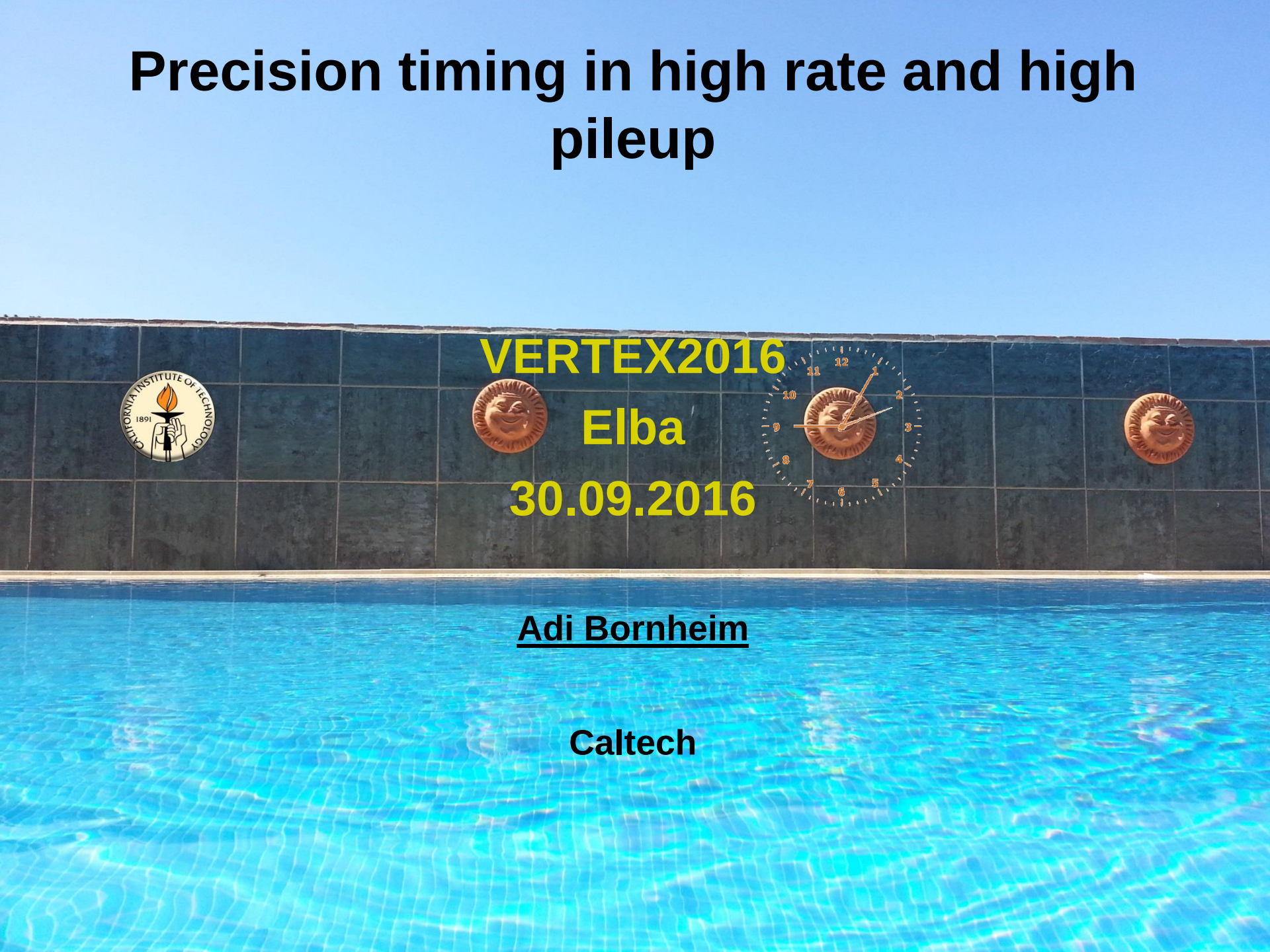
Precision timing in high rate and high pileup



VERTEX2016

Elba

30.09.2016

Adi Bornheim

Caltech

Outline

Covering CMS, ATLAS and LHCb.

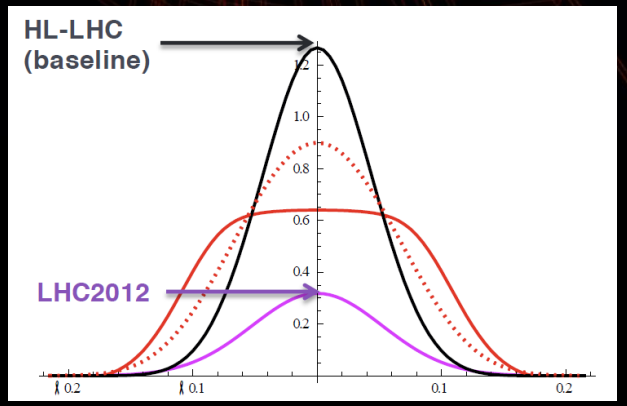
- **Precision timing at HL-LHC for pile-up mitigation**
- **The calorimetric approach (with a CMS bias)**
- **Precision timing for tracks & tracking**
- **Particle ID with precision timing**

Disclaimer : Can not do justice to a very wide range of existing precision timing detectors, R&D projects and upgrade projects on precision timing.

Notably the Forward Spectrometers at ATLAS and CMS, ALICE etc.

See also the recent timing workshop in Kansas.

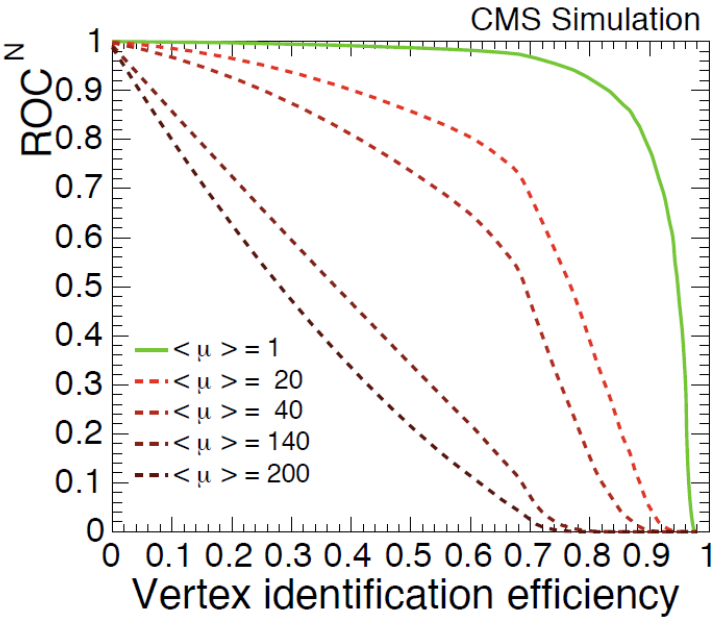
Physics at HL-LHC



H→γγ Vertex ID at HL-LHC

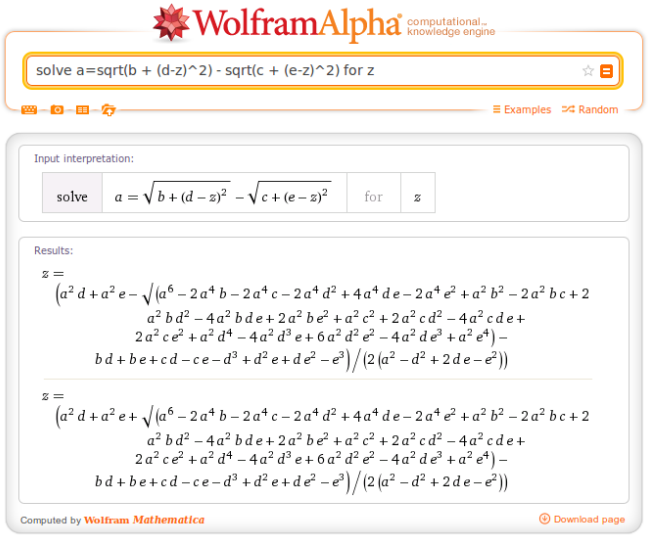
- **H→γγ important mode for precision higgs physics.**
- **Clean signal with large visible cross section makes it a key driver for measurements of Higgs production and decays dynamics.**
- **Standard candle and background for di-Higgs to bbγγ.**
- **Analysis utilizes full detector capabilities – tracking and calorimetry : Holistic event reconstruction.**

