The LXe calorimeter and the pixelated timing counter in the MEG II experiment

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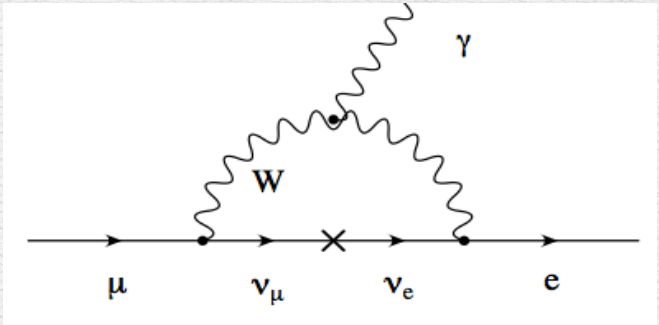
Outline

- Physics Motivation (Lepton Flavor Violation)
- MEG II Experiment
- LXe Calorimeter
- Pixelated Timing Counter

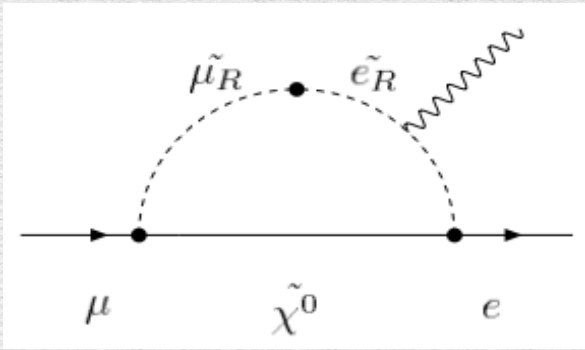
Lepton Flavor Violation (LFV) and μ→eγ search

- Quark mixing : established with CKM matrix in Standard Model (SM)
- Lepton
  - Neutrino : Neutrino oscillation is a hint for new physics
  - Charged lepton : No LFV is observed yet.
- In SM with neutrino mass, BR(μ→eγ)~10^{-54}
- No background from SM!
- Observation of μ→eγ decay is a clear sign of new physics beyond SM
- **Many new physics such as SUSY-GUT, SUSY-seesaw, Extra Dimensions etc. predict large BR(μ→eγ)**
- **μ→eγ search has real chances to discover new physics / to make strong restriction**

SM+Mν

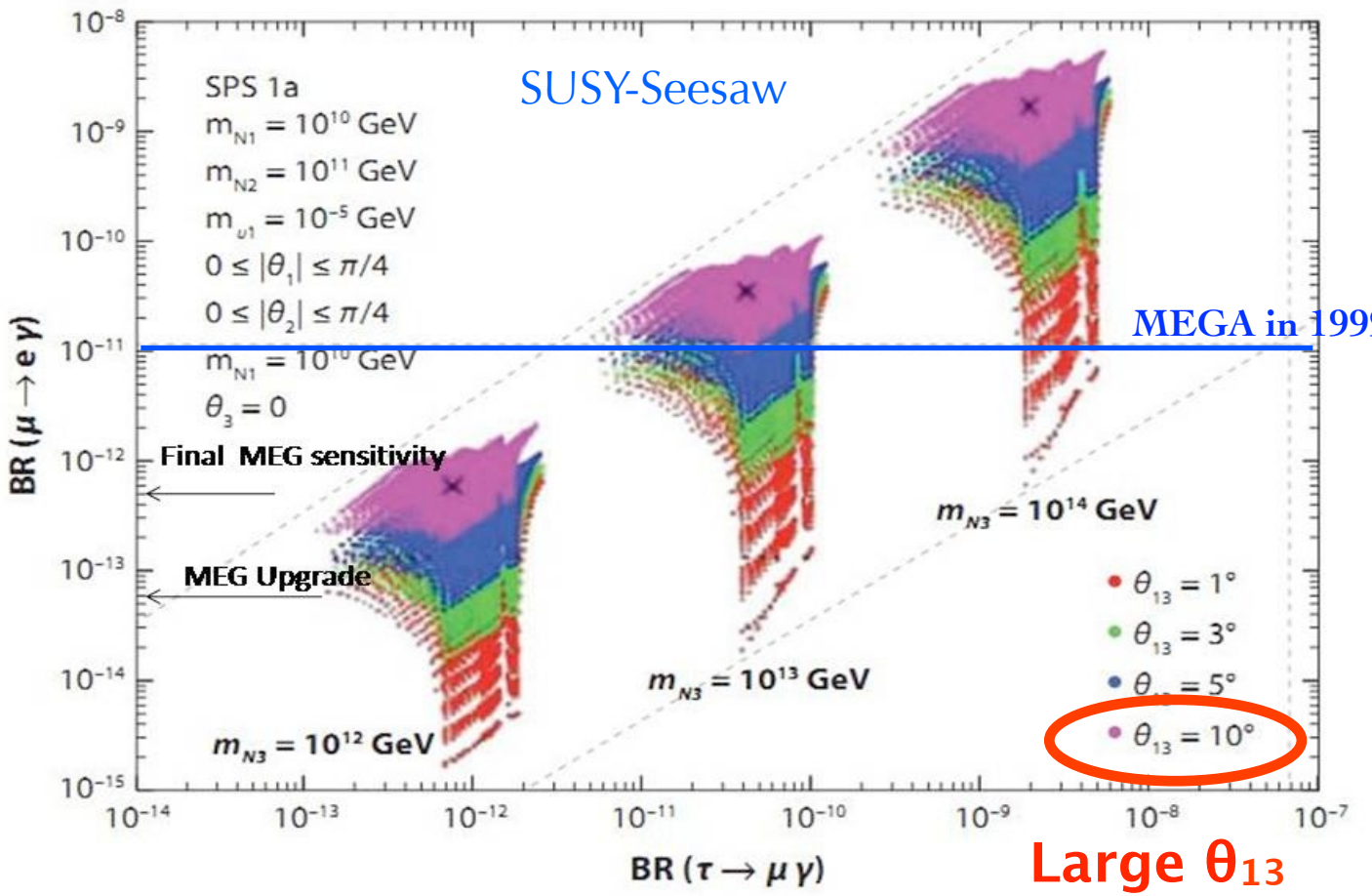


New physics



Charged LFV from the New Physics and the previous experimental upper limit

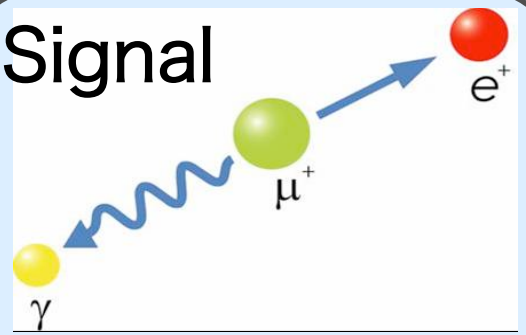
S. Antusch et al, JHEP 0611:090(2006)



Large θ_{13}
→ Large BR(μ→eγ)

μ→eγ signal & background

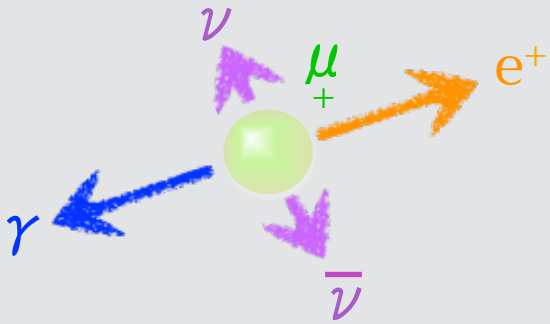
Signal



$E_\gamma, E_e \simeq 52.8\text{MeV}$
$\Theta_{e\gamma}=180°,\ T_\gamma=T_e$

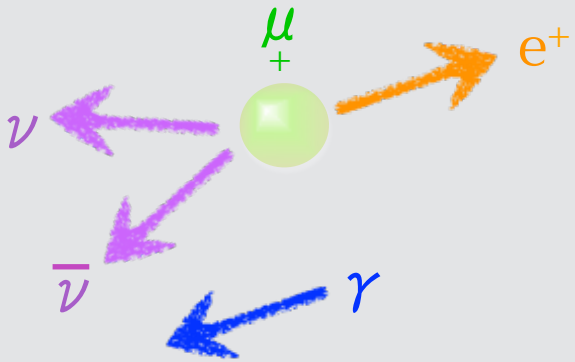
- Simple two body decay

Radiative muon decay background



- timing coincident

Accidental background



- Michel e^+ + random γ from RMD/Annihilation in flight (AIF)

- **Accidental background is our dominant source**
- **$N_{acc} \propto R_\mu^2 \times \Delta E_\gamma^2 \times \Delta E_e \times \Delta \Theta_{e\gamma}^2 \times \Delta t_{e\gamma} \times T$**
- **To get a good sensitivity, all the resolutions should be good!**

MEG Experiment

- 1999 Proposal to PSI
- 2008 Physics run start
- 2013 Physics run finish

Paul Scherrer Institute
in Switzerland
1.3MW high intensity
proton accelerator
World most intense
DC μ^+ beam

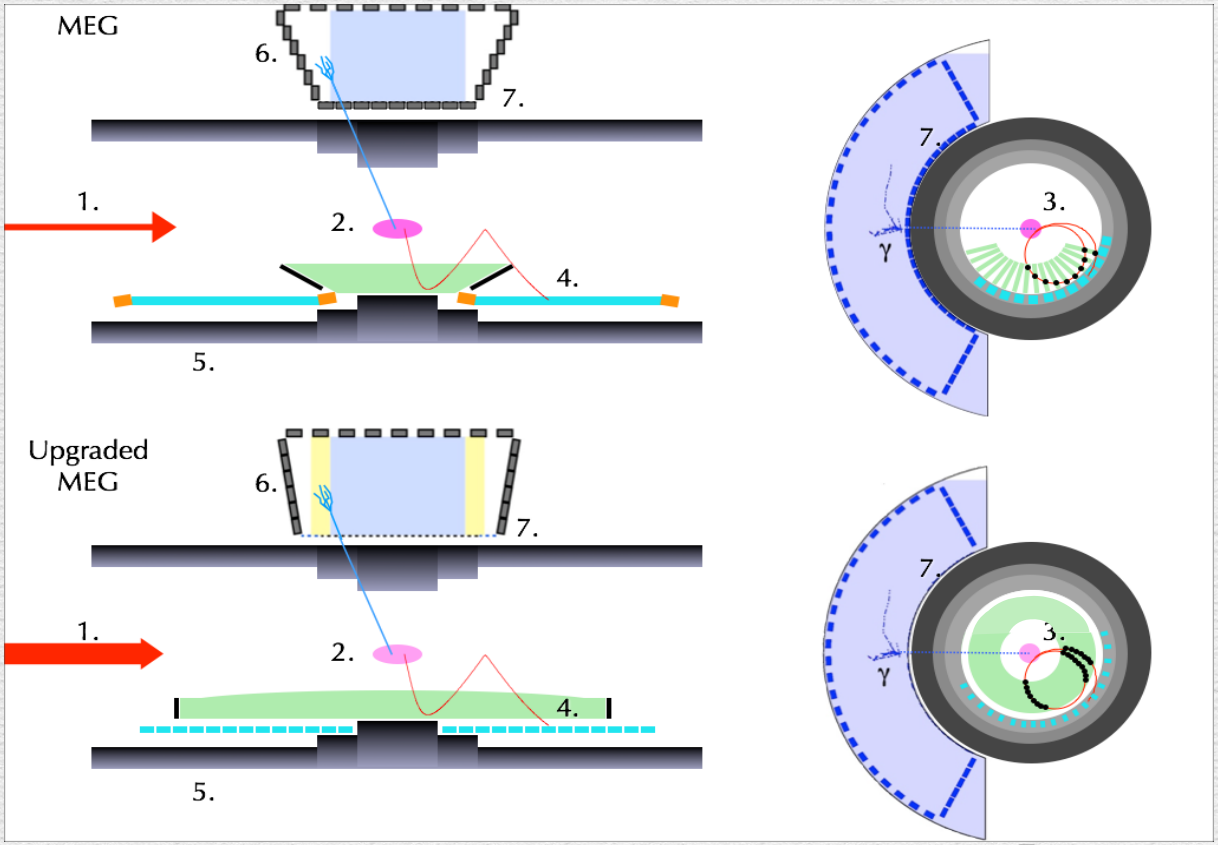
- The latest result based on 2009–2011 data set upper limit of BR($\mu \to e\gamma$) < 5.7×10^{-13} @90%CL
- 2012–2013 data will double the statistics, and the new result will be published at this summer conferences
- MEG Collaborator ~ 60 physicist from Japan, Italy, Switzerland, Russia, and USA

Positron
spectrometer
Superconducting
magnet
Drift chamber
Timing counter

Liquid xenon γ-ray calorimeter
900L LXe and
846 PMTs

What can be improved?

