Calorimeters for Precision Timing Measurements

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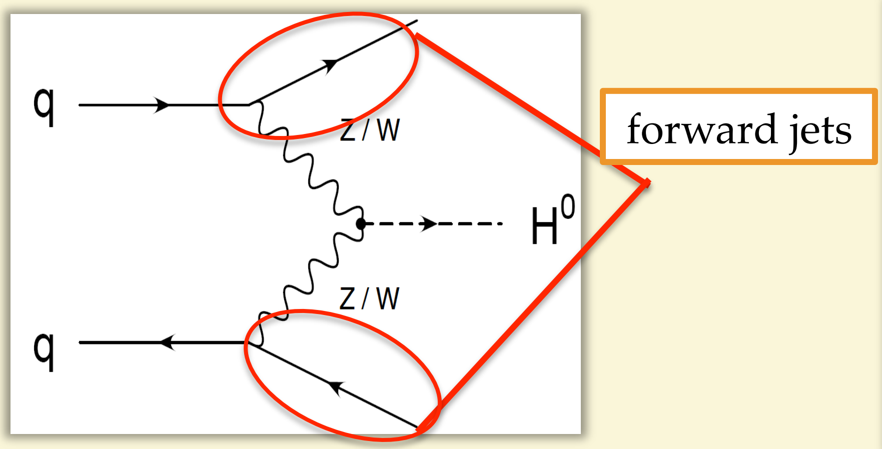
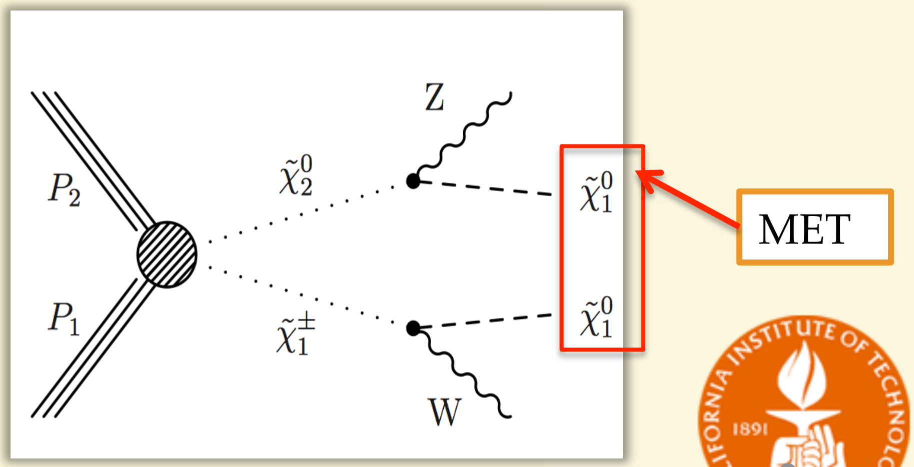
Caltech

Goals of the HL-LHC

- A fundamental scalar boson has been found
  - The study of the Higgs boson will continue to be a central element
  - Precise measurements of the Higgs couplings, tensor structure, rare decays
  - Role of the Higgs in EWK SB through $W_L W_L$ scattering

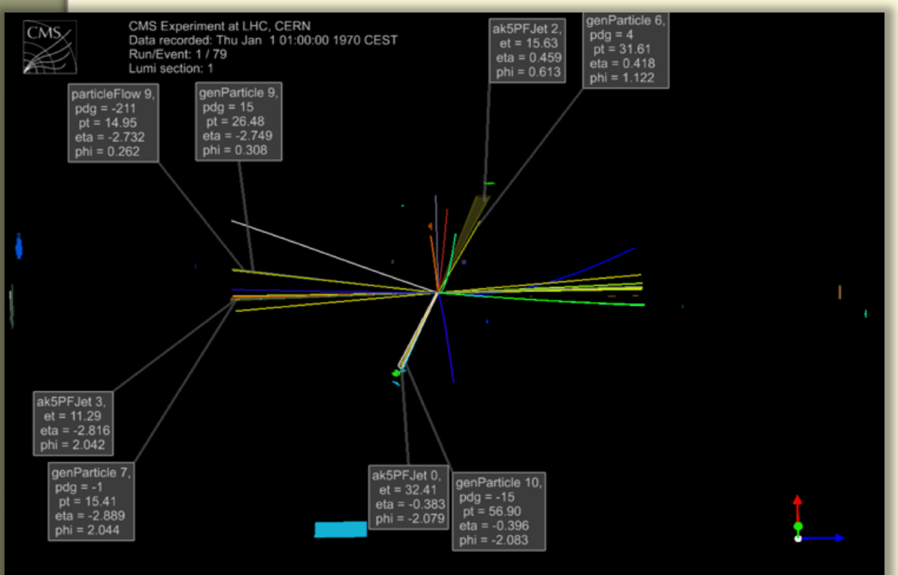
- Possibly exploration of new physics found at LHC
  - Or a significant extension of exclusion reach for various BSM scenarios



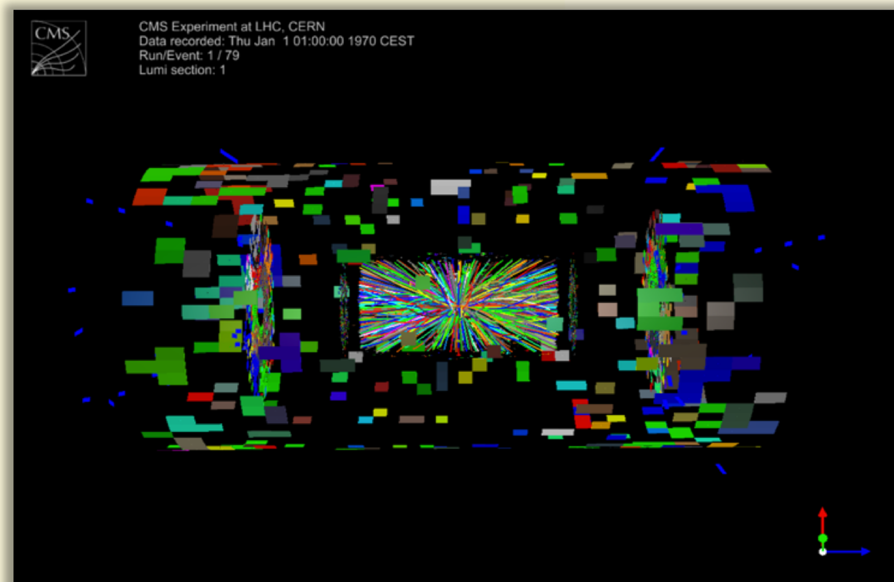


Challenges at HL-LHC

- Large samples needed to fully exploit LHC, goal is to collect x10 more
  - <PU> ≈ 140 at HL-LHC ➔ 50nb/sec , collect 3000 fb^{-1}
- 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 LHC

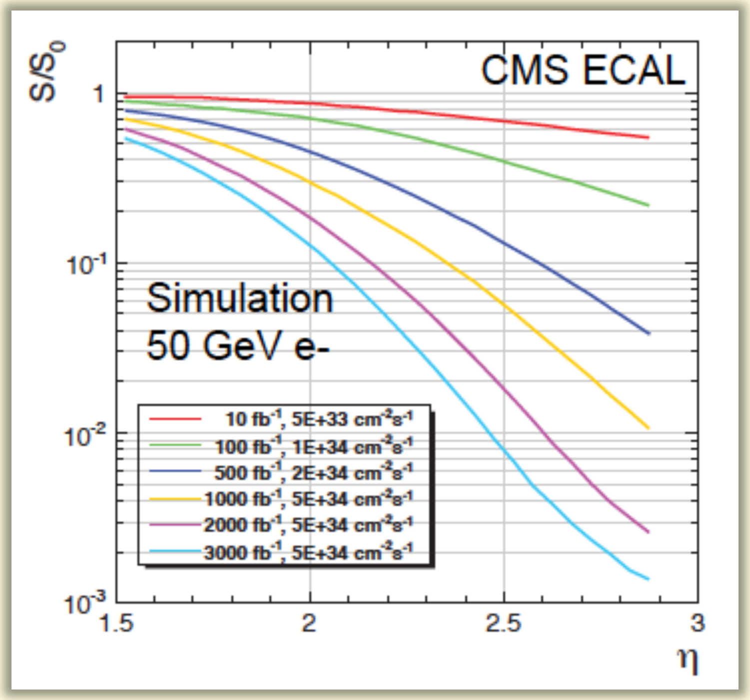


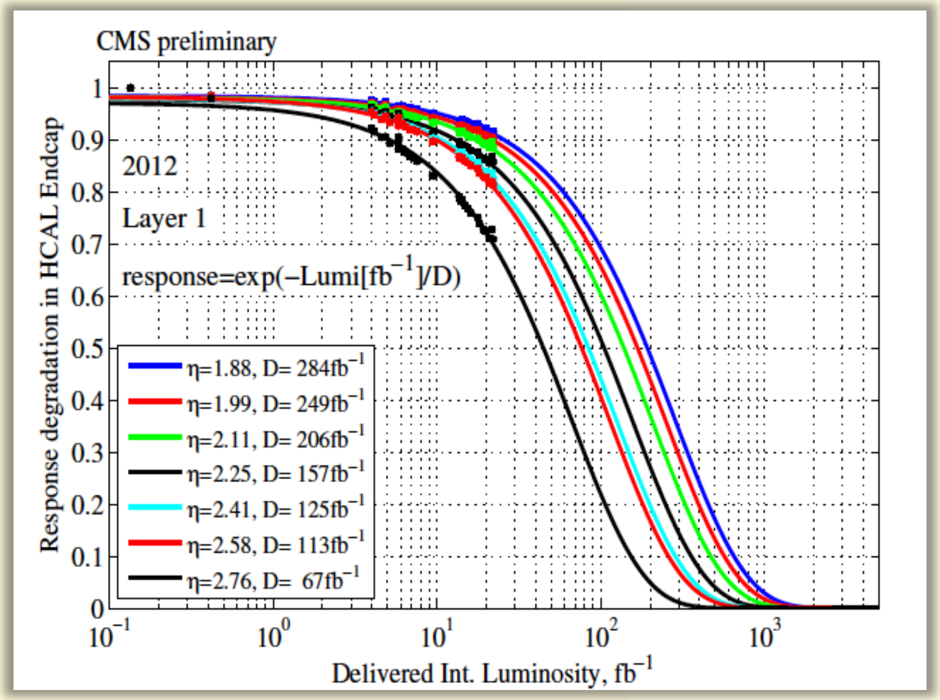
VBF H→ττ at 0 PU



VBF H→ττ at 140 PU

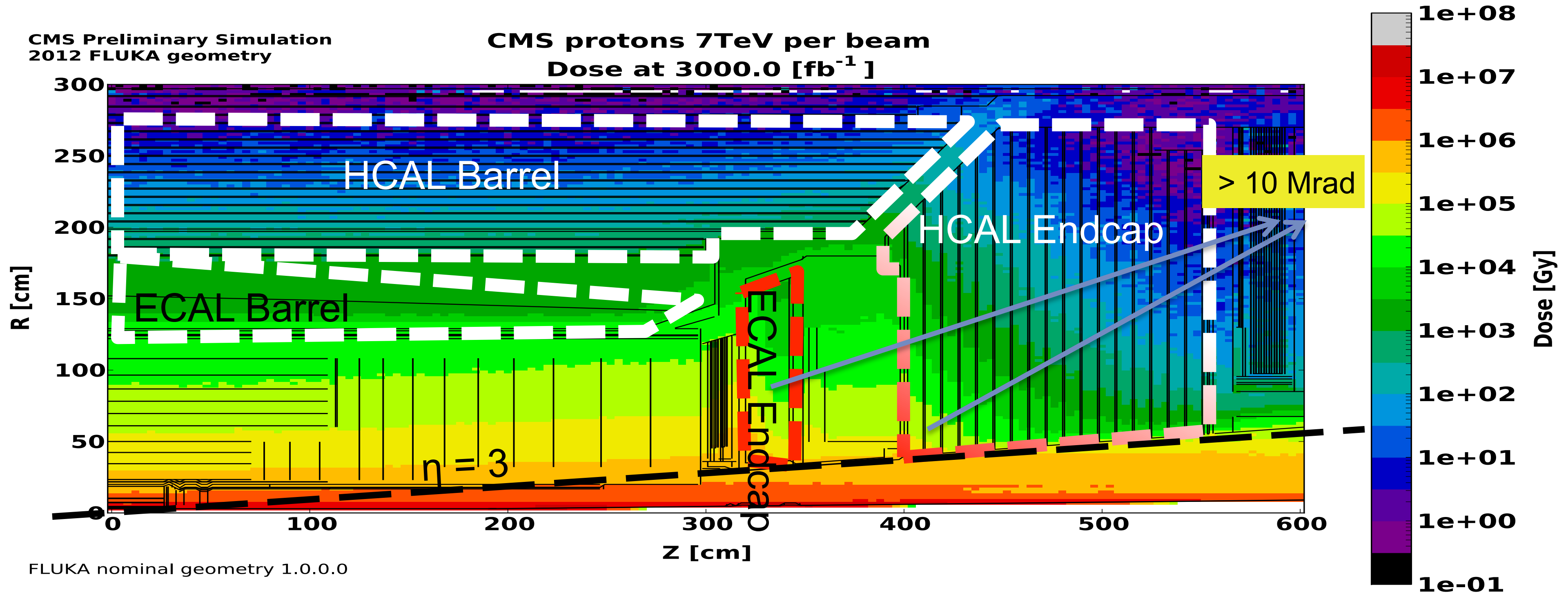
CMS calorimeters in HL-LHC





- Extensive studies of radiation damage
  - Both in test exposures and using the ~30fb^{-1} of CMS data
  - Compared with CMS simulations and radiation model
- Have to replace the CMS endcap (1.5<|η|<3.0) calorimeters
  - Barrel ECAL / HCAL and HF (3.0<|η|<5.0) **can** survive 3000 fb-1
  - **Replace ECAL and HCAL endcaps before HL-LHC (i.e. after L=300-500fb^{-1})**

CMS calorimeters in HL-LHC



Phase 2 Upgrades Strategy

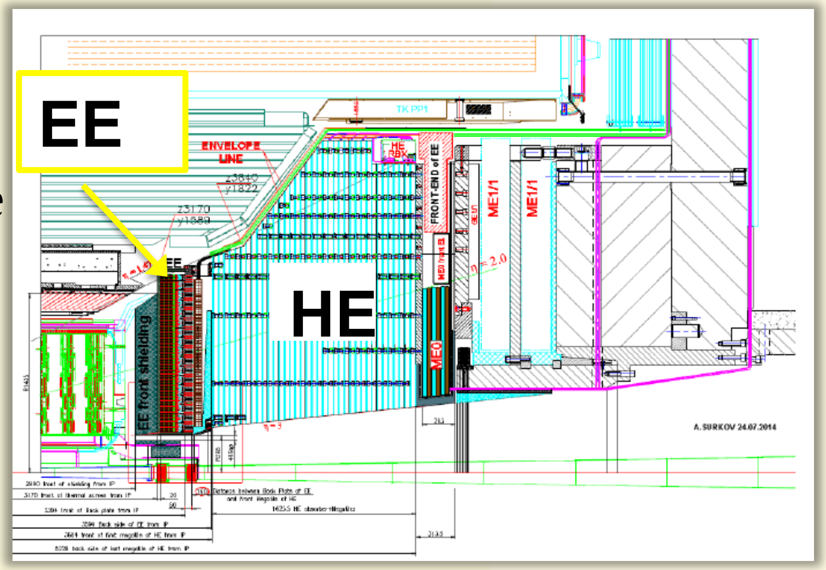
- **Maintain performance at extreme PU**
- **Sustain rates and radiation doses**

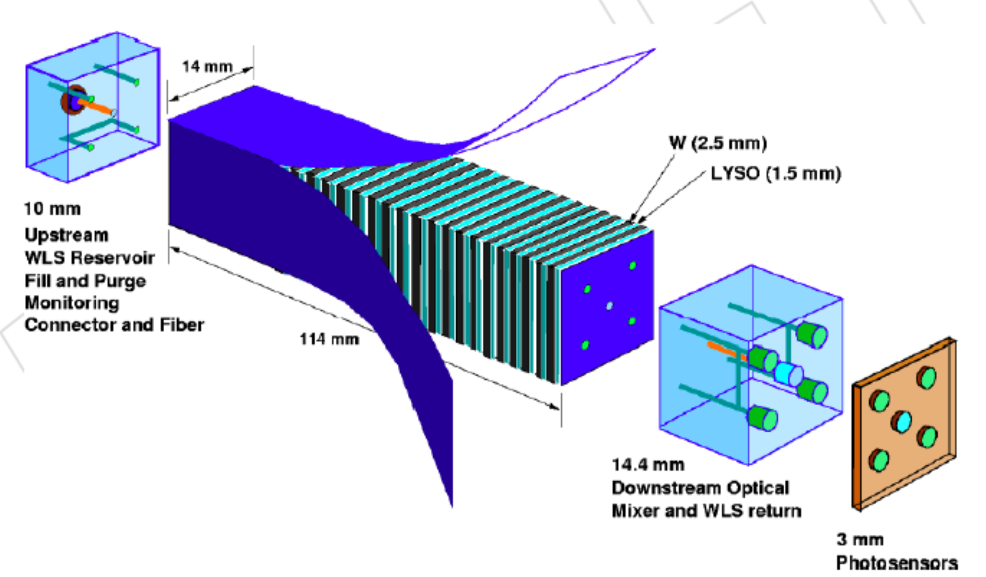
Endcap calorimeter options

- Studying two options:
  - Maintain current geometry (EE Shashlik)
    - Replace ECAL endcap, refurbish HCAL endcap with radiation hard technologies
    - + Rebuild HE with increased depth and rad hard technology
  - High Granularity Calorimeter (HGCal)
    - Finely segmented calorimeter
    - Contains both electromagnetic and hadronic sections
      - 600 m^2 silicon pads in W/Cu struture
      - Readout as much information as possible
    - + Rebuild HE with reduced depth, and rad hard technology

Endcap Calorimeter: EE Sashlik

- W-absorber, LYSO (CeF_3)scintillator
- Compact (~11cm long), small Moliere radius (13.7mm), high granularity ($14mm^2$) to mitigate pileup
- High light yield for good e/γ energy resolution ~10%/√E

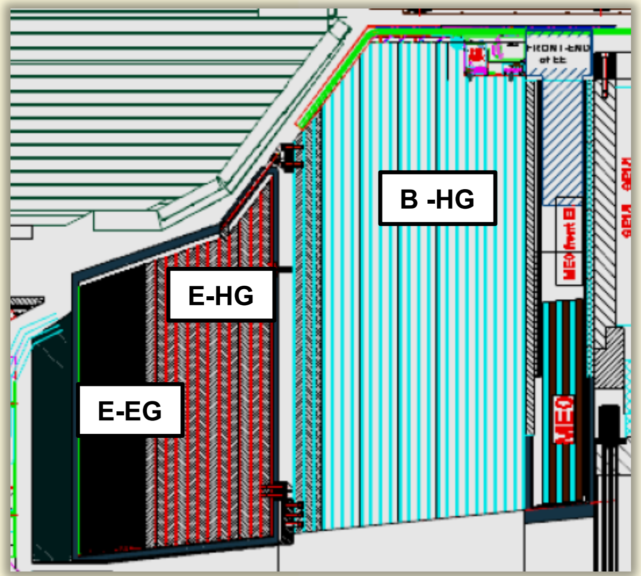


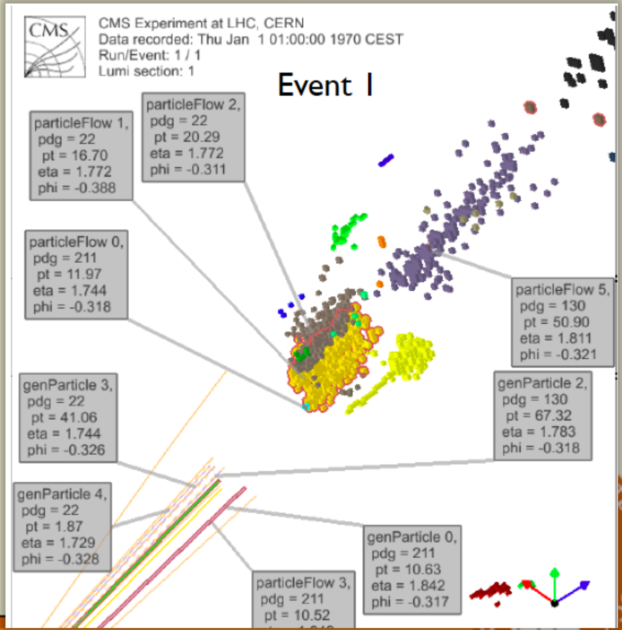


- Readout with capillaries filled with liquid WLS
- Readout options being evaluated now, GaInP or SiPM