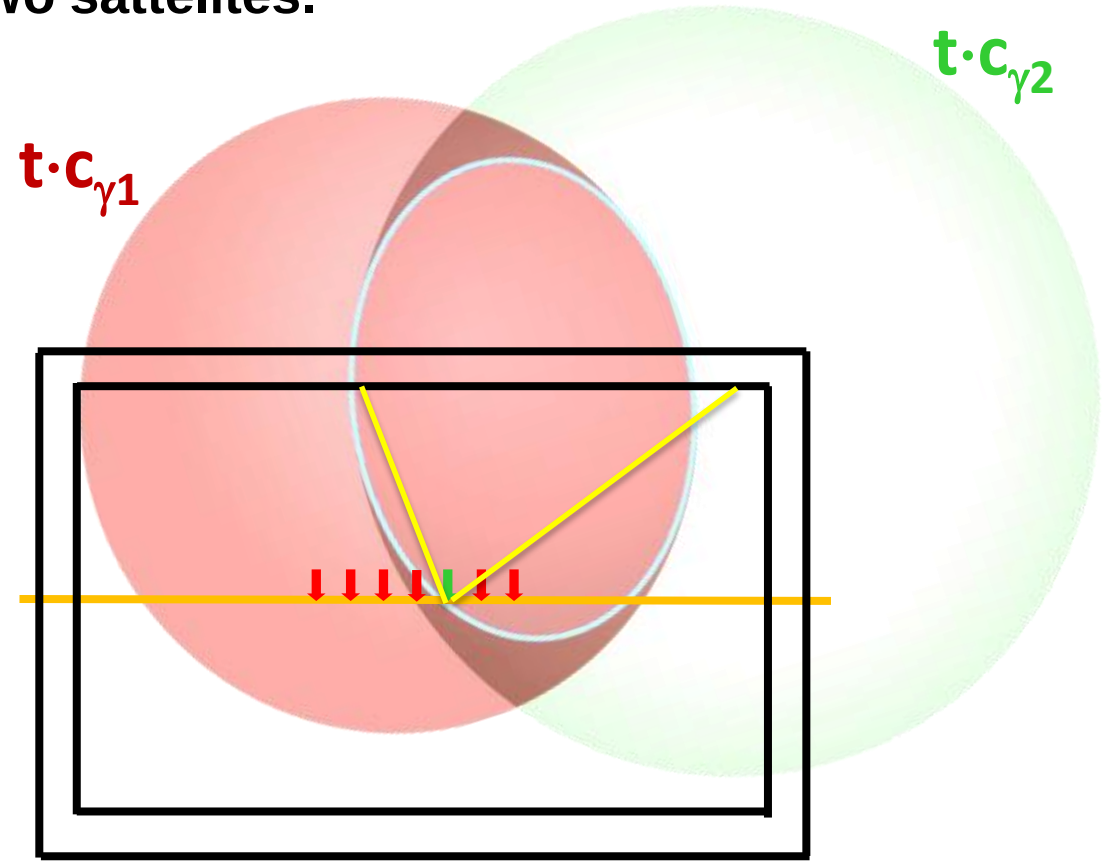
- **Vertex ID uses Σp_T to find hard vertex.**
- **At HL-LHC to many PU vertices with high Σp_T.**
- **With a timing measurement for two photons, can calculate the z and t location of the vertex.**



4D Triangulation with Photon Timing

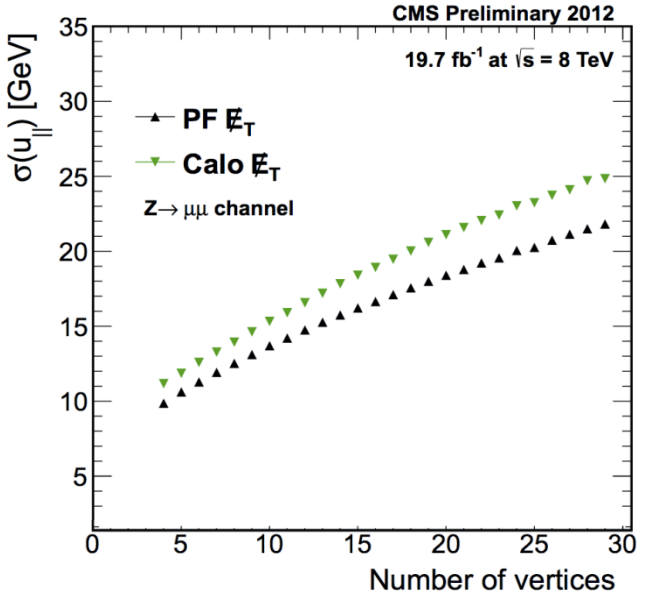
- **With two time and position measurements eg. from two photons and with the constraint from the beam axis x and y location, the vertex x and t can be calculated.**
- **Equivalent to GPS with two sattelites.**

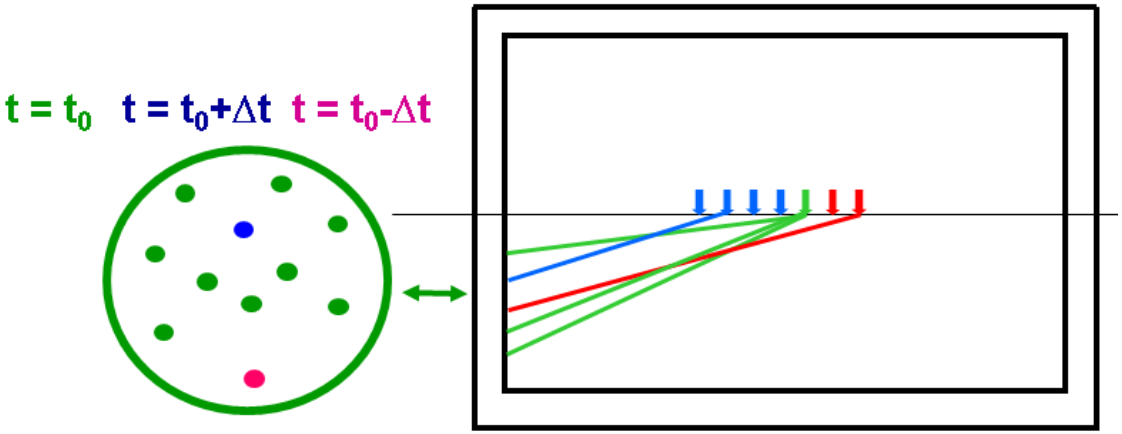


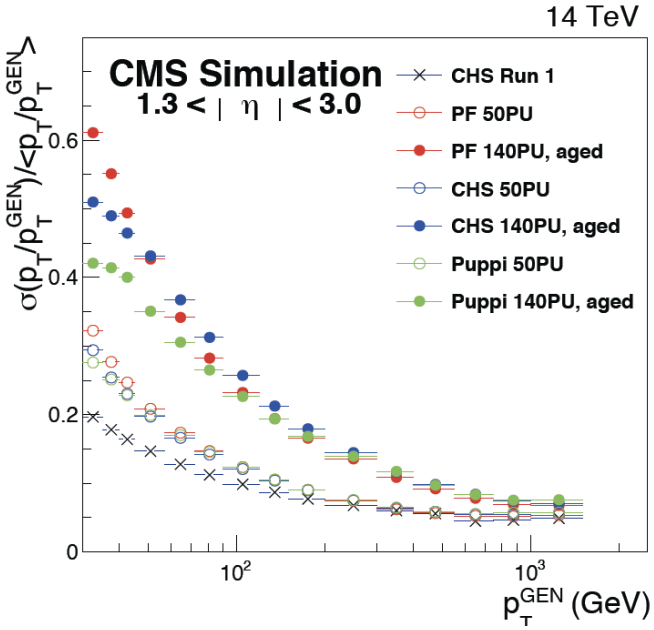


JetMET with Precision Timing

- **High pile-up has major impact on JetMET reconstruction.**
- **At low p_T (40 GeV) PU energy in the jet cone exceeds the jet energy by a factor 2 or more.**
- **Each PU event adds 3 GeV in quadrature to the MET resolution, resulting in about 40 GeV for 200 GeV.**

