Implications of fast timing to VFE board design

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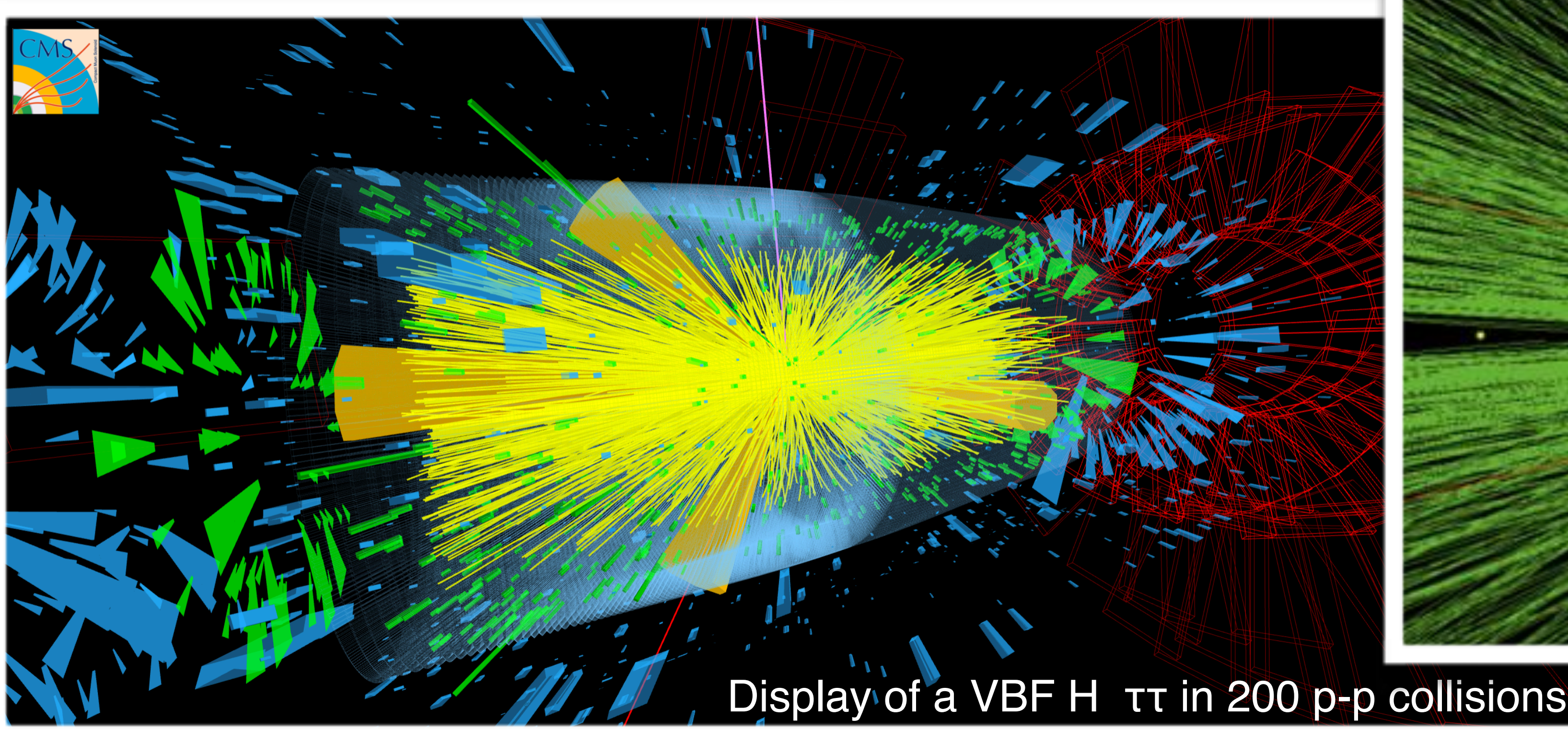
Outline

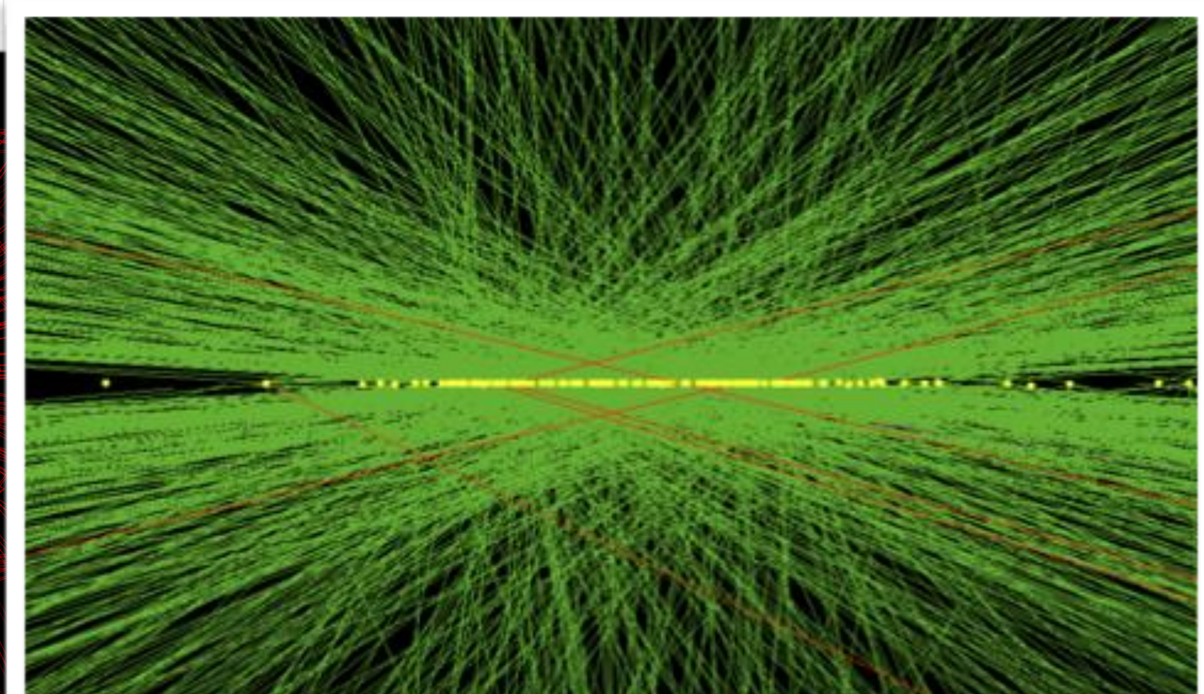
- Why timing?
  - Timing of what + quantitative statements
- Present and future ECAL timing performance
- Fast timing detectors and implications

HL-LHC environment

- HL-LHC **harsh environment**:
  - 140 (→200) collisions for bunch crossing
- “Interesting” interactions are < **1% of produced vertices**
- Individual vertices not resolved → **10% of vertex merging rate**
- **Highest Σp_T^2** not necessarily most interesting collision



Display of a VBF H ττ in 200 p-p collisions



Physics performance @ HL-LHC

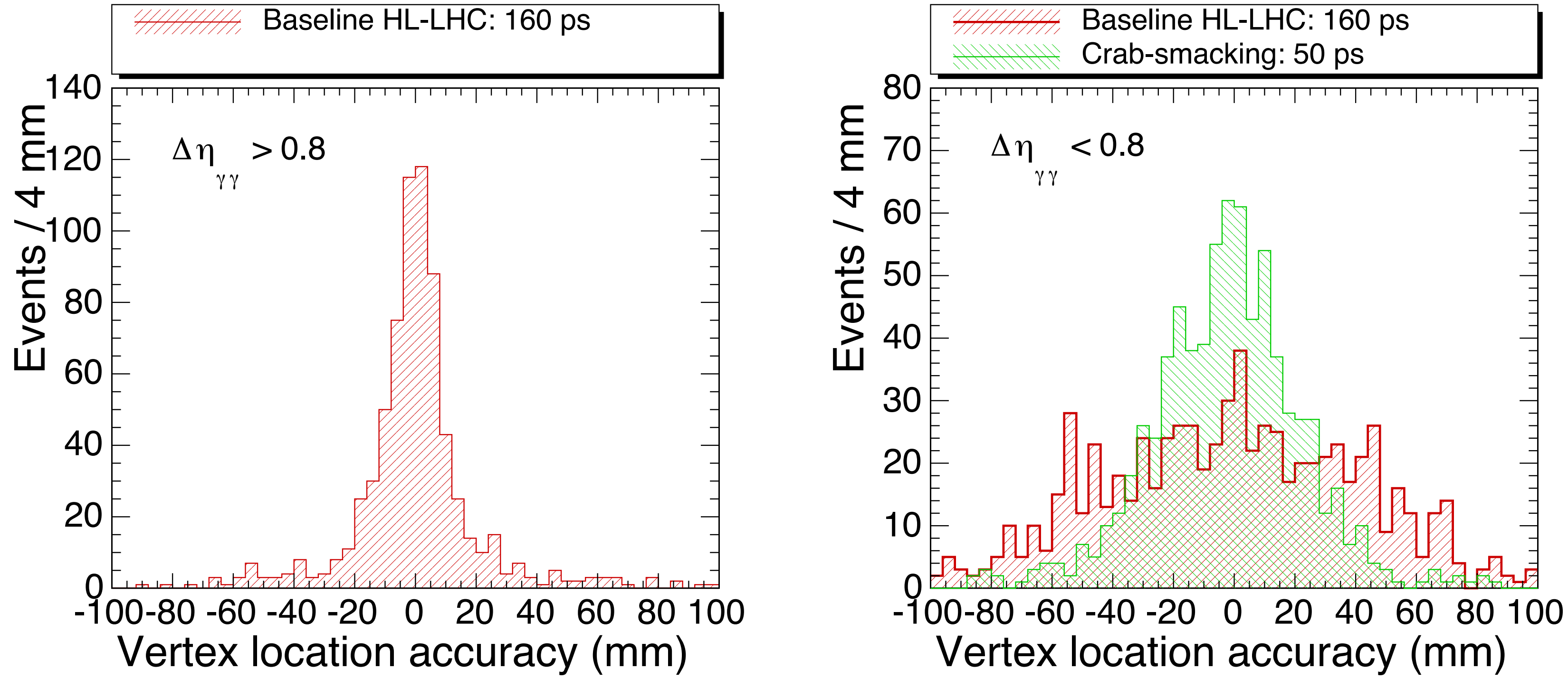
- Many **low-level effects** on object reconstruction:
  - Extra energy in **jets** / **isolation cones** from particle overlap
  - **Merge of vertices** and fake high p_T jets
  - Degraded **Jet/MET performances**
  - Degraded efficiency in **associate photons with vertices**
- Precise time information of different particles can **mitigate these effects:**
  - Timing of **tracks and low p_T photons**:
    - **Vertex reconstruction** using timing info
    - **Pile up mitigation**: removal of extra energies in jets/ isolation cones, improved MET performance
  - Timing of **high pT electromagnetic showers**:
    - Vertex location for diphoton system
      - Compensate efficiency loss in association of $H \rightarrow \gamma\gamma$ photons to vertex

