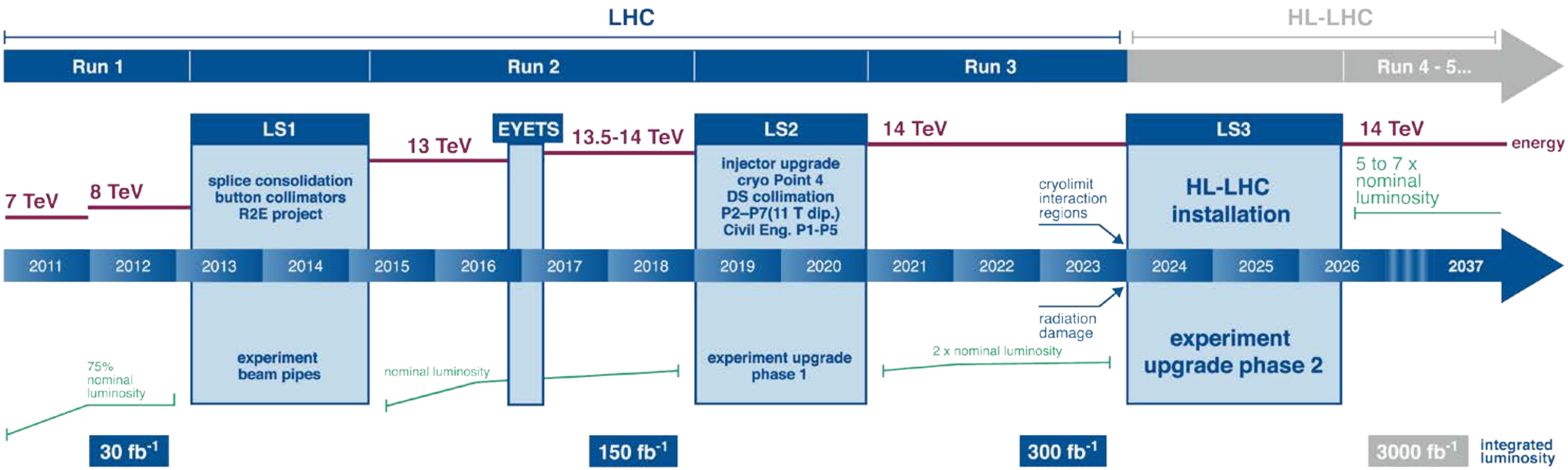
Trigger & Detector Upgrade:
Overview & White Paper Status

Yangyang Cheng

LLP Workshop

May 17, 2018

From LHC to HL-LHC



Searches for long-lived particles beyond the Standard Model at the Large Hadron Collider

The ATLAS and CMS Upgrades

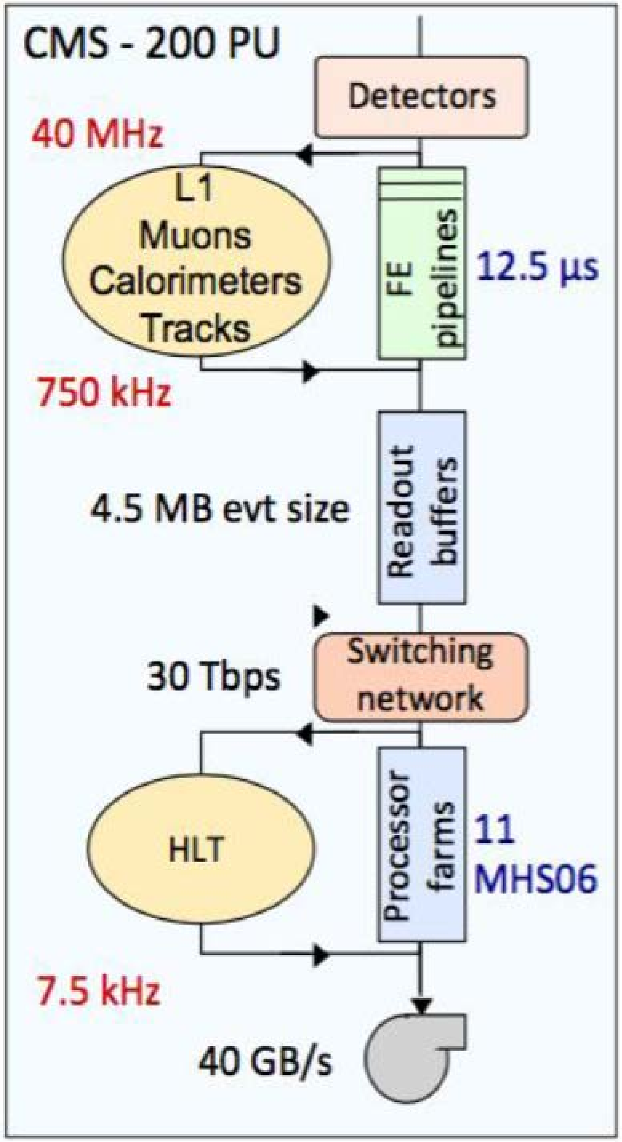
- **Contents**:
  - **Detector and Trigger Upgrades for HL-LHC**
    - ATLAS and CMS scopes side-by-side for each subsystem
  - **Object Performance: Tracking and Vertexing**
    - Focus on basic position and pT resolution
  - **Upgrade Projection: LLP Searches**
    - Completed sensitivity studies in different channels
  - **Open Questions and New Ideas**
    - New studies to be done
    - New detectors for future collider
- **Editors**: Monica Verducci for ATLAS & Yangyang Cheng for CMS
  - Contributions collected from selected individuals, TDRs and TPs, relevant papers from the arXiv
  - All mistakes belong to the CMS editor

ATLAS & CMS: Detector Upgrade

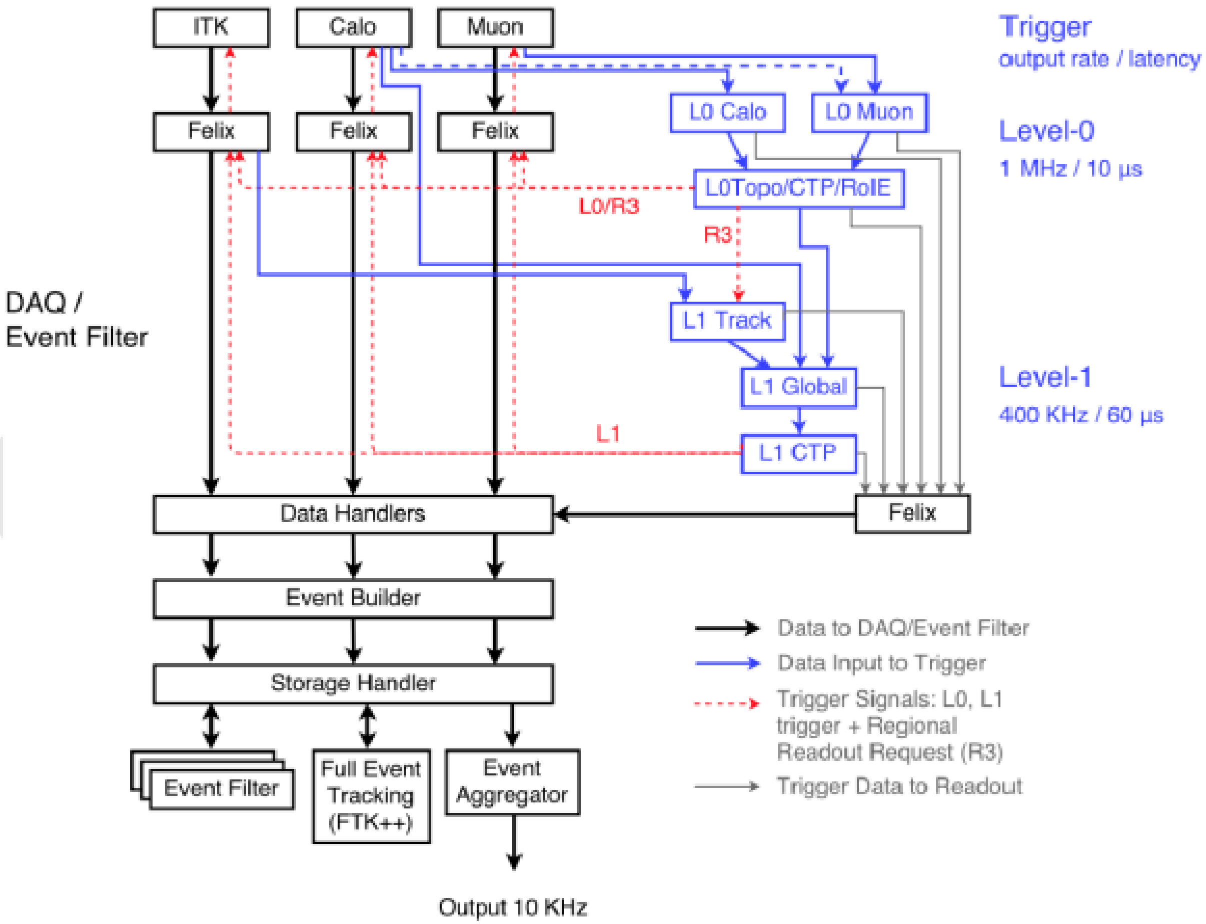
- **Tracker**: full replacement; $|\eta|$~4; high granularity & radiation hard
  - CMS: inner pixel + outer tracker w/ 2-sided sensor modules (PS or SS)
  - ATLAS: inner pixel + outer strip tracker
- **Calorimetry**: upgrade electronics; more info for L1 trigger
  - CMS: replace barrel ECAL electronics for 30ps timing; replace endcap w/ HGCAL
  - ATLAS: keep LAr & TileCal; replace electronics, readout, & power system
- **Muon system**: upgrade electronics; more info for L1 trigger; forward tagger
  - CMS: upgrade DT&CSC electronics; extend forward coverage up to $|\eta|$~2.8
  - ATLAS: New Small Wheel inner muon stations @ LS2; new barrel chambers
- **Timing Detector**: new detector w/ 30ps resolution for MIPs of >= few GeV
  - CMS: MTD; barrel layer + one endcap disk outside tracker up to $|\eta|$~3
  - ATLAS: HGTD; two (four?) endcap disks outside tracker ($2.4<|\eta|<4.2$)

See backup slides for more detailed info on each subdetector upgrade for both experiments!

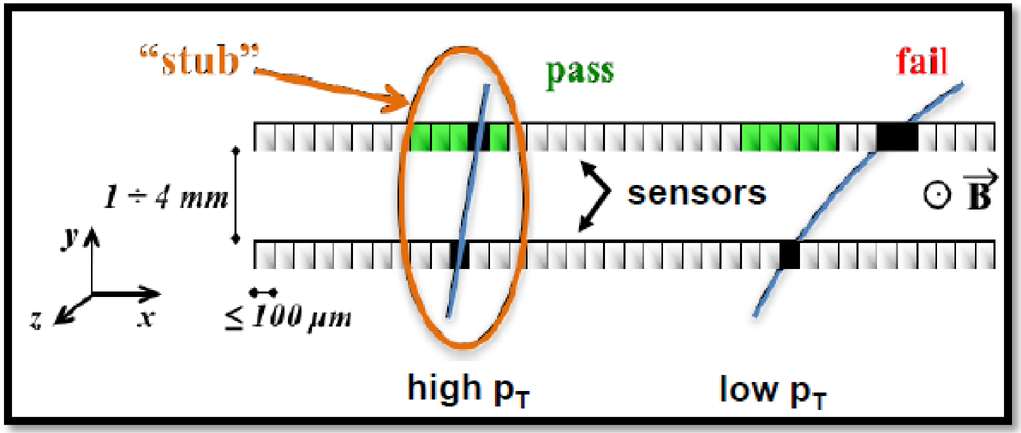
ATLAS & CMS: Trigger Upgrade



- L1 Trigger: more info; increase output & latency
- High-Level Trigger: output rate increase up to 10kHz
  - Processing power scales with pile-up and L1 rate



ATLAS & CMS: Tracker Trigger



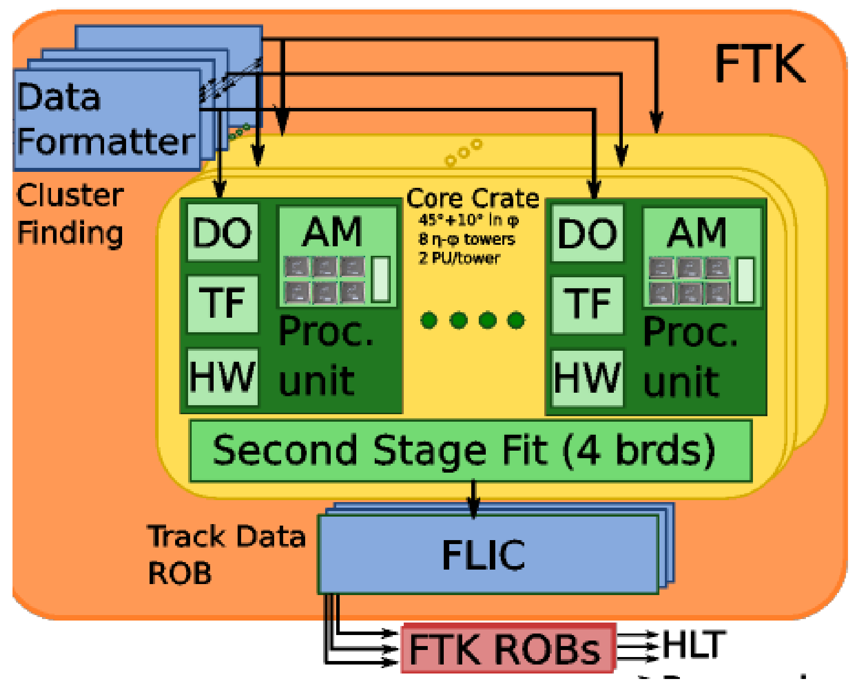
CMS L1 track trigger

- Two-sided sensor modules in OT →stubs: correlated hit pairs, consistent with >=2GeV track
- Stubs form input to track finding at L1 trigger rate of 750kHz (15-20k stubs/BX)
- 12.5μs latency (~4 μs processing time)

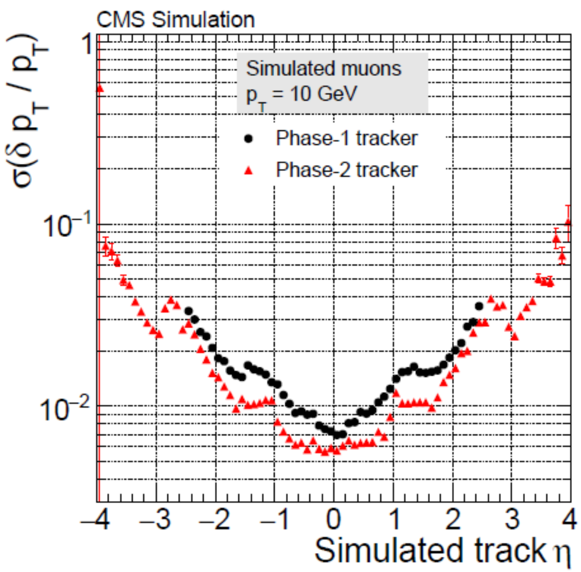
ATLAS Hardware-based track trigger

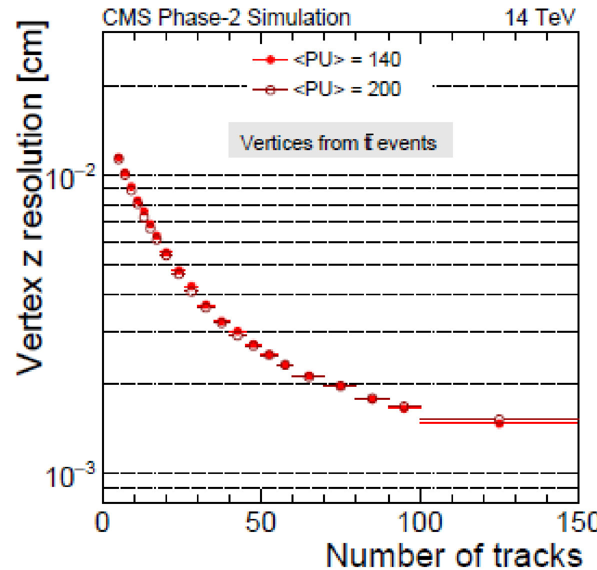
- FTK (current): >=1GeV tracks at 100kHz
- Update for HL-LHC conditions
    - Regional tracking: ~10% of detector, higher rate(1MHz), pT >2-4GeV
    - Global tracking: full detector, lower rate(~100kHz), pT >1-2GeV

Both experiments' tracker triggers adopt <u>pattern recognition</u> and massive <u>parallel processing</u>.



