Timing information in HEP (chiefly at HL-HLC)

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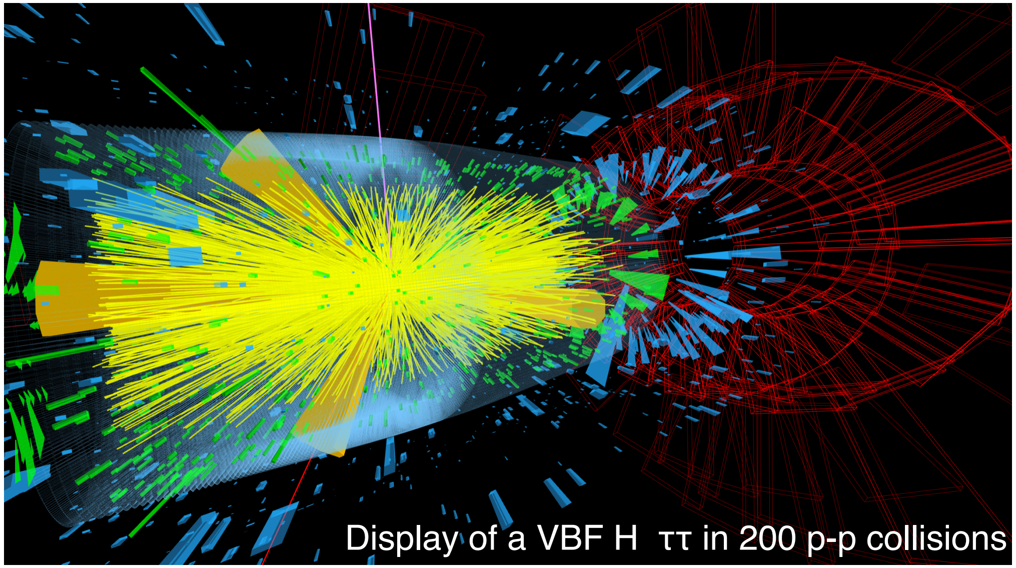
Presentation based on studies performed
for the upgrade of CMS and ATLAS experiments

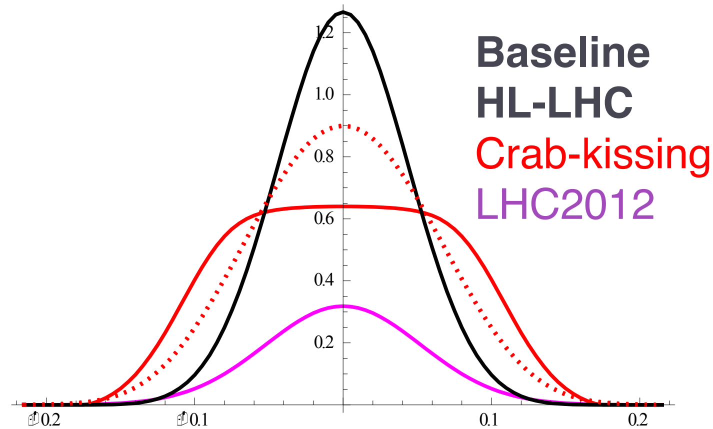
Results available in:
CMS Note: CERN-CMS-DP-2016-008
ATLAS Phase-II Upgrade Scoping Document: CERN-LHCC-2015-020

Statement of the problem
[HL-LHC with 200 collisions per BX event]



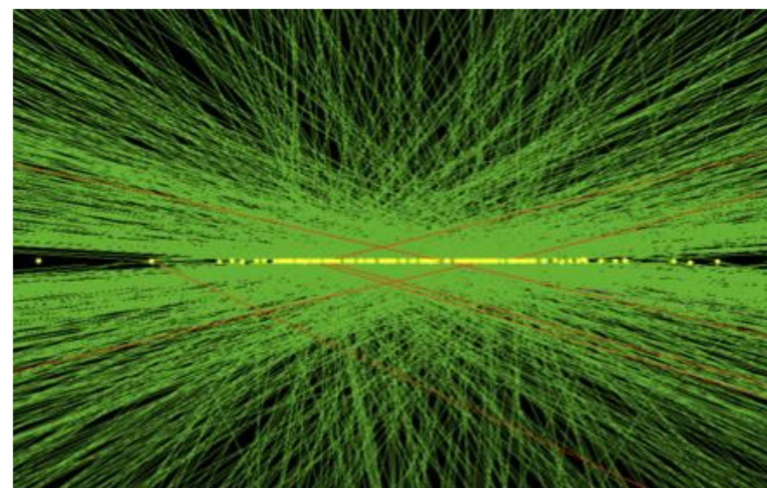
[S. Fartoukh, PhysRevSTAB.17.111001]

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

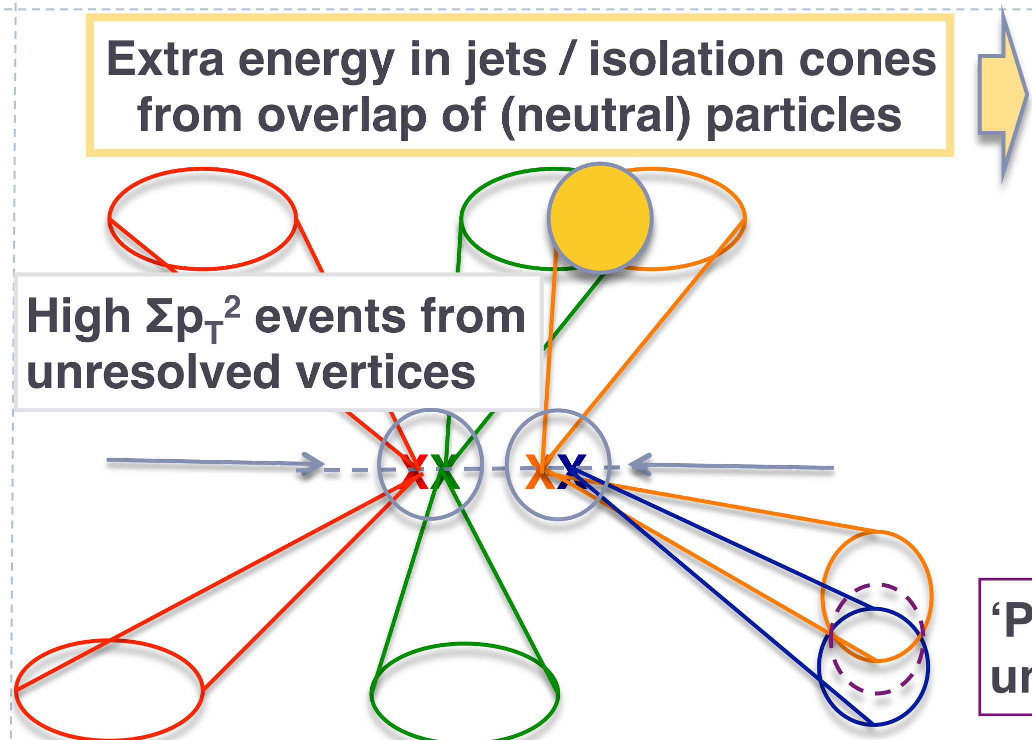


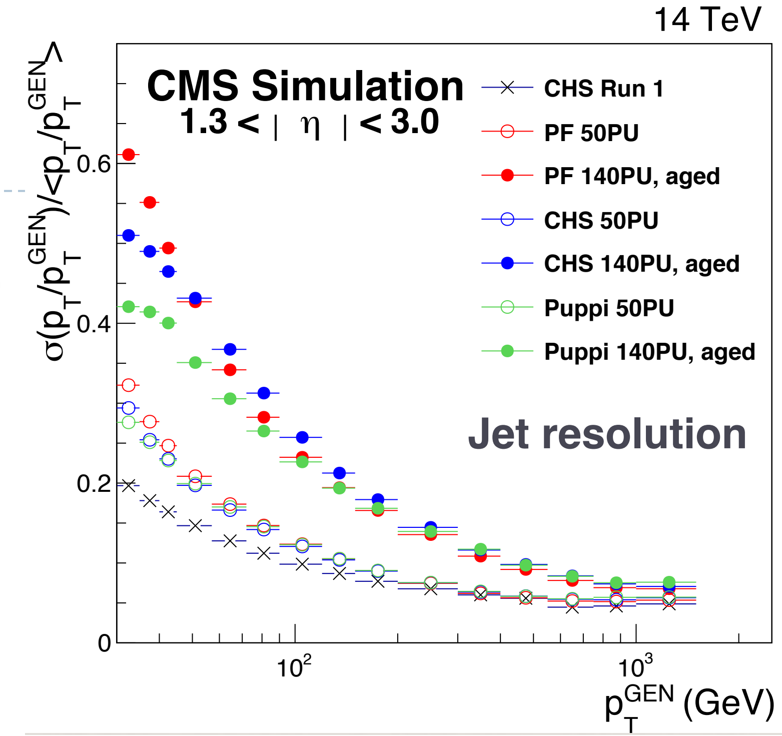
An interaction of interest at less than 1% of the collisions simultaneously produced

- ✓ Vertex merging rate ~**10%**
- ✓ Reduced efficiency of usual metrics – like vertex of highest Σp_T^2 – to identify hardest collision



