“Exotic” exotics – Experimental Prospects

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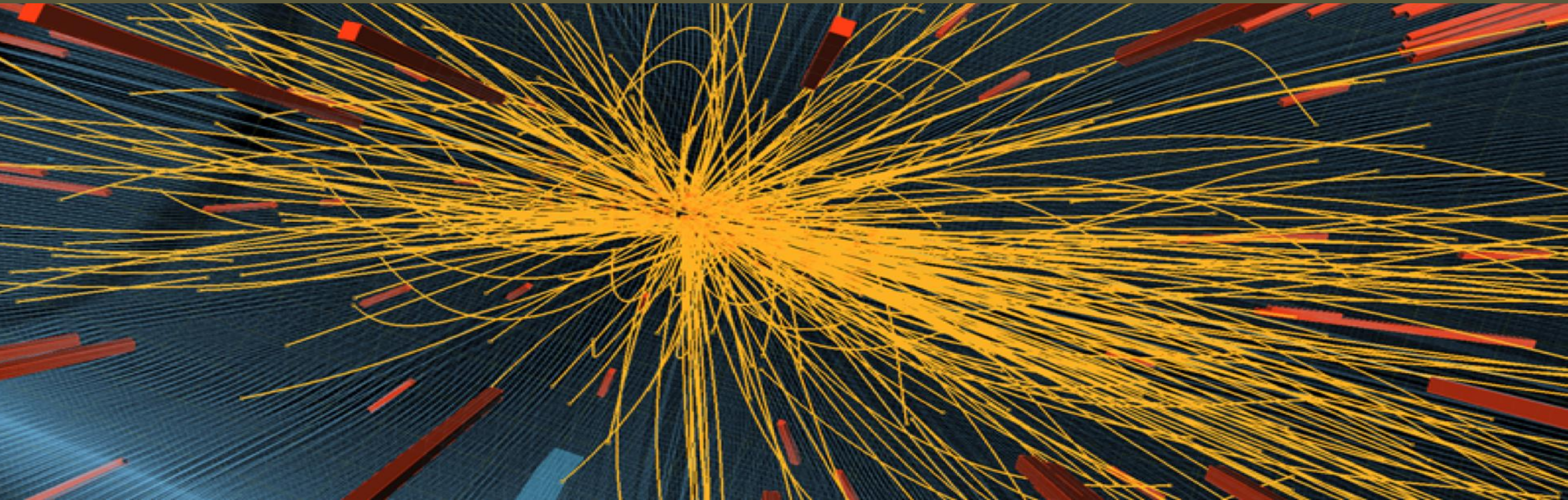
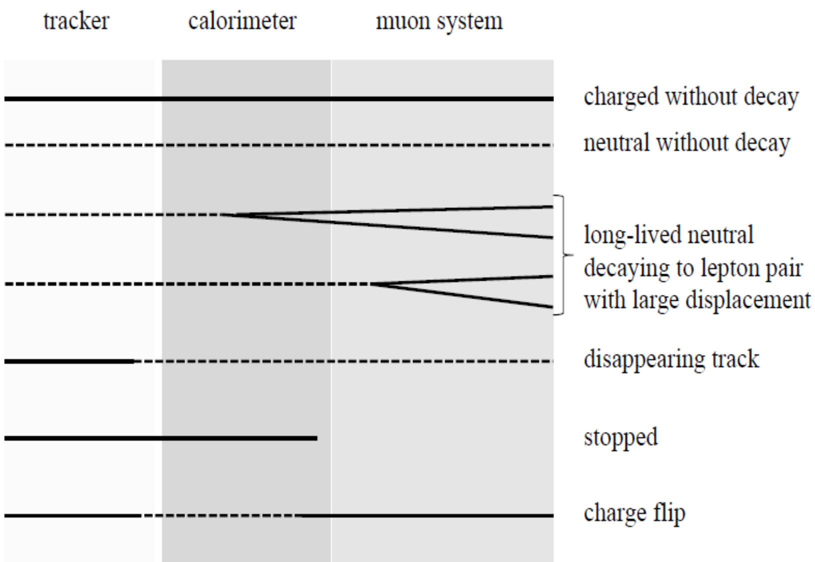
On behalf of the ATLAS and CMS collaborations

HL-LHC Workshop Cern May 2015



Exotic signatures



Unusual signatures.
Often related to SUSY scenarios or BSM Higgs decays.
Also need to be prepared for the unexpected.

1. Detection using anomalous **dE/dx** signatures
2. **Displaced** signatures (muons, jets) from decays of long-lived
3. **Out-of-time** signals (disappearing tracks, stopped signatures, etc.)
4. **Other** signatures

Disclaimer:

Variety of searches for exotic signatures by ATLAS and CMS in run-1, see bibliography in backup.

Unusual signatures require

- Special, dedicated tools developed over time
- Certain detector features

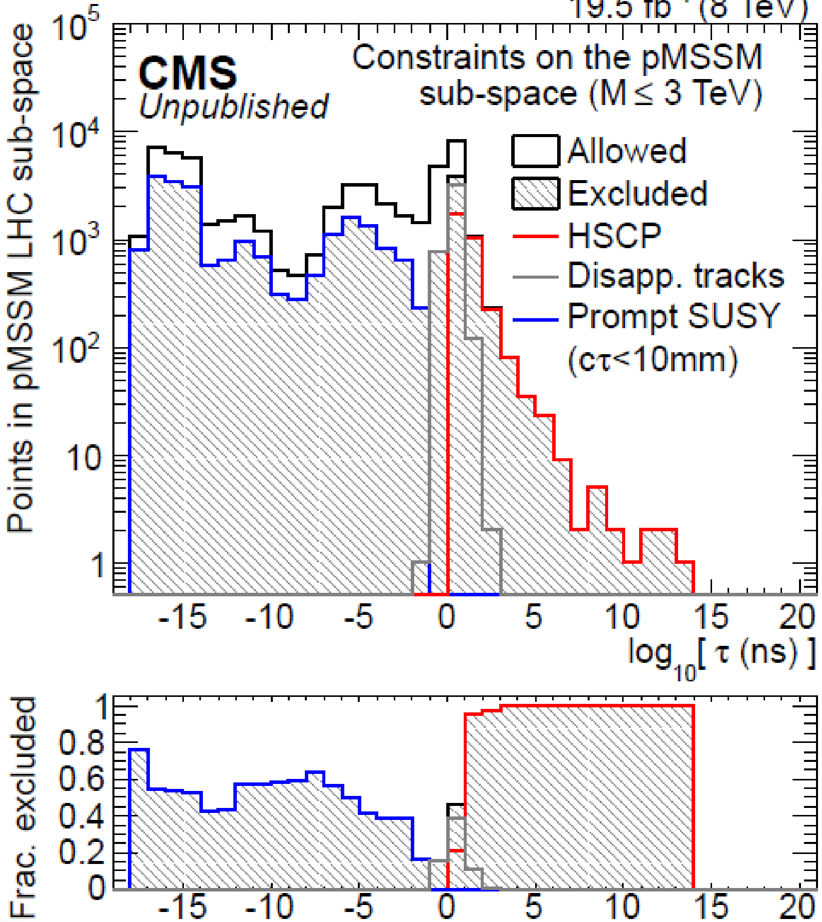
Not many projections for phase-II since dedicated tools to be developed and detector performance to be finalized.

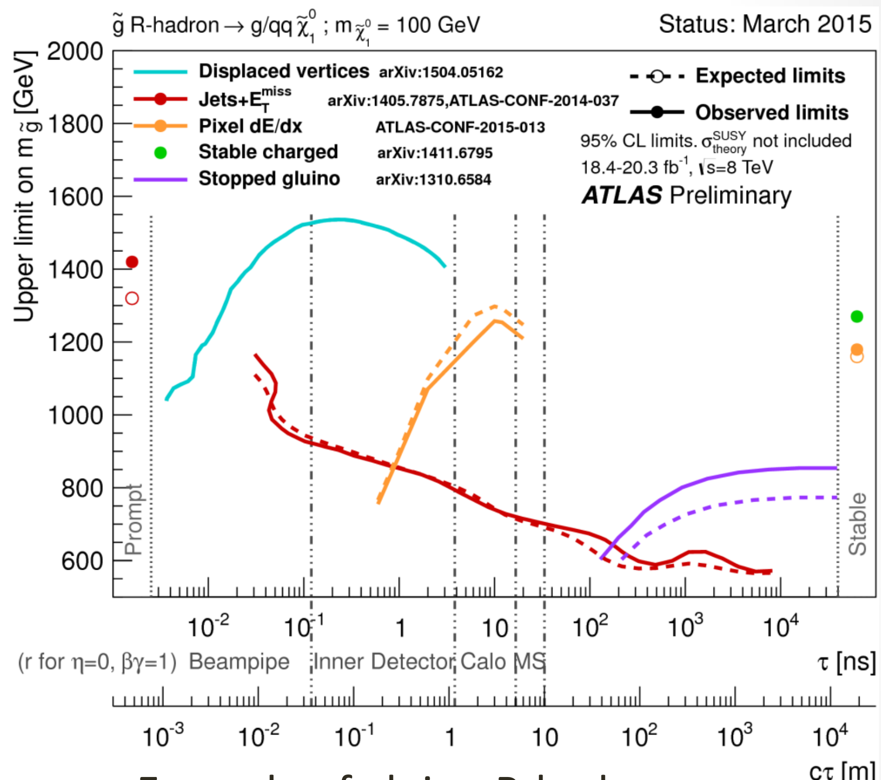
Background mostly instrumental and not limited by theory.

Use run-1 analyses to discuss analysis strategy and techniques.
Available few projections (CMS) use Delphes detector simulation or specialized simulation.

Several Complementary Analyses Needed to Cover full Lifetime Range of SUSY Candidates

CMS run-1 EXO-13-006





Example of gluino R-hadrons decaying to light neutralinos

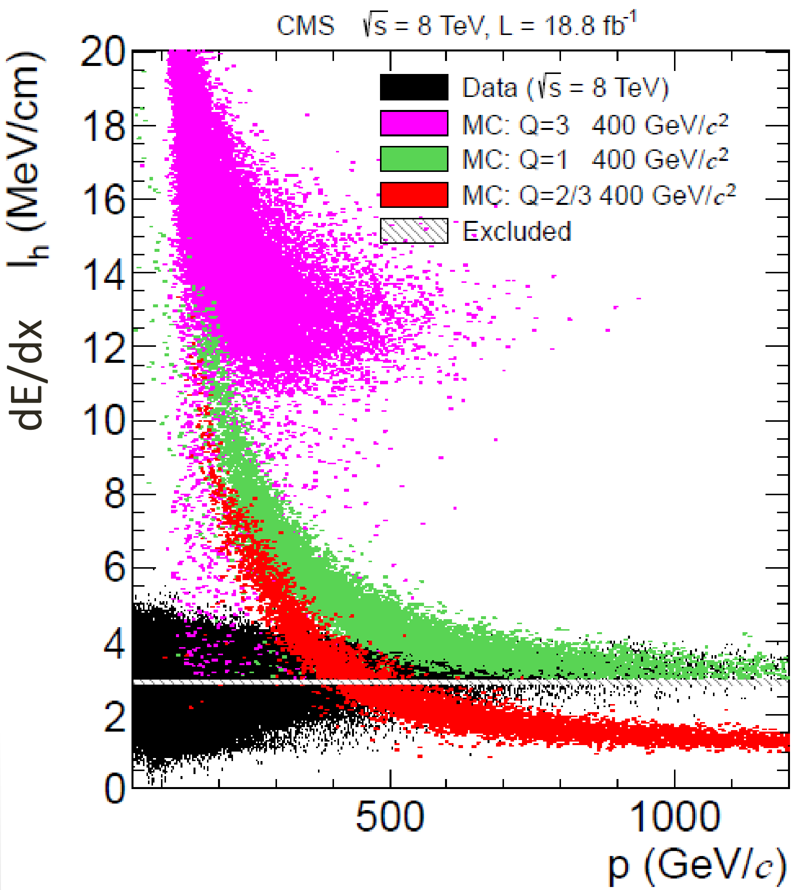
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/ATLAS_SUSY_LLP/

Interpretations in terms of SUSY models, see previous talks.

