Precision Timing and Long-Lived Particles @ HL-LHC

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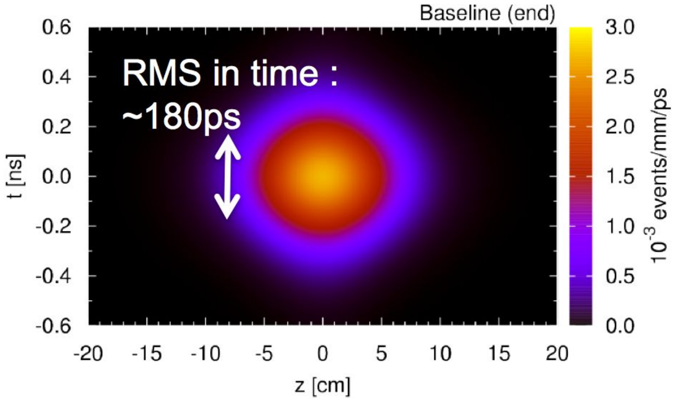
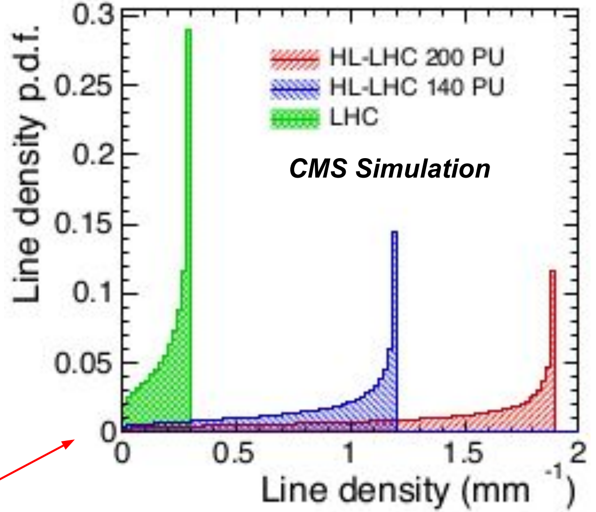
Outline

- Introduction to Precision Timing at the HL-LHC
- Triggers
- Supersymmetry with R-Parity Violation
- Long-Lived Particles (LLP)
- Results
- Summary

Introduction to Precision Timing at HL-LHC

- Upgrade to High-Luminosity-LHC (HL-LHC) by year 2026
- Ultimate luminosity of 7.5×10^{34} $cm^{-2}s^{-1}$, 200 pile-up (PU) vertices
- More collisions at the same energy!





CERN-LHCC-2017-027/LHCC-P-009

Number of pp collisions per unit length of beam axis

Physics at the HL-LHC

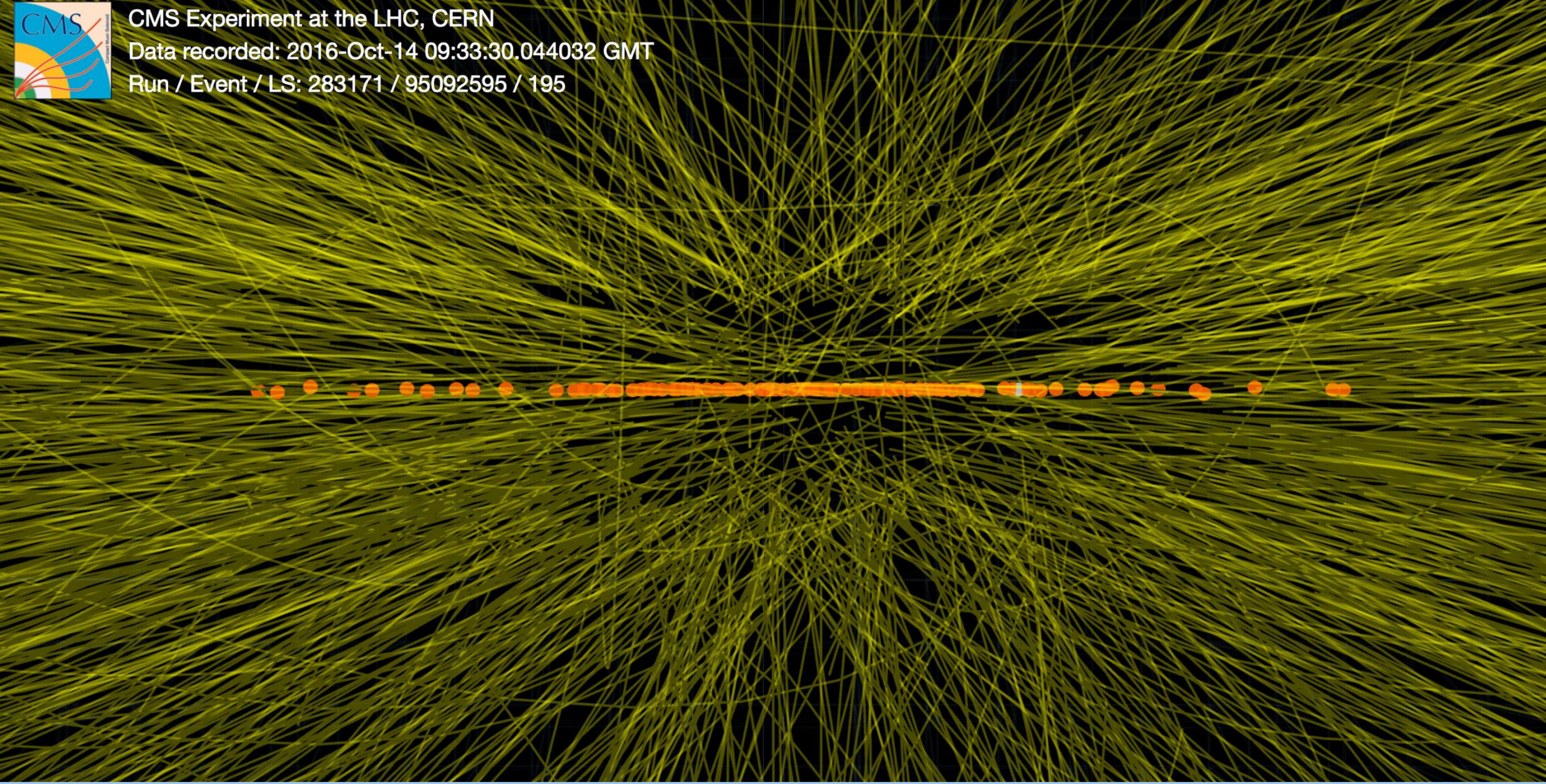
Advantages

- Better chances of finding rare, maybe BSM phenomena
- SM measurements with increased precisions
- New phase space for exploring long-lived particles (LLP's)

Challenges

- Greater spatial overlap between particles →failure of the existing Particle Flow algorithm
- Track-vertex association
- Acceptance reduction for isolated objects
- Reduced resolutions on missing transverse momentum (MET), jet energies, etc.
- **Trigger for rare events**

