

Anti-Coincidence Detector(ACD)

ACD is a positional sensitive plastic scintillator detector in order to reject charged particles for the gamma-rays observation.

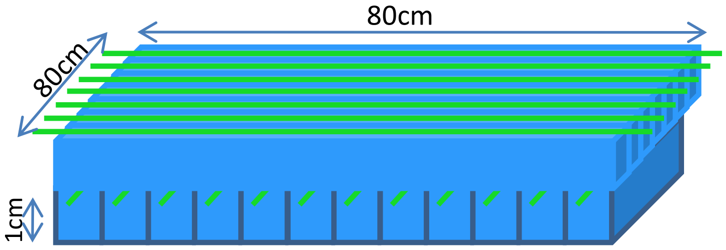
Digital Imaging Calorimeter(DIC)

DIC is a 3D Crystal array, each crystal is a little cube with one face coupled with WLS fiber which collect and guild photons to ICCD camera. All separate cubes are glued together.

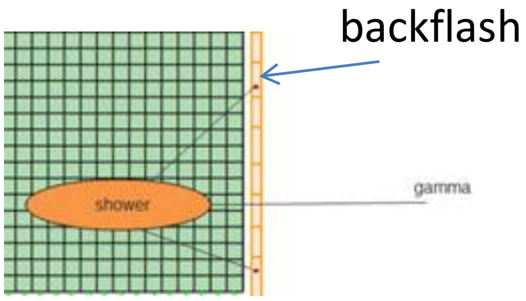


"Digital" means:
for each crystal
Hit mark "1" Non-Hit mark "0"
All the "01" describe the shower image.
We can get the information of particle energy, particle type and incident angle by image analysis.

ACD structure

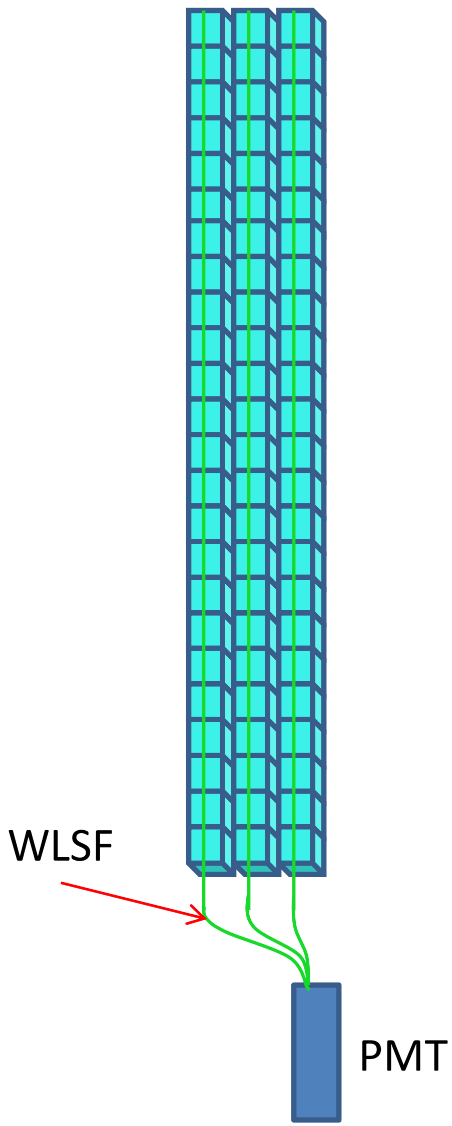


ACD is composed of 1x1x80cm plastic scintillator array along x and y direction which covers more than 5/6 of the main body. Each scintillator has a WLSF inbuilt in a groove on surface.
Read out devoice is SiPM.

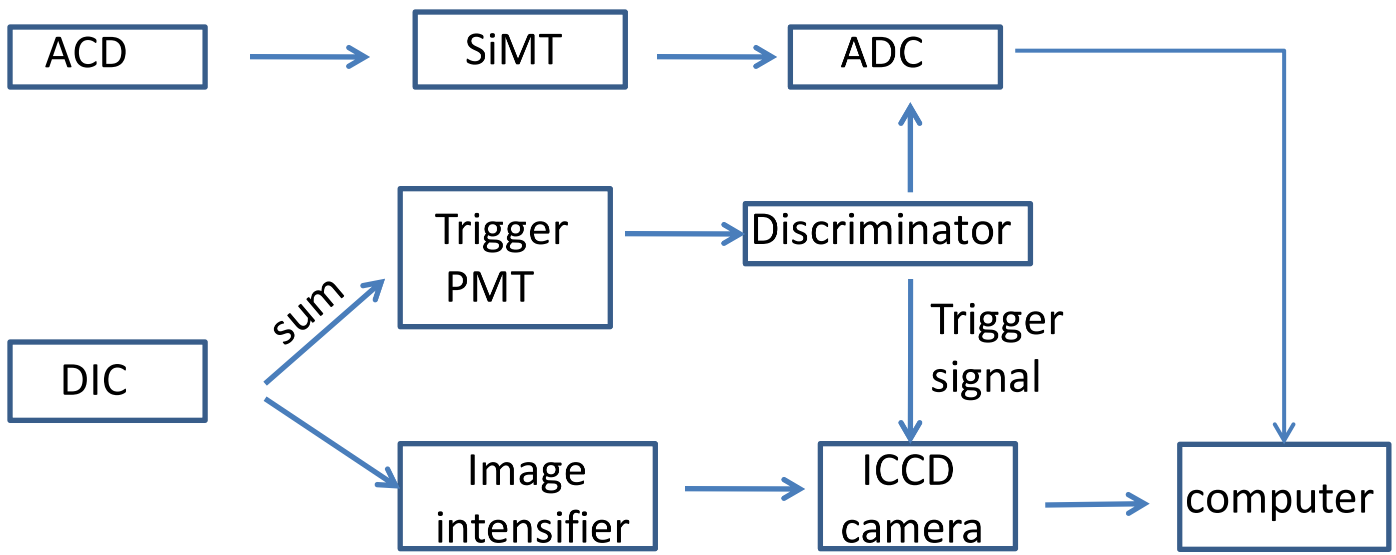


ACD is positional sensitive so the incident position of charged particle can be got associated with the shower axis in DIC.

Trigger structure



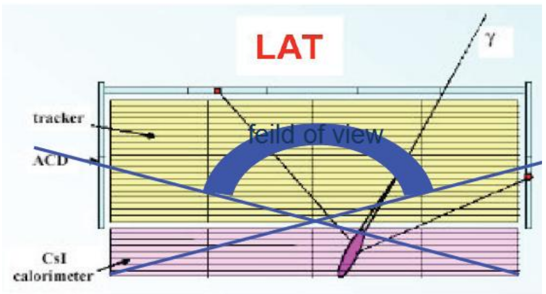
One fiber attach the surfaces of a string of crystals
All fibers coupled with one PMT
when a high energy particle incident, we can get a fast signal(<100ns) which direct proportion the particle energy.
So a threshold can be set for trigger.



