Calorimeters for precision timing measurements in high energy physics

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Caltech

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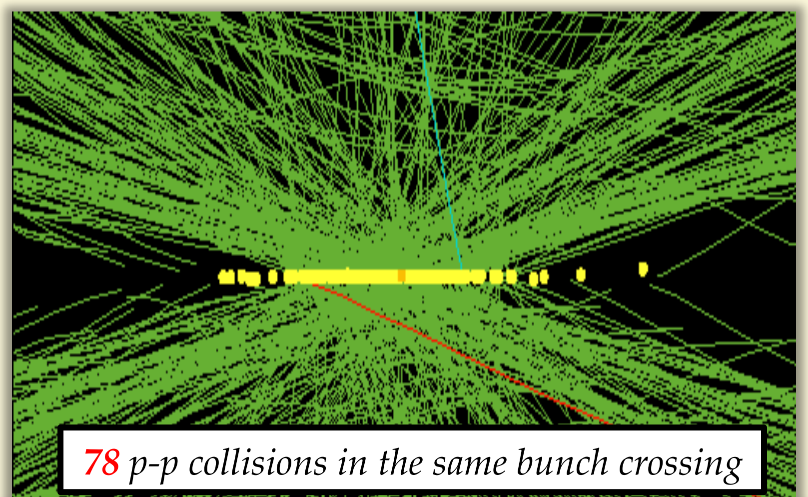
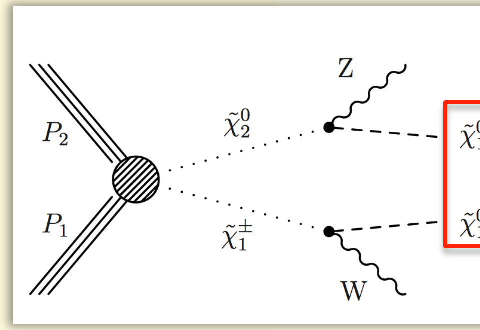
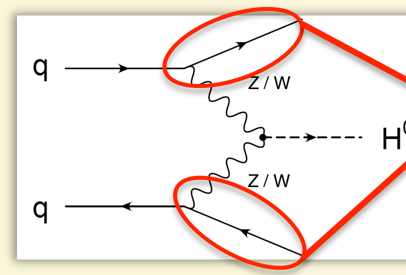
Challenges

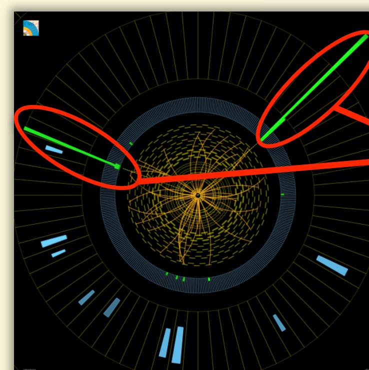
- Some key signatures at HL-LHC
  - Higgs VBF and $W_L W_L$ scattering with ***forward jets***
  - ***Vertex identification*** for H→γγ
  - Searches in final states with ***MET*** from LSP
  - ***Precision studies*** of new physics which may be discovered at the LHC in the next decade
- Large samples needed to fully exploit LHC
  - <PU> ≈ 140 at HL-LHC → 50nb/sec



This event was on the tail of the distribution in 2012, it will be a *"low"* PU event in HL-LHC

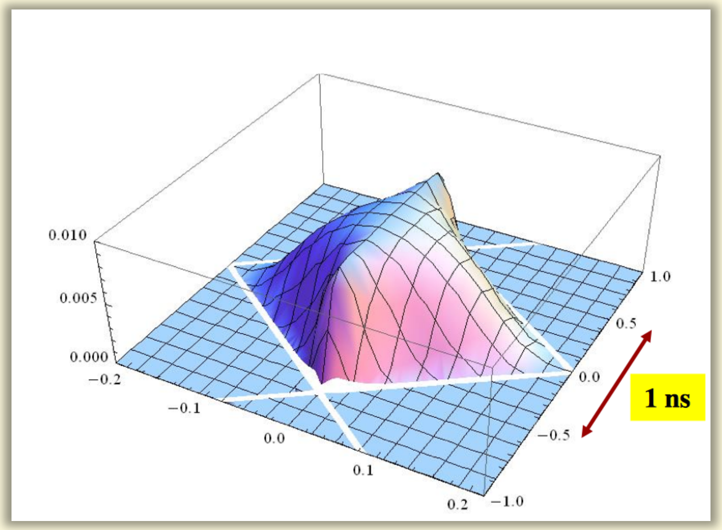


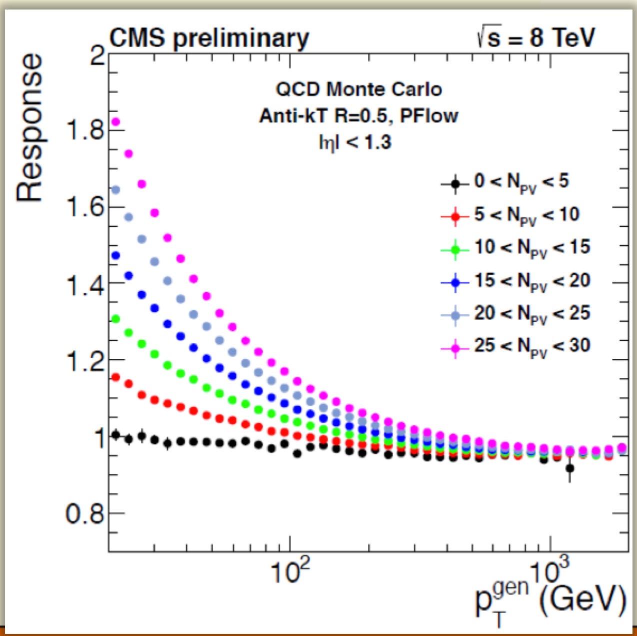




The environment in HL-LHC

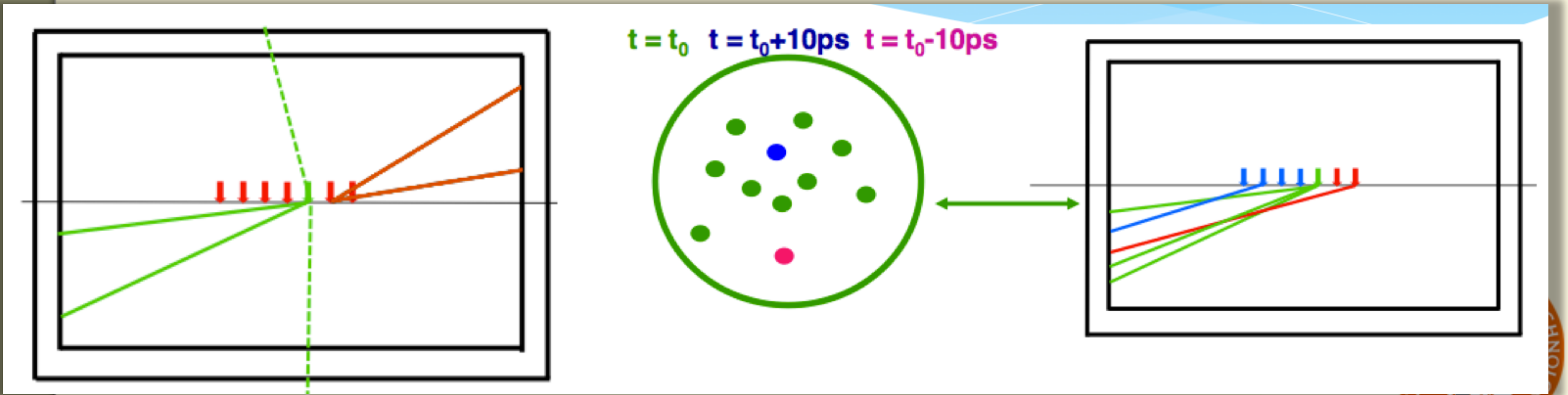
- Two main scenarios for HL-LHC: with and w/o crab-cavities
  - **$(d\langle\mu\rangle/dz)_{max}$ ~ 1.0 → 1.3 event/mm →** i.e. up to 1.4→ 1.8 event/mm
- Precision timing capability to improve event reconstruction in the HL-LHC environment
  - Timing provides an *additional* and *independent* means for PU identification
- **Soft tracks & ~1/3 of jet not reconstructed even with extended tracker**
  - Neutral energy from PU contributes about **~100% to 50 GeVjet @140PU**





Precision timing calorimeters

- Investigating options of high precision timing detector
  - Secondary emitter material as active element in a sandwich type calorimeter
  - Crystal based calorimeter to directly extract timing
  - See A. Bornheim talk at CALOR 2014 (session *O4.12*)
- Target resolution of O(20-30 psec)
  - Allows reconstruction of H→γγ vertex and pileup suppression
- Combined timing + energy measurement to remove jets/ photons/MET contamination from pileup