- **Statistics improvement :**
  - Maximum beam rate(3×10^7 μ^+/s → 7×10^7 μ^+/s stopped on target), Positron detection efficiency (CDC, pixelated TC)
- **Accidental background reduction :**
  - Resolutions of positron spectrometer(CDC, pixelated TC), and of LXe γ-ray calorimeter for shallow events

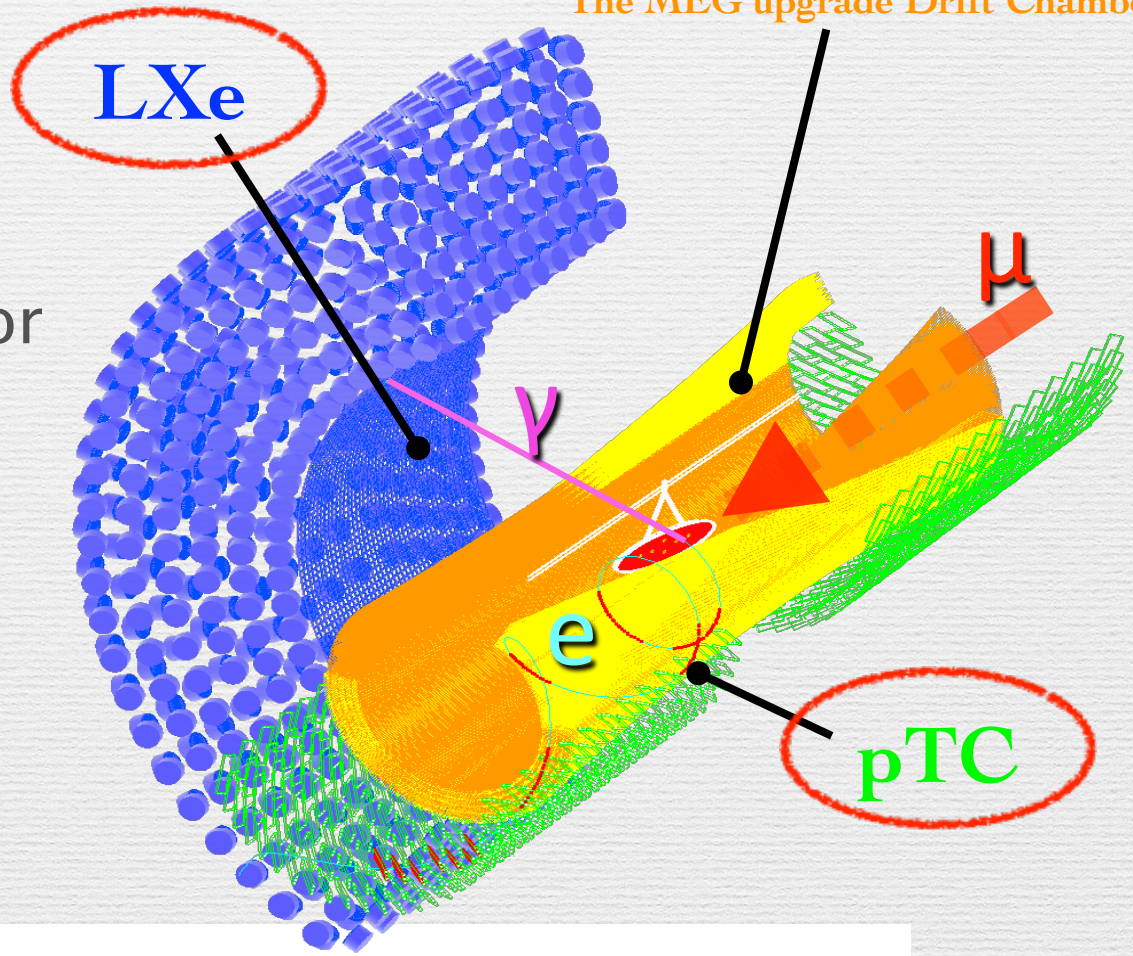


PDF parameters	Present MEG	Upgrade MEG II
e+ energy (keV)	306(core)	130
e+ θ(mrad)	9.4	5.3
e+ ϕ(mrad)	8.7	3.7
e+ vertex(mm)Z/Y(core)	2.4/1.2	1.6/0.7
γ energy(%)(w<2cm)/ (w>2cm)	2.4/1.7	1.1/1.0
γ position (mm)u/v/w	5/5/6	2.6/2.2/5
γ-e+ timing (ps)	122	84
Efficiency		
trigger	≈99	≈99
γ	63	69
e+	40	88

MEG upgrade (MEG II)

- 2013 Upgrade proposal presented to PSI
- 2013–2015 R&D / detector construction
- 2016–2018 physics run
- Target sensitivity down to 5×10^{-14}

CDC
26/Feb
F. Grancagnolo
The MEG upgrade Drift Chamber

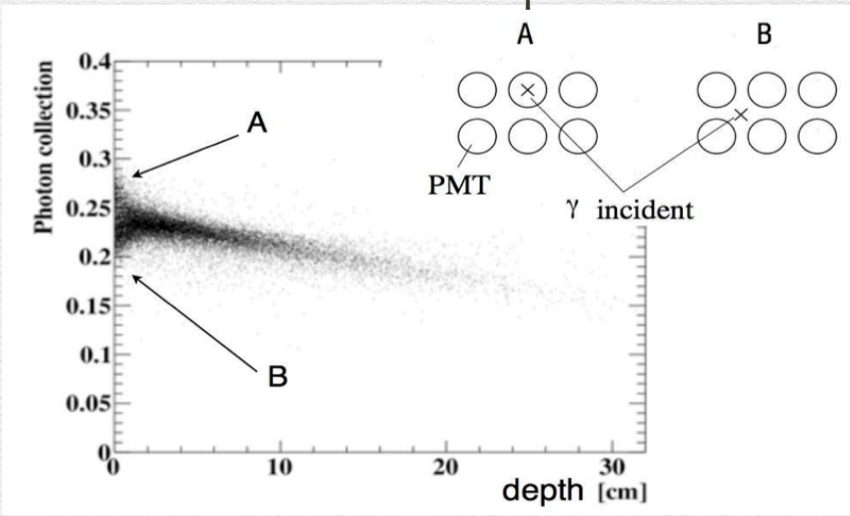


Limitation of the Current LXe Detector

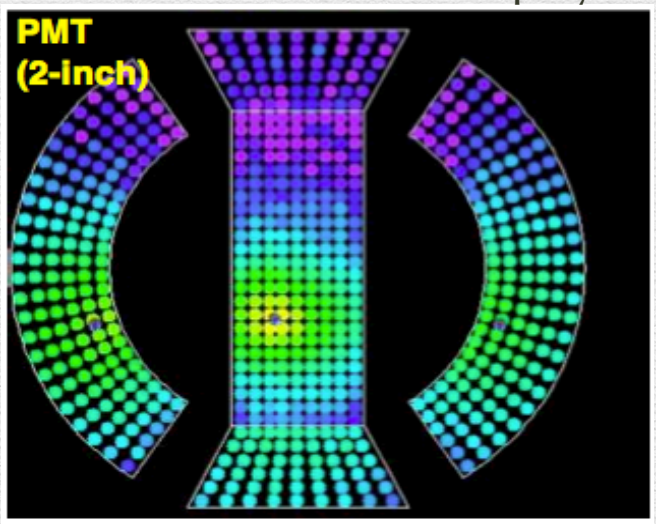
- Limited resolutions for shallow events due to non-uniform PMT coverage

- Idea to improve LXe detector in MEG II
  - Smaller photo sensors (~4000 12x12mm^2 SiPM) for gamma-ray incident face instead of 216 2" PMTs
  - Wider incident face, different PMT angle at lateral face

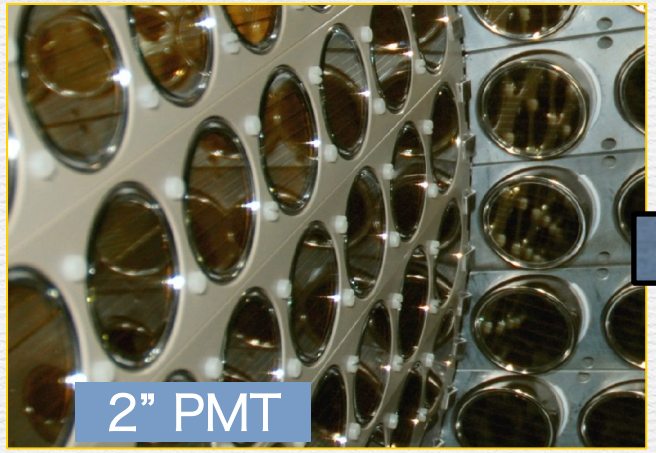
# of photons collected by PMTs as a function of depth