Endcap Calorimeter: HGCal

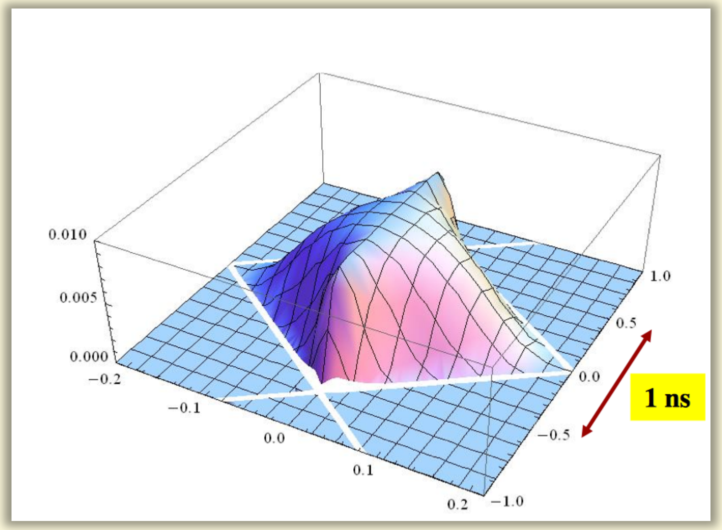
- ECAL (E-HG): ~33 cm, 25 X_0, 1λ:
  - 30 layers of Si separated by 0.5/0.8/1.2 X_0 of alternating W, lead/Cu
- HCAL (H-HG): ~60 cm, 3.5λ:
  - 12 planes of Si separated by 40 mm of brass
- Back HCAL (B-HG) as HE re-build 5.5λ
- ΔE/E ~ 25%/√E;
  - 3D shower reconstruction
  - Use shower topology to mitigate PU effect

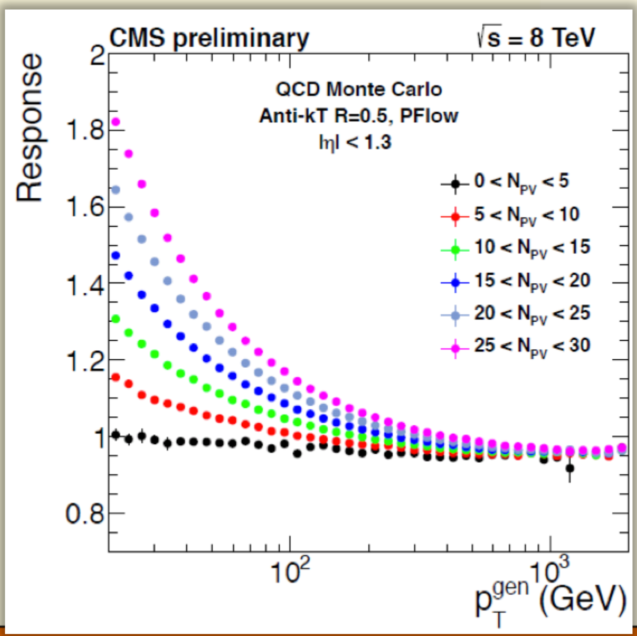




The environment in HL-LHC

- 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 GeV jet @140PU**

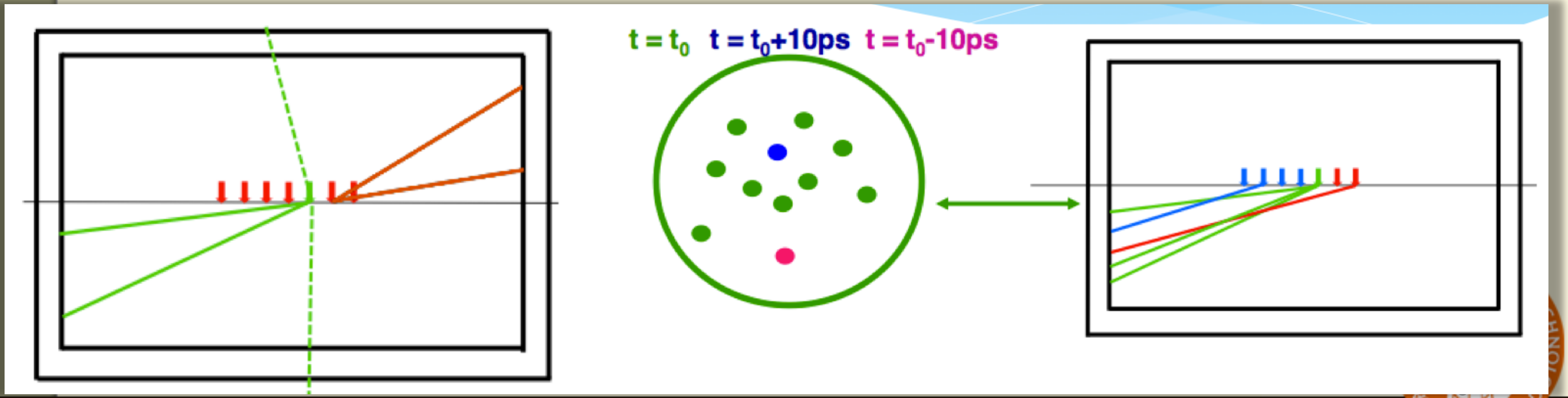




Precision timing calorimeters

- Target resolution of O (20-30 psec)
  - Allows reconstruction of H→γγ vertex and ~x10 pileup suppression

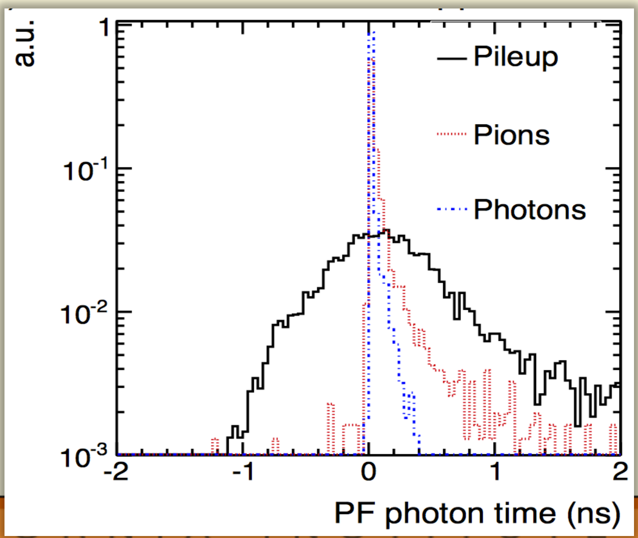
- Possible physics applications of timing information:
  - *the object level* (e.g. **identify forward PU jets** for VBF Higgs, WW scattering)
  - *the single hit level* (e.g. timing-based **ECAL cluster cleaning**)
  - *the event level* (hard scatter **vertex reconstruction,** e.g. for H→γγ)
  - separate **spatially overlapping vertices** that originate at different times

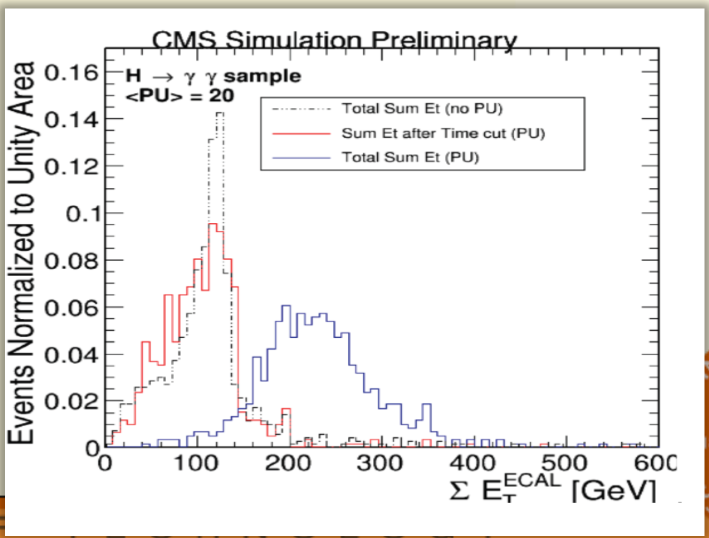


Precision timing calorimeters

- Target resolution of O (20-30 psec)
  - Allows reconstruction of H→γγ vertex and ~x5-10 pileup suppression

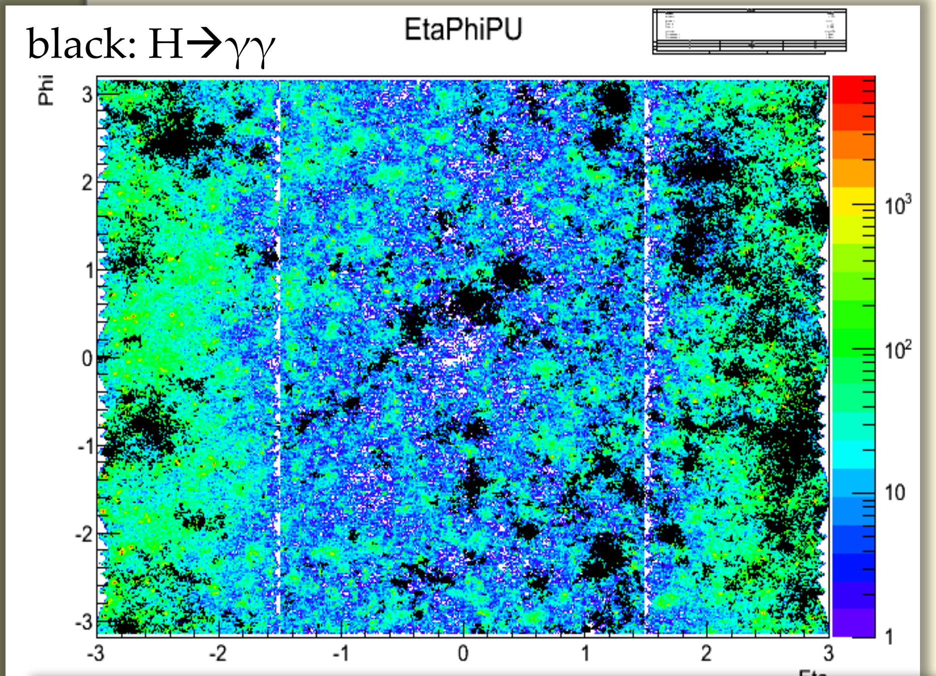
- Possible physics applications of timing information:
  - *the object level* (e.g. **identify forward PU jets** for VBF Higgs, WW scattering)
  - *the single hit level* (e.g. timing-based **ECAL cluster cleaning**)
  - *the event level* (hard scatter **vertex reconstruction,** e.g. for H→γγ), MET
  - separate **spatially overlapping vertices** that originate at different times



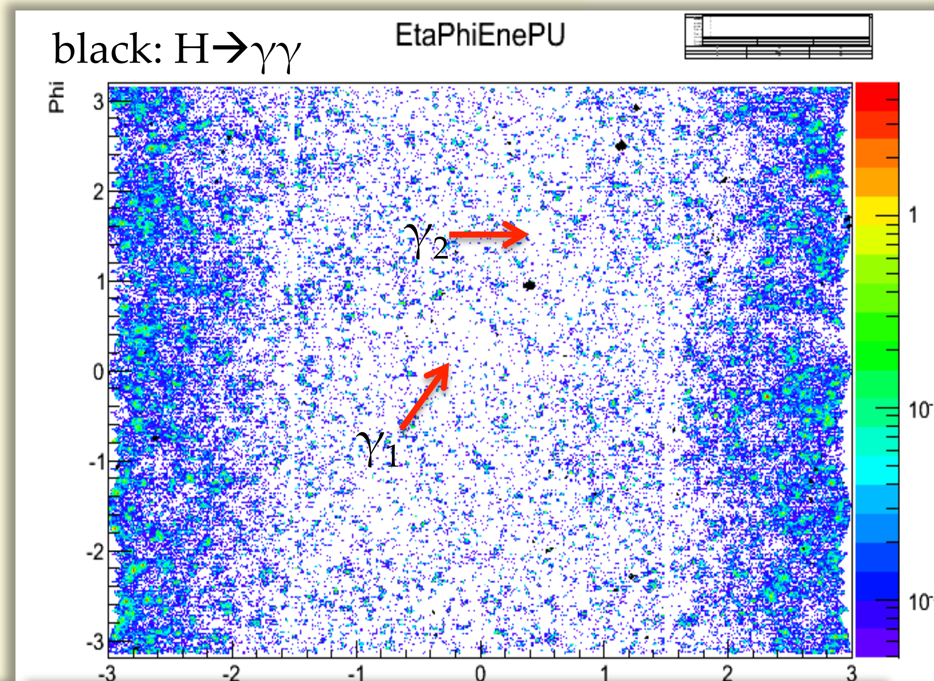


Fast timing in calorimeters

- GEANT simulation studies: overlay H→γγ with 100 MinBias events
- To leverage the PU removal ability, need combined measurement of energy and timing.



η/ϕ hit occupancy map: 100 PU + H→γγ



η/ϕ energy weighted occupancy map:

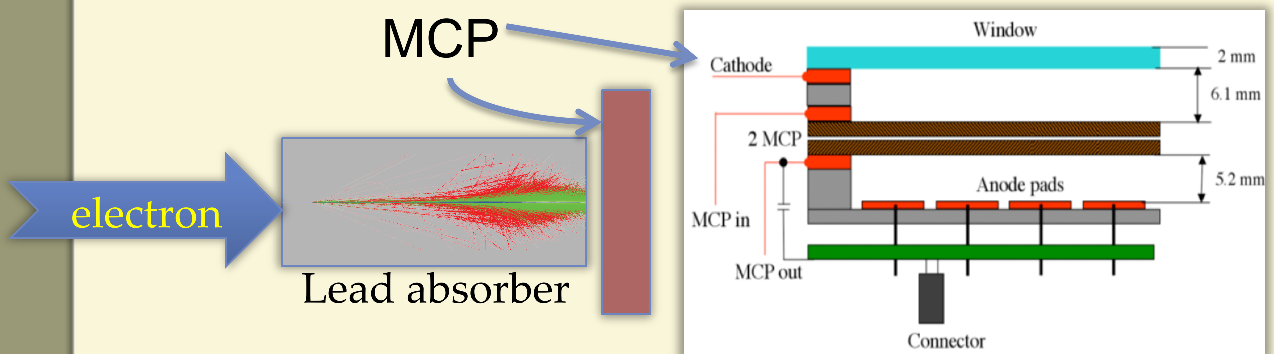
Fast timing in calorimeters

- Investigating options of high precision timing detector
  - Secondary emitter material as active element in calorimeter
  - Crystal based calorimeter to directly extract timing

- Development of prototype detectors
  - Measure the fundamental ingredients, understand limitations
  - Tests of prototype detectors in the lab at Caltech and beams in FNAL

Fast timing: secondary emitter

- Starting point in exploring precision timing in calorimeters
  - Secondary emitter material as active element in a sandwich type calorimeter
  - First proposed: *"On possibility to make a new type of calorimeter: radiation resistant and fast"*, A. I. Ronzhin et. al, preprint IFVE 90-99, 1990.

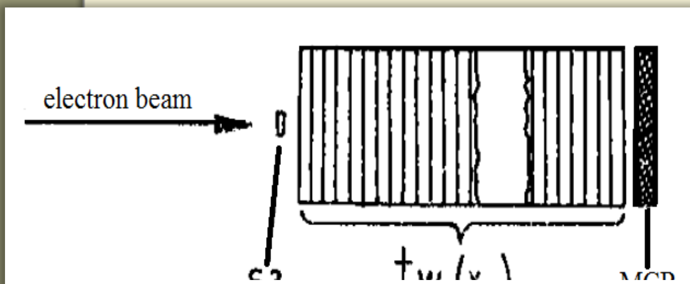


MCP detection efficiency from Hamamatsu catalog

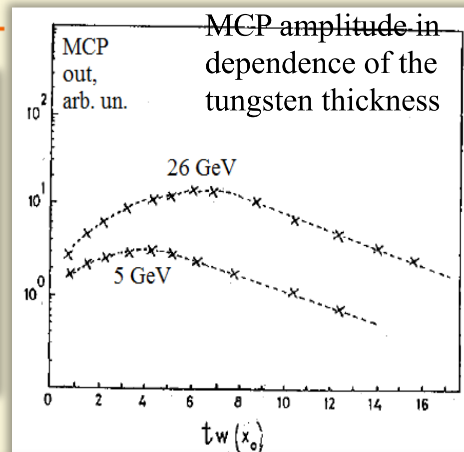
Types of Radiation	Energy or Wavelength	Detection Efficiency (%)
Electron	0.2 keV to 2 keV	50 to 85
	2 keV to 50 keV	10 to 60
Ion (H^+, He^+, Ar^+)	0.5 keV to 2 keV	5 to 58
	2 keV to 50 keV	60 to 85
	50 keV to 200 keV	4 to 60
UV	300 Å to 1100 Å	5 to 15
	1100 Å to 1500 Å	1 to 5
Soft X-ray	2 Å to 50 Å	5 to 15
Hard X-ray	0.12 Å to 0.2 Å	to 1
High energy particle (ρ, π)	1 GeV to 10 GeV	to 95
Neutron	2.5 MeV to 14 MeV	0.14 to 0.64

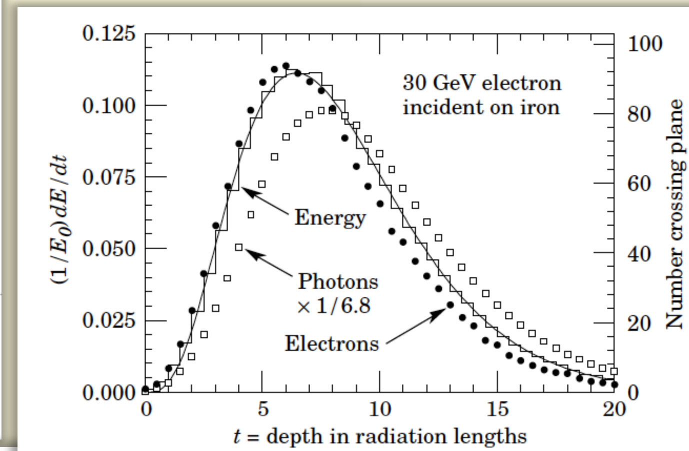
- Secondary particles from EM shower are detected by MCP
  - Signal is proportional to the number of secondaries → energy of parent
  - Most of secondary particles are low energy → MCP very efficient
  - MCP are intrinsically very fast → calorimeter with very fast timing

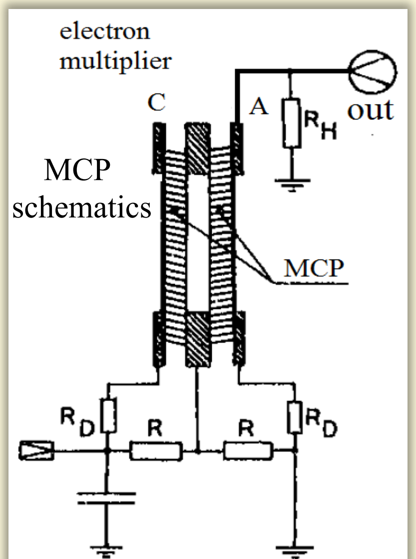
Radiation resistant and fast SM detector

