Fermilab U.S. DEPARTMENT OF ENERGY | Office of Science

Precision timing detectors for the CMS phase 2 upgrade

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SLAC National Accelerator Lab

Introduction

- Physics Goals of HL-LHC program:
  - Accumulate 3,000 fb^{-1} of pp collision data at 14 TeV
  - Precision Higgs measurements, BSM searches at small cross sections, precision measurements of SM decays

- 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 $\eta=2.5$; Neutrons up to 1.9×10^{14} cm^{-2} for $|\eta| \leq 1.5$ (1.1×10^{15} at $\eta=2.5$)

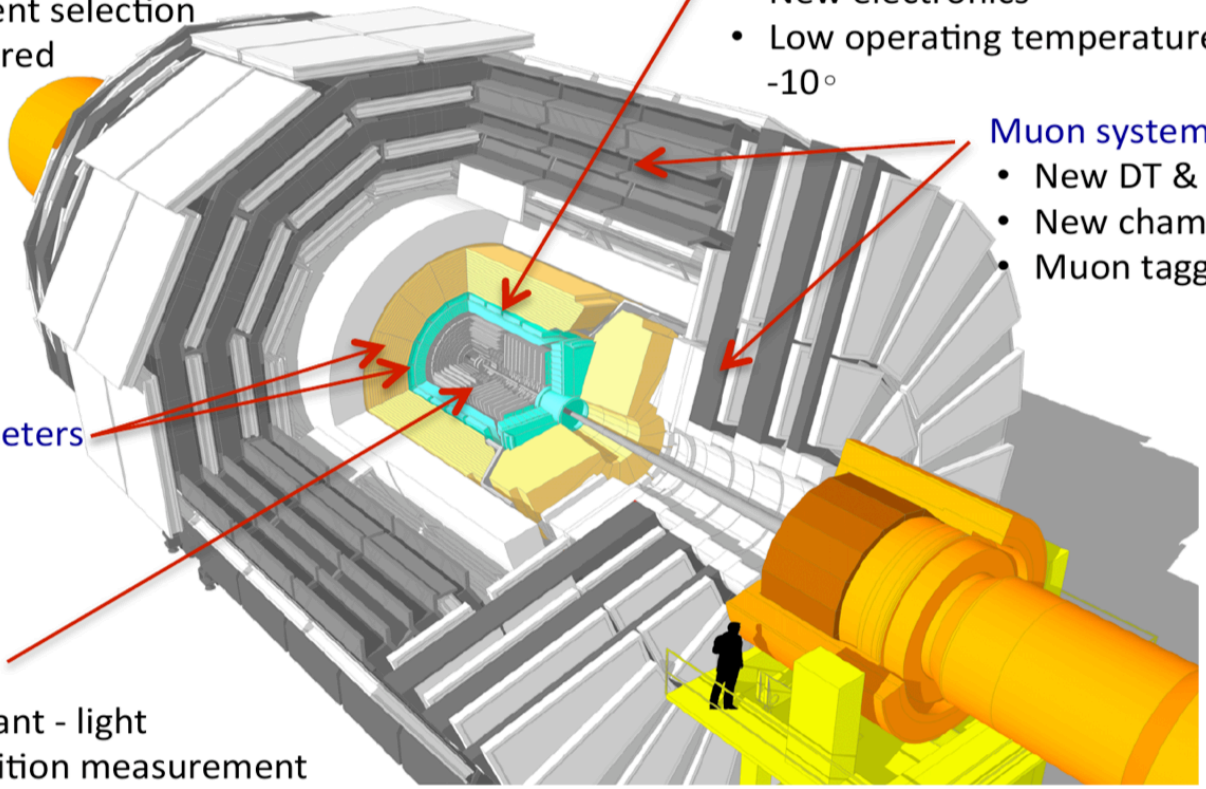
- Major upgrades to CMS to cope with these challenges
  - To reduce the impact of ~200 pileup interactions, upgraded CMS detector will assign a precise time stamp to ALL particles
  - **EM showers**: remove the neutral energy deposits from PU
  - **Charged particles**: remove confusion from overlapping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

CMS Phase 2 Upgrades

Trigger/HLT/DAQ
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered

Barrel EM calorimeter
- New electronics
- Low operating temperature ≃ -10◦

Muon systems
- New DT & CSC electronics
- New chambers $1.6 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$



New Endcap Calorimeters
- Rad. Tolerant
- 5D measurement

New Tracker
- Rad. Tolerant - light
- High Definition measurement
- 40 MHz selective readout for hardware trigger
- Extended Pixel coverage to $\eta \simeq 3.8$

Beam radiation and luminosity
Common systems and infrastructure

J. Butler, LHCP 2017

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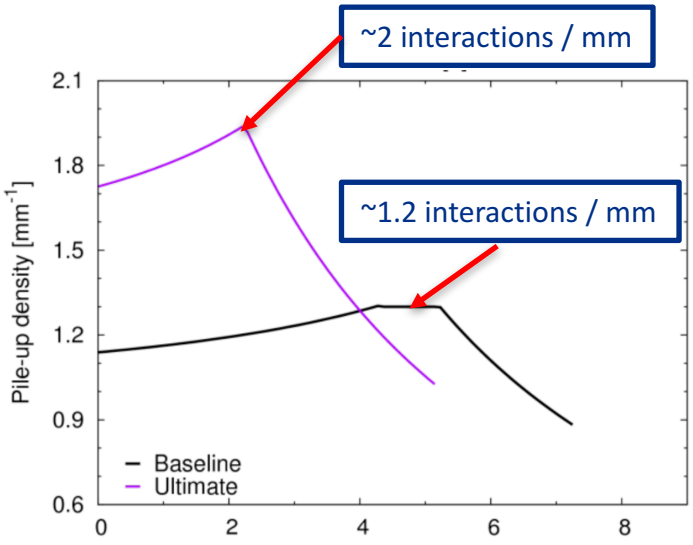
HL-LHC Luminosity scenarios

- 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



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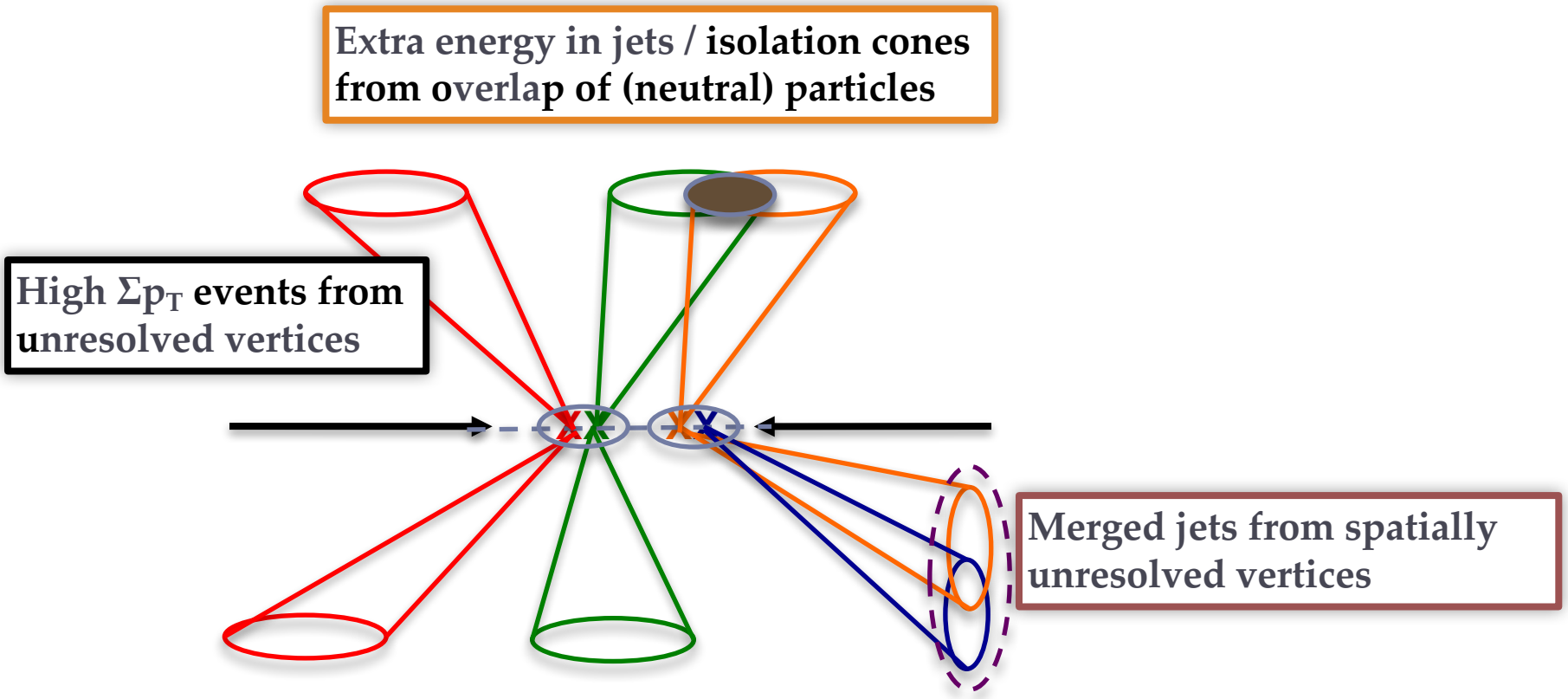
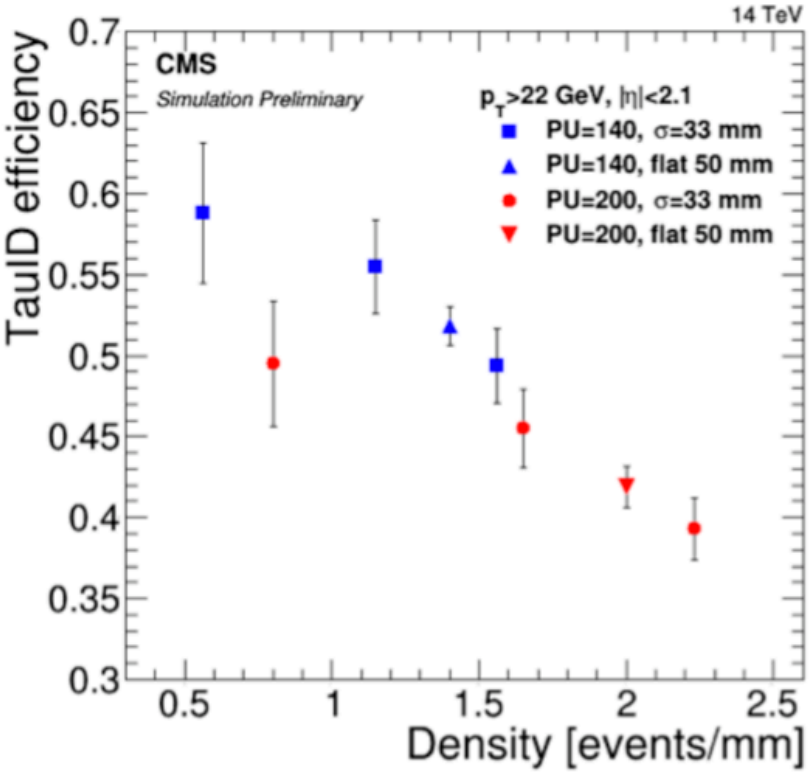
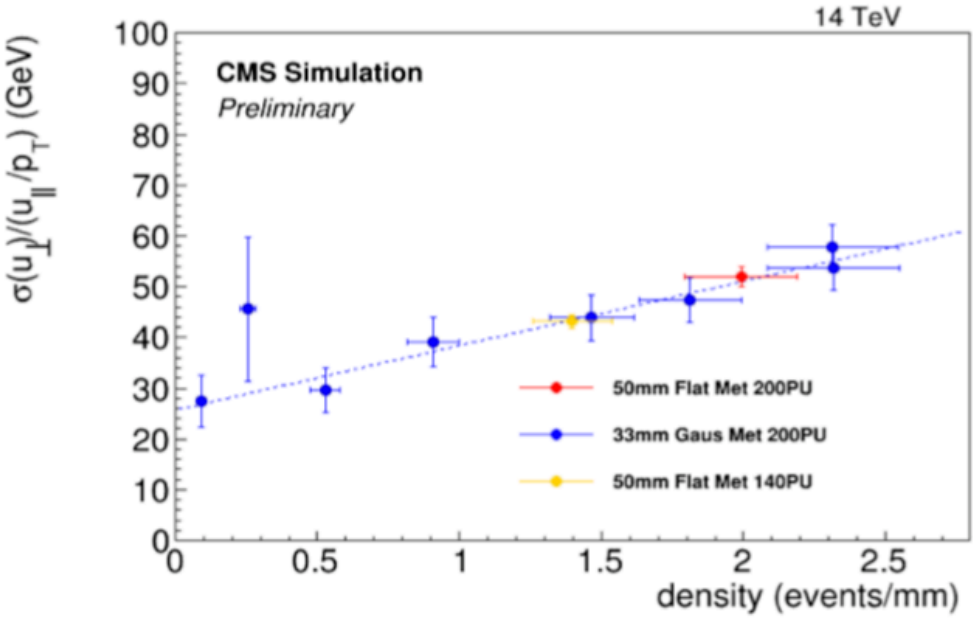
Event reconstruction challenges at HL-LHC

