Searches for Long-Lived Particles at ATLAS & CMS: An Overview

Yangyang Cheng

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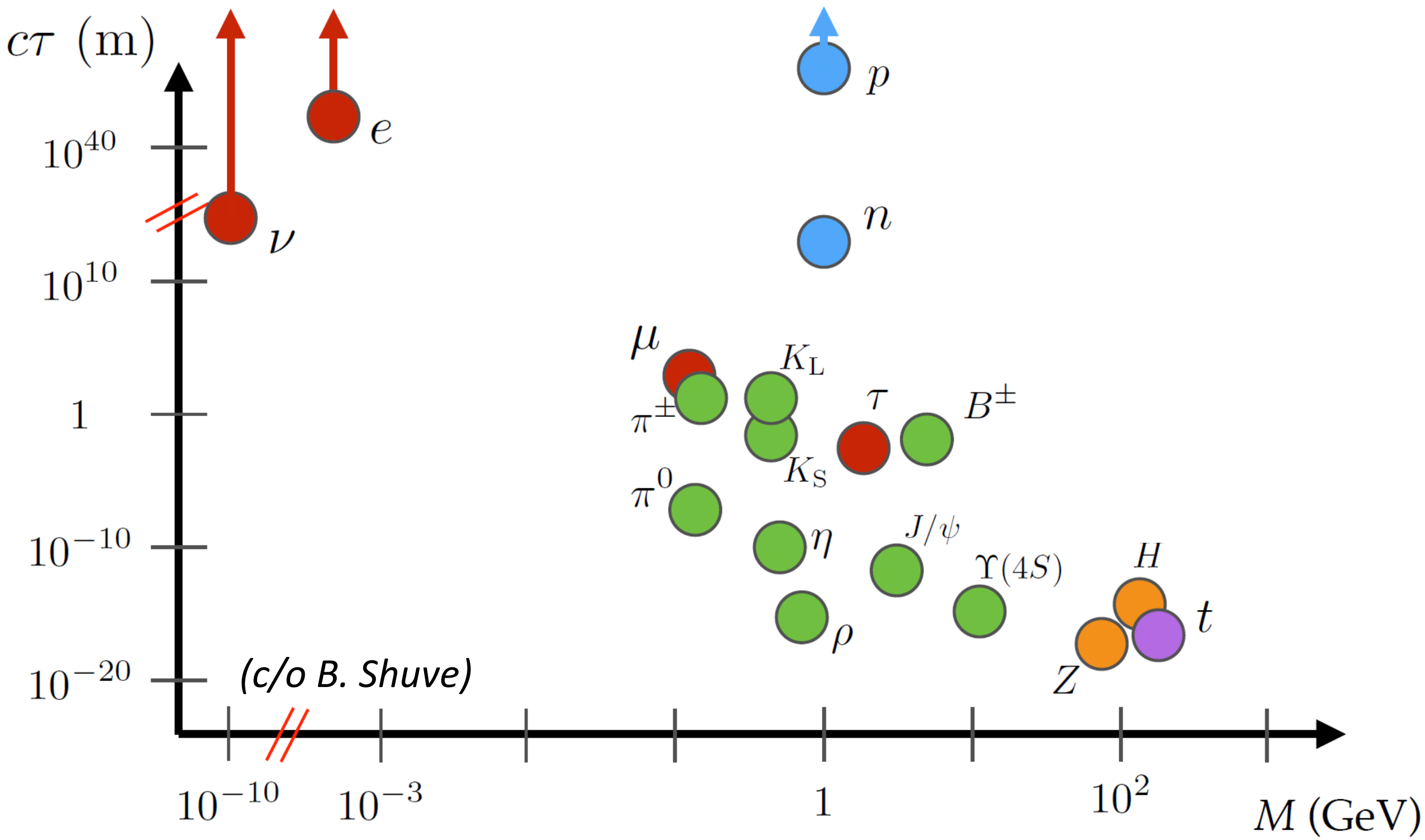
LLP Search: Physics Motivation

SM particles can be long(ish)-lived when the coupling is weak and/or the decay is suppressed. →



Same principles apply to BSM physics:
small couplings and no definite mass scale → <u>long-lived</u> particles (LLPs)!

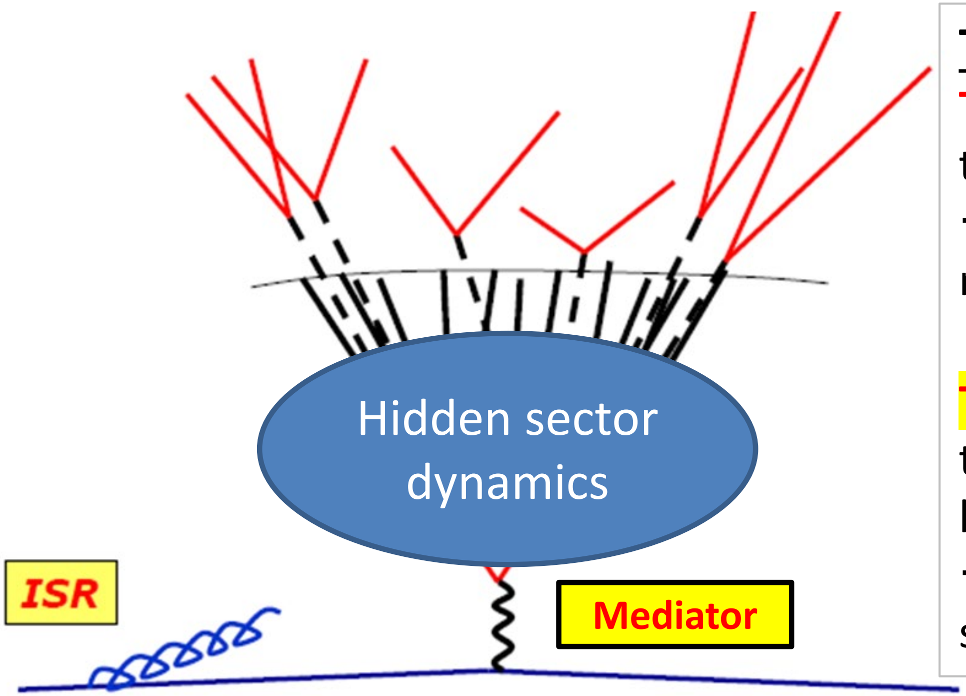
LLP Search: Experimental Challenges

Object reconstruction:

- Conventional reconstruction methods often do not work well for LLPs
- Standard methods to remove noise etc. often remove our signals
    - Increased vulnerability to background
- Rich final state: how to #CatchThemAll?

Background estimation:

- Particles do not point back to primary vertex:
    - detector center: LLPs from SM, pile-up,…
    - detector volume: conversion, …
    - outside detector: cosmics, beam gas, …
- Limits from detector acceptance & resolution



Triggering:

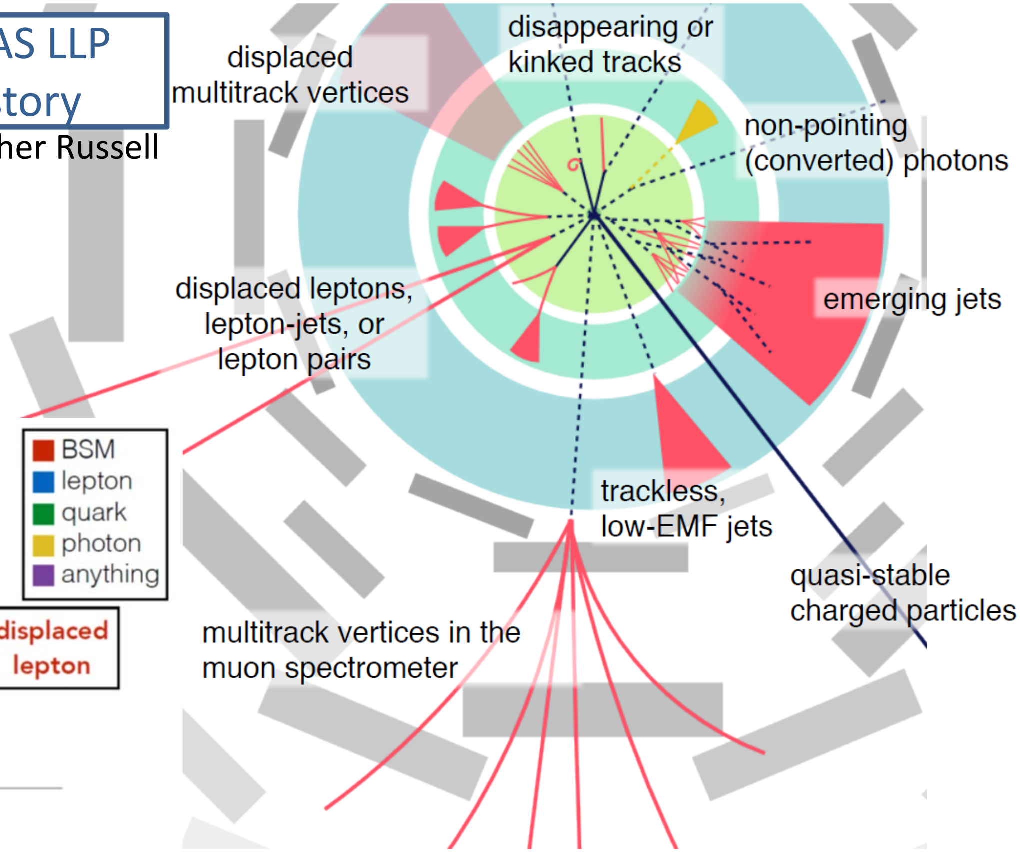
Trigger strategy B:
trigger on decay products
→ displaced objects, soft and/or with high multiplicity, are very difficult to trigger!

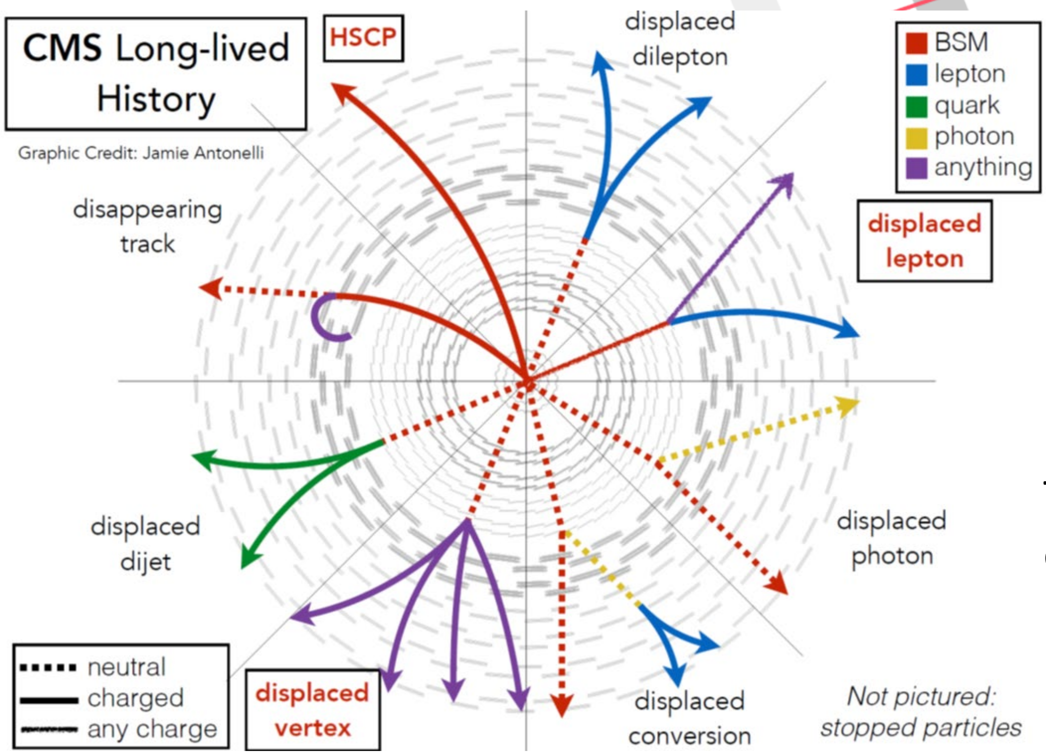
Trigger strategy A:
trigger on production process: ISR or new heavy particle(s) (e.g. HT)
→ high threshold leads to significant loss in signal efficiency

LLP Search: Experimental Landscape

A broad range of ***signature-driven*** LLP searches have been conducted at ATLAS & CMS experiments with LHC Run1 & Run2 data.