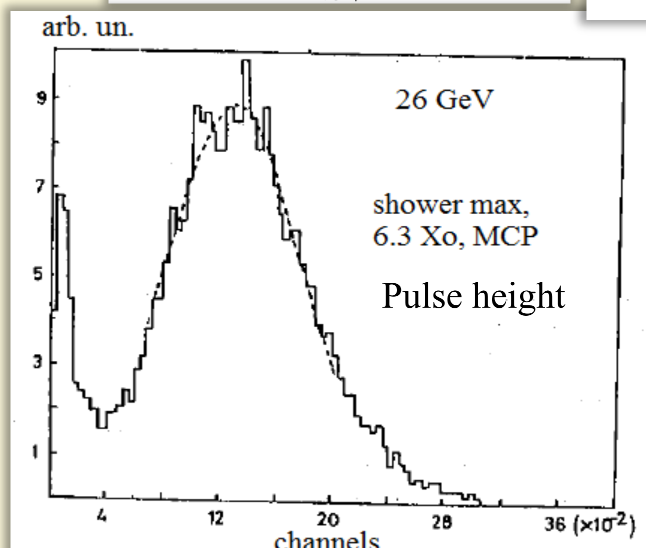


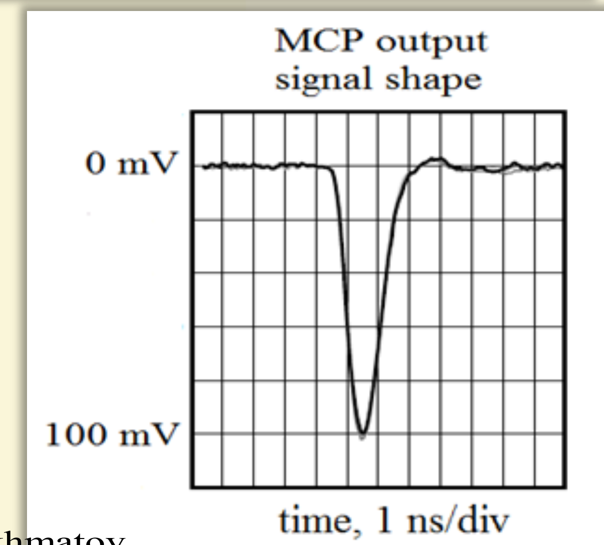
Test beam, tungsten absorber thickness changed







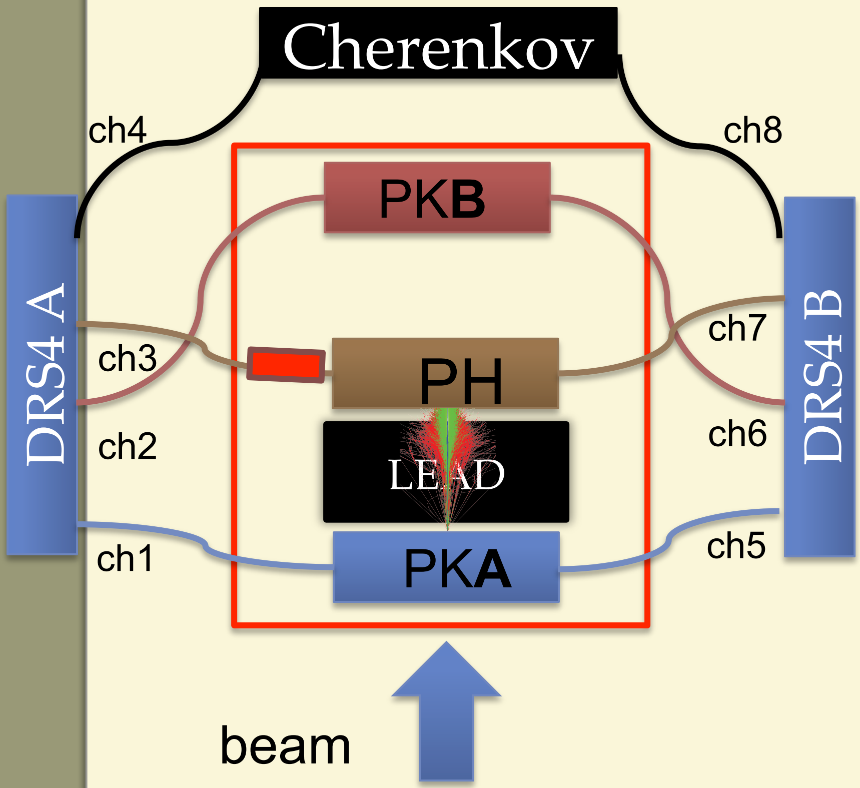




1. A. A. Derevshchikov, V. Yu. Khodyrev, V.I. Kryshkin, V.E. Rakhmatov, A. I. Ronzhin, "On possibility to make a new type of calorimeter: radiation resistant and fast". Preprint IFVE 90-99, Protvino, Russia, 1990.

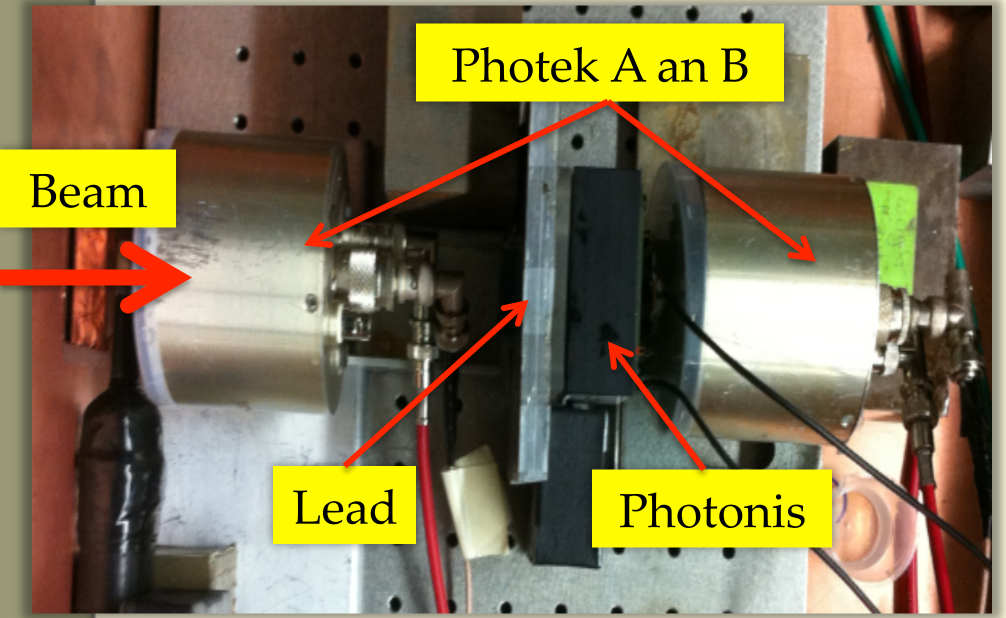
Experimental setup

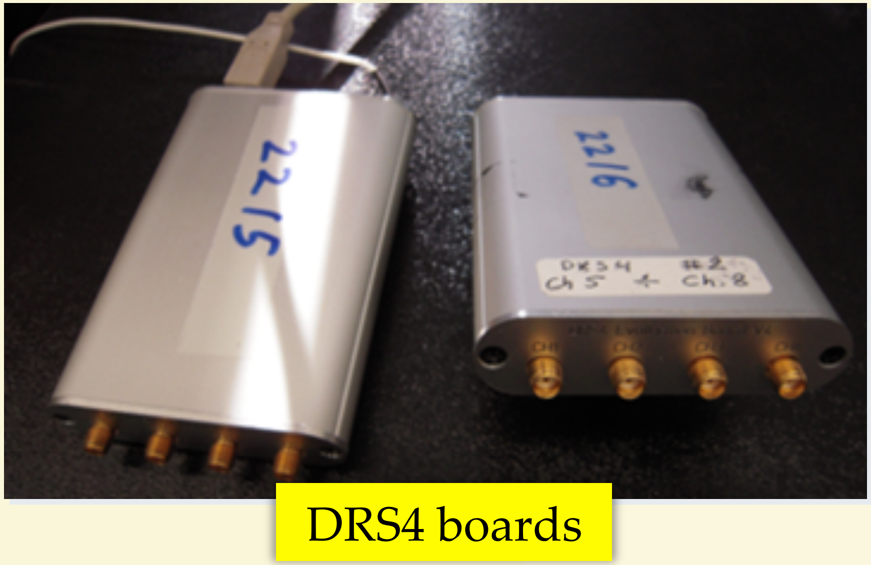
- We performed an experiment in the FNAL MTest area with electron and proton beams (Nov 2013 and Jan 2014):
  - *"Development of a new fast shower maximum detector based on micro channel plates photomultipliers (MCP-PMT) as an active element"*, A. Ronzhin, S. Los, E. Ramberg, M. Spiropulu, A. Apresyan, S. Xie, H. Kim, A. Zatserklyaniy; *NIM **A** 759 (2014) 65-73*



- Two types of MCP-PMTs used
  - 2 units of Photek 240 (***PK A/B***)
  - 1 unit of Photonis (***PH***)
- DAQ is composed of 2 DRS4 waveform digitizer units
  - attenuated input signals from one DRS4 to cover the full dynamic range
  - triggered on scintillator counters
  - Cherenkov radiator used to select electron events

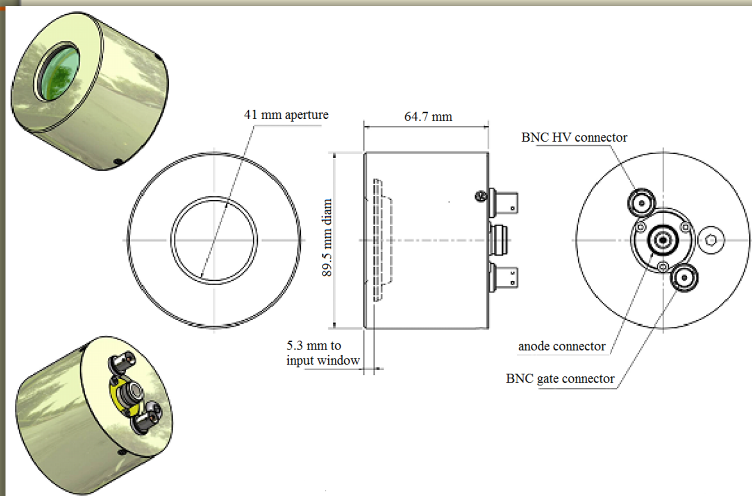
Test beam setup



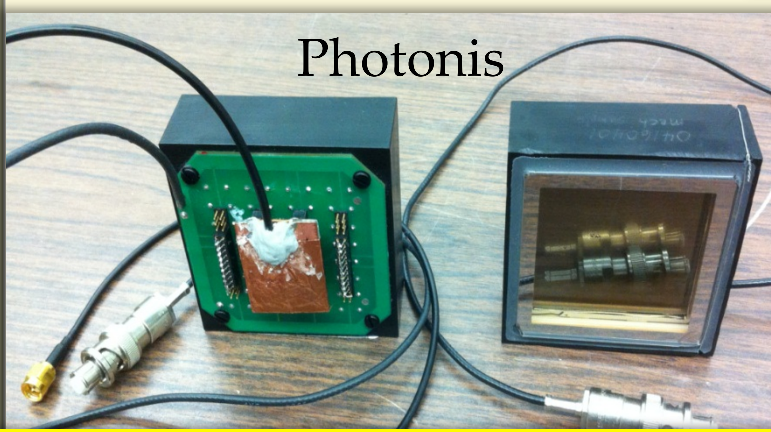


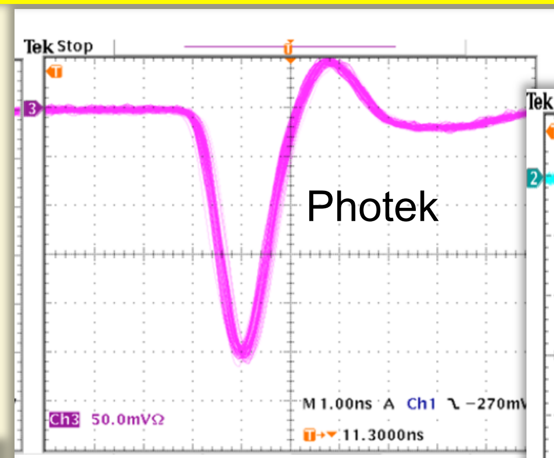
- Primary proton beam: 120 GeV/c, beam of positrons: 12 and 32 GeV/c
- Vary several parameters of the setup
  - Change lead thickness; Add quartz radiators in front of PH

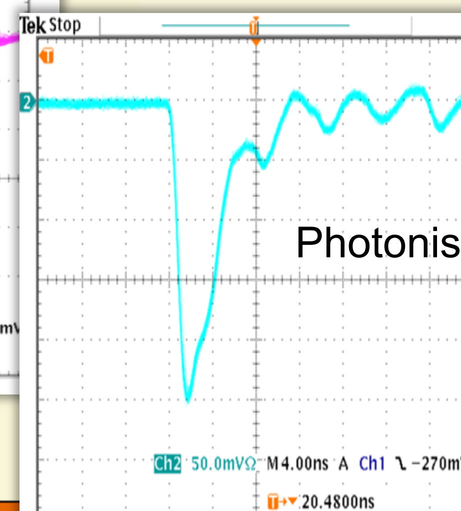
Photek 240 and Photonis MCP-PMT



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



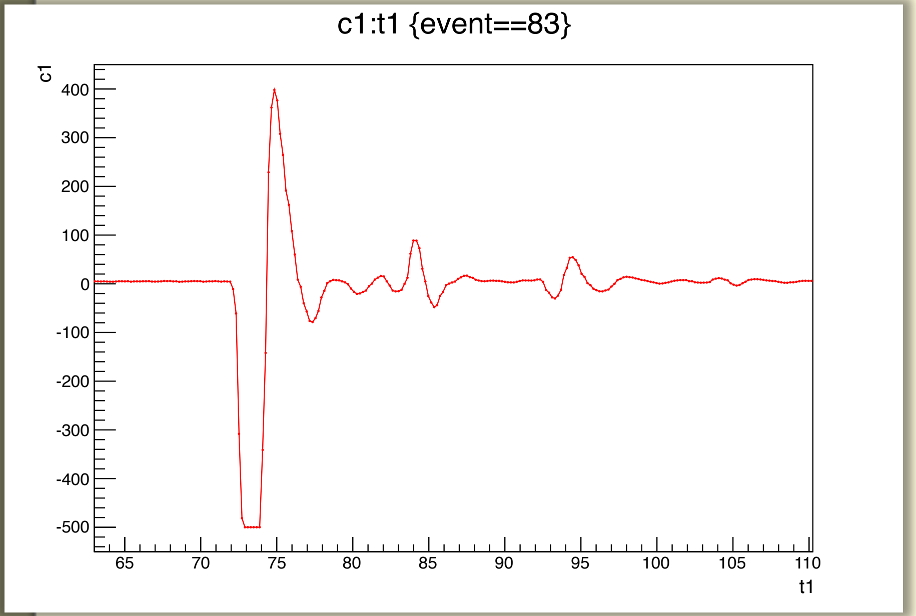


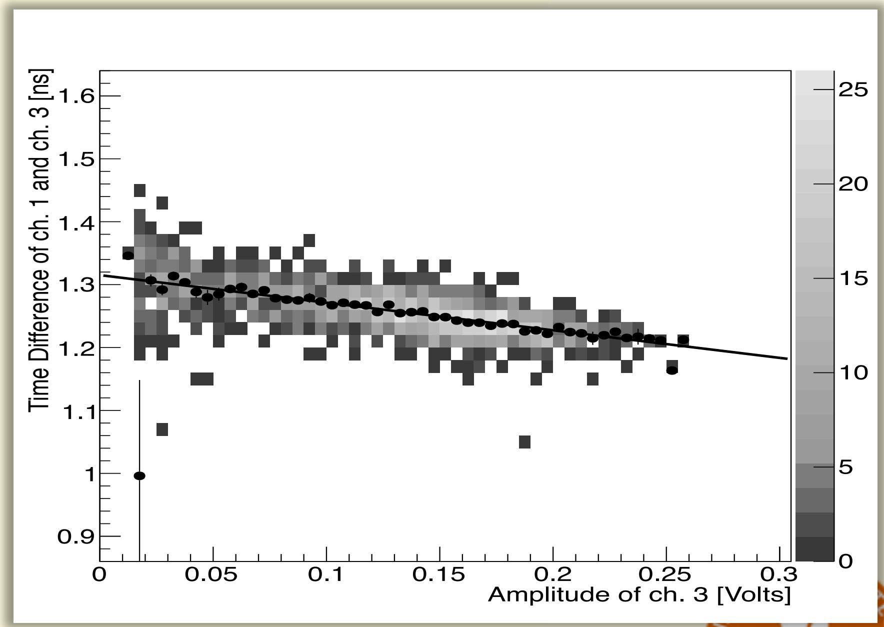


25 μm pore size, 60x60mm^2 sensitive area, rise time~300 ps, SPTR~120 ps, much cheaper than Photek

Event selection and analysis

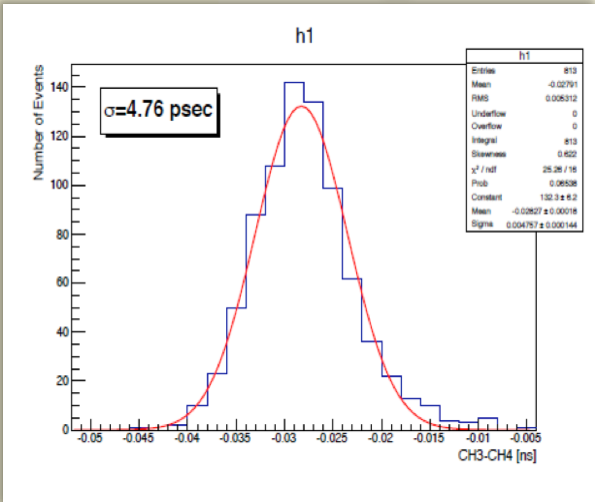
- Assign a time stamp to each event
  - Mean value of Gauss fit to the pulse at maximum
- Event selection to eliminate abnormal pulses
  - Pulses with an irregular peak profile were rejected

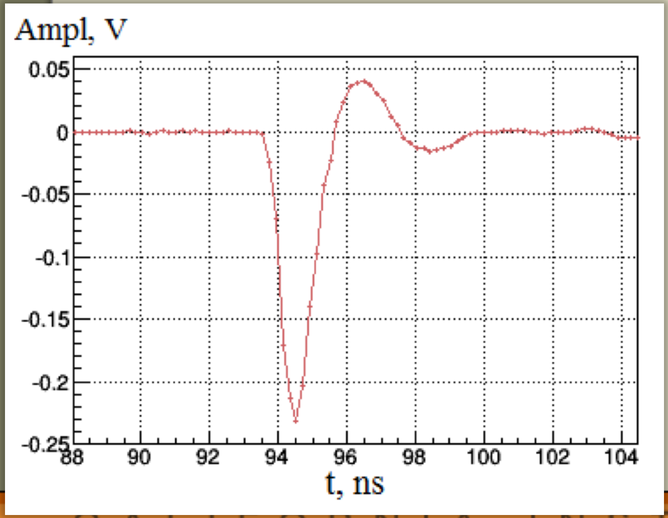




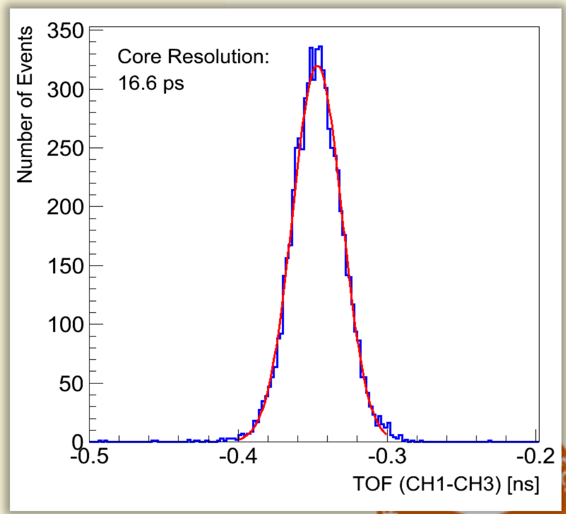
Characterization of the setup

- Electronic time resolution
  - Measure time difference of a split signal from one Photek into same DRS4: **~5 psec**
  - New DRS4 calibration can achieve ~1-2 ps
    - S. Ritt: https://indico.cern.ch/event/306859/session/3/contribution/10
- TOF time resolution for protons
  - Resolution for the two Photek 240 placed in line was found to be **~16 ps**



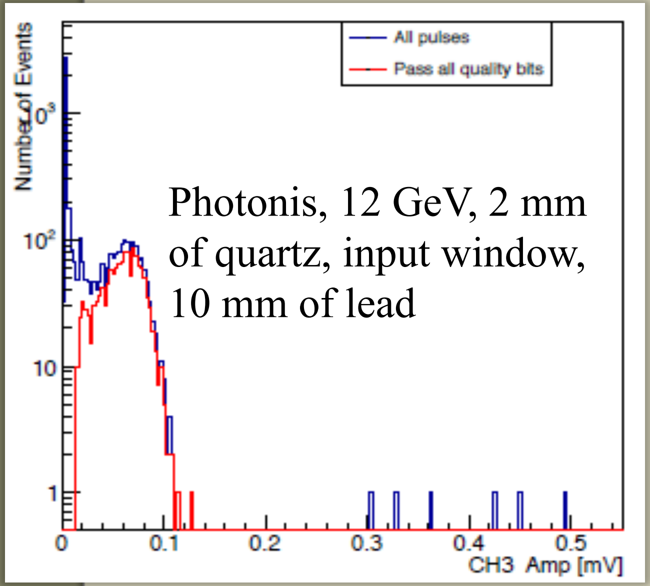


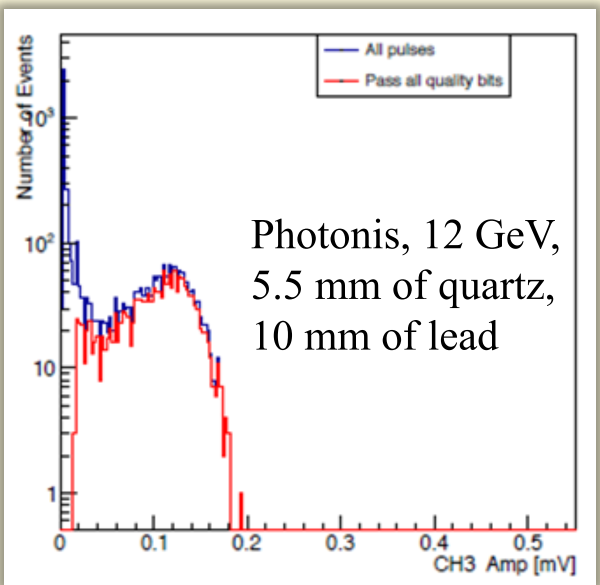
Photek 240 signal recorded by a DRS4 during 120 GeV/c protons run passing through the input window.