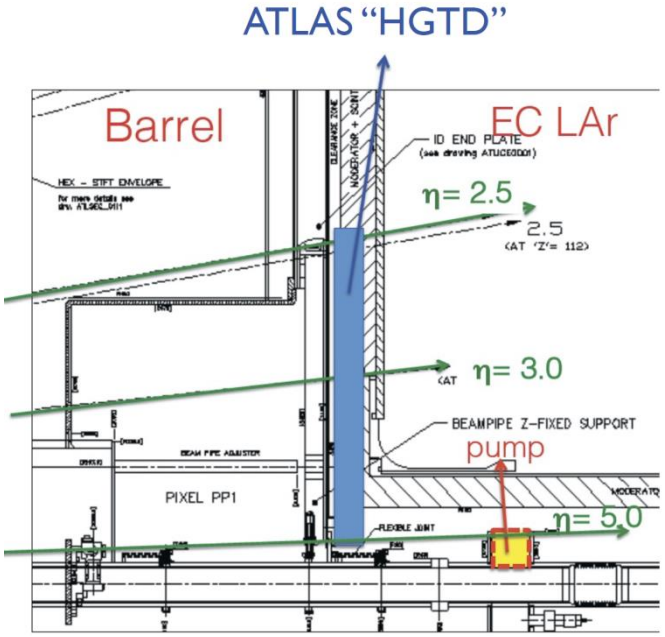


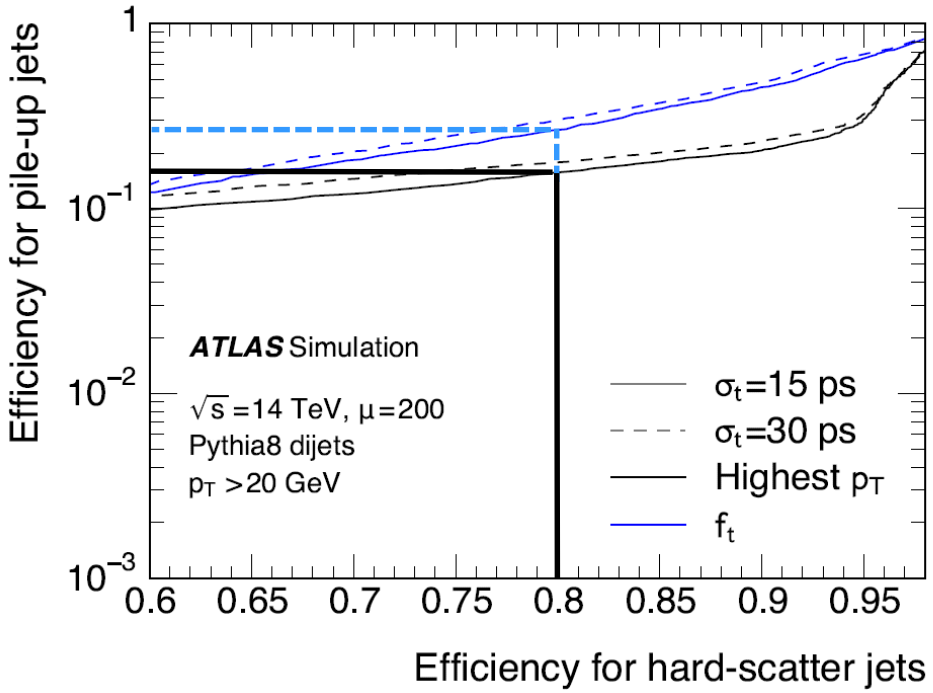




Forward Jet Vertexing with Timing

- **ATLAS study based on the "High-Granularity Timing Device"**
- **Efficiency hard scatter vs pileup: Reduction of pileup as function of the timing resolution**
- **Jet pT > 20 GeV : Rejection factor 10, depending on working point.**
- **Based on Fast Simulation of the HGTD timing resolution.**





Calorimetric Timing in CMS

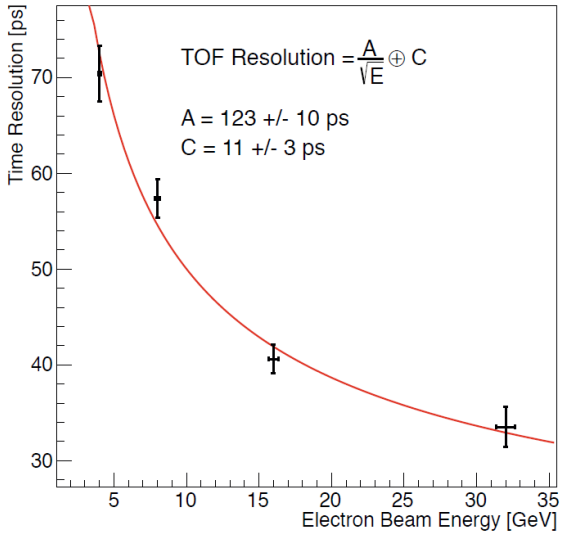
Boundary conditions from CMS Phase II Calorimeter Upgrade :

- **PbWO ECAL Barrel : Replacement of Very Front End and :**
  - **Cope higher L1 rates (750 kHz)**
  - **Mitigate "nuclear counter" induced noise in APDs (spikes)**
  - **Reduce impact of increased noise from APD dark current**
- **Endcap Calorimeter replacement with Silicon/Tungsten & Silicon/Steel calorimeter (EE & FH HGCAL) + Scintillator/Steel Backing HCAL :**
  - **Current CMS Endcap will not withstand HL-LHC radiation doses.**
  - **Cope higher L1 rates (750 kHz)**
  - **Higher transverse granularity in the hadronic section.**
  - **Longitudinal granularity**

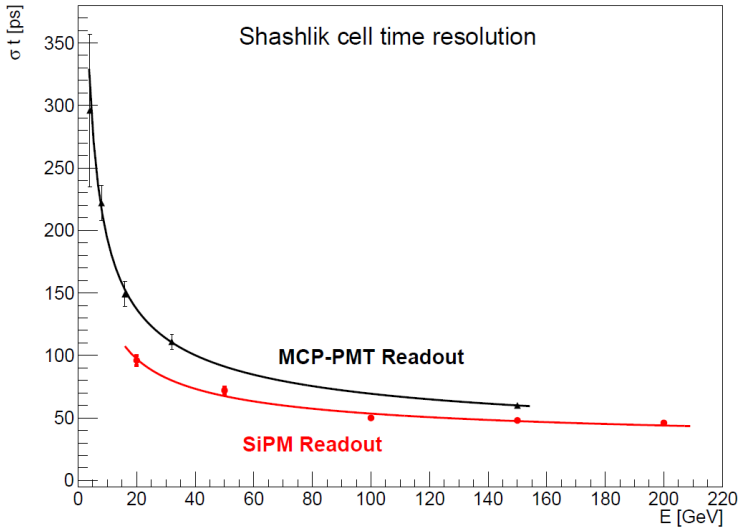
Calorimeter Timing R&D

- **Electromagnetic showers are temporally very coherent and large enough to allow multiple measurements or integrating signals from a larger volume**
- **Large primary signals reduce demand on fast, low noise amplification and very fast digitization.**
- **Precise timing can be extracted from sampling the shower or from the full shower volume.**

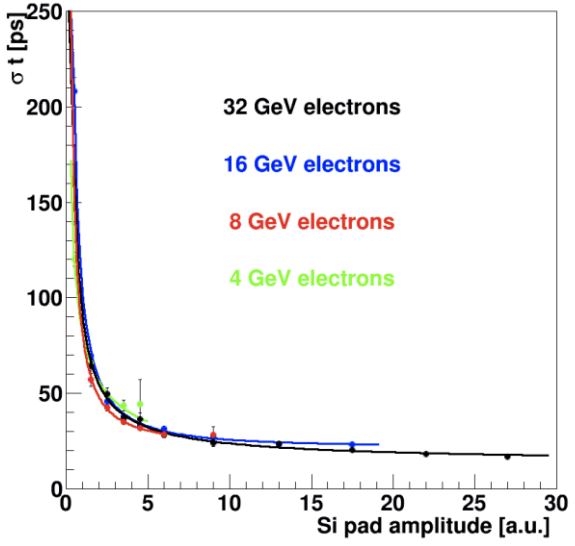
1.7 cm^3 LYSO at shower max with MCP-PMT redout



