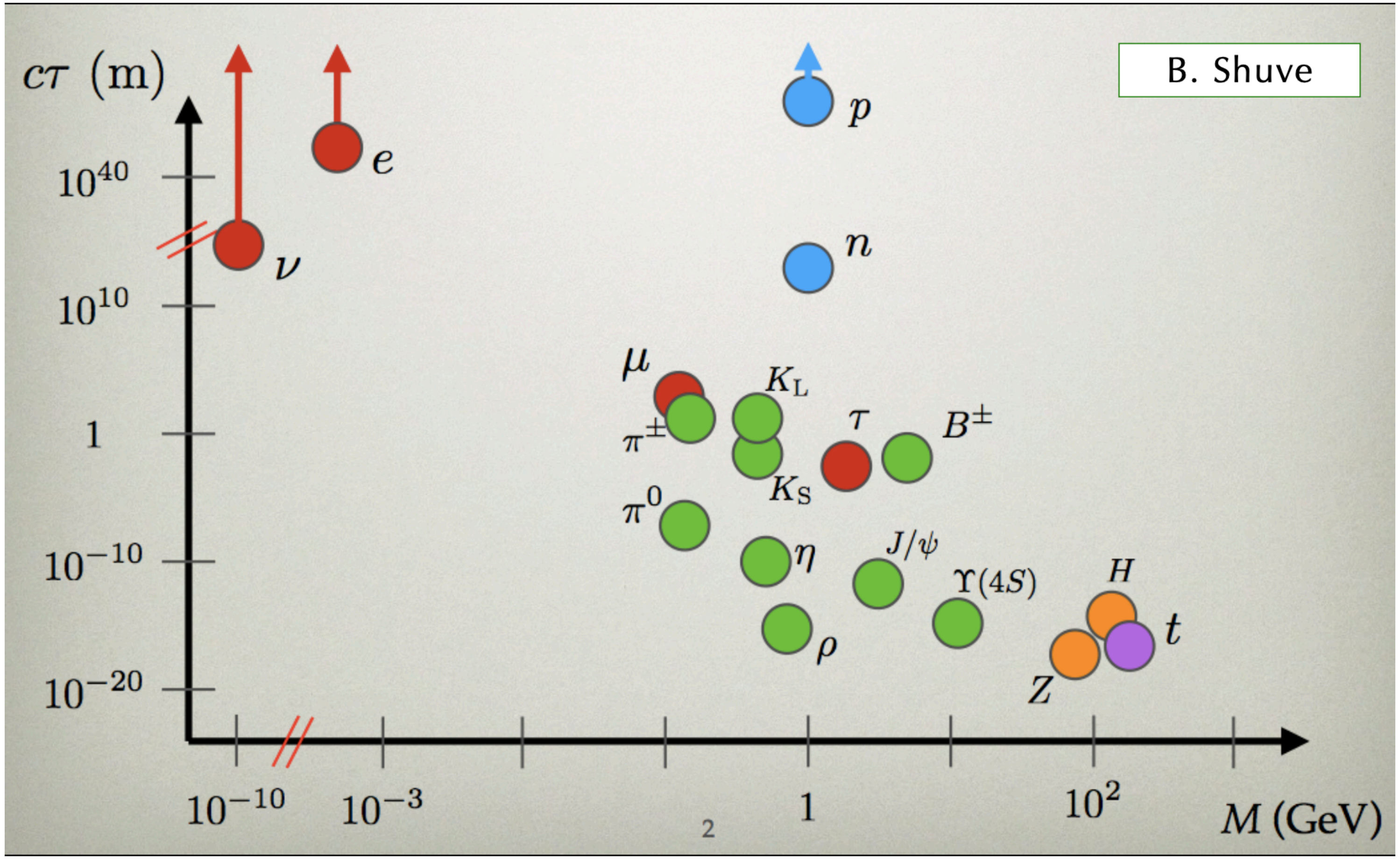
Long Lived Particle Searches at the LHC

J. Boyd (CERN)

11/11/2020

Why search for new LLP at the LHC?



SM particles span a large range of lifetimes – why not BSM particles too?

In SM, particles lifetime usually stems from an approximate symmetry which would make the particle stable. In this case a small symmetry breaking parameter suppresses the decay rate -> long lifetime.

Why search for new LLP at the LHC?

- Many BSM models can naturally lead to LLPs
  - More in this mornings talk by M. McCullough
- e.g. in SUSY:
  - Weak Couplings
    - Example: Weak R-Parity Violating couplings:
      - In many cases if the couplings were stronger they would have led to huge observable effects
    - Example: Weak gravitino couplings:
      - From gravity being such a weak force (SUSY breaking scale)
  - Phase space supressed decays
    - Example: With a pure Higgsino triplet the lightest chargino is almost degenerate with the lightest neutralino. Decay suppresed by phase space – in this case the chargino decays as $\chi_1^+ \rightarrow \pi^+ \chi_1^0$ and is a (shortlived) LLP
  - Decays through heavy mediator particle
    - Example: In split SUSY gluino decays to neutralino through very heavy squark
- And more generally Hidden Valley / Dark Sector models can naturally lead to LLPs
  - Vector portal (Dark photon)
  - Scalar portal (Dark higgs)
  - Neutrino portal (Heavy Neutral Leptons)
  - Axion portal (Axion Like Particles)