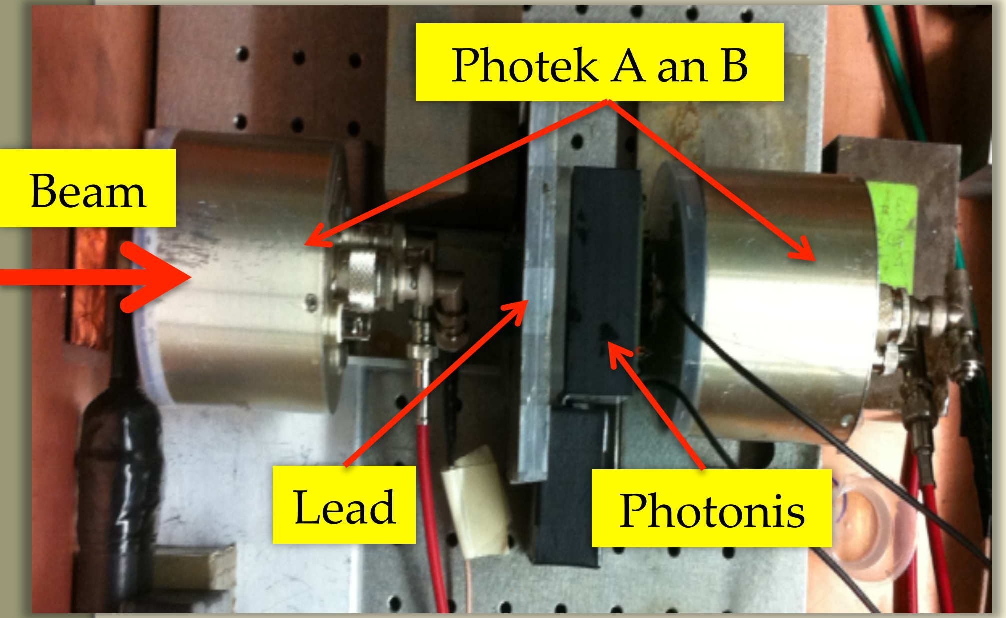
Fast timing in calorimeters

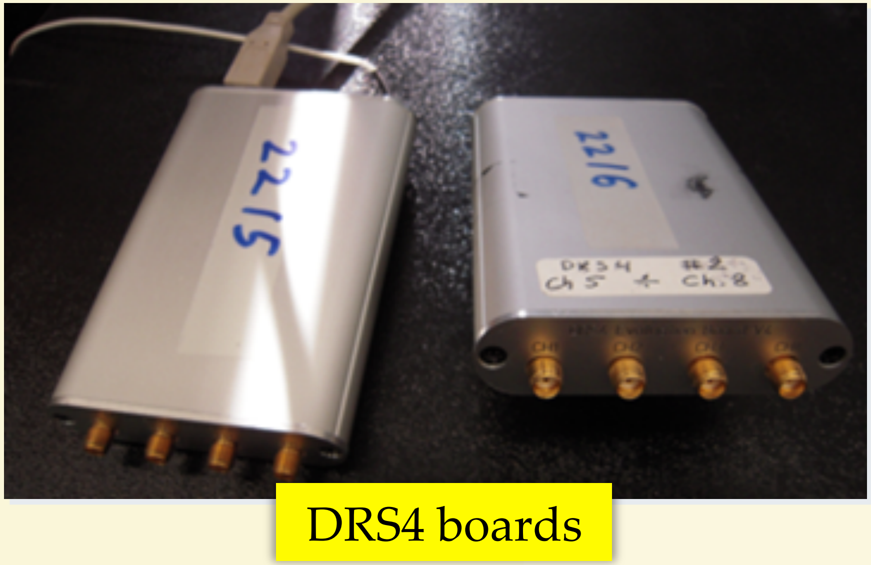
- Starting point in exploring precision timing in calorimeters
  - Secondary particles from EM shower are detected by MCP
  - MCP are intrinsically very fast → calorimeter with very fast timing

- Experiment in the FNAL test beam with electron and proton beams:
  - *"Development of a new fast shower maximum detector based on MCP-PMT as an active element"*, A. Ronzhin, S. Los, E. Ramberg, M. Spiropulu, A. Apresyan, S. Xie, H. Kim, A. Zatserklyaniy; *NIM A* **(***doi: 10.1016/j.nima.2014.05.039***)**
  - A. Apresyan talk at CALOR 2014 (session *O4.13*)

- Investigating the option of using bright fast scintillating crystal to extract fast timing
  - Our experiment in the FNAL test beam with electron and proton beams in March and May 2014
  - Measurements and characterization of components at Caltech
    - A. Bornheim talk at CALOR 2014

Test beam setup

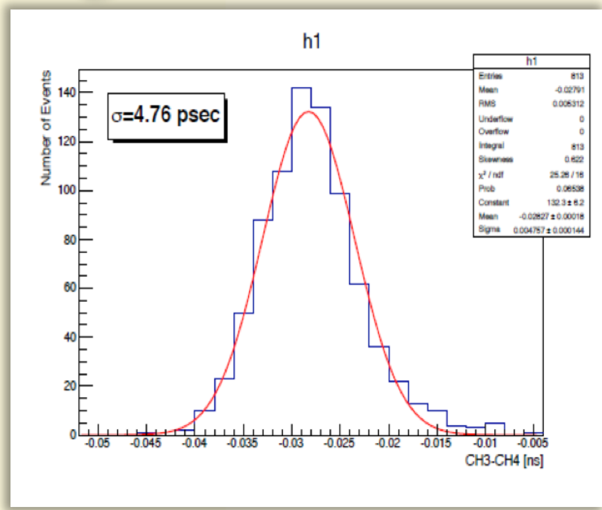


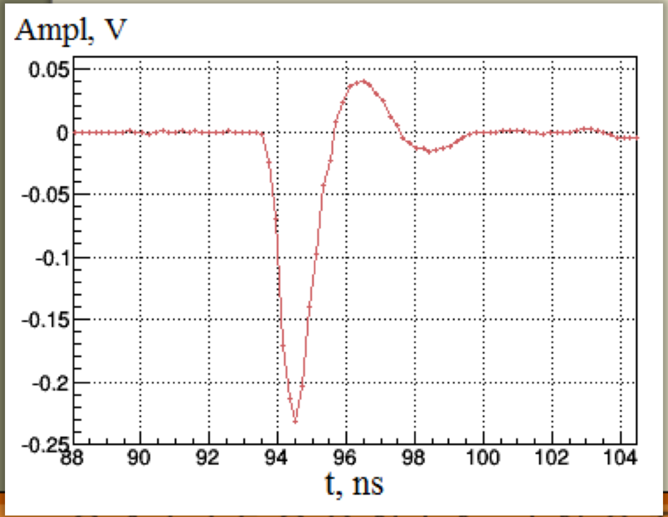


- Two types of MCP-PMTs used: Photek 240 (***A/B***), and Photonis (***PH***)
- DAQ is composed of 2 DRS4 waveform digitizer units
- Primary proton beam: 120 GeV/c, beam of positrons: 12 and 32 GeV/c
- Vary several parameters of the setup
  - Change lead thickness; Add quartz radiators in front of PH

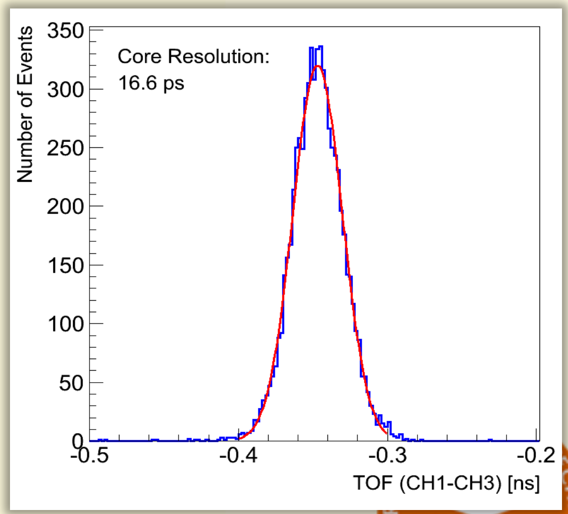
Characterization of the ingredients

- Assign a time stamp to each event
  - Mean value of Gauss fit to the pulse at maximum
- Electronic time resolution
  - Time difference of a split signal into same DRS4
  - Slightly different for two units: **4.8** and **6.7 ps**
- TOF time resolution for protons
  - Resolution for the two Photek 240 placed in line was found to be **~16 ps**