LYSO/W sampling calorimeter, WLS readout, MCP or SiPM readout



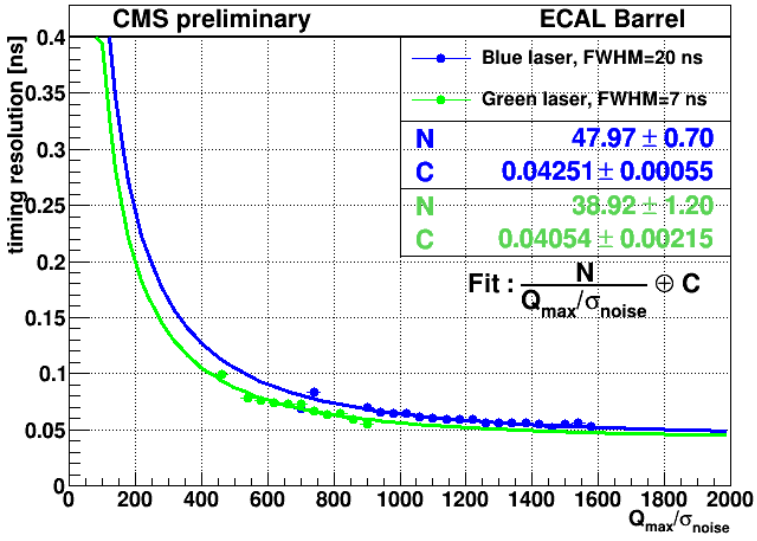
1 cm^2 Si pad at shower max



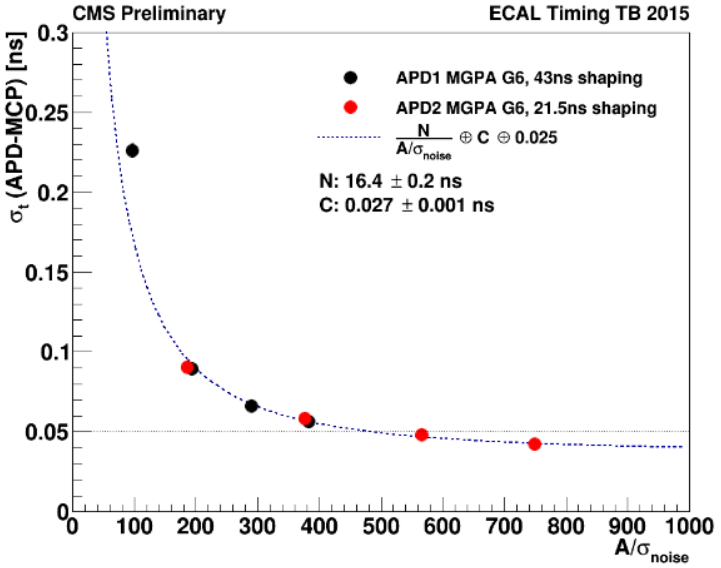
CMS ECAL Barrel HL-LHC Upgrade

- PbWO crystal ECAL, crystals very fast – few 10 ps rise time.
- ECAL timing from LHC Run I : 150 ps global (70 ps local).
- New Very Front End (VFE) with Trans-Impedance Amplifier (TIA) & Oversampling (optimal with 160 Ms/s).
- Full detector readout, L1 accept rate 750 kHz @ 12.5 μs latency.
- Timing performance limited by the APD/cable to VFE.
- Timing resolution expected at 30 ps down to about 20 GeV.

CMS ECAL Laser Timing

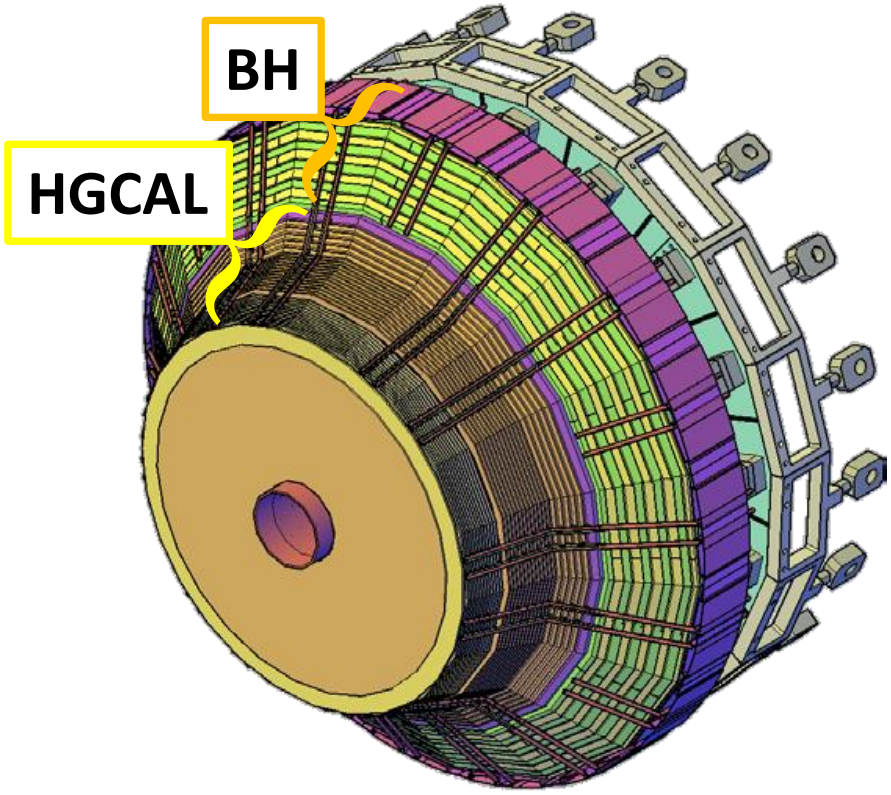


CMS ECAL 2015 Upgrade TB



Timing with Silicon Sampling Calorimeter

- **CMS plans to replace endcap calorimeter with a Si/W – Si/Fe (HGCAL) + Scint/Brass (BH) calorimeter for HL-LHC upgrade.**
- **It has been demonstrated that a <20 ps resolution can be achieved with a single Si pad sensor w/o gain if placed in an EM shower.**
- **An EM shower will have a few 10 pads contributing to the measurement.**
- **Precise timing readout in the design specs of the HCGAL readout chip. See eg. presentation at C. TWEPP2016.**