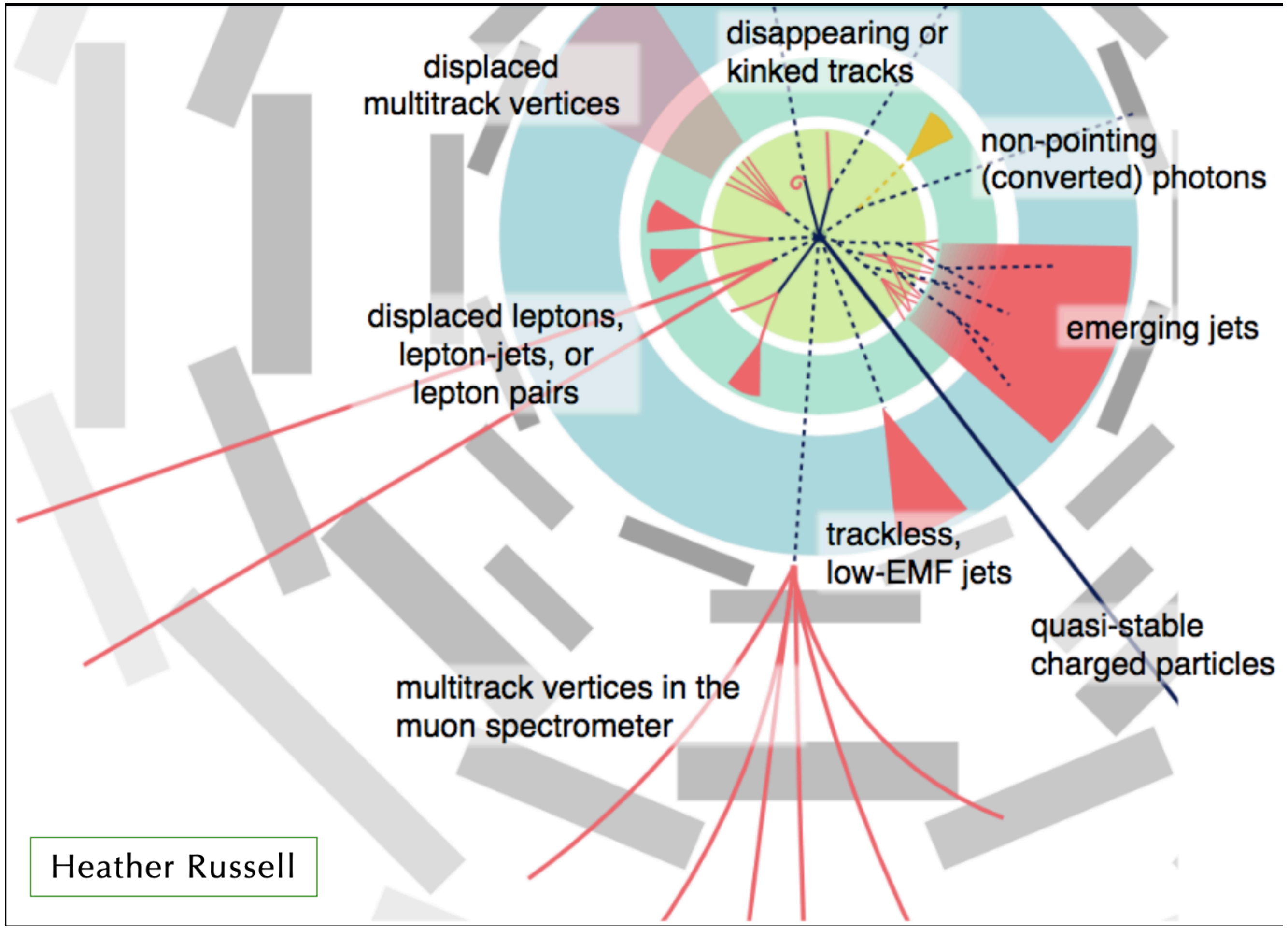
Why search for new LLP at the LHC?

- Another argument is that LLP searches are experimentally difficult, often requiring non-standard techniques:
  - Trigger, Reconstruction, Background Estimation, Evaluation of signal efficiency etc…
- Tends to mean that they are less well covered and (in some sense) are one of the last places (accessible) BSM could be hiding in the LHC dataset

- For this reason LLP searches are also some of the most fun, as the search is less “turning the handle” with existing techniques, but rather inventing new ones…
  - Often trying to use the detector beyond what is was designed for!
- Recently a host of new (small and large) dedicated LLP search experiments have been proposed for the LHC
  - Some being realized now!

https://arxiv.org/abs/1903.04497

LLP searches at ATLAS/CMS



There are a huge number of LLP searches that have been carried out at ATLAS and CMS. Mostly looking for new particles with lifetimes in the range 0.01 – 100ns

In ATLAS and CMS the handles to identify LLP or LLP decays are mostly:

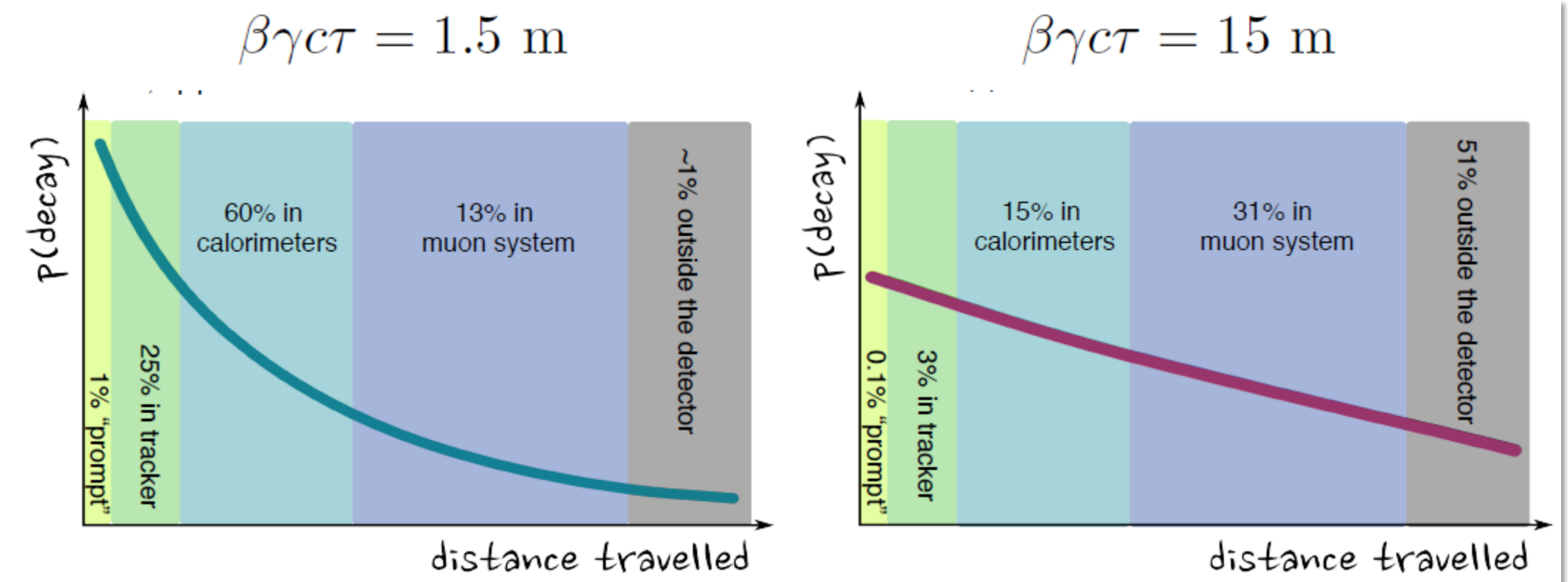
- Timing in calorimeter and/or muon system
- Non-pointing tracks and/or displaced vertices in the tracker or muon detector
- Highly ionizing track signatures
- Disappearing tracks
- Non-pointing calorimeter showers

