Precision Timing For Collider Experiments

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California Institute of Technology

LPC Topic of the Week Seminar

07/26/2016

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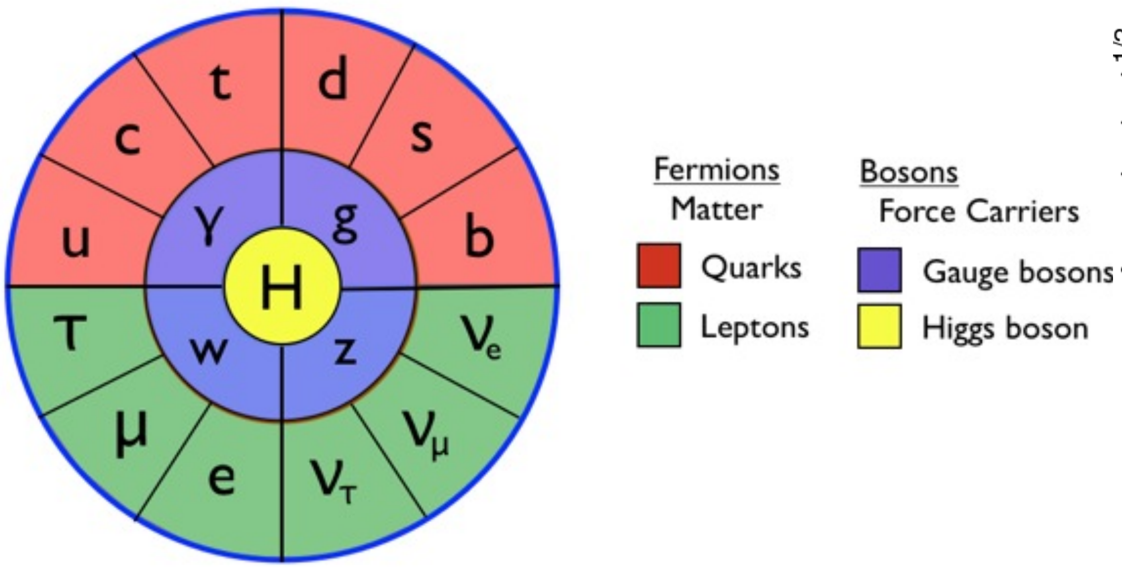
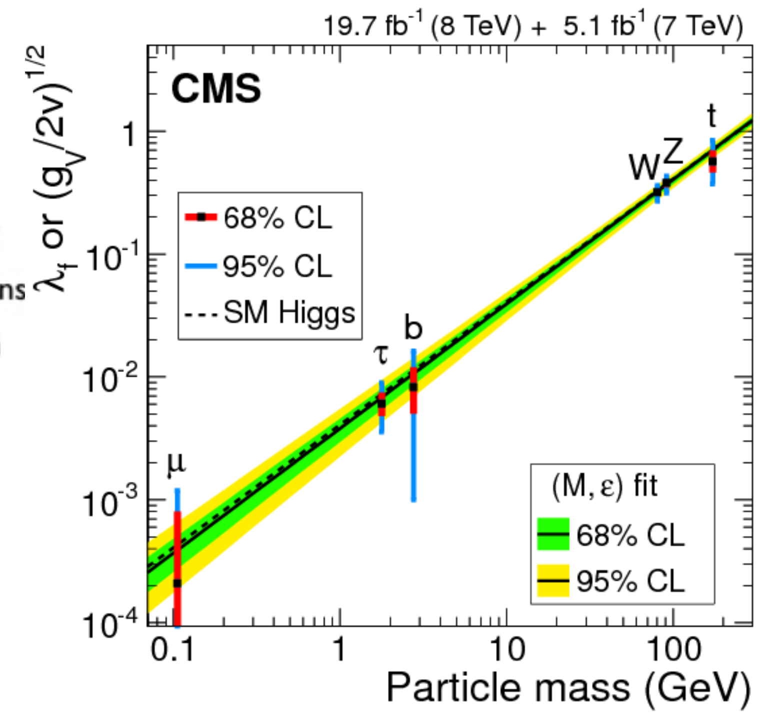
Overview

- Motivations :
  - Why precision timing?
  - What can it do?
- Examples of Specific Technologies:
  - Crystals & Shashlik
  - Secondary Emission Calorimeters
- Charged Particle Fully Hermetic Precision Timing & Future Opportunities

The 2016 View of Particle Physics



Particles of the Standard Model



A complete picture of particles and interactions!

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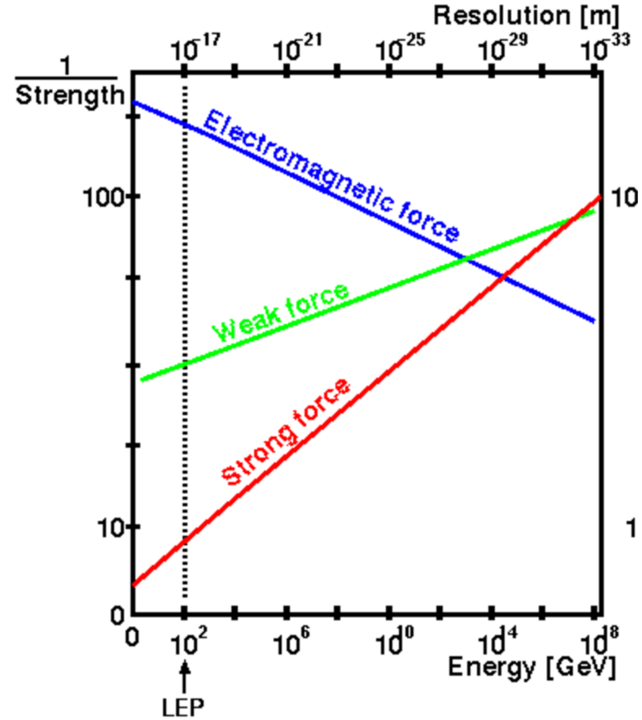
The 2016 View of Particle Physics

10^{19} GeV — **Planck scale**

16 orders of magnitude

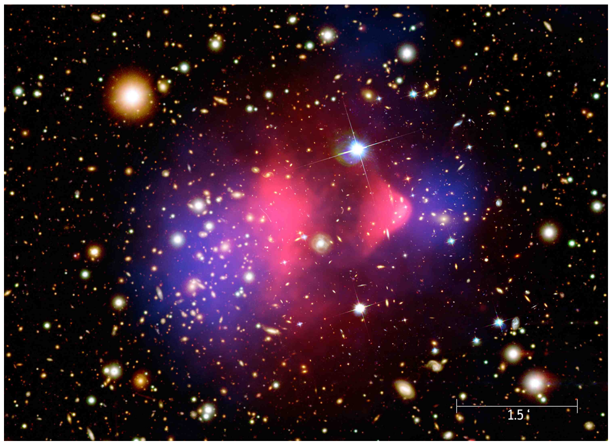
10^{3} GeV — **Weak scale**



…but some features look very odd…

The 2016 View of Particle Physics

Dark Matter?



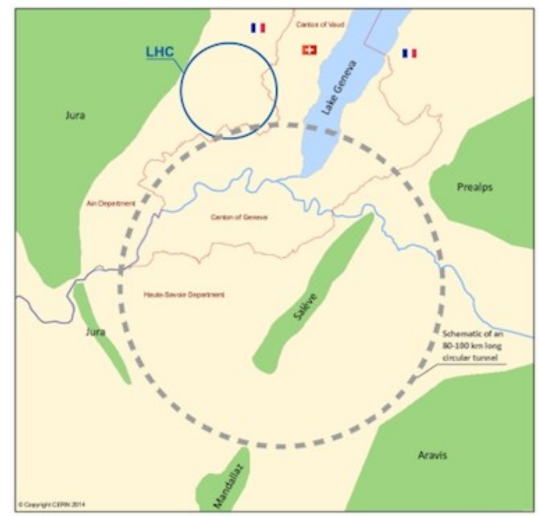
Matter-Antimatter Asymmetry?

Neutrino Mass?

…and many things are left unexplained…

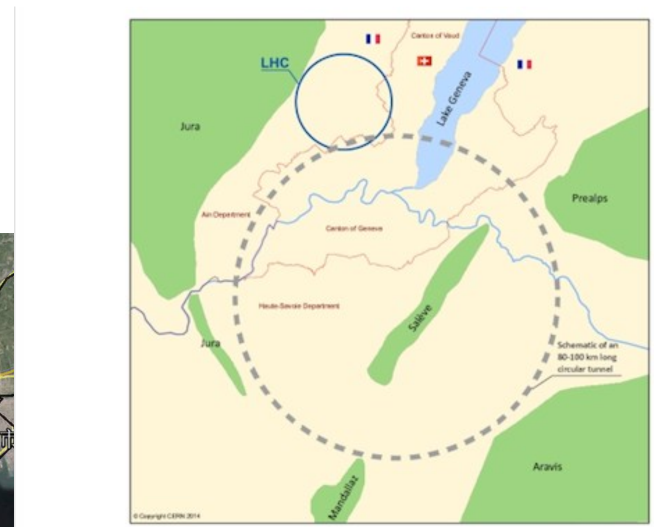
LHC & Future Colliders

- Future colliders likely among the tools to help us answer these questions:
  - LHC (High-Luminosity)
  - Hadron Colliders of even higher energy (FCC, SppC)



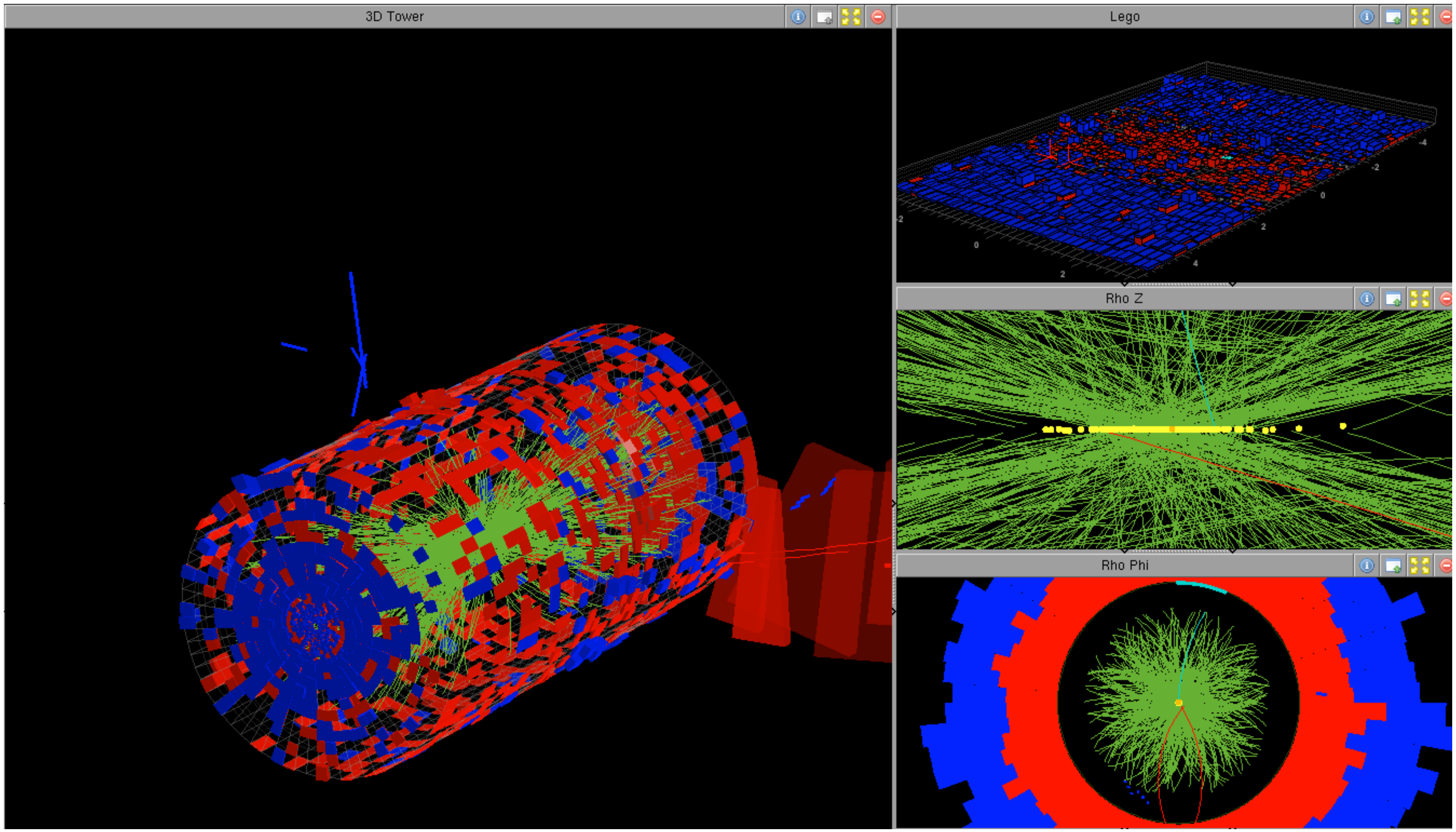
Towards Higher Luminosity

- In all cases, high instantaneous luminosity is required, well in excess of 10^{34} $cm^{-2}s^{-1}$
  - HL-LHC : towards **10^{35} $cm^{-2}s^{-1}$**
  - Future Higher Energy Colliders : maybe even more to probe even more rare processes



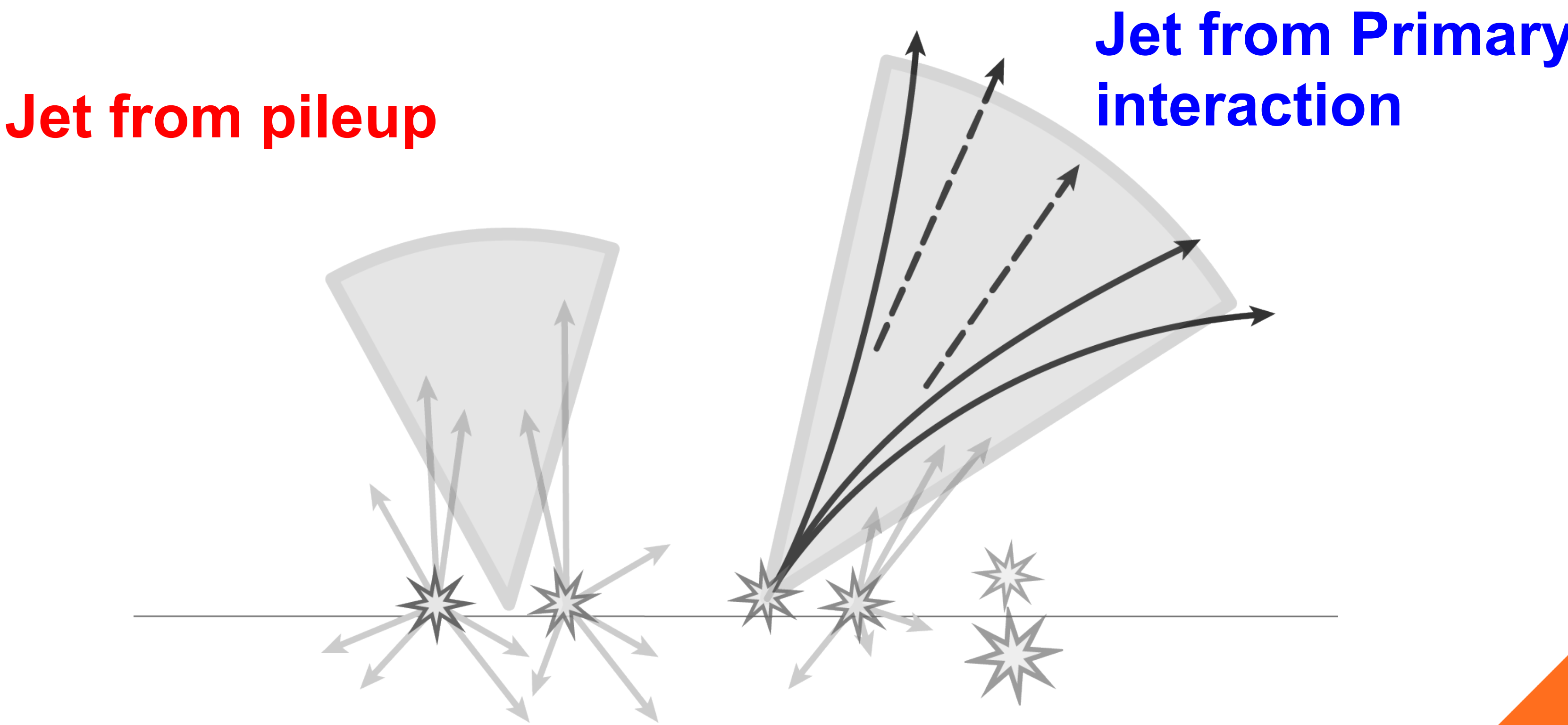
High Luminosity → High Pileup!

A common theme among high luminosity colliders



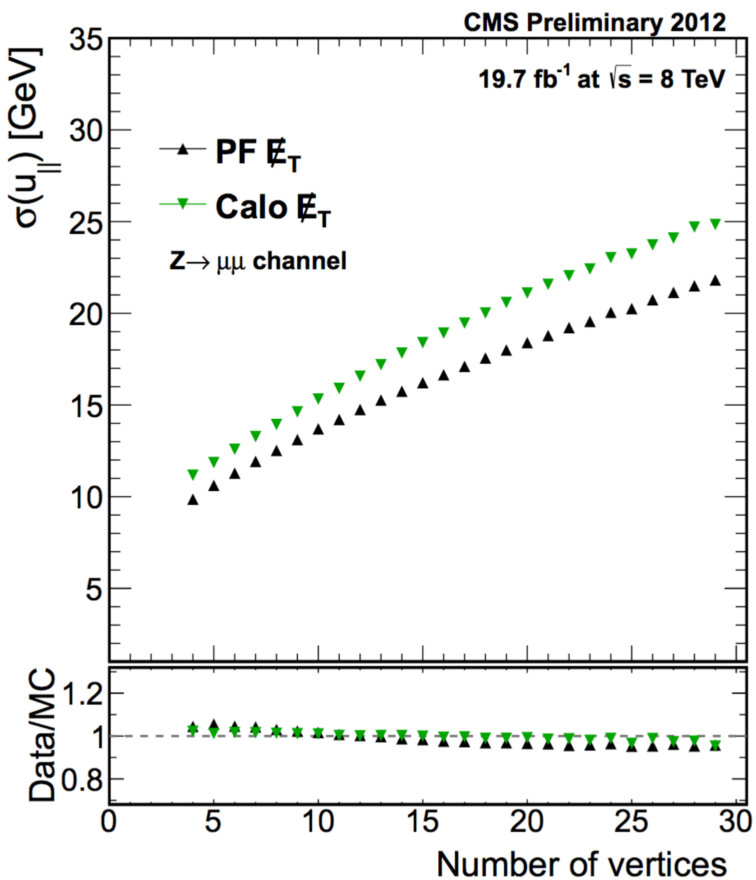
Many Challenges with Pileup

Jets from pileup interactions may be mis-interpreted as part of the main interaction event



Many Challenges with Pileup

Particles and energy from pileup interactions contribute significantly to Missing E_T resolution

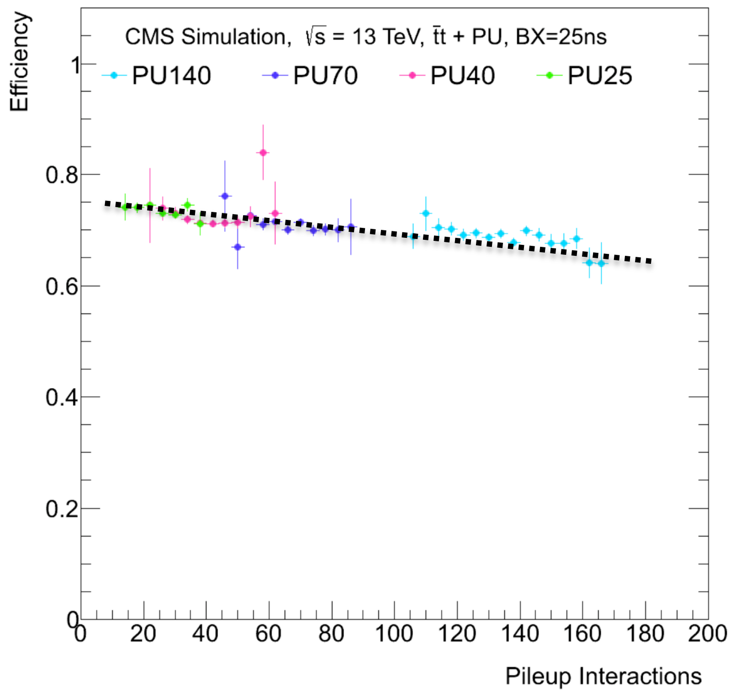


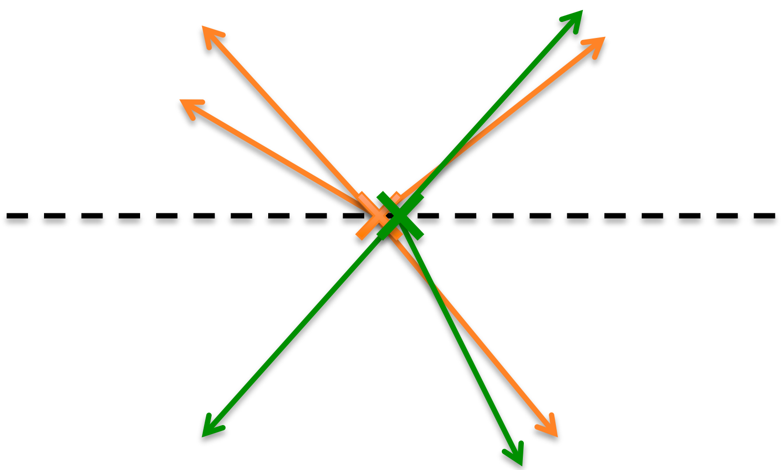
Every pileup interaction contributes ~3 GeV In quadrature to the MET resolution

@200PU → ~40 GeV

Challenges in Pileup

Even tracking and vertexing start to suffer…





Start to have a non-negligible rate of vertex merging

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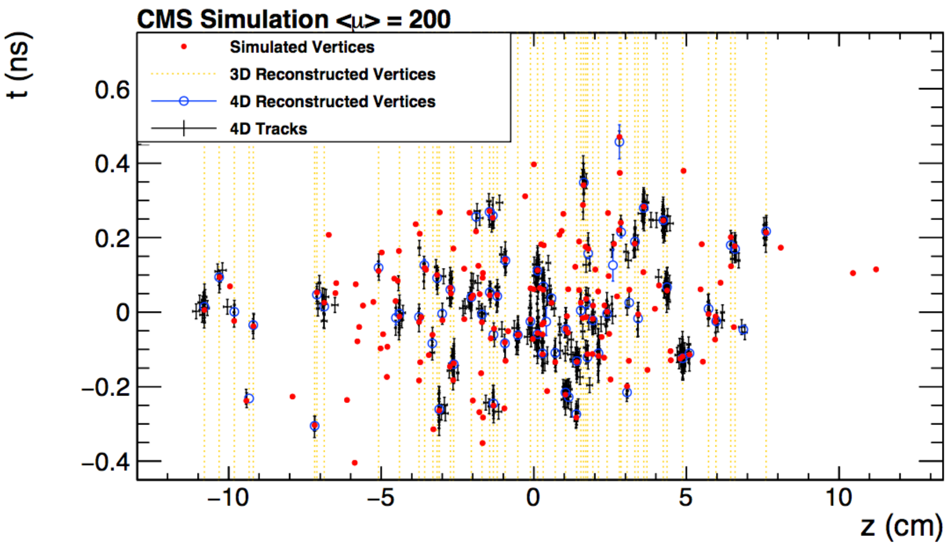
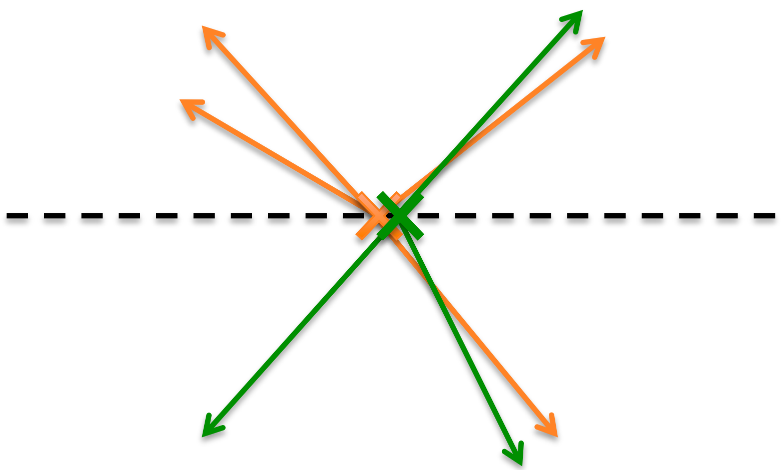
Challenges in Pileup