- Very large pileup: 140-200 interactions per crossing
- **Pileup particles contribute 100% energy to a 50 GeV jet**



Event reconstruction challenges at HL-LHC

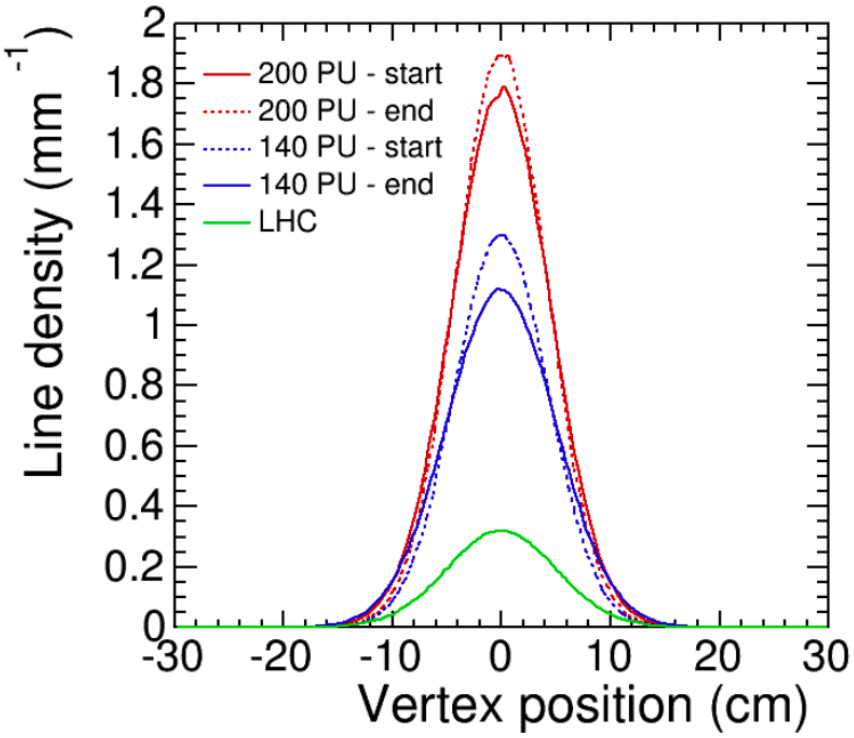


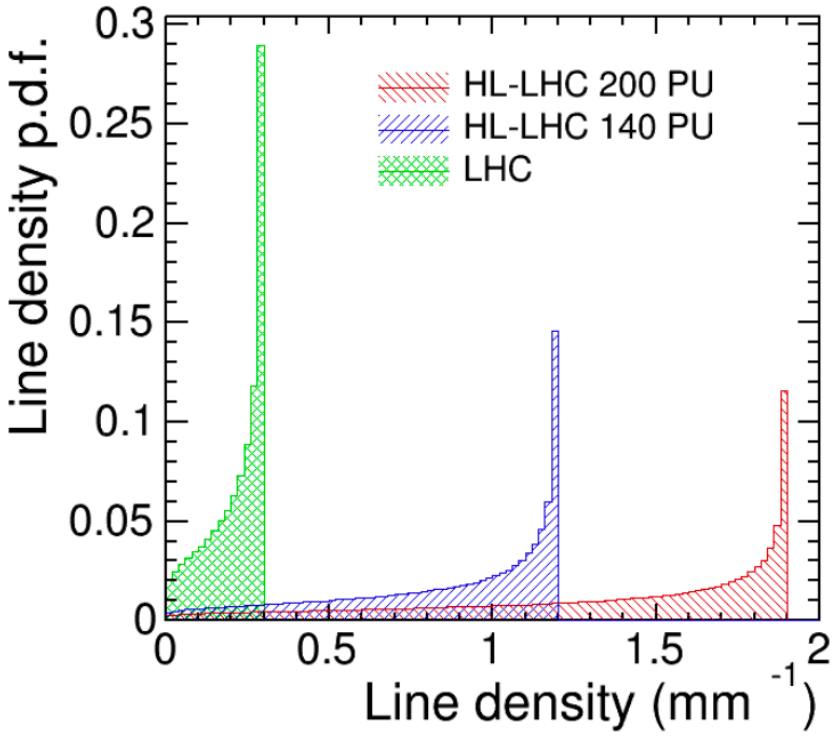


- Significant reduction charged isolation efficiency for leptons
- MET resolution scales with density since charged particles are used to aid in identification of relevant neutrals

HL-LHC beam spread

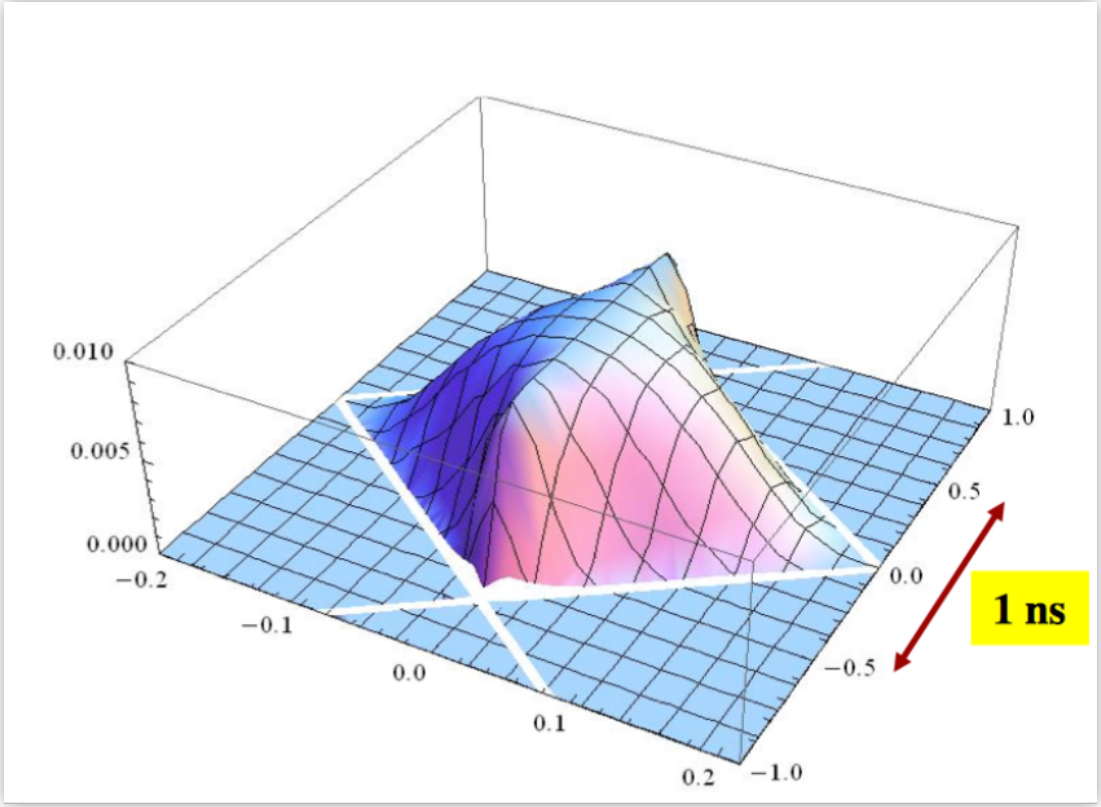
- Total amount of pileup and width of luminous region evolve over the course of a fill
- Linear pileup density varies over the luminous region





HL-LHC beam spread

- Beamspot width in time is several hundred ps (**RMS = 200 ps**)
  - A detector with 20-30 psec timing resolution could meaningfully distinguish between interactions on the basis of timing



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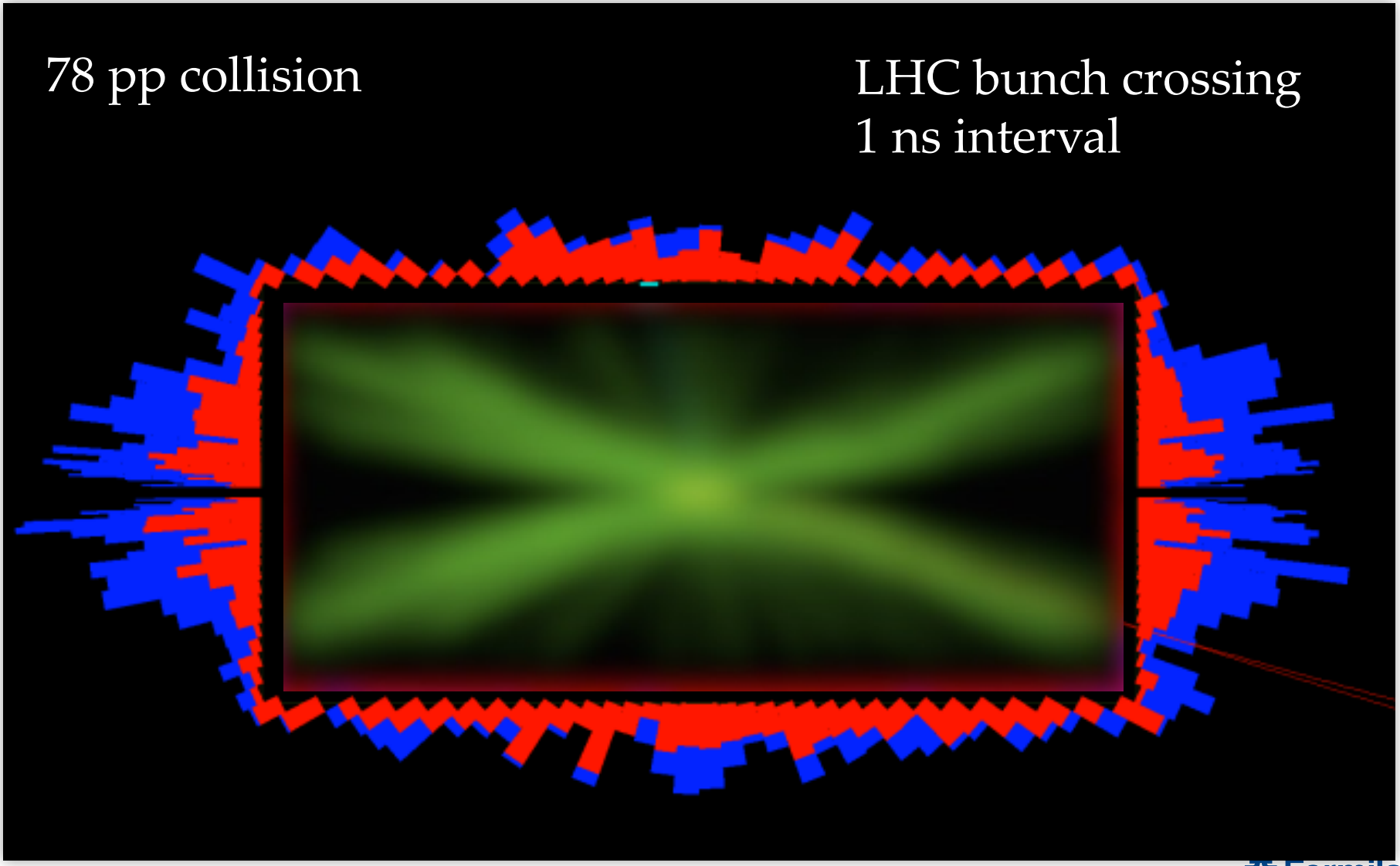
Event reconstruction at HL-LHC