I will go into detail on only a few of these (my personal choices) which I think demonstrate some interesting points…

LHCb also has an active LLP search programme, mostly relying on the excellent vertexing capabilities of the VELO to search for short lifetimes (displaced vertices close to the collision point).

Covering the full lifetime range

Different lifetimes can lead to very different detector signatures.
For the same model the fraction of decays in different detector systems varies with lifetime.
A suite of searches are need to cover the full lifetime range…



H. Russell, LHC LLP Community workshop, 2017; based on ATLAS geometry

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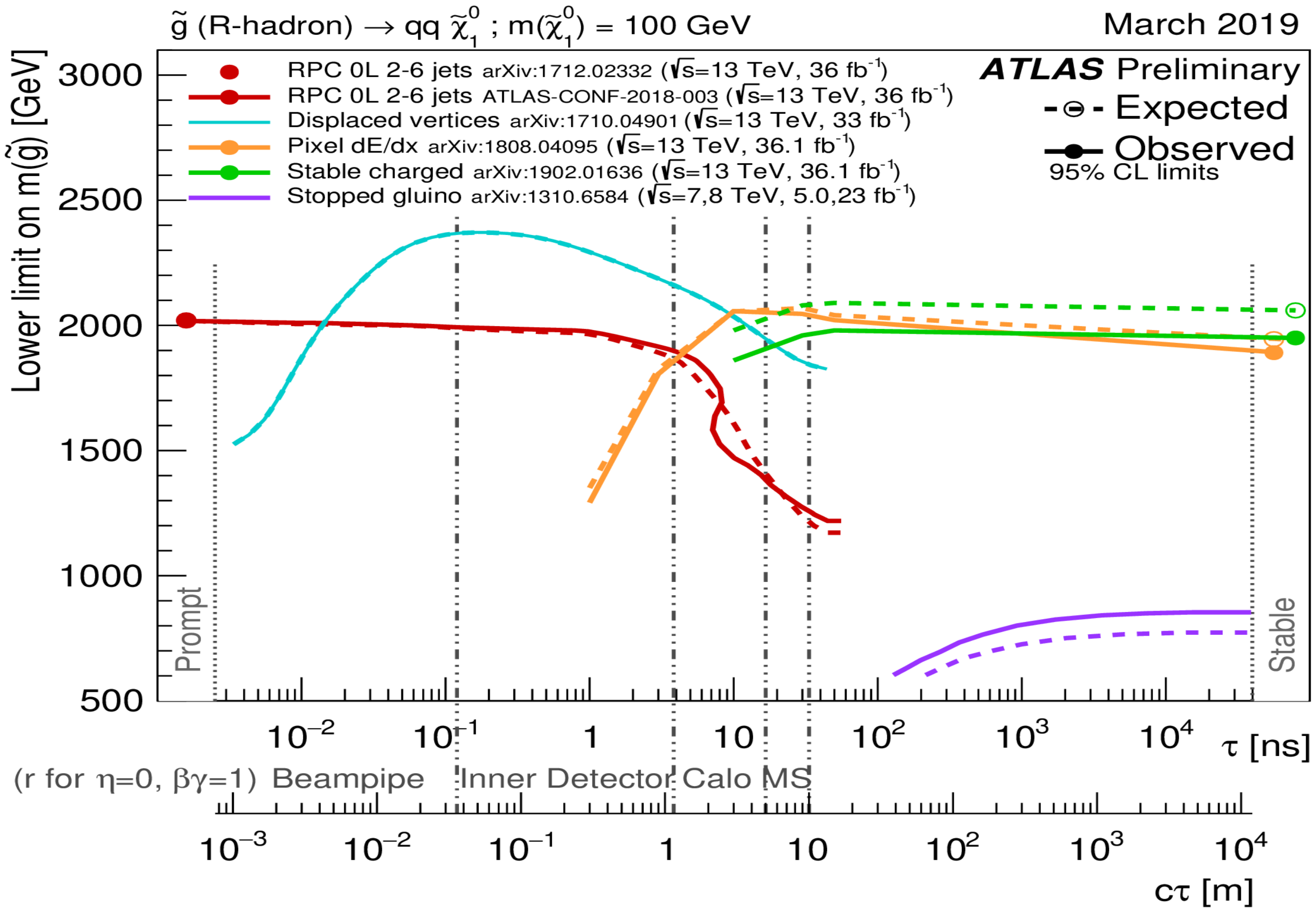