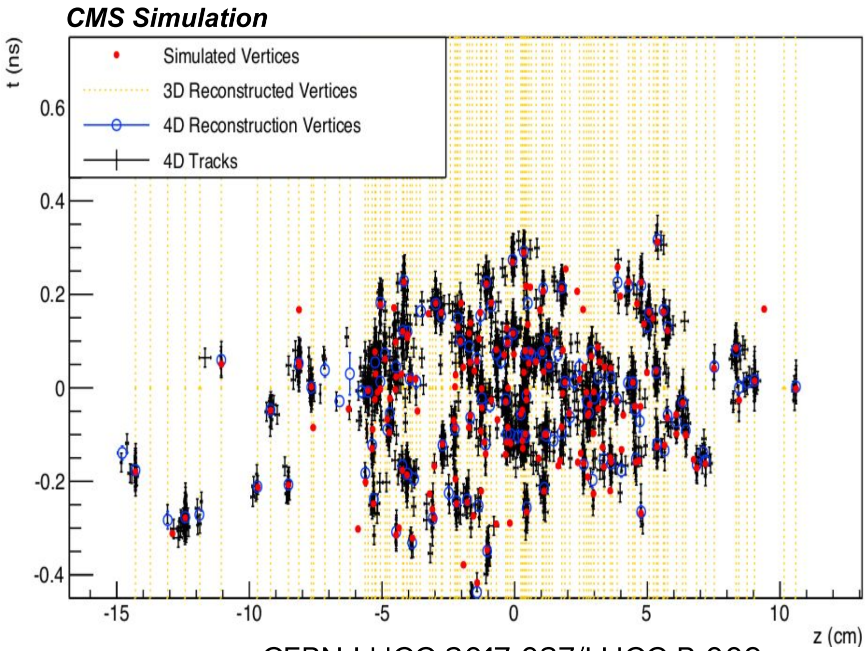
→ **this work**



130 PU vertices reconstructed from a special run in 2016

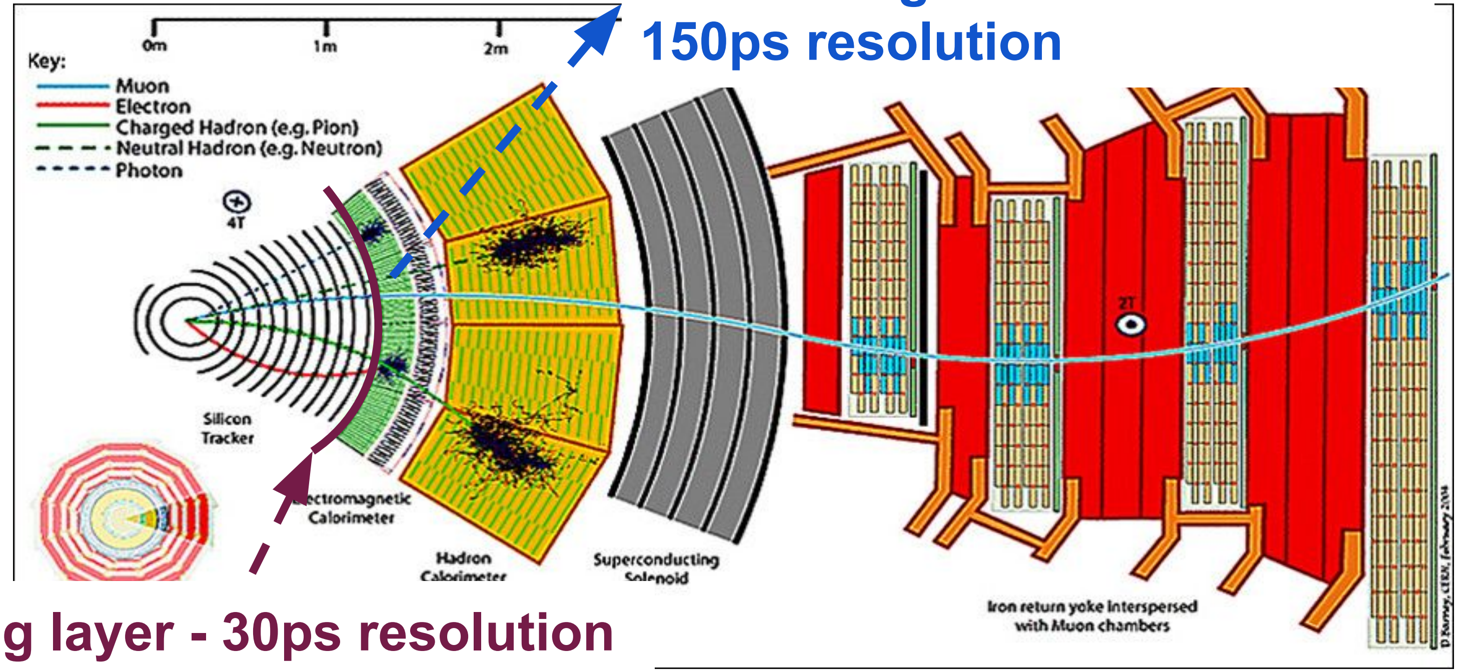
Need for Time-of-arrival Measurement

- Time-of-arrival measurement can separate collisions that are **very close in space, but separated in time**
- Slice bunch crossing in exposures of 30 ps
- PU levels drop to current LHC levels