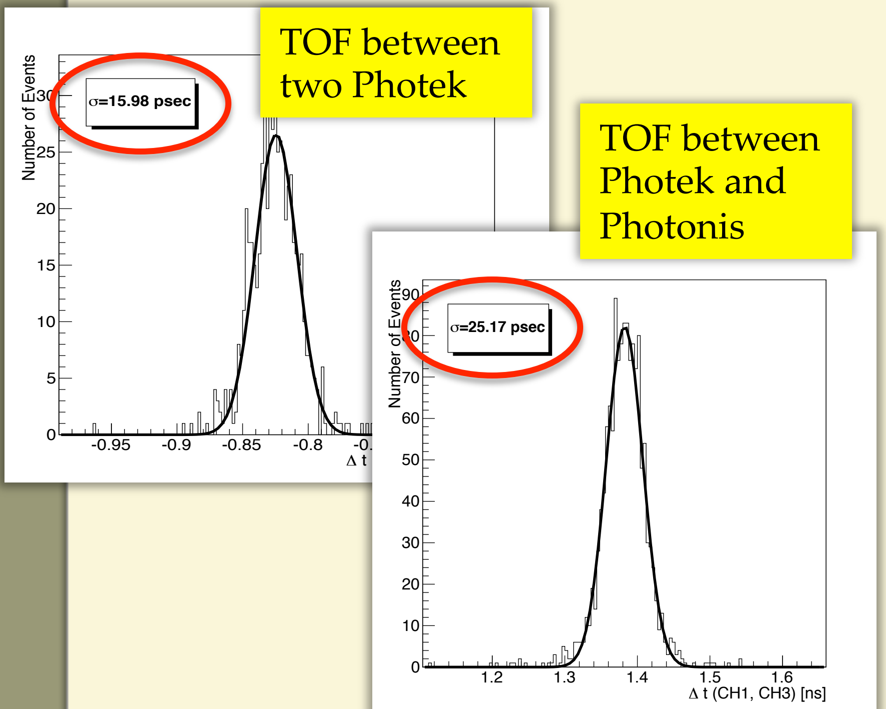


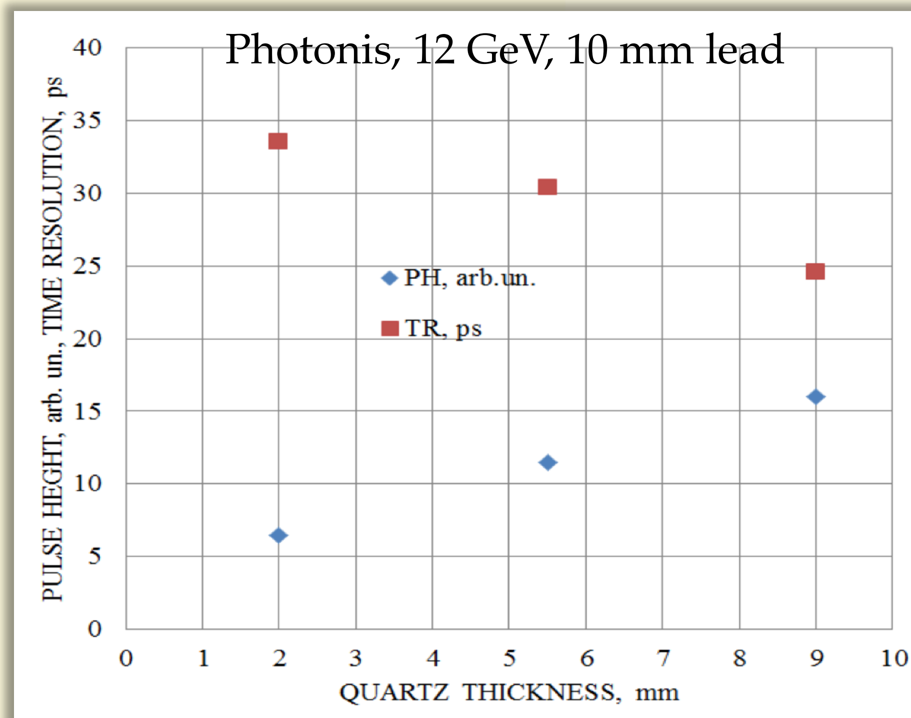


Photek 240 signal recorded by a DRS4 during 120 GeV/c protons run passing through the input window.



Time resolution and secondary emission

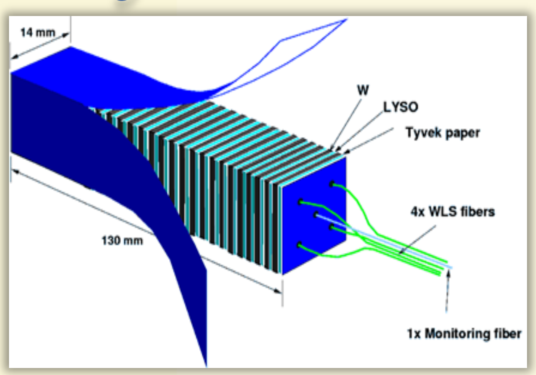


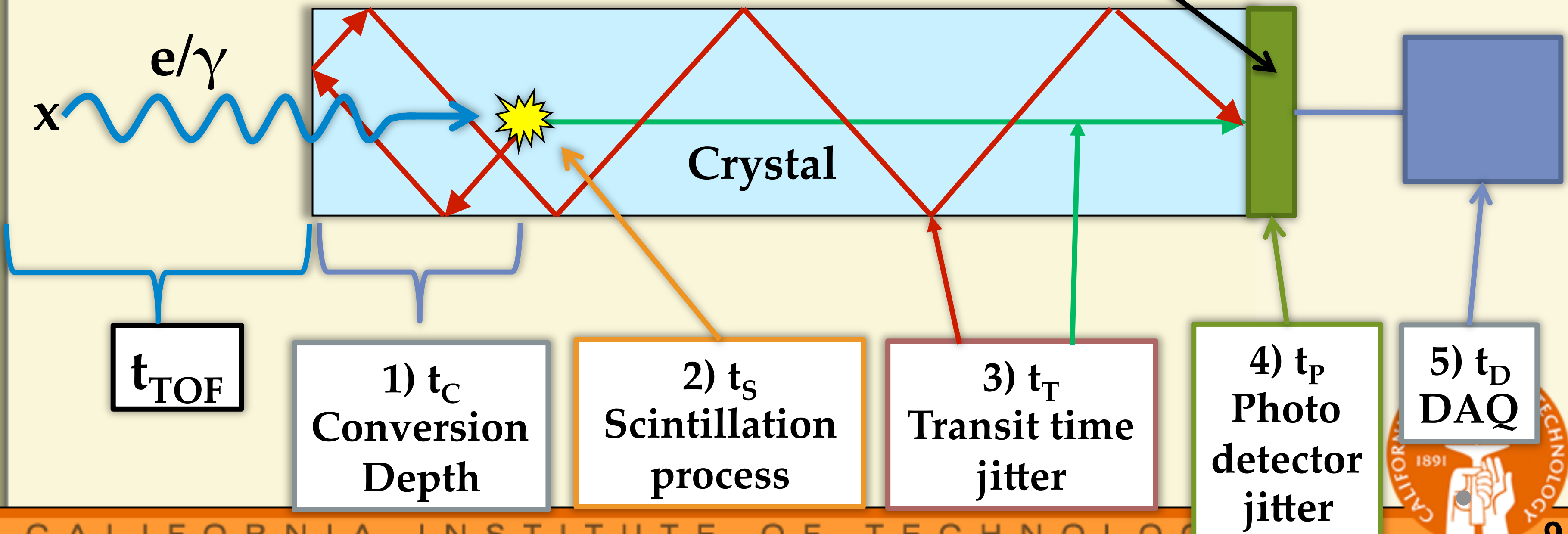


- Time resolution **20-30 ps** achieved in beam for shower arrival
- *No significant difference in TR* at 12 GeV vs 32 GeV beams.
    - No big TR changes *for different lead thickness* in these measurements

Precision timing with crystals

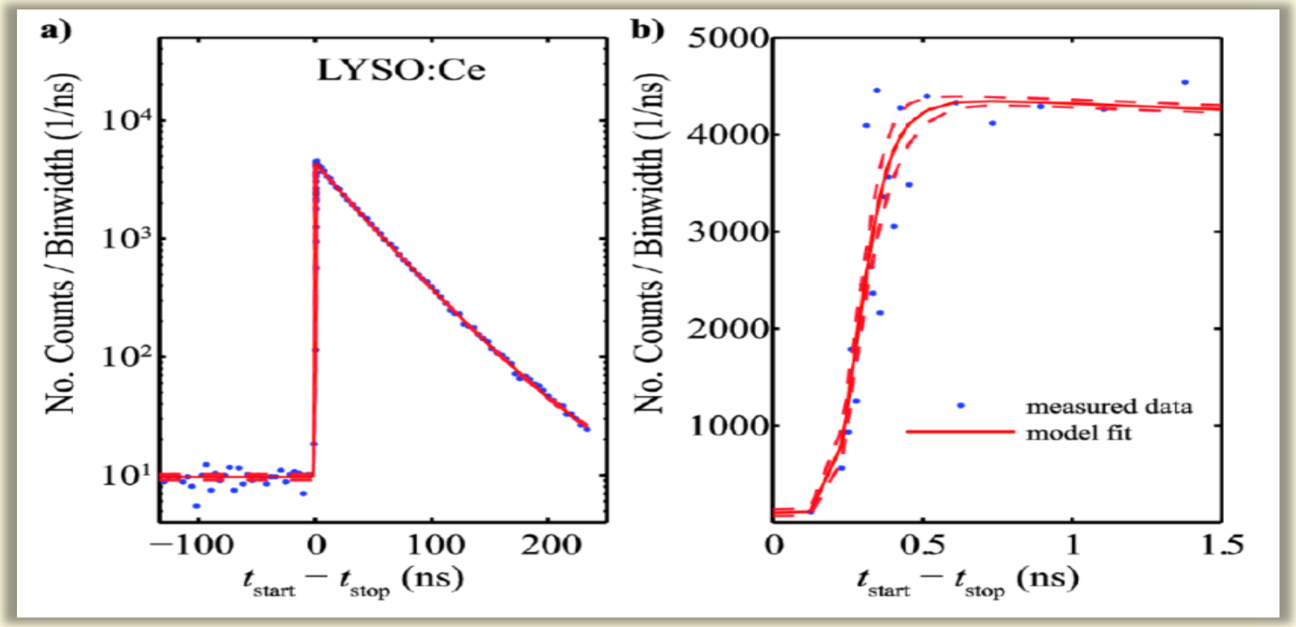
- CMS considers Shashlik with crystals in HL-LHC
  - LYSO/CeF3 with Tungsten, read out with fibers
- We are pursuing an experimental program to extract fast timing from these bright fast scintillating crystals
  - Contributions from **4)** and **5)** are shared between secondary emission and crystal setup