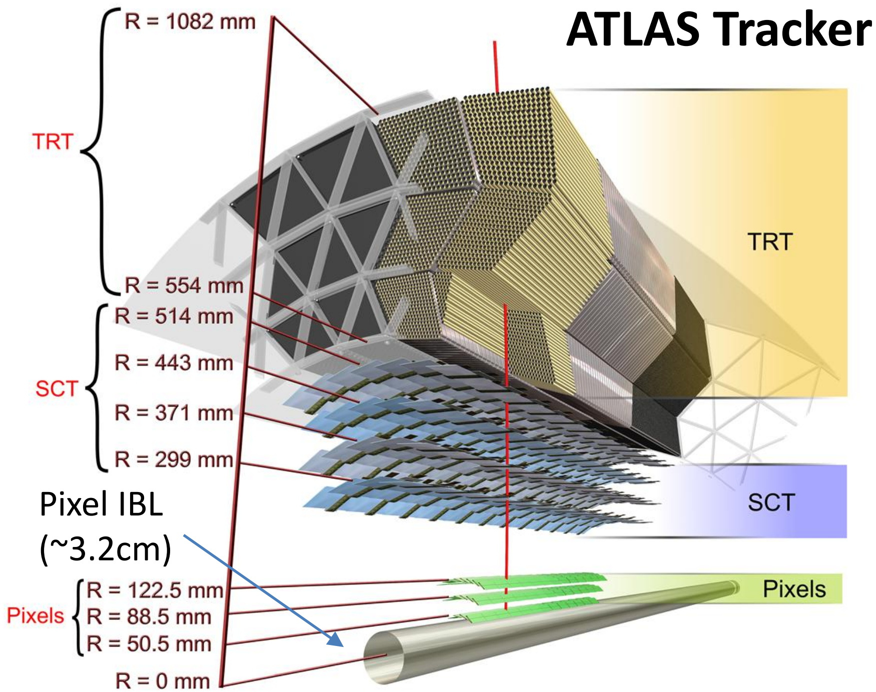
ATLAS LLP history
c/o Heather Russell

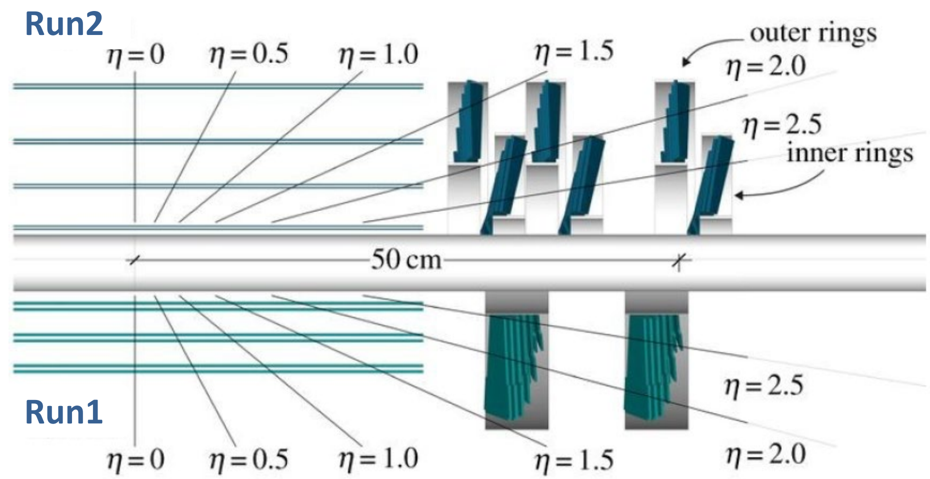


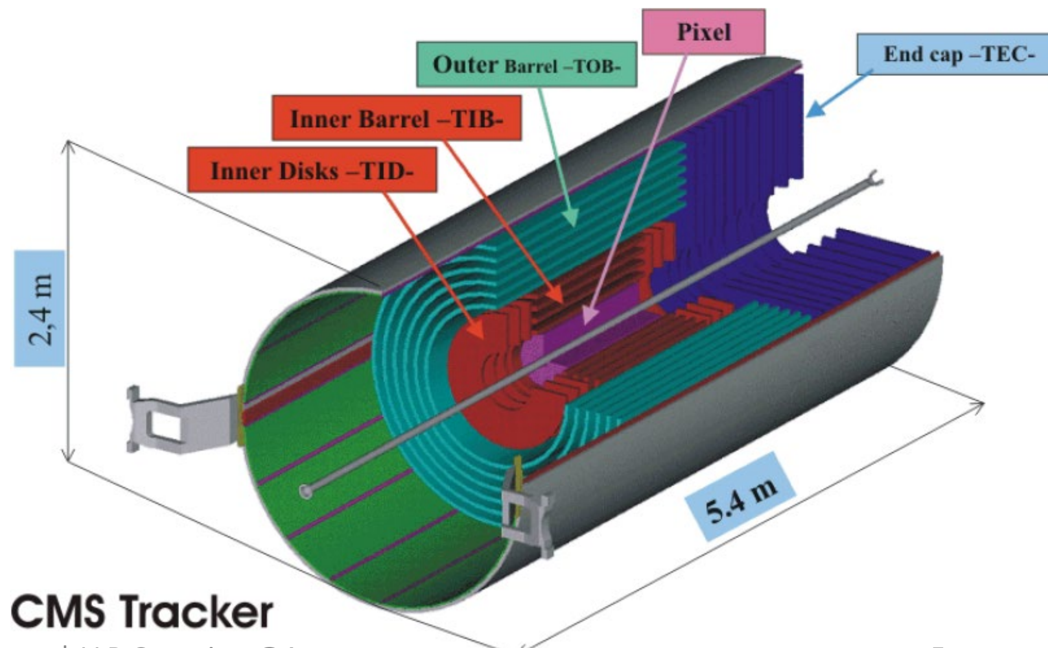


This overview talk will focus on the experimental signatures, trigger & reconstruction strategies, and (very briefly) HL-LHC prospects.

Displaced Decays in the Tracker







For LLPs that decay inside the tracking* volume, displaced vertices or disappearing/ kinked tracks may be reconstructed.

* Focus on inner detectors for now; cases with muons later.

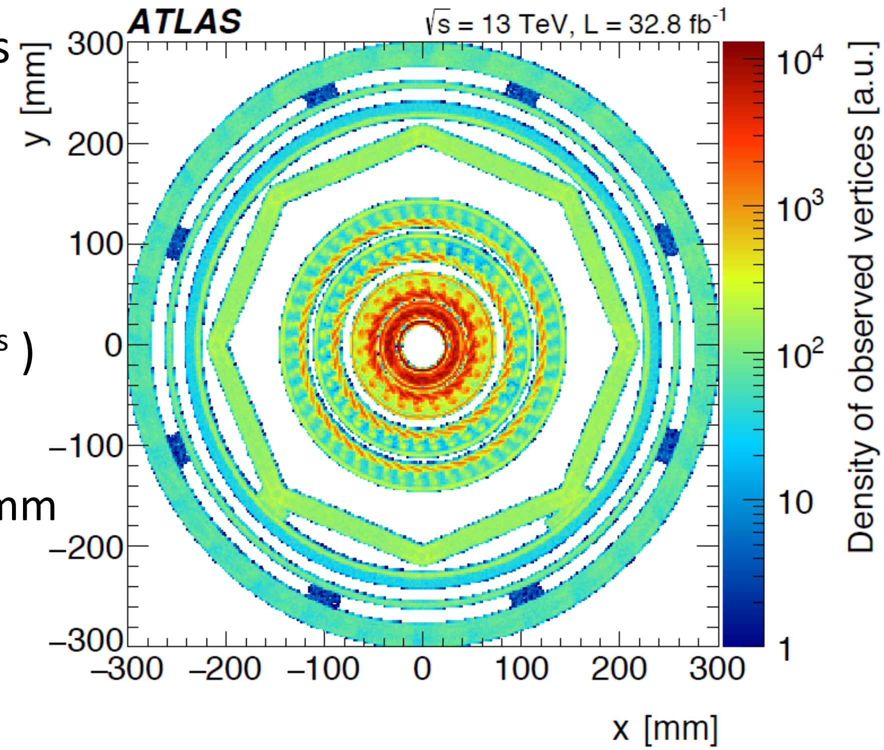
Displaced Vertices: ATLAS

arXiv:1710.04901
13 TeV 33 fb^{-1}
Run 2: DV+MET

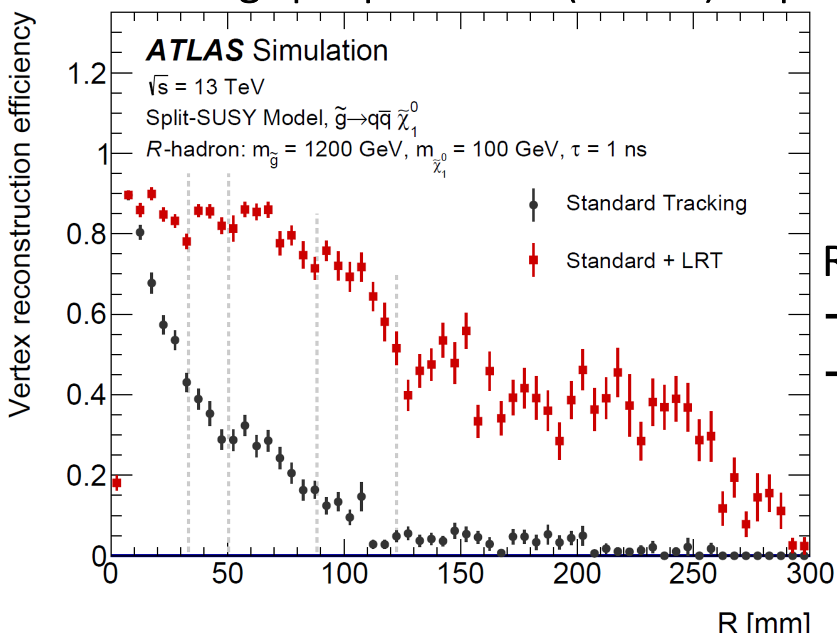
PRD 92 (2015) 072004
8 TeV 20.3 fb^{-1}
Run 1: DV+e/μ, DV+jets, DV+MET

Displaced hadronic decays with a multi-track vertex:

- Cannot trigger on DV
- Trigger on associated production of other particles (jet, e/μ, E_T^{miss})



Dedicated large-radius tracking (LRT) & secondary vertex finding: |d0|<300mm (>2mm) & |z0|<1500mm

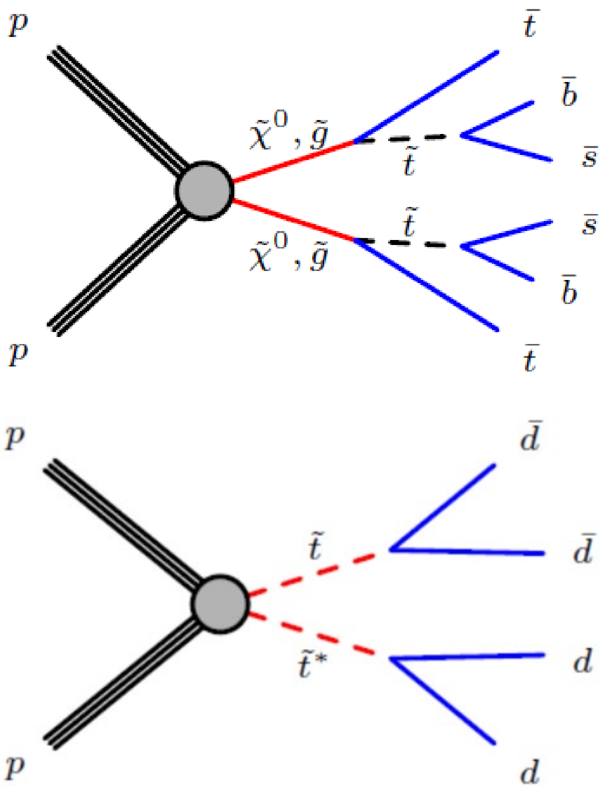


Requiring >=1DV w/ mass >10GeV & nTracks >=5,

→ Effectively remove SM backgrounds

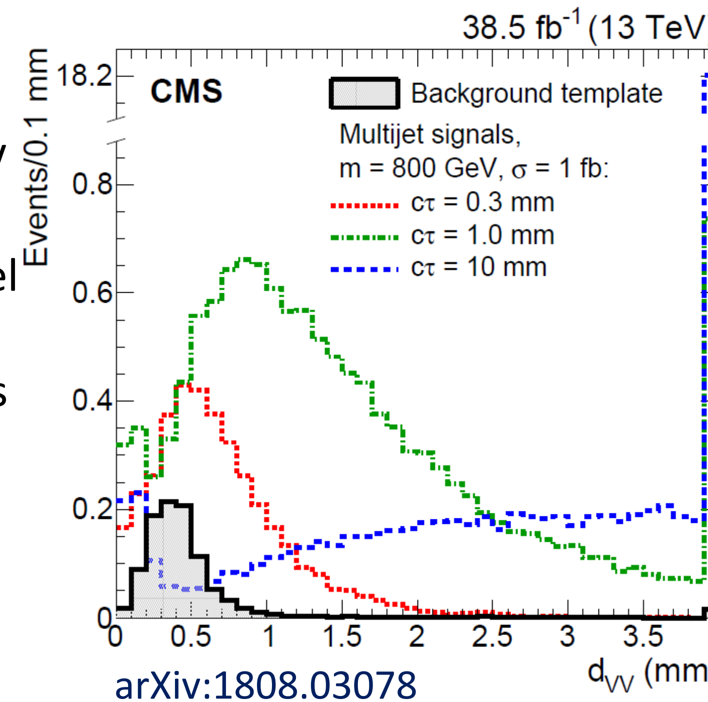
→ Irreducible background from hadronic interactions (lower mass & fewer tracks; apply material veto), merged vertices, & accidental crossings: data-driven estimation

Displaced Vertices: CMS



Hadronic LLP decays in dijet & multijet channels

- HT trigger: 800 (900) GeV
- >=2 DVs, each >=5 tracks
  - hit in innermost pixel
- dVV: distance in xy between the two vertices with highest mass & number of tracks
- Fit dVV templates for signal & background, binned by displacement
- Main background: multijet & tt, esp. with b's



arXiv:1808.03078

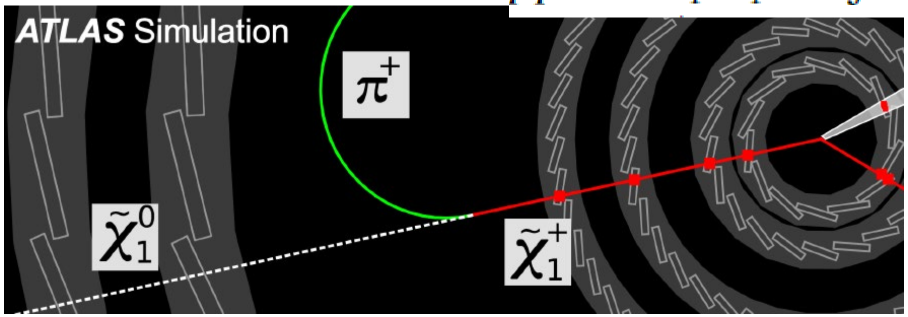
d_{VV} range	Fitted background yield	Observed	Predicted multijet signal yields 0.3 mm	1.0 mm	10 mm
0–0.4 mm	0.51 ± 0.01 (stat) ± 0.13 (syst)	1	2.8 ± 0.7	3.5 ± 0.8	1.0 ± 0.2
0.4–0.7 mm	0.37 ± 0.02 (stat) ± 0.09 (syst)	0	2.0 ± 0.5	3.7 ± 0.9	0.5 ± 0.1
0.7–40 mm	0.12 ± 0.02 (stat) ± 0.08 (syst)	0	1.1 ± 0.3	11 ± 3	31 ± 7

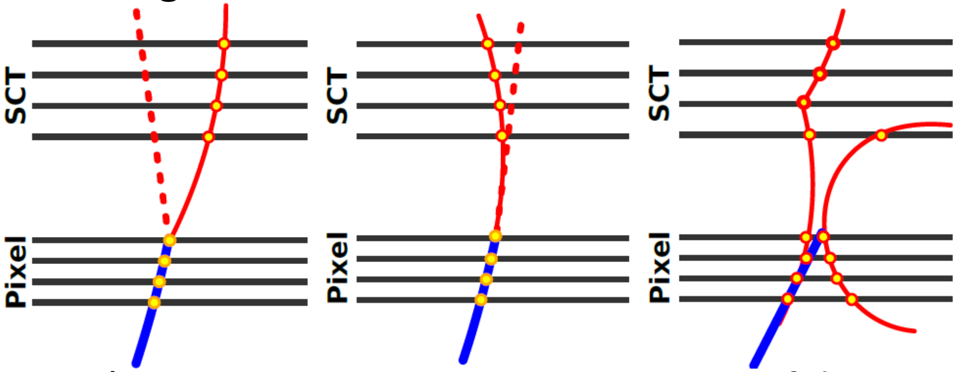
Disappearing Tracks: ATLAS

Charged particle with lifetime 0.01ns – 10ns decays to invisible particle + soft charged particle:

- Trigger on E_T^{miss}
- Two search channels
  - electroweak: ISR jet + E_T^{miss}
  - strong: multijet + E_T^{miss}
- "Disappearing" tracklet reconstruction
  - hits in each of the first four pixel layers
  - no hits in the SCT layers
  - isolated; pT > 20 GeV
- Backgrounds:

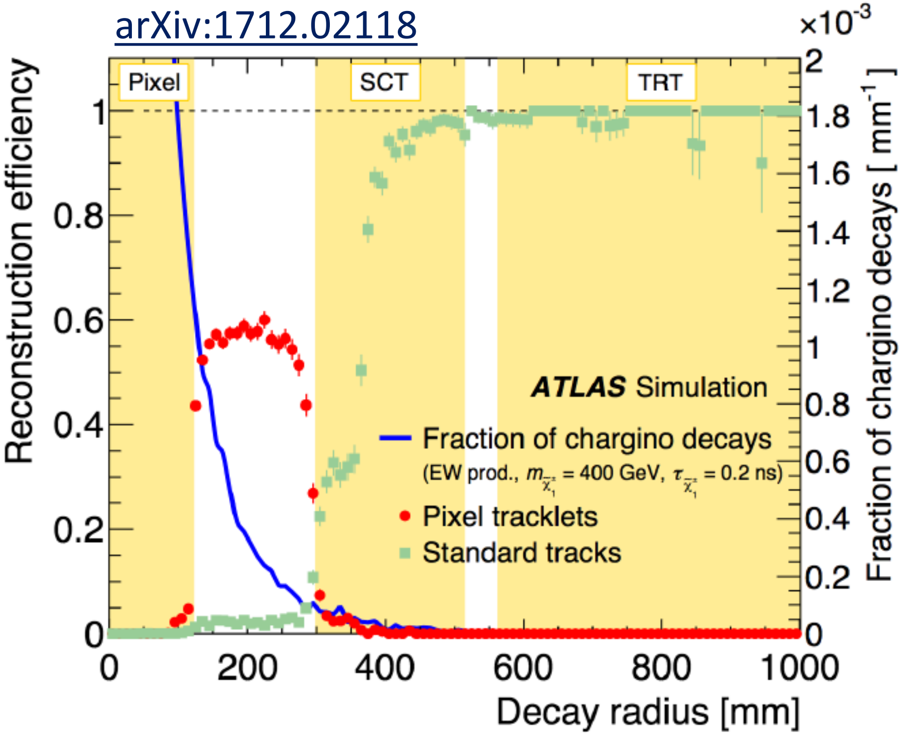
$pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- + \text{jet}$





Hadronic interaction | Lepton emitting hard photon | fake tracklet

arXiv:1712.02118

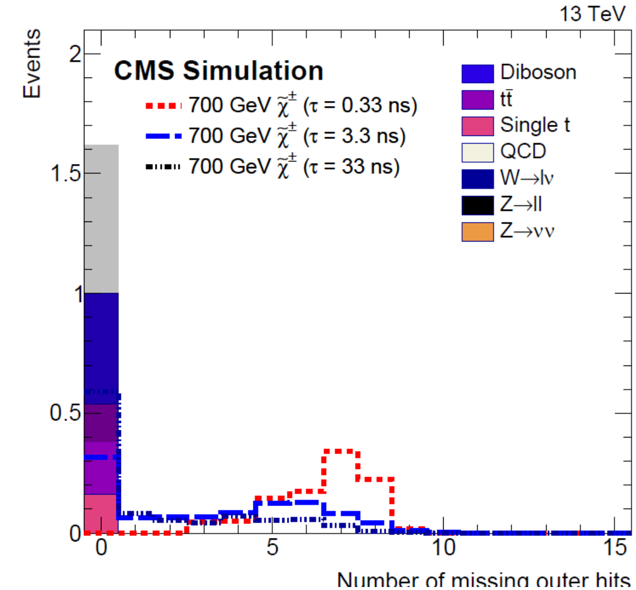


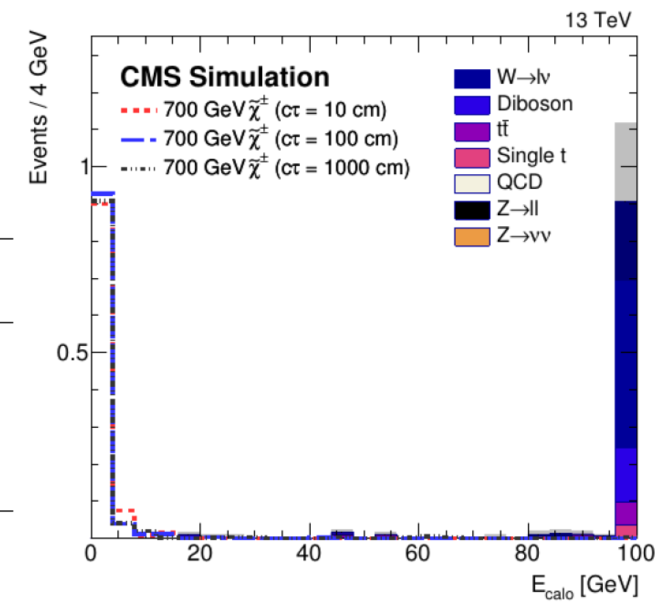
Disappearing Tracks: CMS

- Signal lifetime: 0.1ns – 100ns
- Trigger: p_T^{miss} >100GeV
- Disappearing track reconstruction:
    - isolated >55GeV track, originating from IP
    - missing >=3 outer tracker hits
    - associated calorimetry energy (dR<0.5) < 10GeV
- Main backgrounds:
    - Charged leptons
    → lepton veto
    - Spurious tracks
    → estimated from data in large d0 sideband

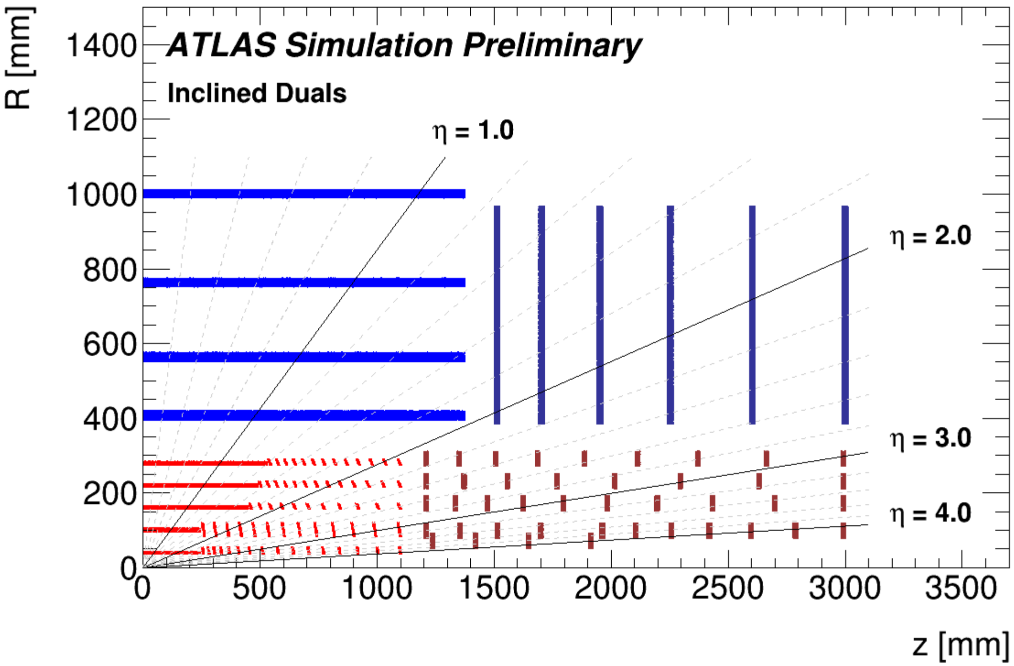
arXiv:1804.07321

Run period	Estimated number of background events: Leptons	Spurious tracks	Total	Observed events
2015	0.1 ± 0.1	$0^{+0.1}_{-0}$	0.1 ± 0.1	1
2016A	$2.0 \pm 0.4 \pm 0.1$	$0.4 \pm 0.2 \pm 0.4$	$2.4 \pm 0.5 \pm 0.4$	2
2016B	$3.1 \pm 0.6 \pm 0.2$	$0.9 \pm 0.4 \pm 0.9$	$4.0 \pm 0.7 \pm 0.9$	4
Total	$5.2 \pm 0.8 \pm 0.3$	$1.3 \pm 0.4 \pm 1.0$	$6.5 \pm 0.9 \pm 1.0$	7





Tracker Upgrade: HL-LHC Prospects



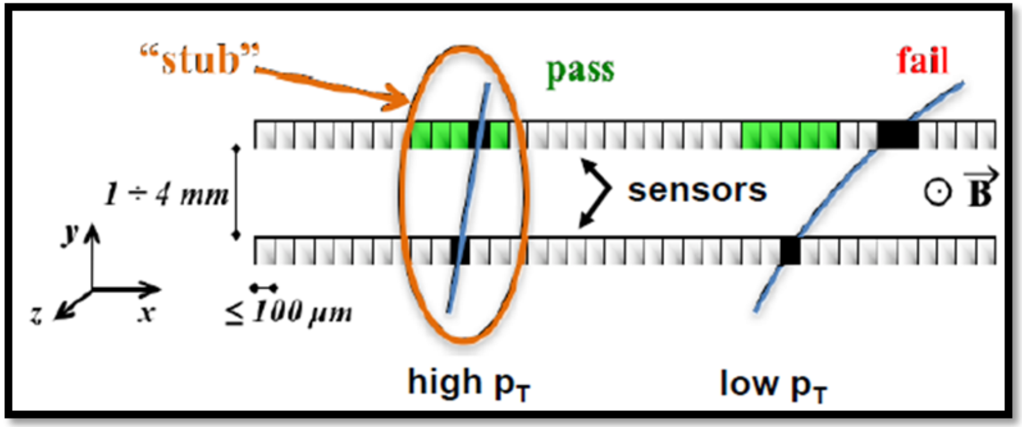
Both ATLAS & CMS trackers will be fully replaced for HL-LHC conditions

- high granularity & radiation hard
- extended |η|~4
- tracking @ L1 hardware trigger
- CMS: inner pixel + outer tracker w/ 2-sided sensor modules (PS or SS)
- ATLAS: inner pixel + outer strip tracker (silicon based; no more TRT)

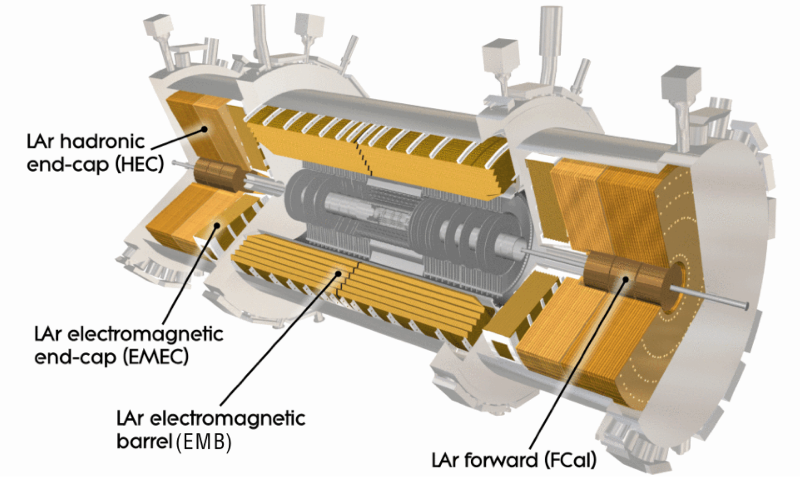
CMS L1 track trigger (L1TT)

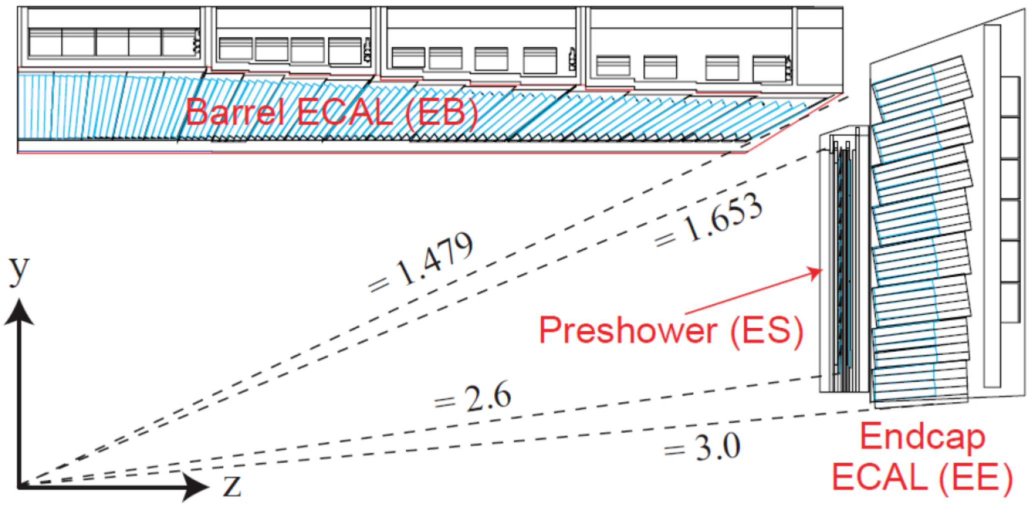
• Two-sided sensor modules in OT
→stubs: correlated hit pairs, consistent with >=2GeV track

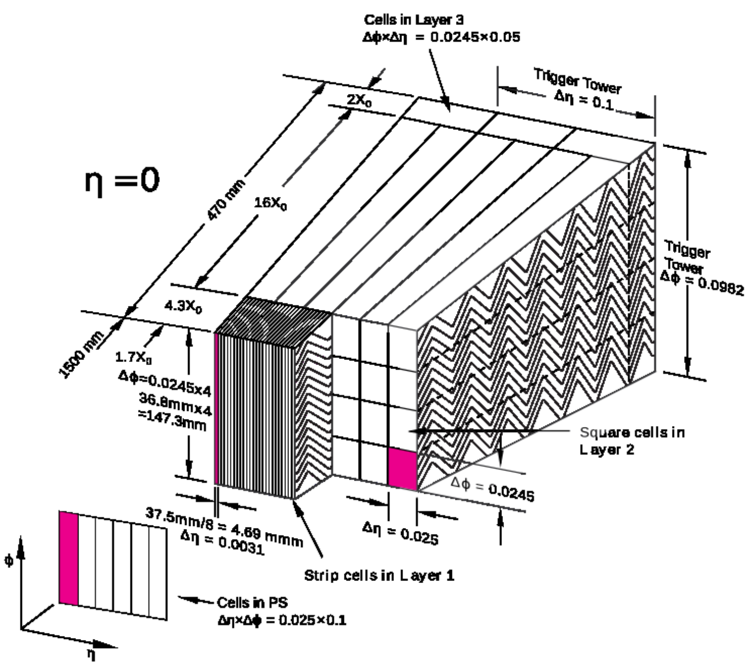
• Stubs form input to track finding at L1 trigger rate of 750kHz