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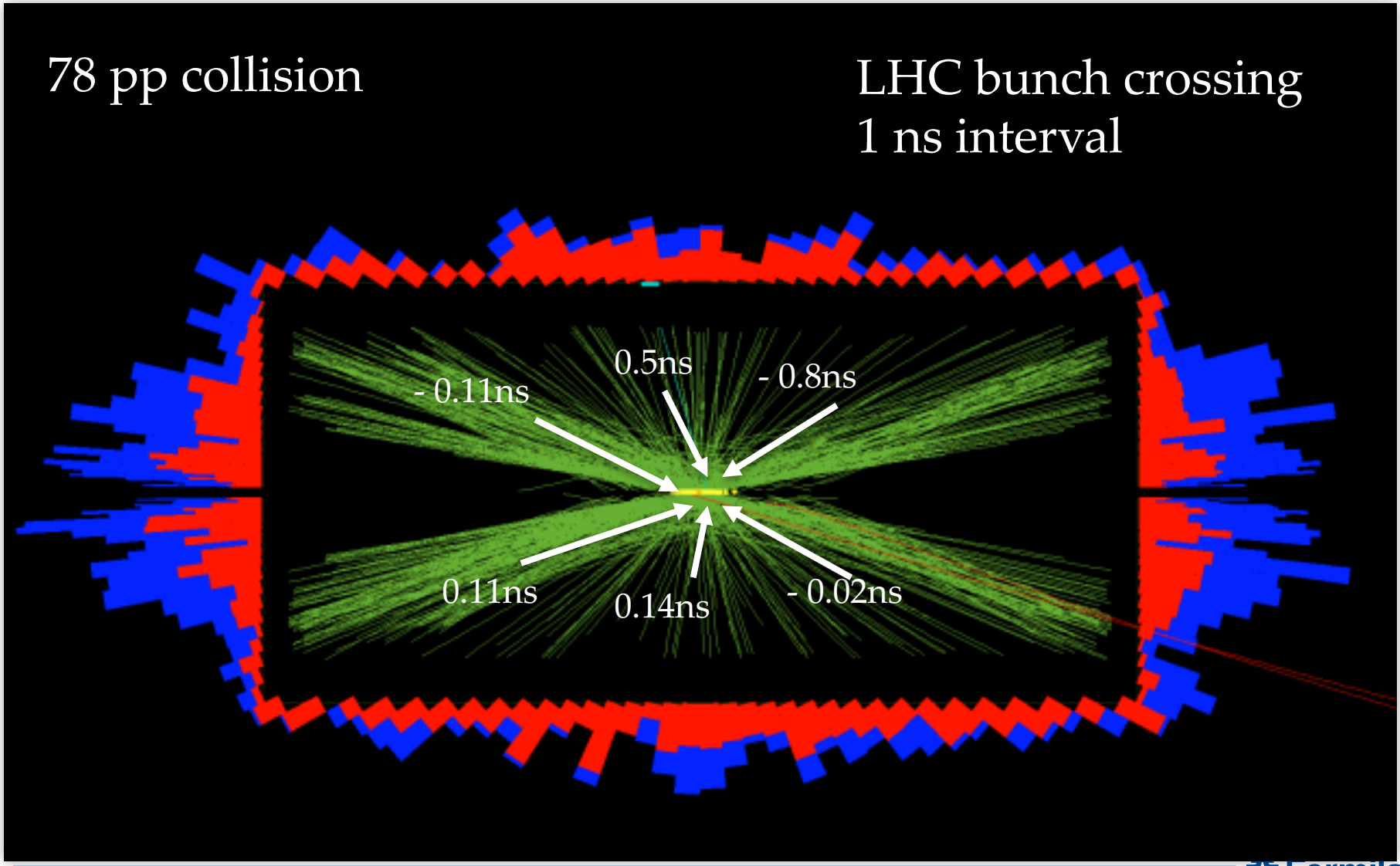

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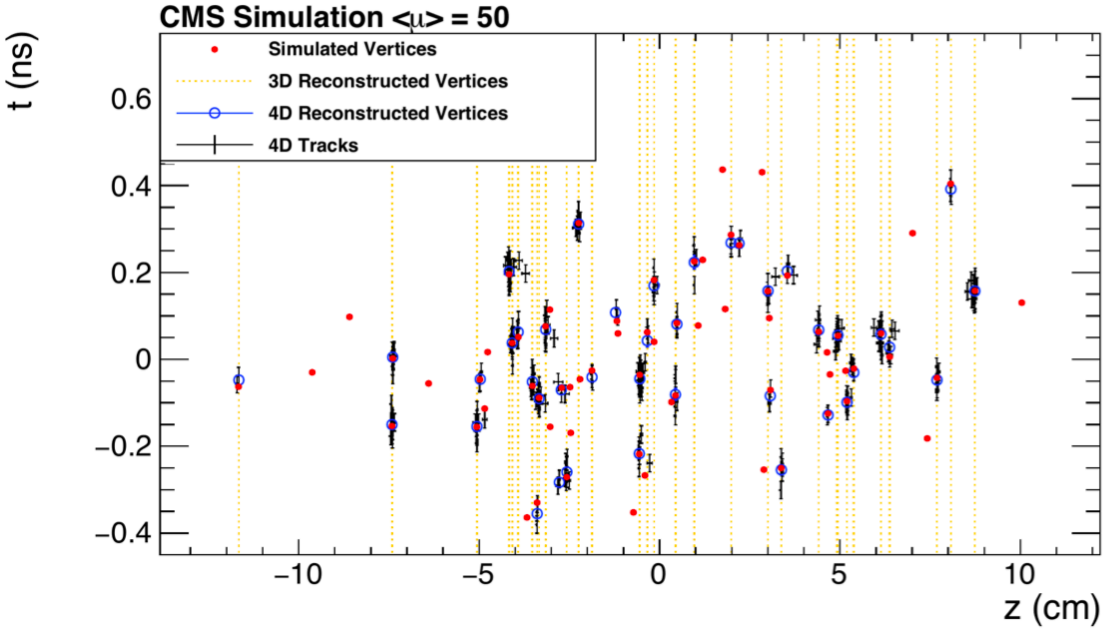
Precision timing for charged particles

- Traditional **three-dimensional** vertexing can be upgraded to a **four-dimensional** fit
  - Pileup vertices explicitly reconstructed in position along the beamline and time within the bunch crossing
- Further suppression of charged particles from pileup for jets, MET, lepton isolation, etc…



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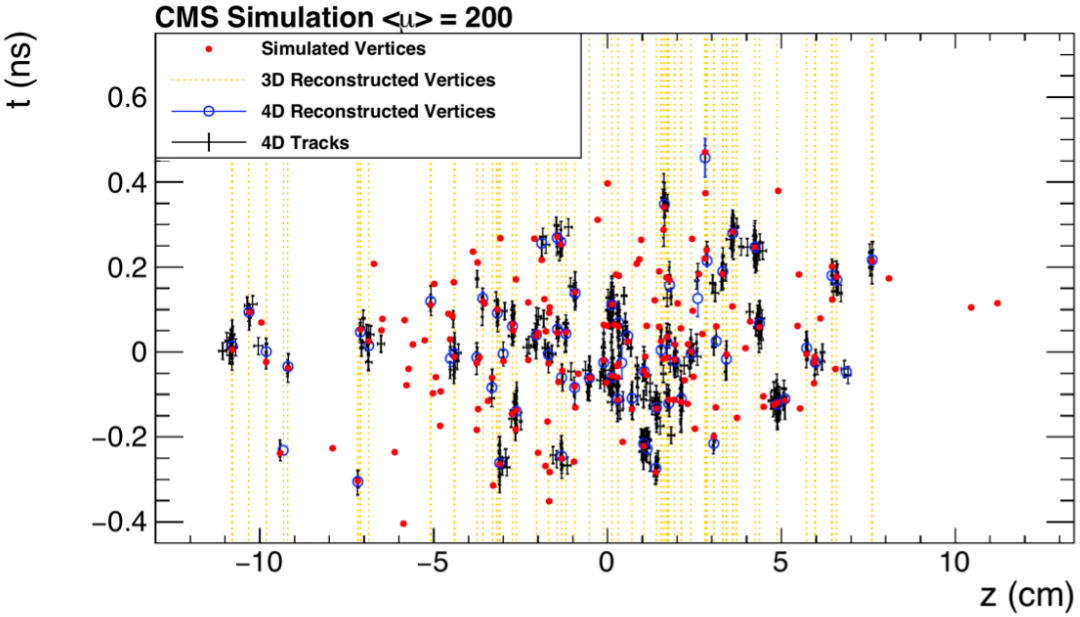

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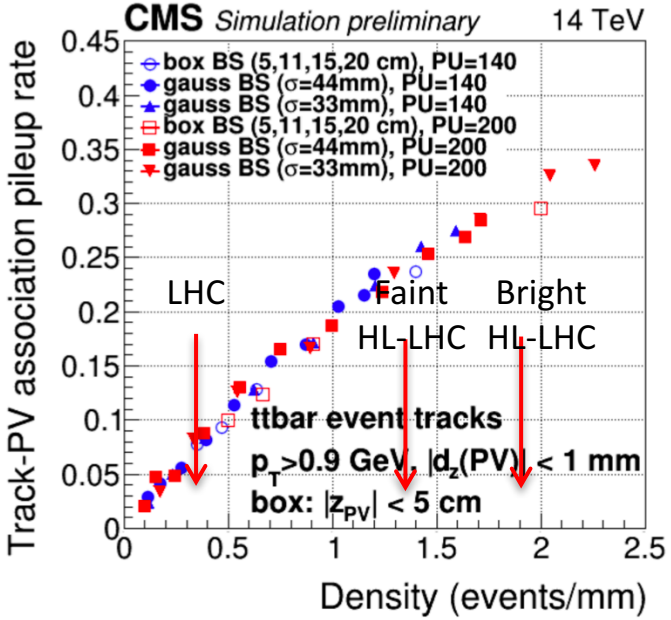
Precision timing for charged particles