Detection using anomalous dE/dx

Non-standard dE/dx behaviour is the key for detecting fractionally or multi-charged particles, slowly moving stable particles or meta-stable particles decaying before calo/mu.

dE/dx also allows useful cross checks in case a hint of a signal is seen.



MIP average dE/dx ~3 MeV/cm nearly independent on momentum

HSCP (singly and fractionally charged) dE/dx shows strong dependence on momentum

Multi-charged particles have order of magnitude higher dE/dx

CMS arXiv:1305.0491, 1502.02522
ATLAS arxiv:1411.6795, CONF-2015-013/

Multi-Charged |q| = ze

ATLAS
arXiv:1504.04188

Suggested by several models (TC, LR symmetric predicting doubly charged Higgs). |q|=2e may explain DM observation.

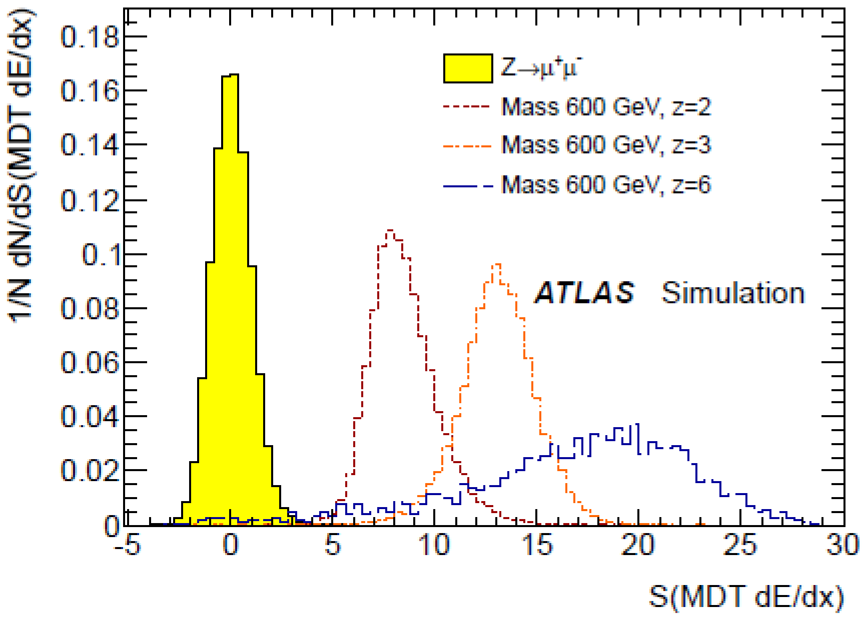
Experimental issues:

- dE/dx → depending on traversed radiation length. Both experiments reduce tracker material (rad length) in phase-II. ATLAS replaces TRT (many hits) with full silicon tracker.
- Energy loss increases with z^2 (z = charge factor), e.g. MIP in calo = 3 GeV but z=6 loses 110 GeV. Limits efficiency ~40% for z=2, ~5% for z=6. Unlikely to change substantially in phase-II; limits reach of z.
- Track curvature proportional to pT/z → pT measurement underestimated by factor z as z=1 is assumed
- Triggered by single muon trigger using Tk + MDT → TOF matters, limiting sensitivity to beta=v/c>0.6. Needs stand-alone muon trigger in phase-II

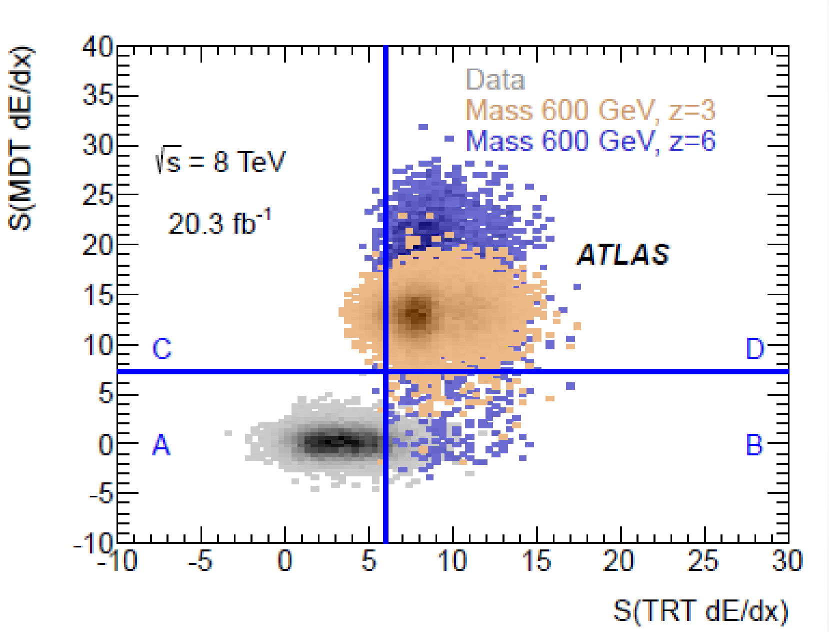
dE/dx is a Powerful Tool

ATLAS
arXiv:1504.04188

dE/dx signficance strongly depends on particle‘s charge (z) and its velocity



dE/dx can be determined in various subdetectors, muon chambers (MDT), tracker, TRT

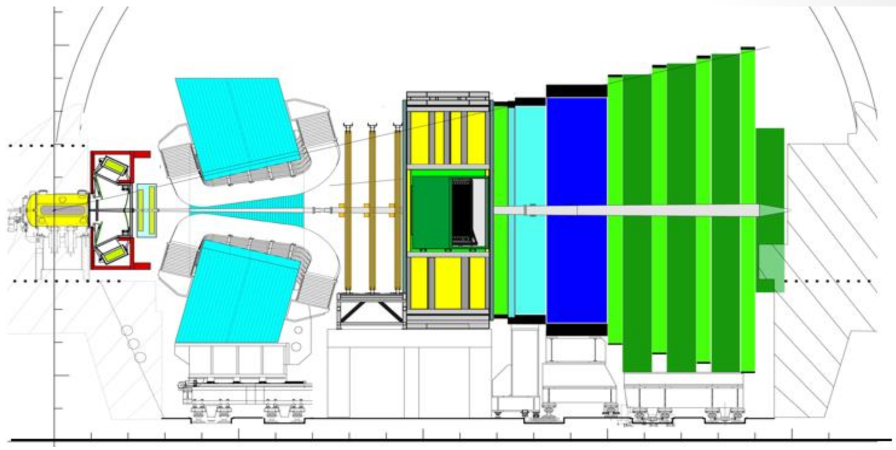


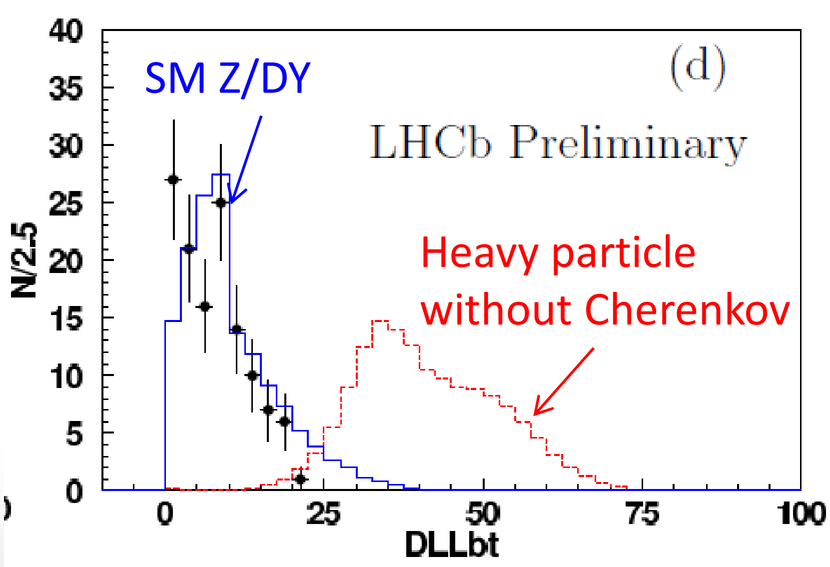
Note: Meta-stable particles decaying before calorimeter/muon system can only be detected via dE/dx (ATLAS run-1 ATLAS-CONF-2015-013)

Search for Long-Lived Stau's with LHCb

LHCb-CONF-2014-001

Complementary to ATLAS/CMS as unique use of RICH detector. Heavy stau's have much higher momentum threshold for Cherenkov radiation → no ring in RICH, „below-threshold-particle" (DLLbt)





Main source of inefficiency (slow staus give delayed signal) = readout window in the outer tracker and muon chambers (effectively limited to beta < 0.80).

LHCb run-1 excludes stau between 124 and 309 GeV.

dE/dx in Phase-II ?

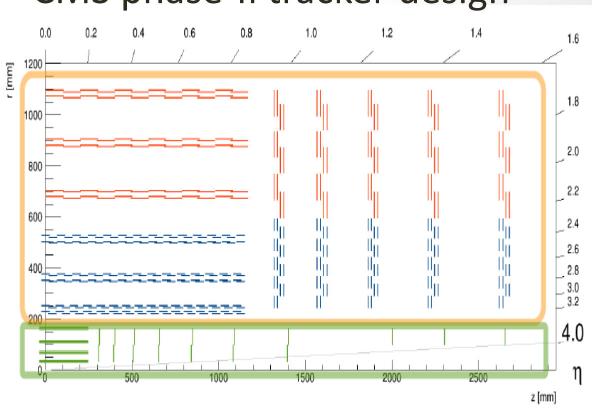
CMS EXO-14-007

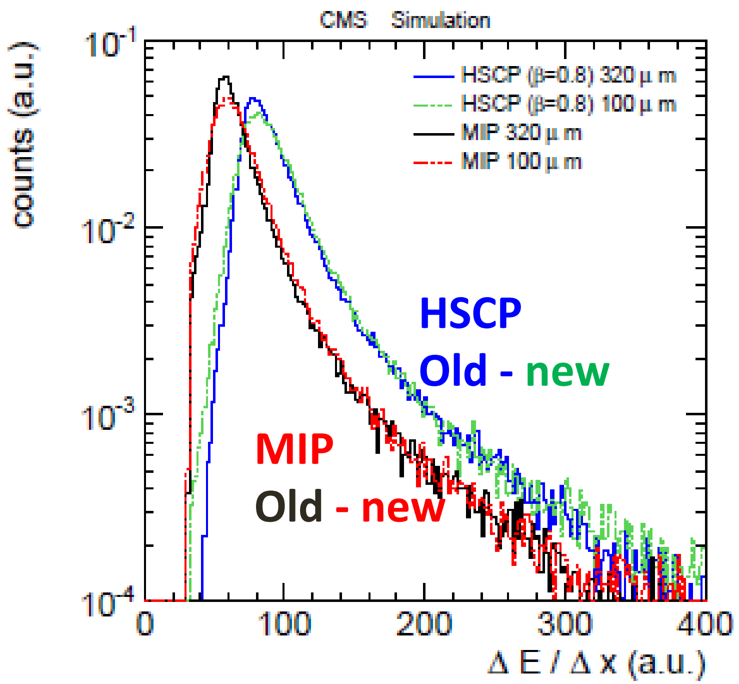
In Run-I ATLAS and CMS used dE/dx readout in tracker/pixel.