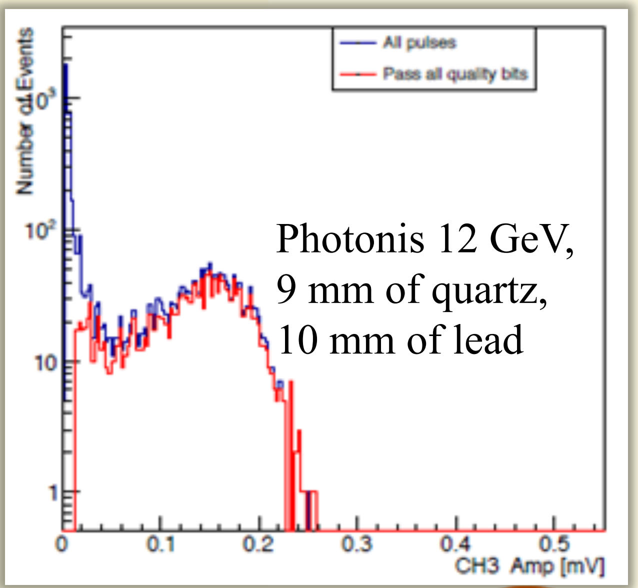


Measurements with e^+ beam

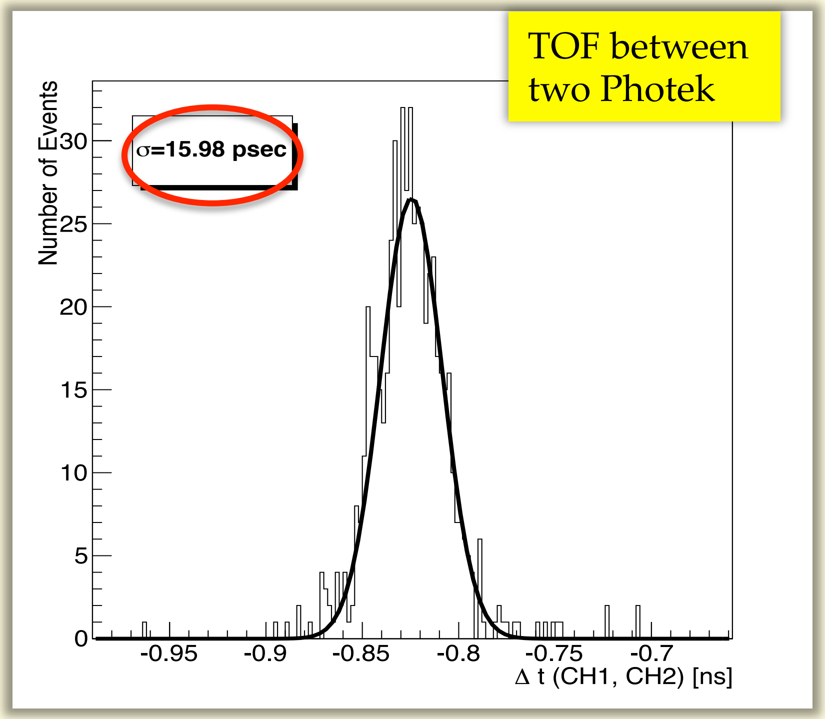
- Observe increase in amplitude with increased quartz thickness

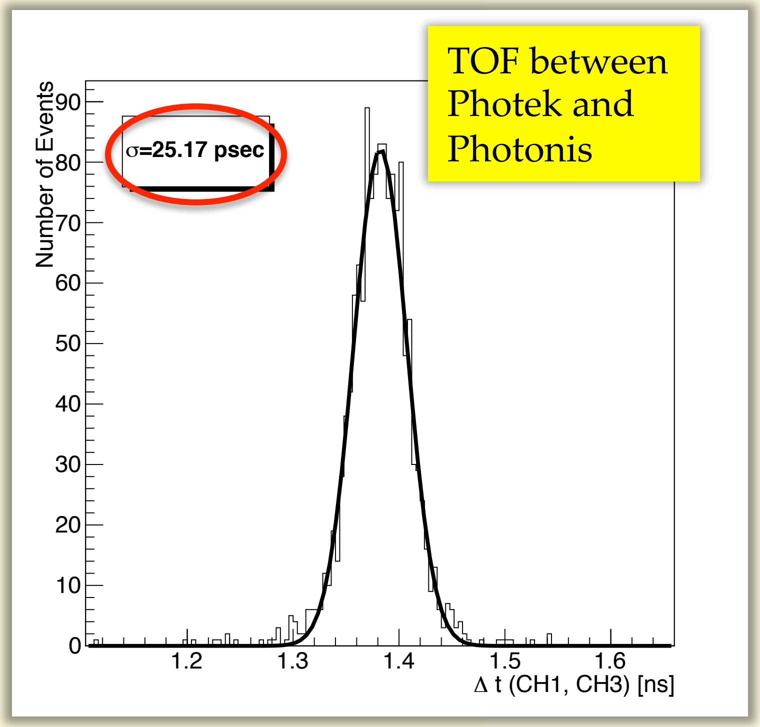






Time resolution and secondary emission



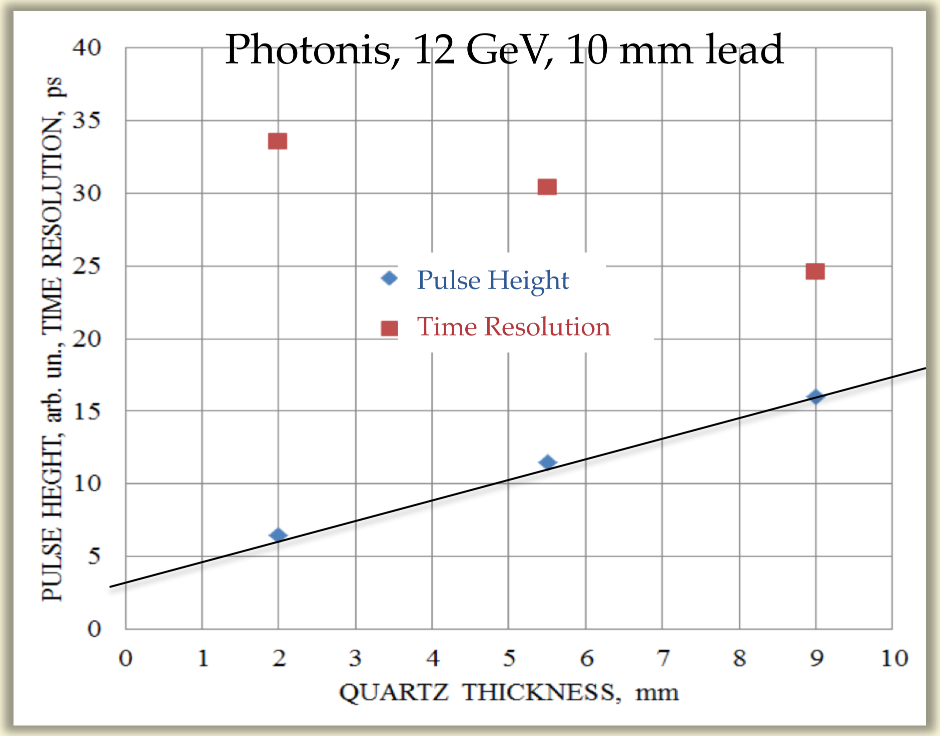


- Time resolution **15-30 ps** achieved in beam for shower arrival

- *No significant difference in TR* at 12 GeV vs 32 GeV beams.
  - No big TR changes *for different lead thickness* in these measurements

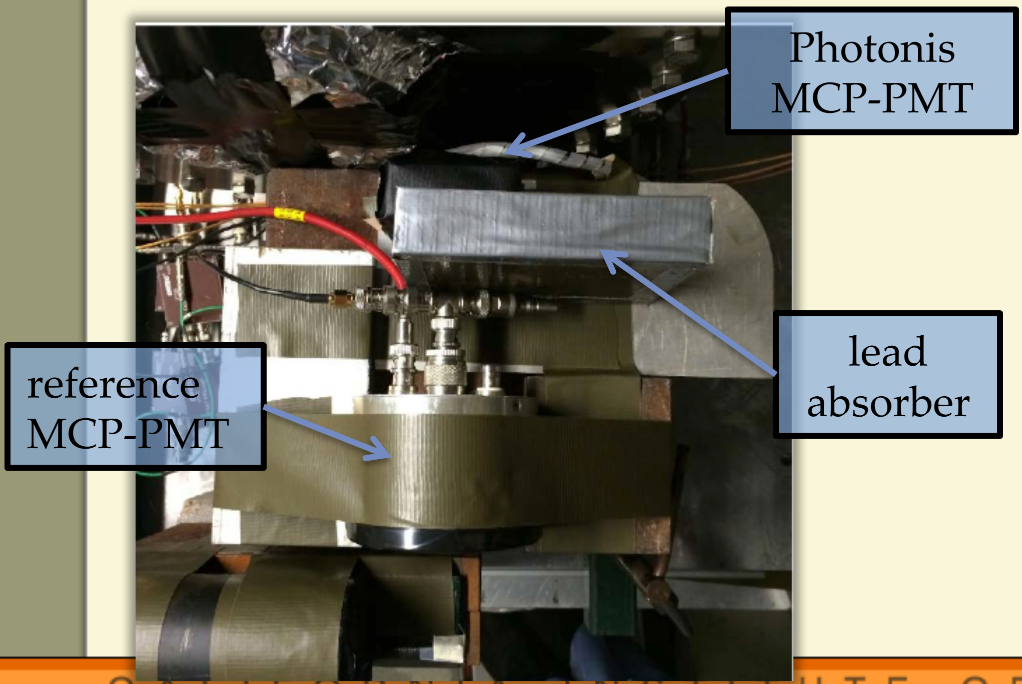
Measurements with e^+ beam

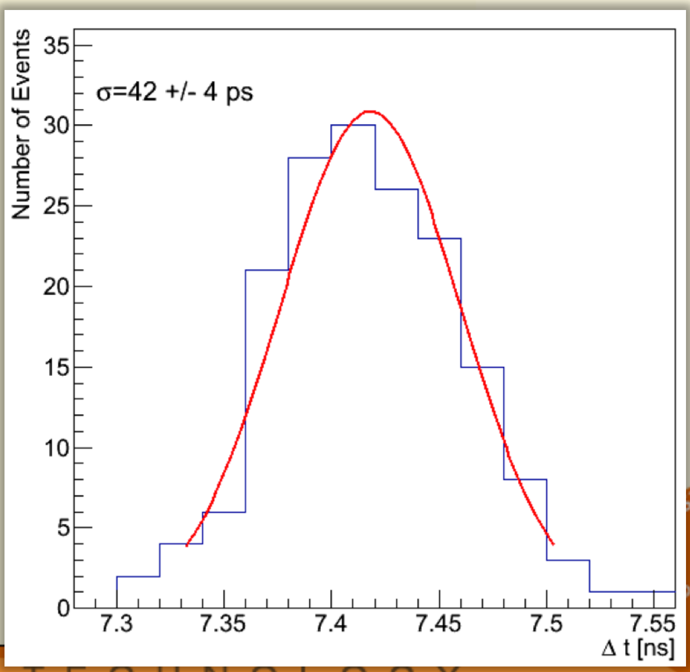
- Shower particles are detected **both** through Cherenkov (in the entry window) **AND** *direct interaction* with the MCP.
  - Significant component from direct detection of the secondary emission
- ~ 70% of the MCP-PMT response is due to the ***secondary emission*** and 30% is due to Cherenkov light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



T-1058: Secondary Emission Calorimeter

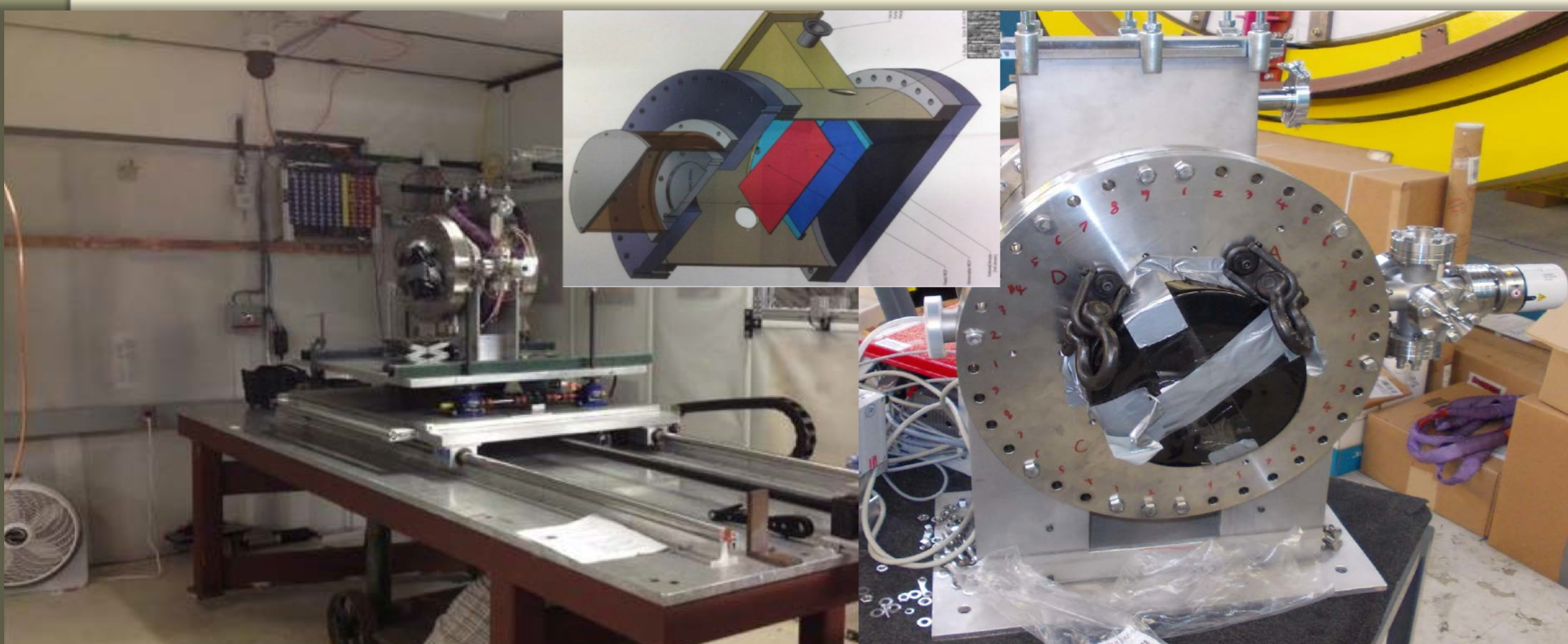
- Similar setup as on previous slide, but using Photonis MCP which allows reverse bias voltage on PC
  - Turn off Photocathode, remove ambiguity Cher/Secondary emission
- Achieve 40 ps resolution, as expected from extrapolation of data from previous page.





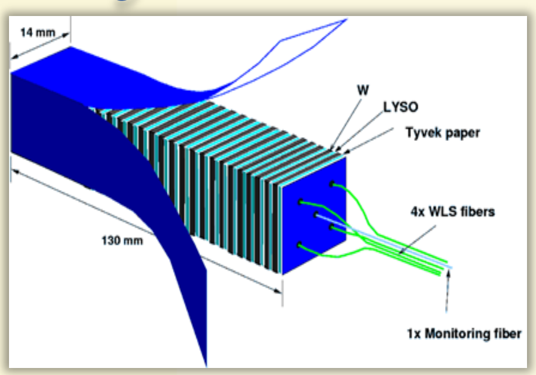
T-1058: Secondary Emission Calorimeter

- Tungsten / MCP sampling calorimeter in a vacuum vessel.
- PSEC4 or DRS4 readout, LAPPD MCP layer.
- First beam test 2 weeks ago with one MCP layer live.
- Option for a shower max timing layer in LHC detectors.