- As vertices start to overlap within tracking resolution, rate of pileup tracks associated to PV increases
  - Degradation of charged isolation, b-tagging, Jet/MET performance
  - Time resolution of ~30 psec recovers the current LHC performance



(a) PU Tracks attached to hard PV

At nominal HL-LHC about 20% of tracks associated to PV are from pileup

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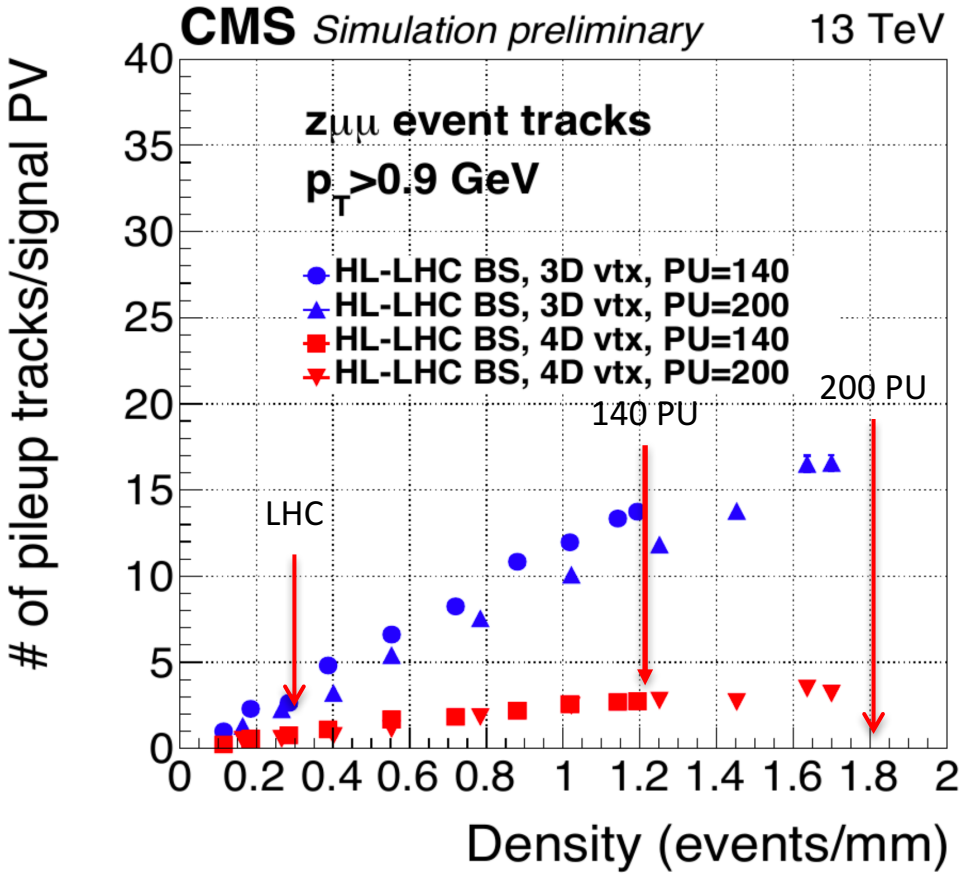
Vertex reconstruction with timing



- ~ 5x reduction in effective pileup in terms of charge multiplicity

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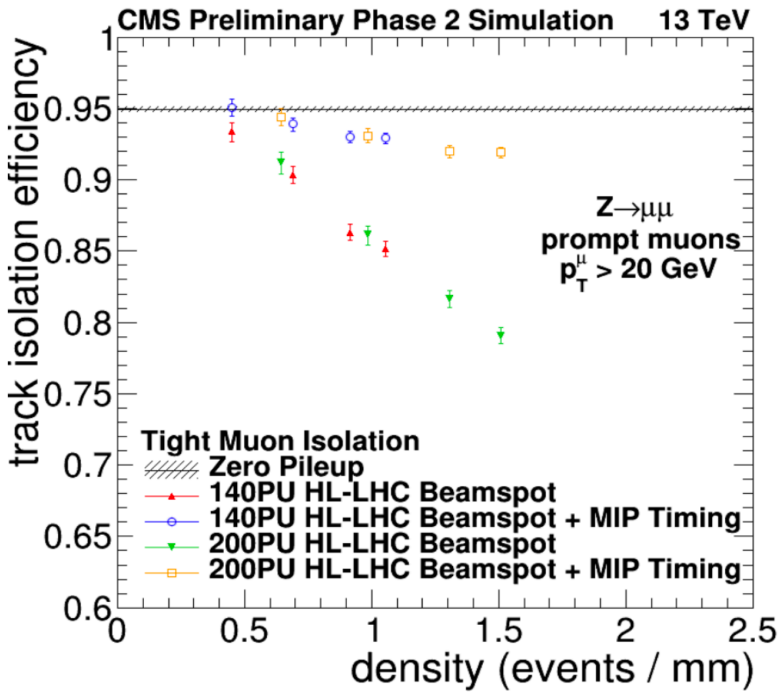
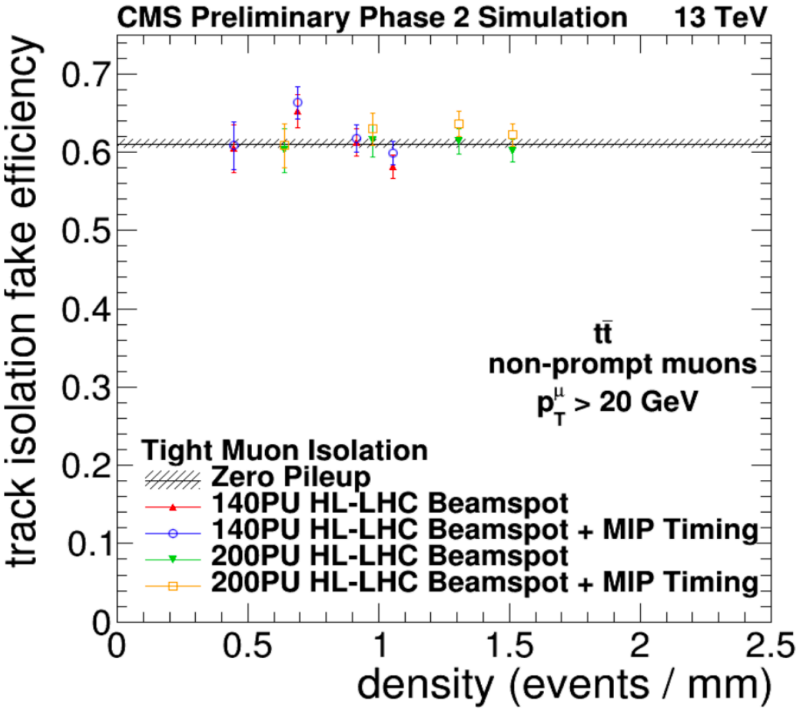
Muon reconstruction



(a) Prompt μ Efficiency



(b) Efficiency for fakes

- Muon charged isolation efficiency in Z → μμ and ttbar (fake) events
- Timing yields 10% improvement per muon

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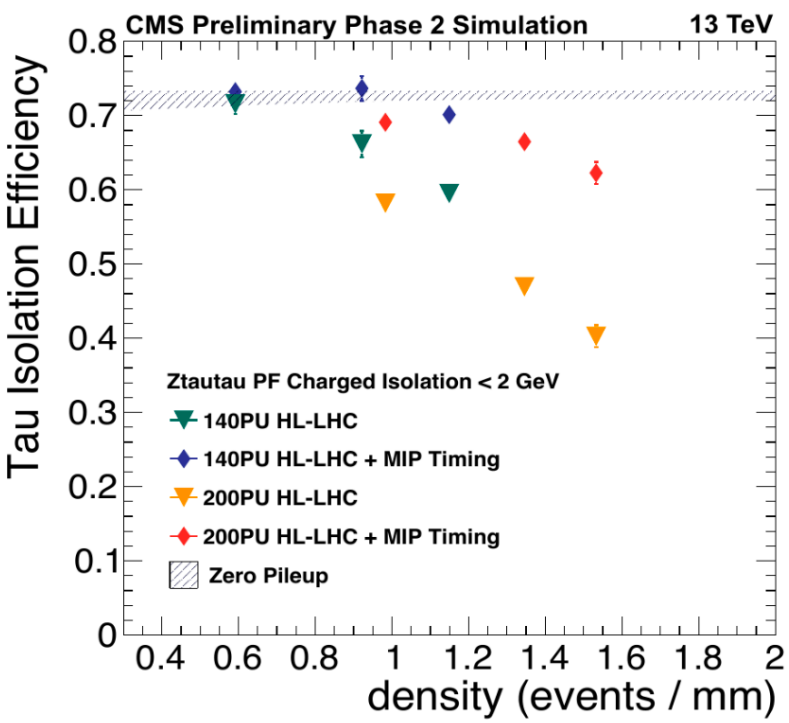
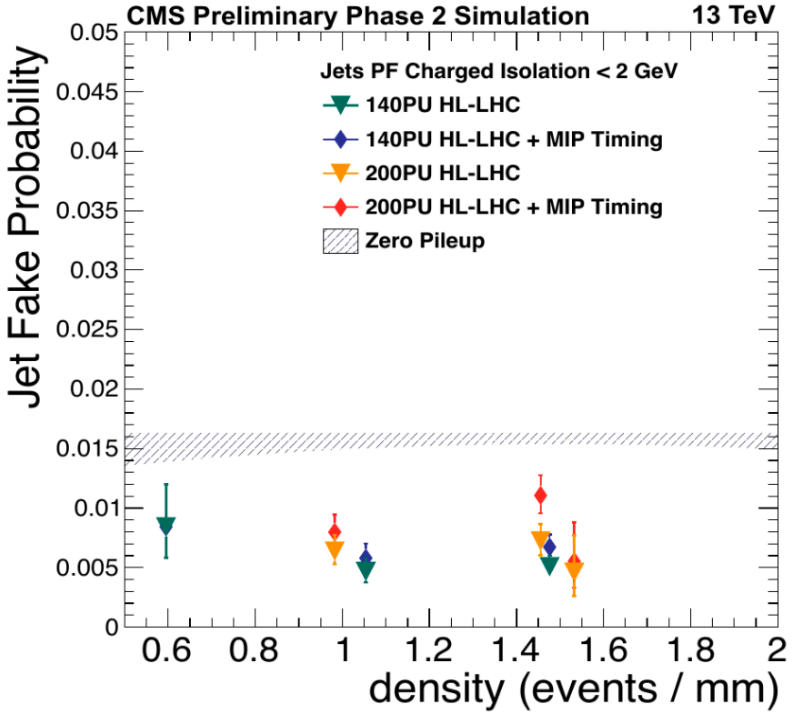
Tau reconstruction