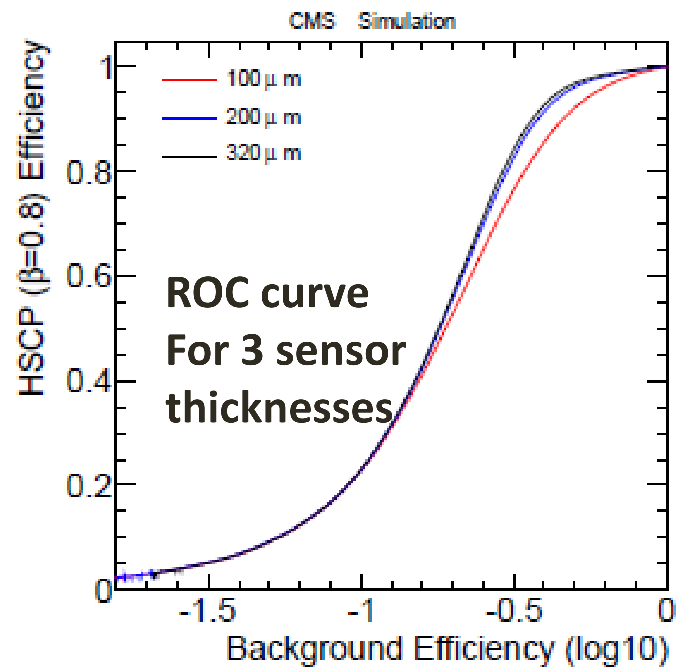
CMS phase-II trackers will have **less layers and thinner sensors** (320 um → 200 um).

Simulation to study impact of sensor thickness on heavy stable charged particles (HSCP)

CMS phase-II tracker design







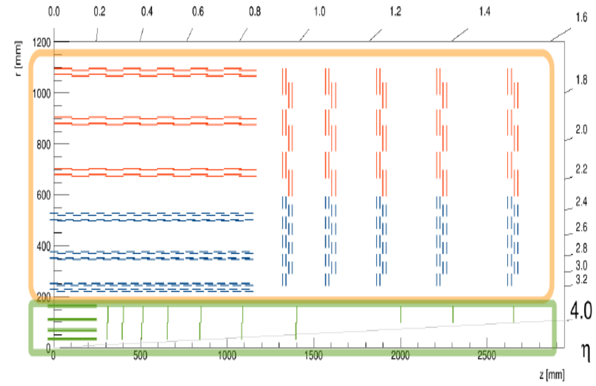
Both experiments study if/how to enable dE/dx readout in phase-II

Impact on Signal

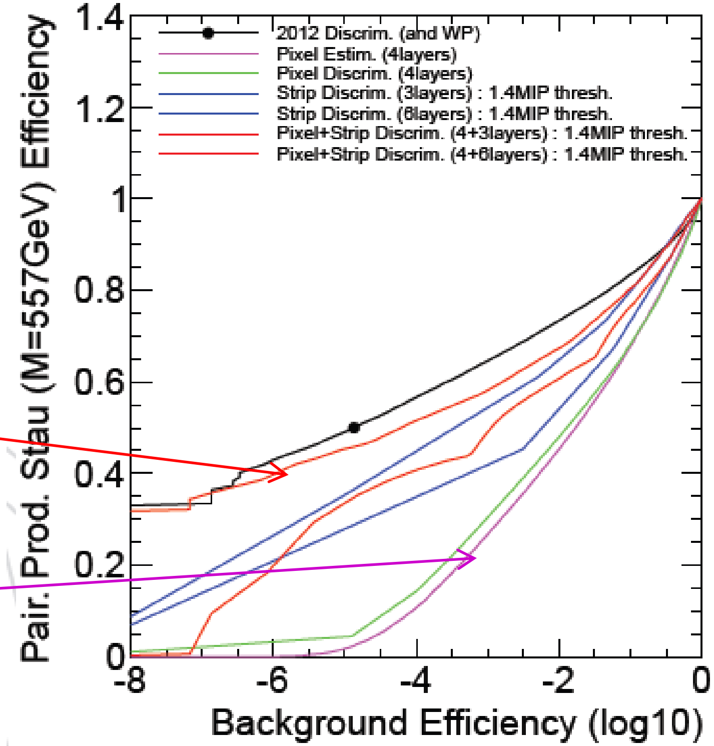
CMS Phase-II study

CMS studied different detection scenarios.

Instead of full dE/dx readout, simple hit-over-threshold (HoT) bit in a limited number of layers.



- Combination of 4 pixel layers dE/dx + 3 tracker layers HoT ≈maintains run-1 sensitivity
- Pixel alone (4 layers) is not sufficient for physics



Note: background mostly instrumental.

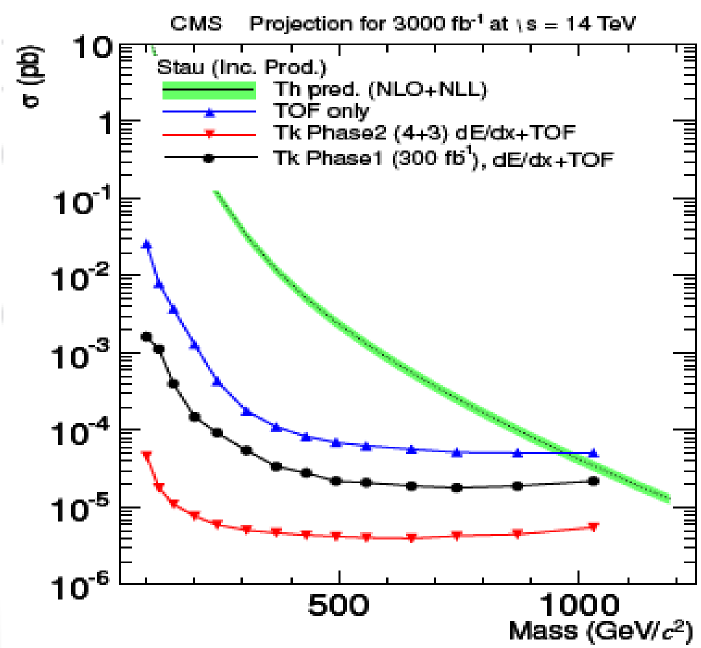
CMS EXO-14-007

Projected Sensitivities

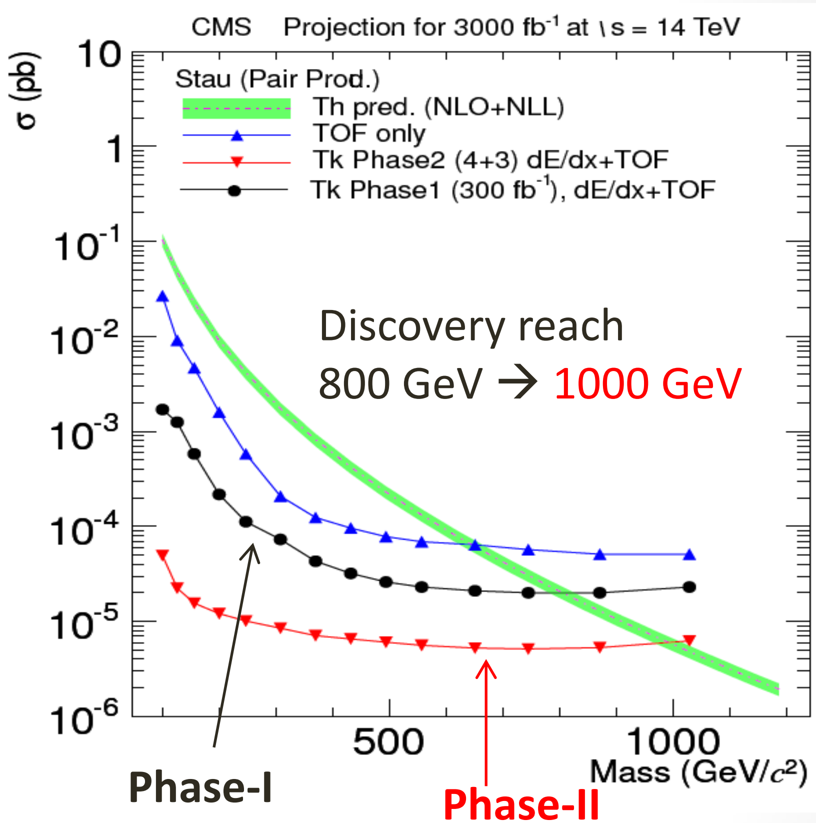
CMS phase-II study

CMS
EXO-14-007

Impact on physics sensitivity:
HoT bit in 3 tracker layers + pixel provides nearly phase-I sensitivity per fb^{-1} . Gain with increasing luminosity.



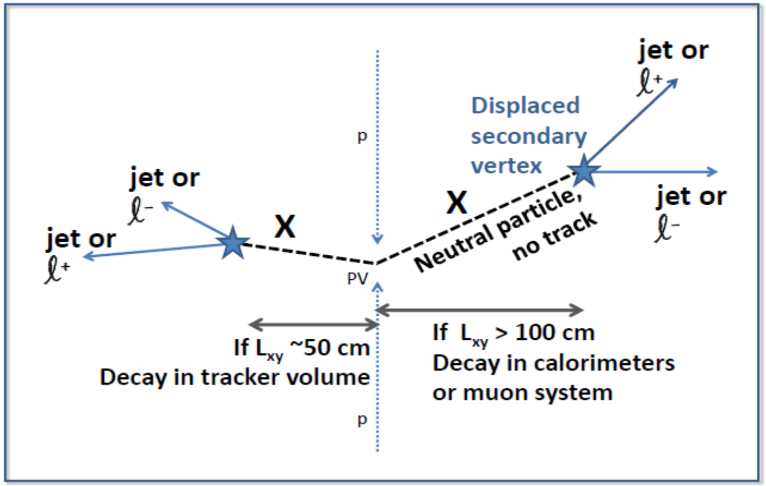
Stau pair production



5σ discovery

Model	300 fb^{-1}	3000 fb^{-1}
Stau PP	0.8 TeV	1.0 TeV
Stau incl.	1.1 TeV	1.3 TeV
Stop	1.5 TeV	1.8 TeV
Gluino f=10%	2.0 TeV	2.2 TeV

Long-Lived (LL) Particles



Many models suggest new particles, e.g. non-SM Higgs, dark sector, etc. Decaying into long-lived (neutral) particles.