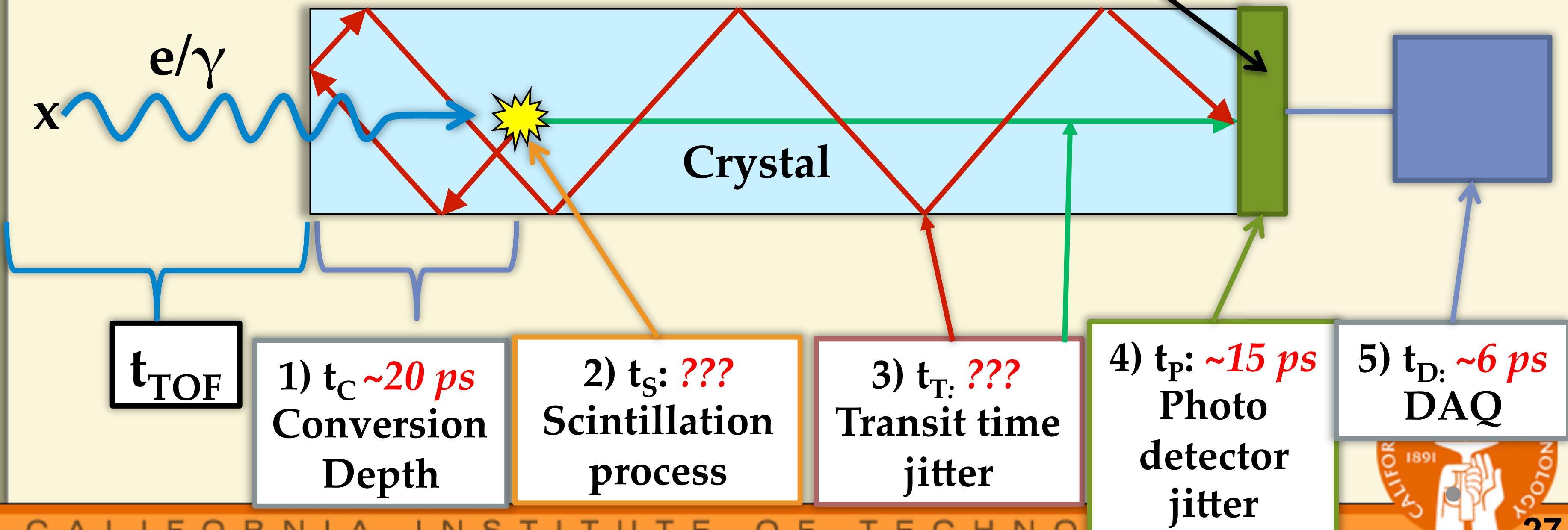


Crystal calorimeters

Precision timing with crystals



- Main ingredients can be factorized
- EM shower development (t_C) shown ~*20* psec; *NIM* **A** *749* (2014) p 65-73
  - In the same paper we studied the effects of t_P and t_D: ~15psec and 6psec
- Test beam in August: focus on studies of t_S and t_T



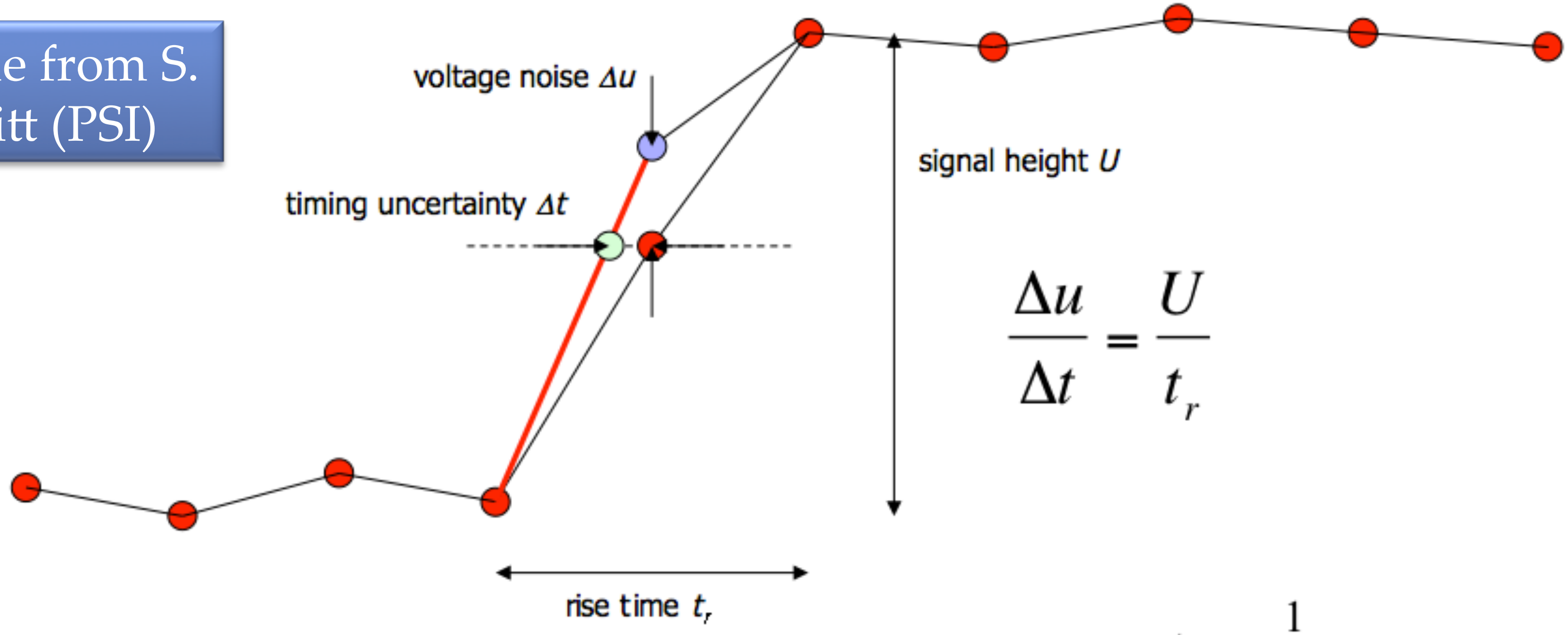
Precision timing with crystals

- With the secondary emission setup we showed that
  - Timing resolution of the MCP-PMT (t_P) is about 11 ps
  - The electronic time resolution of the (t_D) DAQ system is about 6 ps
  - Time of arrival of the front of an electromagnetic shower can be determined with a precision < 20 ps.
  - ➔ we conclude that the associated time scale t_C does not contribute significantly to the time resolution of our experimental setup.

- To complete the characterization of the TOF resolution
  - Focus on contributions due to fluctuations in the scintillation process (t_S), and in the optical transit (t_T) to the photodetector.

How is timing resolution affected?

Slide from S. Ritt (PSI)



$$\frac{\Delta u}{\Delta t} = \frac{U}{t_r}$$

$$t_r \approx \frac{1}{3 f_{3dB}}$$

$$\Delta t = \frac{\Delta u}{U} \cdot t_r = \frac{\Delta u}{U\sqrt{n}} \cdot t_r = \frac{\Delta u}{U} \cdot \frac{t_r}{\sqrt{t_r \cdot f_s}} = \frac{\Delta u}{U} \cdot \frac{\sqrt{t_r}}{\sqrt{f_s}} = \frac{\Delta u}{U} \cdot \frac{1}{\sqrt{3 f_s \cdot f_{3dB}}}$$

number of samples on slope

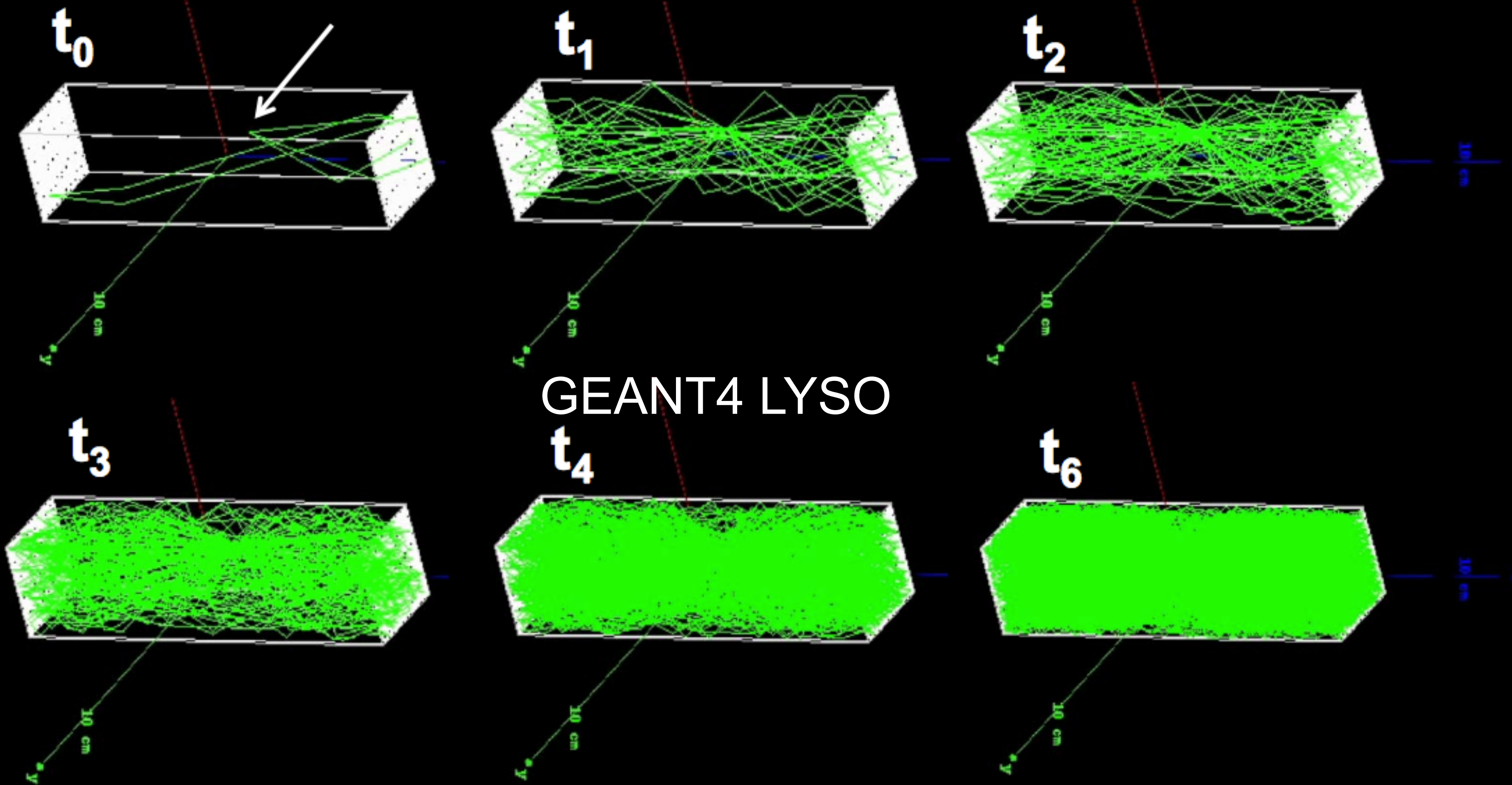
Simplified estimation!

Precision timing with crystals

- Characterize the impact of t_S and t_T we use two independent setups which isolates the two components.
  1. Effect of scintillation (t_S): → measure TOF resolution with a sampling calorimeter composed of a (1.7cm)3 LYSO cube as the active scintillating element behind about $4.5X_0$ of lead.
  2. Optical transport effects (t_T): → measuring TOF resolution with a LYSO/W shashlik calorimeter, with light extracted through WLS fibers as well as through direct optical coupling to the edges of a few LYSO layers.

Photon Traces in LYSO Crystal

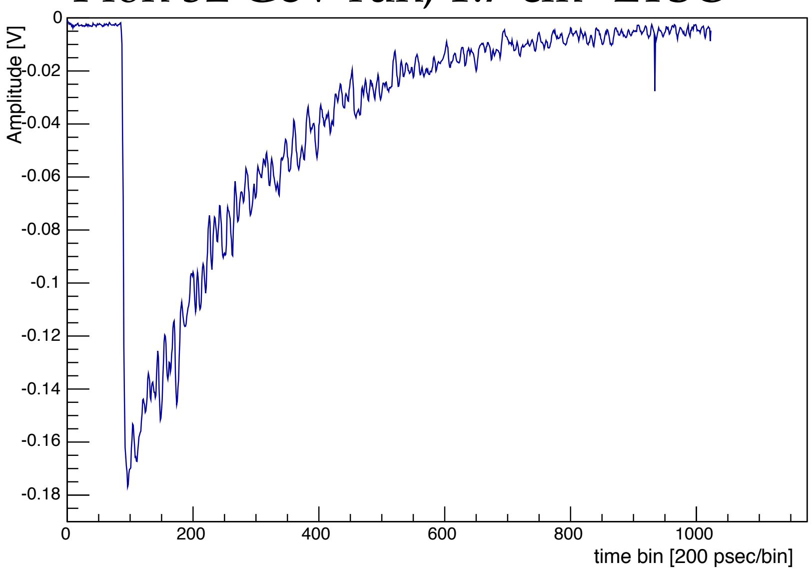
- For high energy showers in high light yield crystals, number of scintillation light yield is very large (>10^5 / GeV).
- Photon detection at one location in the crystal will be an averaged transit time spectrum



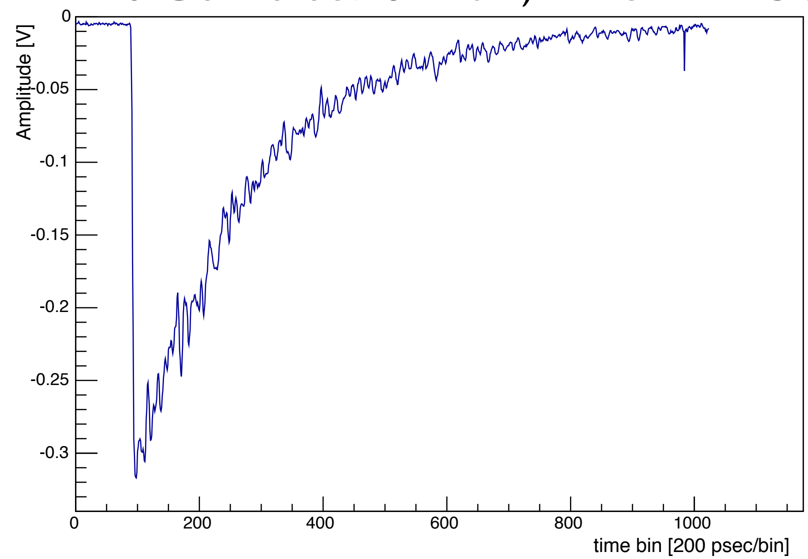
Beam runs

- *120* GeV proton, and *4, 8, 12, 16, 32* GeV runs with electrons
  - Very fast rise time of scintillating crystal.
  - No obvious pulse shape dependency on particle type.

Pion 32 GeV run, 1.7 cm^3 LYSO

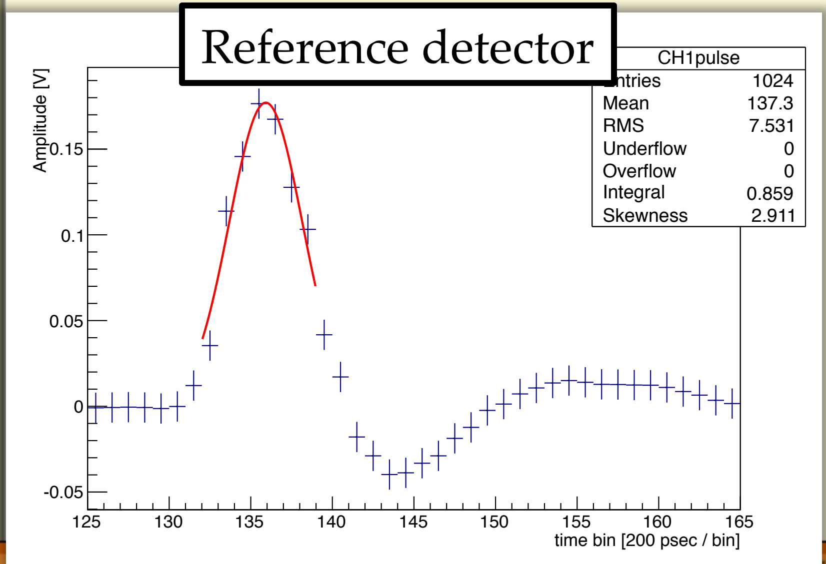


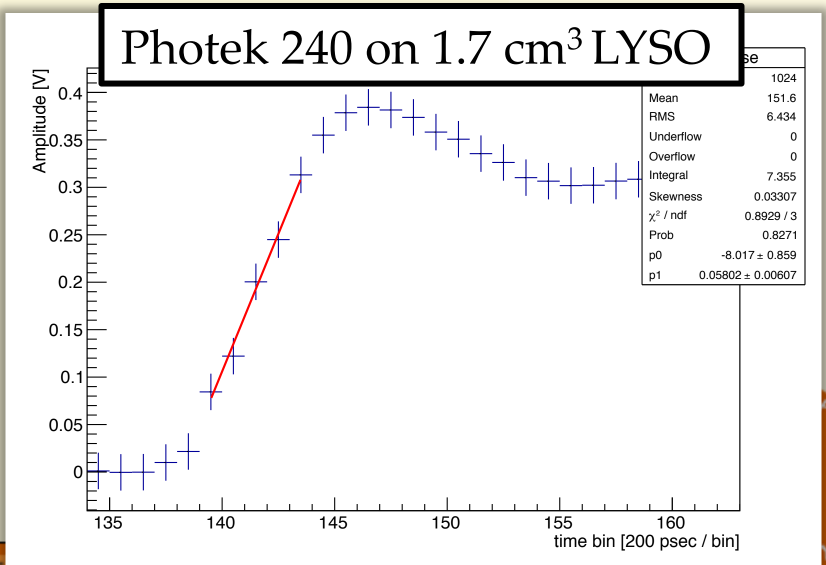
16 GeV electron run, 1.7 cm^3 LYSO



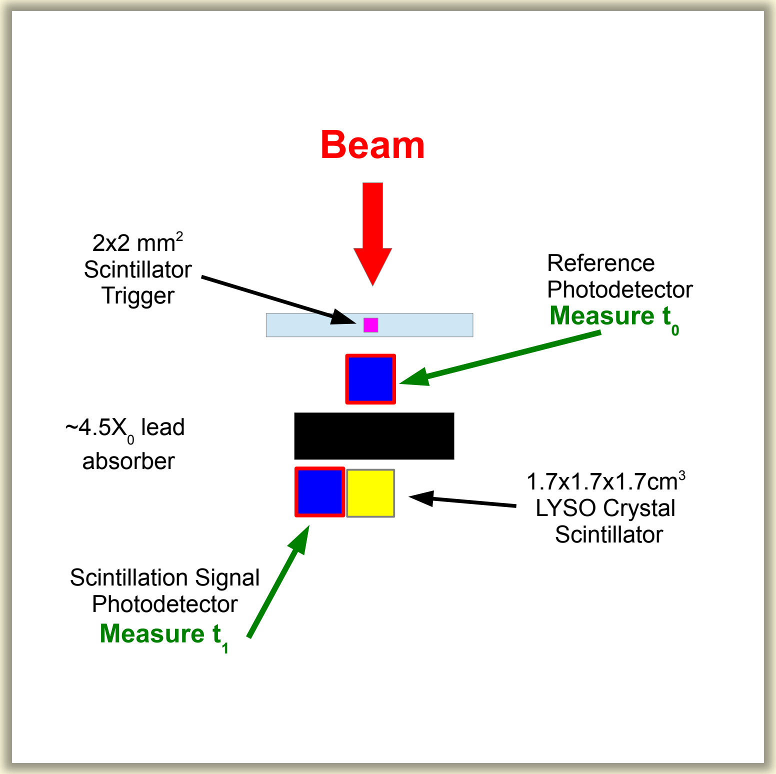
Time reconstruction

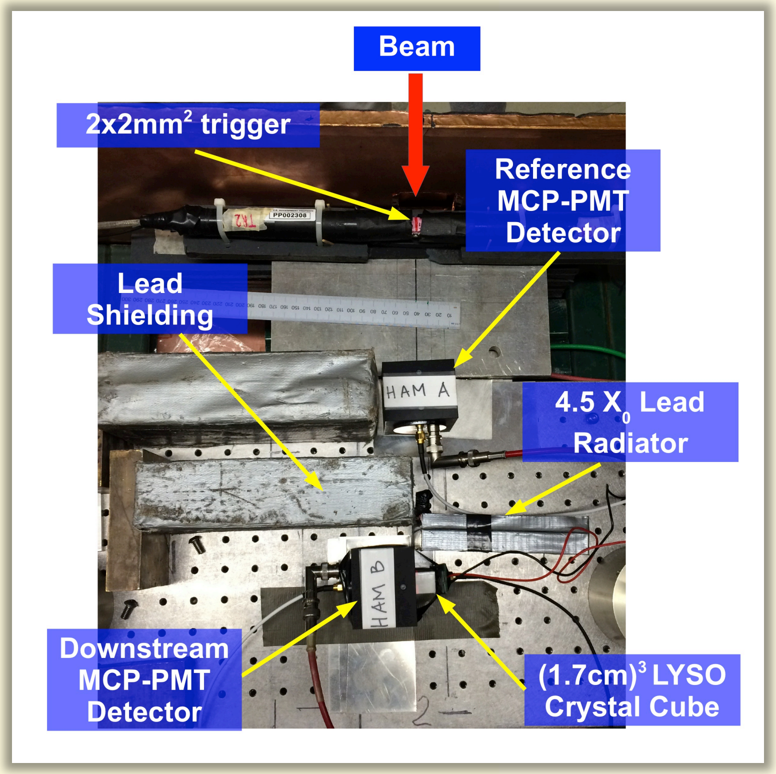
- Measure the time of flight resolution between reference MCP-PMT and scintillation light
  - Signal in the reference are from Cherenkov light in the MCP-PMT window
- Time stamps in the detectors are reconstructed with:
  - Mean of a Gauss fit near the pulse maximum for the reference detector
  - Constant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