Even tracking and vertexing start to suffer…



13% of vertices are merged for 200 PU

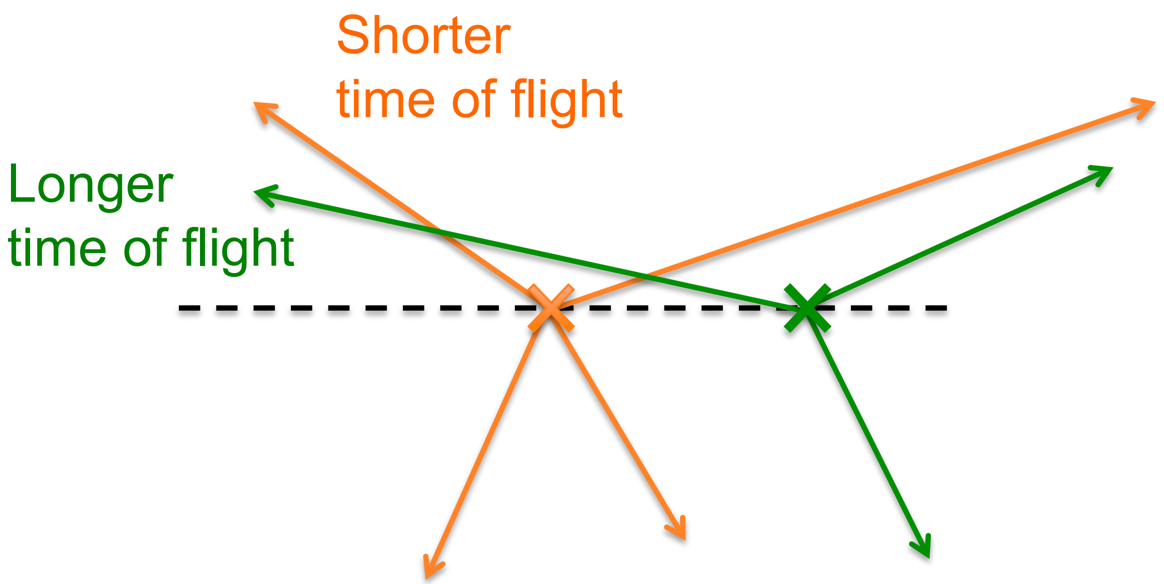


Start to have a non-negligible rate of vertex merging

Precision Timing As a Solution

An obvious solution…

Measure the time stamp of a particle at the interaction point → Identify which vertex it came from



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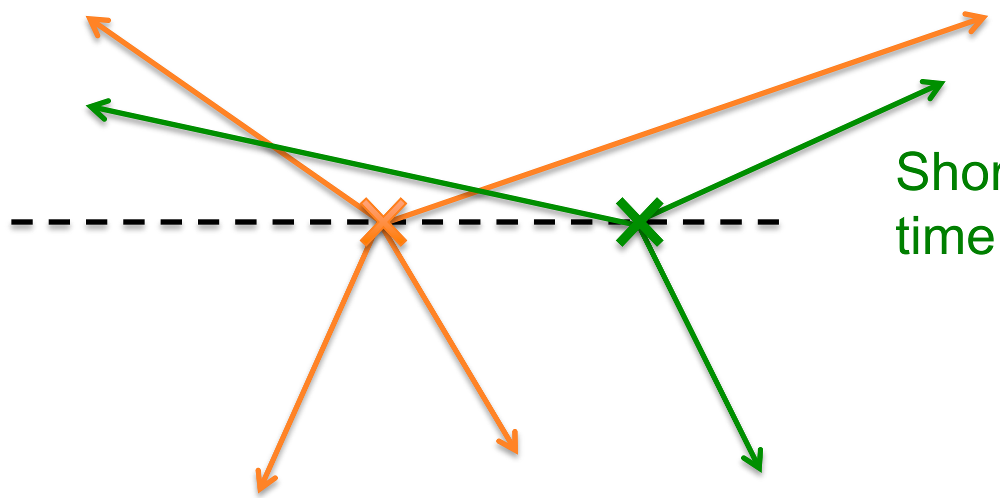
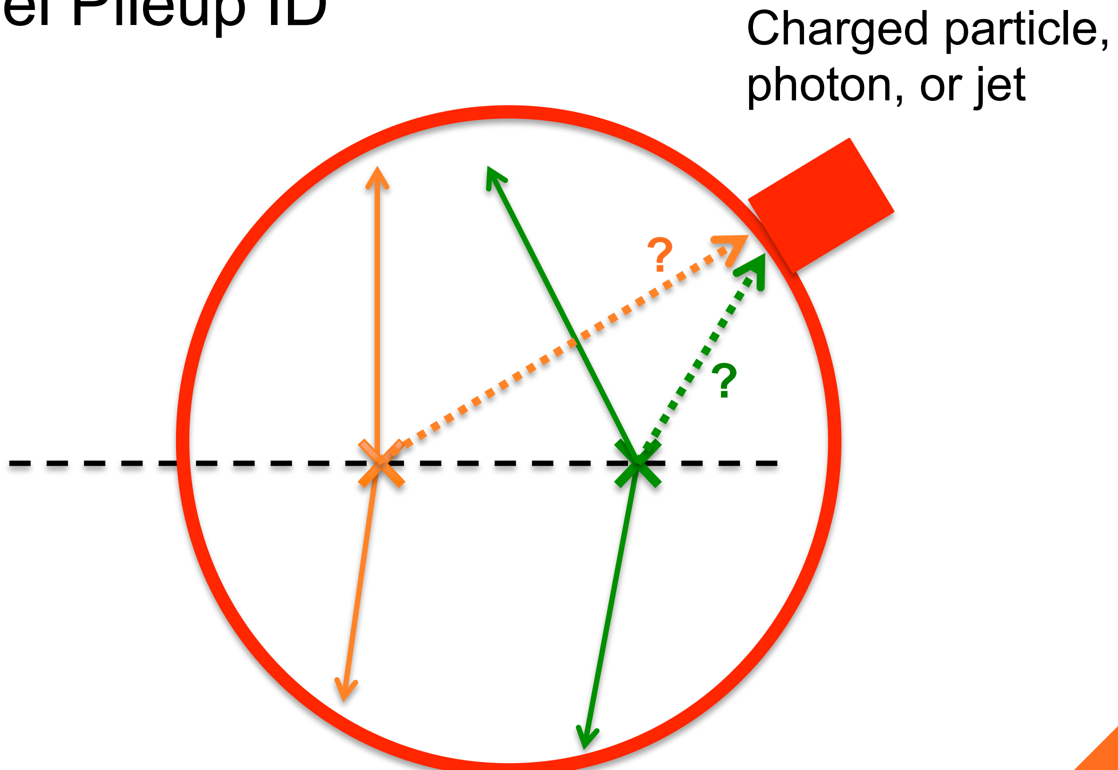


How to use Time Information?

More concretely, we can use time information to achieve the following goals at high pileup collider experiments:

- Object Level Pileup ID



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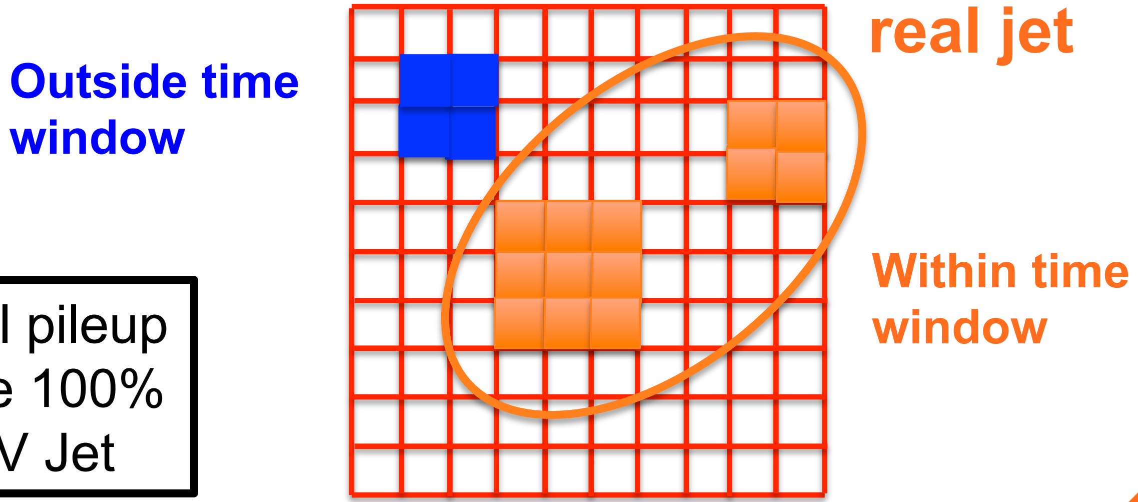
- Object Level Pileup ID
- Single Hit Level Pileup ID



At 140 PU, Neutral pileup particles contribute 100% energy to a 50 GeV Jet

How to use Time Information?

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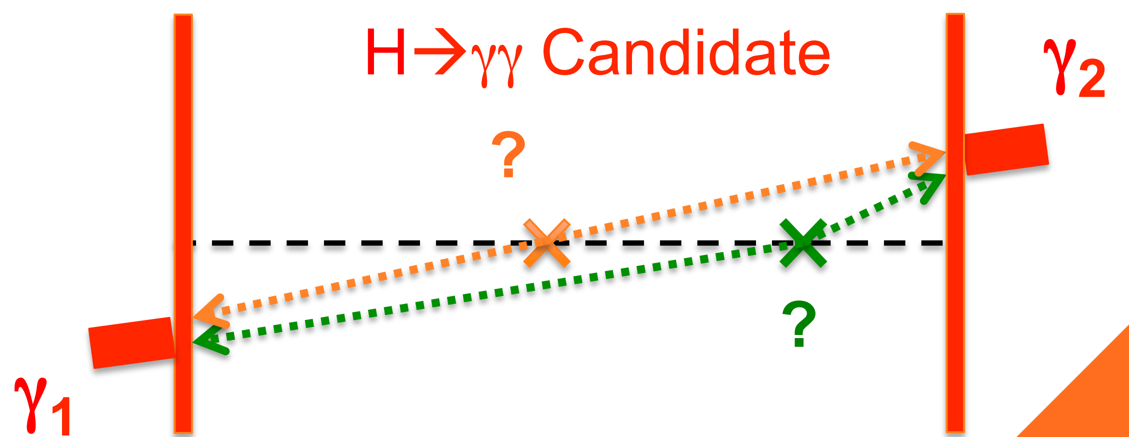
- Object Level Pileup ID
- Single Hit Level Pileup ID
- Event Level Vertexing



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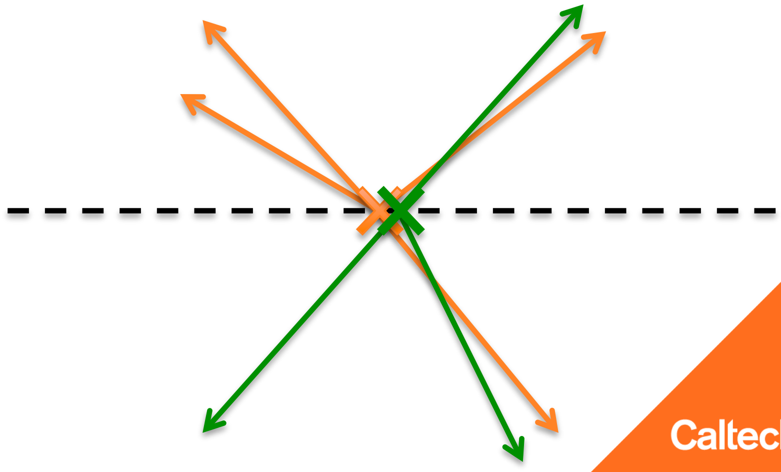

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How to use Time Information?

More concretely, we can use time information to achieve the following goals at high pileup collider experiments:

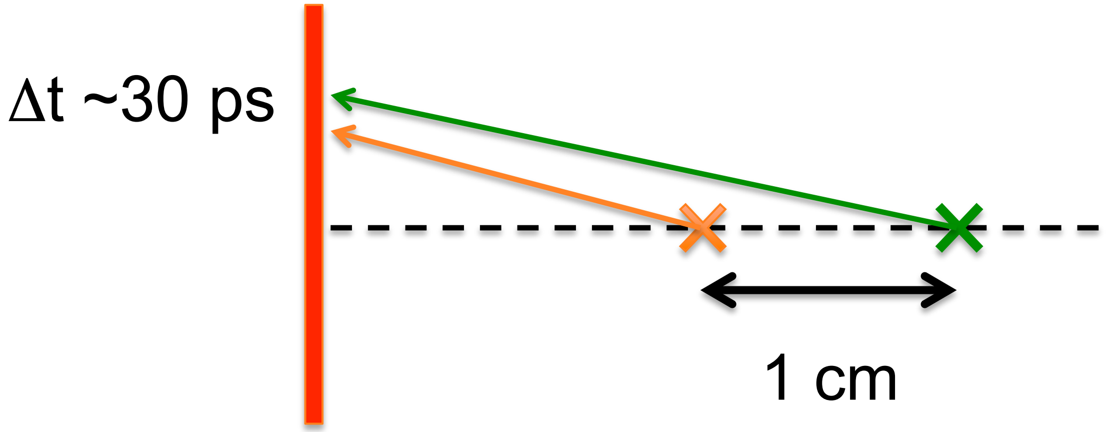
- Object Level Pileup ID
- Single Hit Level Pileup ID
- Event Level Vertexing
- Distinguish spatially merged vertices
- Enabler for various displaced / lifetime based searches

- Of the possible local measurements : (x,y,z,time) & (E,p_x,p_y,p_z)
  → Time is only one not used

Time Measurement Precision?

Precision needed follows very basic logic :

- Particles travel at near speed of light
- 1cm distance is traversed in ~33 ps
- To distinguish pileup vertices separated by 1cm in space, need time resolution of 30ps
- Typical collider beamspots are ~10cm in z
  → rejection factor of 10



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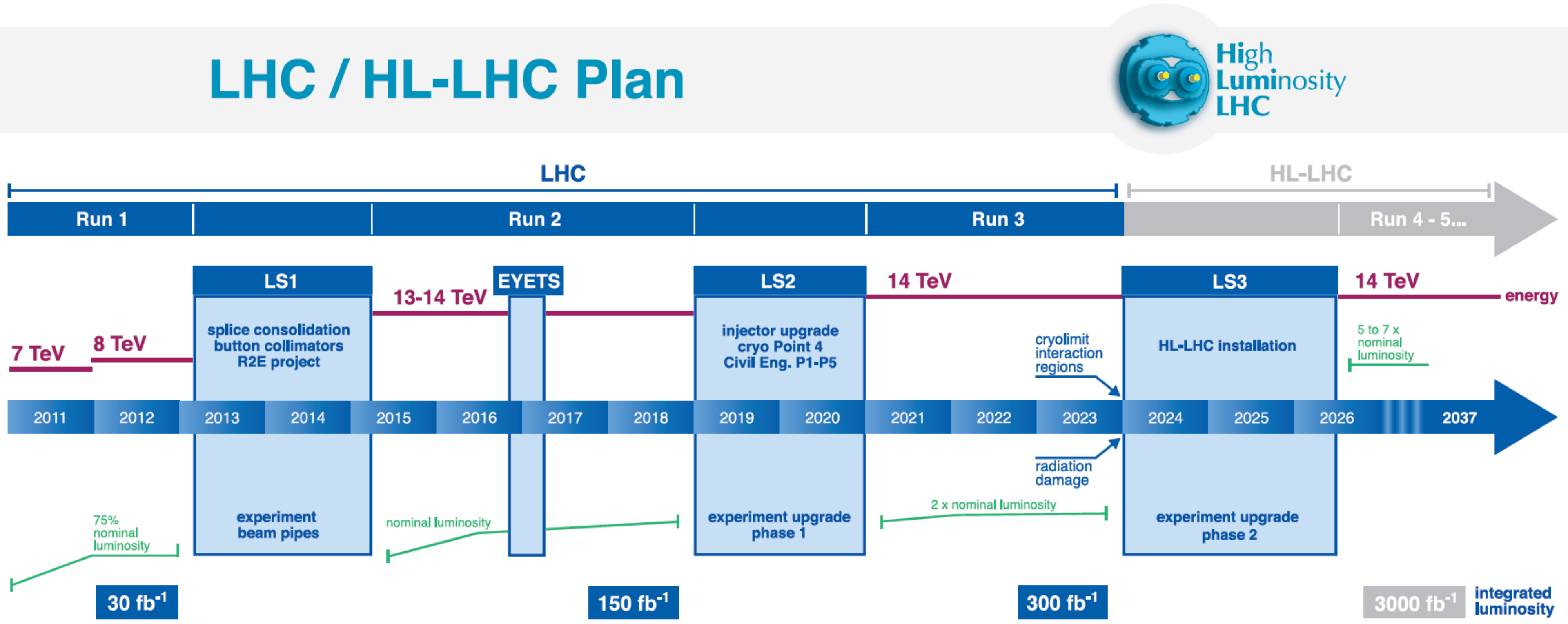
HL-LHC

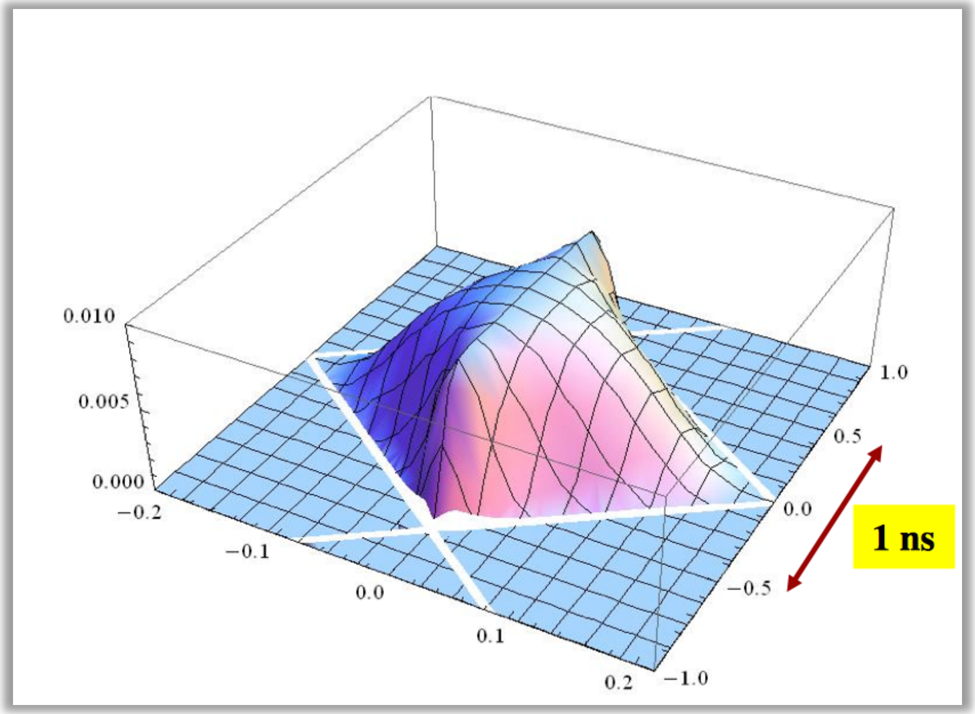
High-Luminosity Upgrade of the LHC is the future of the LHC



Instantaneous Luminosities ~ 5-7 x 10^{34} $cm^{-2}s^{-1}$

→ Implies an average pileup of **140-200**

HL-LHC Beam Spot

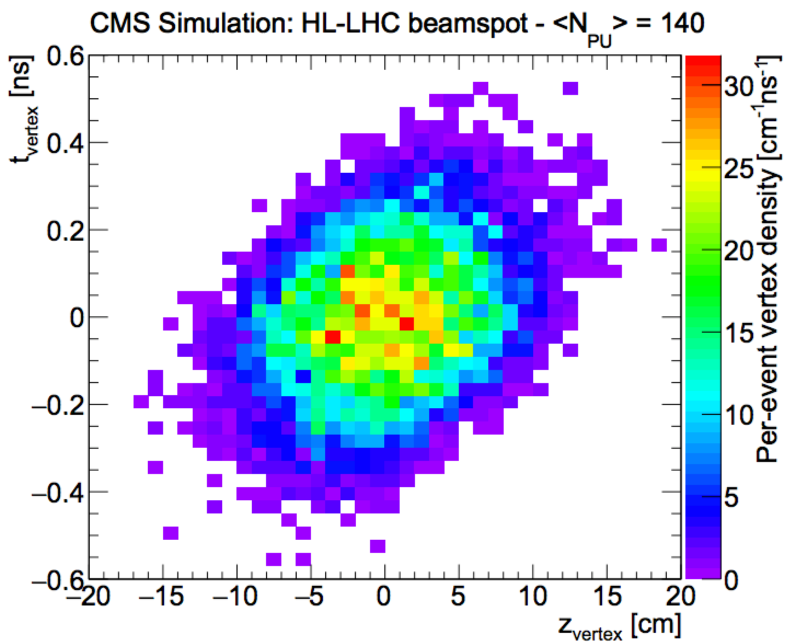


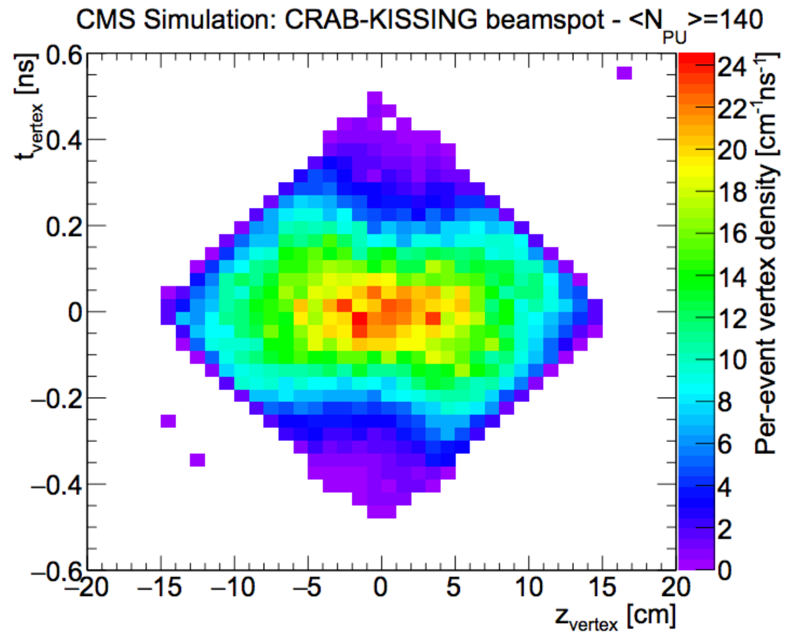
Beamspot width in time is several hundred ps

HL-LHC Beamspot is spread out **along z and in time**

- This implies:
  - Time can discriminate between vertices even for particles pointing to the central barrel
  - Time can discriminate between vertices even when they are very close in the z-coordinate

HL-LHC Beam Spot





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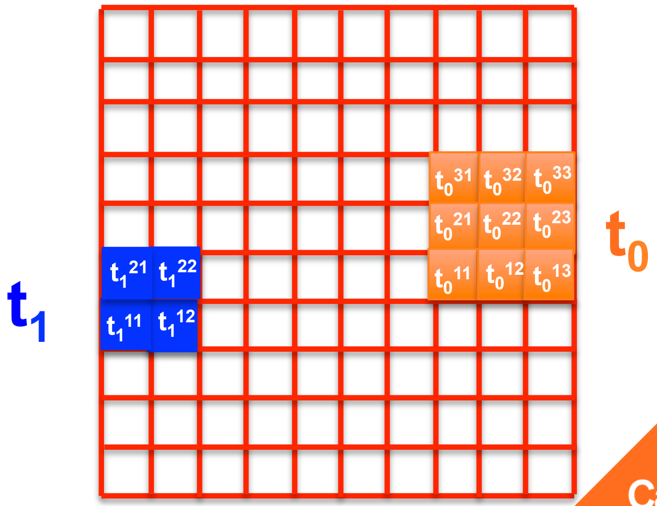
Calorimetric Precision Timing

- Make a time measurement for each calorimeter cell
  - ECAL is typically ideal for this