HGCAL and/or additional detectors (last slides)

Calo-timing: ECAL could have a key role

Calo-timing: H→$\gamma\gamma$ as case study

- **Diphoton vertexing efficiency ($|z_{vtx}-z_{true}|<1$cm)** in H→$\gamma\gamma$:
  - Phase I LHC: **~75-80%**, it goes to **30%** for HL-LHC
  - With 30 ps resolution for photons:
    - For $|\Delta\eta_{\gamma\gamma}|>0.8$: **68% for vertex location with photon timing alone** (50% of total events)
    - For $|\Delta\eta_{\gamma\gamma}|<0.8$: Poor performance on vertex location with photon timing alone



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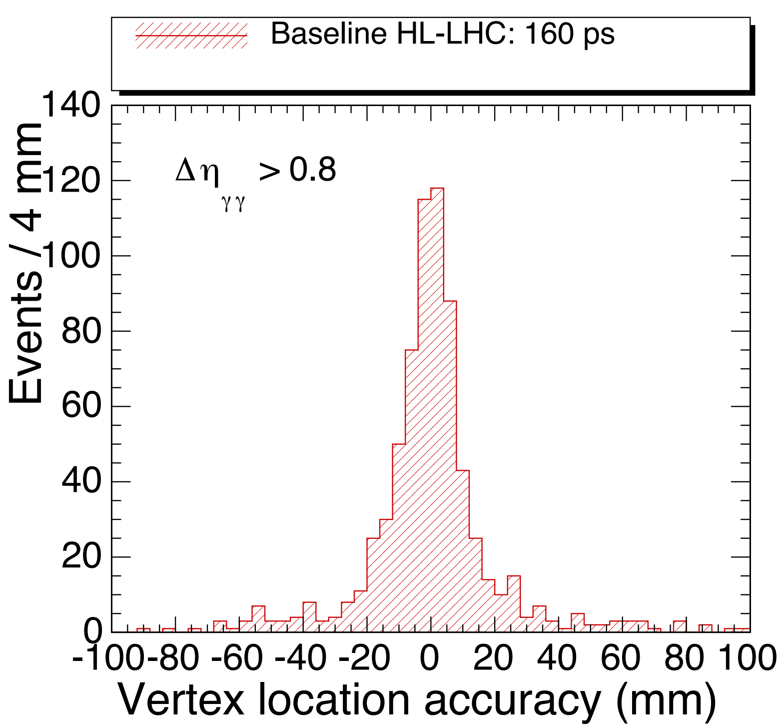
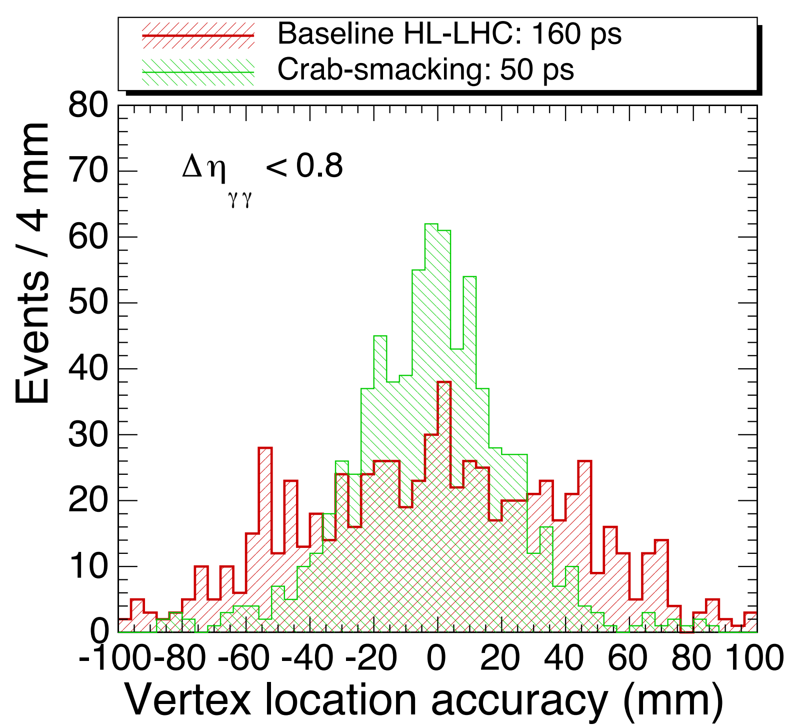
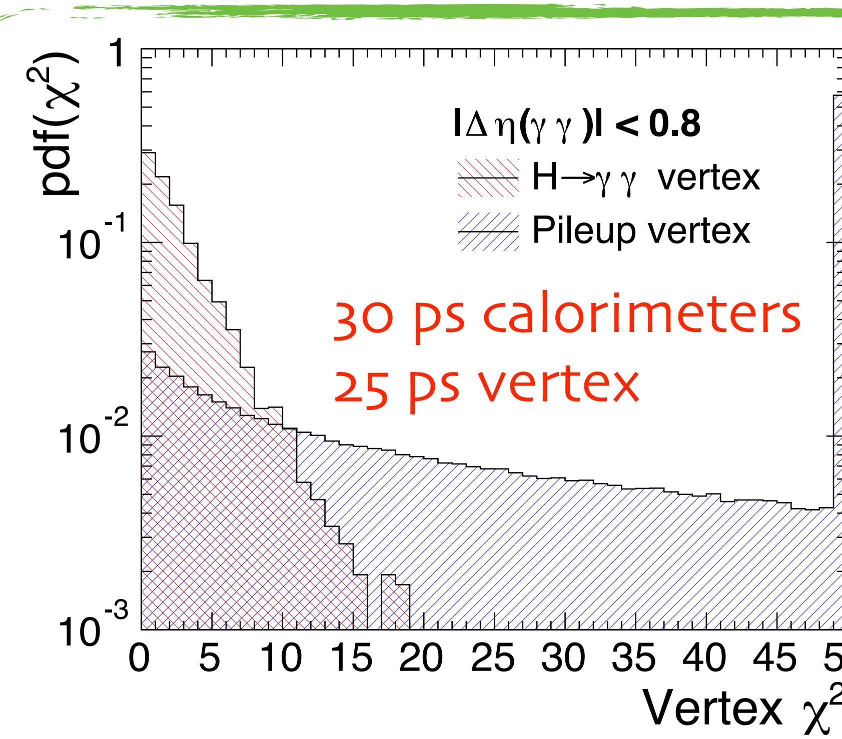
  - For central events time of vertex and/or kinematics also needed

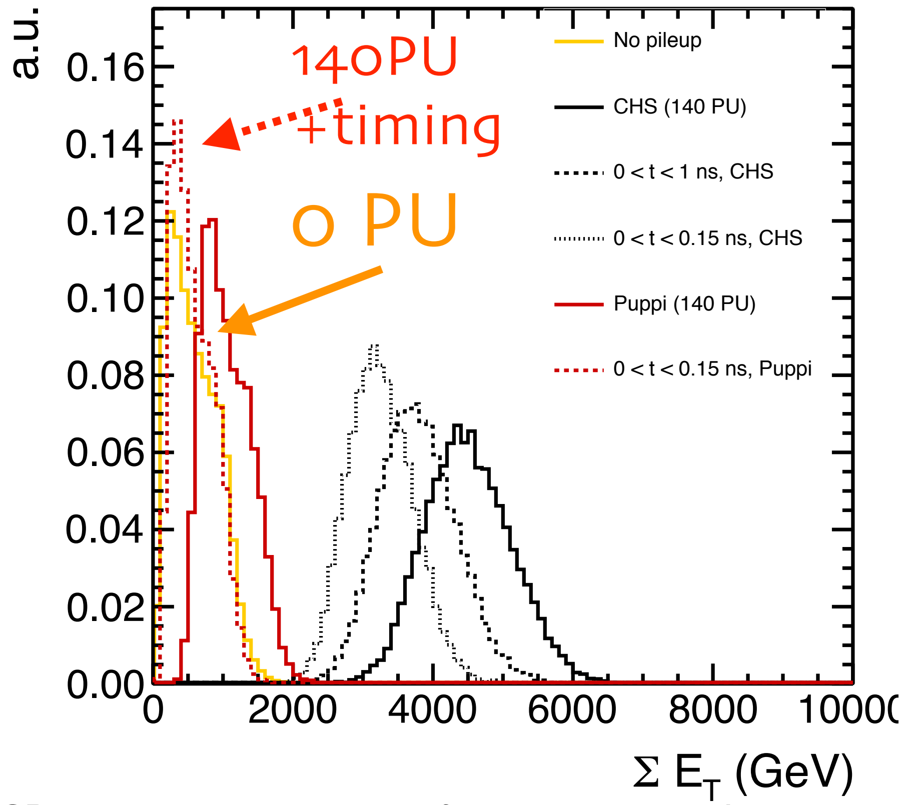






MIP and low energy photons timing

- With **O(25) ps** resolution on both **neutrals** and **tracks** **50 PU performance recovered**
- **Vertex merging** reduced by ~1 order of magnitude
- With **hermetic timing system** pileup mitigation recover performance loss of PF reconstruction



QCD event sample: p_T sum of all reconstructed particles

"The greatest performance benefits are observed when timing information from neutrals is matched with time-zero information from the vertices, extracted from charged tracks."

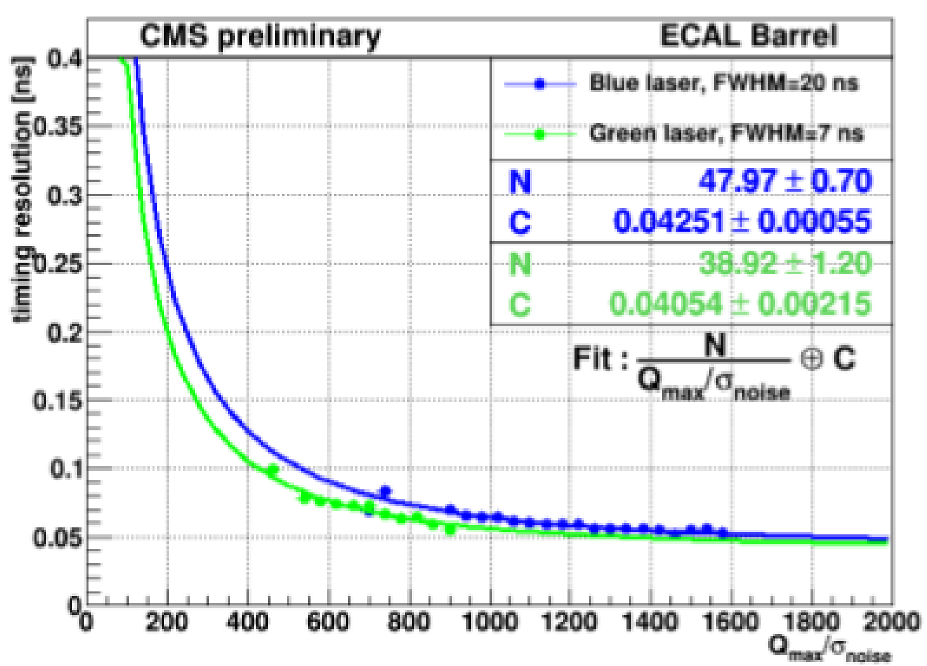
More details with case studies on both calo and tracking timing here: Fast Timing Working Group Report