Adverse effects of pileup

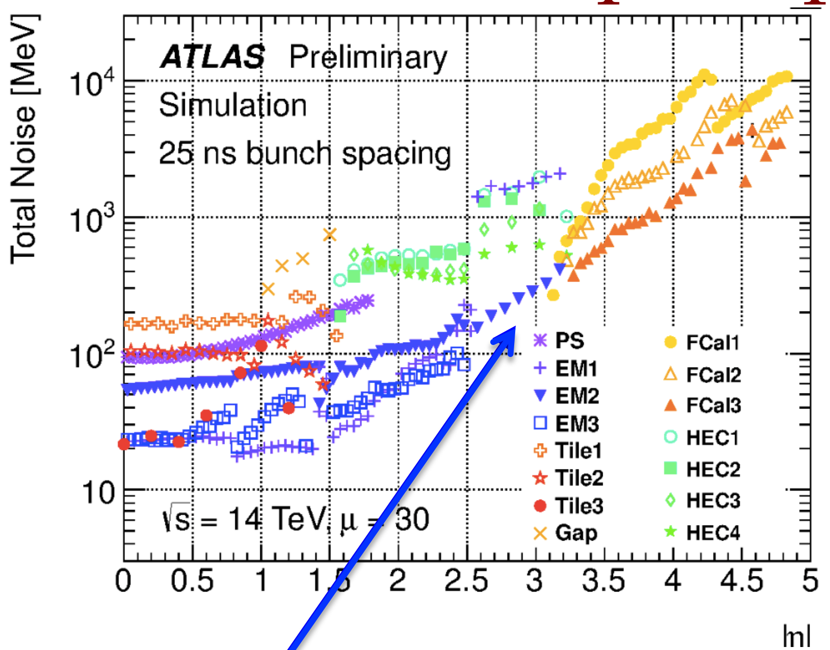


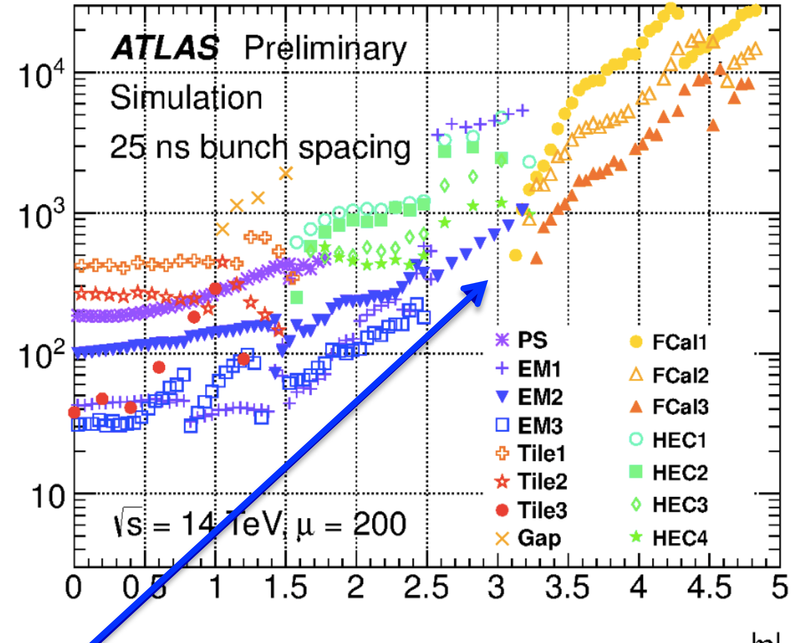


'Promoted' jets from spatially unresolved vertices

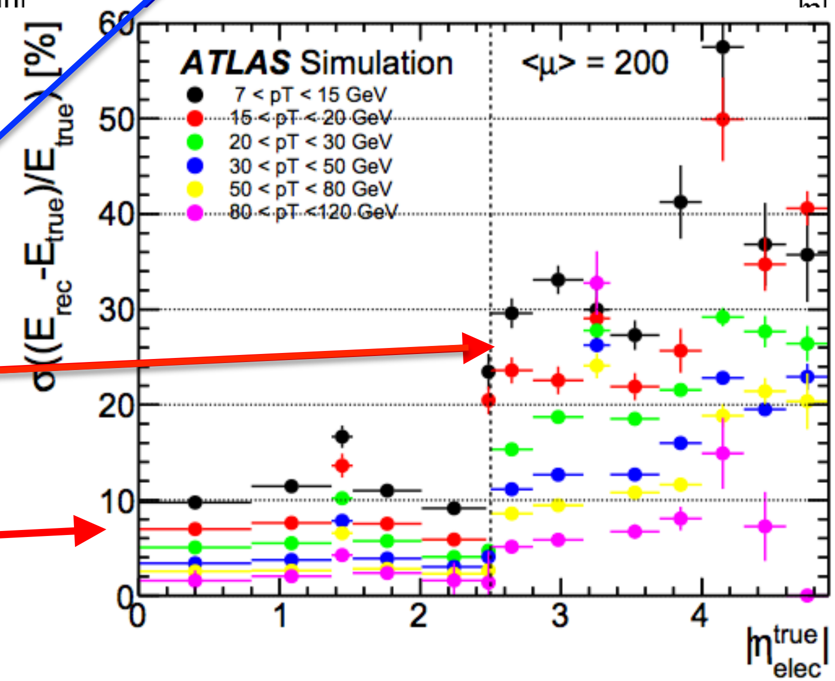
- **Unfavorable low level effects:**
  - Fake vertices and high p_T jets from merging
  - Efficiency loss to associate signal particles (chiefly photons) to vertices
  - Significantly degraded jet and MET performance
- **One avenue for pileup mitigation: *precision timing***

Adverse effects of pileup - II





- **LAr endcap calorimeter pile-up noise contribution dominant at HL-LHC**
  - At 2.5<|η|<3.2 resolution from **2 GeV for μ=30** to **3-5 GeV for μ=200**

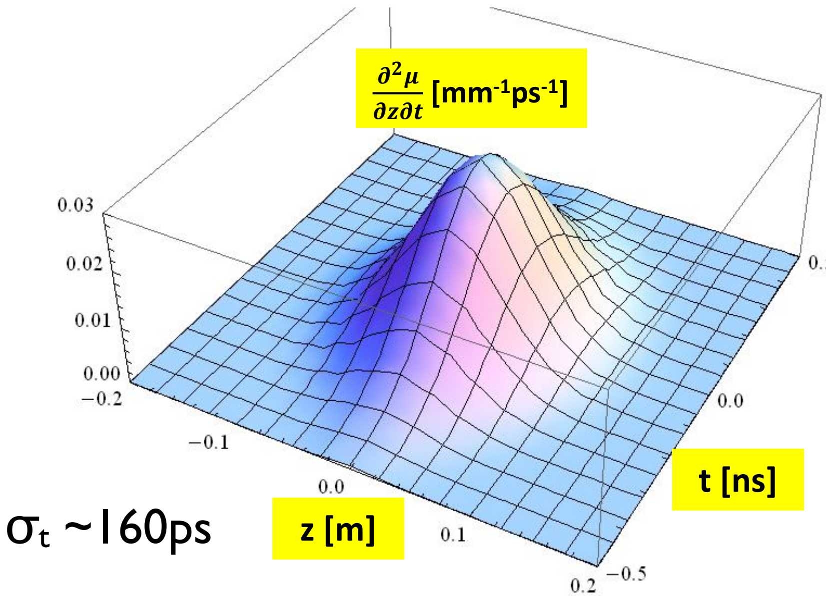


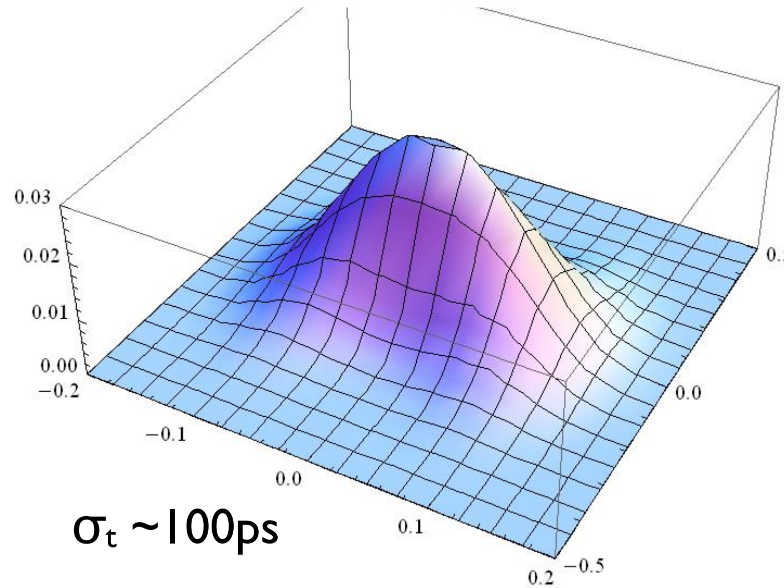
- **Also looking at EM energy resolution**
  - Large PU effect for |η|>2.5
  - Coarser granularity of the EM calorimeters for |η|>2.5
  - Weak sensitivity to pileup for |η|<2.5

Time spread of the HL-LHC luminous region

HL-LHC baseline optics:
- $\sigma_z \sim 5$ cm; $\sigma_t \sim 160$ ps

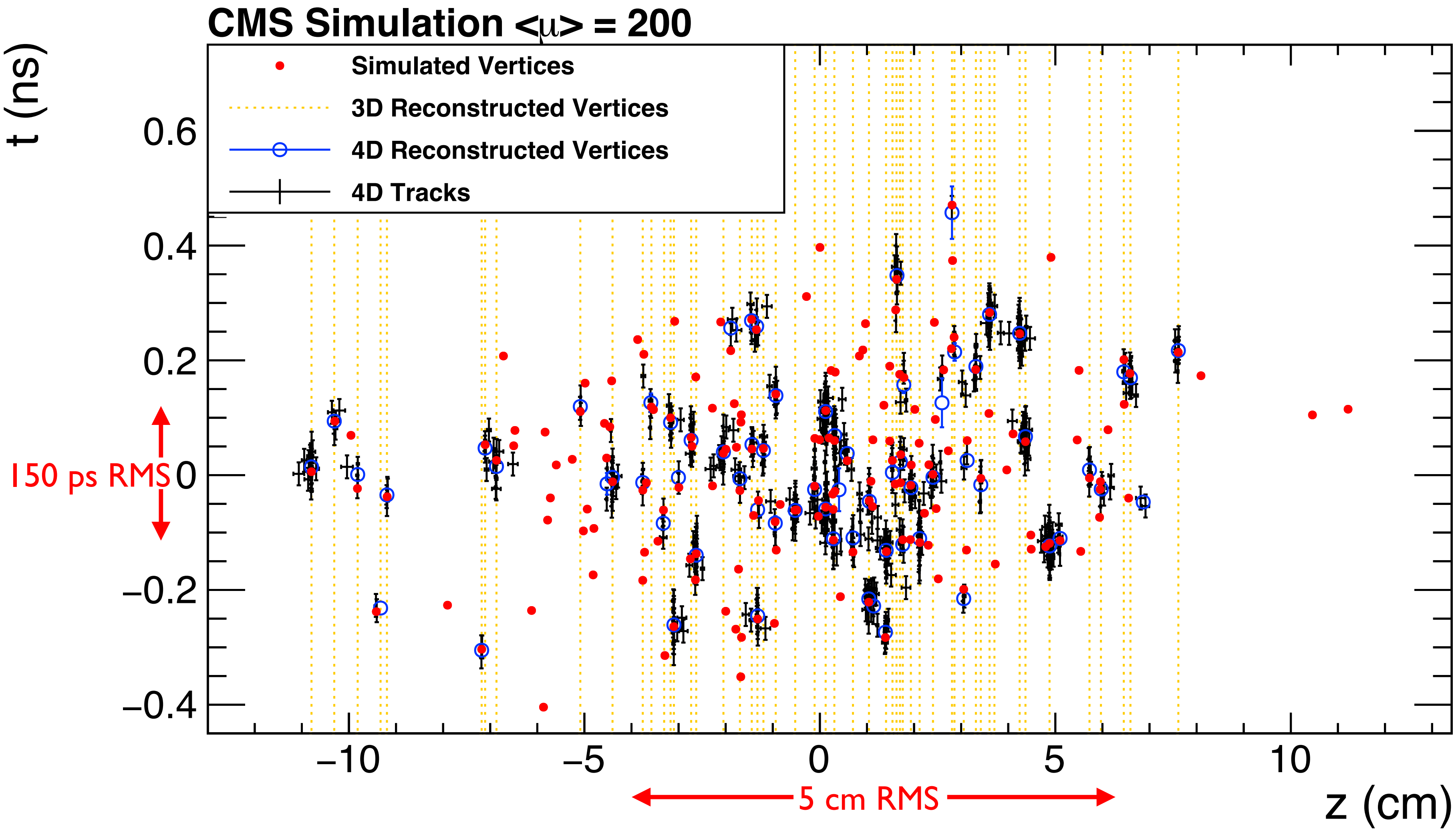
HL-LHC Crab-kissing :
- $\sigma_z \sim 7$ cm; $\sigma_t \sim 100$ ps
- Vertex density down by a factor 2