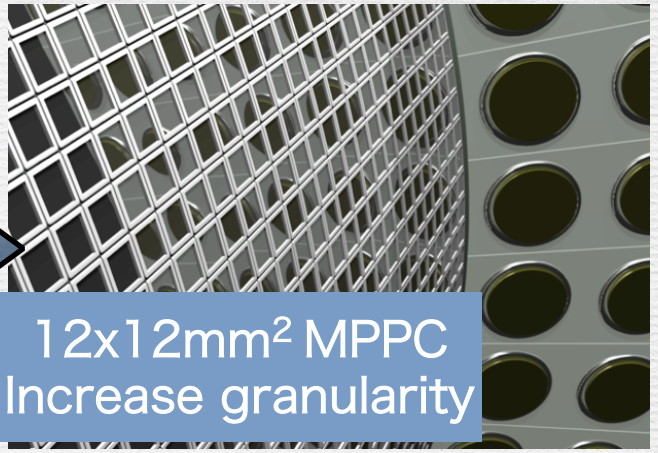


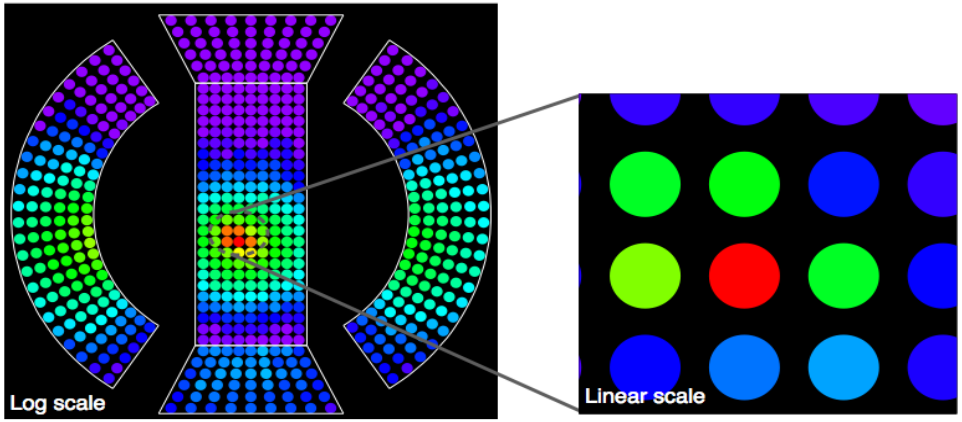
LXe detector event display

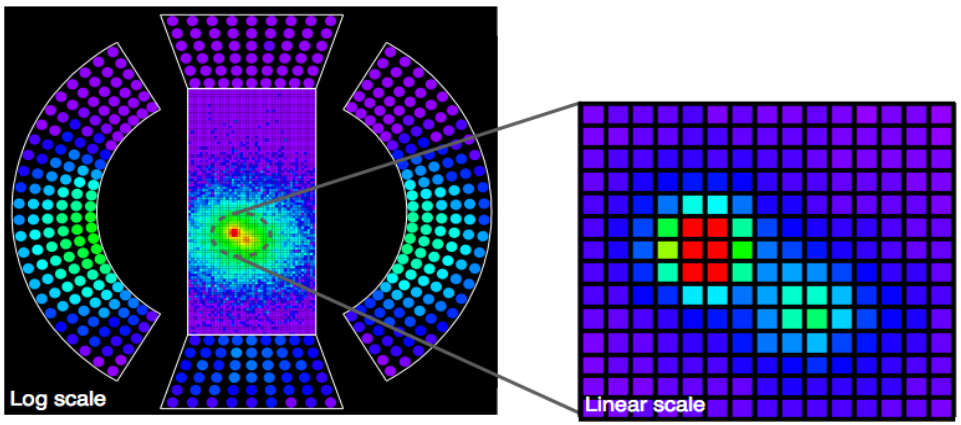


LXe upgrade concept

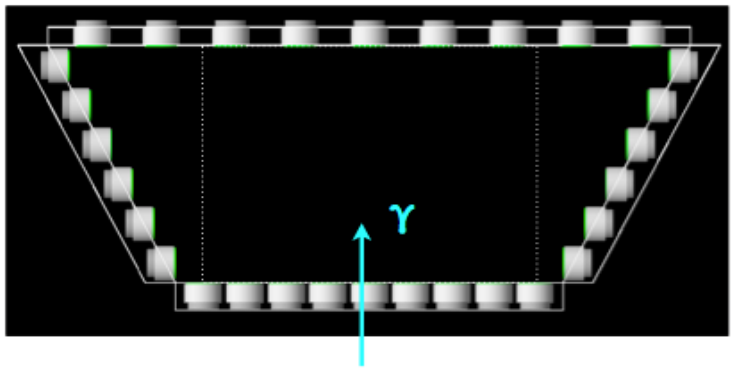




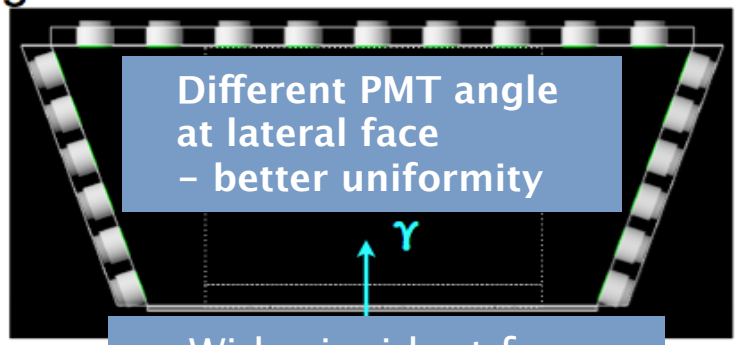




Present



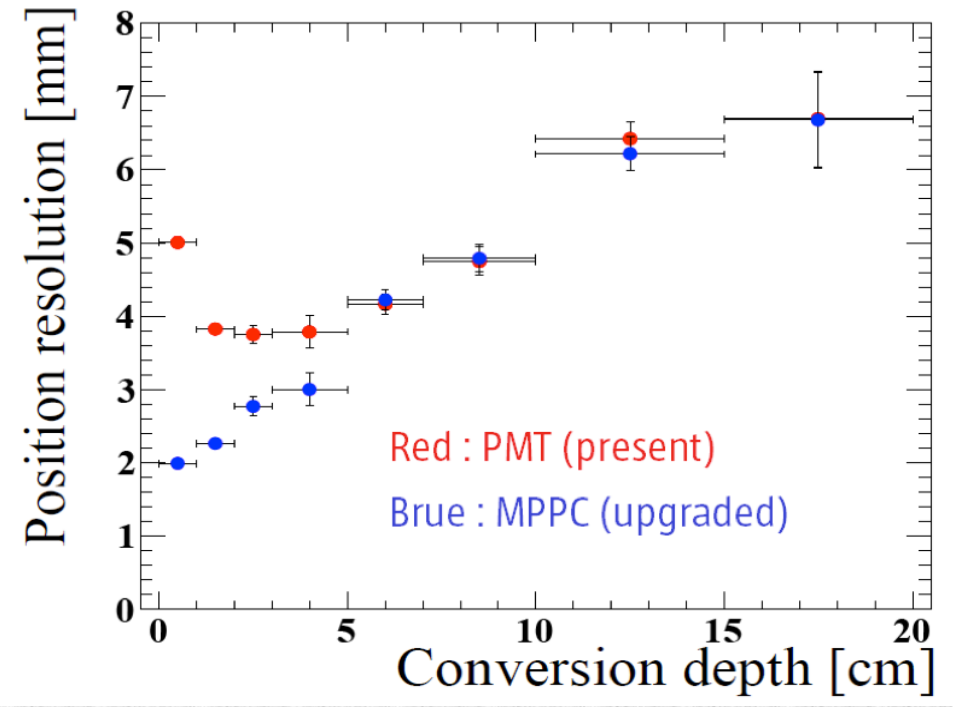
Upgraded



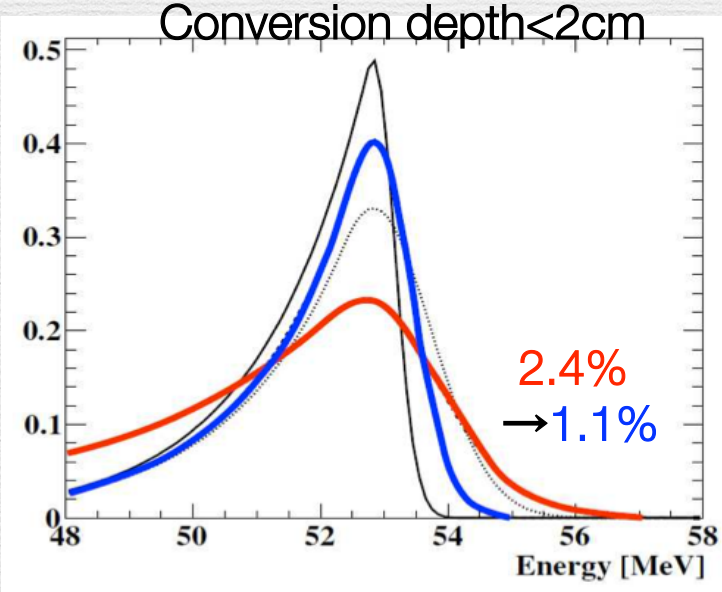
Wider incident face
– reduce shower leakage

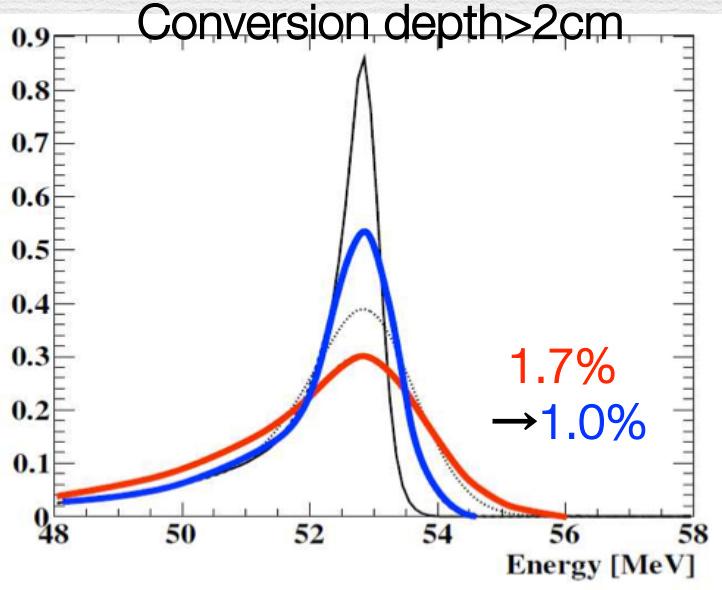
Expected performance

- Detection efficiency
  - improved by 10% by thinner MPPC
- Position resolution
- Energy resolution



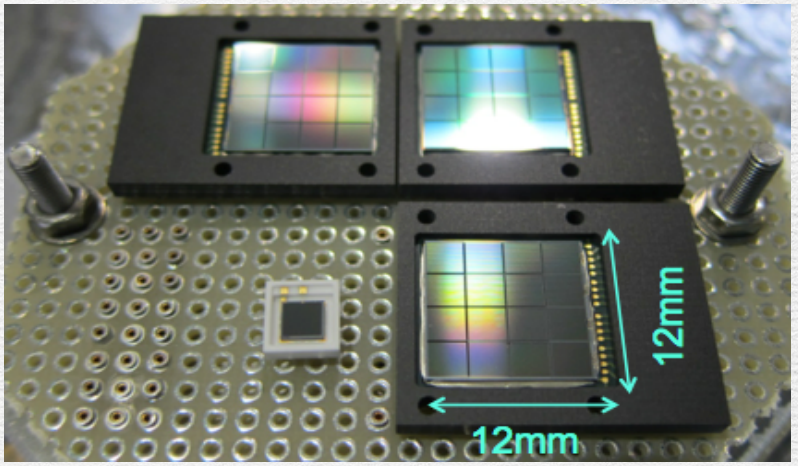
Energy spectra

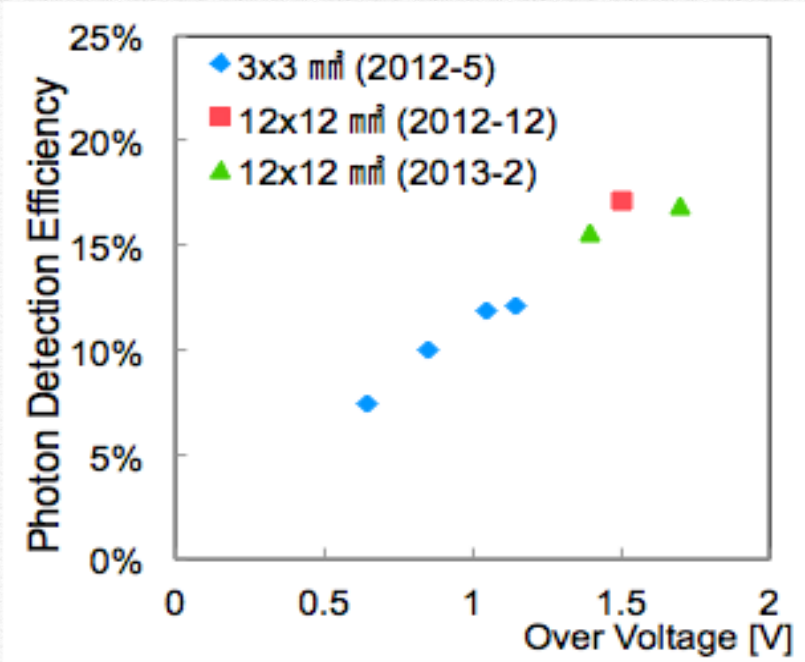




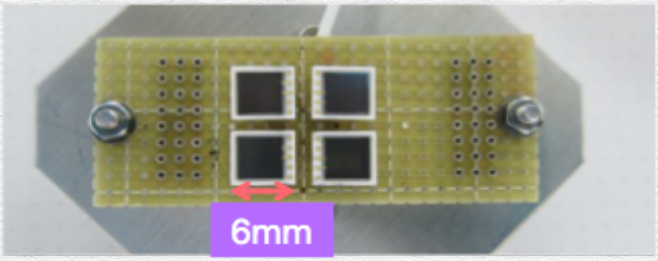
UV-sensitive MPPC

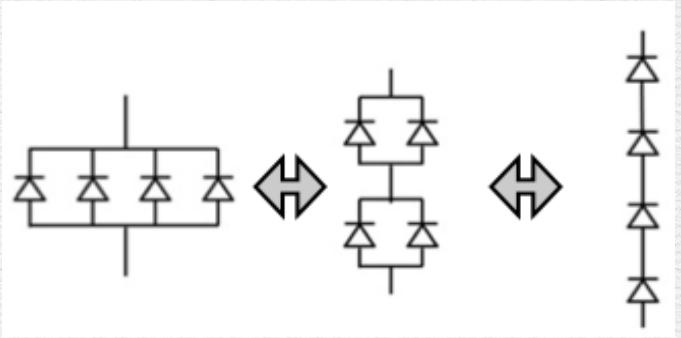
- Requirements
  - **Sensitive to LXe scintillation light(175nm)**
    - Photon Detection Efficiency of commercial SiPM (PDE) for UV light(~175nm) is nearly zero.
  - **Large area (12x12mm^2) to avoid too many readout channel**
- We developed UV-sensitive MPPCs with HPK
  - No protection layer, thinner insensitive layer
  - Optimize anti-reflection coating
  - Matching of refractive index
  - Metal quench suitable at low temp.
- **PDE ~ 15% @175nm achieved**
- **Single photoelectron peaks are resolved with 12x12mm^2 sample**
  - **Dark rate is suppressed at LXe temp. (165K) by five orders of magnitude.**
- **Long waveform tail ~ 200ns due to large sensor capacitance**