Experimental setup: Scintillation Time t_S

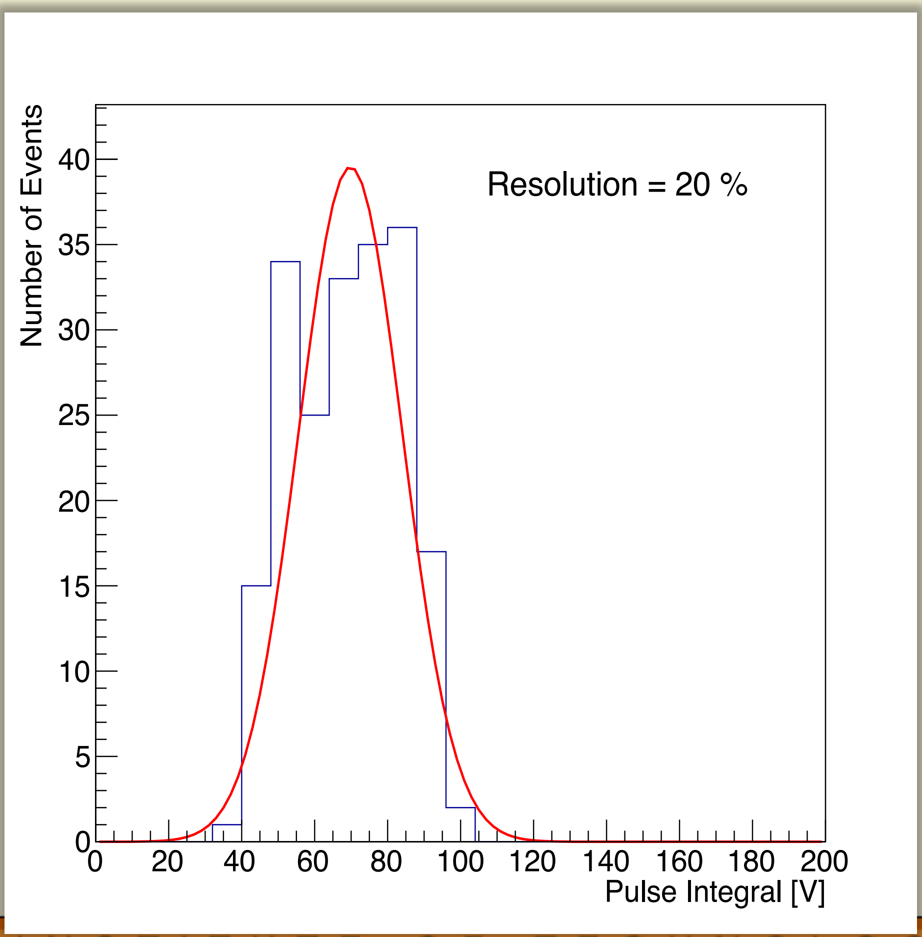




- Study the effect of scintillation (of LYSO) on time resolution
  - Minimize the effect of optical transit by using a relatively small LYSO crystal (1.7cm x 1.7cm x 1.7cm cube)

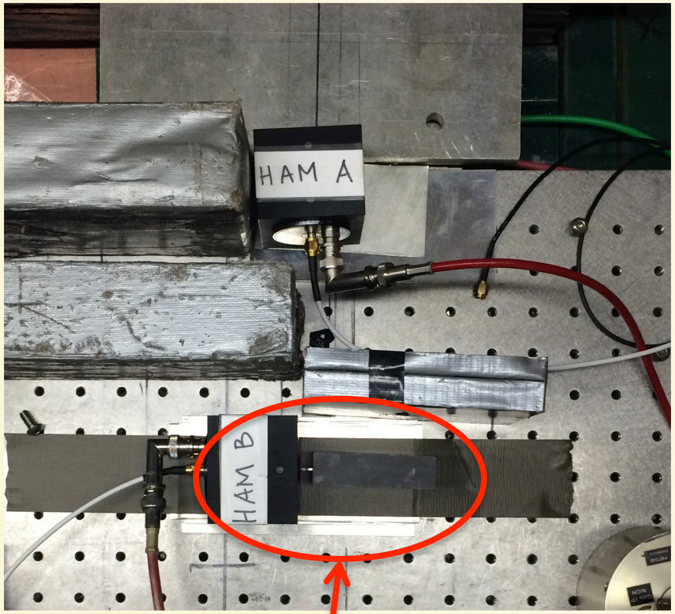
An aside on light detection

- LYSO cube is small in size, capture small portion of shower
  - ~20% resolution at 32 GeV e^- beam



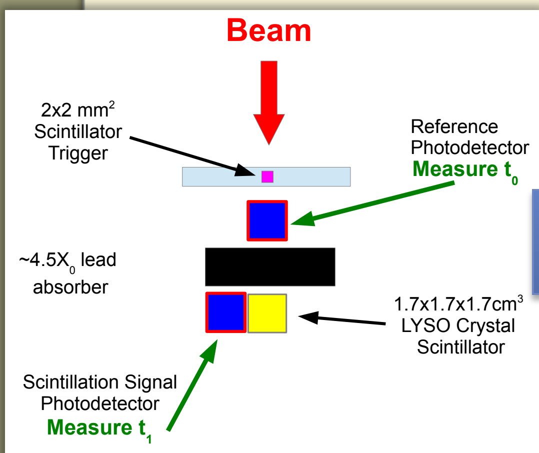
An aside on light detection

- Dedicated runs with no LYSO in the beam
  - Stray *"shower-type"* events with Photek **> *80%*** contamination: *scintillation* signal can't be reliably extracted
  - Same setup with Hamamatsu has **< *10%*** contamination: negligible effect on the scintillation signal.
  - ✧ ***Use Hamamatsu MCP in the following***

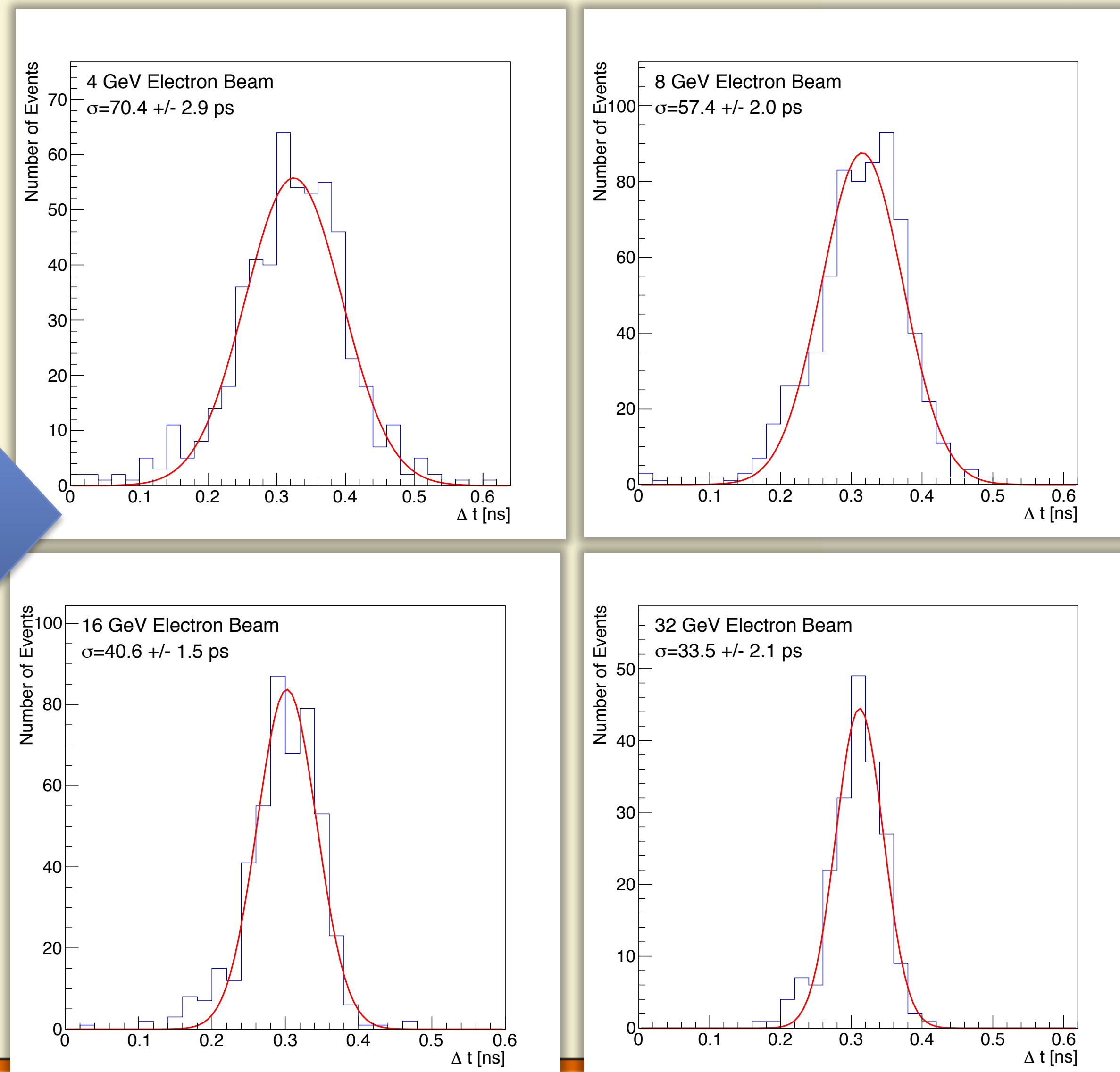


NO LYSO

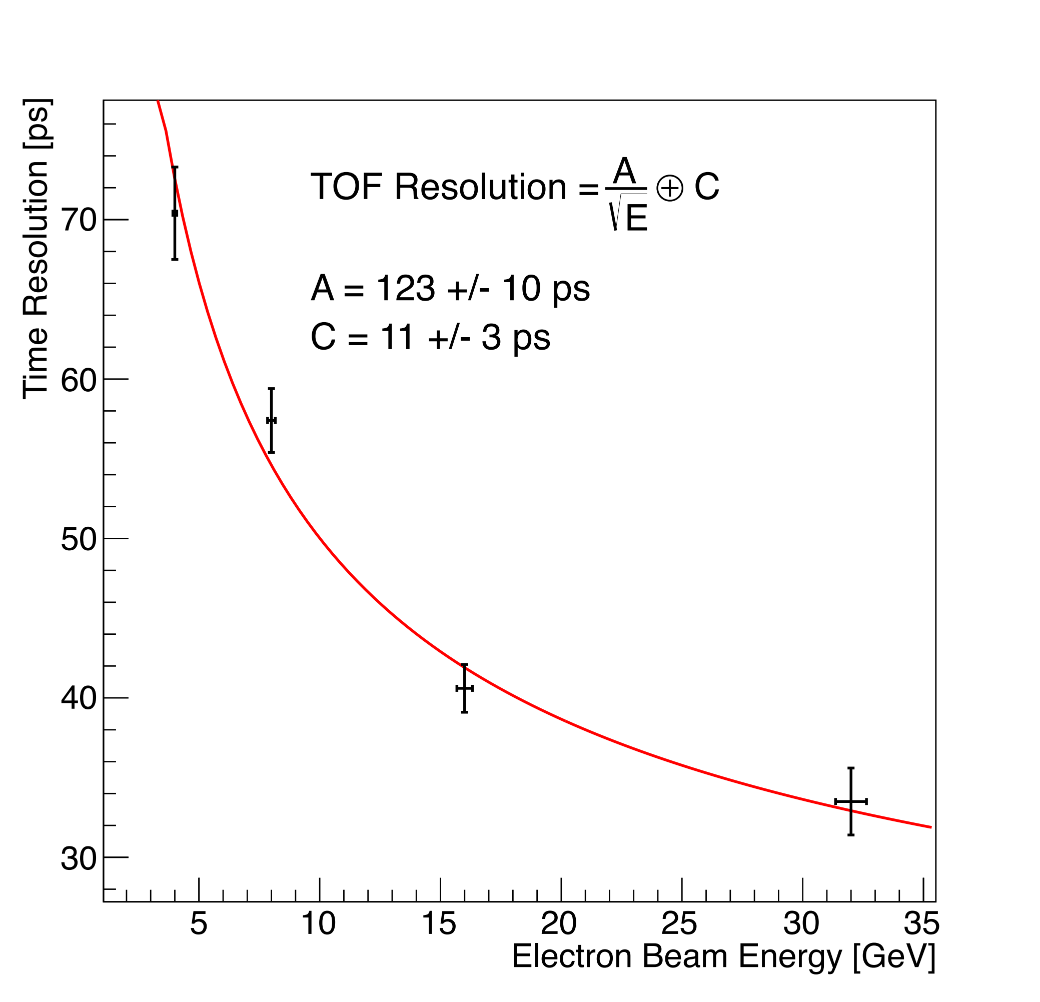
TOF Measurements (1.7 cm^3 LYSO)



measure t_1-t_0

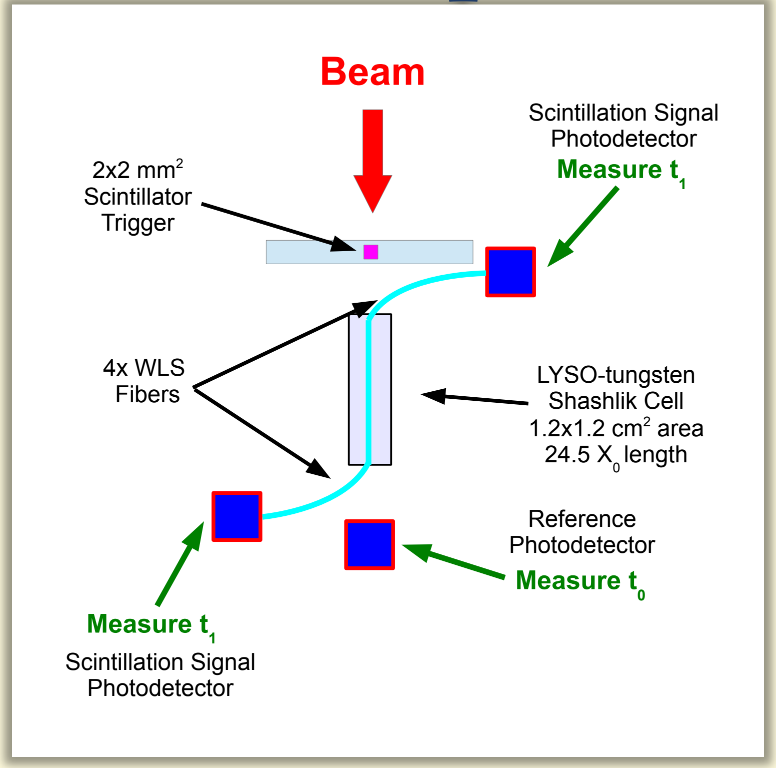


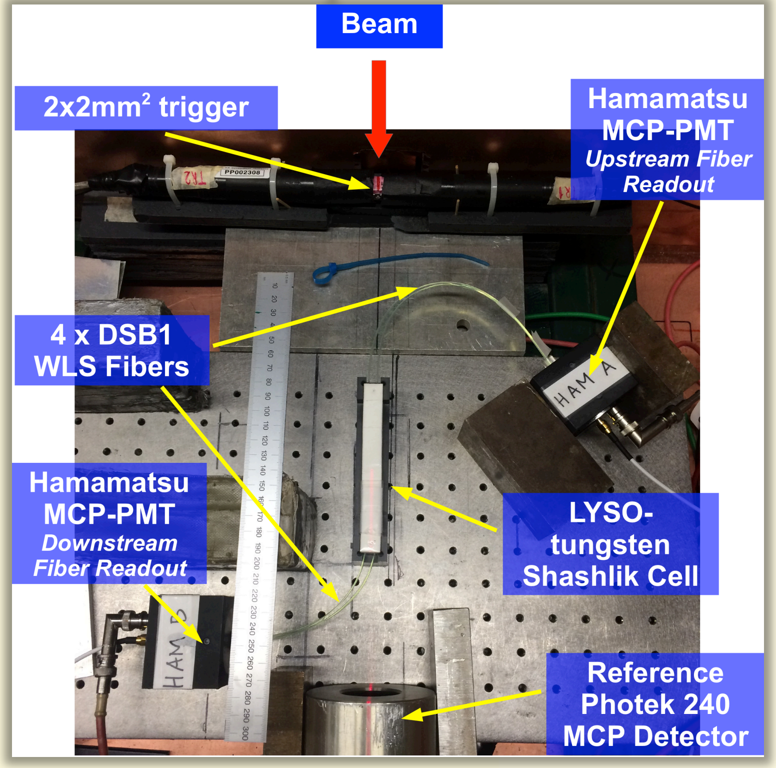
Time resolution



- Note: energy contained in the cube is a small fraction of beam energy
- Subtracting the contributions from DAQ, PMT and trigger size: **t_S<20 ps**

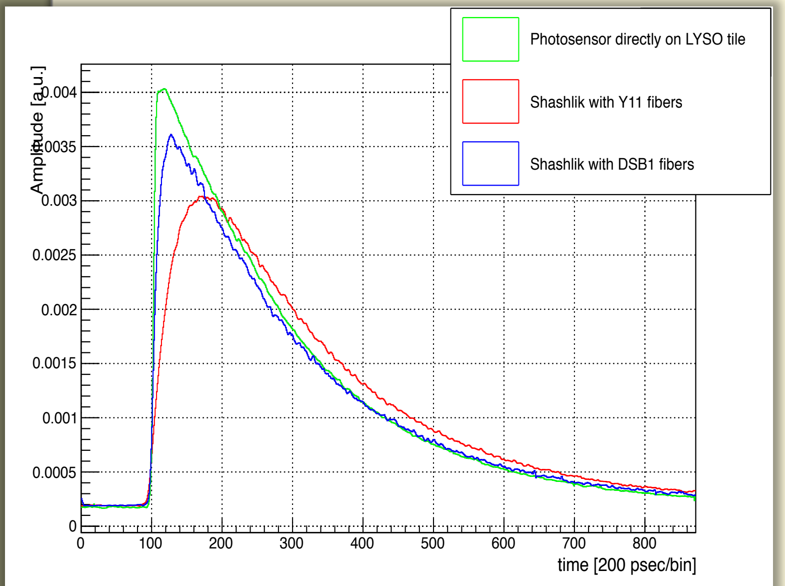
Experimental setup: Optical Transit t_T

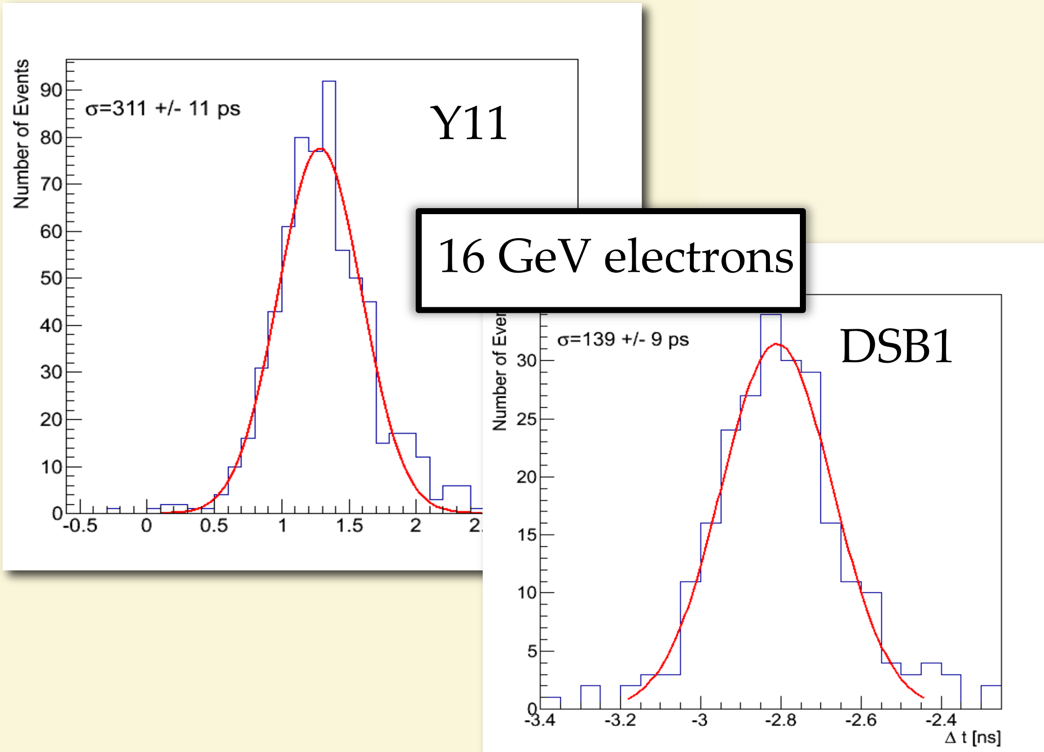




1. **Maximize** optical transit time jitter: read Shashlik cell fibers
   - WLS fiber readout further modulates the pulse: study the effect
2. **Minimize** optical transit jitter: directly couple the PMT on a single LYSO tile

