Picosecond Timing: Applications and Technologies Towards Mitigating the Effects of High-Pileup

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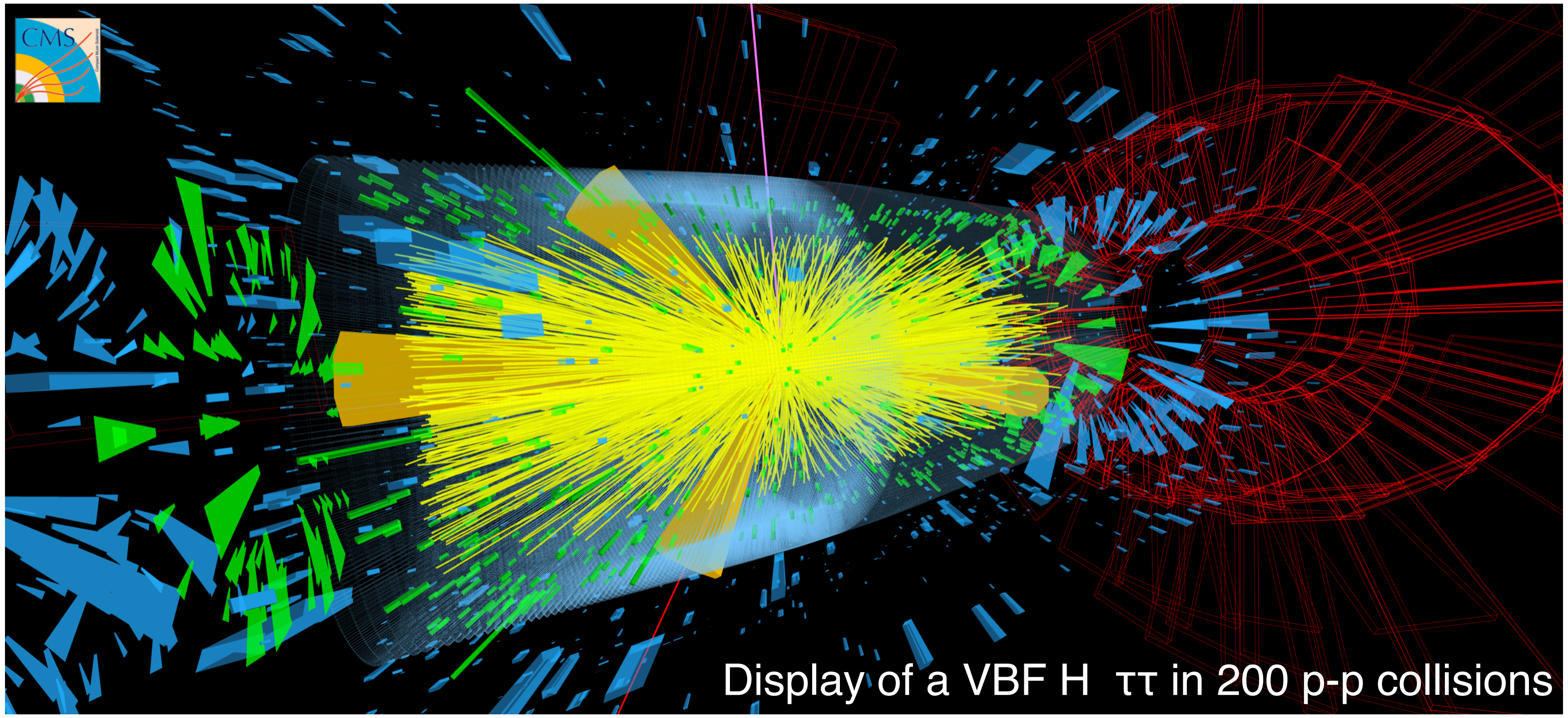
on behalf of the ATLAS and CMS Collaborations

2016 ACES Workshop

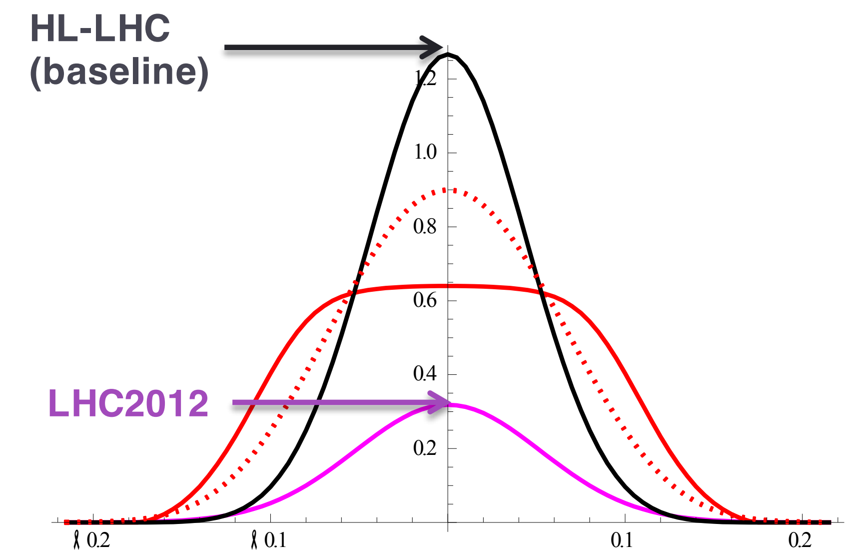
8 March, 2016

CMS results available in: http://cds.cern.ch/record/2143491?ln=en

Characterizing the 200 PU HL-LHC


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

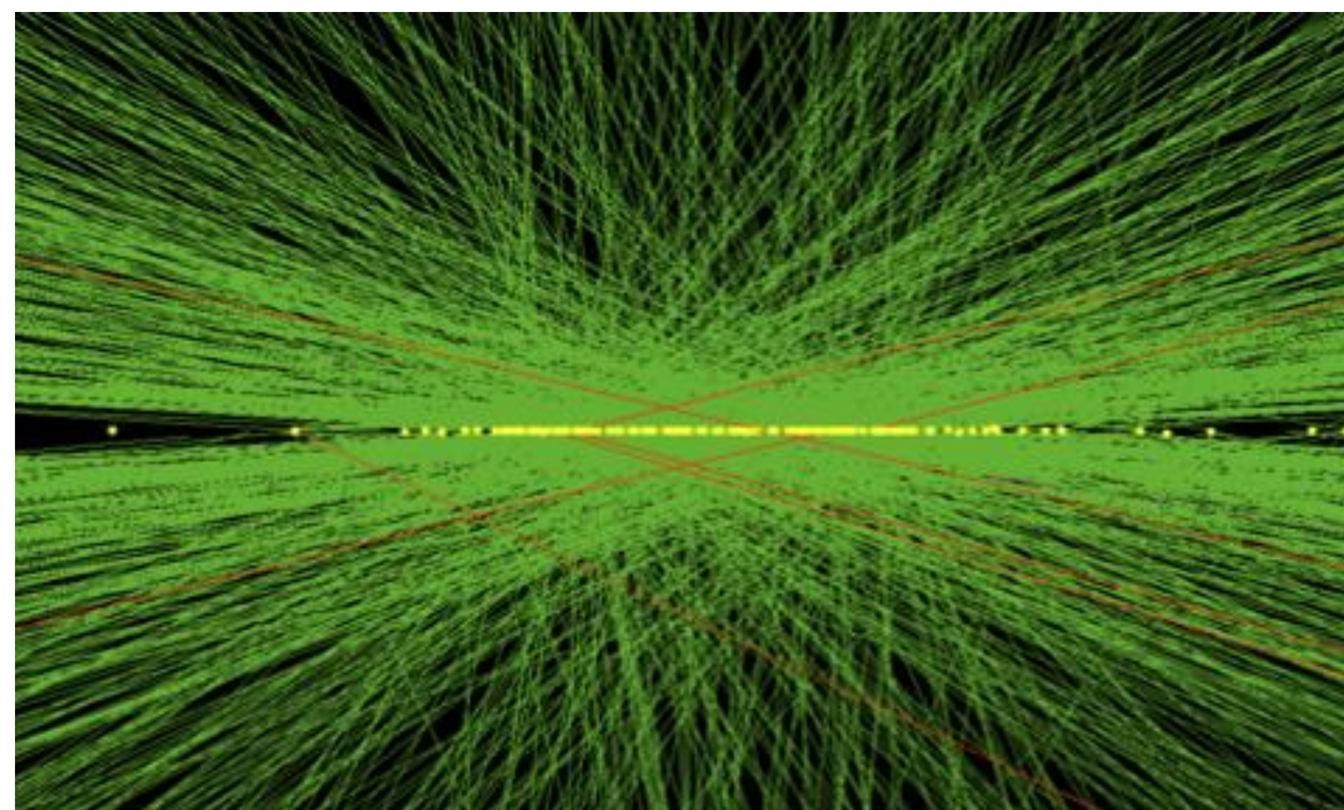
[S. Fartoukh, PhysRevSTAB.17.111001](#)



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

Hard scatters are < 1% of all vertices produced

"Vertex merging" rate ~10%

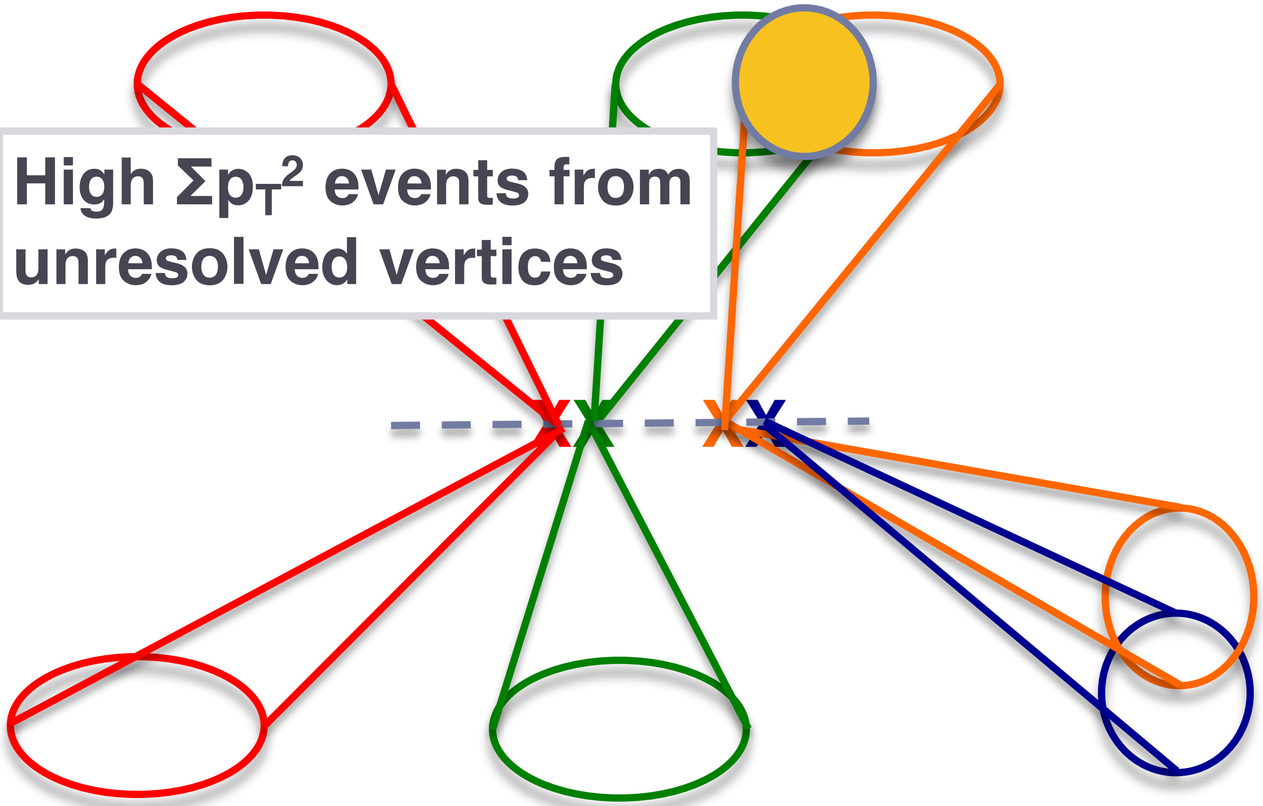


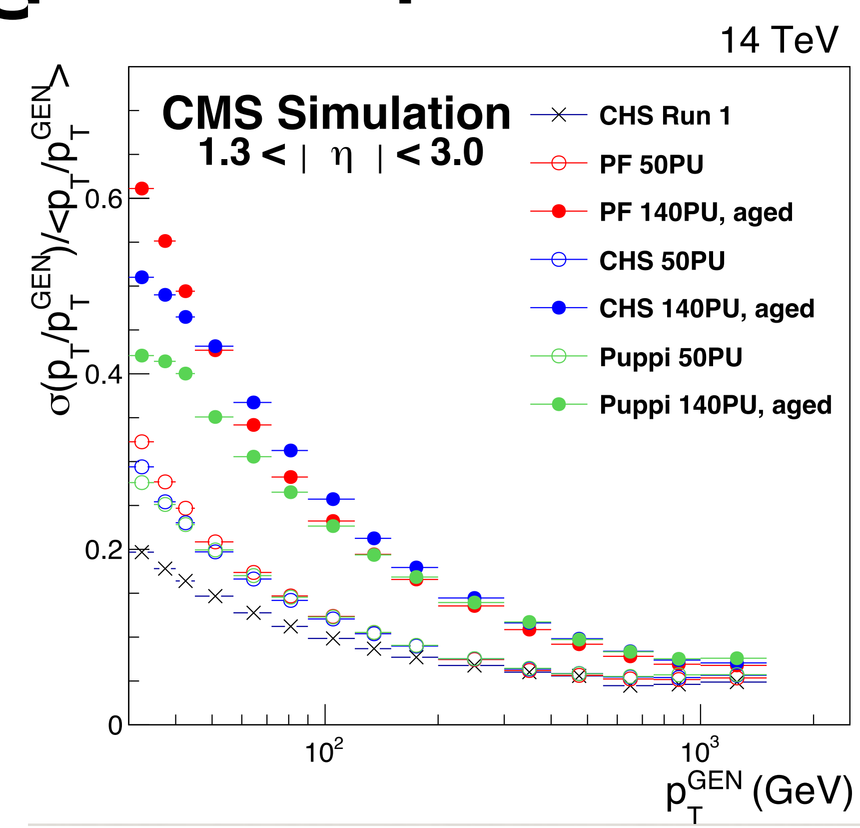
Usual metrics of how "interesting" a vertex is, like Σp_T^2, can have reduced efficiency.

