TIMING DETECTORS AND THE HL-LHC

Future of Collider Searches for Dark Matter at the LPC

July 27, 2017

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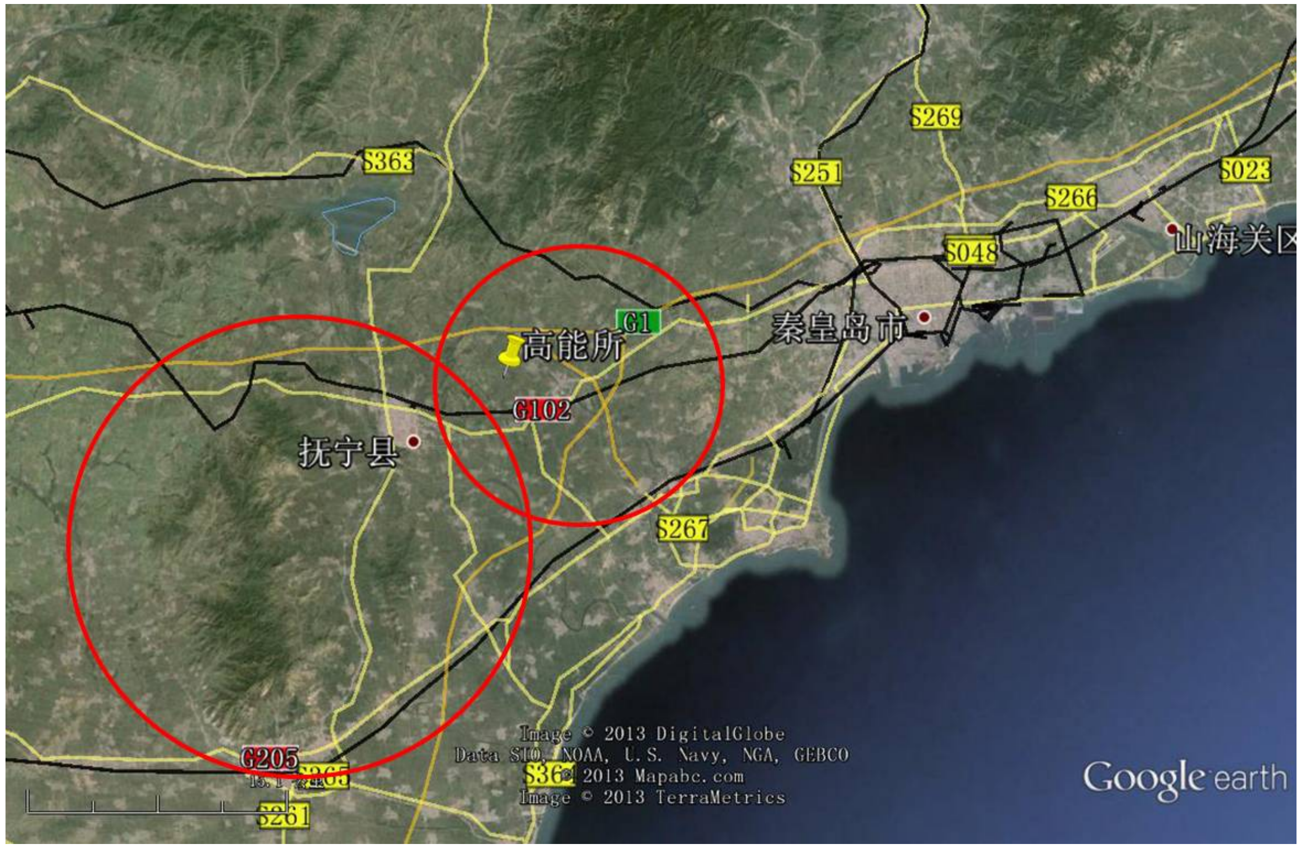
HIGH LUMINOSITY ENVIRONMENTS

- The LHC and possible future colliders will play a key role in answering fundamental questions by probing rare processes
- High instantaneous luminosities (larger than 10^{34} cm^{-2}s^{-1})
  - HL-LHC: aiming at 5.3-7.6 $\times 10^{34}$ cm^{-2}s^{-1}
  - Future collider: even higher in order to probe more exotic processes

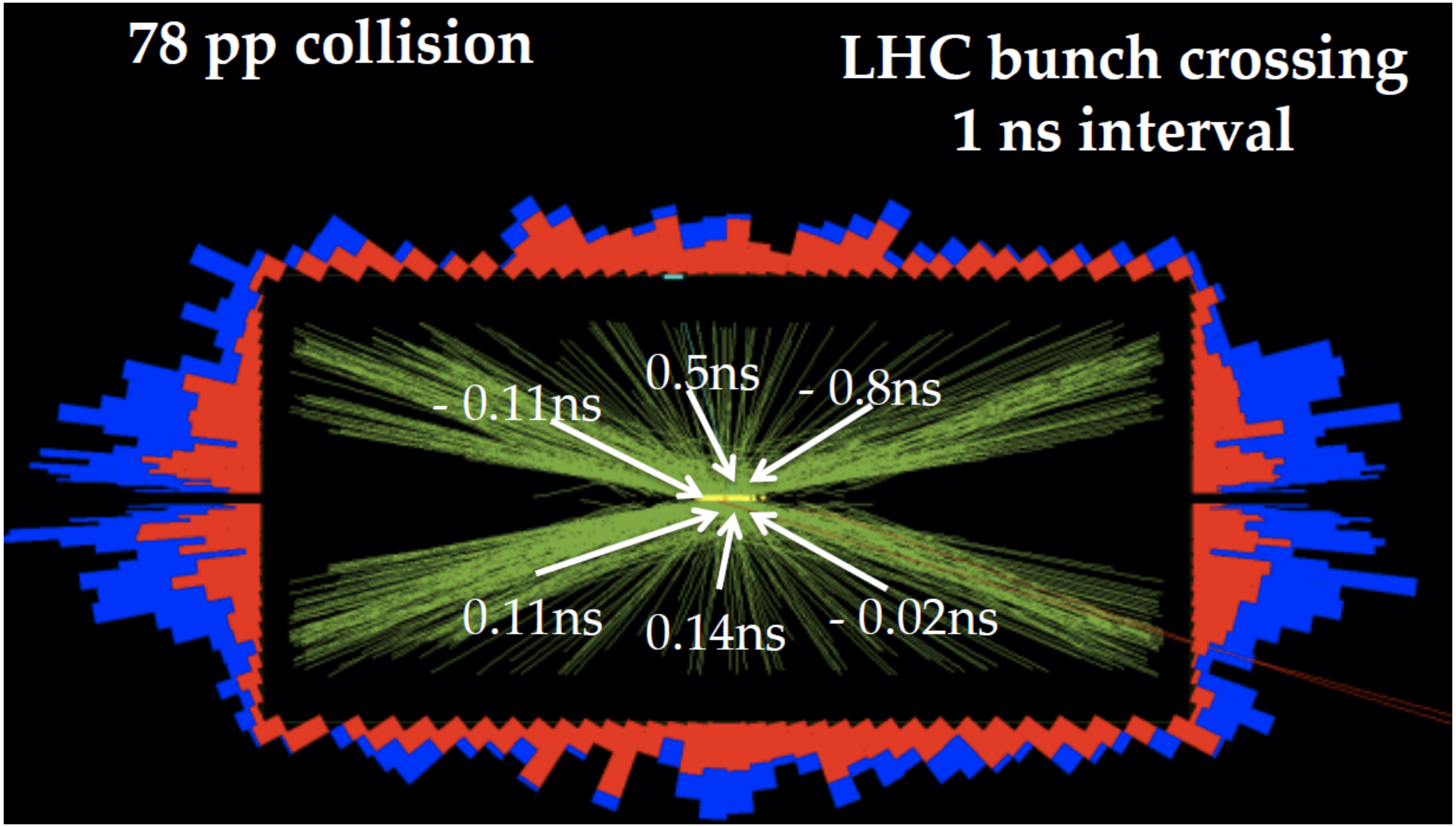


- **Extremely harsh experimental conditions expected in HL-LHC**
- Ionizing doses up to 250 kGy at $\eta = 2.5$;
- Ch. hadrons up to 2.3×10^{14} at η=2.5;
- Neutrons up to 1.9×10^{14} cm^{-2} for $|\eta| \leq 1.5$ (1.1×10^{15} at η=2.5)

- **Major upgrades to CMS to cope with these challenges**
- To reduce the impact of ~200 pileup interactions, upgraded CMS detector will assign a <u>precise time stamp to all particles</u>
  - EM showers: remove the neutral energy deposits from PU
  - Charged particles: remove confusion from overlapping vertices

HIGH LUMINOSITY ENVIRONMENTS

High Luminosity ⇒ High pileup



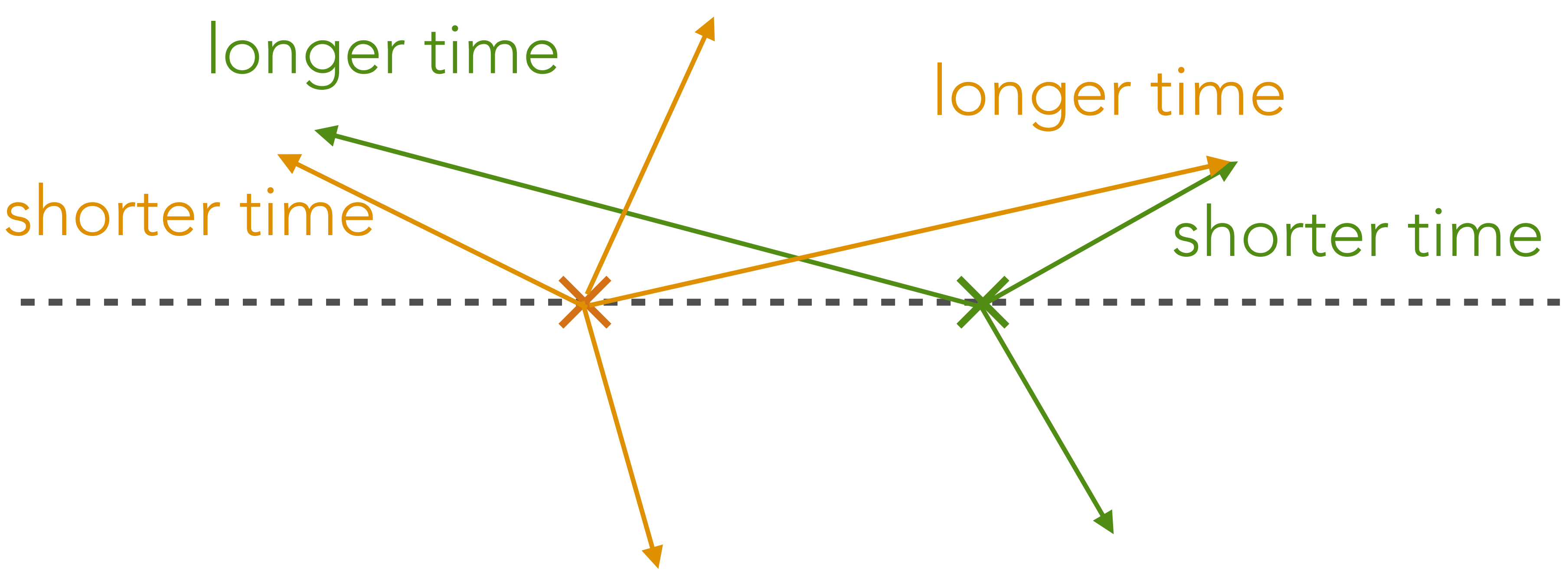
Multiple pp collisions close to each other: deteriorate physics performance.

Up to 200 pileup interactions at the HL-LHC

PRECISION TIMING AS A SOLUTION

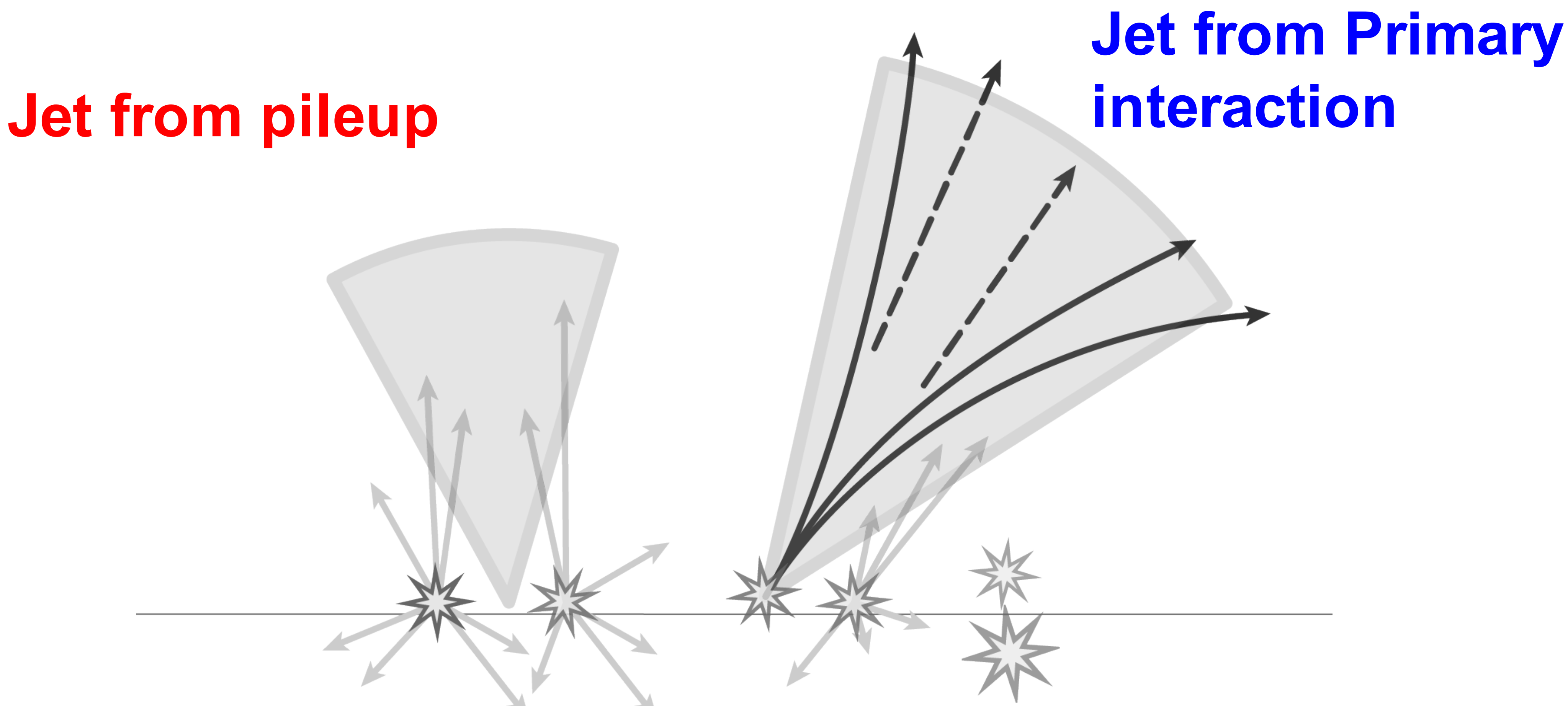
A possible solution is to use precision timing

measure time stamp of a particle at the detector — then → Identify from what vertex it was produced



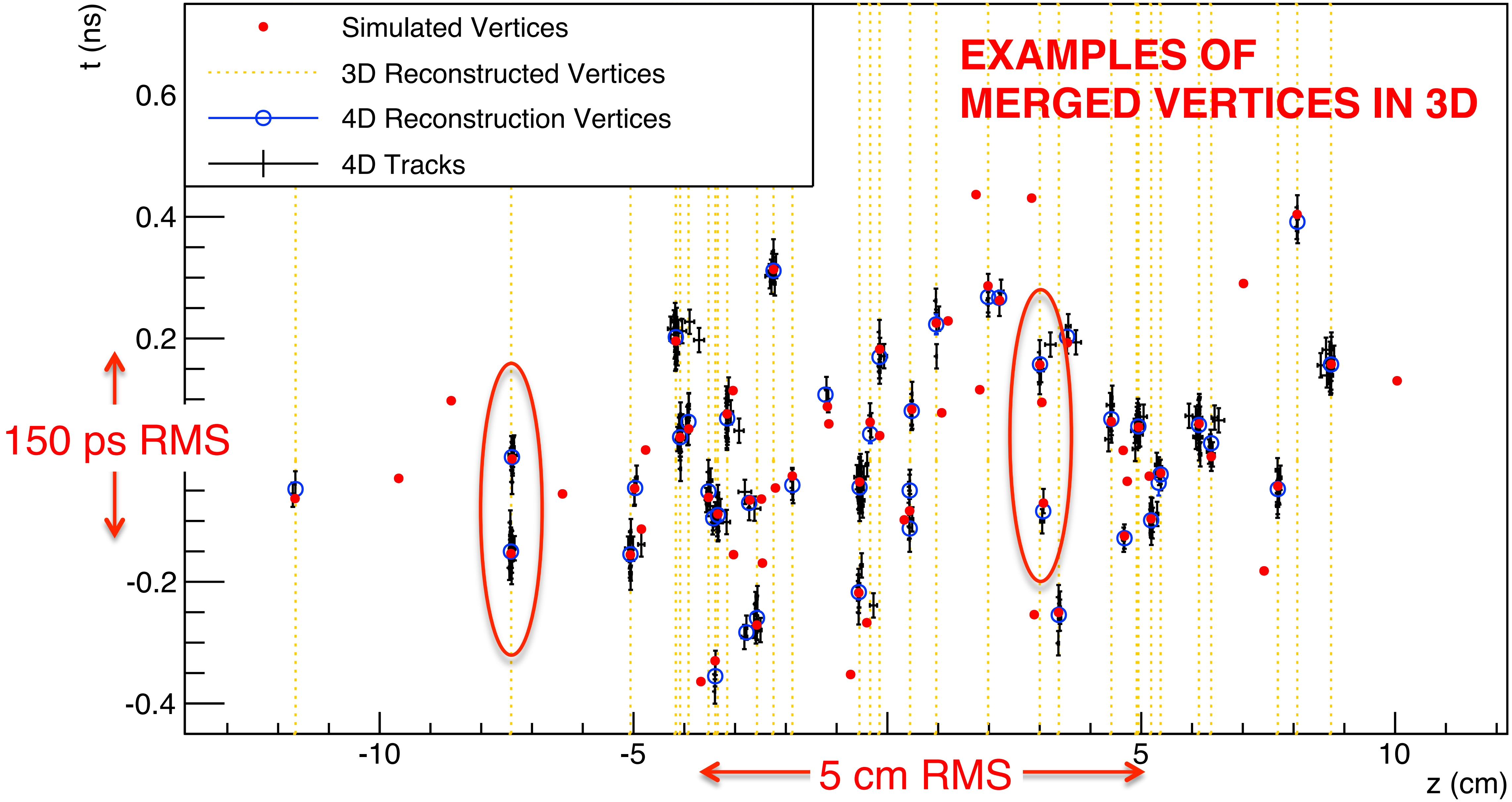
Many challenges come with high pileup:

- Jets from pileup could be associated with the main interaction
- Pileup particles merging with particles coming from main interaction
- Vertices could overlap in the longitudinal direction



CMS time-aware vertex reconstruction

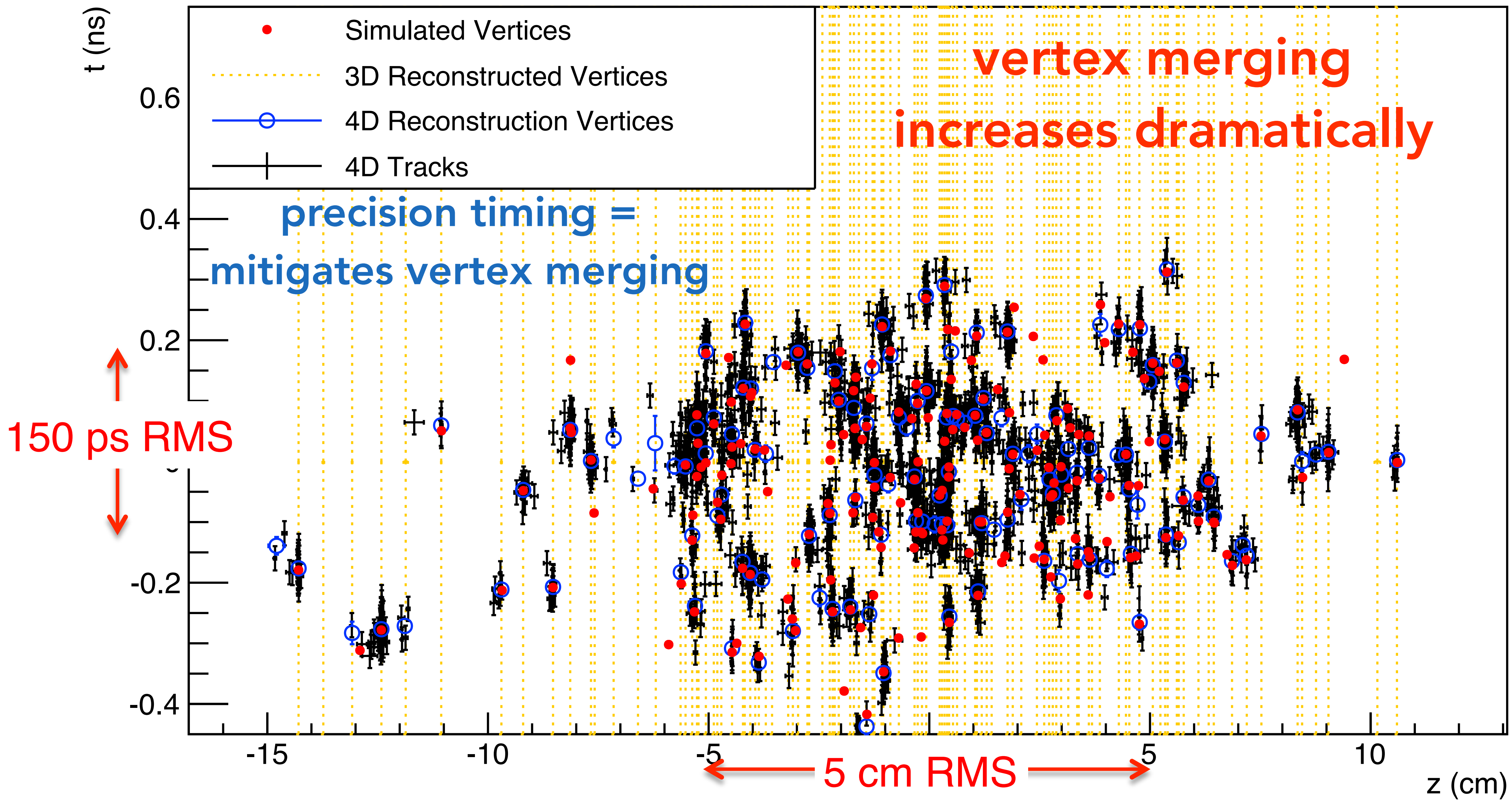
50 pileup collisions



4D vertex reconstruction with track-timing at the ~25 ps level

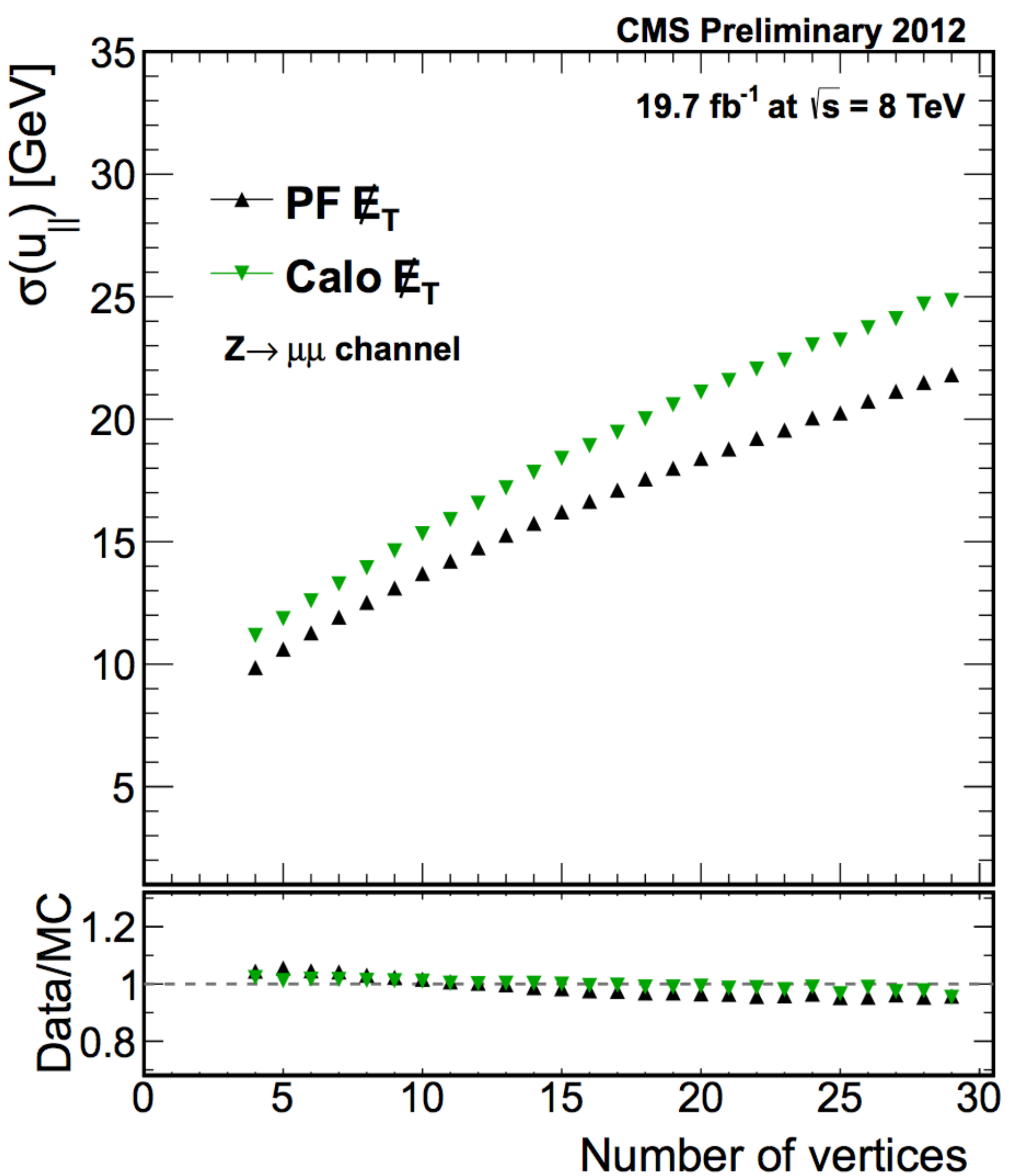
CMS time-aware vertex reconstruction

200 pileup collisions



HL-LHC conditions: 150 ps RMS spread, 4.8 cm RMS on Z

Missing transverse energy is very important for many BSM physics searches



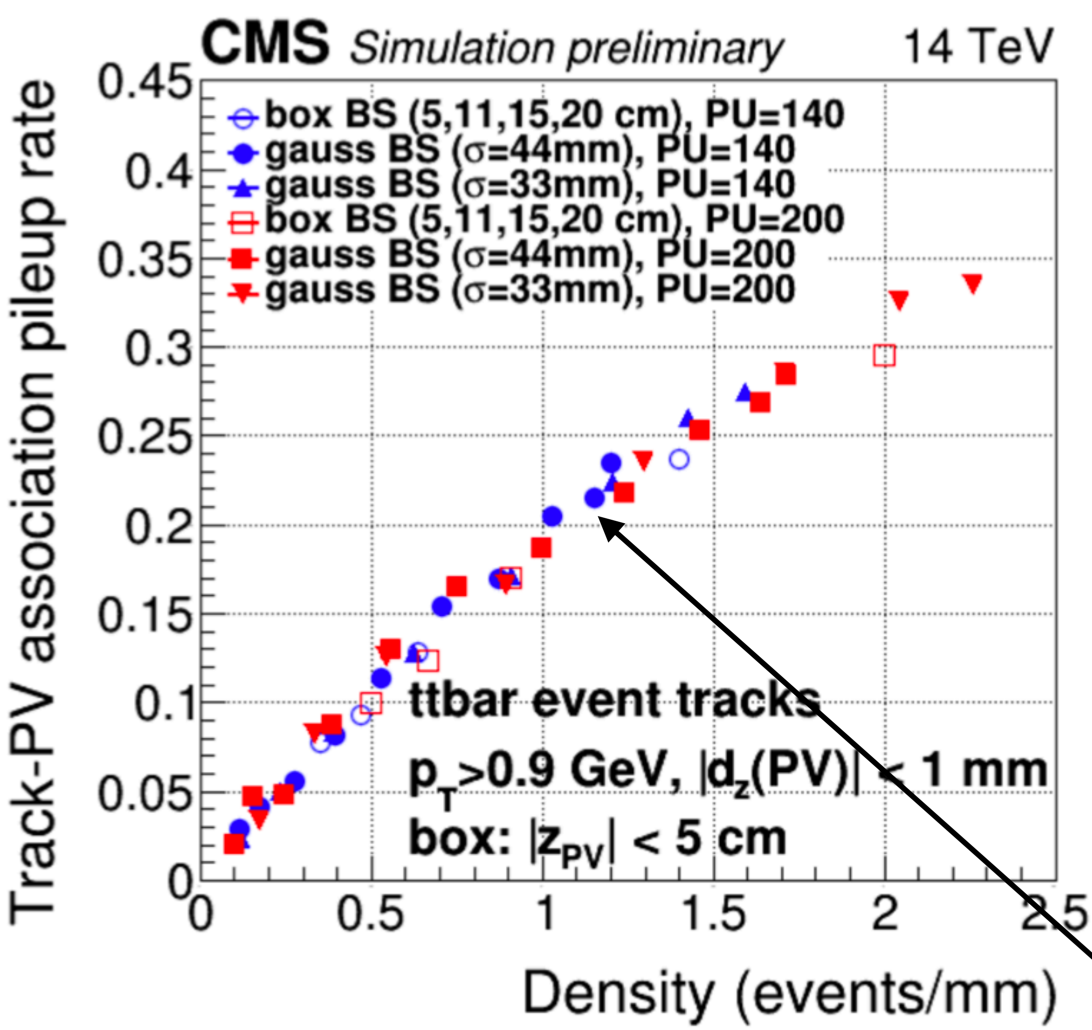
- Every pileup interaction contributes ~ 3 GeV to the missing E_T resolution in quadrature
- At 140 pileup interactions, the missing E_T resolution due to pileup will be ~40 GeV

pileup particles significantly contribute to the missing E_T resolution

PARTICLE ISOLATION AND ID

Precision timing for charged particles

more pileup → increased pileup rate associated to primary vertex (PV)

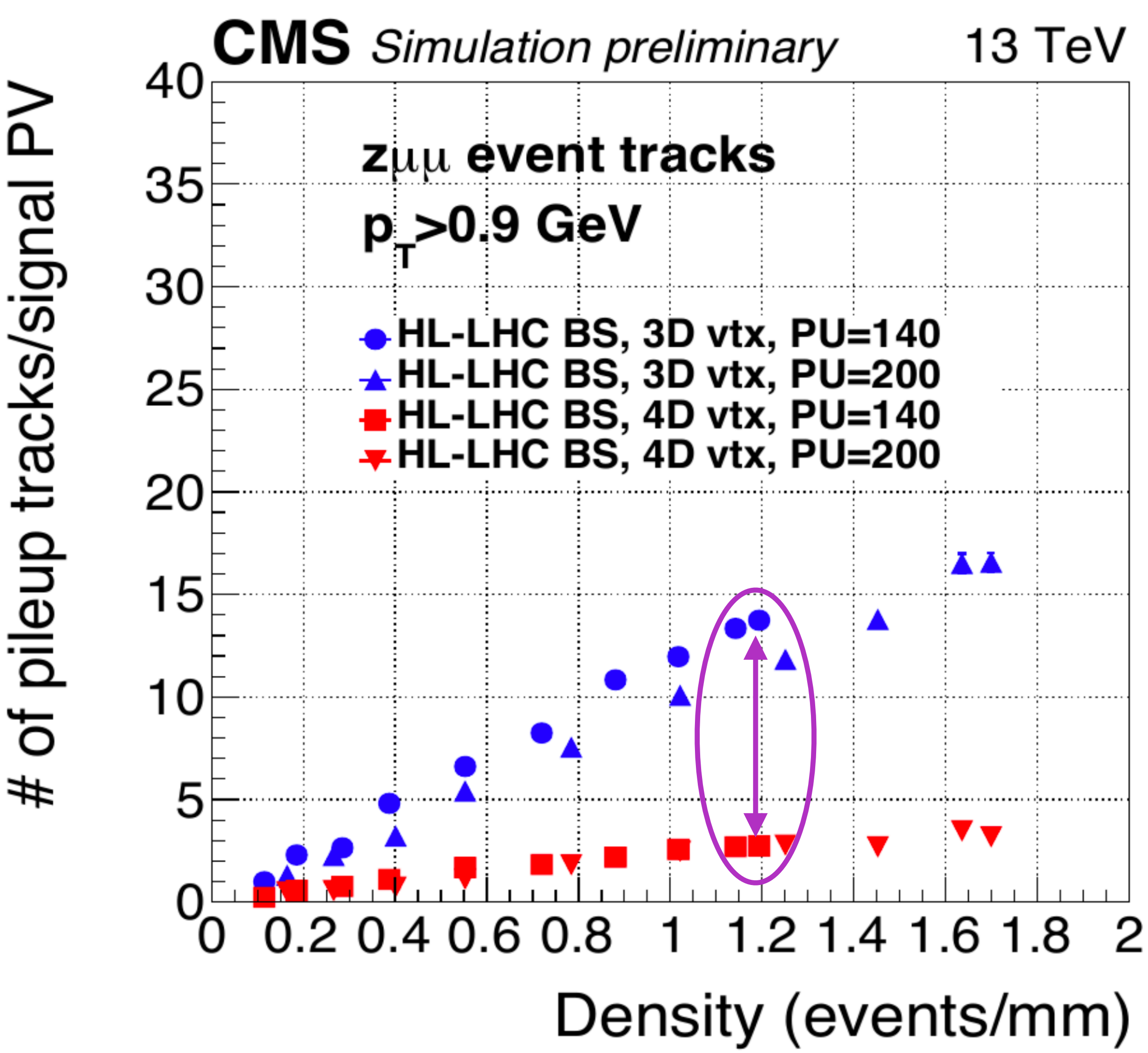


(a) PU Tracks attached to hard PV

- Degradation of charge isolation, b-tagging, JET/MET performance
- ~30 ps time resolution recovers current performance