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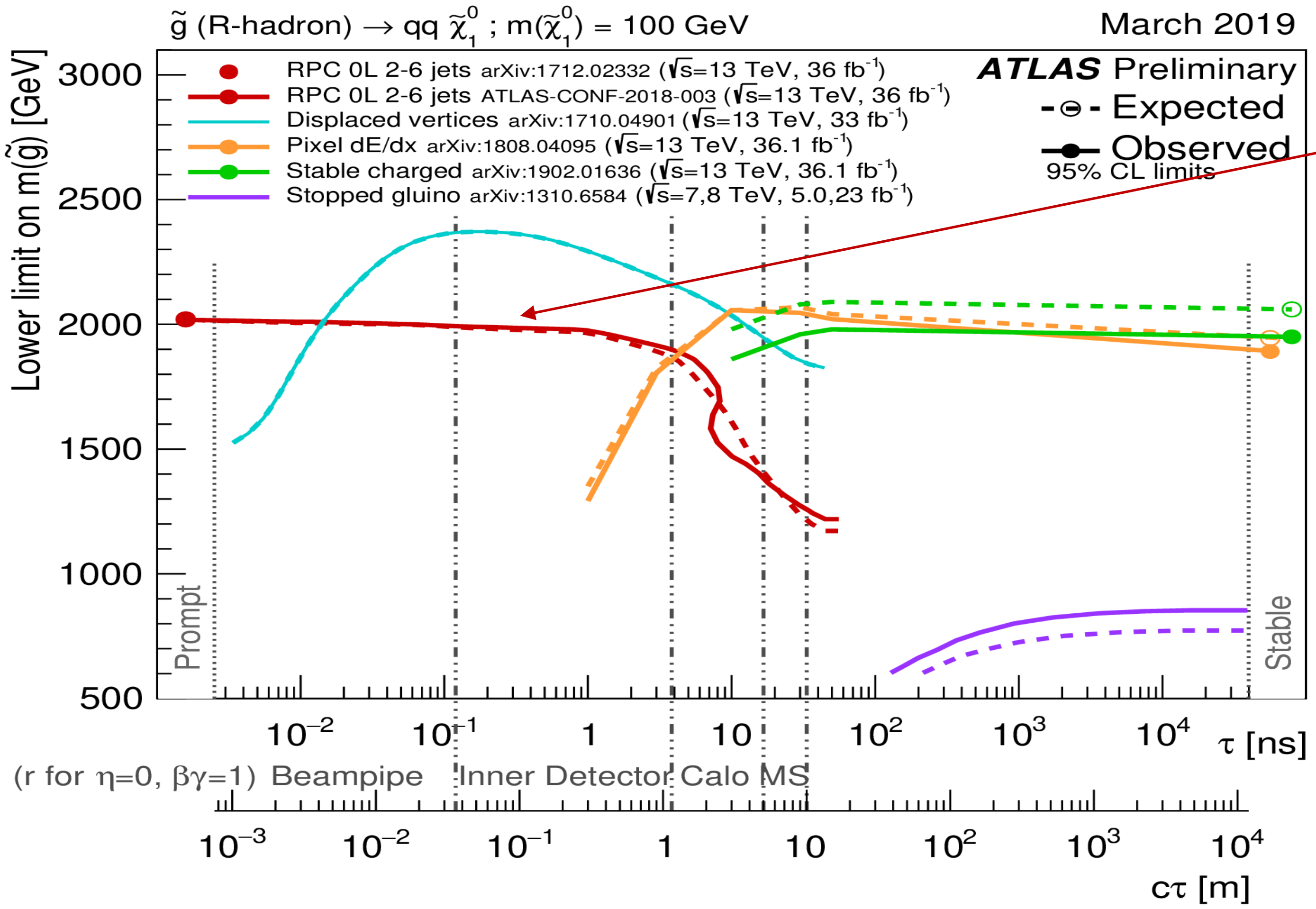
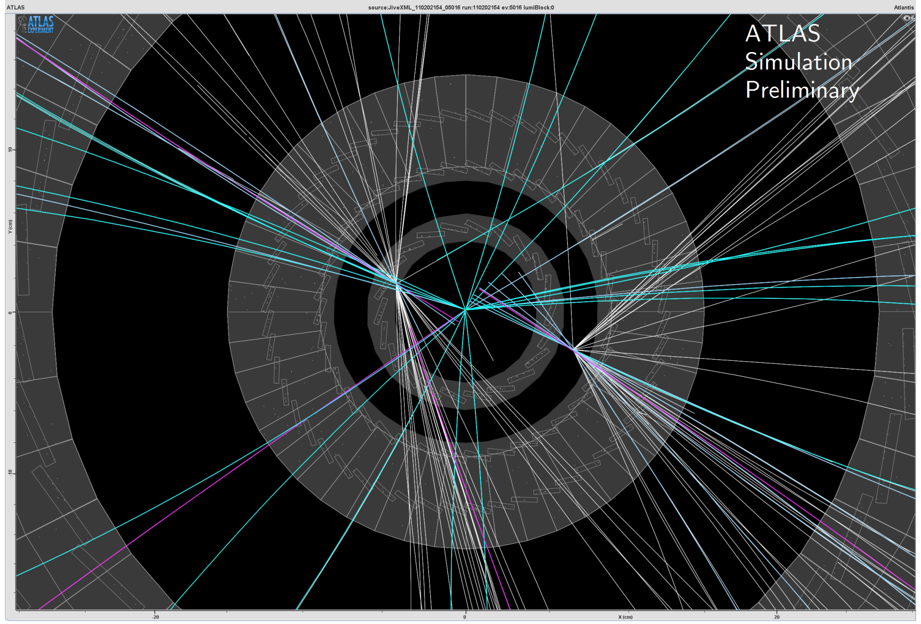


Even re-interpretting 'prompt' searches in LLP scenarios can provide good sensitivity depending on the details of the requirements on the reconstructed objects.