Scintillation and shower properties

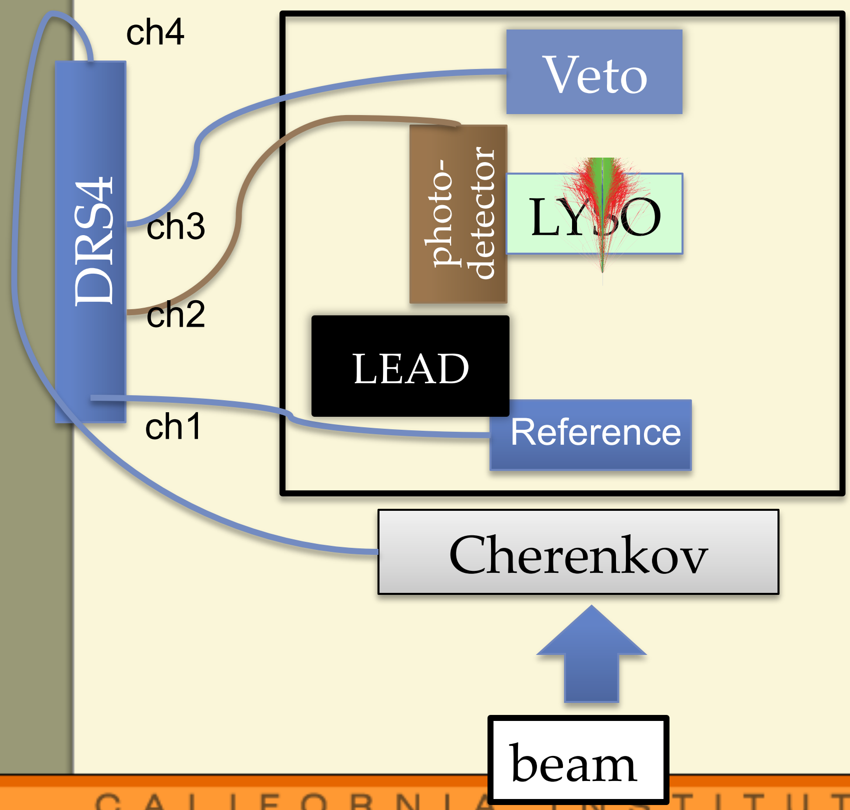
- Timing information is extracted from the leading edge of the signal – the rise time of the light output is important.
  - LYSO: Scintillation light rise time t_R = 75 ps*, ~30K photons/MeV
- From simulation: shower fluctuations in high P_T photon showers cause fluctuation of the mean shower time of O(10) psec, dominated by the conversion depth.

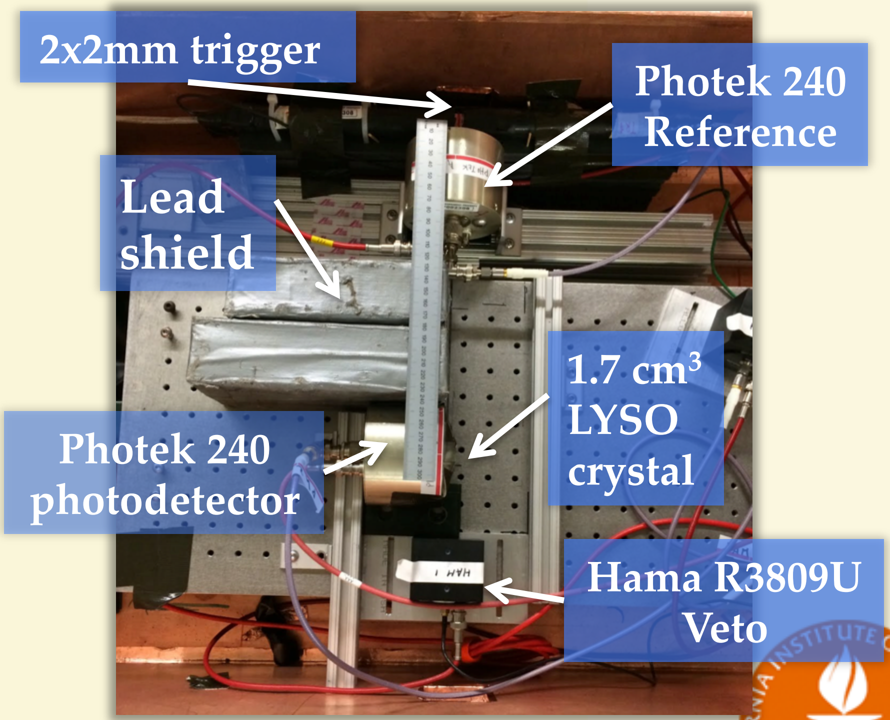


* S. Seifert, J H L Steenbergen, H T van Dam and D R Schaart, 2012 *JINST* 7 P09004. doi:10.1088/1748-0221/7/09/P09004

Experimental setup

- Measurements at Caltech and Fermilab test beam facility to characterize timing properties of crystal based system
  - Photek 240, DRS4 shared with p 6-8; also Hamamatsu R3809U MCP-PMT
  - Latest measurements last week: some results are preliminary

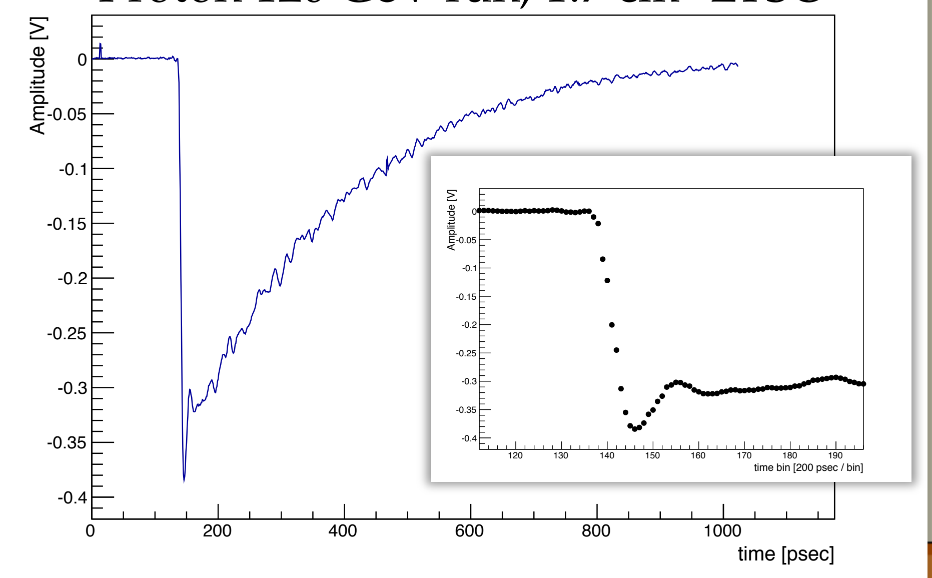




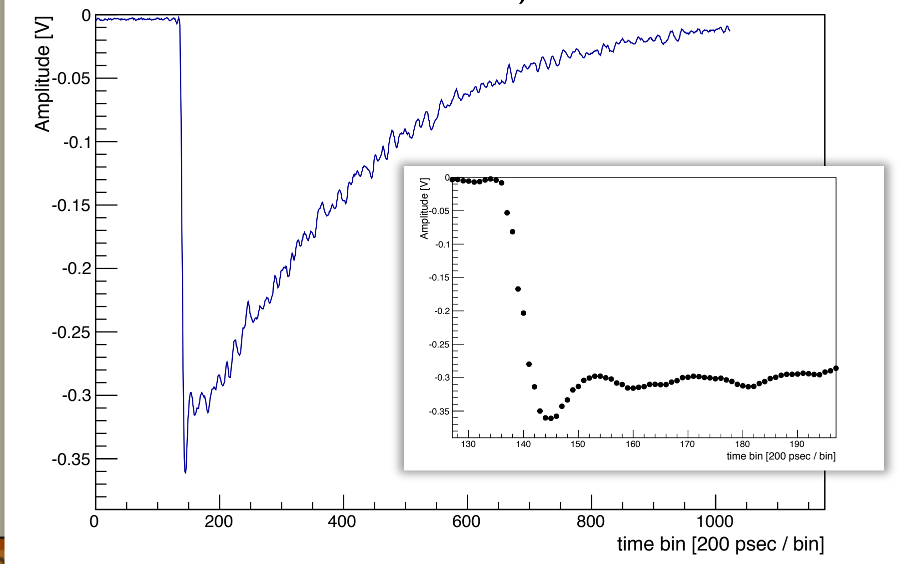
Beam runs

- 120 GeV proton, and 4, 8, 12, 16, 32 GeV runs with electrons
- Cherenkov counter upstream for particle ID
- The DAQ system based on DRS4: ~5 psec resolution
- Photek 240 or Hamamatsu R3809U used for light detection, ~20 psec resolution
  - Lead bricks in front of the MCP to avoid direct hits into the MCP