About 20% of tracks are from pileup at HL-LHC conditions

4D vertex reconstruction provides significant improvement

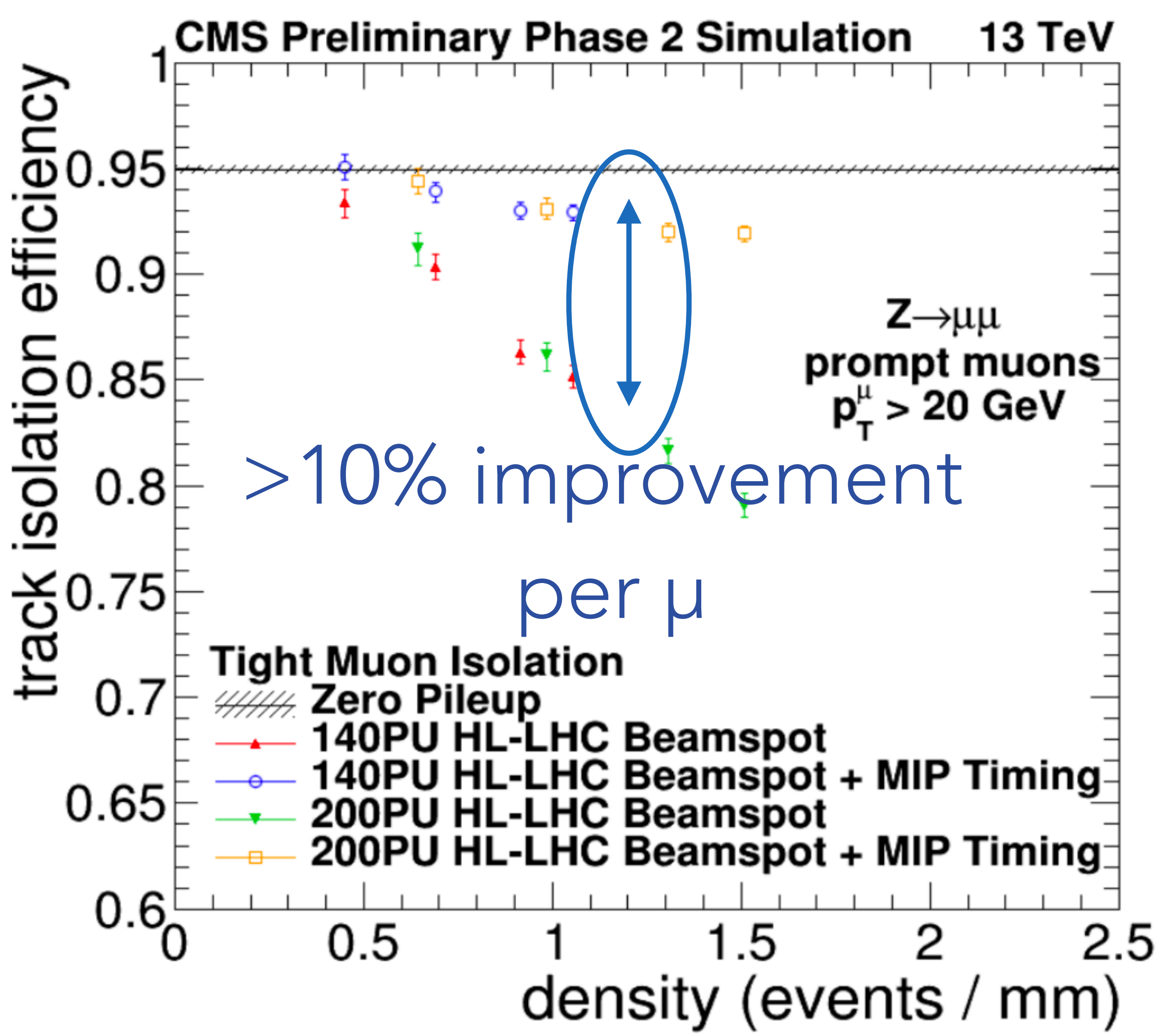


- Pileup charge multiplicity reduced five-fold

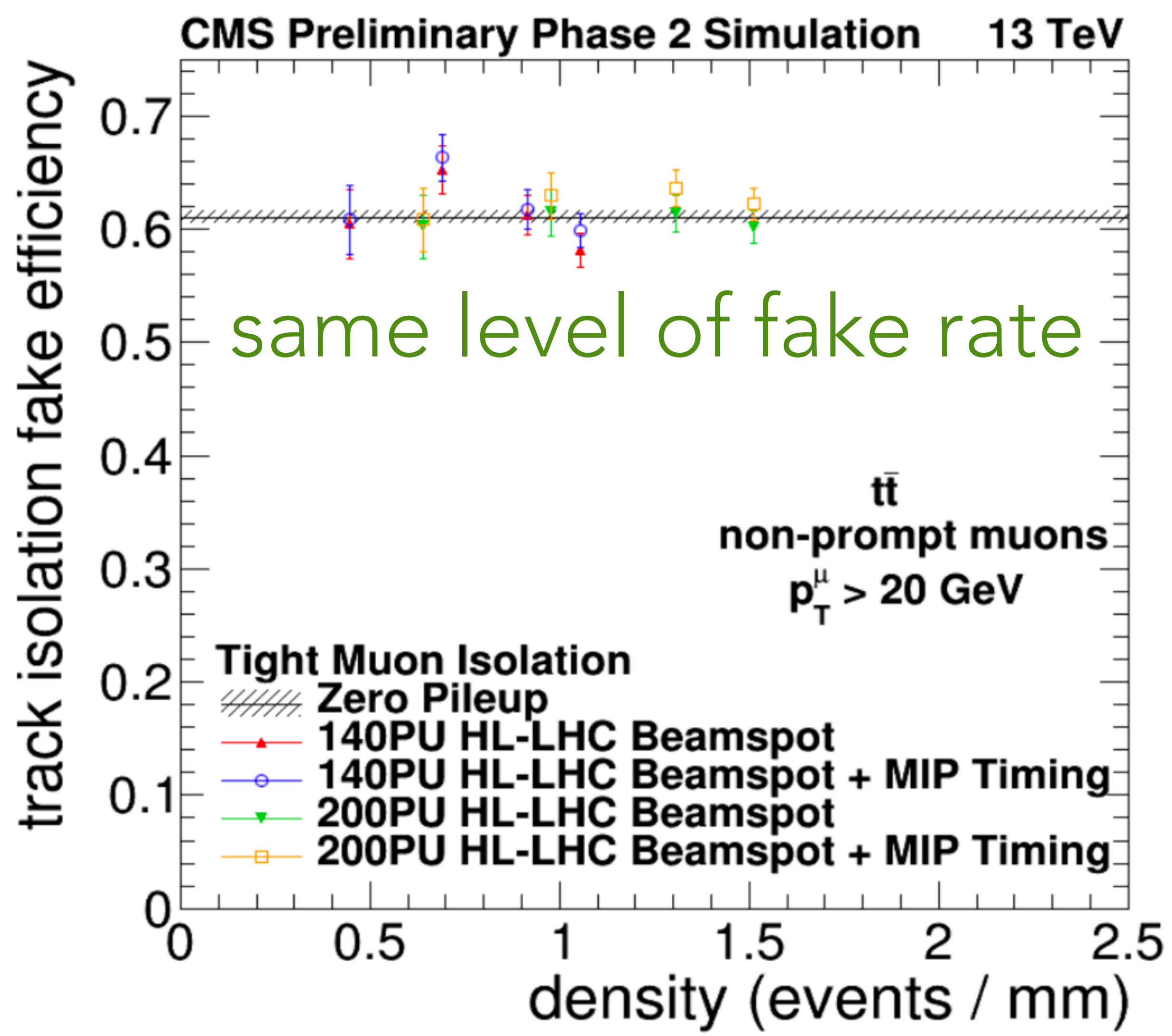
recover current performance

MUON RECONSTRUCTION

MIP timing provides considerable improvement in muon isolation



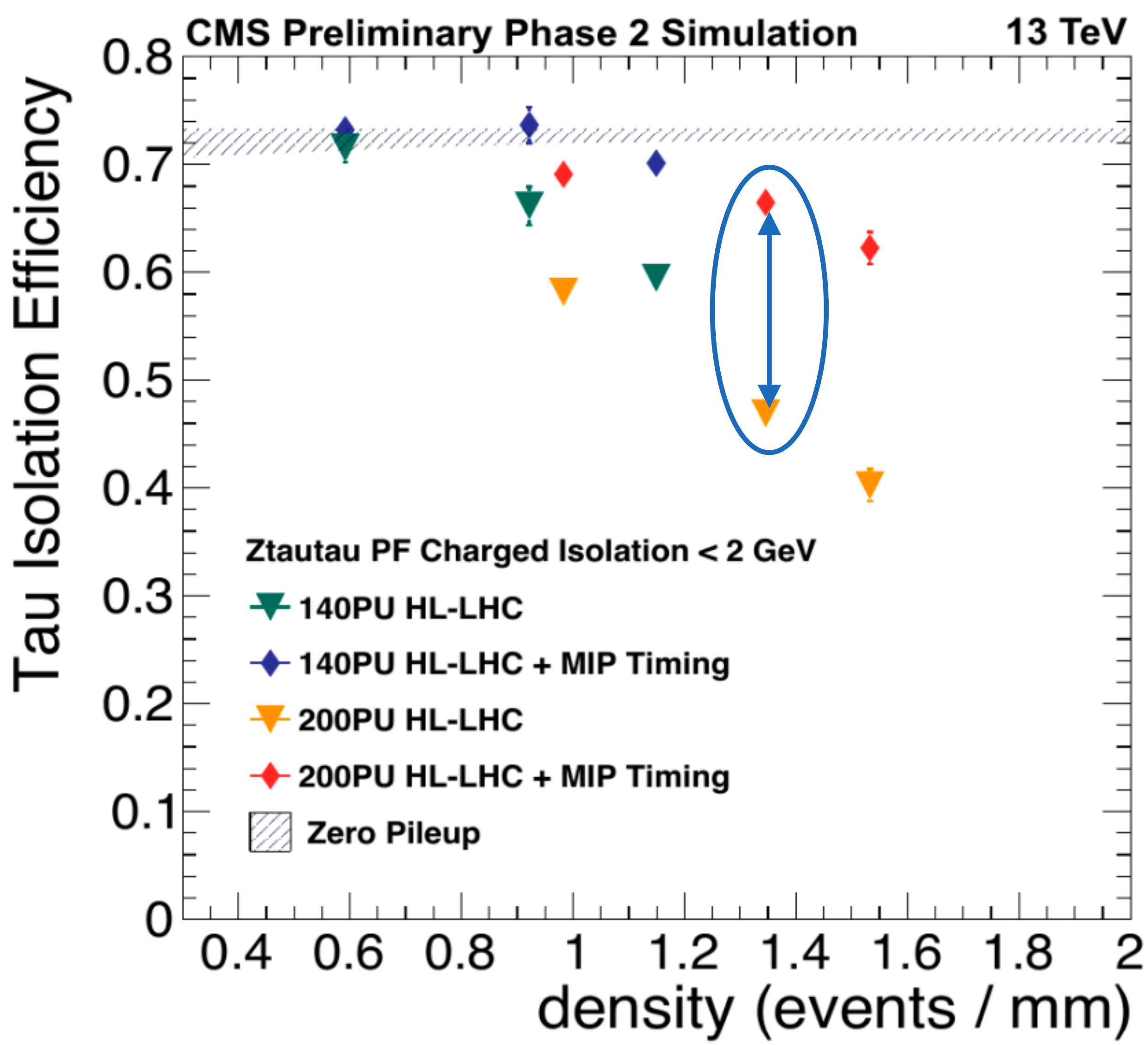
(a) Prompt μ Efficiency



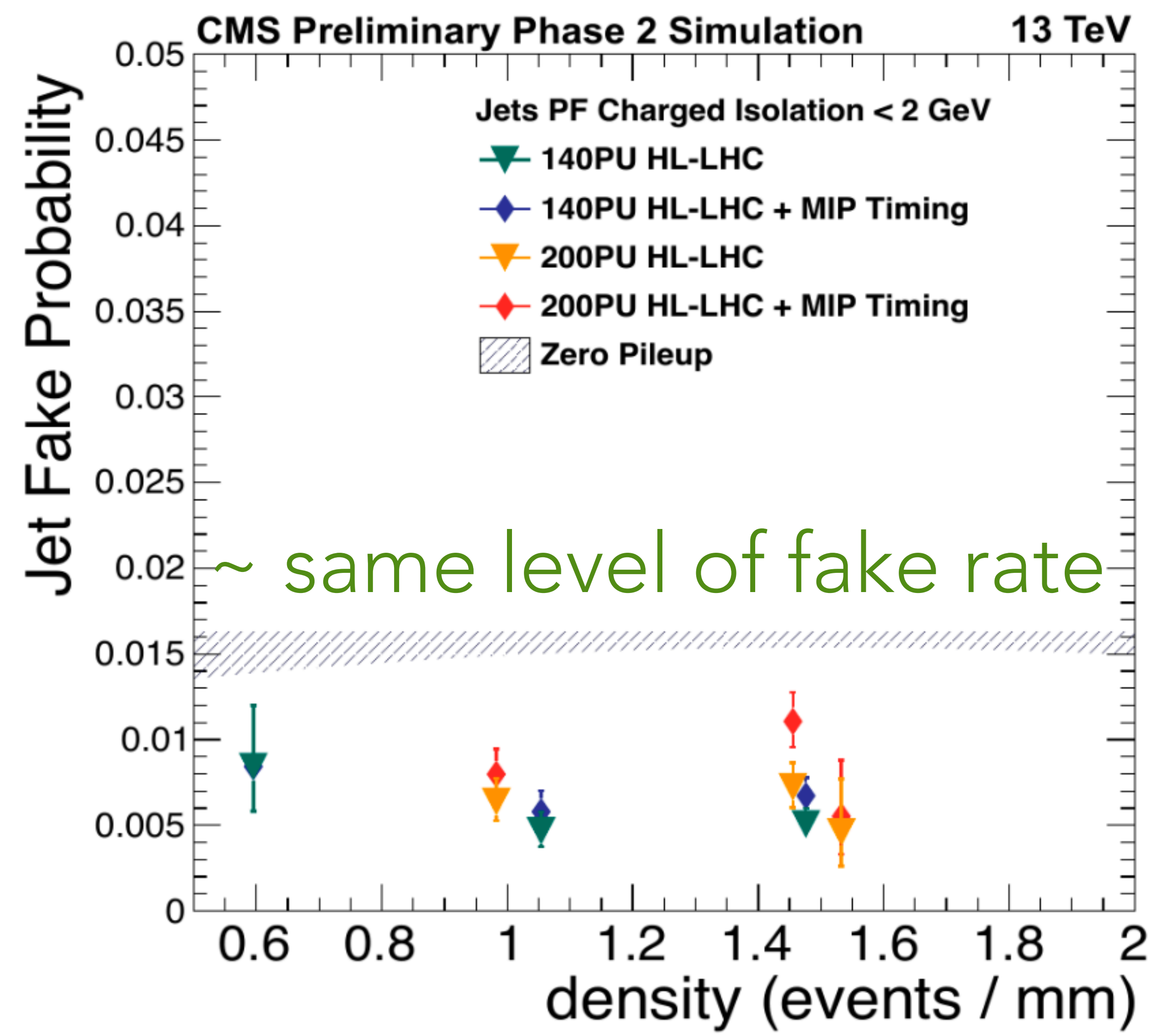
(b) Efficiency for fakes

TAU RECONSTRUCTION

MIP timing also provides considerable improvement in tau isolation



(a) Prompt τ Efficiency



(b) Efficiency for fakes

>20-30% improvement per τ

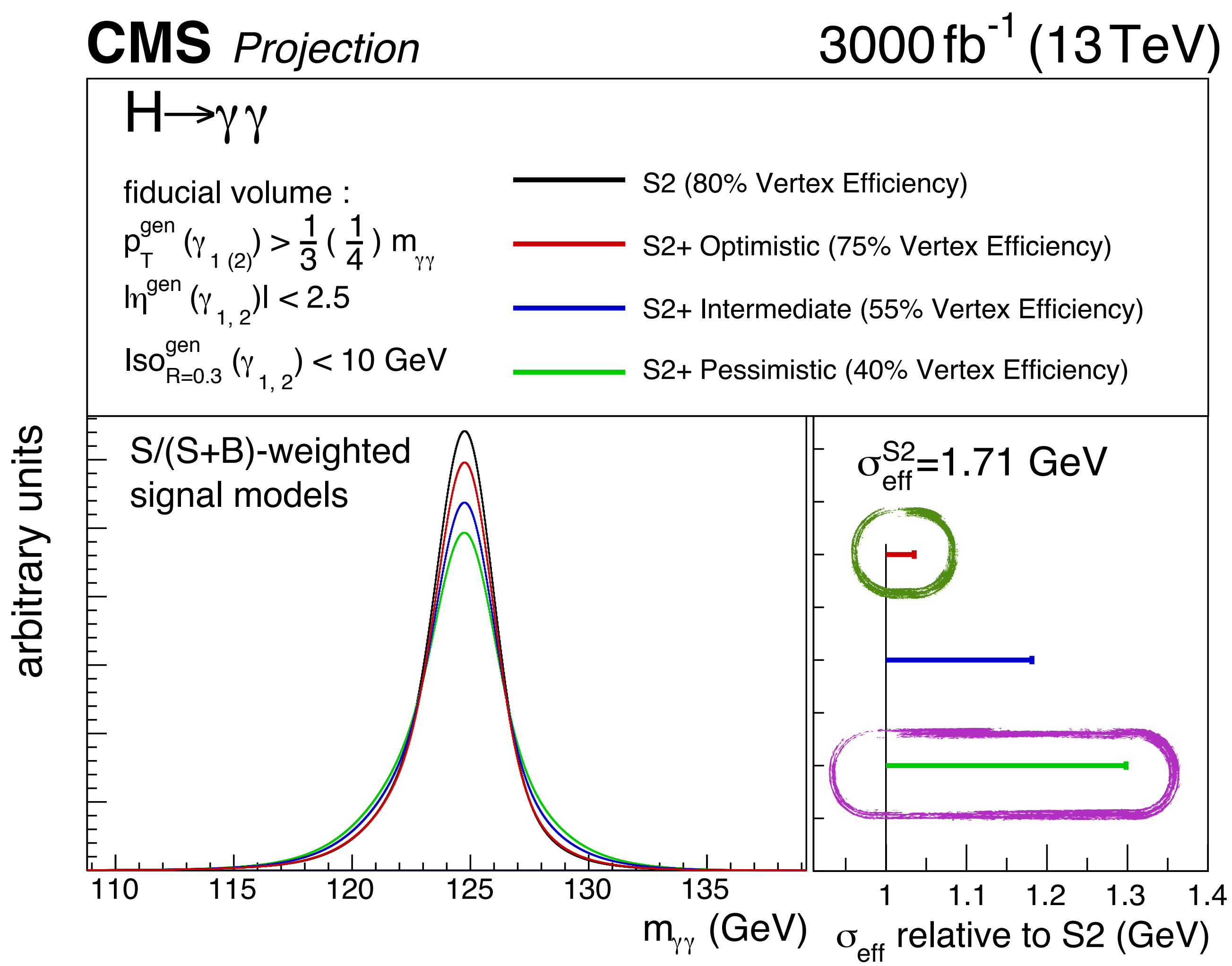
H→ γγ PROJECTION AT HL-LHC

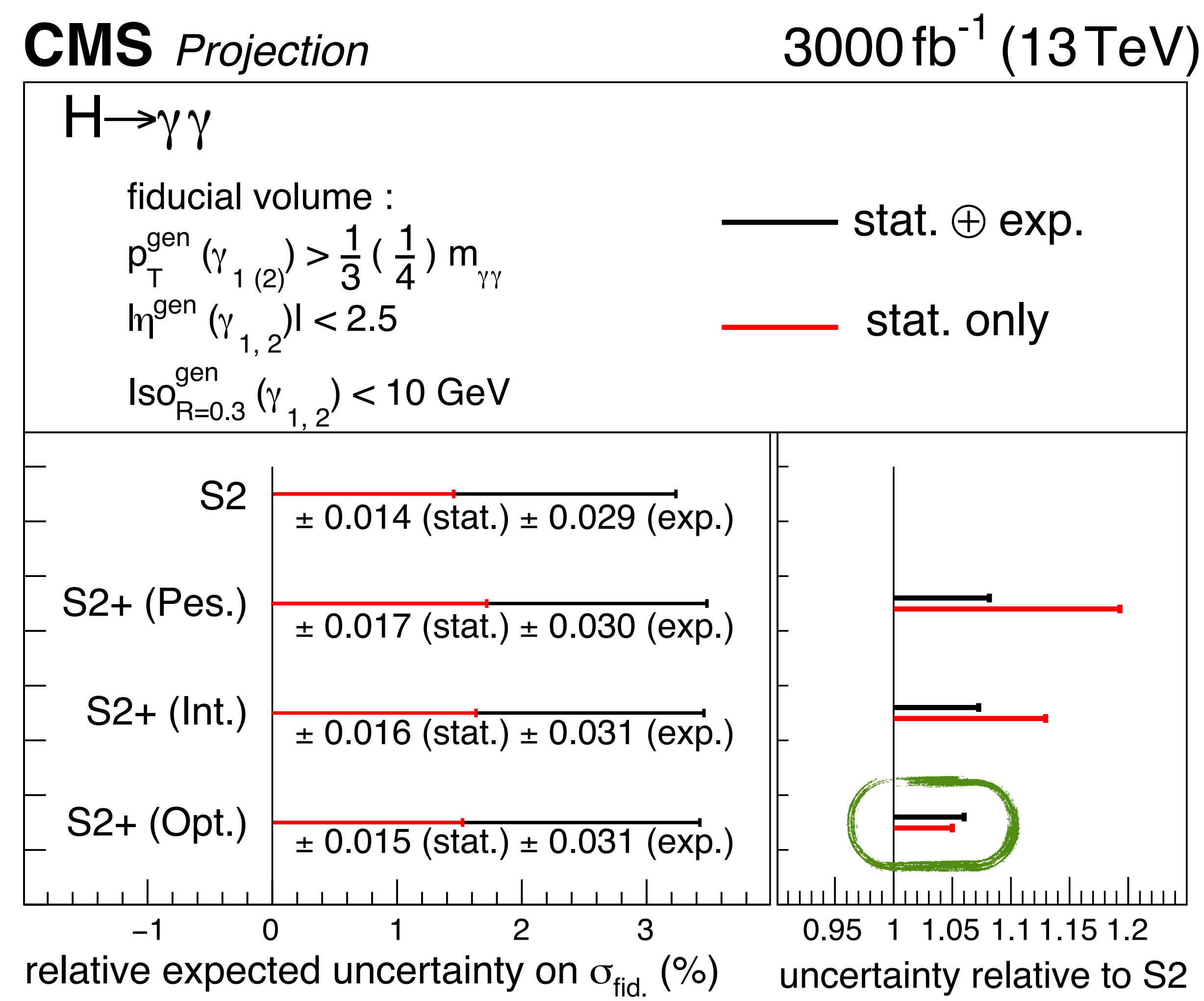
200 PU scenario has a dramatic impact on vertex reconstruction:

30% increase in effective H→γγ resolution

Performance ~recovered by using global timing + photon vertexing:

30% improvement on H→γγ resolution

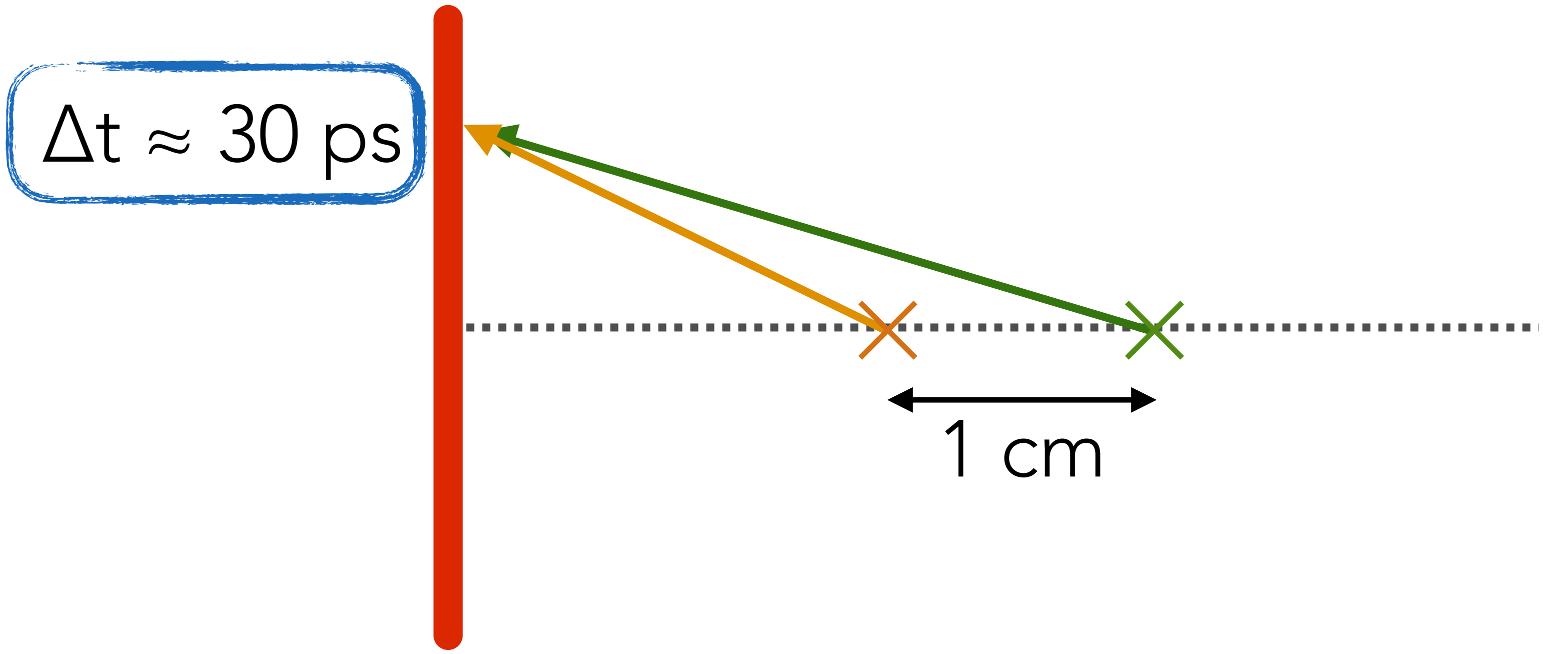




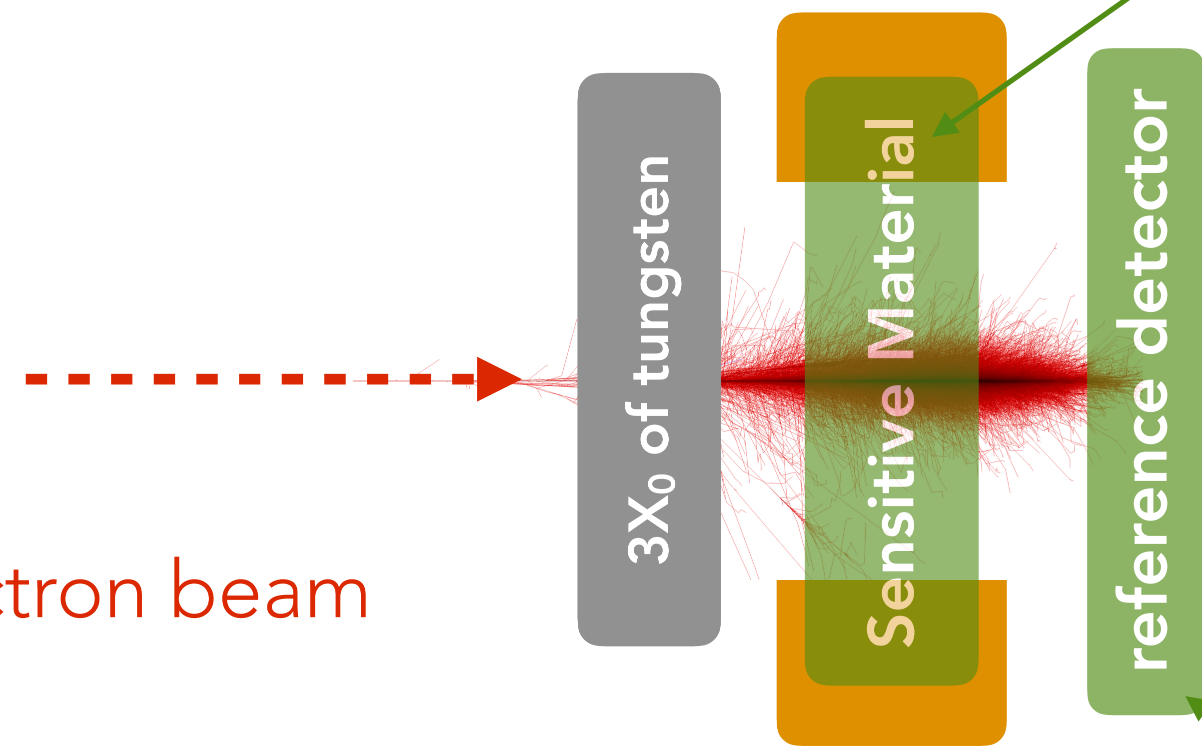
Only a ~5% effect on cross-section uncertainty

How precise does the timing measurement need to be?

- Particles travel at near the speed of light
- 1 cm is equivalent to ~33 ps
- To distinguish pileup interactions separated by 1 cm requires a time resolution of ~30 ps
- Typical collider beam-spots are ~10 cm ⇒ *rejection factor of 10*



One possible solution:



Possible sensitive materials:

Multichannel plate

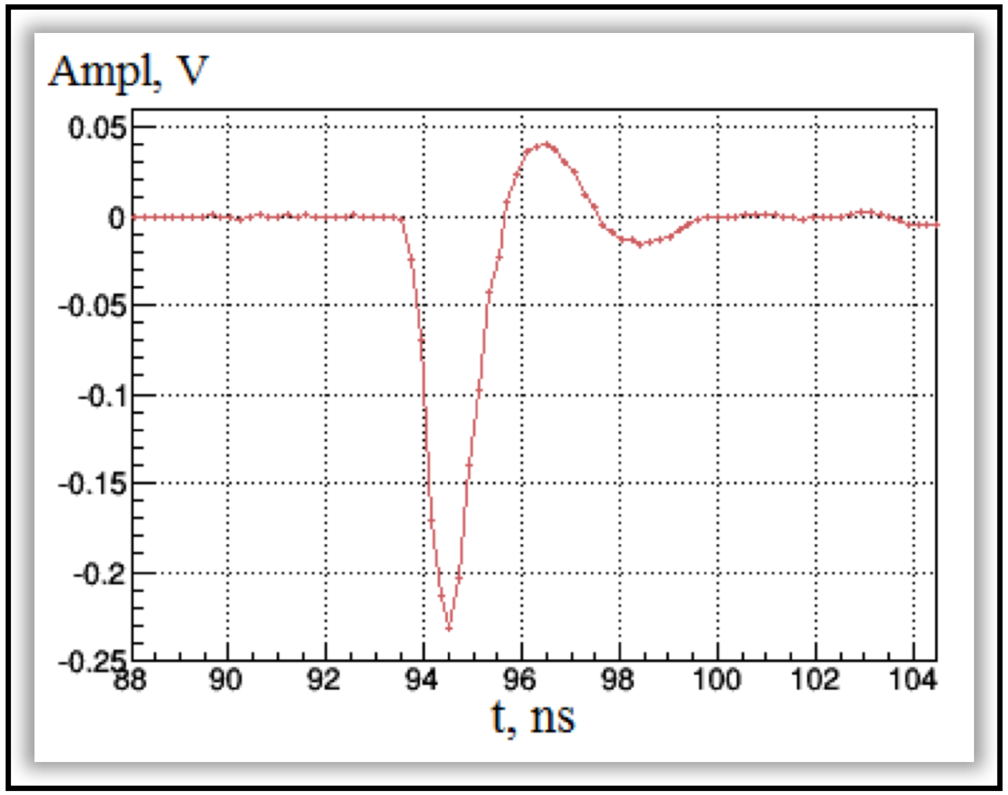
silicon

cadmium-telluride

SECONDARY EMISSION DETECTORS

Secondary emission calorimeters provide some intrinsic advantages:

- Radiation hard
- No optical transparency issues
- No optical transport issues
- Intrinsically fast:
  - Signal formation and decay are fast (full pulse in a few ns)
  - Major advantage for future colliders (enables higher bunch crossing rate)

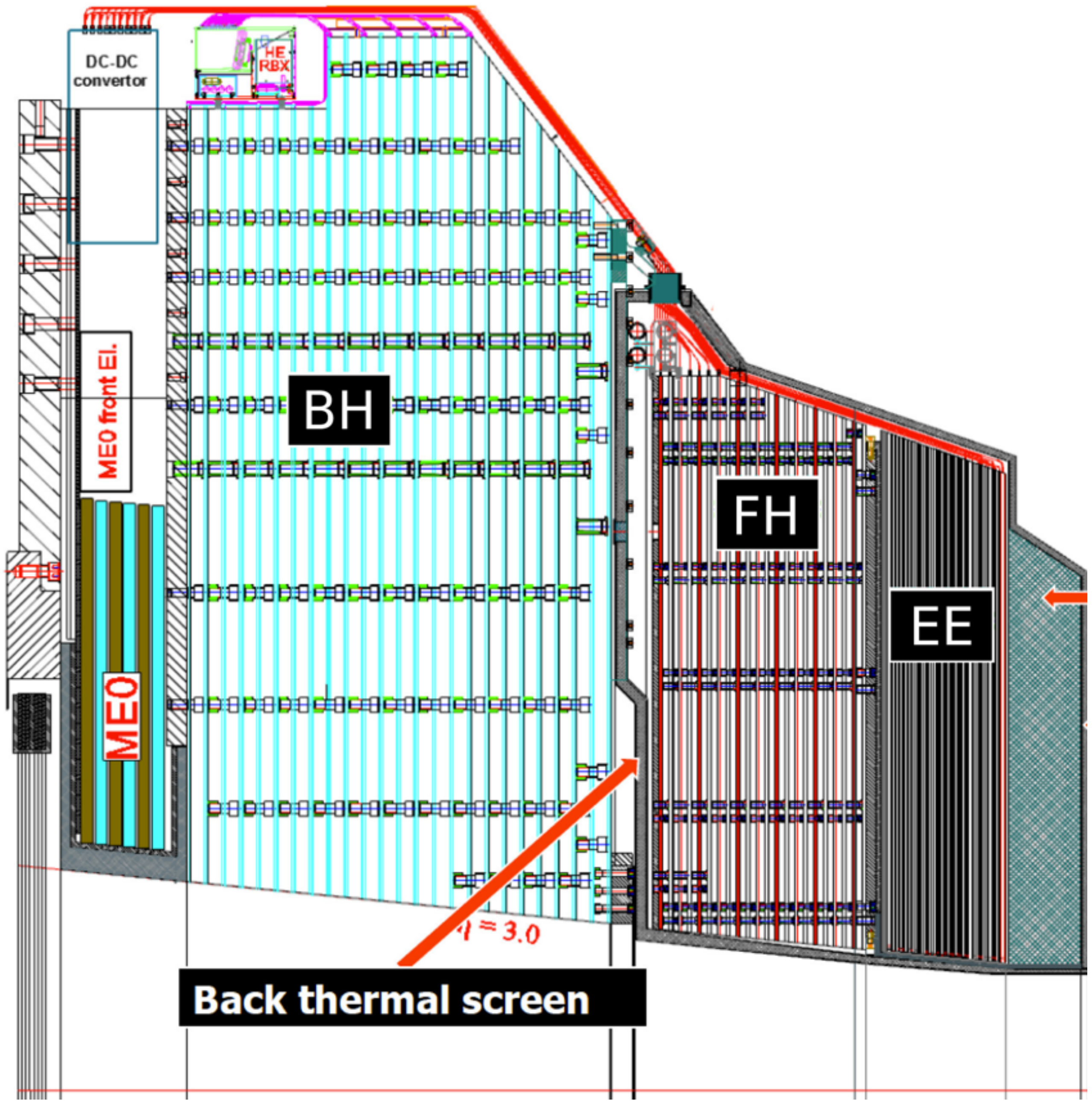


MCP example pulse:

2 ns pulse width

HGC Timing Modules

THE HIGH-GRANULARITY CALORIMETER



EE: silicon + tungsten absorber

28 layer: 25 X_0 , 1.3 **λ**

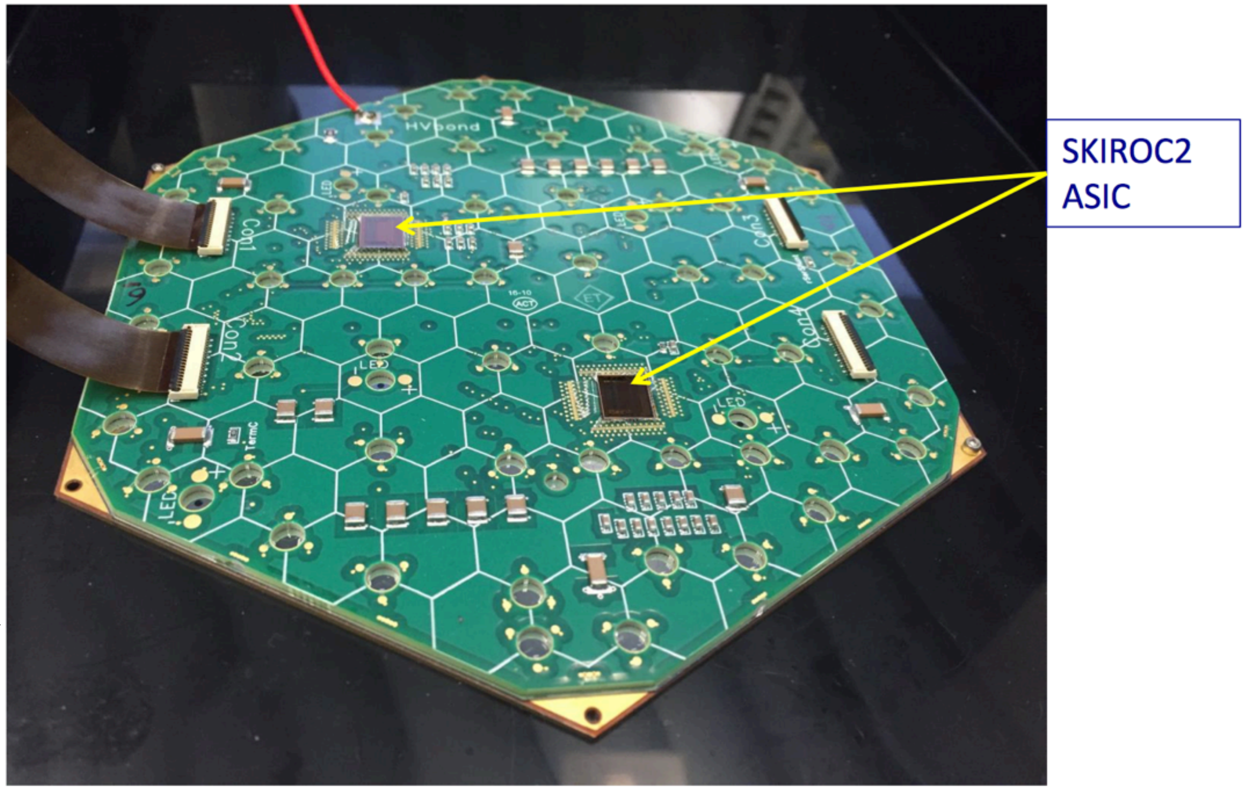
FH: silicon + brass absorber

12 layer: 3.5 **λ**

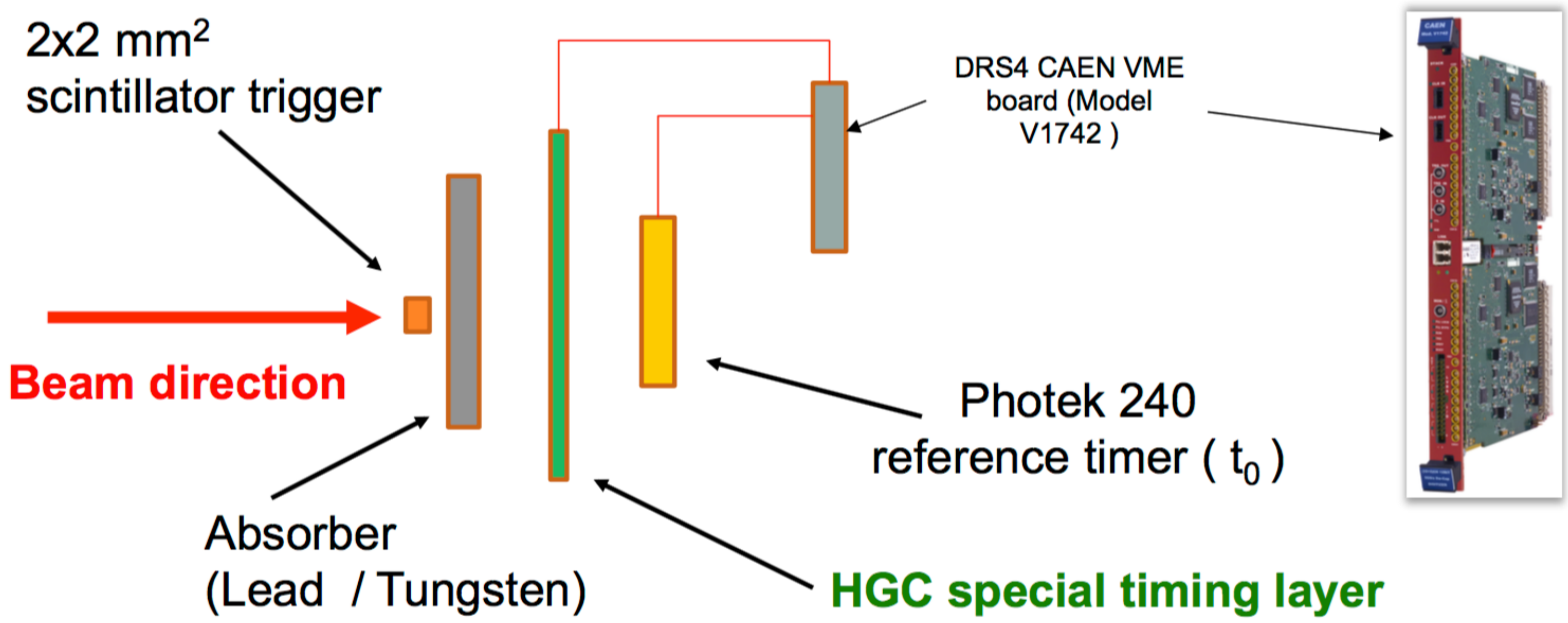
BH: scintillator + brass absorber

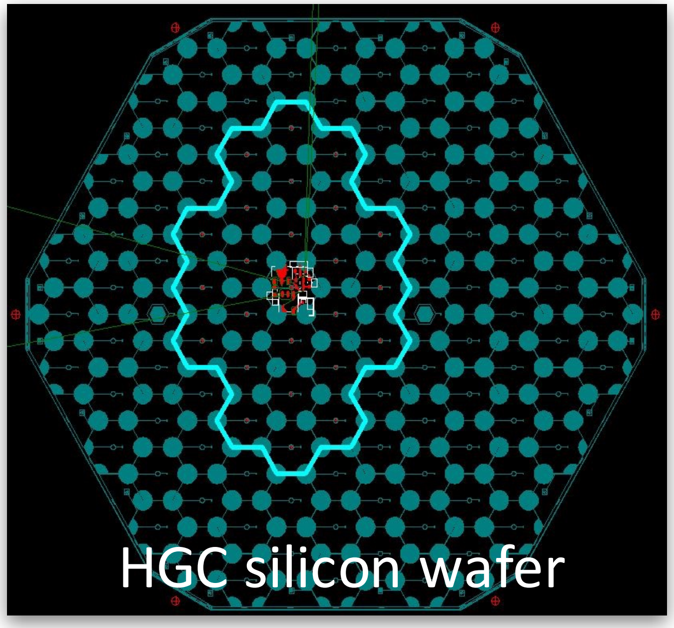
11 layer: 5.5 **λ**

silicon wafer
(hexagonal 128 pixels)



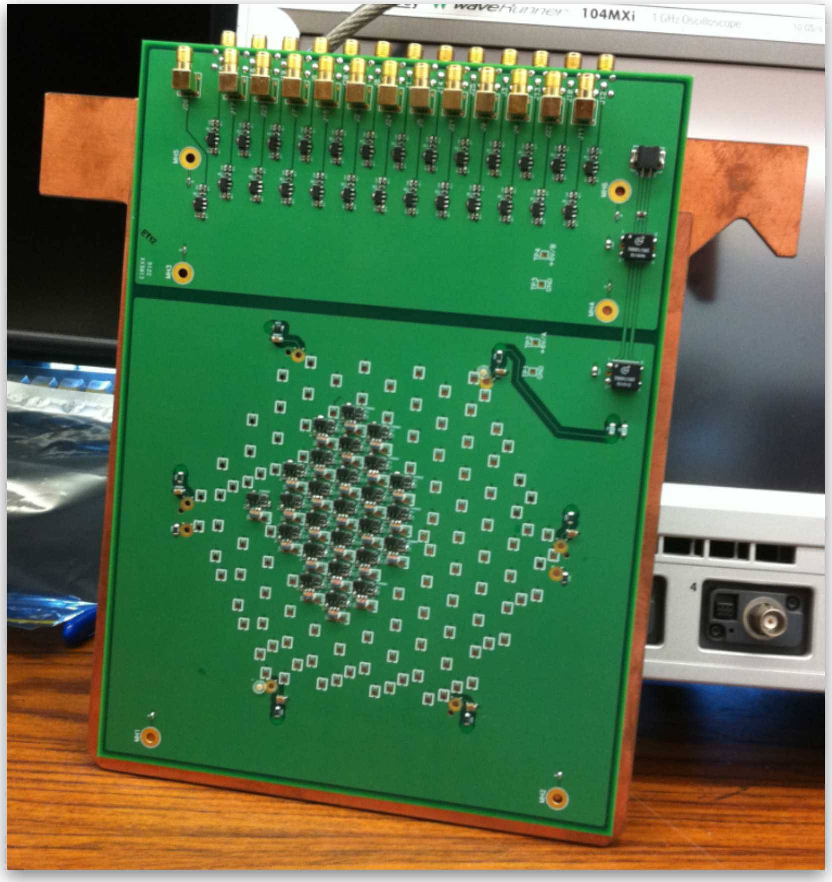
SAMPLING CALORIMETER TIMING

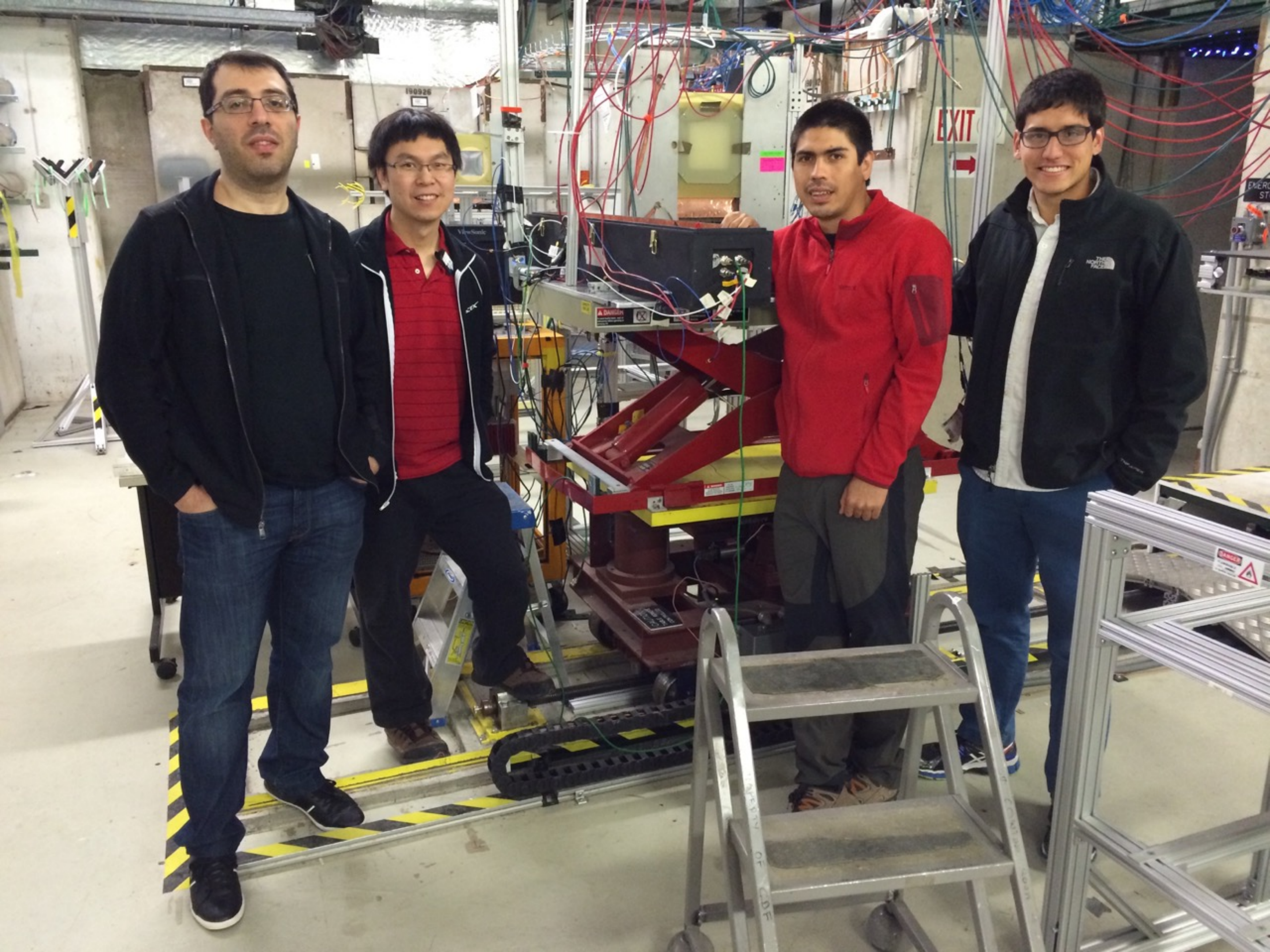




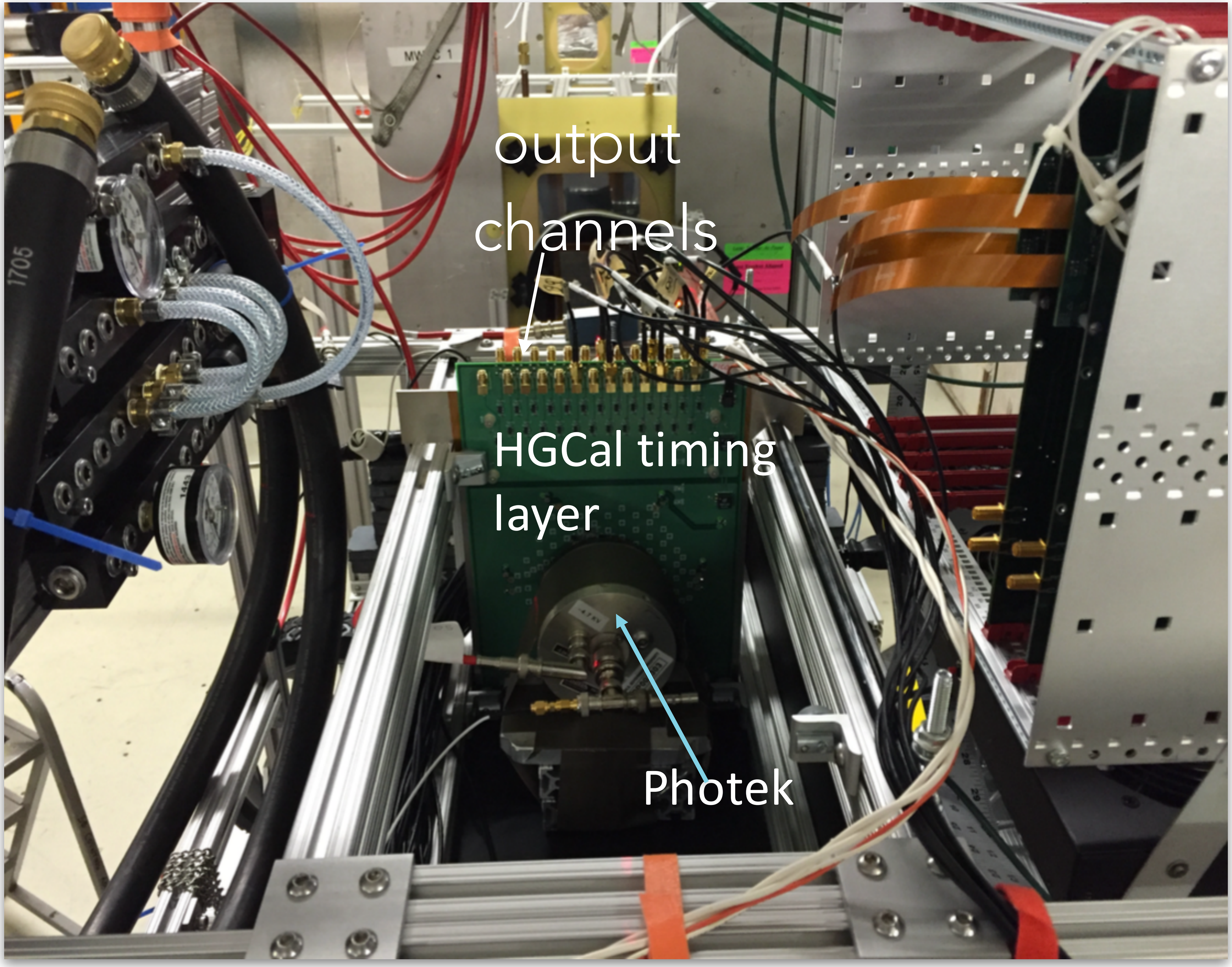
Equipped one HGCal sensor with fast readout electronics

- 300 μm sensor thickness, 25 cell instrumented
- Each channel is amplified by 120x

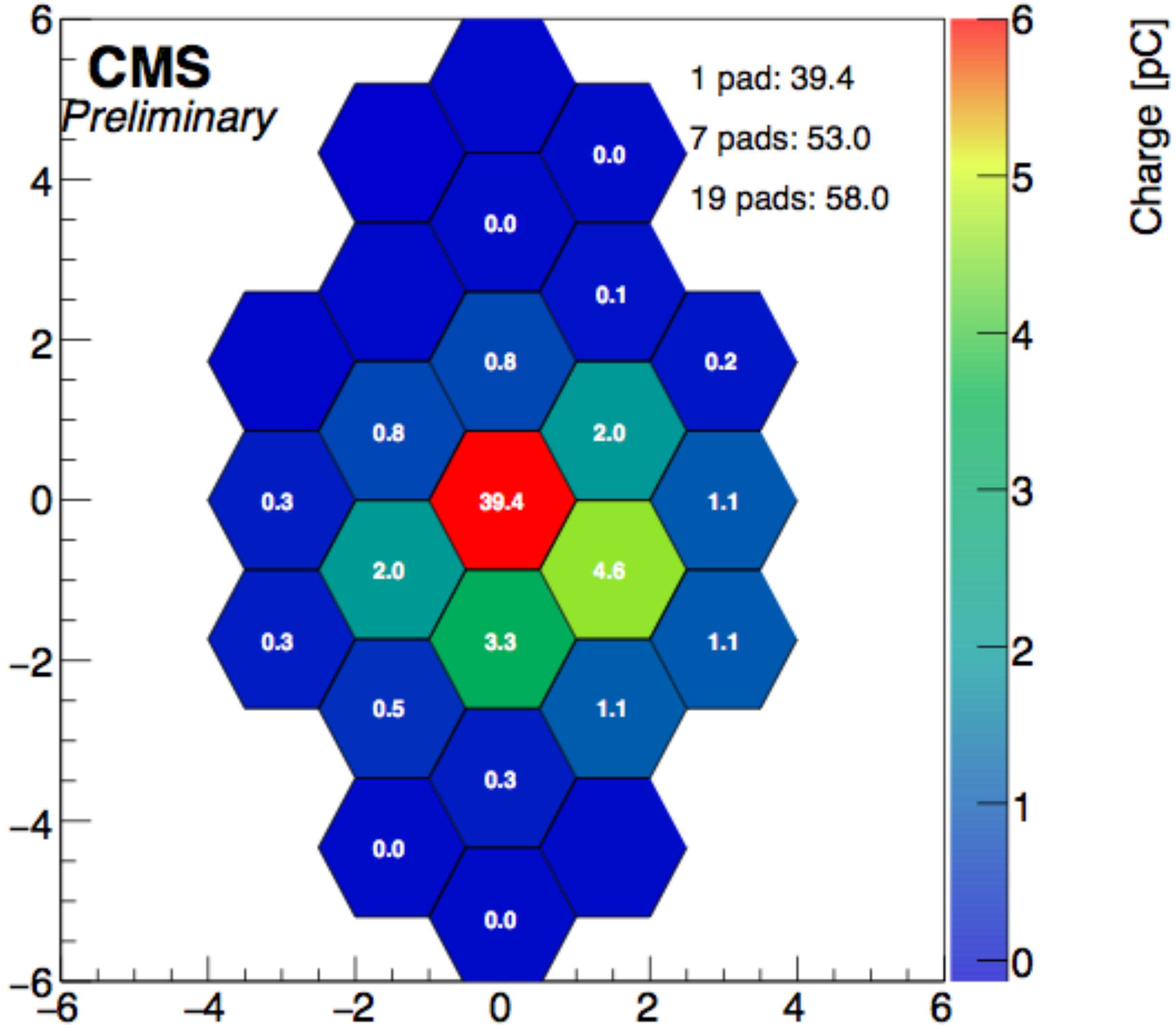


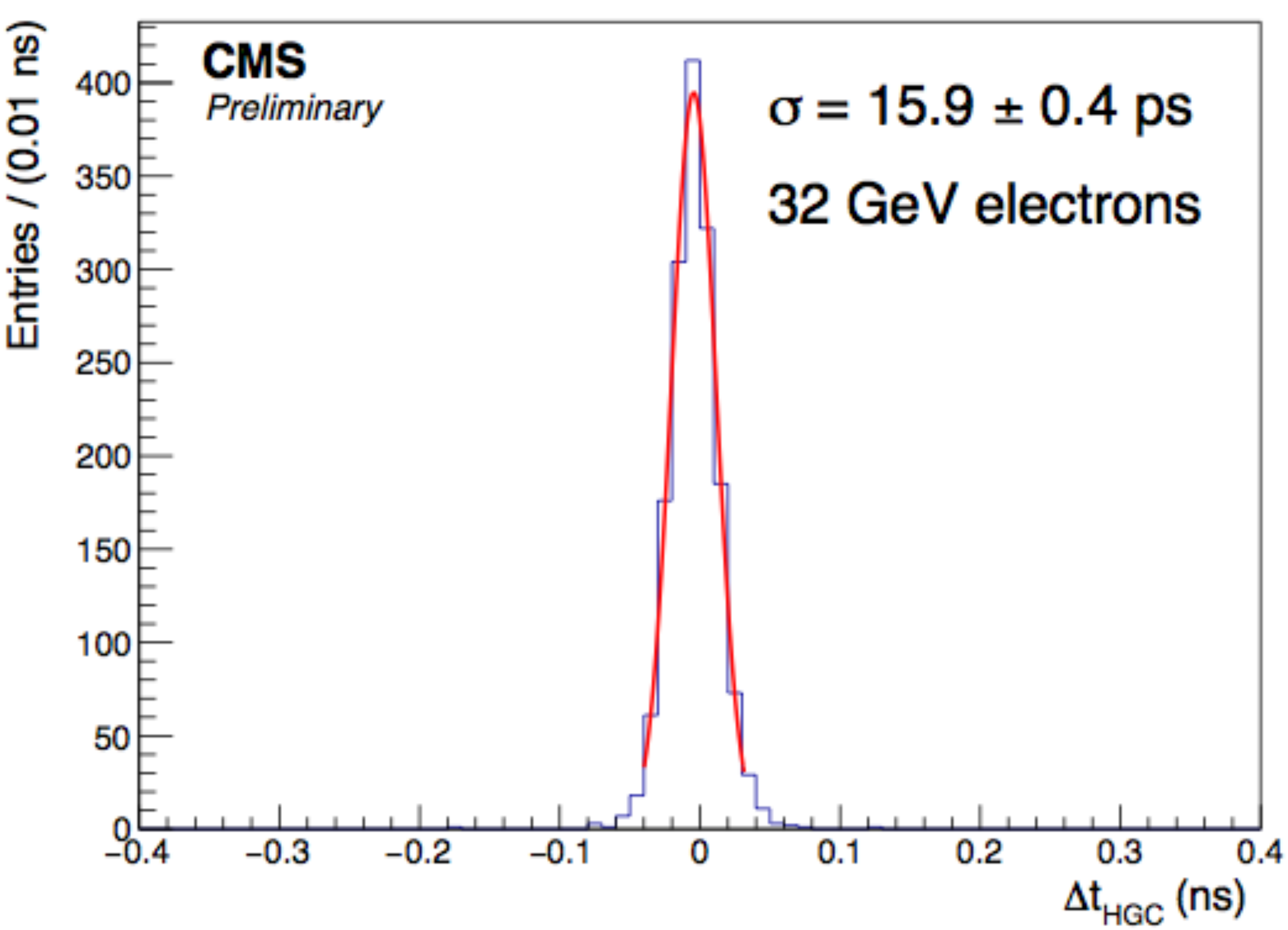

EXIT

EXPERIMENTAL SETUP



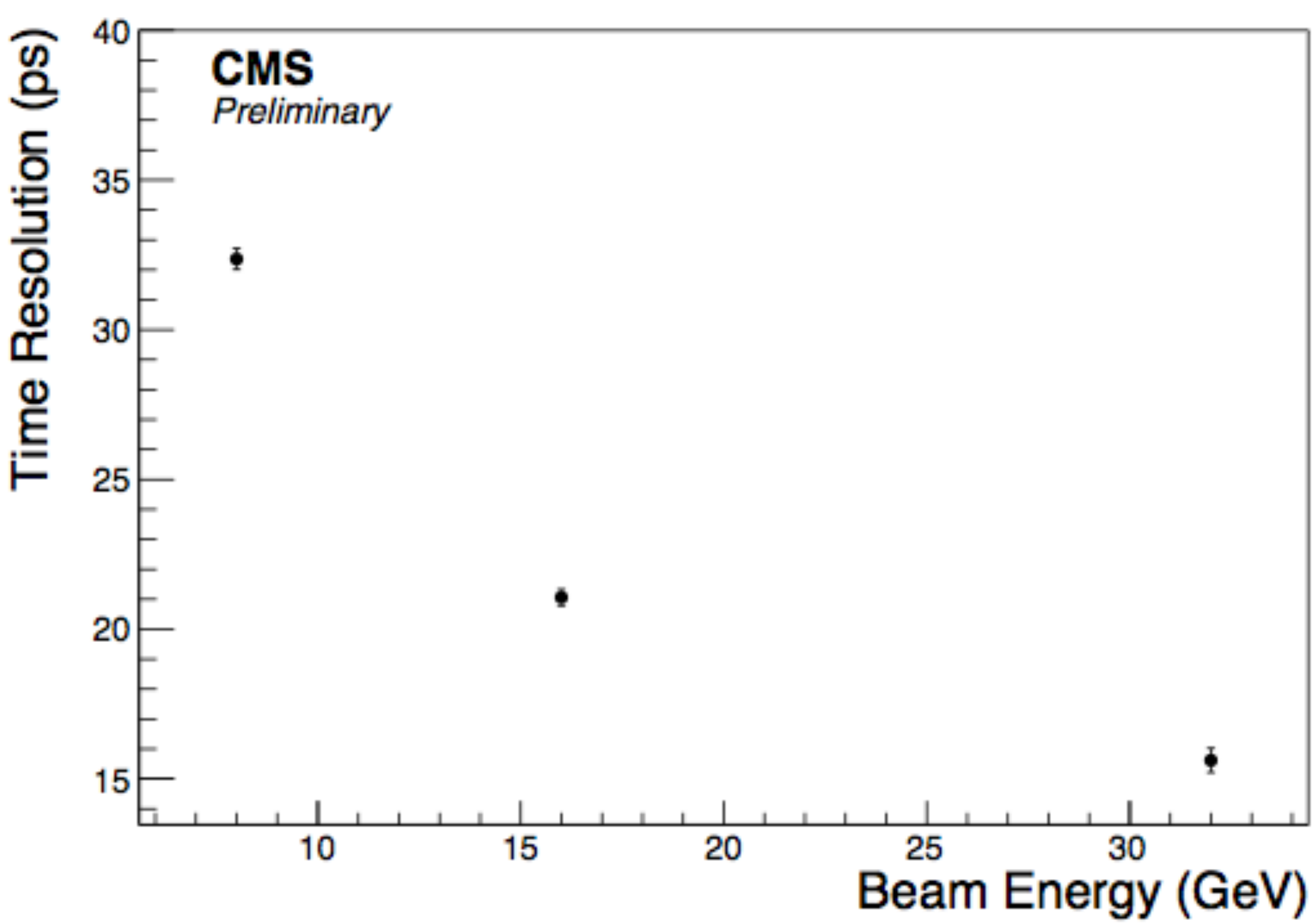
TIMING RESOLUTION (SINGLE LAYER)

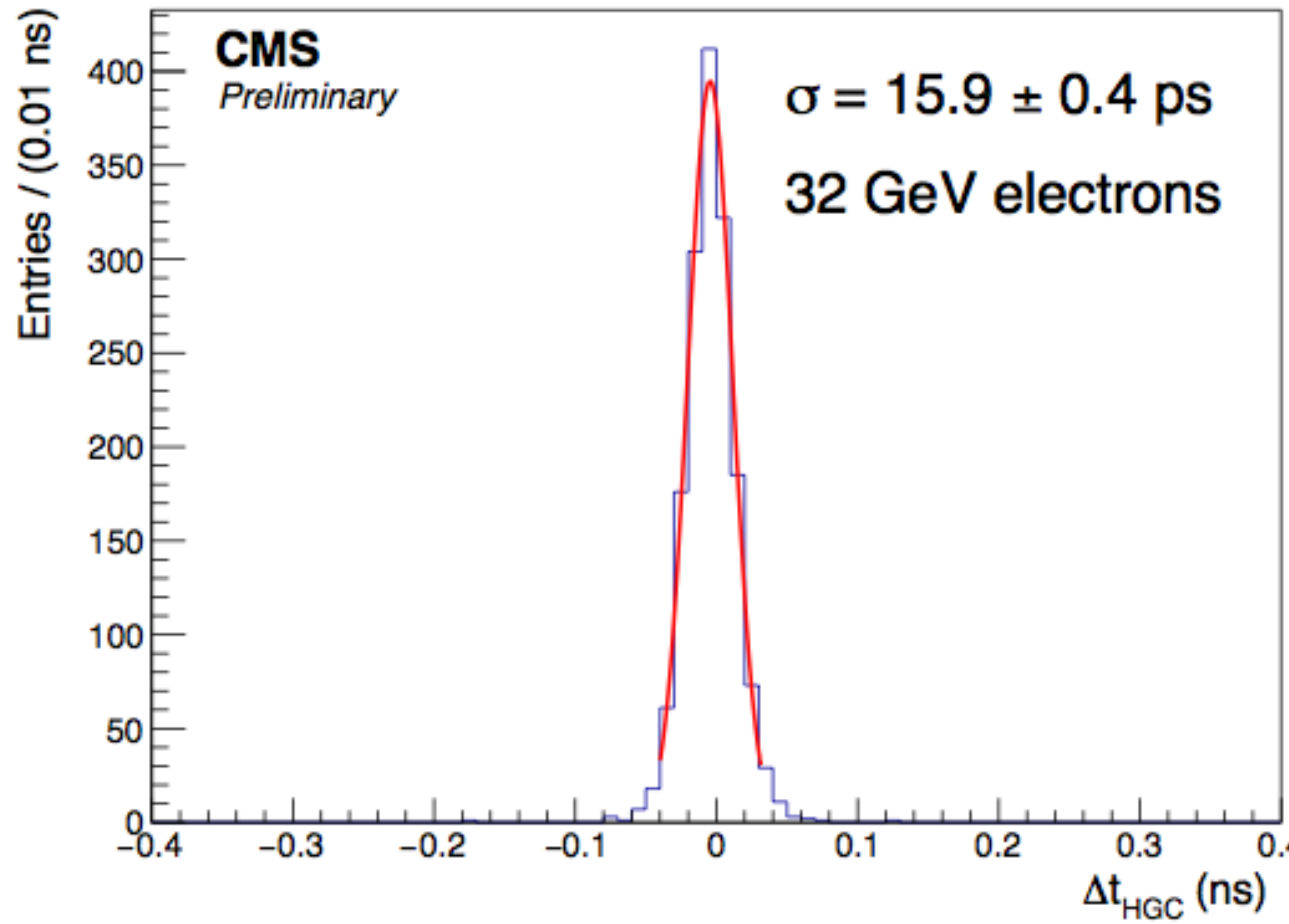




- Time stamp is determined by combining 7 pads around the center
- Time resolution of ~15 ps with a single timing layer