ATLAS & CMS: Tracking Performance

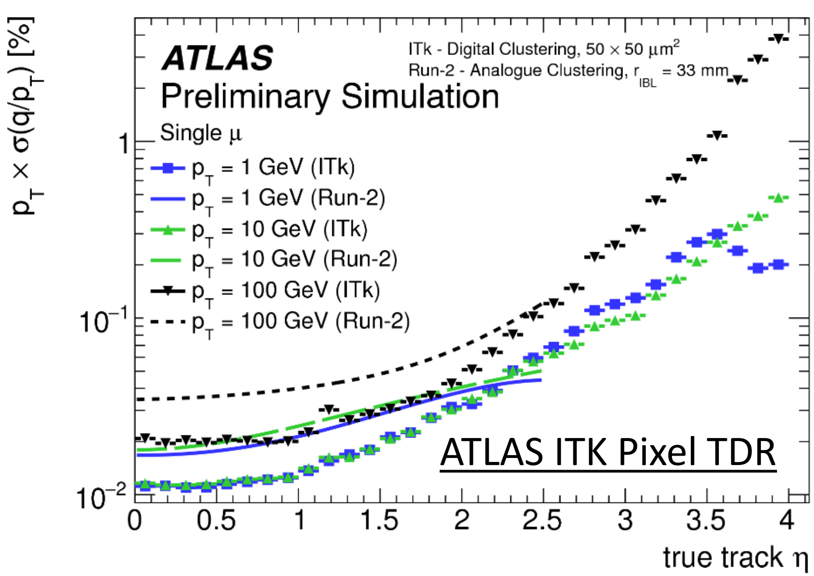




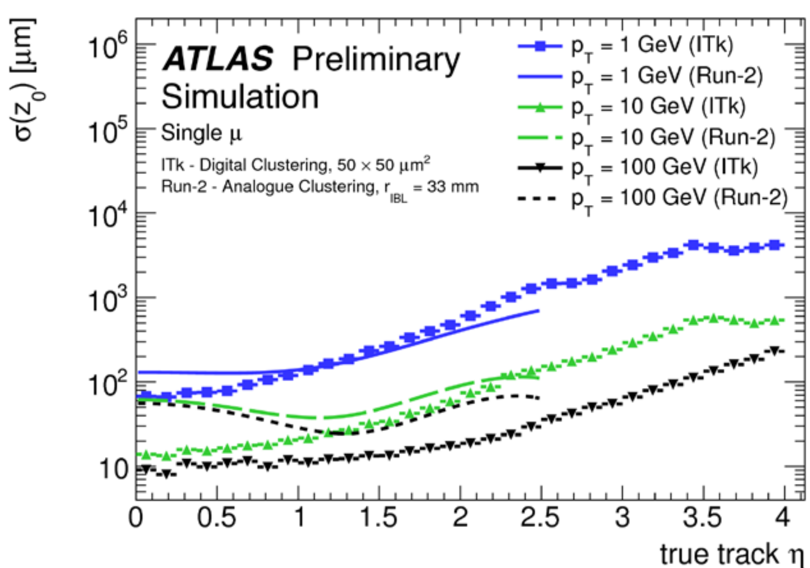
Excellent tracking and vertexing resolution and efficiency:

- increased coverage in forward
- maintain and improve upon current detector performance at HL-LHC conditions w/ 200PU

CMS-TDR-17-001



ATLAS ITK Pixel TDR

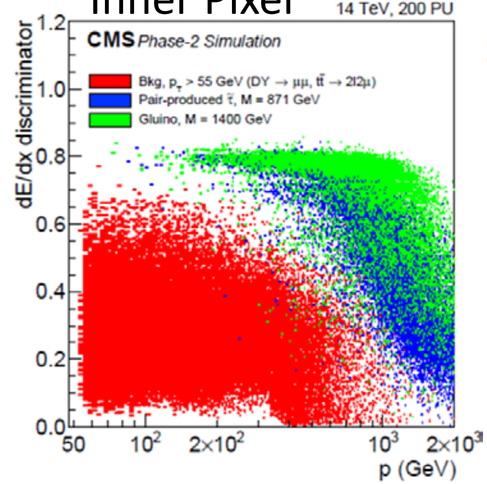


CMS: Heavy Stable Charged Particles

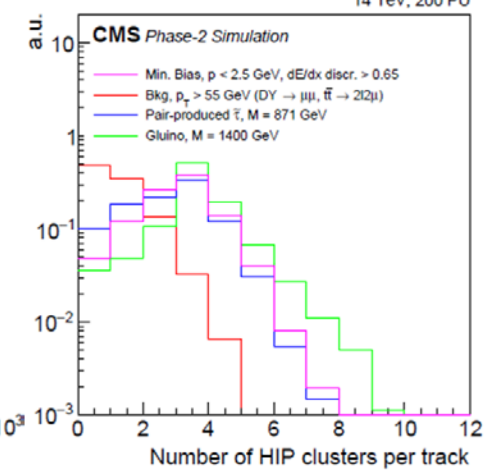
Tracker Upgrade CMS-TDR-17-001

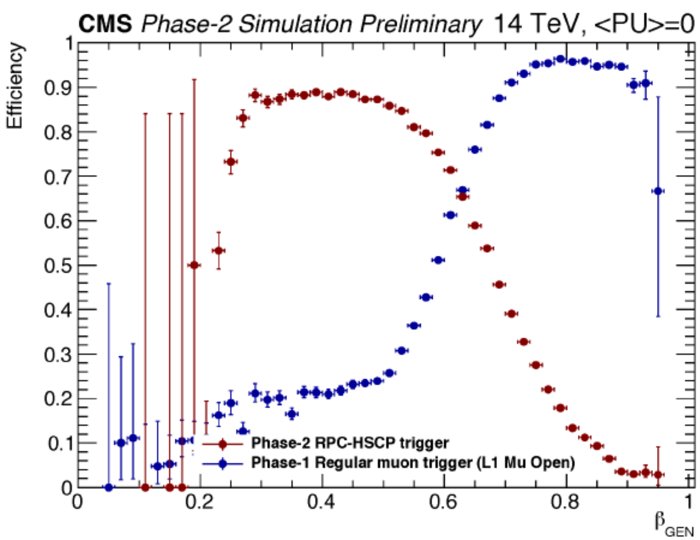
- HSCP: high dE/dx in silicon sensor
- Phase2 inner pixel has analogue readout:
  - 4-bit time-over-threshold: good resolution
  - Potential dual-slope digitizer: cover larger range of charge deposit for highly ionizing particles
- Phase2 outer tracker has digital readout + dedicated overthreshold bit (HIP flag) with programmable threshold (currently set at 1.4MIP)

Inner Pixel



Outer Tracker



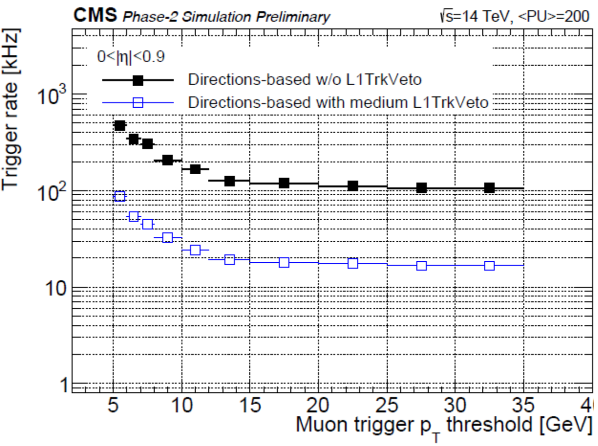


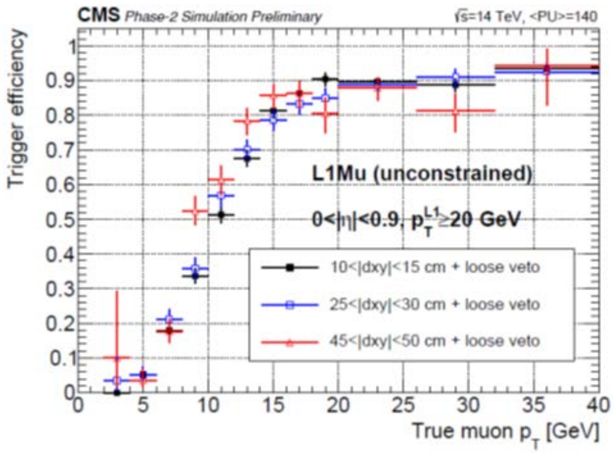
Muon Upgrade CMS-TDR-17-003

HSCP: heavy, slow-moving, highly-ionizing → muon system

- **RPC upgrade**: ~1.5ns TOF resolution to each RPC station → **RPC-HSCP trigger**: linear fit to time vs distance from IP
- Improve mass resolution:
  - Ph2 trigger level comparable to Ph1 offline level
- Ability to trigger on, at the correct BX, HSCP with velocity as low as β~0.25
  - Increase reconstruction efficiency for low β

CMS: Displaced Muon





New GEM stations: measurement of muon direction to distinguish low pT prompt muon and high Pt displaced muon

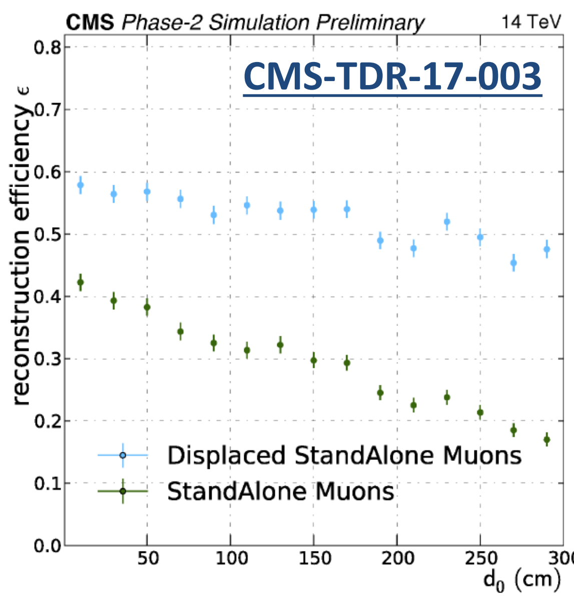
L1 tracking: veto events with L1Mu candidates matched to L1 track

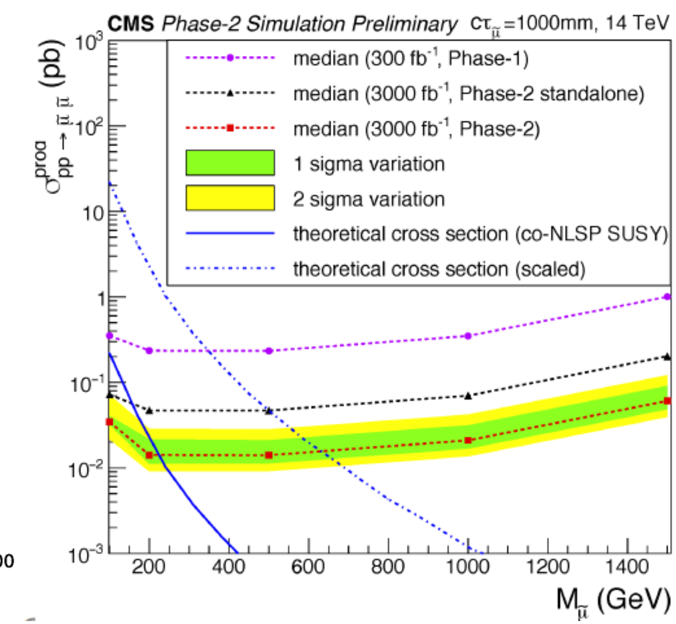
→ **Displaced muon trigger at L1:**

- Keeps trigger rate under control
- High efficiency in barrel+endcap

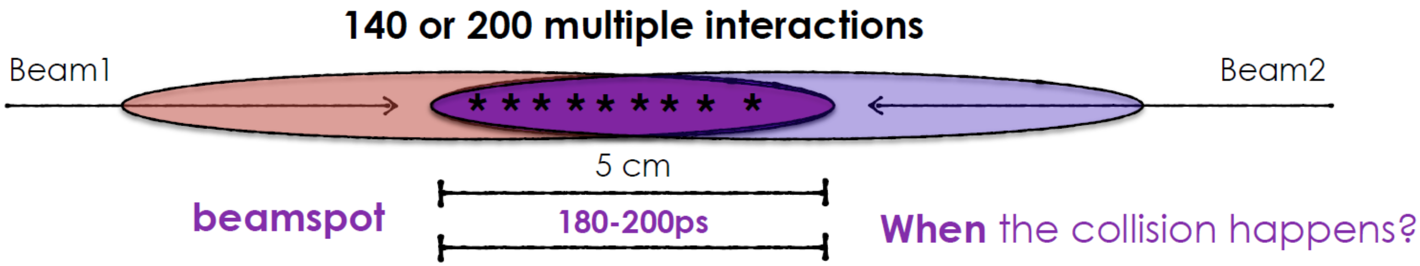
Dedicated "**Standalone displaced muon**" **reconstruction** algorithm w/ HL-LHC upgrade, using on hits in muon system w/o constraints wrt IP:

Improve reconstruction eff. & sensitivity (GMSB smuon projection) compared w/ "Standalone muon"



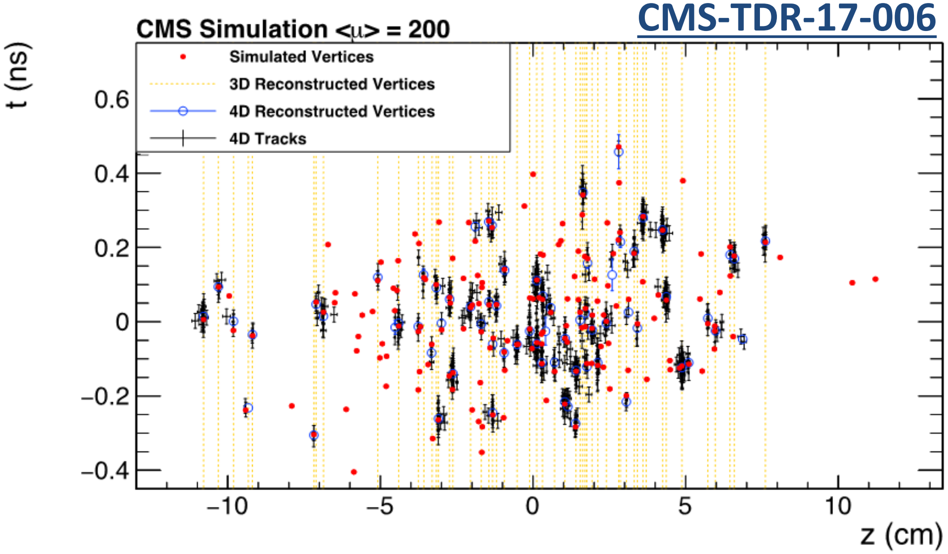


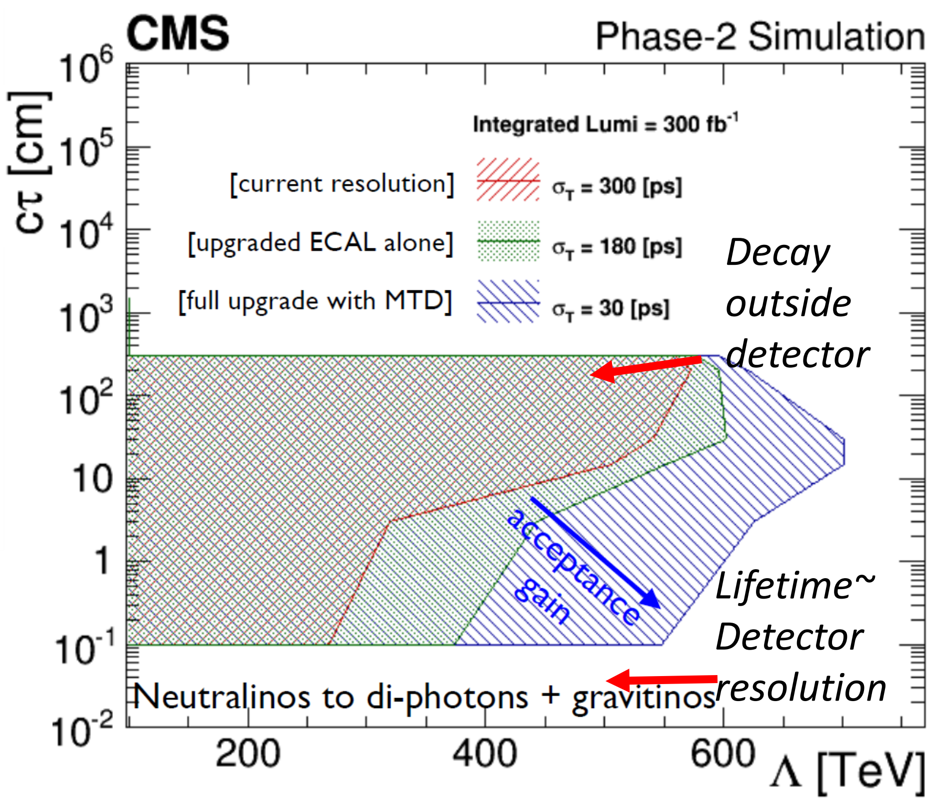
CMS: Displaced Photon w/ MTD



ECAL timing upgrade will help. But limited by beamspot & only works for higher energy particles.

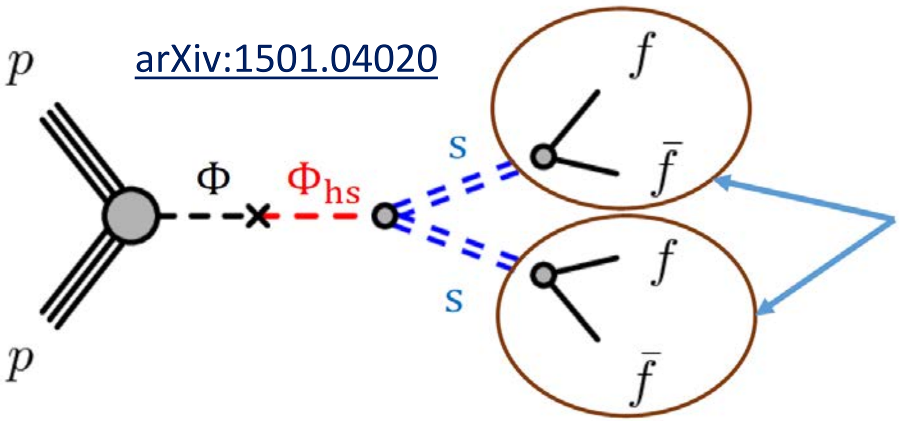
CMS-TDR-17-006





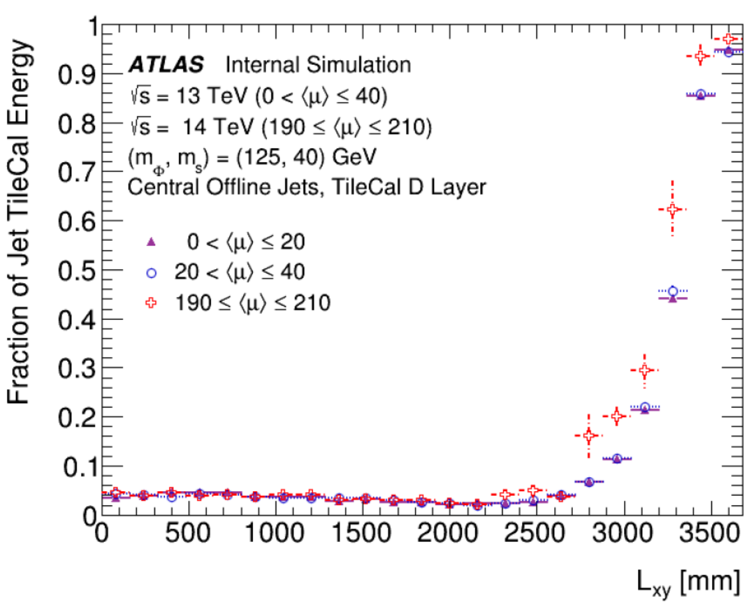
Precision timing w/ MTD will help remove spurious secondary vertices & tracks from PU; improve mass resolution in reconstruction; & open up new capabilities in LLP searches.

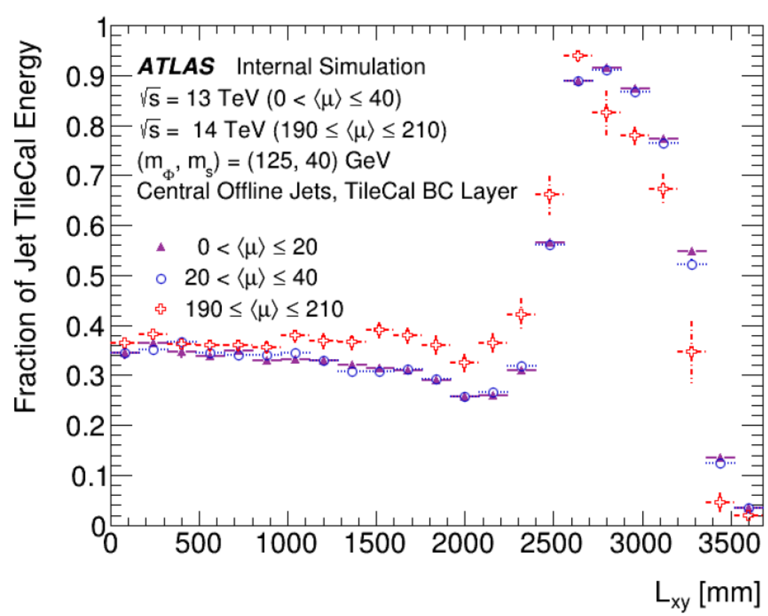
ATLAS: Displaced Jets



Displaced jets from the hidden sector mediator decaying to **two** scalars, S, which then decay to quark-antiquark pairs.
This analysis focused on trackless jets that appear in the HCAL (or on edge of ECAL) with dedicated "CalRatio" trigger.

The analysis can be improved by using HCal info splitting the B-C layers to identify scalar decay position. The spitted BC layer will help to gain more info on the longitudinal shower profile.

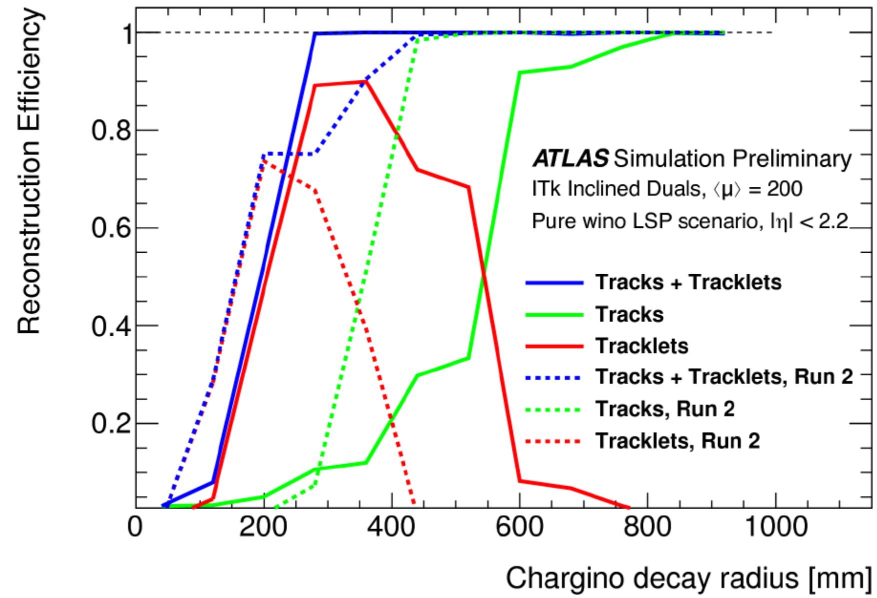


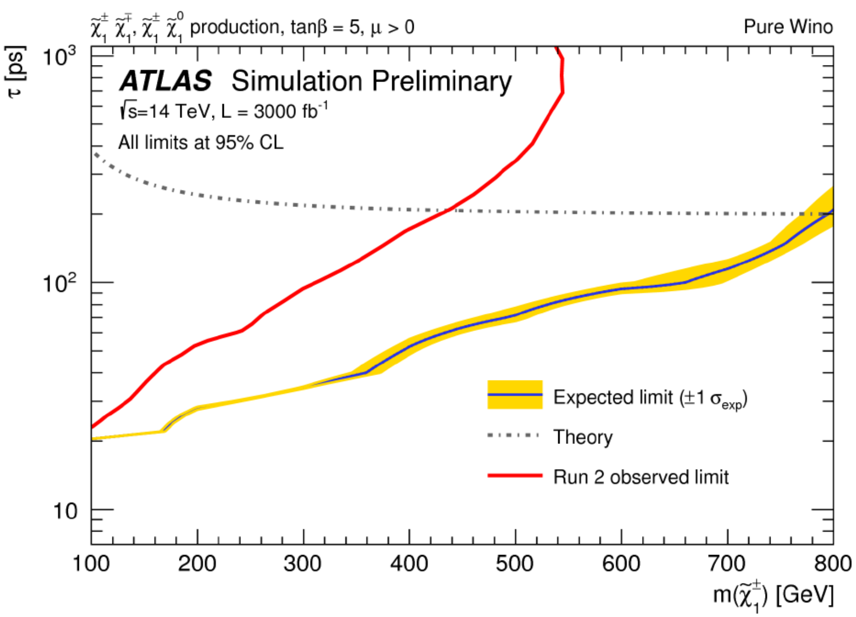


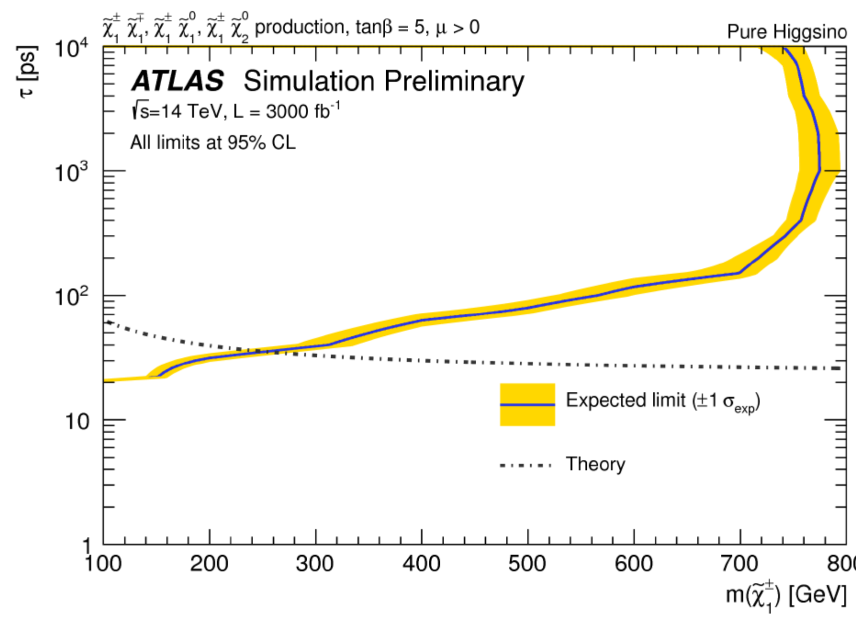
ATLAS: Disappearing Tracks

Searches for particles with a disappearing track, such as predicted in anomaly-mediated SUSY breaking scenarios, where the chargino can acquire a relatively long lifetime, and leave multiple hits in the traversed tracking layers before decaying. Events are required to contain at least one short track, called a tracklet.