Schematic view of the system

Chief feature of Detector

- Digital imaging so has no amplitude saturation problem
- 5 sensitive faces so has a large field of view
- High level of granularity so has Good particle identify power and Good angle resolution
- CCD read out with low power ~10w
- ACD is positional sensitive to suppress backflash charged particle



Fermi detector

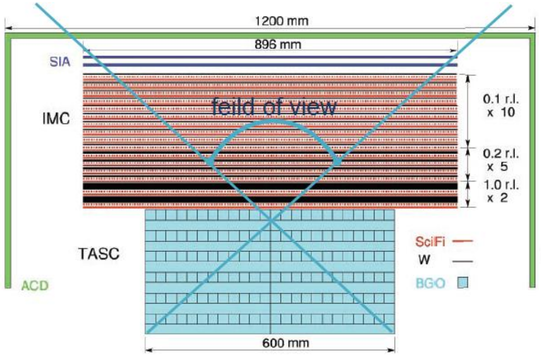
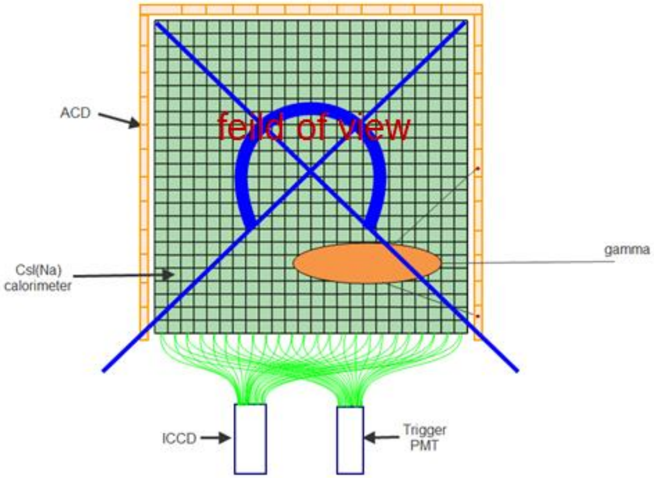


Fig. 9. A schematic side view of the CALET detector cor

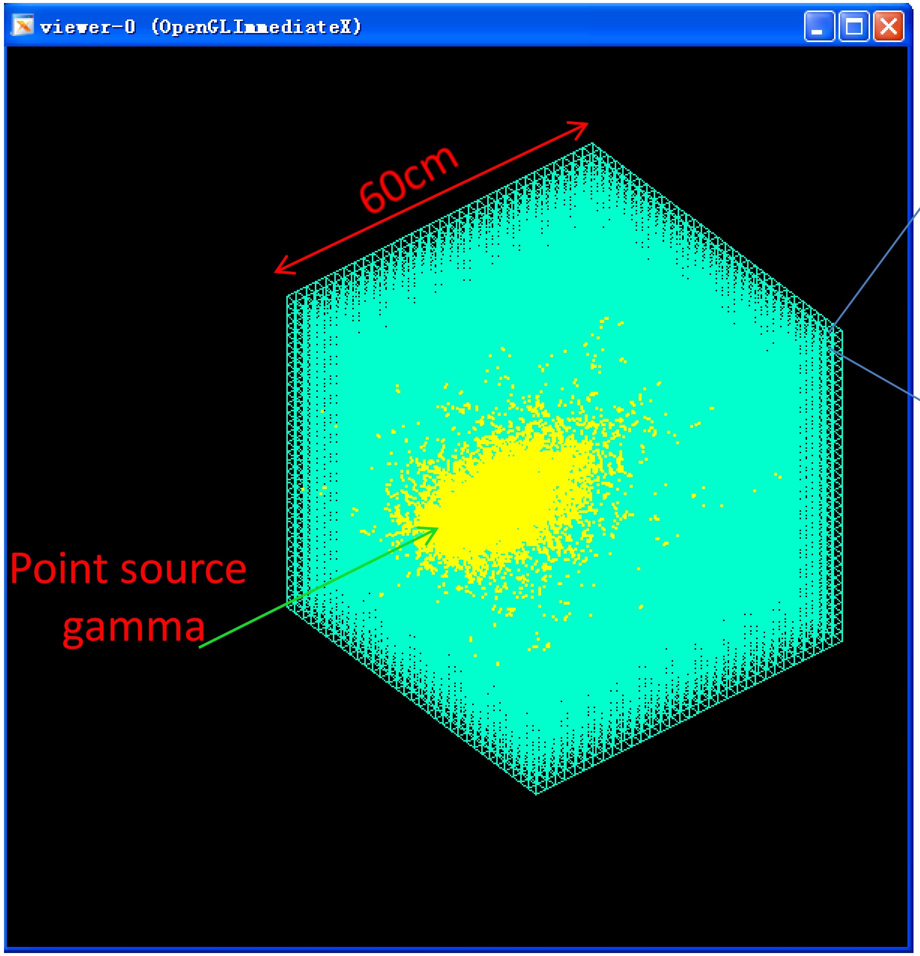
CALET detector

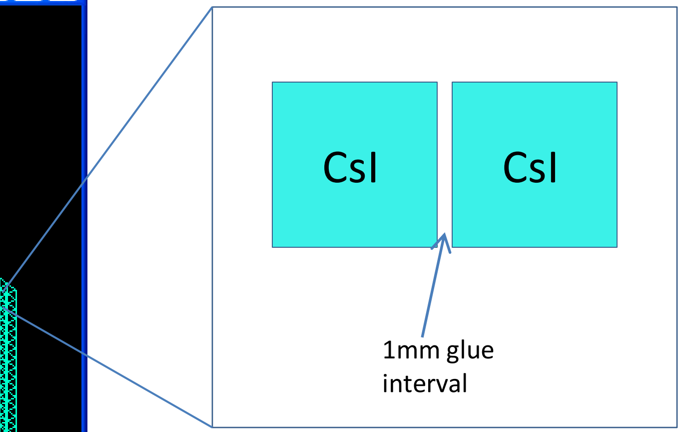


Simulation study on performance

- Energy N_{hit} relationship
- Energy resolution
- Angular resolution
- Gamma/proton separation