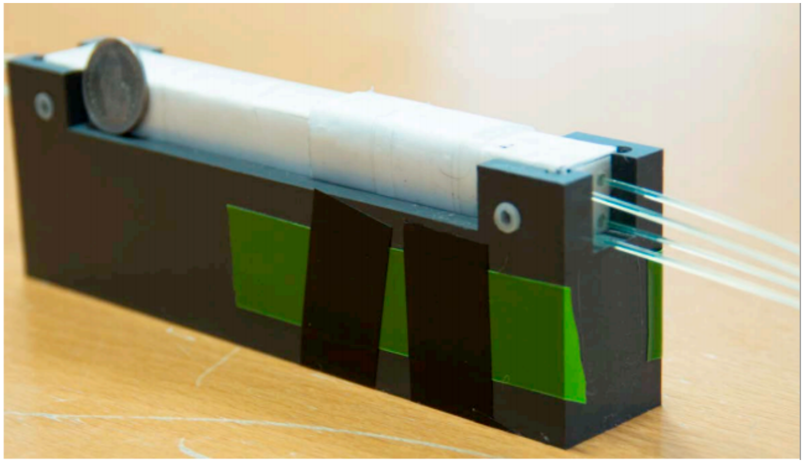
- Multiple calorimeter cells may be clustered and identified with a specific EM object (photon or electron)
- A time-stamp can be assigned to the EM object based on the time-stamps of the constituent cells

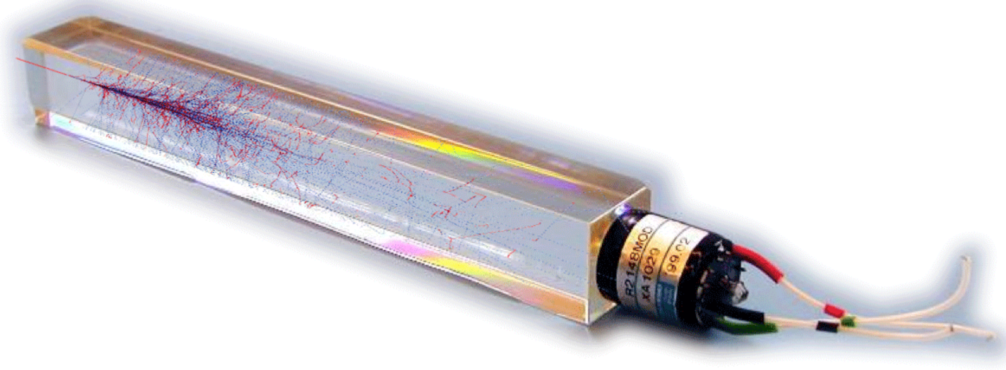
- Based on the object timestamp, identify if object is from pileup vertex or main vertex



Crystal Calorimeters

- Large light yield makes them ideal for precision timing
- Lots of experience in the field & existing CMS expertise





Secondary Emission Calorimeters

- Measure energy through detection of shower secondaries
  - No auxiliary scintillation mechanisms
  - No need for optical transport
- Examples :
  - Stacks of silicon sensors between absorbers
  - Large area MCP (micro-channel plate) sensors

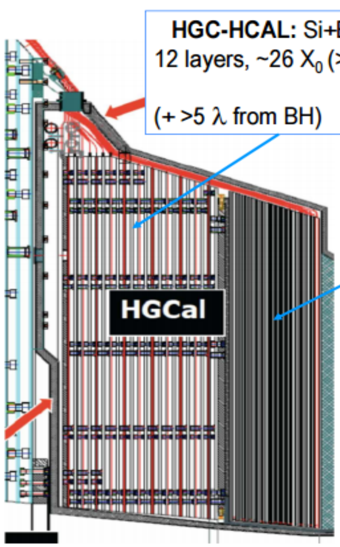


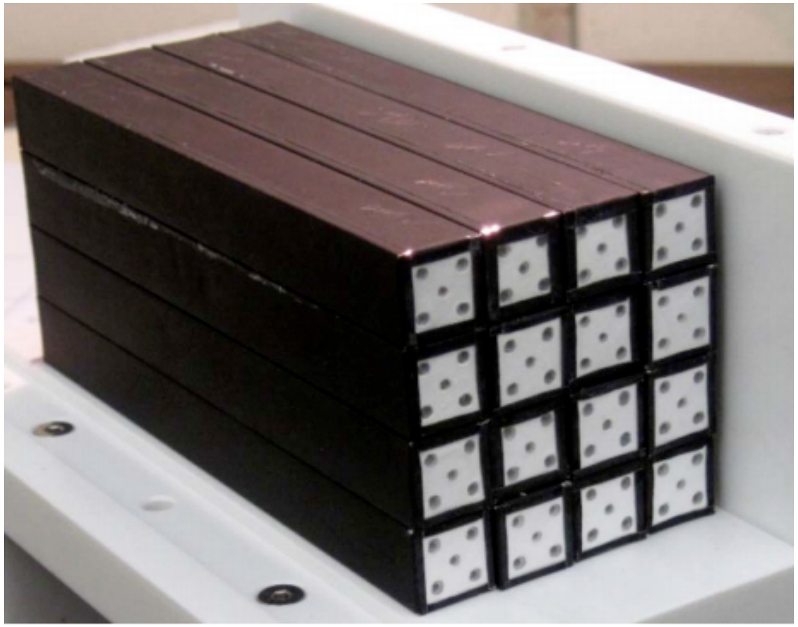
Table 3.2: Parameters of the EE and FH.

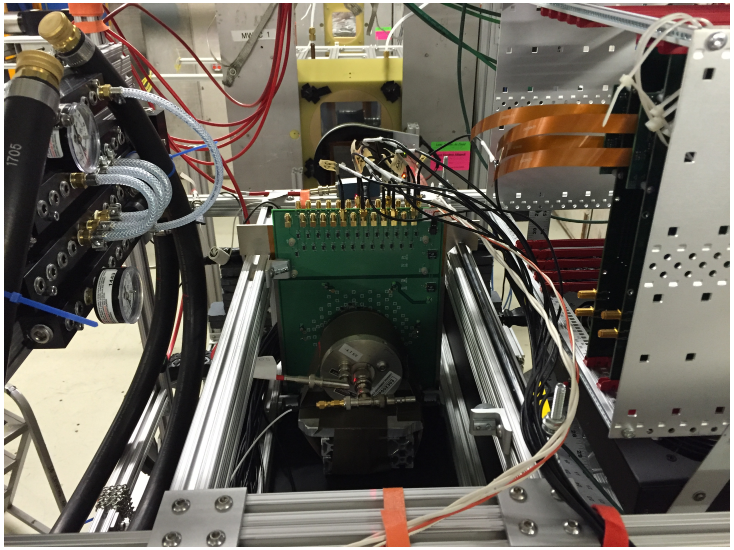
	EE	FH	Total
Area of silicon (m^2)	380	209	589
Channels	4.3M	1.8M	6.1M
Detector modules	13.9k	7.6k	21.5k
Weight (one endcap) (tonnes)	16.2	36.5	52.7
Number of Si planes	28	12	40

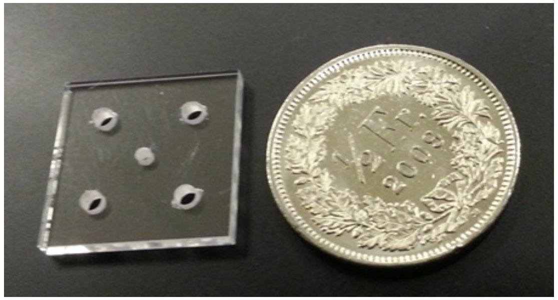
CMS High Granularity Calorimeter

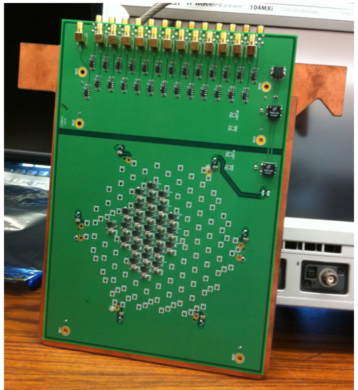
Systematic Characterization

- Characterize ultimate timing performance of different calorimeter types and understand intrinsic limitations



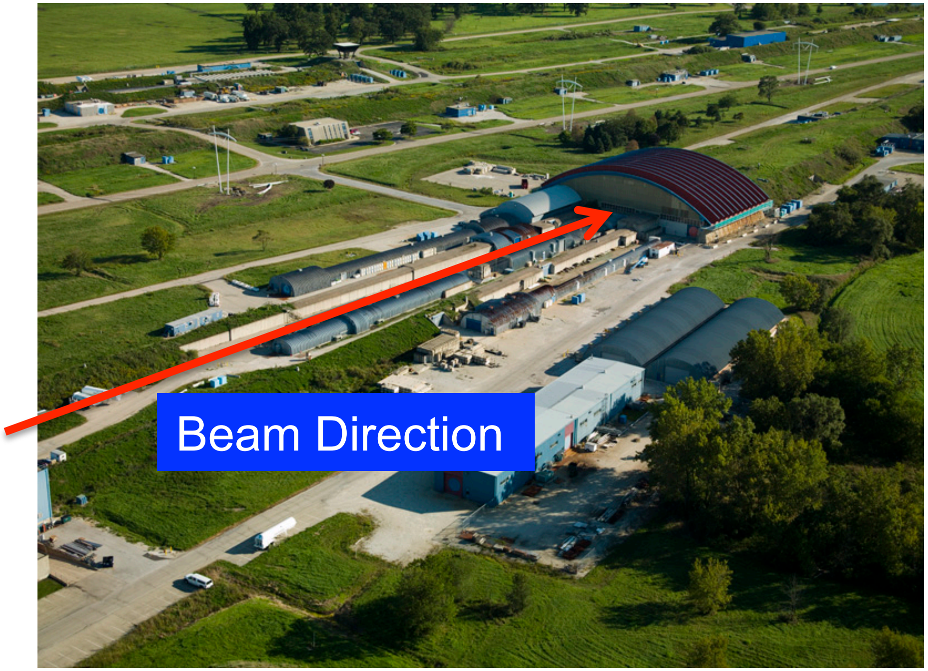




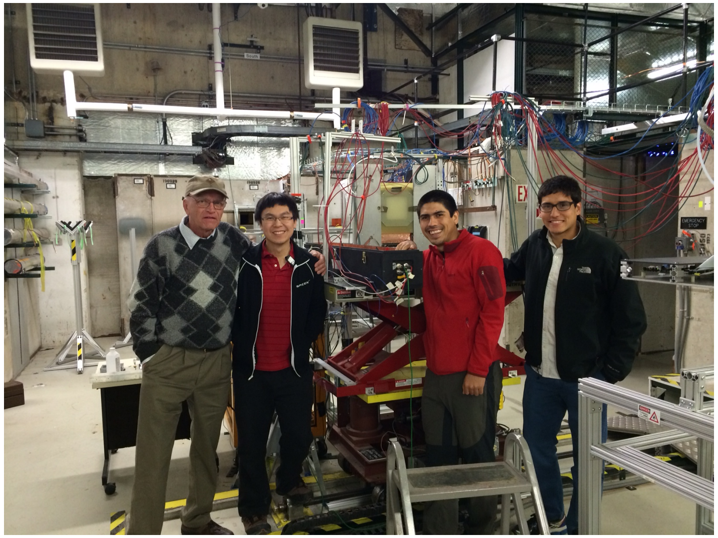


Beam tests @ Fermilab

- Fermilab (FTBF) provides excellent facility for beam tests of detector prototypes
- Since 2013, our team has had 7 testbeam periods dedicated to Precision Timing experiments (last one was in June)



Experimental Hall Area



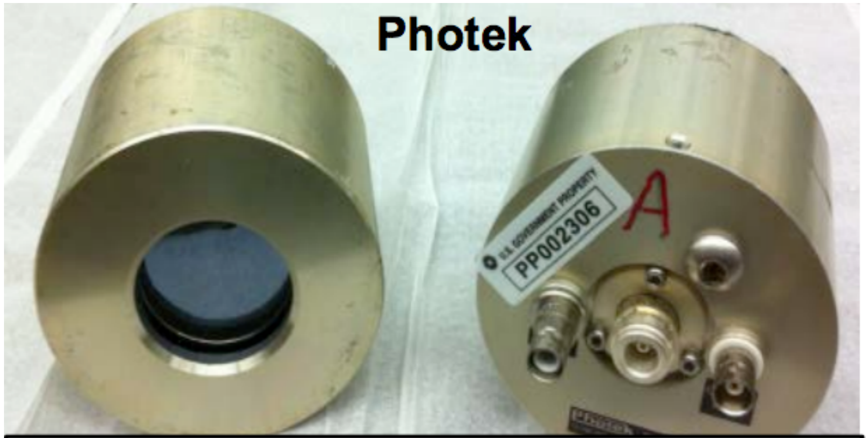
First Establish Control of Timing Measurement

- Need to understand & control contribution to time resolution of various **systematic** effects:
  - Reference timer device
  - Digitization electronics
  - EM shower fluctuations

Reference Timer

- To measure time of flight, need a reference "start" timer
- Best device on the market: Photek 240 MCP-PMT

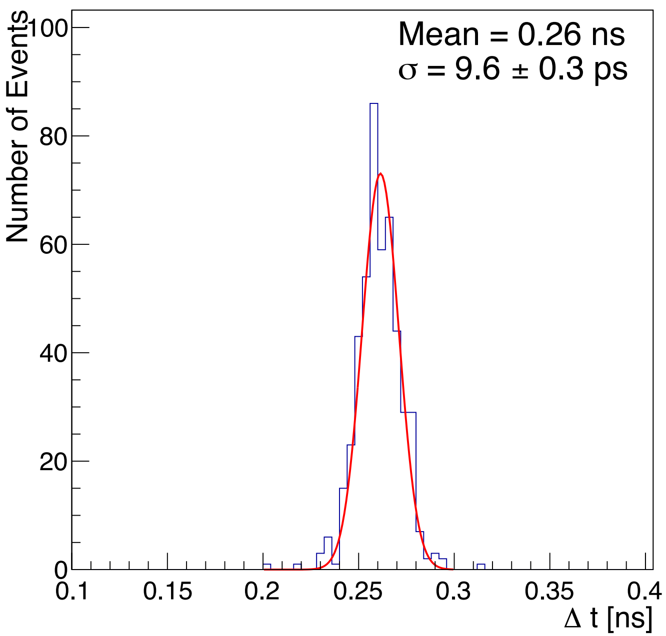
- Put 2 of them in line and measure time of flight resolution to establish precision of reference timer

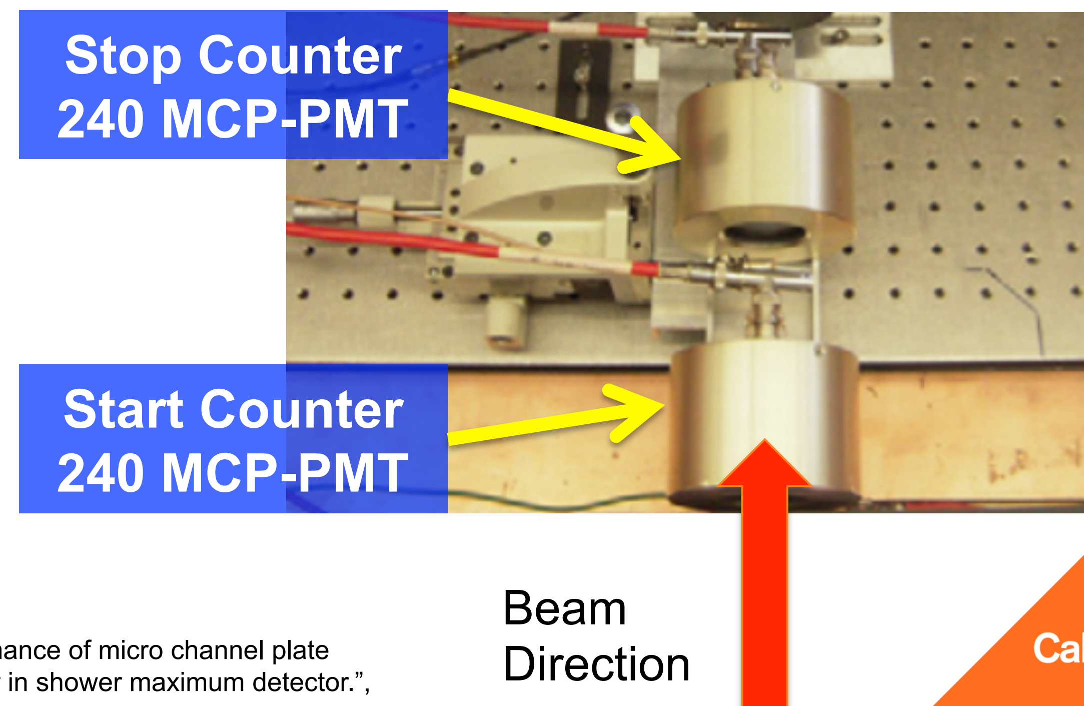


10 μm pore size, 41mm aperture, PC-MCP distance ~5mm, rise time~60 ps, SPTR~40 ps

Reference Timer

- We measure ~10ps time of flight resolution
  → Implies 6 – 7 ps single device resolution
- An excellent reference timer for subsequent measurements

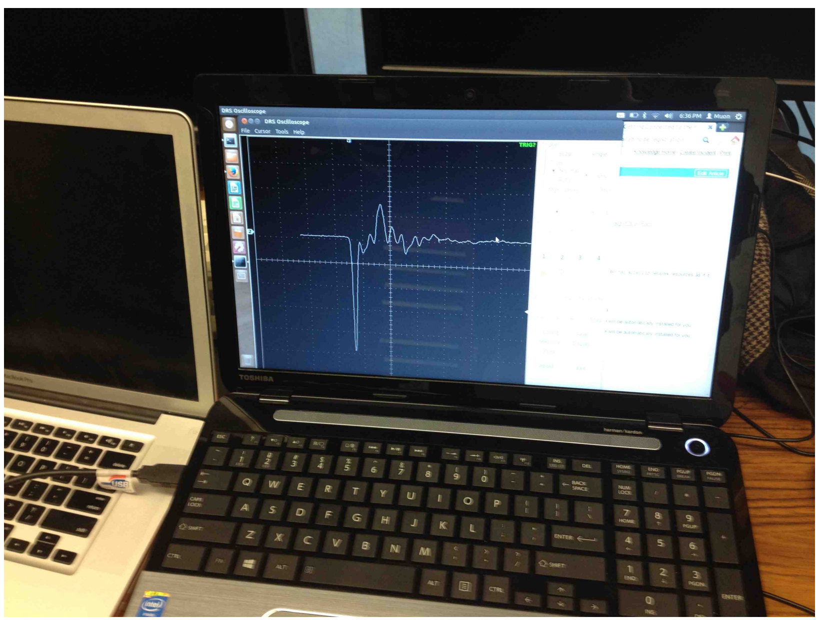


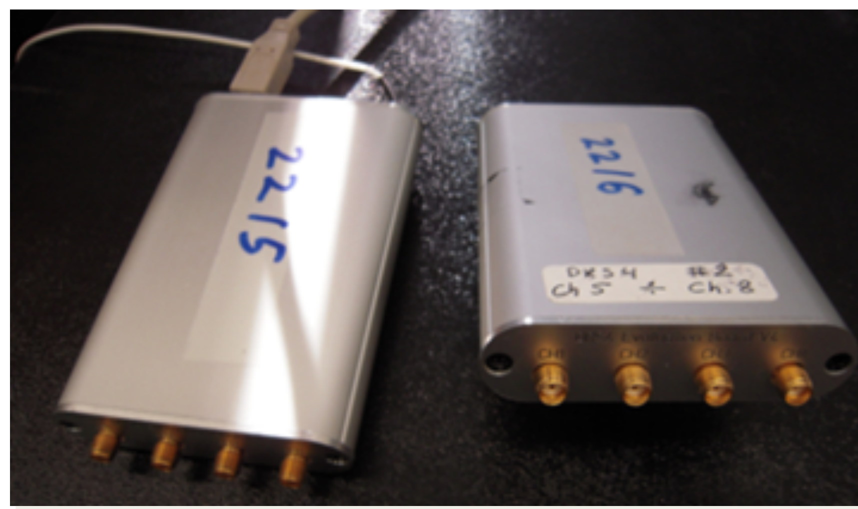


S. Xie, et al: "Study of the timing performance of micro channel plate photomultiplier for use as an active layer in shower maximum detector.", NIM A, 795 (2015) p. 288-292

Digitization

- Use DRS4 (Domino-Ring-Sampler) Evaluation Board developed by Stefan Ritt at PSI for MEG2 experiment
- Analog bandwidth of 750 MHz
- Up to 5 GSPS (samples per second) → 200ps samplings
- Well validated software and scope application
- **Electronic time resolution measured to be about 4 ps**





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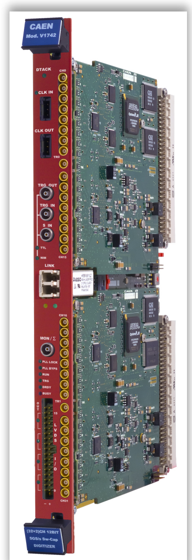
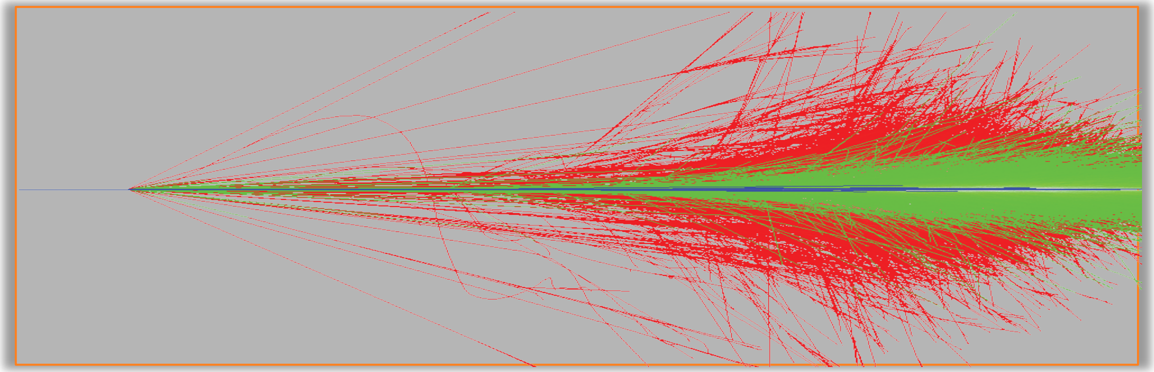


Also exists in crate format
With 32+4 channel readout

Shower Fluctuations

- EM shower fluctuations can induce time jitter on signal pulses
- Need to quantify this impact on time resolution



Shower Fluctuations

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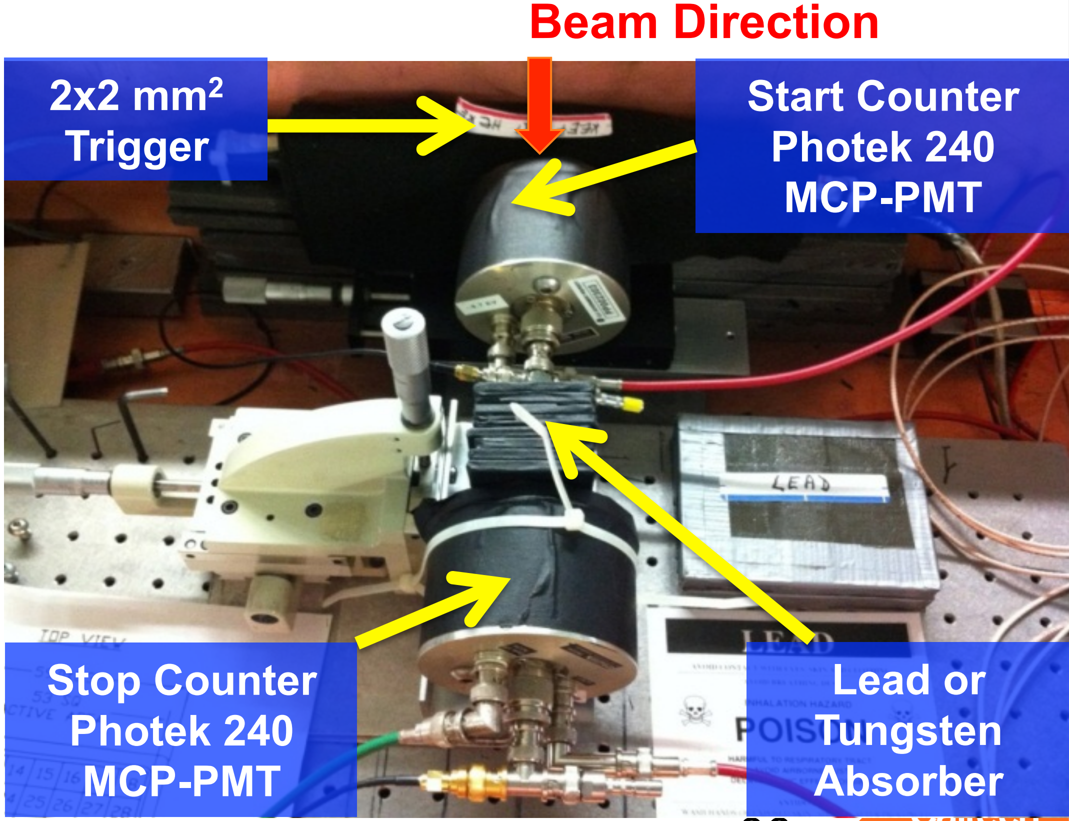
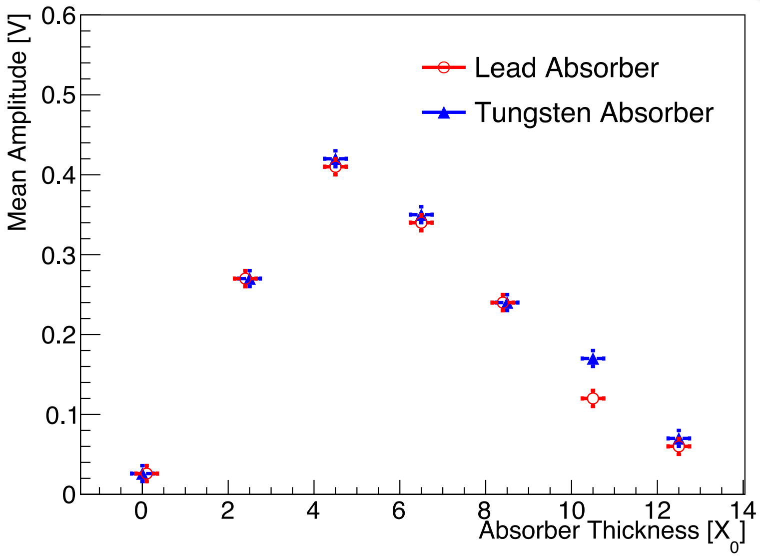
- Need to quantify this impact on time resolution