The tracker upgrade for HL-LHC at ATLAS (ITK), can improve the reconstruction efficiency of tracklets, hence improving the sensitivity.



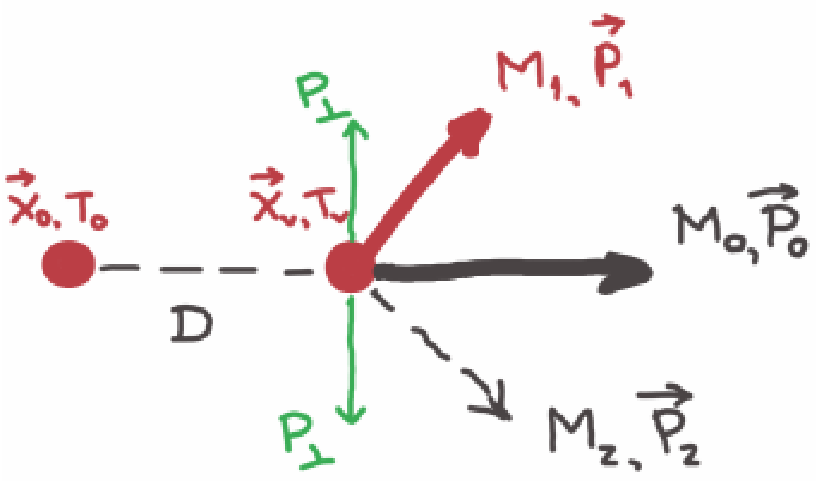




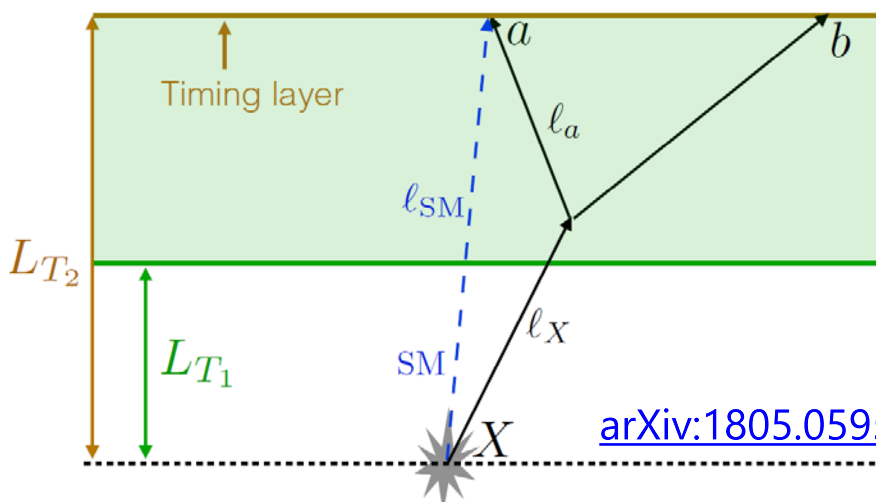
ATLAS: Displaced Vertices

- Massive and long-lived particles with lifetimes of the order of O(10)ps to O(10)ns, such as a SUSY gluino that hadronizes into an R-hadron, can decay inside the inner tracker into charged and stable particles.
- The products of these decays are reconstructed as tracks with measurably distant impact parameters with respect to the prime vertex.
- Sensitivity projections using ATLAS tracker upgrade for HL-LHC (ITk) for this signal has been tested with a simplified simulation, which has a description of the ITk active sensors and a modelling of the magnetic field. The kinematics and location of the decay products of the R-hadron are injected into the simulation and their trajectories are extrapolated through the detector model.
  - The probability of producing at least seven silicon hits in the ITk geometry is tested.

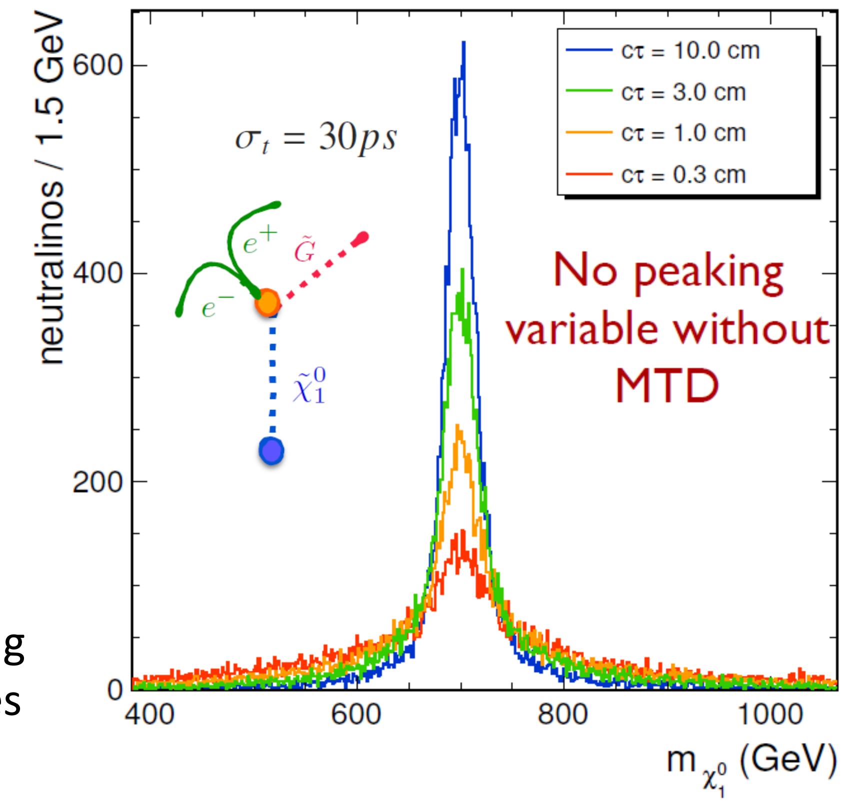
LLP Searches with Precision Timing



With displacement & additional timing info, scenario has unique solution
→ Allows for reconstruction of peaking variable (mass or mass splitting depending on how velocity relates to model structure)

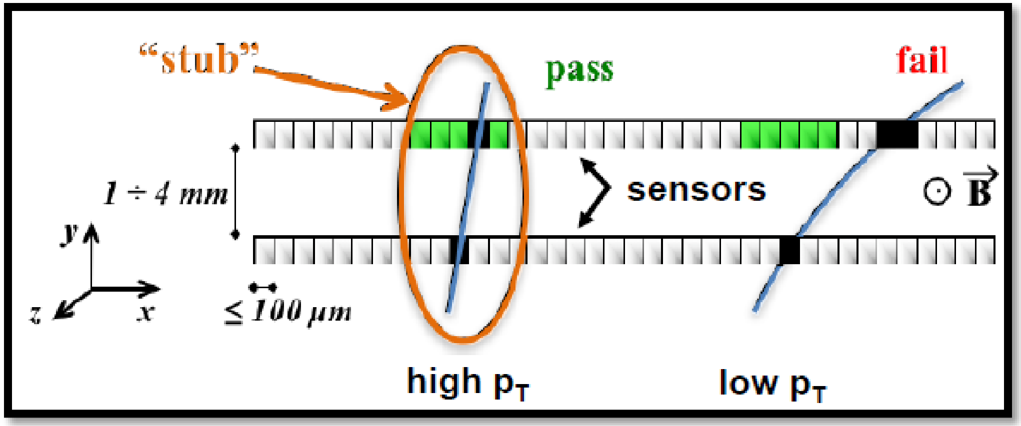


arXiv:1805.05957

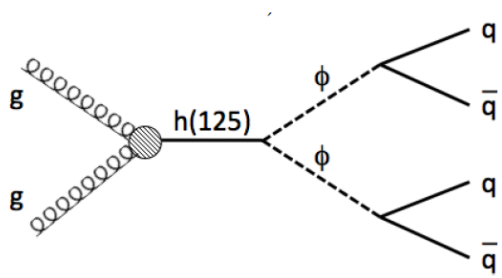


Using a prompt ISR jet to timestamp + cut on timing delay → new trigger strategy + significantly reduces background (See talk from Zhen Liu)

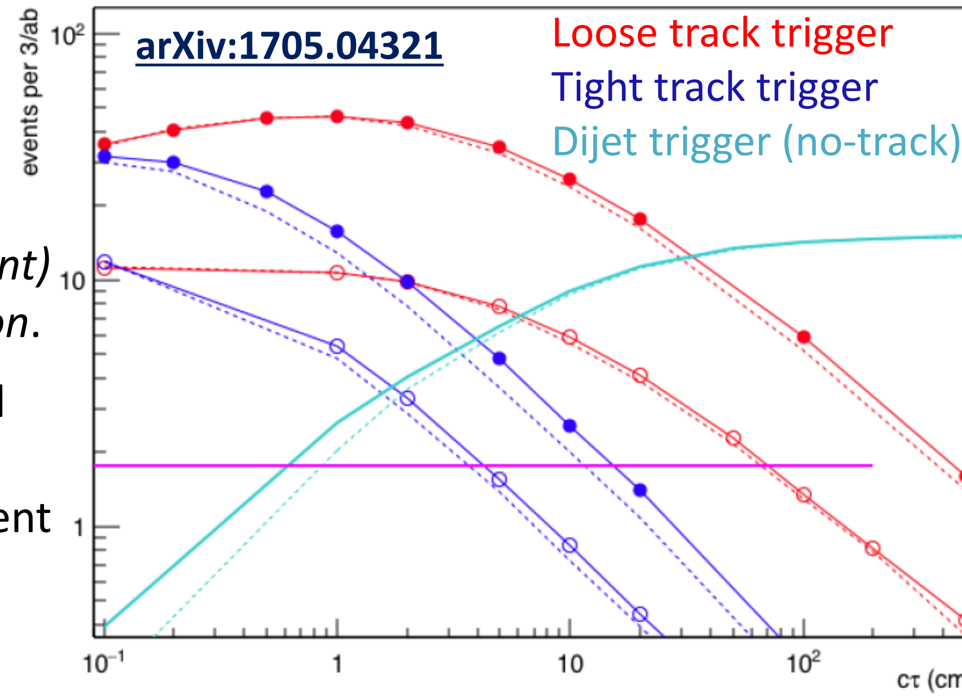
LLP Searches with Displaced Track Trigger



CMS L1 track trigger
- Two-sided sensor modules in OT
→stubs: correlated hit pairs, consistent with >=2GeV track
- Stubs form input to track finding at L1 trigger rate of 750kHz (15-20k stubs/BX)
- 12.5μs latency (~4 μs processing time)



Toy study shows increased signal acceptance with "loose track"(no beamspot constraint) trigger in simulation.



Consider the capability to **trigger on displaced tracks (jets) with the L1 track trigger**

- Preserve low pT LLPs with small displacement
- Various well-motivated physics scenarios
- Does require more hardware resources

New Studies for HL-LHC

- ATLAS & CMS upgrades differ in detailed implementation but similar in concept and scope: same LLP search projections can be done for both experiments to evaluate complementarity
- New search channels for upgrade projection
  - Soft displaced leptons:
    - As seen in inelastic dark matter; SIDM; dark showers
    - Muon upgrade: lower pT threshold in displaced muon trigger turn-on
    - Timing detector: timing info for mass (splitting) reco for iDM
  - Emerging/semivisible jets from dark showers
  - Long-lived stop searches with fast timing
  - Boosted object reconstruction with fast timing
  - Add your suggestions here!

New Detectors at Future Collider

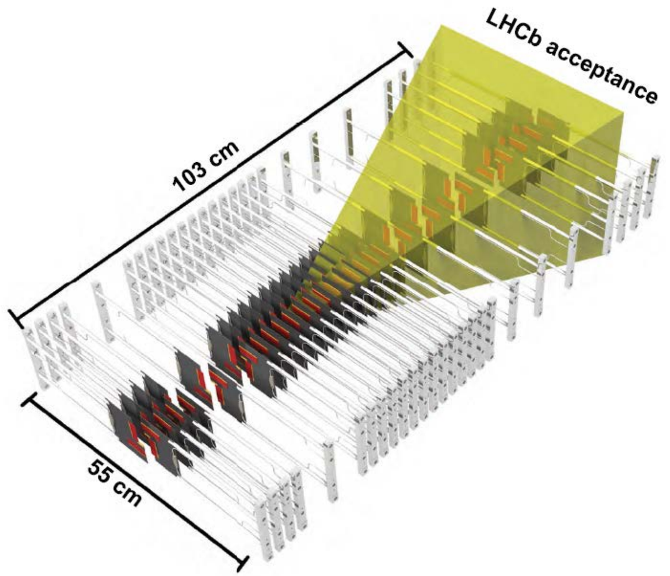
- 4-Dimensional trackers with fast timing
  - ☺ ToF between layers powerful discriminant in choosing hits to reconstruct a track; reduce combinatorics
  - ☹ Need to develop fine-pitch sensors, powering, electronics
- Timing detector outside ATLAS muon system
  - ☺ More substantial timing delay for LLP due to longer travel distance: further suppress background
  - ☹ Not in HL-LHC upgrade scope
- (Double-sided?) tracking layer very close to the beamline
  - ☺ Extend sensitivity to even smaller displacements
  - ☹ Ain’t got no space + radiation&data rate too high
- Add your suggestions here!