Detector geometry



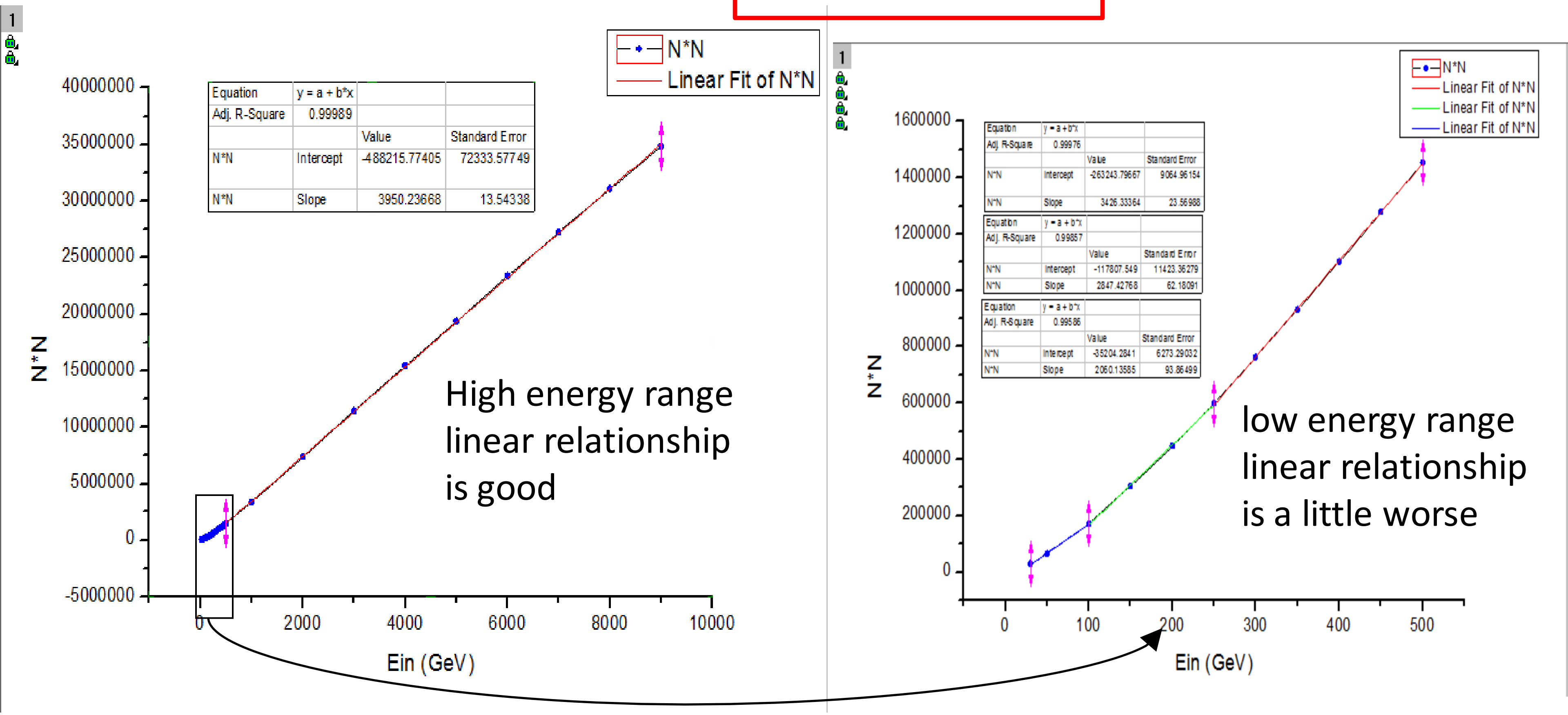


Total length is 60cm,~32r.l.
Little crystal cube side length is 1.5—4.5 cm
There is a 1mm glue interval between two crystals
Code: Geant4
Physics list: QGSP
Particle vertical incident
Digital energy cut is 12MeV for each crystal

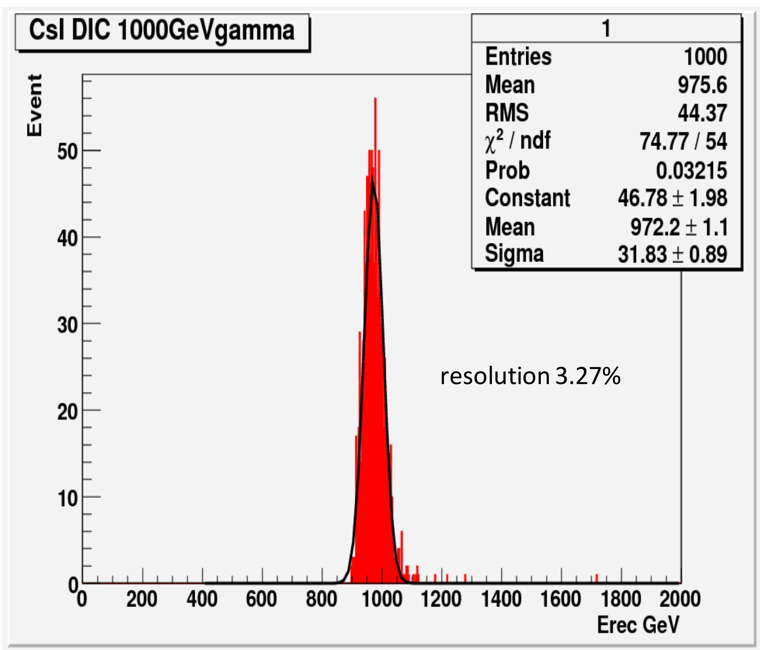
Energy N_{hit} relationship

From the MC data we found the relationship is:

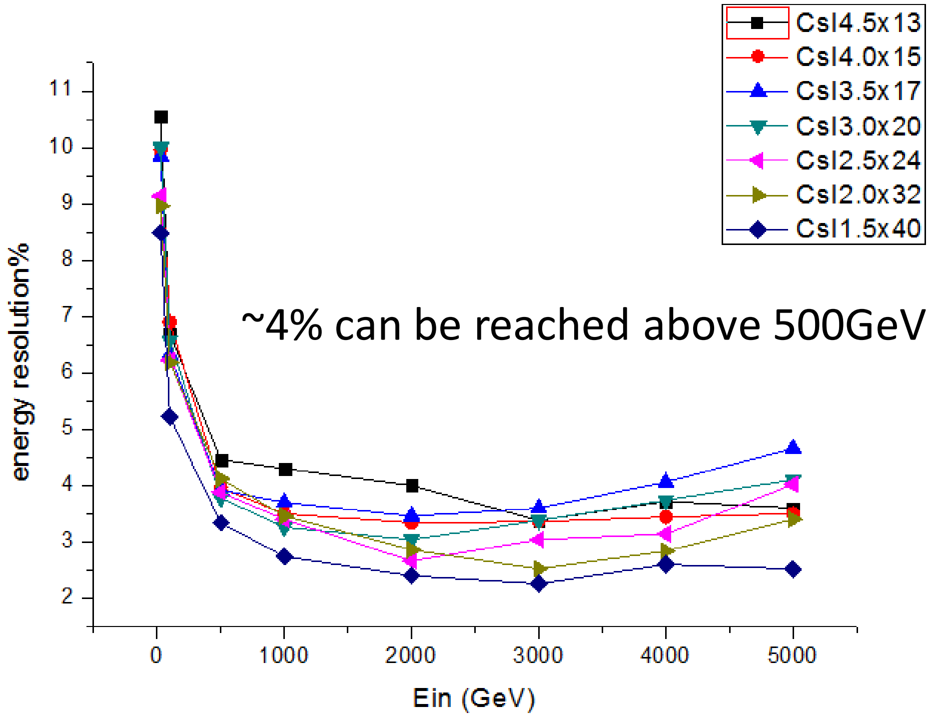
$$N_{hit}^2 \propto E_{incident}$$



Energy resolution



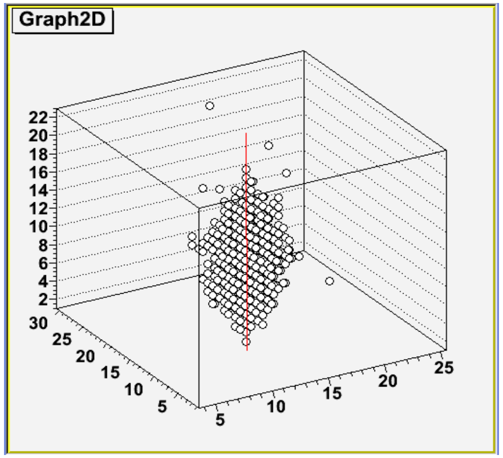
Energy reconstruction distribution of 1000GeV gamma-ray