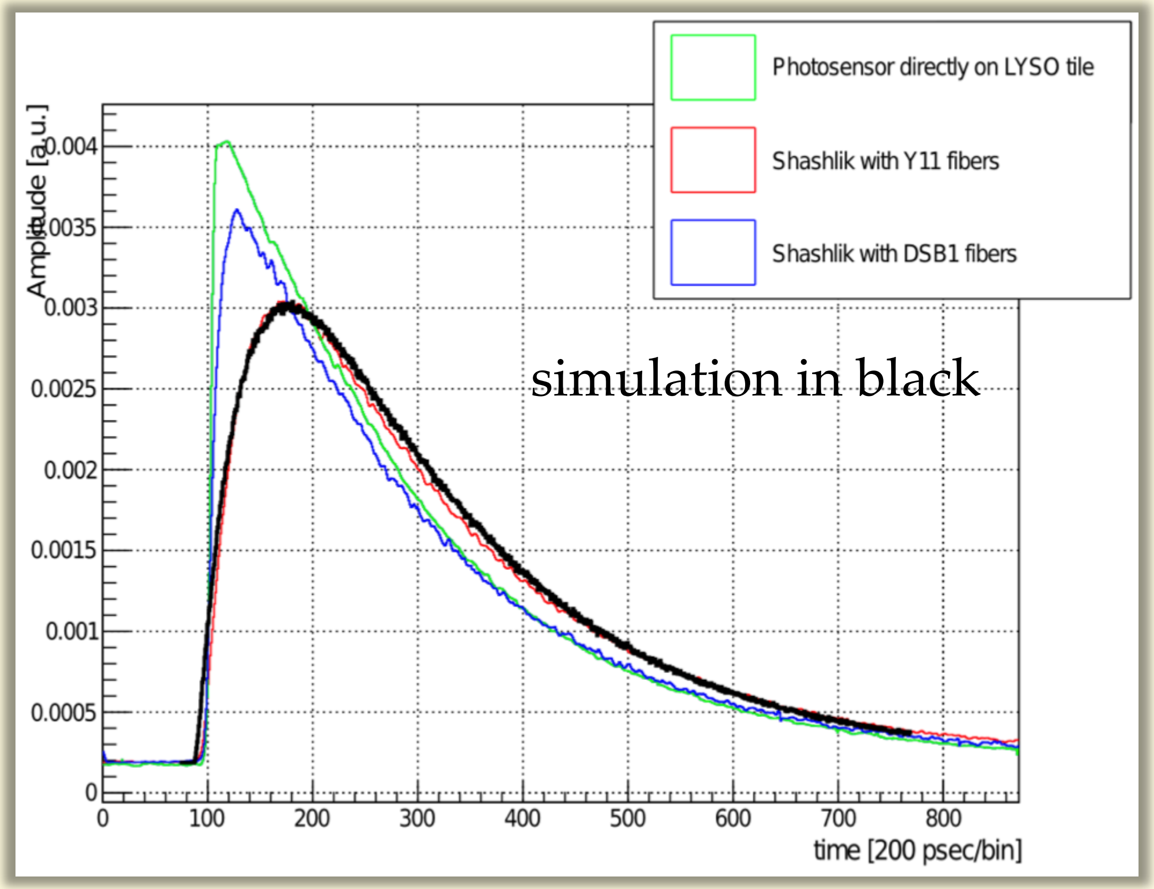
Impact of the WLS material





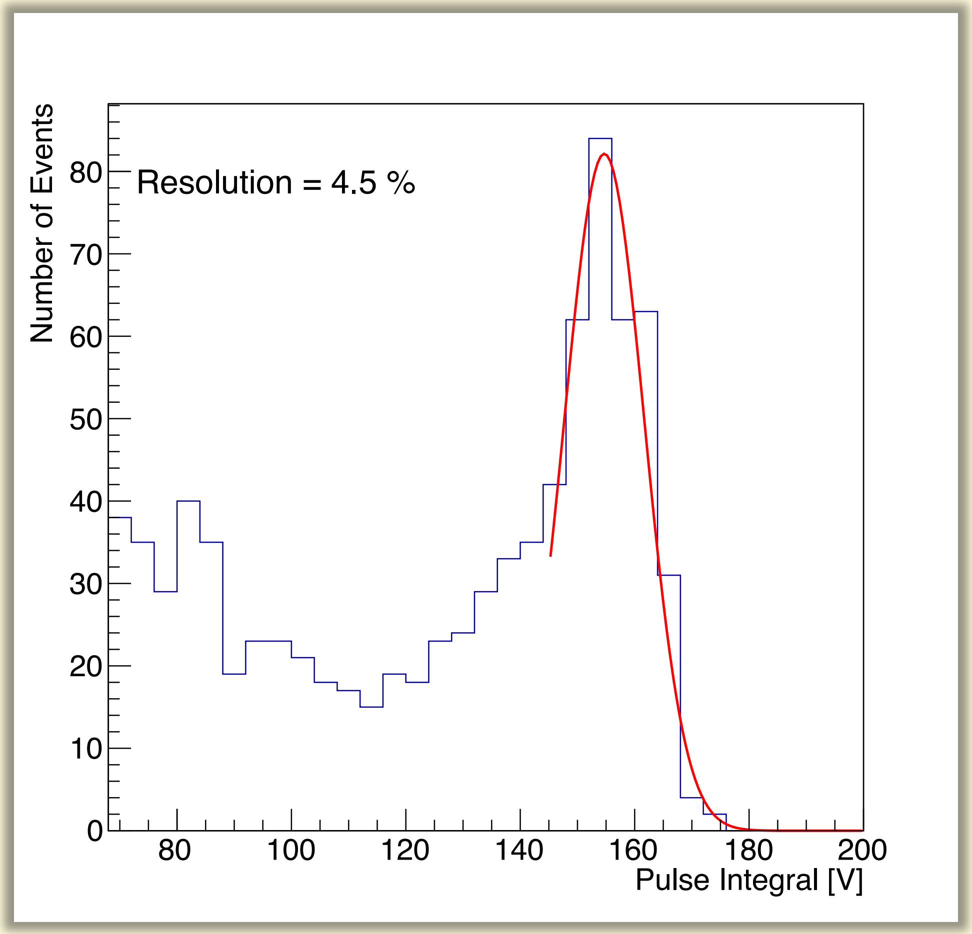
- Compare pulse shapes of different WLS materials : Y11 vs DSB fibers provided by Randy Ruchti
  - Significantly faster rise time with DSB (~2.4 ns) compared to Y11 (~7.1 ns).
- Timing resolution expected to scale accordingly

Simulation of pulses



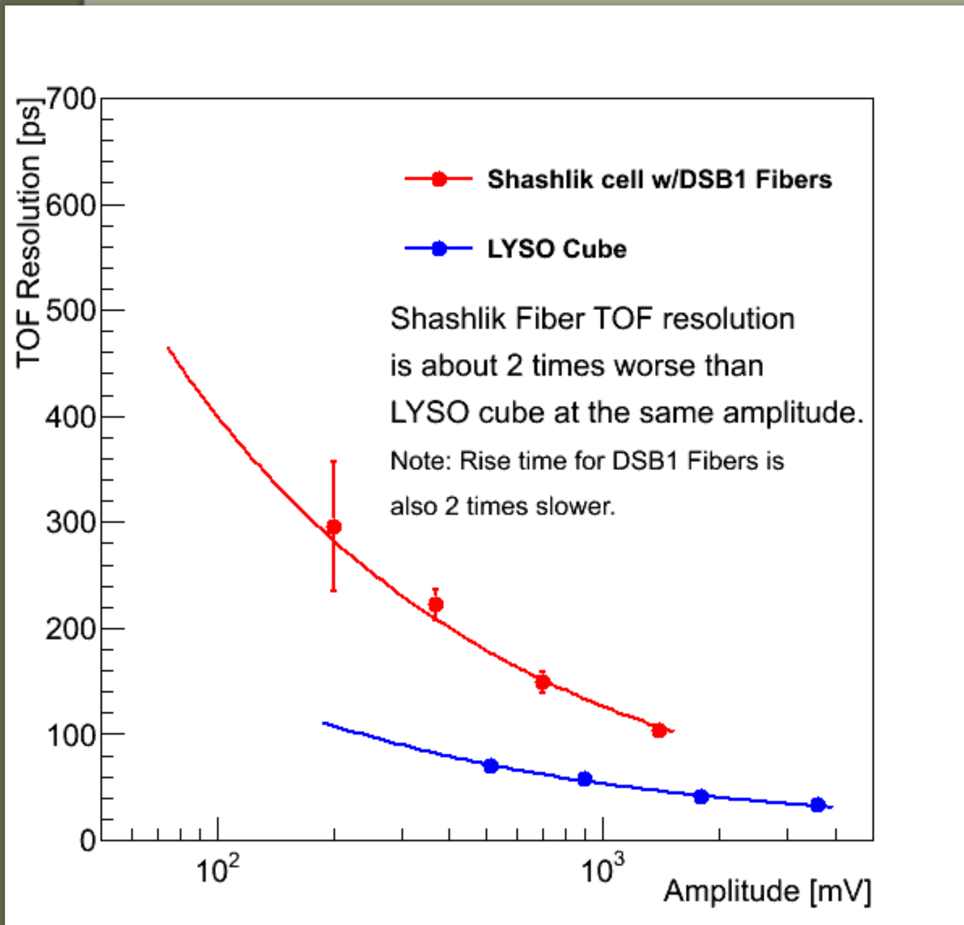
- SLitrani simulation including the LYSO, Y11 properties

Energy measurement



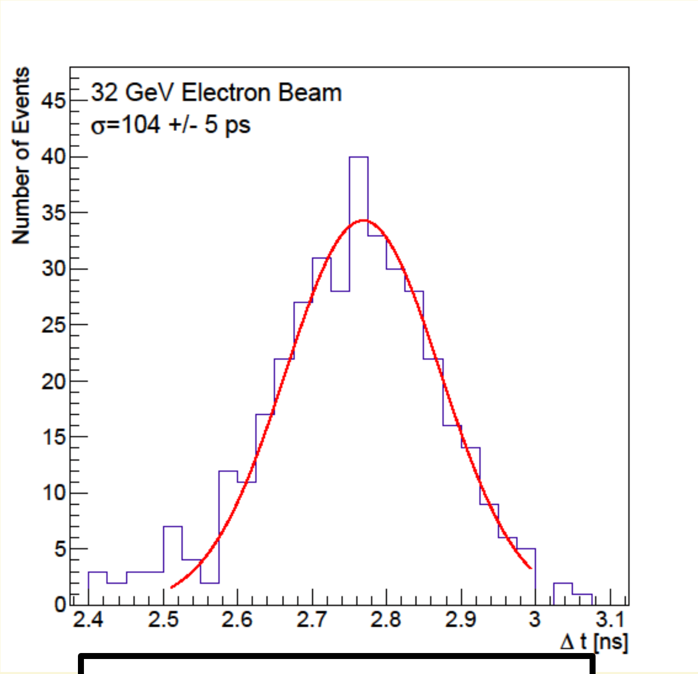
Histogram of the pulse integral for events recorded using the LYSO-tungsten shashlik calorimeter using the DSB1 fibers for a 32 GeVbeam

Time resolution

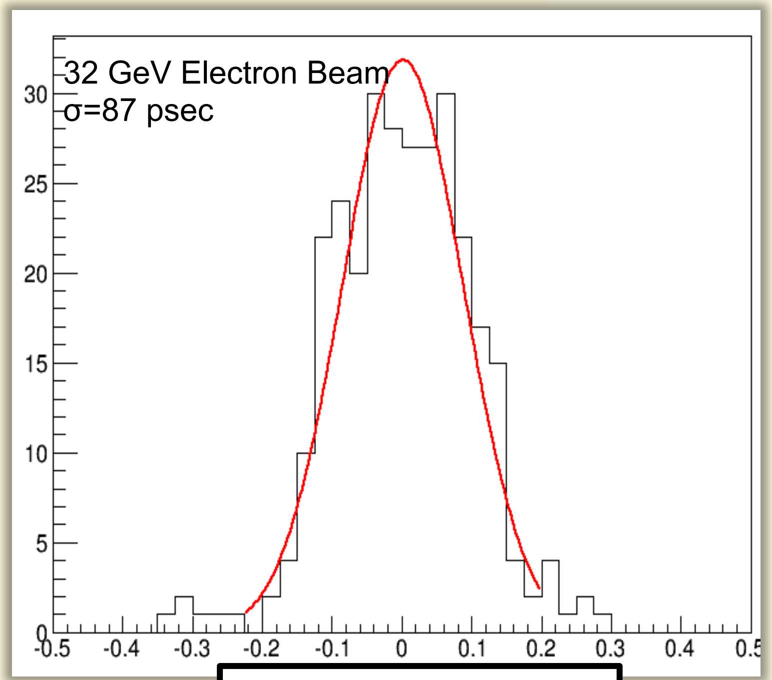


- Observe 1/√E dependence of time resolution
- Contributions from reference time measurement etc.:~20 ps
- ***Few 10 psec resolutions shown to be achievable with Shashlik setup***
- ***Effects of optical transit time jitter seem to become sub-dominant at high photo-statistics***

Algorithm developments



Rising Edge Fit



Full pulse fit

- Indications that the results will improve with better extraction of the time stamp from the events

Future plans

- Optimize light output onto photo detector:
  - Shorter WLS fibers, thicker fibers (currently 1 mm→ go to 1.2 mm)
  - Test capillaries with fast WLS as soon as available
- Optimize pulse reconstruction.
  - Current results use rising edge only: pulse shape should gain performance.
- Better time reference:
  - Need order few ps tag on the incoming particle
- Reduce noise of the DAQ: PSEC4 vs DRS4
- Use full matrix to ensure shower containment:
  - Relative time resolution among adjacent channels.
- SiPM/GaInP photosensors
  - Optimization of the PCB board in collaboration with FNAL experts

Summary

- Timing can be a solution for PU mitigation @HL-LHC
  - Is part of CMS Phase 2 upgrade Technical Proposal
  - Prototype detectors that achieve time resolution of ~20 psec
  - Ongoing work towards developing a technology applicable to the CMS endcap calorimeter upgrade

- New type of calorimeter (SEC) under development at FNAL, in collaboration with UChicago and FNAL

Backup

Photo-detector timing performance

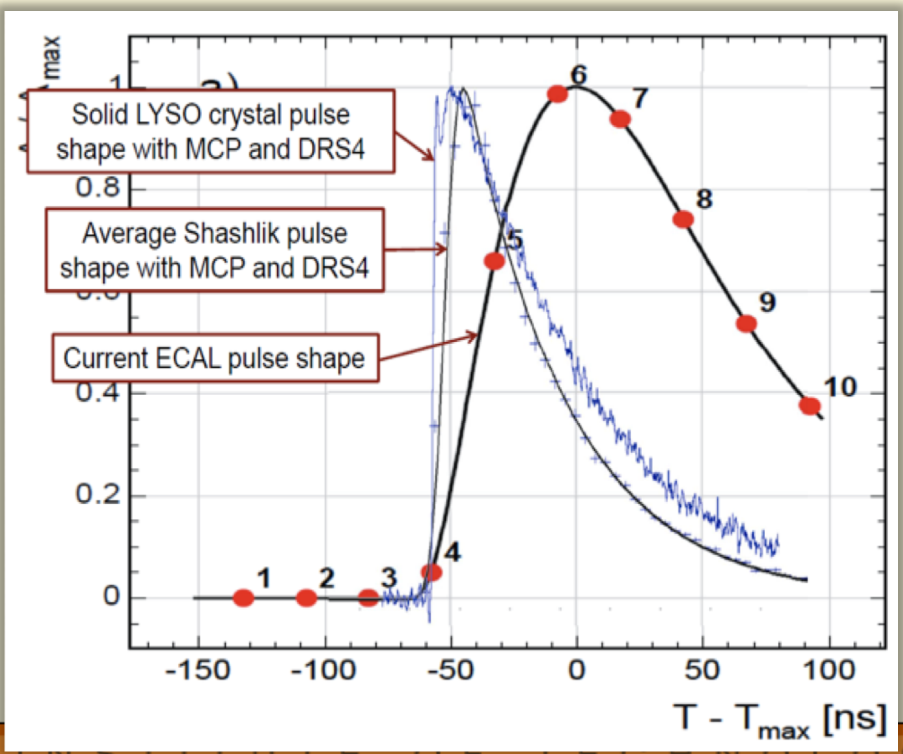
- Typical timing performance parameters of photo detectors
  - rise time, single photon timing jitter, n-photon timing jitter.
- We measure signals with many photons there may be additional factors typically not quoted by manufactures, e.g. the 100000-photon timing jitter.
  - Part of our program is to characterize the timing performance of various photo detectors, such as PMTs, SiPM, GaInP, MCP

Hamamatsu MCP-PMT

Rise Time Ⓖ	150	—	ps
Fall Time Ⓗ	360	—	ps
I.R.F. (FWHM) Ⓘ	45 Ⓙ	—	ps
T.T.S. (FWHM)	—	25 Ⓚ	ps

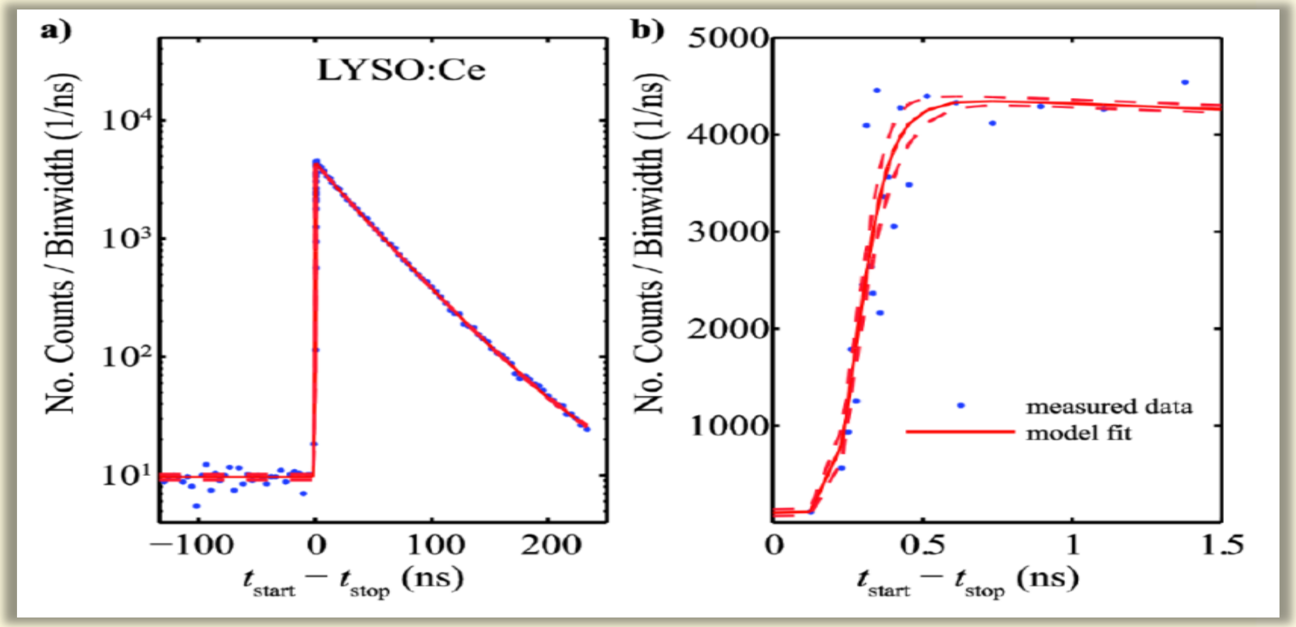
Pulse shape and rising edge

- Solid crystal directly coupled to MCP: rise time ~0.7 ns
  - WLS and solid LYSO rise times are 1 order of magnitude faster than current ECAL
- Plan to do these studies with PbWO; improved timing for EB electronics upgrade