CERN-LHCC-2017-027/LHCC-P-009

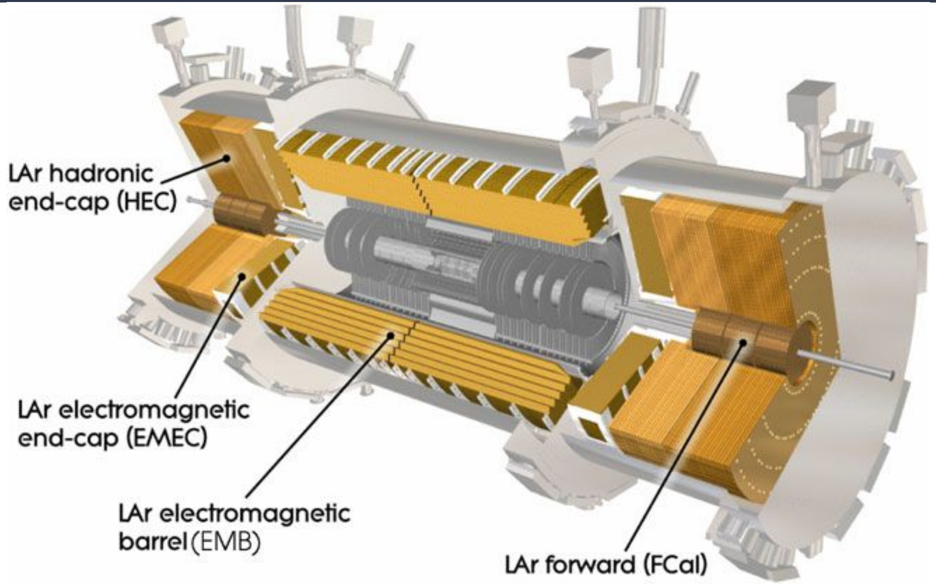
CMS Detector Upgrade



Electromagnetic Calorimeter- 150ps resolution

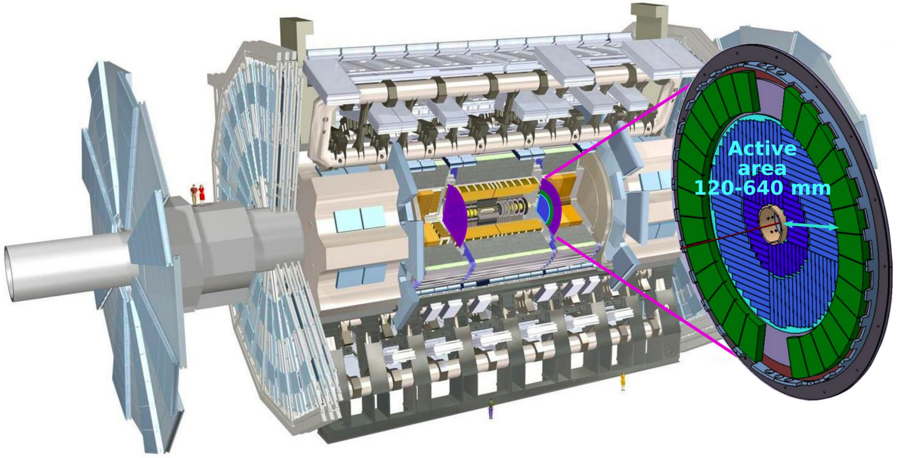
Timing layer - 30ps resolution for charged particles

ATLAS Detector Upgrade



LAr Timing - 150ps resolution

High-Granularity Timing Detector (HGTD) - 30ps resolution for charged particles



[ATLAS HGTD talk - ICHEP ‘18]

Triggers in Particle Physics Experiments

ATLAS Trigger system (Run 2)

Bunch crossing (40MHz)

↓ ~2.5μs

Level 1 Trigger (100KHz)

↓

High Level Trigger (1KHz)

↓ ~250ms

Storage (1kHz)

Similar system for CMS!

Aim of Trigger System

Decide ***online*** whether to store a given event from a bunch-crossing.

Level 1: *rate defined by ATLAS readout capability*

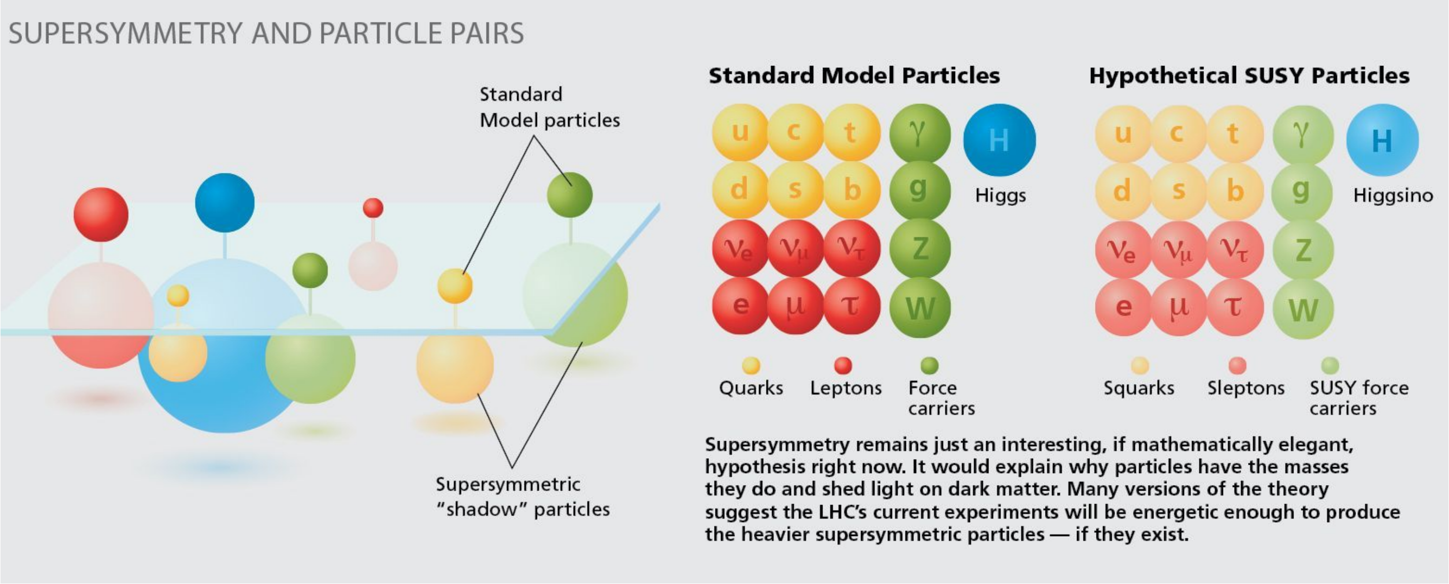
Hardware-based Level 1 Trigger

Receiving inputs from L1 calorimeter, L1 muon triggers, etc.

Trigger objects: electrons, photons, tau leptons, jets, MET, muons

No existing triggers uses timing information at the low-level!

Supersymmetry (SUSY)



- Mathematically elegant
- Coleman-Mandula Theorem
- Can solve the hierarchy problem
- Gives a candidate for dark matter

R-Parity Violating (RPV) SUSY

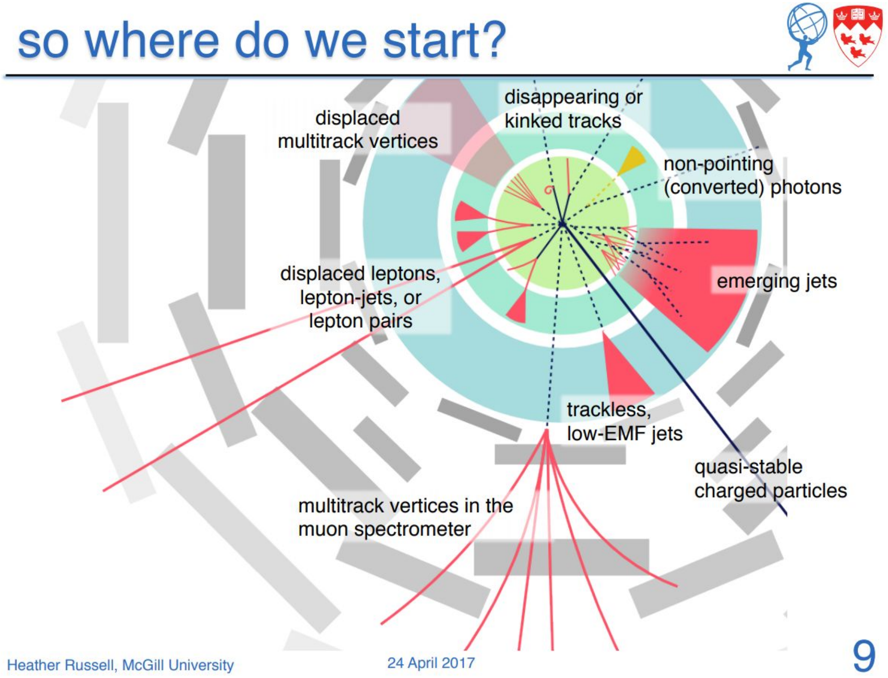
- Superpartners of the Z boson (zino), the photon (photino) and the neutral higgs (higgsino) mix to form four mass eigenstates called **neutralinos**
- Lightest of the four neutralinos is denoted as $\tilde{\chi}_1^0$

$$P_R = (-1)^{3(B-L)+2}$$

- $P_R = +1$ for SM particles, $P_R = -1$ for SUSY particles
- R-Parity conserving: a SUSY particle decay must contain a SUSY particle
  - Lightest SUSY particle cannot decay ⇒ MET
- R-Parity violating: the LSP can further decay to SM particles.
  - SUSY $\rightarrow$ fully SM decay ⇒ **no/low MET**