Simulated gluino event with 1ns lifetime

Particular challenges for LLP searches at the LHC

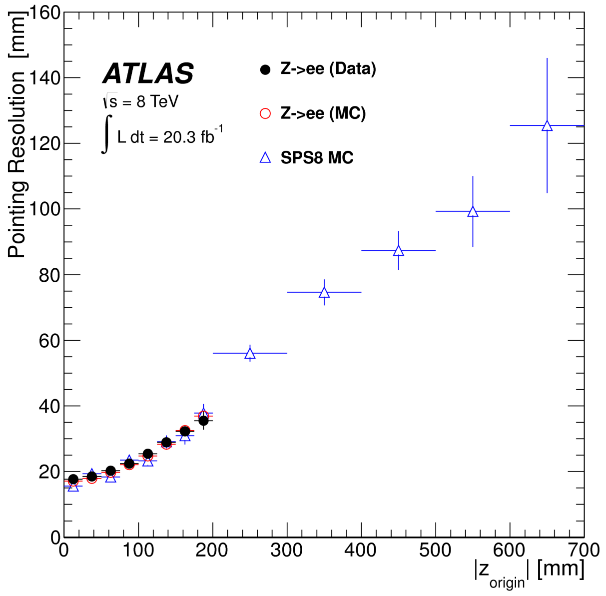
- Triggering
  - Especially L1 trigger, usually does not have sufficient information to trigger on LLP particle/decay
  - Instead often use standard ‘prompt’ physics trigger (e.g. ISR jet)
    - Can substantially reduce sensitivity and increase model dependence of result
- Reconstruction
  - Non-standard reconstruction needed
  - Extra work to optimize this, but not a show stopper
- Background estimatation
  - Again, extra work / thinking – but usually not a show stopper
- Data driven estimatation of signal efficiency
  - Often not possible, as no SM standard candle giving sufficiently LLP signatures / decay signatures to use to evaluate the efficiency
    - E.g. For prompt lepton can use Z->ll tag and probe to measure the efficiency
    - For lepton from LLP decay have to extrapolate efficiency from prompt result using simulation
    - (Sometimes can try clever tricks e.g. use cosmic muons to estimate displaced muon efficiency)

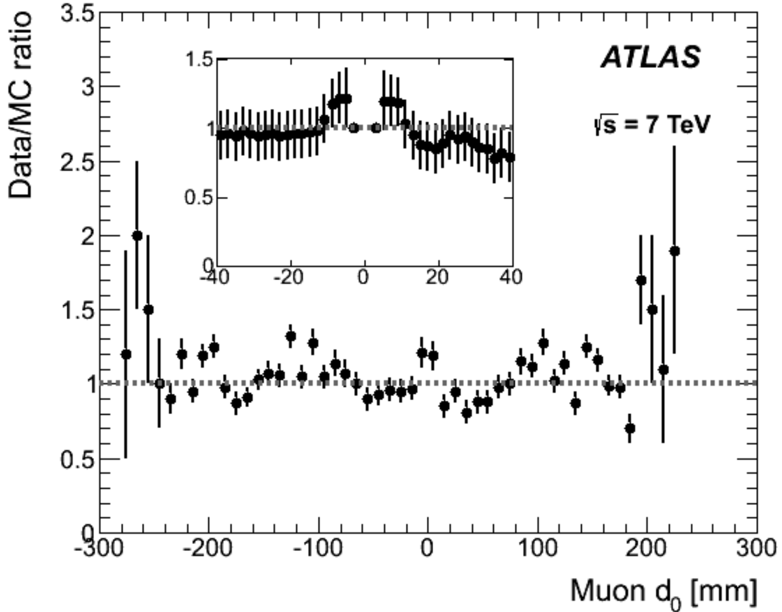
Examples of data driven efficiency estimates

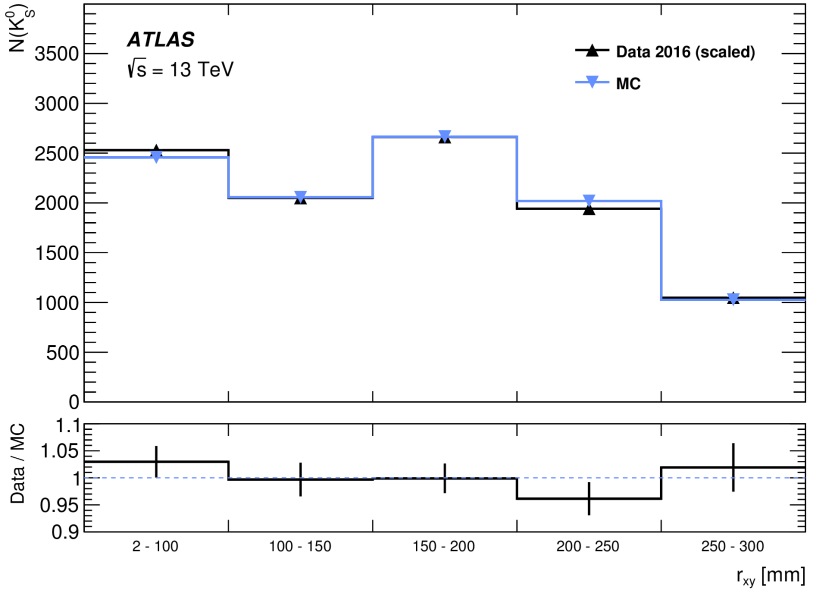
Looking at the pointing resolution of photons in the ATLAS calorimeter, as a function of Z_{origin} (the photon origin point, along the beamline). Can validate in data using Z->ee decays for Z_{origin} values within the LHC luminous region. For larger values need to use simulation.

Validating the muon reconstruction efficiency for muons with large transverse impact parameter (d_0) using cosmic ray muons. The plots shows the ratio of cosmic ray data to cosmic ray MC as a function of d_0.

Validation of large radius tracking efficiency in MC, using Ks decays in data and MC.