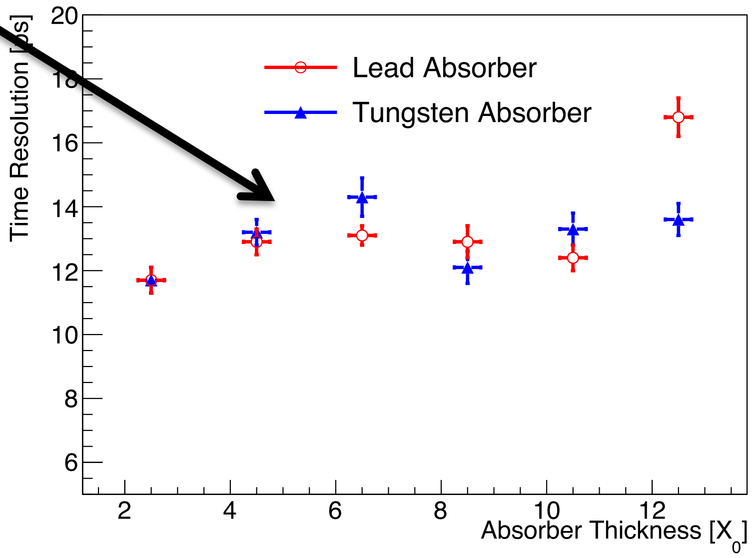
- Measure time jitter for a prototype sampling calorimeter with precision time capability
- Use Photek 240 to detect shower secondaries



Shower Fluctuations

- We measure time resolution of ~13 ps throughout the shower
- Implies that shower fluctuations contributes less than 10 ps to the time jitter





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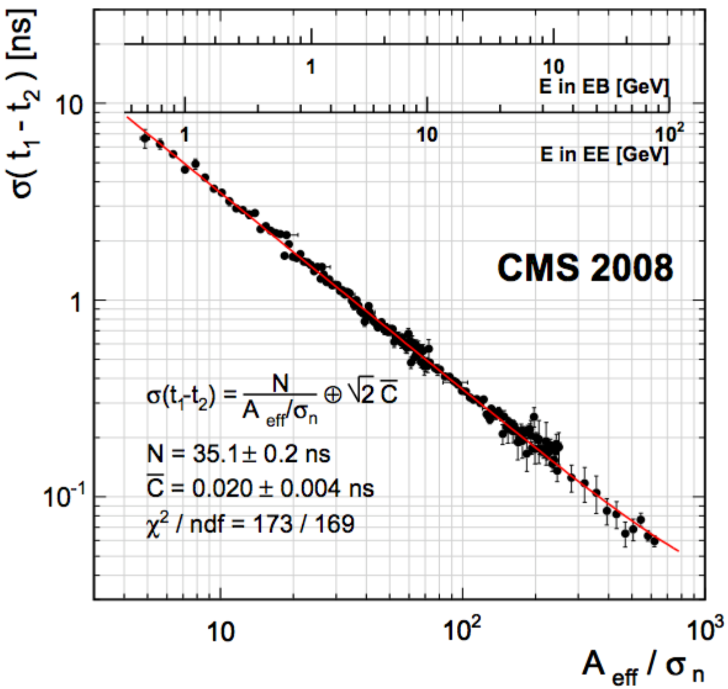
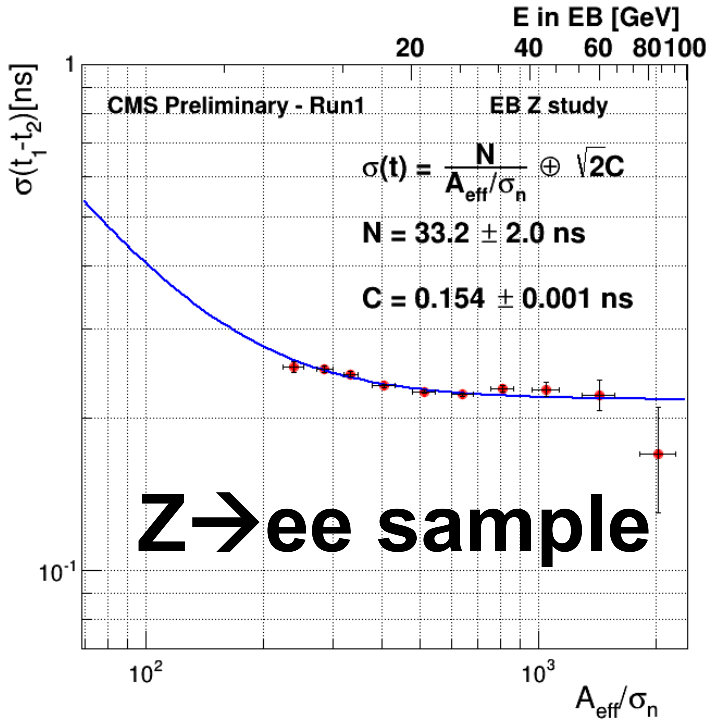
CMS ECAL Timing

- Existing CMS ECAL already has pretty good timing precision
  - Above 10 GeV, can get 100ps resolution → **S/N limited**
  - Clock (non)synchronization affects different readout modules at the level of ~120ps

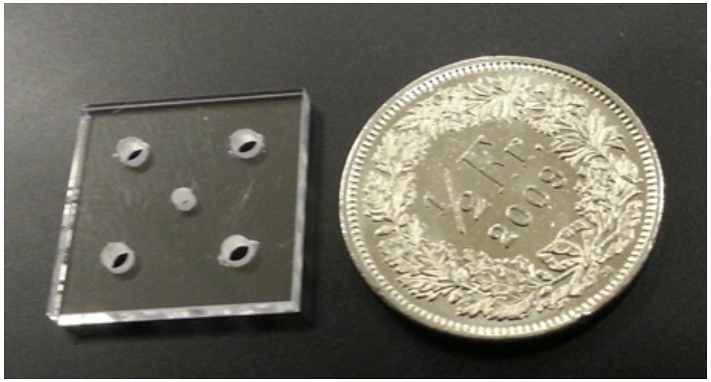
Test-beam

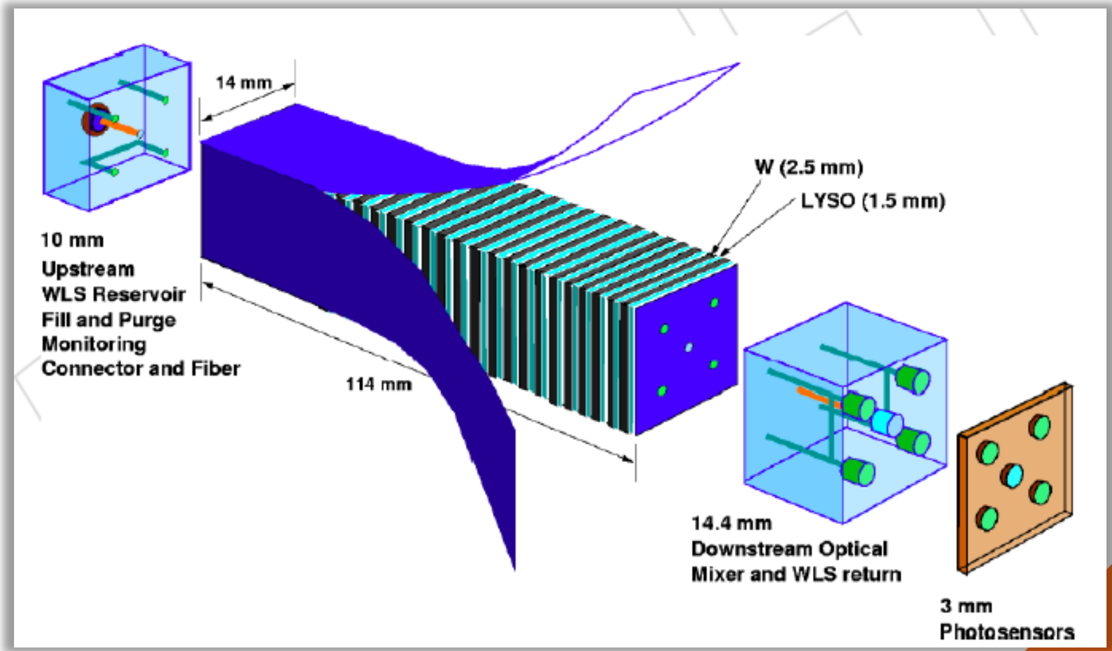




LYSO-Tungsten Shashlik ECAL

- LYSO light yield is very large → more stable pulse shape → better time measurement
- Was studied as one of the CMS Phase 2 Options

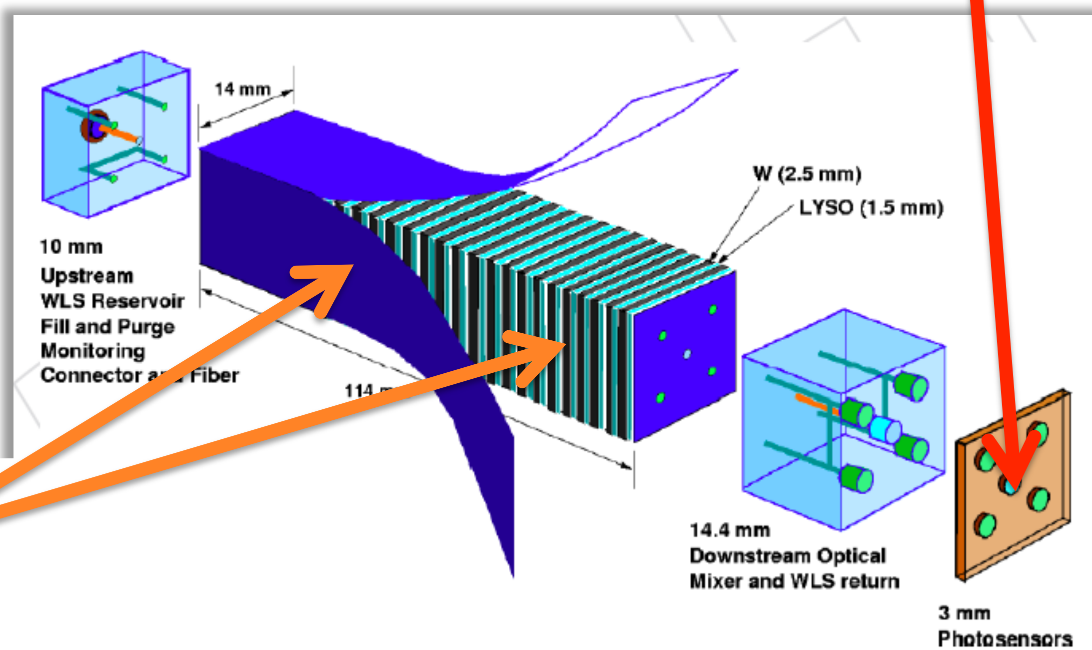




LYSO-Tungsten Shashlik ECAL

- Two options explored:
  (1) Read out light at specified layers
  (2) Read out light via fibers

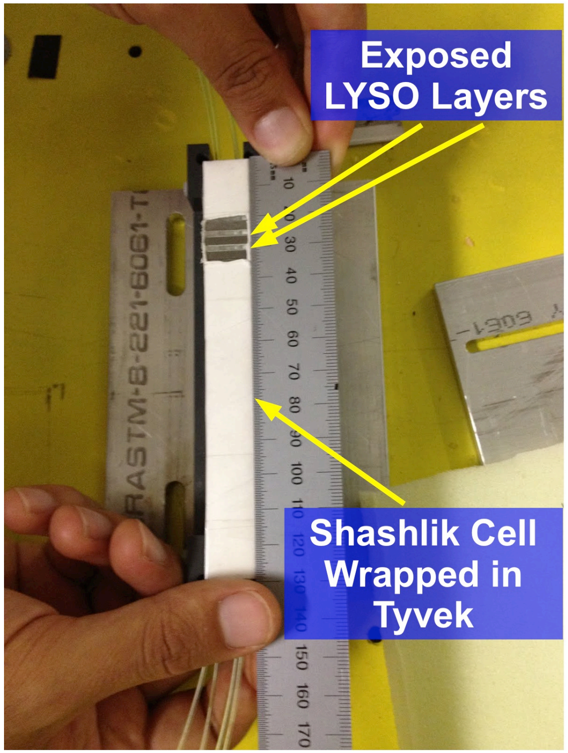
Option (2) : Extract light from fibers

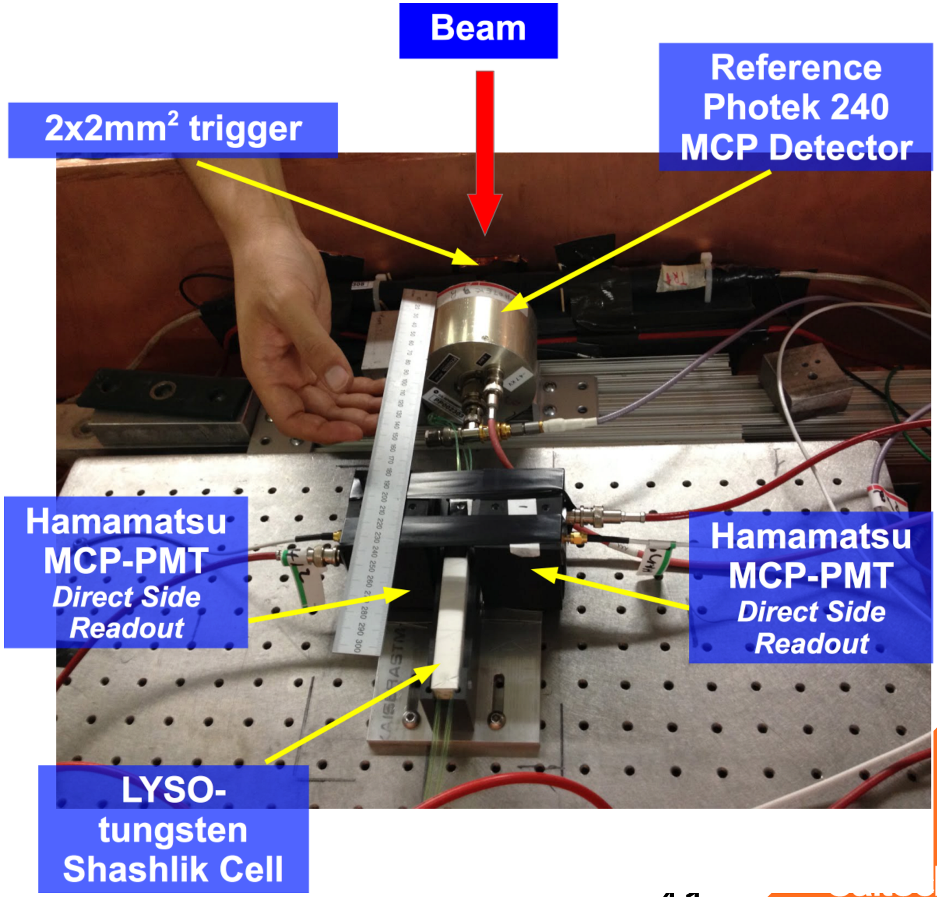


Option (1) : Extract light from specific layers

LYSO-Tungsten Shashlik ECAL

- Option (1): sample slices at ~5 X_0

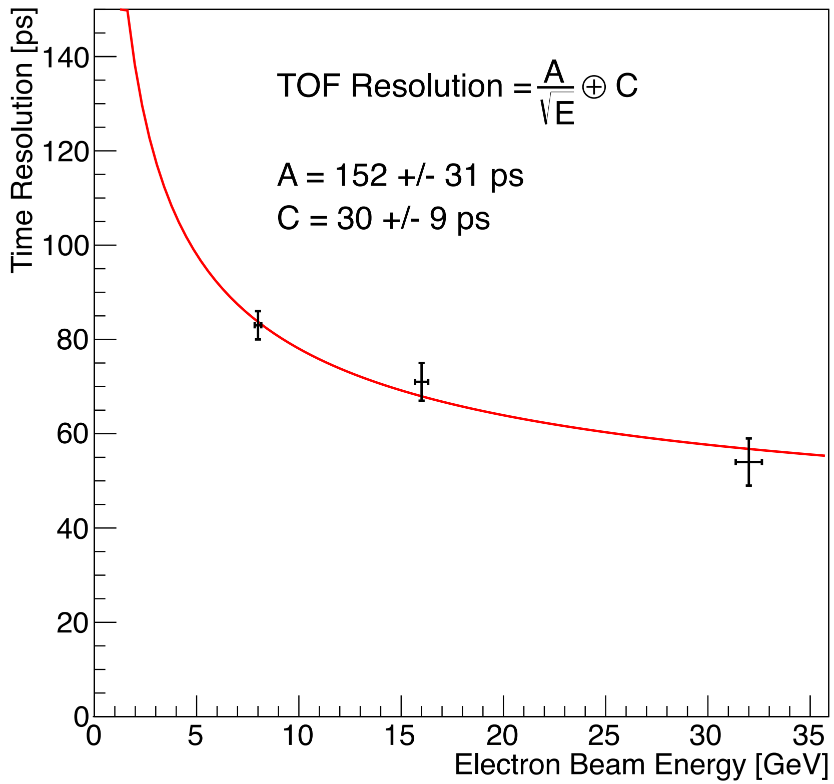




Shashlik Beam Tests

- Option (1): sample slices at ~5 X_0

- Measure time resolution of ~60ps at 32 GeV
- Resolution driven by limited photon statistics and S/N
- Fit vs energy points to constant term being ~30ps

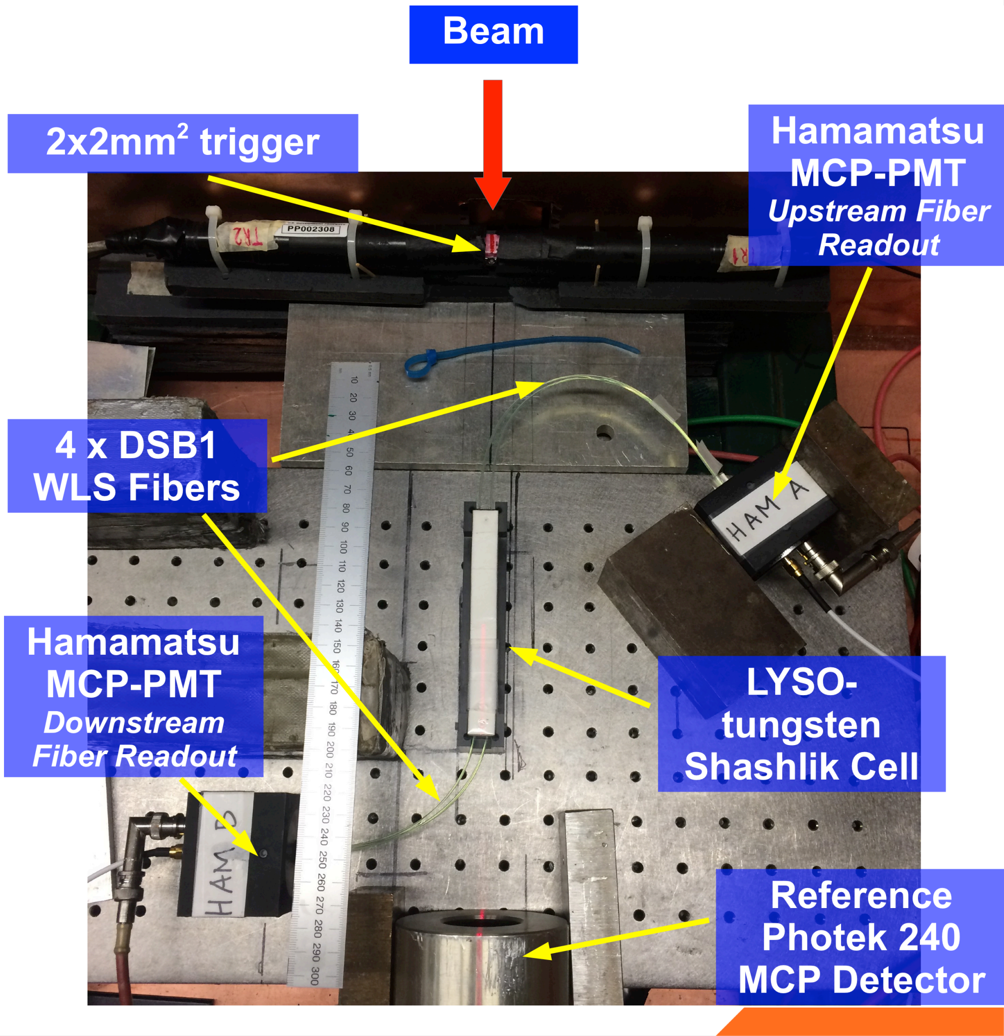


S. Xie, et al: "On timing properties of LYSO-based calorimeters", NIM A, 794 (2015) p. 7-14

Shashlik Beam Tests

- Option (2): extract light from fibers

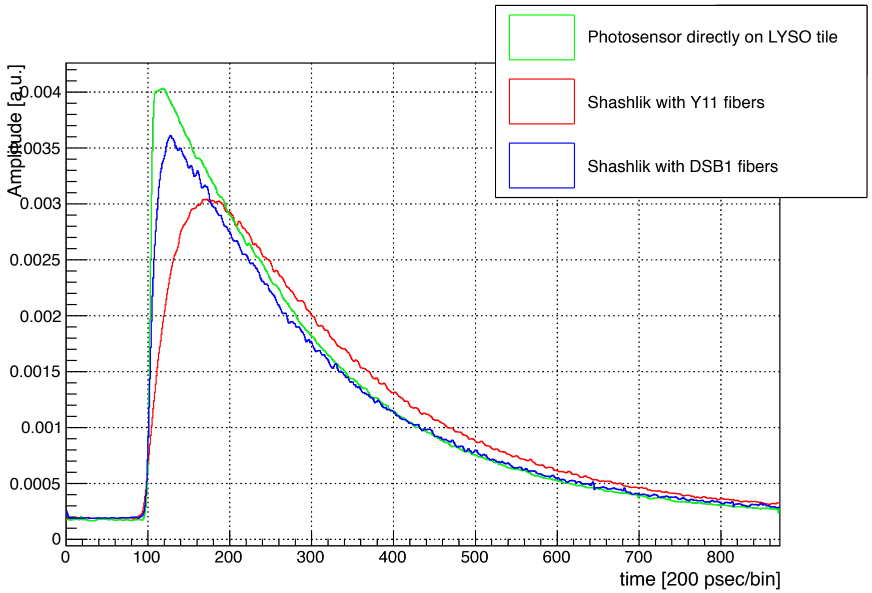
WLS fibers are read out by fast MCP-PMTs & SiPMs