Proton 120 GeV run, 1.7 cm^3 LYSO

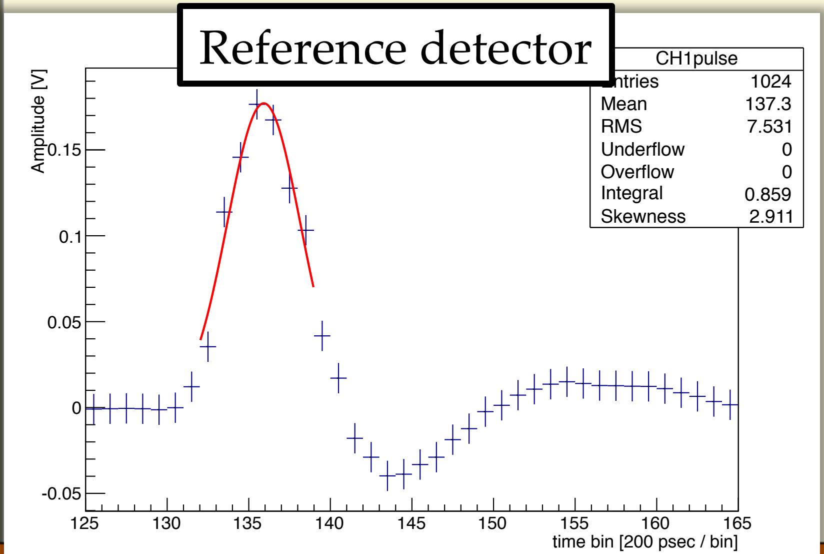


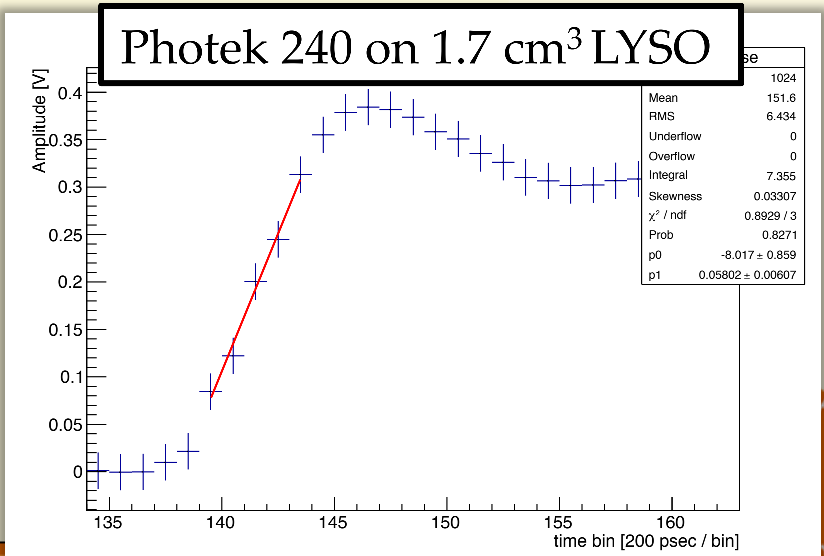
8 GeV electron run, 1.7 cm^3 LYSO



Time reconstruction

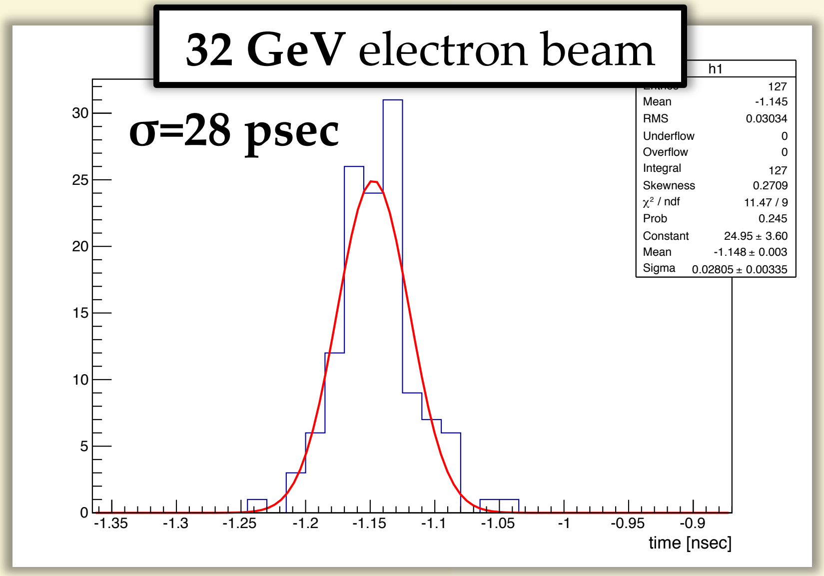
- Measure the time of flight resolution between reference MCP-PMT and scintillation light
  - Signal in the reference are from Cherenkov light in the MCP-PMT window
- Time stamps in the detectors are reconstructed with:
  - Mean of a Gauss fit near the pulse maximum for the reference detector
  - Constant fraction, fit on the rising edge for the LYSO detector

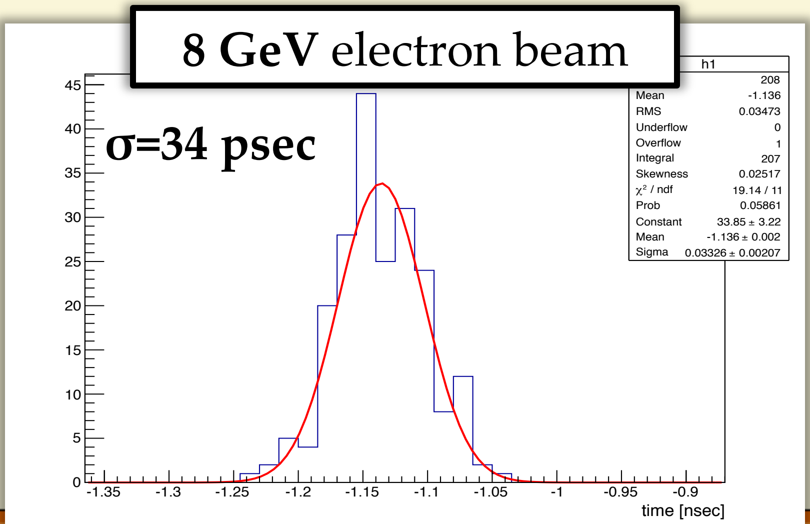


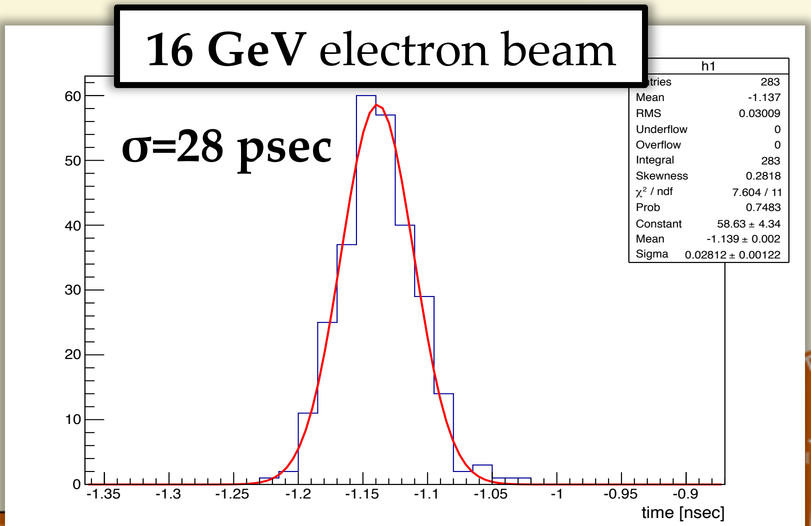


Time of flight resolution: small xtal

- Event selection:
  - Cherenkov counter tag electron evts; Large signal in veto MCP to identify showers
- Special runs XP2020, or LYSO mounted ⊥ to the beam
  - Pulses are dominated by scintillation
- TOF resolution **~30 psec** for various beam energies