Adverse Effects of High-Pileup

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

High Σp_T^2 events from unresolved vertices

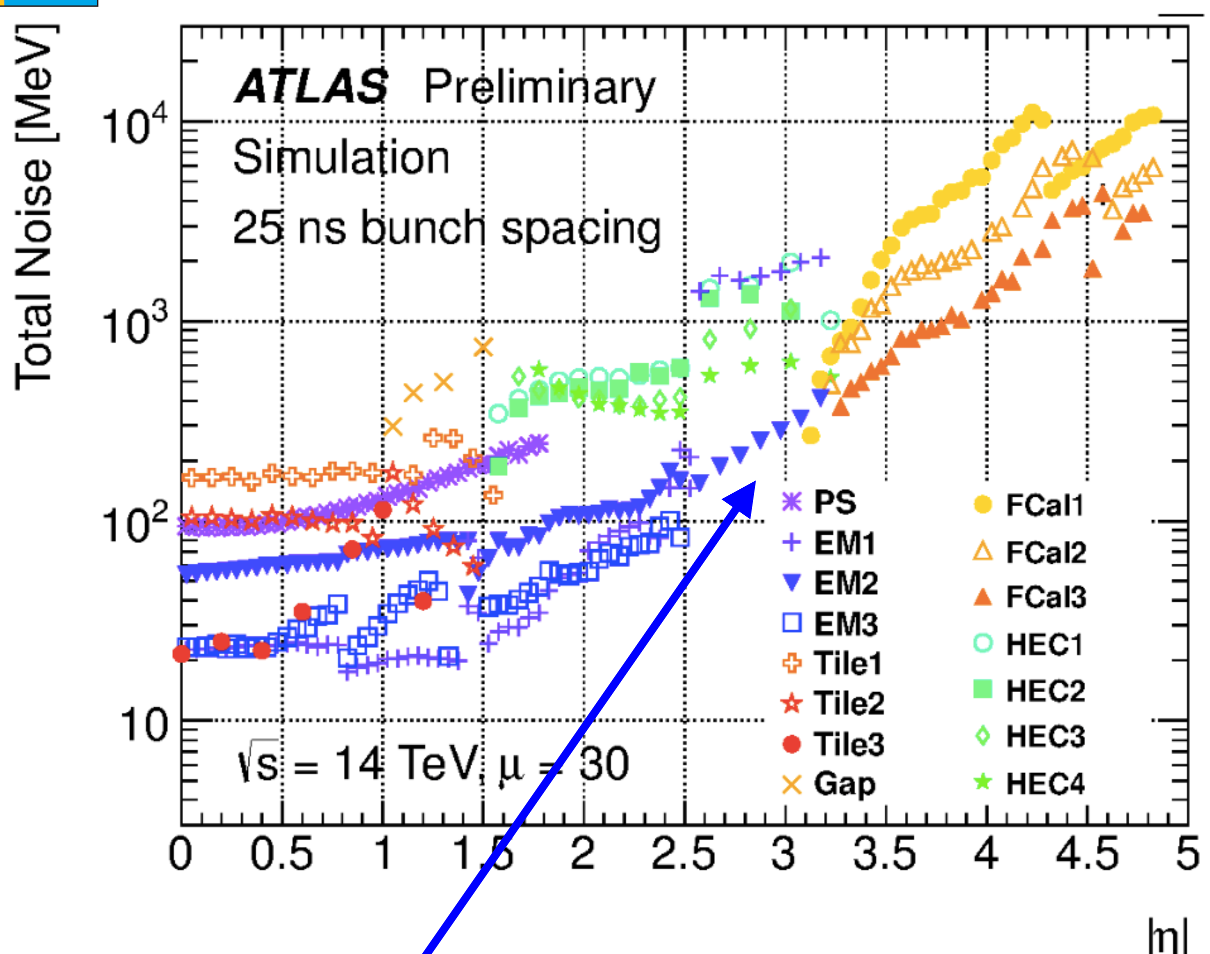


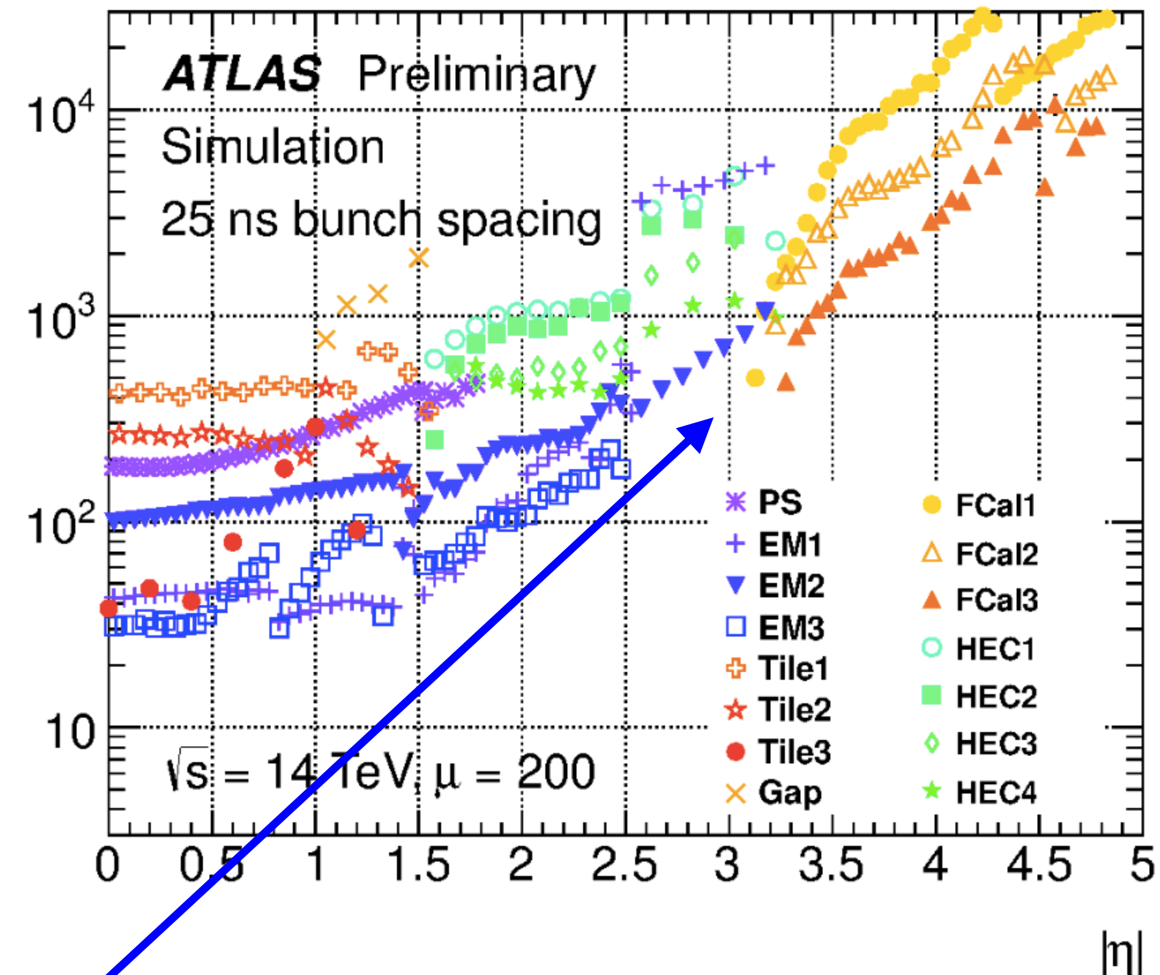


'Promoted' jets from spatially unresolved vertices

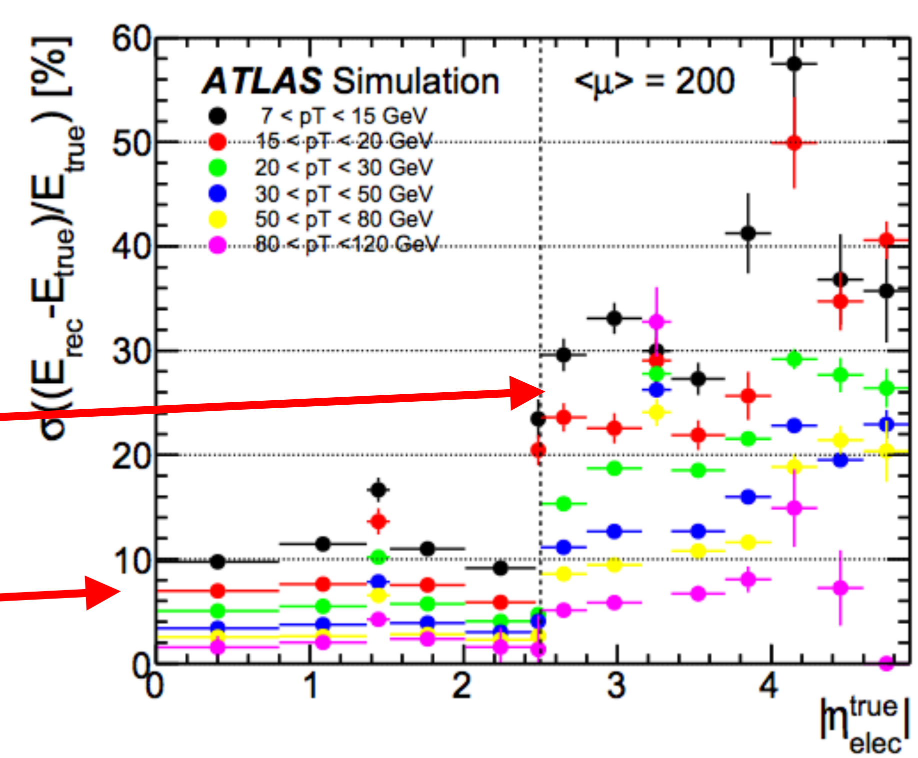
- A number of unfavorable, low level effects
  - Merged vertices and fake high p_T jets
  - Loss of efficiency to associate high energy photons to vertices
  - Significantly degraded MET performance
- These issues are being looked at by both collaborations, in addition to studying detector, electronics, and reconstruction technologies that fit the required performance
  - One avenue for pileup mitigation that is being investigated now is *fast timing*

Adverse Effects of High-Pileup



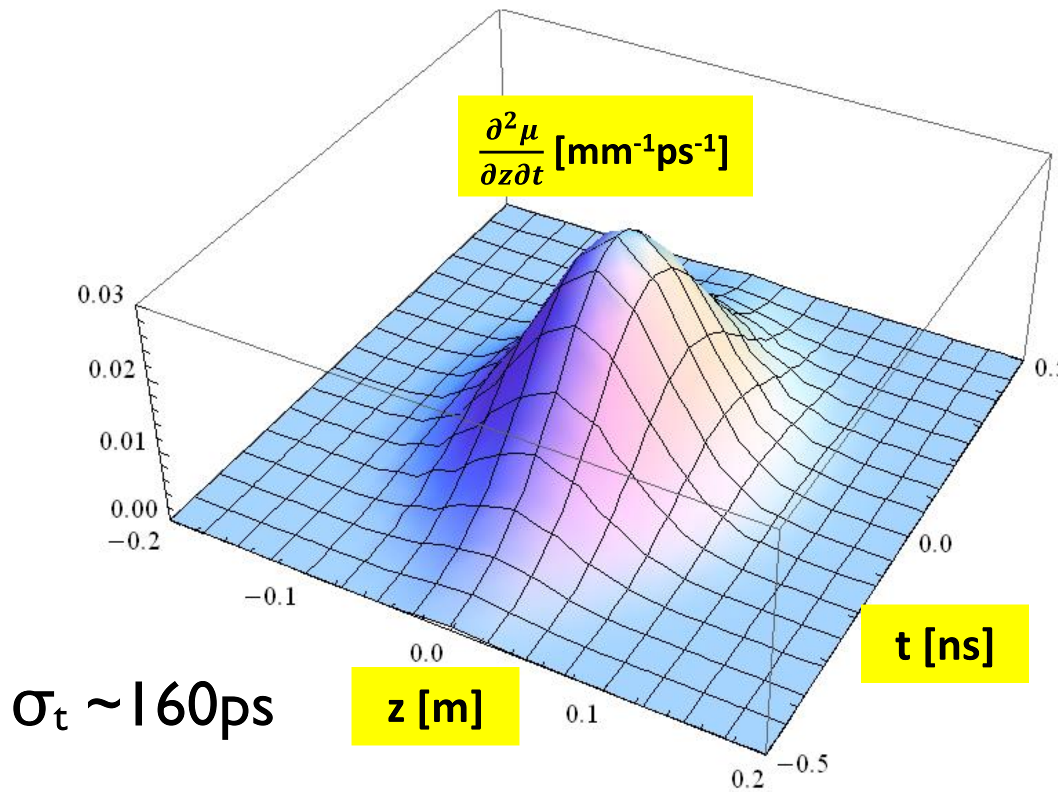


- LAr end-cap calorimeter pile-up noise contribution becoming dominant at HL-LHC
  - Resolution of 2 GeV for μ=30 goes to 3-5 GeV μ=200 in 2.5<|η|<3.2
- Also looking at EM energy resolution
  - Large PU effect for |η|>2.5
  - Coarser granularity of the EM calorimeters for |η|>2.5
  - Weak sensitivity to pileup for |η|<2.5

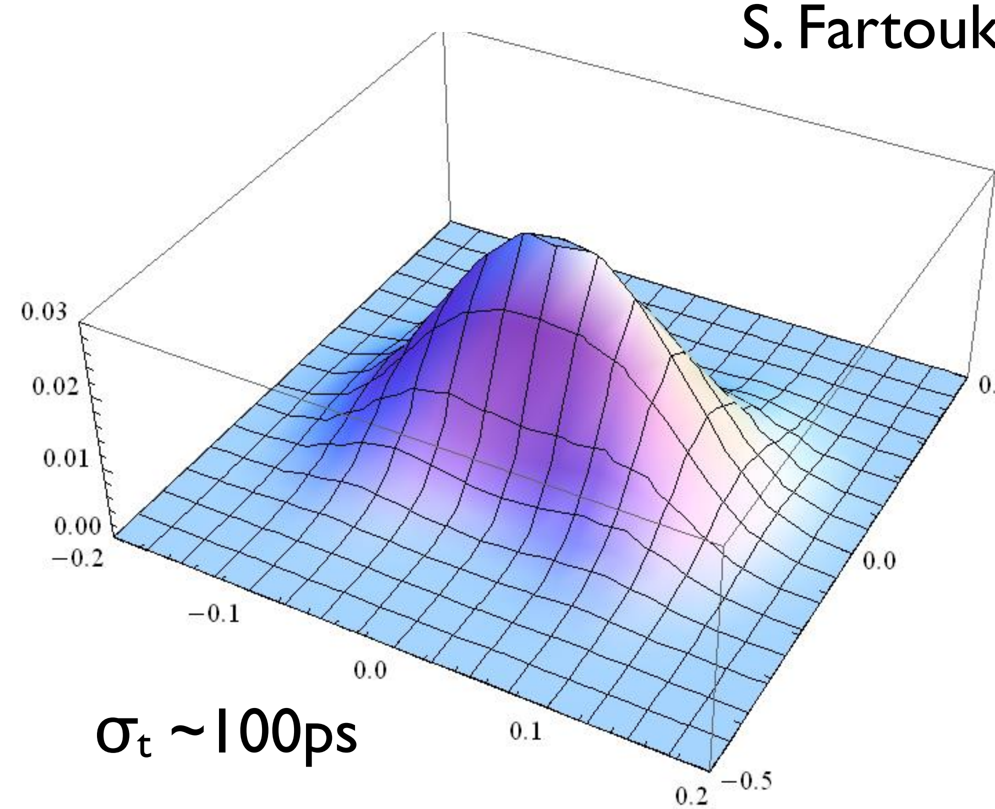


Time-Spread of the HL-LHC Beamspot

S. Fartoukh



HL-LHC Baseline



Crab-Kissing

If one imagines time as an additional stretching of the beam-spot (i.e. in the limit of perfect time resolution), converting ps^{-1} to mm^{-1} and taking the square-root, you arrive at ~0.3 mm^{-1} max. density, similar to the Run1 max. line density.

If we then consider a detector with finite timing resolution **O(25) ps** the beamspot can be decomposed into time exposures where the density in each exposure is roughly the Run 1 levels.