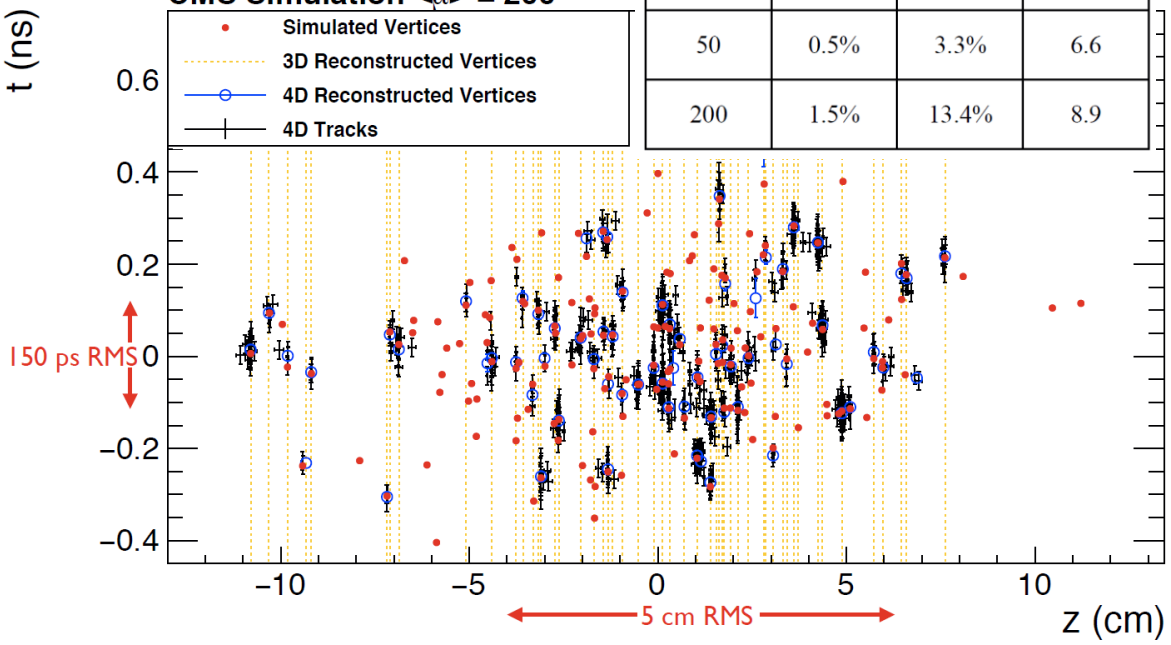


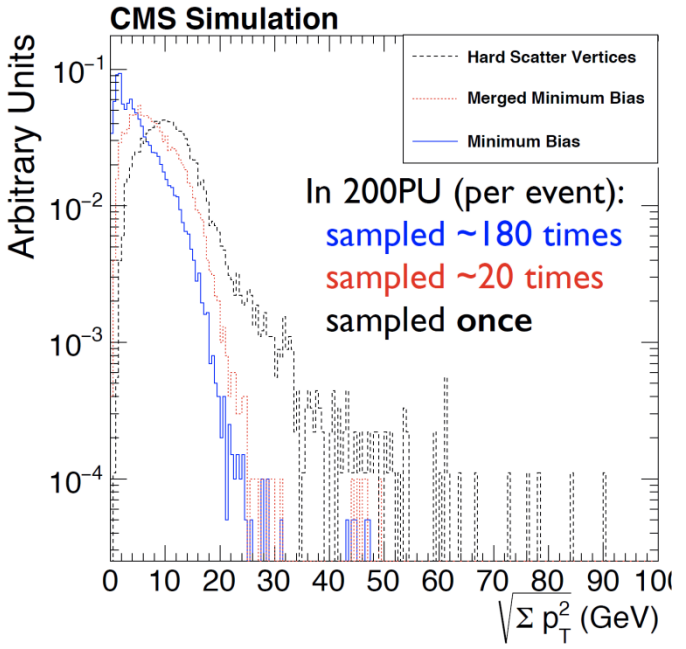
Track Time Tagging

- At 200 PU, increasingly difficult to separate nearby vertices.
- Vertex merging causes degradation in isolation and MET variables.
- Σp_T of merged vertices promotes PU events to be ranked higher than hard interaction in vertex ID.
- Further studies ongoing on rate of PU track merging to vertices.
- For more details see 2016 ACES workshop

CMS Simulation

<μ>	4D Merged Vertex Fraction	3D Merged Vertex Fraction	Ratio of 3D/4D
50	0.5%	3.3%	6.6
200	1.5%	13.4%	8.9

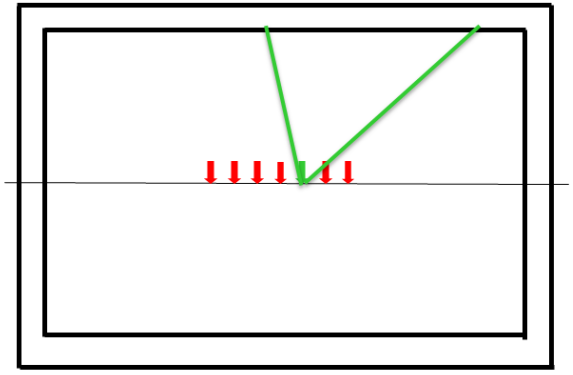




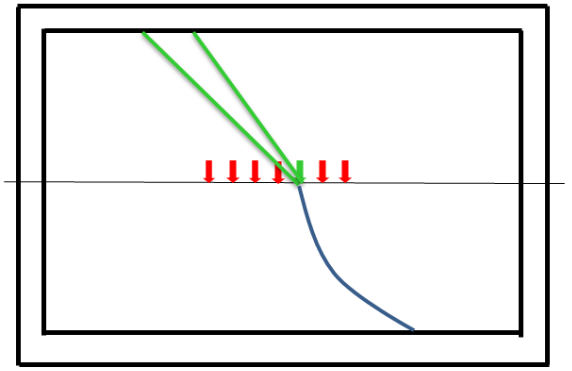
Combined Calo and Track Timing

- **Synergies between Calorimetric and MIP timing : Increased efficiency for time vertexing.**
- **$H \rightarrow \gamma\gamma$ use case : Vertex ID efficiency 80% in Run I, 40% expected in HL-LHC, 55% with photon-only time vertex, 75% with photon+track time vertex.**
- **Results corresponds to a 10% and 30% increase in equivalent luminosity.**
- **Results to be presented at the ECFA workshop in Aix les Bains.**

ECAL only timing



ECAL+MIP timing



Further Applications

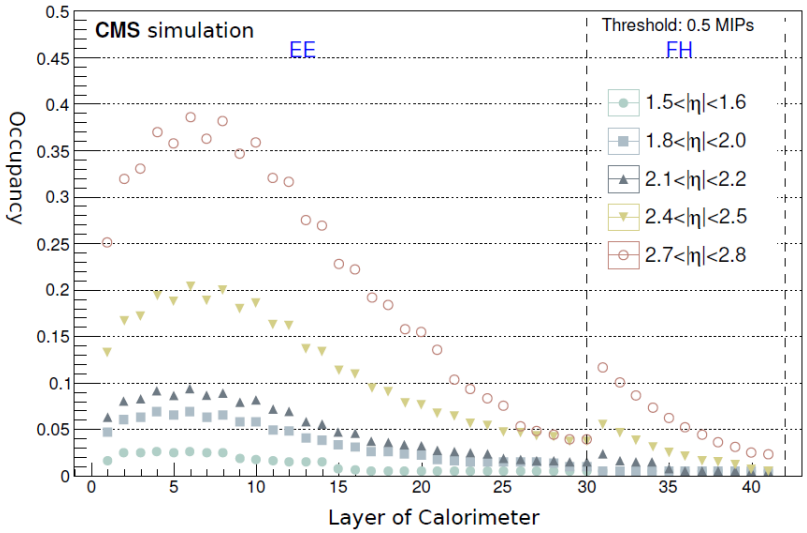
- **Look at statistically limited measurement (not inclusive cross section measurements) : Differential Higgs cross section.**
- **More advanced vertexing algorithms for Hgg events (photon + jets instead of two photons) $\Rightarrow$ Maximize η-coverage.**
- **Cleaning of isolation cones from PU contributions $\Rightarrow$ Mostly low p_T particles.**
- **Background cleaning in W/ZH (especially Z(nunu)H)**
- **Tau reco with π^0 time matching.**
- **Jet cleaning, jet vertexing, b-tagging.**
- **Associating photons to vertices eg. in $H \rightarrow Z\gamma$ to suppress background.**
- **Particle ID $\rightarrow$ See later slides.**

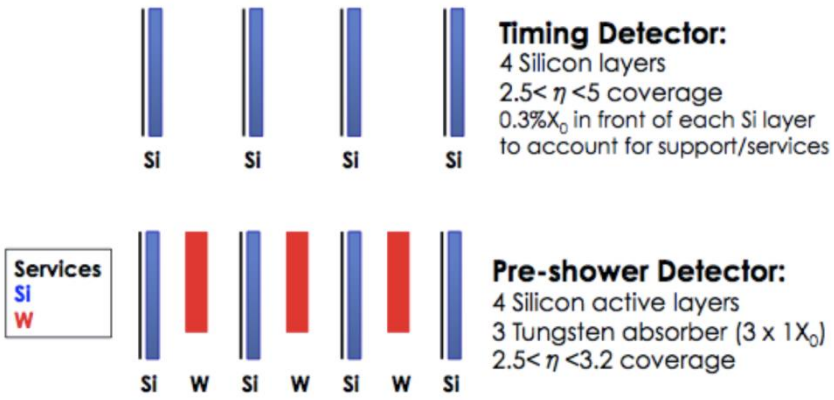
$\Rightarrow$ All of these need (or would benefit a lot) from extending the usable p_T range for timing to lower values – down to the MIP.