Displaced Decays with the ECAL

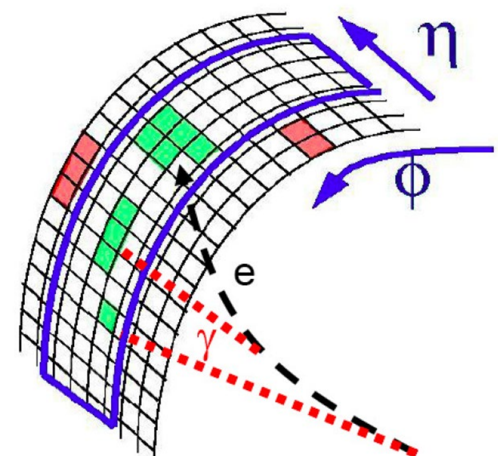






← ATLAS liquid argon calorimeter

CMS ECAL →
(lead tungstate crystal)



Displaced Photons: ATLAS

Search for neutral LLP (350ps-100ns) decay to photon + invisible particle

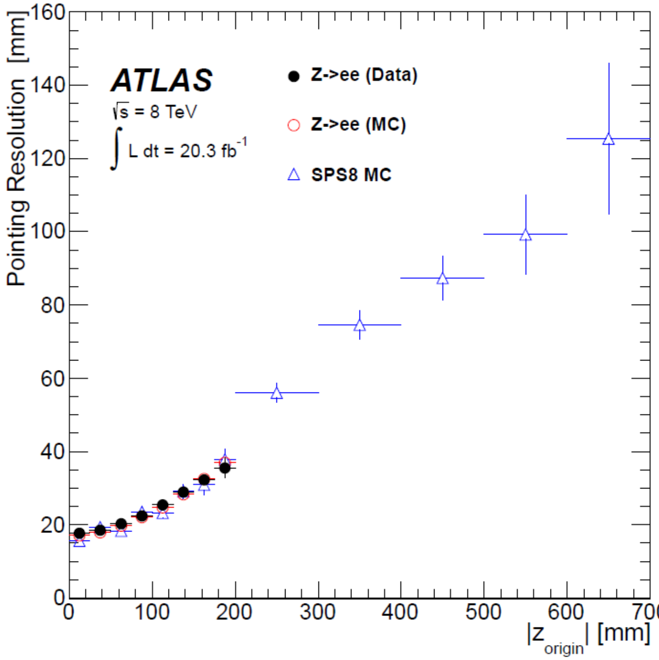
- Trigger: diphoton, >35(25)GeV, no timing constraint
- Offline:
  - diphoton, >50GeV
  - |t|<4ns to remove satellite bunches

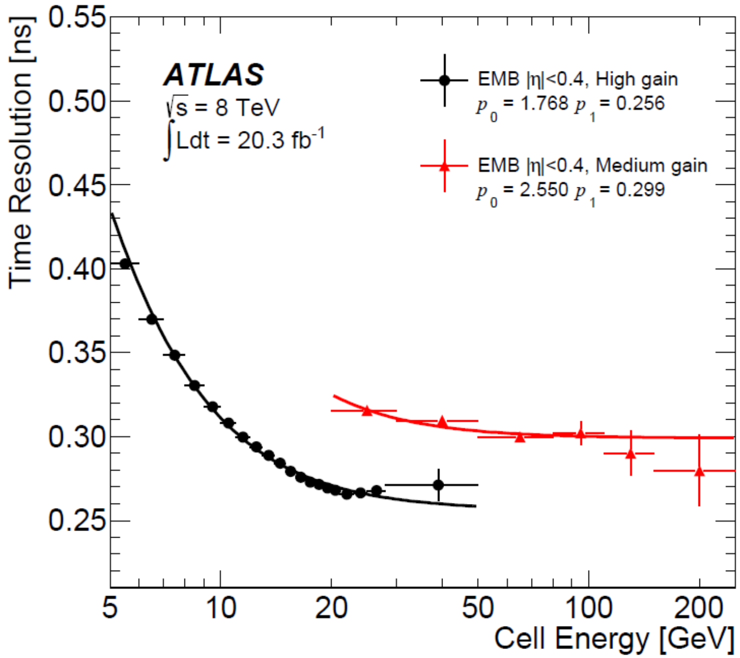
ATLAS LAr ECAL provides both photon direction & time measurements

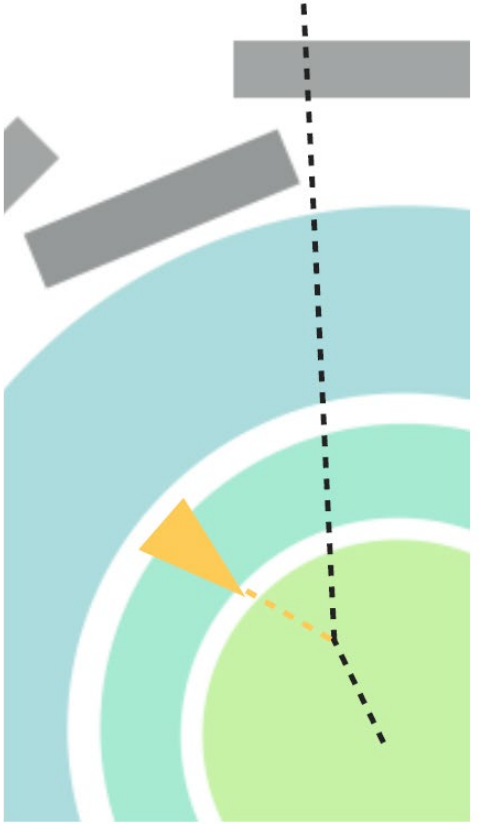
→ 8TeV analysis uses both pointing & timing (7TeV only used pointing)

→ data-driven Nx1D fit: in bins of |Z|, 1D fit of photon time

PRD 90 (2014) 112005
8 TeV 20.3 fb^{-1}
Run 1: di-photon + MET Final State

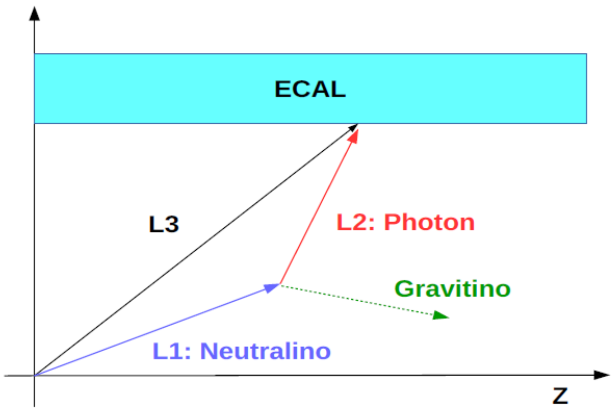


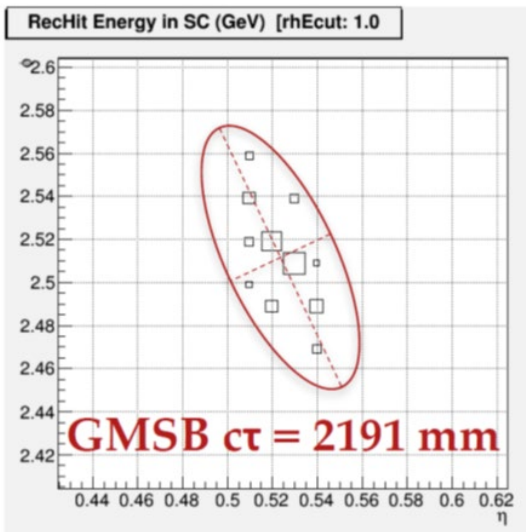




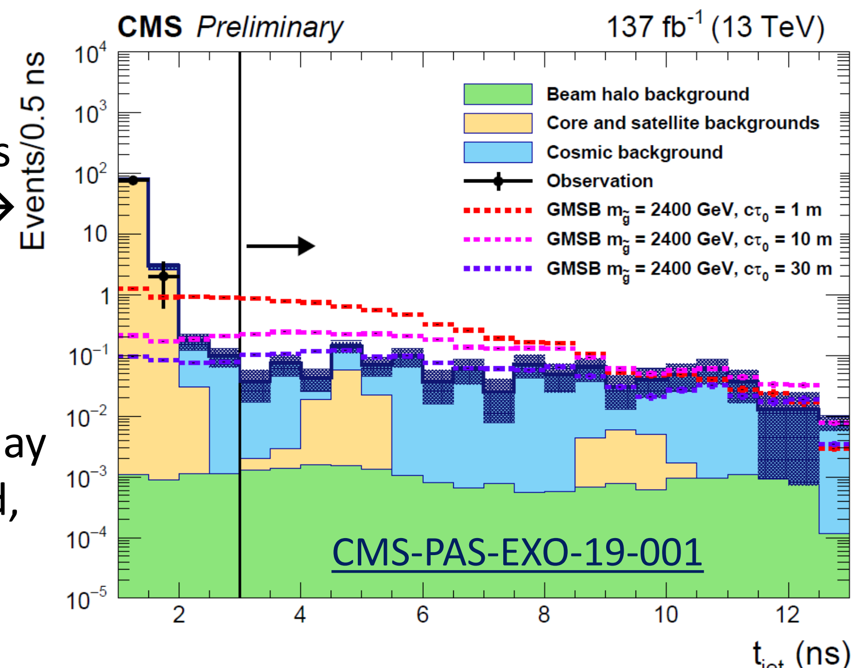
Delayed Photon/ Jets: CMS

CMS ECAL: good timing & energy resolution but no pointing
For Run2 displaced photon search, include ECAL cluster shape information in the trigger & OOT photon reconstruction:
OOT photon cluster shapes more elliptical than prompt photons
Trigger: single displaced photon (>60GeV+shape) + HT (>350GeV)
OOT photon reco: OOT seed + photon energy, shape, iso etc.
Signal selection: >=1 tightly-ID OOT photon, >=3 jets, HT>400GeV
Data-driven background fitted in 2D of vs photon time



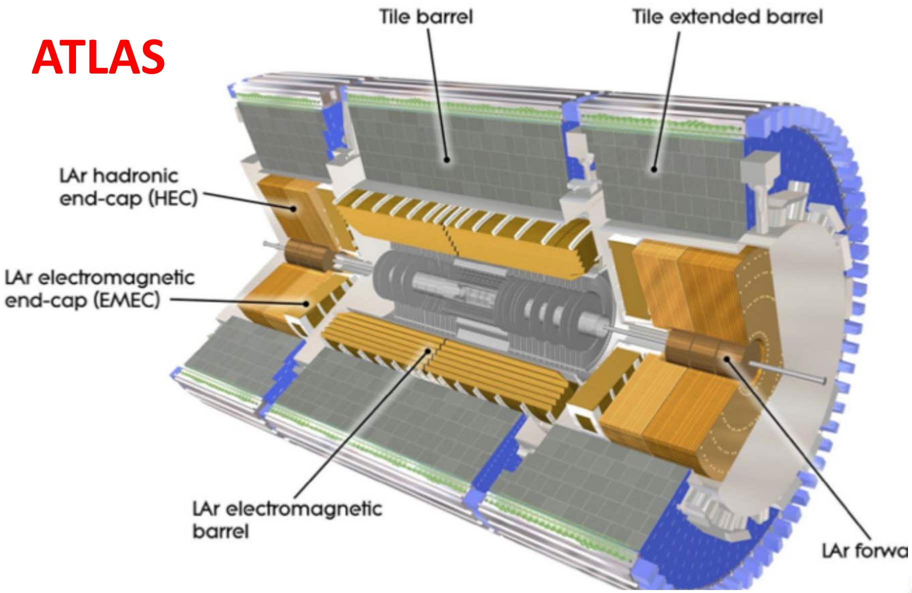


New delayed jet search with ECAL timing (~200ps resolution for >50GeV) →
Trigger: E_T^{miss} >120GeV
Signal selection:
E_T^{miss} >300GeV
jets: pT >30GeV, time delay >3ns & small time spread, large HCAL fraction

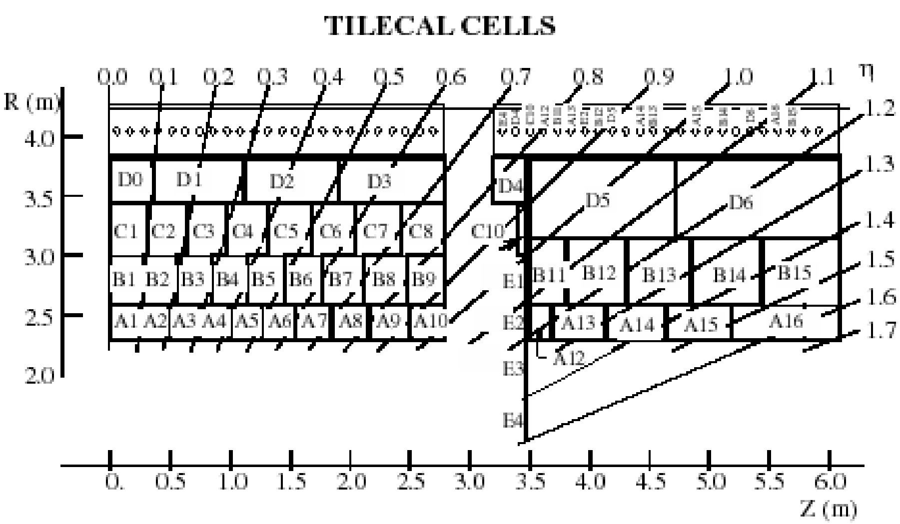


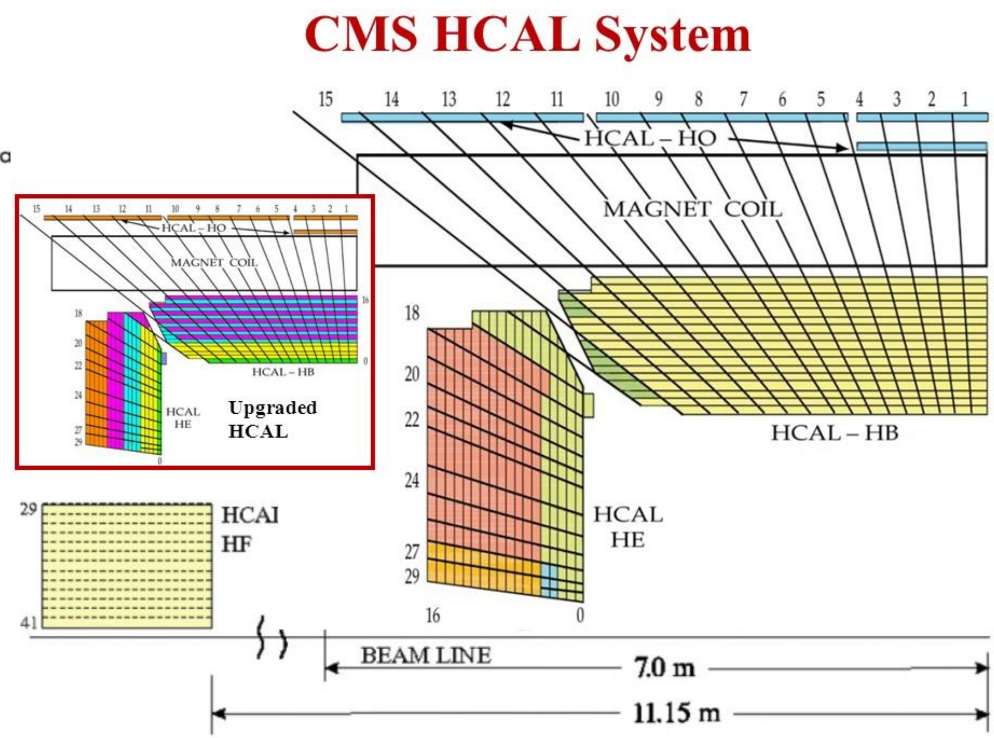
Displaced Decays with the HCAL

ATLAS

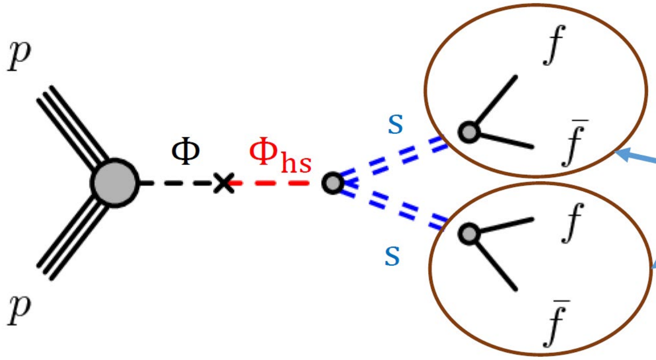


ATLAS & CMS experiments have hadronic calorimetry with different materials and designs.
→ Searches for non-prompt jets at both experiments take advantage of the HCAL designs in triggering and reconstruction.