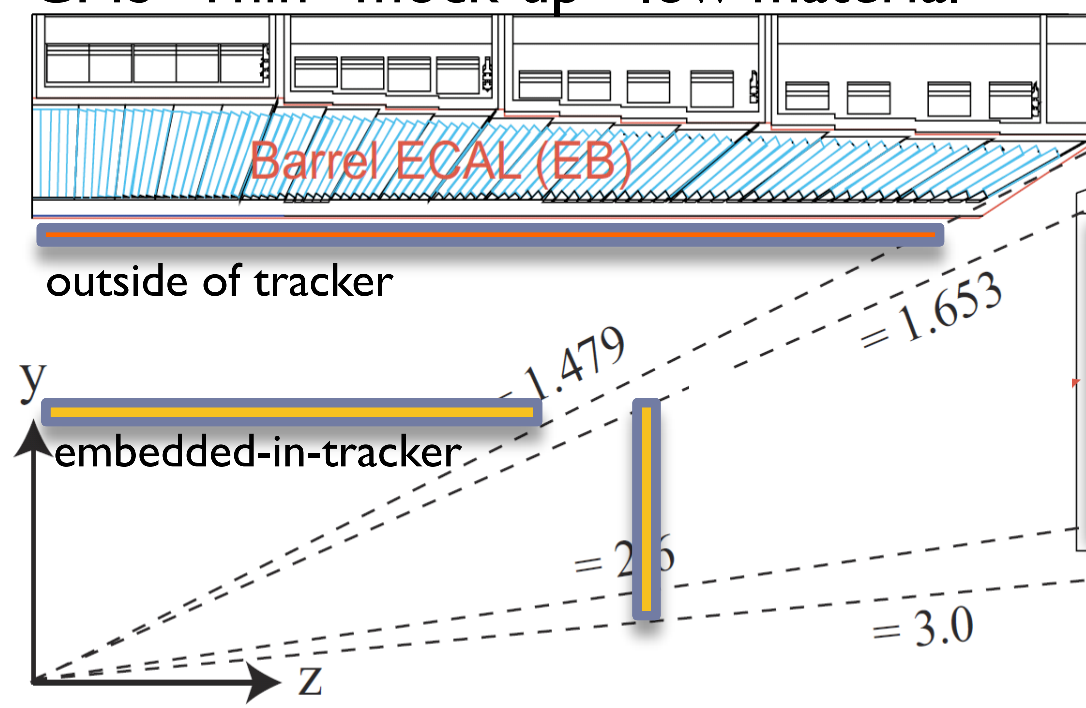
Timing Layer Ideas in CMS

- Both detectors investigating dedicated timing devices (**no proposals yet!**)
  - Fast timing already embedded in CMS calorimetry upgrade projects (in TP)
    - See talks of M. Mannelli & M. Dejardin
    - HGC photon timing E > 3 GeV (40 ps), also able to time-tag hadrons from 20 GeV (investigating)
    - ECAL upgrade photon timing: E > 20 GeV (40 ps)

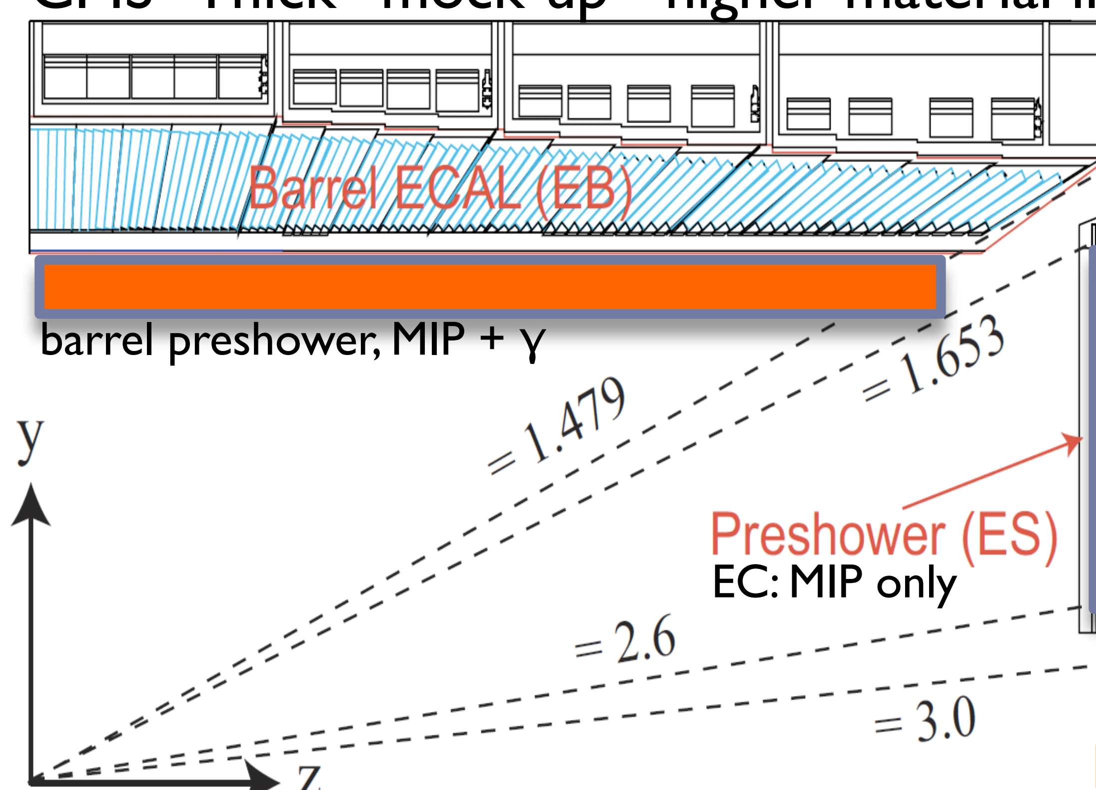
σ_t gets better with energy

- CMS timing layer options being considered in addition to existing fast timing in calorimetry
  - Quantifying need, use, and coverage
    - i.e. building physics cases, cost/benefit
  - Finding suitable detector technologies [1,2,3,4]
    - and complimentary electronics
  - Understanding placement, radiation tolerance of candidate technologies

CMS "Thin" mock-up - low material

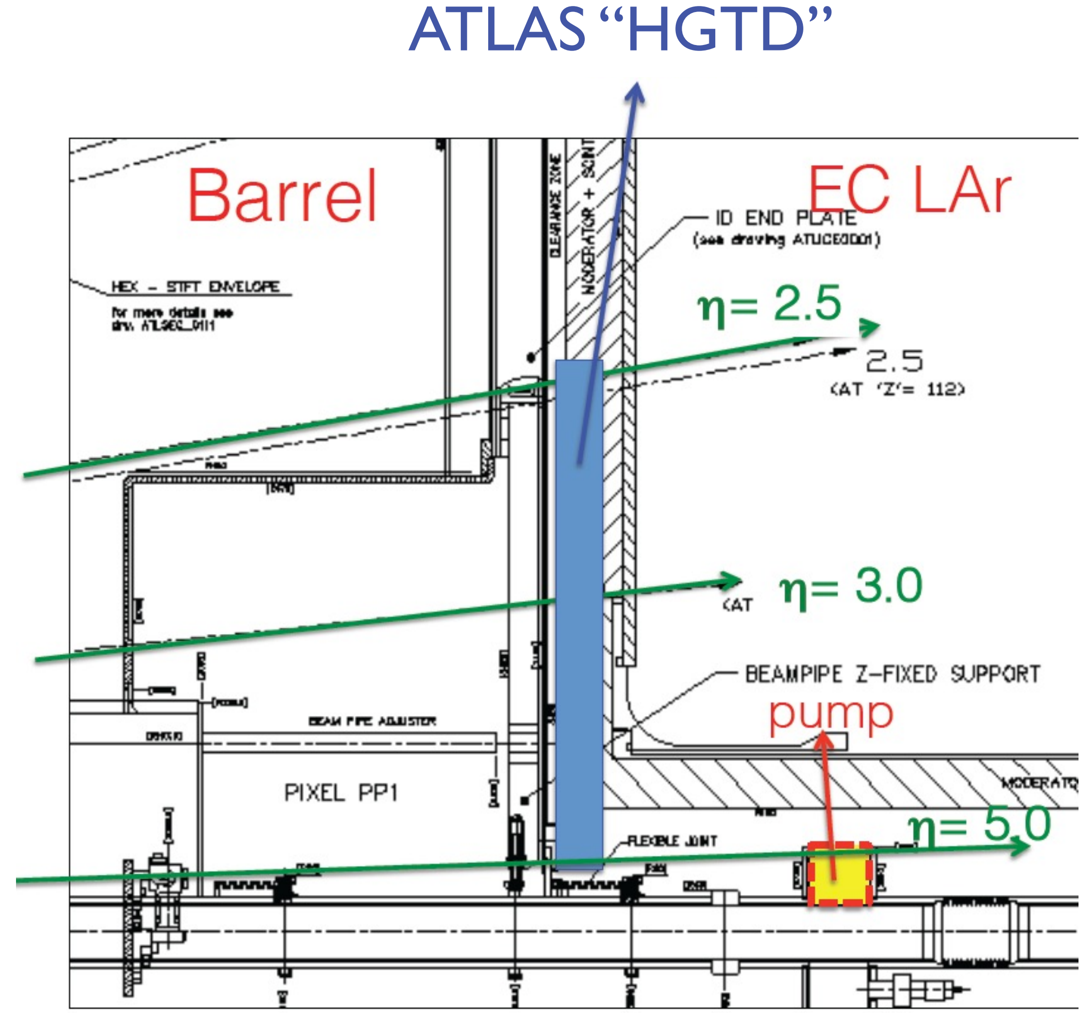


CMS "Thick" mock-up - higher material in EB

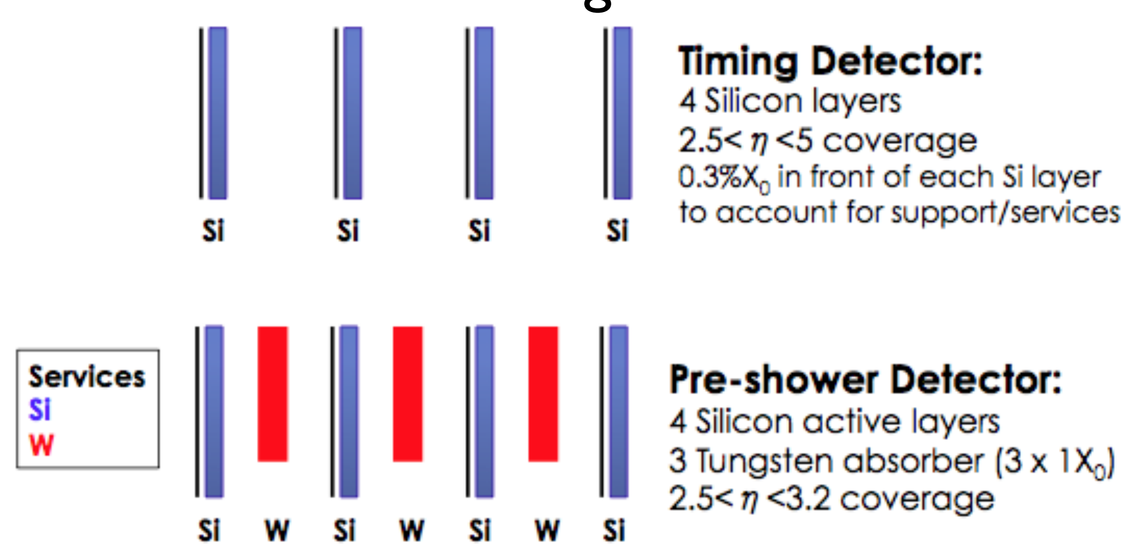


Timing Layer Ideas in ATLAS

- ATLAS proposes a baseline design of a timing device in Scope Document
  - "High-Granularity Timing Device"
  - Considering multi-layer MIP-focused device or preshower-style device
- Focusing on Silicon in baseline design
  - ATLAS planning testbeam late summer
  - **Big effort in ATLAS/CMS moving towards full G4**



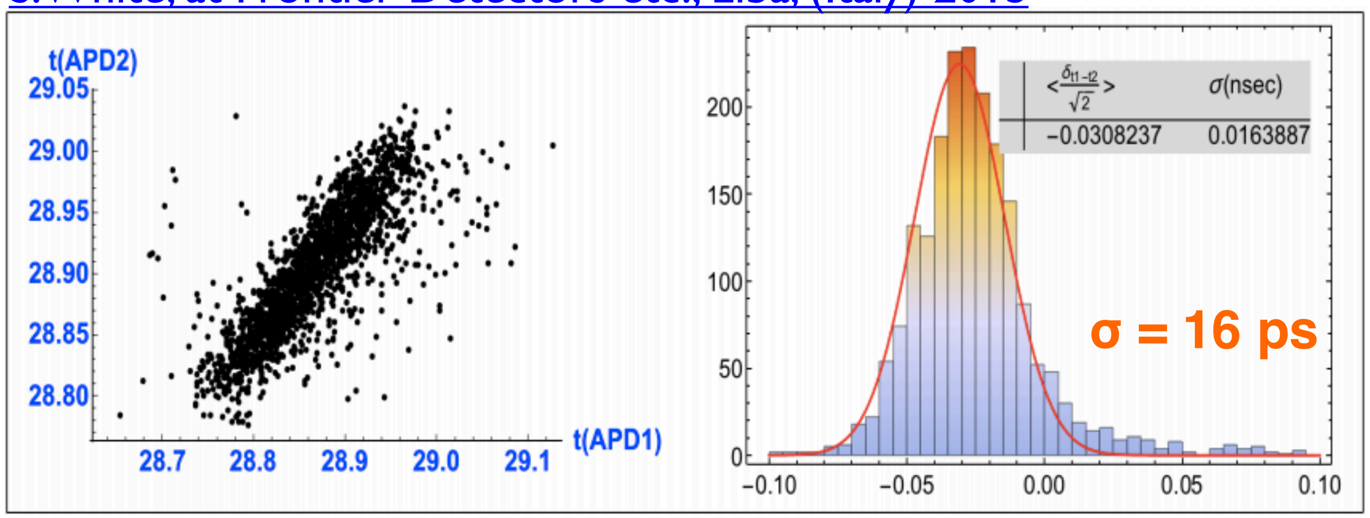
ATLAS reference design:



Silicon Timing Detectors [1]

- Silicon sensors with internal gain
  - Use gain to extract clean MIP signature and sharpen rise time for precise timing measurement
- R&D on high gain APDs with field shaping and capacitative readout in 1 cm^2 pads
  - "Hyperfast Silicon": S.White, at Frontier Detectors etc., Elba, (Italy) 2015

Tested to 0.9e14 1 GeV n. eq.



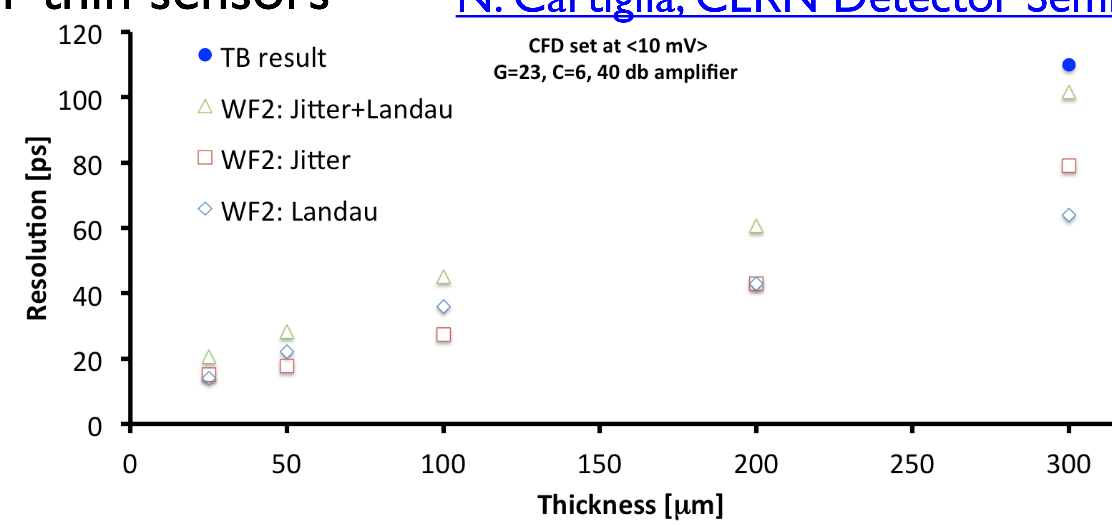
Looking at transimpedance amplifier from Newcomer, et. al. (Penn)

- Further R&D includes "Low-Gain Avalanche Device" (LGAD)
  - "Ultrafast" Silicon Device (UFSD) expect 30-50 ps for thin sensors
  - Measured 120 ps using thick sensor in test beam
    - New samples on the way, validate sim. expectations

Tested to ~1e14 1 GeV n. eq.
Some radiation issues known.