MIP Timing Detector

For HL-LHC upgrades – with ~todays technology:

- **Assuming a timing layer between tracker and calorimeter, choose granularity such that each track can be time tagged and occupancy below 10% to avoid double hits.**
- **Use CMS HGCAL simulation (1 cm² Si pads) to estimate occupancy.**
- **1 cm² granularity sufficient up to eta ~2.4.**
- **Impact point taken from tracker to associate time tag to track.**
- **CMS Timing Layer : Barrel area ~40 m² , Endcap ~9 m²**
- **ATLAS HGPT coverage : 2.5 < eta < 5.**



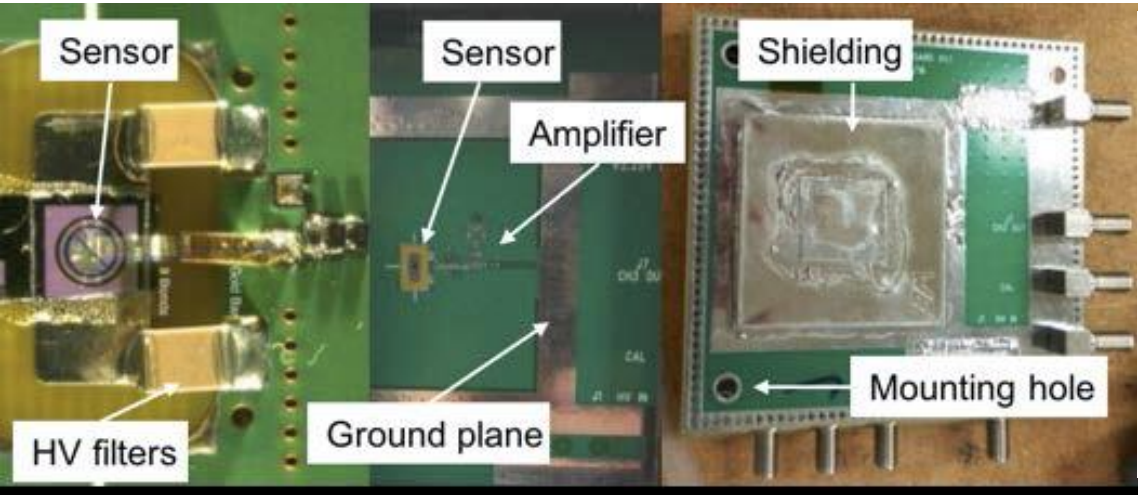


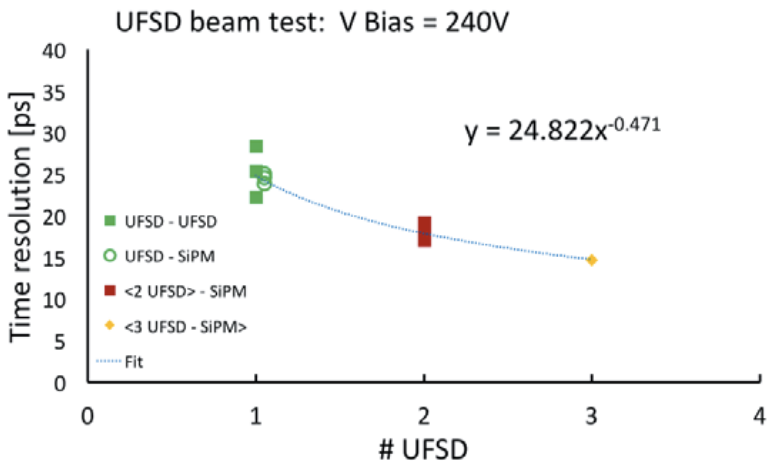
Precision Timing Tracker ?

- **Landau fluctuations in Si sensors limit timing precision.**
- **Tracker aims to minimize material budget at all cost – with todays technology, ps precision still needs more services (power, data).**
- **Tackers have >10 layers – combination of information may allow to relax single sensor performance.**
- **Full power of timing shows in a full event reconstruction – need to look at physics objects to judge.**
- **Strict separation of sub-detectors may be a thing of the past : As calorimeters learn how to do tracking, trackers may learn how to do calorimetry and both learn how to do timing.**

Silicon Timing : LGAD

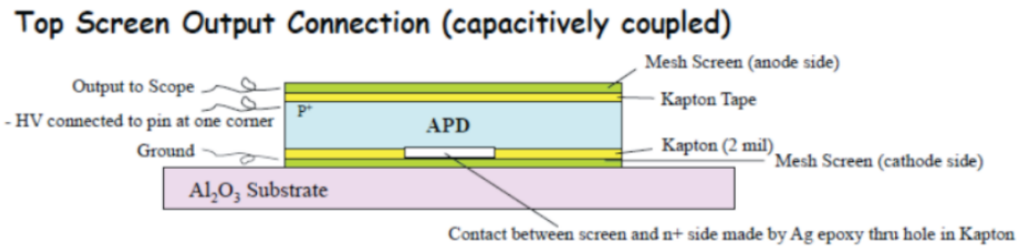
- **Recent results from N. Cartiglia arxiv 1608.08681**
- **Low-Gain Avalanche Detectors (LGAD) design, employing n-on-p silicon sensors with internal charge multiplication in a thin, low-resistivity diffusion layer below the junction.**
- **UFSD used in this test belongs to the first production of thin (50 μm) sensors, with an pad area of 1.4 mm^2.**
- **With three sensors aligned on a track, 15 ps are achieved.**
- **ATLAS HGPT based on this sensor.**

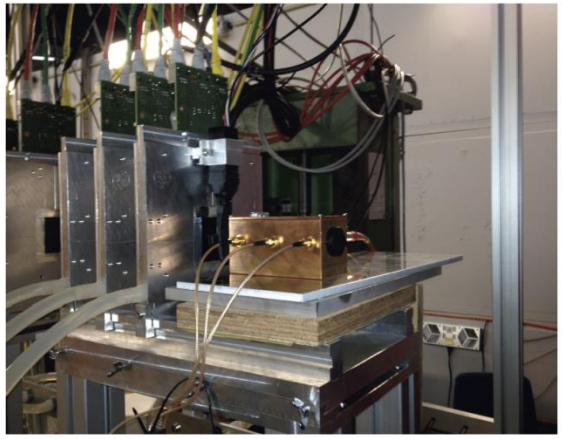


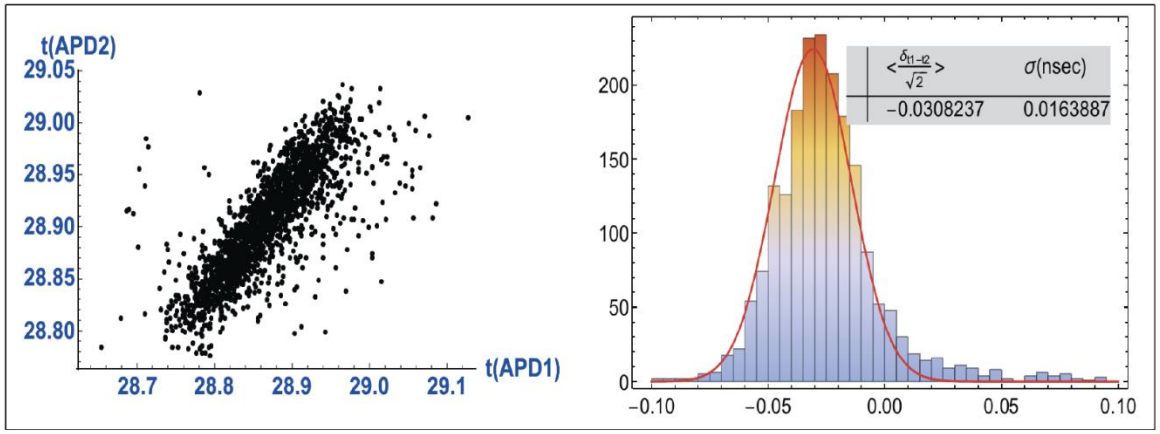


Hyper Fast Silicon

- **Deep Depleted APD with micromegas mesh readout**
- **Large MiP signal (3600 eh pairs × 3 internal APD gain of few 100)**
- **Weighting field controlled with sintered Au (bottom) and MicroMegas (top) layer, Landau contribution limited, may offer additional benefit due to its electrical properties.**
- **See eg. S. White, Elba, 13th Pisa Meeting on Advanced Detectors [Fast Timing Detector R&D for the HL-LHC era]**