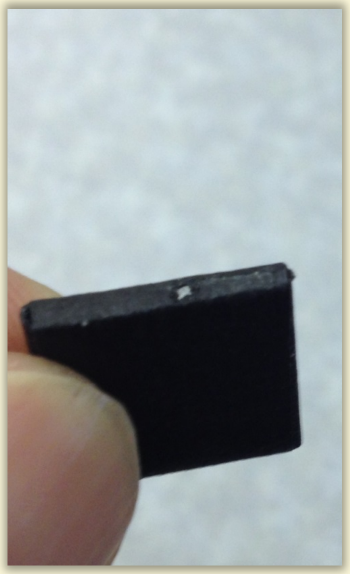


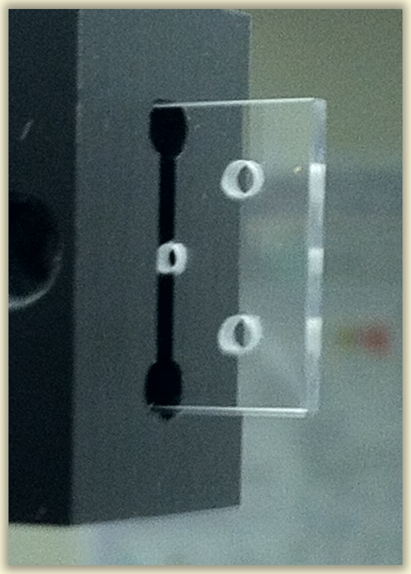


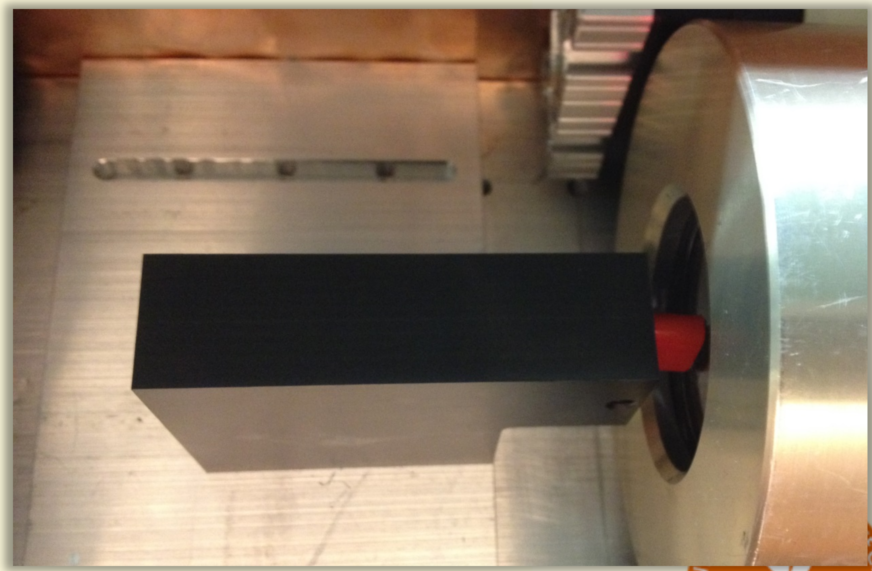


Time of flight resolution: Shashlik tile

- Small LYSO plates (1.4x1.4x0.15 cm) as from LYSO/W Shashlik prototype.
- Measure time resolution around 50 ps for 8 GeV electrons,
  - Difficult to control alignment, impact of direct hits on MCP window
  - Measurements taken with XP2020, normal incidence mounting on MCP



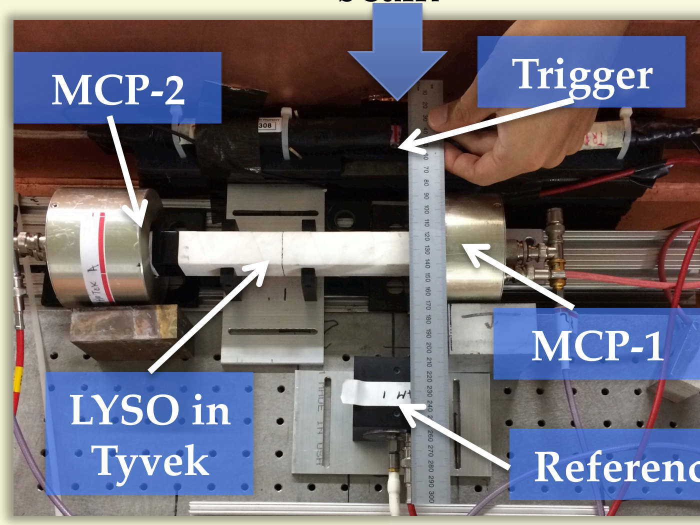




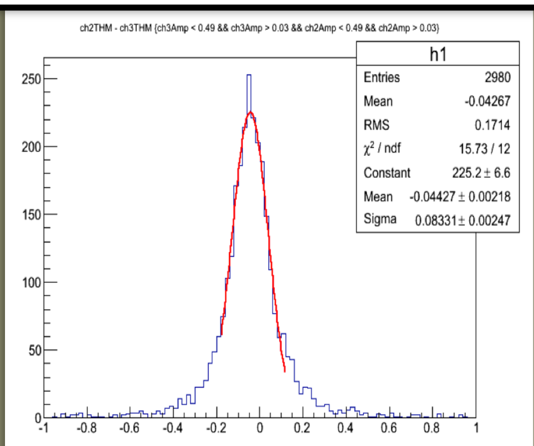
Time of flight resolution: large xtal

- 120 GeV proton runs
- 20cm LYSO crystal perpendicular to the beam, 2x2 mm^2
- MCP readout on both ends scan in position along the crystal
  - Resolution between reference and either of MCP around **60 psec**

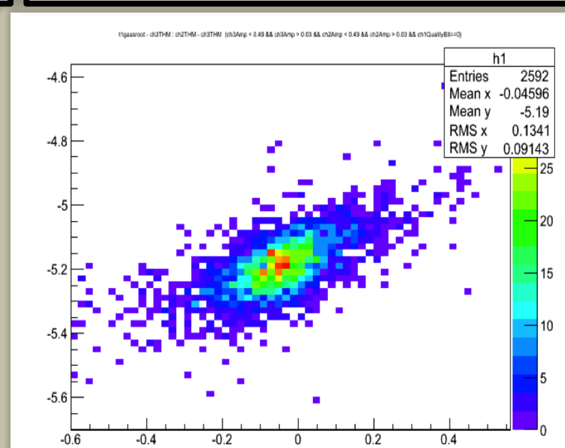
beam



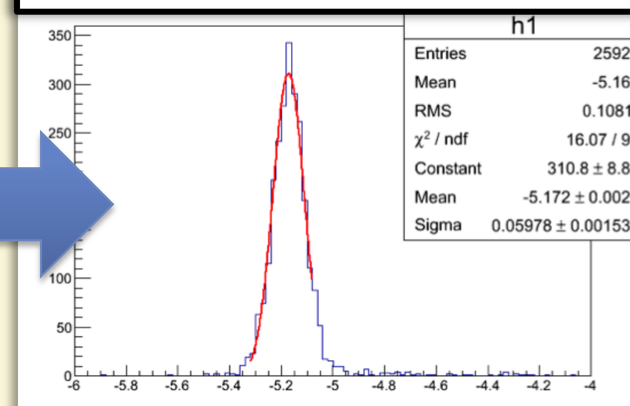
σ between ref and one end



correlation between two ends

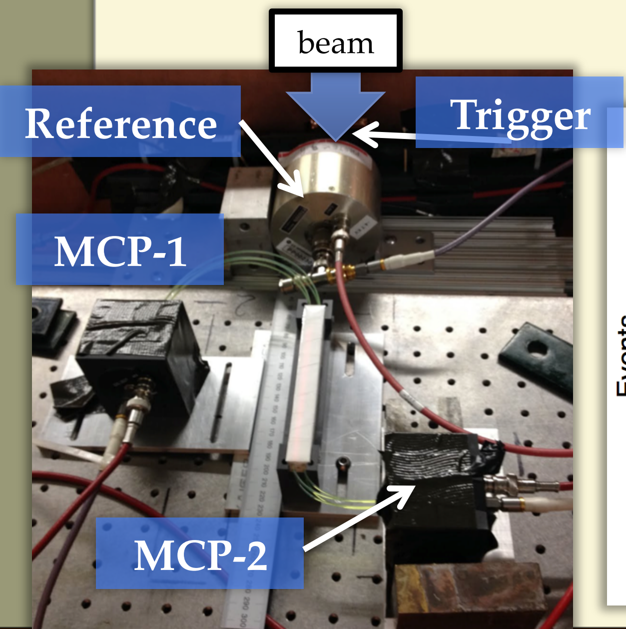


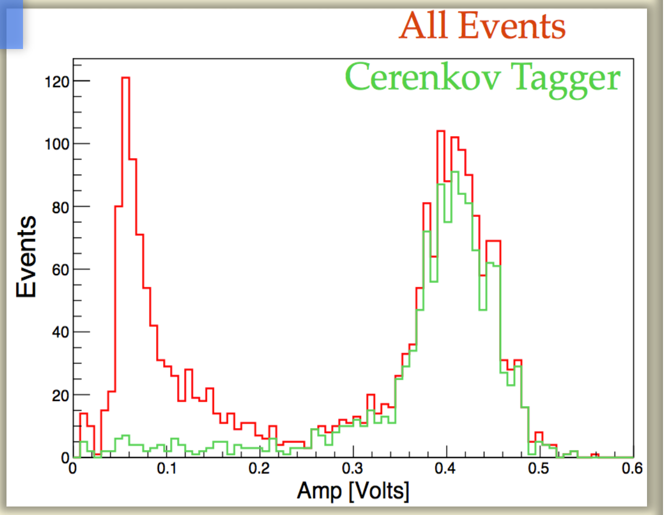
σ between ref and one end after correction