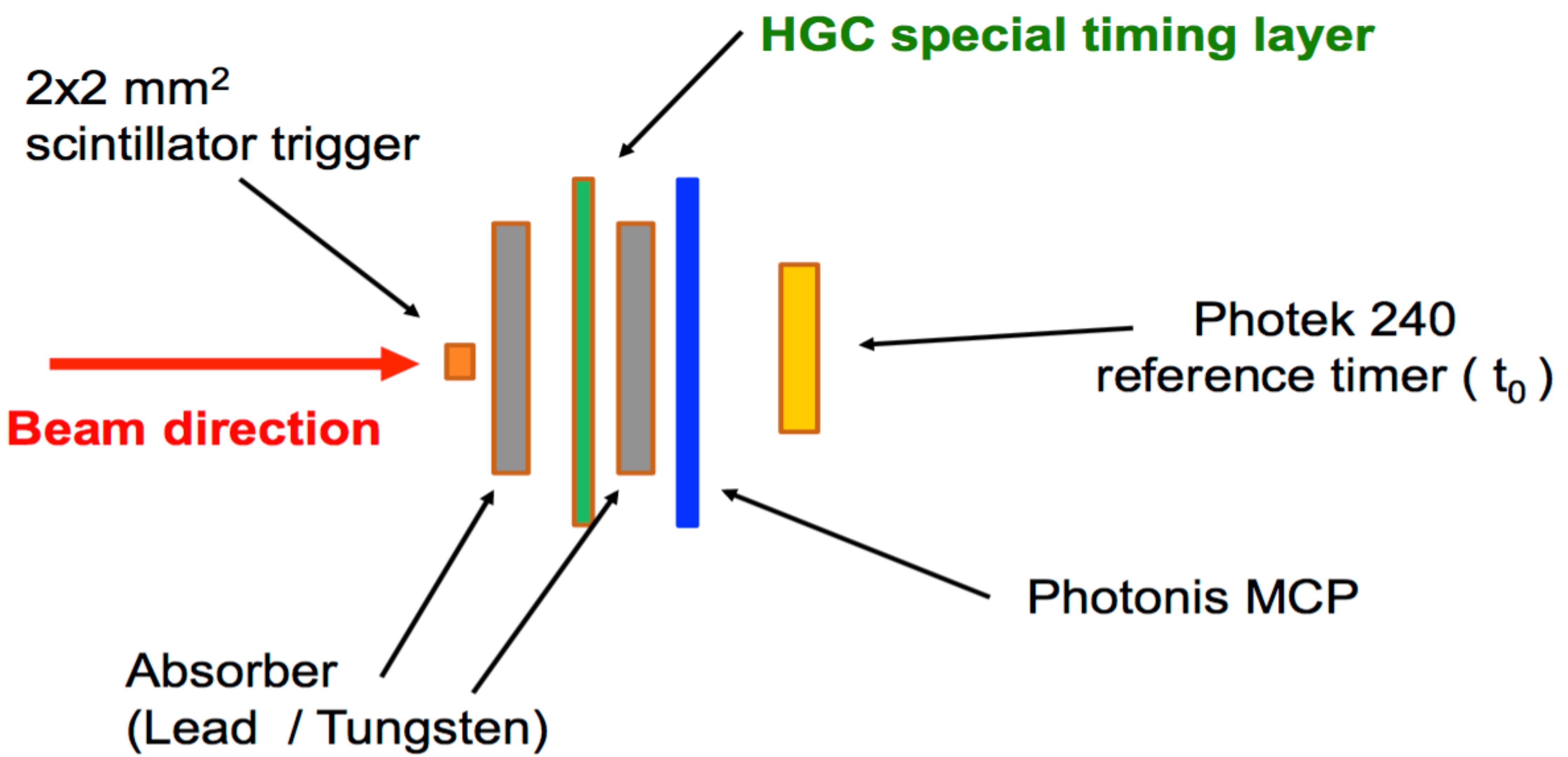
TIMING RESOLUTION (SINGLE LAYER)



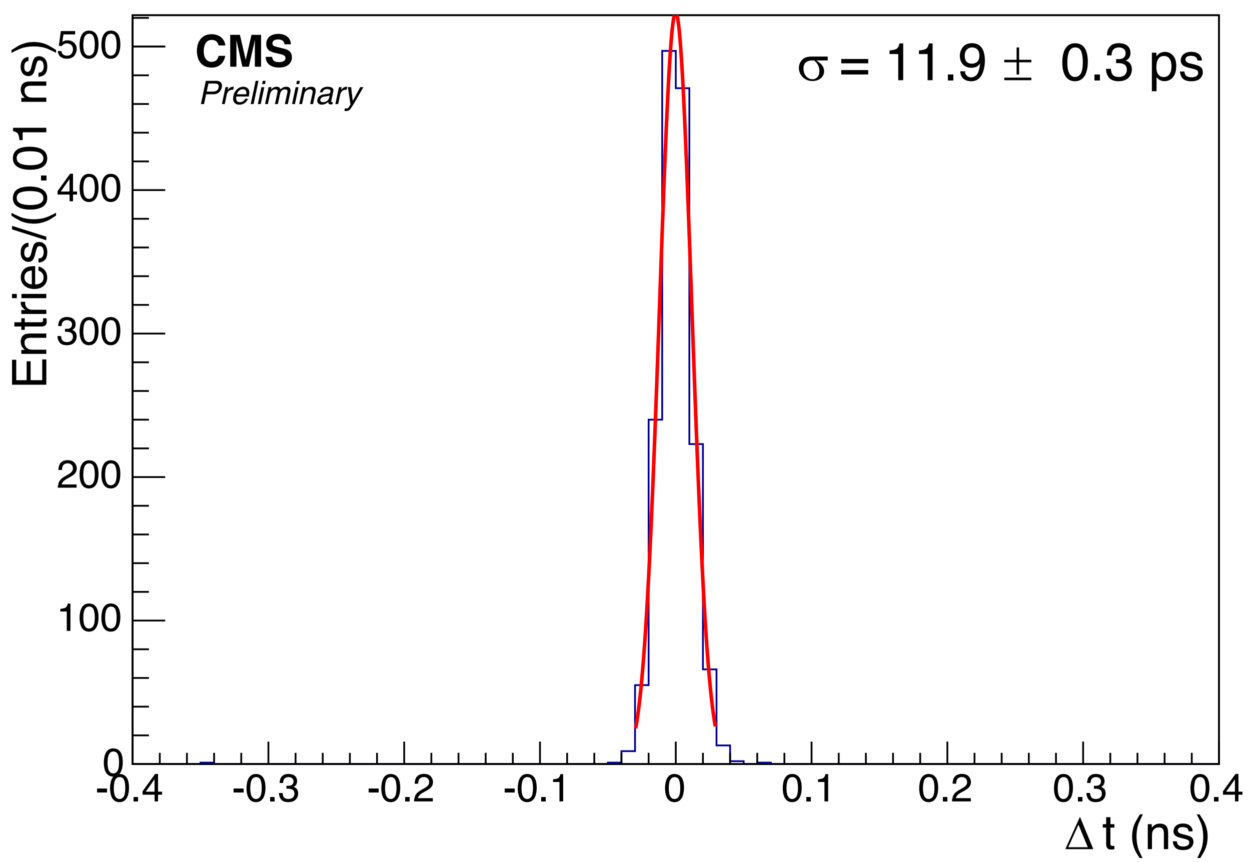


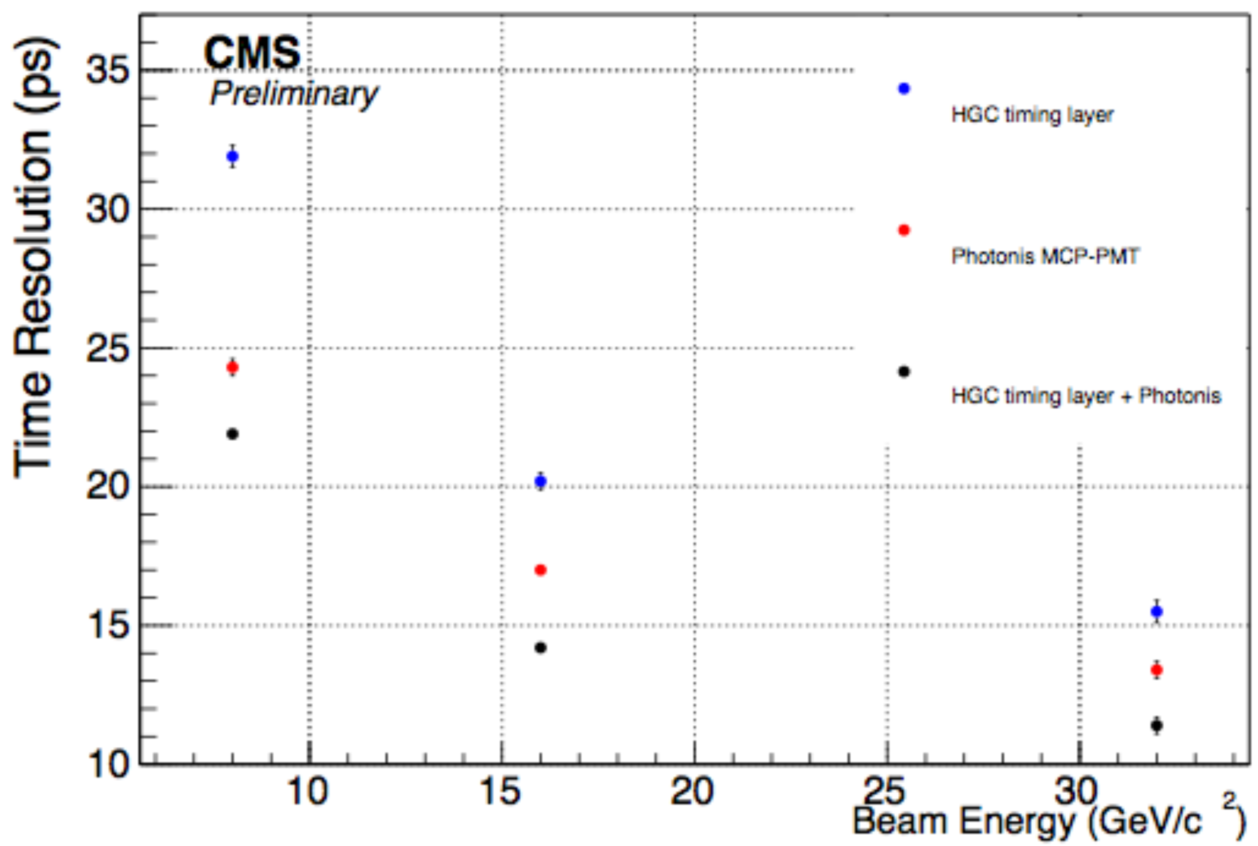
- Time resolution improves as a function of energy
- Time resolution of ~15 ps with a single timing layer

Study the impact on time resolution by combining multiple sampling layers



Two layer time resolution



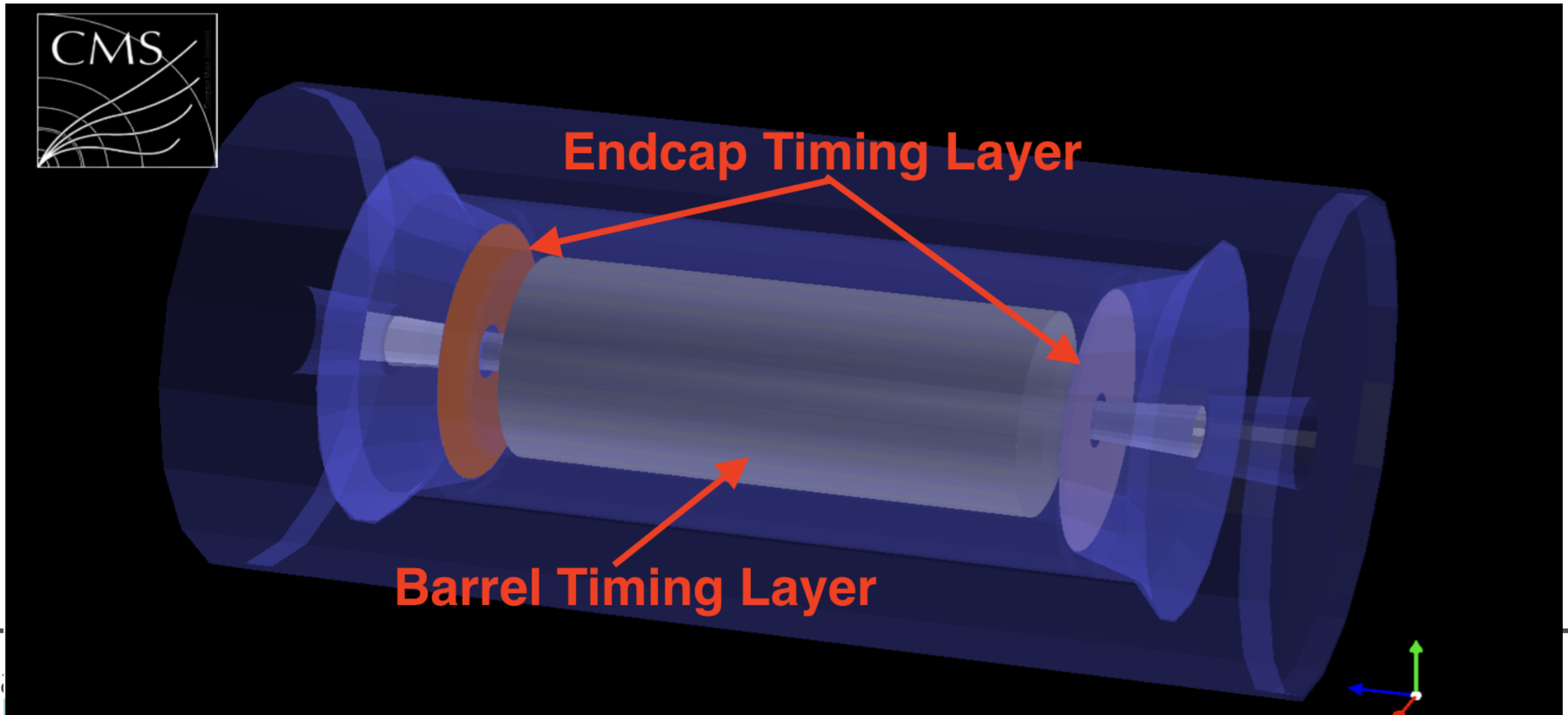


- Combined two layer (average) improves the time resolution
- Time resolution of ~12 ps with a two timing layer at about the shower maximum

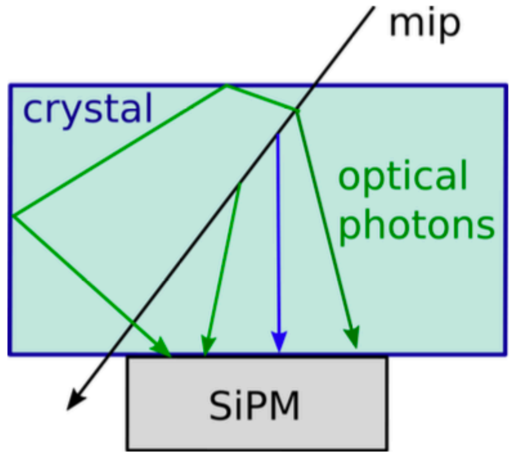
CMS Timing Layers

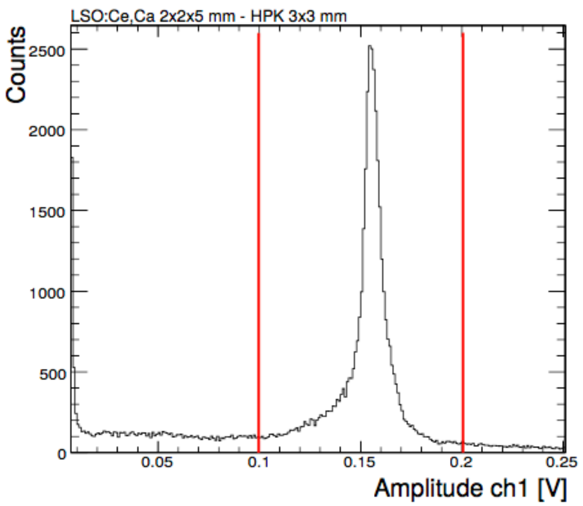
PRECISION TIMING IN CMS

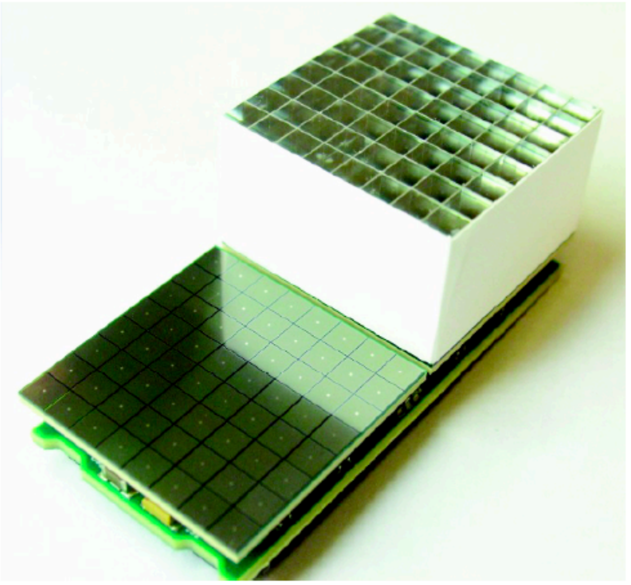
- **CMS Phase 2 upgrade** aims to achieve high precision timing measurements
  - **In ECAL barrel**: new electronics to achieve ~30 ps resolution for 30 GeV photons
  - **In HGCal**: design to achieve ~50 ps timing resolution per layer in EM showers, multiple layers can be combined
  - **MIP timing detector:** cover up to |η|<3.0 to time stamp charged particles in the event: ~30 psec timing resolution
  - **LYSO + SiPM** layer in the barrel, Low Gain Avalanche Detector (LGAD) layer in the endcap



BARREL TIMING LAYER (BTL)





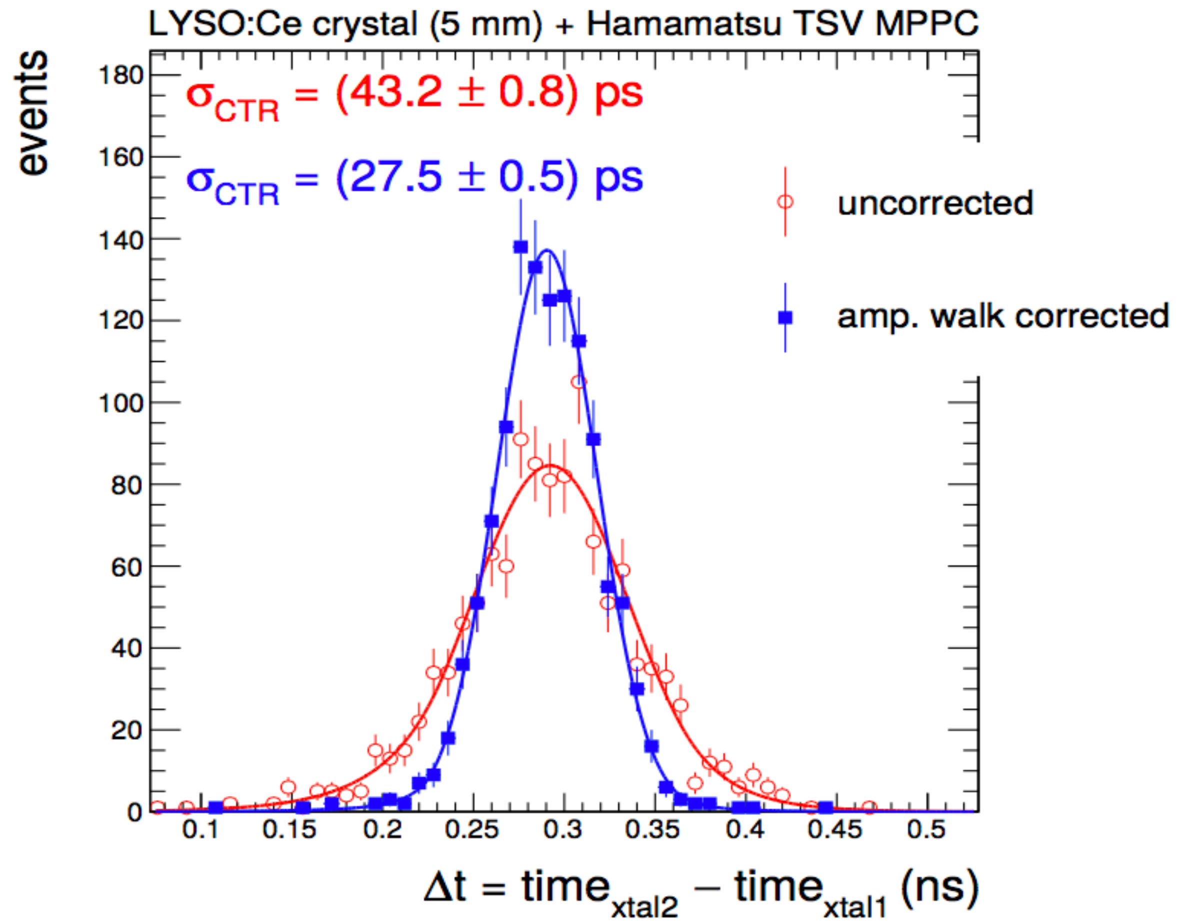


- Use thin (few mm) scintillating crystals to generate light:
  - LYSO crystals provide a very bright signal to a single MIP (up to ~40k photons per mm)
  - 100% efficient to MIP with good S/N
  - Good radiation tolerance to HL-LHC conditions
- Light read-out using SiPMs:
  - Fast and compact devices
  - Vast experience (CMS HCAL) and testing for radiation hardness, collaboration with manufacturers,
  - Strong knowledge from R&D for TOF-PET scanners

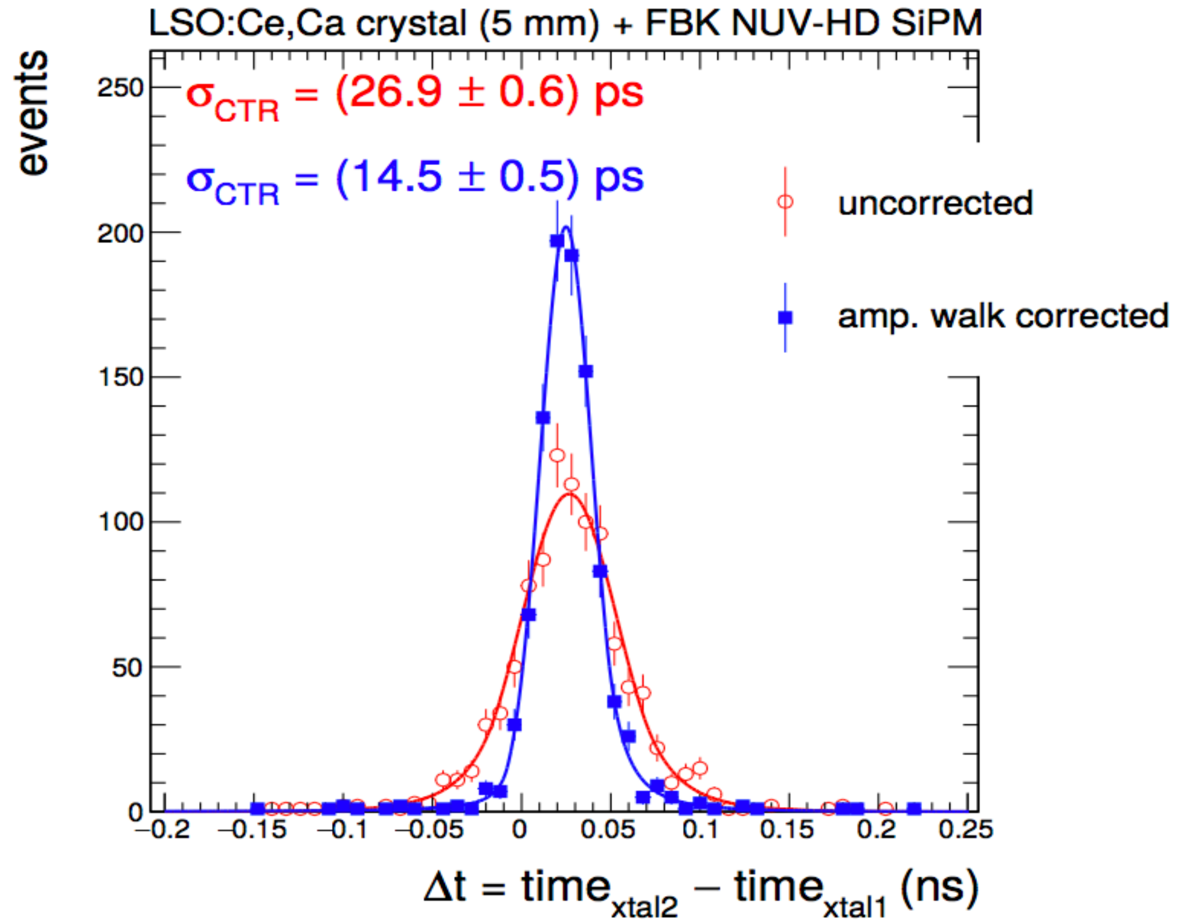
TEST BEAM RESULTS

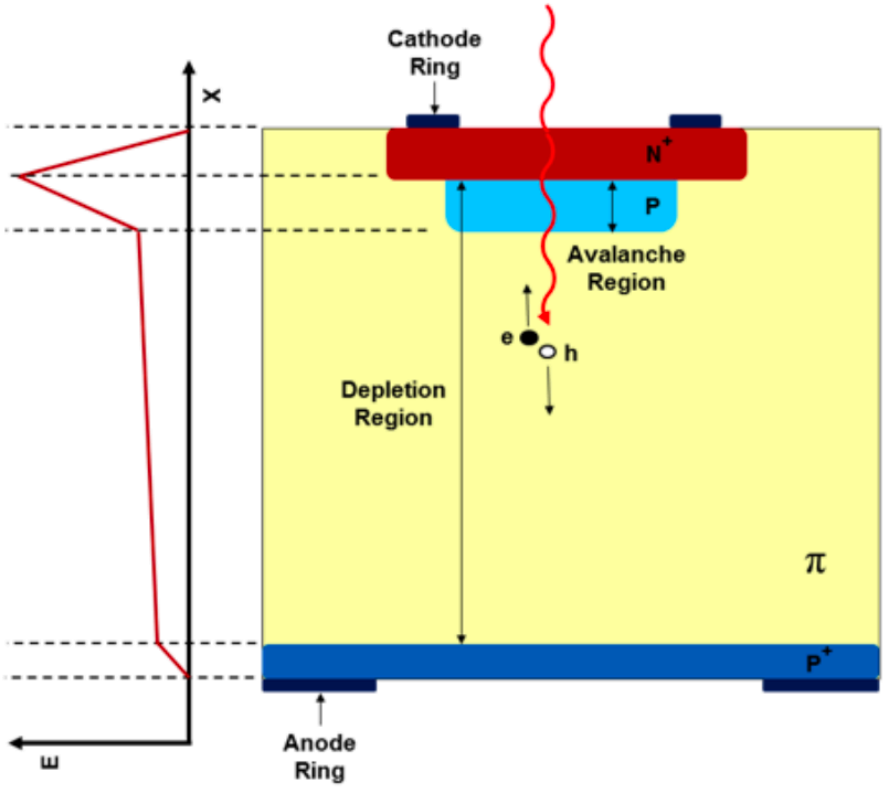
- Evaluate timing performance of different crystals and SiPM options using 150 GeV muons
- Best results with 5 mm thick LSO:Ce,Ca + NUV-HD FBK SiPMs
  - R&D on SiPMs has large potential for improvement of timing

$\sigma_t^{\textbf{single}} = 19.4\ \textbf{ps}$

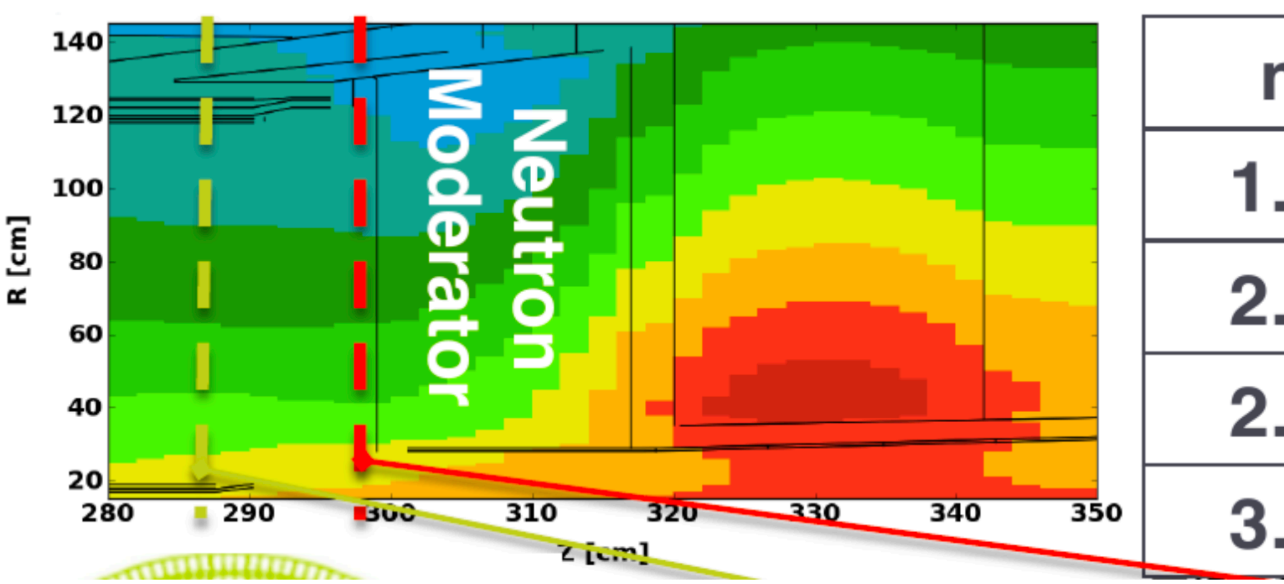


$\sigma_t^{\textbf{single}} = 10.3\ \textbf{ps}$

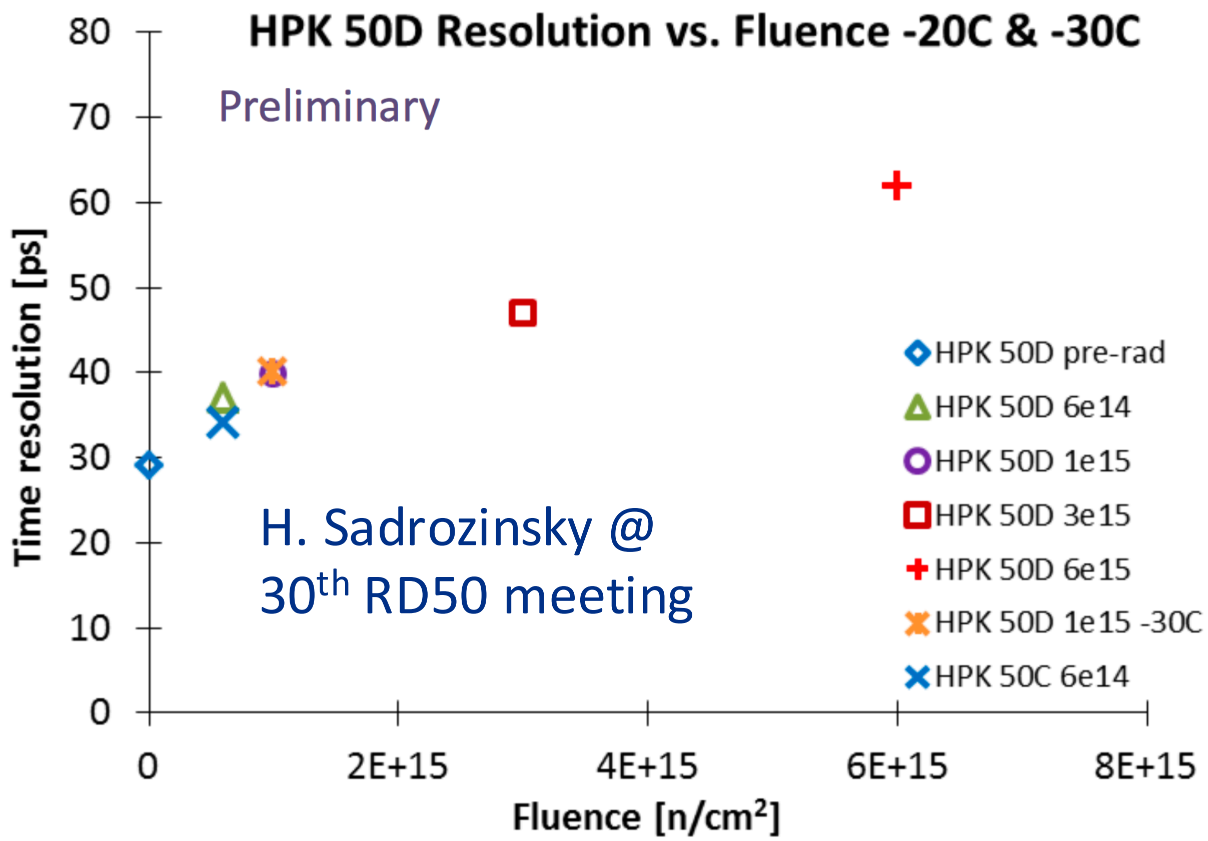




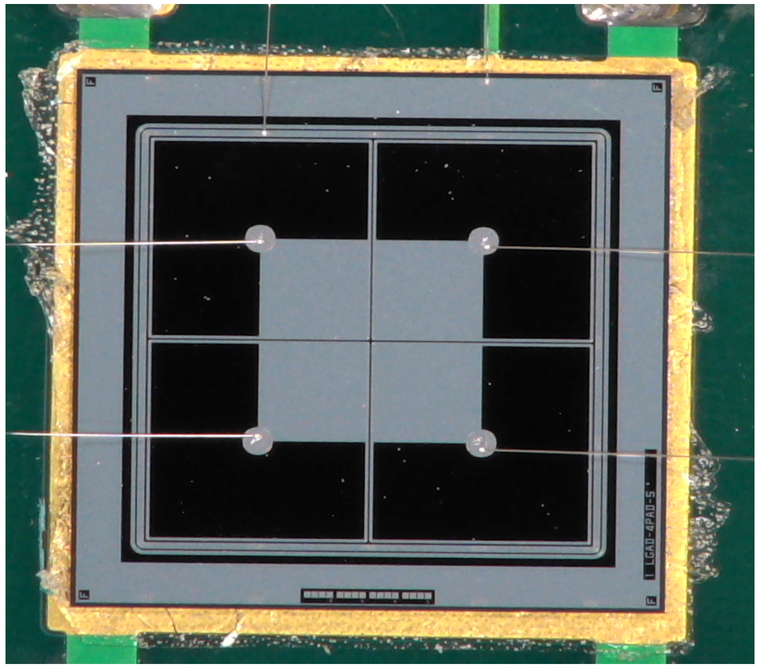
- Much harsher radiation environment in the endcap region
- Silicon sensor with specially doped thin region that
  - produces high electric field produces avalanche providing signal 15-30 gain
  - Large community: RD50 collaboration, several manufacturers (CNM, FBK, Hamamatsu)
  - Key Challenge: achieve radiation tolerance up to 2×10^{15} n_{eq}/cm^2 at $|\eta|$ = 3.0 for 3000 fb^{-1}