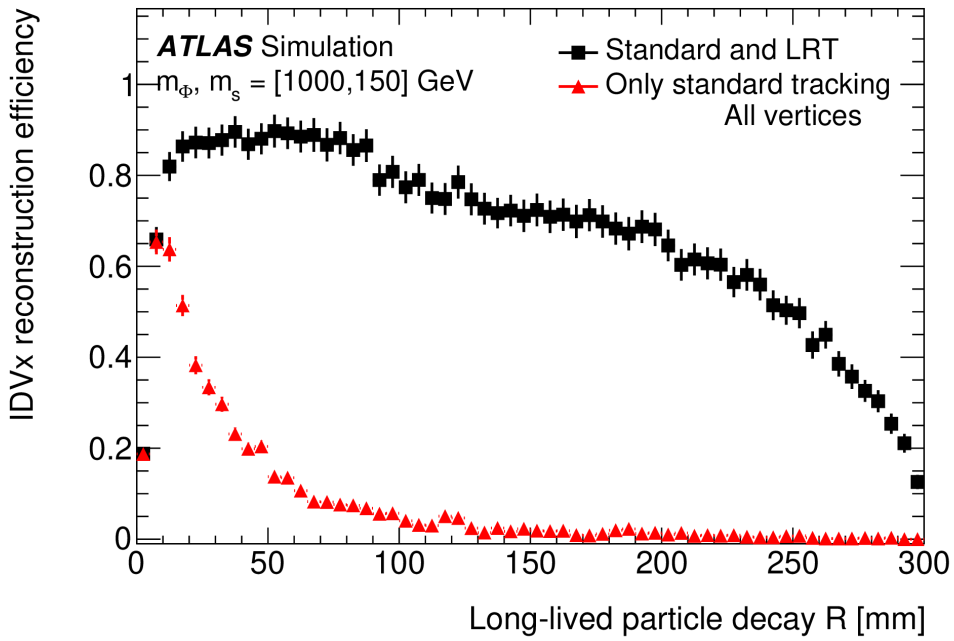


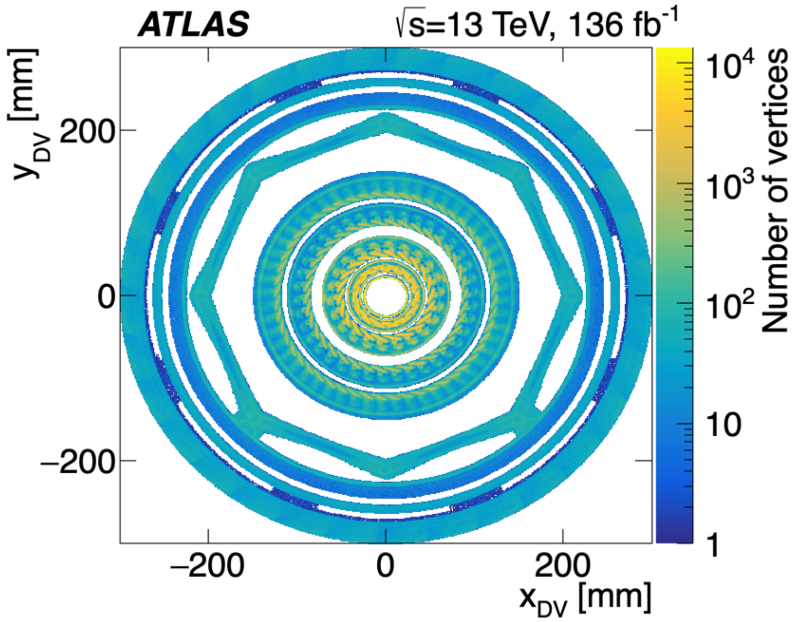


Example Searches

Search for displaced verticies from LLP decays

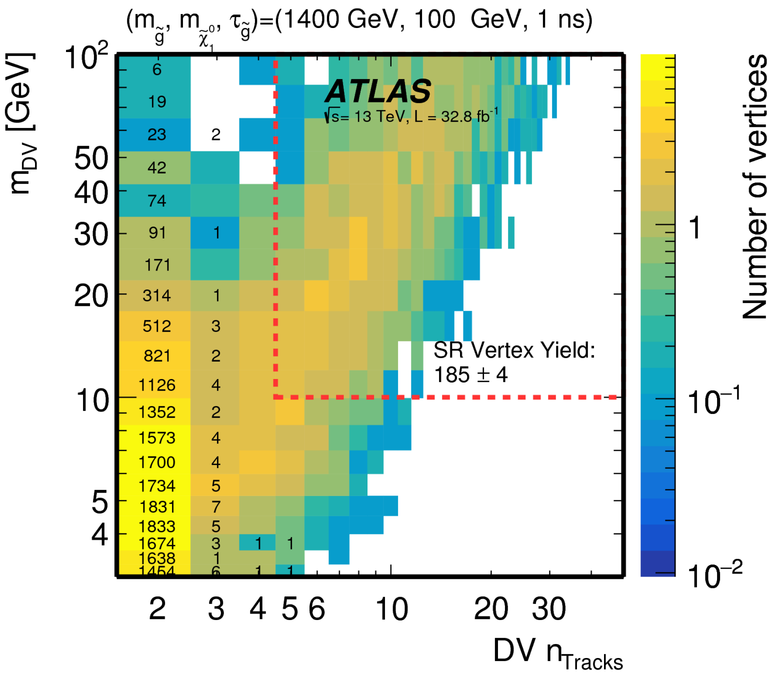
- LLPs with lifetimes in the range 10ps – 10ns that decay hadronically can lead to a displaced vertex in the tracker
- In ATLAS, dedicated Large Radius Tracking is run to find tracks with large impact parameters (using tracker hits not included on standard tracks). In CMS the standard tracking has good efficiency for such tracks.
- To reduce the large background from hadronic interactions with the detector material, a “material map” is used to veto vertices where there is material in all experiments
- Selection applied on number of tracks in vertex and mass of vertex
- Main backgrounds from random crossing of tracks and merging of close-by low-mass displaced vertices and are evaluated from the data