(a) Prompt τ Efficiency

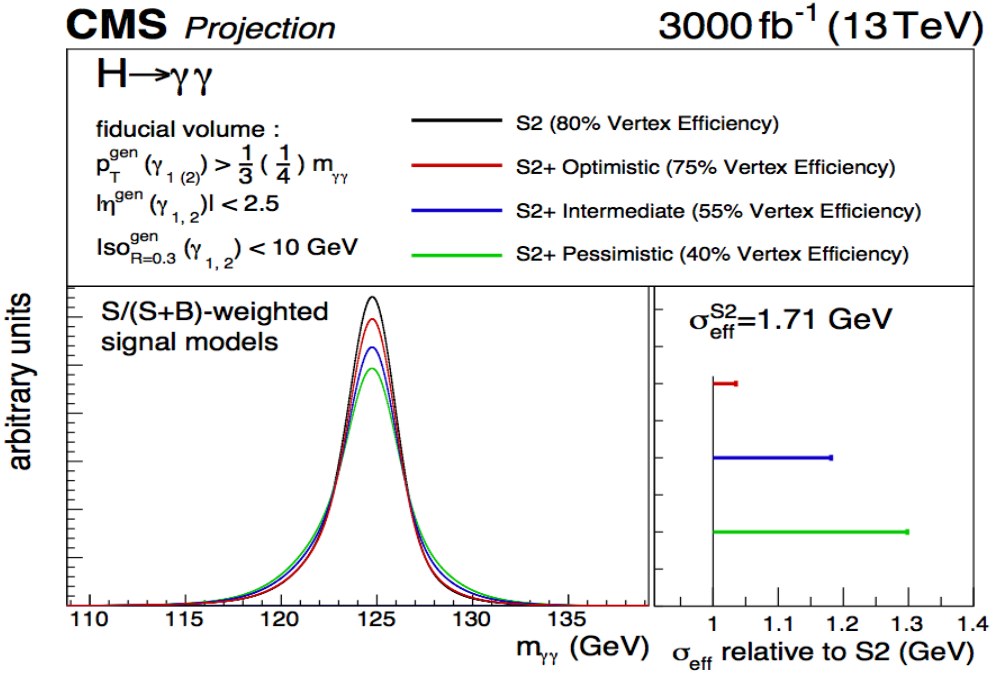


(b) Efficiency for fakes

- Large effect on tau reconstruction, about 20% improvement per tau, with constant fake rate

Precision timing for photons from H → γγ

- No pointing information in CMS Ecal: hadronic recoil balancing and conversion pointing to find primary vertex
  - Increasingly difficult to locate the primary vertex at very high pileup
  - Vertex selection efficiency drops from **~80%** (now) to **~30%** at HL-LHC
- Partially recovered by calorimeter timing,
  - Almost fully recovered by calorimeter + MIP timing (**~ 30% gain in Lumi**)



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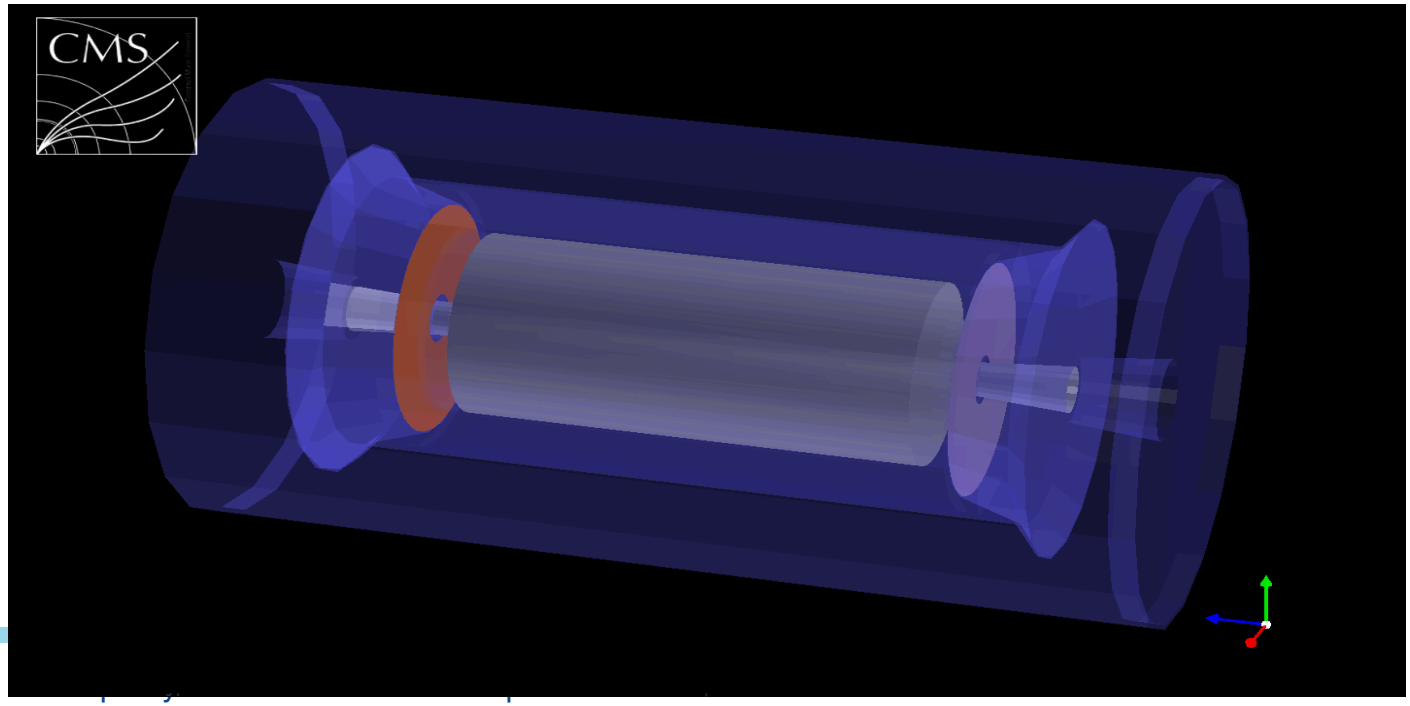
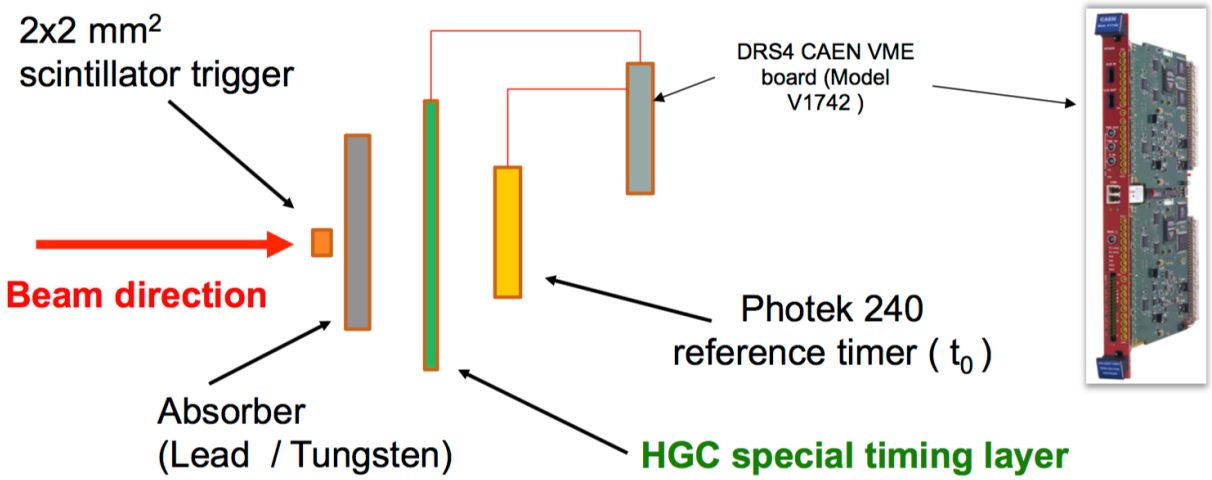
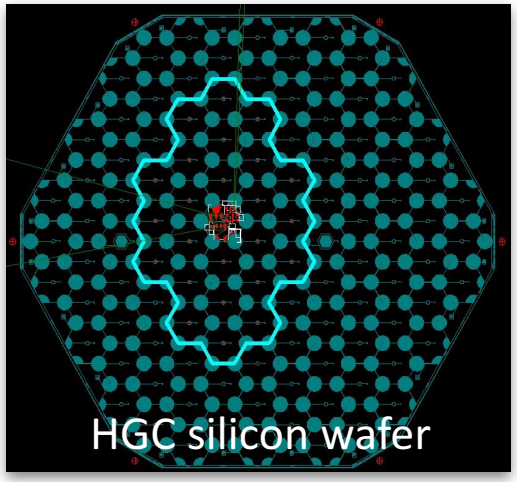
Precision timing for CMS in HL-LHC