Long-lived Particles (LLP's)

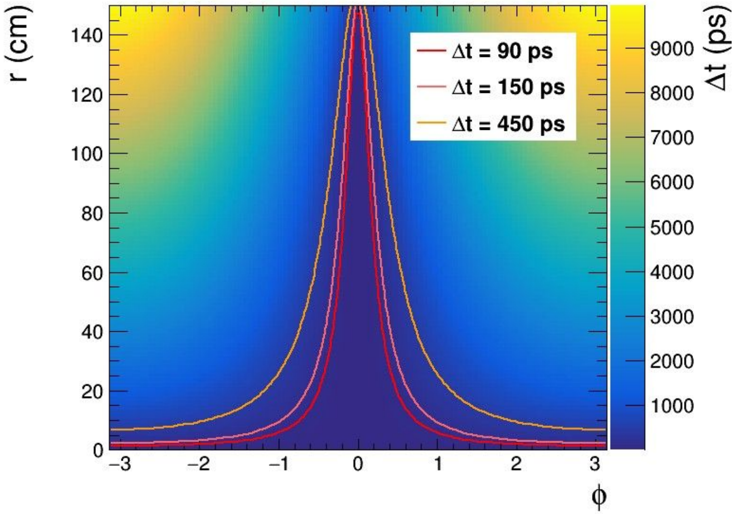
- SUSY/BSM particles with lifetimes of ~few ns or longer
- Macroscopic, reconstructable path length / time difference
- Experimental signatures:
  - Displaced objects
  - Non-pointing/kinked objects
  - "Muons" without inner tracks
  - **Delayed objects**



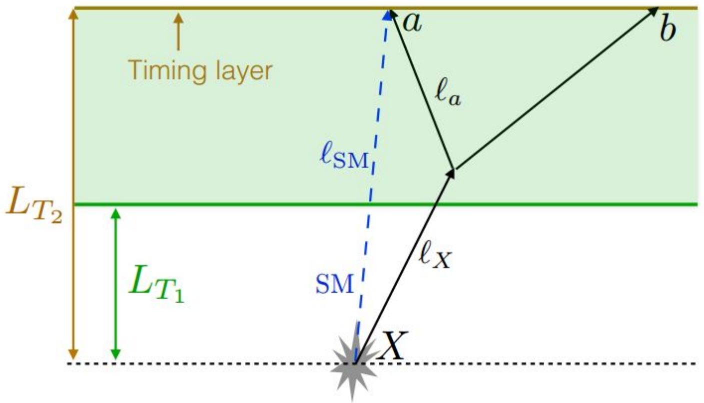
Timing the Delayed Objects

In non-prompt productions, there might be ***delay in arrival time*** due to:

- Longer path traveled
- Slow, long-lived intermediate X



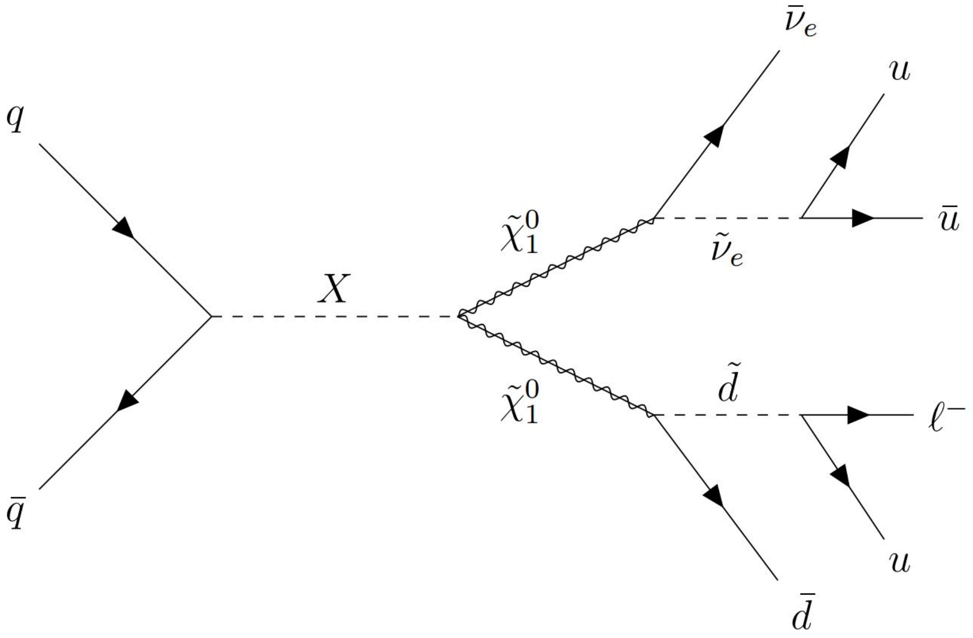
$$X(\mathrm{SUSY}) \longrightarrow ab(\mathrm{SM})$$



$$\Delta t_a = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{\mathrm{SM}}}{\beta_{\mathrm{SM}}}$$

where $\beta_a, \beta_{\mathrm{SM}} \approx 1$

RPV SUSY with Long-lived Neutralinos



$\tilde{\chi}_1^0$ is long-lived and slow

⇒ ***Displaced, delayed di-jets with MET/lepton***

L1 Trigger Design Ideas

Delayed Jet triggers

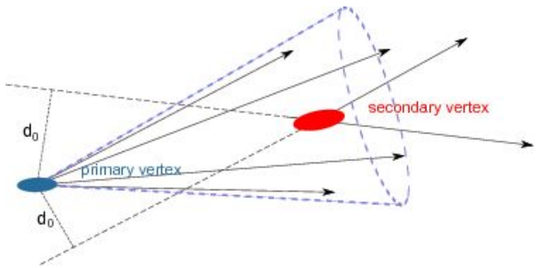
- Sum of energy deposits in the calorimeter clusters but tag the region as delayed if sufficiently separated in time from bunch crossing (eg. 600 ps)

Delayed H_T (scalar sum of tower E_T) trigger

- Total sum of all delayed calorimeter energy deposits
- ***Our choice for this work***