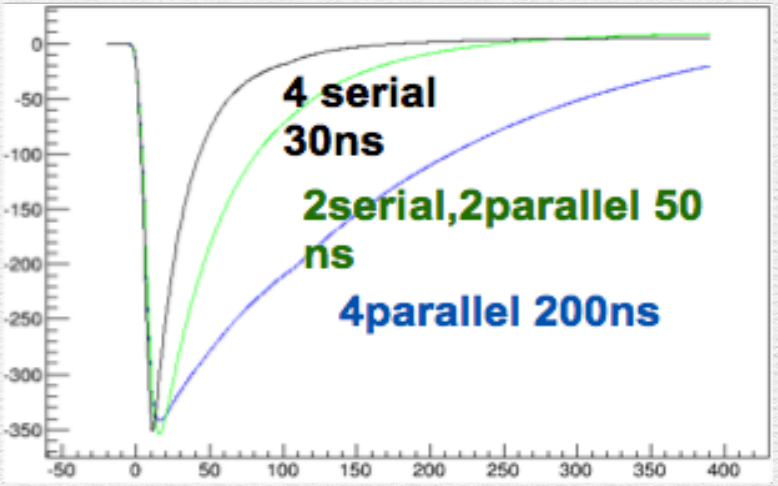




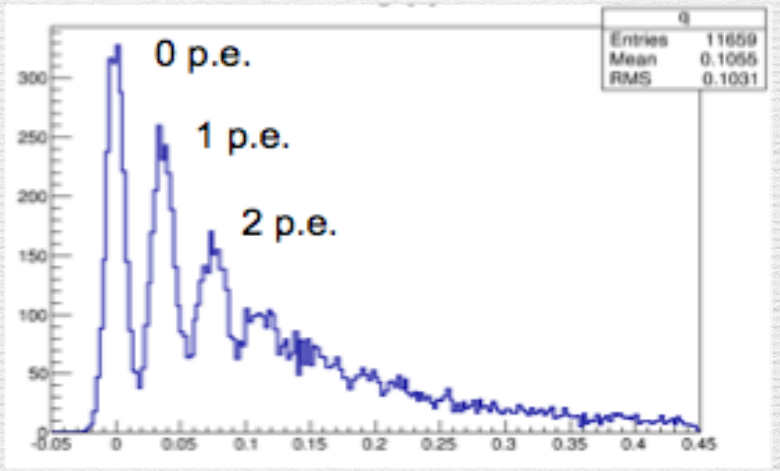
Large area MPPC





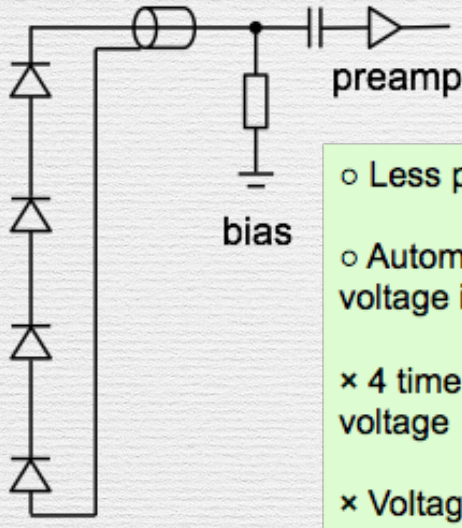


- A 12x12mm^2 sensor is segmented into four segments and al the segments are connected in series to reduce the overall capacitance
- We tested series connection with 4-segmented 6x6mm^2 MPPCs to get one 12x12mm^2 MPPC
- **Signal tail became 30-50ns**
- **Single photoelectron peaks are resolved**
- Still 4-5x10^5 gain is available
- Signal is connected in series, and bias is connected in parallel, "Hybrid" connection



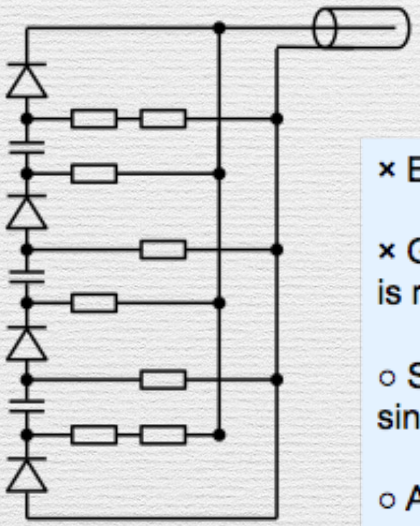
MPPC assembly

Simple serial connection



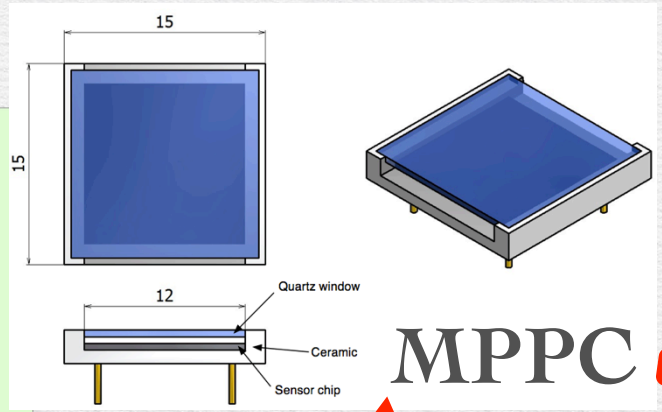
- ○ Less parts
- ○ Automatically over voltage is adjusted
- × 4 times higher voltage
- × Voltage difference between each sector

Hybrid connection

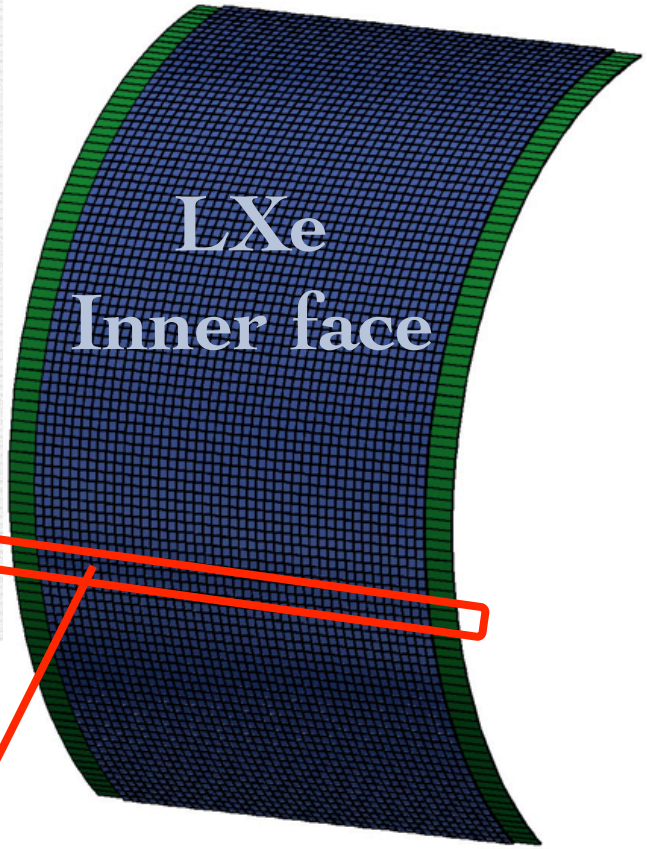


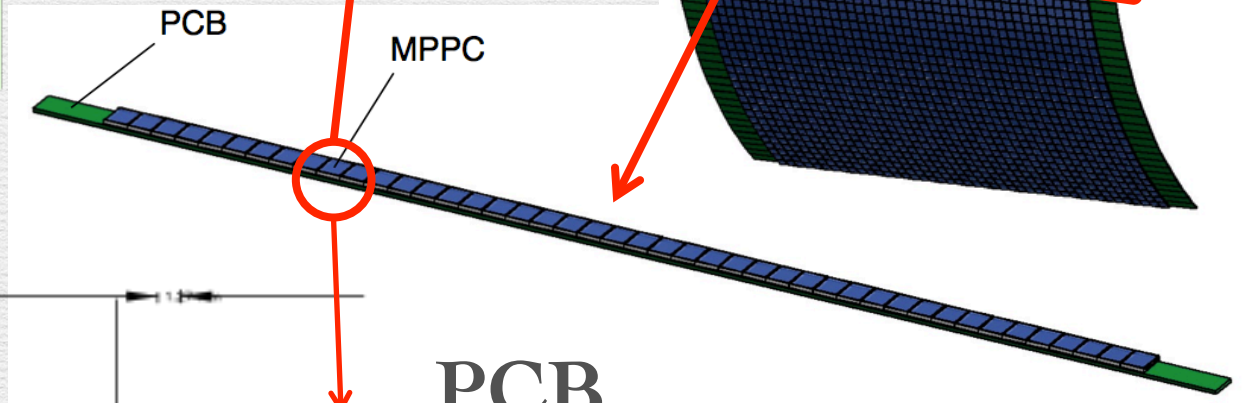
Serial – signal
Parallel - bias

- × Extra parts
- × Gain uniformity is required
- ○ Same voltage as single MPPC
- ○ All sectors have common voltage