Typical signature if decay within instrumented area:

- Secondary vertex **displaced** by significant amount (cm - m) L_{xy} → standard secondary vertex reconstructors not sufficient
- Decay length decides in which subdetector (tracker, calo, muon)
- Sizable **impact parameter** d_{xy}
- Kinematics ΔR and L_{xy} strongly model dependent

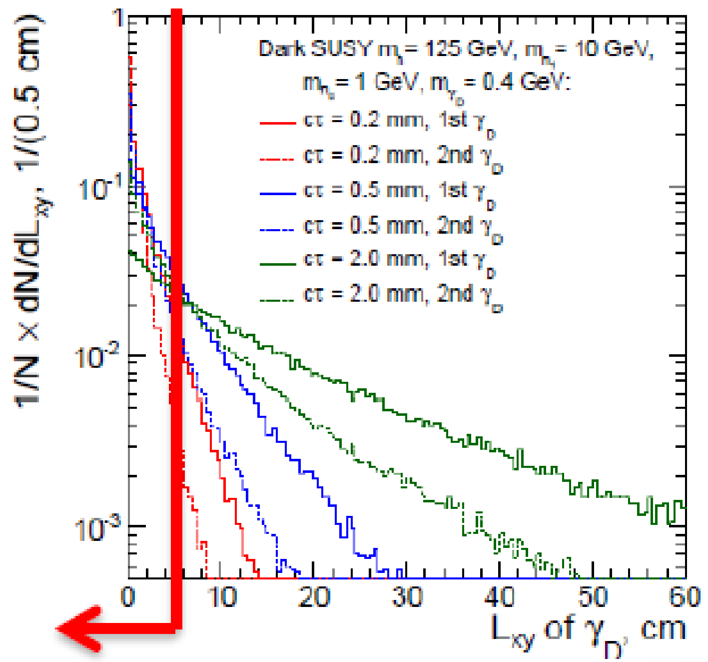
Experimental issues with such signatures:

(1) Trigger

(2) Reconstruction

- If NP particles are of low mass → produced with large boost
  - Probably less in phase-II since low masses already addressed.
  - Tools are in hand for run-1. Need to be ported to upgrade.

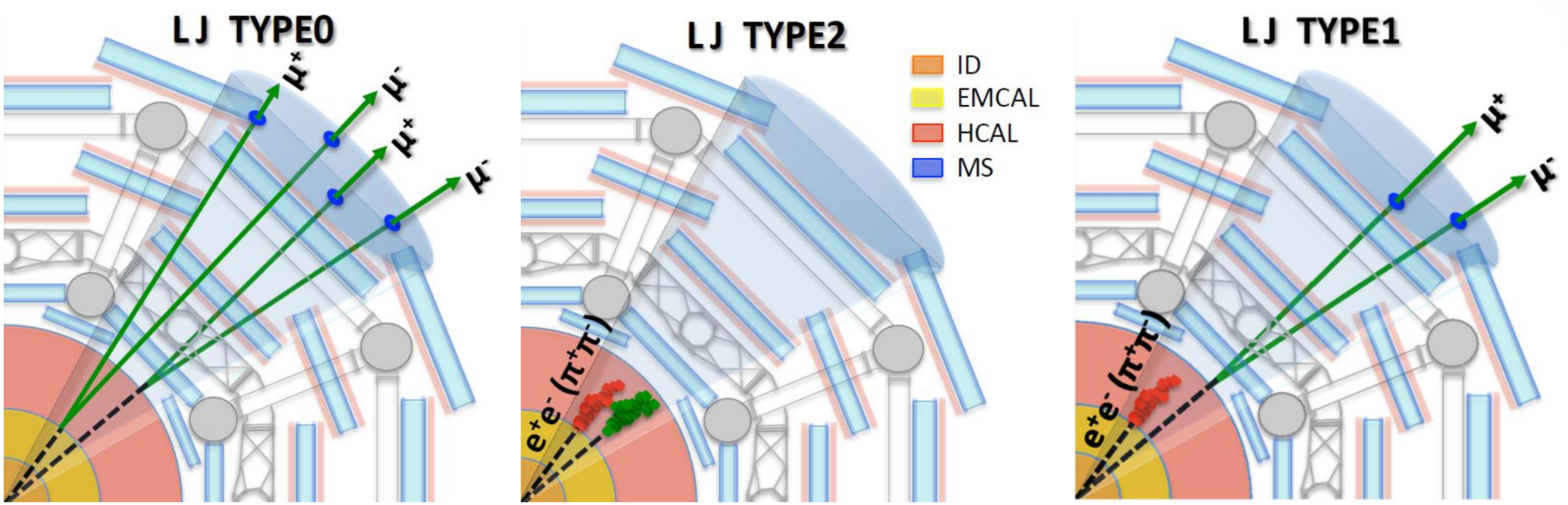
- Due to weak interaction → can have non-negligible lifetimes
  - Impact parameter increases with $c\tau$
  - Probably even more in phase-II
  - Natural limit from detector dimension (combine LHC detectors?)
  - Requires displaced trigger



- Branching fraction and lifetime are model dependent. Also particle multiplicity and shape of lepton jet depend on model.

→Therefore signature-oriented search, model independent

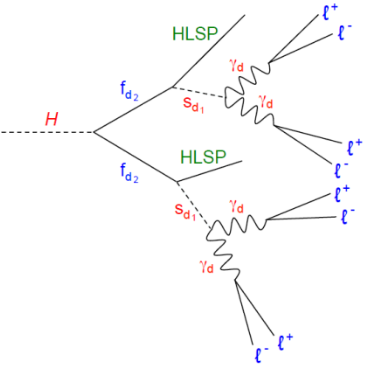
Common: Decay of Long-Lived Particles Yields Signatures with Large Displacement



Jets with anti-kT algorithm R=0.4

ATLAS run-1 arXiv:1409.0746
Also ATLAS SUSY-2014-02
CMS run-1 HIG-13-010

Short or even no tracks in inner tracker



„Late“ decay in calorimeter or muon system

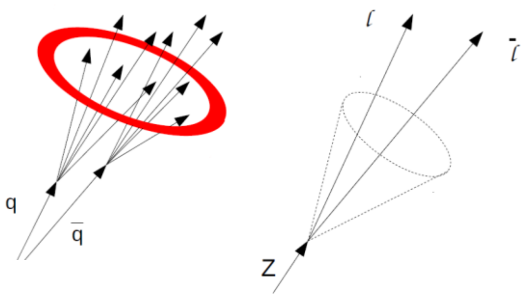
Decay products might be boosted (lepton jets)

CMS only muons in final state. Paper in CWR.
ATLAS (ref) uses mu, ele, pions in final state

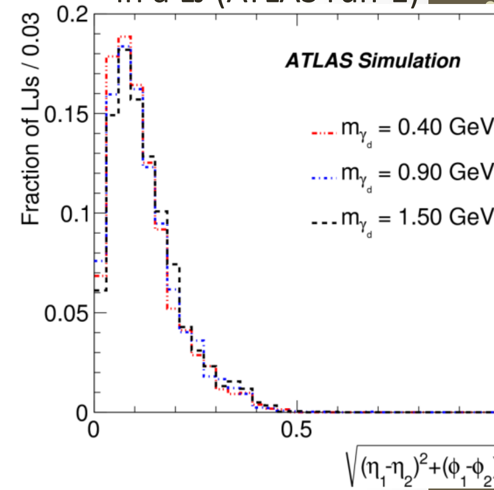
Experimental Issues (Reconstruction)

Needs dedicated reconstruction to handle displacement & boost (for light particles)

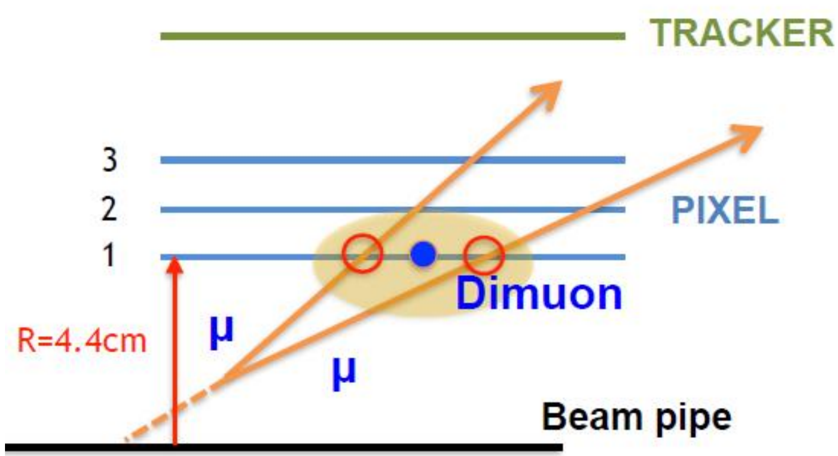
- Overlapping isolation cones
  Reco as lepton jets with common isolation for jet.



Small opening angle between 2 muons in a LJ (ATLAS run-1)



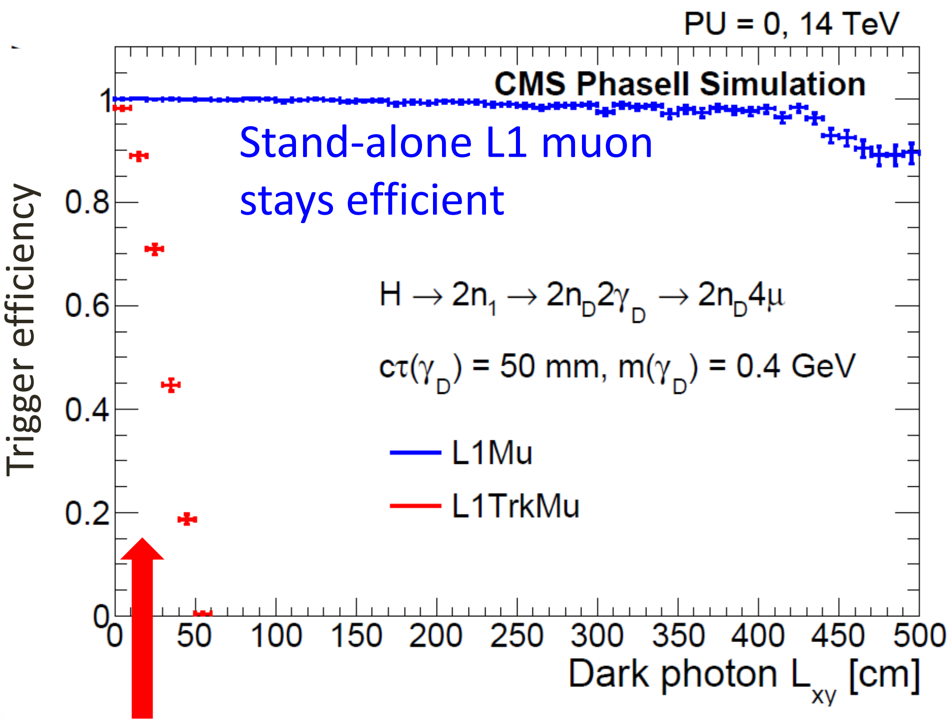
- Sharing pixel/tracker hits



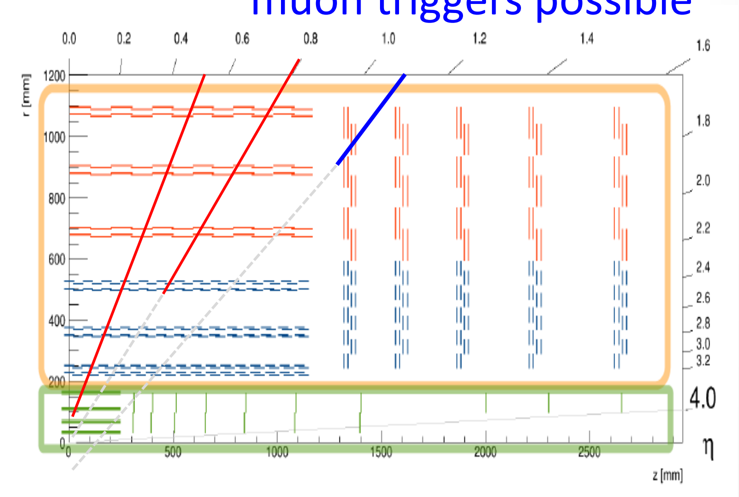
Challenge: Trigger Displaced Signatures

Case 1: Pointing to vertex but only few hits due to neutral LL particles

L1 track trigger needs ≥3 hits (stubes) to trigger efficiently



If insufficient – no hits in tracker only stand-alone calorimeter or muon triggers possible



CMS L1 TT (TrkMu) trigger only efficient up to decay length Lxy >50 cm.