The LHCb Upgrade

- Contents:
  - Introduction
    - Designed to search for long-lived particles: b-&c-mesons
    - Forward coverage of 2<|η|<5; reduced luminosity compared w/ ATLAS & CMS
  - LHCb detector & trigger upgrade for Run3 (Phase1)
  - Upgrade LHCb projections: LLP signatures
  - After Phase1 upgrade: Phase2 and more
- Editors:
  - Martino Borsato and his friends

	Current Conditions	Phase-I Conditions	Phase-II Conditions
$\mathcal{L}$	$4 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
$\int \mathcal{L}$	$8\mathrm{fb}^{-1}$ by 2019	$50\mathrm{fb}^{-1}$ by 2030	$300\mathrm{fb}^{-1}$ by 203x
$\sqrt{s}$	13 TeV	14 TeV	14 TeV
μ	1.1	5.5	50

LHCb: Phase1 Upgrade

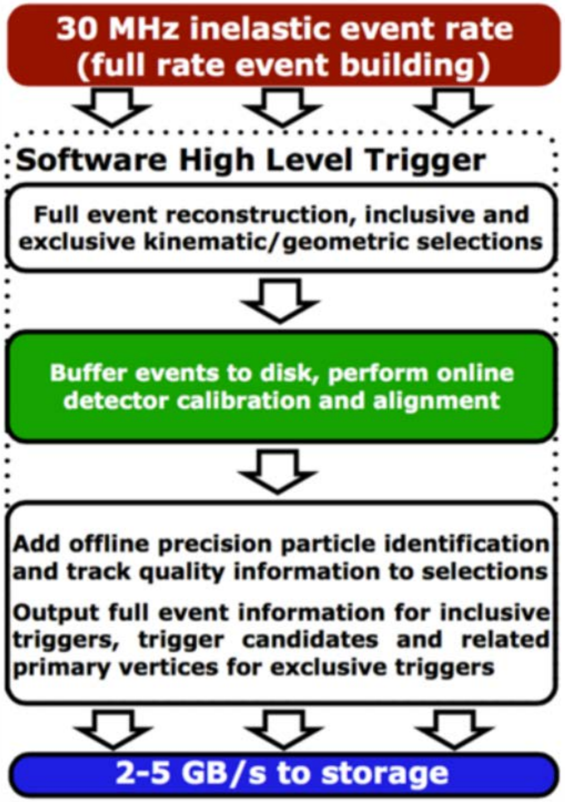


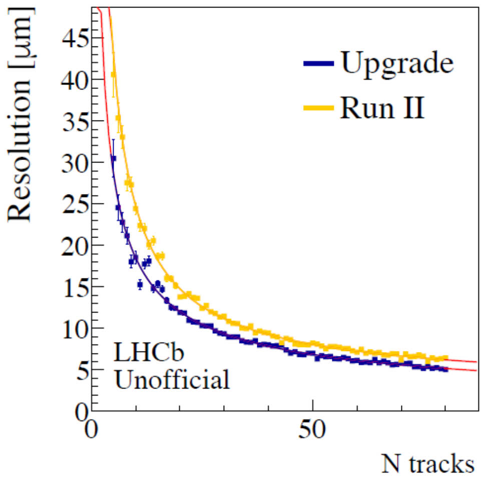
Upgrade VELO (Vertex Locator): + add Upstream Tracker

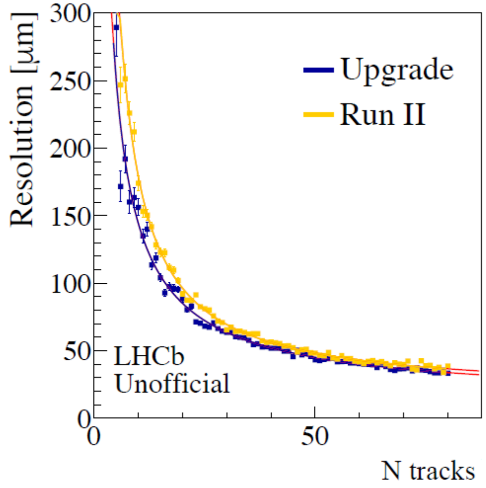
- Strip → Pixels;
- Closer to beamline (8mm→5mm)
- Better resolution & fewer fakes

Upgrade trigger:

- 5x current event rate
- Triggerless readout + full software trigger
  - Remove pT threshold
- Turbo stream ++ / SP

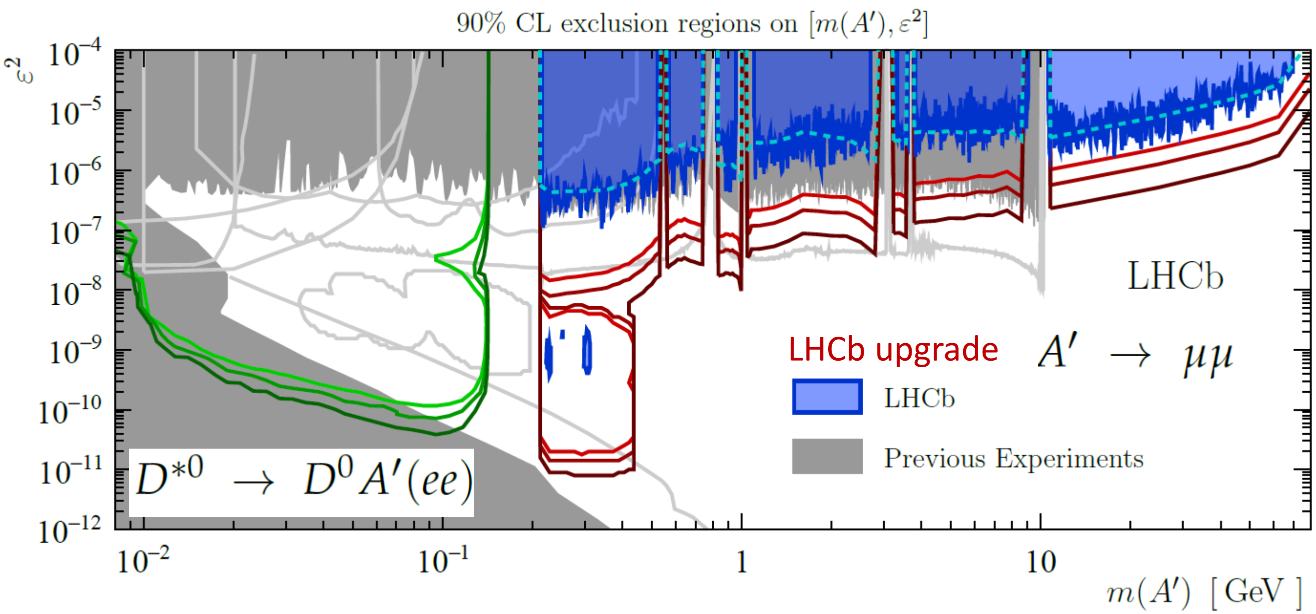


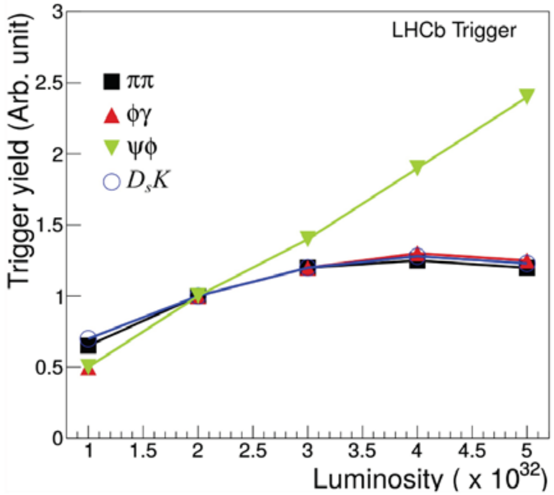




LHCb: LLP Prospects @ Phase1

- Displaced di-leptons:
  - Expect exceptional sensitivity to low-mass displaced dilepton signatures thanks to mass resolution, excellent vertexing and online selection allowed by trigger-less readout.
  - Extend reach for A'→μμ & new feasibility to probe radiative charm decay
- Displaced jets
  - Focus on low lifetime; benefit from better vertexing & less material
- Displaced mesons
  - Designed for heavy flavor decays → competitive for dark mesons
  - Benefit from software trigger for better efficiency





Trigger yields for different B-meson decays

LHCb: Phase2 (HL-LHC) Upgrade

Suggestions for upgrades:

- Triggers on "downstream" tracks:
  - Improve sensitivity to LLPs with displacements > 20cm: only info from tracking statins not VELO
- Magnet stations for "upstream" tracks
  - For soft charged tracks bending out of detector acceptance from LLP decaying in VELO, add magnets to improve tracking of low pT tracks
- Reduce material interactions
  - Remove RF foil: VELO envelope ~5mm from beamline

Naïve projections: see white paper

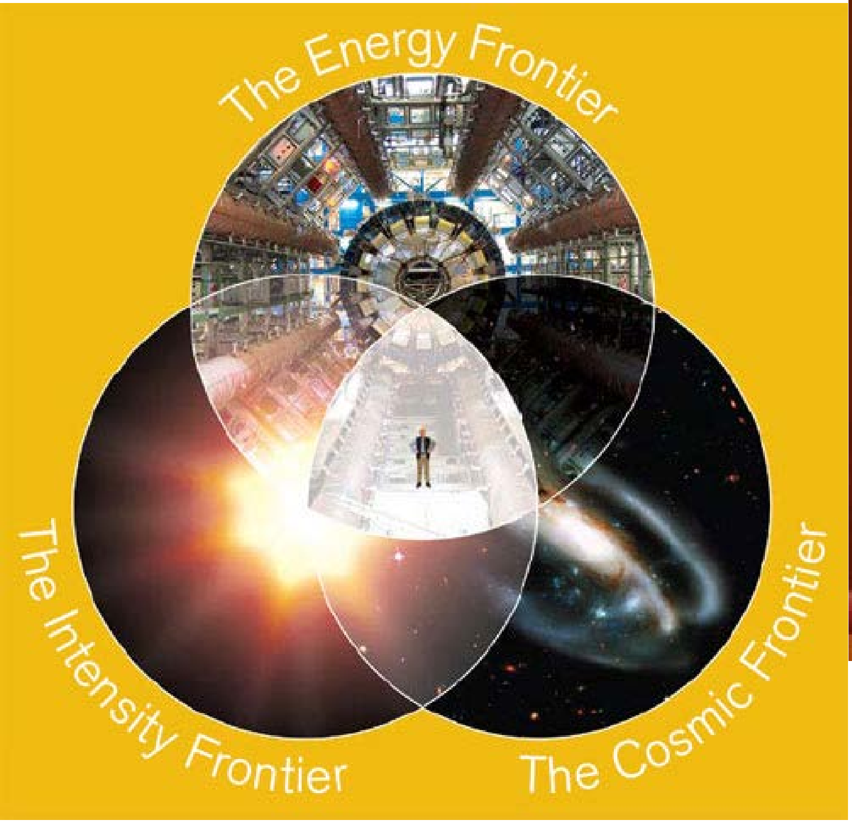
Dedicated Detectors for LLPs

- Contributions from individual dedicated detectors for LLPs
  - For ultra-low mass, ultra-long lifetime, unusually charged LLPs beyond ATLAS/CMS/LHCb reach
- See talks from this afternoon and tomorrow!

Conclusions and Outlook

- Comprehensive upgrade program to meet HL-LHC conditions and extend physics potential of LLP searches
- ATLAS&CMS upgrades:
  - improved spacial resolution: tracker; HGCAL; …
  - increased forward coverage: pixel extension; muon; …
  - additional timing information: HGCAL; MIP; electronics; …
  - improved trigger capabilities: more info, higher rate, L1 tracking etc.
- LHCb upgrades for Phase1 & 2 with unique capabilities for LLPs
- Dedicated detectors for LLPs being explored
- We would like your input: what more can we do?
  - Search channels, trigger methods, reconstruction methods, hardware capabilities, …

THANK YOU!

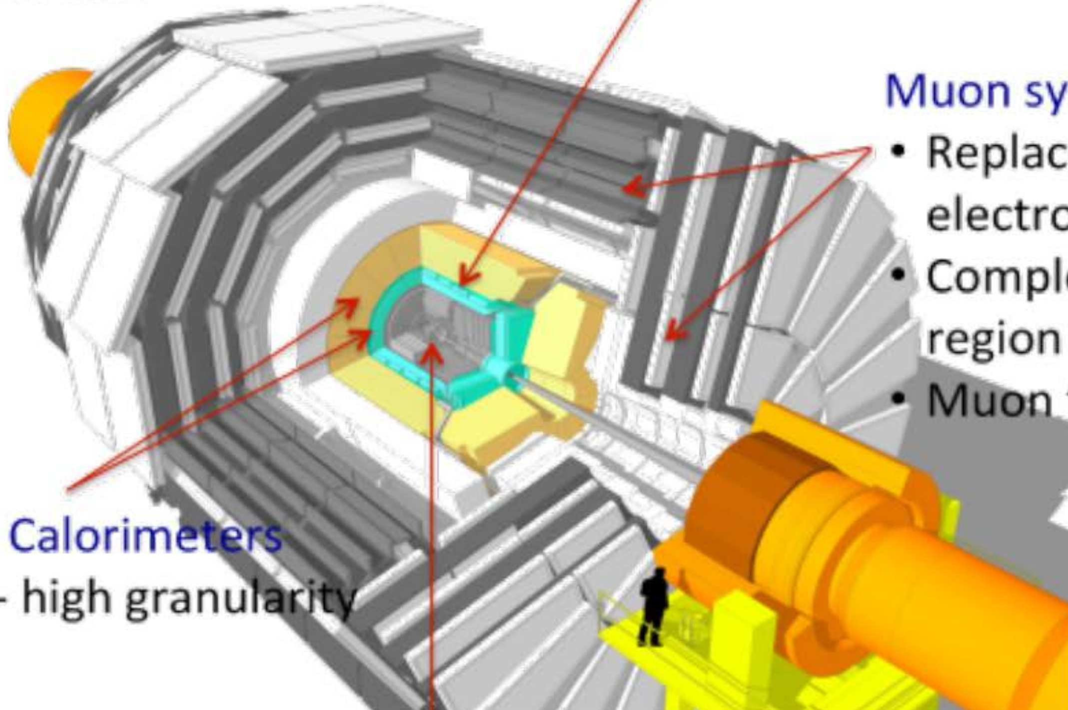


Keep looking with a magnifying glass; you never know what you might find…

HL-LHC Upgrade: CMS Overview

Trigger/HLT/DAQ
- Track information at L1-Trigger
- L1-Trigger: 12.5 μs latency - output 750 kHz
- HLT output ≃7.5 kHz

Barrel EM calorimeter
- Replace FE/BE electronics
- Lower operating temperature (8∘)