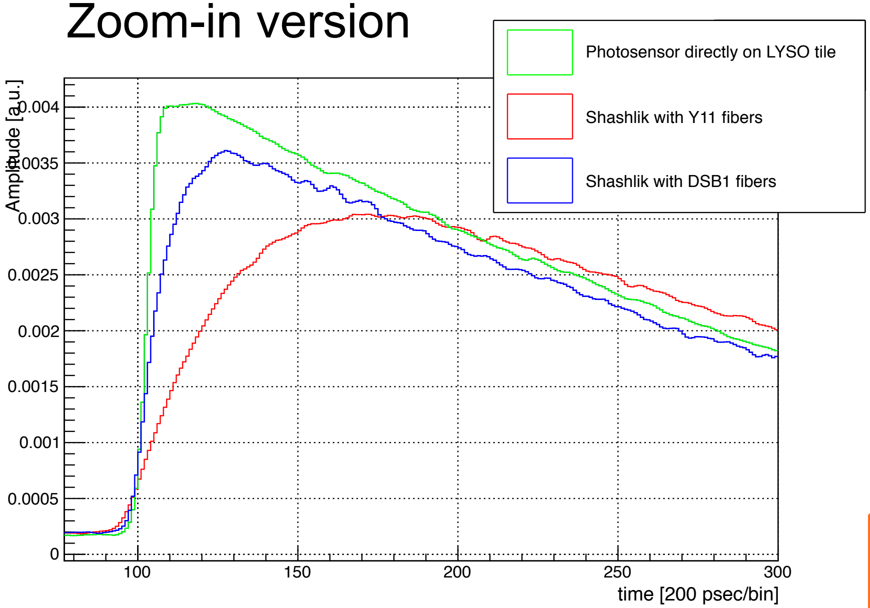
Si Xie

Pulse Shapes from WLS fibers

- Pulse shape (rise-time) has significant dependence on type of WLS fiber
- DSB1 fibers have significantly faster rise-time than Y11
  - ~2ns (DSB1) compared to ~7ns (Y11)
  - Direct contact with LYSO crystal gives ~1ns



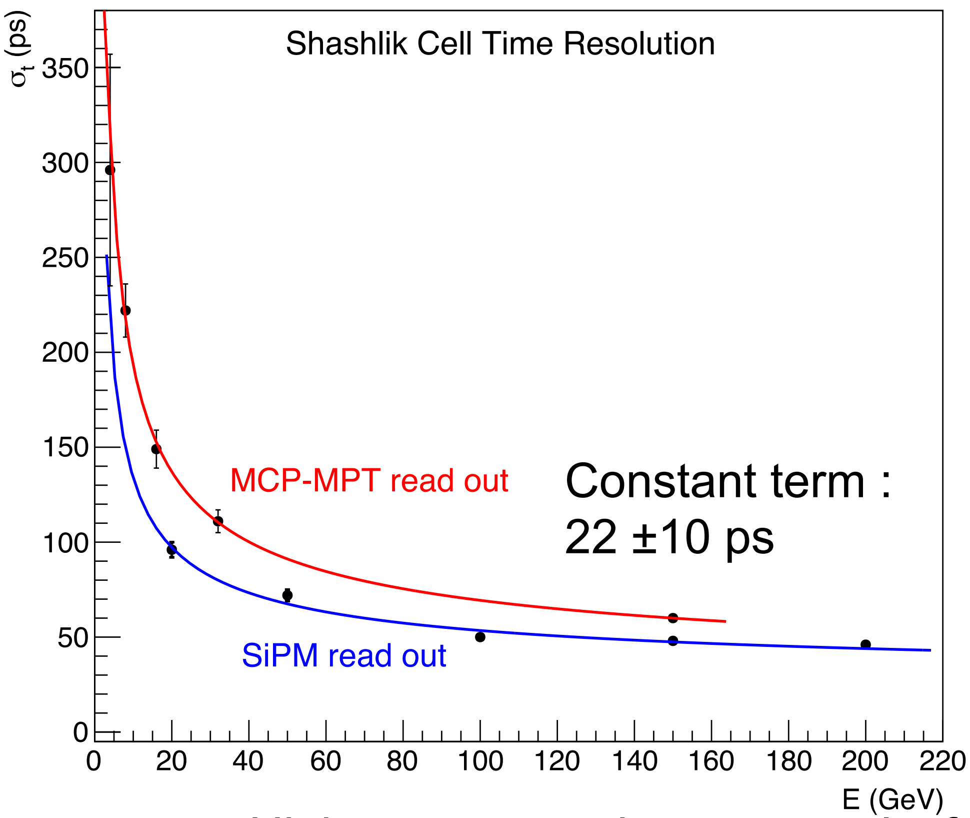
Zoom-in version

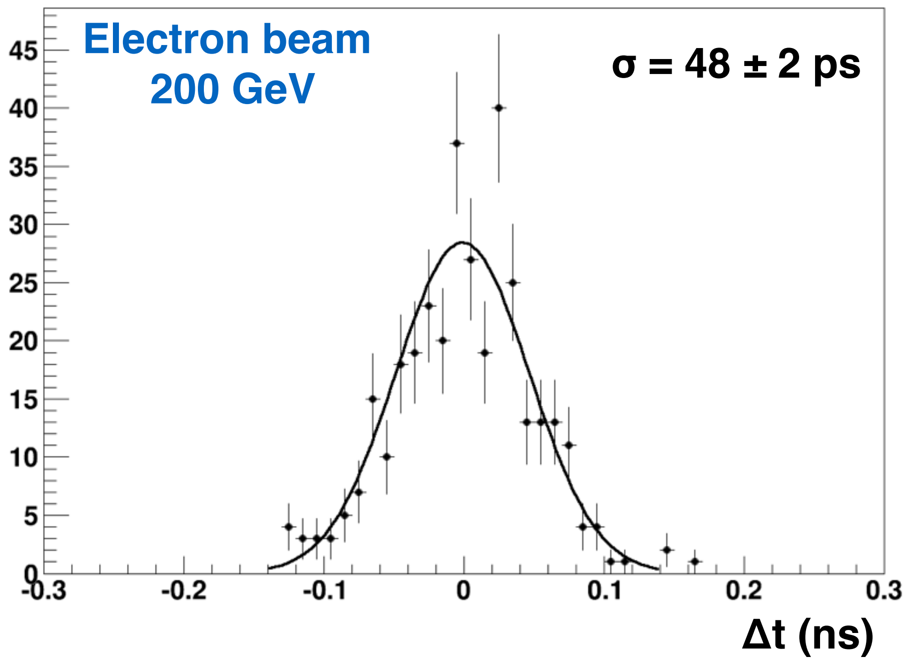


Caltech

Shashlik Time Resolution

- Observe 50ps resolution at 200 GeV, with constant term ~20ps
- Time resolution limited by light yield and S/N

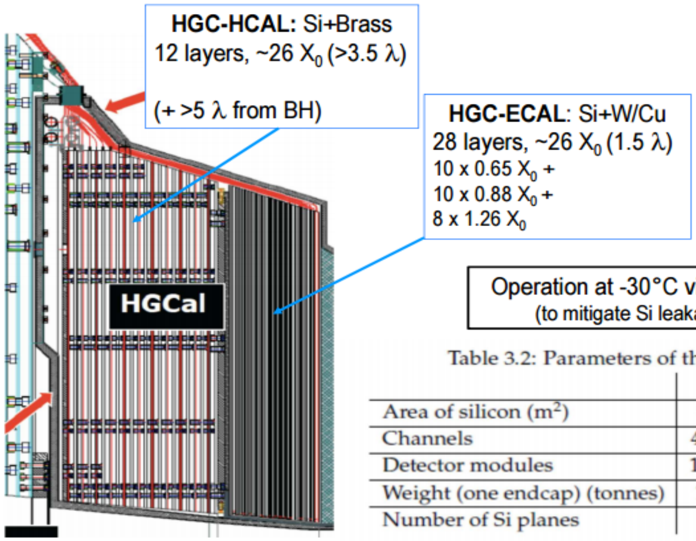




Higher energy points are results from our measurements at CERN SPS

Secondary Emission Calorimeters

- Intrinsic Advantages:
  - Intrinsically Radiation-Hard
    - Silicon and MCPs are radiation hard
    - No optical transparency issues
    - No optical transport issues
    - No photocathode issues



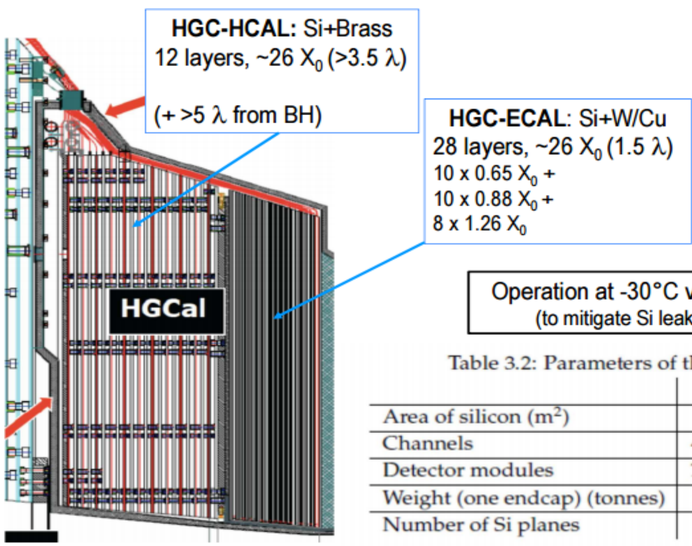
Operation at -30°C via CO_2 Cooling
(to mitigate Si leakage current)

Table 3.2: Parameters of the EE and FH.

	EE	FH	Total
Area of silicon (m^2)	380	209	589
Channels	4.3M	1.8M	6.1M
Detector modules	13.9k	7.6k	21.5k
Weight (one endcap) (tonnes)	16.2	36.5	52.7
Number of Si planes	28	12	40

Secondary Emission Calorimeters

- Intrinsic Advantages:
  - Intrinsically Fast
  - Signal formation and decay both fast (full pulse in few ns)
  - A major advantage for future colliders → enables faster bunch-crossing rate (5-10 ns)



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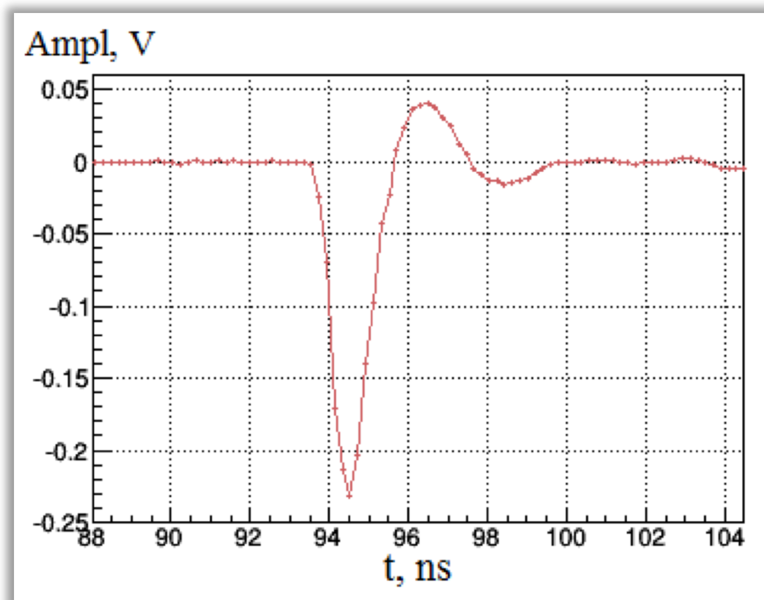
Number of Si planes	28	12	40

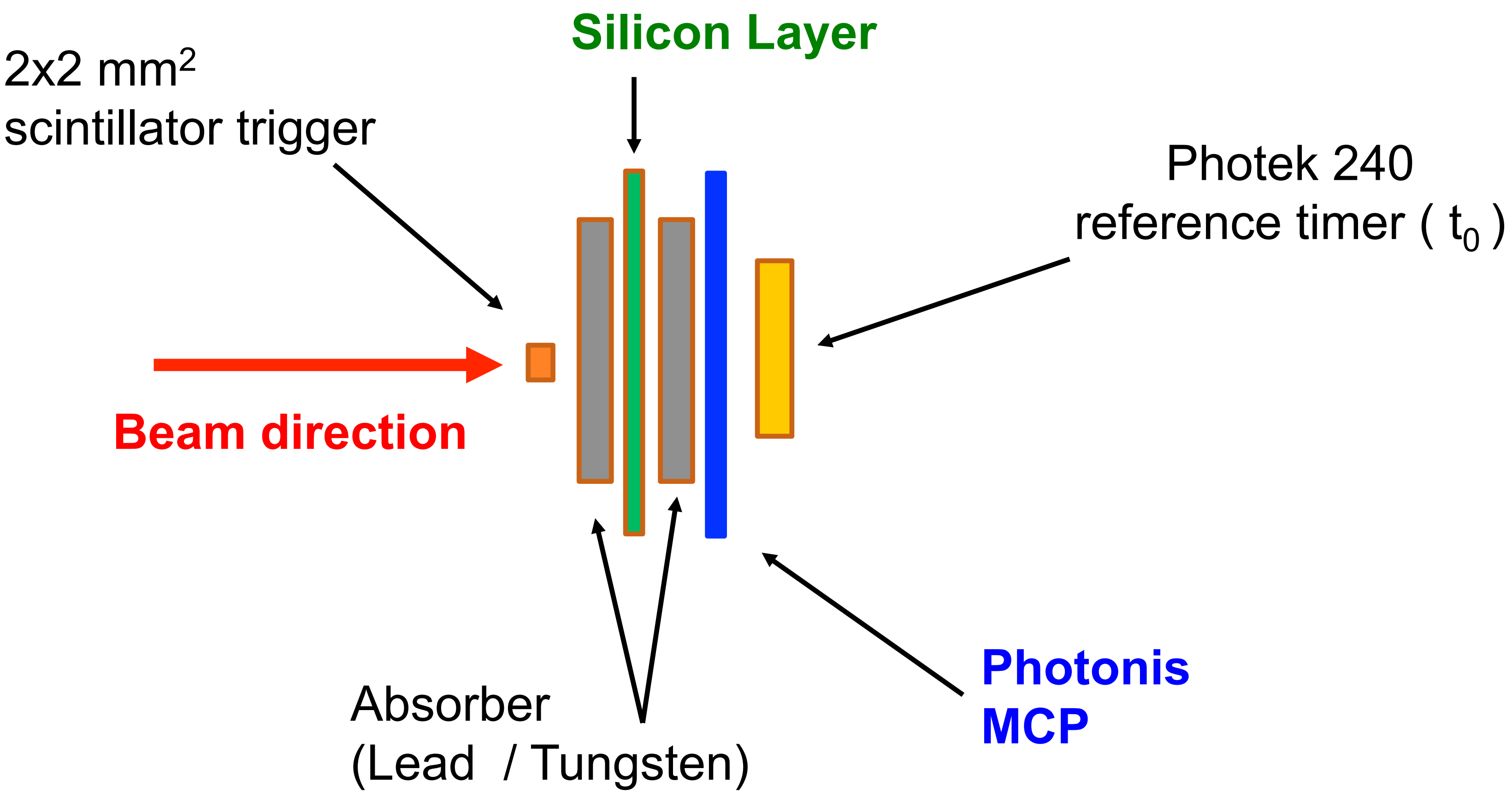
MCP Example → 2ns pulse width



Si Xie

Latest Secondary Emission Calorimeter Experiment

June 2016

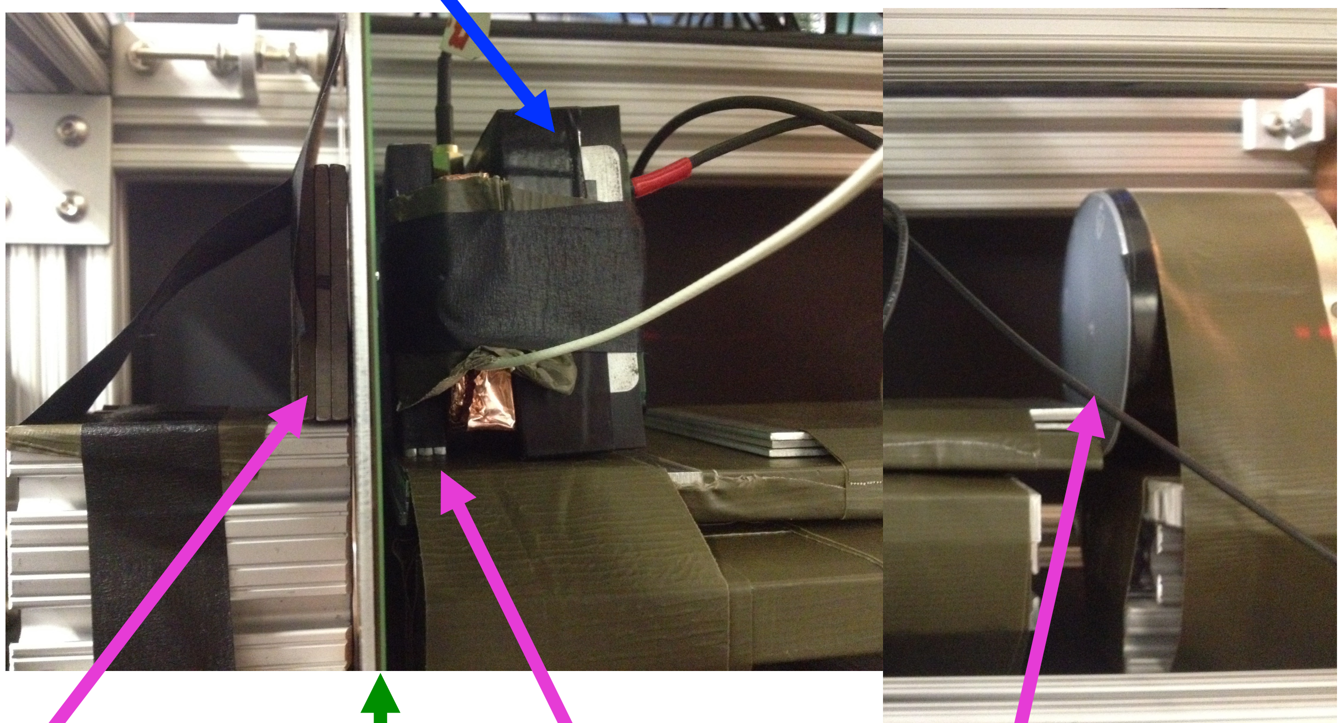


Latest Secondary Emission Calorimeter Experiment

June 2016

Photonis MCP

Beam direction



Tungsten Absorber

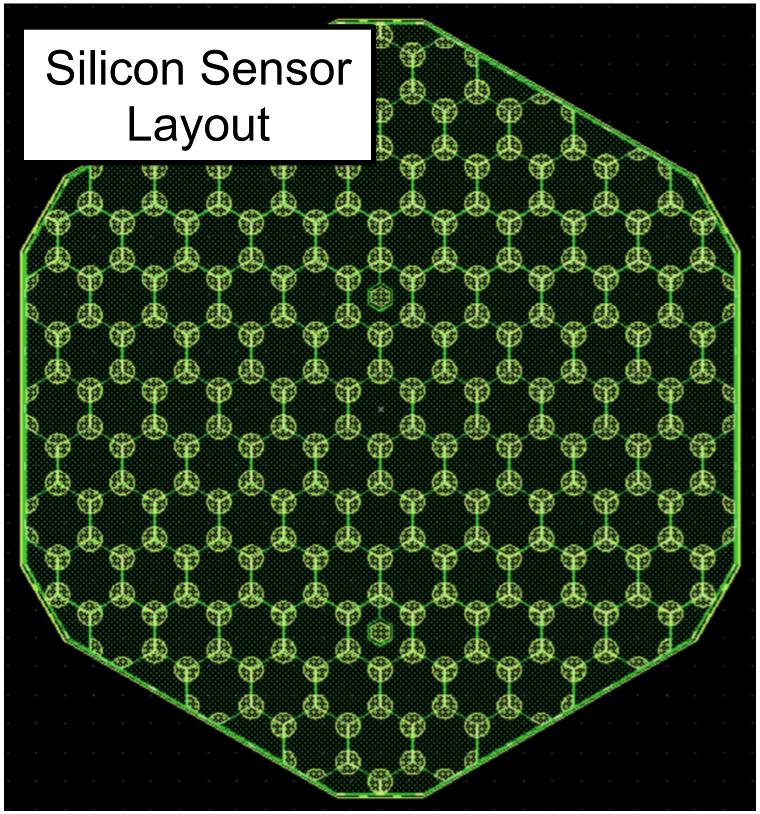
Silicon Layer

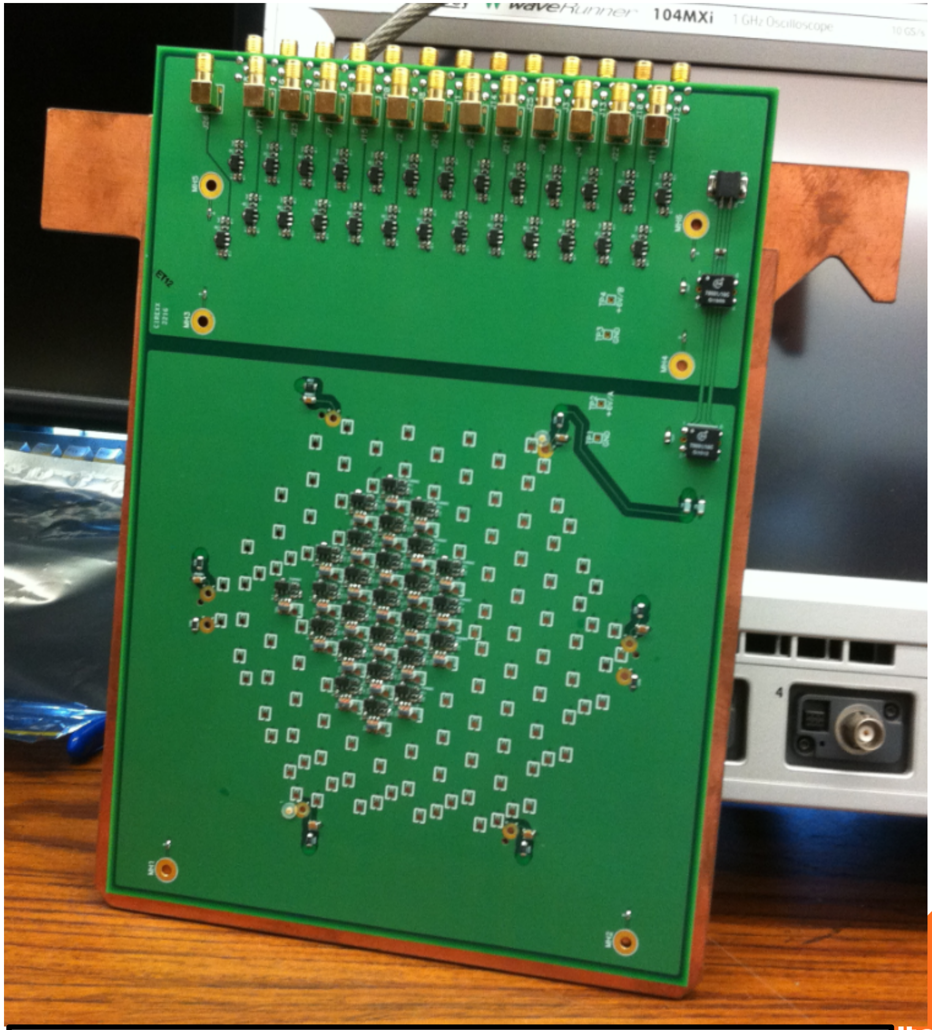
Tungsten Absorber

Photek 240 MCP-PMT

Silicon Layer

- Identical Batch of Silicon Wafers purchased for HGC prototype





- 300 *μm* sensor thickness
- 25 cells are instrumented with separate amplifier chain (gain=120)

PCB designed by Sergey Los (FNAL)