Displaced/Delayed vertex trigger

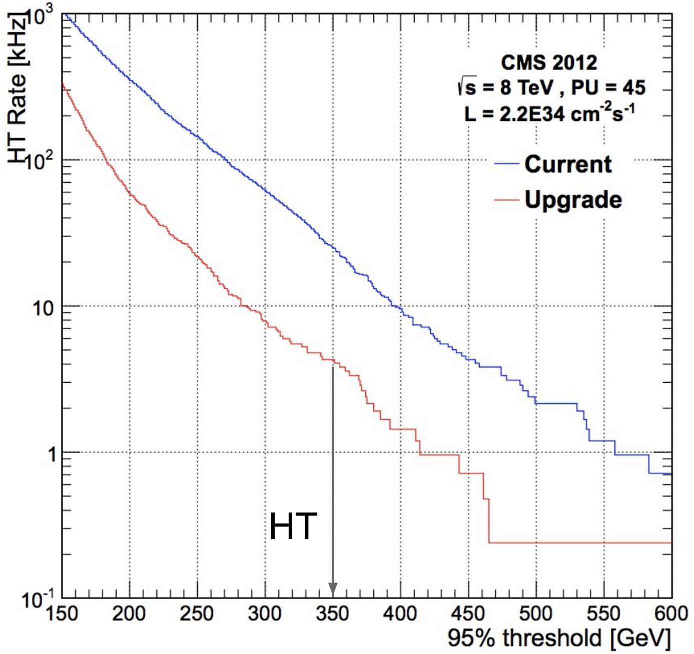
- HL-LHC upgrade plans to include L1 tracker trigger
- Use time and vertex information to tag displaced/delayed jets
- If LLP's have lifetimes of a few ns, very well separated from the displaced b-tagged vertices



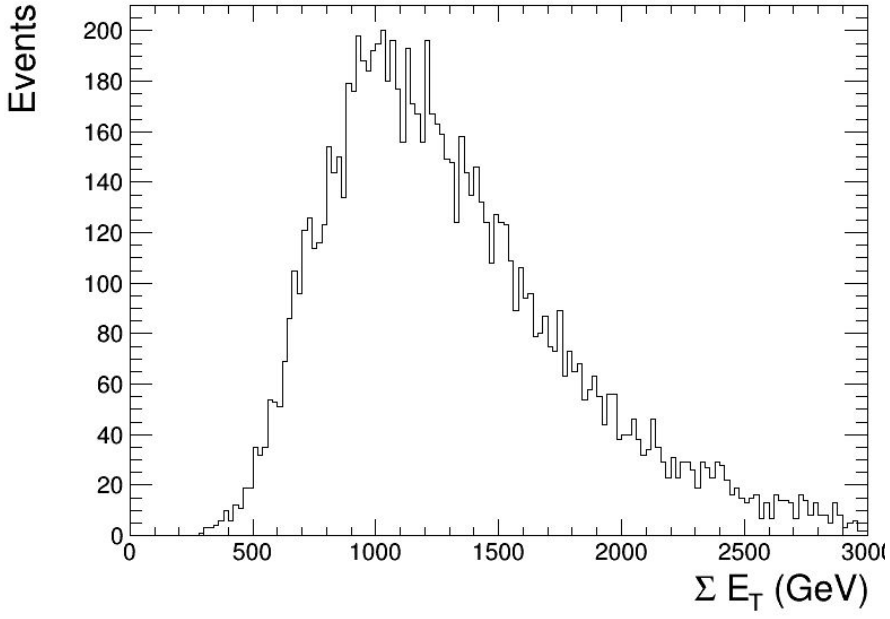
Trigger Rates (current & estimate)

- Require time delay significantly longer than the time spread across beams (~200ps)
  ⇒ Reject background, 600ps ~ 3$\boldsymbol{\sigma}$
  - Not considering out of time rate

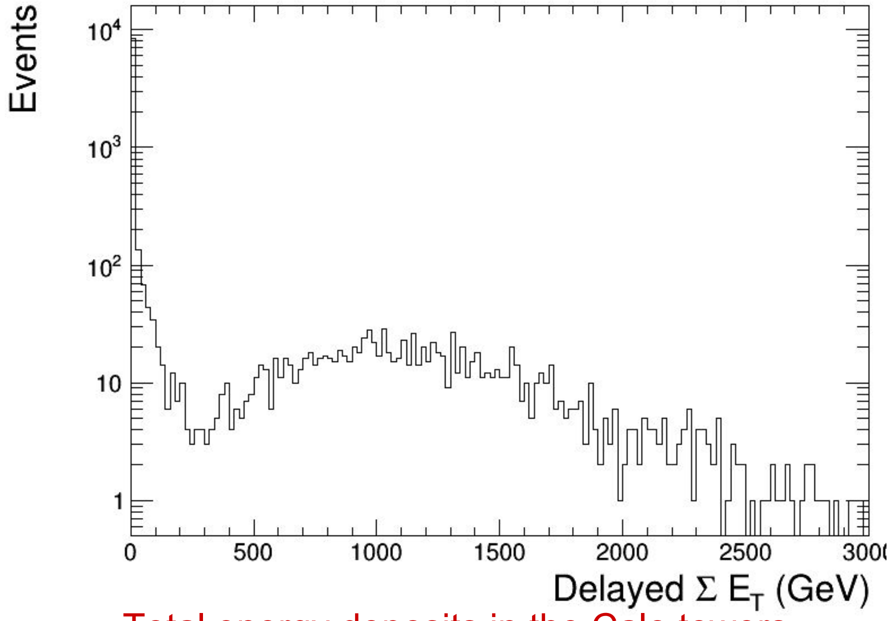
- H_T Trigger Thresholds
  - 350 GeV ⇒ rate ~4 kHz
  - Delay of 600ps, 180 GeV
    ⇒ rate ~0.1 kHz



Effects of New Timing Trigger (delayed H_T)



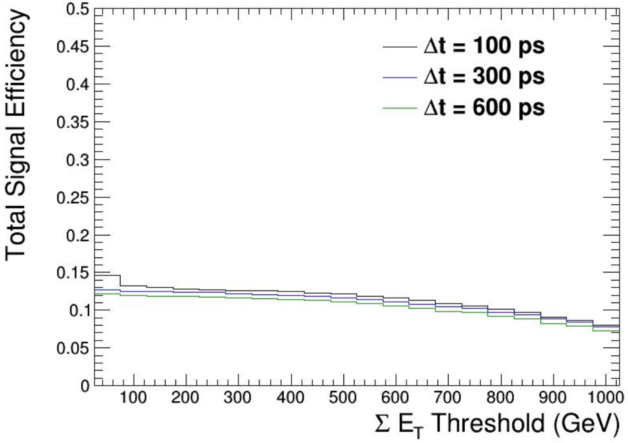
Total energy deposits in the Calo towers



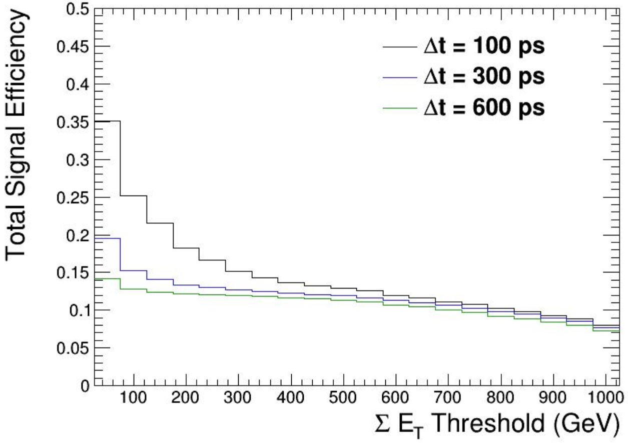
Total energy deposits in the Calo towers with Δt > 600 ps