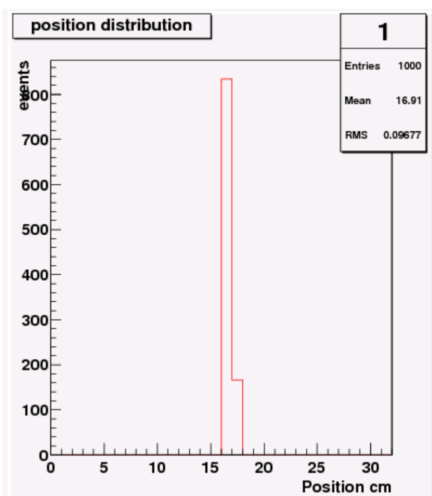
~4% can be reached above 500GeV

Energy resolution compare of different granularity 1.5—4.5 cm

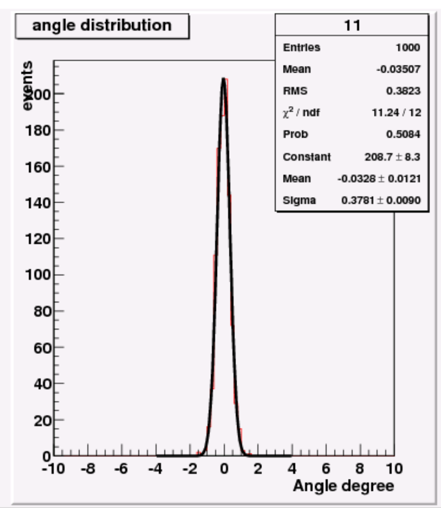
Angular resolution



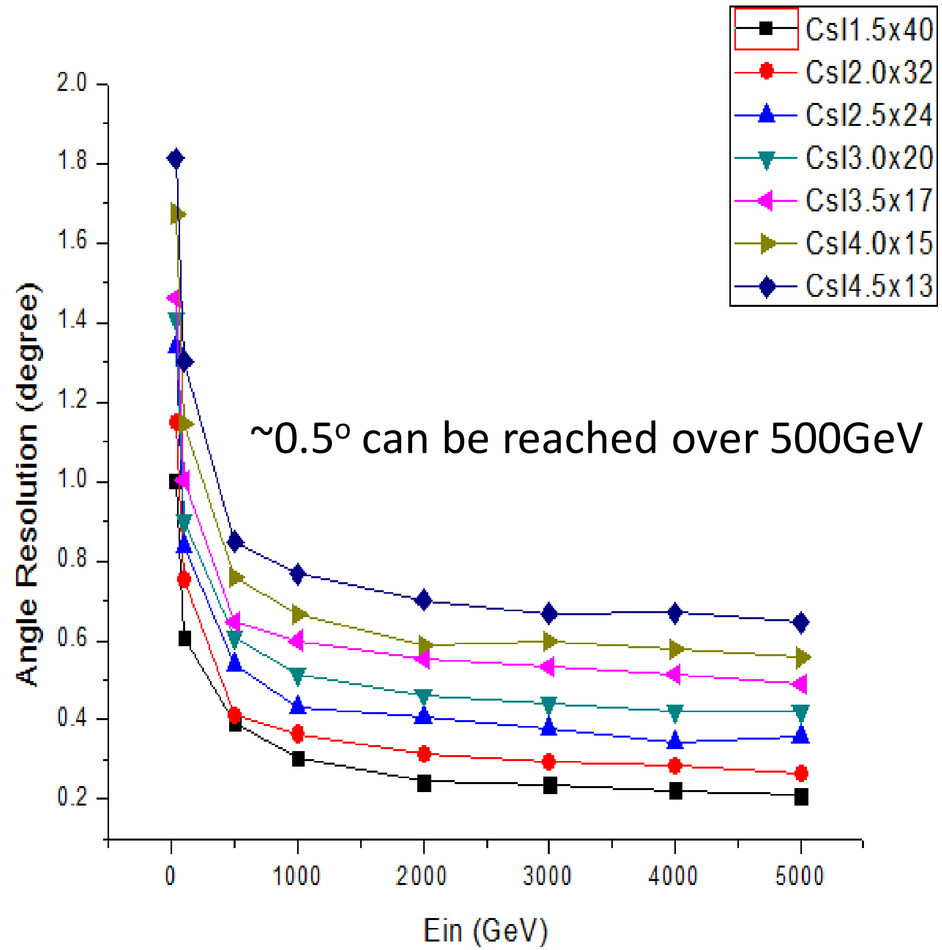
Reconstruction of shower axis



position distribution of incident particle



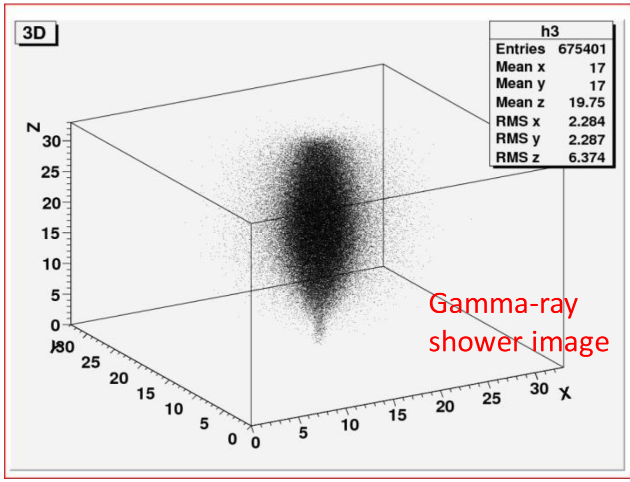
angular distribution of incident particle



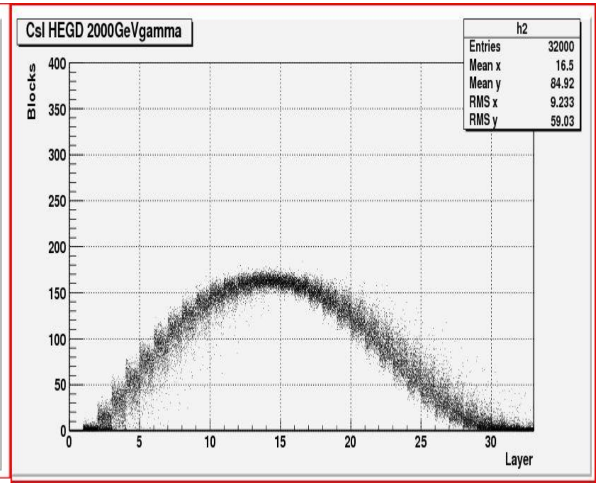
~0.5° can be reached over 500GeV

angular resolution compare of different granularity 1.5—4.5cm

Particle Identification(PID)



3D gamma-ray shower

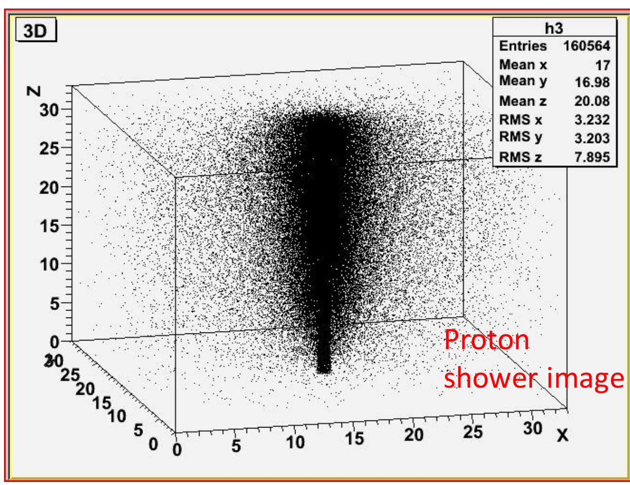


2D gamma-ray shower

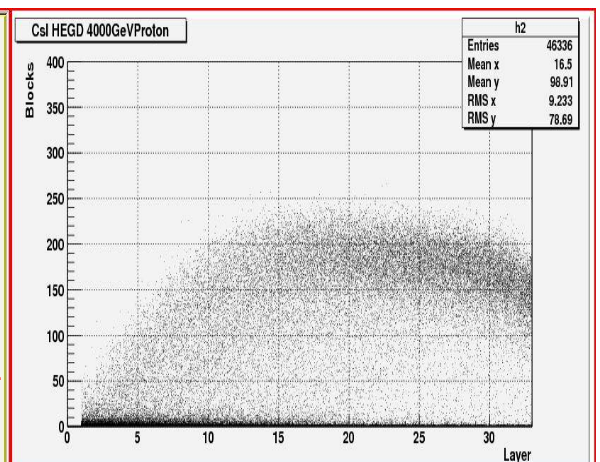
Two main differences :

1.Proton induced showers are longitudinally wider than electron showers due to the spread of secondary particles in nuclear interactions.