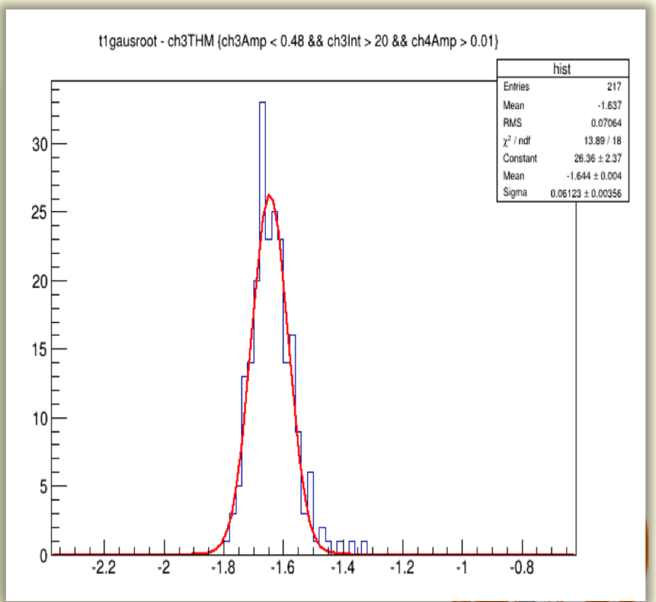


LYSO/W Shashlik cell

- Characterization and optimization of the readout of the Shashlik cell (1.4x1.4x14cm^3 LYSO/W)
  - Separate test with readout both options: through fibers, or single LYSO tile
  - Analysis ongoing, results look very promising
- Resolution around **~60 psec** achieved in the first attempt with electron beam





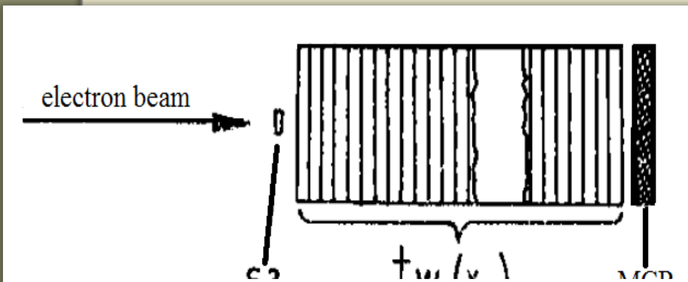


Conclusions

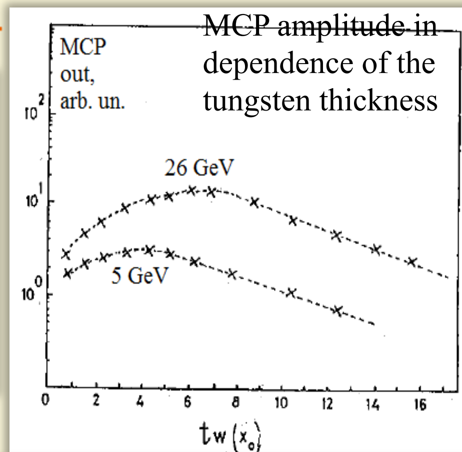
- Precision timing in calorimetry is demonstrated to be possible, achieved 20-30 ps in test beams
  - Numbers are *before* unfolding the DRS4, photo sensors…
  - Becoming sensitive to the DAQ limitations, bandwidth, reference resolution
- Ongoing work towards developing a technology applicable to the CMS endcap calorimeter upgrade
  - Further beam tests planned later in the summer and in fall this year
- Single channel time resolution of a few 10 ps seems achievable for incident particle energies of a few GeV

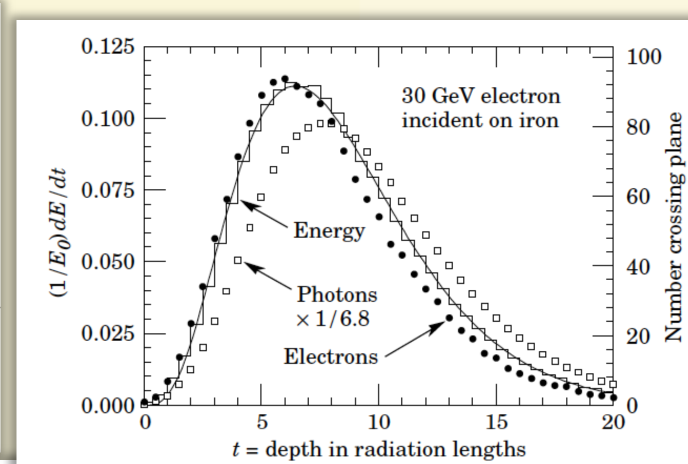
Backup

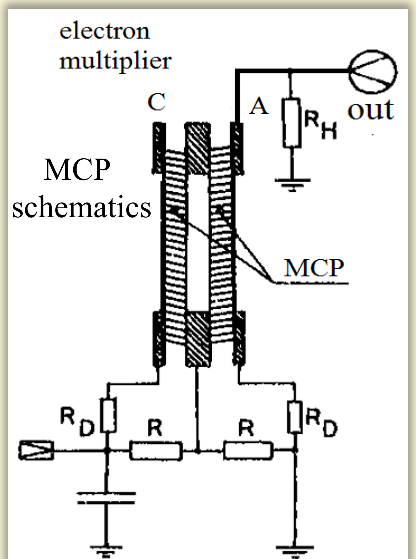
Radiation resistant and fast SM detector

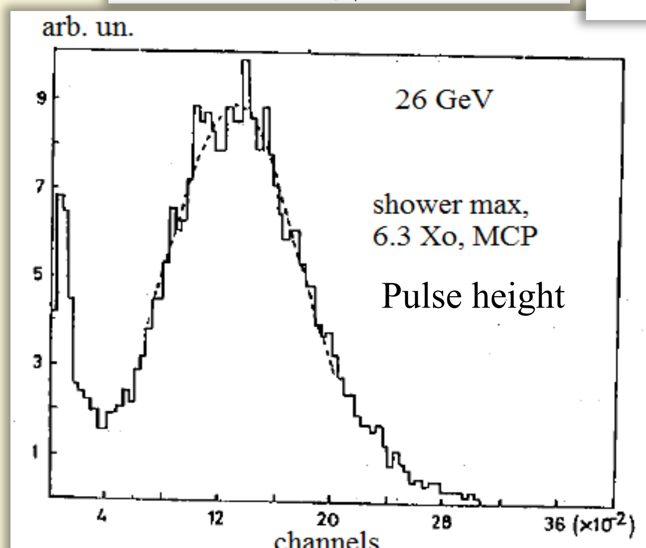


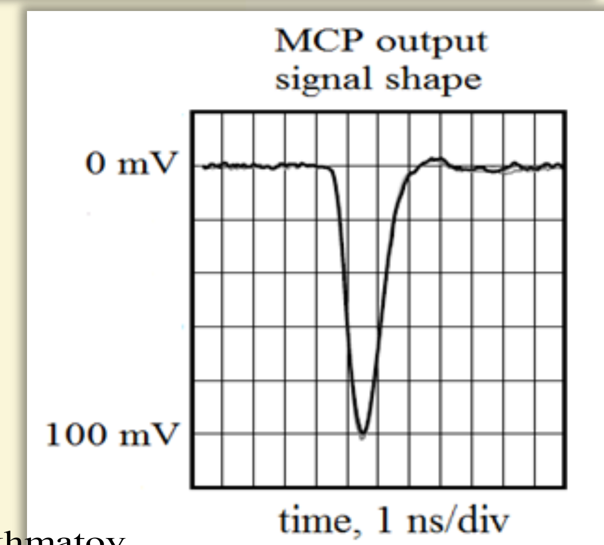
Test beam, tungsten absorber thickness changed







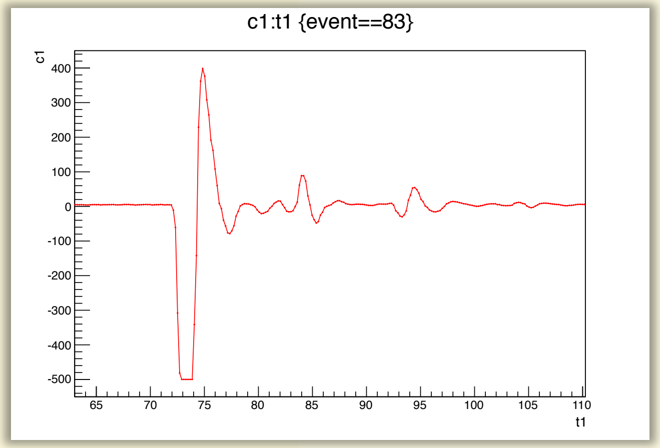


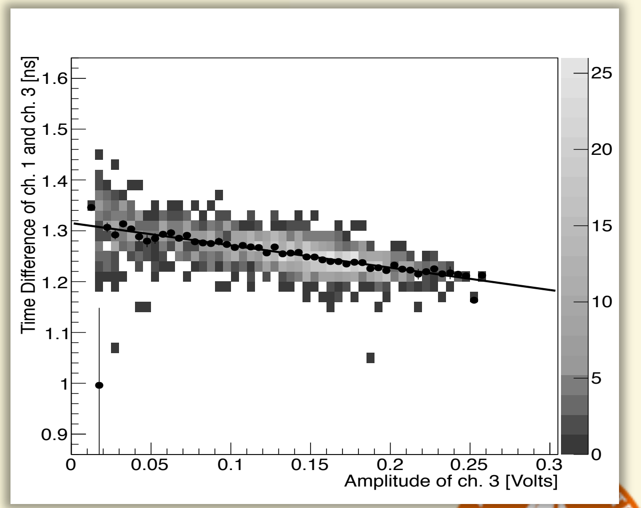


1. A. A. Derevshchikov, V. Yu. Khodyrev, V.I. Kryshkin, V.E. Rakhmatov, A. I. Ronzhin, “On possibility to make a new type of calorimeter: radiation resistant and fast”. Preprint IFVE 90-99, Protvino, Russia, 1990.