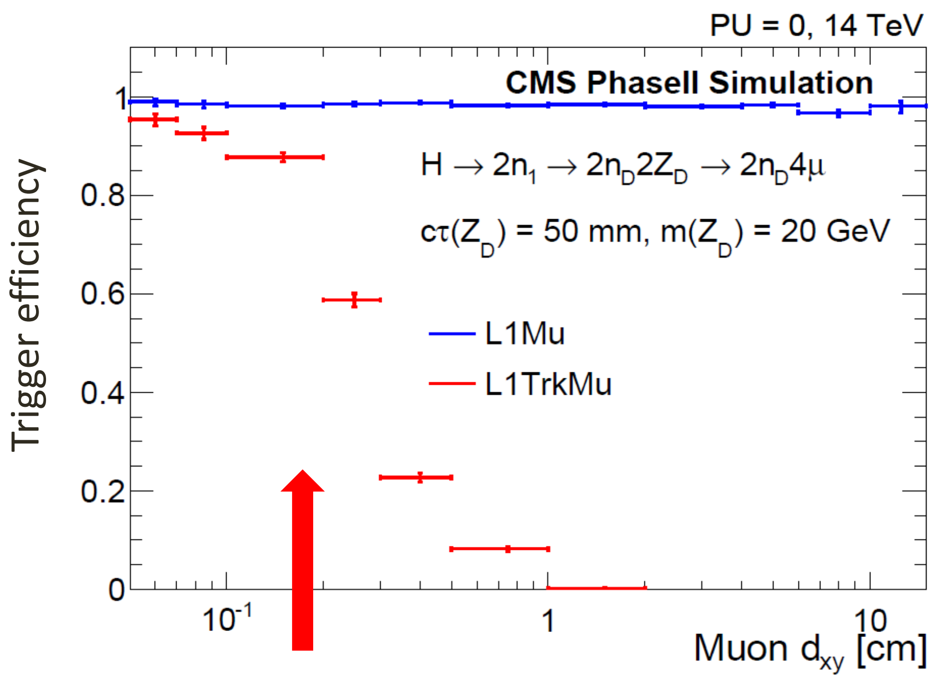
ATLAS/CMS envisage a L1 track-trigger for phase-II, providing p_T measurement from silicon tracker already at L1.

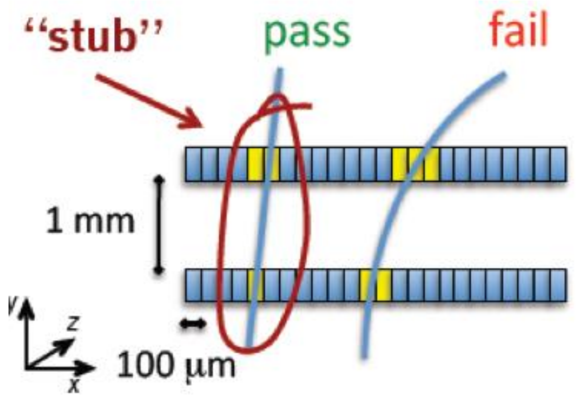
Challenge: Trigger Displaced Signatures

CMS GE1/1 TDR

Case 2: Large impact parameter

Track trigger has implicit vertex constraint.





CMS track-trigger concept
Strong bending in B = 3.8 T

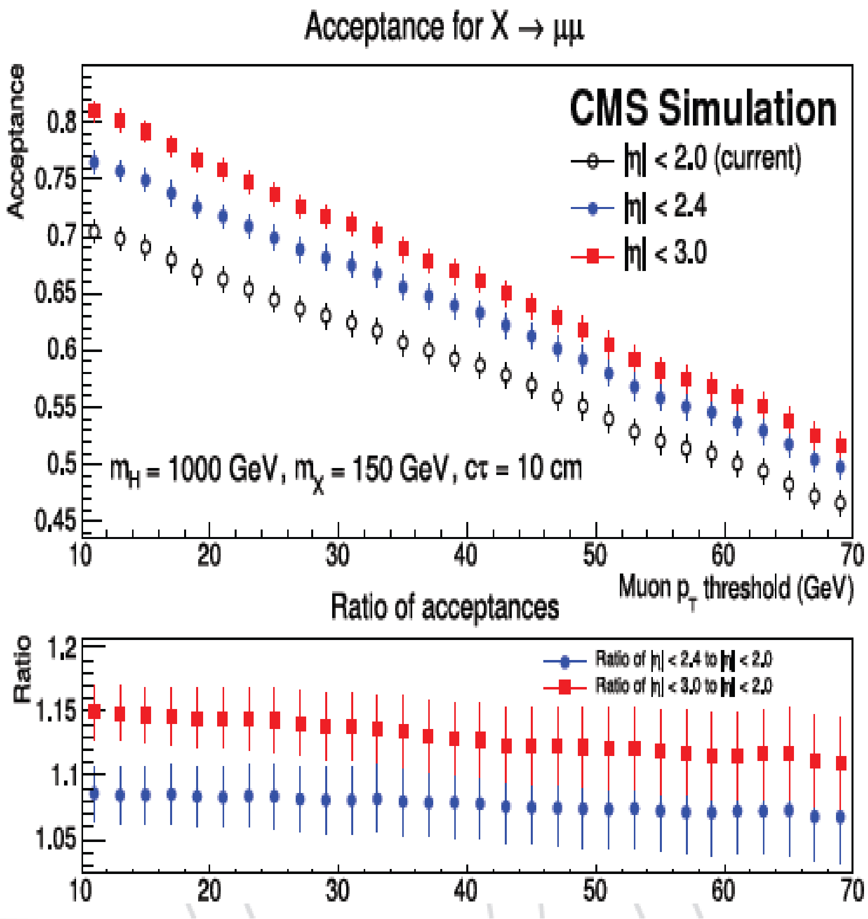
L1TrkMu trigger only efficient up to impact parameters <1 cm.

Stand-alone L1 muon stays efficient

Acceptance studies

CMS
EXO-14-007

Displaced signatures, CMS phase-II study



Higgs → 2X → 2(μ+μ−)
(MH,MX)=(1000,50) GeV

Challenges: triggering and reconstructing displaced signatures.

Impact of acceptance:
Current track-based analysis only |η|<2 to avoid fakes.
Phase-2 tracker with **extended acceptance** up to |η| < 3.0
→ yields ~15% higher acceptance

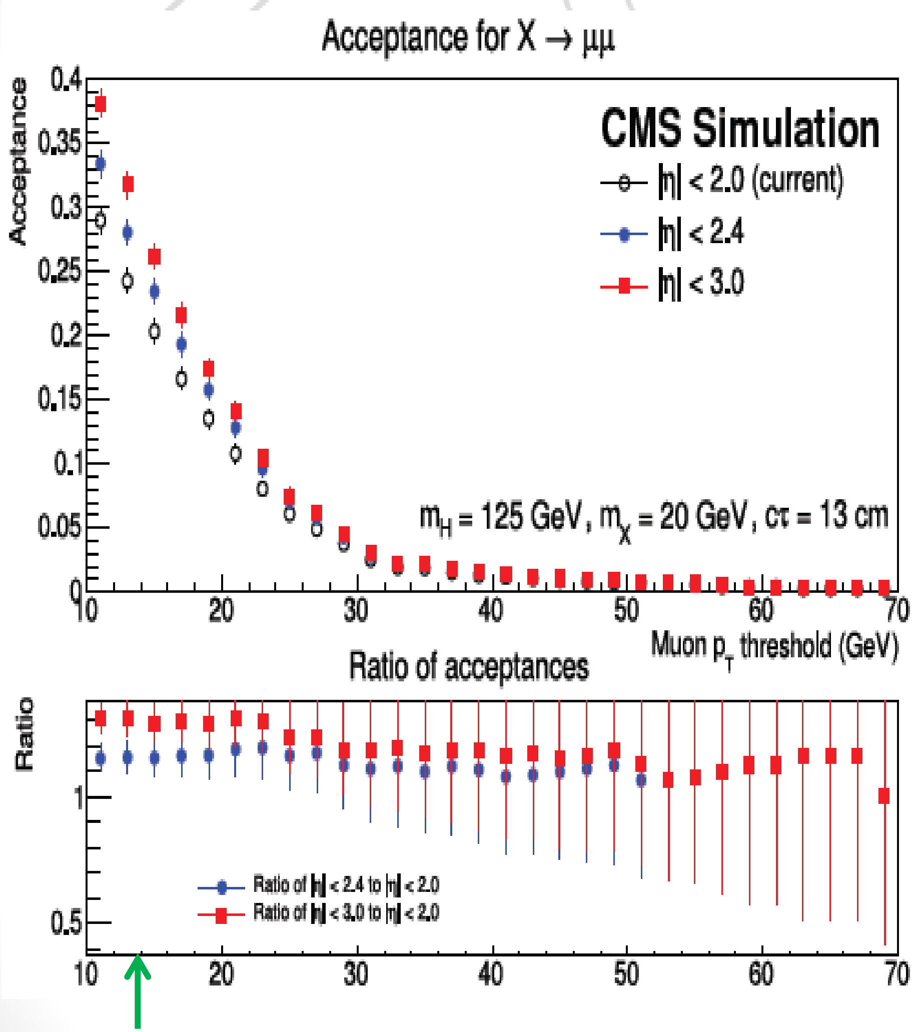
Compensates reduced acceptance due to less tracker layers
L_{xy} 35 cm/50 cm= 0.7 times lower

Acceptance studies

CMS
EXO-14-007

Displaced signatures, CMS phase-II study

Higgs → 2X → 2(μ+μ–)
(MH,MX)=(125,20) GeV



Needs low trigger thresholds

Additional challenge of keeping trigger thresholds low.

Here also strong dependence on p_T threshold. Needs ≈ p_T < 20 GeV. Trade off threshold ←→ rate.