2.An electron induced shower will start and die off earlier than a proton shower

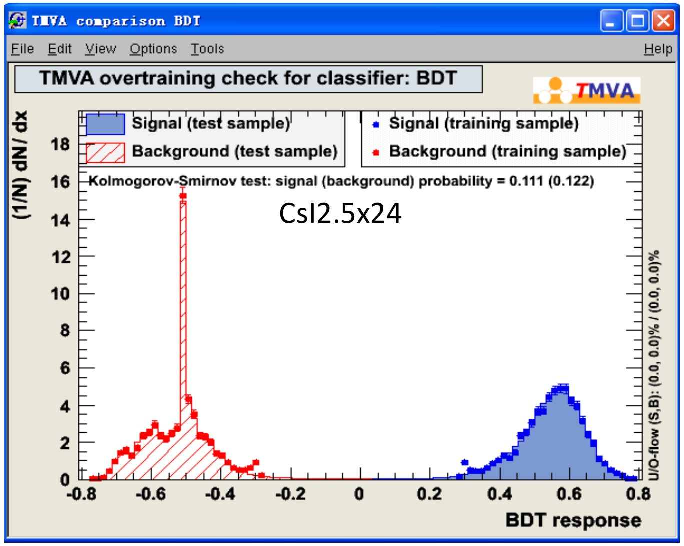


3D proton shower



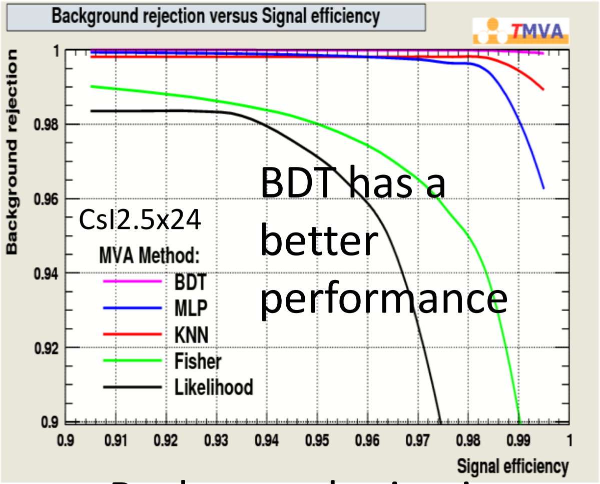
2D proton shower

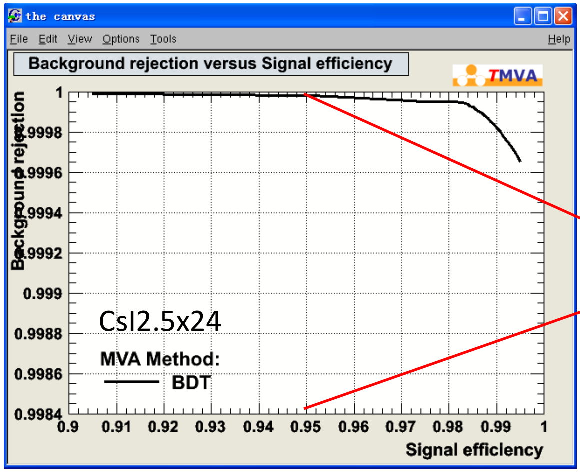
Gamma/proton separation by TMVA



TMVA output of gamma/proton separation

The input is
Signal: gamma-ray 100GeV
140000 events
Background: proton 100GeV—5000GeV
power law 2.7
1M events

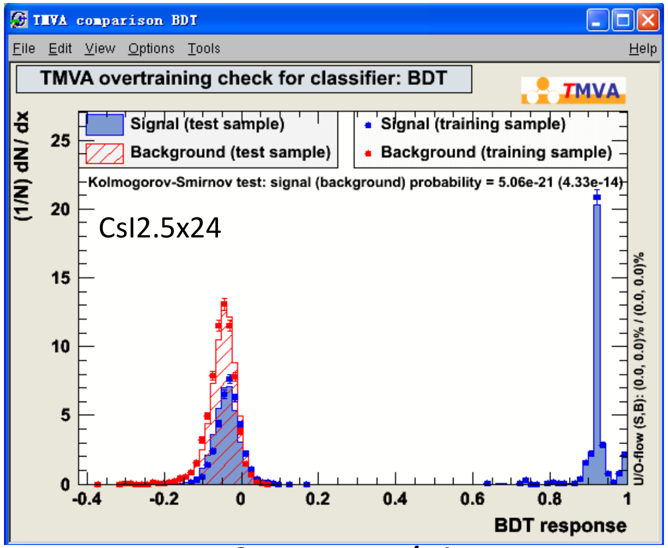




proton rejection power ~5x10^5
Signal efficiency 95%

Background rejection versus signal efficiency

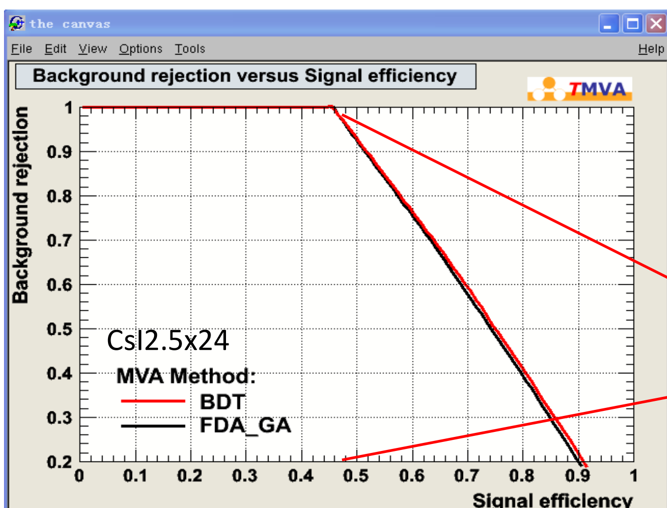
Gamma/electron separation by TMVA



TMVA output of gamma/electron separation

Difference:
Electron shower start earlier than gamma-ray shower

The input is
Signal: gamma-ray 100GeV
140000 events
Background: electron 100GeV
160000 events



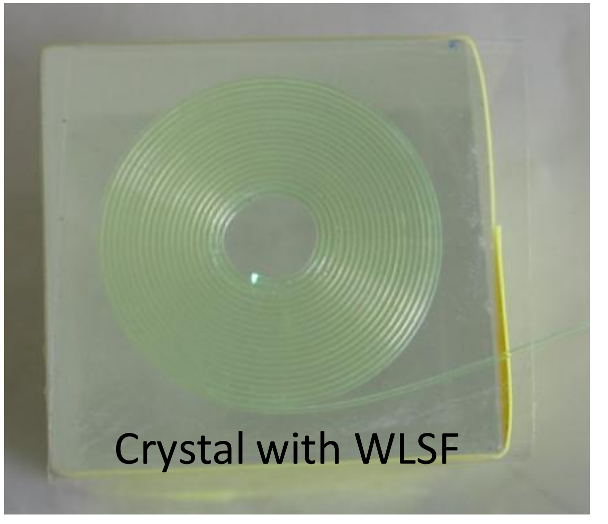
electron rejection power ~$1x10^4$
Signal efficiency 45%