Looking at electronics from UCSC/Torino

N. Cartiglia, CERN Detector Seminar



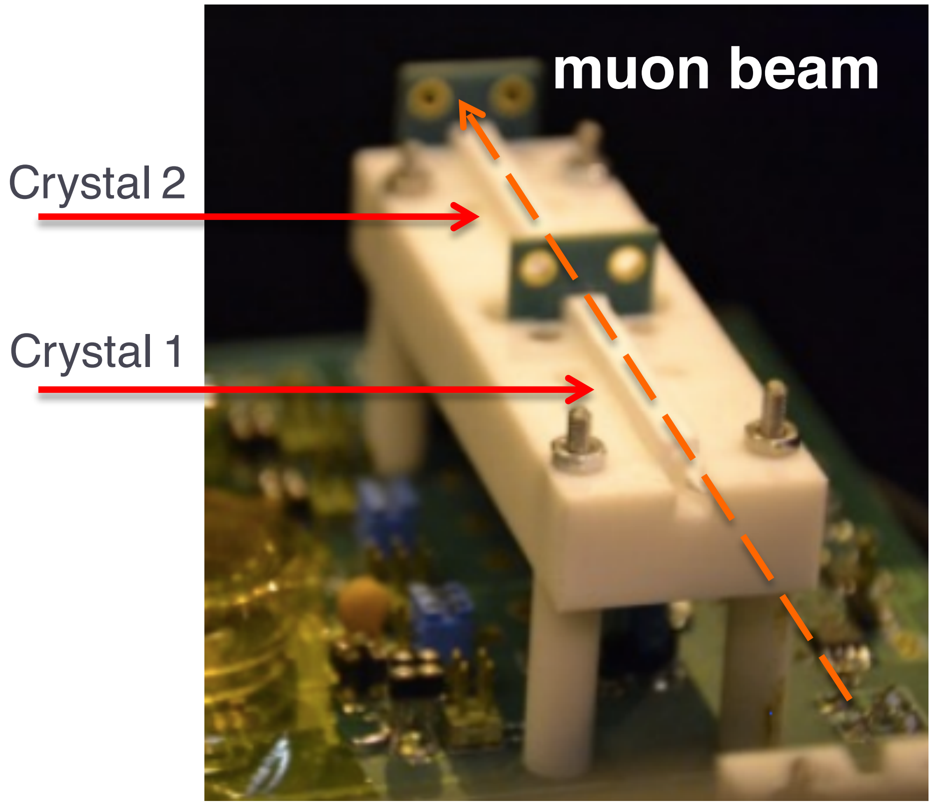
Lindsey Gray, FNAL

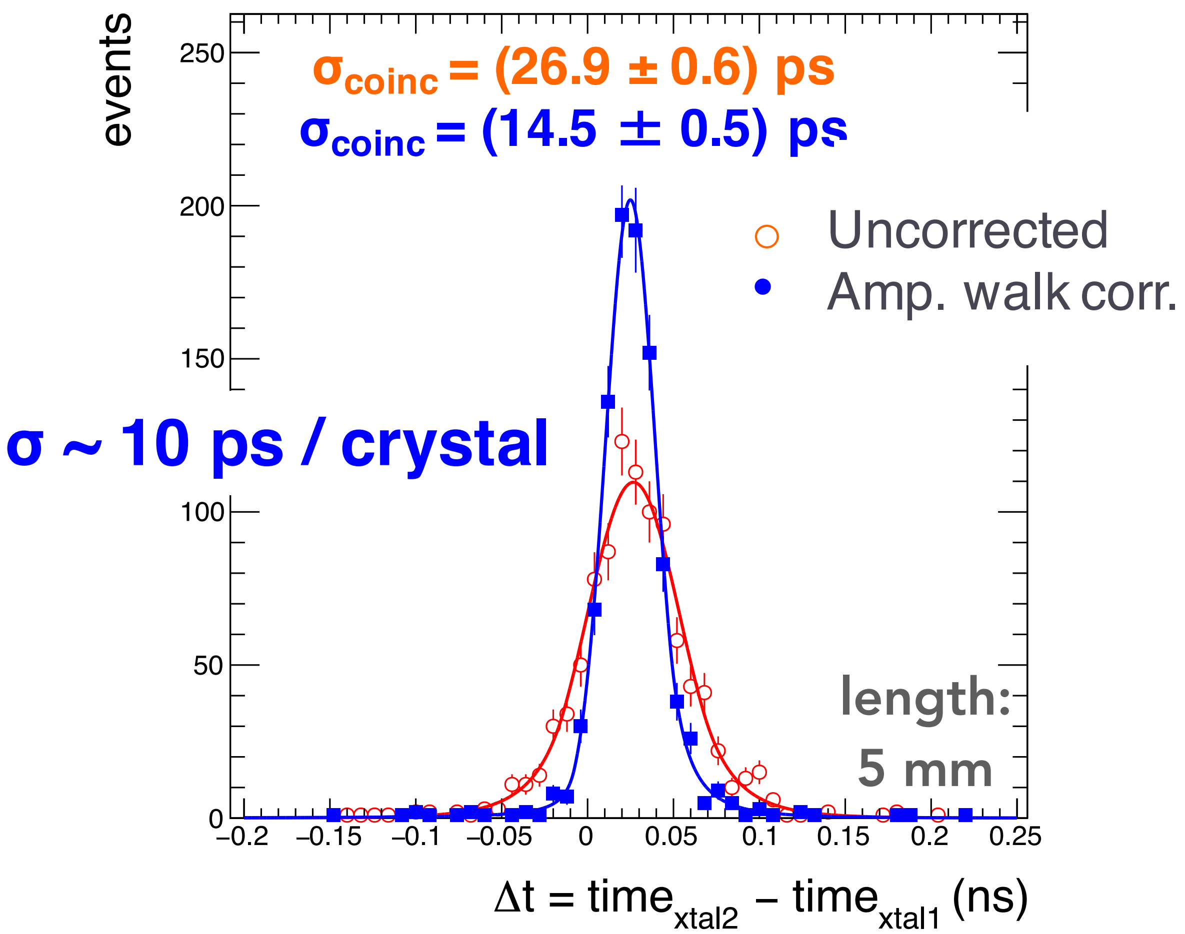
Scintillating Crystal Timing Detectors [2]

- Thin Crystals with Fast Photosensor
  - LYSO with SiPM + NINO tested with muons
  - Small crystals reduce light dispersion
    - Efficient, prompt photo-statistics
    - 3 mm x 3 mm x 5-30 mm in test beams

More technologies in backup!

Test beams in spring & summer for further testing.



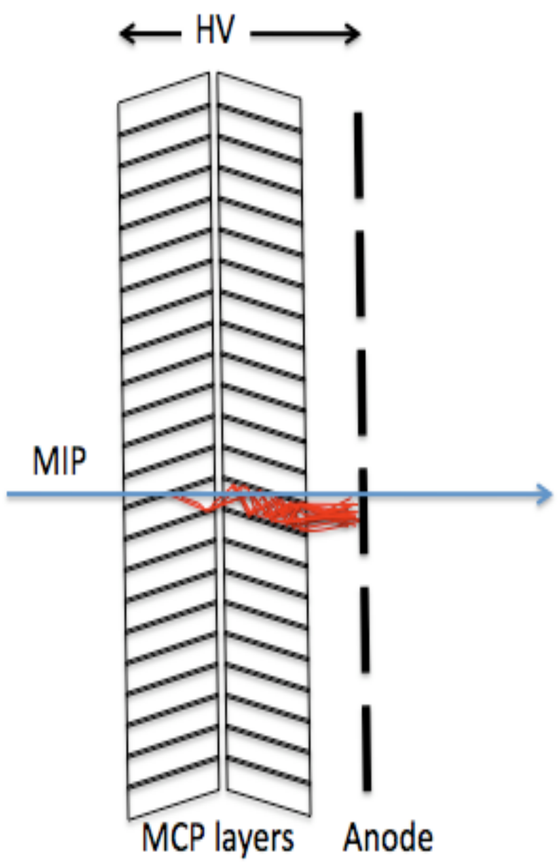


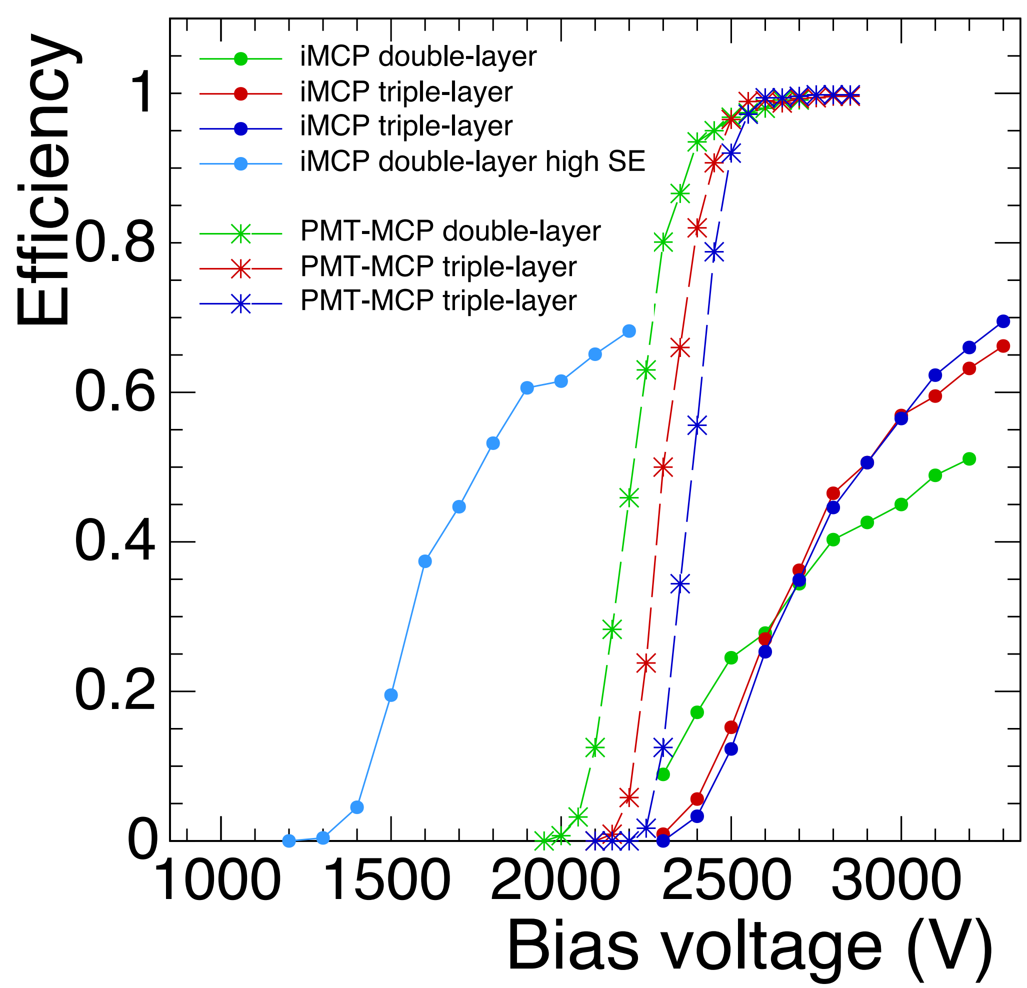
[A.Benaglia, P. Lecoq, et al., Pub. in Preparation](#)

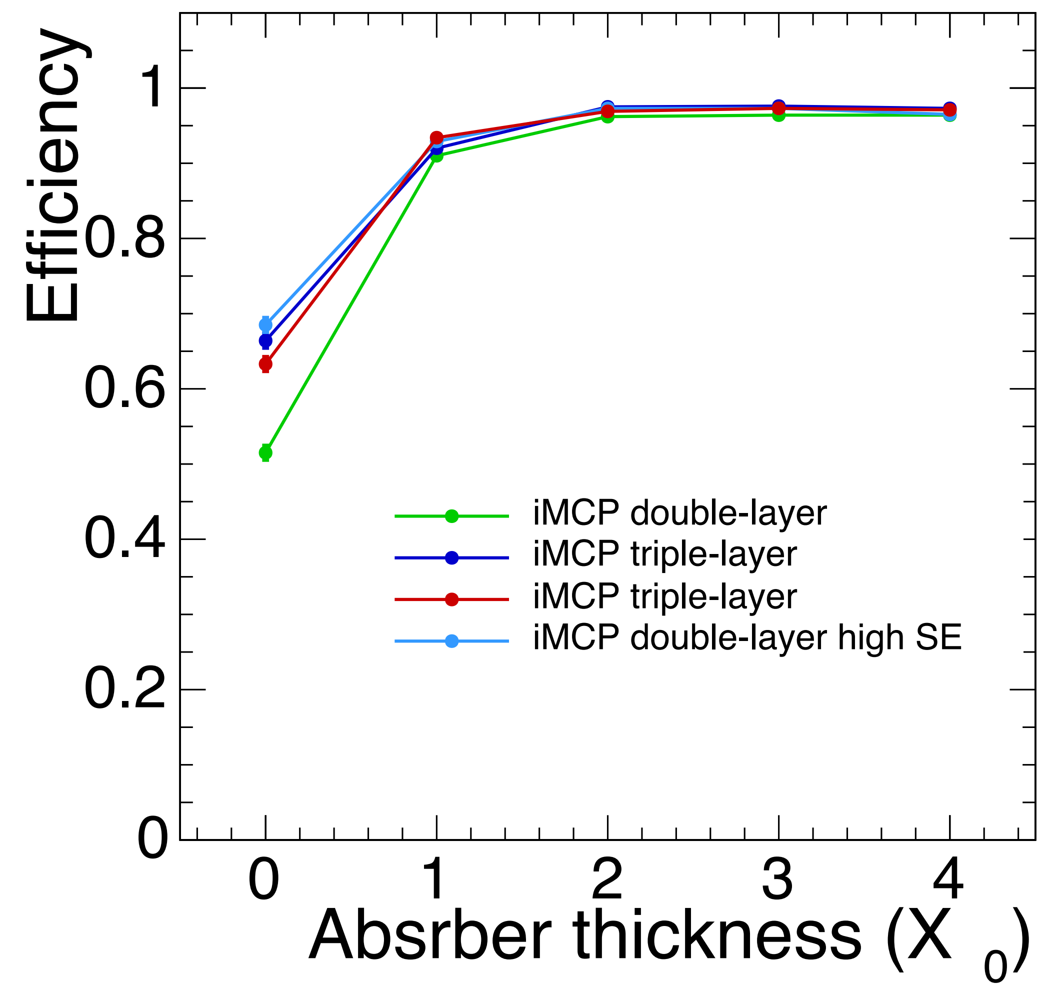
[On the Properties of Crystal Timing in LYSO](#)

Micro-channel Plate Timing Detectors [3]

- ~20-30 ps accuracy as secondary emission and amplification device
- 70% efficiency to MIPs, full efficiency to (pre)showers







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

The Uses of Fast Timing in High-Pileup

- Outlined the challenges faced by detectors in high pileup environments
  - Large vertex line-density leading to vertex merging
    - Spurious promotion of jets and vertices
  - Large neutral component from multiple overlaid vertices
    - Noise in isolation cones, jet clustering
- Demonstrated there are technologies that could achieve the goal of O(25ps) precision
  - At test beam level, in multiple implementations
  - Technologies exist that cover needs of ATLAS and CMS
- Now, we start to show we can use these technologies

4-Dimensional Vertex Reconstruction 1

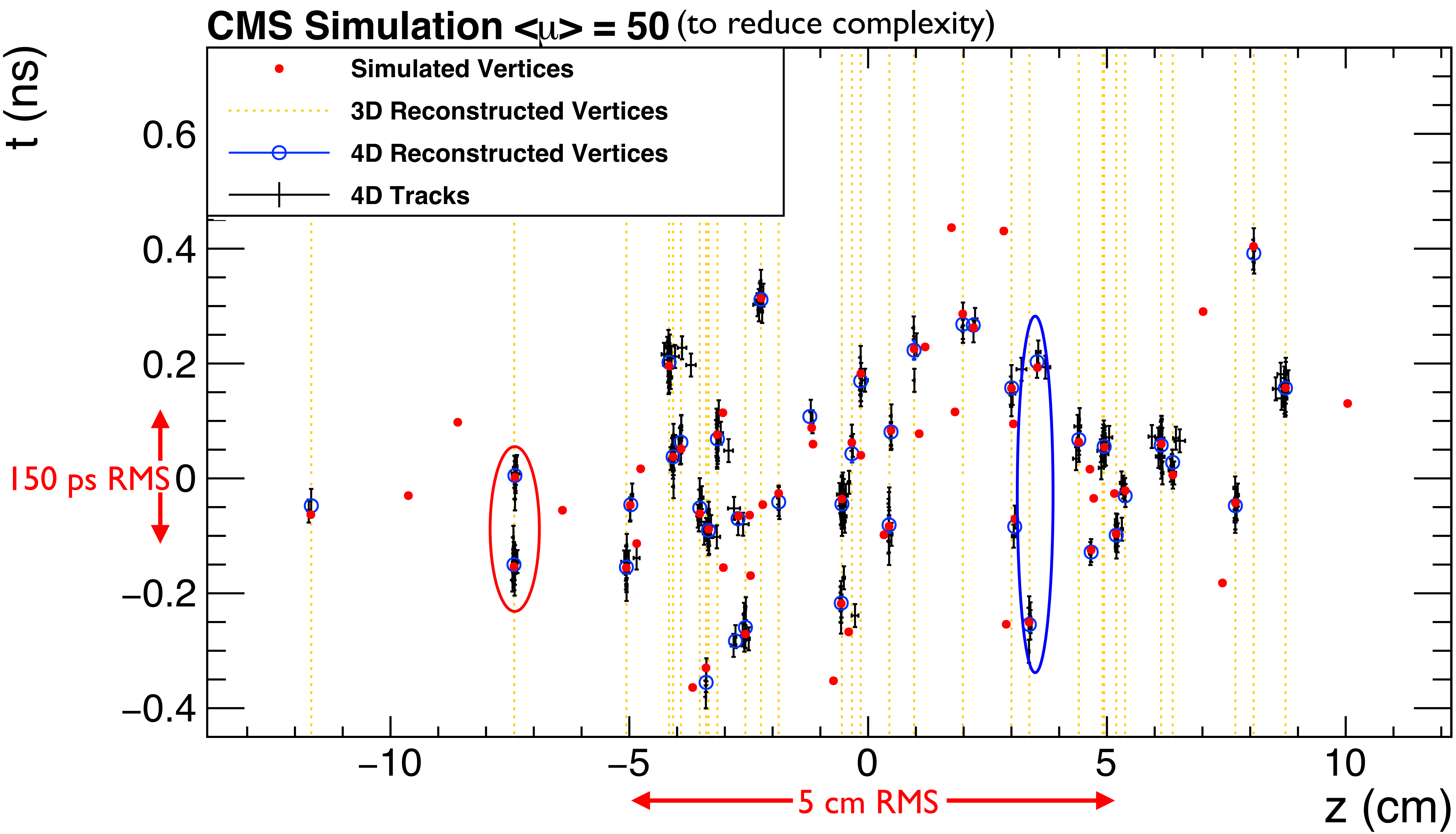
The space-time structure of simulated and reconstructed vertices assuming a mock-up of a fully covering fast-timing layer in 50 (slide 13) and in 200 (slide 14) pileup events shown, the hard scatter event is $H\gamma\gamma$. The assumed timing resolution per track is 20 ps. The input simulated vertices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