Signal Efficiency of Our Delayed H_T Trigger

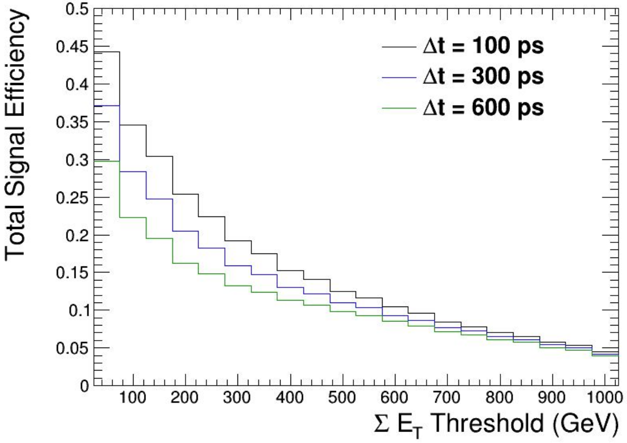
$$\text{Signal efficiency} = \frac{\#\text{ of events with } \Sigma E_T^{\text{delayed}} > \text{threshold}}{\#\text{ of all events}}$$



$c\tau = 10\text{mm}$

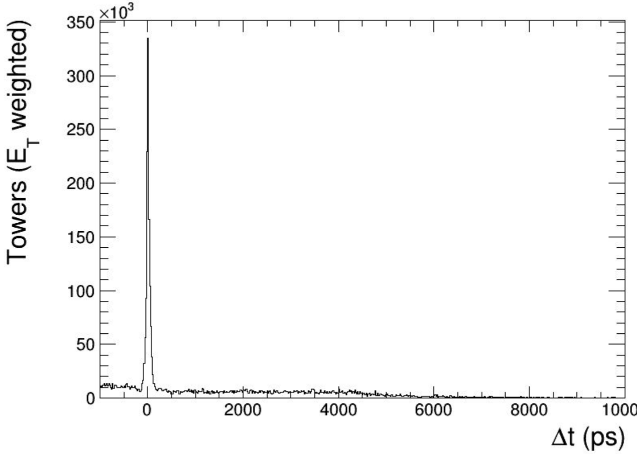


$c\tau = 100\text{mm}$

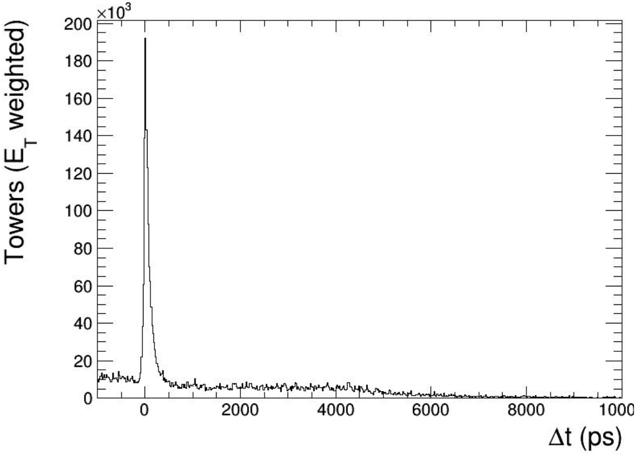


$c\tau = 1000\text{mm}$

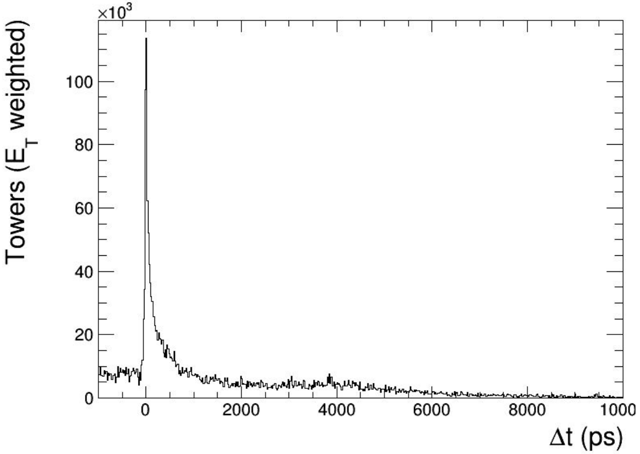
Delayed Towers due to Slow LLP’s



$$c\tau = 10\text{mm}$$



$$c\tau = 100\text{mm}$$



$$c\tau = 1000\text{mm}$$

Summary

Key points

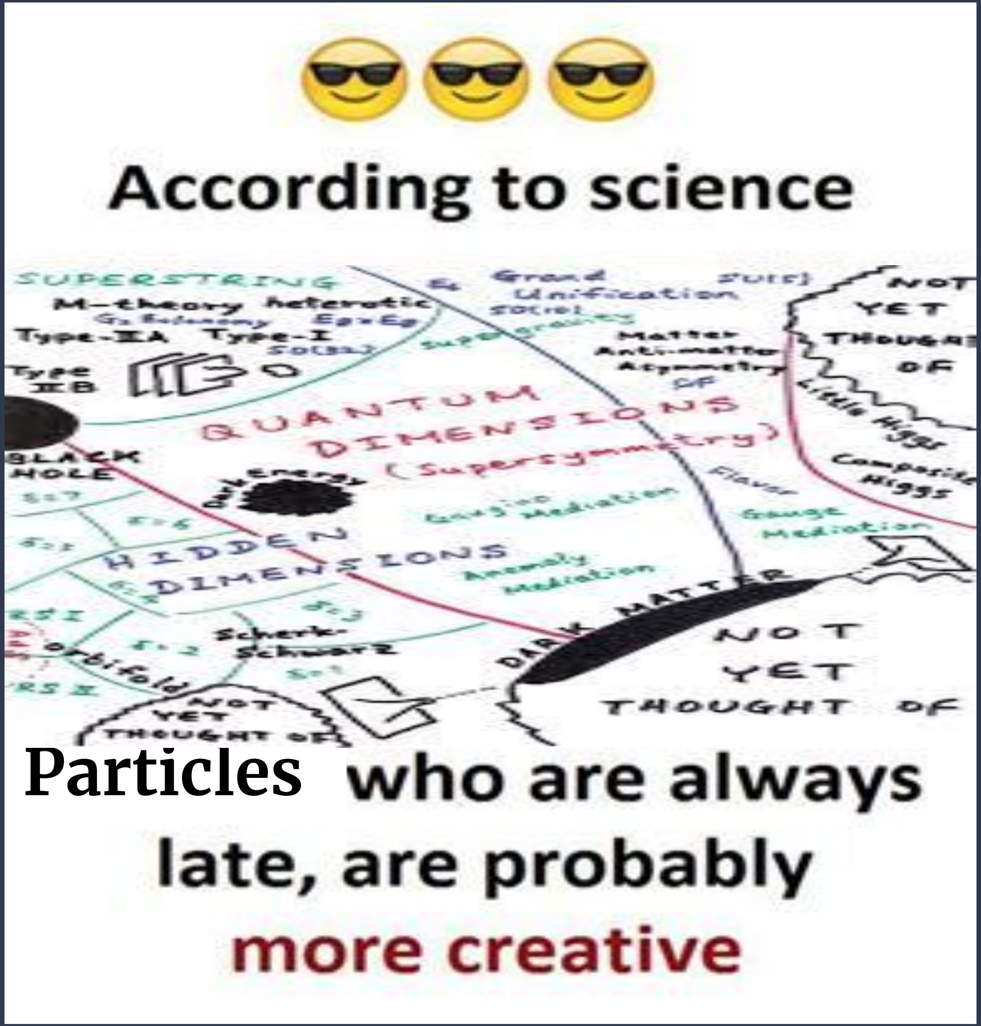
- Timing upgrades at ATLAS & CMS expands our reach to explore BSM physics
- New low-level trigger possibilities
  - Current triggers might not catch LLPs
  - Simple delayed-H_T trigger can be sensitive to late jets
    - cτ≈O(1m) can be triggered with the proposed detectors
    - Significantly lower H_T cut with reduced prompt/in-time backgrounds
    - Even for lighter particles, displaced vertices create enough delay