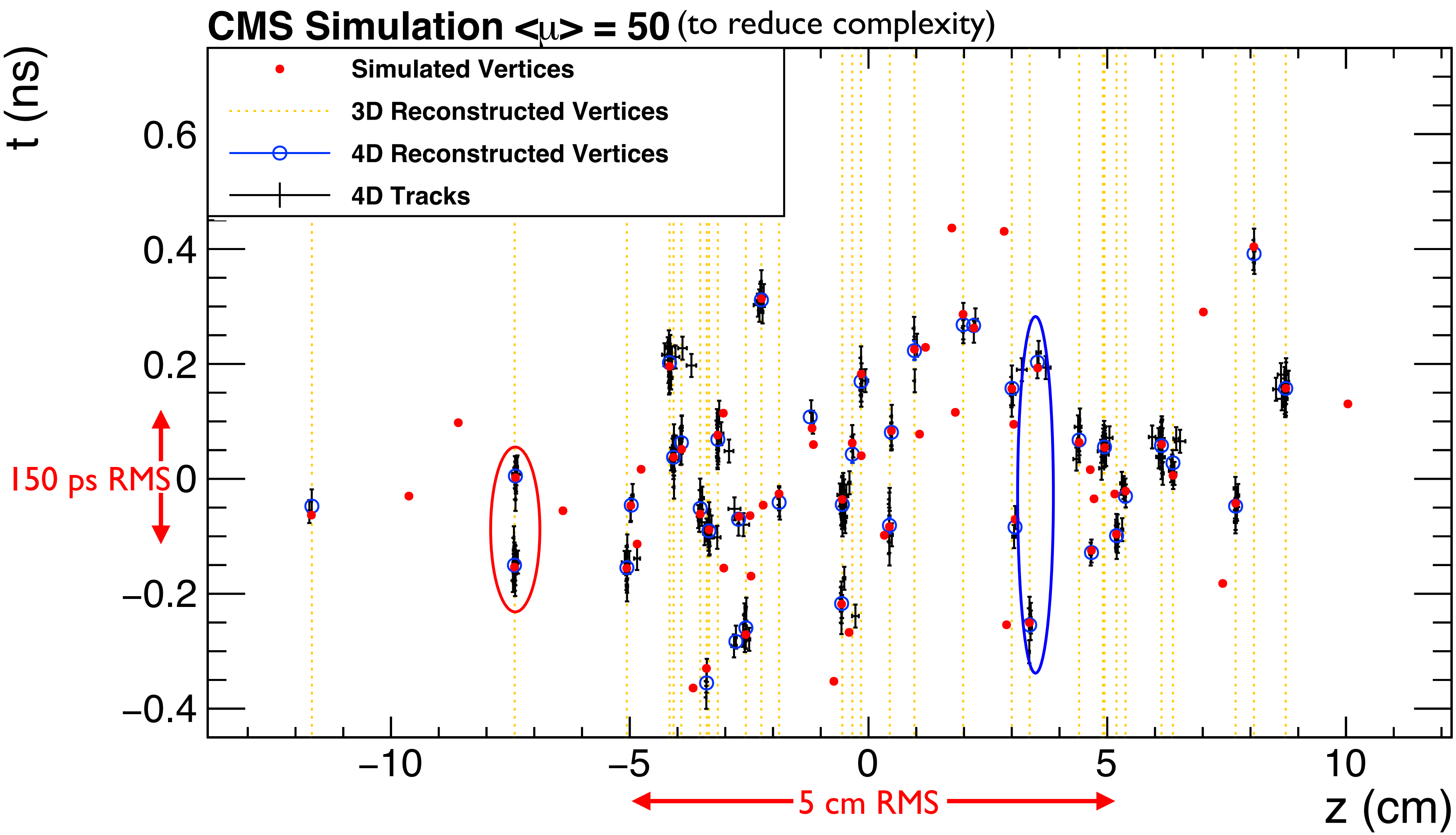
- **If beam-spot sliced in successive O(25) ps time exposures, the number of vertices per time exposure drops down to Run 1 LHC pileup levels (beam spot time spread ~160 ps)**
  - Vertex density down by about a factor eight

Time-aware vertexing



- HL-LHC baseline optics (crab-crossing)

Time-aware vertexing

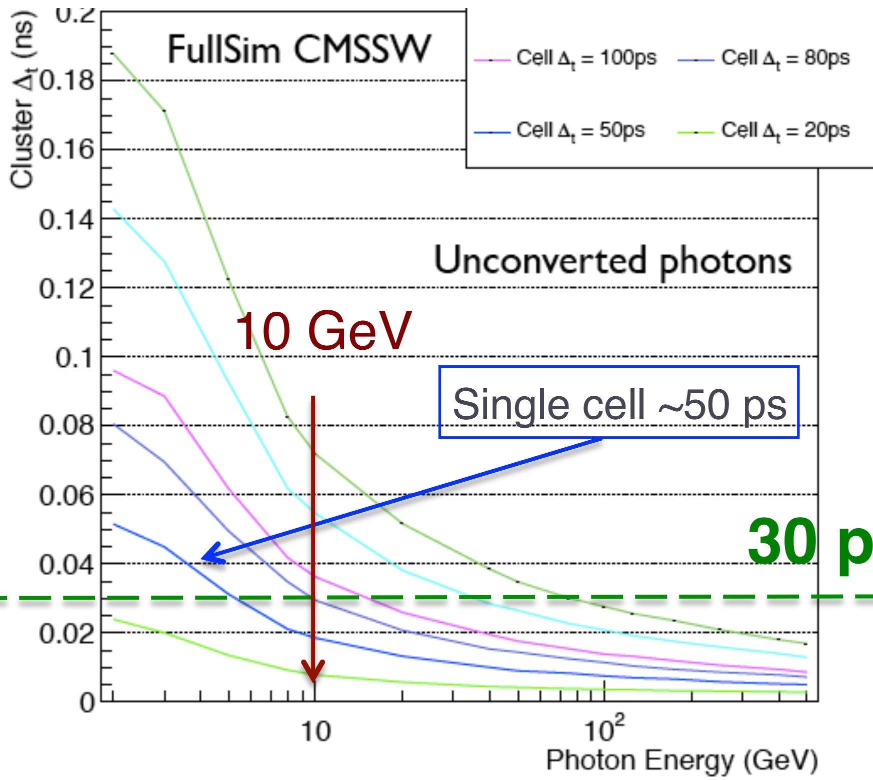


- Examples of vertices merged in 3D algorithm circled

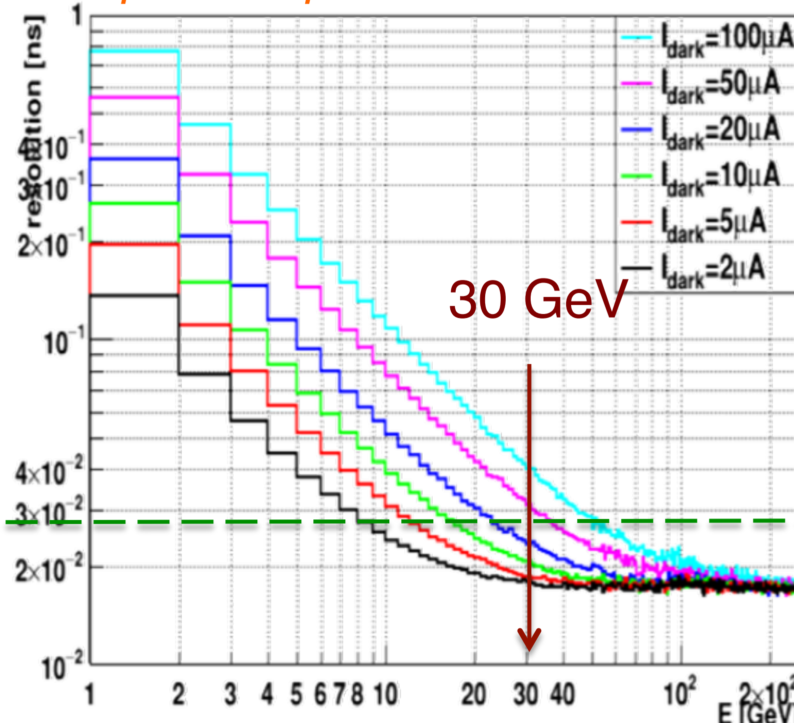
Timing in CMS upgraded systems

- **Calorimeters (photons):**
  - HGCal – Si/W/Cu (left): Single cell timing for more than 30 MIP signals
  - ECAL – $PbWO_4$ (right): Seriously considered for the upgrade (new VFE)

[both plots for perfect clock distribution]