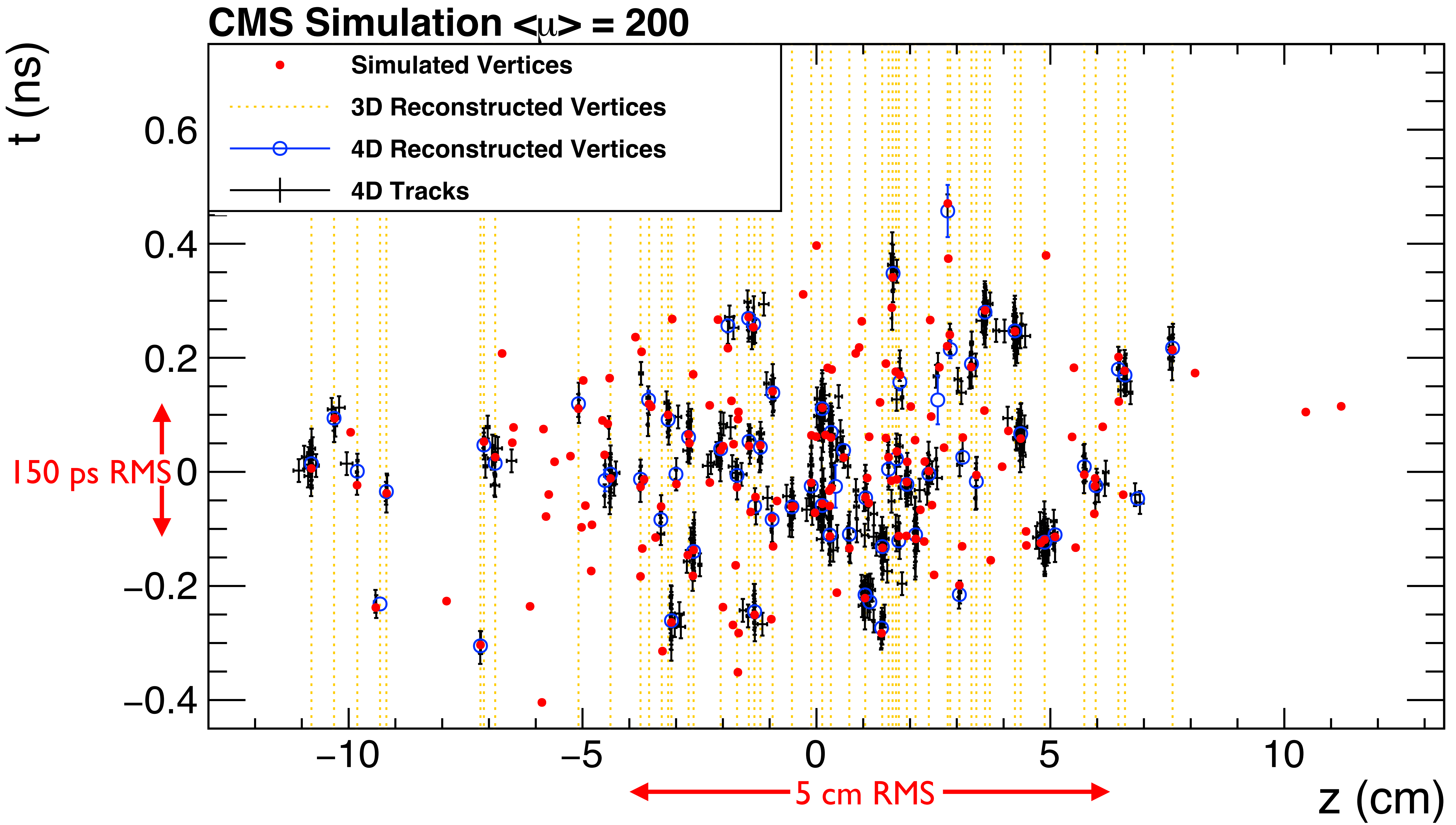
[1] https://cds.cern.ch/record/865587

4-D Vertex Reconstruction 2



Examples of vertices merged in 3D algorithm circled

4-D Vertex Reconstruction 3



Merged Vertex Rate Reduction

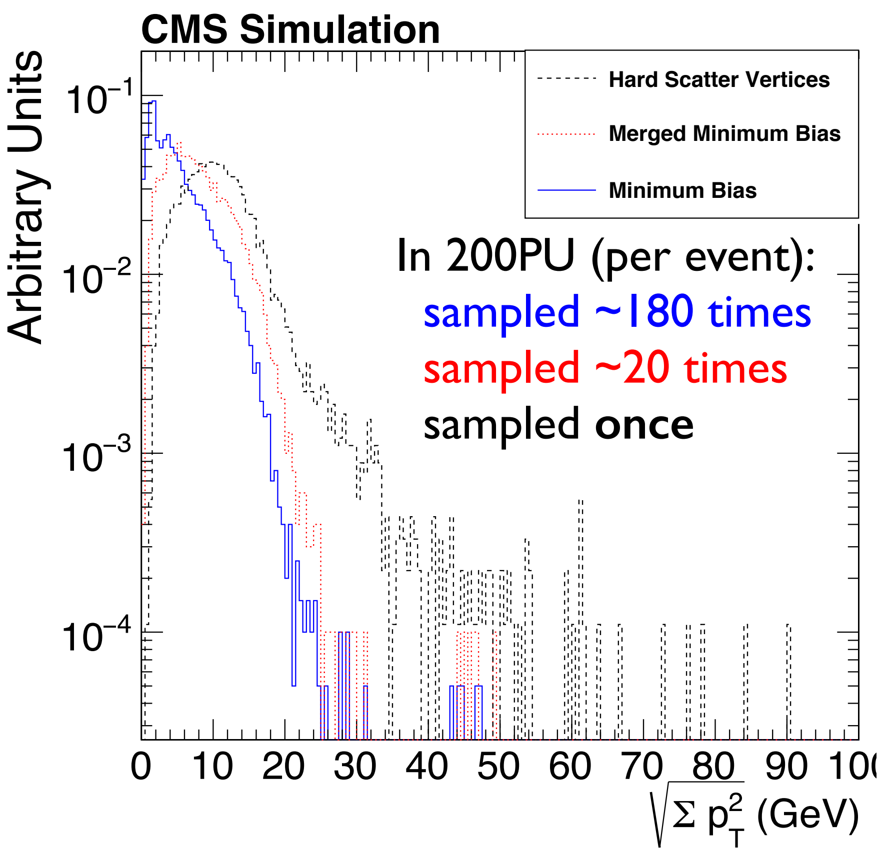
A merged vertex is defined by a 3D (4D) reconstructed vertex that is matched in space (and time) to more than one simulated vertex. The matching window defined to be $3\sigma_z$ up to a maximum of 1mm, and $3\sigma_t$, when timing information available.

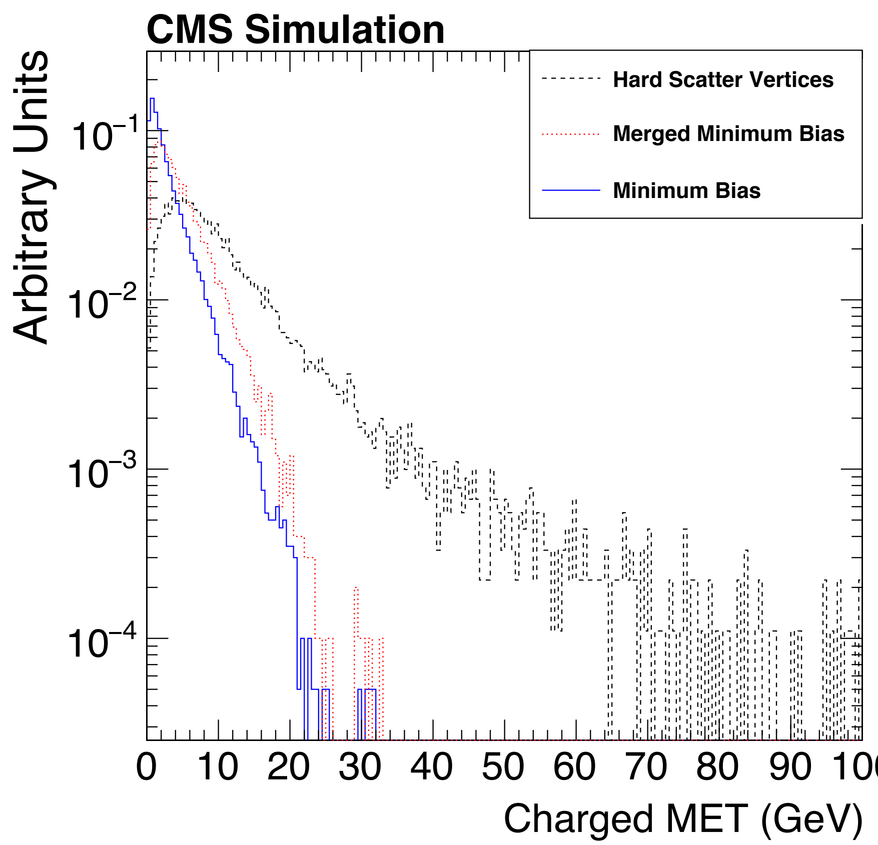
CMS Simulation

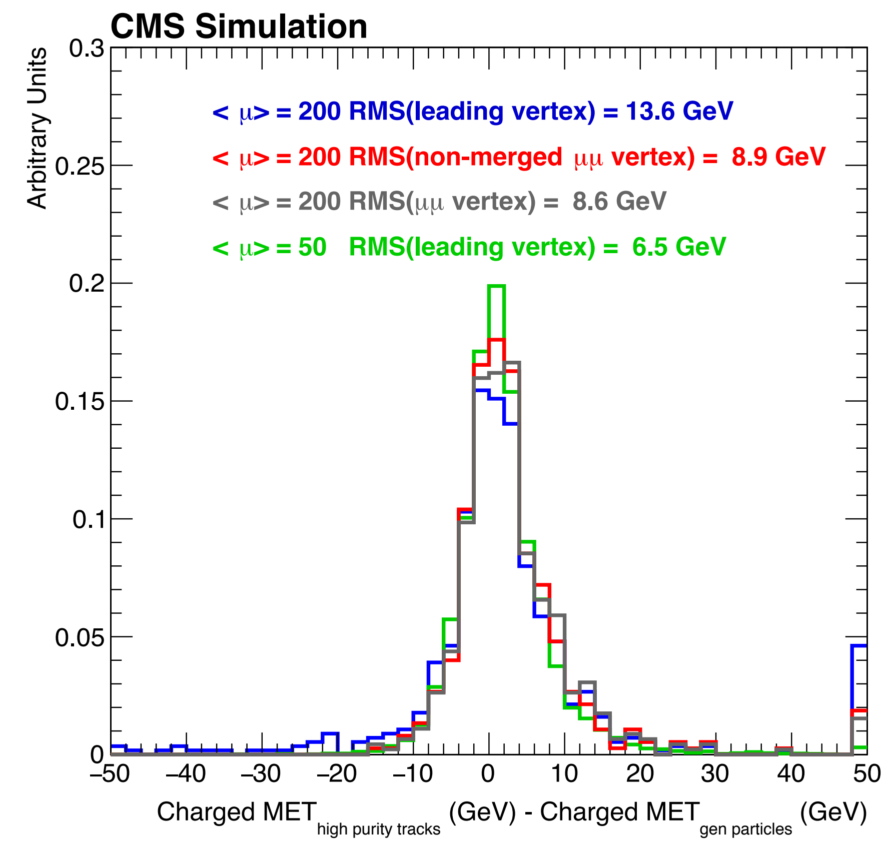
<μ>	4D Merged Vertex Fraction	3D Merged Vertex Fraction	Ratio of 3D/4D
50	0.5%	3.3%	6.6
200	1.5%	13.4%	8.9

The table describes the fraction of merged vertices for 3D and 4D vertex reconstruction in Run 1, 50 pileup, as well as Phase 2, 200 pileup, scenarios. The vertexing performance of the Run 1 detector in 50 pileup is recovered when using the 4D vertex reconstruction.

Effects of Vertex Merging



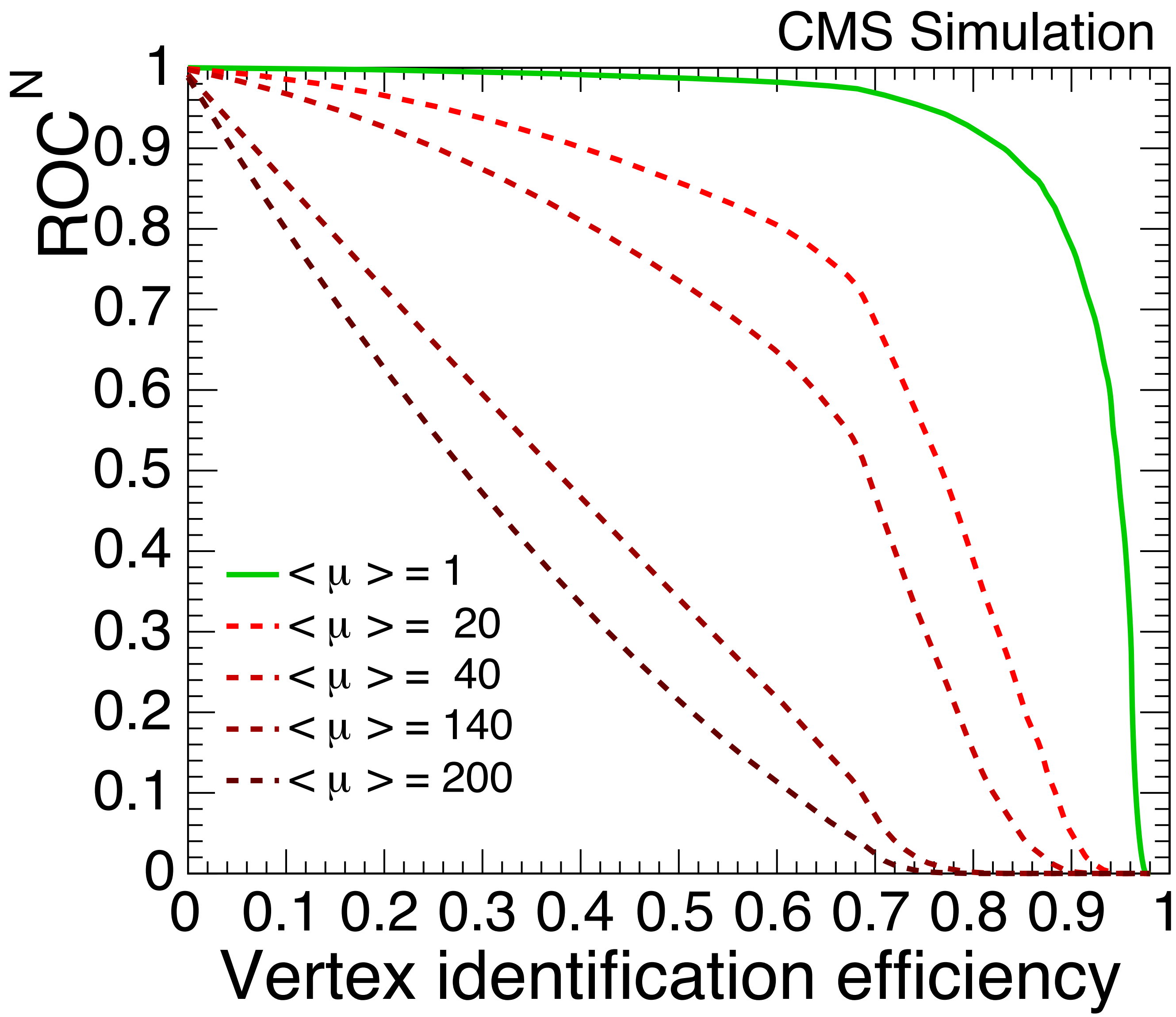




Left: The RMS p_T distributions of hard-scatter, Z(μμ), (dashed), emulated merged minimum bias where two minimum bias vertices are manually overlaid with each other (dotted), and minimum bias vertices (solid) demonstrating the large promoting effect that merging has on minimum bias vertices. This variable is the primary variable used to identify the hard scatter vertex.
Middle: The track-only missing transverse energy (MET) distribution of hard scatter, merged minimum bias, and minimum bias vertices indicating that reaching low track-only MET could be affected by tails from merging.
Right: The track-only MET resolution in 50PU and 200PU, showing that knowledge of the correct vertex plays a major role in improving the track-only MET resolution.