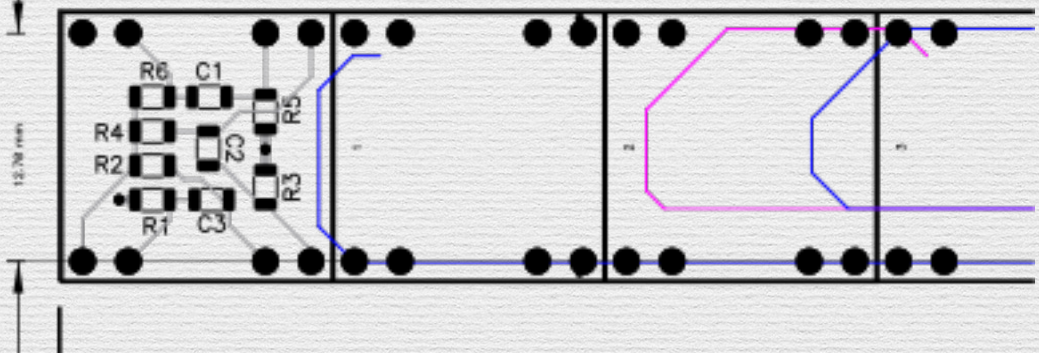


MPPC



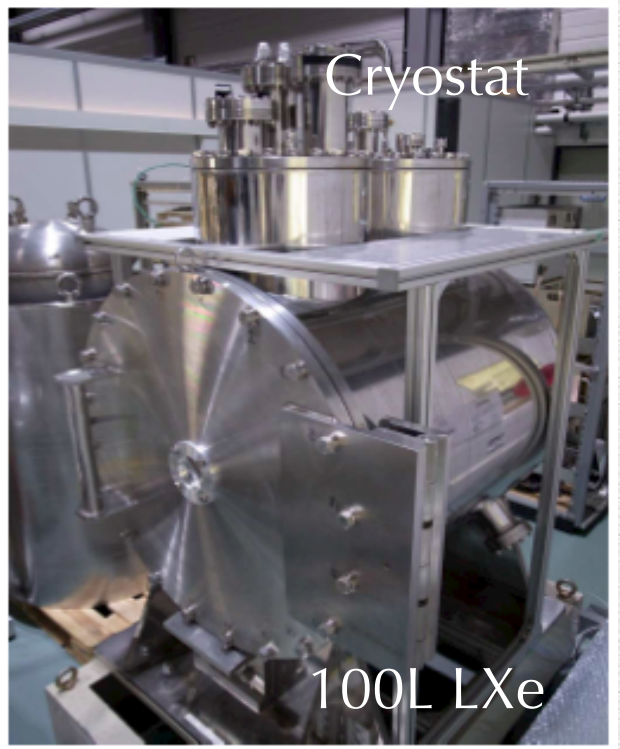


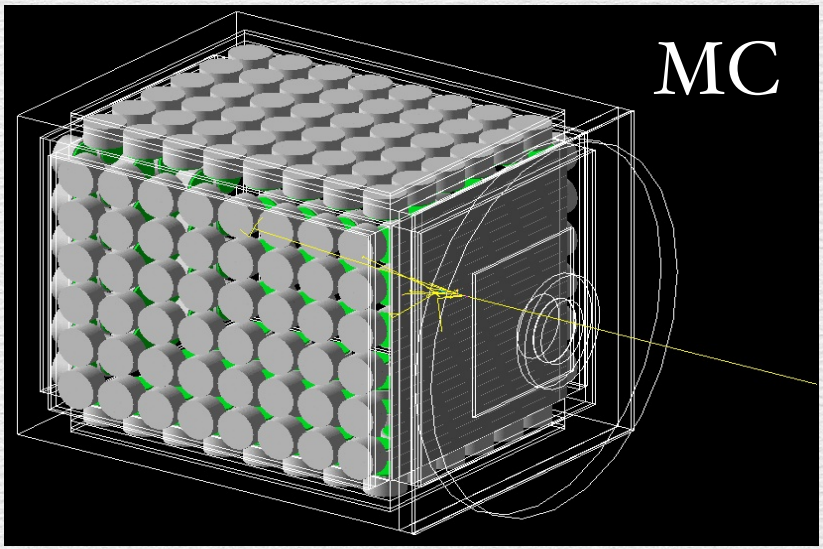
PCB



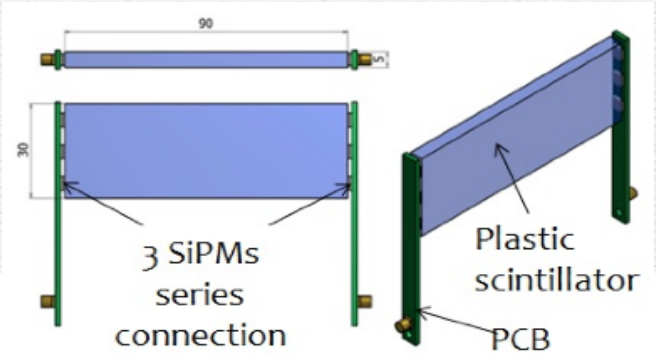
MPPC Prototype Test

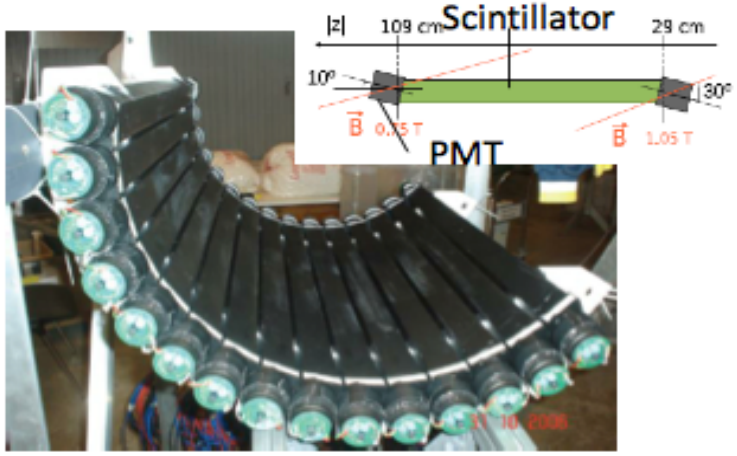
- Four independent sensor chips are connected in series on the assembly PCB
- In March 2014, 600 MPPCs will be delivered.
- Mass test at room temp.
- The 100L LXe prototype will be used to test 600 MPPCs at LXe temp.
- In November, a beam test with charge exchange reaction ($\pi^- p \rightarrow \pi^0 n$, $\pi^0 \rightarrow \gamma\gamma$) will be done to evaluate energy, position, and timing resolutions at 55MeV γ-ray



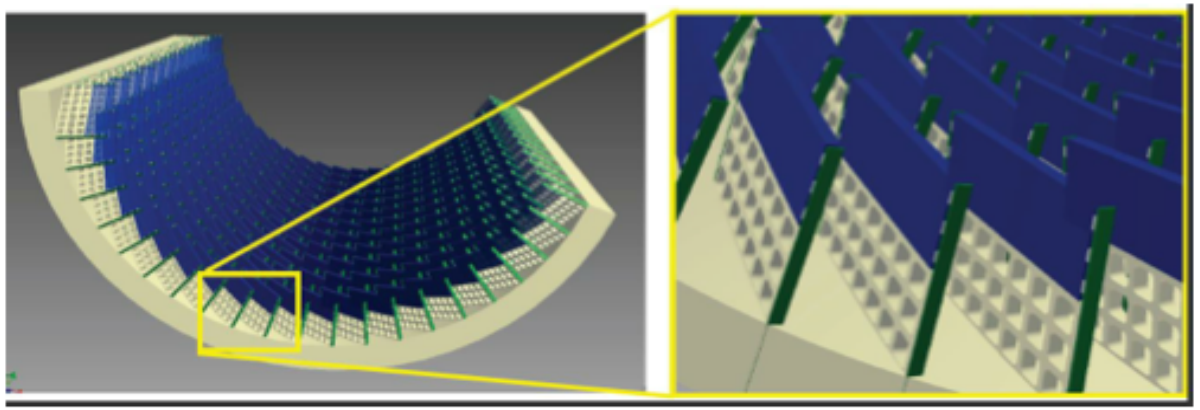


What can be improved for Timing counter?





~300 counters × 2



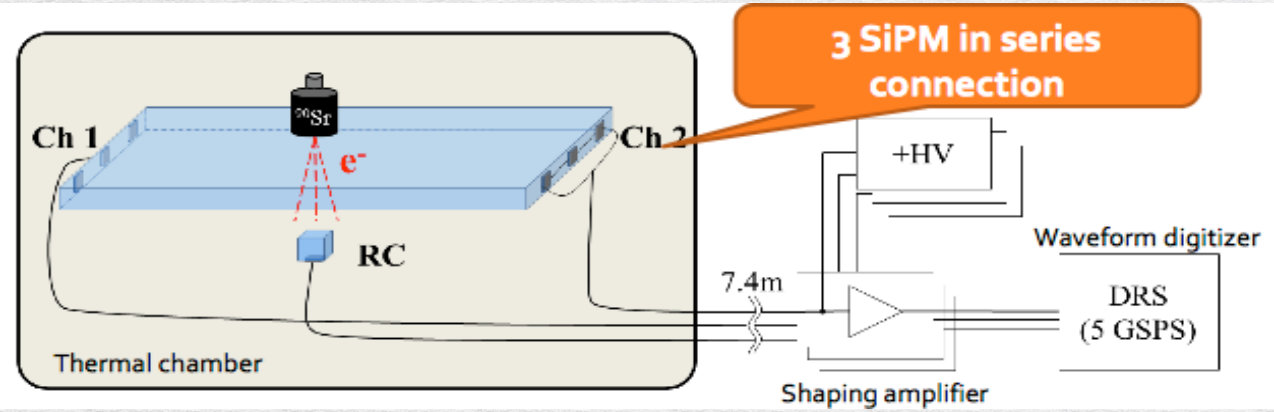
present

upgrade

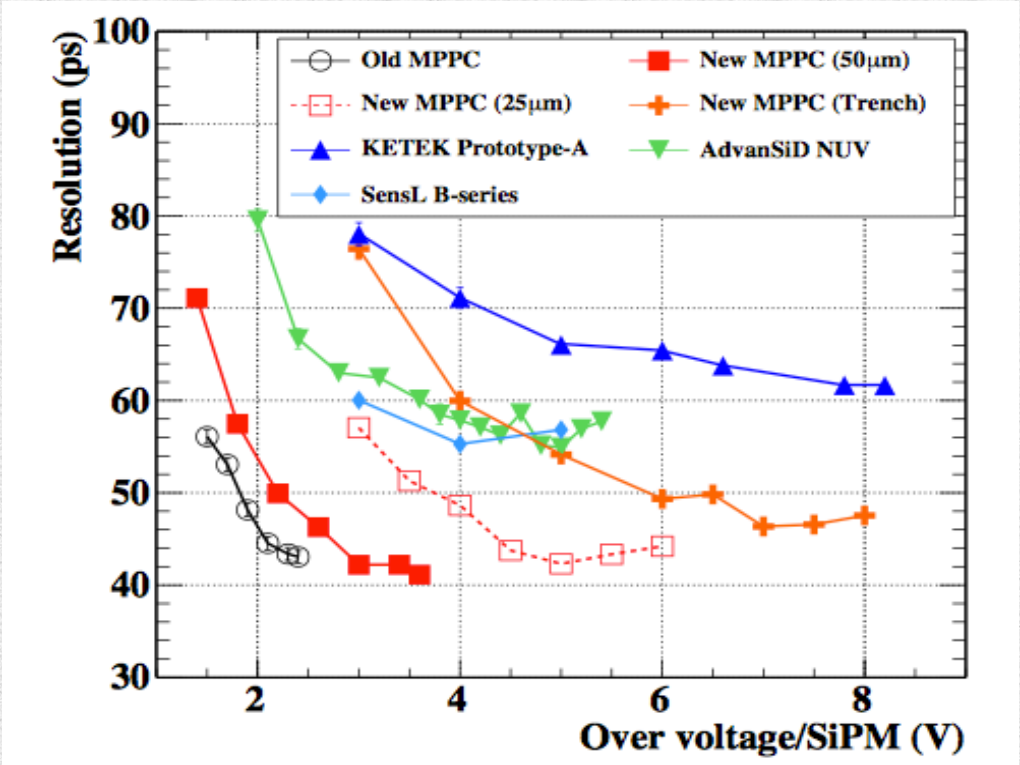
- 2x array of 15 scintillating bars readout by PMTs
- 40x40x800mm^3 scintillator
- Mean resolution ~ 65ps