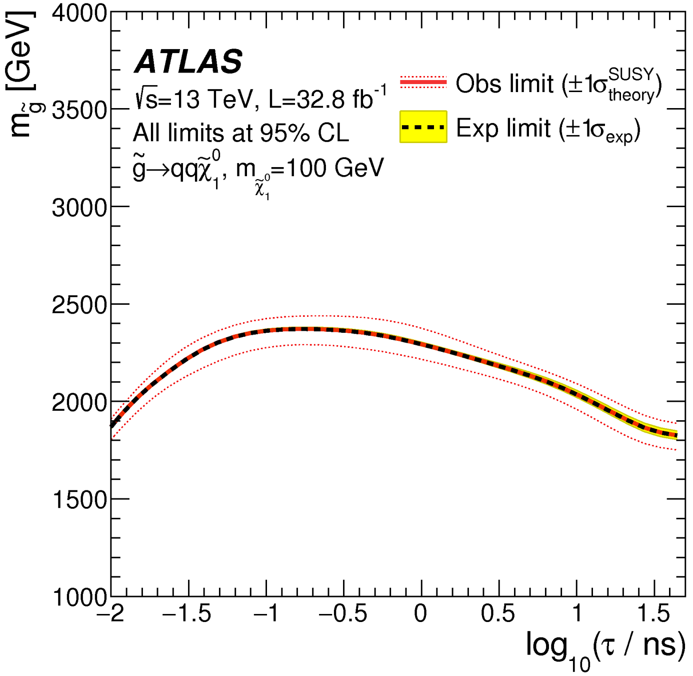




Search for displaced verticies from LLP decays

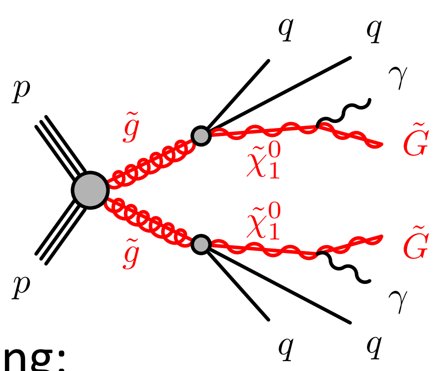
- Not possible to trigger (at L1) inclusively on displaced vertex in tracker
  - Track triggers at L1 may allow this after the Phase-II upgrades for HL-LHC
- Searches use prompt physics triggers: lepton, high pT jet(s), MET
- Example result for MET triggered events (MET>250 GeV):
  - Very low background expected ($0.2_{+0.1}^{-0.2}$) with 0 events observed
  - Sets very stringent limits on gluino mass (best limits on gluinos from any search!)

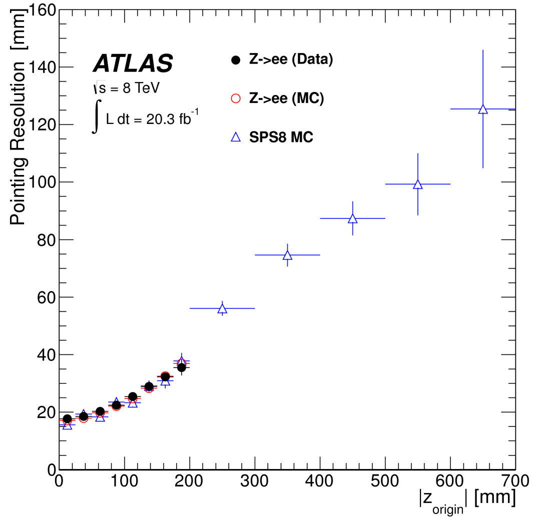




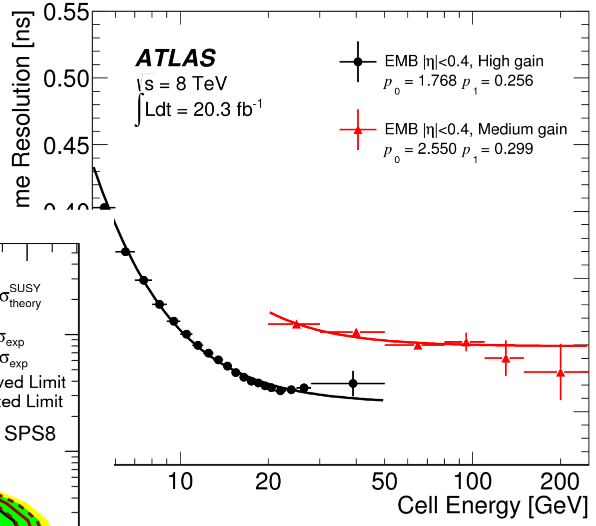
Similar searches with leptons associated to DV, or DV in jet.