These plots together show that if you reduce the vertex merging rate, as on slide 5, you greatly reduce the amount of times the merged minimum bias vertices (that have increased tails) are sampled, and therefore increase the probability that the real hard scatter vertex is ranked first.

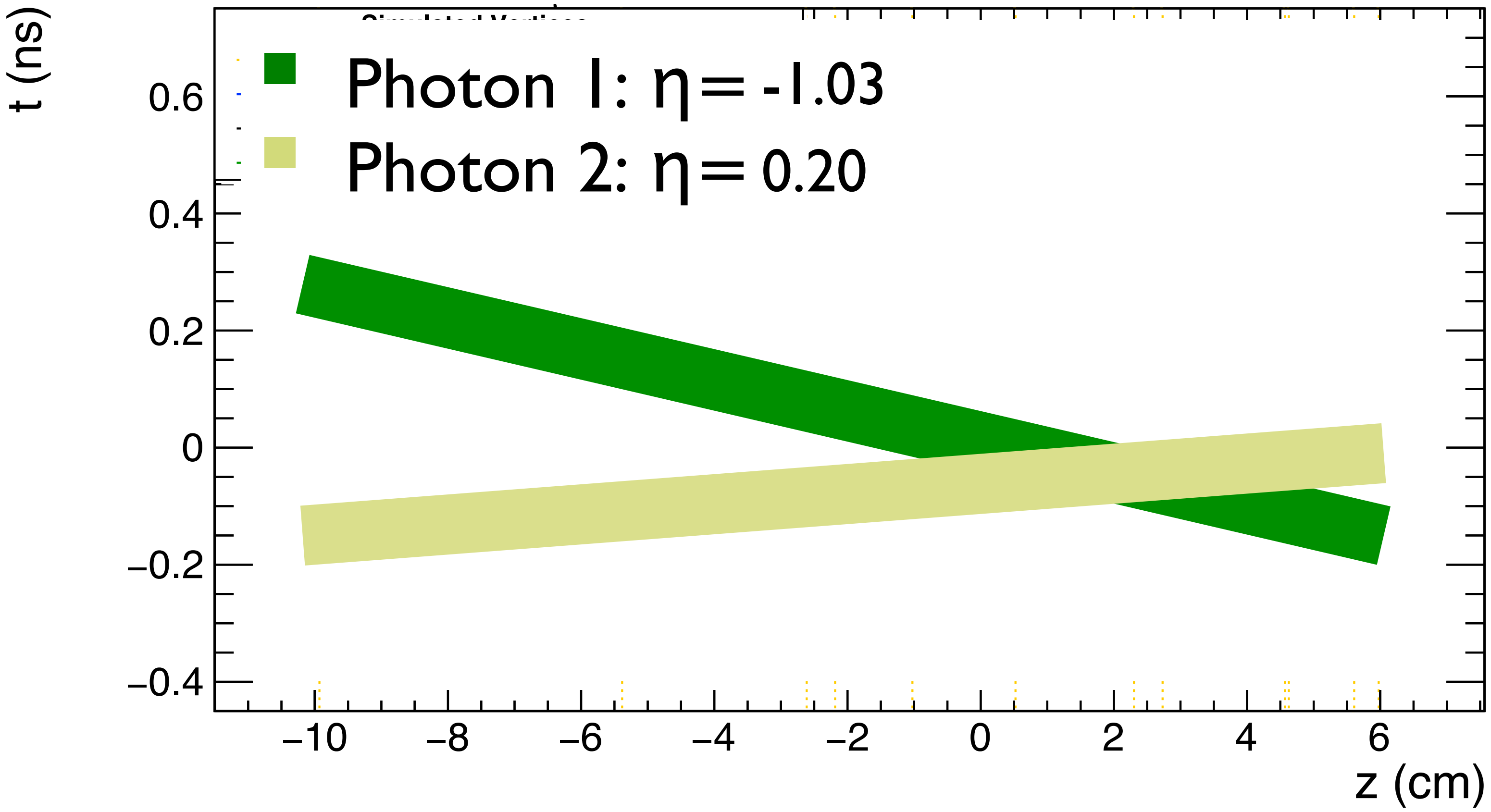
Hγγ Primary Vertex Identification in High PU

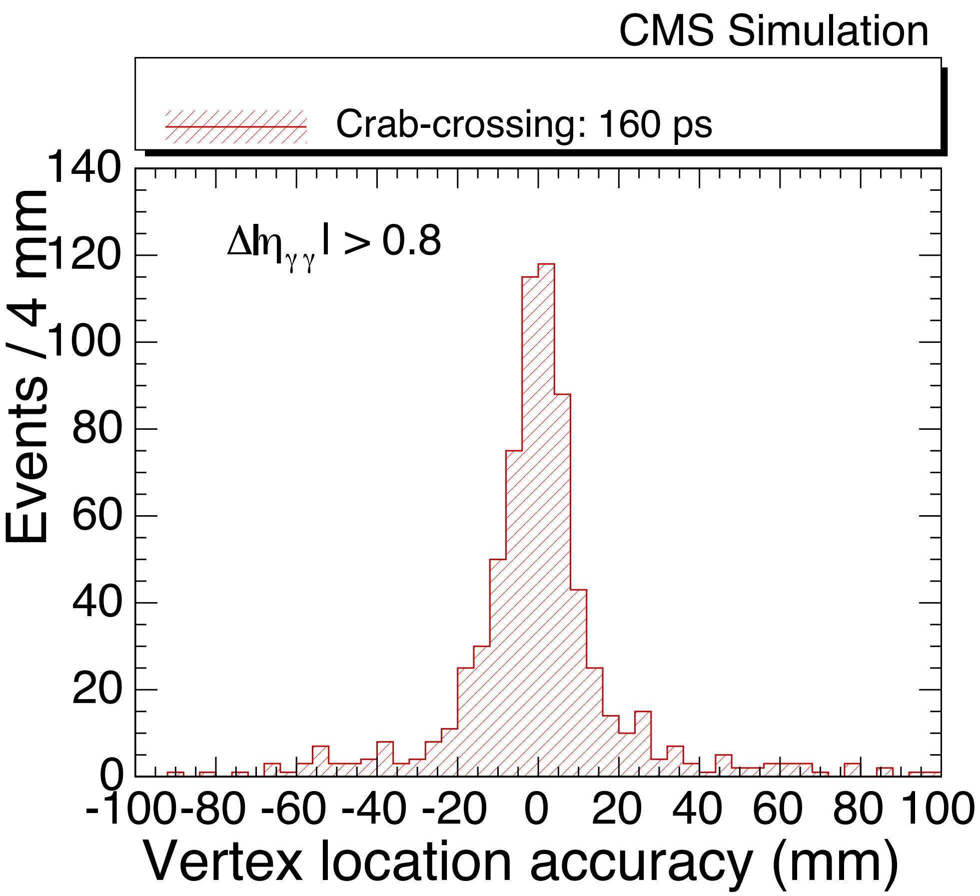


The primary vertex for the Run 1 H → γγ analysis is chosen using a ranking from a kinematic BDT [2]. The vertex identification efficiency is defined as the fraction of events in which the vertex chosen by the kinematic BDT is located within 1 cm of the true vertex. The solid line is the ROC (receiver operator characteristic) curve for vertex identification, i.e. the efficiency to rank the correct vertex first, with the Run 1 CMS detector (85%-70% efficient). The dashed lines are several ROC^N curves for average pileup multiplicity μ relevant at LHC and HL-LHC operations. The vertex identification efficiency is the integral of these curves, where at 200 pileup the efficiency is roughly 30%.

[2] http://arxiv.org/abs/1407.0558

Vertexing With Calorimeter-Only Timing





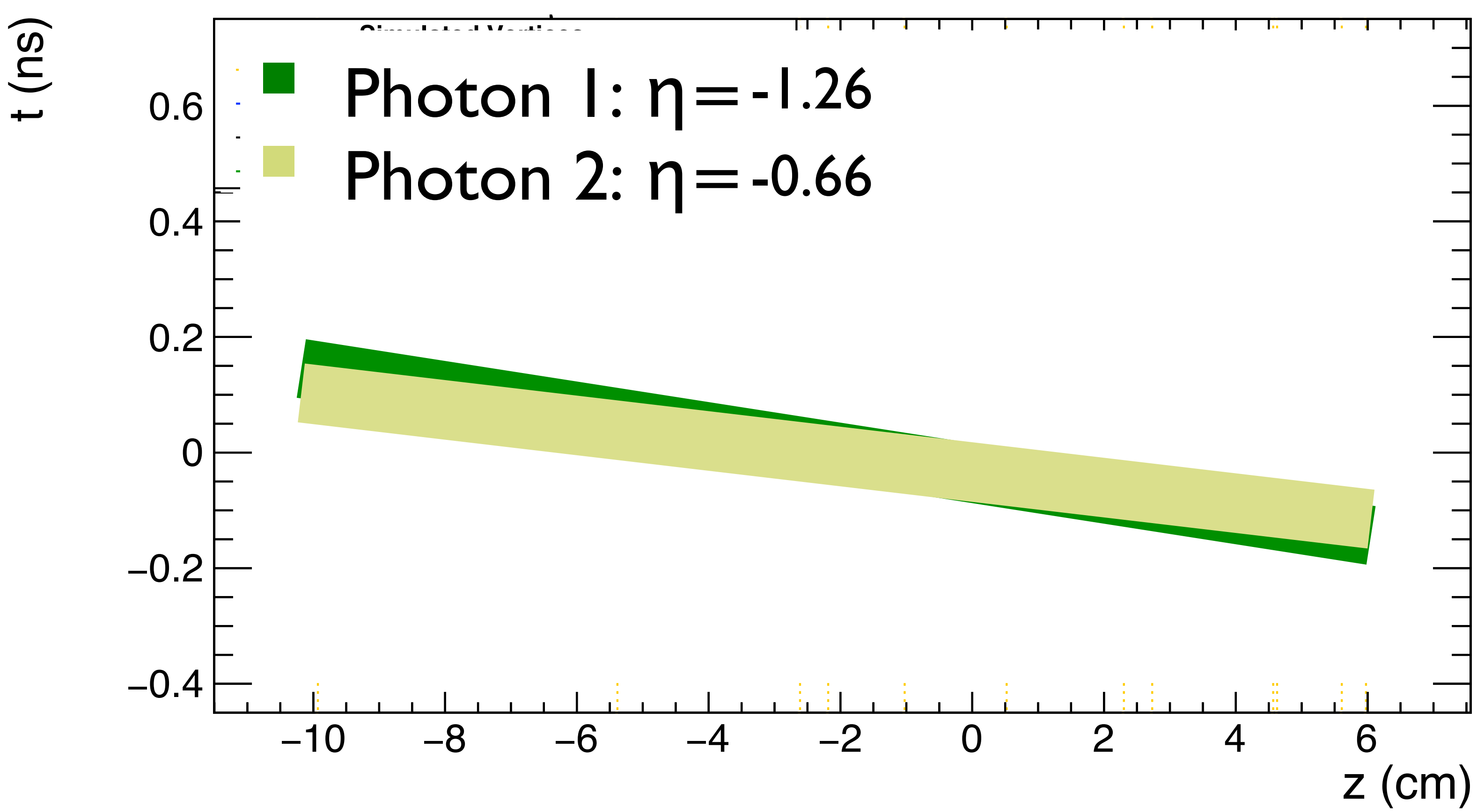
Calorimeter timing is exploited to reconstruct a "virtual" vertex position using triangulation, as demonstrated schematically in the **left** plot, showing a zoom-in of the beamspot region in (z,t) where the photon virtual vertex positions are compatible with the measured time of each photon. A common vertex position is defined via minimization of:

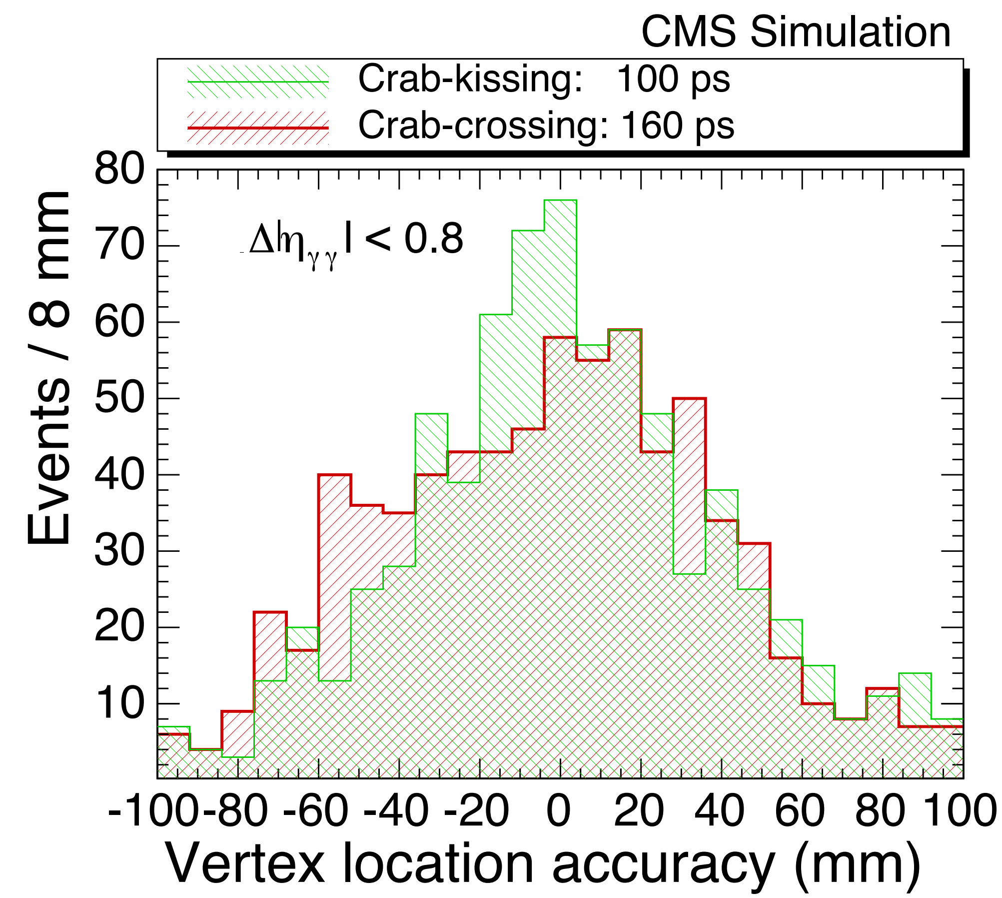
$$\chi^2 = \Sigma_{i=1,2} [t_i^{meas} - t_i(z,t_0)]^2 / \sigma_i + \textit{beam-spot cons.}$$

For events with decays into photons with pseudorapidity gap of $|\Delta\eta| > 0.8$, roughly 50% of $H \rightarrow \gamma\gamma$ decays, the vertex can be located with an RMS precision of about 1 cm, as displayed in the **right** plot, showing the distance between the virtual vertex position and the true vertex position along the beam direction, z, for gaussian resolutions of 30 ps in the measurement of the photon time.

Vertexing With Calorimeter-Only Timing

For events with decays into photons with pseudorapidity gap of $|\Delta\eta| < 0.8$, roughly 50% of $H \rightarrow \gamma\gamma$ decays, the vertex **cannot** be accurately located with only calorimeter timing information, as displayed in the **right plot** that shows the distance between the virtual vertex and the true vertex position along the beam direction, z, for gaussian resolutions of 30 ps in the measurement of the photon time.