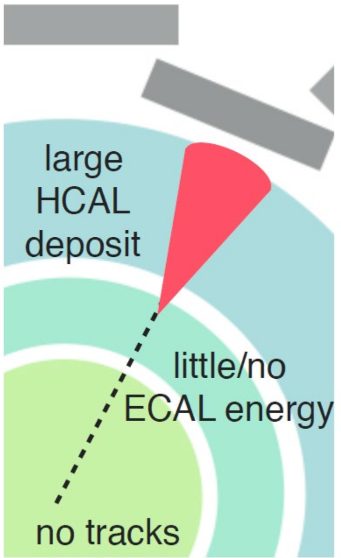
Displaced Jets: ATLAS



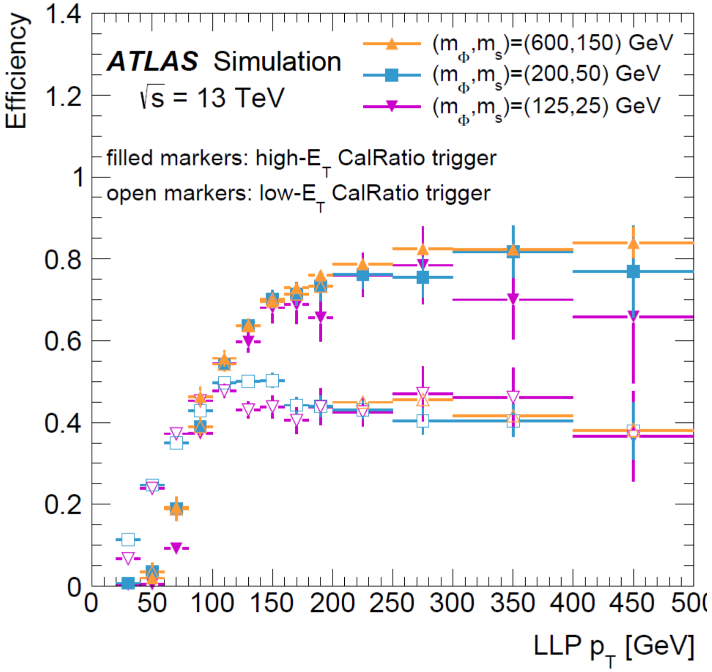
Narrow, trackless jets that appear in the HCAL (or on edge of ECAL)

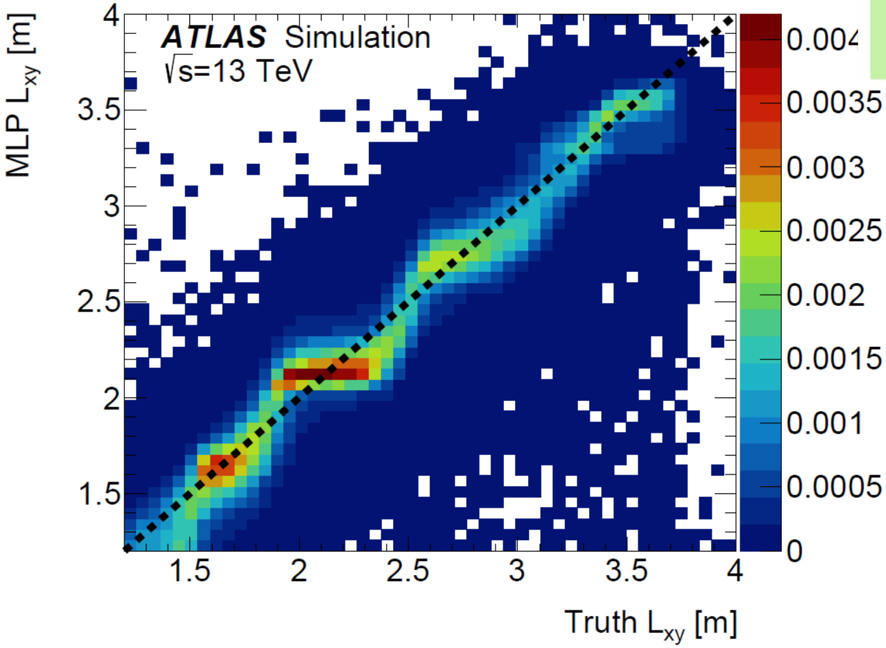
- "CalRatio" trigger: >60(30)GeV
- Multi-Layer Perceptron (MLP):

MVA to determine jet decay position from energy deposits in each ECAL & HCAL layer; trained on signal, multi-jet background, beam-induced background



arXiv:1902.03094

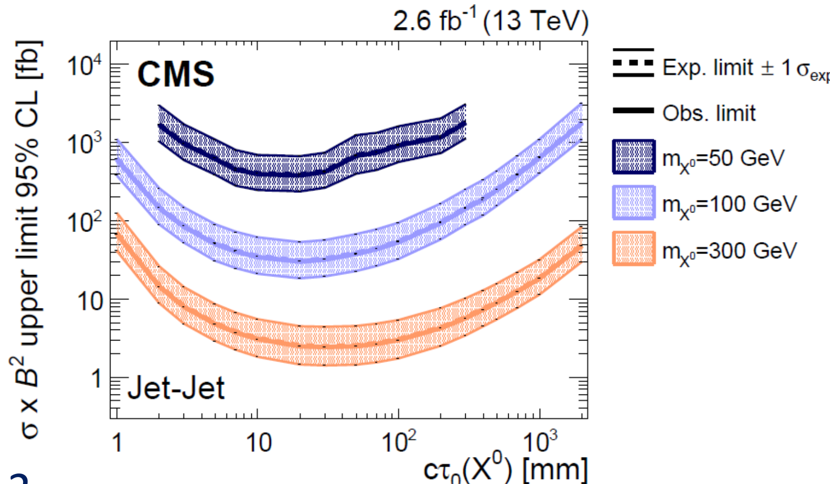




← Good prediction with visible effect from calorimetry layers

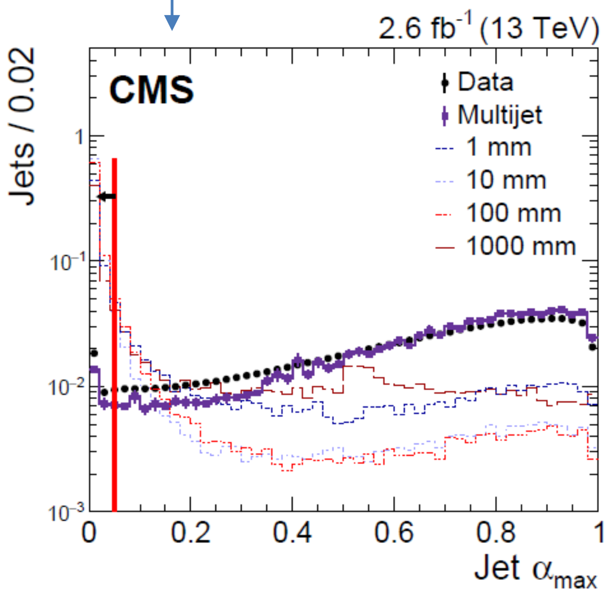
Inclusive Displaced Jets: CMS

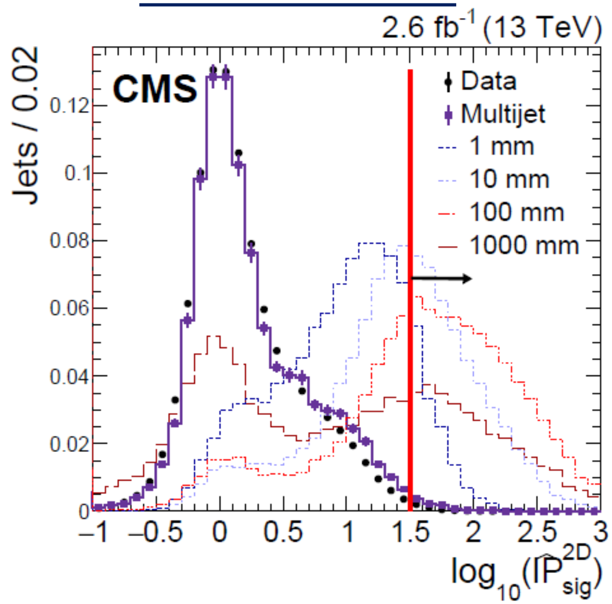
- Trigger: >=2 jets w/ pT>40GeV; HT>500GeV
- Displaced jet tagging:
  - based on PV compatibility, displacement significance, & emission angle (track, parent)
  - tag ==2 or >=3 jets
- Inclusive final state with no lepton veto

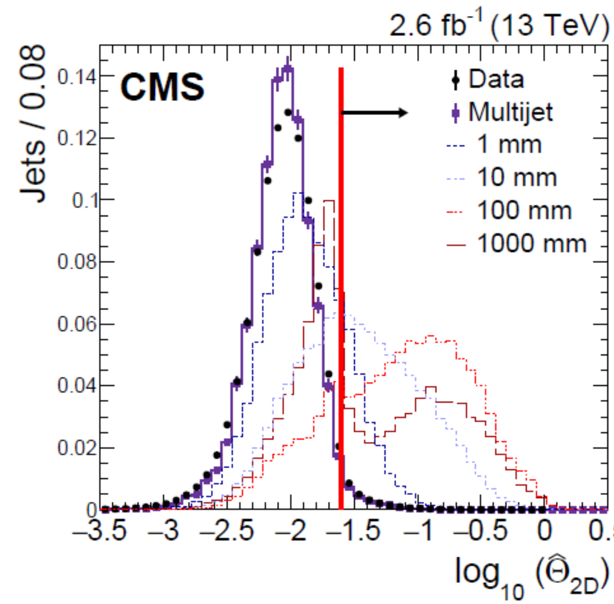


$$\alpha_{\rm jet}({\rm PV}) = \frac{\sum_{{\rm tracks} \in {\rm PV}} p_{\rm T}^{\rm tracks}}{\sum_{\rm tracks} p_{\rm T}^{\rm tracks}}$$

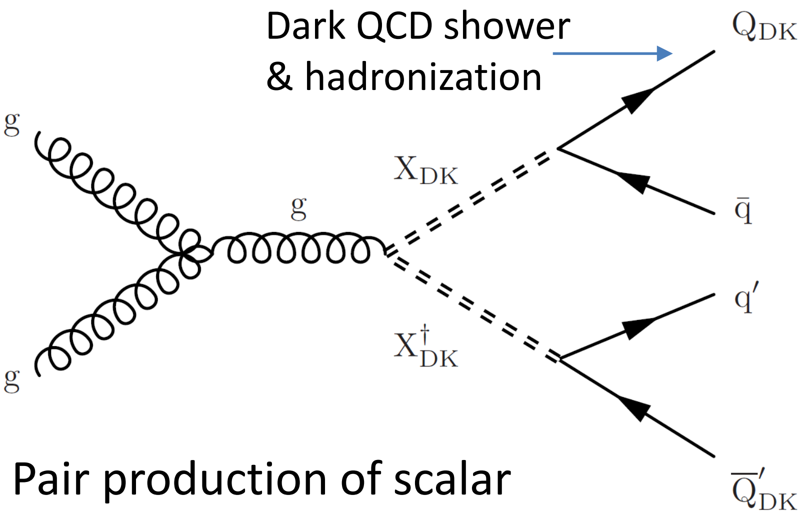
arXiv:1711.0912







Emerging Jets: CMS



Trigger: HT>900GeV

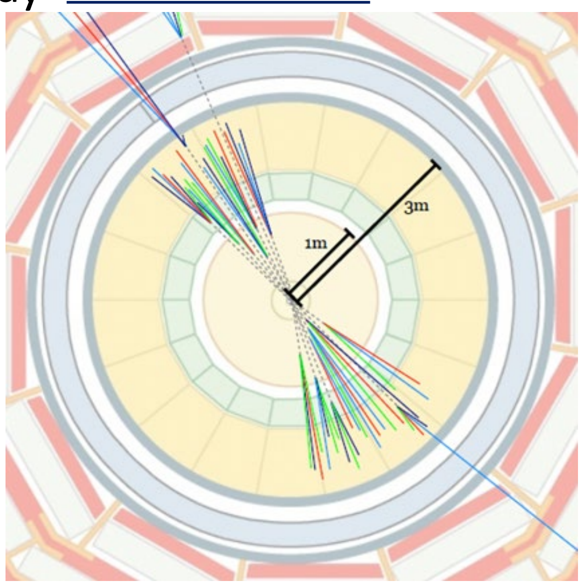
Signal selection: 4 jets passing pT & HT cuts; of which 2 "emerging" jets or 1 "emerging" jet + large P_T^{miss}