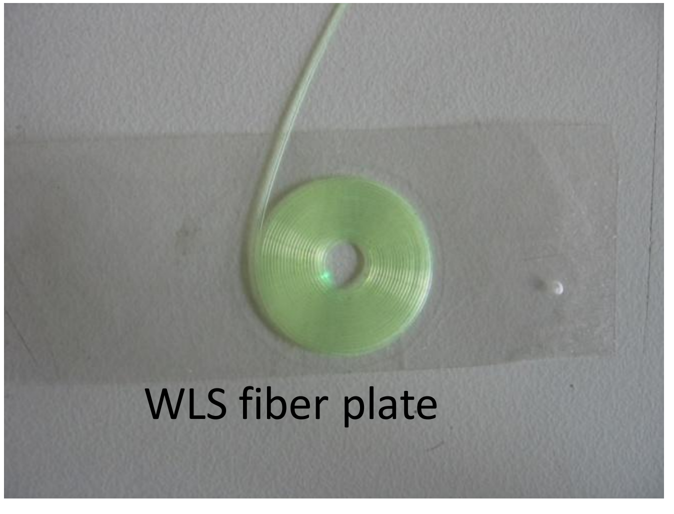
Background rejection versus signal efficiency

Experiment study

- Unit structure
- Prototype 2x2x6 array
- Muon test
- Capacity analysis

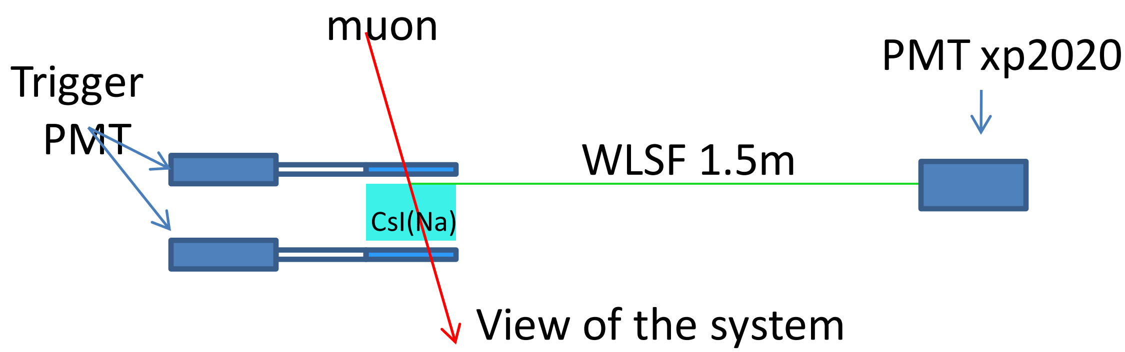
unit structure



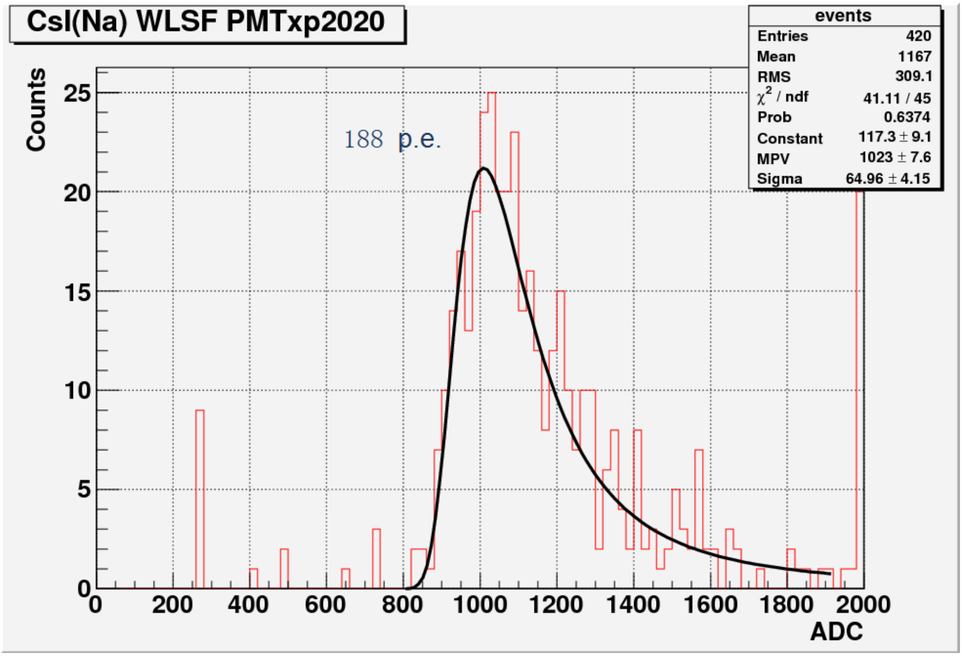


Crystal side length: 2.5cm
WLS fiber diameter: Φ300um

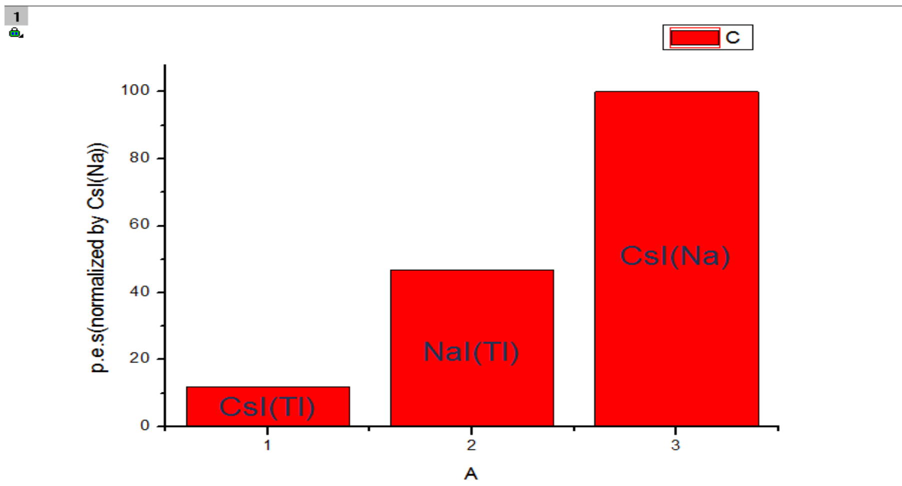
Unit muon test



View of the system



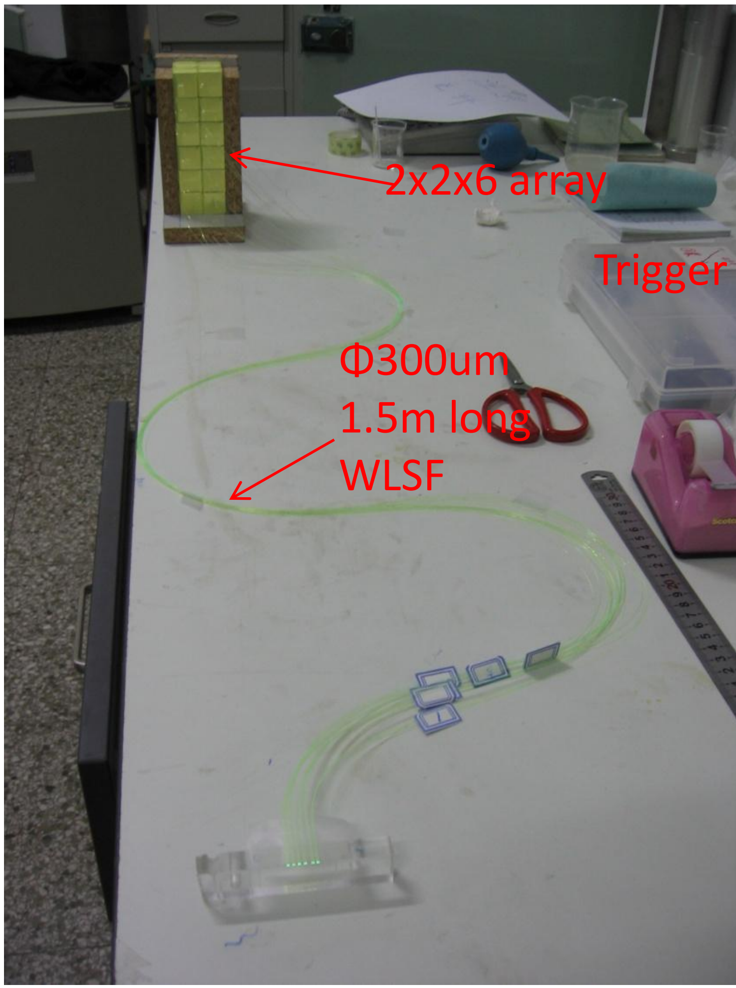
muon MIP spectrum

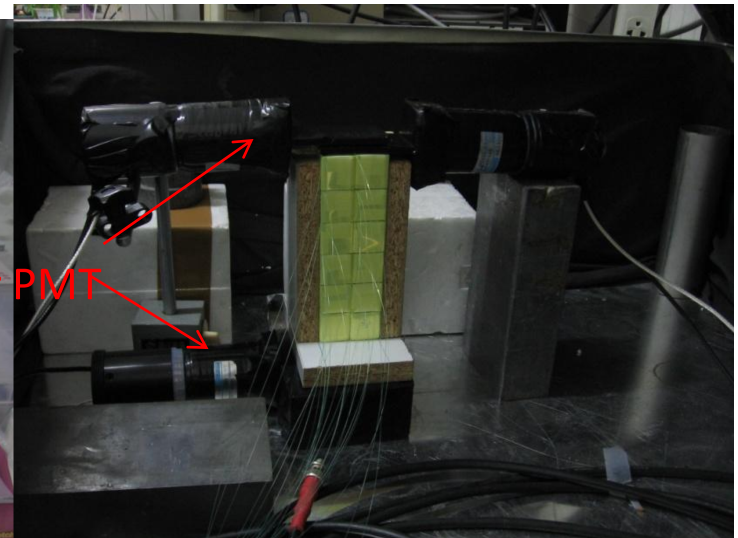


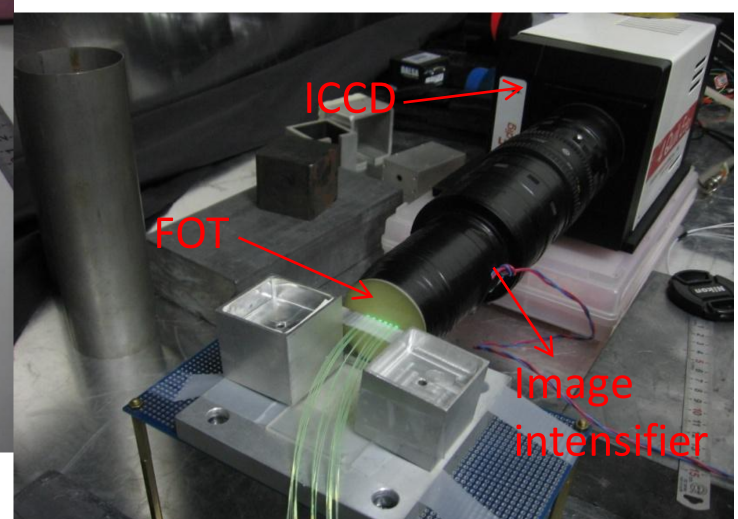
Differern crystal compare

CsI(Na) has better performance