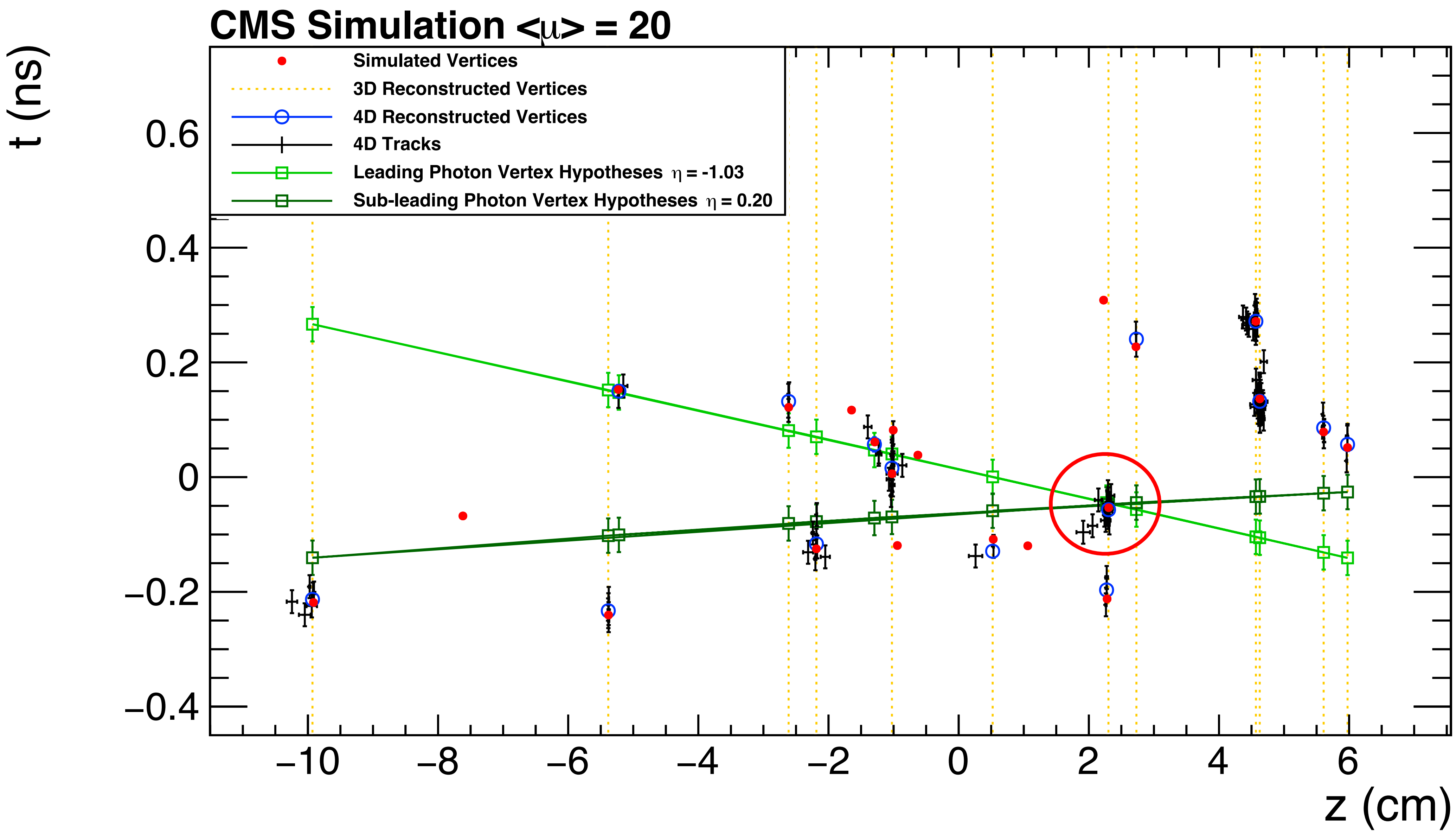




The red histogram shows the for the HL-LHC baseline optics (Crab-crossing), with a luminous region time-spread of 160 ps. The green histogram shows that the vertex location accuracy only marginally improves with the Crab-kissing options, with a luminous region time-spread of 100 ps (which would decay to 160 ps over the physics coast).

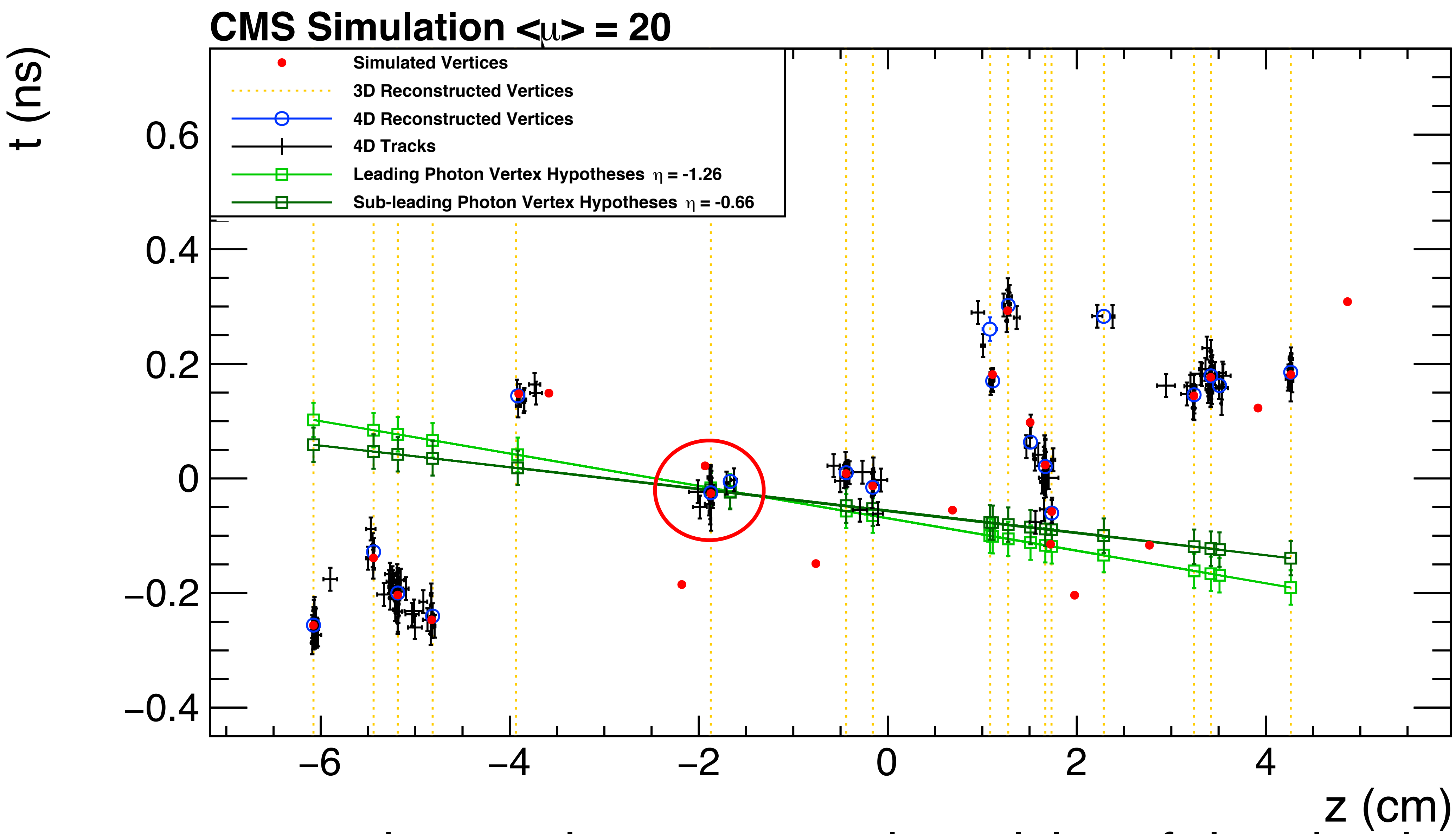
 Vertex location for these events requires time-zero information from the vertices (see slide 21)

Matching Neutrals to 4D Vertices 1



Above is a space-time diagram displaying ability to correlate calorimetric timing with track timing, using a $H \rightarrow \gamma\gamma$ 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.

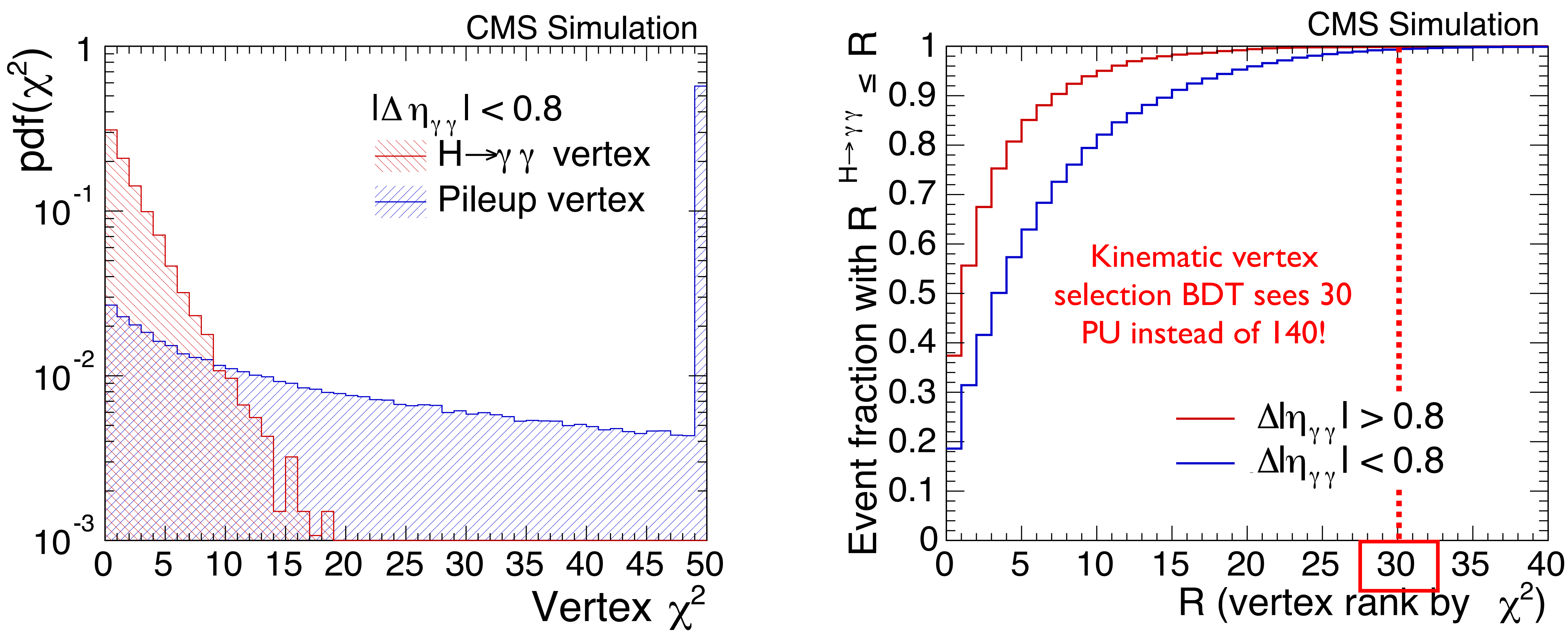
Matching Neutrals to 4D Vertices 2



Above is a space-time diagram demonstrating the inability of close-by photons to resolve a vertex alone, using a H → γγ decay as illustration. The reconstructed time for the photons from the hard scatter, in green, must be cross referenced with the time information of the 4D vertices in order to accurately identify the originating vertex. A triple coincidence, seen at (-2 cm, -.02 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.

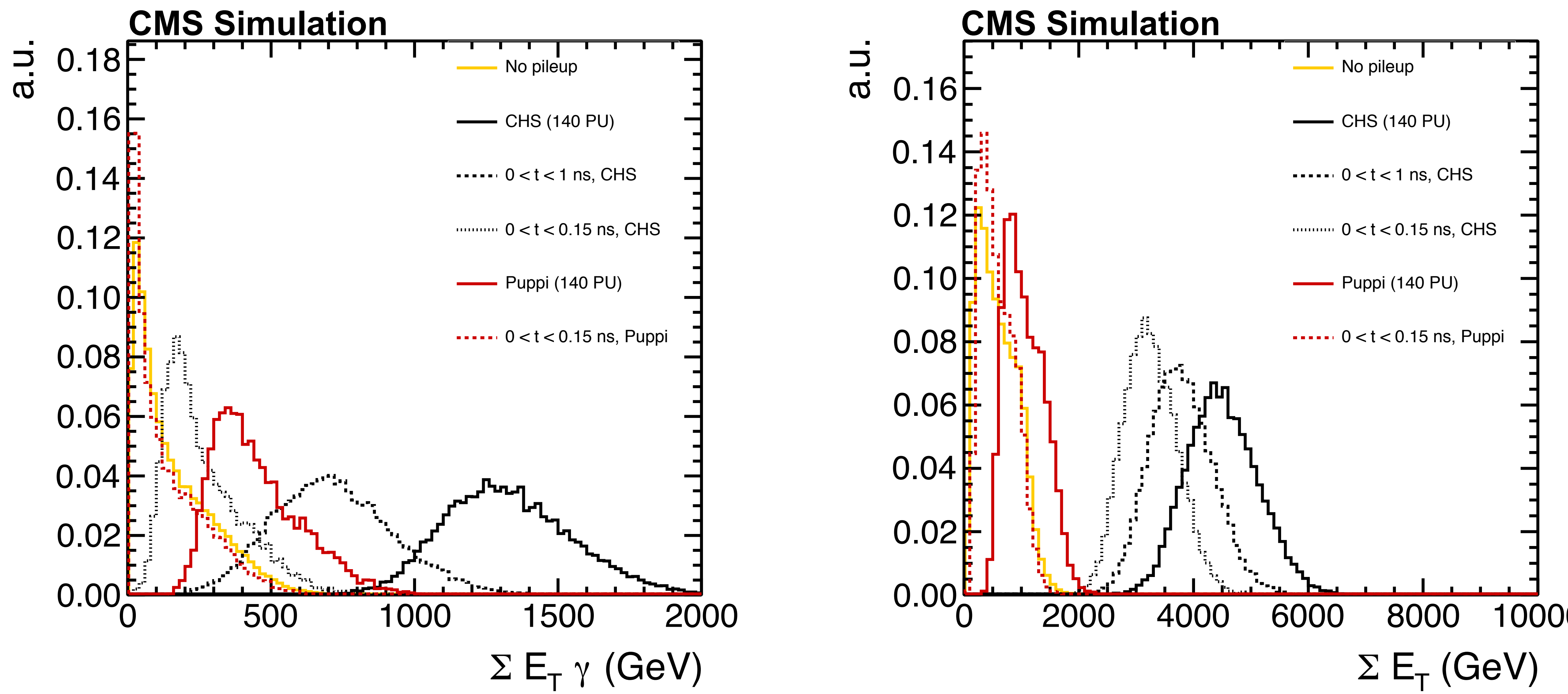
Exploiting Vertex Timing in Hγγ

Left: Distribution of the χ^2 of diphoton vertices (red histogram) and of pileup vertices (blue histogram), for 30 ps resolution in the calorimeters, 25 ps resolution in vertex timing, HL-LHC baseline optics, and a selection of photon pairs with $|\Delta\eta| < 0.8$.



Right: Fraction of events in which the diphoton vertex has a rank equal or better than the rank in the horizontal axis, for events with an average number of 140 simulated vertices. The reduced, "effective", pileup corresponds to 85-75% efficiency for the ROC on slide 7, and is similar to Run 1.

MET Performance with Timing



Distribution of the E_T sum of all reconstructed PF photons (left) and all reconstructed PF particles (right) for a QCD event sample with a flat E_T distribution without pileup and three different scenarios (orange) and for an average of 140 pileup interactions and different pileup subtraction scenarios (black: charged hadron subtraction, loose and tight timing selection; red: Puppi, with and without tight timing selection).