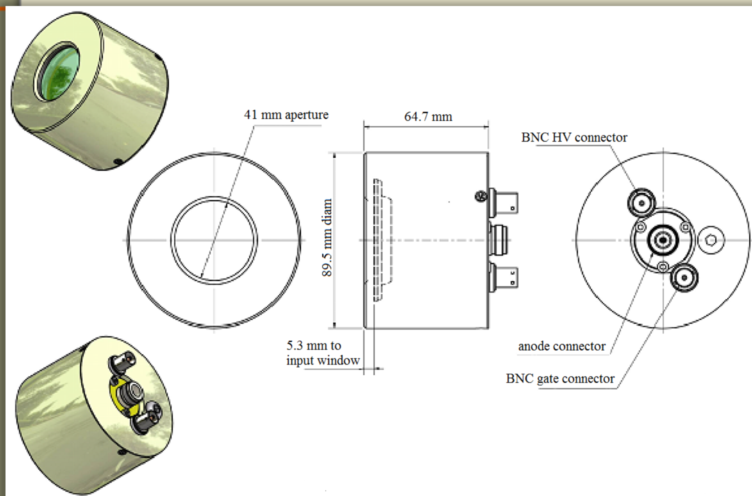
Event selection and analysis

- Assign a time stamp to each event
  - Mean value of Gauss fit to the pulse at maximum
- Event selection to eliminate abnormal pulses
  - Large signals above 500 mV were rejected because they saturated the DRS4 inputs.
  - Pulses with an irregular peak profile were rejected
  - Selected the pulses with larger than 20 mV amplitude for analysis.
- For Photonis linear dependence of the ΔT is observed
  - Perform a time correction for each event on the measured amplitude.

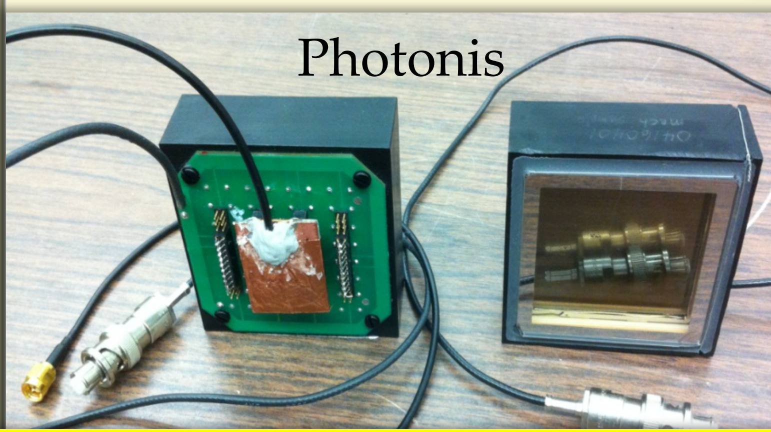


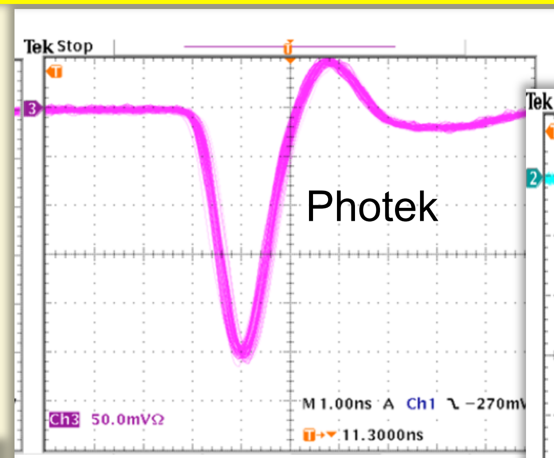


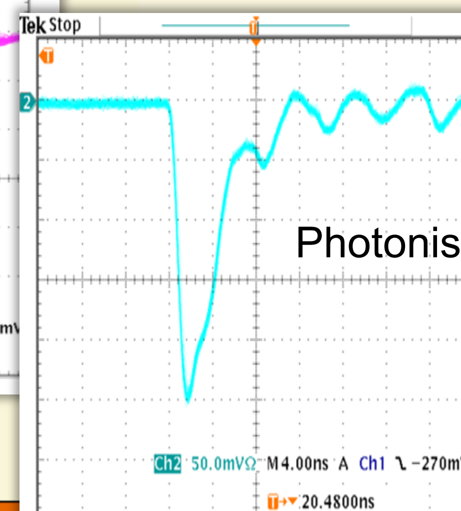
Photek 240 and Photonis MCP-PMT



10 μm pore size, 41mm aperture, PC-MCP distance ~5mm, rise time~60 ps, SPTR~40 ps



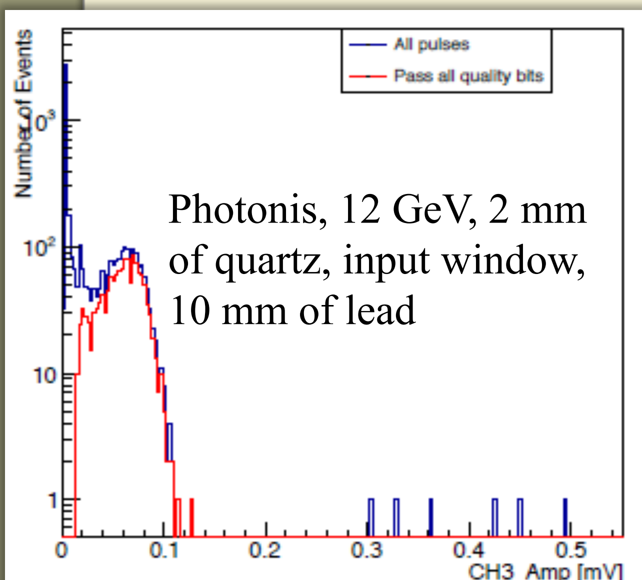


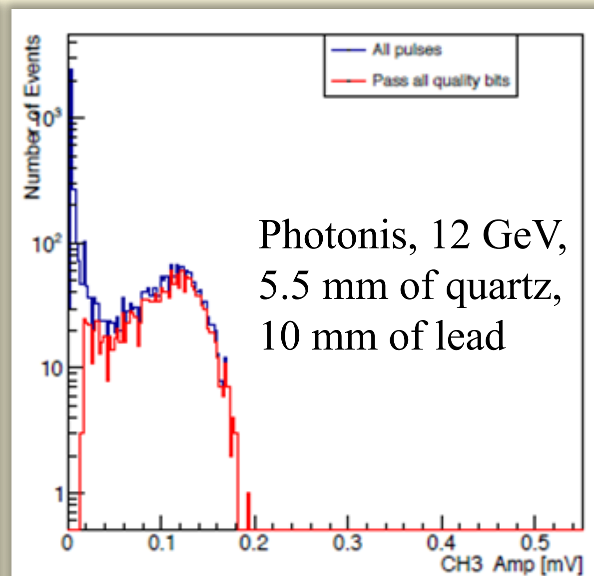


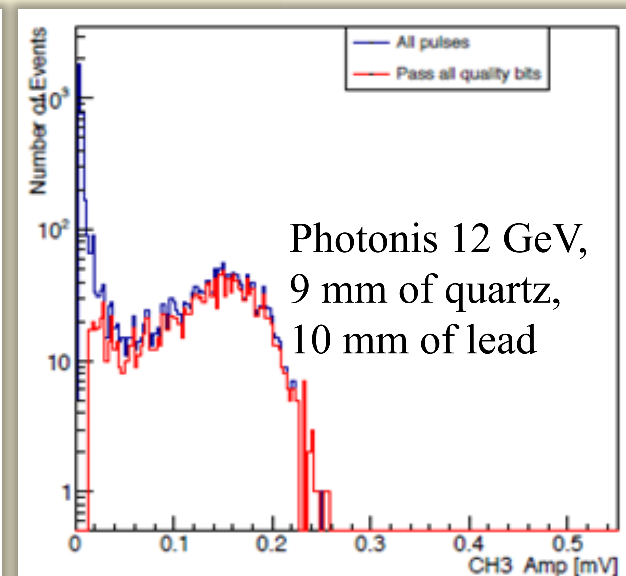
25 μm pore size, 60x60mm^2 sensitive area, rise time~300 ps, SPTR~120 ps, much cheaper than Photek

Measurements with e^+ beam

- Measure the dependence of the *signal amplitude* and *time resolution* on the *lead thickness,* and Cherenkov by varying the *quartz thickness*







Measurements with e^+ beam

- Shower particles are detected **both** through Cherenkov (in the entry window) **AND** ***direct interaction*** with the MCP.
  - Significant component from direct detection of the secondary emission
- **~ 70%** of the MCP-PMT response is due to the ***secondary emission*** and 30% is due to Cherenkov light in the 2 mm thick input window.