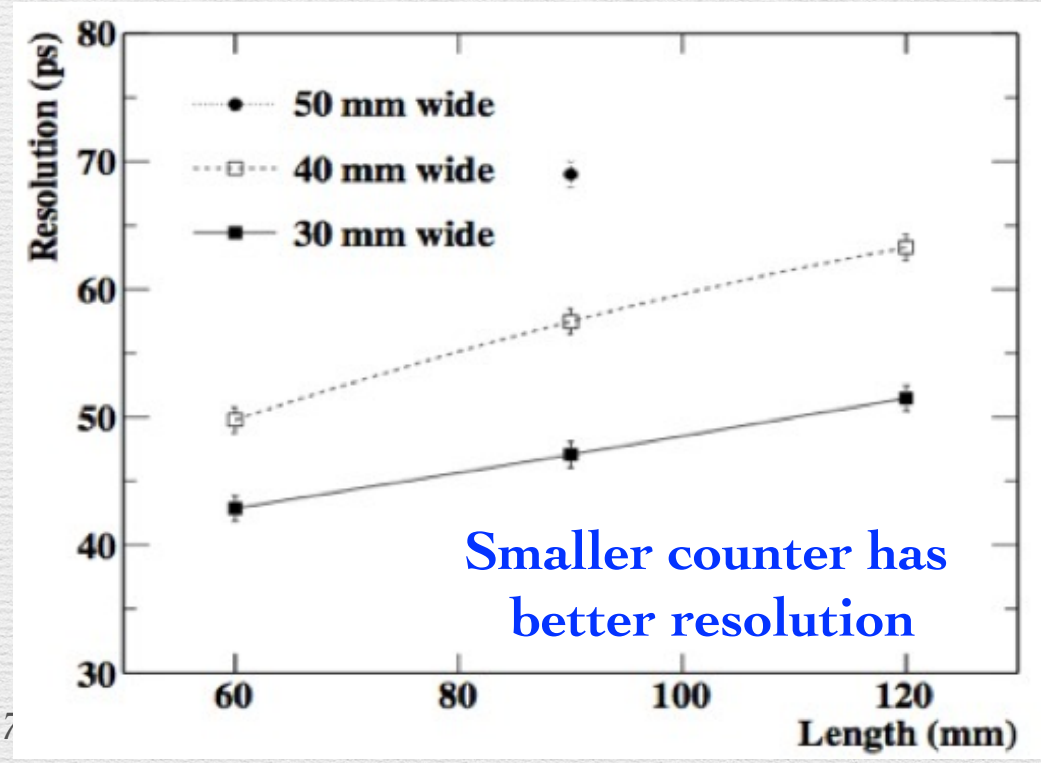
- Higher granularity 2x300 of small scintillator plates(90x(40-50)x4mm^3) readout by SiPM
- Resolution down to 30ps
  - High single pixel resolution
  - Further improvement with multi-counter hits
- Thin scintillator for less multiple scattering
- Less pile-up also with higher beam intensity

Single Pixel Study



arXiv:1402.1404[physics.ins-det]
submitted to IEEE Trans. Nucl. Sci.





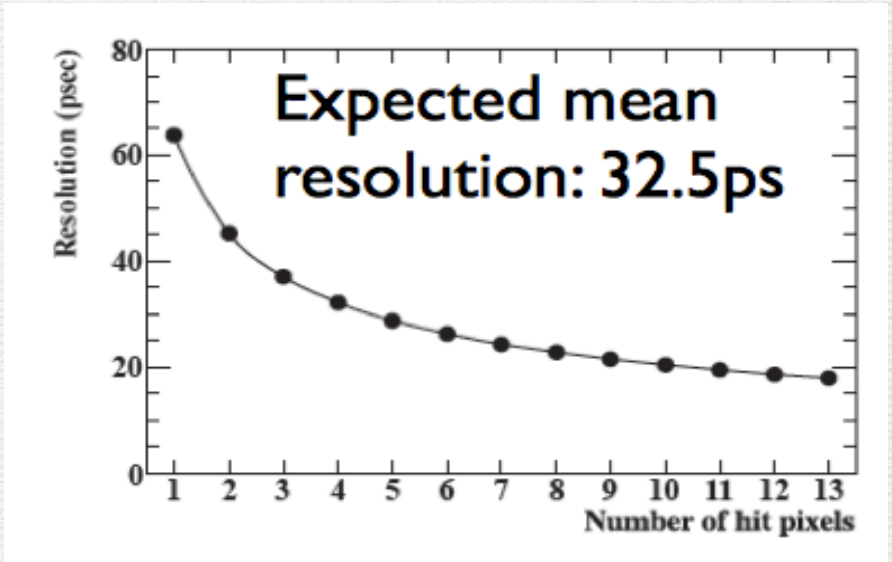
Multiple hit scheme

- Overall timing counter resolution is

$$\sigma^2_{total}(N_{hit}) = \frac{\sigma^2_{single}}{N_{hit}} + \frac{\sigma^2_{inter-counter}}{N_{hit}} + \sigma^2_{MS}(N_{hit})$$

30-40 ps

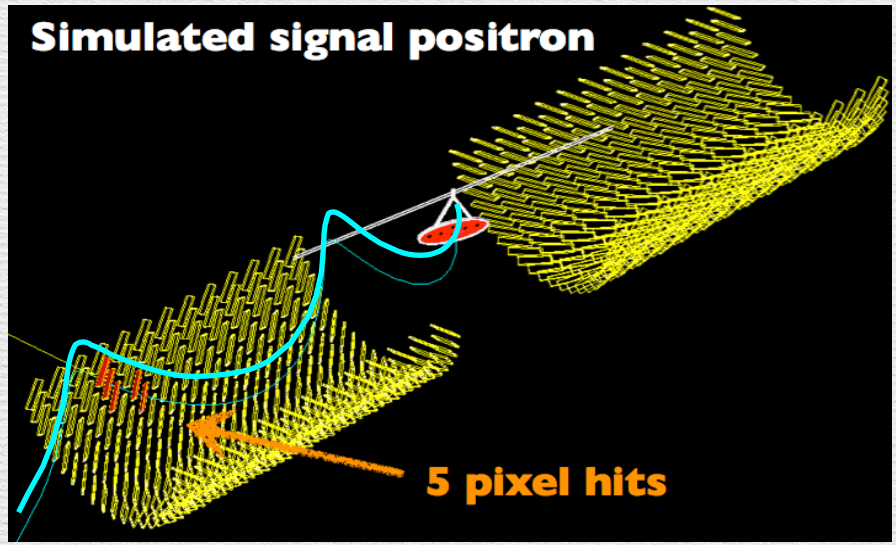
~5ps

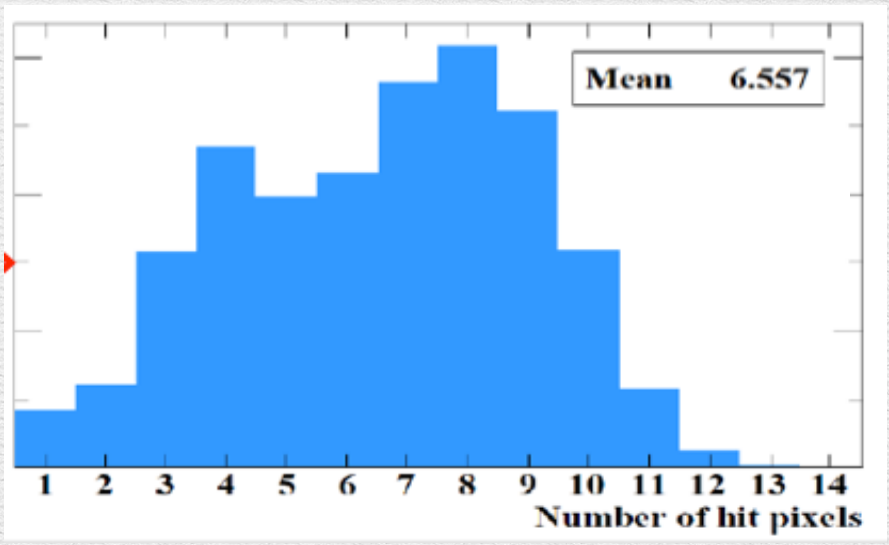


  - Good single counter resolution&less pileup -> smaller counter
  - Many counter hits -> larger counter

σ_{single} : single counter resolution
$\sigma_{inter\text{-}counter}$: inter-counter resolution
σ_{MS} : multiple scattering effect

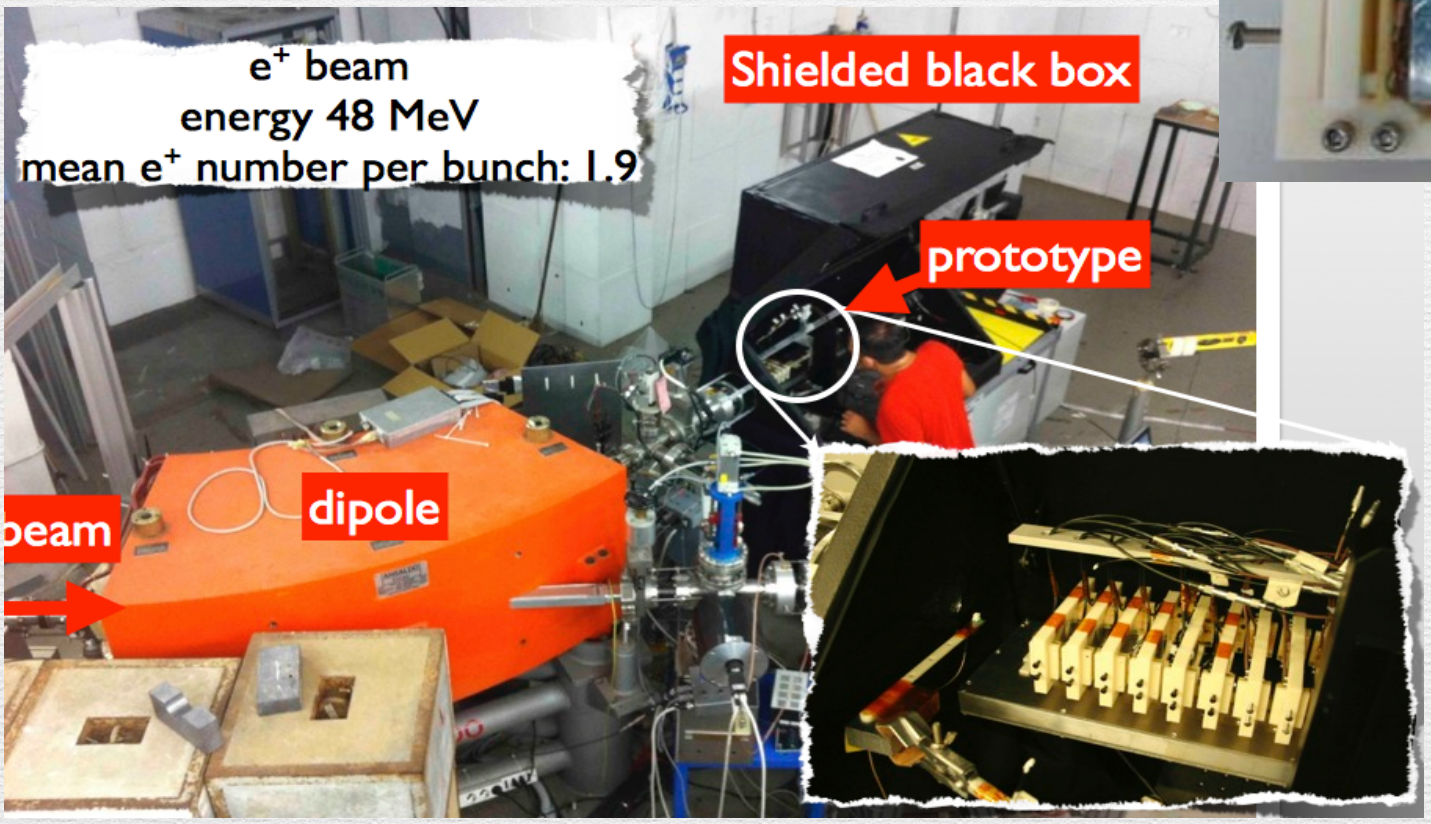
- The best performance with 500-600 counters of 90x(40-50)x4 mm^3





Beam test with multi-counters

DAΦNE Beam Test Facility @Frascati
2013 Sep.