- 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

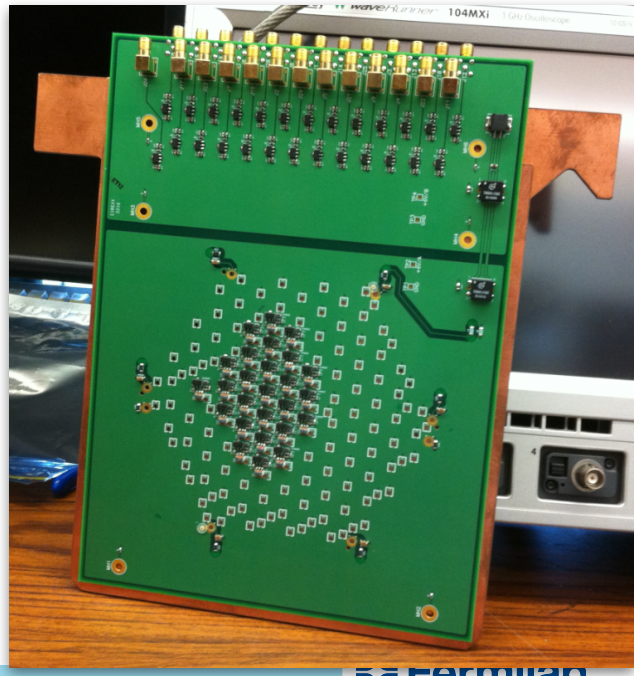


Photon precision timing with HGCal

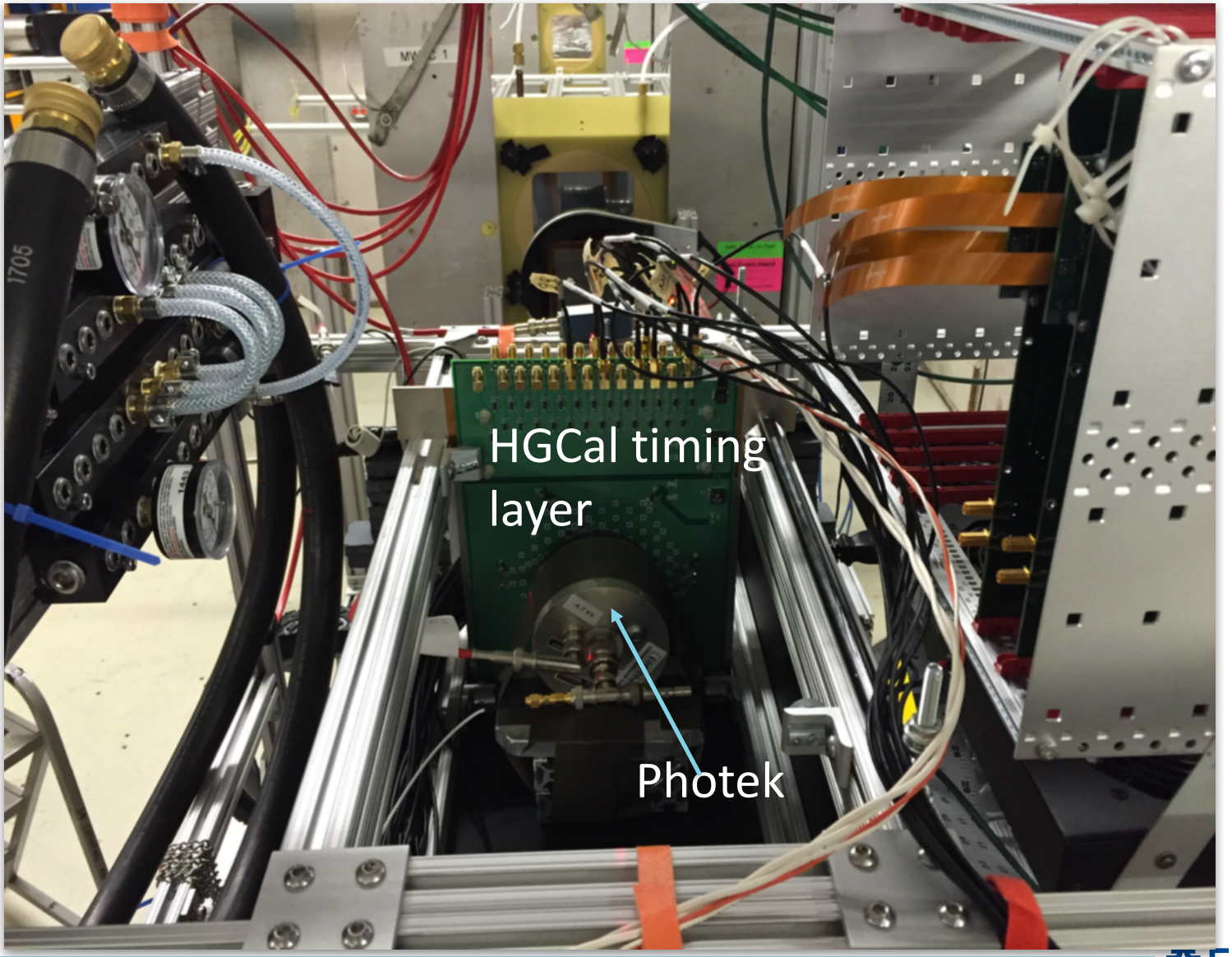




- Equip one layer in HGCal test beam prototype with fast readout
  - 300 μm sensor thickness, 25 cells are instrumented and read out
  - Each channel is equipped with its own amplifier chain (total gain = 120)



Experimental Setup



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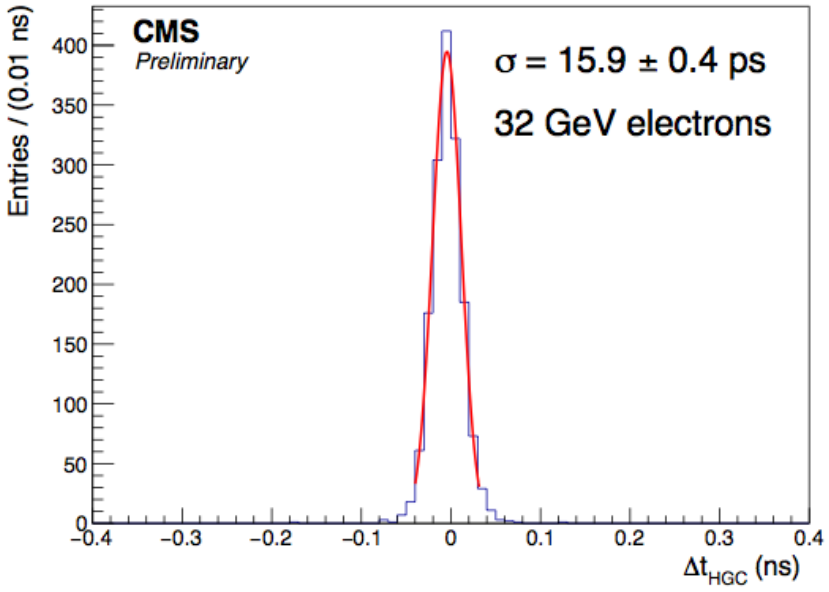
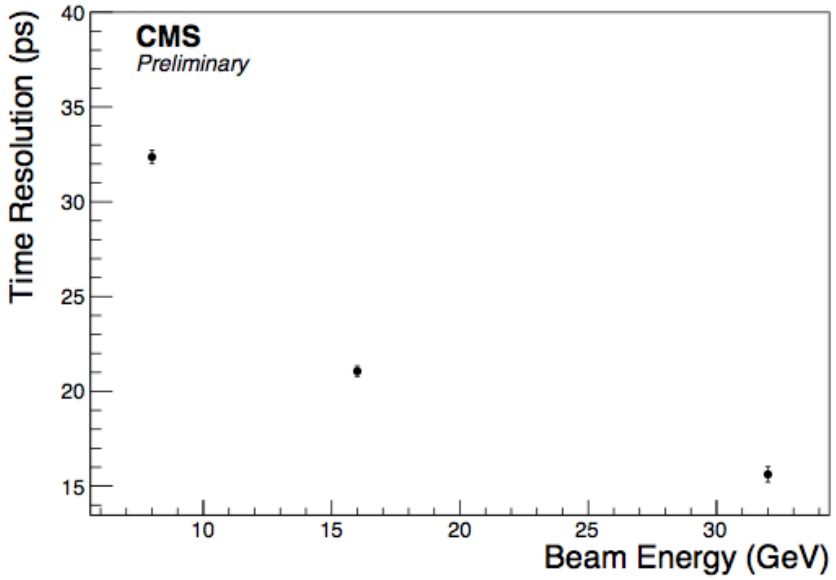
Time resolution with one timing layer





- Time stamp for HGC timing layer is determined by combining the 7 central pads around the core of the shower
  - Pads are combined as a charge-weighted average
- Time resolution of about **15 psec** obtained for one layer of HGC in EM showers

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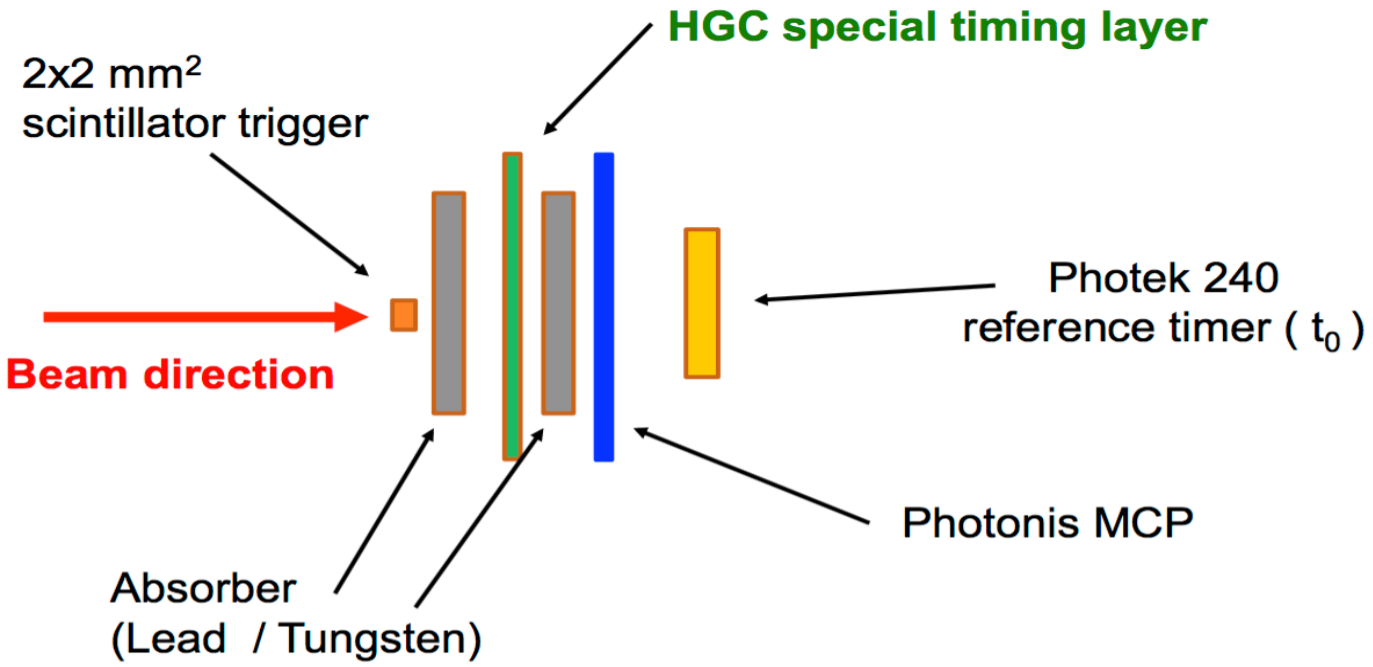
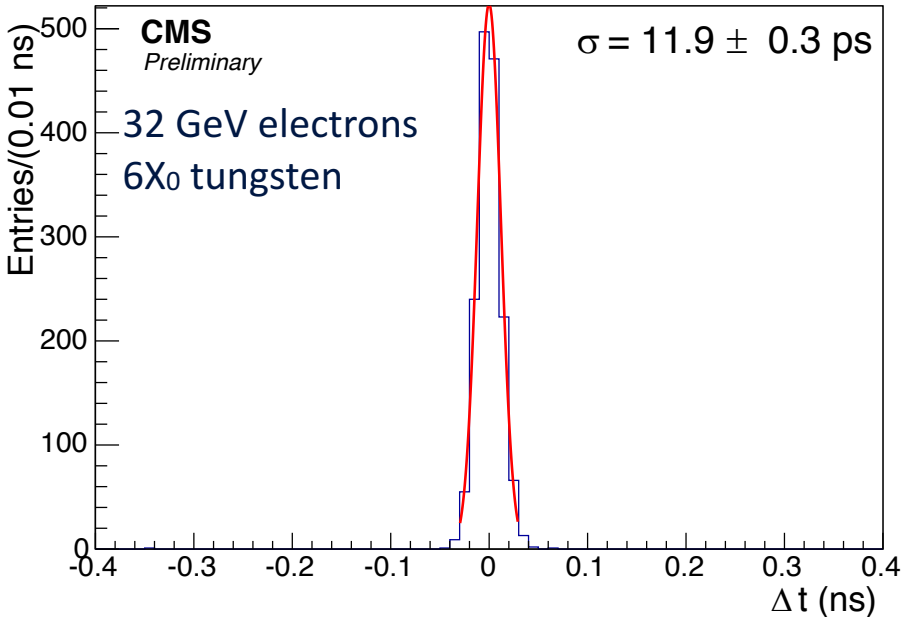
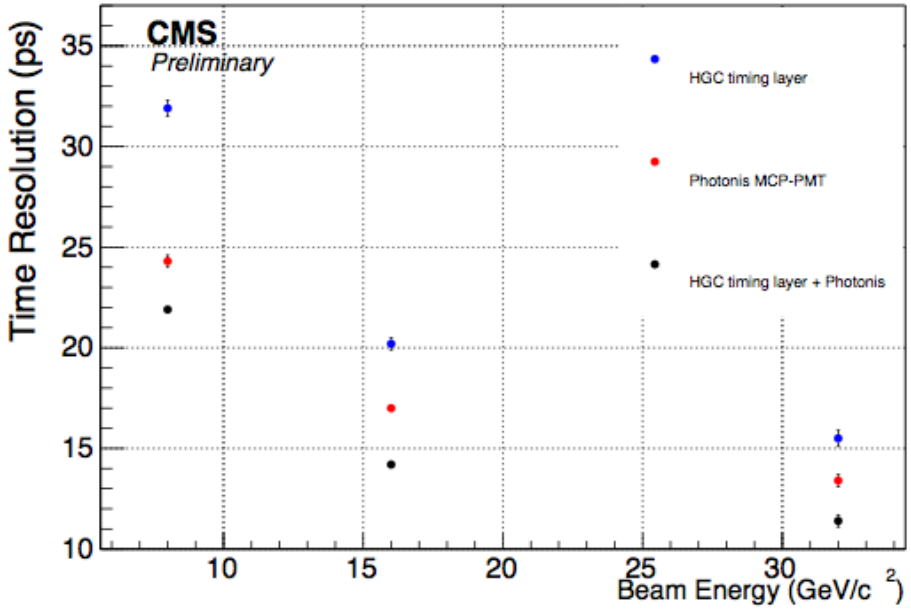
Additional Longitudinal Layers