Acceptance (|η|<2) in general lower (30%) than for heavy M_H. Larger gain from **extended tracking acceptance** up to |η| < 3 → yields ~40% higher acceptance for low p_T muons

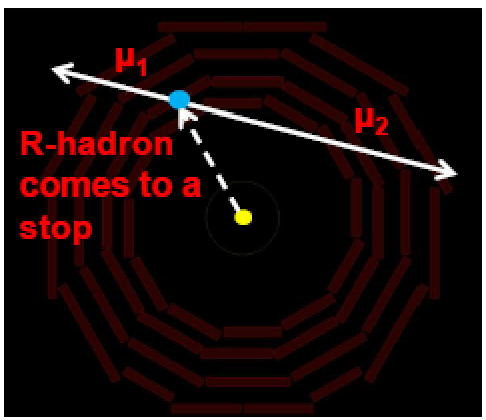
Out-of-time Signals

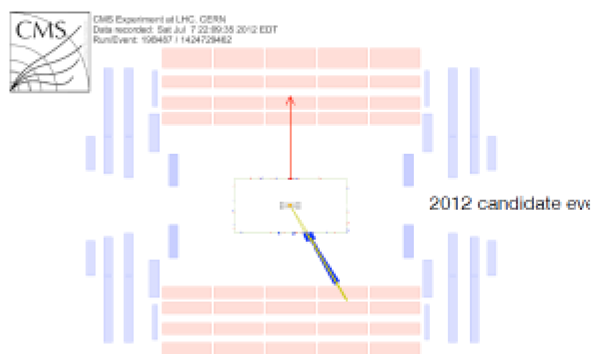
Long-lived particles with very low kinetic energy (<0.45 c)

→ dE/dx large enough that particles come to stop in detector

- Stop in densest regions (calorimeters, CMS iron yoke)
- Stopped R-hadrons decay to leptons or jets ns, sec, min or days later

Delayed Muons Search:	Stopped Particles Search:
Non-pointing muons when no collisions	Hcal E deposit when no collisions



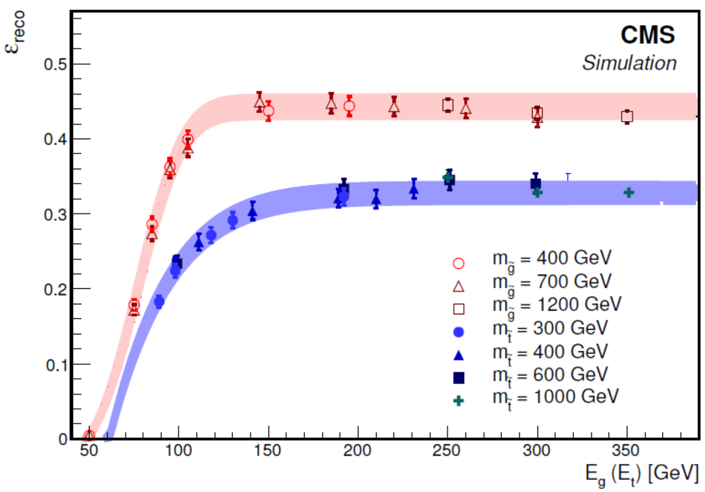


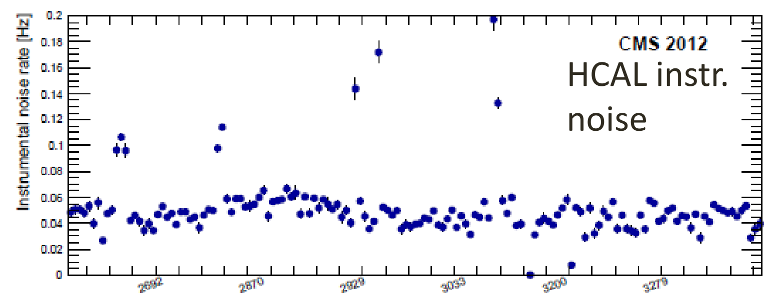
Stopped Particles

CMS run-1 arXiv:1501.05603
ATLAS run-1 SUSY-013-03

- **Signal: randomly timed**, relatively **large energy response** in a few channels. Stops most likely in calo because of high density.
- Can be observed **out-of-time** (no collisions) where bkgr is only due to cosmics, some beam-related bkgr and instrumental noise. Bkgr suppression: no muon hits, HCAL signal timing profile

Signal efficiency run-1



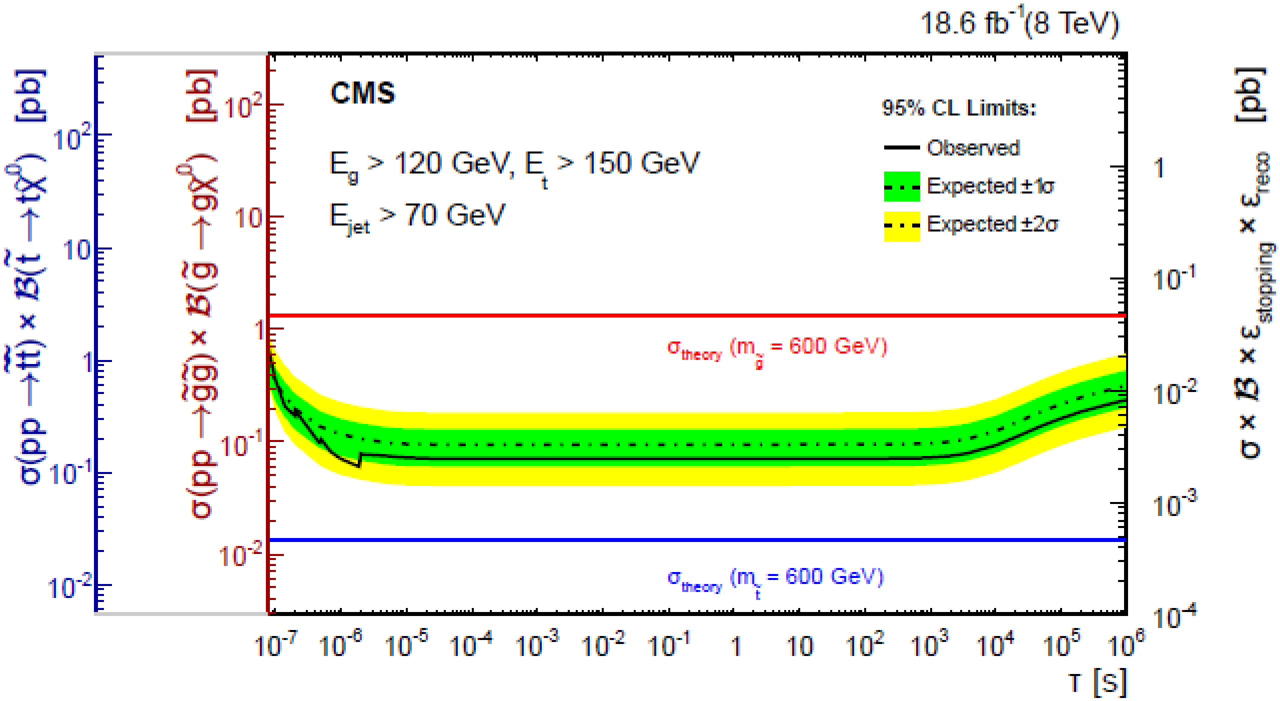


- Trigger: BPTX (no signal) * calo jet (deposited energy ≈ pp-jet)
- Signal efficiency ~40% (gluinos) and 30% (heavy stop)

Sensitivity
for Stopped Particles (run-1)

CMS run-1 arXiv:1501.05603
ATLAS run-1 SUSY-013-03

Limited by lifetime of LHC (upper limit) and bunch spacing (25 ns).



Potential impact of phase-II performance: (to be studied)

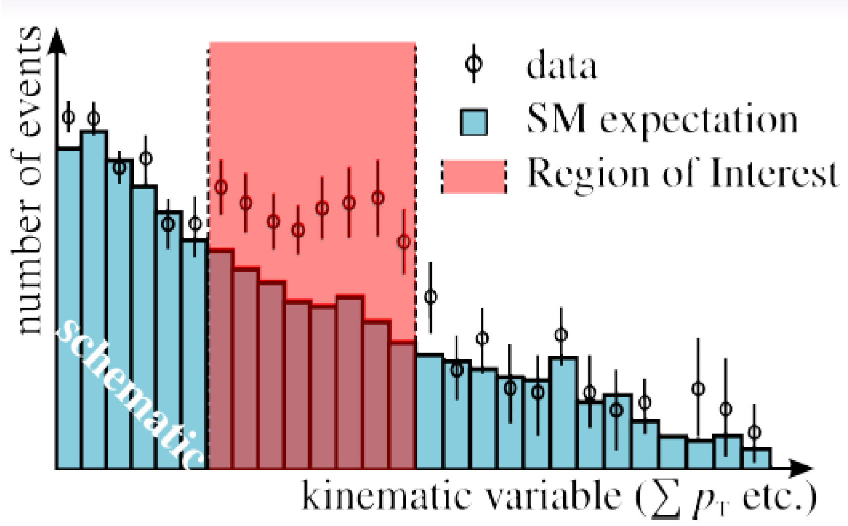
- Increasing OOT PU may affect sensitivity. In particular HCAL noise.
- Will profit from extended phase-II acceptance and extended LHC lifetime.

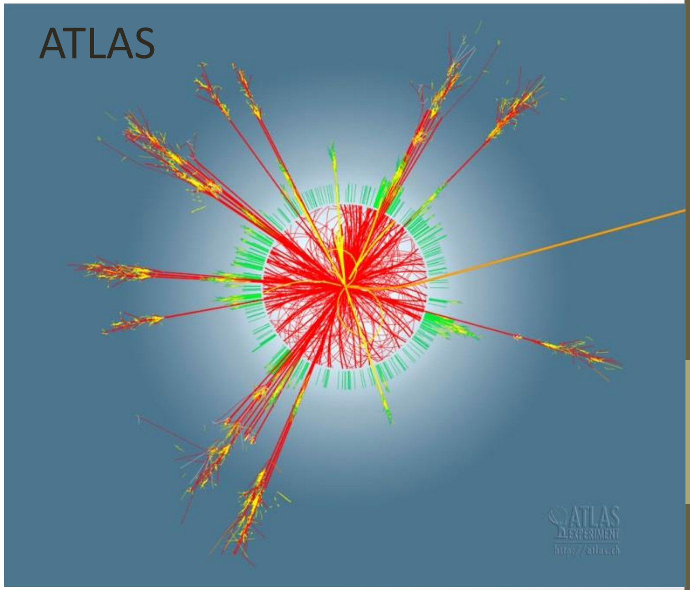
Not Too Miss Anything…

- Keep an eye on very exotic final states, not covered by dedicated analyses and potentially not predicted by theory.

- Signature-driven, model-independent searches in ATLAS & CMS.
- No phase-II projections but maintain capability.
- O(100) classes (inclusive, exclusive) with different final states. Search for deviations (excess OR deficit).

- Main challenge: understand SM background and detector performance





Massive Vector-like Quarks T´

CMS
FTR-13-026
Snowmass 2013

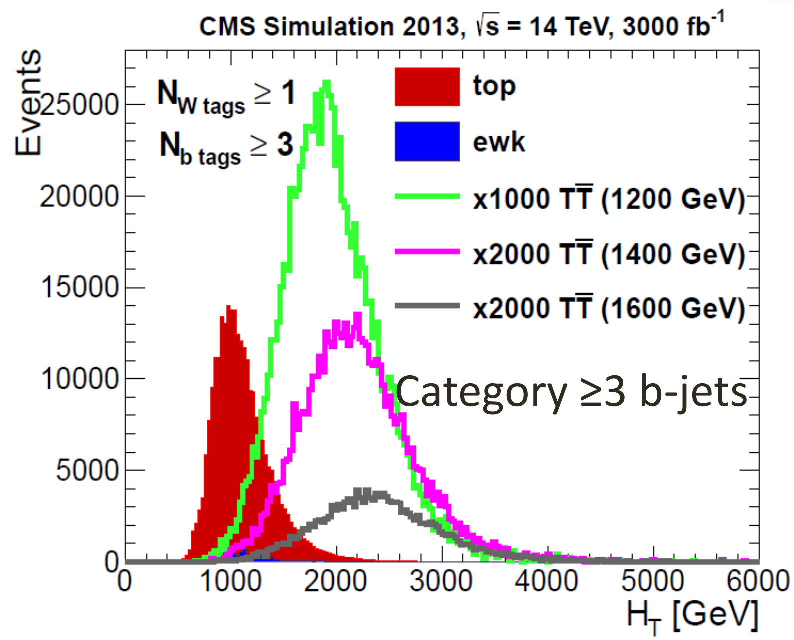
- Phase-II study with upgraded tracker and parametrized (Shashlik) calorimeter performance. Eta coverage up to 2.4

- Pair production of T´. Decay via tH (BR 25%), Zt (BR 25%), Wb (BR 50%). Yield 2-4 bosons and ≥2 b-jets → several leptons and b-jets in large number of search channels

- With increasing T´mass overlapping jets. Use Cambridge-Aachen algorithm for „fat" jets and top-tagging tools
- Assume 20% uncertertainty on bkgr
- 5% systematics on signal selection eff.