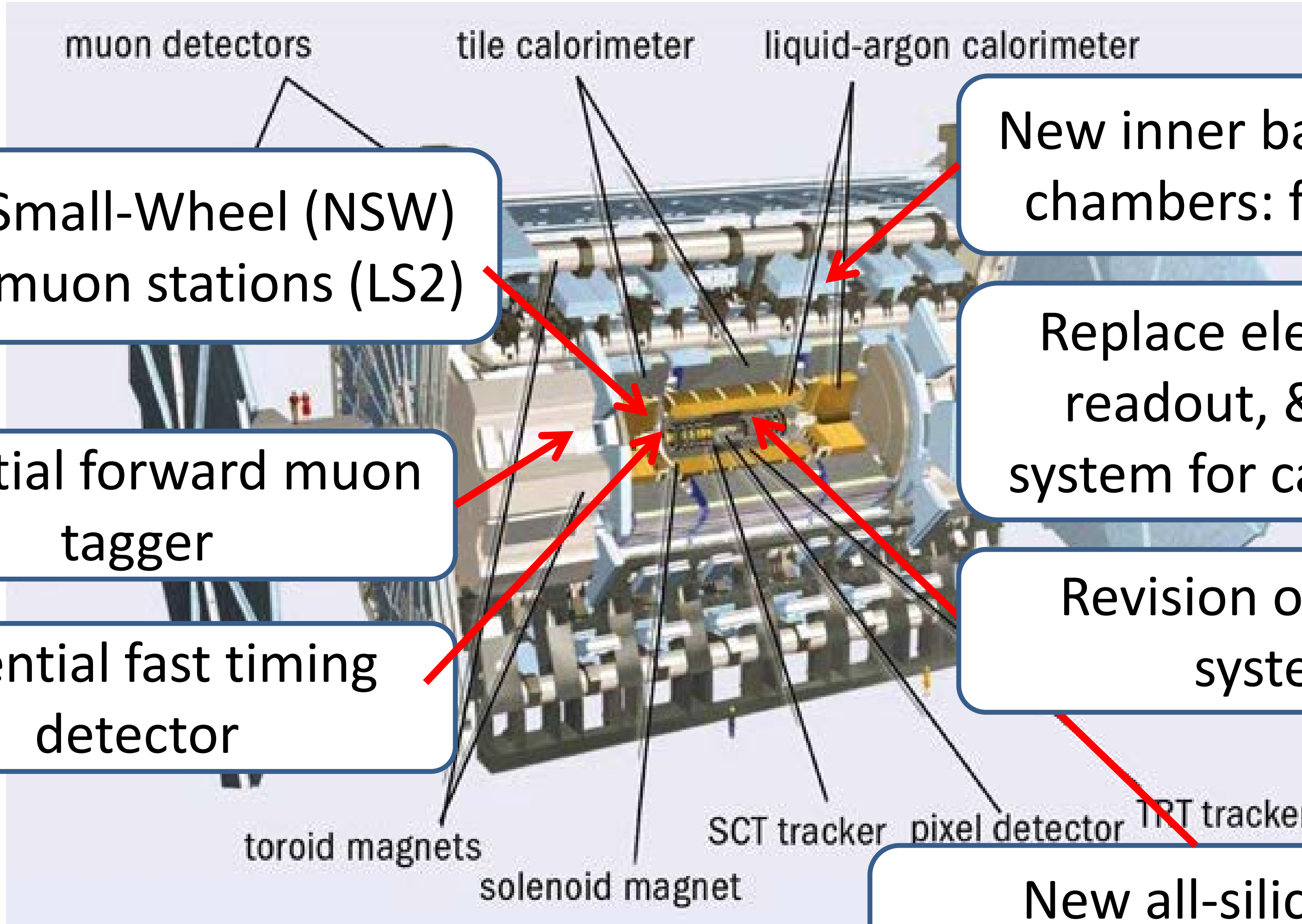
Muon systems
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

Replace Endcap Calorimeters
- Rad. tolerant - high granularity
- 3D capability

+Timing layer (outside tracking volume)

Replace Tracker
- **Radiation tolerant; high granularity**
- **Extend $|\eta|$ coverage up to 4**

HL-LHC Upgrade: ATLAS Overview



New Small-Wheel (NSW) inner muon stations (LS2)

Potential forward muon tagger

Potential fast timing detector

New inner barrel muon chambers: for trigger

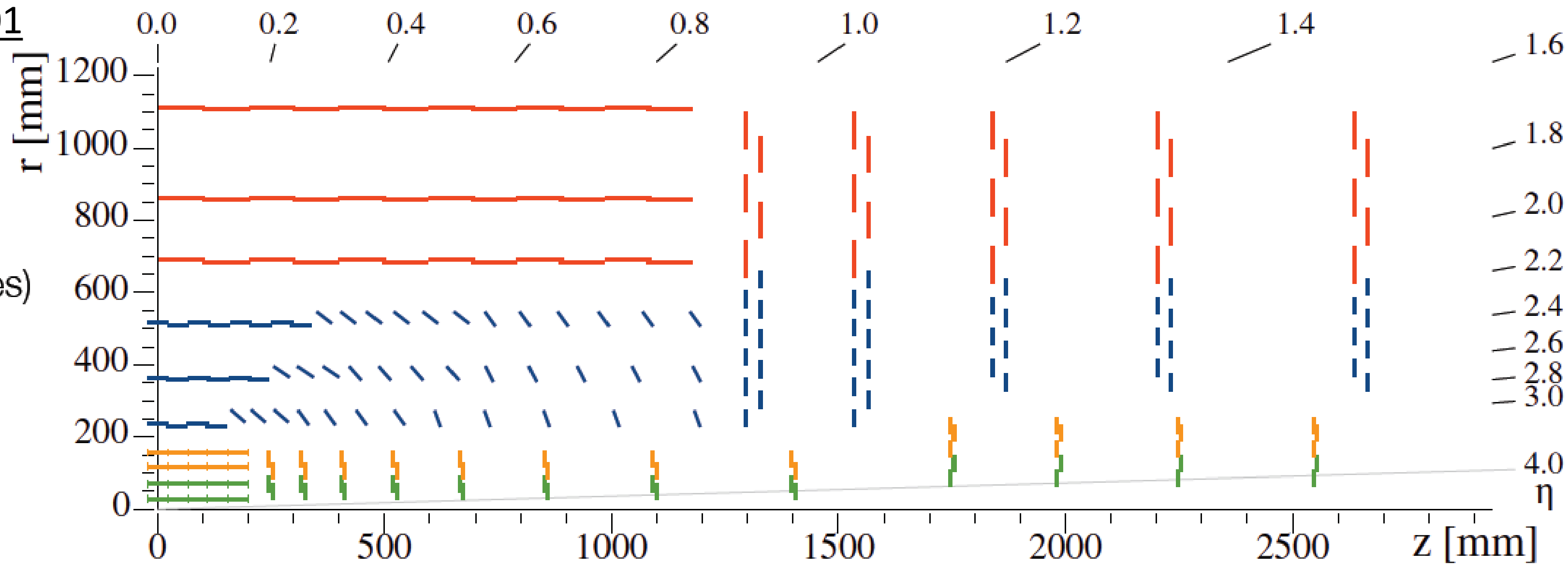
Replace electronics, readout, & power system for calorimetry

Revision of trigger system

New all-silicon inner tracker (ITK)

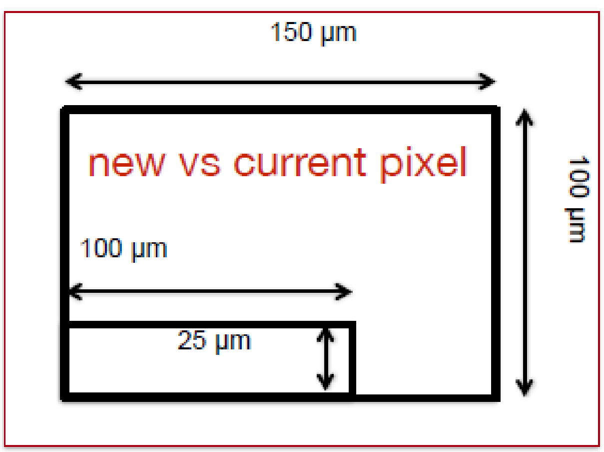
Tracker Upgrade: CMS

CMS-TDR-17-001



Outer Tracker
(PS vs 2S modules)

Inner Pixel
(1x2 vs 2x2 chip modules)



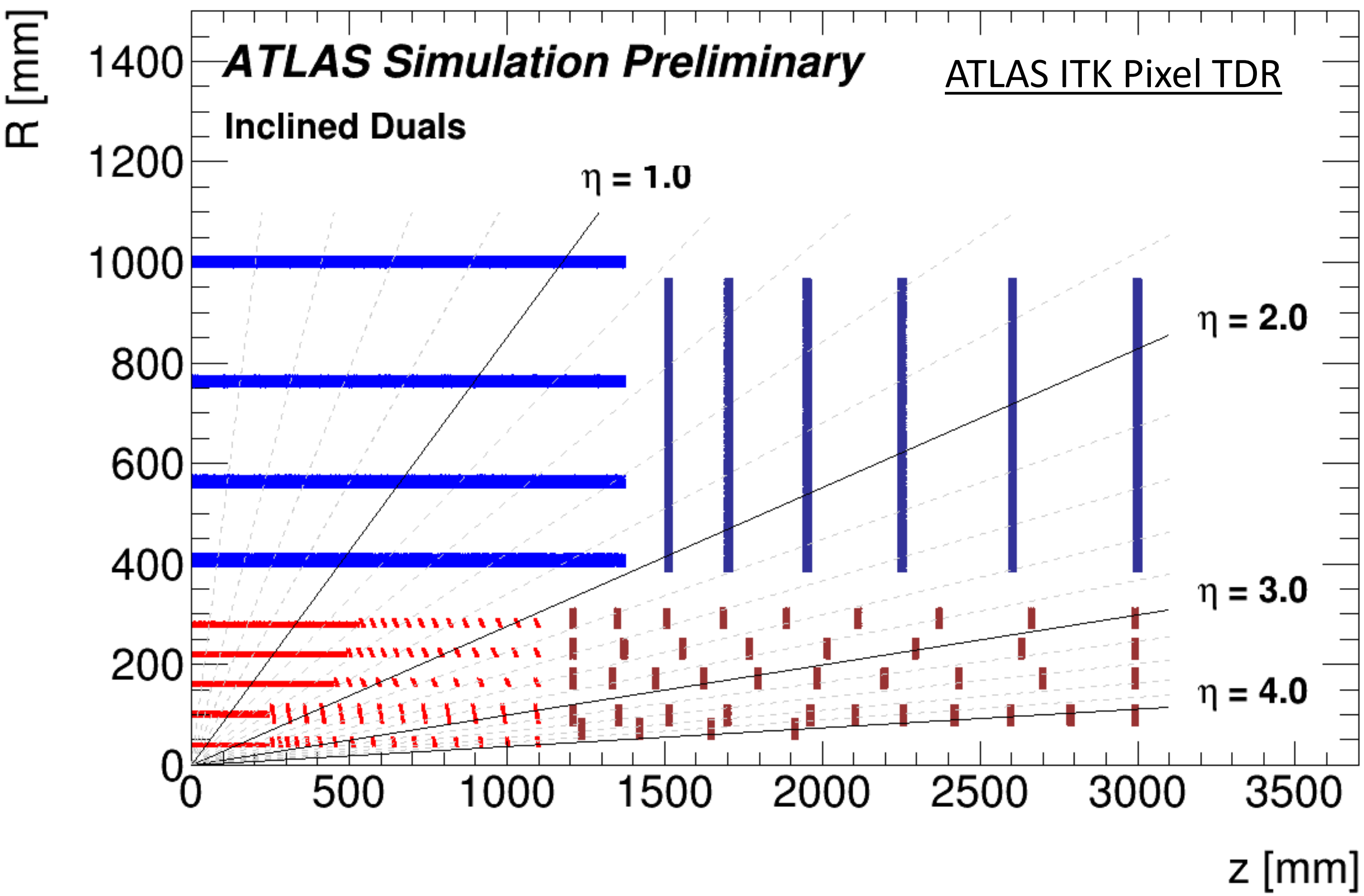
Inner pixel detector:

- 4 layers + (8+4) disks: increase coverage; |η|~2.5 → |η|~4
- Thinner pixels (285µm →150µm): radiation hard
- Smaller pixels: improve resolution, maintain occupancy

Outer Tracker:

- 6 layers + 5 disks of pixels-strip/ strip-strip modules
- Two-sided sensor modules → stubs → L1 tracking finding

Tracker Upgrade: ATLAS



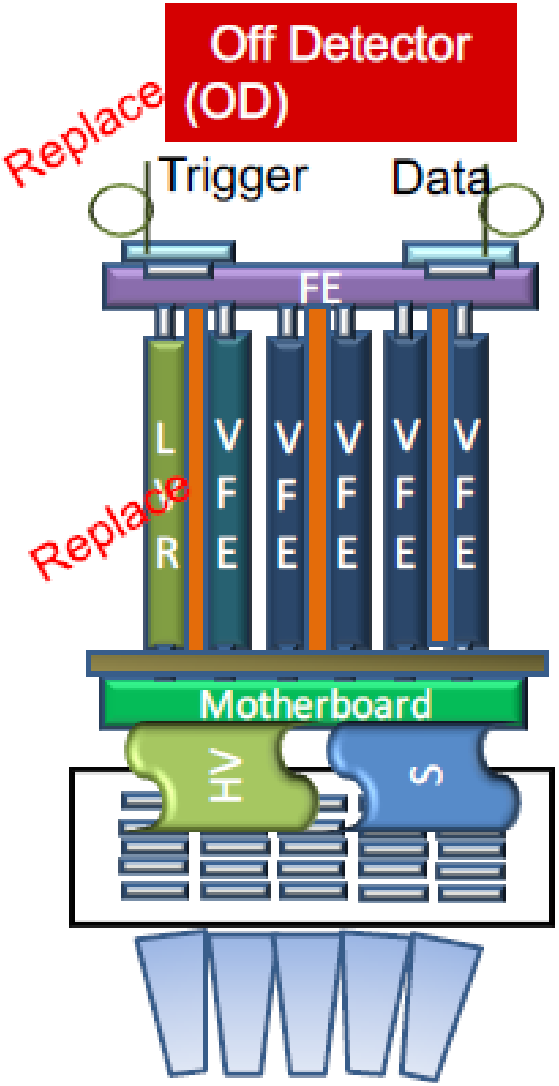
Outer strip detector:

- 4 barrel layers + 5 endcap disks
- covers |η|~2.6
- tilted modules at 52 (40) mrad in barrel (endcap) for 2D measurements

Inner pixel detector: small (50x50) & thin pixels with extended |η|~4

- 5 barrel layers with inclined sensors starting at |η|~1
- In endcaps: rings instead of disks to reduce material

Calorimetry Upgrade: Barrel



For the CMS detector:

- The crystals in the ECAL will be kept for duration of LHC
- The **FE & BE electronics will be replaced** for more precise timing, useful in both pile-up mitigation and searches for new physics
- Target (hardware fundamental limit):