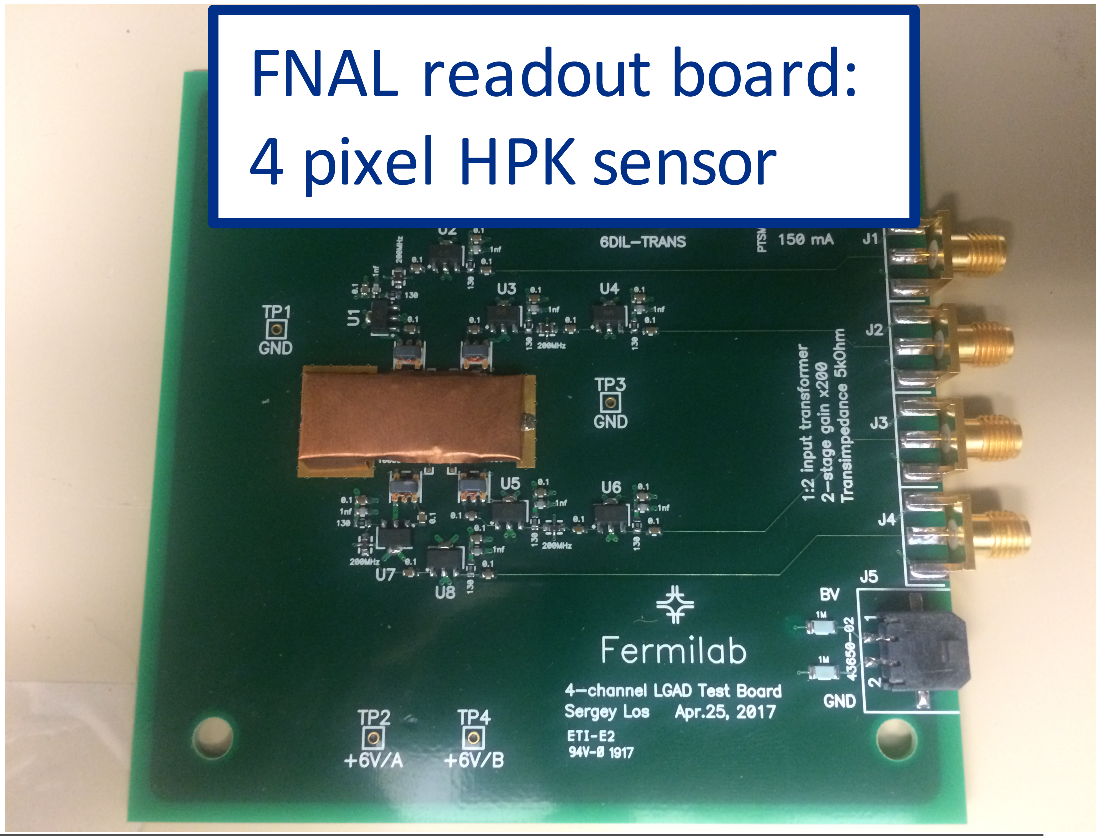
η	TK / HGCal nose
1.6	1.1×10^{14}
2.0	2.1×10^{14}
2.5	4.8×10^{14}
3.0	10.0×10^{14}



Hamamatsu 2x2 LGAD array3x3 mm^2 pixels



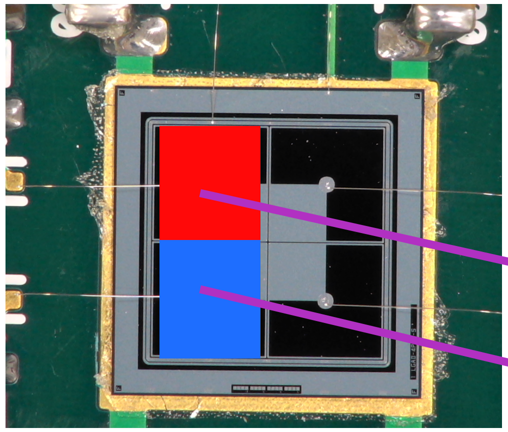
FNAL readout board:
4 pixel HPK sensor



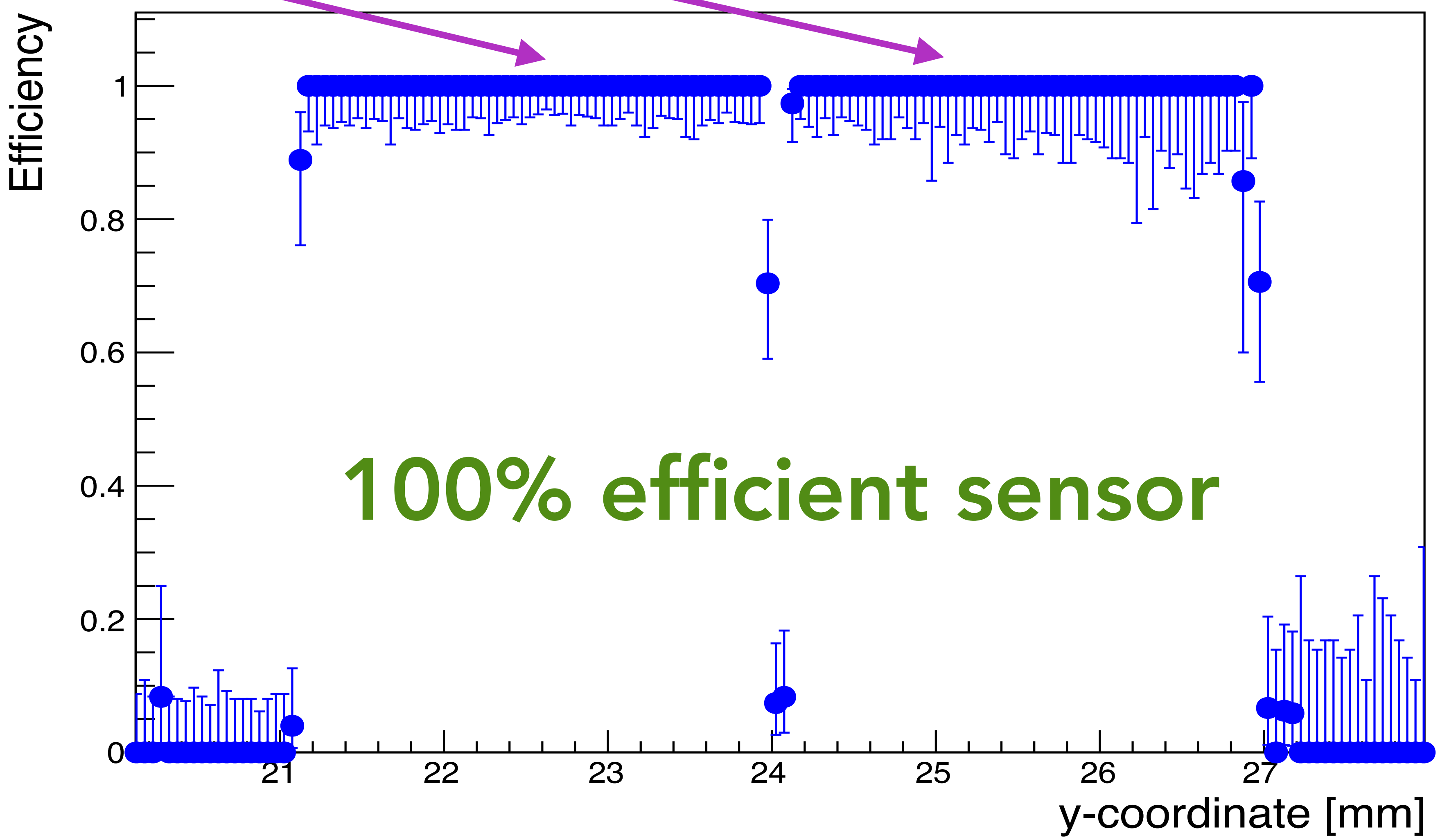
- Time resolution of 30-40 psec demonstrated up to 10^{15} n_{eq}/cm^2
- Active R&D is ongoing to increase the radiation tolerance
- Alternative dopants: boron, gallium, boron+carbon, gallium+carbon

LGAD SENSOR UNIFORMITY

Recent test beam at FNAL



Precision tracking detector available at FTBF allowed high precision characterization of the sensor uniformity



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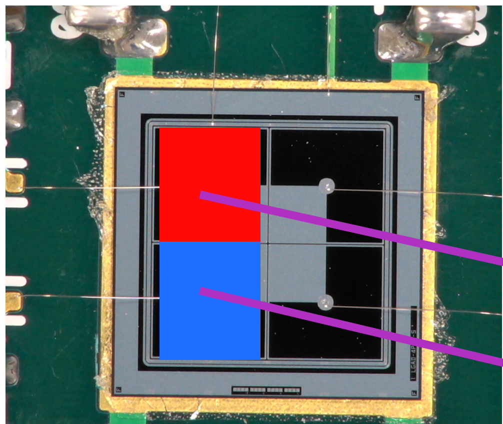

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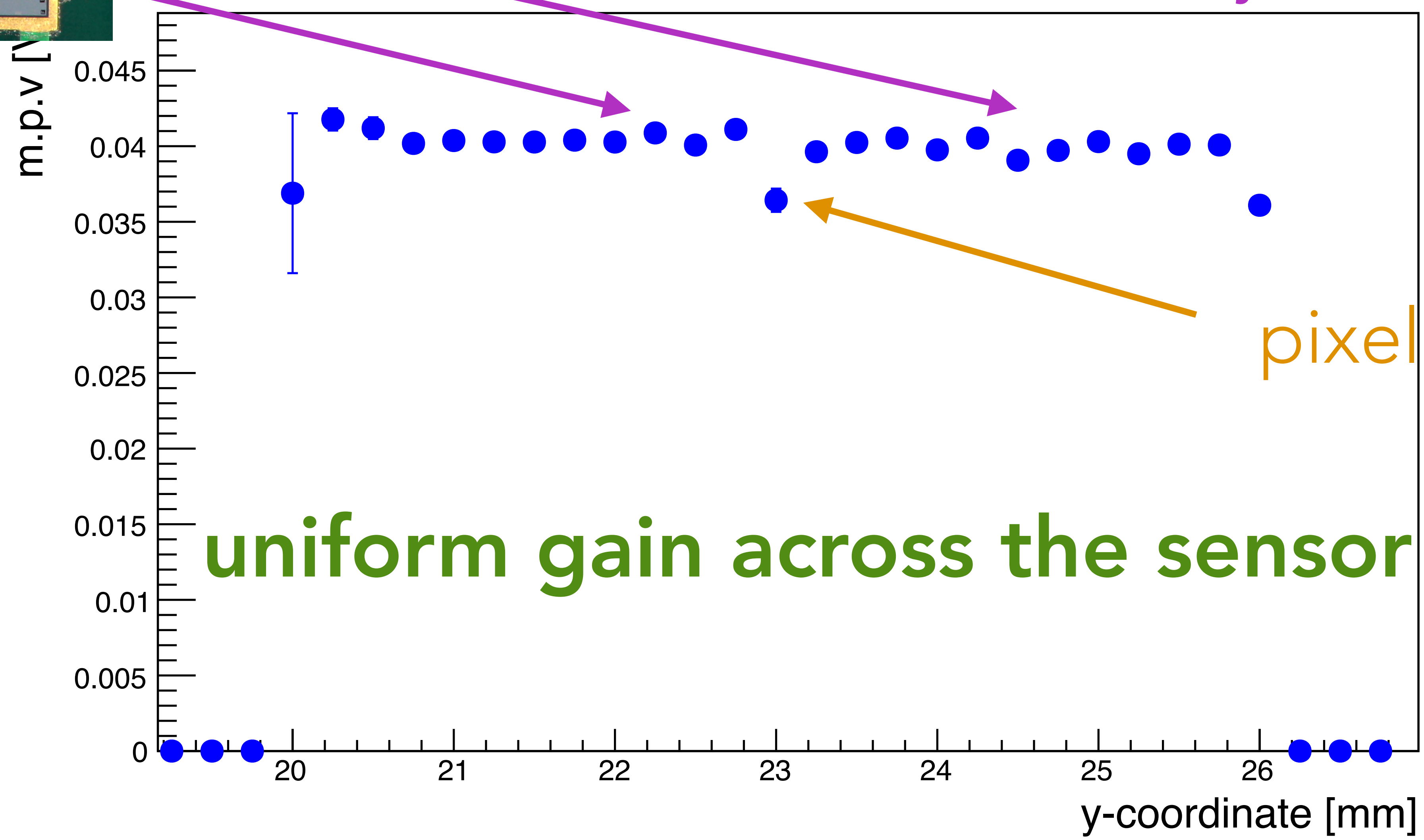


pixel boundary

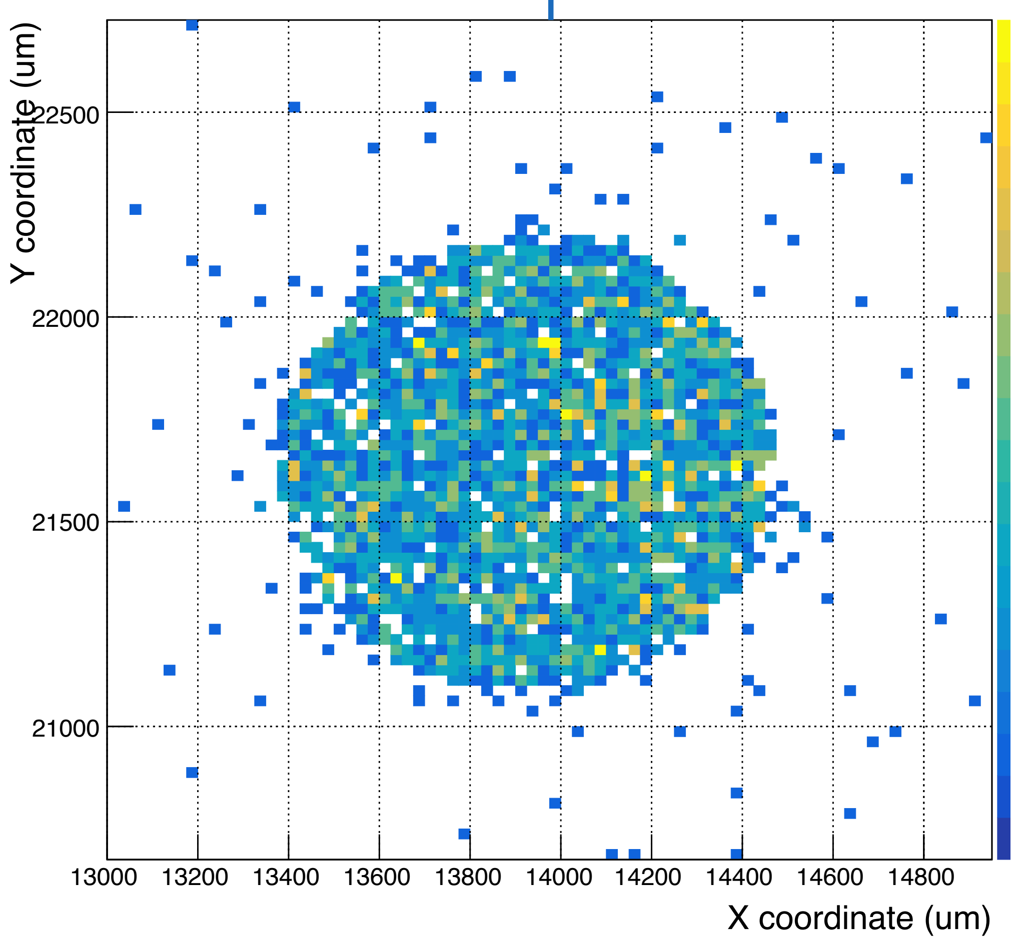
uniform gain across the sensor

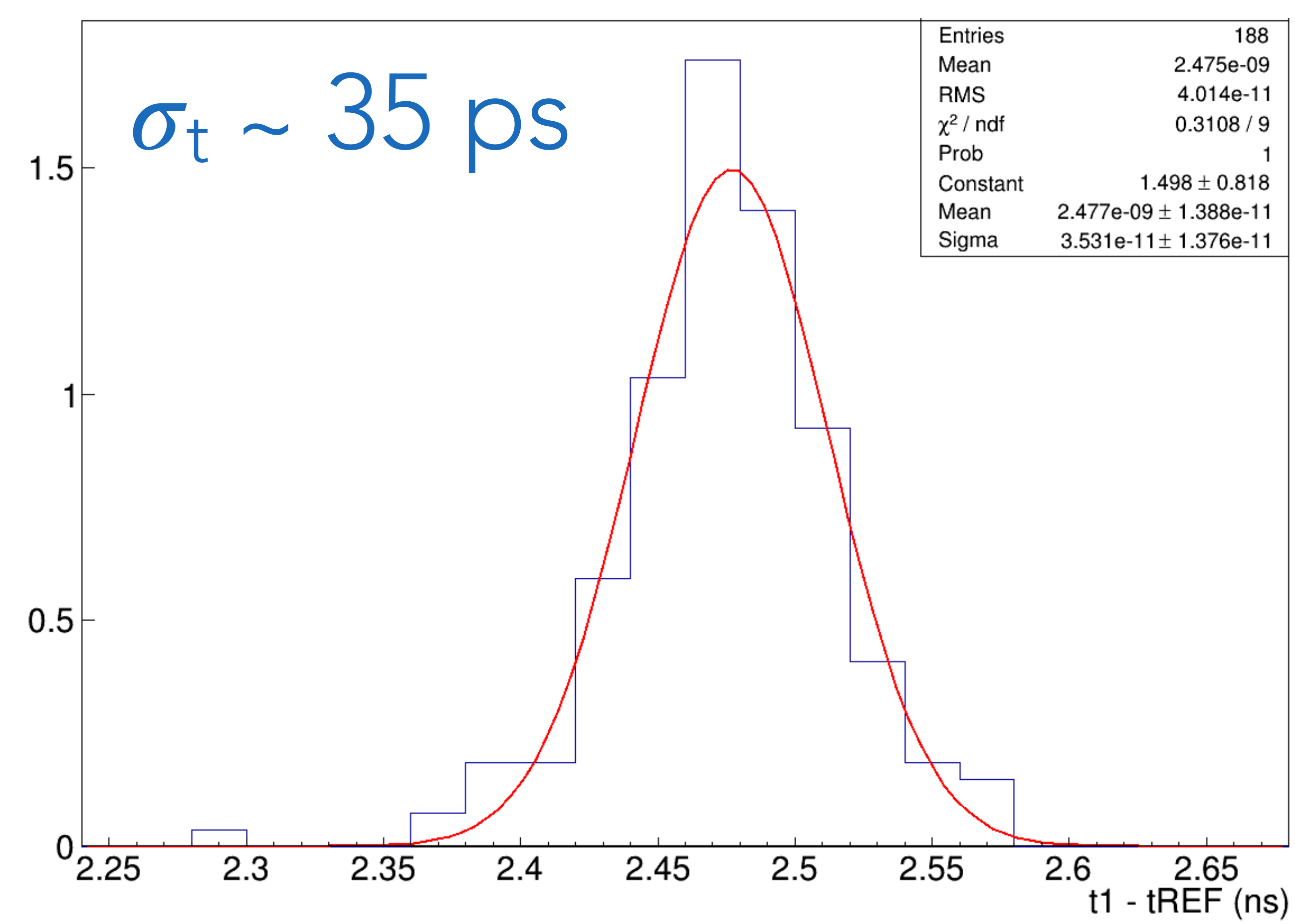
IRRADIATED SENSOR PERFORMANCE

FNAL TB

- Irradiation causes gain layer to fade
- To preserve time resolution and gain, need to increase the operating bias voltage
- Excellent uniformity of signal across the irradiated HPK sensor area

HPK 6 x 10^{14} n.eq/cm^2 at 600V BV



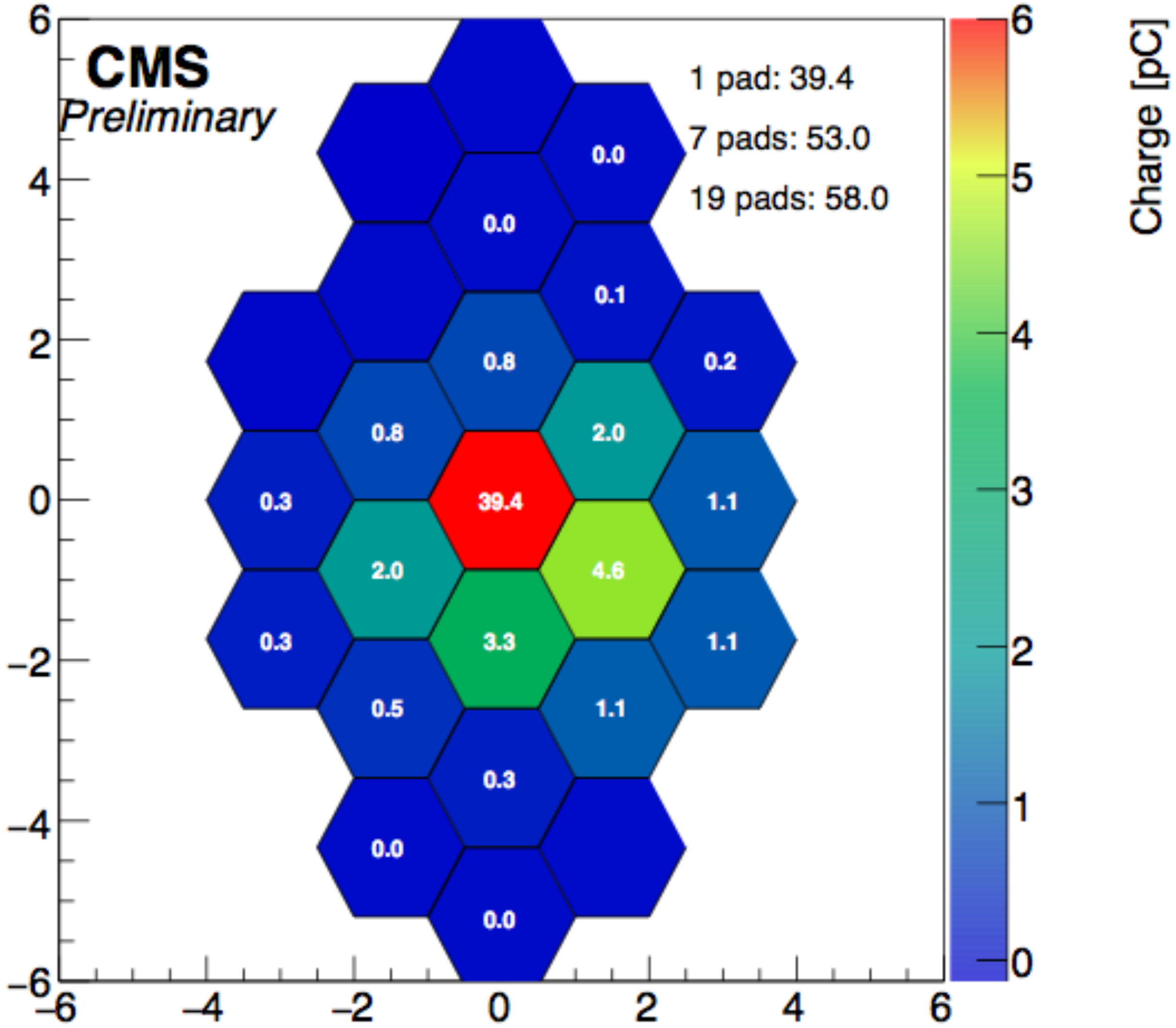


SUMMARY

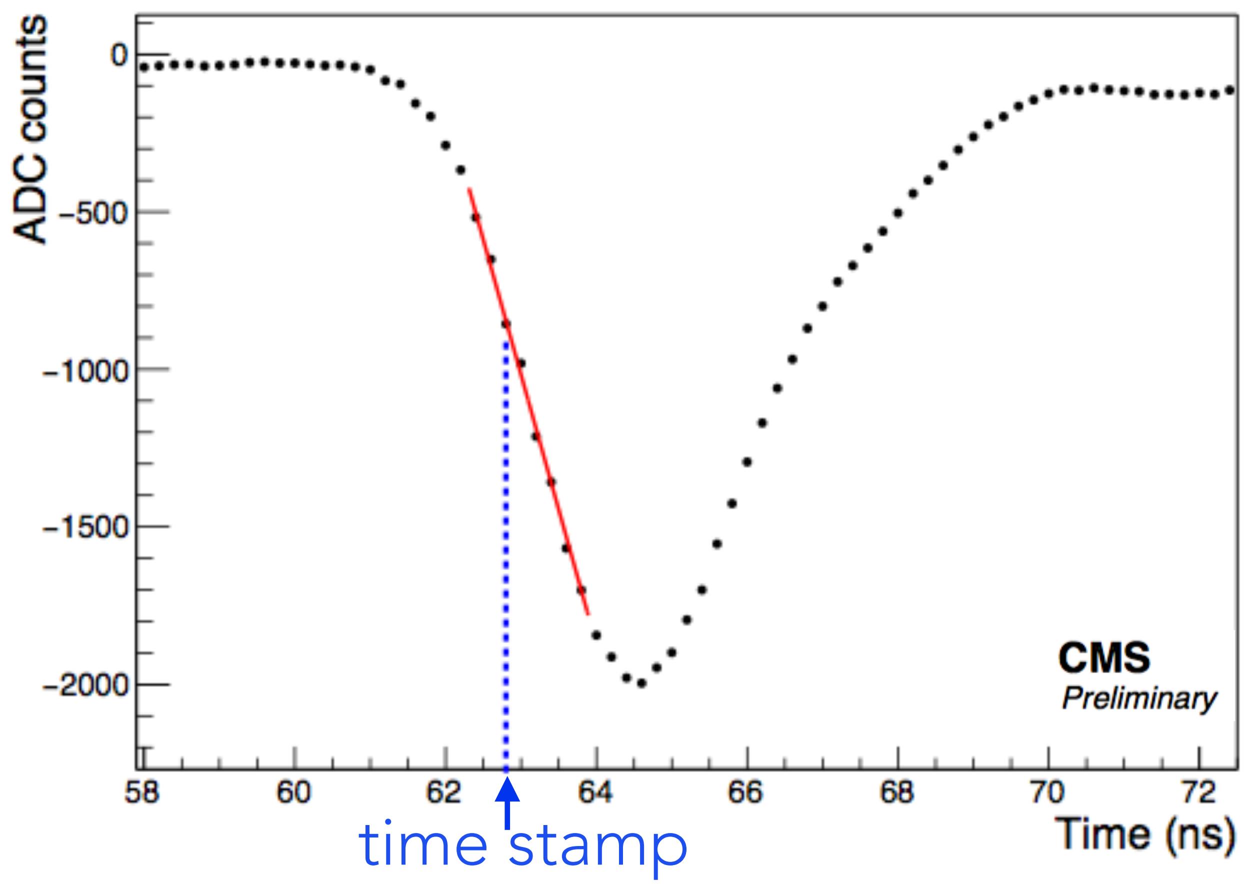
- A detector equipped with precision timing capabilities will cope with the effect of large pileup at the HL-LHC and beyond
  - Could be use at various level: vertex reconstruction, particle ID and isolation, increase S/B in physics analysis
  - Positively disruptive technology
- Time resolutions of 20-30 ps already achieved with several technologies
  - Complementarity between calorimetry and tracking
  - Calorimeters: expect to maintain good time resolution with highly irradiated sensor and multiple layers
  - Endcap regions detectors are approaching the required time resolution for the expected high doses.

Backups

32 GeV electron shower



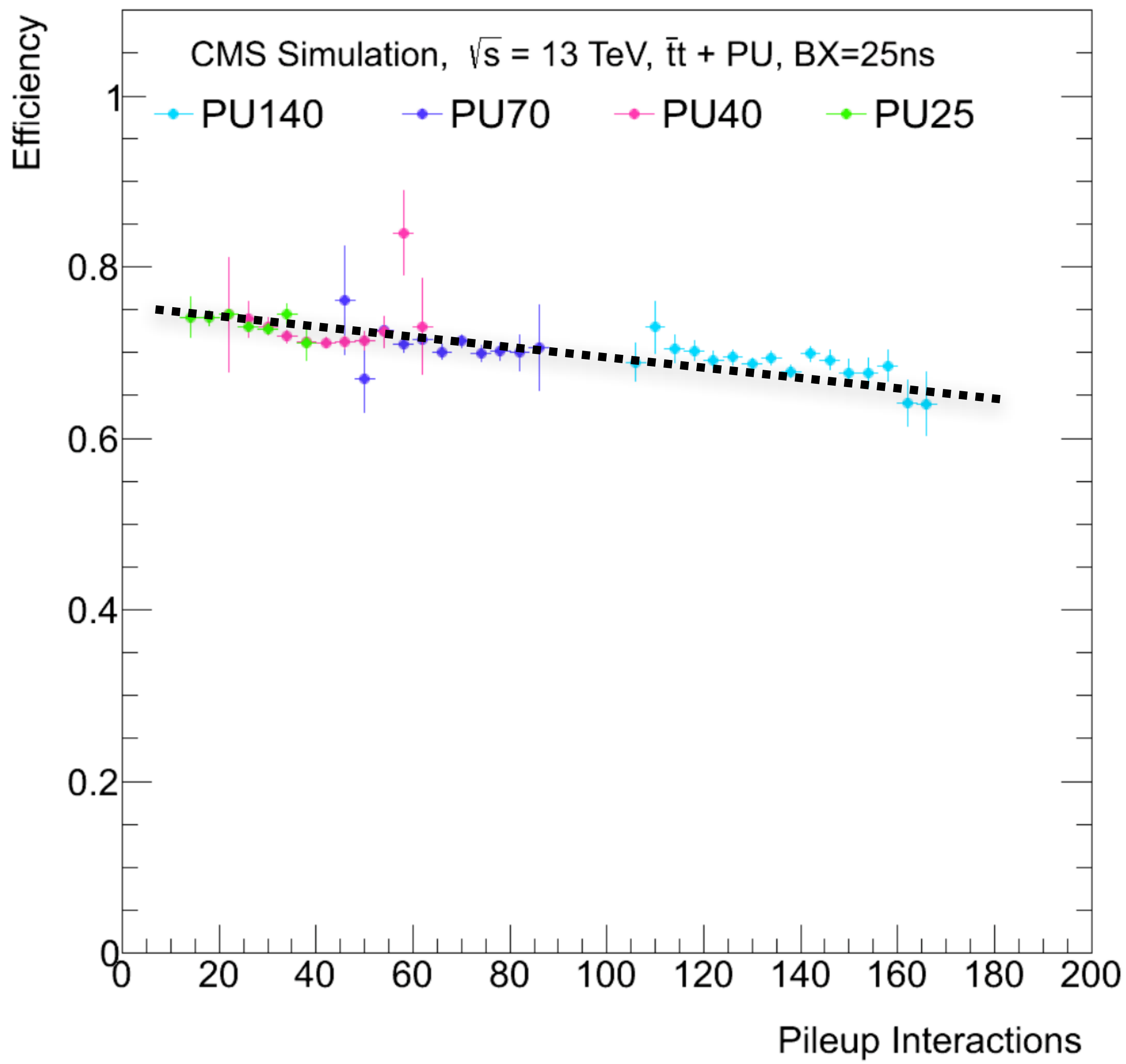
Reconstructed charge in each pixel

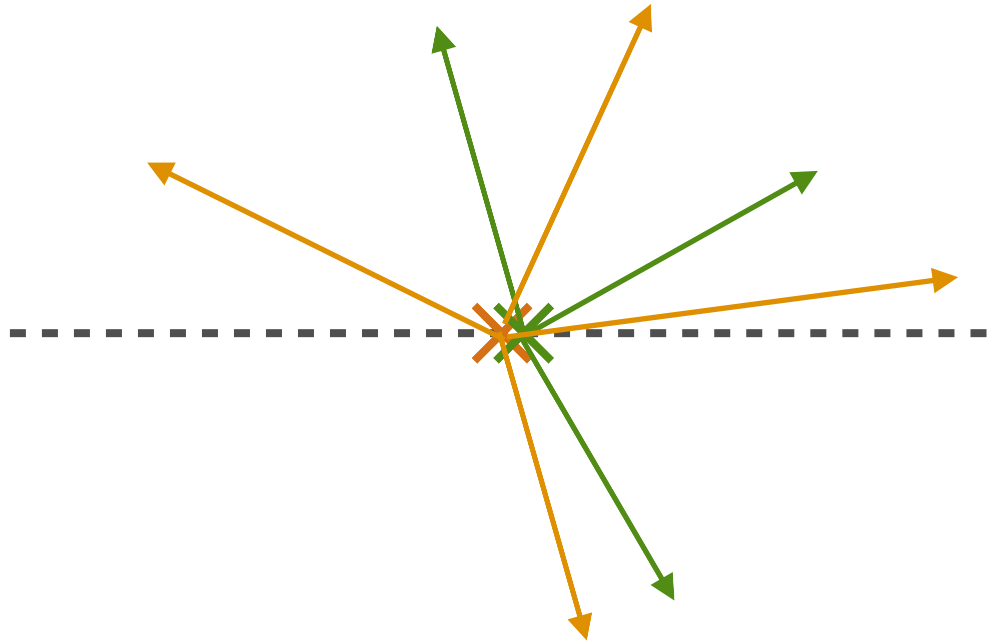


Central pixel pulse and time stamp

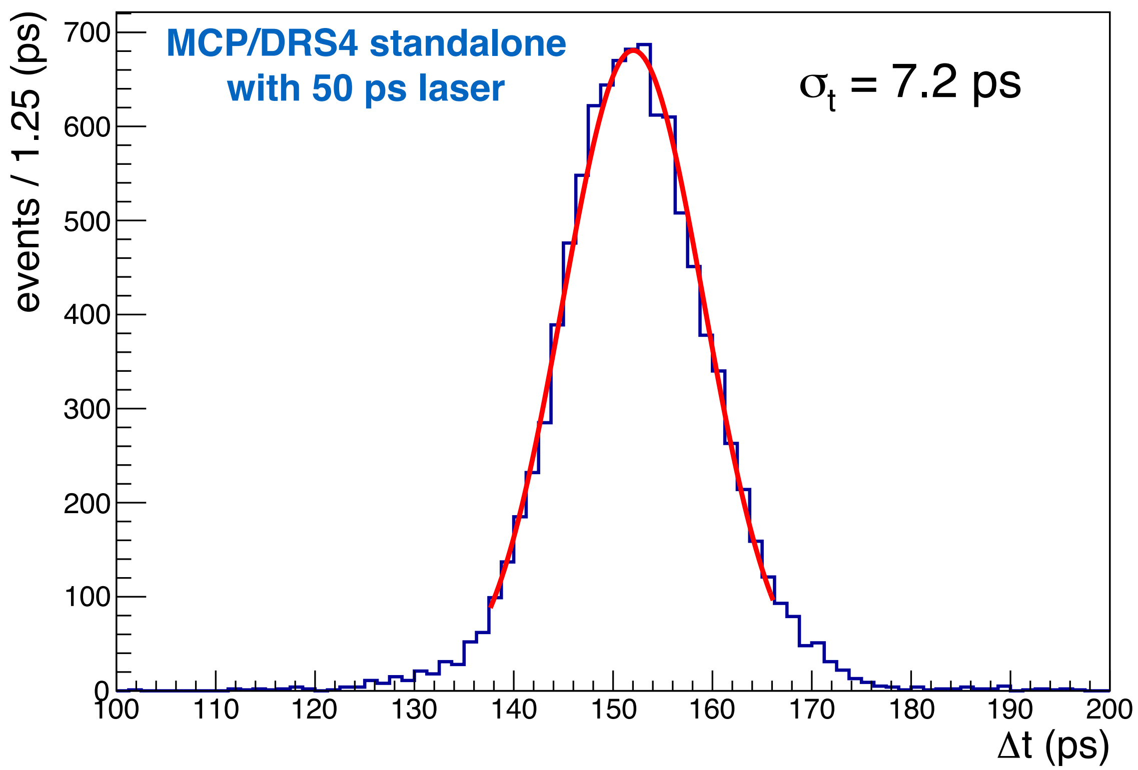
Search for New Physics in High-Mass Diphoton Events