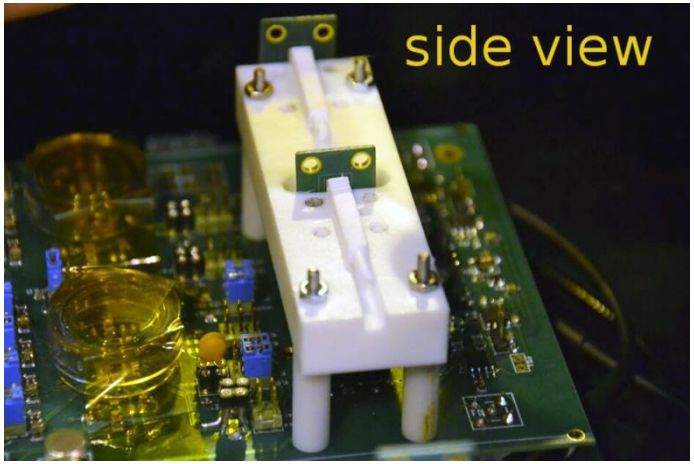


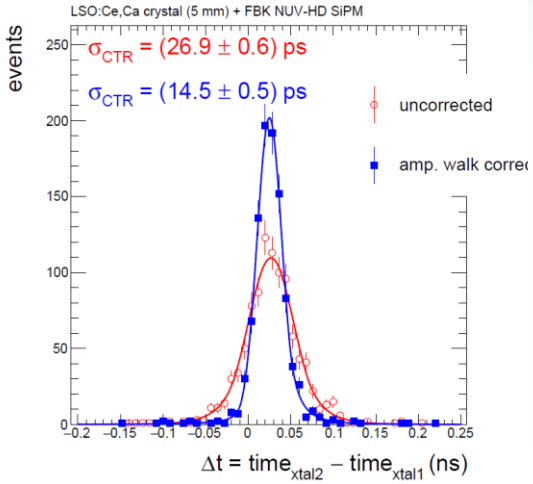


Crystal MIP Timing

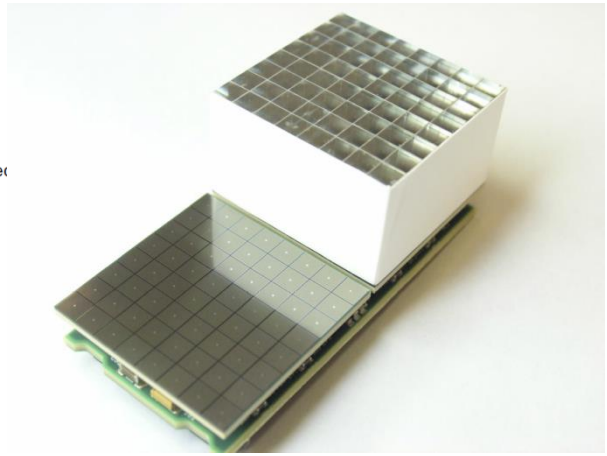
- **Timing precision <20ps for MIPs can be achieved with LYSO crystals of a few mm thickness with SiPM readout, granularity ~1 cm^2**
- **Thin layer detector : Total thickness including VFE in a few cm (<0.5 X_0) between tracker and calorimeter.**
- **LYSO has shown to be radiation hard up to HL-LHC doses.**
- **SiPM radiation hardness has been improved a lot in recent years. May sufficient for CMS Barrel region already with cooling.**

M. Lucchini et al, CALOR2016, CALOR2016





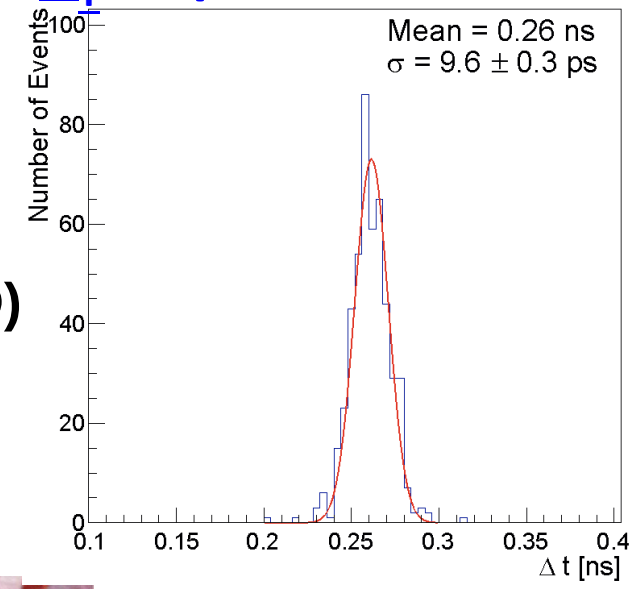
TOFPET, CERN



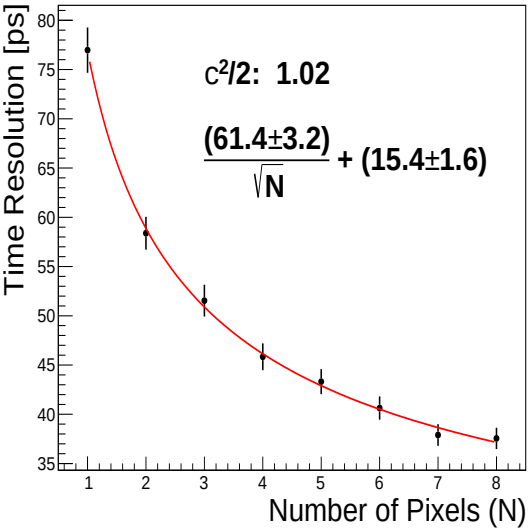
Micro Channel Plates

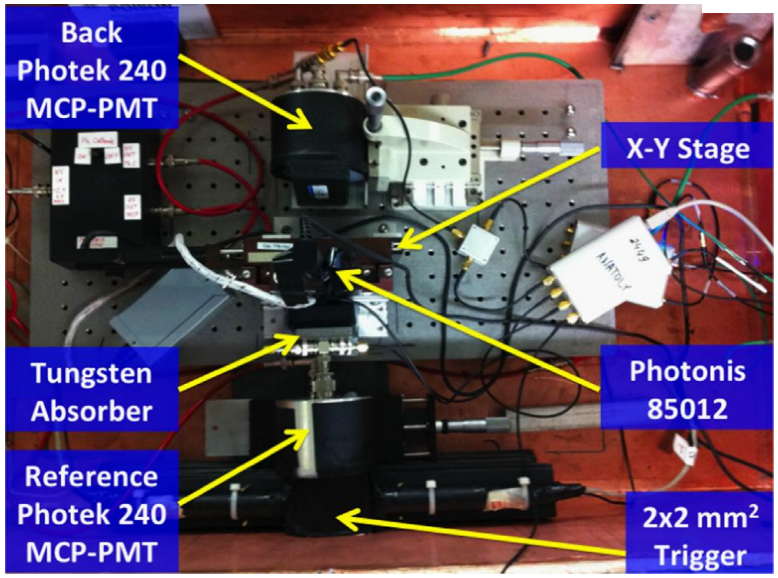
- MCPs achieve <10 ps resolution for MIPs.
- Crucial tool to study timing detectors.
- Operation in secondary emission mode avoids the need for a photo cathode.
- Significant R&D for large area MCPs (LAPPD)
- For LHC, would need large area, radiation hard, segmented and high rate capable.

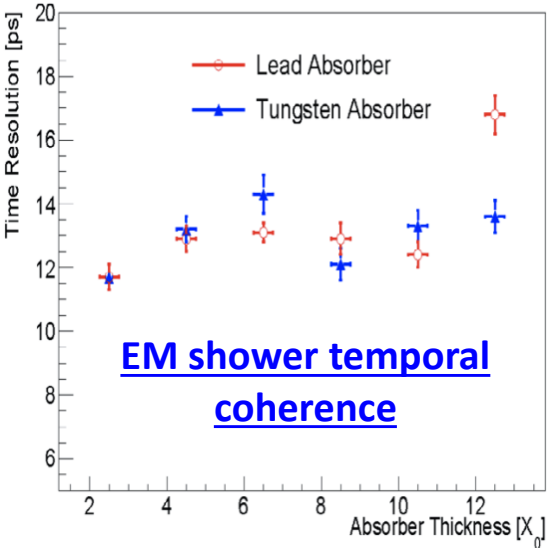
σ_T : 7 ps (single device : 9.6/√2)