Much more work to do…

- Understand the existing results
- Study w/ full simulations
- Background studies

Warning : Latecomers will not go unnoticed!

Thanks!

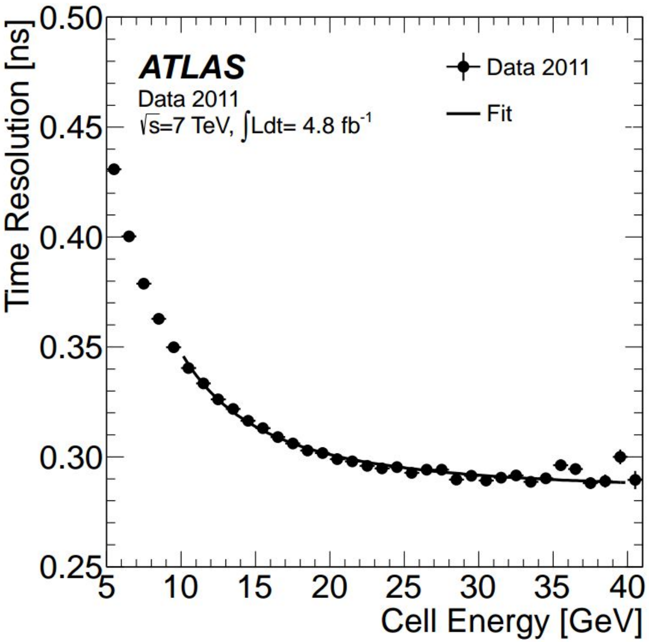

According to science
SUPERSTRING
M-theory heterotic
Type-IIA Type-I
Type IIB
Grand Unification
Matter Anti-matter Asymmetry
NOT YET THOUGHT OF
QUANTUM DIMENSIONS (Supersymmetry)
BLACK HOLE
Dark Energy
Little Higgs
Composite Higgs
Gauge Mediation
Anomaly Mediation
HIDDEN DIMENSIONS
Scherk-Schwarz
orbifold
DARK MATTER
NOT YET THOUGHT OF
NOT YET THOUGHT OF
Particles who are always late, are probably more creative

Backup

ATLAS: Timing in LAr Calorimeter

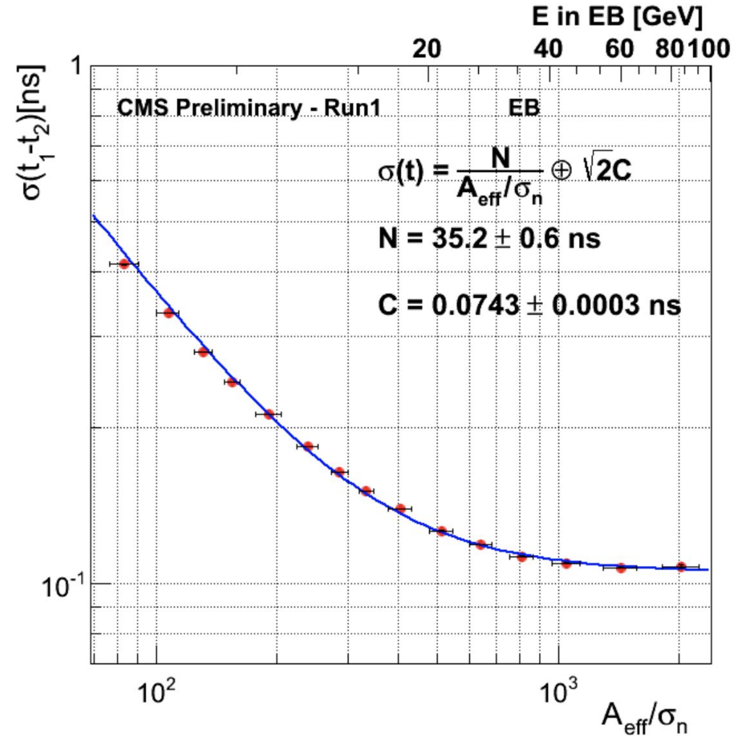
Current LAr calorimeter has decent timing!

- Study based on $W \rightarrow e\nu$ and $Z \rightarrow ee$ samples
- Timing resolution ~290ps for high-energy EM cell
  - 220ps due to beam spread
  - 190ps intrinsically due to LAr
- Expected to be higher for unbiased QCD jets