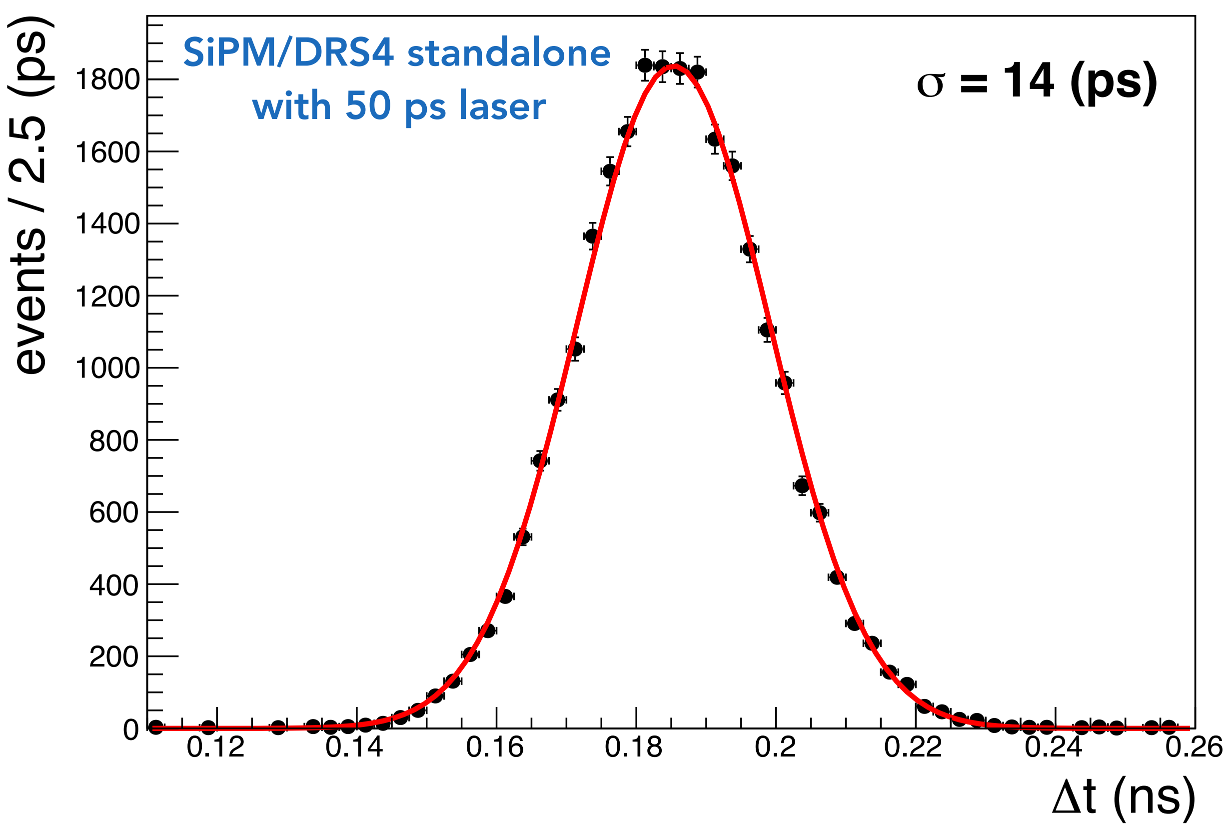
Tracking based vertexing also starts to suffer at such high pileup conditions



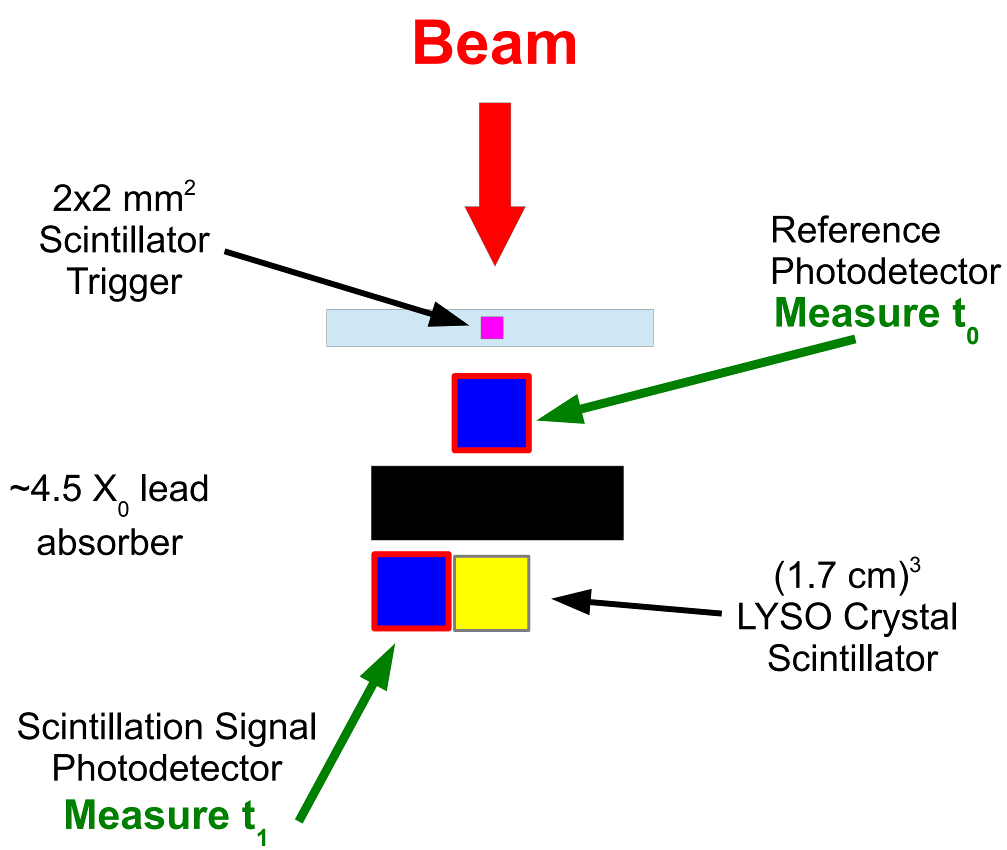


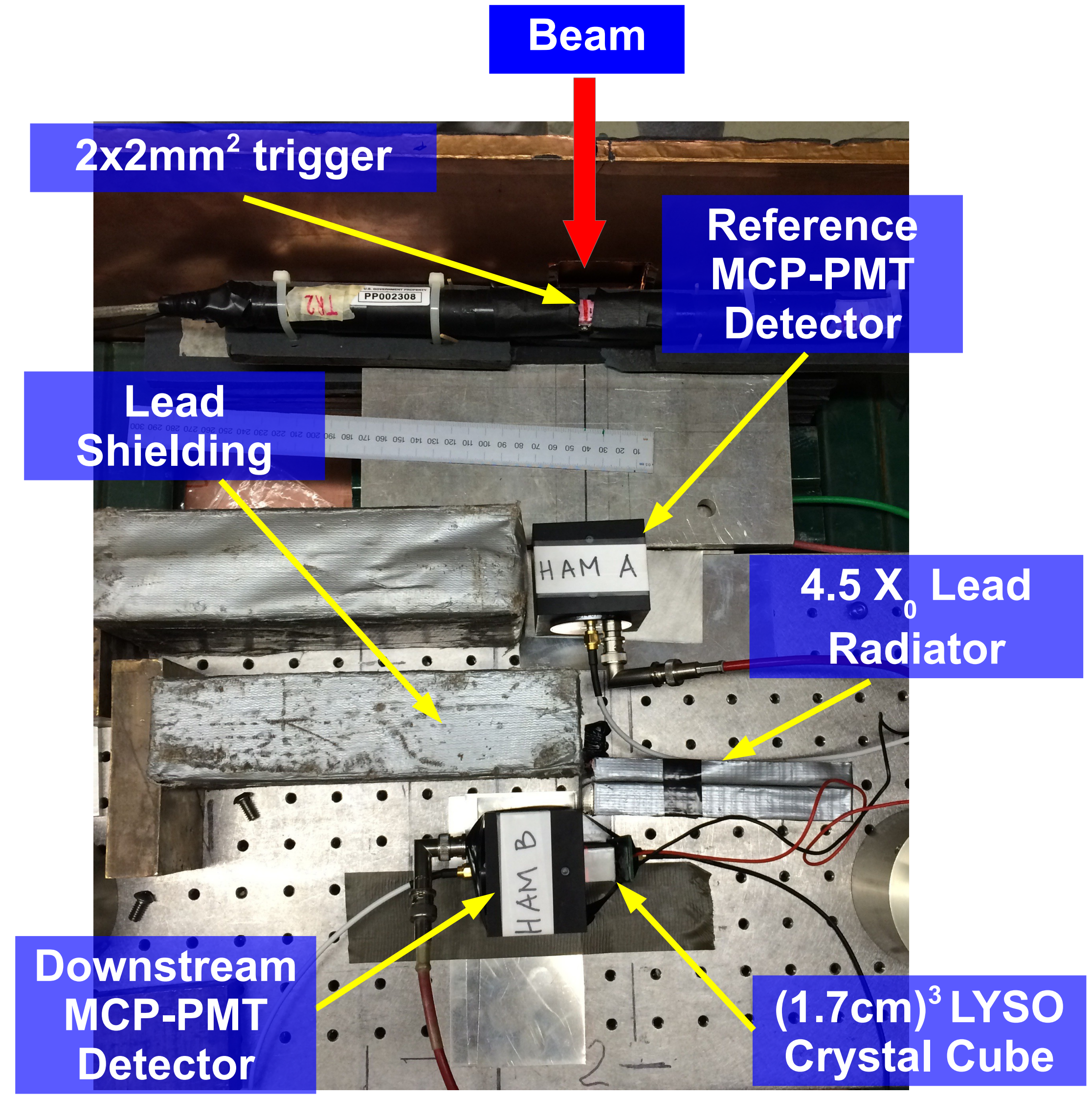
start to have overlapping vertices


MCP/DRS4 standalone
with 50 ps laser
σ_t = 7.2 ps
events / 1.25 (ps)
Δt (ps)
0
100
200
300
400
500
600
700
100
110
120
130
140
150
160
170
180
190
200


SiPM/DRS4 standalone
with 50 ps laser
σ = 14 (ps)
events / 2.5 (ps)
Δt (ns)
0
200
400
600
800
1000
1200
1400
1600
1800
0.12
0.14
0.16
0.18
0.2
0.22
0.24
0.26

LYSO-BASED SAMPLING CALORIMETERS



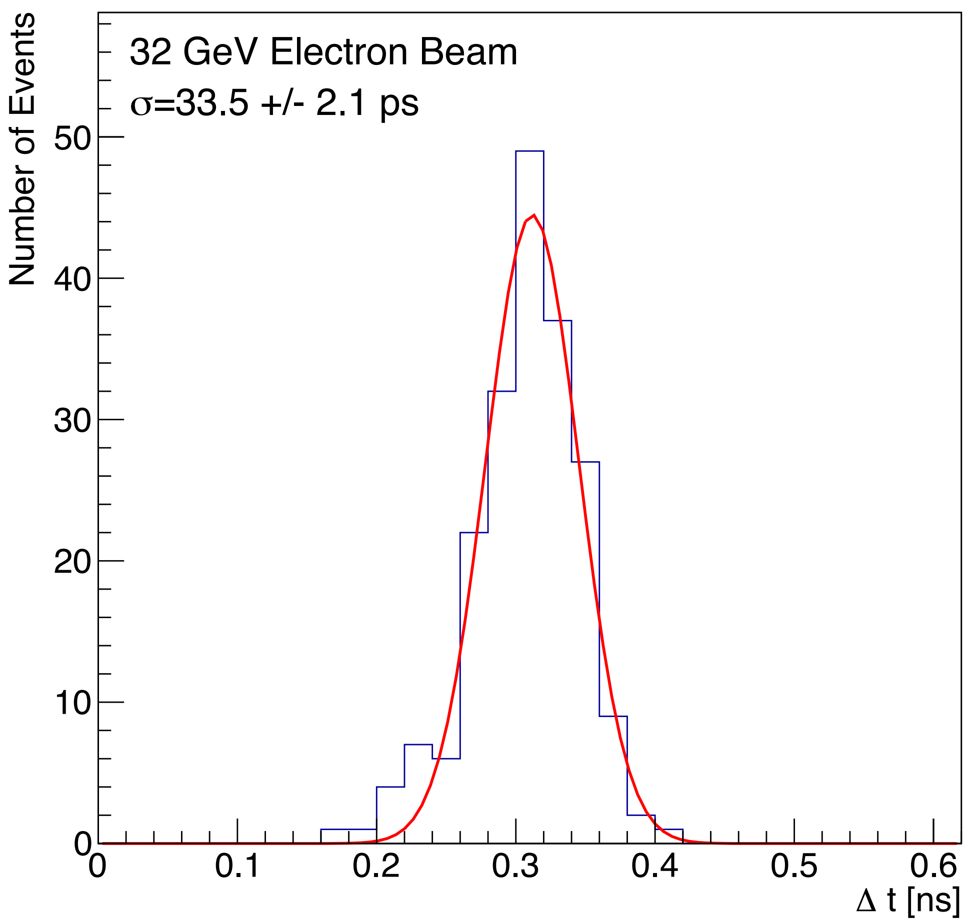


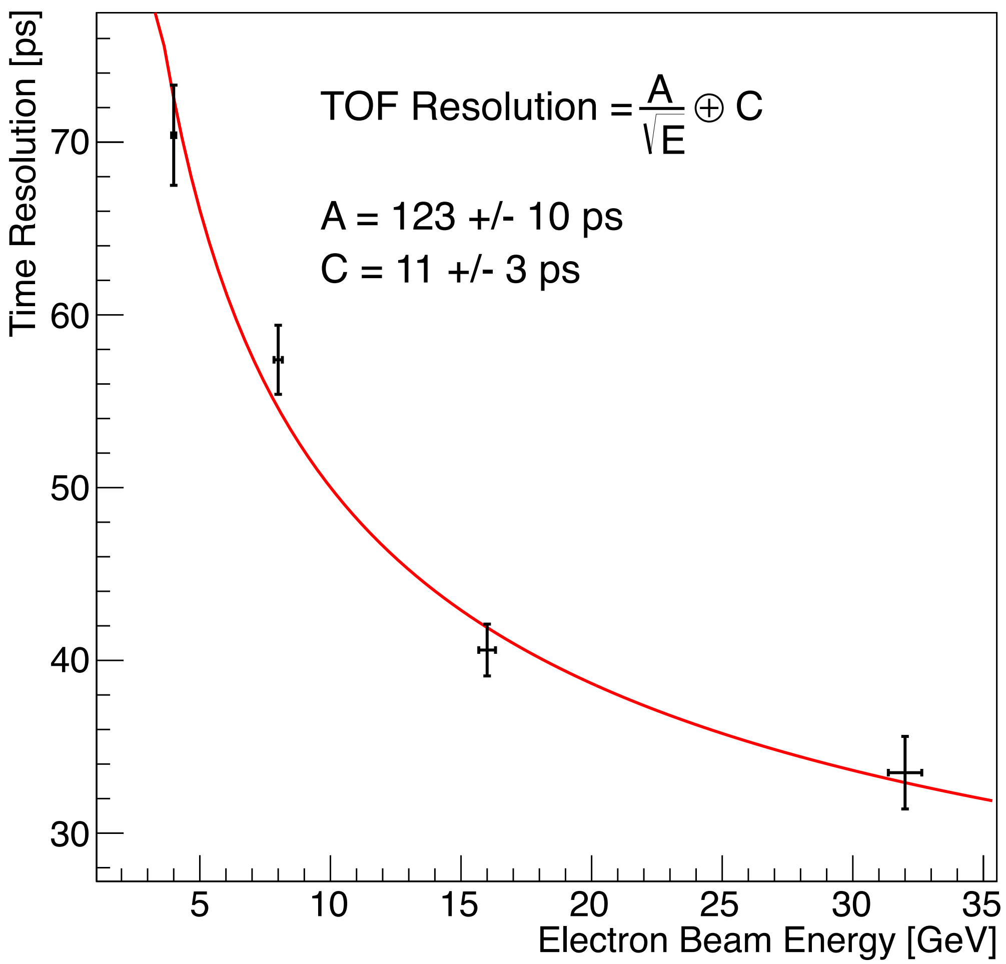
$\Delta t = t_1 - t_0$: LYSO - MCP (reference)

t_0: time stamp for MCP-PMT, using mean of a Gaussian fit

t_1: time stamp for (LYSO+MCP), CFD using linear fit

RESULTS



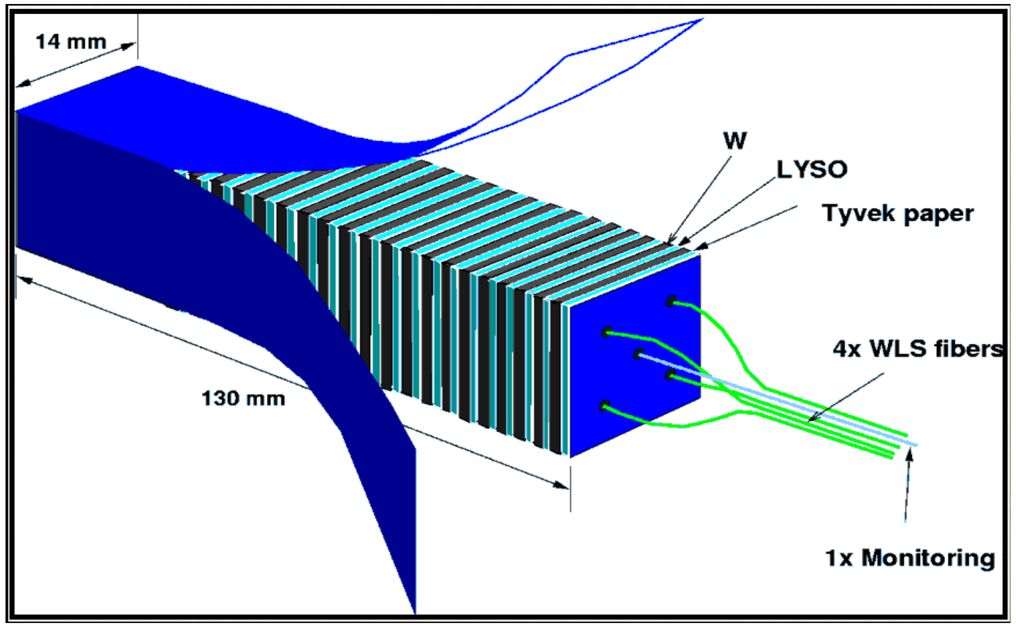


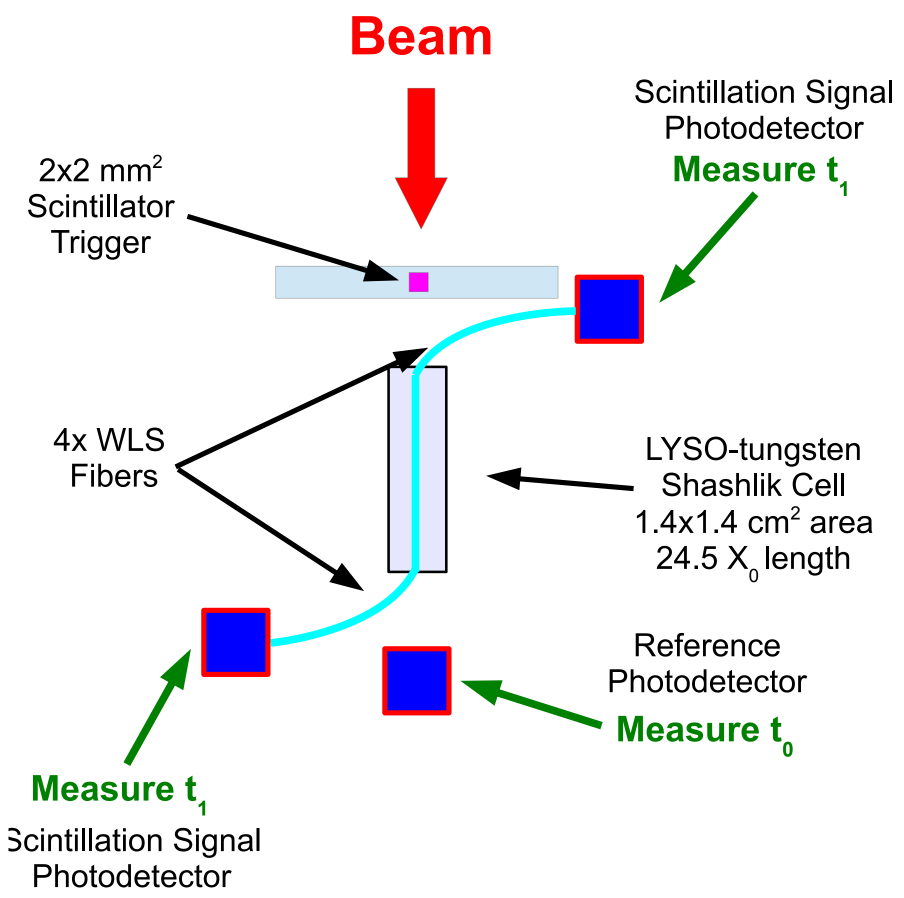
~34 ps time resolution for 32 GeV electron showers

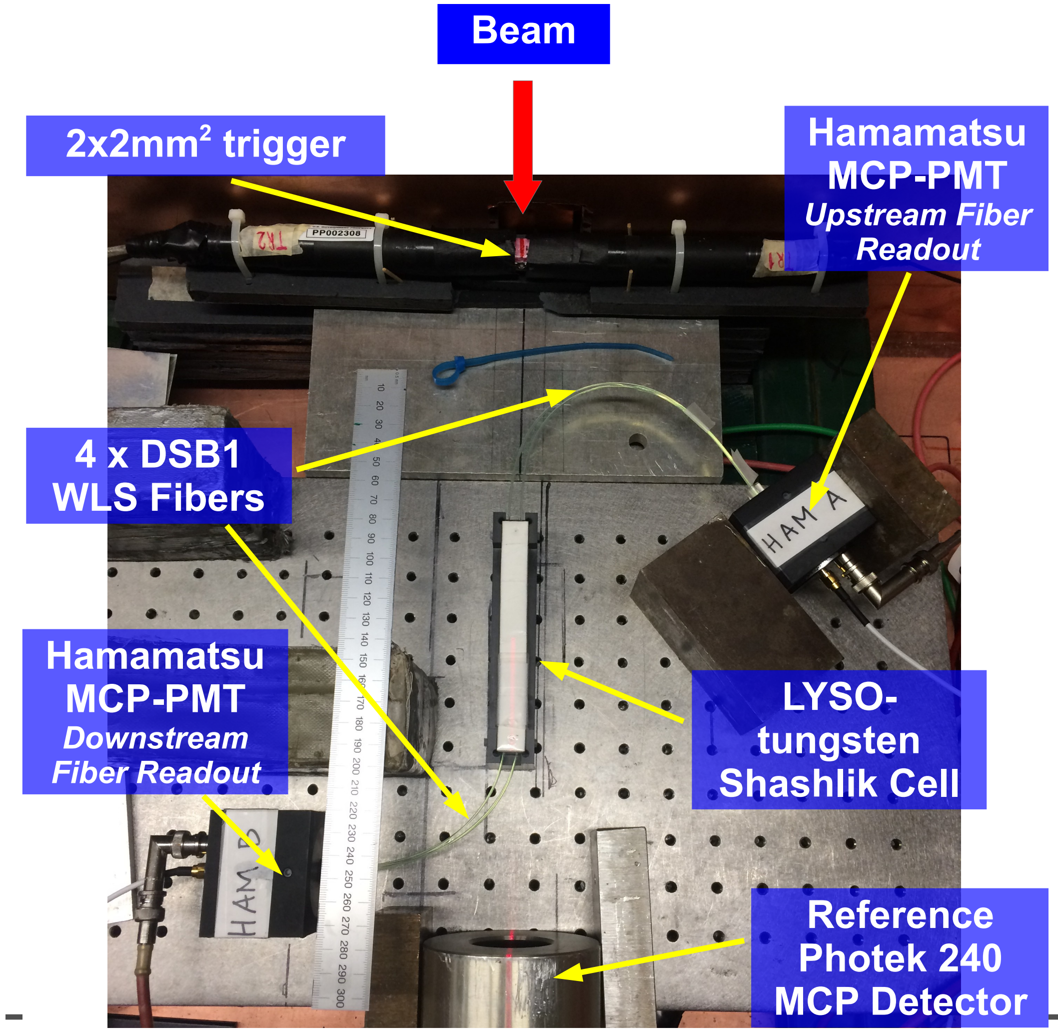
Time resolution is the width of the Gaussian fit

time resolution follow $1/\sqrt{E}$ shape

Shashlik: 28 layer of LYSO/W readout with WLS fibers



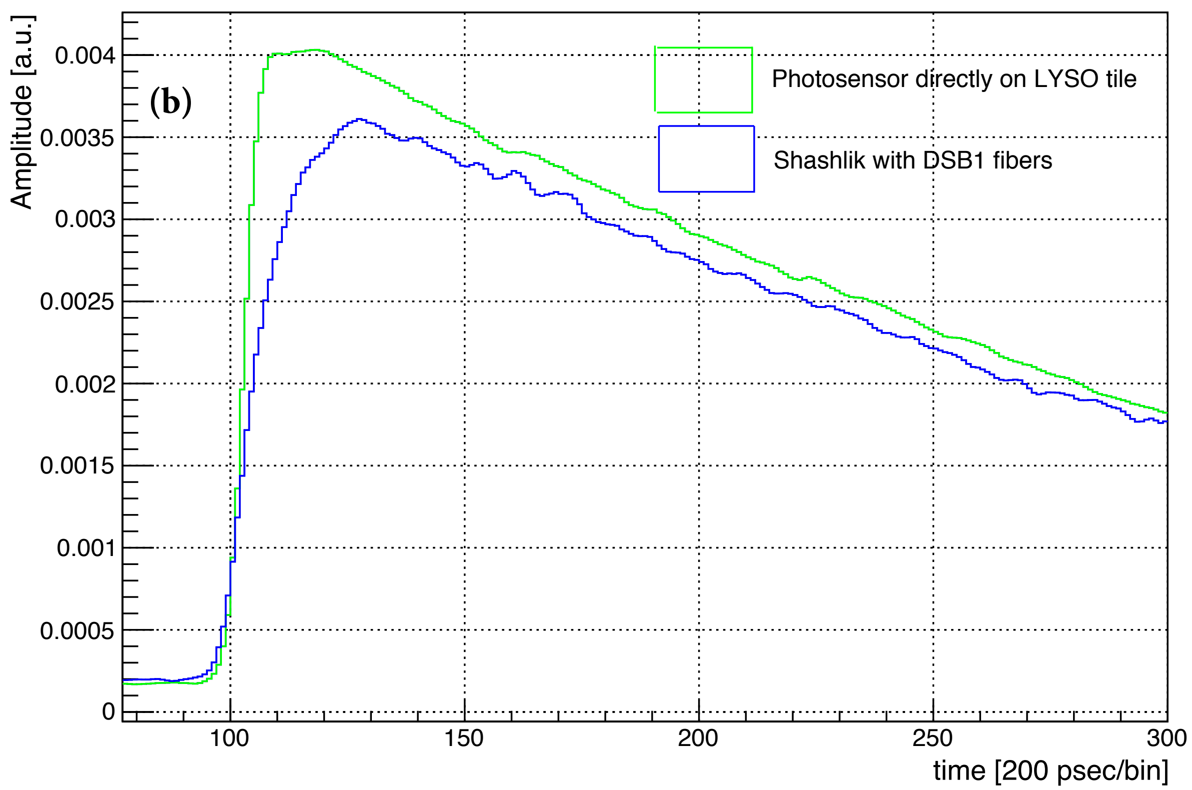




RESULTS

normalized pulse shapes;

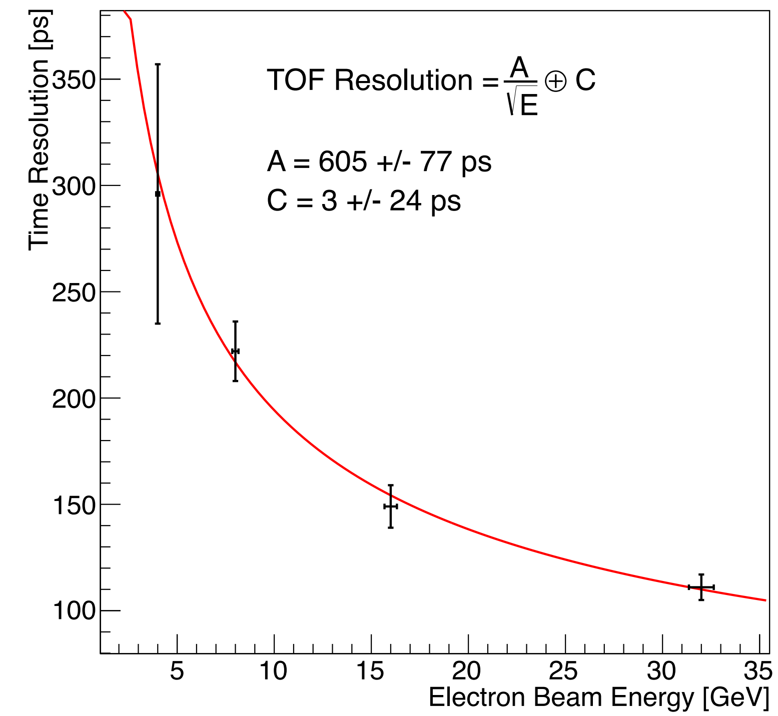
rise time differences



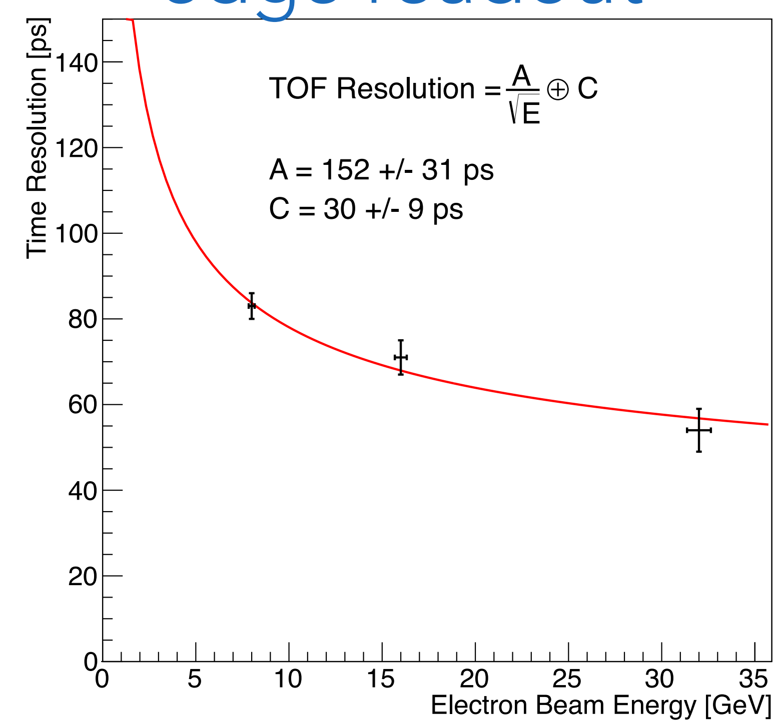
Faster rise time improves time resolution

~60 ps time resolution (32 GeV)