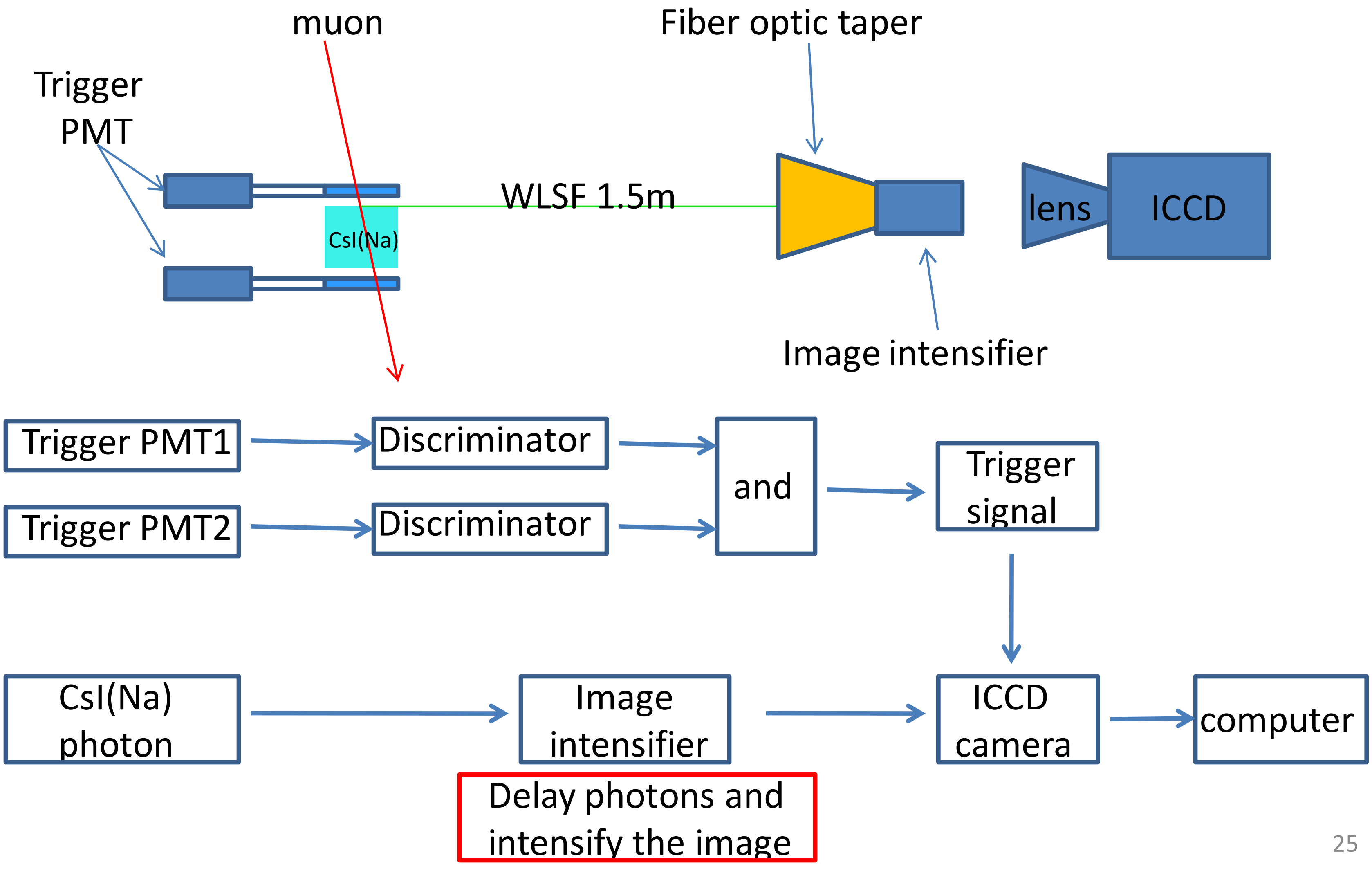
Prototype 2x2x6 array



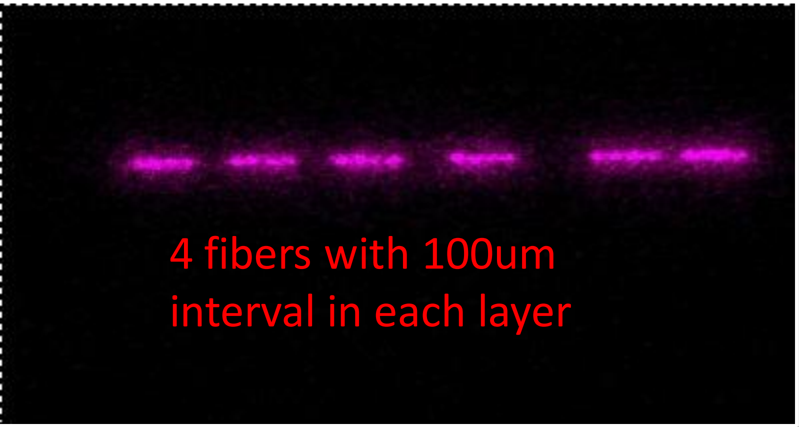


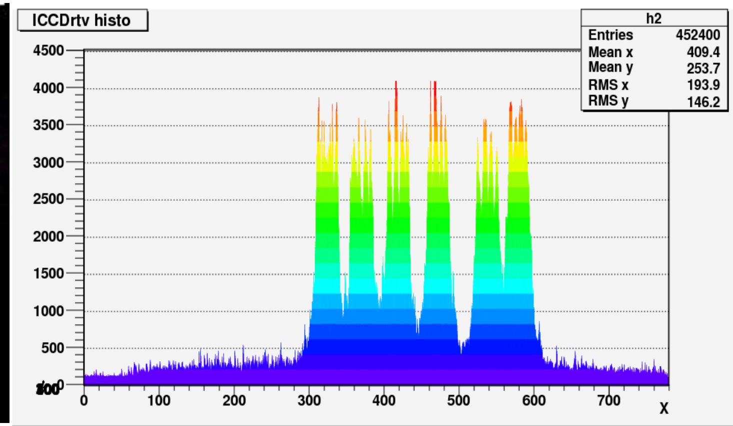


Schematic view of the muon test system



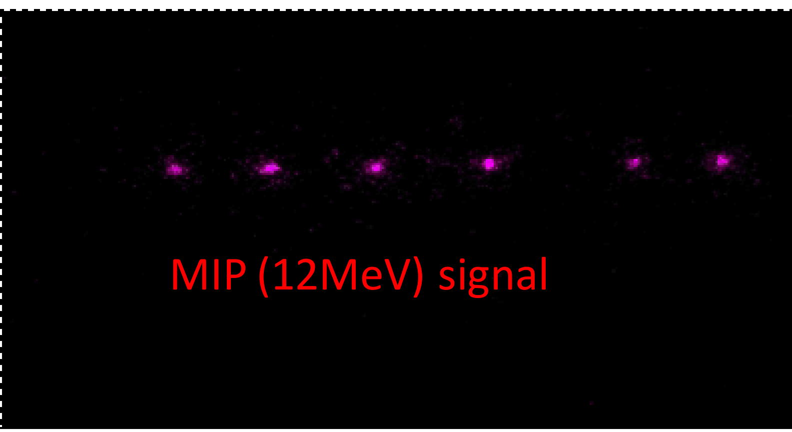
Muon test result

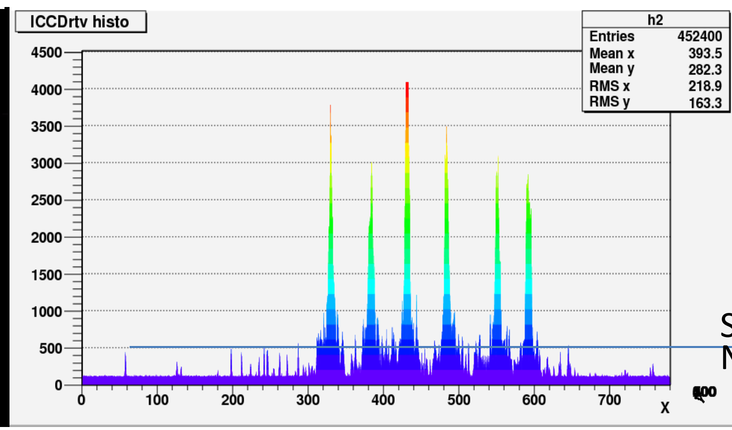




Position calibration

Signal is clear
And the system works well

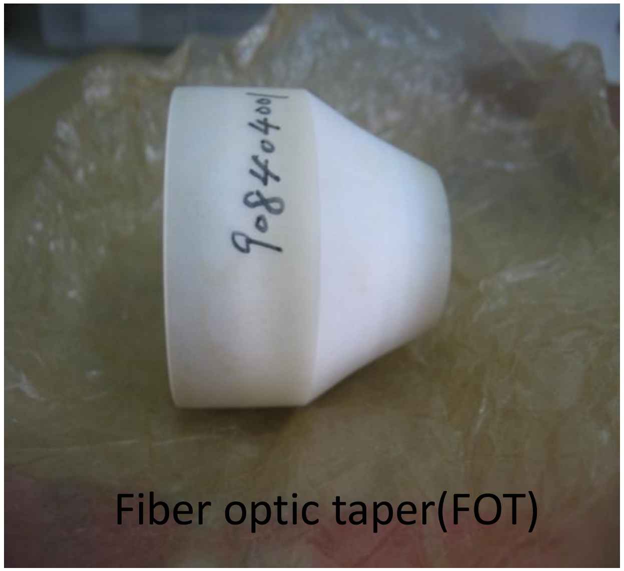




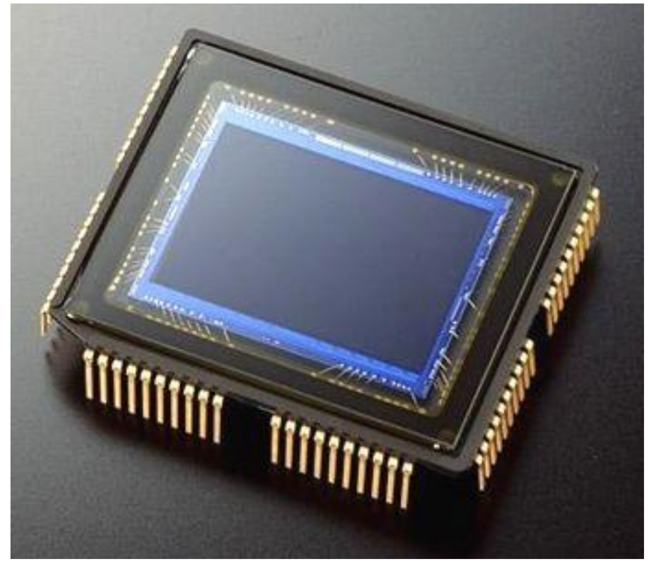
$\frac{\text{Signal}}{\text{Noise}} = 8$

muon event

Capacity analysis



Fiber optic taper(FOT)



Magnification of FOT and size of CCD are the key factors for capacity.

For ϕ300um fiber with 100um interval and 450000 pixels CCD

Magnification	capacity
2:1	~4500 fibers
5:1	~28000 fibers

28000 can cover a 30x30x30 array

Only one CCD system needed for the whole calorimeter.

Summary

- A scheme of 60cm cube CsI(Na) array is proposed:
  5 faces sensitive~3.3m^2sr,digital image,32r.l. ~1T, 30GeV—5TeV

- The preliminary simulation is done.
  gamma/proton separation ~5×10^5 (95% eff. DIC only)
  electron/proton separation ~1×10^4(45% eff. DIC only)
  Energy resolution ~4%
  Angular resolution ~0.5^o

- The prototype has been built and test.