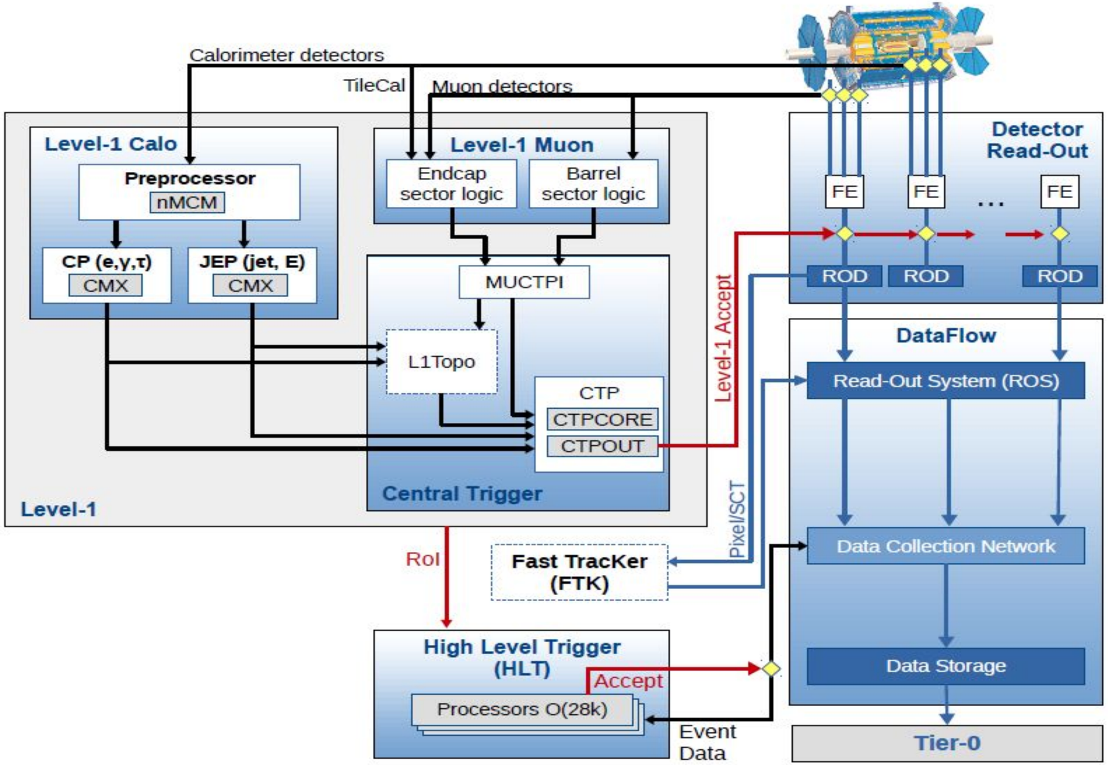


ATLAS Run-I Analysis

CMS Timing in PbWO4 Crystal ECAL

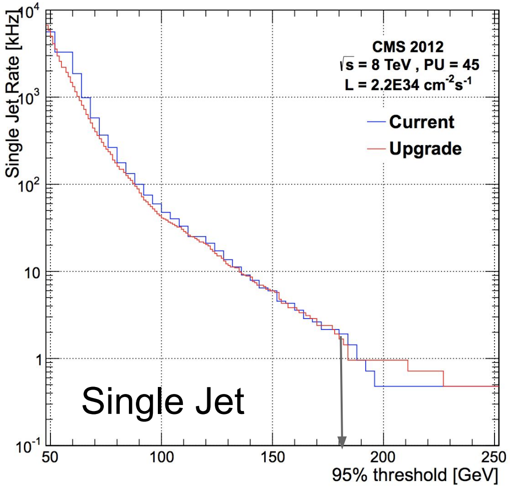


ATLAS DAQ system run2

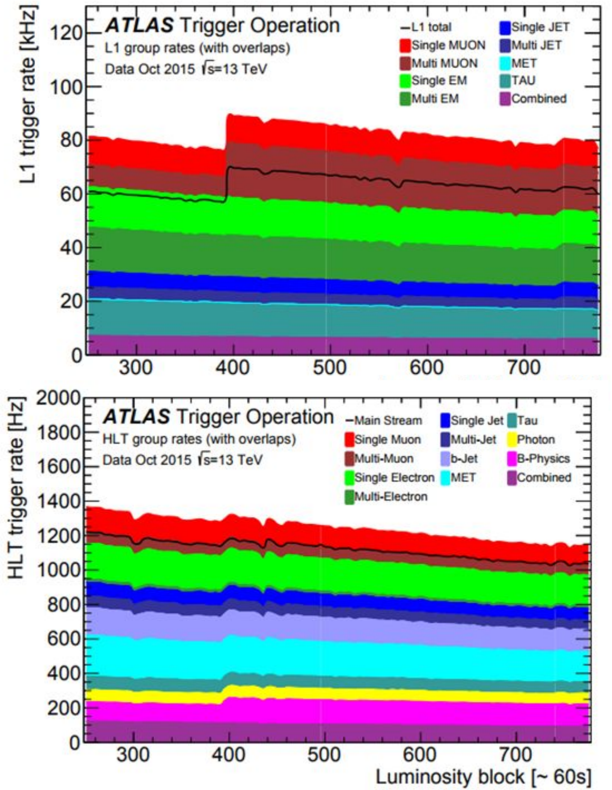


CMS Single Jet Trigger Rate

- Single Jet
  - Threshold of 180 GeV @rate ~2.5 kHz
  - Threshold @ 0.1 kHz with delayed energy cut ~ 80-100 GeV



Trigger performance and challenges for LLP



LLP Trigger Challenges:

L1: no existing trigger for LLP. relay on other “random” triggers like: Jet+MET, leptons, photons… -> cannot directly trigger on it?

HLT: very few analyses dedicated HLT path -> not sure about the signature we should use based on current trigger system?

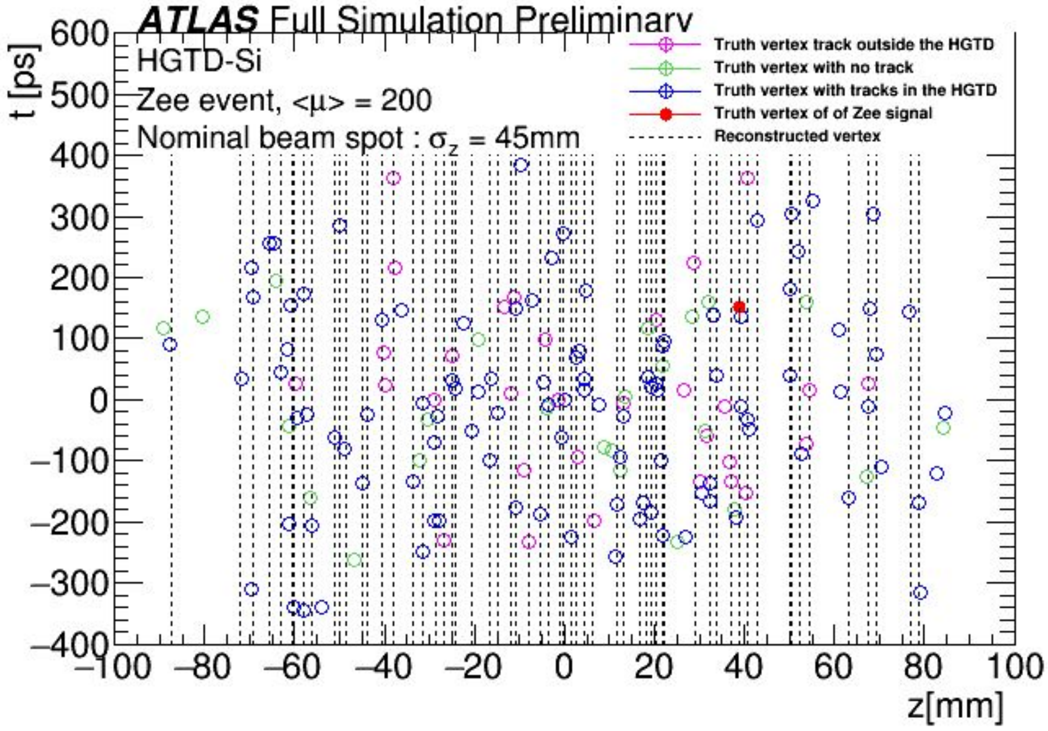
As a results: Acceptance of LLP $< 10^{-3}$

Uncertain decay place -> fixed in this project ->(try to trigger LLP directly) how well calorimeter will trigger on diJets about few ns?

ATLAS HGTD upgrade

Exploit the time spread of collisions to reduce pileup contamination

- Results in sizable improvement in various analyses techniques (PU jet tagging, b tagging, lepton isolation..etc)



Signal: Delayed Towers