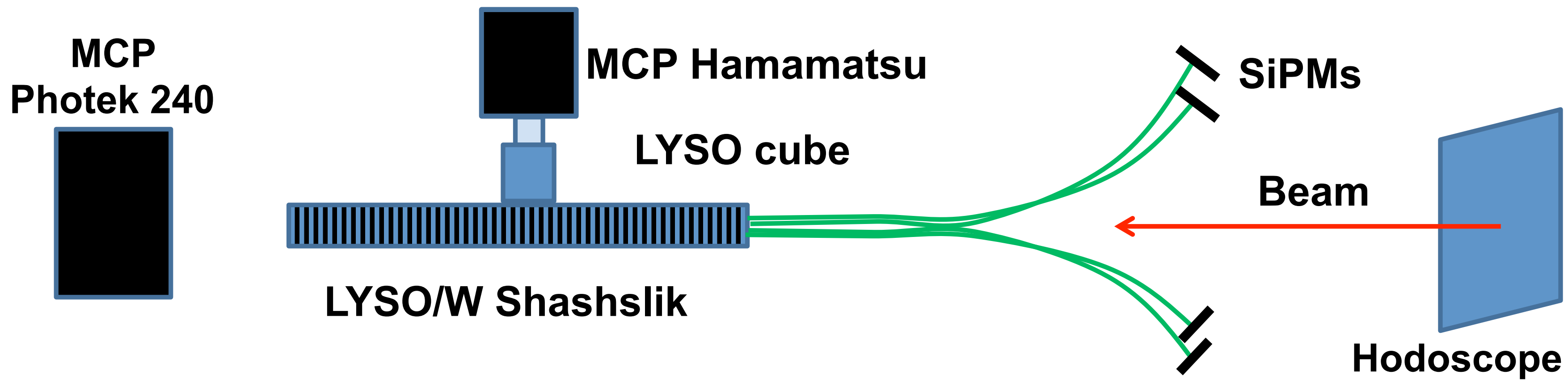
DSB1 readout

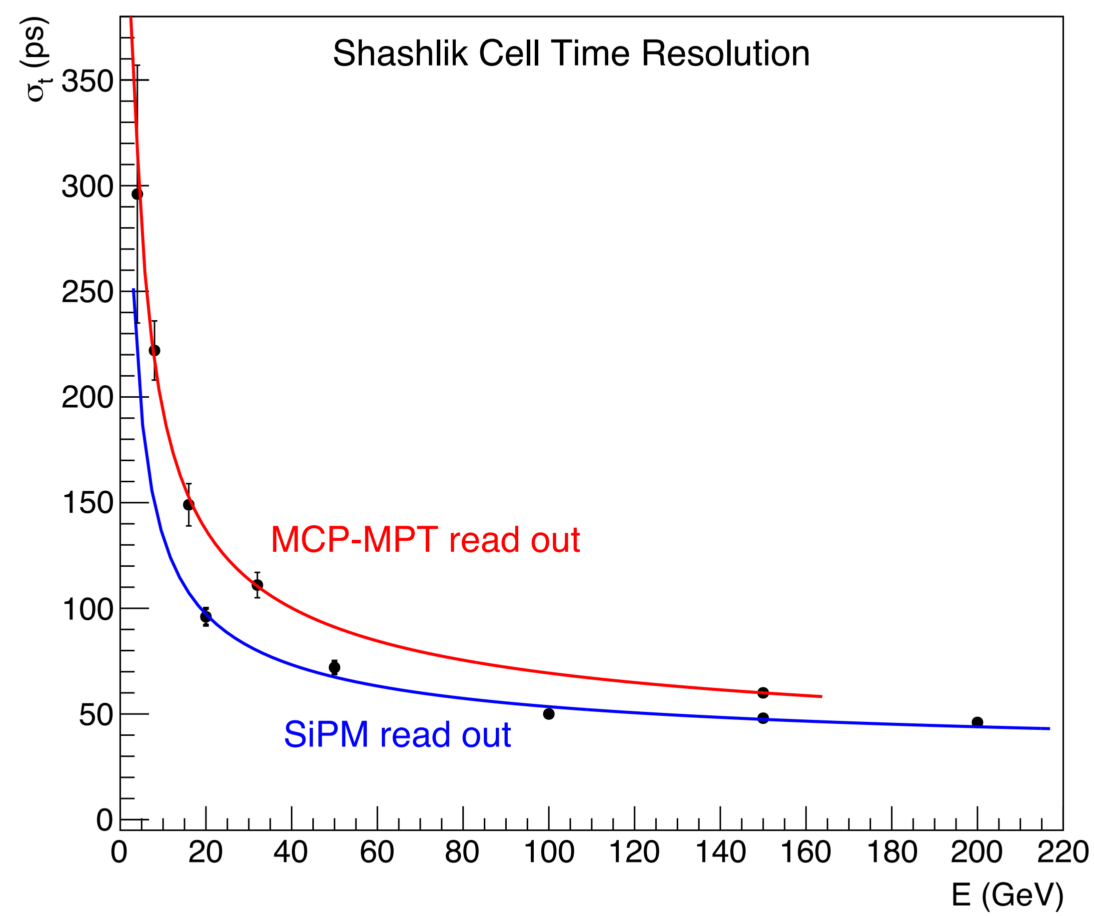


edge readout



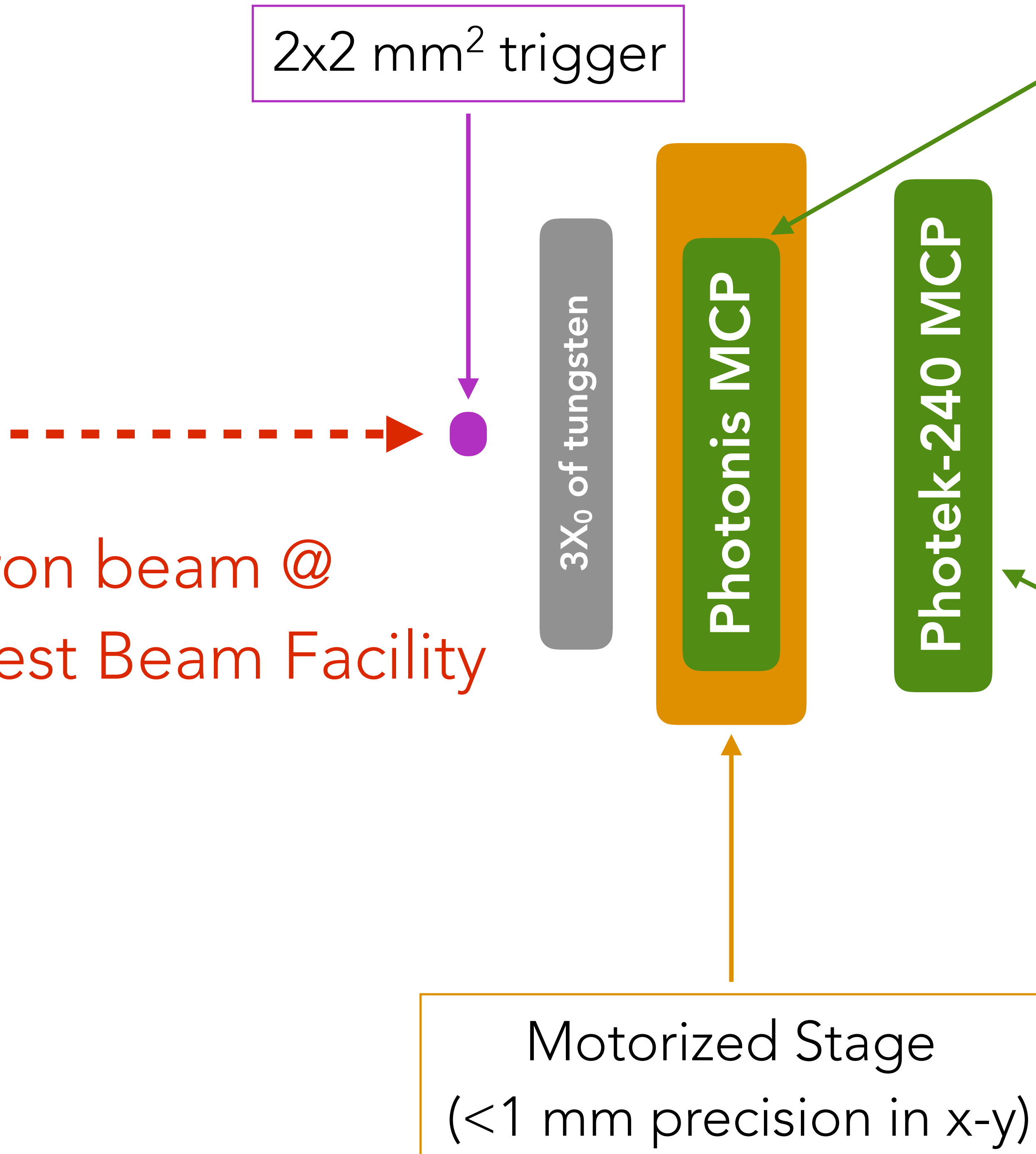
RESULTS; SiPM READOUT



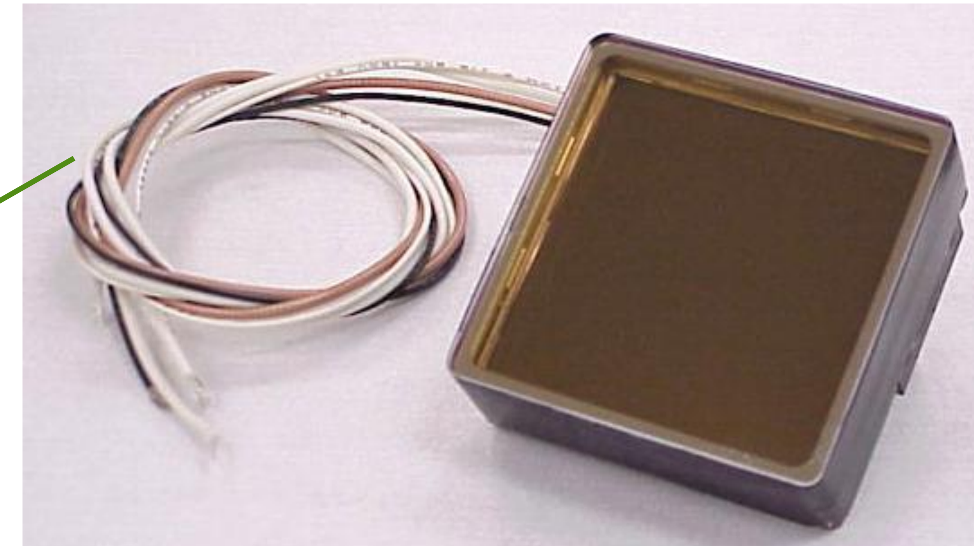


SiPM readout reaches 50 ps time resolution; very competitive option

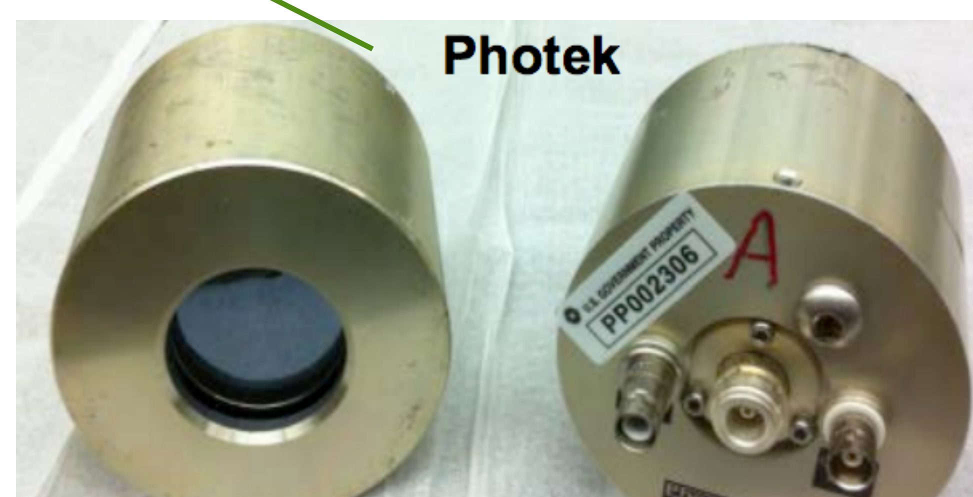
MCP DETECTORS



Electron beam @
Fermilab Test Beam Facility



25 µm pore size; 5.3x5.3 cm² active area;
64 pixels (8x8), 6.5 mm pitch per pixel;
rise time ~0.6 ns, pulse width ~1.8 ns.

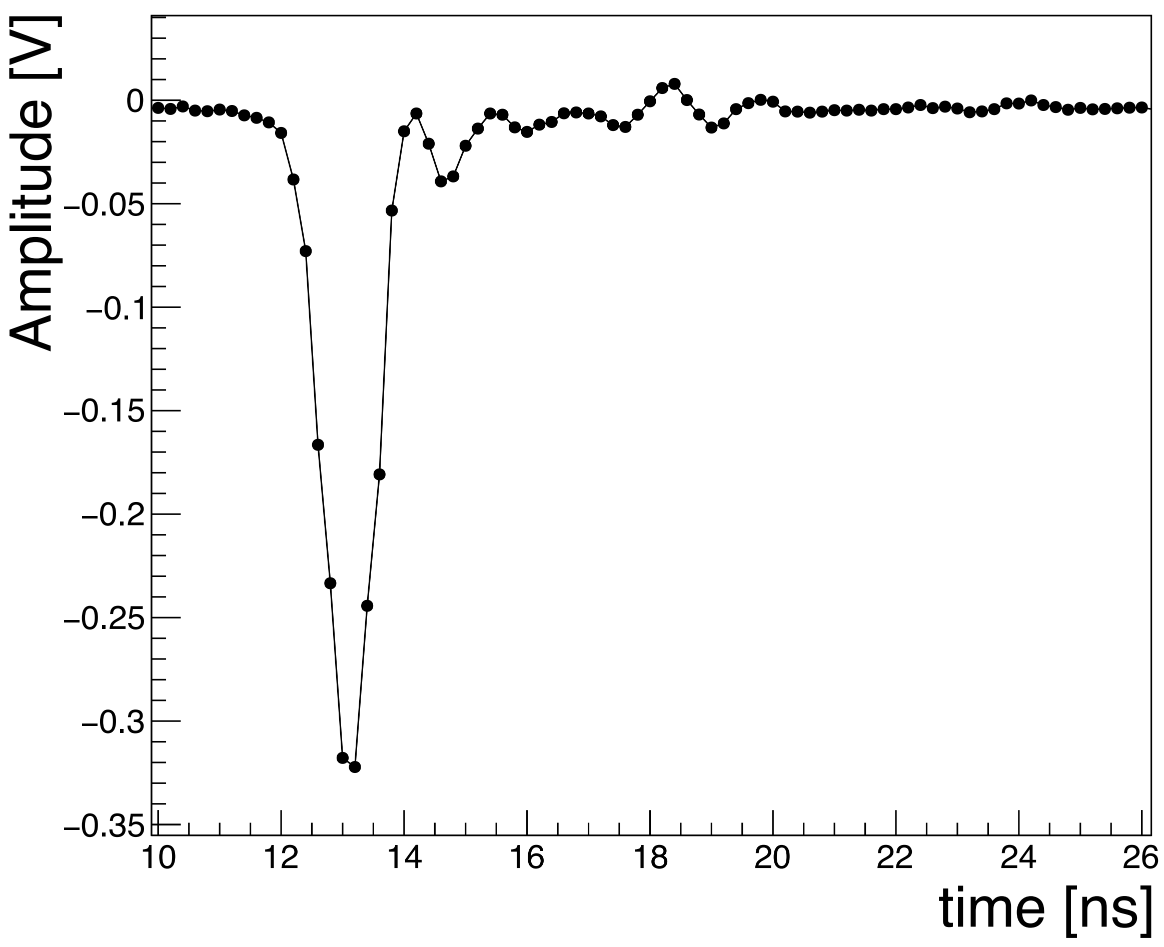


10 µm pore size, 41mm aperture, PC-MCP
distance ~5mm, rise time~60 ps, SPTR~40 ps

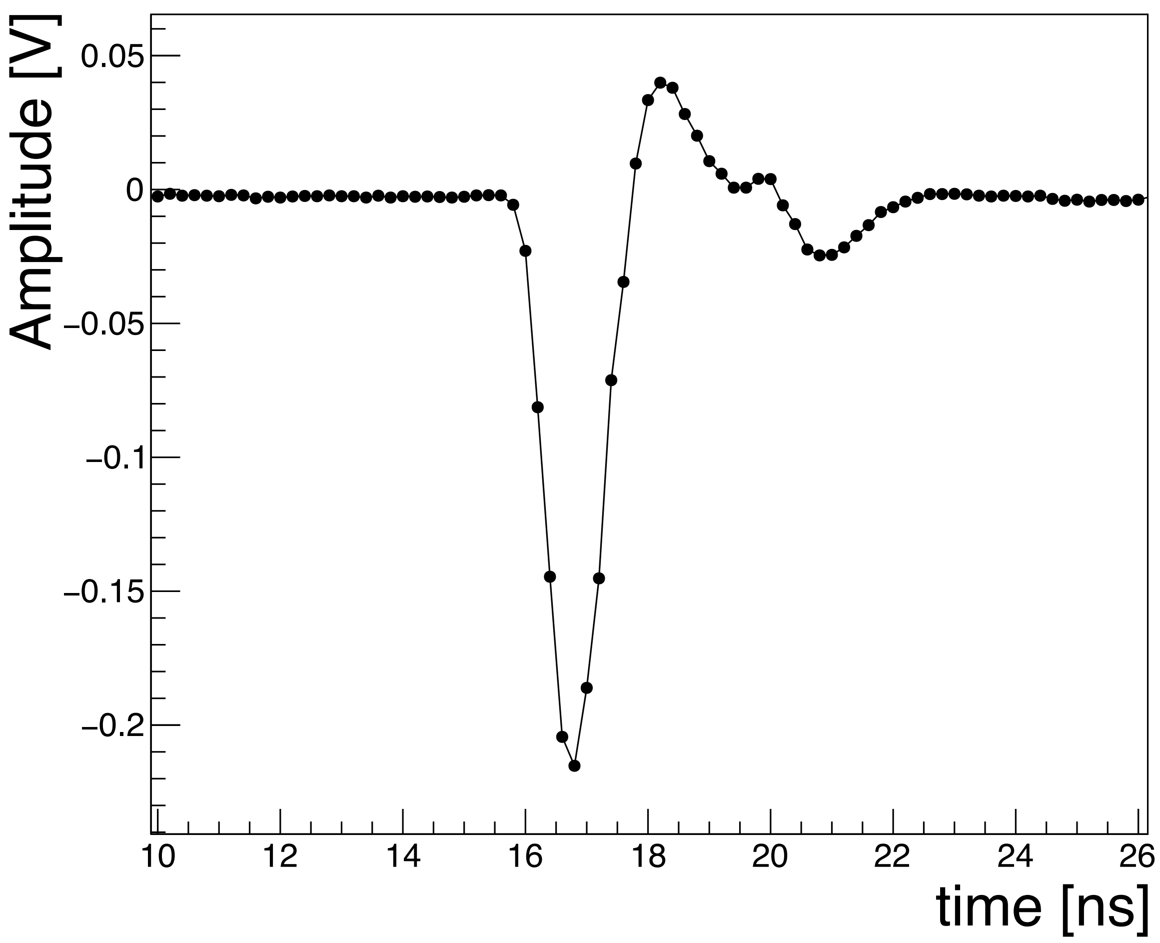
NIM. A 828 (2016), pp. 1–7

MCP SIGNAL

MCP signal pulses in this setup

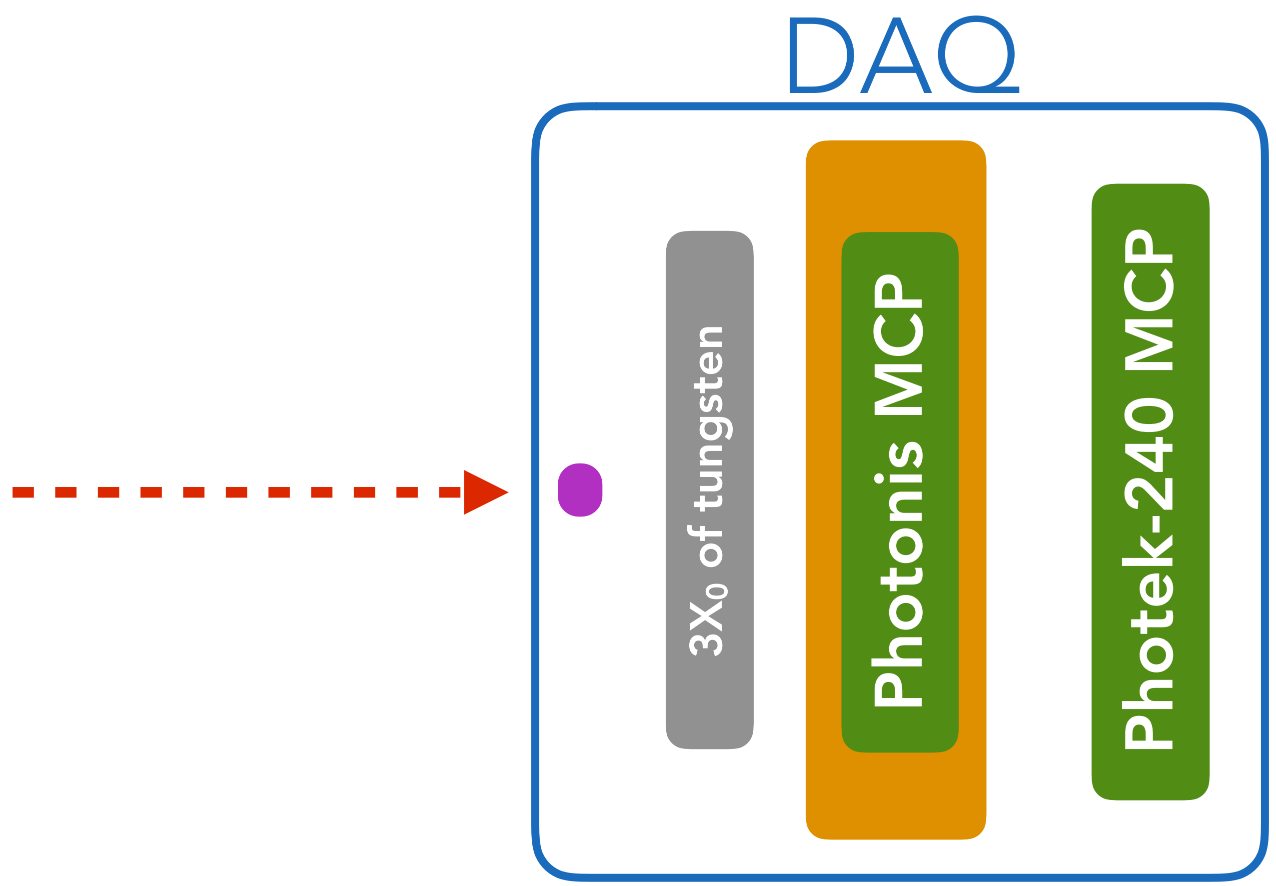


Photonis MCP pixel



Photek-240 MCP

Different sources contribute to the time resolution



relevant source

II: Photonis MCP + Shower

other sources

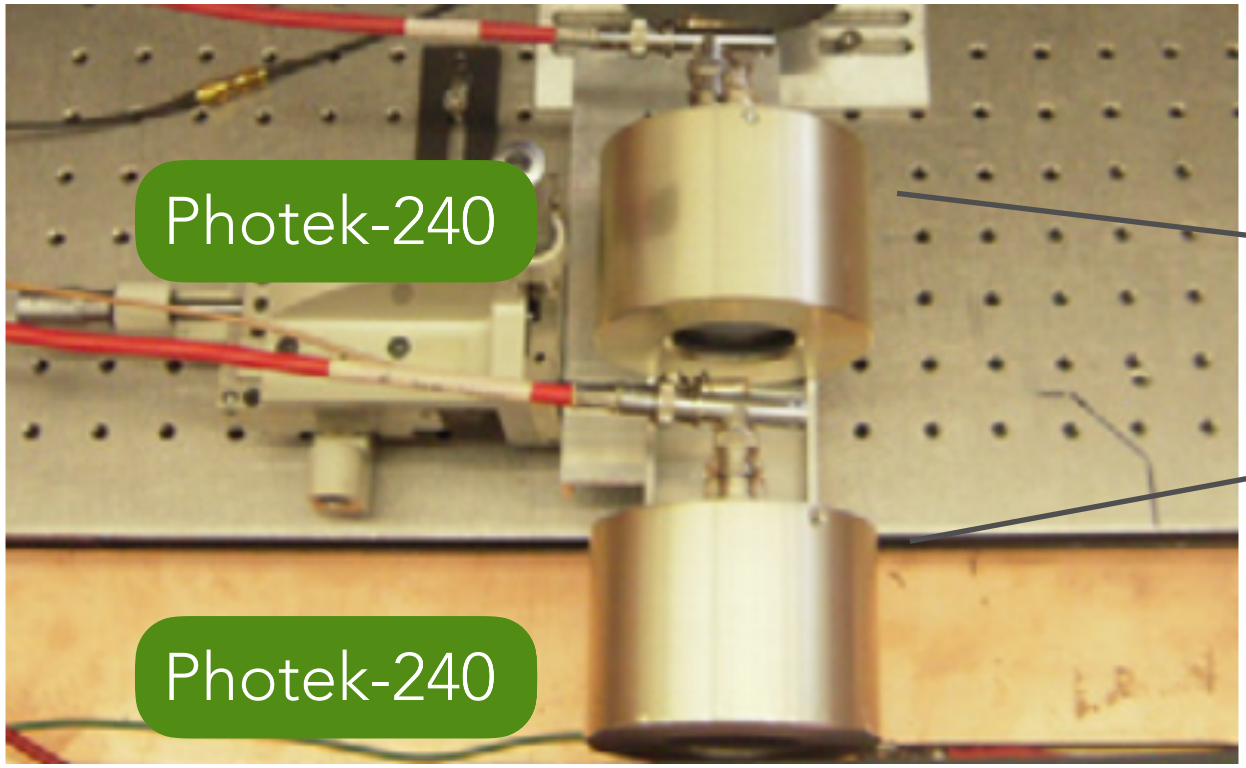
I: shower fluctuations

II: Reference Timer

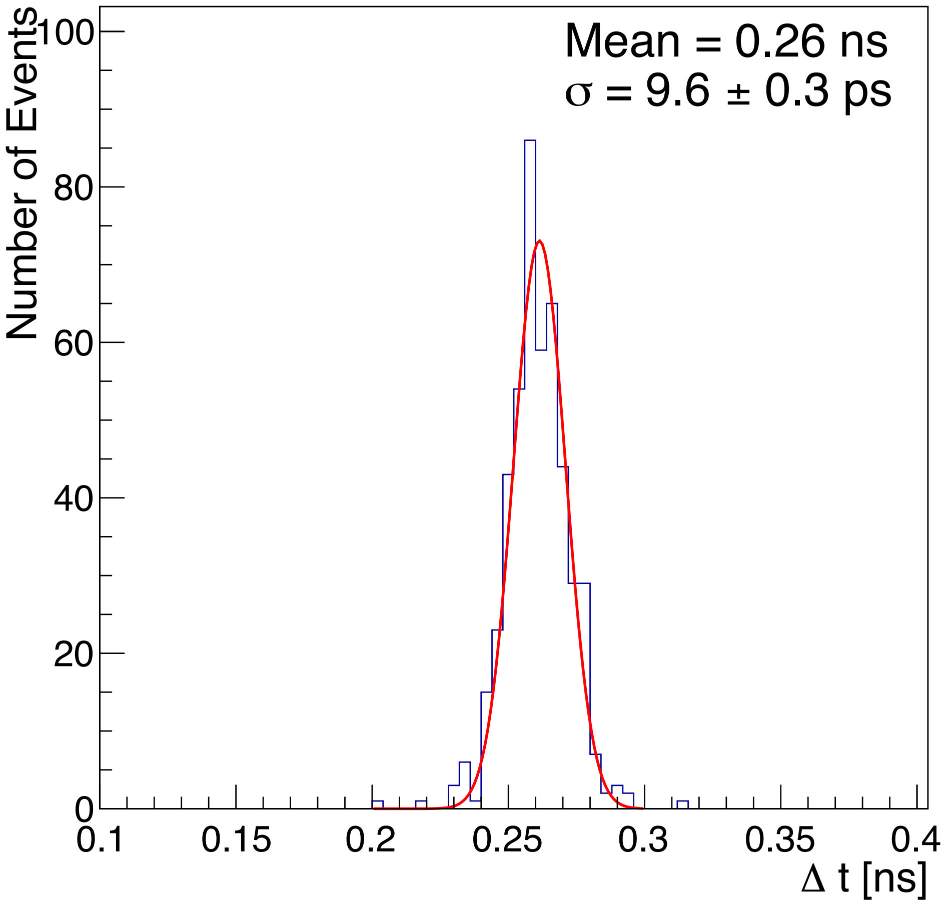
III: Digitization/DAQ

REFERENCE TIMER

- Measure ~10 ps time-of-flight resolution
  - Single device time resolution ~6 ps
- Excellent reference timer for subsequent measurement



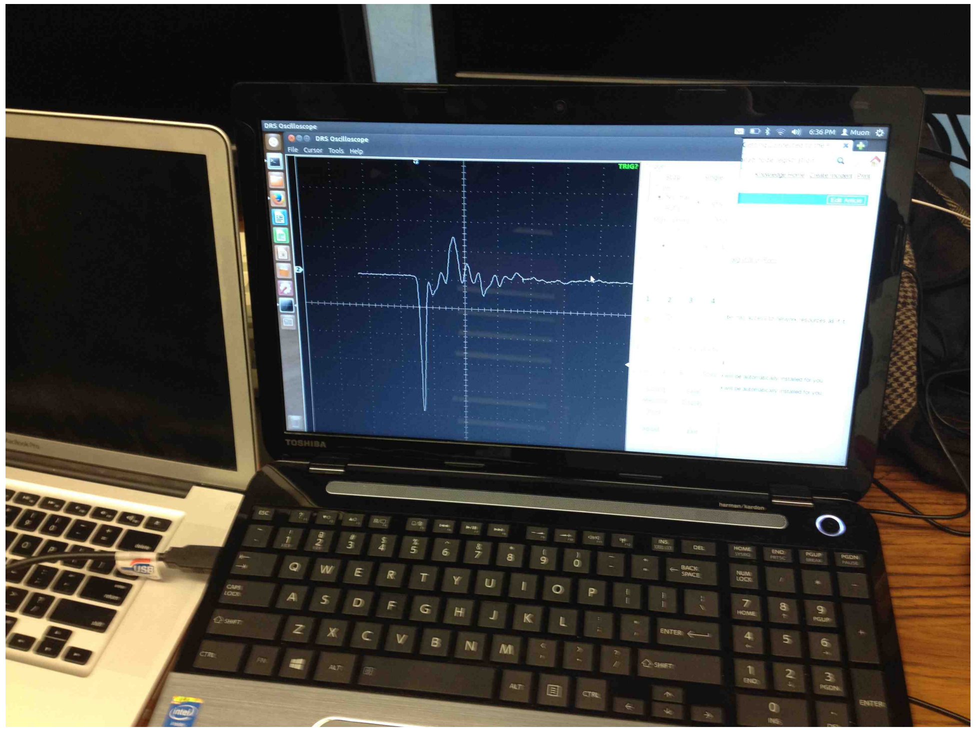
Beam direction
(120 GeV protons)



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 AND DAQ

- Use DRS4 (Domino-Ring-Sampler) Evaluation Board developed by Stefan Ritt at PSI for MEG2 experiment
- 750 MHz of analog bandwidth
- 5 Gsamples/s (i.e. 200 ps per sample)
- Well validated software and scope applications
- Measured electronic time resolution to be about 5 ps

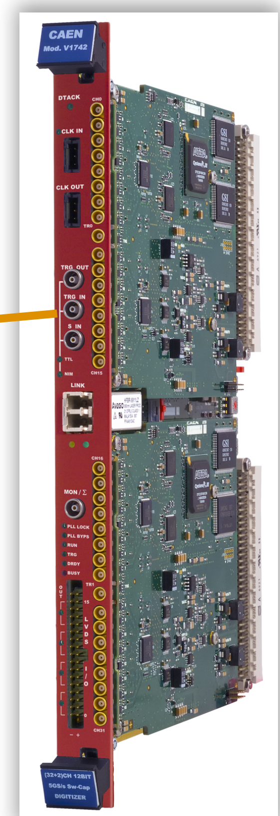


scope application

DRS4 Units

DIGITIZATION AND DAQ

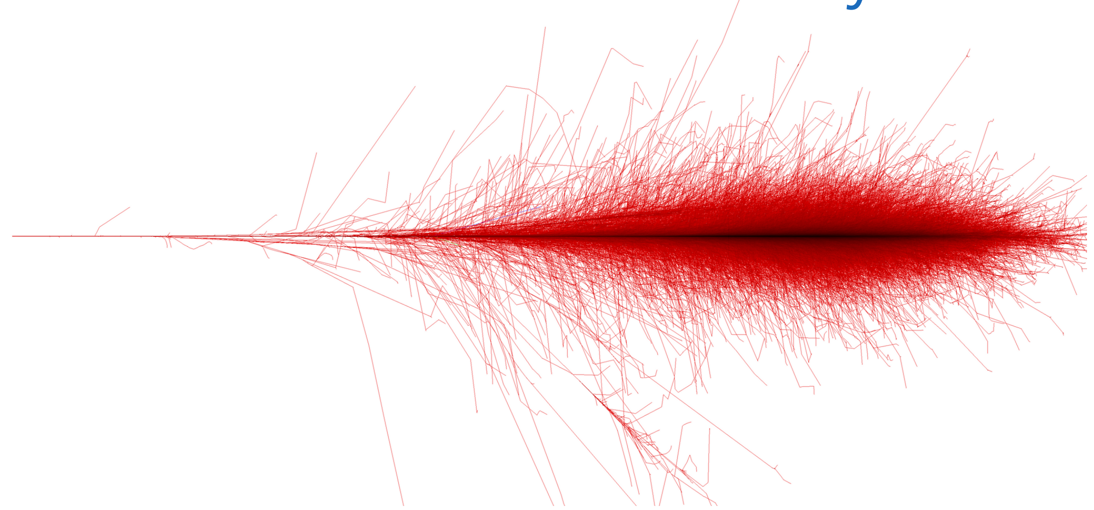
- Use DRS4 (Domino-Ring-Sampler) Evaluation Board developed by Stefan Ritt at PSI for MEG2 experiment
- 750 MHz of analog bandwidth
- 5 Gsamples/s (i.e. 200 ps per sample)
- Well validated software and scope applications
- Measured electronic time resolution to be about 5 ps

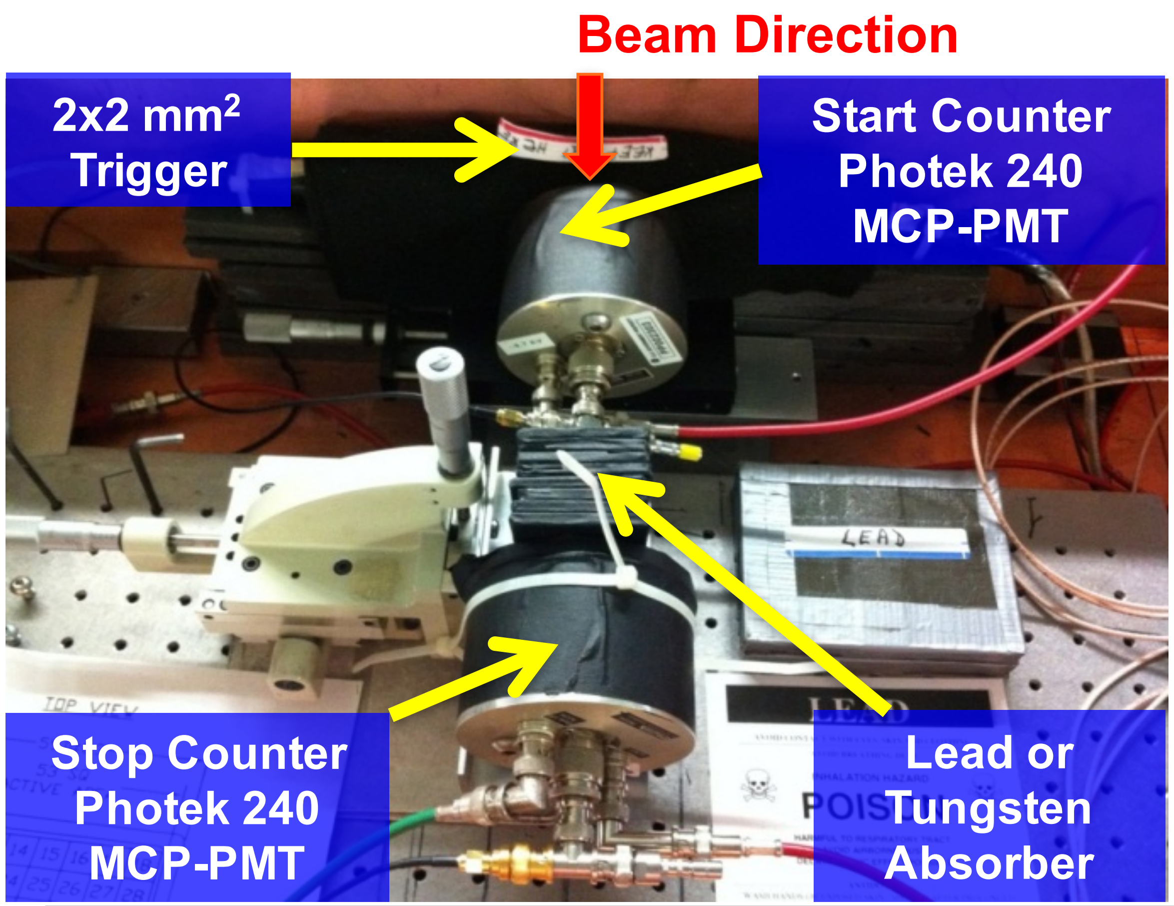


Also available as a crate module: 32+4 channels

SHOWER FLUCTUATIONS

- Shower fluctuation may result in time jitter on the signal pulses
- Quantification of this contribution is key