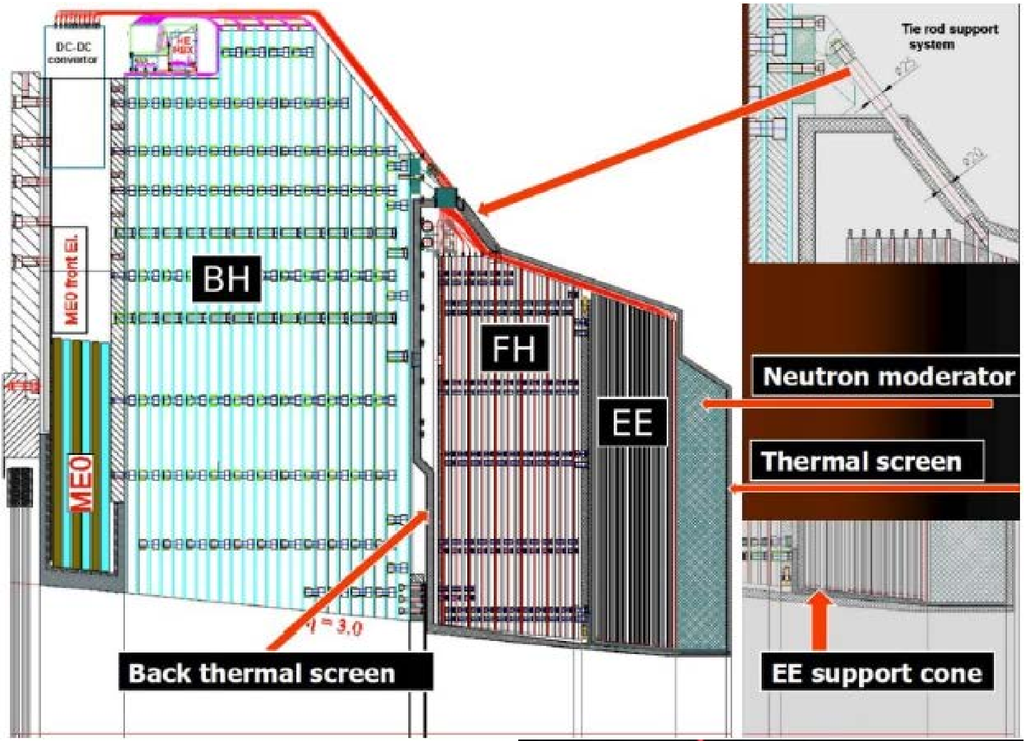
~30ps for E > ~30GeV (1/10 of current limit)

- Current studies on HCAL Barrel radiation damage suggest no need for replacement at HL-LHC: pending further study

For the ATLAS detector:

- The liquid argon ECAL and tile HCAL are expected to be functional through the lifetime of the LHC
- The front & back end electronics, and power supplies will be replaced for HL-LHC conditions
- Readout upgrade will allow high res. info at L0 trigger

Calorimetry Upgrade: Endcap



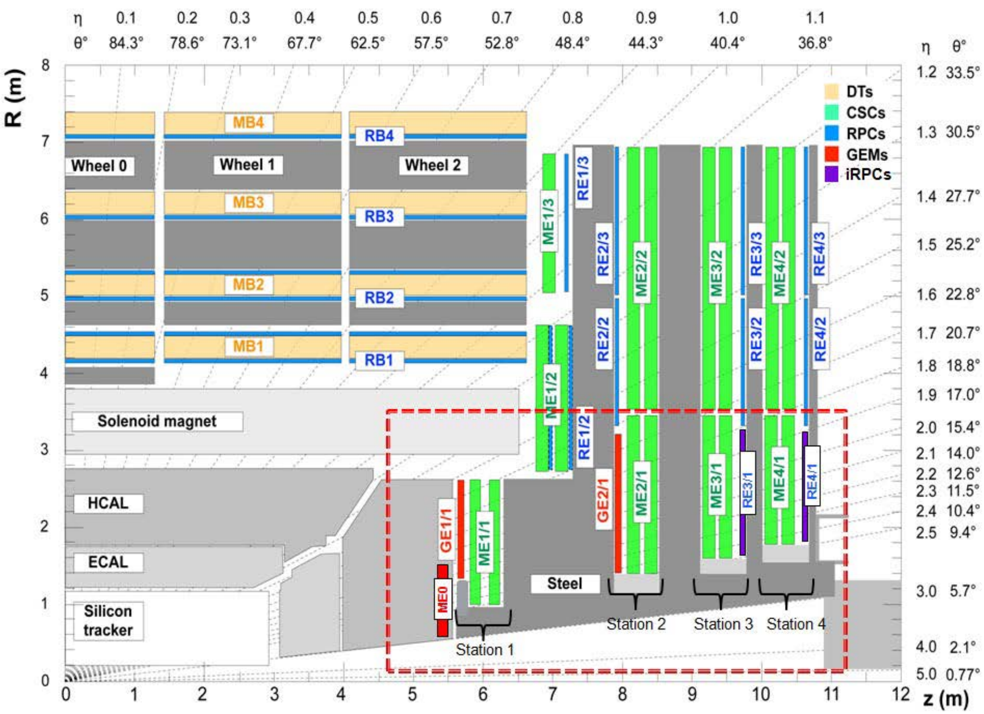
<u>For the CMS experiment</u>, the endcap calorimeter will be replaced with a silicon-based calorimeter (**HGCAL**):

- High granularity and 3D imaging to help mitigate PU
- Fast signal collection (<10ns) and **fast timing capability (few tens of ps)**

→ 4D info in space-time to reconstruct showers

- Other than the CMS endcap calorimeter (HGCAL), upgrades to calorimetry is limited
- Better timing resolution on electronic upgrades, and more calo info at trigger level, should help with hadronic/γγ/ee reconstruction
    - ~30ps timing resolution for particles of tens of GeV @ CMS upgrade
- HGCAL@CMS offers high granularity spatial and timing resolution for charged particles & photons: prospects for B physics?

Muon Upgrade: CMS

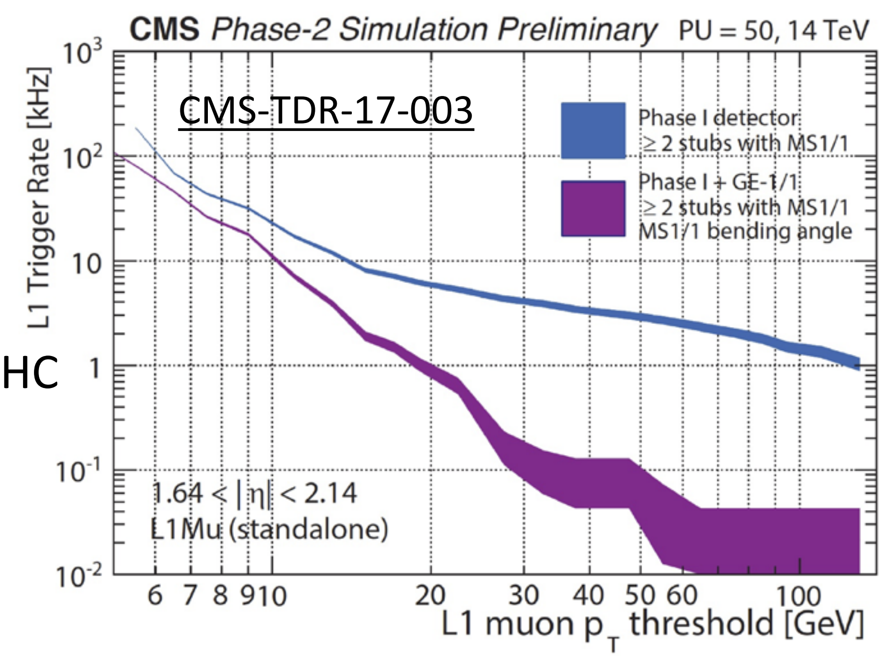


Muon system upgrade scope for HL-LHC:

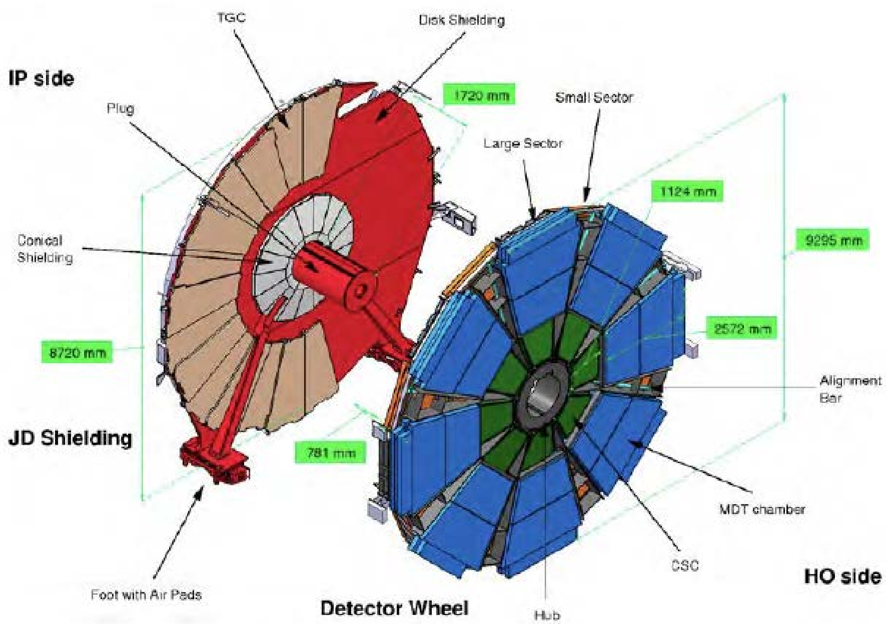
- Existing detectors:
  - upgrade barrel DT and endcap CSC electronics for 40MHz readout
- Extend forward coverage:
  - GEM & RPC detectors: 1.6<η<2.4
  - ME0 (for trigger): 2.4< η<2.9

Standalone muon trigger at L1:

- Keep rate under control:
  - single muon threshold 20-25GeV @ HL-LHC
- Provide good resolution and efficiency
- Provide capabilities not covered by L1 track trigger, e.g. displaced tracks & slow moving particles



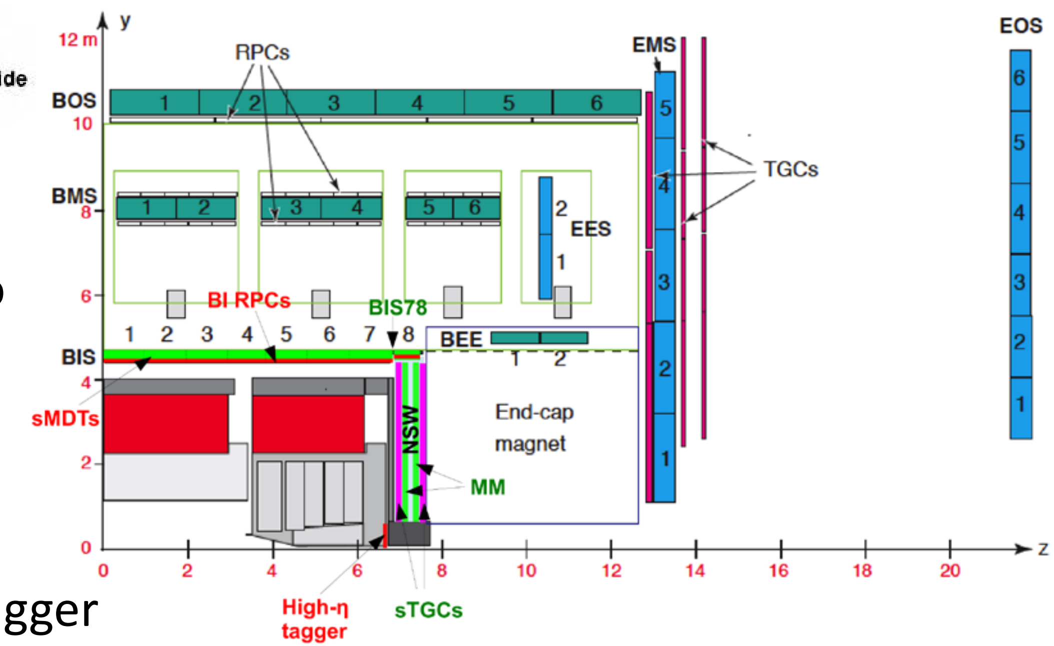
Muon Upgrade: ATLAS



Phase-1 (ongoing, installation during LS2):

- New Small Wheel (NSW) with Micromegas (MM) & small-strips Thin Gap Chambers (sTGC) to replace the innermost endcap
- Upgrades to barrel RPCs

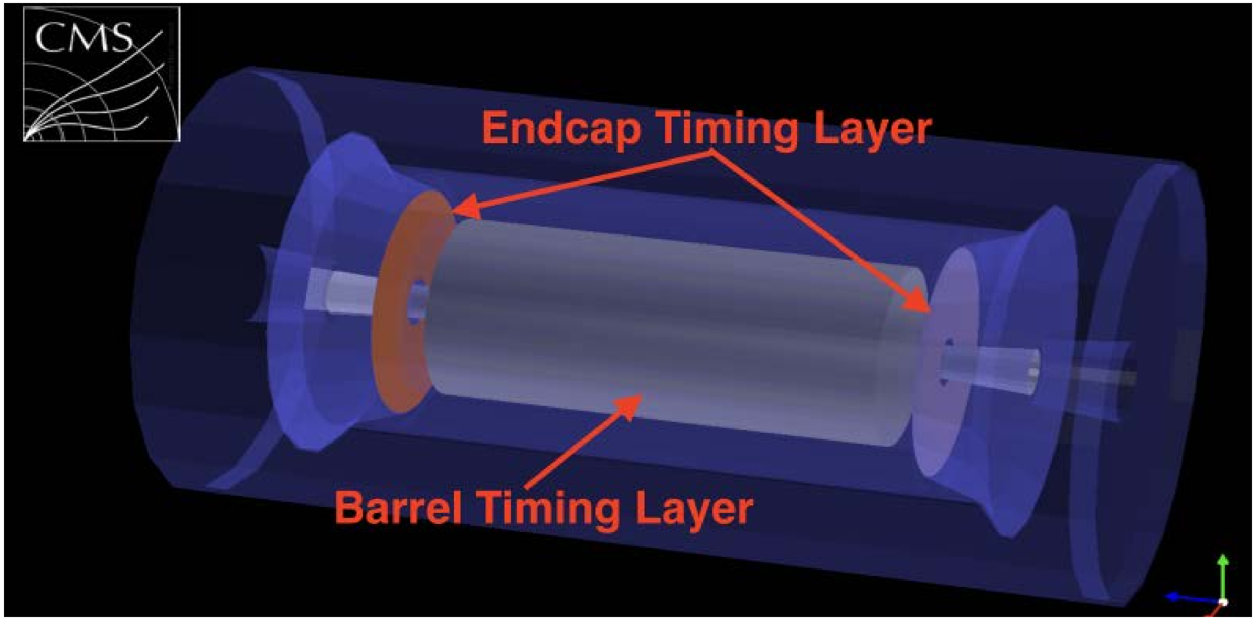
→ Maintain momentum resolution and keep single muon trigger rate under control