Phase-II profits from

- Improved B-jet performance
- Reduced charge-misID



CMS upgrade study. configuration 3
FTR-13-026

Projected Sensitivity with 3000 fb^{-1} for heavy vector-like quark T′

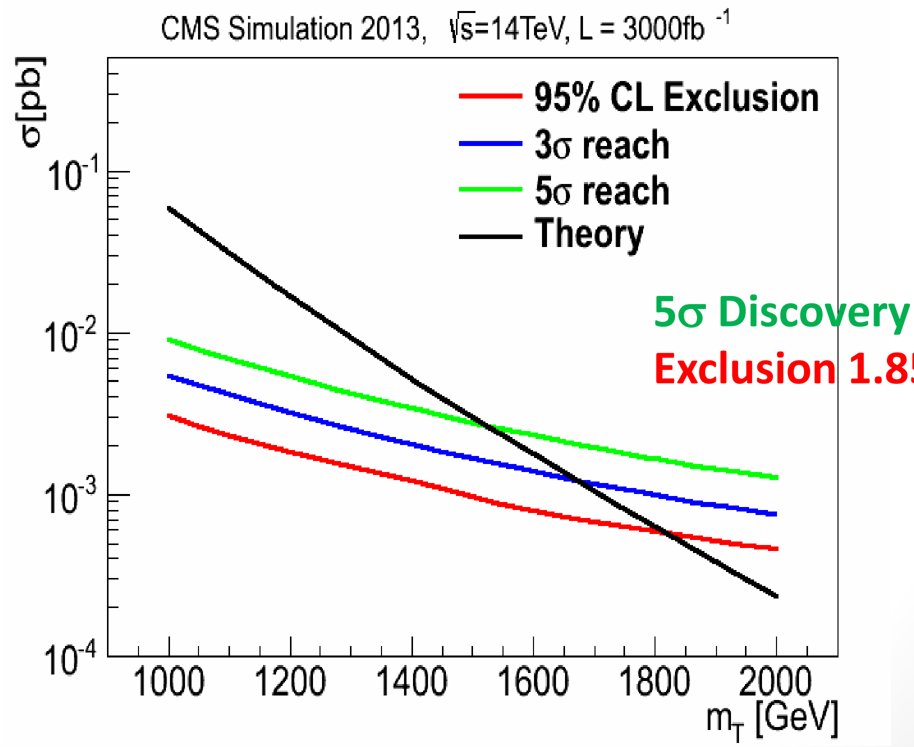
CMS
FTR-13-026

Analysis channels.

- Single lepton (from W) and 3 jets (≤3 b-tagged jets)
- 2 leptons (incl. Charge requirement) OS or SS
- Backgrounds due to EWK processes and ttbar

Projected sensitivity when combining all channels:

Run-1 exclusion limits 700-900 GeV depending on channel
CMS B2G-12-015, 12-014



5σ Discovery 1.55 TeV
Exclusion 1.85 TeV

Summary

- **Exotic** deays provide a **unique** window to NP
- Keep capability for **signature-driven, model-independent** analyses in order not to miss the unexpected.
- Sensitivity in phase-II mostly constraint by **instrumental** aspects, less from theory. Experimental studies to be done.
  - Searches with dE/dx and large displacement will be mostly limited by detector performance.
  - Triggering displaced signatures to be implemented.

BACKUP

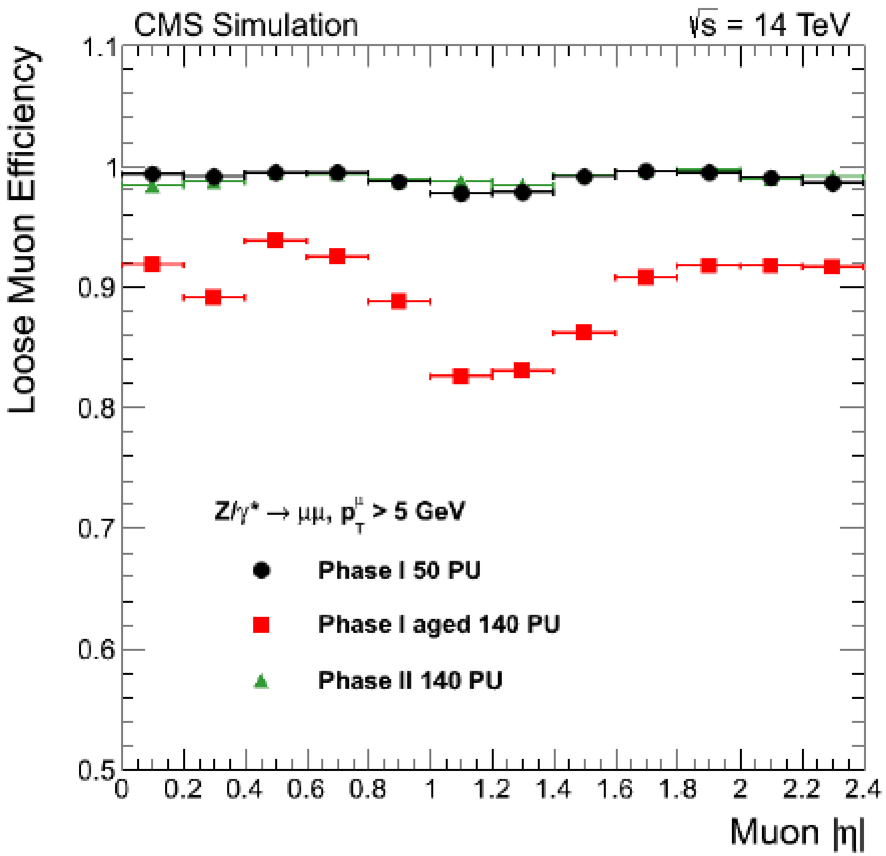
ATLAS References

- arxiv:1504.04188 Search for heavy long-lived multi-charged particles in *pp* collisions at *s*√ = 8 TeV using the ATLAS detector
- Search for long-lived neutral particles decaying into lepton jets…. arXiv:1409.0746 EXOT-2013-22/
- Search for long-lived, weakly-interacting particles that decay to displaced hadronic jets …. EXOT-2013-12/
- Search for pair-produced long-lived neutral particles decaying in the ATLAS hadronic calorimeter… EXOT-2012-28/
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2013-22/
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-013/
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2014-02/
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2013-03/
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2013-01/
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/ATLAS_SUSY_LLP/ATLAS_SUSY_LLP.png

CMS References

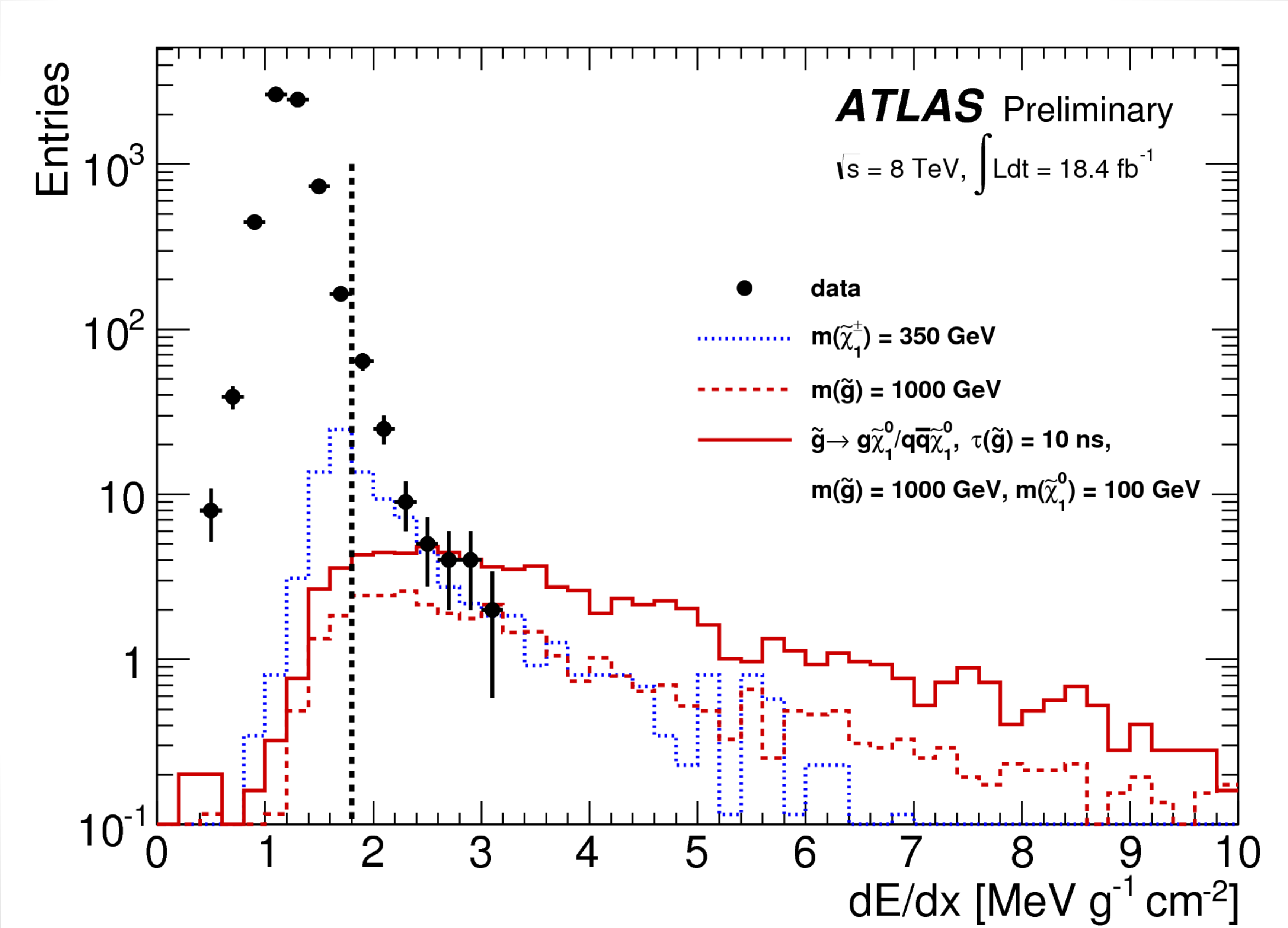
- CMS: Reinterpretation of HSCP Analysis in the pMSSM and other scenarios arXiv:1502.02522 EXO-13-006
- CMS: Search for Stopped Long-Lived Particles arXiv:1501.05603 EXO-12-036
- CMS: Search for displaced dilepton pairs arXiv:1411.6977 EXO12037
- CMS: Search for long-lived neutral particles decaying to dijets arXiv:1411.6530 EO-12-038
- CMS: Search for disappearing tracks arXiv:1411.6006 EXO-12-034
- CMS phase-II FTR-13-016 Top FCNC
- CMS phase-II FTR-13-026 Search for massive vector-like quarks T´
- CMS Technical Proposal: performance of phase-II detector (plots from approval session Wed)
- CMS Search for BSM physics with upgraded detector (PAS-EXO-14-007 in preparation, plots from approval session Wed)

Muon reconstruction efficiency with phase-I and phase-II detector



Tracker aging reduces tracking efficiency.