Prototype counters

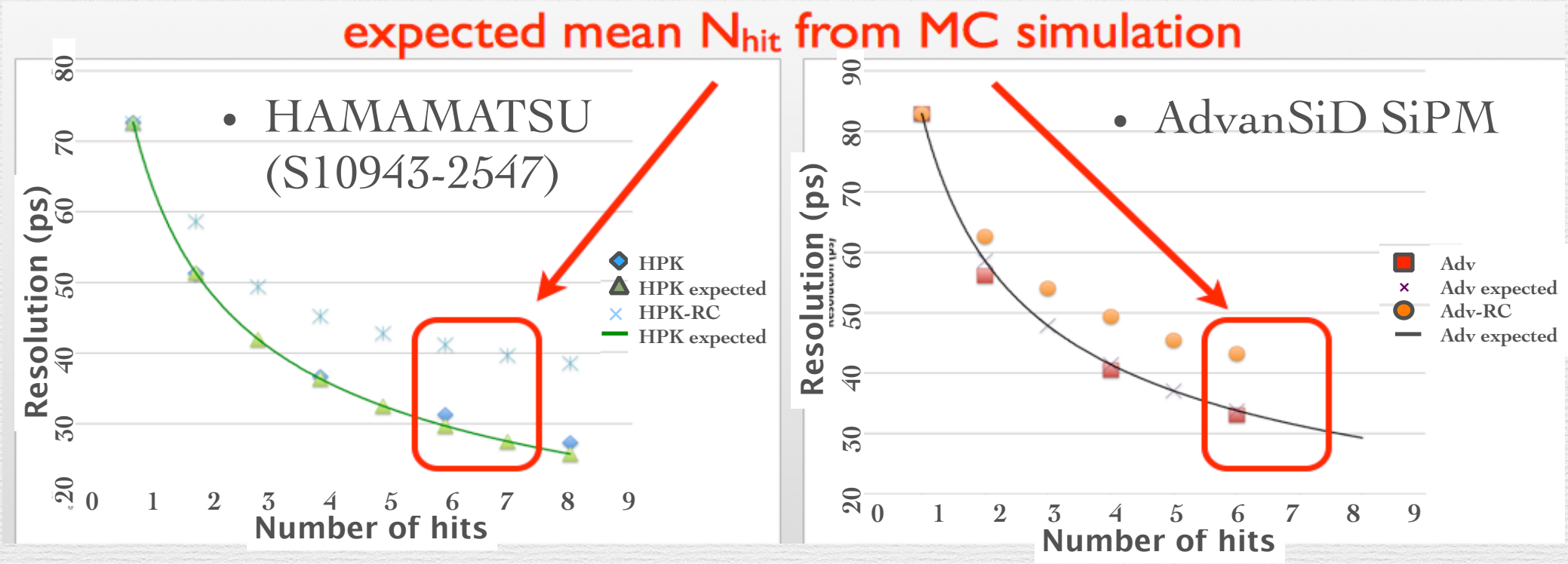
- 90x40x5mm^3, BC418
- 8 counters with HAMAMATSU(S10943-2547, 3x3mm^2, 50μm-3600pixels) SiPMs
- 6 counters with AdvanSiD SiPMs

Reference counter

- 5x5x5mm^3, BC422, 1 HAMAMATSU SiPM) for time reference & trigger

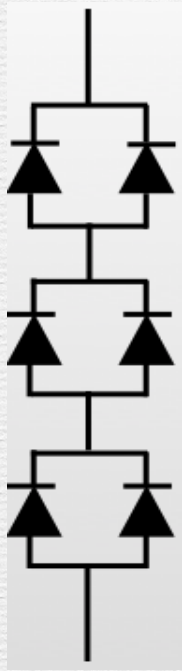
To confirm the multi hit scheme

Multiple hit resolution

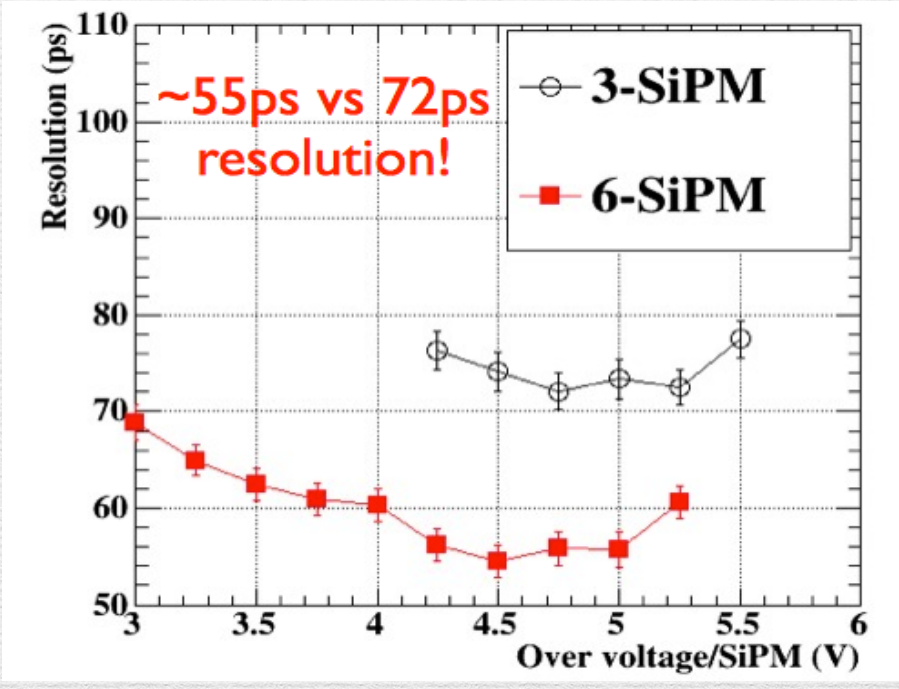


- $1/\sqrt{N_{hit}}$ behavior confirmed
- A resolution of ~30ps with 6-7 pixel is achieved, both with Hamamatsu and AdvanSiD devices

Improvements & Prospects



- Further improvements
  - AdvanSiD SiPMs (6500) are ordered. We can increase #ch (6SiPMs/side from 3SiPMs/side now) which improves time resolution further
  - Series of 3 couples of SiPMs in parallel connection has been tested. It shows better resolution than 3-SiPM series connection. 6 series connection was also tested, and the preliminary result shows even better resolution.
- Prospects
  - Two beam test this year
    - A larger number of counters
    - High rate environment
    - Final electronics
- Final pTC will be ready in 18 months.



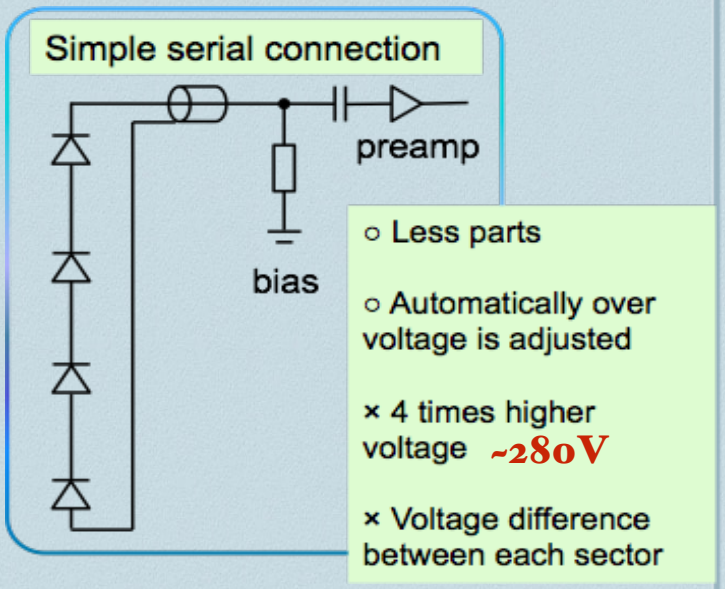
Summary

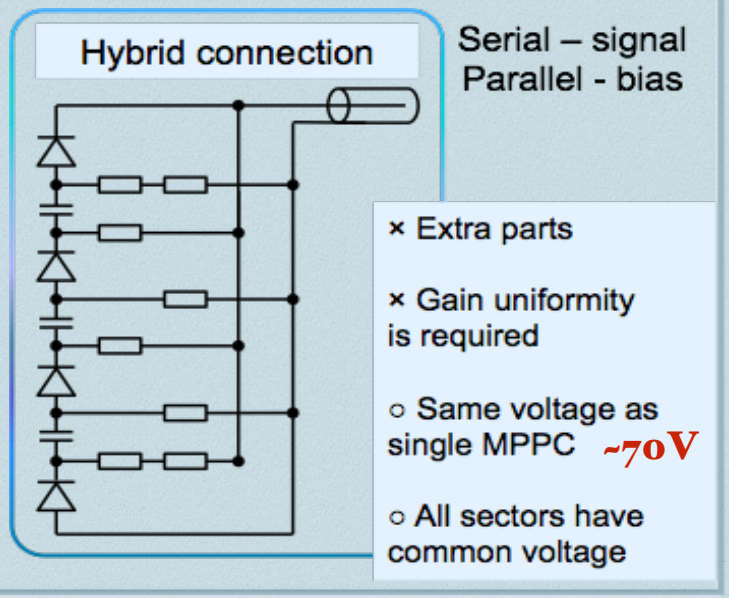
- The most stringent upper limit of BR(μ→eγ) < 5.7×10^{-13} @90%CL has been set by MEG based on 2009-2011 data. The The final result including 2012-2013 data will be published this summer.
- MEG upgrade proposal was accepted by PSI committee in 2013. The target sensitivity of MEG II will be 5×10^{-14} (10 times better than MEG).
- The main concept of MEG II will be the higher muon beam intensity and the higher detection efficiency to increase the statistics, and the better detector resolutions to reduce accidental background.
- All the detector components will be ready in 2015, and physics run will continue 2016-2018 to reach our target sensitivity.

Backup

Series connection

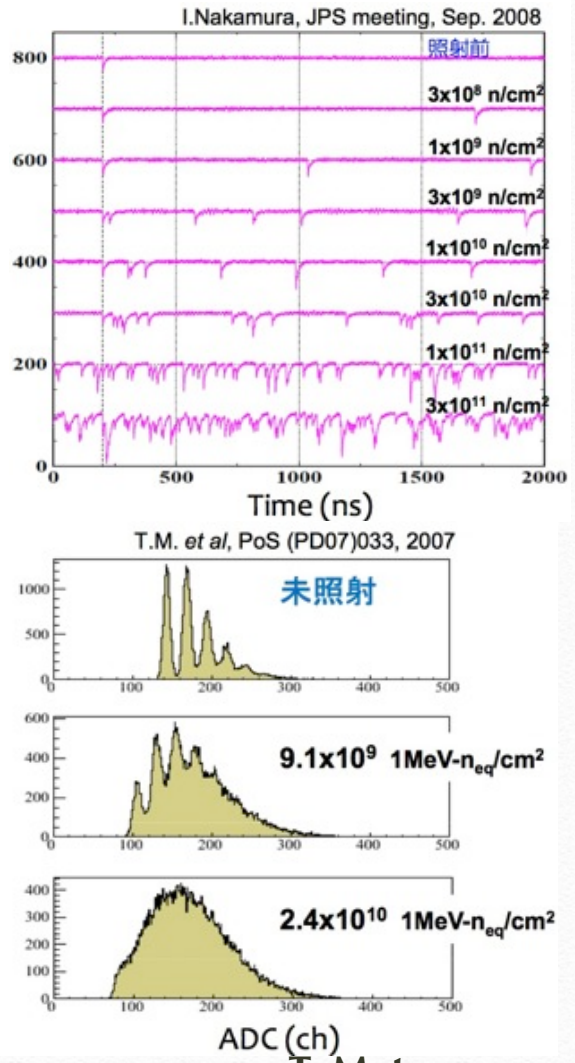
- Two options for series connection
  - Simple series
    - Signal and bias are in series
  - Hybrid
    - Signal is in series, and bias is in parallel
- Both options work, but hybrid option is more advantageous.