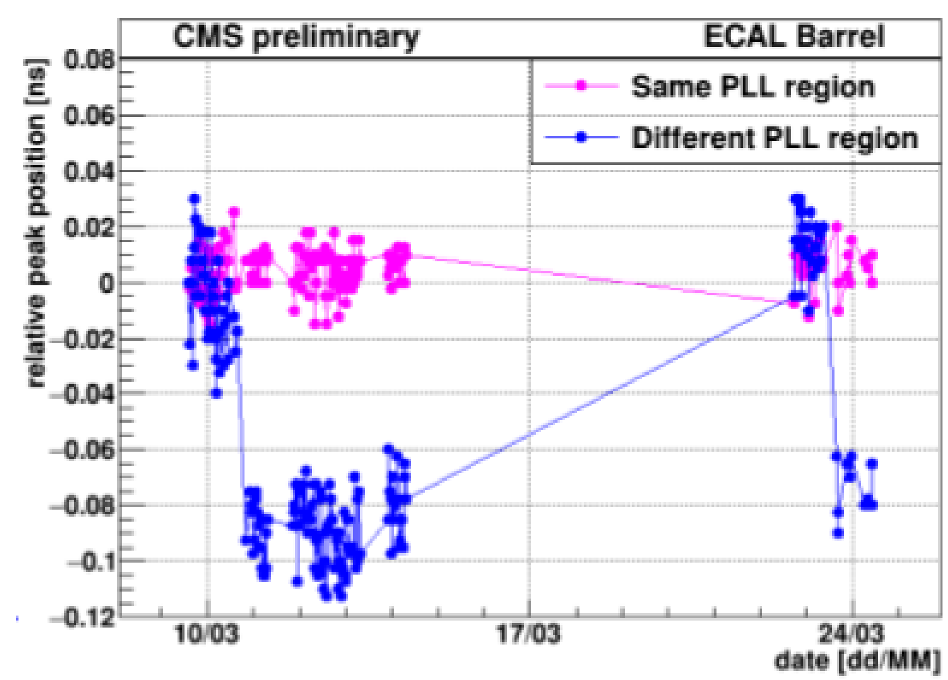
More thoughts on implications slides 13-16

Current timing performance

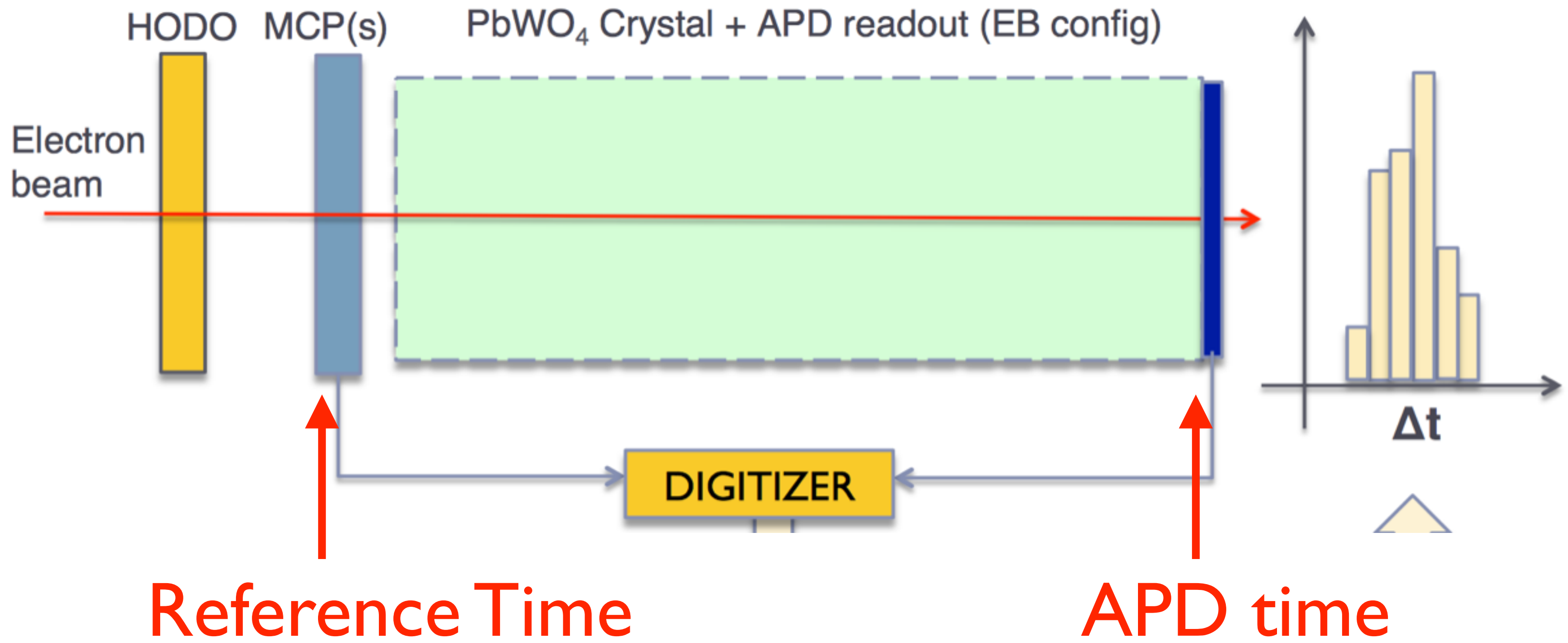
- ECAL performance @ **LHC collisions at 8 TeV:**
  - **Ecal Timing paper of 2009 shows constant term 40ps on neighbouring xtals**
  - ~**150-250 ps** for electron from Z → ee events
- To achieve detector-wide good resolution **clock stability** is needed
- Clock distribution **monitored with laser system**:
  - Timing resolution of ~ 40 ps measured for crystals illuminated at the same time
  - Instabilities measured over time due to power cycle for channels in same token ring

- Absolute time of laser could be used as **reference to equalize different regions** and improve resolution



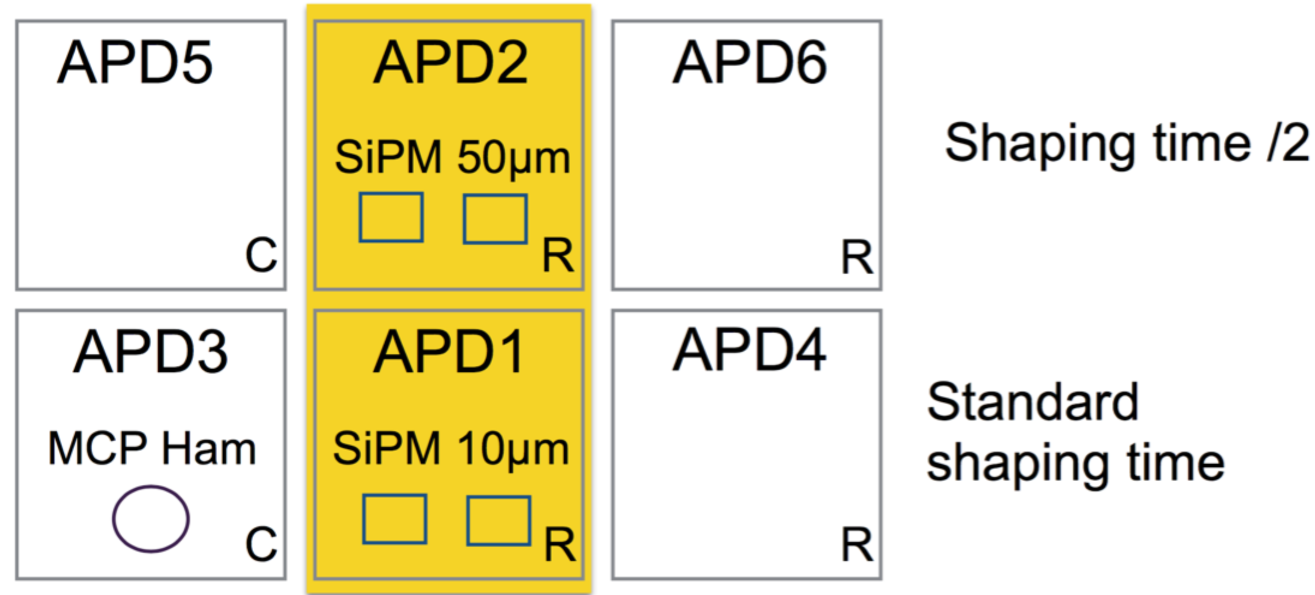


Precision timing test beam



- Fall 2015:
  - Test beam in H4 with **electrons up to 200 GeV**
  - 2x3 barrel xtal matrix, different photodetectors configuration:
    - **APD** (back), **MCP** (front) (→ to give **reference time**), SiPM-MCP (front)
- Previous TB: timing studies looking at xtals in same shower
- This TB: We measure time wrt **time of entrance of electron on the xtal**