Forward Pileup Jet Mitigation with HGTD

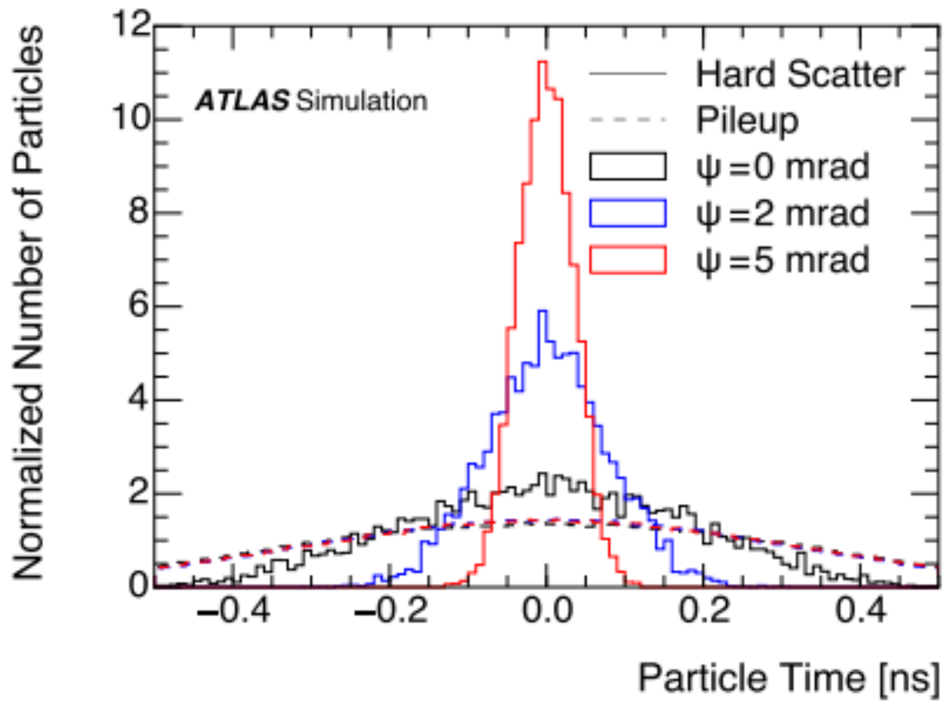


Figure 92. Arrival time spread for hard-scatter and pile-up particles for different bunch collision schemes (crab-kissing angle ψ), assuming that the z position of the hard-scatter vertex is known.

HGTD information with Crab Kissing

- Assumption: z position is known
- Crab kissing reduces the time spread of the hard scatter, but this decays over the fill
- On-going similar studies in non CK scheme

ψ = 0 mrad ~ σ_t =160 ps
ψ = 2 mrad ~ σ_t =100 ps
ψ = 5 mrad ~ σ_t = 50 ps

Efficiency hard scatter versus pileup:

- Reduction of pileup as function of the timing resolution
- Jet p_T > 20 GeV
- Rejection of factor 10 possible
  - Depends on working point

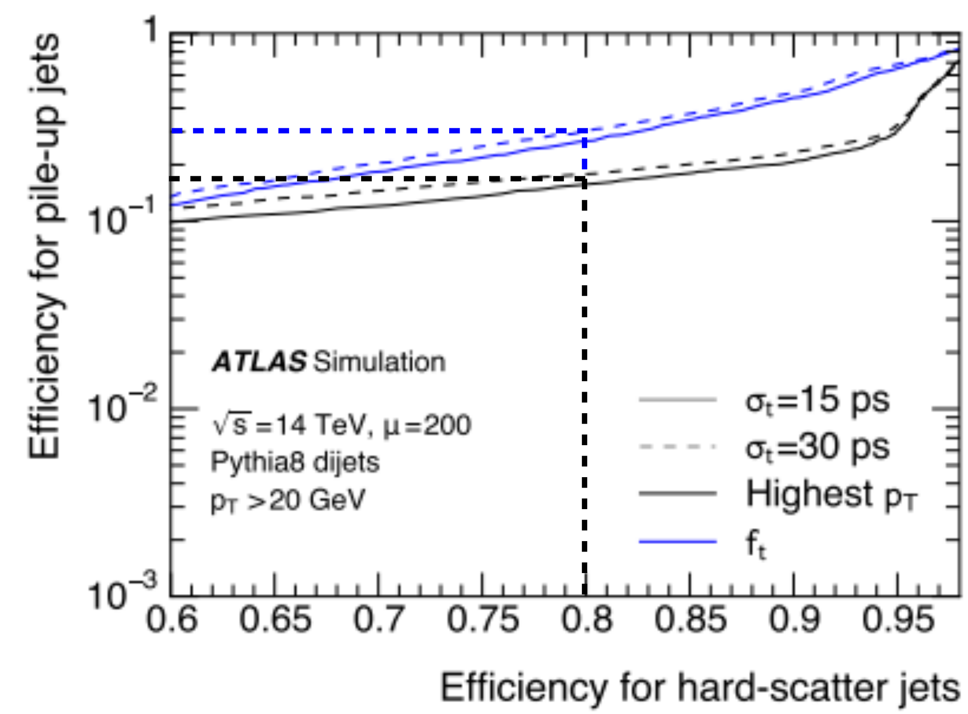


Figure 93. Efficiency for selecting pile-up jets as a function of the efficiency for selecting hard-scatter jets using the jet time from the highest p_T particle (black) and the time fraction f_t (blue) as discriminant, assuming a crab-kissing scheme with ψ = 5 mrad.

Based on Fast Simulation for two values of the HGTD timing resolution.

Conclusions

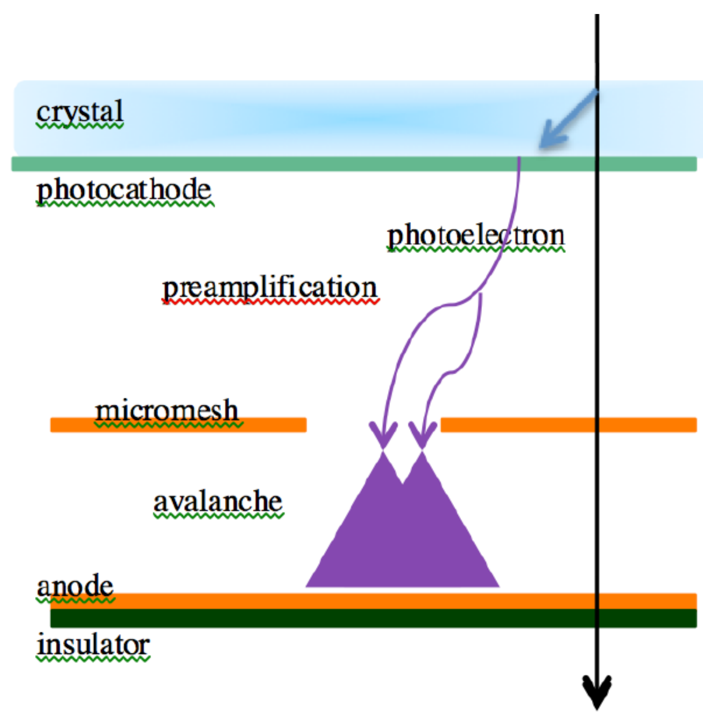
- ATLAS and CMS are exploring the possibility of dedicated timing detectors (layers)
  - 200 PU starts to have serious performance drawbacks
    - Timing, both MIP and calorimetric, can be used to exploit space-time structure of beam-spot
  - New technologies exist and tested in beam at single-device scale
    - Radiation studies are underway, but need to broaden current R&D effort
    - Some technologies still progressing towards final design
  - Challenging R&D program
    - Collaboration with RD50/51 should be looked into
- Uses and need of such detectors are starting to be explored by both collaborations
  - CMS - baseline improvements to tracking, $H\gamma\gamma$
    - Understand how to complement the already baseline calorimetry timing
    - Indications of complete recovery of Run 1 performance when timing layer included (to study further)
  - ATLAS - forward jet cleaning
    - Up to factor of 10 rejection of forward jet fakes in fast simulation
- Both collaborations aiming to arrive at a position next year

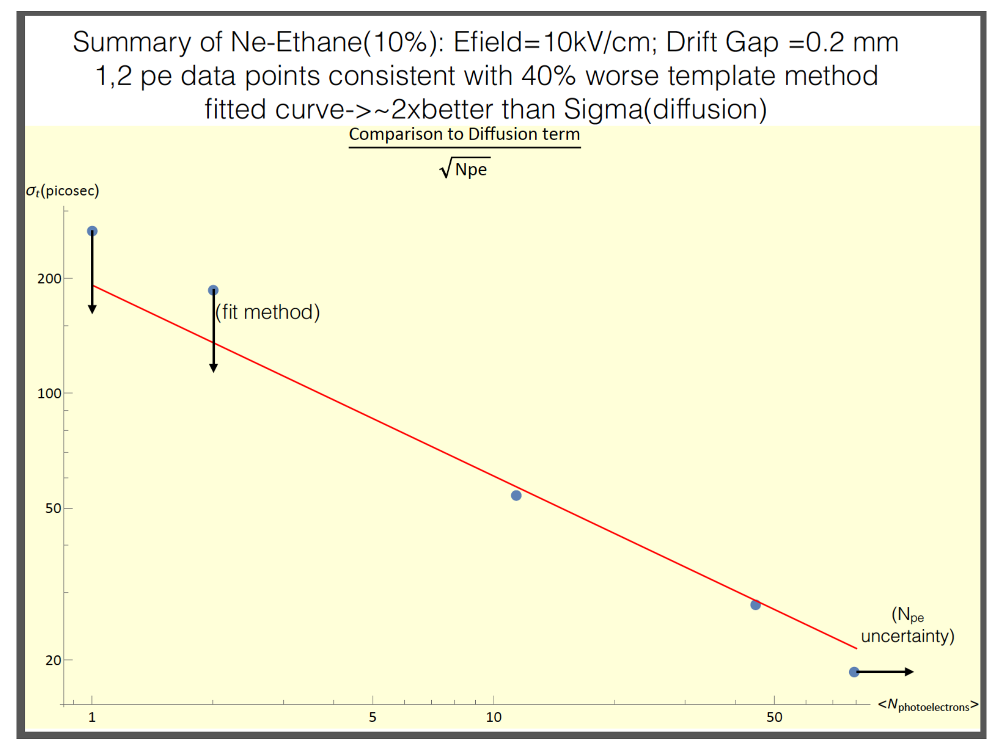
Backup

Micro-pattern Gas Detectors [4]

- GasPMT: thin gas-detector (Micromegas) with radiator window (σ_t = 30 ps)
  - Localize primary ionization in photocathode
  - Resolution determined by longitudinal diffusion in the gas
  - First prototype assembled and tested with laser at Saclay
    - Promising

S.White arxiv:1409.1165, arxiv:1601.00123

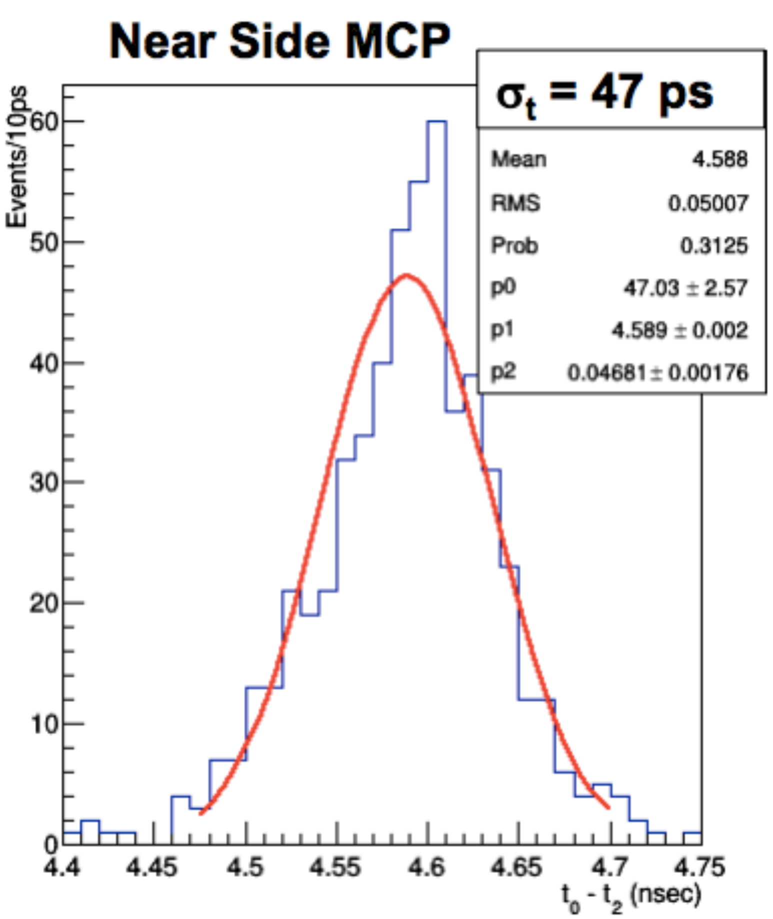


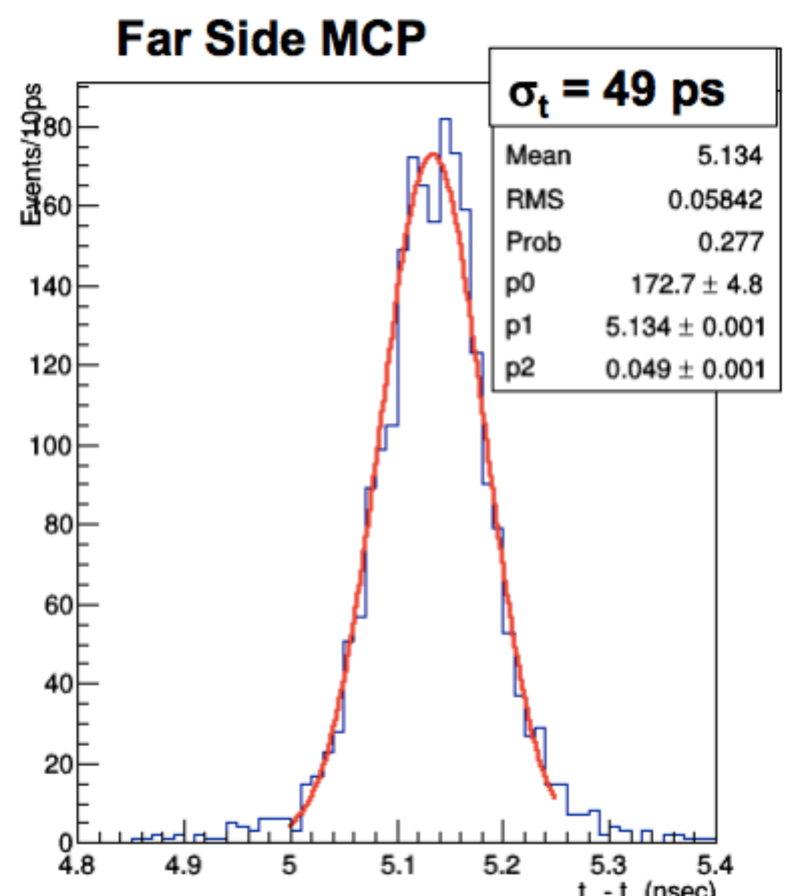


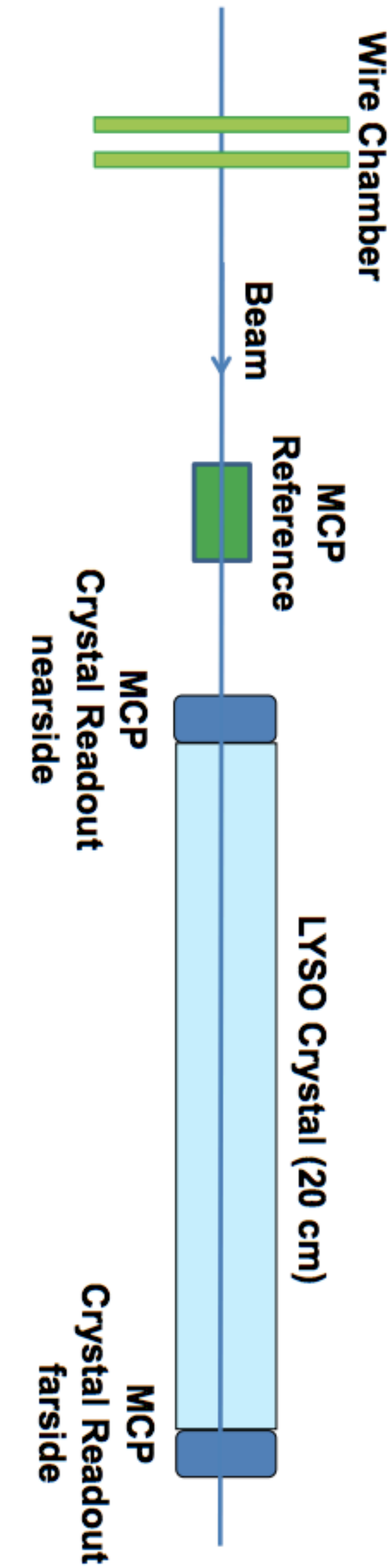
- Multi thin-gap GEMs (muons): R.De Oliveira, M.Maggi, A.Sharma, arXiv:1503.05330
  - Similar to multiple RPCs, with GEM as amplification stage, High rate capability (σ_t = 2 ns)
  - Thin gaps provide small time diffusion; efficiency from multiple gaps

Scintillators with Fast PMT + LYSO

- Photek MCP 4 mm2 area: reference time
- Hamamatsu MCPs 8 mm2 area: crystal readout
- Time resolution from full crystal ~50 ps
  - Indications that further gains are possible







A.Bornheim, Frontier Detectors, Elba 2015
D.Anderson et al. NIM A 294 (2015) 7