Precision timing in high rate and high pileup

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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 $\Sigma p_T$ to find hard vertex.
- At HL-LHC to many PU vertices with high $\Sigma p_T$.
- 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 satellites.
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.

$t = t_0$  $t = t_0 + \Delta t$  $t = t_0 - \Delta t$
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 $p_T > 20$ 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
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
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.
- $\sum p_T$ 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
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 correspond 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) ⇒ Maximize \( \eta \)-coverage.
- Cleaning of isolation cones from PU contributions ⇒ Mostly low \( p_T \) particles.
- Background cleaning in W/ZH (especially Z(nunu)H)
- Tau reco with \( \pi^0 \) time matching.
- Jet cleaning, jet vertexing, b-tagging.
- Associating photons to vertices eg. in \( H \rightarrow Z\gamma \) to suppress background.
- Particle ID → See later slides.

⇒ 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 today’s 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 mm².
- 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 cm².
- Thin layer detector: Total thickness including VFE in a few cm (<0.5 X₀) 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.

$\sigma_T : 7 \text{ ps} \quad \text{(single device : } 9.6/\sqrt{2})$

Mean = 0.26 ns
$\sigma = 9.6 \pm 0.3 \text{ ps}$
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?

For more details, see:
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!