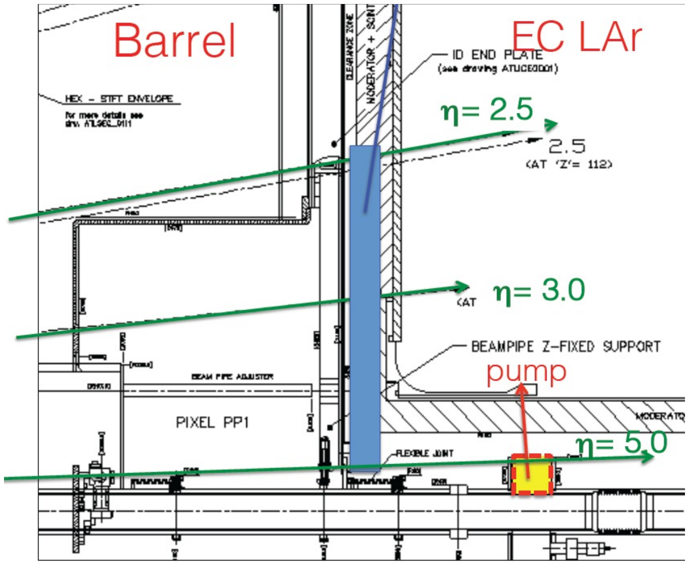
30 ps



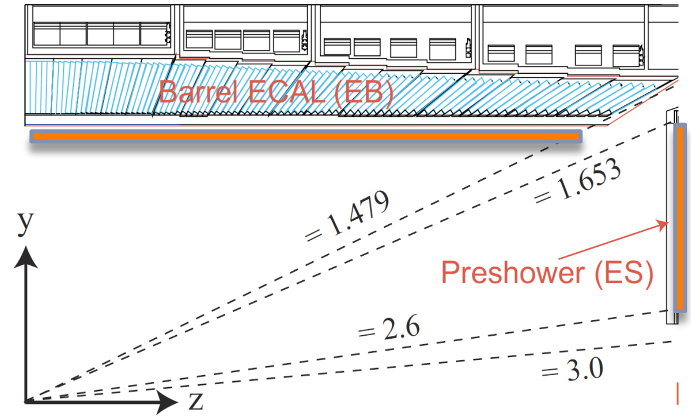
- **Limited / no timing performance for charged tracks (MIPs)**
- To investigate hadrons further in HGCal

Timing layer ideas

- **ATLAS (reference design):**
  - "High-Granularity Timing Device" (Endcap)
  - Considering multi-layer MIP-focused device (2.5<|η|<5) or preshower-style (2.5<|η|<3)
    - Focusing on Silicon in baseline design



- **CMS:**
  1. Thin layer in both barrel and endcaps
     - *A low-mass accompaniment to the tracker, sensitive to MIPs*
  2. Thicker layer in the barrel ('preshower')
     - *Sensitive to MIPs and photons*
     - Several technologies being investigated



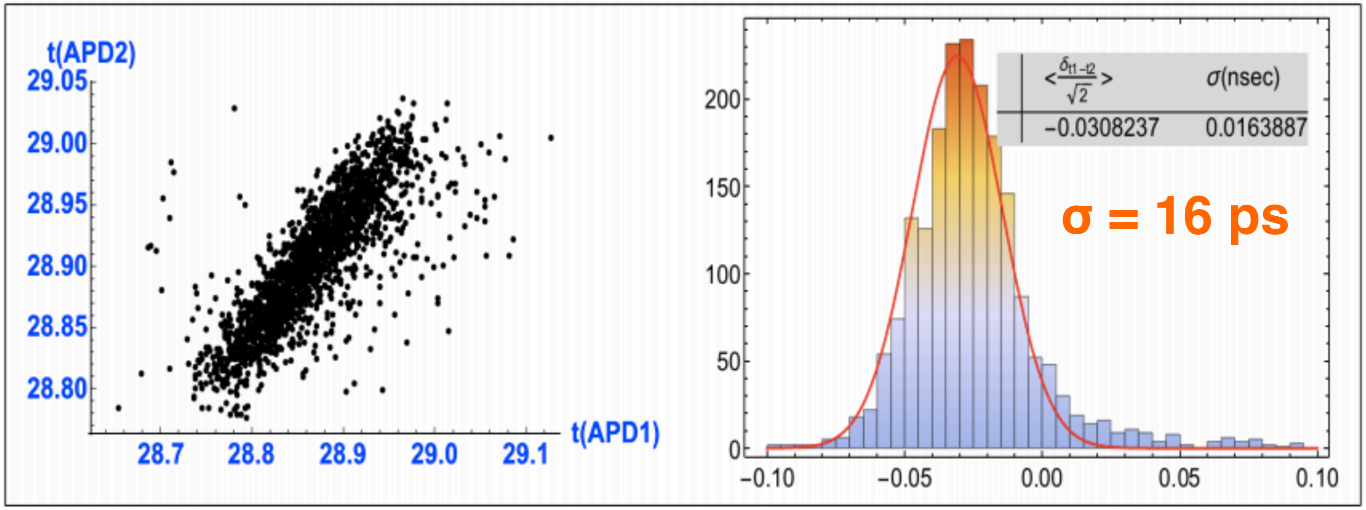
- **Layout**
  - Granularity of order 1 cm^2 (time-walk, occupancy, shower size)
  - Rate capability up to : 10^6-10^7 Hz
  - Radiation hardness up to: 50 Mrad – 3×10^{15}/cm^2

Front of the endcaps

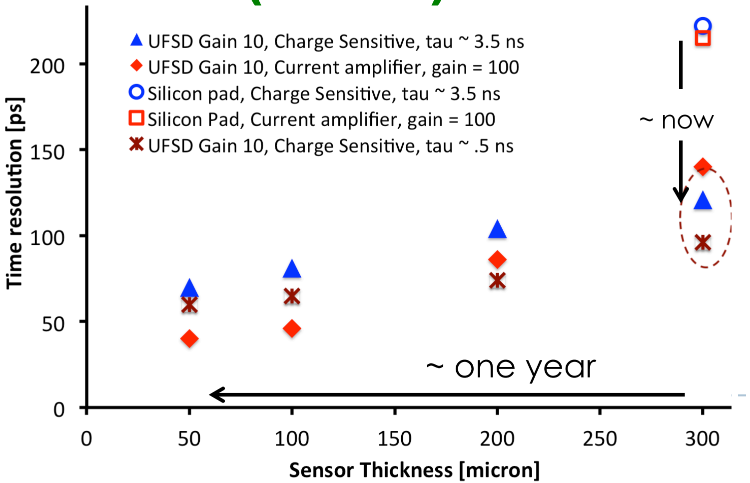
Detector technologies: Silicon sensors with internal gain

- **R&D on high gain APDs with field shaping and capacitive readout in 1 cm^2 pads – *"Hyperfast Silicon"***

[[S.White, Frontier Detectors etc., Elba, (Italy) 2015](#)]



- **Further R&Ds: "Low-Gain Avalanche Device" (LGAD)**
  - Expect 30-50 ps timing in thin sensors [current generation (thick sensors) 120 ps]
  - New sensors on the way to validate simulations



[[N.Cartiglia, CERN Seminar, 2014]](#)

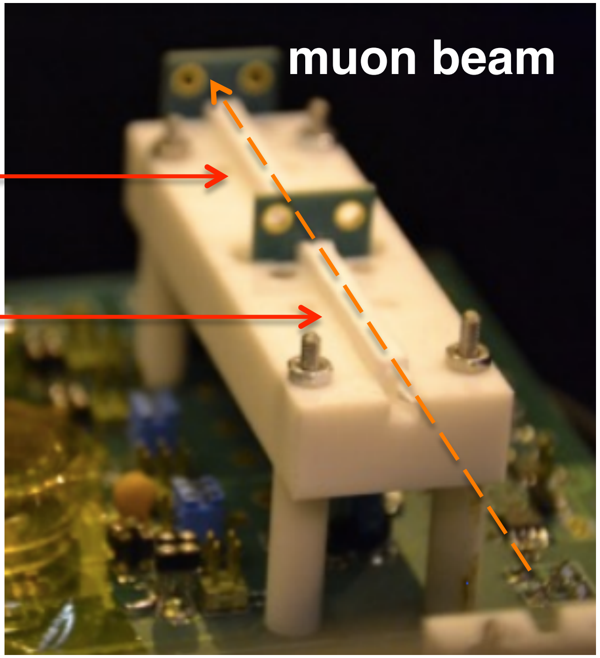
Detector technologies: Crystals with fast photosensors

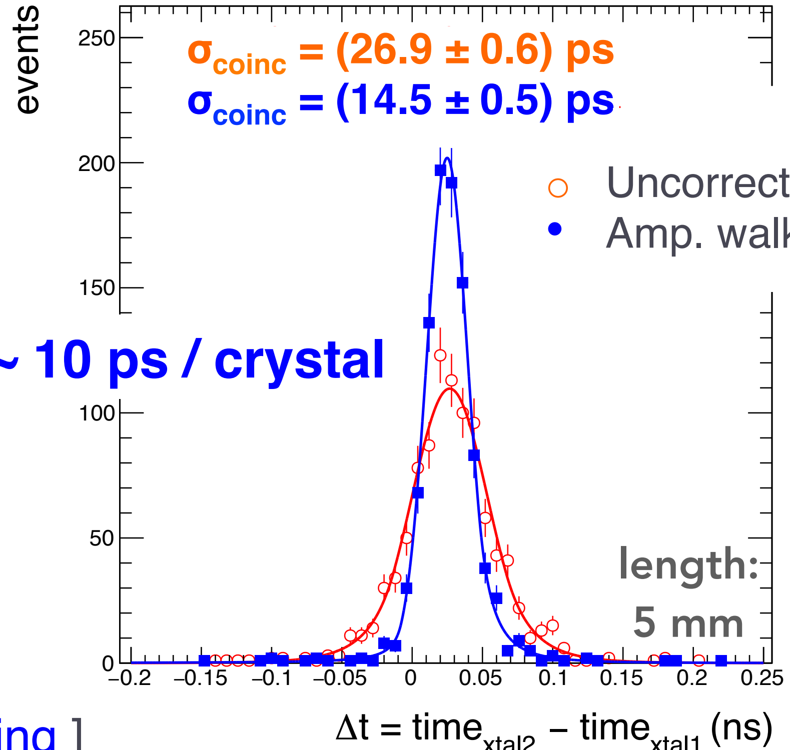
- **Use light to boost MIPs signal**
  - LYSO:Ce with SiPM+NINO readout tested with **muons**
  - Small size crystals (small light path dispersion):

    3 x 3 x L mm^3 (L=5÷30 mm)