Si Xie

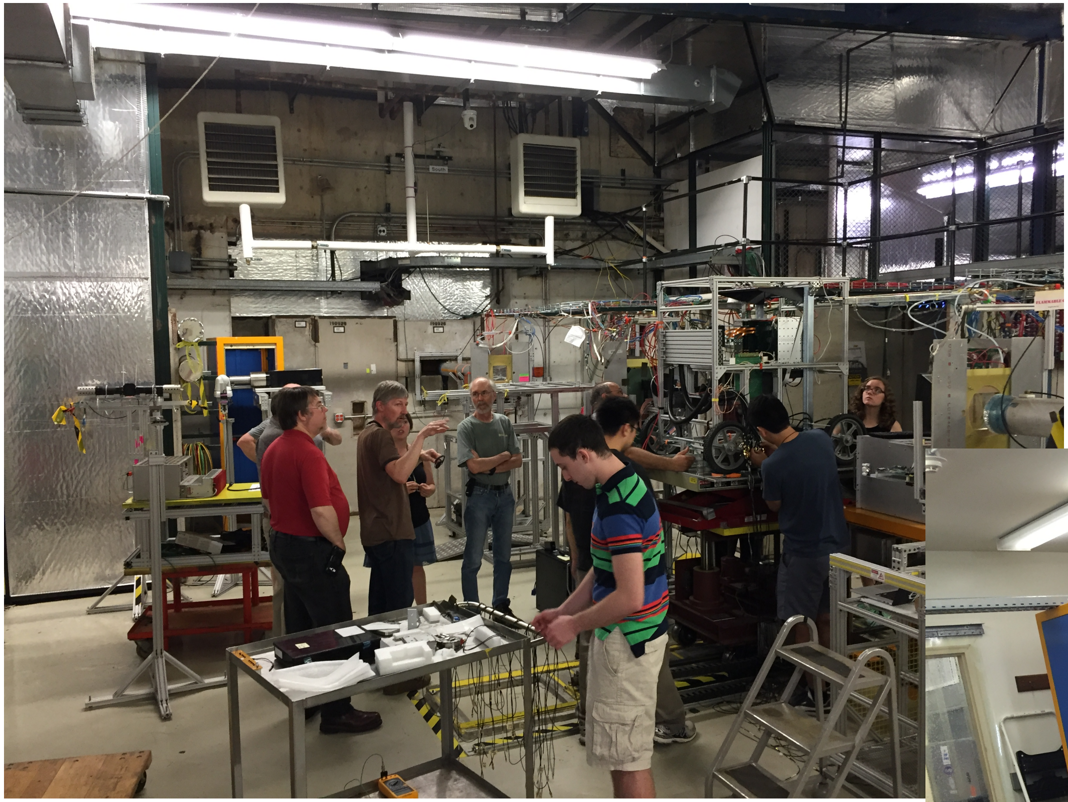
Photonis Micro-Channel Plate (MCP)

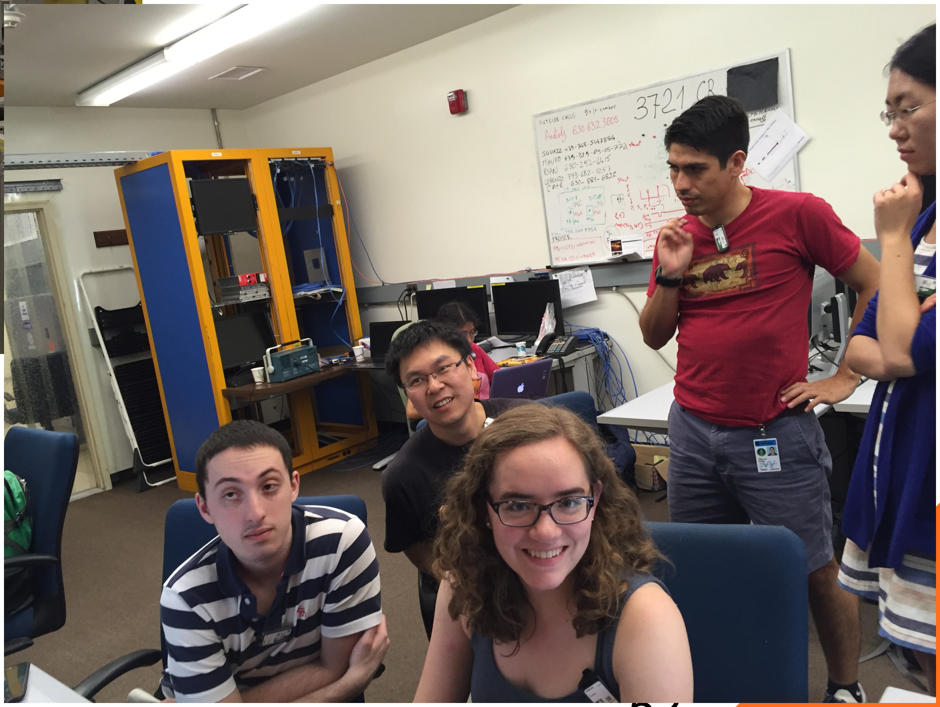
- Pixelated 8x8 , 6.5mm pitch per pixel
- 25 μm pores
- Active area 5.3cm x 5.3cm
- Standard Operating Gain: 10^5

Photonis 85012
MCP

Si Xie

Many experimental challenges!





Special Recognition to
Caltech undergrads:
Daniel Gawerc
Gillian Kopp

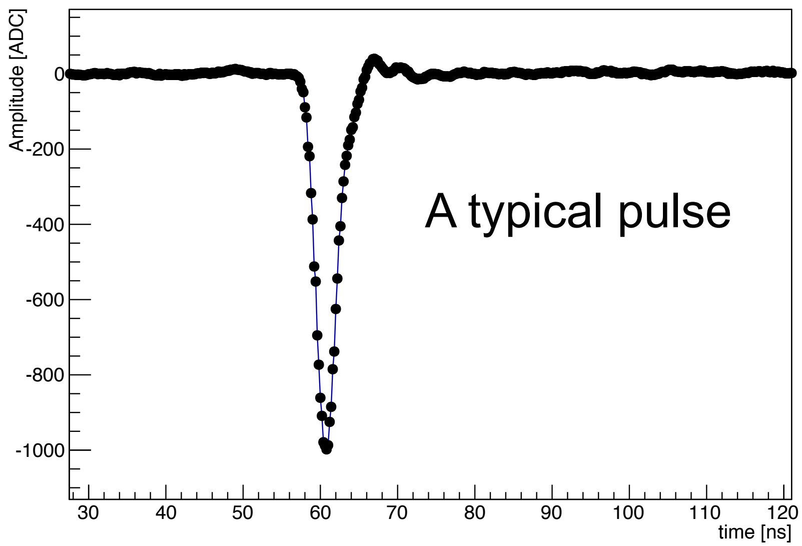
Many experimental challenges!

Many experimental challenges!

Si Xie

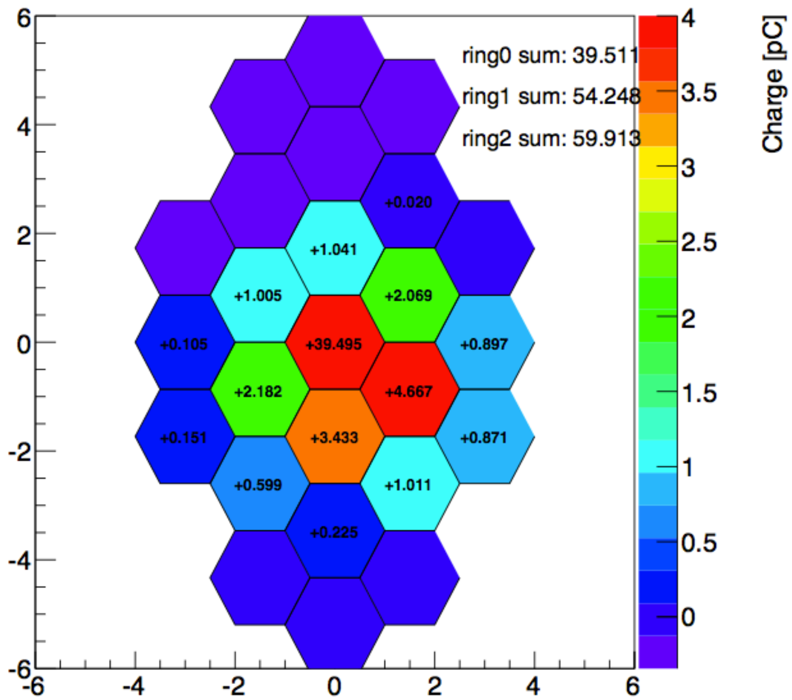
Caltech

Silicon Layer Timing



32 GeV electrons, $6X_0$ Tungsten

Avg distribution of shower



- Signal-to-Noise about 40:1 for 32 GeV electrons
  - Noise properties dominated by first stage amplifier noise

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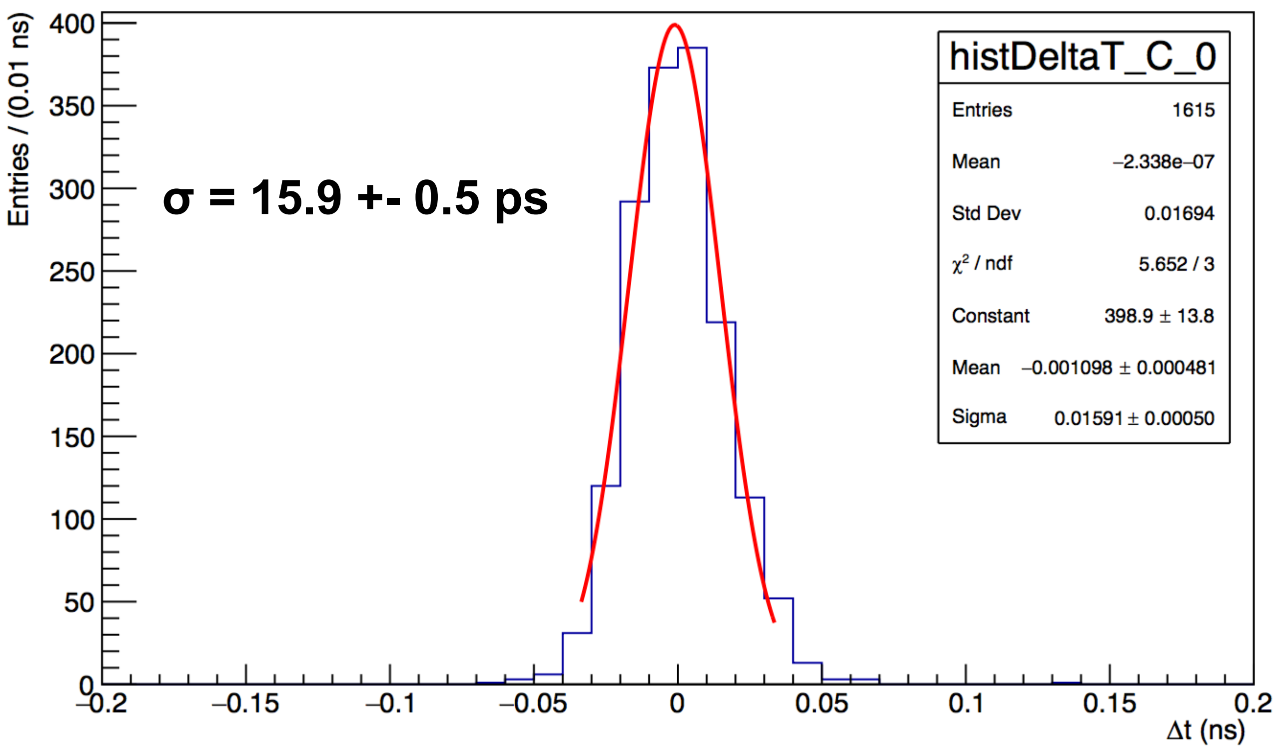
Silicon Layer Timing

- Measure time with respect to Photek 240 reference timer

Central Pixel Only

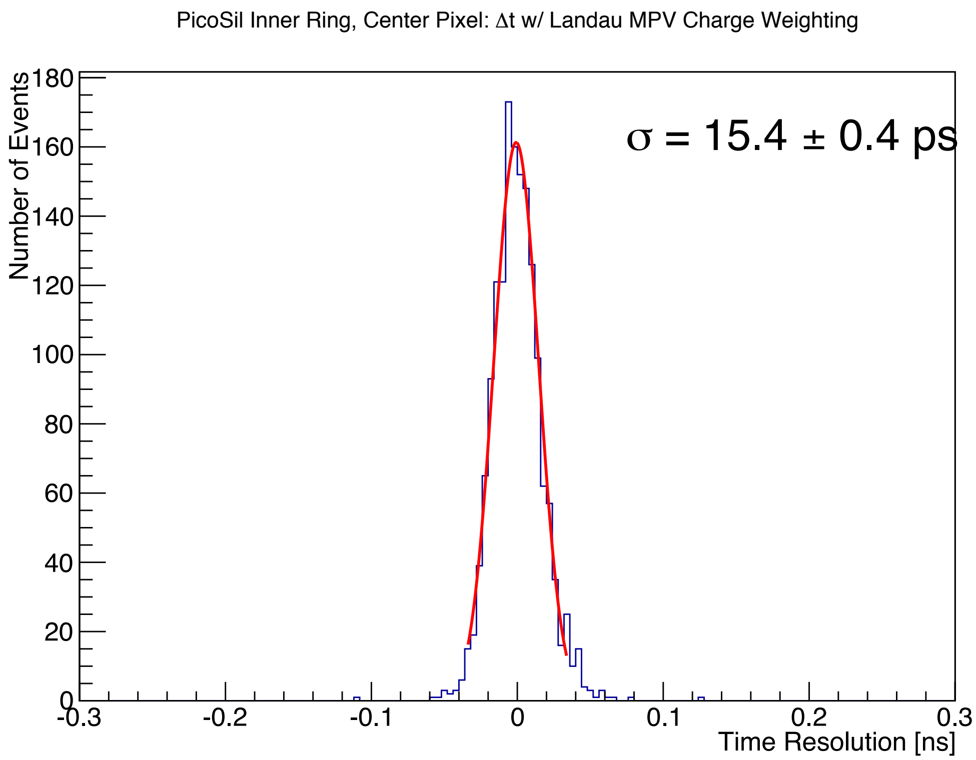


- Achieve an impressive resolution of 15.9 ps

Silicon Layer Timing

- Measure time with respect to Photek 240 reference timer

Combine all channels containing the shower



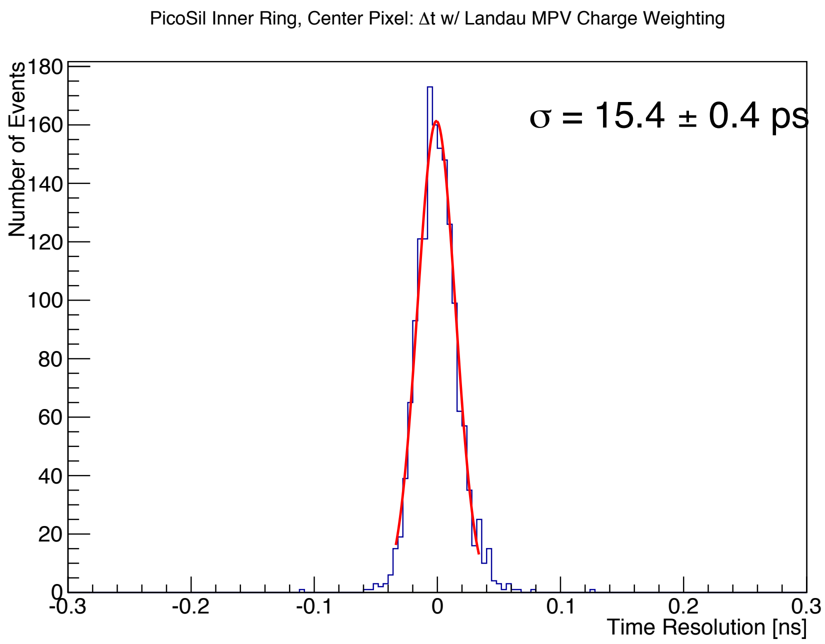
- Resolution improves from 15.9ps to 15.4ps

Caltech

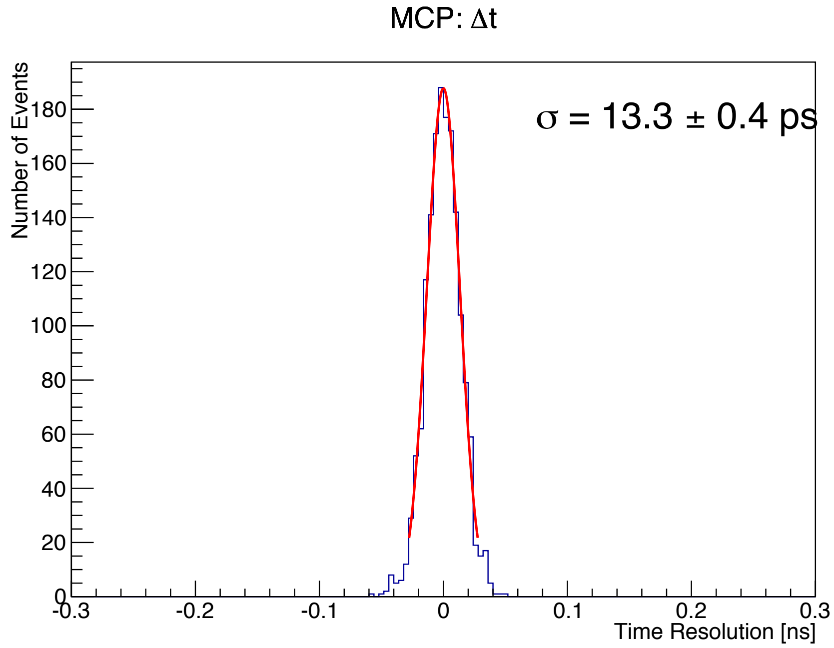
Si Xie

Combine Multiple Measurements

- If time resolution is dominated by S/N, then adding multiple measurements will lead to improvement
  - Try combining Silicon Layer timing with MCP timing



Silicon Layer



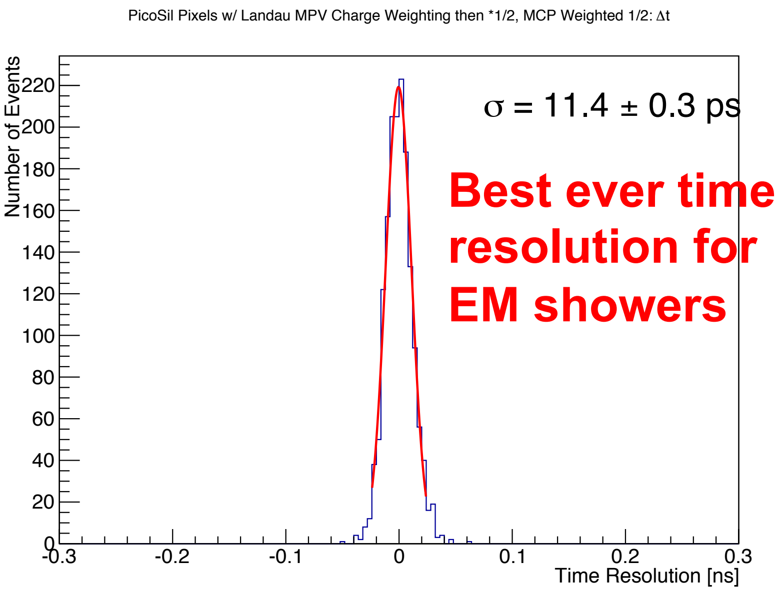
MCP

- Each layer measures time resolution of 15.4 & 13.3 ps

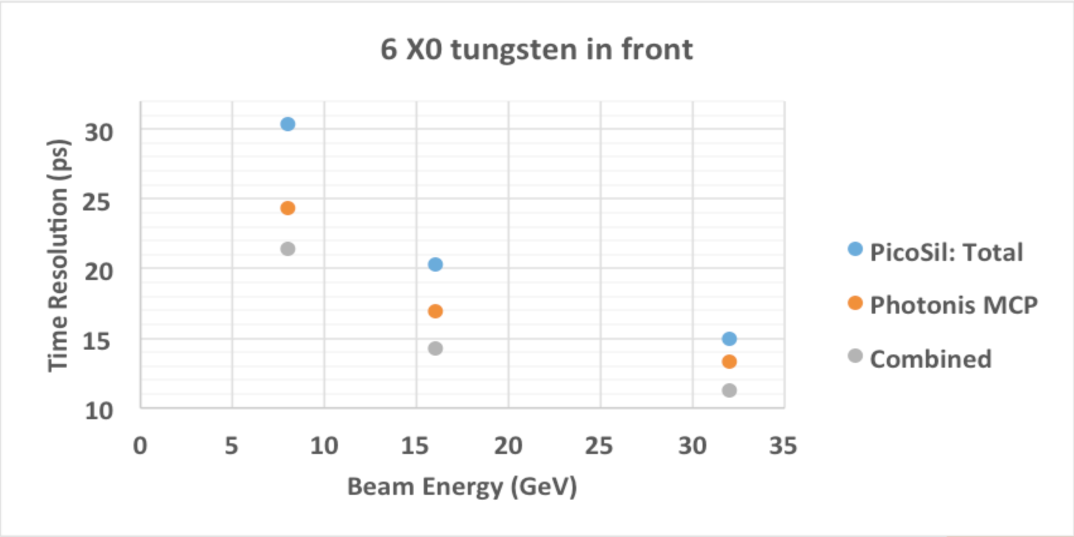
Combine Multiple Measurements

- If time resolution is dominated by S/N, then adding multiple measurements will lead to improvement
  - Try combining Silicon Layer timing with MCP timing

- Simple 50-50 averaging yields significant improvement
- Improvement is observed for all beam energies



Best ever time resolution for EM showers



Si Xie

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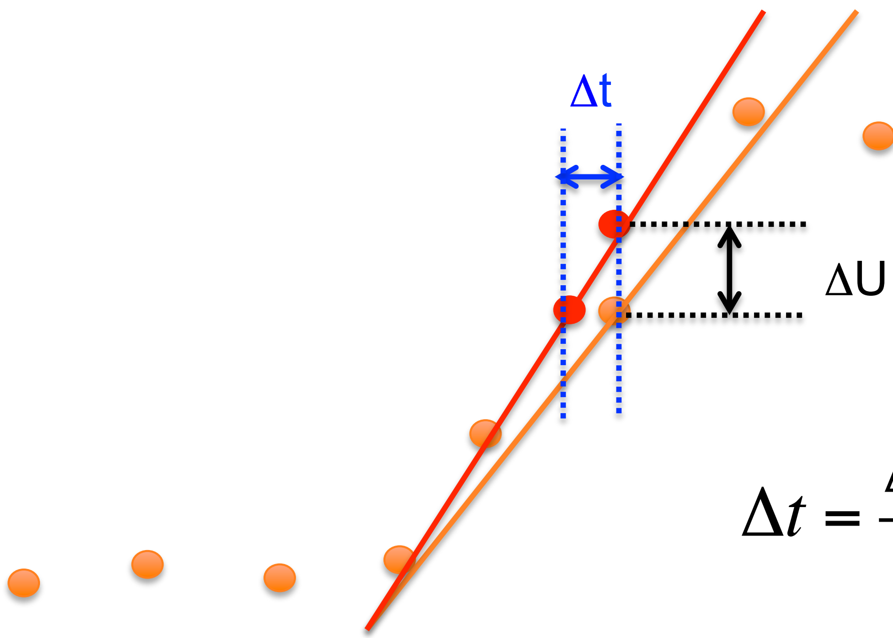
Calorimetric Timing Summary

- CMS ECAL : 100ps @ 10 GeV
  - Limited by front-end electronics
- LYSO-Tungsten Shashlik
  - Direct Optical Coupling : 60ps @ 32 GeV
  - Wave-length shifting fiber readout : 48ps @ 200 GeV (80ps @ 32 GeV)
- Secondary Emission Calorimeter
  - Silicon Layer : 15.4ps @ 32 GeV
  - MCP : 13.3ps @ 32GeV
  - Silicon + MCP : 11.4 ps @ 32 GeV

A Few Generic Lessons in Precision Timing

Time Resolution Rule of Thumb



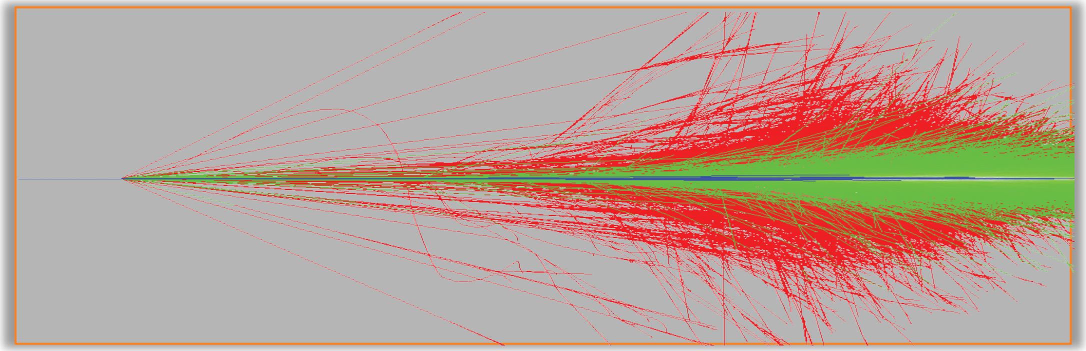
$$\Delta t = \frac{\Delta U}{U} t_{rise} = \frac{1}{U} \frac{\Delta U_i}{\sqrt{n_{samples}}} t_{rise}$$

For good time resolution, need:

- fast rise time (t_{rise})
- high Signal-to-Noise ($U/\Delta U$)
- more time samples ($n_{samples}$)

Geometric Time Jitter

- For most situations, time jitter has geometric sources. Eg:
  - Transverse spread of particle shower
  - Fluctuations in secondary flight paths
  - Signal formation in photodetectors



Cables!