Timing TB setup

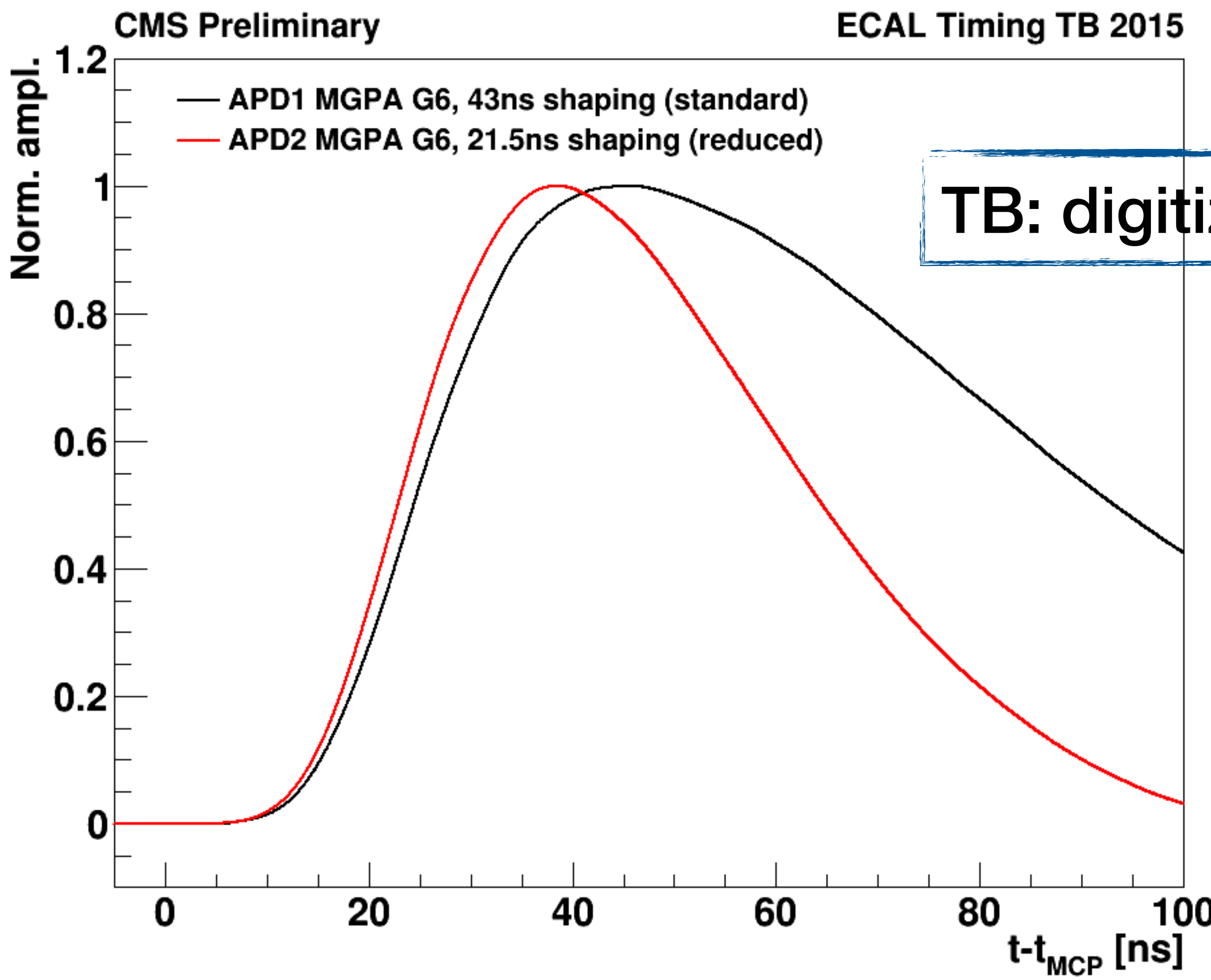


View from the front

- **2x3 barrel** PWO crystals:
  - **VFE board** interfaced with fast digitizer
  - one row with **standard MGPA electronics**, one row with MGPA **shaping time reduced by a factor 2** (dV/dt x 2 at the same shower energy).
  - Using MGPA GAIN 6 (to fit within digitiser dynamic range for all energies)
- 3 crystals with **photodetectors from the front**: 2 crystals with HPK SiPMs, 1 crystal with HPK MCP
- 2 MCP in front of the crystal matrix used as reference timing for the electron
- **Time resolution of MCP reference time ~25ps** (subtracted in quadrature for coming resolution plots)

APD: Test beam results

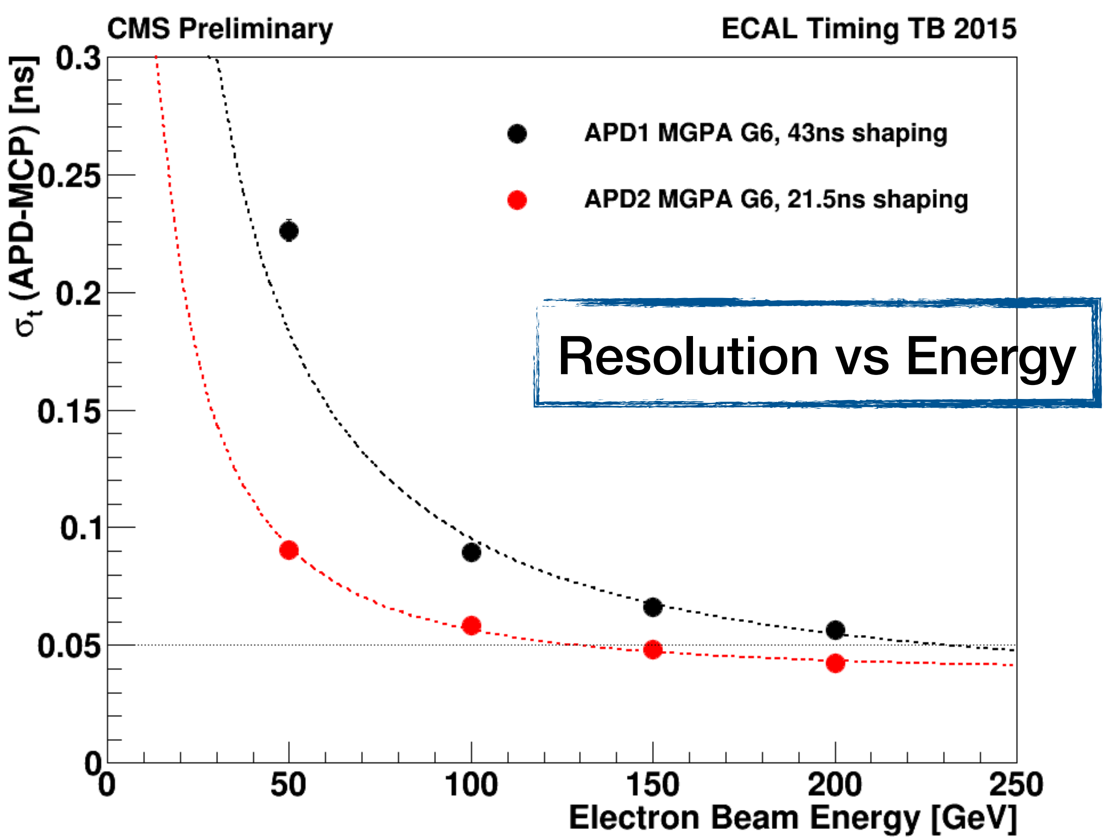
- Waveforms **sampled at 5Gs/s**
- **Two shaping time configuration** tested: 43 ns (standard) and 21.5 ns

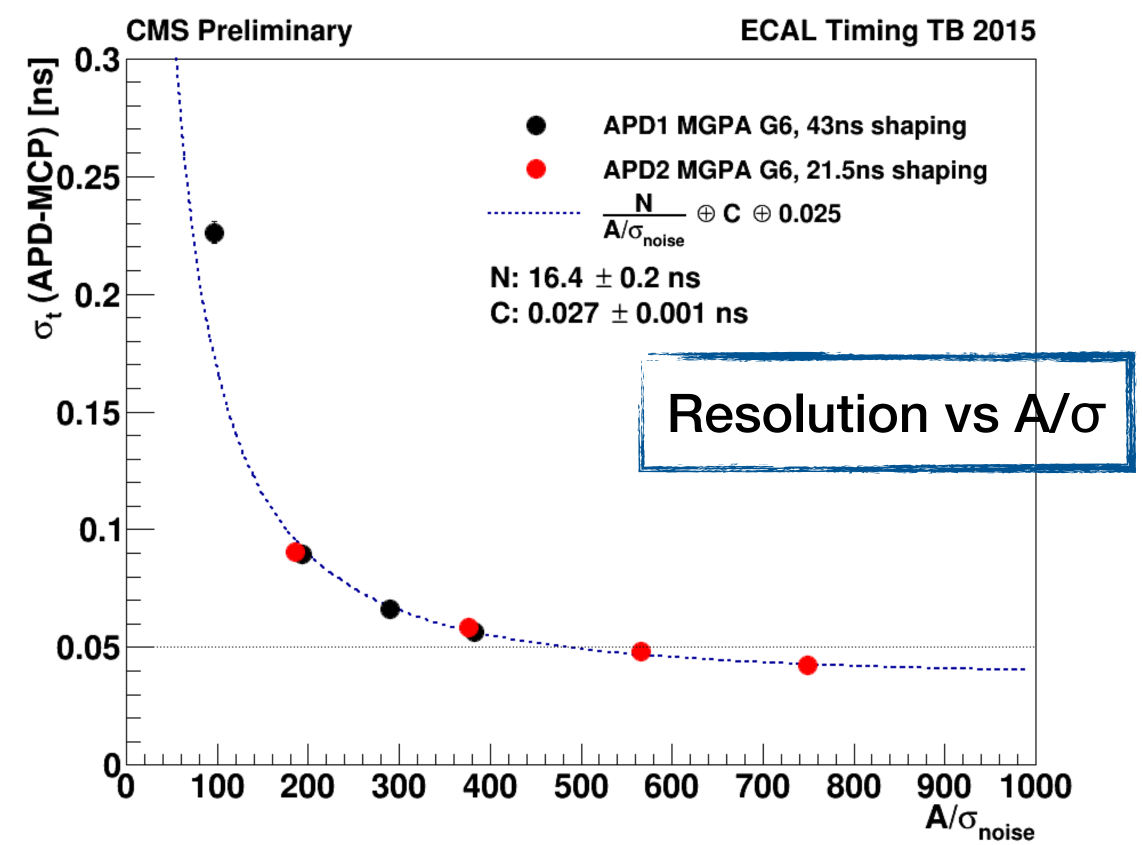


TB: digitized APD signal

- APD signal time obtained from a **template fit to the digitised pulse shape** (160 samples used in the fit)

APD: Resolution vs amplitude





Noise dominated by **test beam electronics**:

Noise of the differential to single ended buffer used to send the signal to the digitiser (same noise level for APD1 & APD2, but APD2 has ~ x2 dV/dt).

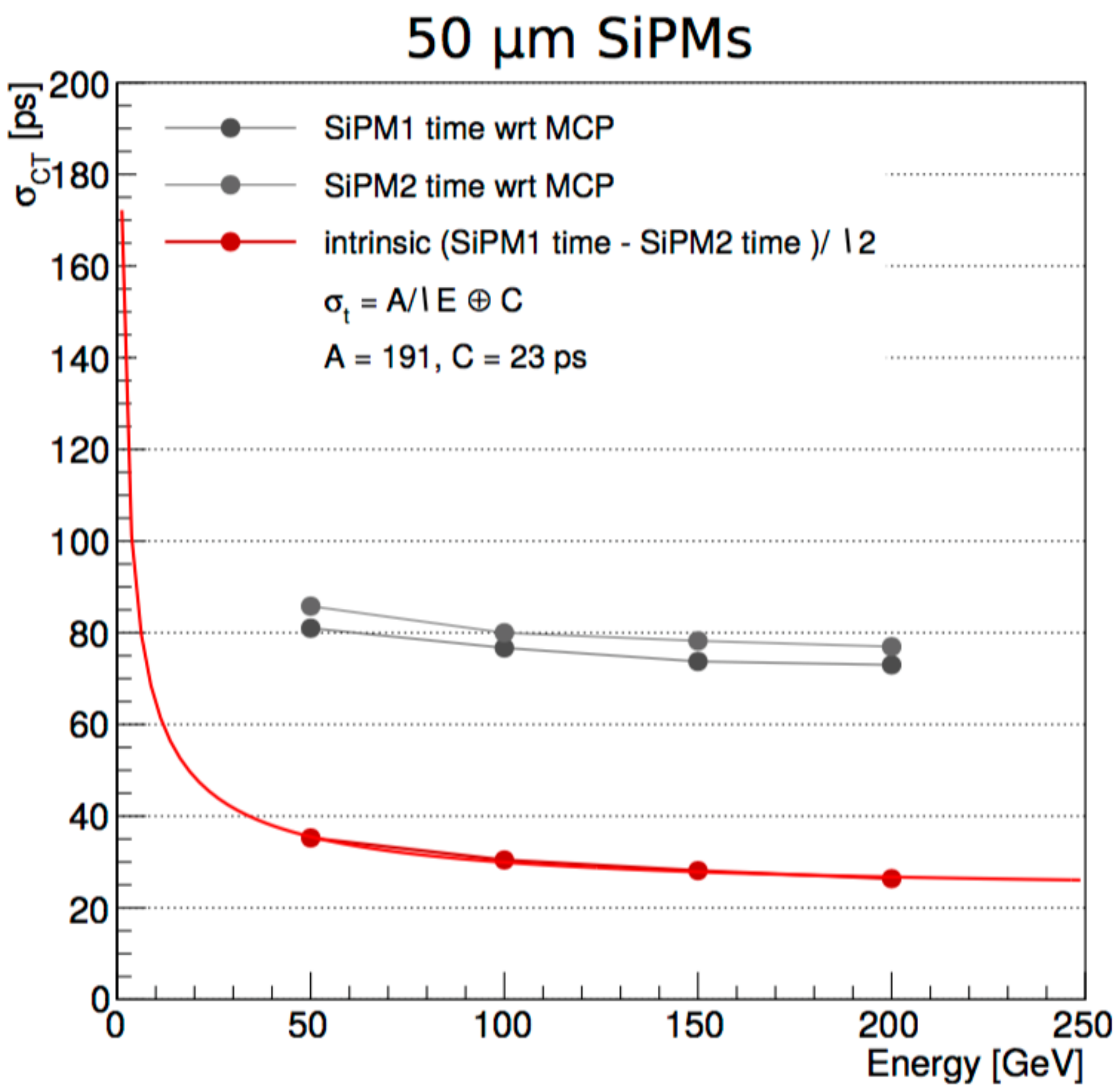
Resolution as a function of A/σ follows a common curve for APD1&2.