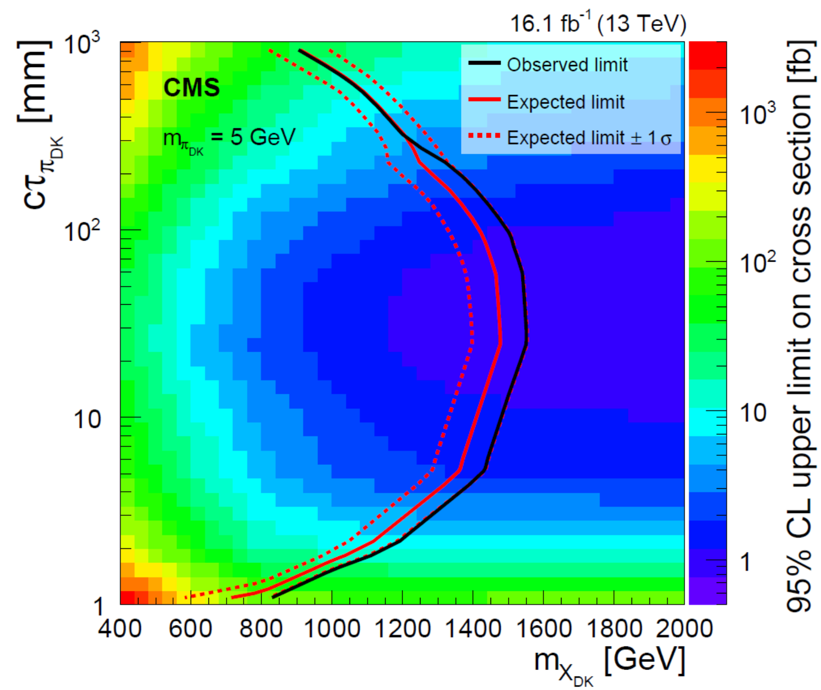
- "Emerging" jets: tracks w/ large impact parameters & less jet pT associated w/ prompt tracks

Background: SM four-jet process with B's and/or significant pT mismeasurement (fake P_T^{miss})

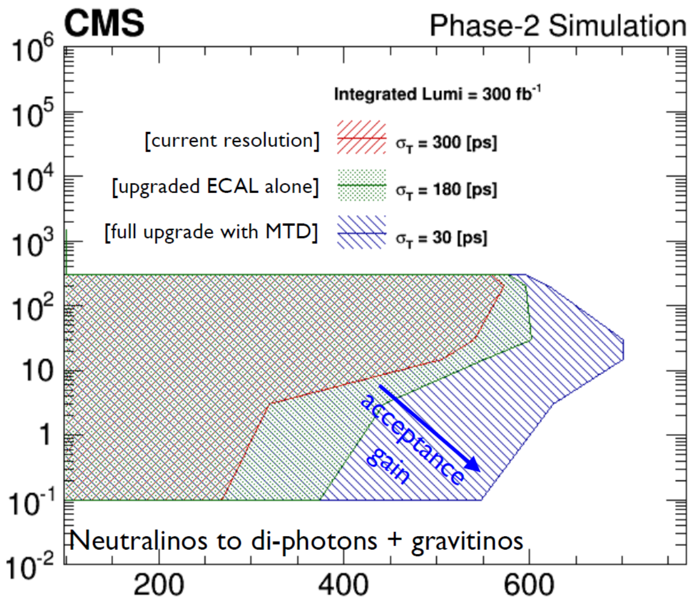
Pair production of scalar mediators X, each decay to q-dark & q pairs
→ two QCD jets, two emerging* jets
* few tracks starting at a distance

arXiv:1810.10069

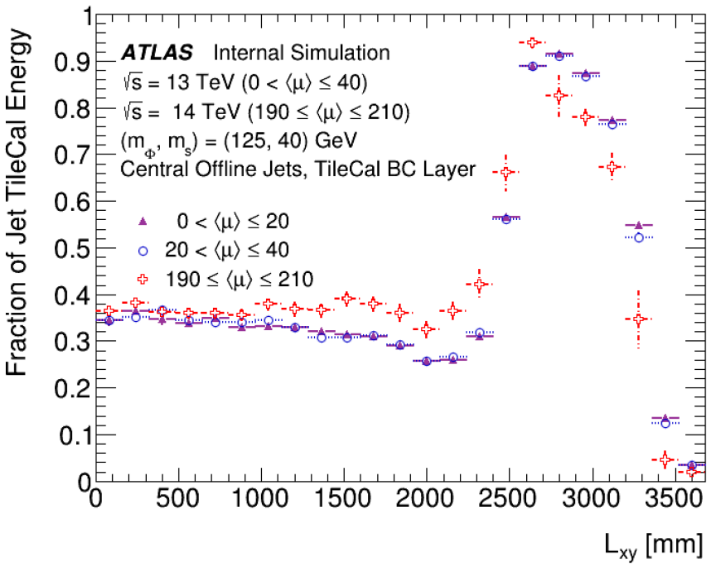




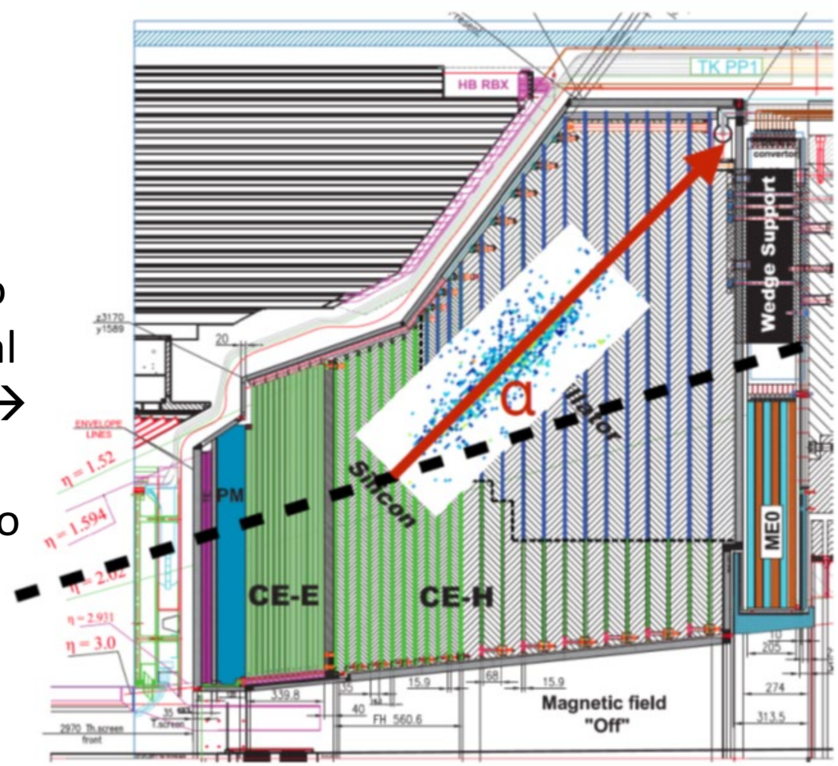
Calorimetry Upgrade: HL-LHC Prospects



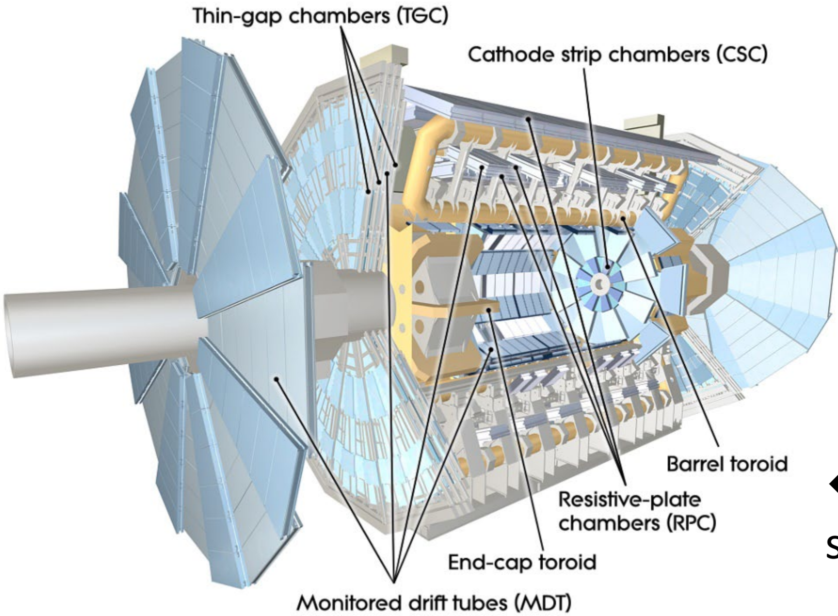
- Calorimeter upgrades (ECAL electronics + HGCAL) at CMS will provide precise timing (10s of ps) for high energy photons in barrel + high energy hadrons/photons in endcap
- MIP Timing Detector (MTD) outside tracker volume at CMS, can provide precision timing (~30ps) for charged hadrons & converted photons down to a few GeV.

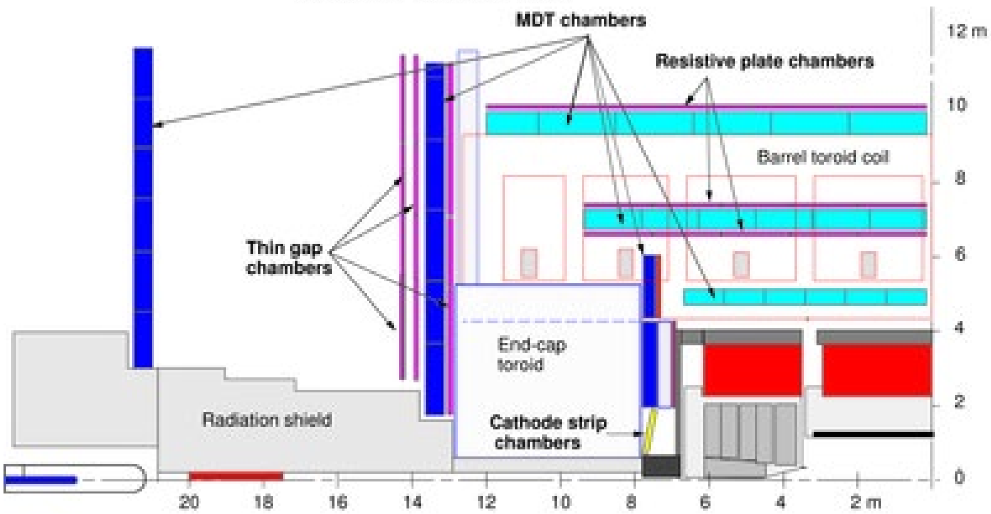


Additional spacial segmentation info ← at ATLAS TileCal and CMS HGCAL → can provide shower profile info in triggering & identifying LLP hadronic decays.

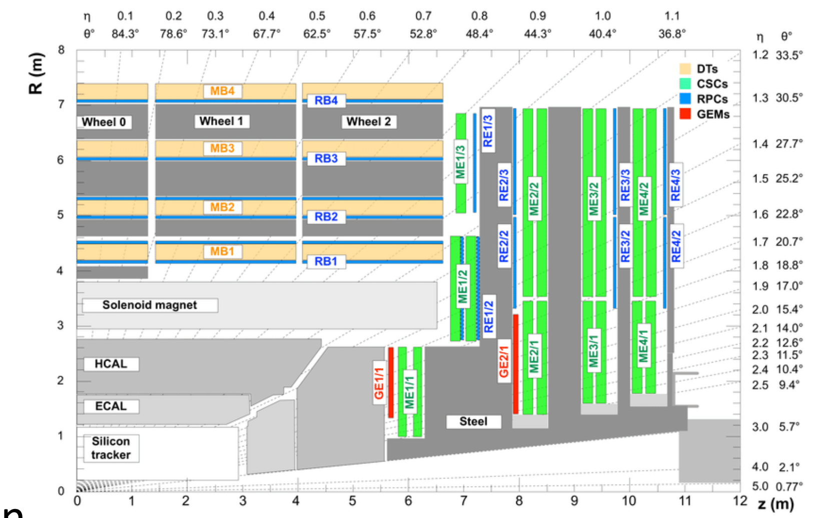


Displaced Decays with Muon System

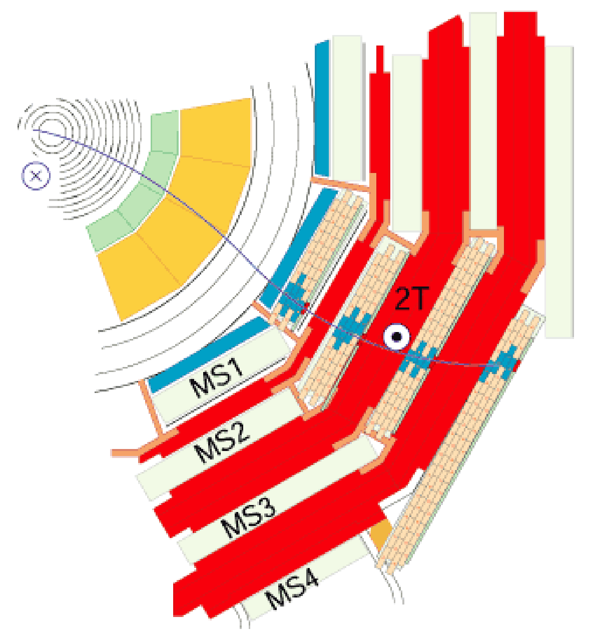




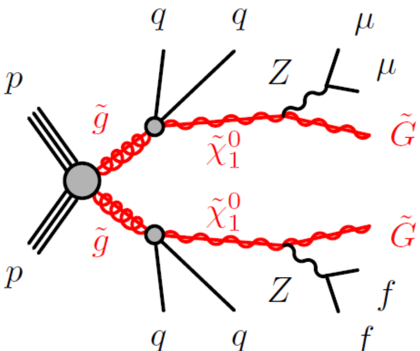
← ATLAS muon system



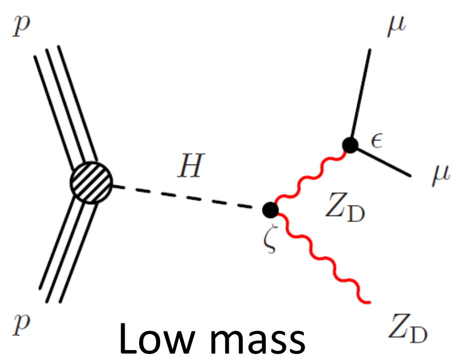
CMS muon system →



Displaced Muons: ATLAS



High mass

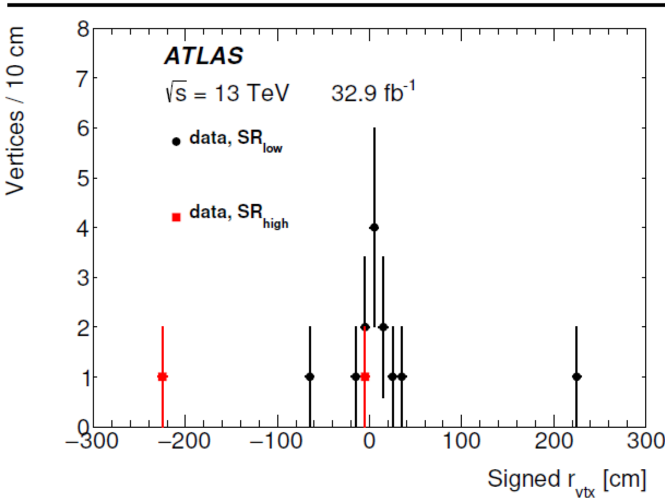


Low mass

- Opposite-sign muons with vertex up to 4m from interaction point
- Two search regions: high & low mass
- Muon reconstruction: starting from MS tracks and extrapolate to IP; small displacement matched to ID tracks