- Evaluate the impact of multiple samplings within the EM shower, using a second sampling layer

Time resolution with two timing layers





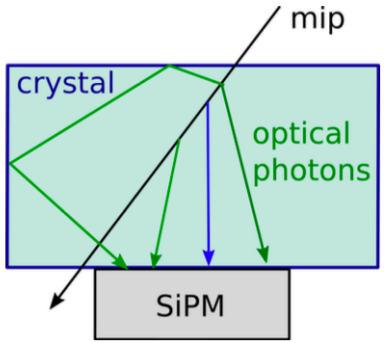
Combined time resolution of 2 timing layers in HGC test beam

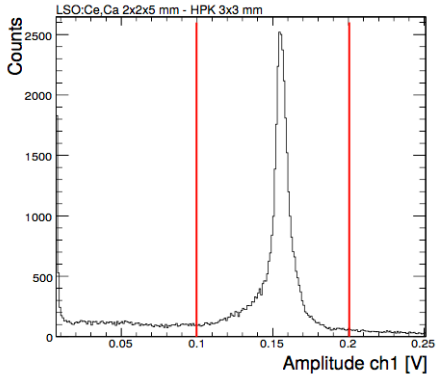
- Combining two layers using a 50-50 weighting between the two layers
- Additional information from the second layer significantly improves time resolution
  - Time resolution of around 12 psec when combining 2 layers in EM shower

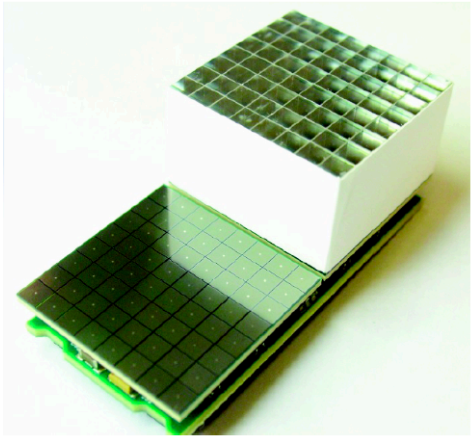
Timing layer in the barrel

- Use thin (few mm) scintillating crystals to generate light:
  - LYSO crystals provide a very bright signal to a single MIP (up to ~40000 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







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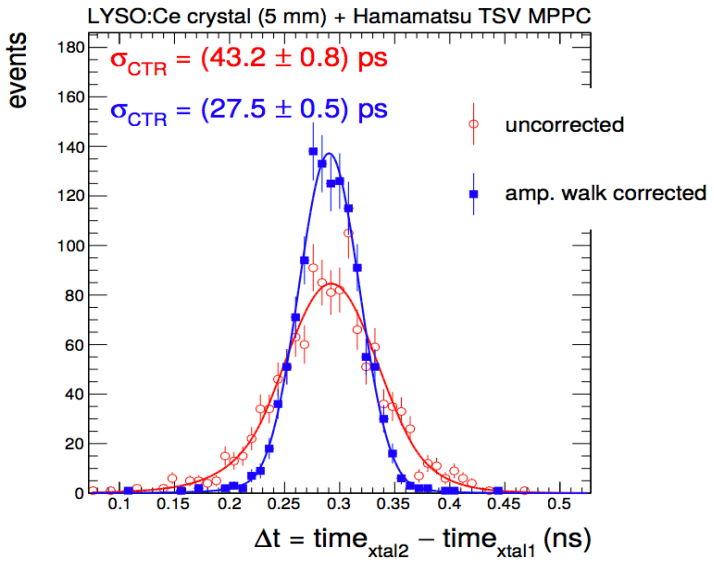
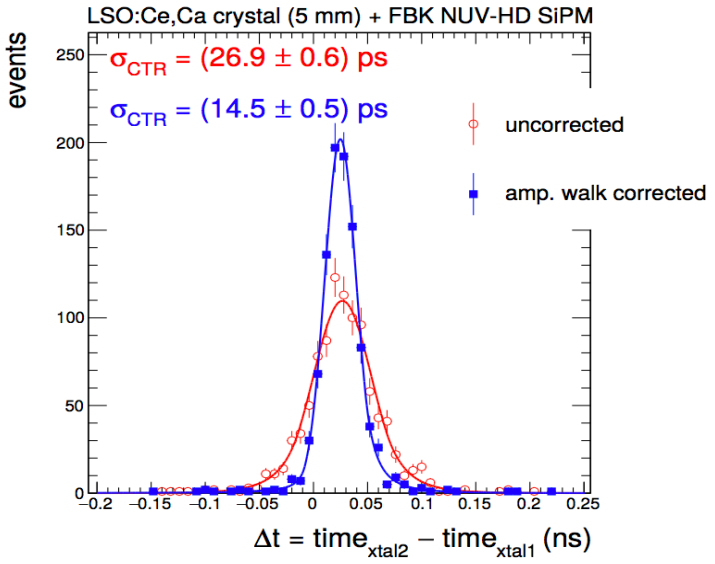
Time resolution

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

$\sigma_t^{\text{single}} = 19.4$ **ps**



$\sigma_t^{\text{single}} = 10.3$ **ps**



M. Lucchini talk at ECFA 2016

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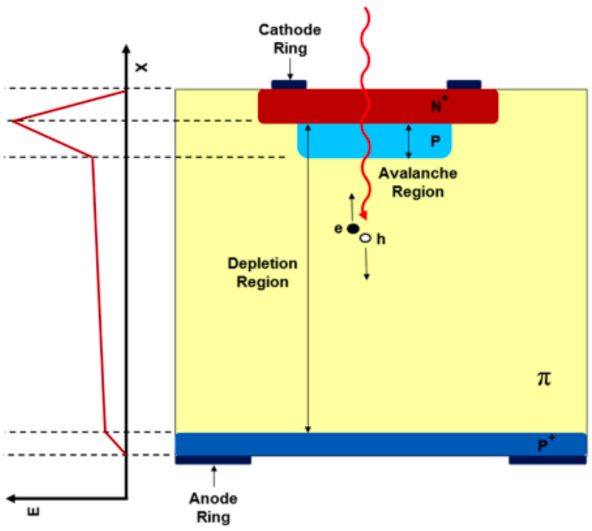
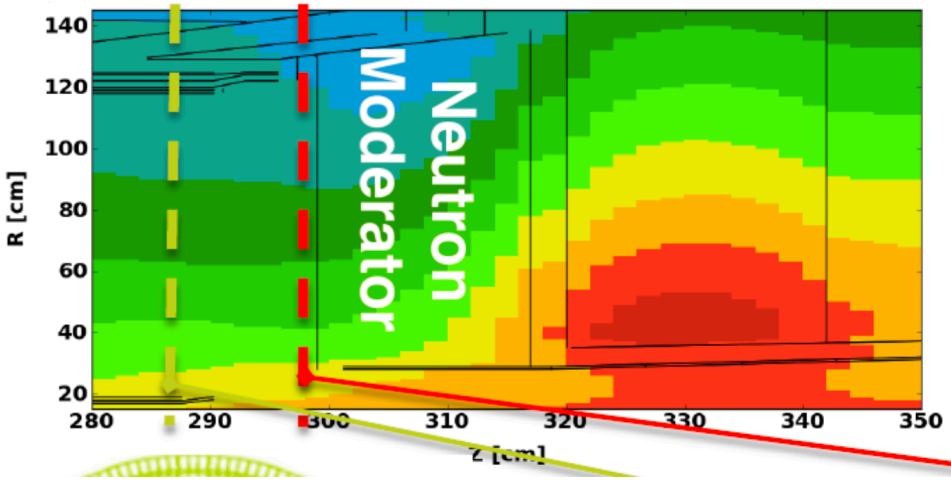
Timing layer in the endcap

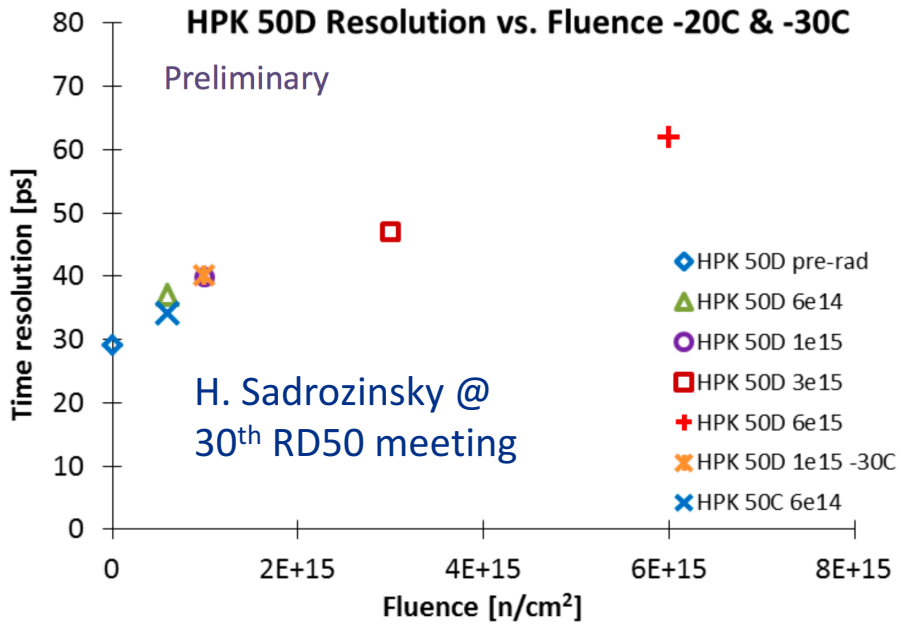
- Much harsher radiation environment in the endcap region
- Silicon sensor with specially doped thin region that produces high electric field→ produces avalanche providing signal 15-30 gain
  - Large community: RD50 collaboration, several manufacturers (CNM, FBK, Hamamatsu)
  - Key Challenge: achieve radiation tolerance up to $2x10^{15}$ n_{eq}/cm^2 at $|\eta| = 3.0$ for 3000 fb^{-1}



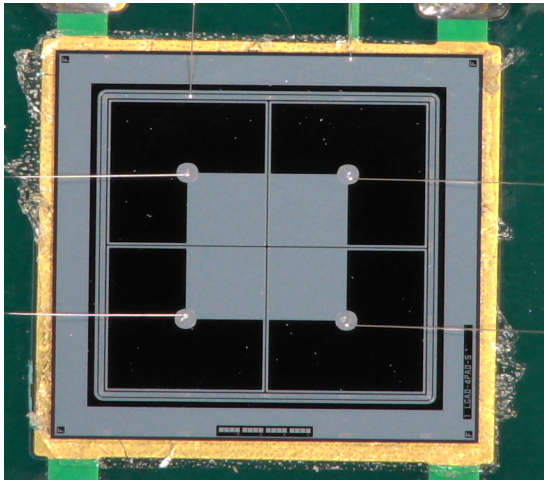


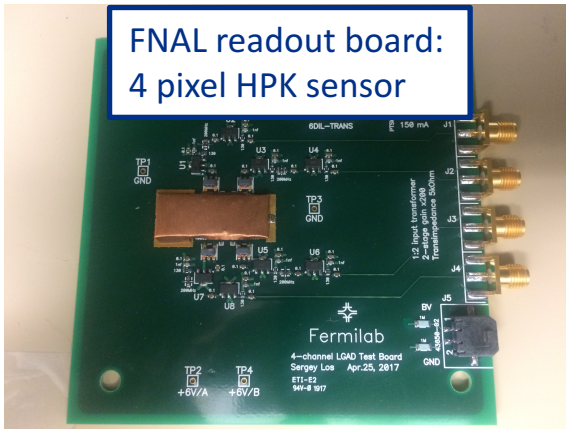
η	TK / HGCal nose
1.6	1.1×10^{14}
2.0	2.1×10^{14}
2.5	4.8×10^{14}
3.0	10.0×10^{14}