In CMS for **50 GeV shower A/σ ~ 800**

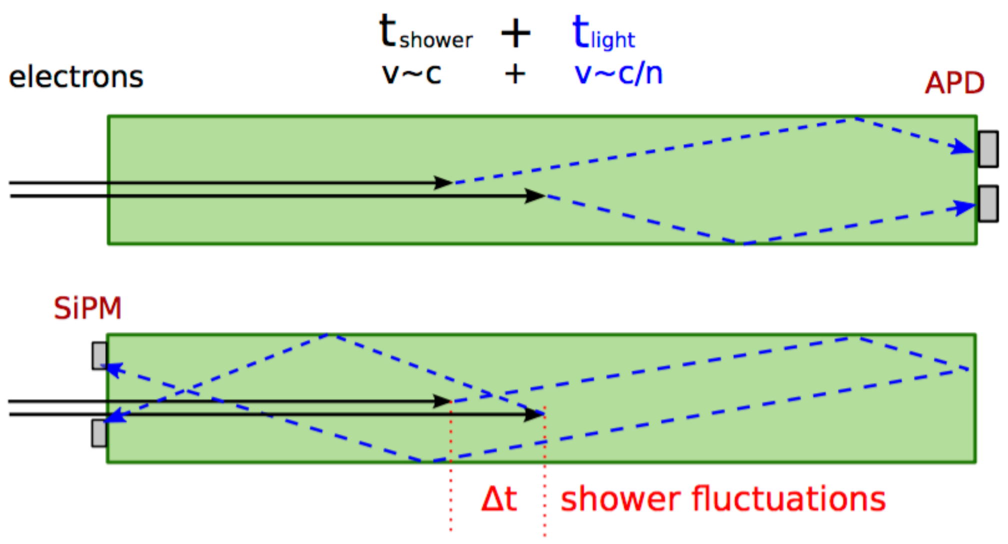
Constant term below 30ps indicates that intrinsic $PbWO_4$+APD jitter is below this value.

SiPM: Front face light collection

- Two SiPM attached to the **crystal front face**. Time extracted with a NINO board.
- Coincidence between the two SiPM proves that SiPM + NINO has **resolution ~25 ps**
- Comparison with reference MCP time yields to a timing resolution **limited to 70-80 ps**.



- Largest time resolution component in reading from the front could come from **shower fluctuations**
- **Dimensions** of the SiPM also matter
- Necessary to iterate with two SiPM on the bottom and different SiPM

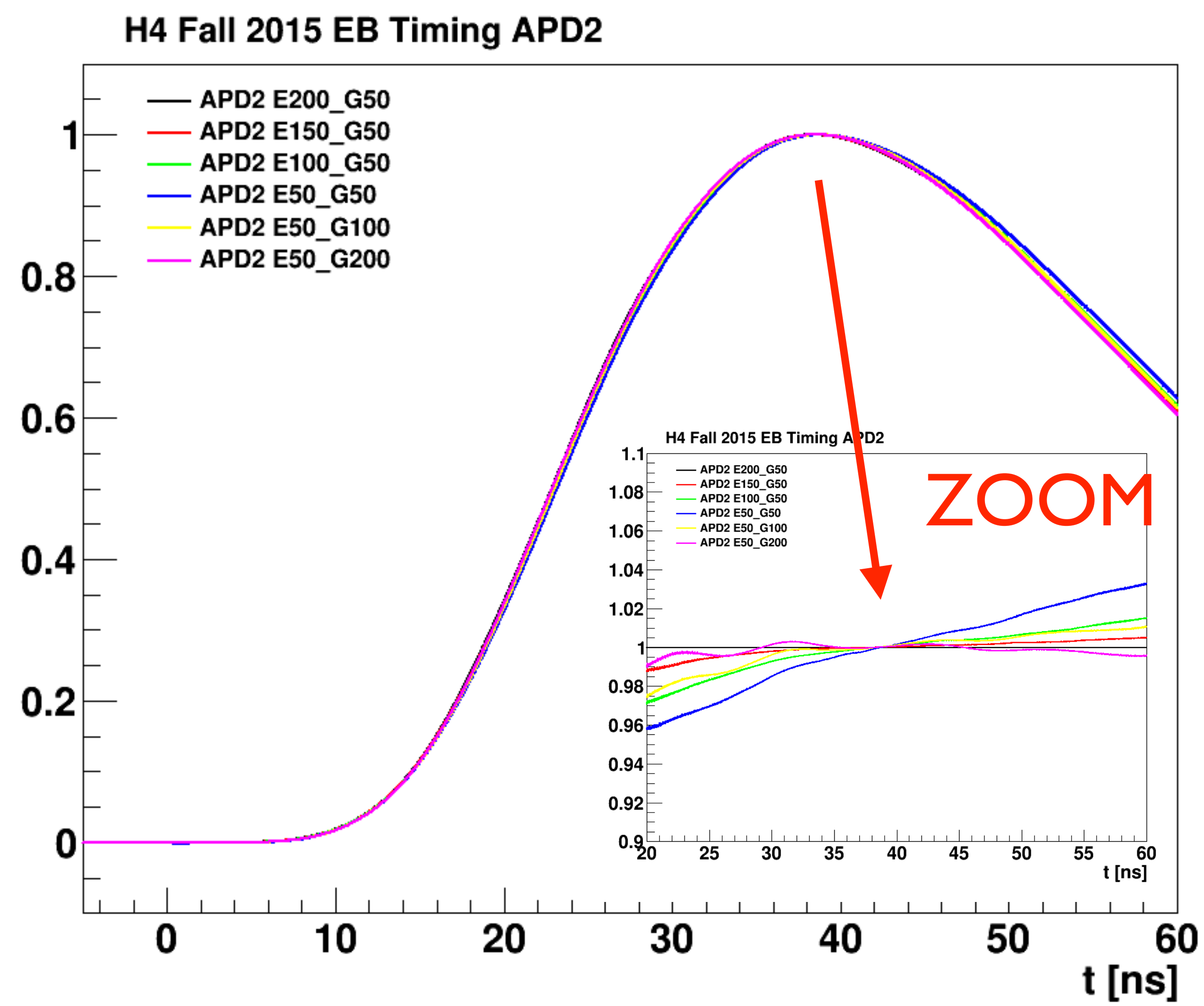


ECAL Timing resolution

- **ECAL Timing resolution**:
  - Time intrinsic resolution **better then 30ps** is possible for PWO+APD (for shower >30 GeV)
  - In the TB, main time resolution contribution dominated by **external noise** (not coming from the MGPA). Resolution scales with dV/dt as expected.
  - **Bandwidth limit of the APD+kapton** (35 MHz) limits fast rise time. Could be another important limiting factor. (see Marc slides)
  - Jitter depends on **many factors**: which parts of the pulse is used, radiation damage, shaping or not pulses (see Sasha's slides). To be studied further on both simulations and data.
- **Front face readout promising,** needs more understanding of limitations
- **Promising,** to be demonstrated:
  - **Clock stability** needed to achieve detector wide timing resolution of ~ 40 ps can be maintained with laser monitoring system

Future plans

- Final assessment of **intrinsic timing performance** for EB Phase II electronics will require further studies both on simulation and test beam:

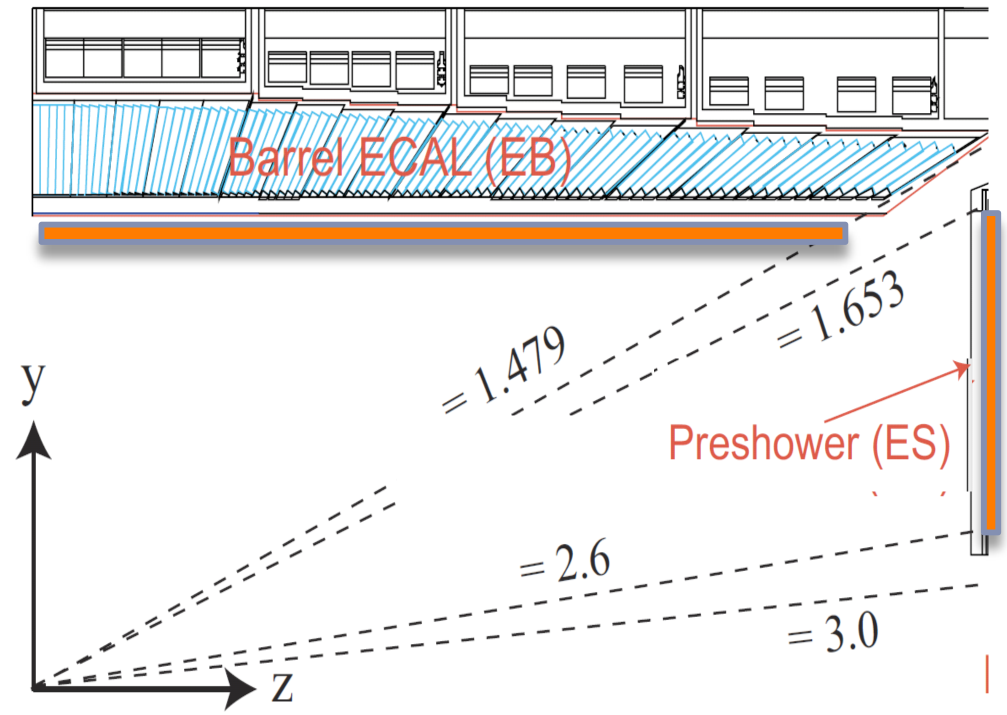


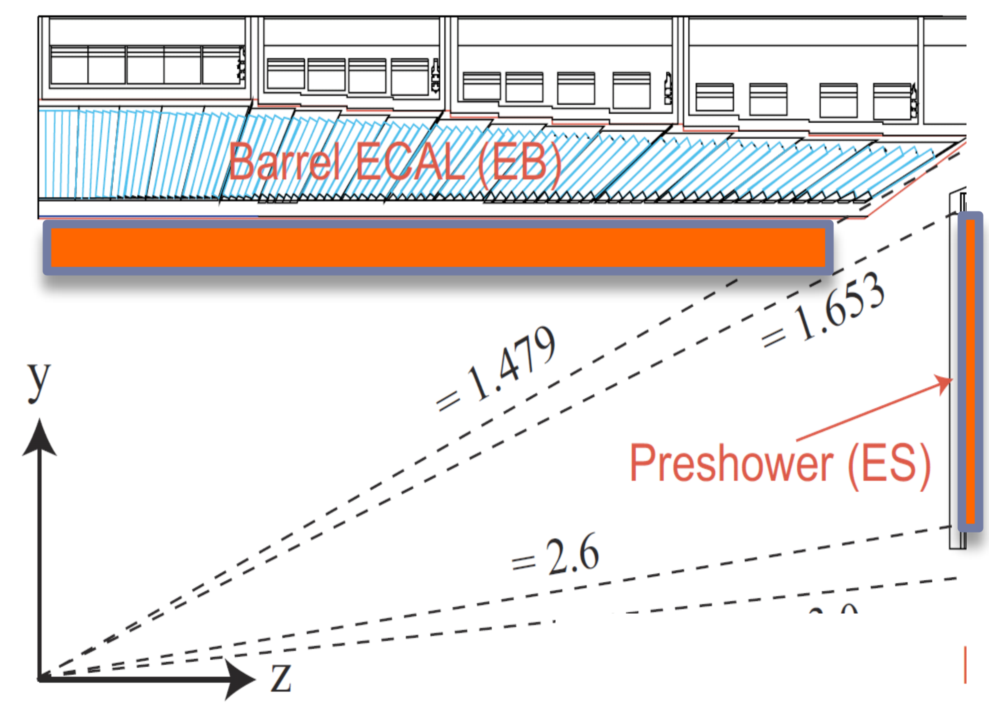
- Slightly different waveforms at different energies:
  - Probably electronics but could be related to time of arrival of photons
- Important to assess **linearity of electronics**:
  - Linearity study of TB electronics in lab with LED/LASER on APD envisaged
  - This study can be done also on new electronics

- **Final goal** of this test beam season:
  - Intrinsic timing of shower on APD and non-linearities to correct (shower development & fluctuactions)
  - **Test beam** with new electronics: **Matrix 30 xtals**, with APD (also irradiated and blackened) in Summer

Fast timing layer

- An integration/alternative is a **fast timing layer** before ECAL: (see slides 2-4)
  - Two possible configurations:
  - **Thin layer** :
    - Timing for **MIPs**
    - Can be inside tracker
      - Constraints from tracker upgrade → probably outside
  - **“Thick” preshower-style layer** :
    - Timing for **MIPs** and **photons**
    - Strictly outside tracker
  - **Layout**
    - Granularity of order 1cm
    - Rate capability up to 10^6-10^7 Hz





Possible technologies

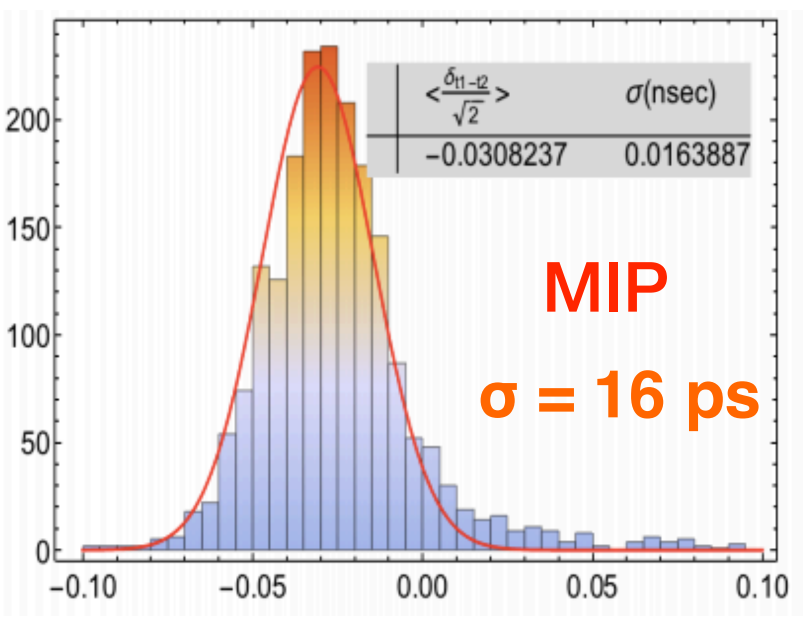
- **Silicon timing detectors:** S.White, at Frontier Detectors etc., Elba, (Italy) 2015
  - Fast silicon sensors with **internal gain**
    - Use gain to extract clean **MIP** signature and sharpen rise time for precise timing measurement
- **Thin crystals with fast photosensors (SiPM):** A.Benaglia, P. Lecoq, et al., Pub. in Preparation
  - Different **scintillating crystals** (LSO, LYSO, LuAG)
  - Small crystals reduce time dispersions
- **Micro-channel plate devices (MCPs):**
  - Direct ionization and Cherenkov radiatior configuration tested

A.Ronzhin et al, Nucl. Instrum. Meth. A795 (2015) 52–57; L.Brianza et al. Nucl. Instrum. Meth. A797 (2015) 216–221; A.Bornheim, Frontier Detectors, Elba 2015; Dustin Anderson et al., Precision timing calorimeter for high energy physics

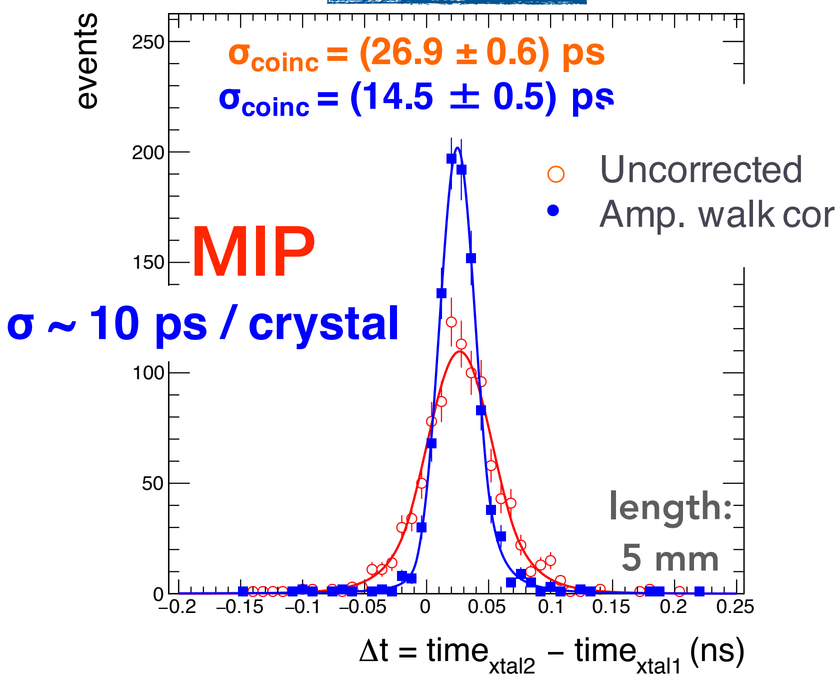
Possible technologies - II

- Big test beam program ongoing:
  - Last test beam campaign finished two weeks ago
  - Devices tested with muons, pions and electrons in H2 and T9
- Technologies are different but in general similar performance in terms of **timing resolution**:
  - Resolution ~ 20-30 ps achievable