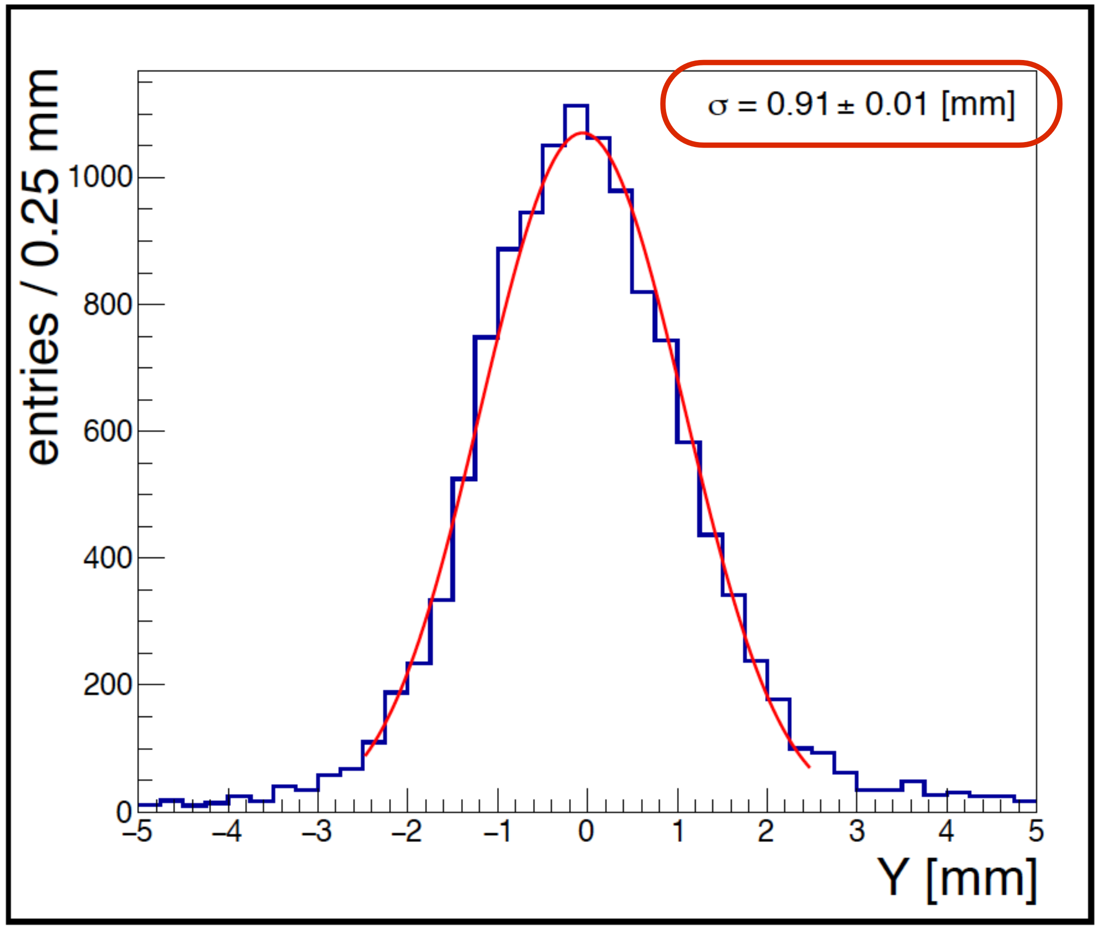


- Measure time jitter for a prototype sampling calorimeter with precision time capability
- Use Photek-240 as reference
- Use Photek-240 to detect shower secondaries

SHOWER POSITION RESOLUTION

- Model the shower position as the convolution of the beam profile with a Gaussian (resolution)
- We fit the data to extract the resolution (width of the Gaussian)

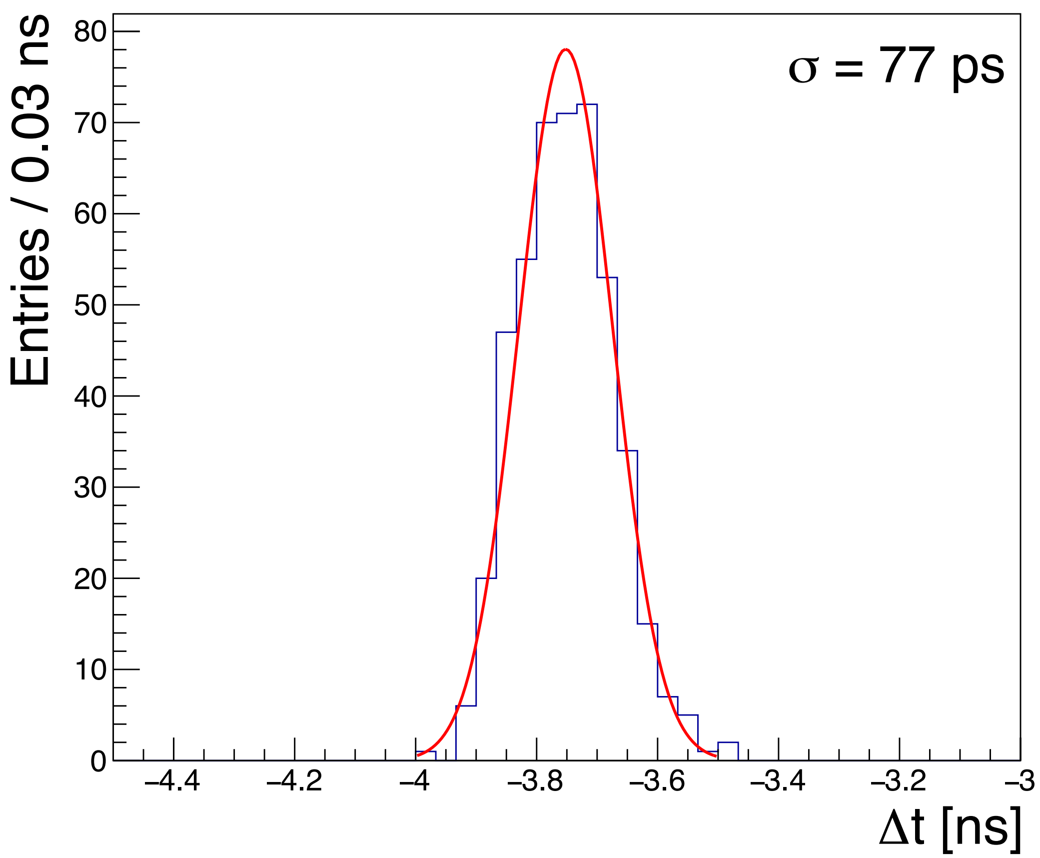
  - Obtain a position resolution of ~1 mm
  - Recall that each pixels is 5.9 mm in size



NIM. A 828 (2016), pp. 1–7

Look at individual and combined time resolution

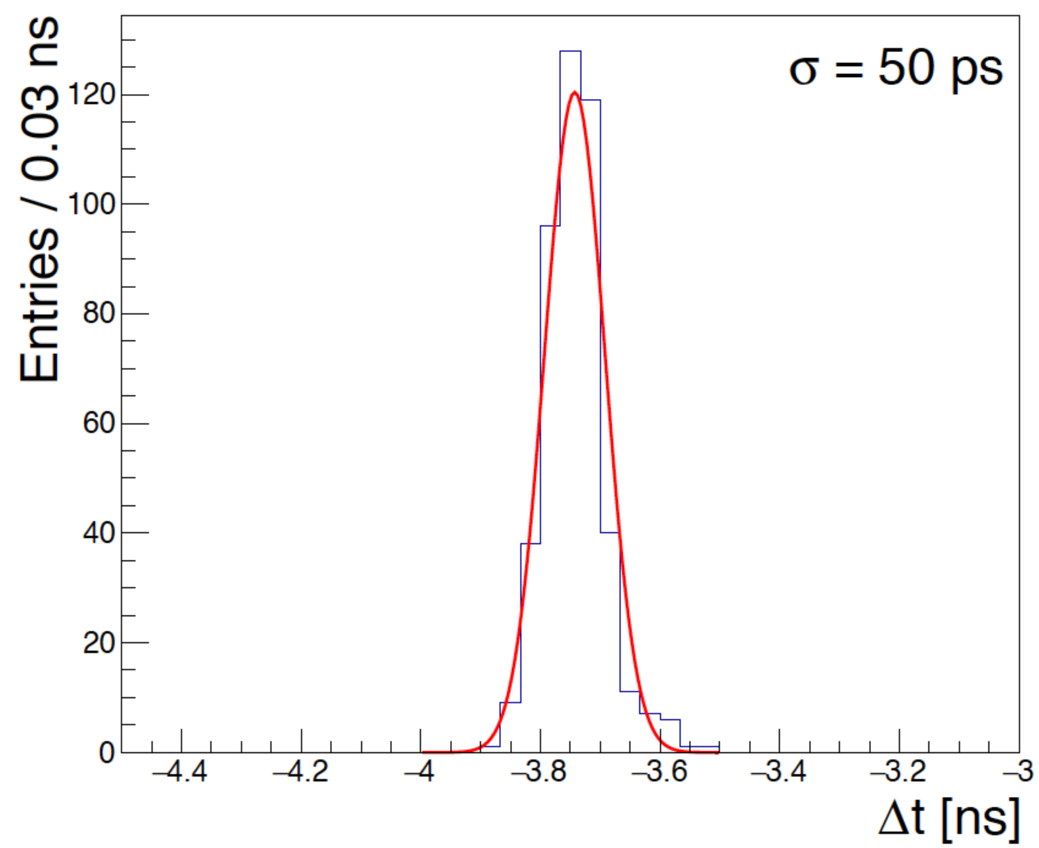
single pixel time resolution



combine all pixels

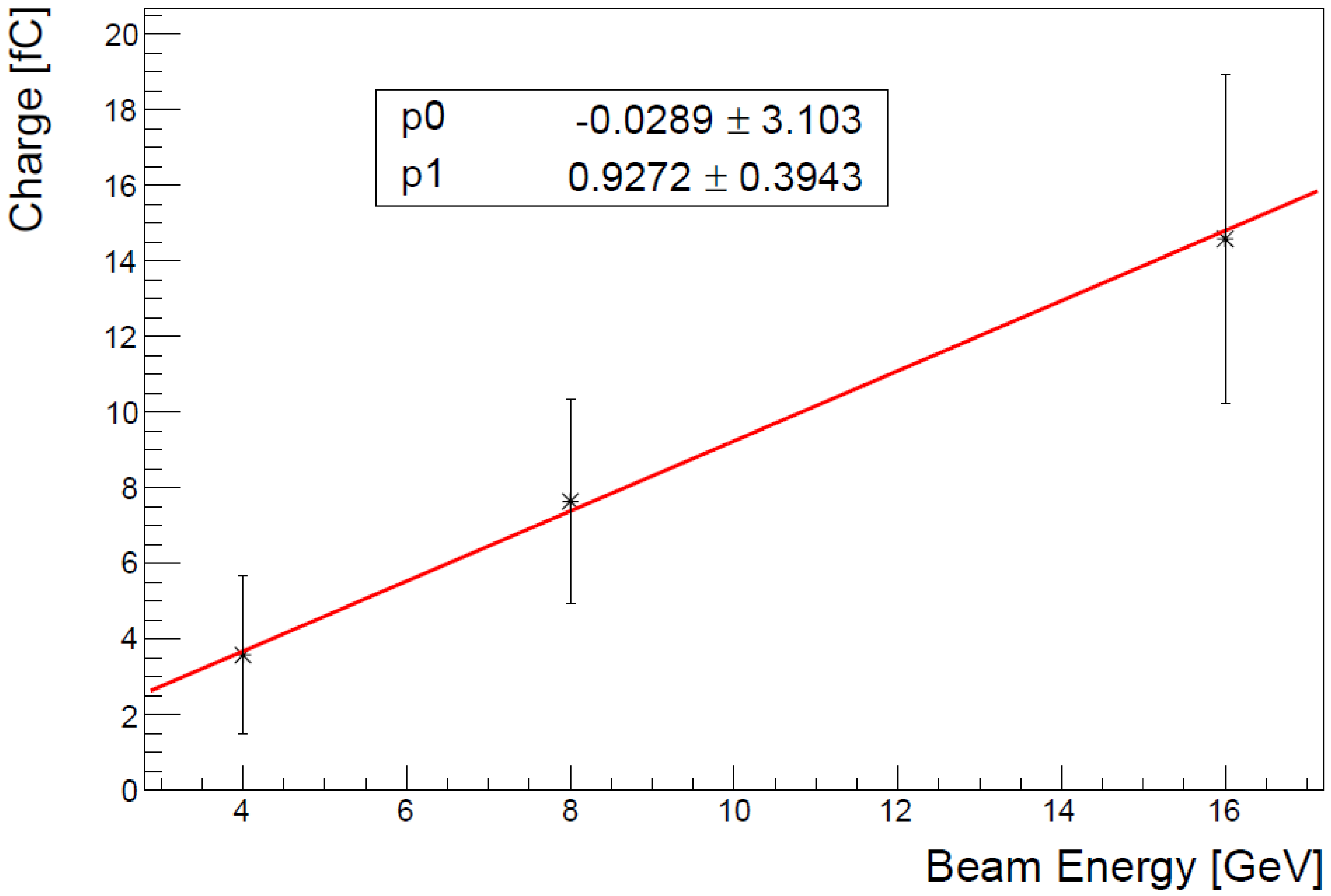
combined time resolution

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



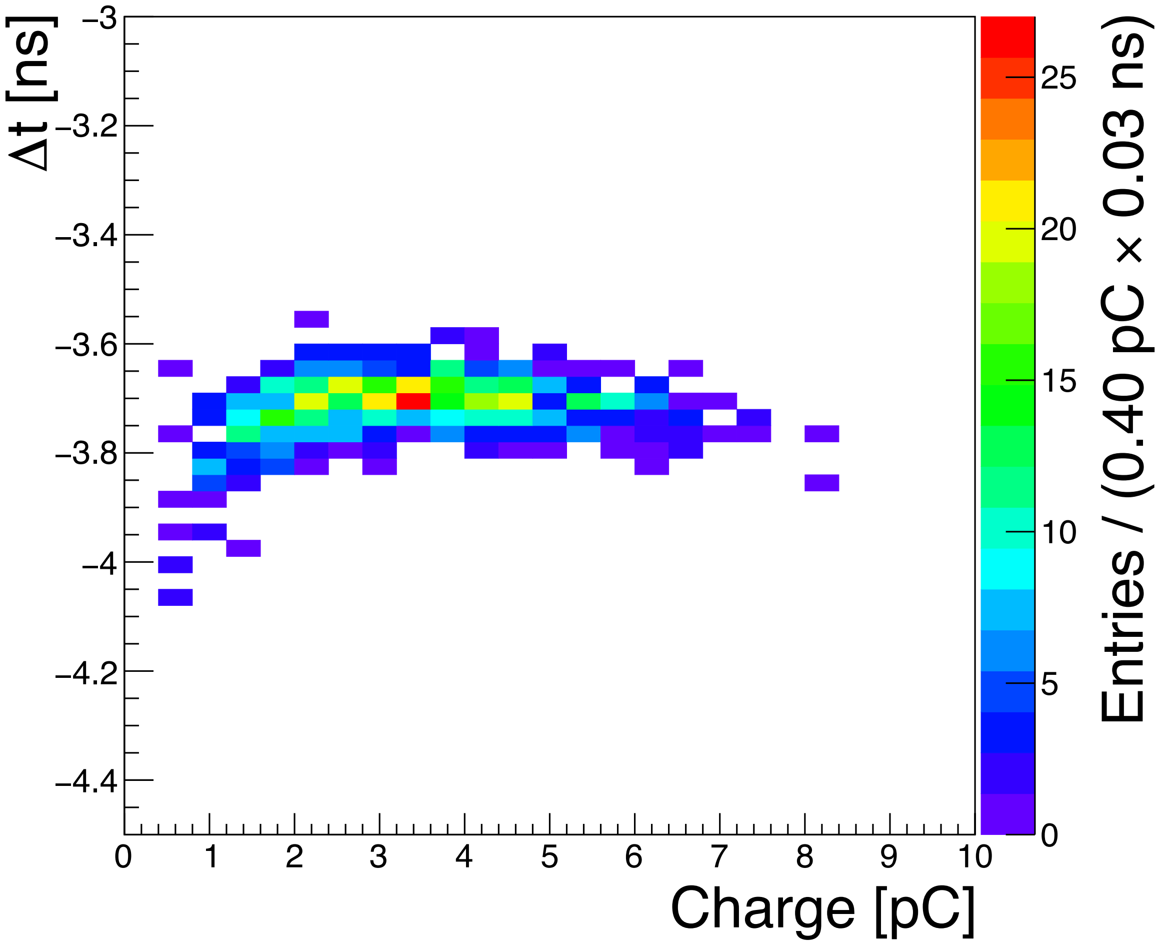
NIM. A 828 (2016), pp. 1–7

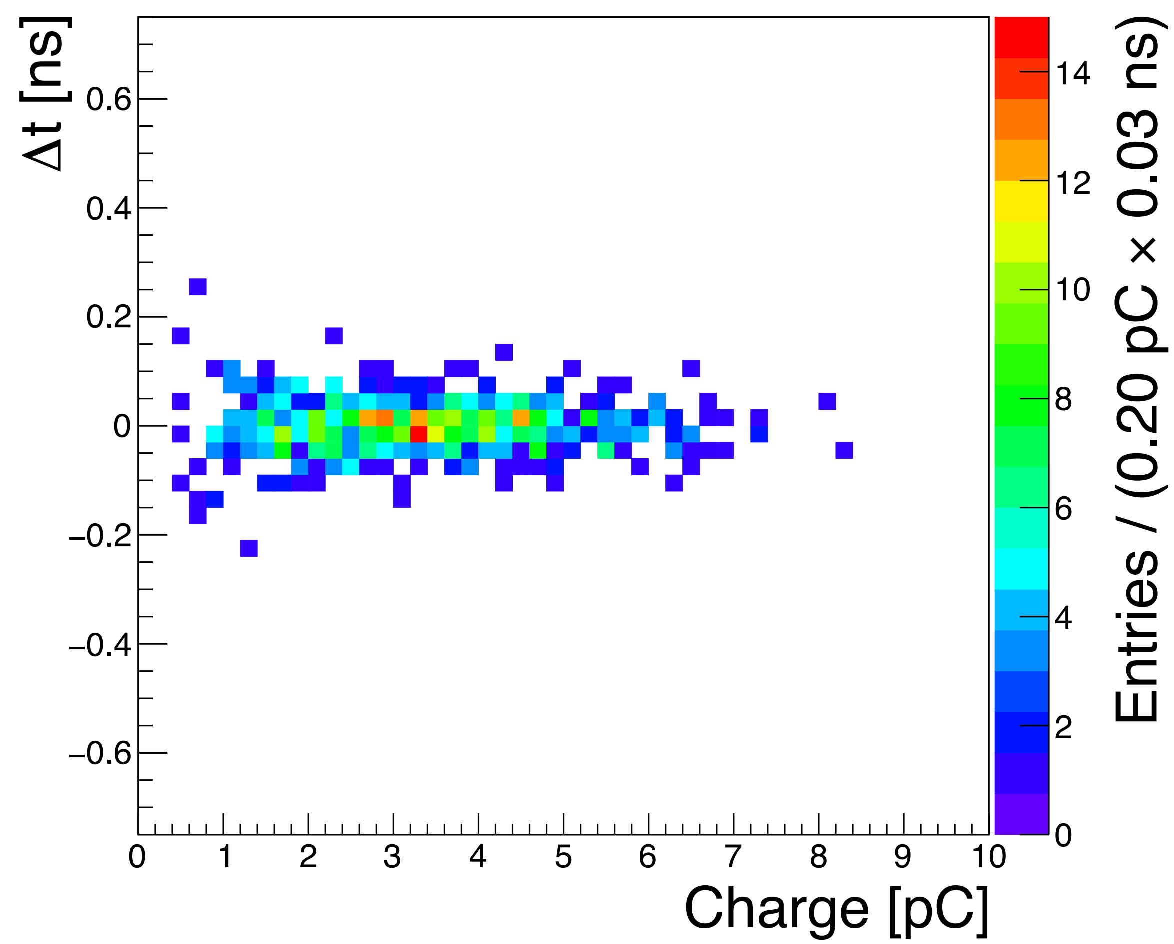
CHARGE VS BEAM ENERGY



CHARGE CORRECTION

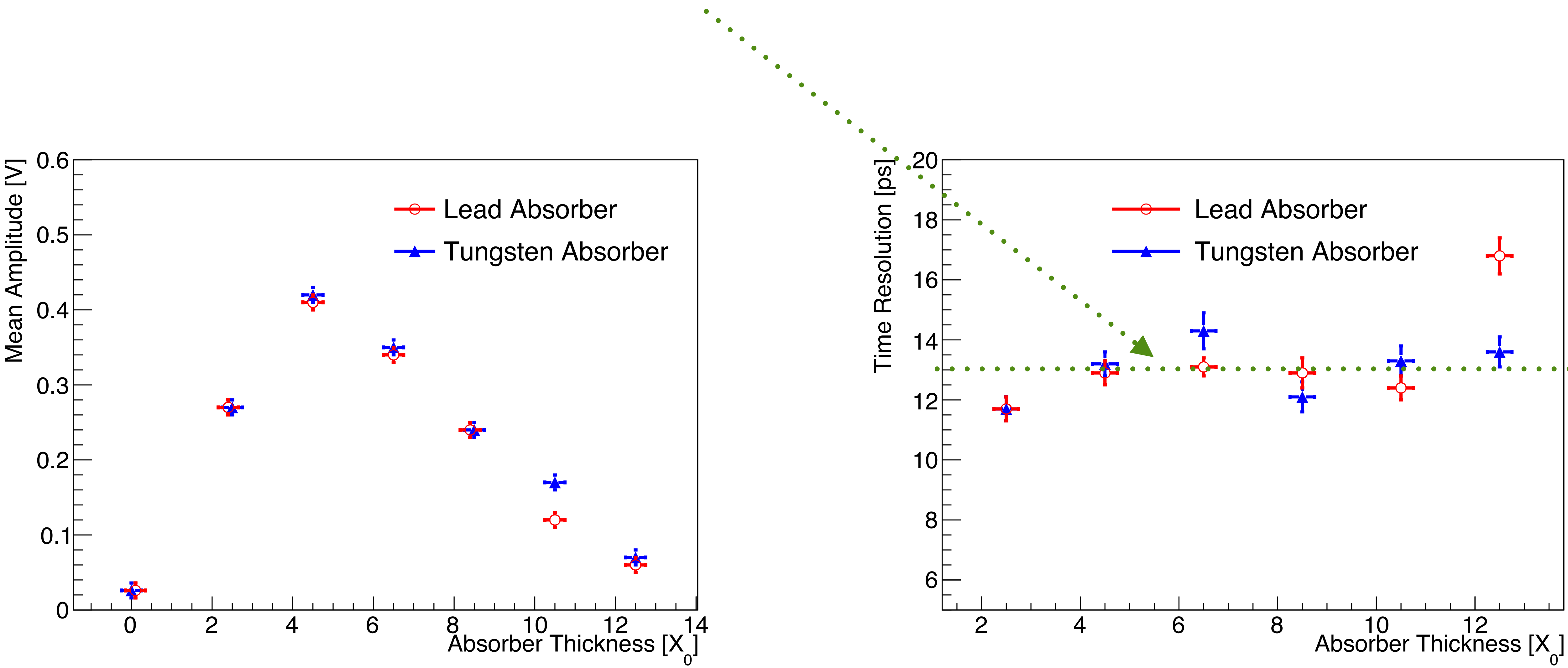
charge correction →



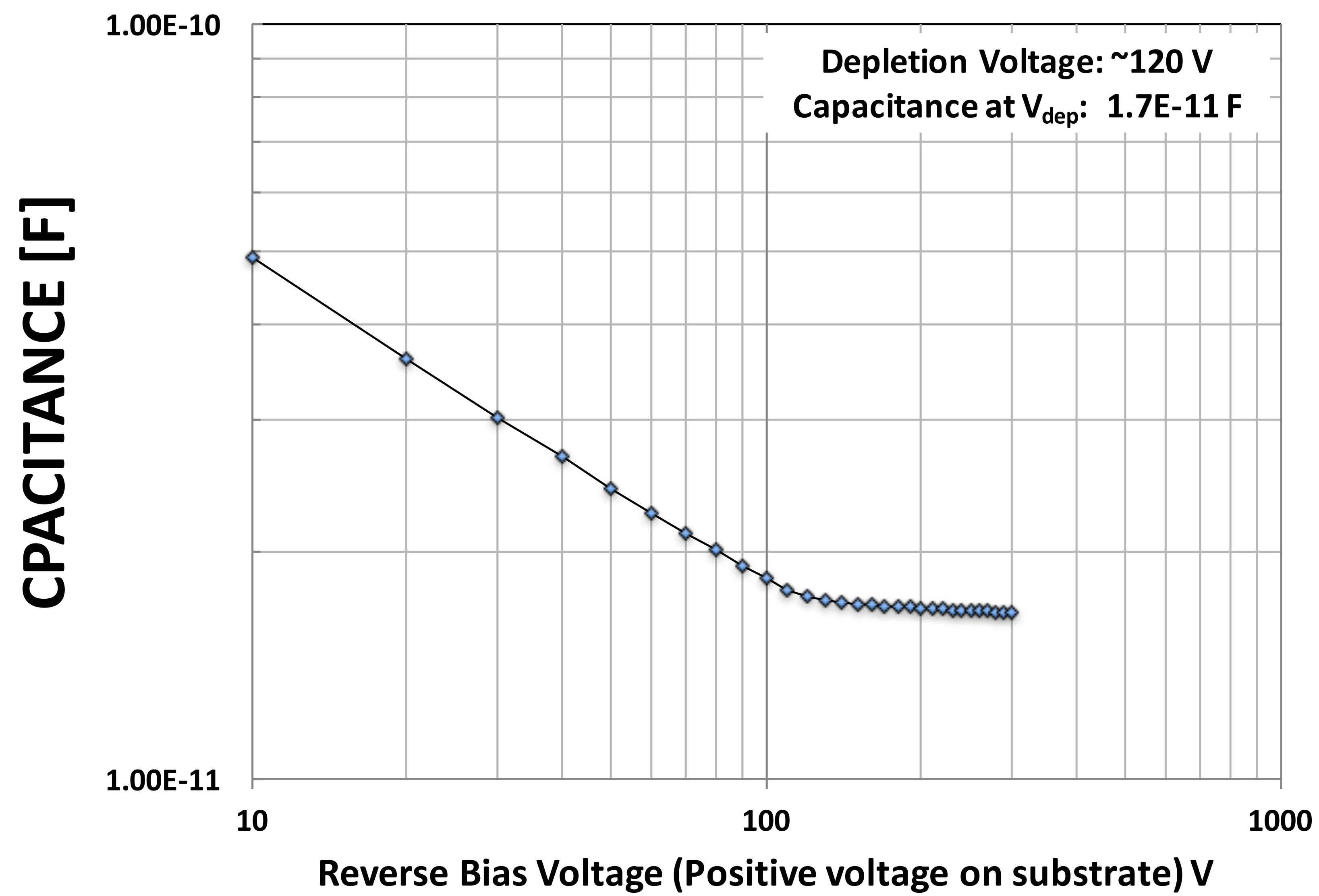


SHOWER FLUCTUATIONS

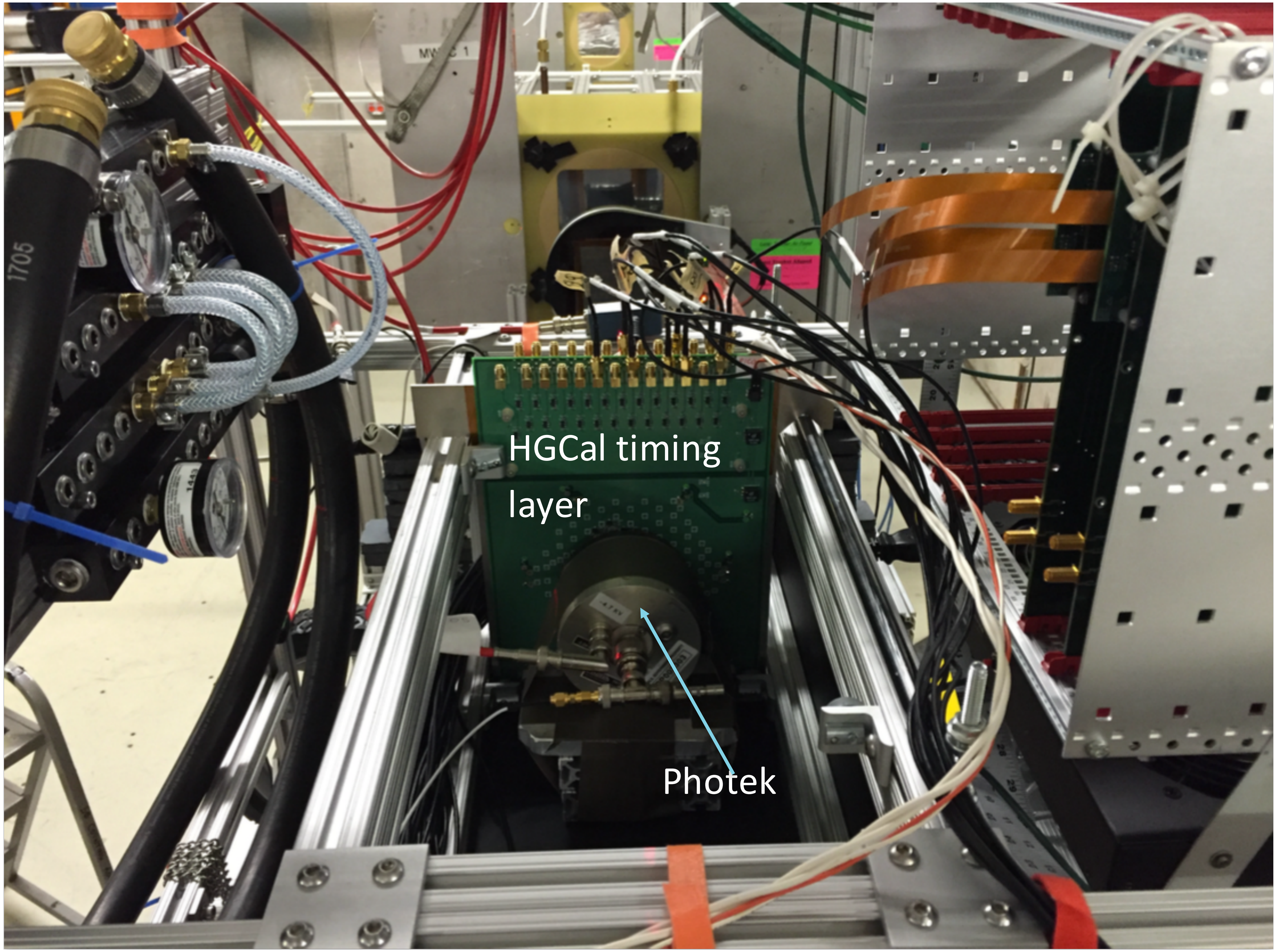
- We measured the time resolution throughout the shower at ~13 ps
- Suggest that shower fluctuations contribute less than 10 ps to the time jitter — taking into account the detector jitter.



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*


Depletion Voltage: ~120 V
Capacitance at V_{dep}: 1.7E-11 F
1.00E-10
1.00E-11
CPACITANCE [F]
10
100
1000
Reverse Bias Voltage (Positive voltage on substrate) V

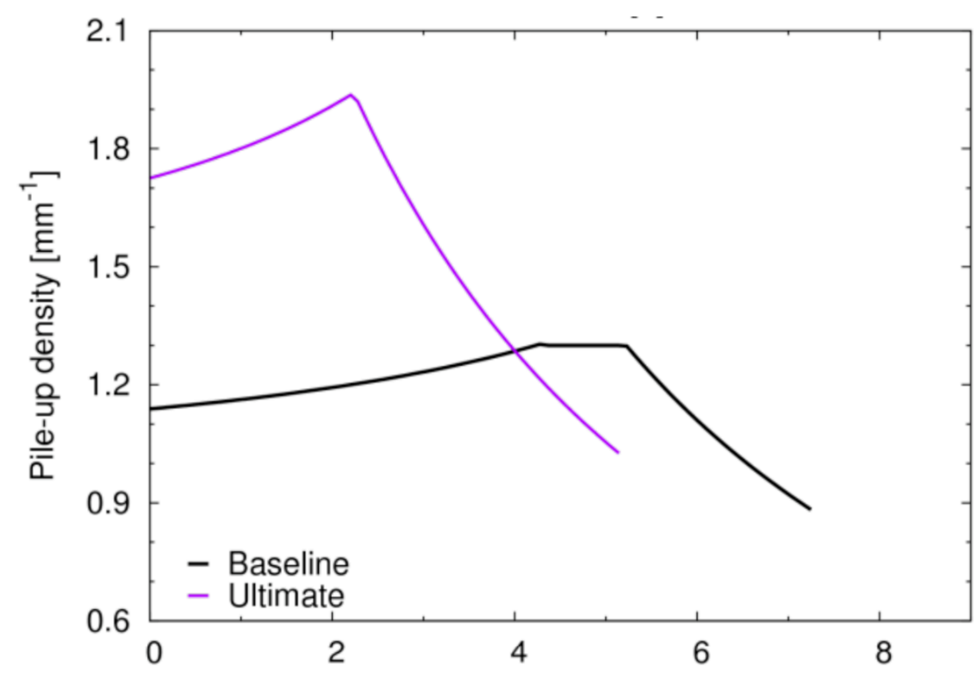
HGC TIMING TEST BEAM



HL-LHC Luminosity scenarios

- Leveling luminosity:
  - 5.3×10^{34} $cm^{-2}s^{-1}$ and 140 pileup (**Baseline**)
  - 7.6×10^{34} $cm^{-2}s^{-1}$ and 200 pileup (**Ultimate**)
- Collect 3 to 4 ab^{-1} of pp data at 14 TeV

Scenario	Max. PU [events/xing]	Max. PU density [events /xing/mm]	Luminous Region long. r.m.s. size [cm]	$\Delta L_{int}/L_{nom}$ [%]	Additional HW [Y/N]
Nominal	140	1.3	<4.8	0	N
Ultimate	200	1.9	<4.5	+33	N
8b+4e	140	1.3	<5	-25	N
200 MHz	140	1.3	<4.8	-14	Y
Flat	140	1.1	<5.5	0	May be
Crab kissing	140	0.6-0.65	<7	-5	Y



G. Arduini, R. Thomas, ECFA 2016