Crystal 2

Crystal 1





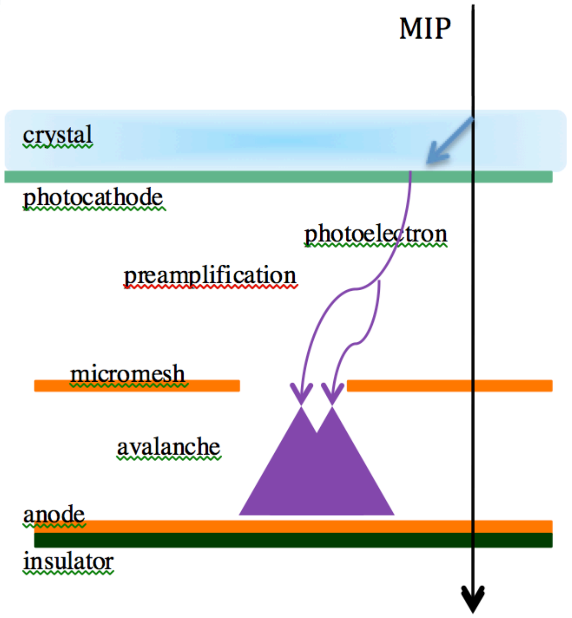
σ ~ 10 ps / crystal

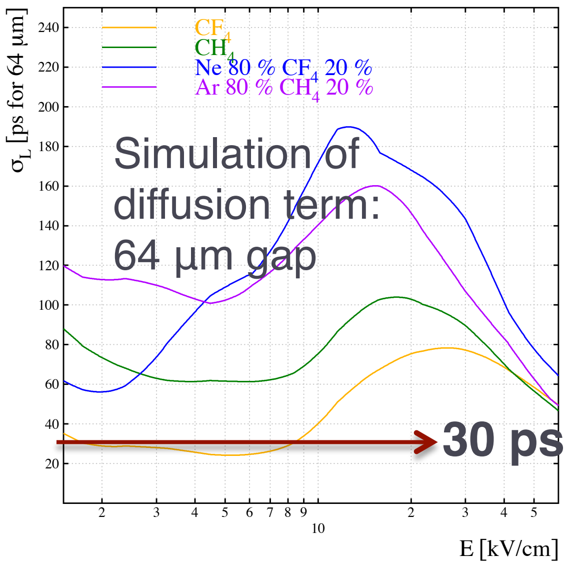
[A.Benaglia et al., ECAL Upgrade Meeting]

Detector technologies:
Micro pattern gas detectors with radiator

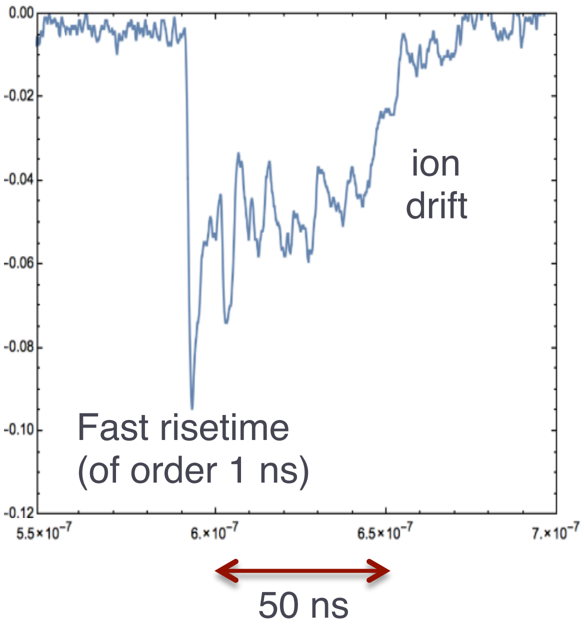
- **GasPMT: thin micromegas with radiator window**
  - Localize primary ionization in photocathode
  - Limit longitudinal diffusion in the gas

[S.White, arXiv 1409.1165]
[T.Papaevangelou et al. arXiv 1601.00123]





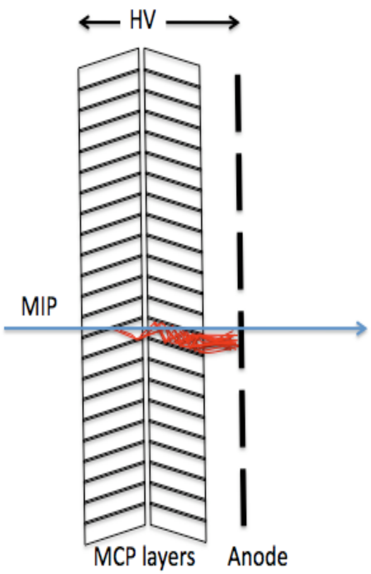
MIPs pulse at test beam
Ne-Ethane_CF4
[May 31st 2016]

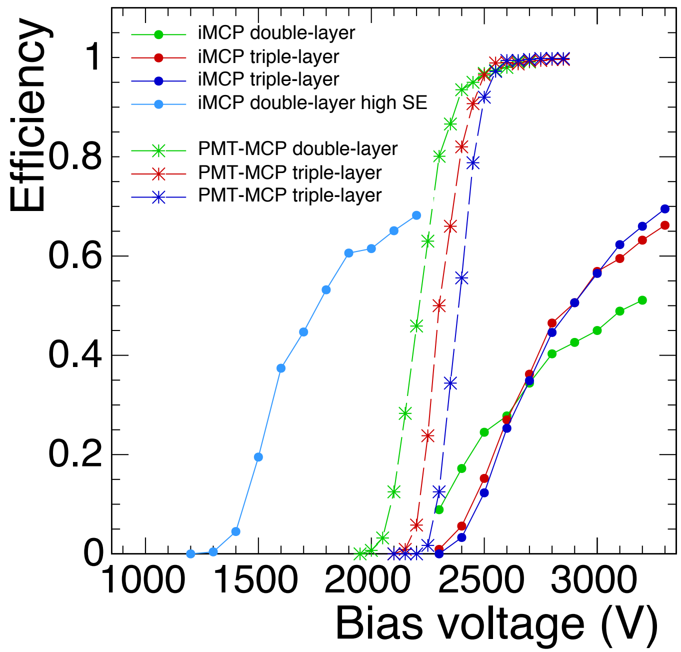


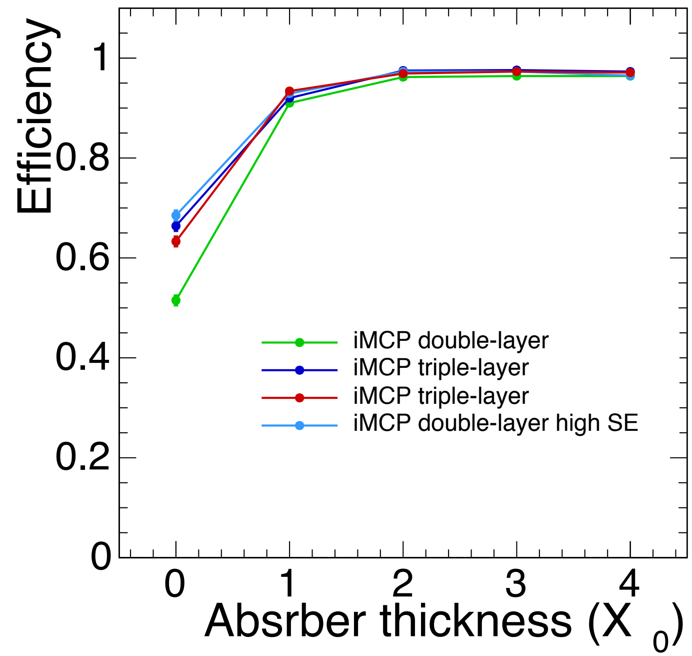
Detector technologies: Micro-channel plates (with or without radiator)

Micro-channel plates without radiator

- Robust design / increased radiation hardness (no photocathode)
- ~20-30 ps 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]

(*) Reached close to 90% in recent MCPs with MgO coating

[V.Ciriolo et al. talk at CALOR 2016]

Use of fast timing in high-pileup

- Outlined the challenges faced in high pileup environments
- Indicated technologies that could achieve O(25ps) precision

- **Now, case studies to illustrate performance benefits from timing**
  1. Vertex reconstruction with track timing
  2. Vertex definition in diphoton events
  3. General PU mitigation with 4D vertexing

- Studies decoupled from specific detector layout/technology:
  - Mockup of a fast timing layer with full coverage (up to |eta|<2.5)
  - Assumed single particle timing of 30 ps
  - Time of reconstructed vertices + constant smearing (25 ps)

Merged vertex rate reduction

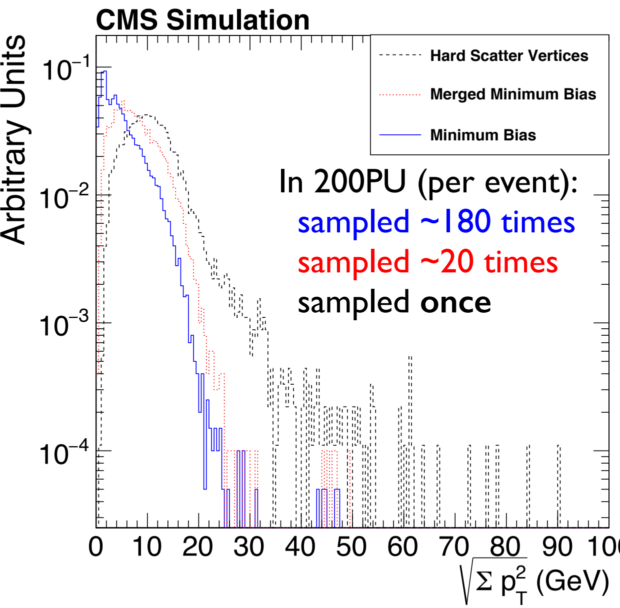
- A merged vertex is defined by a 3D (4D) reconstructed vertex that is matched in space (and time) to more than one simulated vertex. The matching window defined to be $3\sigma_z$ up to a maximum of 1mm, and $3\sigma_t$, when timing information available.

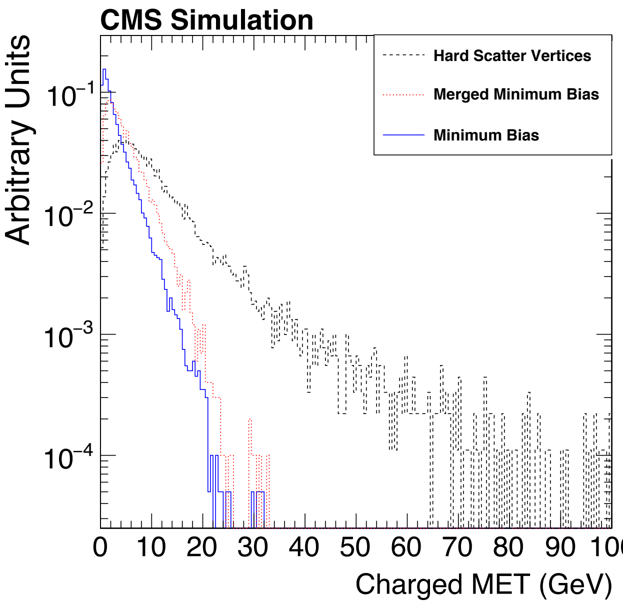
CMS Simulation

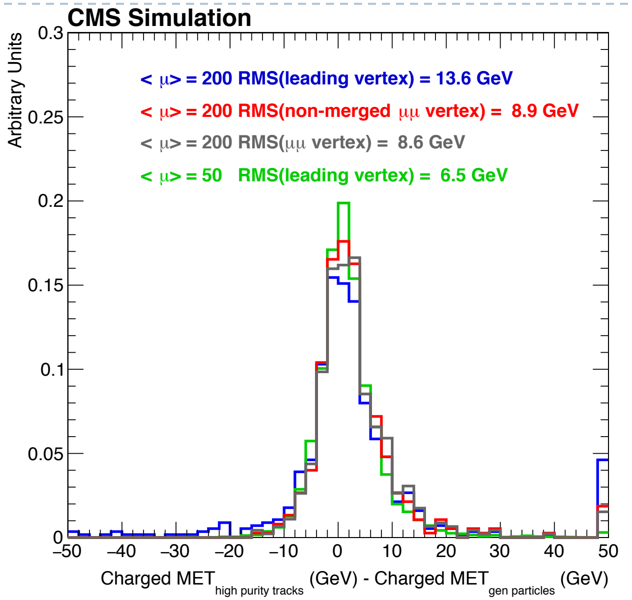
<μ>	4D Merged Vertex Fraction	3D Merged Vertex Fraction	Ratio of 3D/4D
50	0.5%	3.3%	6.6
200	1.5%	13.4%	8.9