Pixelated MCP, multiple measurements on a shower



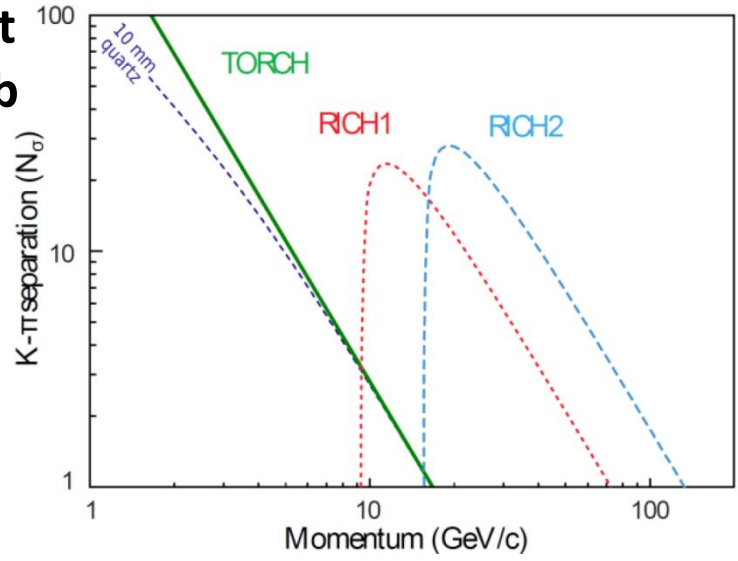


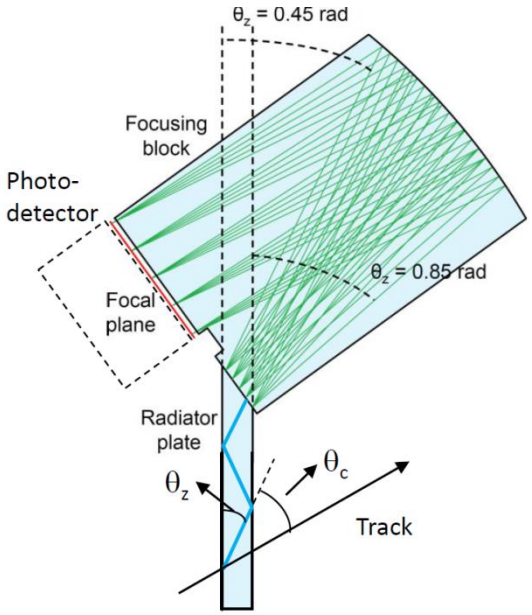


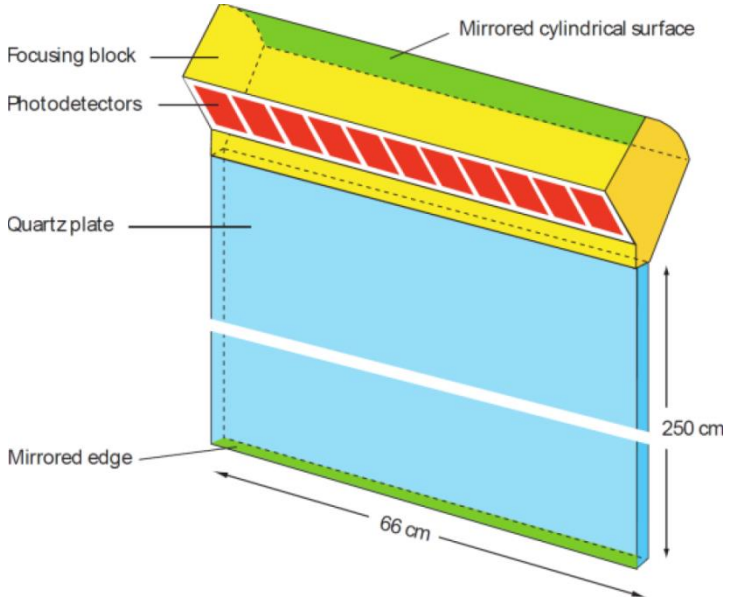
LHCb : Particle ID with TOF

TORCH: Time Of internally Reflected Cherenkov light

- **DIRC-like detector, proposed as upgrade for LHCb**
- **TORCH has the potential to complement the existing PID system (RICH1, RICH2) in the low momentum regime (2-10 GeV/c) Principle of operation**
- **Precision timing at known p provides PID :**
- **ΔTOF(π-K) = 37.5ps at 10 GeV/c ,**
- **Target (three sigma separation) is ~15ps / track**

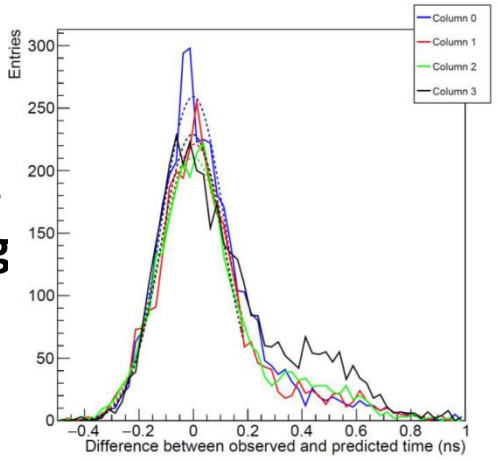




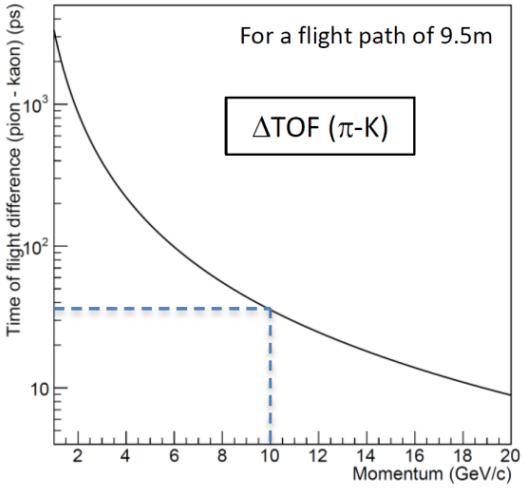


TORCH TOF Test Beam

- **Best time resolution with 2015 test beam data : 117 ps**
- **Recently 2016 test beam with significant improvement.**
- **CMS/ATLAS have ~7 less lever arm, but with 10 ps timing may be of interest for TOF PID ?**



LHCb TOF PID



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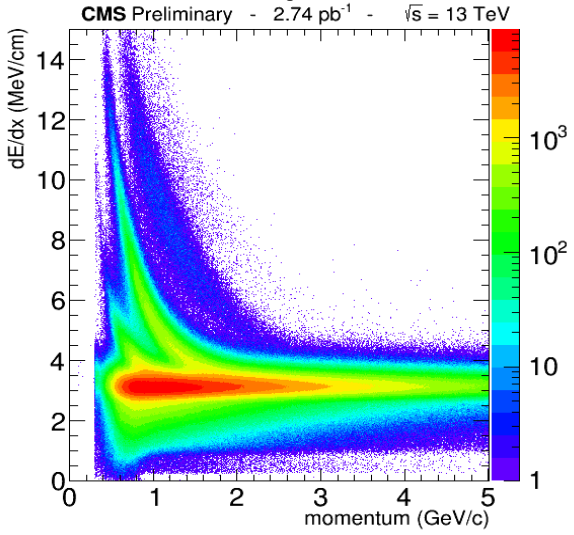

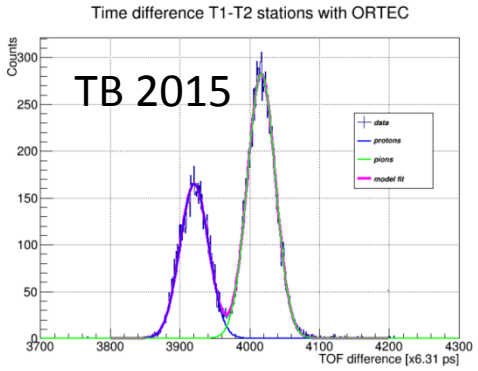

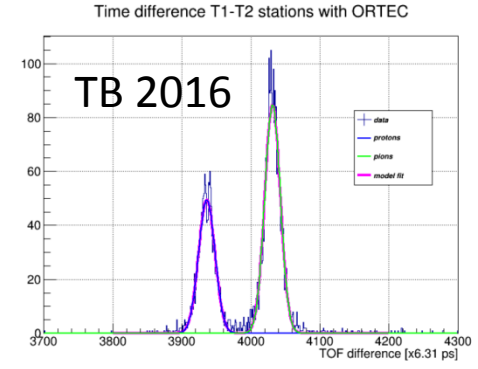

For more details, see :

T. Gys :"The TORCH detector R&D: Status and Perspectives", 09/2016, RICH2016

Maarten Van Dijk : "The TORCH project Testbeam results & current status", 09/2016, Picosecond Timing Workshop Kansas

Summary

- **Precision timing can be a powerful handle to mitigate pile-up effects at HL-LHC.**
- **A wide range of sensor and detector technologies allow timing at the 10 ps level.**
- **Very active R&D towards the HL-LHC upgrades to enhance existing detectors or add additional timing detectors.**
- **Holistic event reconstruction in the HL-LHC era challenges the traditional sub-detector division.**

Great environment to inject new ideas !

Backup