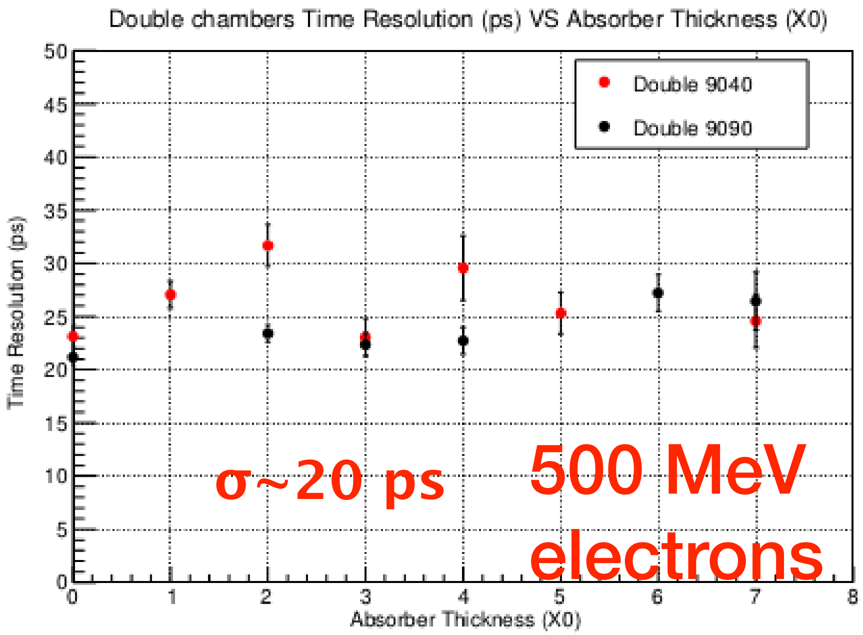
Silicon



Crystals

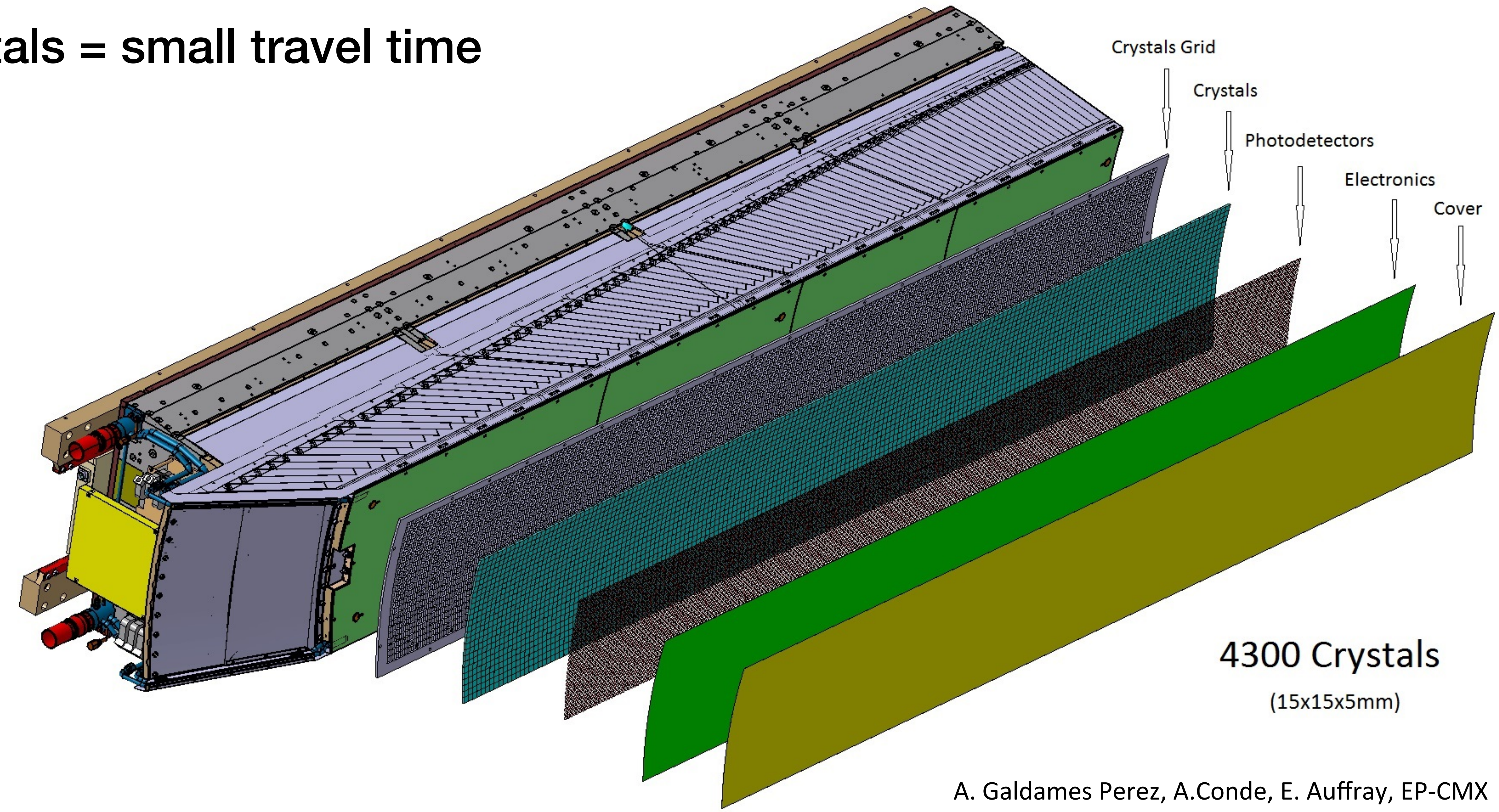


MCP



A tentative scenario

- **Preshower style xtals + fast photodectors** in equipped layer in front of ecal
- Has to be taken “cum grano salis” but not so unrealistic
- Dimensions could be of the order of ~1 cm on 3 dimensions:
  - **Small xtals = small travel time**



A. Galdames Perez, A.Conde, E. Auffray, EP-CMX

Implications on ECAL upgrade

- Fast timing layer in **preshower configuration**:
  - Timing of both high and **low energy electromagnetic shower** (not possible for ECAL)
  - Timing in ECAL **still useful** (hits cleaning, spike rejections, association, pulse shape studies…)
  - Impact on energy resolution should be **marginal**
- Preshower for mips and low-energy photons + ECAL would allow to fully exploit timing potentiality associating ECAL info to vertex time.
- Fast timing schedule is **tight**:
  - First report establishing **proof of principle and case studies** already out:
    - Physics case showing that **50PU performance are recovered**
  - Studies ongoing on:
    - Reconstruction and **physics performance**, **devices** and **detector design** and cost
- First report at ECFA 2016 in **Autumn**, final report **~March 2017**

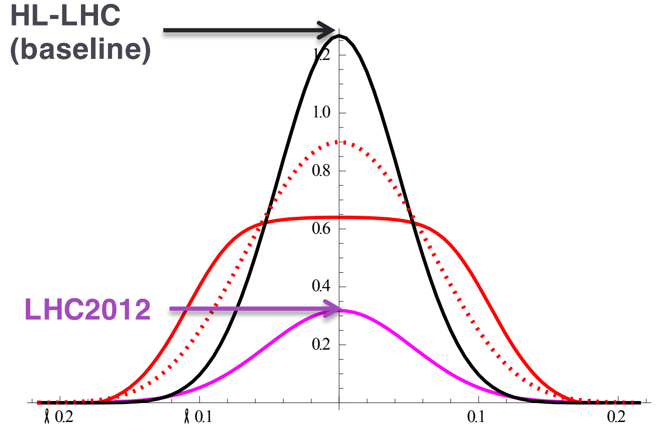
Conclusions

- ECAL with **stand-alone timing** is promising:
  - PWO intrinsic timing resolution of **PbWO4 + APD system** **better then 30 ps**
    - Main time resolution contribution in this TB is dominated by external noise
    - **Some non-linearities** to be understood with lab tests and simulations
  - If **clock stability** achieved detector wide:
    - Promising monitoring with laser system
  - **Fast timing layer** could be an interesting upgrade option:
    - **Unlikely to get better then 30ps for E<30 GeV with ECAL**, low energy photons important for **PU cleaning of Jets/MET** (Assessment of JET cleaning and MET performance w or w/o low pT photons in ECAL interesting future study)
    - Best performance when we **combine ECAL time info together with vertex time**
    - Technology and final physics performance studies ongoing

BACKUP

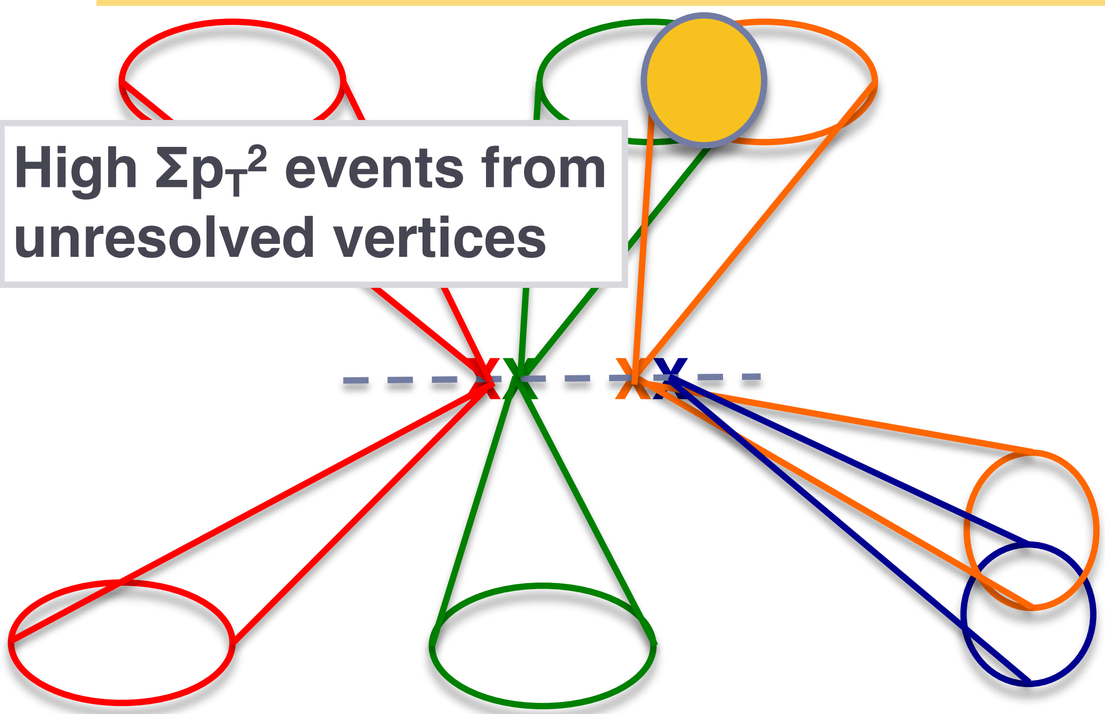
HL-LHC environment

S. Fartoukh, PhysRevSTAB.17.111001

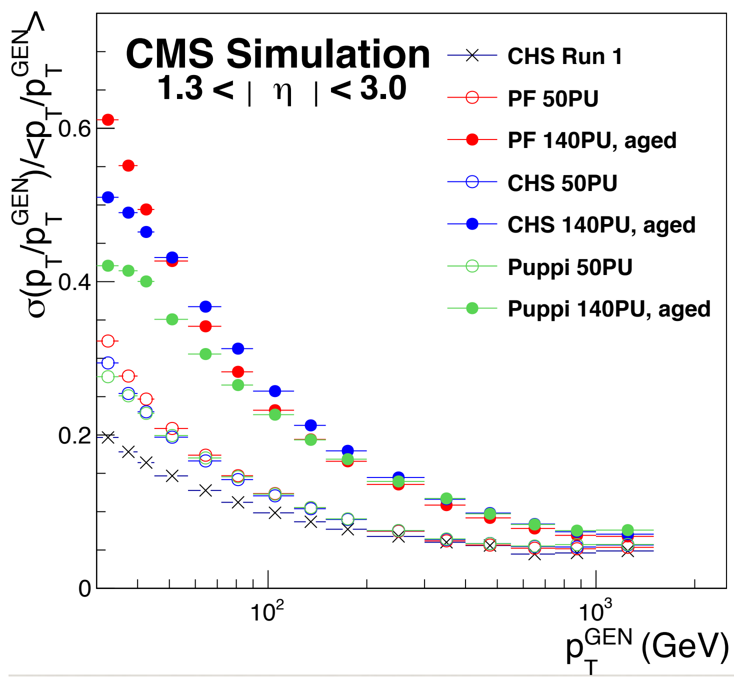


Peak density: 1.3 (1.8) mm^{-1} for 140 (200) collisions per BX

Extra energy in jets / isolation cones from overlap of (neutral) particles



High Σp_T^2 events from unresolved vertices



'Promoted' jets from spatially unresolved vertices

4-Dimensional vertex reconstruction

Slide from L. Gray

4-Dimensional Vertex Reconstruction 1

The space-time structure of simulated and reconstructed vertices assuming a mock-up of a fully covering fast-timing layer in 50 (slide 13) and in 200 (slide 14) pileup events shown, the hard scatter event is Hγγ. The assumed timing resolution per track is 20 ps. The input simulated vertices are shown for reference.