- Cabling and Connectors are sometimes important
  - Impact of extra noise & connector bandwidth
  - We have observed impact at the 10-15 ps level

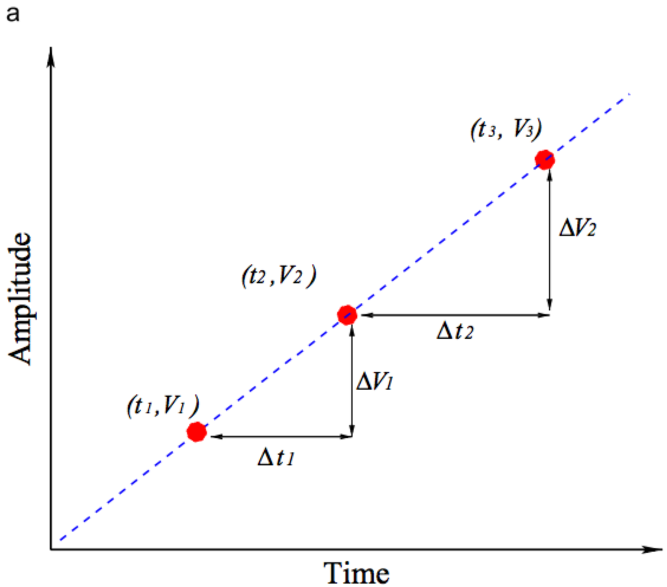
BNC connectors

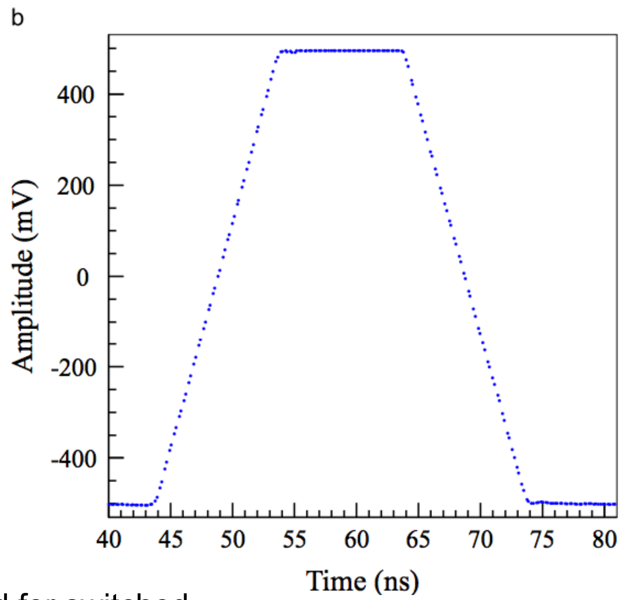
SMA connectors

Digitizer Calibration

- Calibration of digitizer is important
  - Bad calibration can lead to 10-15 ps degradation in resolution

Calibrate with a pulse shape generator





H. Kim, et al, "A new time calibration method for switched-capacitor-array-based waveform samplers"

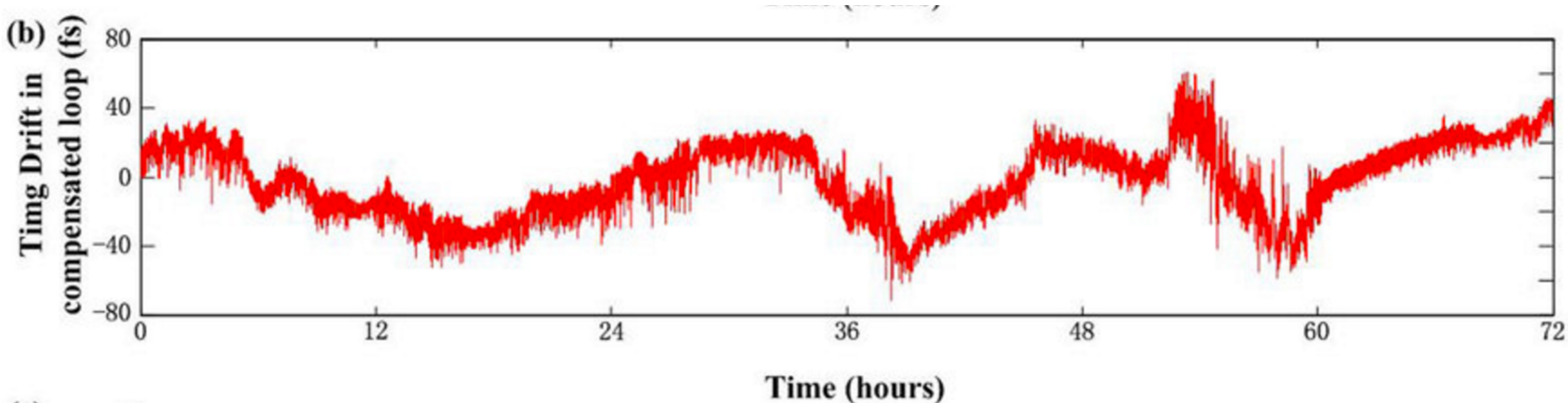
Time Reconstruction Algorithms

- Better time stamp reconstruction algorithm can help but is a 2nd order effect
  - We have tested a wide range of pulse shape fits & noise suppression / smoothing algorithms
  - They help but only at the 20% level
  - Constant fraction discrimination on rising edge works very robustly
  - Probably simpler is better

Clock Synchronization

- Synchronization over a large system is tricky, but R&D exists but may need significant integration effort
- One of the main areas where more work in HEP is needed

Using optical-microwave phase detectors achieve time jitter as low as **3.8 fs over 10km** fiber link



B.Ning, et al., "High-Precision Distribution of Highly Stable Optical Pulse Trains with $8.8x10^{-19}$ instability", Nature Scientific Reports 4, Article number 5109 (2014), doi: 10.1038/srep05109

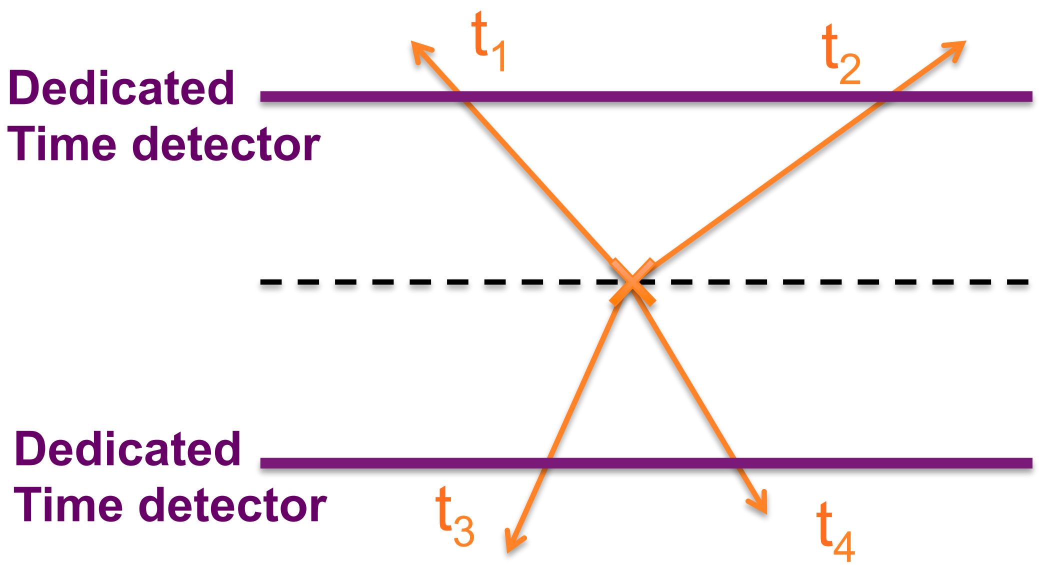
Overview

- Motivations :
  - Why precision timing?
  - What can it do?
- Examples of Specific Technologies:
  - Crystals & Shashlik
  - Secondary Emission Calorimeters
- Charged Particle Fully Hermetic Precision Timing & Future Opportunities

Charged Particle Timing

- A dedicated detector layer within tracking volume with capability for precision time measurement
  - Could be a part of the silicon tracker
  - Could be a different detector entirely

- Geometric proximity allows to associate the time measurement with each track (each charged particle)

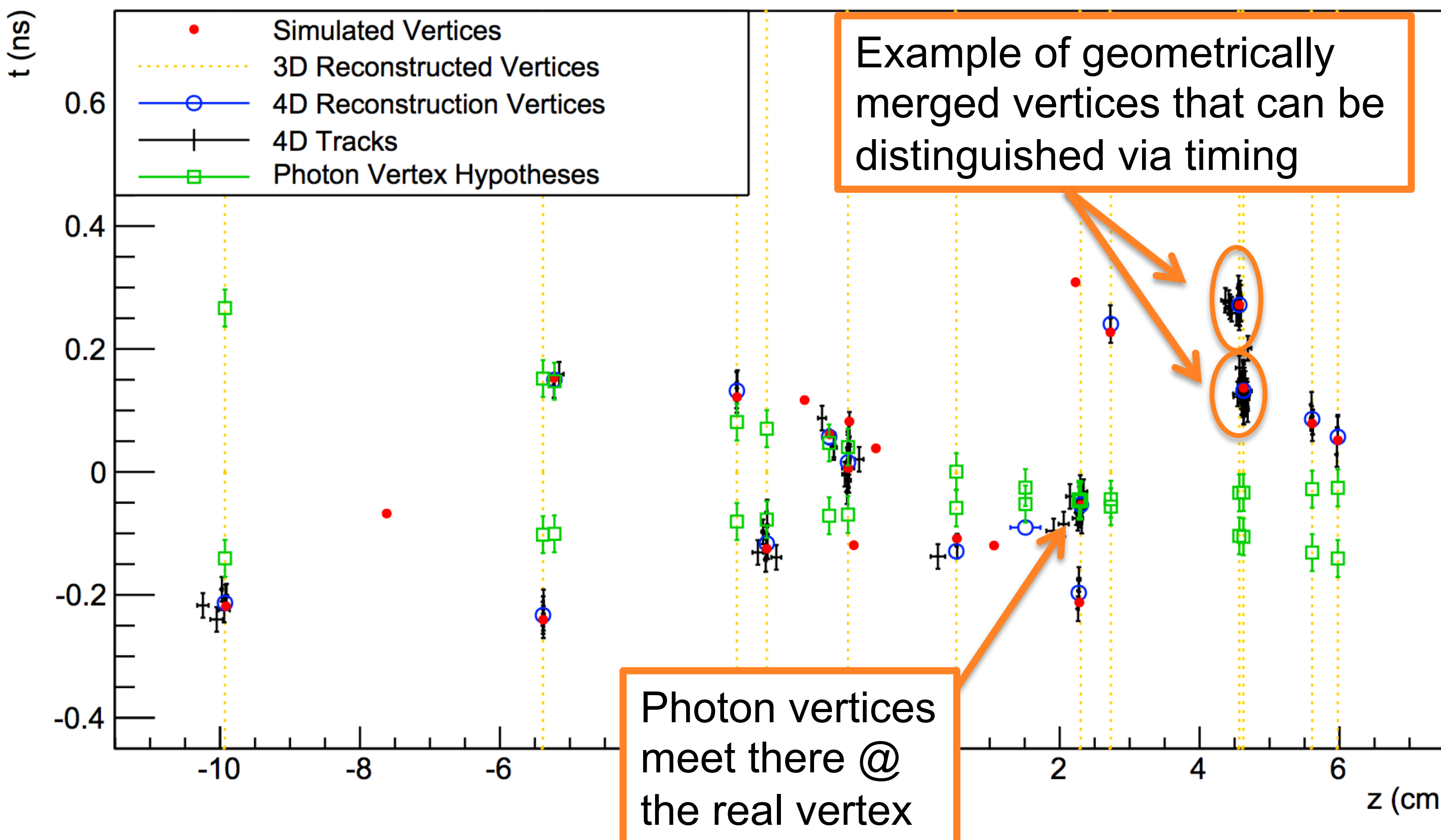


Charged Particle Timing

What can it do?

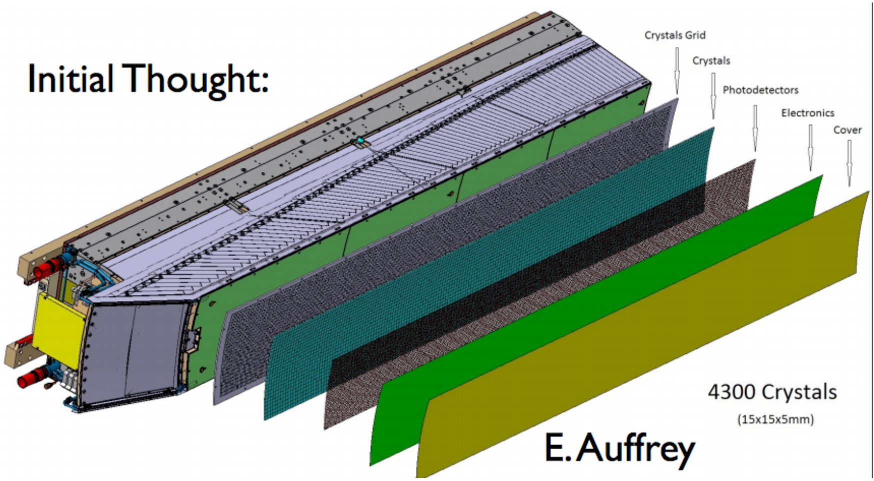
- Allows to time-stamp the interaction vertex
- Ability to distinguish geometrically merged vertices
- Gives reference time-stamp for events without a dominant calorimetric object
- Improve tracking, vertexing, pileup ID via 4-D tracking

Holistic Precision Timing : A Simulation Event

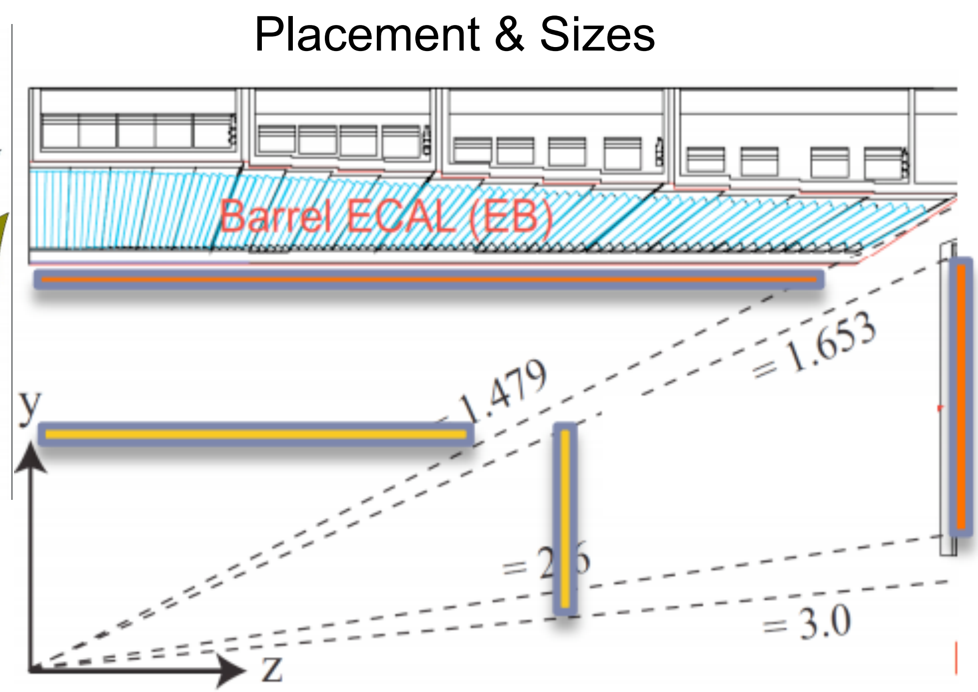


Charged Particle Timing Layer in CMS?

- Progress being made towards a proposal



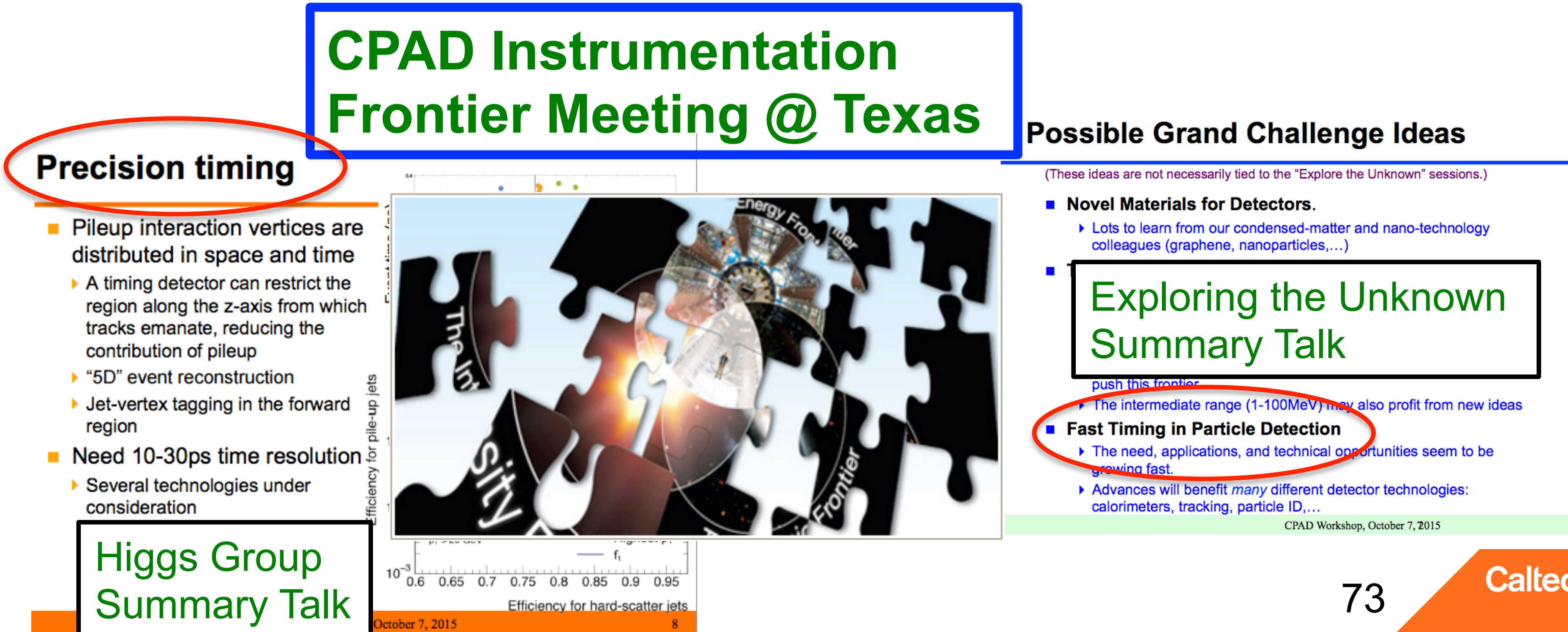
LYSO crystals
SiPM photo-detectors



- Silicon-based alternatives also being considered:
  - Low Gain Avalanche Diodes (LGAD)
  - Deep diffused APDs

Summary

- Precision timing starting to come of age @ LHC
- Approaching the 20-30 ps level precision needed for substantial pileup reduction
- R&D starting to happen on multiple fronts:
  - Calorimeter, charged particles, crystals, silicon, …



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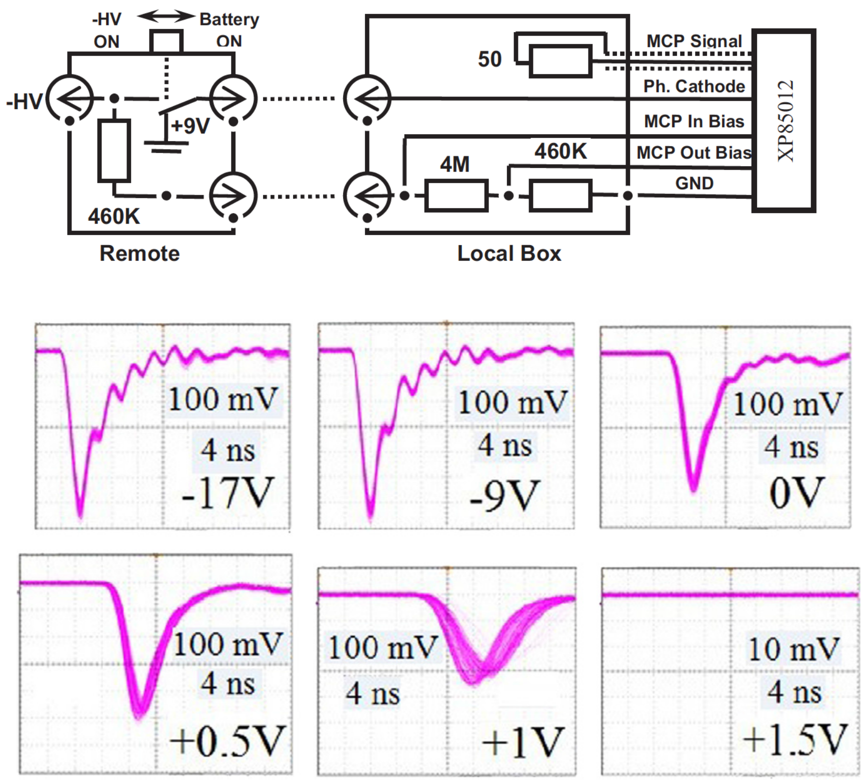
Backups

Apply a reverse bias voltage to the photocathode

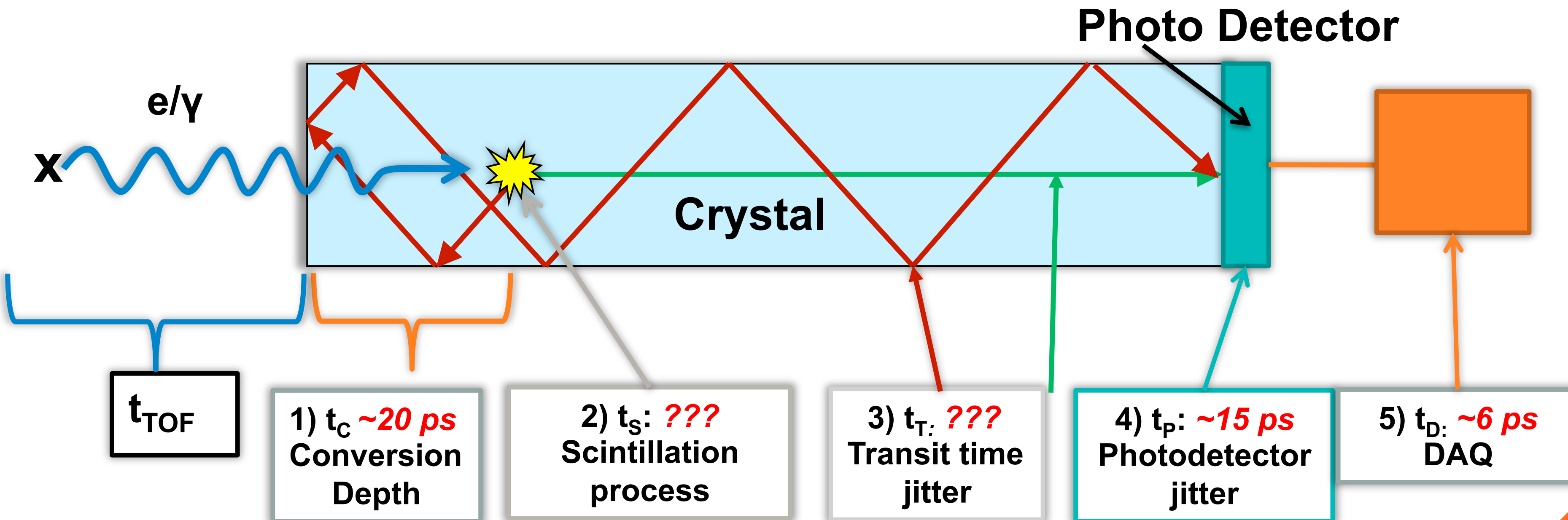


- A +9 V battery used to apply a voltage across photocathode to prevent photo-electrons from entering MCP
- Laser measurements verify that above +1.5 V, no more photo-electron signals are made