Signal type	Trigger	Description	Thresholds
High mass	E_T^{miss} *or* single muon	missing transverse momentum single muon restricted to the barrel region	$E_T^{miss} > 110$ GeV muon $\lvert\eta\rvert < 1.05$ and $p_T > 60$ GeV
Low mass	collimated dimuon trimuon	two muons with small angular separation three muons	p_T of muons > 15 and 20 GeV and $\Delta R_{\mu\mu} < 0.5$ $p_T > 6$ GeV for all three muons

arXiv:1808.03057



All muon candidates (MS-only or matched to tracks) form muon pairs → extrapolate from MS to find vertex

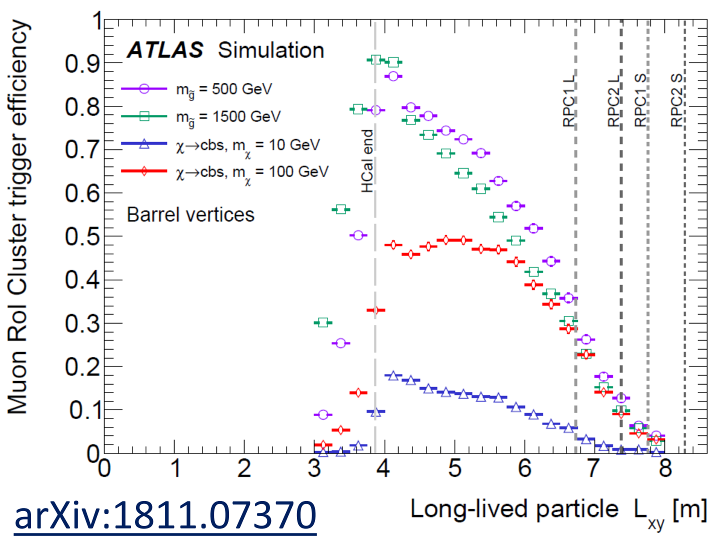
→ angular separation > 0.1, vertex position |r|<4m & |z|<6m

→ dimuon mass > 15GeV to remove conversion & multijet

→ Background estimated from same- & opposite- sign dimuon CRs in data for prompt & non-prompt muons

Displaced Muon Vertices: ATLAS

LLP hadronic decays with vertices between end of HCAL & start of 2nd muon station
Trigger: cluster of three (four) muon ROIs in the barrel (endcaps) within dR<0.4; no tracking or calo requirements



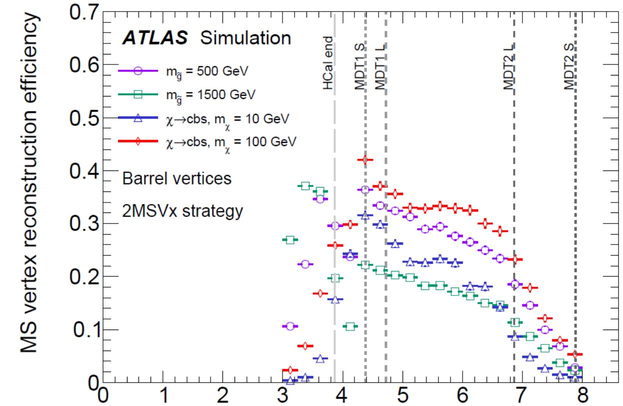
arXiv:1811.07370

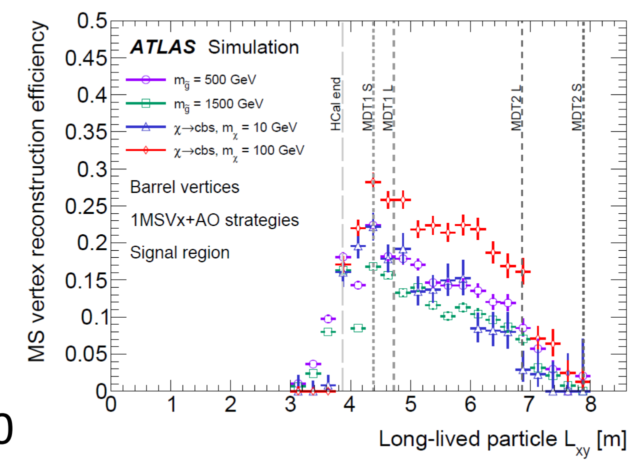
Two strategies:

- >=2 DV
- 1DV + associated objects

Vertex reconstruction uses tracklets from multilayer MDT hits

Backgrounds: punch-through jets & non-collision



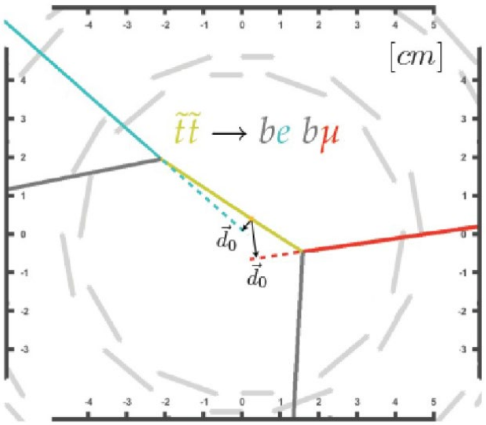


expected <1, observed 0

2MSVx	At least 2 MS vertices	
1MSVx+Jets	Exactly 1 MS vertex At least 2 jets with $E_T > 150$ GeV	
1MSVx+E_T^{miss}	Exactly 1 MS vertex $E_T^{miss} > 30$ GeV	

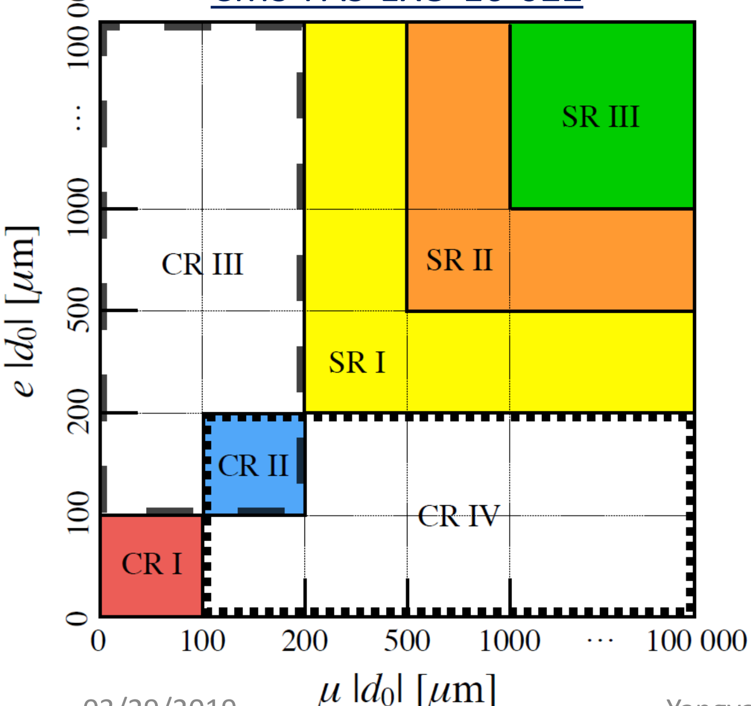
Region	A	Expected background	B	C	D
Barrel	14	15 ± 3 (stat.) ± 3 (syst.)	2,057	25	3,414
Endcaps	4	11 ± 3 (stat.) ± 9 (syst.)	560	15	761
Barrel	224	243 ± 38 (stat.) ± 29 (syst.)	42	132,000	22,800
Endcaps	489	497 ± 51 (stat.) ± 30 (syst.)	94	165,800	31,390

Displaced Muons: CMS



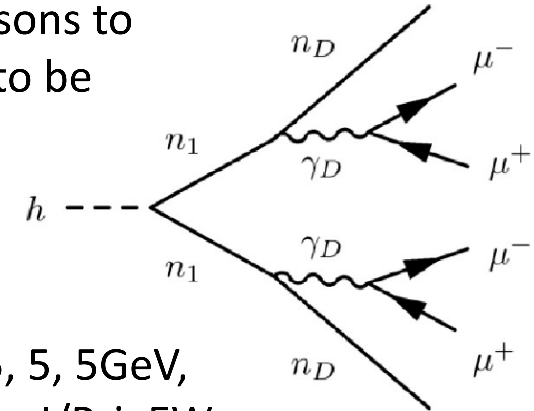
← Single displaced leptons not from the same vertex; focused on e-mu state

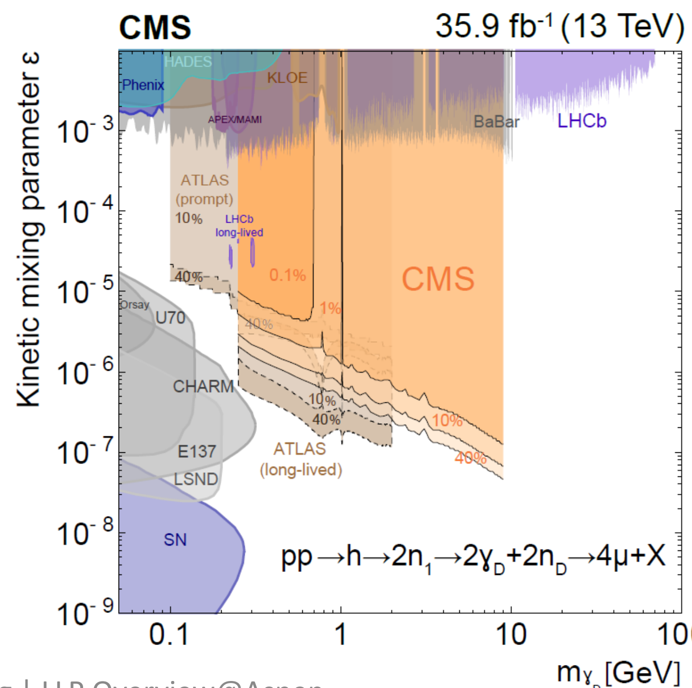
CMS-PAS-EXO-16-022



Higgs decay to light bosons to muon pairs: extended to be sensitive to small displacement (inside pixel volume): dxy<9.8cm, dz<46.5cm

- Tri-muon trigger: 15, 5, 5GeV,
- Backgrounds: bb-bar, J/Psi, EW

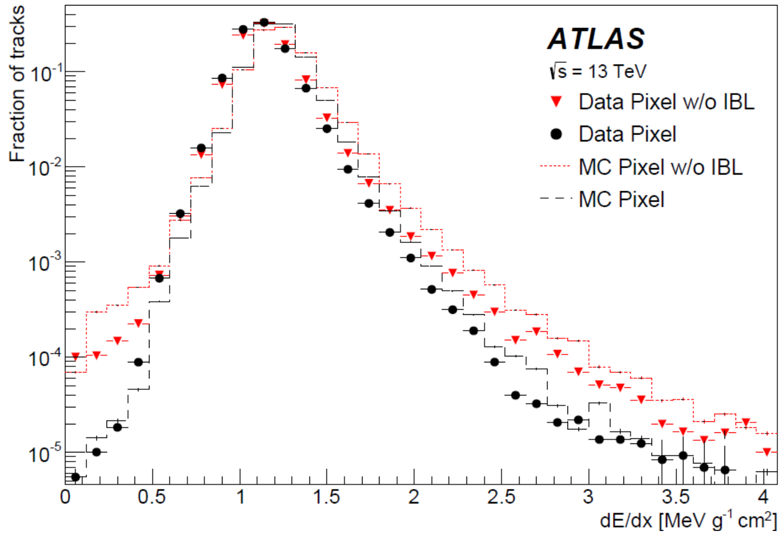




arXiv:1812.00380

Additional CMS Run2 analysis-in-progress on displaced dimuon/ lepton jets …

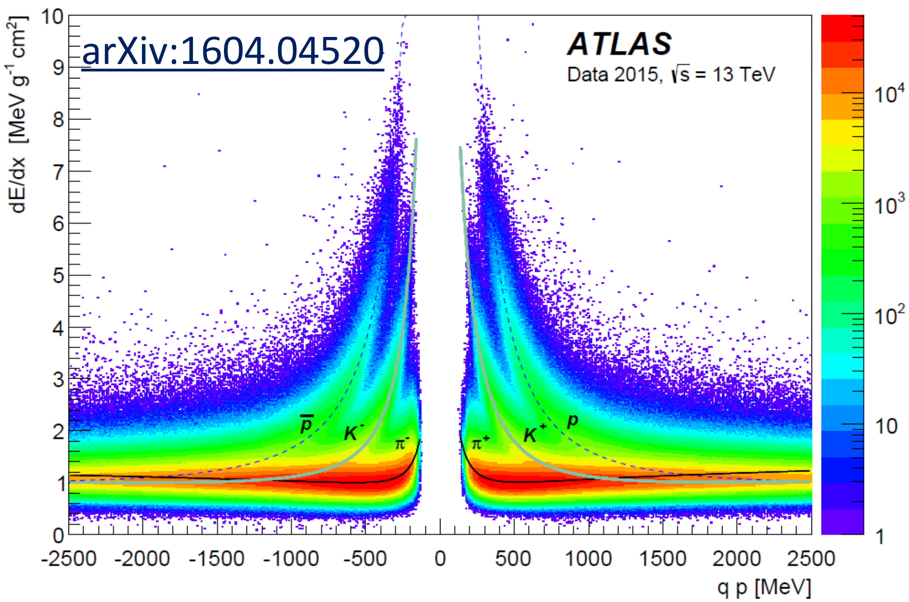
Heavy Stable Charged Particle: ATLAS



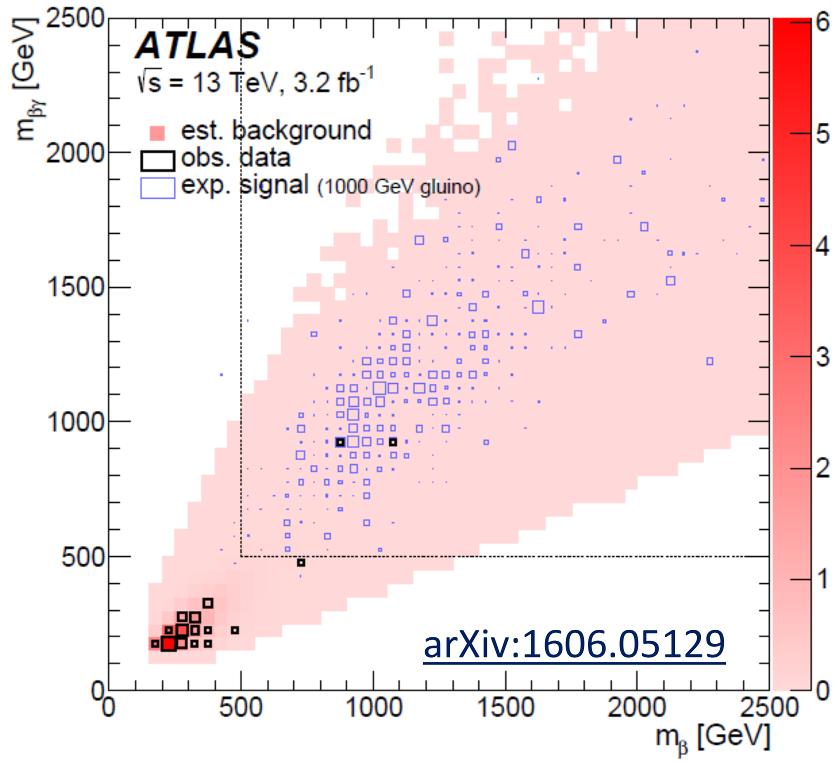
← ATLAS pixel detector dE/dx measurement improves with IBL: reduces tails at both low & high ends