Time resolution



Hamamatsu 2x2 LGAD array3x3 mm^2 pixels

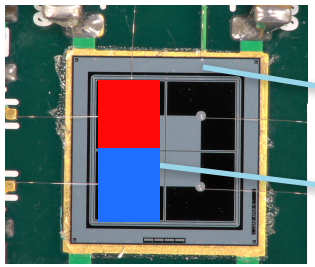




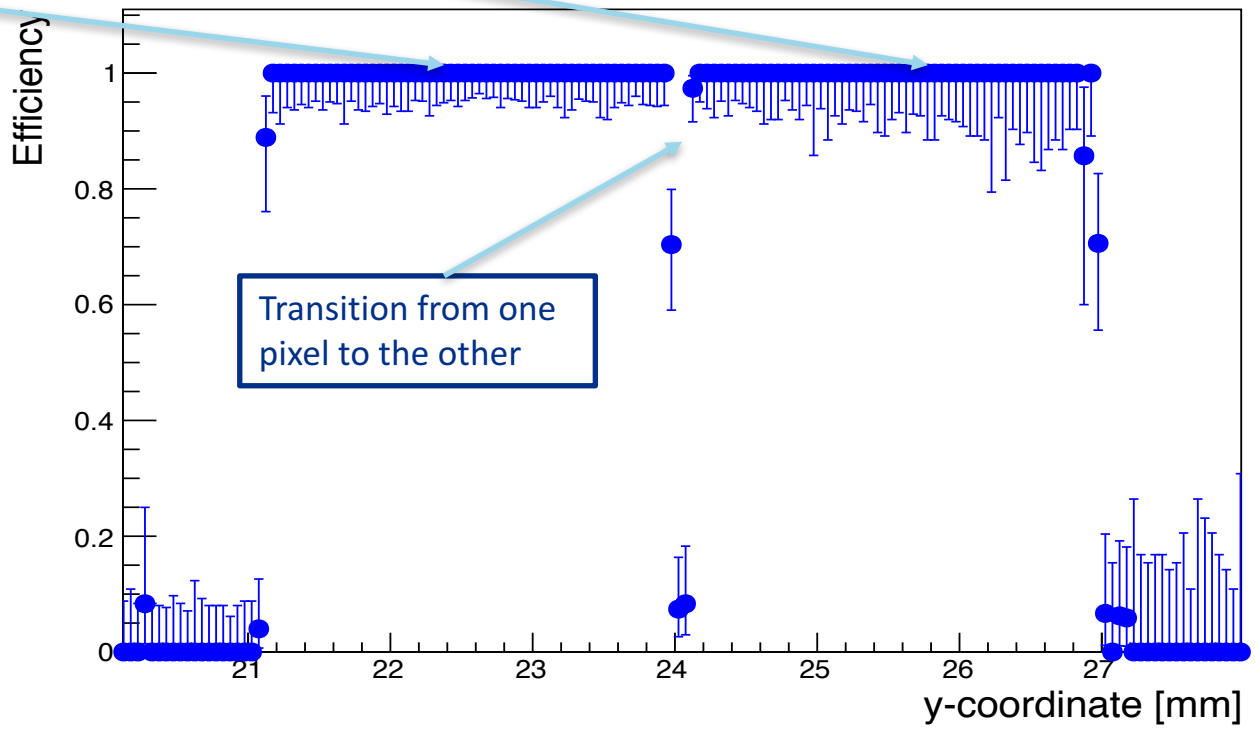
- Time resolution of 30-40 psec demonstrated for fluences up to 10^{15} n_{eq}/cm^2
  - Active R&D is ongoing to increase the radiation tolerance
  - Alternative dopants: boron, gallium, boron+carbon, gallium+carbon)

LGAD sensor uniformity

- Recent test beam at FNAL
  - Precision tracking detector available at FTBF allowed high precision characterization of the sensor uniformity



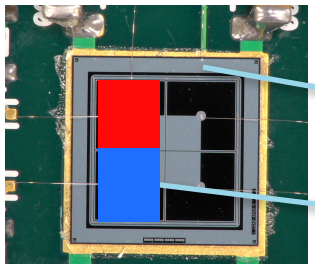
100% particle detection efficiency across the sensitive area



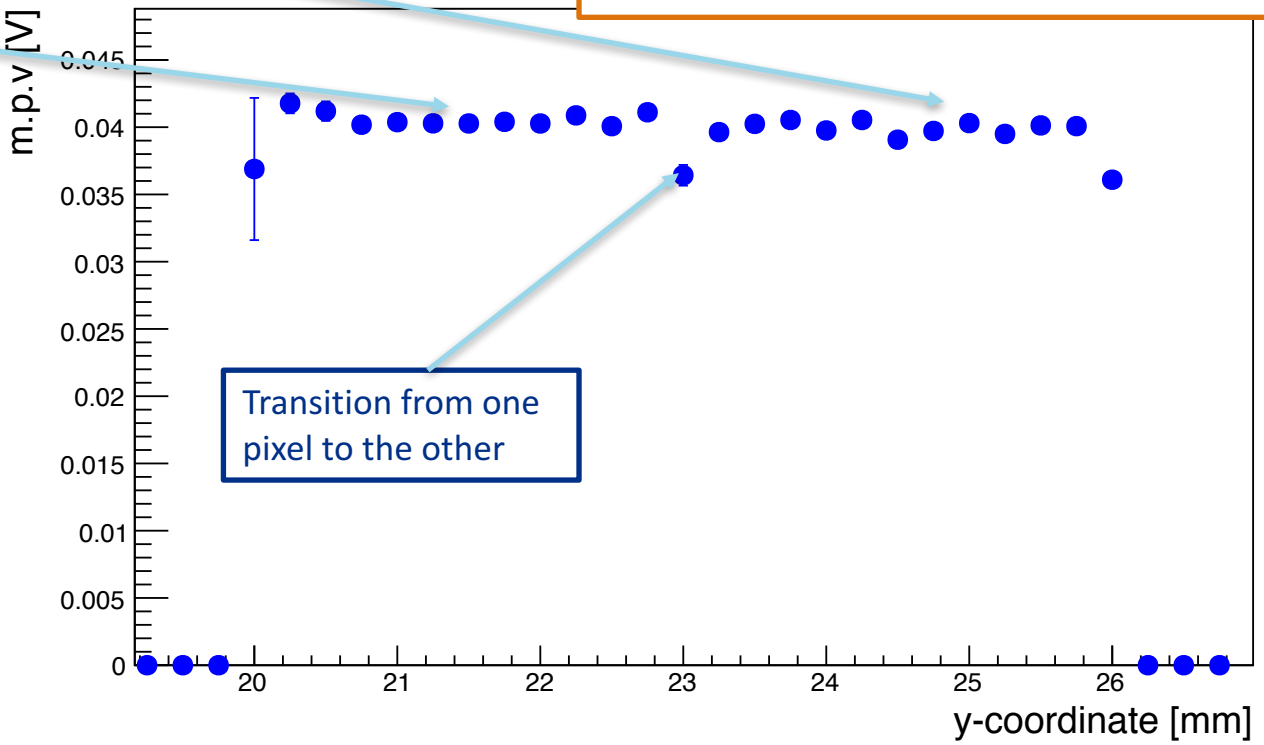
Fermilab

LGAD sensor uniformity

- Recent test beam at FNAL
  - Precision tracking detector available at FTBF allowed high precision characterization of the sensor uniformity



Very uniform gain distribution across sensor surface



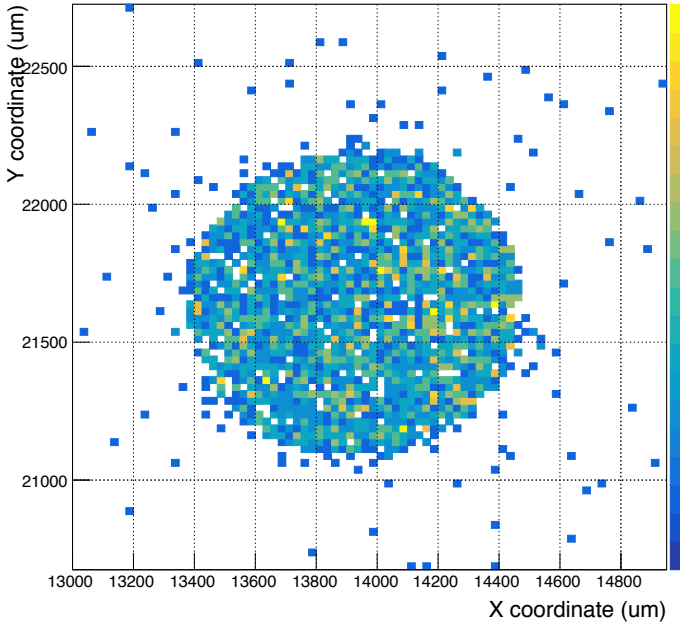
Transition from one pixel to the other

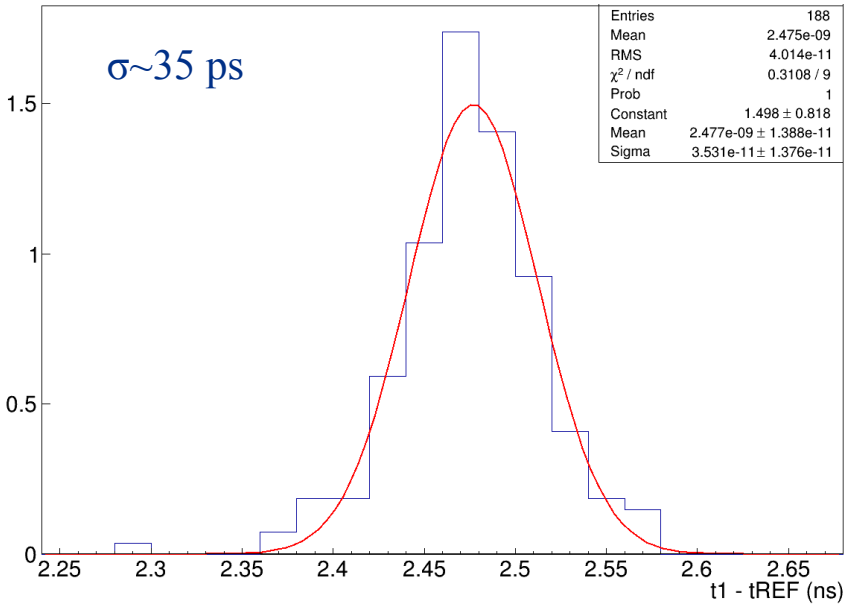
Fermilab

Irradiated sensors performance

- 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





High uniformity of signal over irradiated sensor area

Summary

- High precision timing capabilities can serve as a new tool in reducing the effects of large pileup in hadron colliders
  - Could be a disruptive technology change for future planned collider experiments, HL-LHC and beyong

- Timing precision of 20-30 ps achieved with several technologies
  - Complementarity in the technologies and applications for **calorimetry** and **tracking**
  - For calorimeters: expect to maintain good time resolution with highly irradiated sensors and multiple samplings
  - Radiation tolerance of endcap timing detectors is fast approaching the required levels