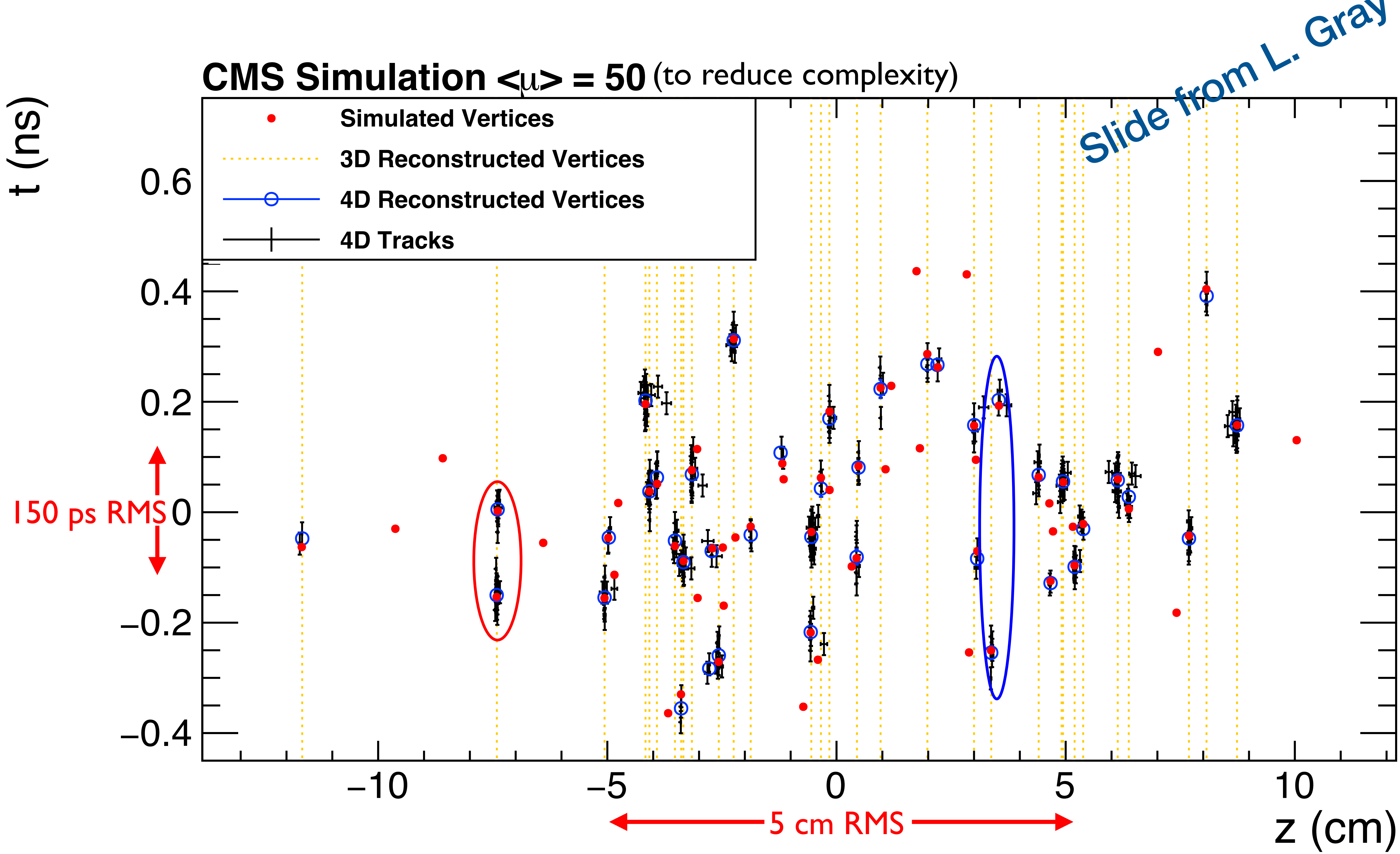
The 4D vertices are reconstructed using a simulated annealing algorithm that is a higher dimensional extension of the vertexing algorithm [1] used presently in CMS. 4D Tracks are constructed by determining the time-stamp at the distance of closest approach using smeared simulation information. A p_T cut of 1 GeV is required for tracks to enter the vertex fit.

Instances of vertex merging for the 3D algorithm can be seen in 50PU at −7.3 cm and 3 cm, and throughout the 200PU plot.

[1] https://cds.cern.ch/record/865587

12

4-Dimensional vertex reconstruction

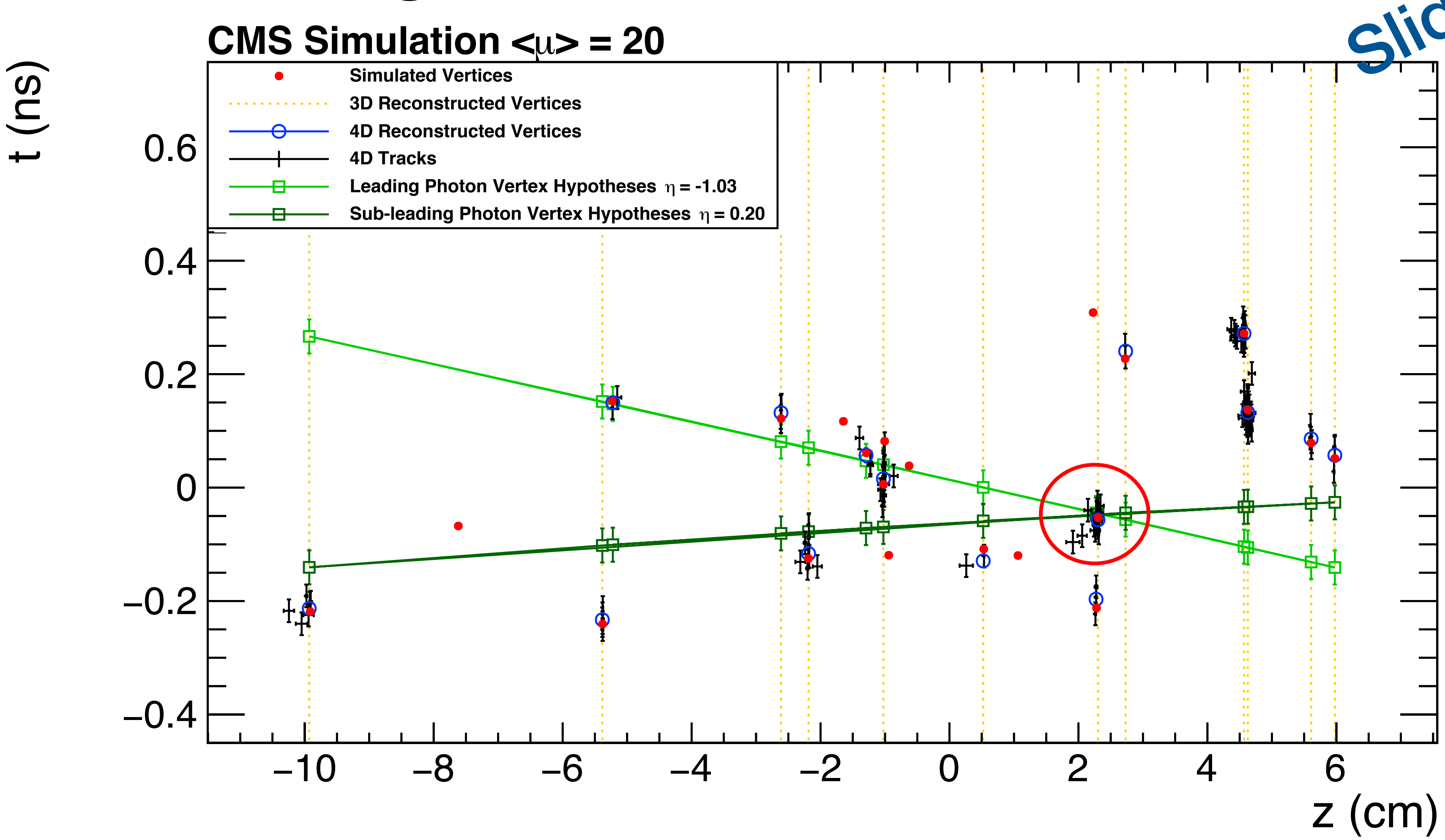


Examples of vertices merged in 3D algorithm circled

Vertexing with high pT photons

Matching Neutrals to 4D Vertices I

Slide from L. Gray



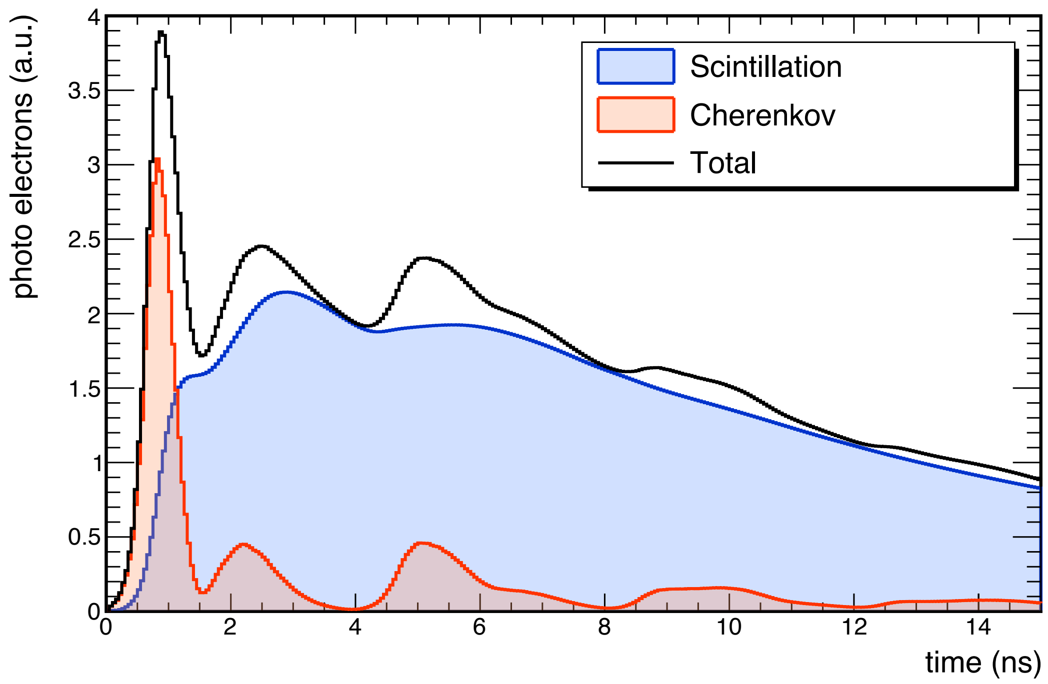
Above is a space-time diagram displaying ability to correlate calorimetric timing with track timing, using a H → γγ decay as illustration. The reconstructed time for the photons from the hard scatter, in green, can be cross referenced with the time information of the 4D vertices. A triple coincidence, seen at (2.4 cm, -0.05 ns), of the two photons and a track vertex in space-time indicates uniquely the signal vertex. The event is generated from a pileup distribution with mean 20 to improve clarity.

PWO pulse shape from simulation

Contribution from Cherenkov radiation is estimated to be about 11%
by simulating photons in EM showers within full range of detectable λ = 300 – 1000 nm

Relative light output of Cherenkov and scintillation photons in $PbWO_4$ was determined by simulating experimental results for 150 GeV muons reported in N. Akchurin et al., *"Contributions of Cherenkov light to the signals from lead tungstate crystals"*, NIM A582 (2007) 474-483

Due to *instantaneous* emission of Cherenkov photons, most of them arrive earlier than scintillation photons



Slide from A. Ledovskoy