- Tungsten Moliere radius : 0.93cm
- Tungsten radiation length: 0.35cm

Shower Fluctuations

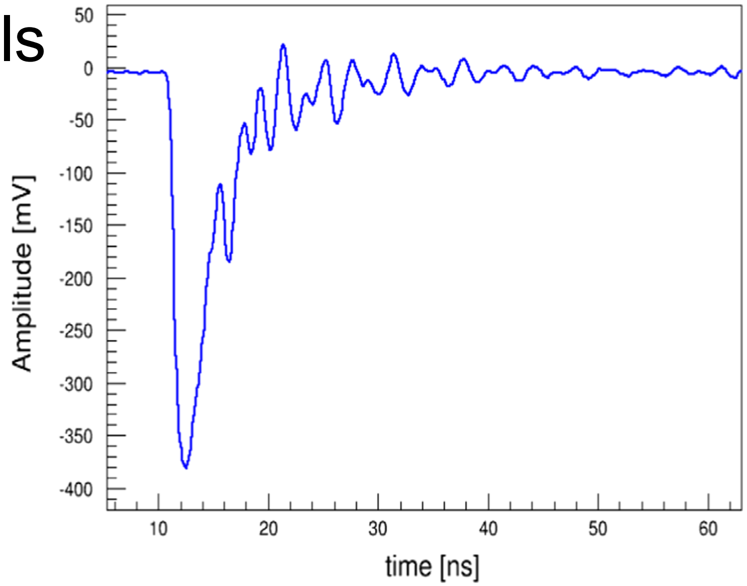
- EM shower fluctuations can induce time jitter on signal pulses
- Want to quantify this impact on time resolution

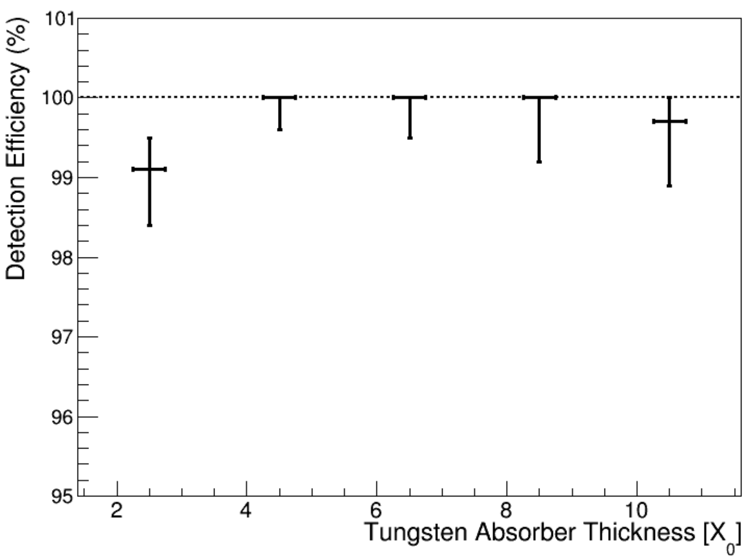


Pure secondary emission signals

Examples of secondary emission signals

- 8 GeV electron beam
- 4 X_0 of tungsten absorber

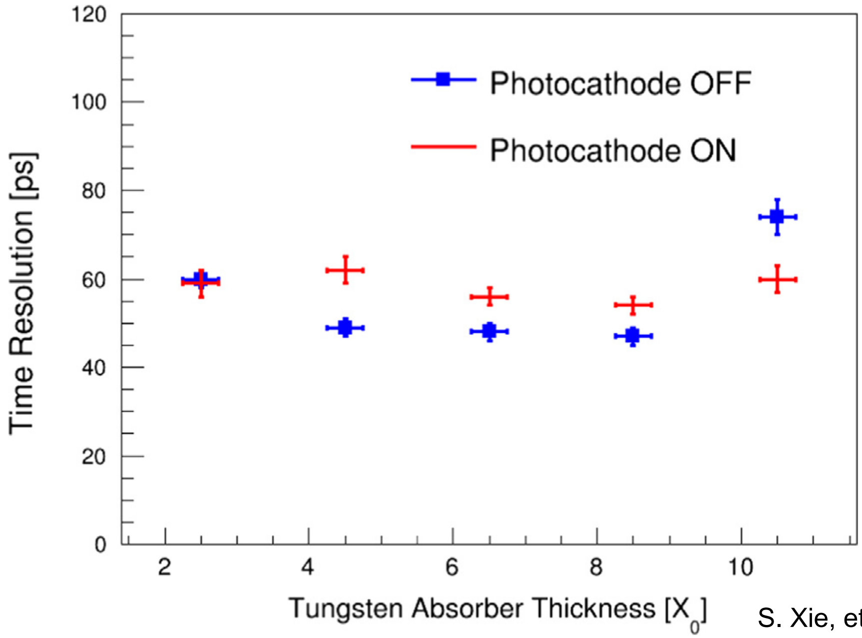




- Near 100% detection efficiency for EM showers

S. Xie, et al: "Direct tests of micro channel plates as the active element of a new shower maximum detector", NIM A, 795 (2015) p. 52-57

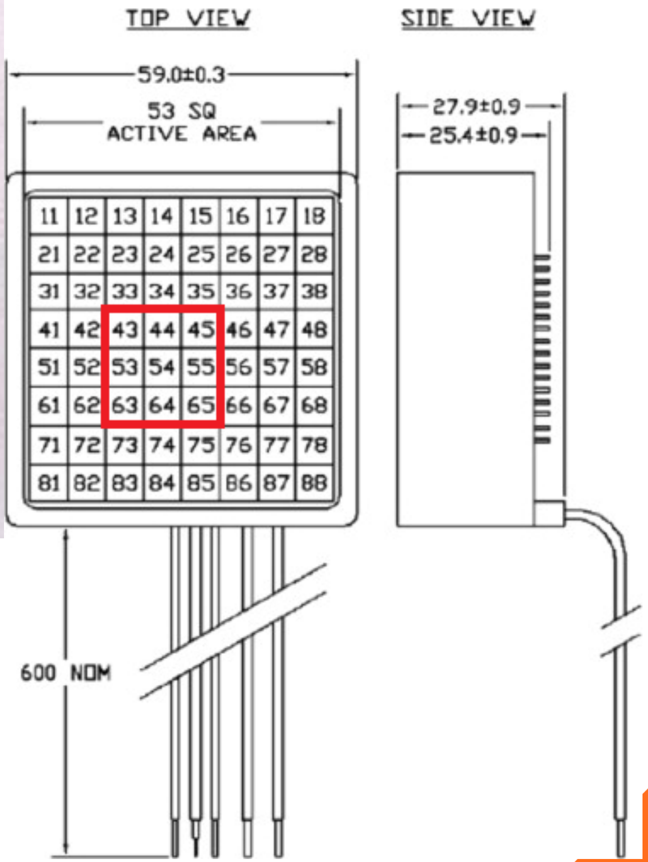
Time Resolution



S. Xie, et al: "Direct tests of micro channel plates as the active element of a new shower maximum detector", NIM A, 795 (2015) p. 52-57

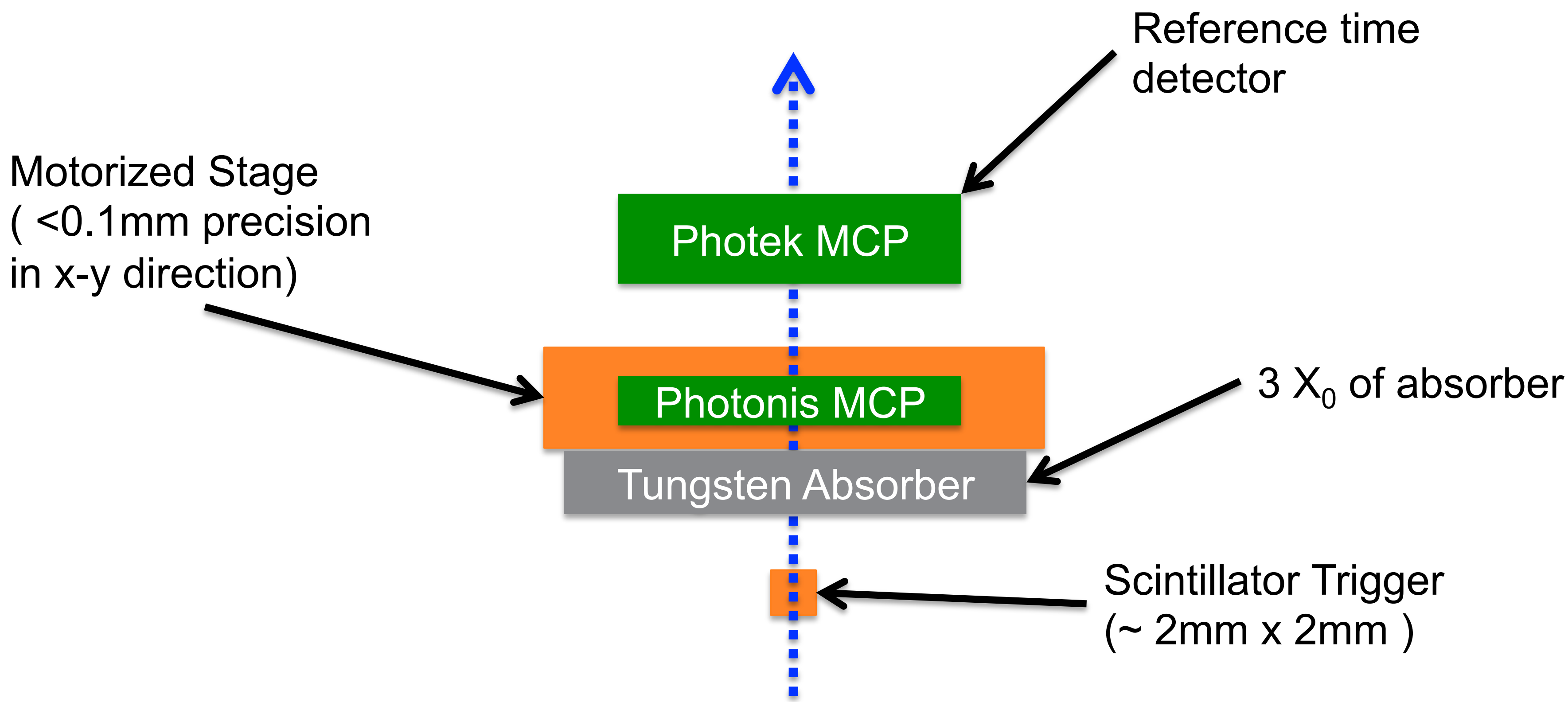
- Achieve ~50ps time resolution everywhere in the EM shower
- Likely limited by non-uniformity over the MCP or S/N

Shower Position Studies with Pixelated Readout



Option to read out each 6mm x 6mm pixel as separate channels

MCP on Motorized X-Y Stage

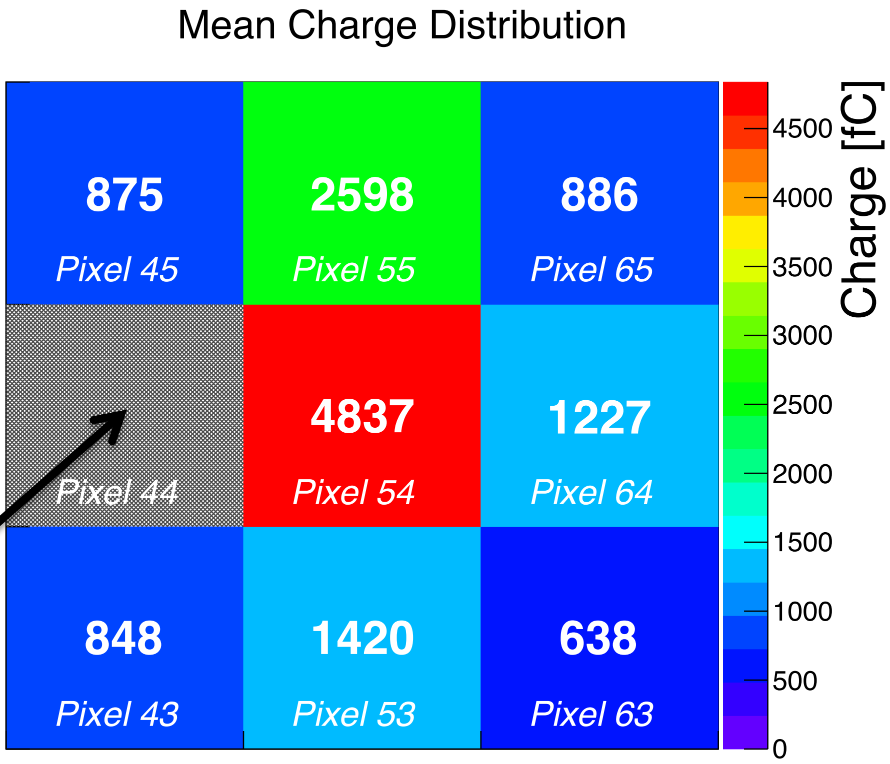


Electron Beam @
Fermilab Testbeam Facility

Shower Position Reconstruction

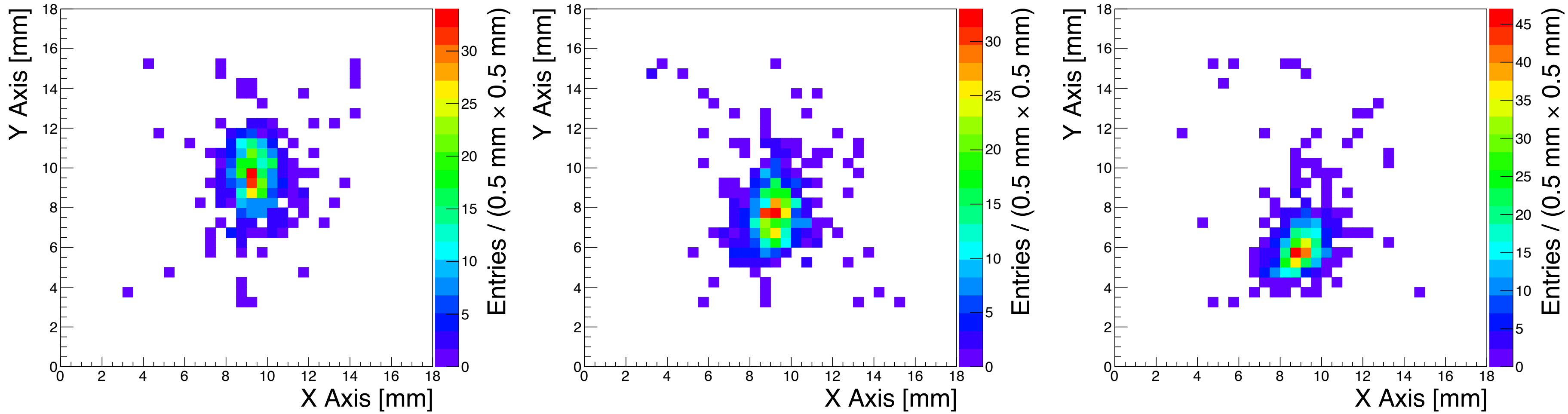
Use a simple energy-weighted position reconstruction

$$\vec{\mathbf{p}} = \frac{\sum_{i \in \text{pixels}} Q_i \vec{p}_i}{\sum_{i \in \text{pixels}} Q_i}$$

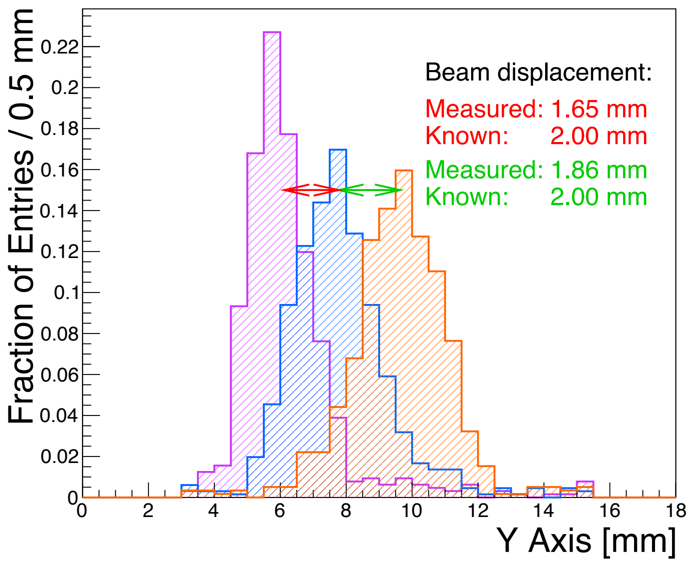


Unfortunately 1 pixel turned out to be dead

Three example beam positions

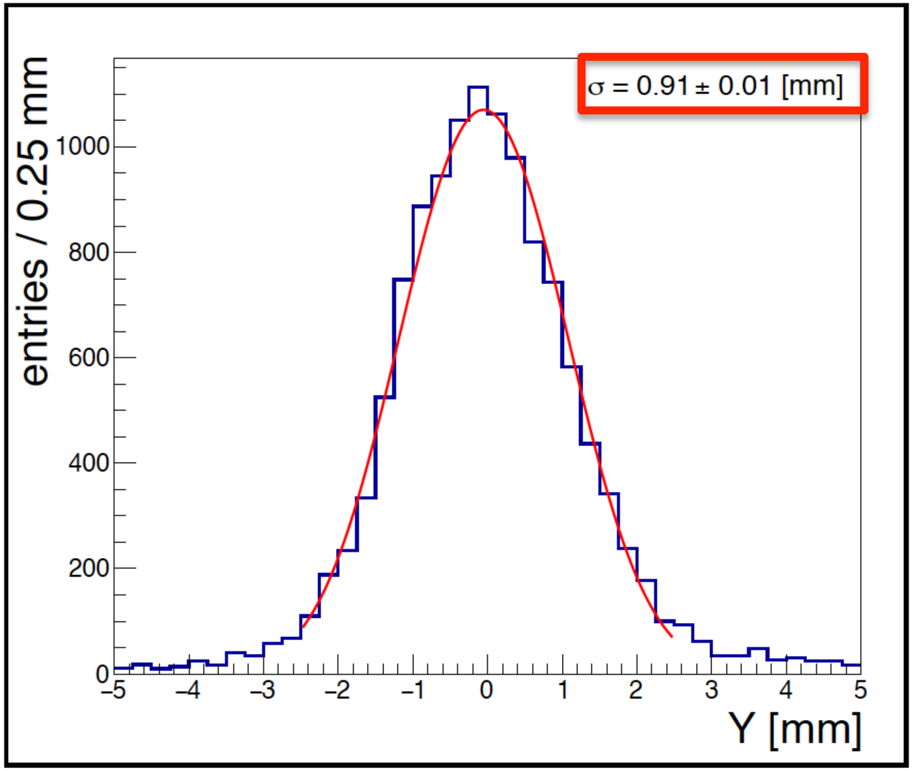


We observe shower positions are well reconstructed on average



Position Resolution

- Model the observed shower center position as a convolution of the beam profile with a gaussian
- Fit to the data to extract the resolution (width of gaussian)

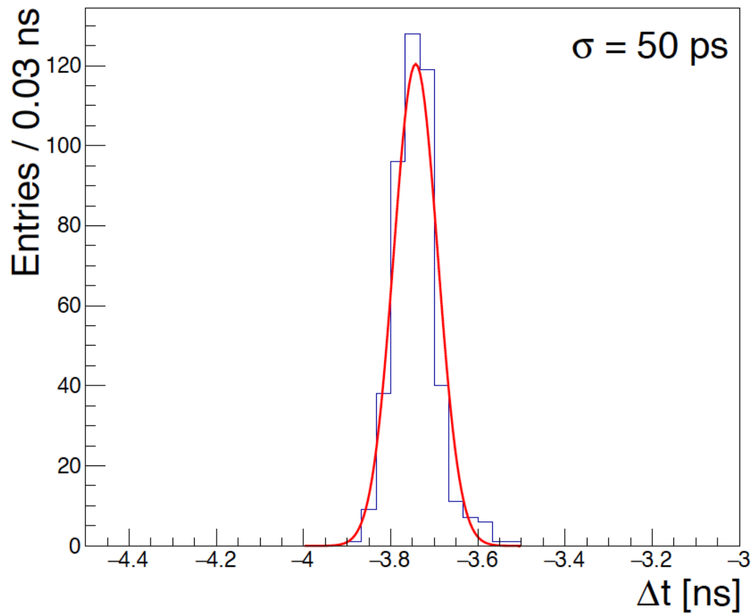


- Obtain position resolution just under 1mm.
- Recall that the pixel was a 6mm square

Time Resolution

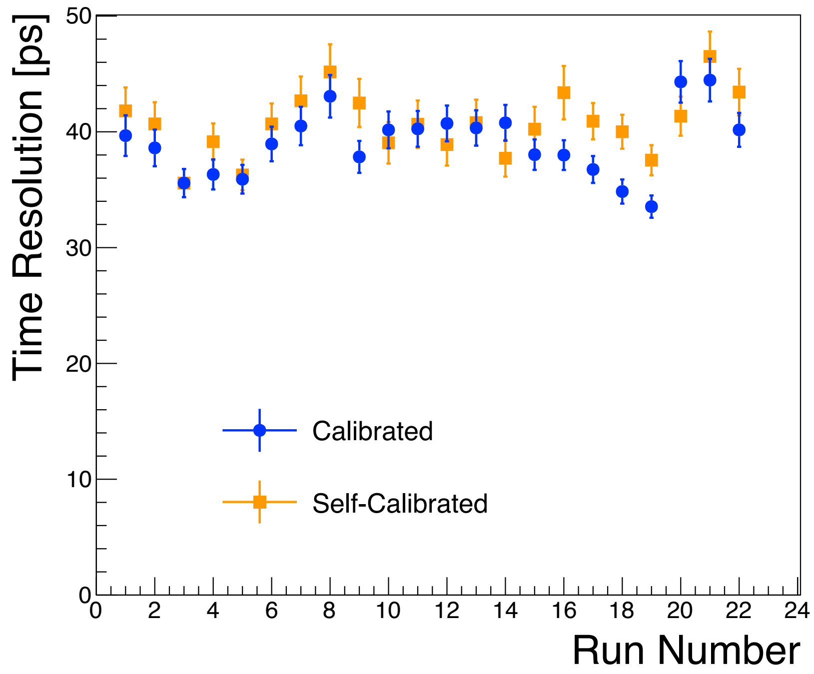
- Shower time-stamp reconstructed using simple charge / energy weighting

$$t = \frac{\sum_{i\in\text{pixels}} Q_i t_i}{\sum_{i\in\text{pixels}} Q_i}$$



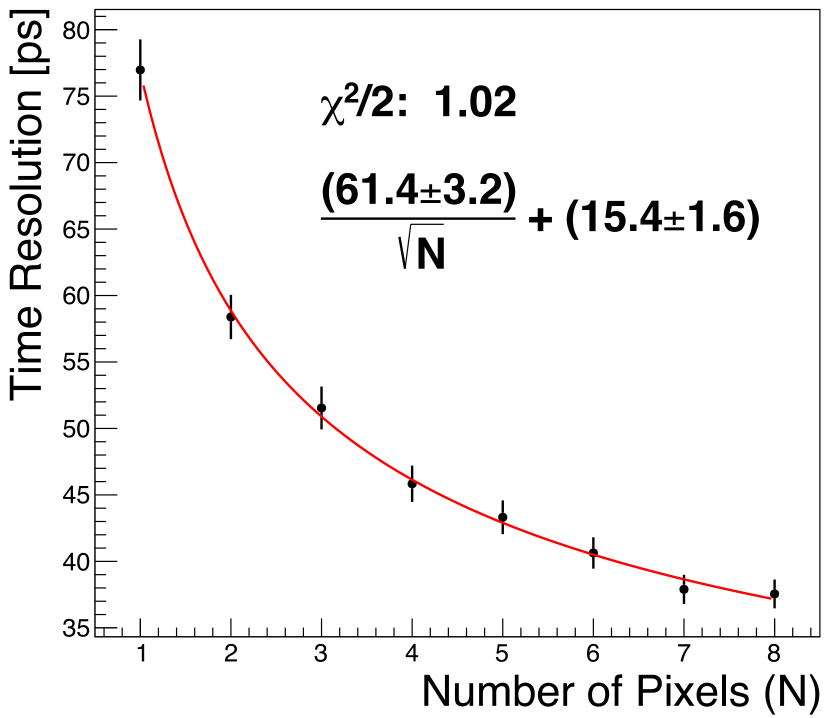
Time Resolution

- Achieve time resolution at the level of 35-40 ps using the pixelated information



Caltech

Time Resolution vs Number of Pixels



- Study time resolution as a function of how many pixels are included in the reconstruction
- Observe consistency with 1/sqrt(N) behavior

- additional information in transverse direction helps