Highly-ionizing, slow-moving heavy particles can be identified at ATLAS with dE/dx from tracker and TileCal time of flight: 1.3-2.5ns timing resolution; σ(β)~0.1

- Muon TBA



arXiv:1604.04520



arXiv:1606.05129

HSCP & Stopped LLPs: CMS

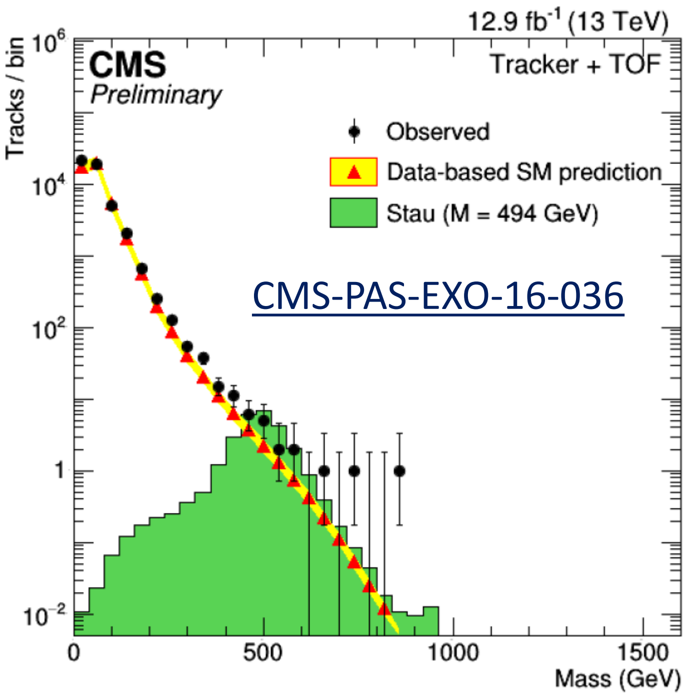
Searches for HSCP on CMS uses dE/dx measurement in the inner tracker & time-of-flight in the muon system

Two strategies:

- tracker-only
- tracker + TOF

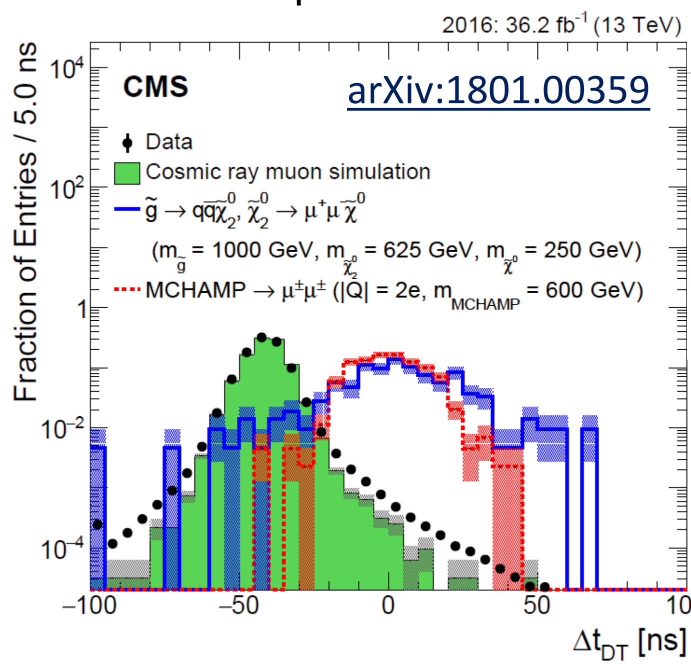
$$I_h = K\frac{m^2}{p^2} + C$$

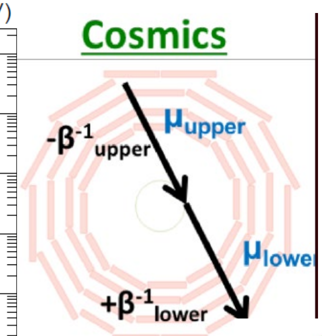
$$\beta^{-1} = 1 + \frac{c\delta_t}{L}$$

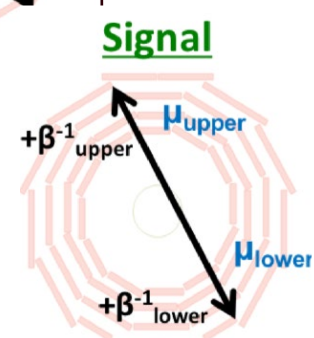


Energy loss can result in particles "stopping" in the detector → large lifetimes (10^-7 – 10^6s)

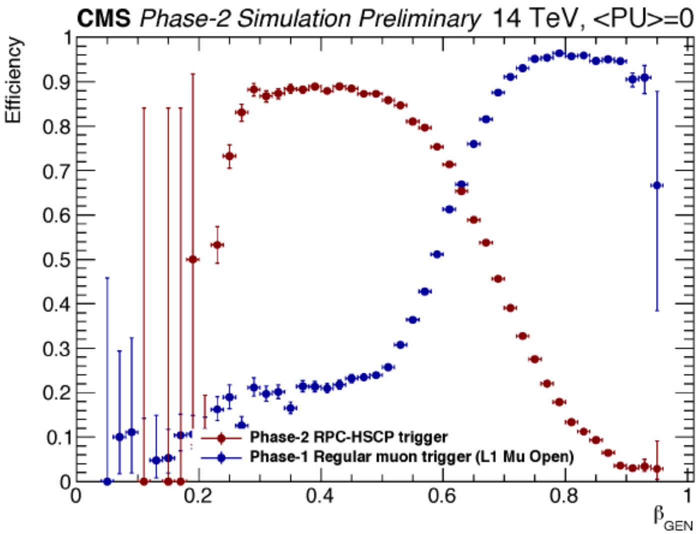
- Decay in the calorimeter:
  - asynchronous hadronic activity
  - E> 70GeV, |η|<1, 2 BX away from collisions
- Decay in the muon system:
  - displaced muon pairs; 2 BX away from collisions
  - displaced standalone muon reco, pT>50GeV





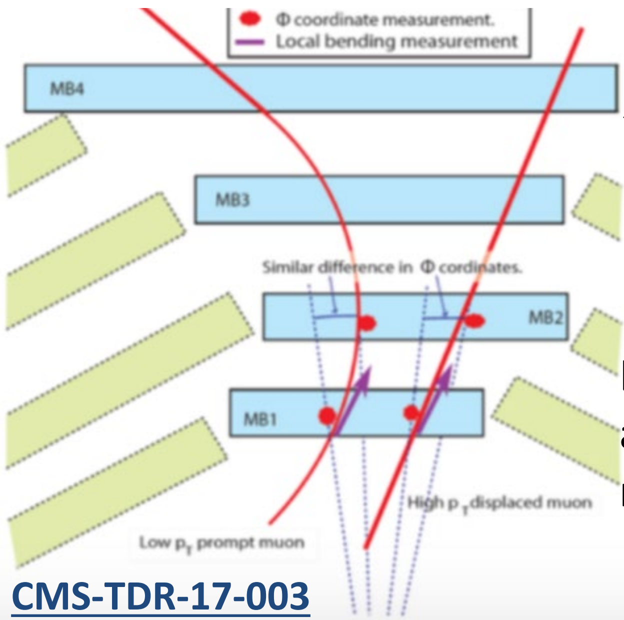


Muon Upgrade: HL-LHC Prospects



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

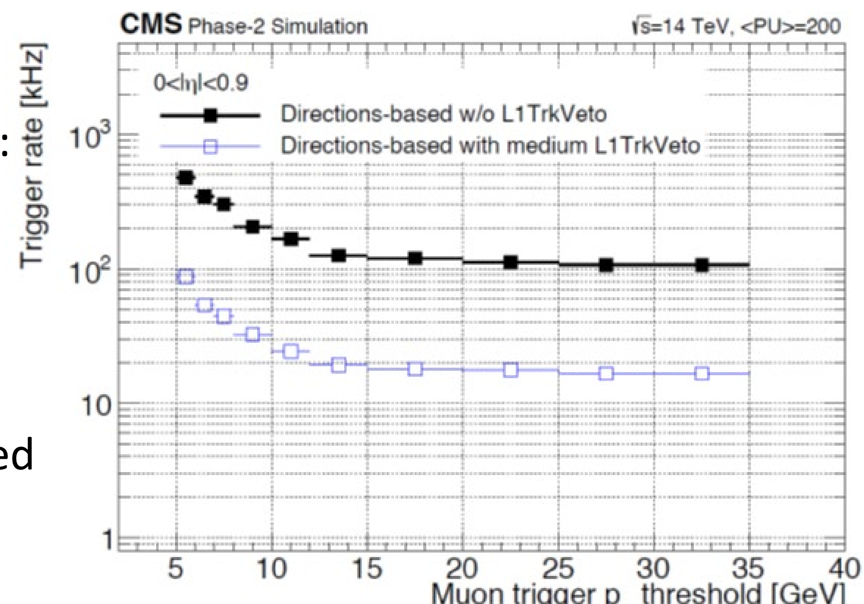
- **RPC upgrade**: ~1.5ns TOF resolution to each RPC station → **RPC-HSCP trigger**: linear fit to time vs distance from IP
- Improve mass resolution:
  - Ph2 trigger level comparable to Ph1 offline level
- Ability to trigger on, at the correct BX, HSCP with velocity as low as β~0.25
  - Increase reconstruction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



CMS-TDR-17-003

← New GEM stations: high pT displaced muon vs low pT prompt muon

L1 track trigger: used as veto for L1 displaced muon trigger →

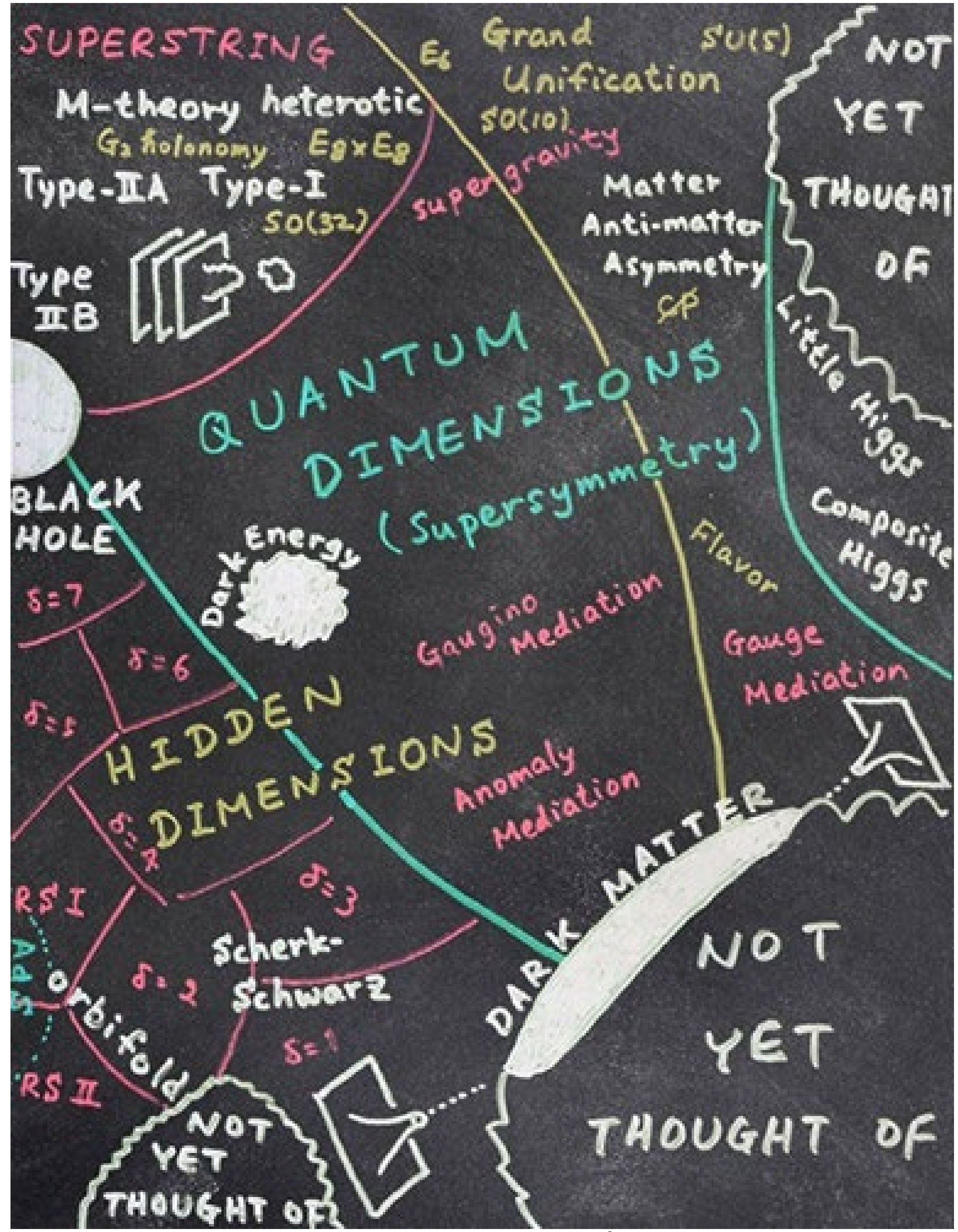


Conclusions & Outlook

- Long-lived particles are predicted in a wide range of BSM scenarios
- Rich, exotic final states present unique, under-explored search opportunities
  - Broad range of lifetime & decay products
- Various *signature-driven* LLP searches performed on ATLAS & CMS experiments
  - Results have broad reinterpretation value
  - Challenges in trigger, reconstruction, & background estimation
- Detector and trigger upgrades @HL-LHC bring tantalizing prospects
  - Increased forward acceptance and improved resolution
  - New timing & L1 trigger capabilities open up new possibilities

  → Stay tuned for Zhen's talk!

THANK YOU!



c/o Hitoshi Murayama