Displaced signatures rely mainly on outer layers, hence impact should be less significant. Muon system needs to be fully efficient and low fake rates.

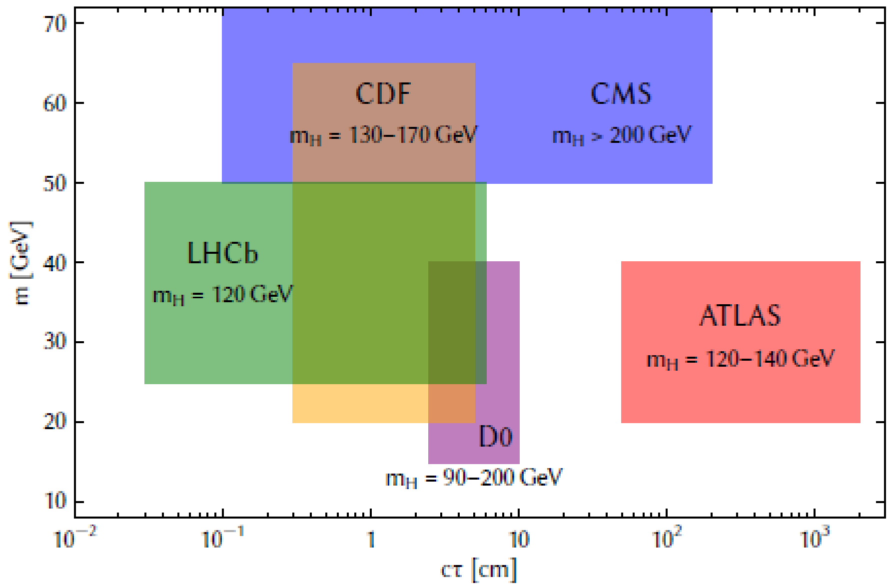


ATLAS Preliminary
$\sqrt{s}$ = 8 TeV, $\int Ldt$ = 18.4 fb^{-1}
data
$m(\tilde{\chi}_1^{\pm})$ = 350 GeV
$m(\tilde{g})$ = 1000 GeV
$\tilde{g} \rightarrow g\tilde{\chi}_1^0/q\bar{q}\tilde{\chi}_1^0$, $\tau(\tilde{g})$ = 10 ns,
$m(\tilde{g})$ = 1000 GeV, $m(\tilde{\chi}_1^0)$ = 100 GeV
Entries
10^3
10^2
10
1
10^{-1}
0
1
2
3
4
5
6
7
8
9
10
dE/dx [MeV g^{-1} cm^{-2}]

Search for LL particles also performed by LHCb

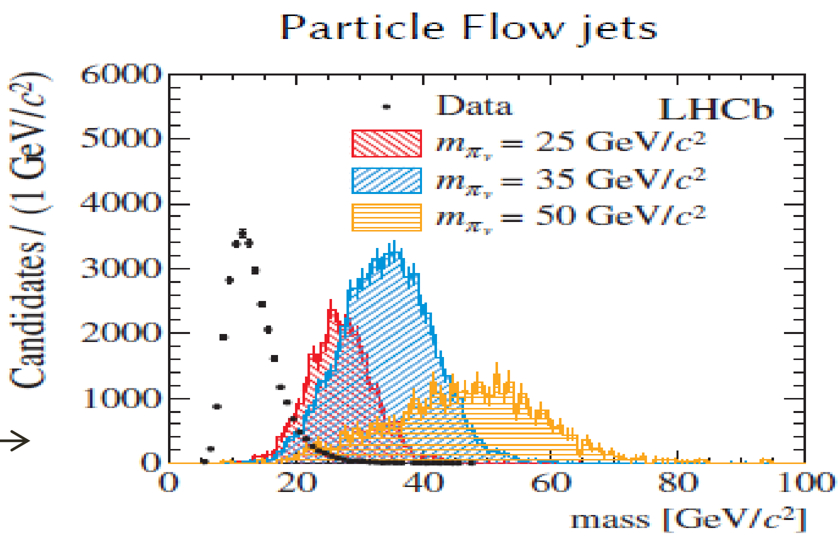
arXiv:1412.3021

LHCb searches for exotic LL particles with mass 25-50 GeV, lifetime 1-100 ps ($\gamma\beta c\tau \leq 20$ cm). Complementary to ATLAS/CMS as lower masses and lifetimes are addressed (lower trigger thresholds).



benchmark signal: $H \to \pi_v \pi_v$, $\pi_v \to b\bar{b}$

- Select only one decay arm (forward spectrometer)
- Signature: heavy PF jets from displaced vertex →

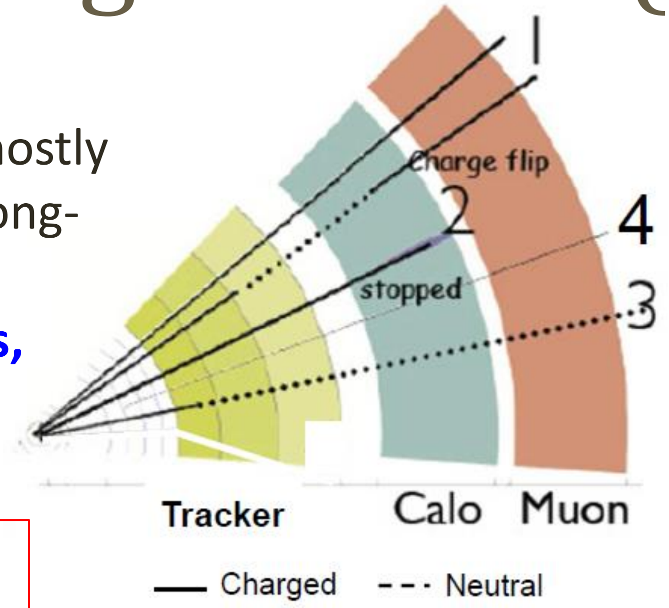


Heavy Stable Charge Particles(HSCP)

Signature oriented search

Various origins of such particles, mostly in the framework of pMSSM (e.g. long-lived gluinos, stau, stop).

Complementarity to SUSY analyses, targeting "long" lifetimes.



Key for detection = anomalous dE/dx deposition

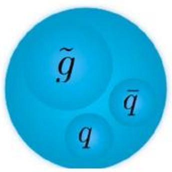
Lepton-like (= 4 in sketch)

e.g. long-lived slepton manifest as a "heavy muon"

Two possible signatures:

- **time-of-flight (TOF)** to outer mu system. Particle velocity v<c
- Anomalous **dE/dx** deposition

Hadron-like (colored particle)

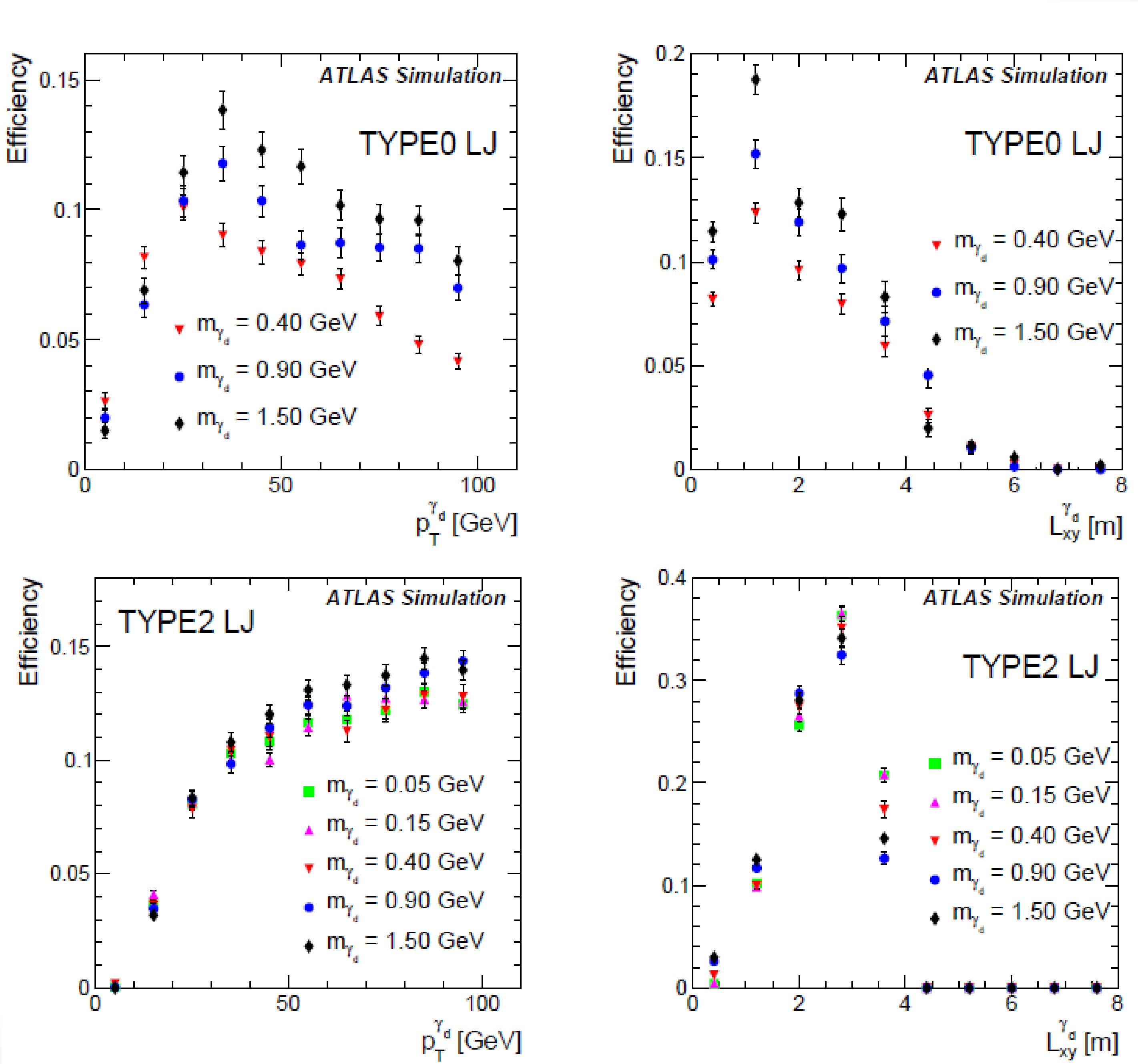


If lifetime > hadronization time scale then gluino/squark R-hadrons or gluinoballs can form. Can change sign and leave no signal in mu system → **This search cannot be performed without dE/dx.**

Reconstruction efficiency for muons and electromagnetic objects (ATLAS run-1)

Muons

Electrons/pions



Disappearing Tracks

CMS run-1 EXO-12-034
ATLAS run-1 SUSY-2013-01

Chargino nearly mass-degenerate with lightest neutralino (AMSB models)

Signature:
- little-no calo deposited energy,
- missing hits in outer tracker

Experimental issues:
- Fake tracks
- Calorimeter dead/noise channels to be known and subtracted

Results: limits on chargino lifetime and mass, mass splitting chargino-neutralino, cross section

Phase-II (under study): tracker with less layers will impact sensitivity

High number of TRT hits in ATLAS run-1.
Efficiency ~1 for charginos decaying before TRT