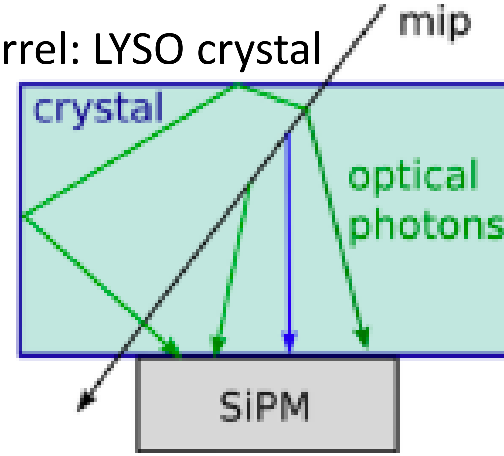
Phase 2 (for HL-LHC)

- NSW will be kept for HL-LHC
- Major upgrades to the muon barrel to increase acceptance&robustness
    - new inner RPC stations
    - remove some old MDTs
- MDT info added to hardware trigger
- Potential addition of forward muon tagger

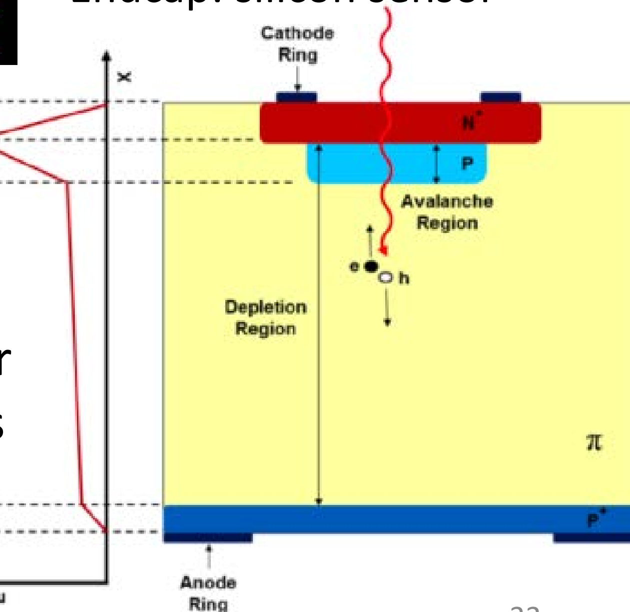
Fast Timing Upgrade: CMS



Barrel: LYSO crystal



Endcap: silicon sensor

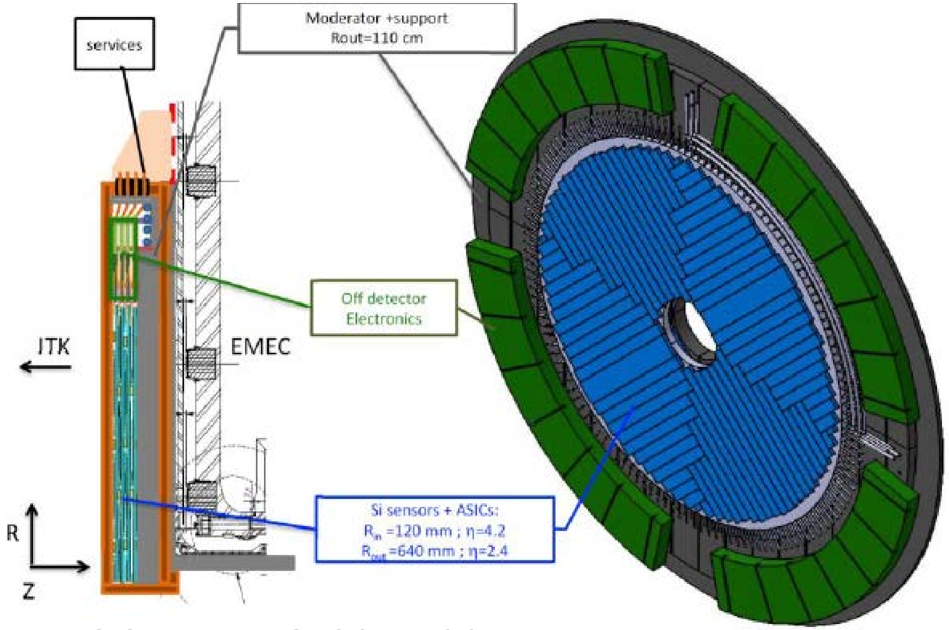


- Calorimeter upgrades (ECAL electronics + HGCAL) will provide precise (a few 10s of ps) timing for high energy photons in barrel and high energy hadrons/photons in endcap
- **Additional timing layer (barrel+ endcaps** outside tracker volume) can provide precision timing for charged hadrons & converted photons down to a few GeV.
- Traditional 3D vertex fit upgraded to a 4D fit

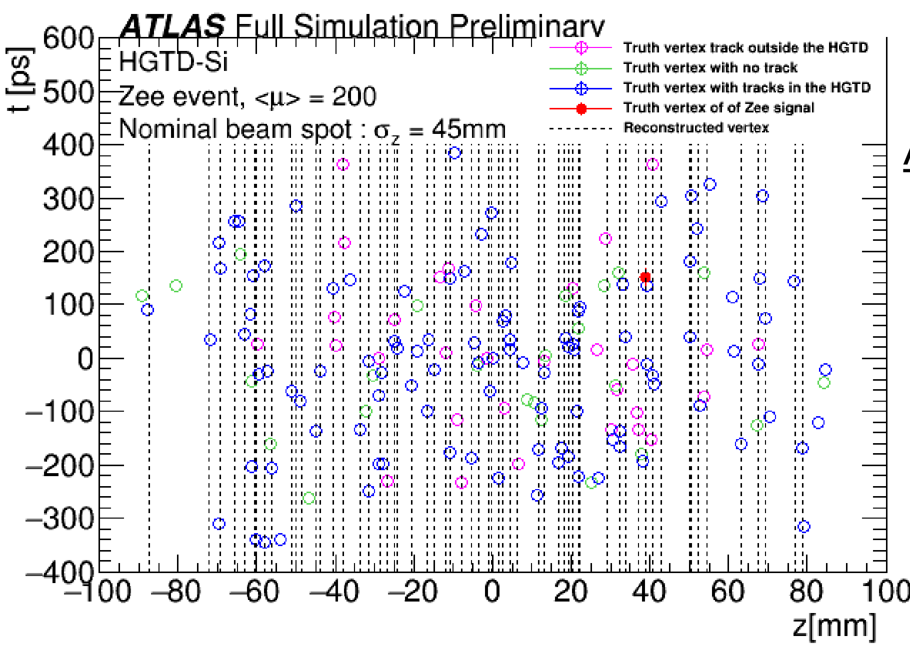
Fast Timing Upgrade: ATLAS

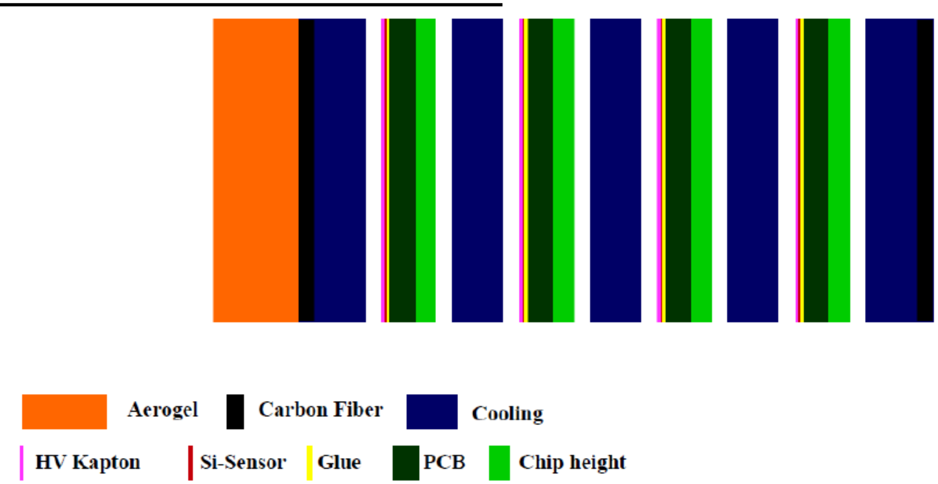
The **High Granularity Timing Detector (HGTD)** for ATLAS upgrade will be located just outside the ITK envelop at z~3500mm

- 120mm to 640mm in radius
- covers the forward region of **2.4<|η|<4.2**
- Consists of **four silicon layers**
  - 1.3mmx1.3mm silicon pads



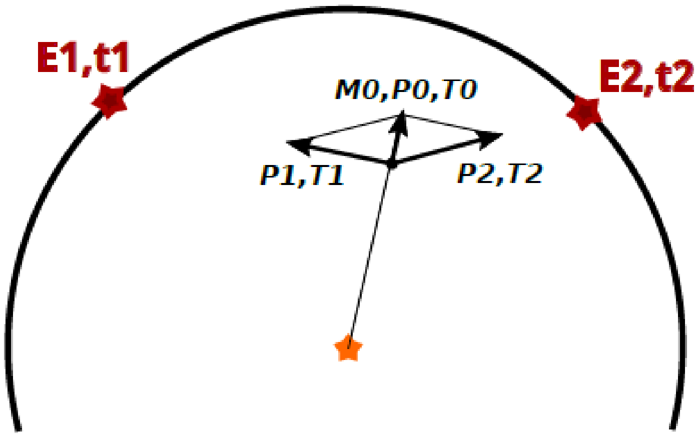
ATL-COM-LARG-2017-025



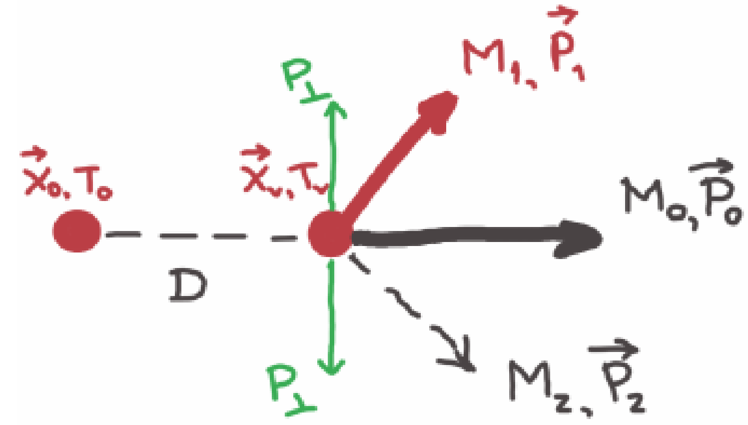


Timing Upgrade: LLP Prospects

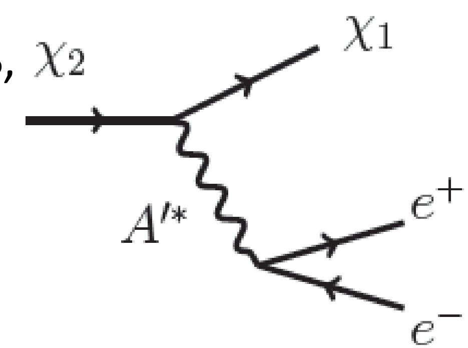
(Illustrations c/o A. Ledovskoy)



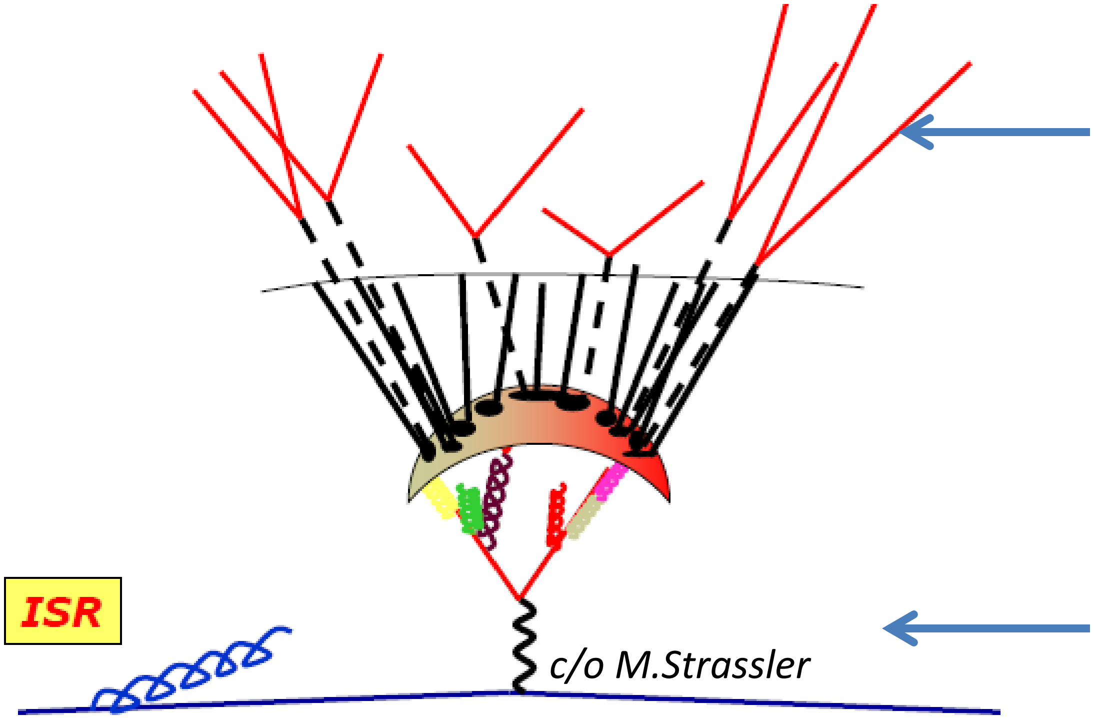
Scenario 1: Long-lived particle (neutral or charged) is produced at IP, & at secondary vertex (SV), decays into two observable particles (neutral or charged)
→With timing info (t1,2→T1,2; T0=T1=T2)
the scenario has unique solution for SV
→ full reconstruction!



Scenario 2: LLP decays to visible + invisible particles.
If the invisible particle mass is known + additional timing info → enough constraints for unique solution
→applicable for GMSB, iDM dark photon etc.



Experimental Challenge: Trigger



Trigger strategy B:
trigger on the decay final products (back to SM particles), e.g. jets, leptons, photons

<u>The two strategies can be combined in cross-triggers!</u>
(e.g. displaced photon search)

Trigger strategy A:
trigger on the new heavy particle(s) (e.g. HT) and/or its production process (e.g. ISR)

Many dark sector processes pose unique challenges for the trigger:
• the multitude and mass of new particles → more but softer final objects, esp. μ, γ
• the displacement of the decay inside the detector affects the efficiency of prompt triggers → ability to design displaced triggers?