- 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



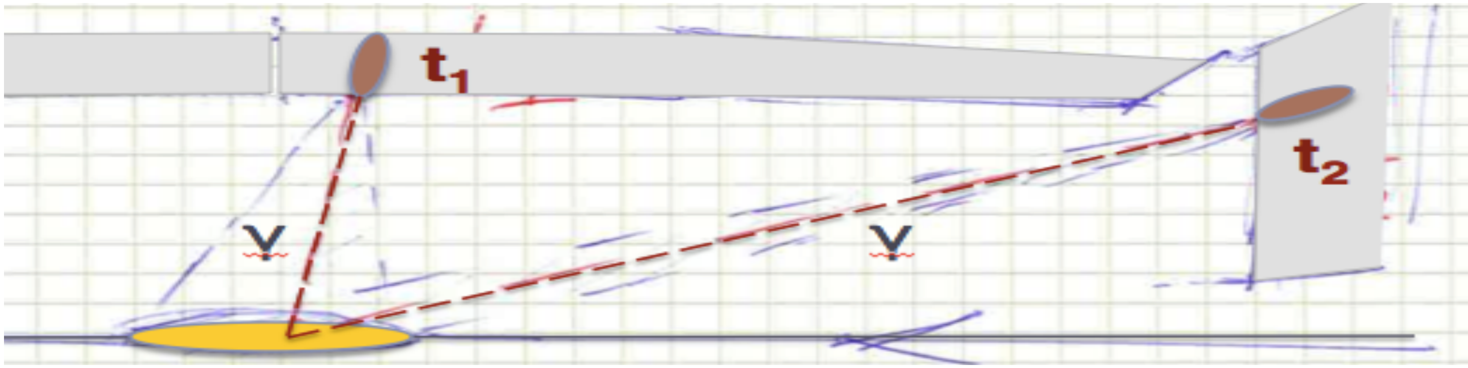




- **Left**: The **RMS p_T distributions** of hard-scatter, Z(μμ), (dashed), emulated merged minimum bias – where two minimum bias vertices are manually overlaid with each other (dotted) –, and minimum bias vertices (solid) demonstrating the large promoting effect that merging has on minimum bias vertices. **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 the vertex merging rate is reduced, 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.

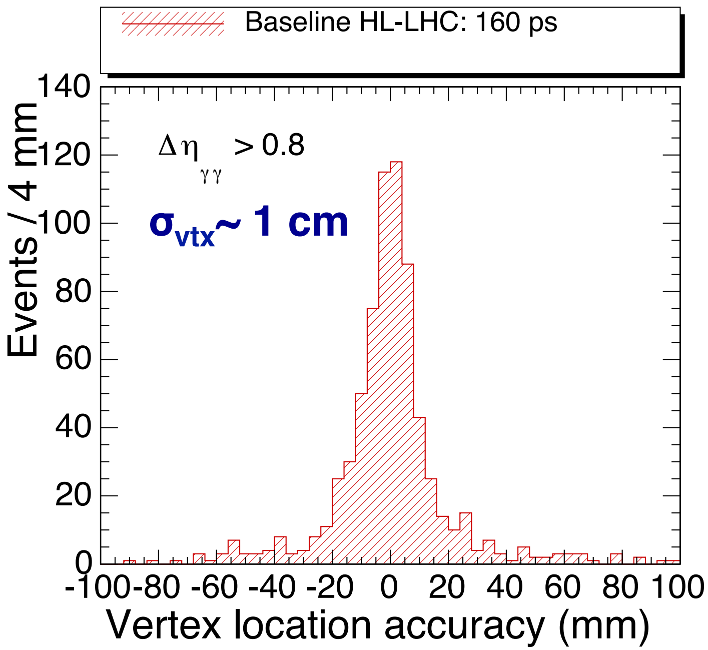
Diphoton vertexing in H→γγ

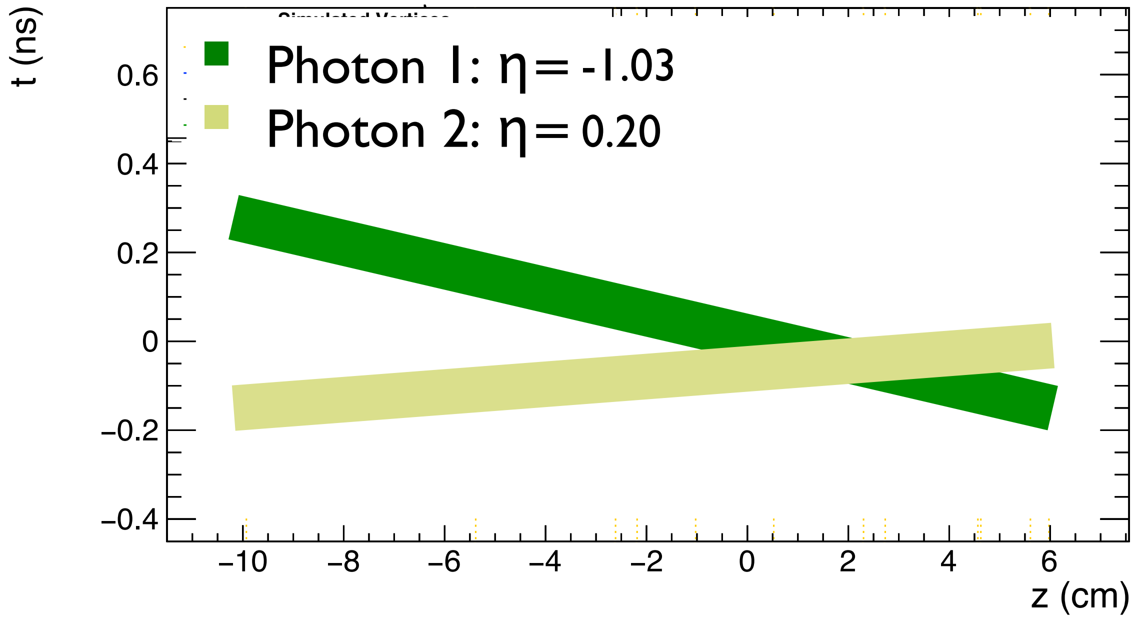
- **Phase I: vertex identification from event kinematics**
  - BDT analysis → ability to locate the vertex within 1 cm
  - $\varepsilon(|z_{vtx}-z_{true}|) < 30\%$ at 200 PU (~75÷80% in Phase I)
- **Vertex location from photon timing:**
- Standalone method (i.e. no track/vertex information)
  - $\chi^2 = \Sigma_{i=1,2} [t_i^{meas} - t_i(z,t_o)]^2 / \sigma_i^2$ + *beam spot constr.*



  - *Assumed σ_t=30 ps (E_T>30 GeV);*
  - *Minimize for z_{vtx} and float t_0* (with beam spot constraint)
- Performance studied for events with $|\Delta\eta_{\gamma\gamma}|<0.8$ and $|\Delta\eta_{\gamma\gamma}|>0.8$

Vertexing With Calorimeter-Only Timing

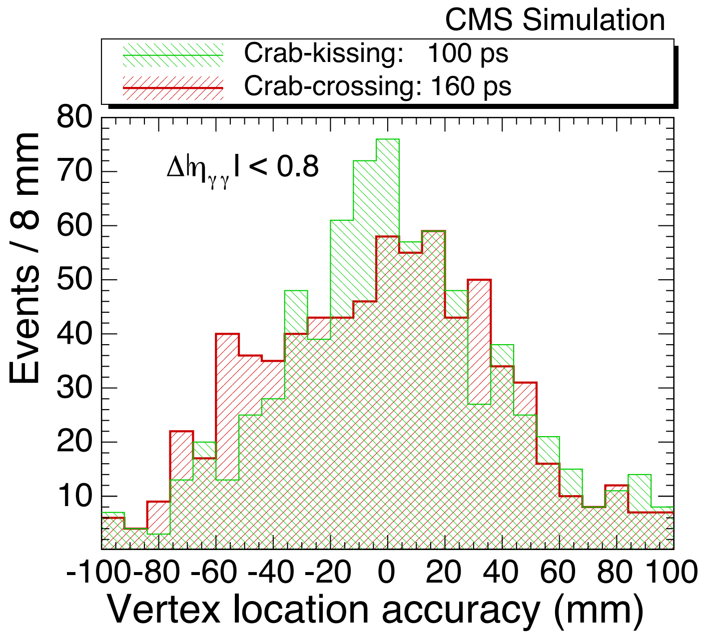


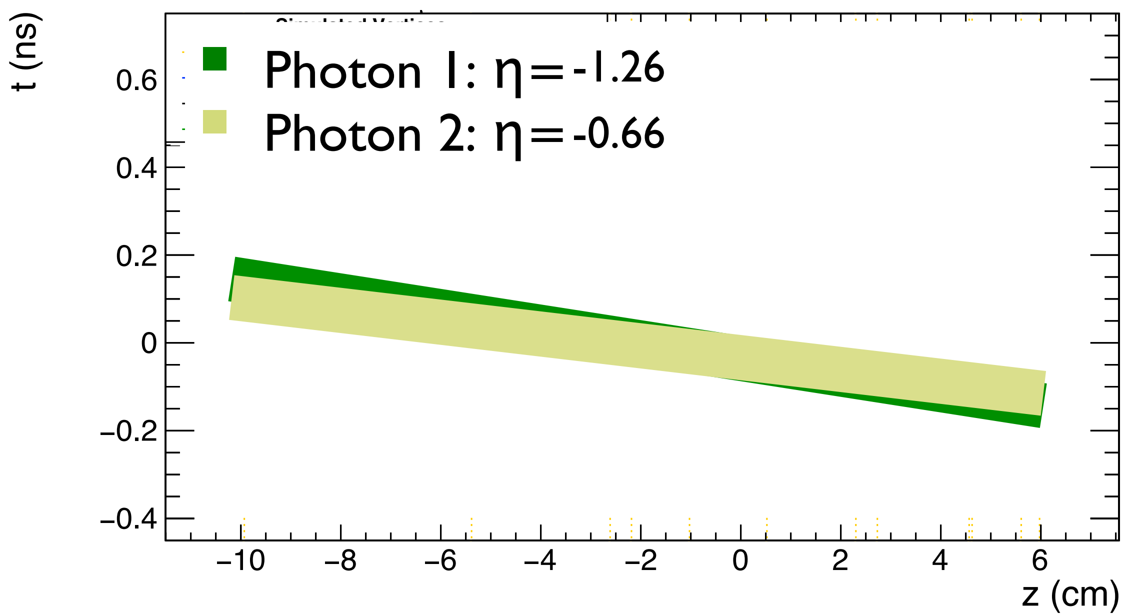


Caption: Distance between the virtual vertex position and the true vertex position along the beam for a resolutions of 30 ps in the measurement of the photon time