Radiation hardness

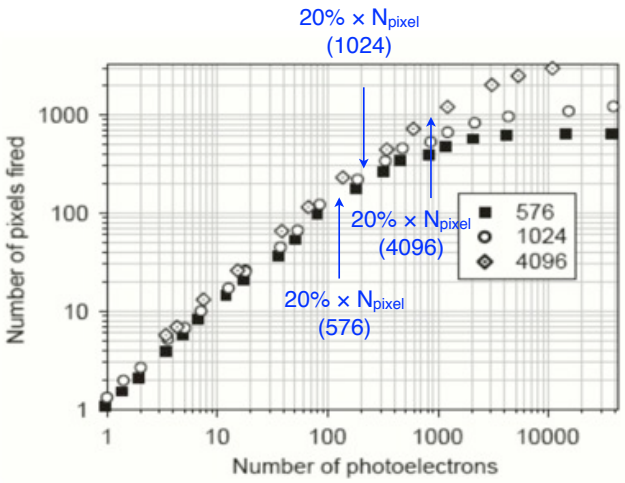
- Radiation produces defect in silicon bulk or Si/SiO_2 interface
  - Dark count rate, leakage current, PDE, ...
- Fast neutron
  - $>10^8$ n/cm^2 Increase of dark count rate
  - $>10^{10}$ n/cm^2 Loss of single p.e. detection capability
  - <1 n/s/cm^2(>0.1MeV) ~ $<1.6\times10^8$ n/cm^2 for full 5-years operation in πE5 area in PSI
  - ~3.5n/s/cm^2 ~ 10^7 n/cm^2 for one week CEX run per year for 5-years
- γ-ray
  - 200Gy Increase of leak current
  - MC: 0.58Gy with 10^8 μ/s for 5-years for MEG
- Radiation damage might not be an issue for MEG.

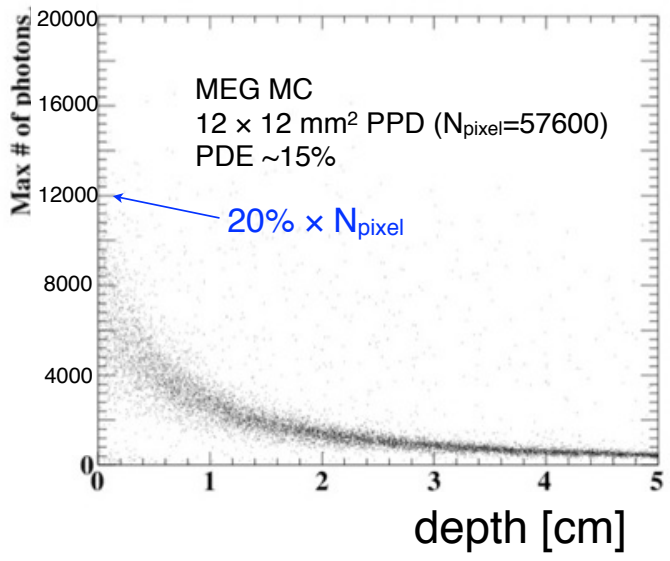


T. Matsumura et al.

Dynamic range

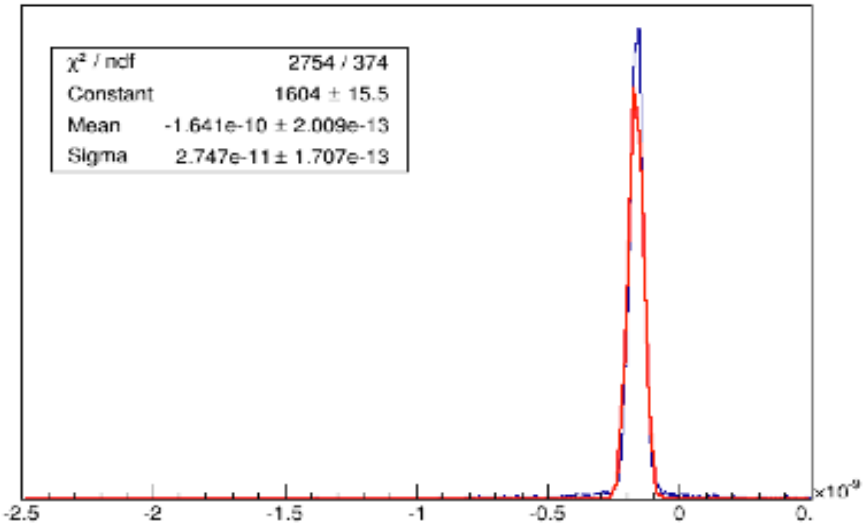
- PPD response shows a non-linearity if the number of detected photons is large relative to total number of pixels
- Optimal condition $N_{p.e.} < N_{pixel}$
- Might be an issue for very shallow events for MEG LXe detector.





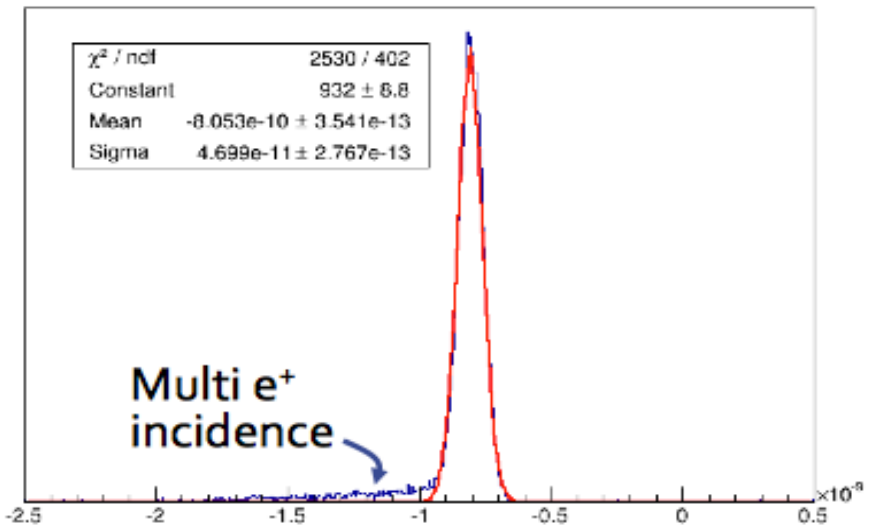
Multiple counter resolution

$(t_{odd} - t_{even})/2$



From (even counter average time - odd counter average time), resolution with 8 counters of **27.5 ps** can be obtained.

$t_{counters} - t_{ref}$



we can obtain the resolution of **47.0 ps** with 8 counters and reference counter.

Calibration

MEG
Mu-E-Gamma Collaboration

- **Important item for actual operation**
- **Laser calibration**
  - **Light pulse from a laser system**
    - Hamamatsu PLP10-040
      - 70 ps width, 405 nm wavelength
  - **Distribute via optical fibers**
- **Michel (track-based)**
  - **in-situ calibration using data itself**
  - **Develop a technique similar to position alignment**
    - like Millipede or Linear-fit algorithms
    - to calibrate all channels simultaneously
- **Finally, with RMD**

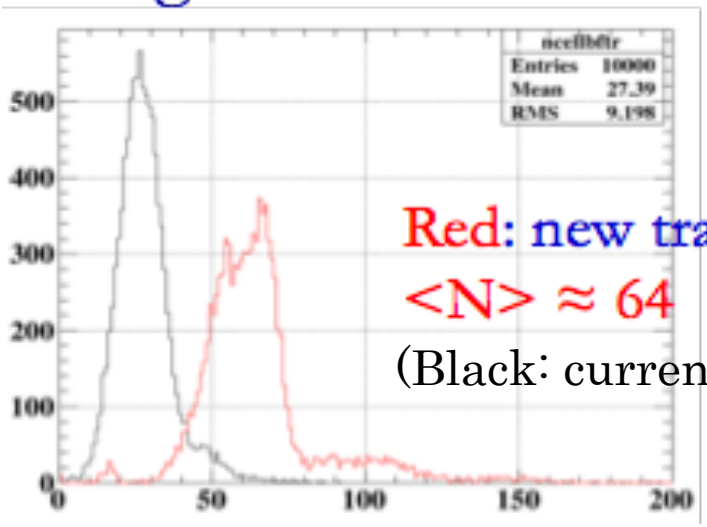
Drift chamber

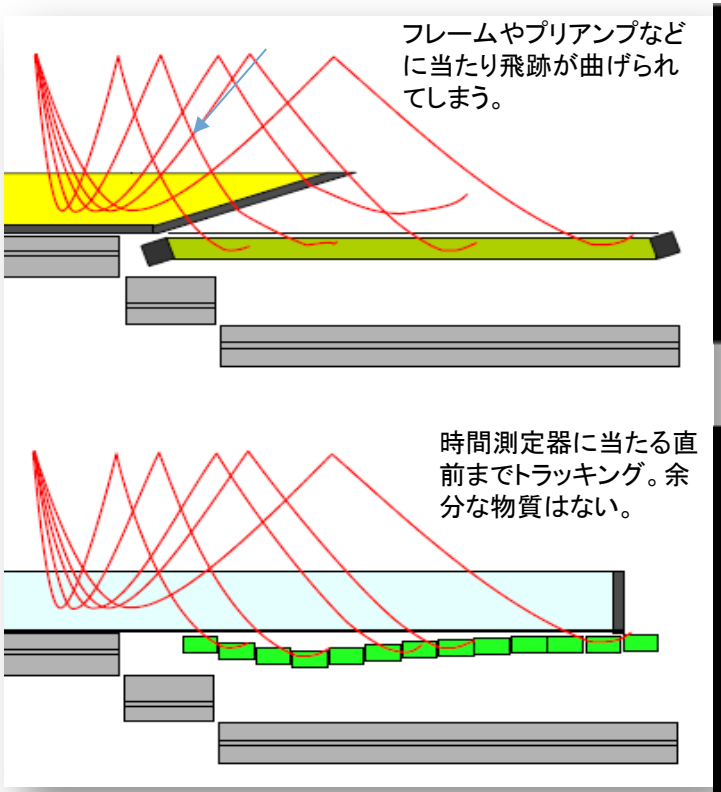
- Single volume gaseous detector
- Stereo wires along z
- Finer granularity, better resolution
- Larger acceptance DC + TC

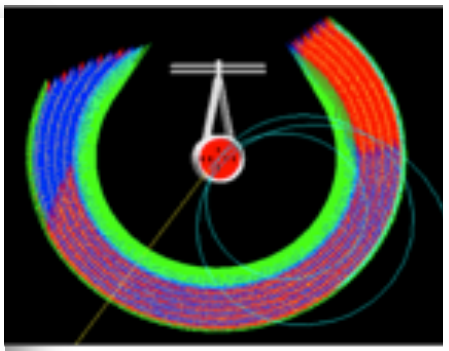
Challenging

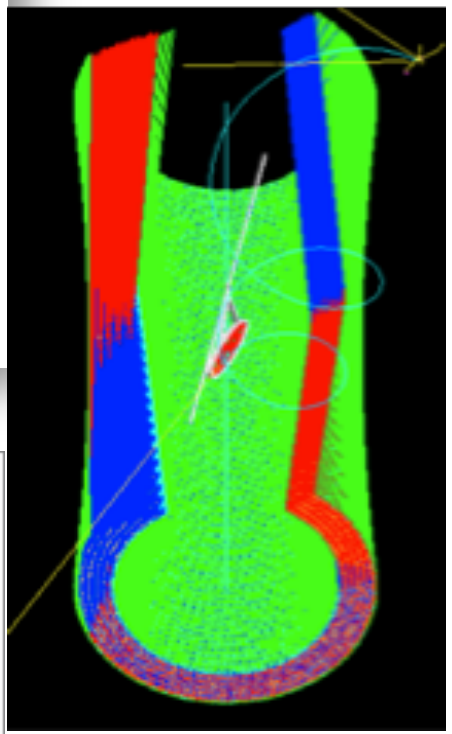
Long wires : ~200cm
High rate environment

Large number of hits









Expected Performance

Momentum ~130 keV (350 keV)
Angular ~5 mrad ; ~5mrad (9mrad ; 11mrad)
Vertex ~1.2 mm ; ~0.7 mm (1.8 mm ; 1.1 mm)
DC-TC matching eff. ~ 90 % (41%)

DAQ/Trigger

- More channels, higher rate
  - XEC MPPC (inner face) : ~4000
  - XEC PMT (other faces) : 630
  - pTC MPPC : ~1200
  - DC : 2760 (1GHz bandwidth)
- WaveDREAM
  - Higher density, compact
  - Waveform digitizer(DRS)+bias voltage supply+amplifier +simple trigger