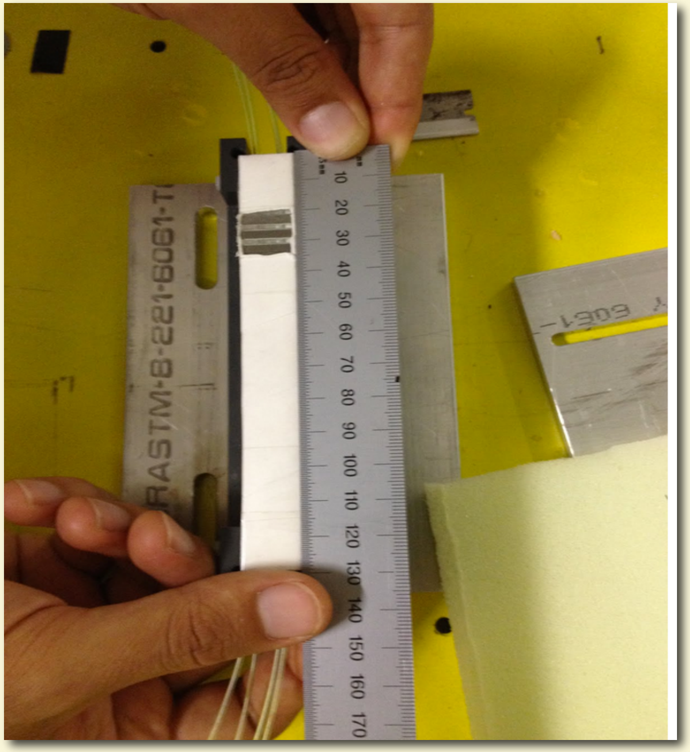
Scintillation and shower properties

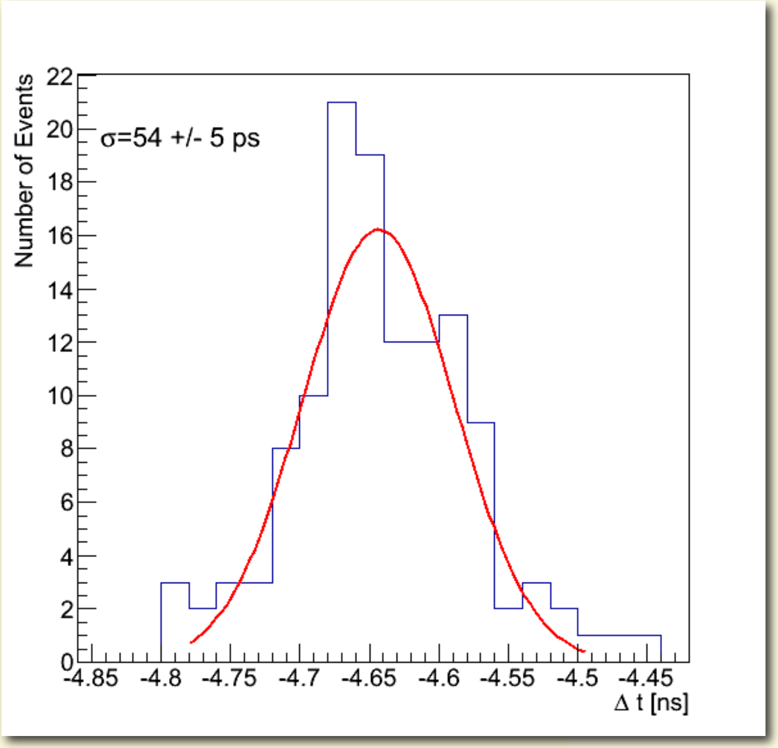
- Timing information is extracted from the leading edge of the signal – the rise time of the light output is important.
  - LYSO: Scintillation light rise time t_R = 75 ps*, ~30K photons/MeV
- From simulation: shower fluctuations in high P_T photon showers cause fluctuation of the mean shower time of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

Local tile readout



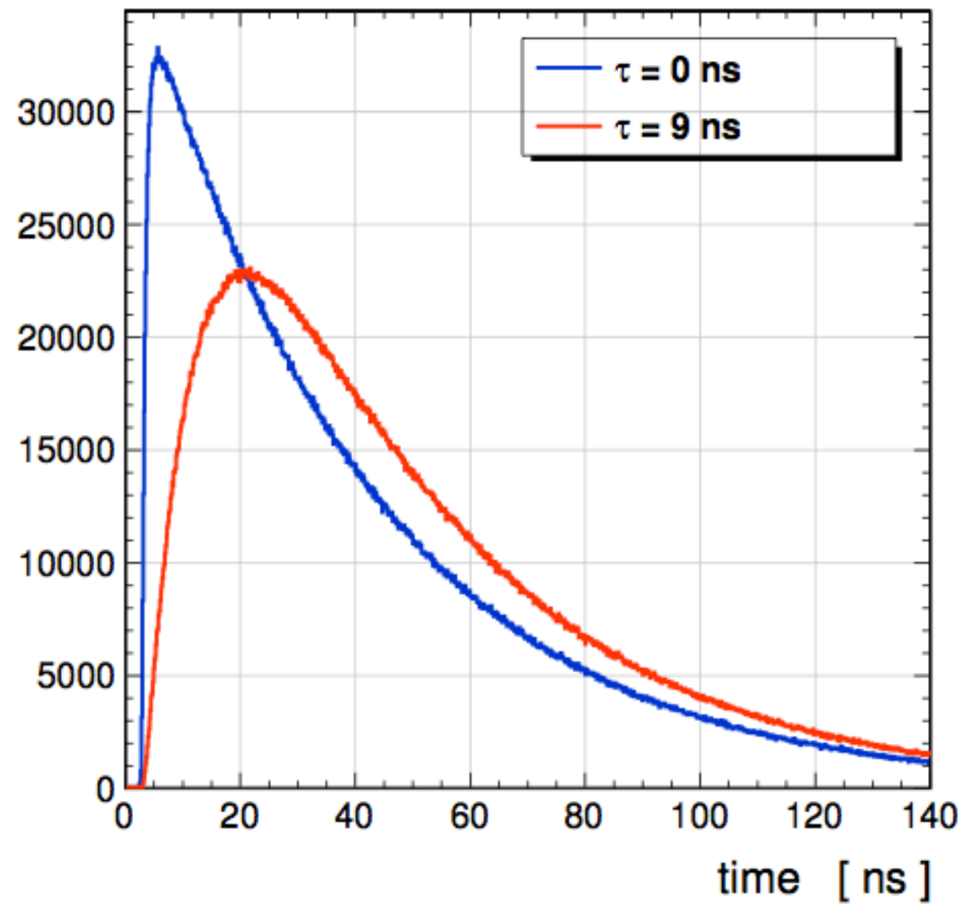


- Directly mount MCP on LYSO tiles
- Also observe 1/√E dependence on time resolution
- Need to improve light collection efficiency, similar to fibers

Simulation of the full chain

Time of arrival of photons at the photo-detector

- Ideal WLS (τ=0 ns)
- Kuraray Y11 (τ=9 ns)



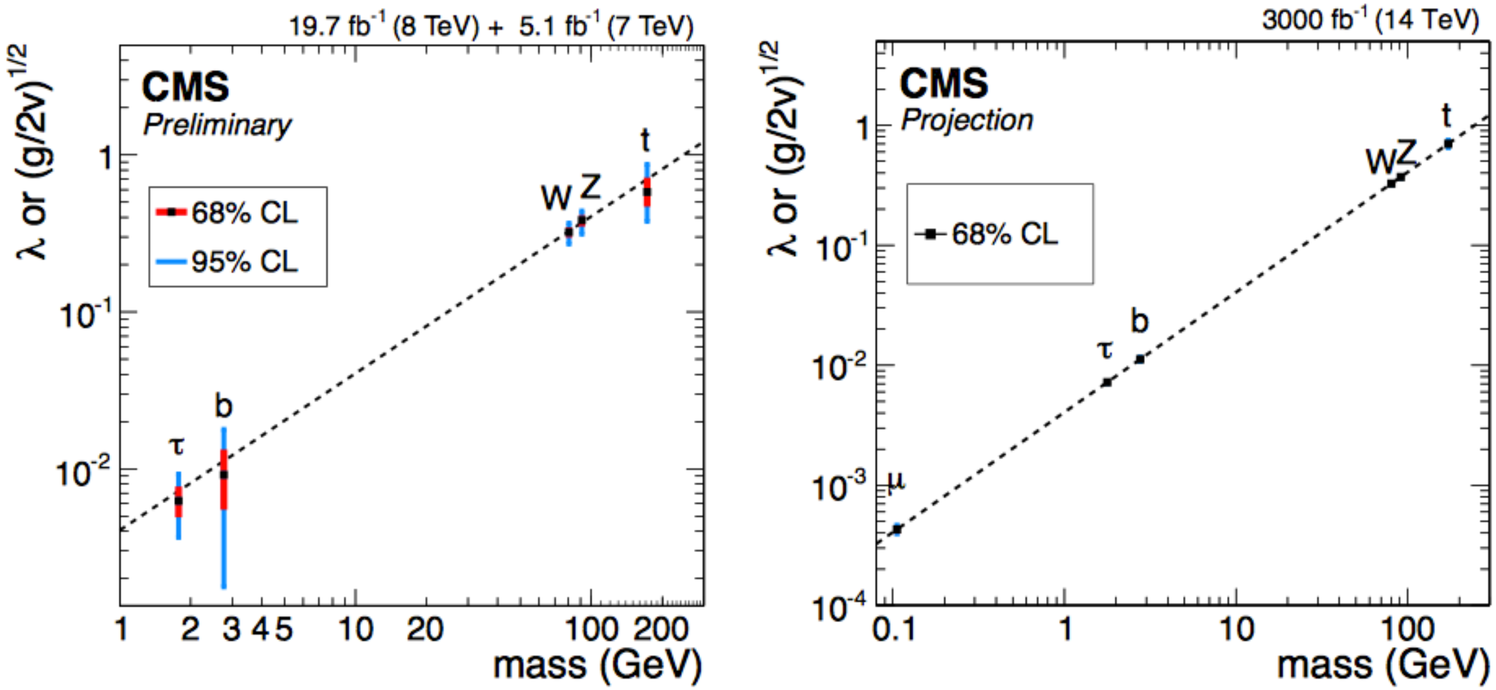


Figure 1.1: Observed and projected precision on Higgs boson couplings as function of boson or fermion masses.

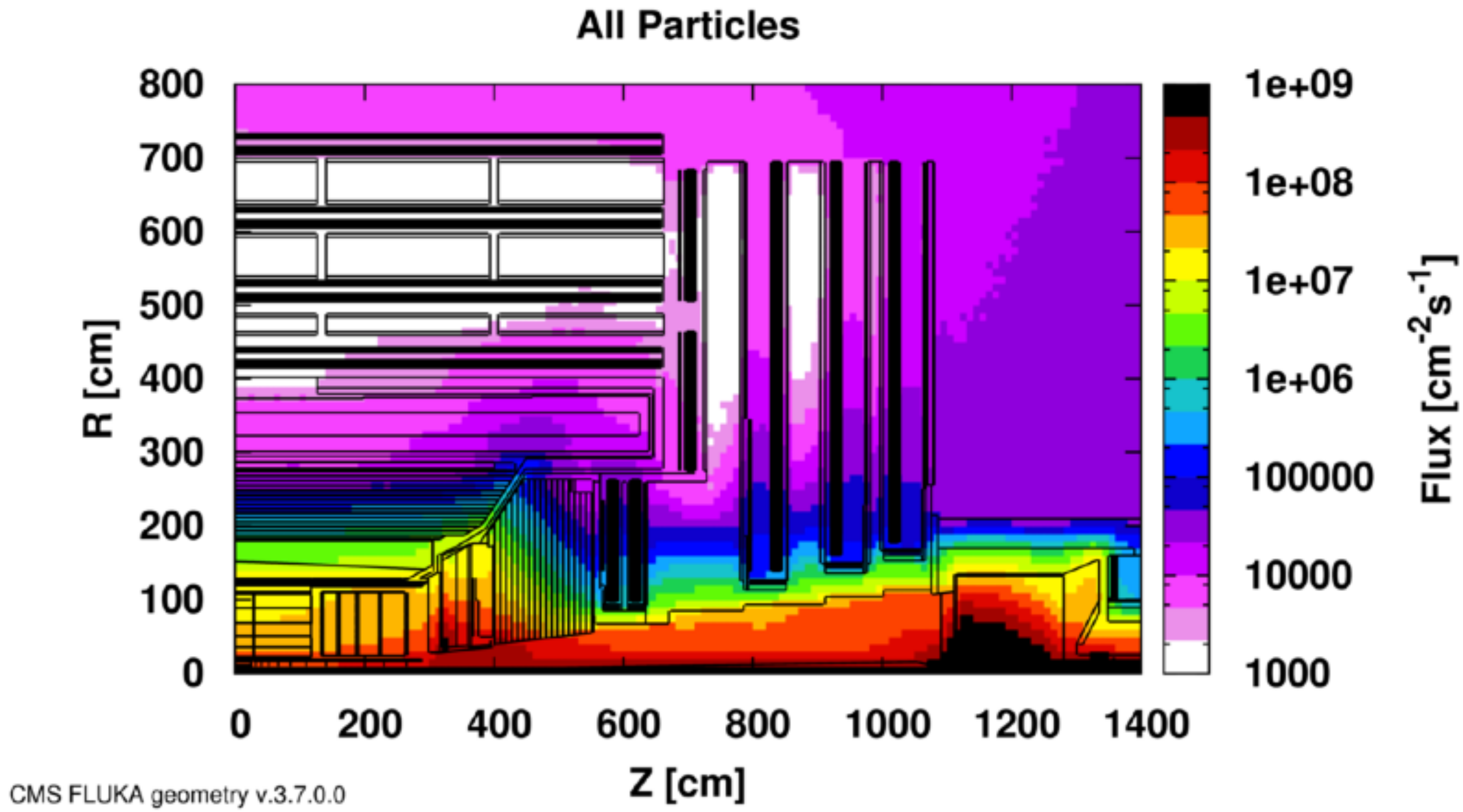


Figure 1.5: Flux of all particles in the CMS cavern at an instantaneous luminosity of $5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

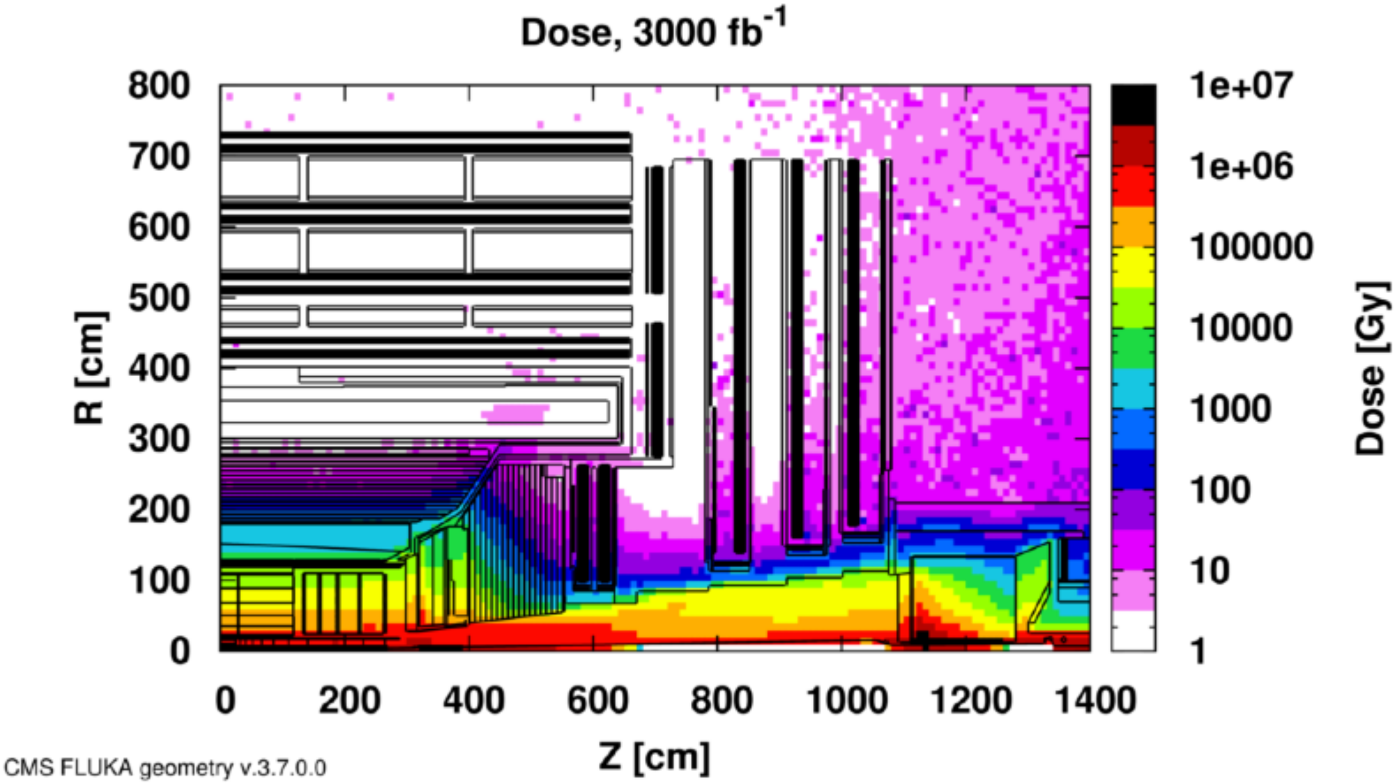


Figure 1.6: Absorbed Dose in the CMS cavern after an accumulation of 3000 fb^{-1} delivered luminosity.

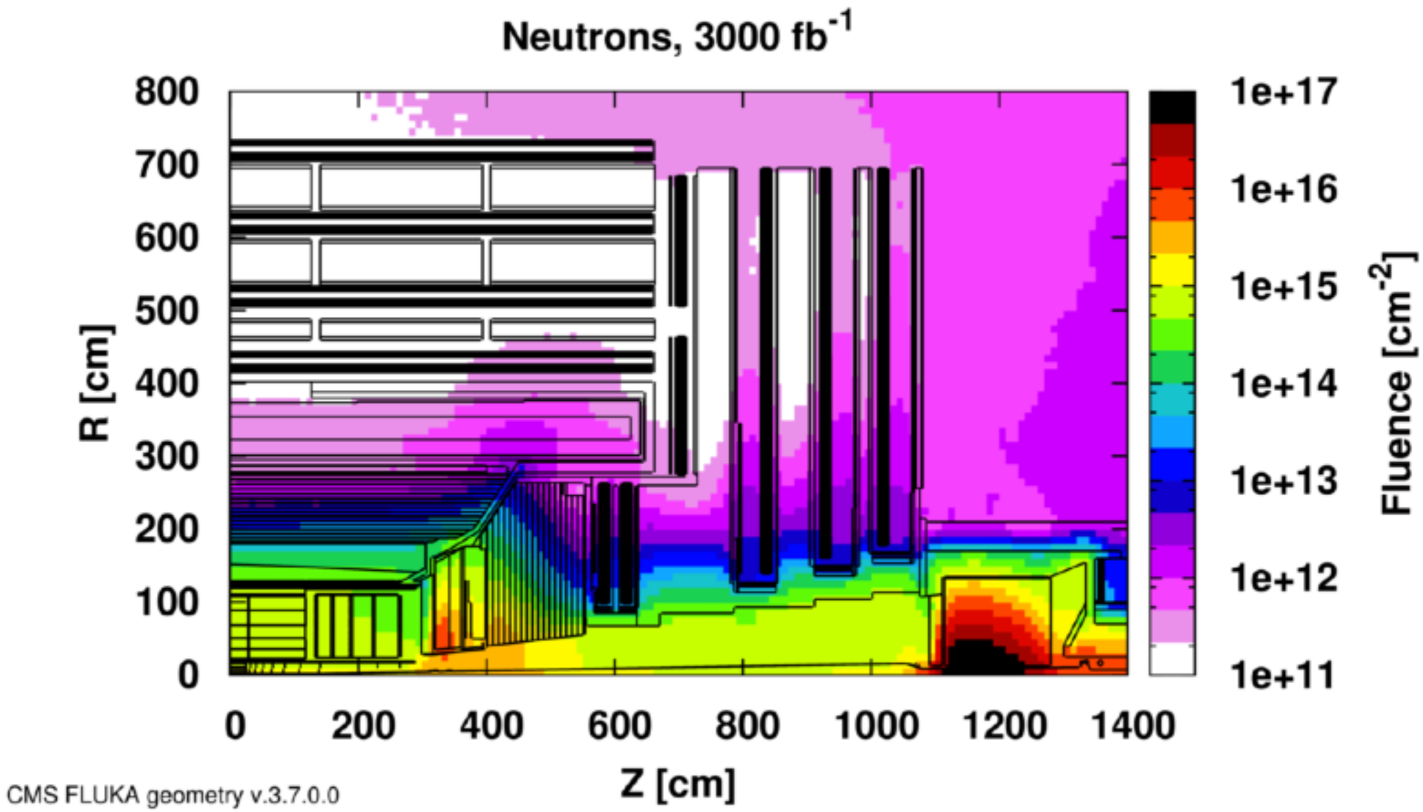


Figure 1.7: Neutron Fluence in the CMS cavern after and accumulation of $3000\,\text{fb}^{-1}$ delivered luminosity.

Optical transit time jitter

- Simulate time of arrival of scintillation photons inside a LYSO crystal.
- Optical transit time jitter small along the evolution of the shower, even in large crystals