- **Good vertex location (RMS ~ 1 cm) for diphotons at |Δη|>0.8**
  - Roughly 50% of the H→γγ sample
  - ε (|Δz|<1 cm) ~ 68% from timing alone

Vertexing With Calorimeter-Only Timing



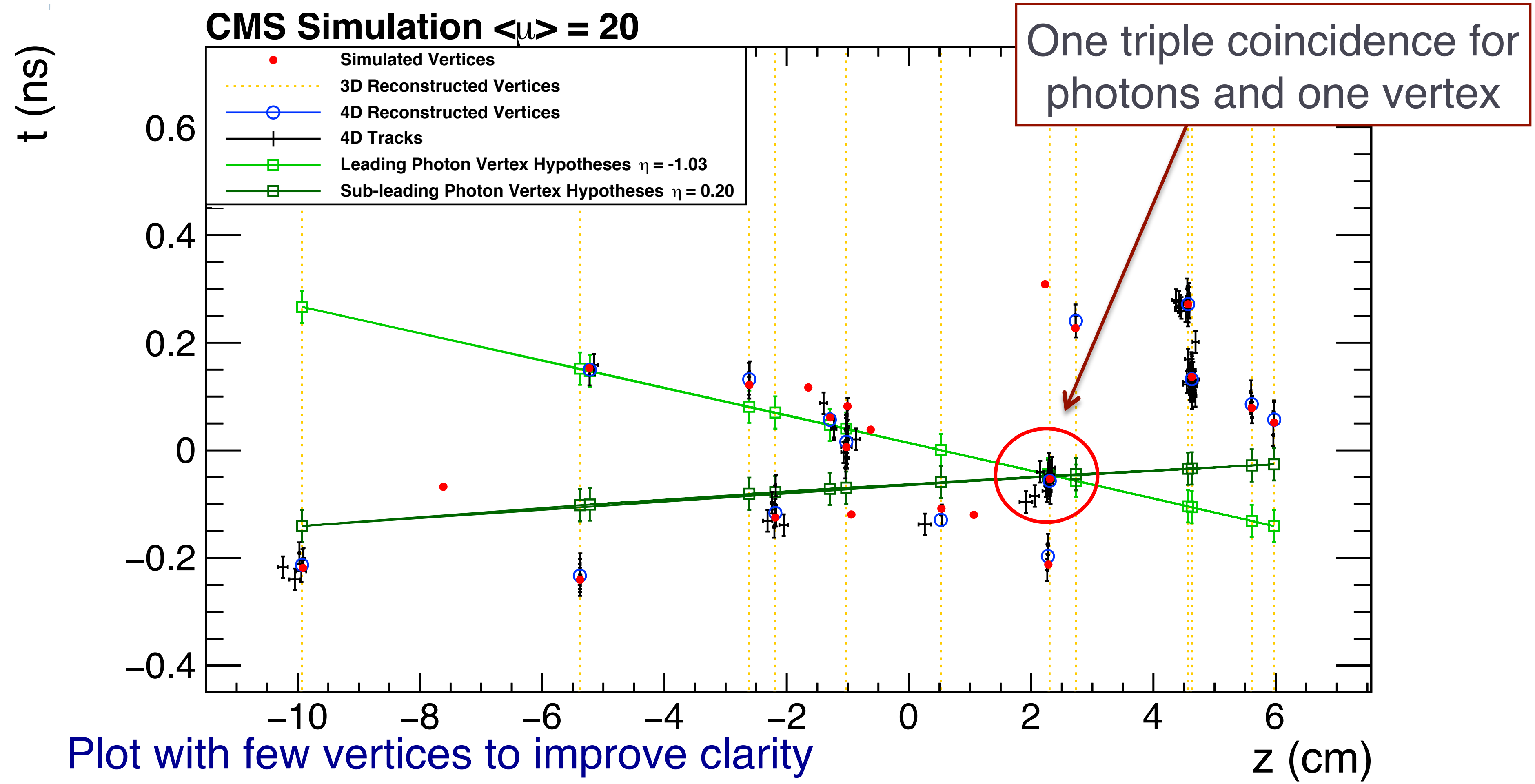


Caption: The red and green histograms show the vertex location accuracy for a luminous region time-spread of 160 ps (HL-LHC baseline) and of 100 ps (crab-kissing optics at the beginning of the physics coast)

- **Insufficient vertex location accuracy for |Δη|<0.8**
  - 50% of the H→γγ sample, *and most central events*
  - *[No improvement even with small beam time spread]*
    - For these events time-zero information from the vertices needed

Matching neutrals to 4D vertices

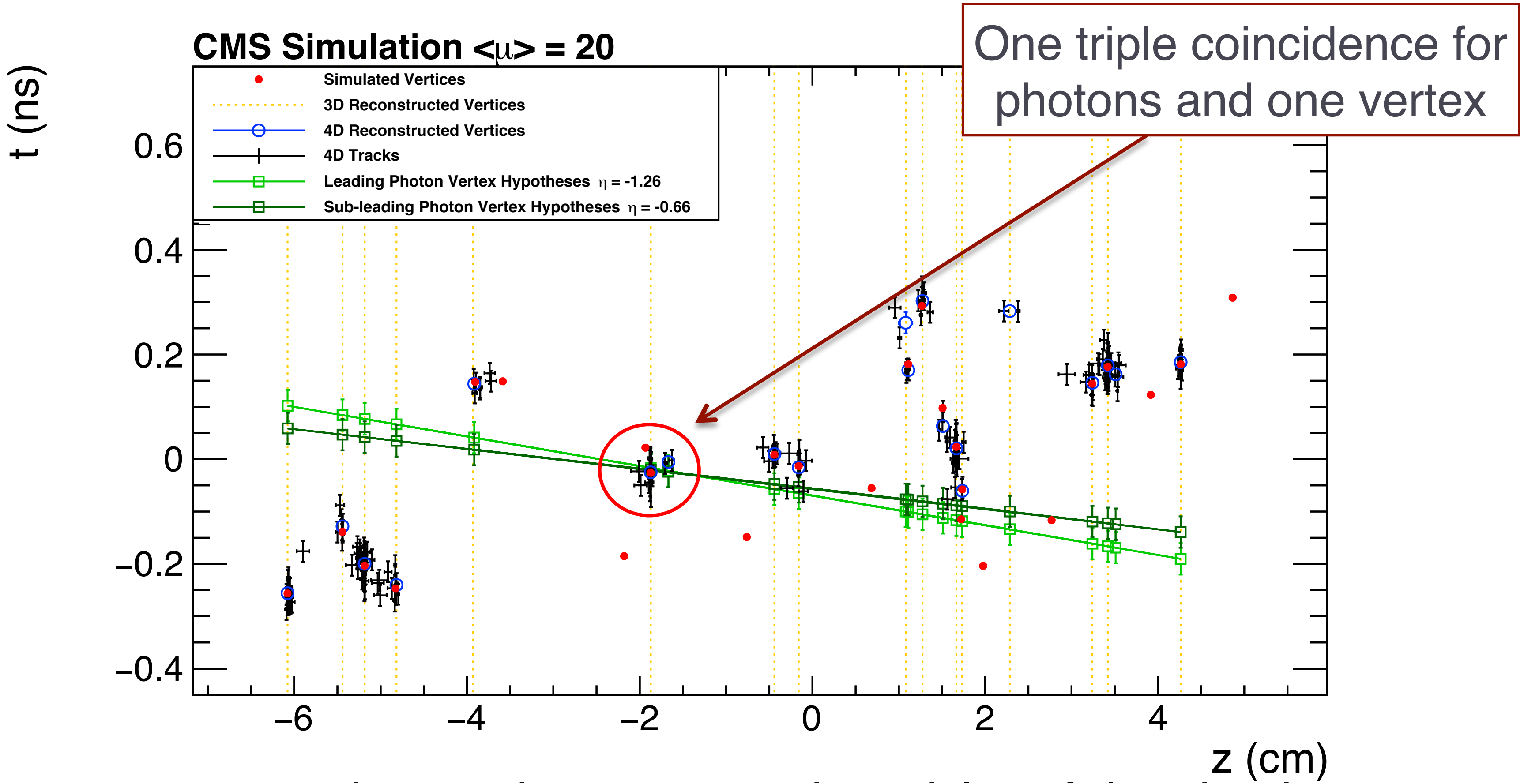
- **Ability to correlate calorimetric timing with track timing using a H → γγ decay as illustration**



Plot with few vertices to improve clarity

Matching neutrals to 4D vertices

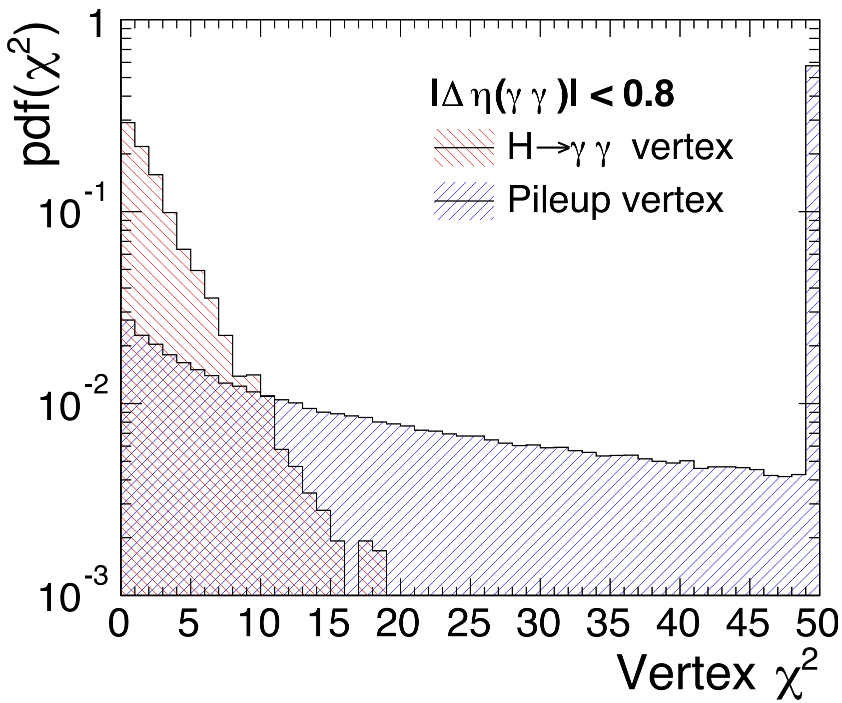
- **Inability of close-by (in η) H→γγ to resolve a vertex:**
  - The vertex is resolved via correlation of calorimetric timing with track timing

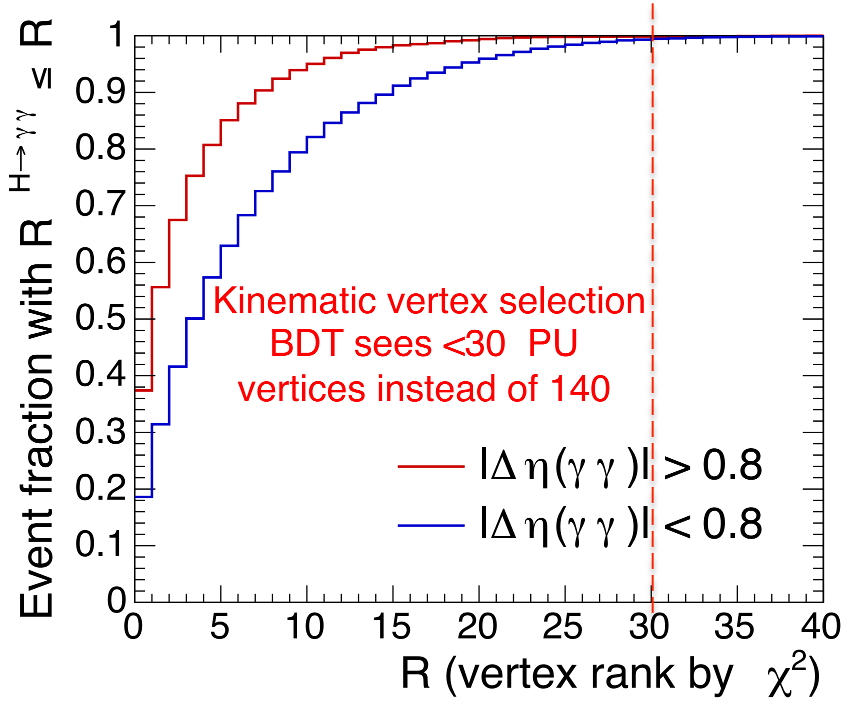


Plot with few vertices to improve clarity

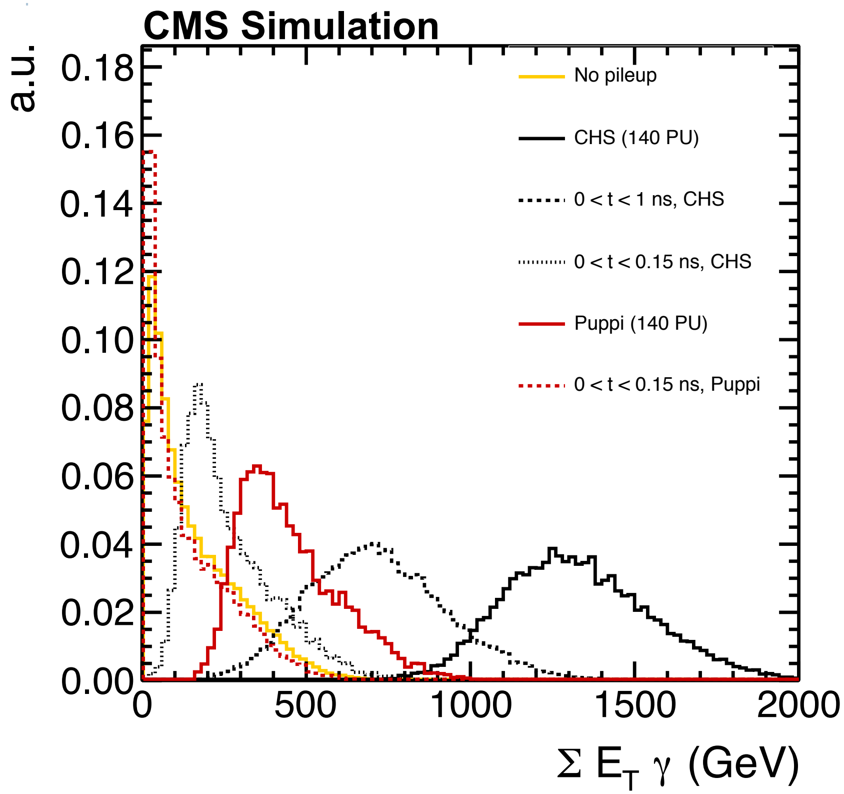
Exploiting vertex timing in H→γγ

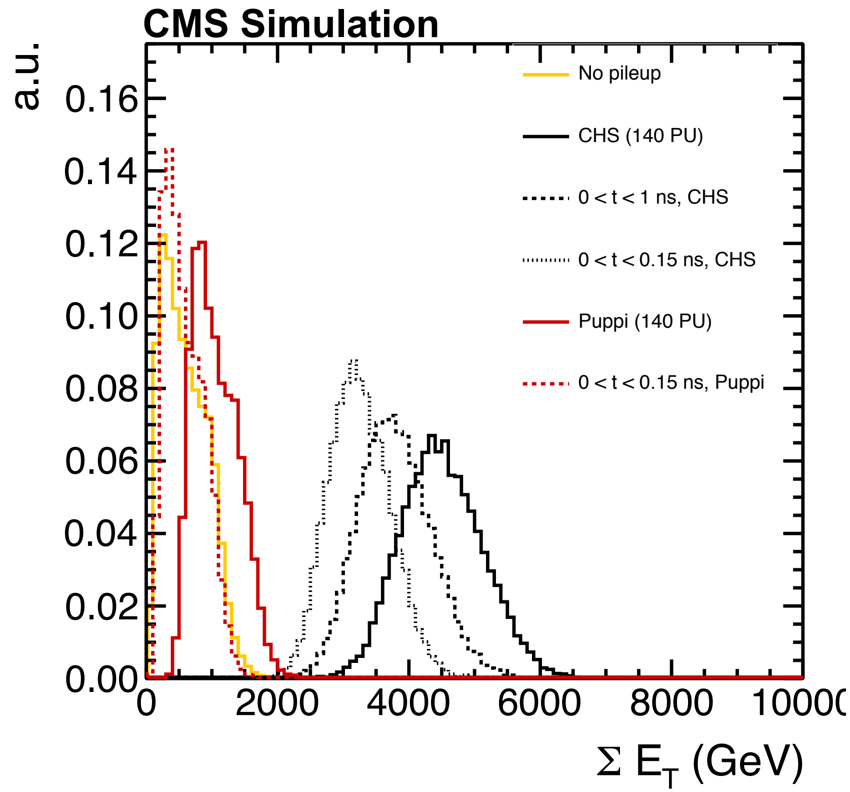
- **Left**: Distribution of the χ^2 of diphoton vertices (red histogram) and of pileup vertices (blue histogram), for 30 ps resolution in the calorimeters, 25 ps resolution in vertex timing, HL-LHC baseline optics, and a selection of photon pairs with $|\Delta\eta| < 0.8$.
- **Right**: Fraction of events 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 Run 1 conditions





MET Performance with timing





- Distribution of the E_T sum:
  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

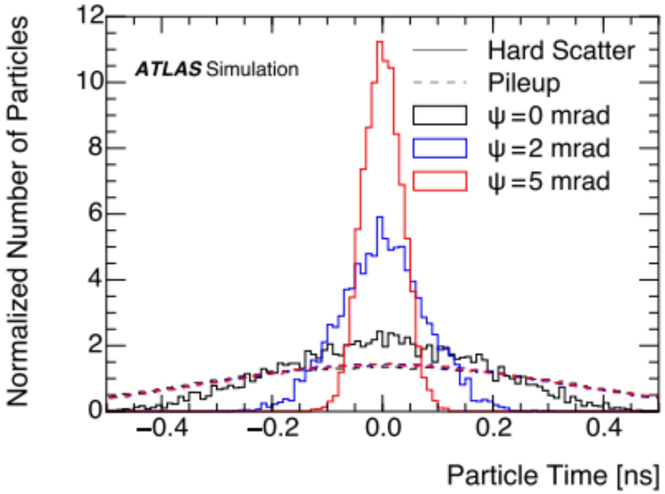


Figure 92. Arrival time spread for hard-scatter and pile-up particles for different bunch collision schemes (crab-kissing angle ψ), assuming that the z position of the hard-scatter vertex is known.

HGTD information with Crab Kissing

- Assumption: z position is known
- Crab kissing reduces the time spread of the hard scatter, <u>but this decays over the fill</u>
- 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

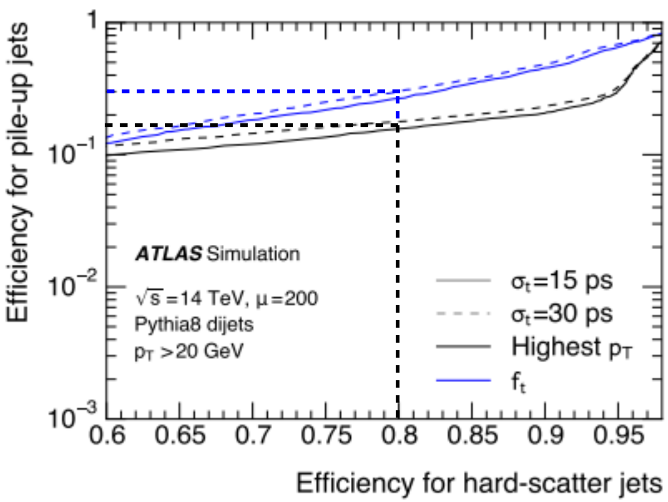


Figure 93. Efficiency for selecting pile-up jets as a function of the efficiency for selecting hard-scatter jets using the jet time from the highest p_T particle (black) and the time fraction f_t (blue) as discriminant, assuming a crab-kissing scheme with ψ = 5 mrad.

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

Conclusions

- **ATLAS and CMS are exploring the possibility of dedicated timing detectors**
  - 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
  - Challenging R&D program to scale to a full detector
    - Collaboration with RD50 (and others) should be looked into
- **Performance benefits are being assessed in dedicated studies:**
  - CMS - baseline improvements to tracking, Hγγ
    - 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**