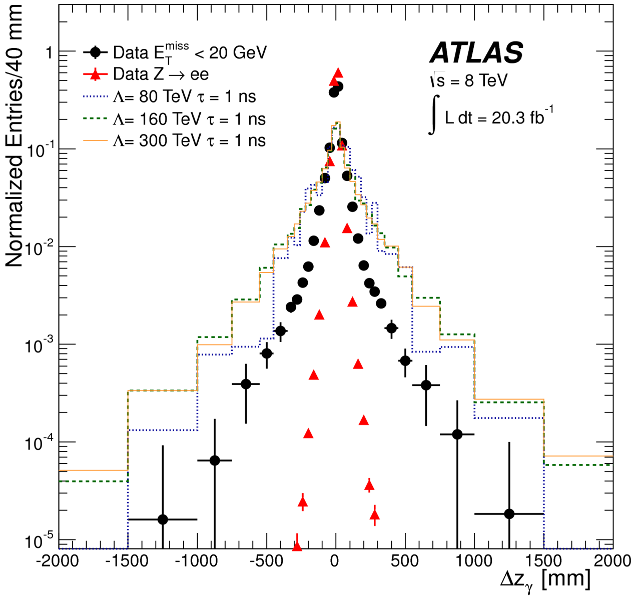
Displaced / Late photons

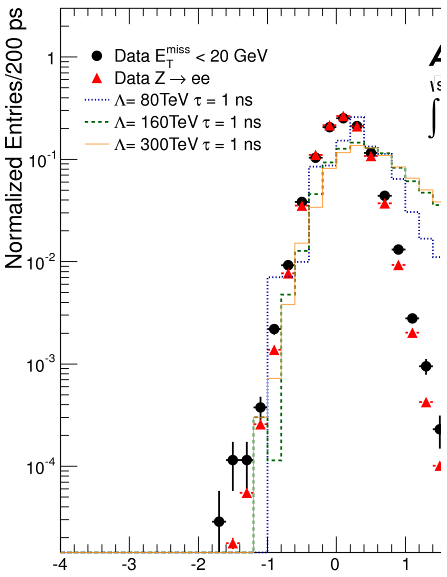


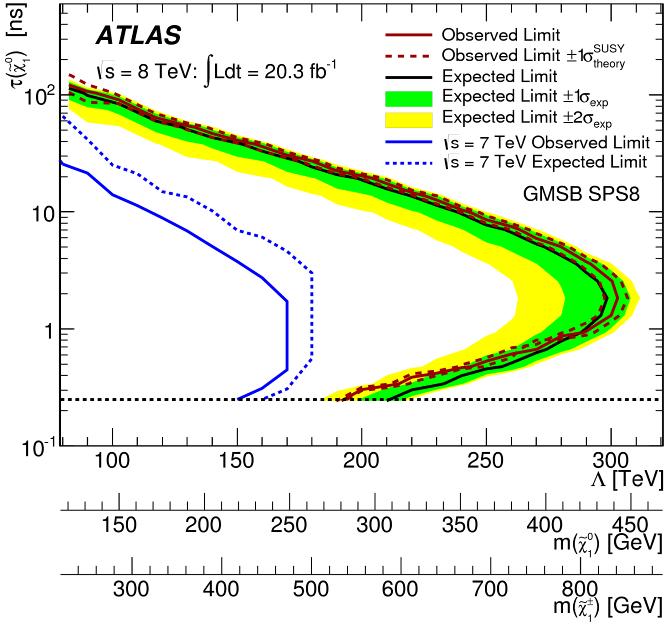


- In GMSB SUSY models can have long lived neutralino decaying to a photon and a gravitino
- ATLAS analysis distinguishes signal and background using:
  - the time of the photon (~300ps resolution)
  - Pointing direction of photon shower along beam line (~20 – 100mm resolution)
- Trigger on photons with loose enough identificantion to have efficiency for photons originating far from the collision point.









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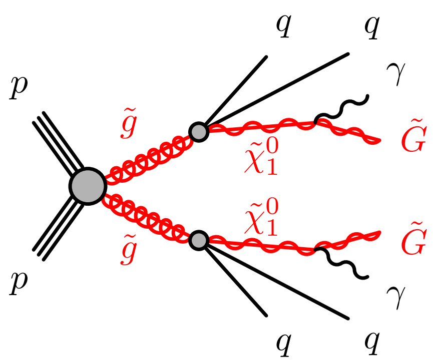

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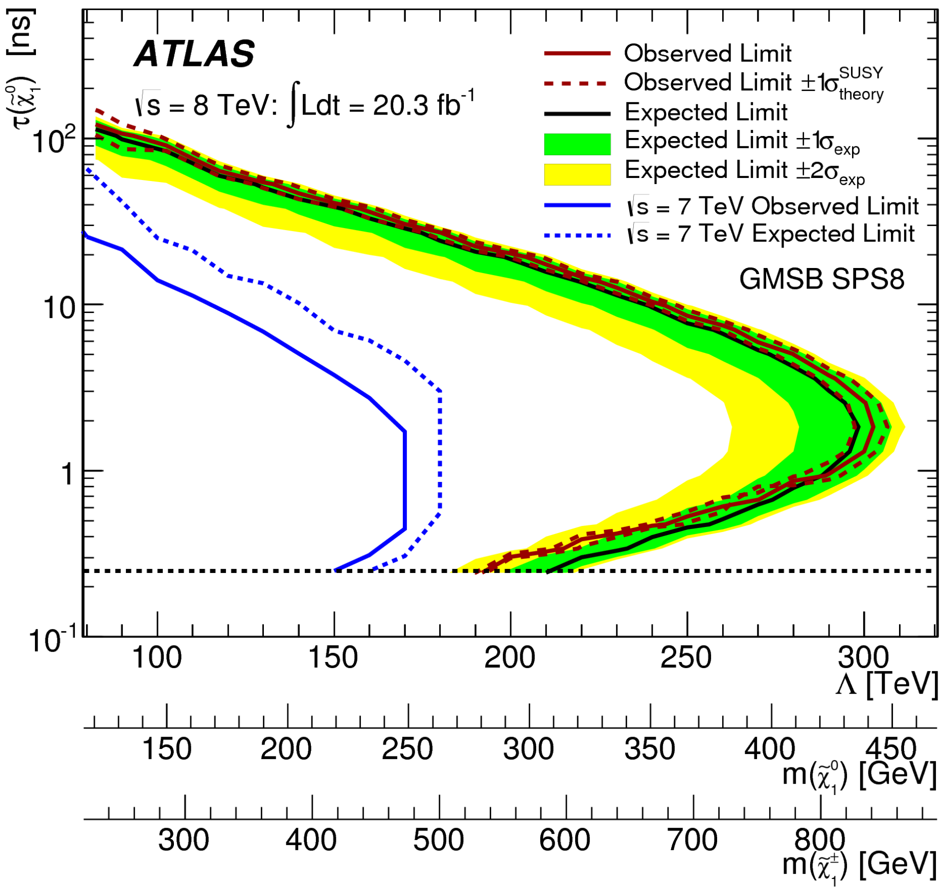
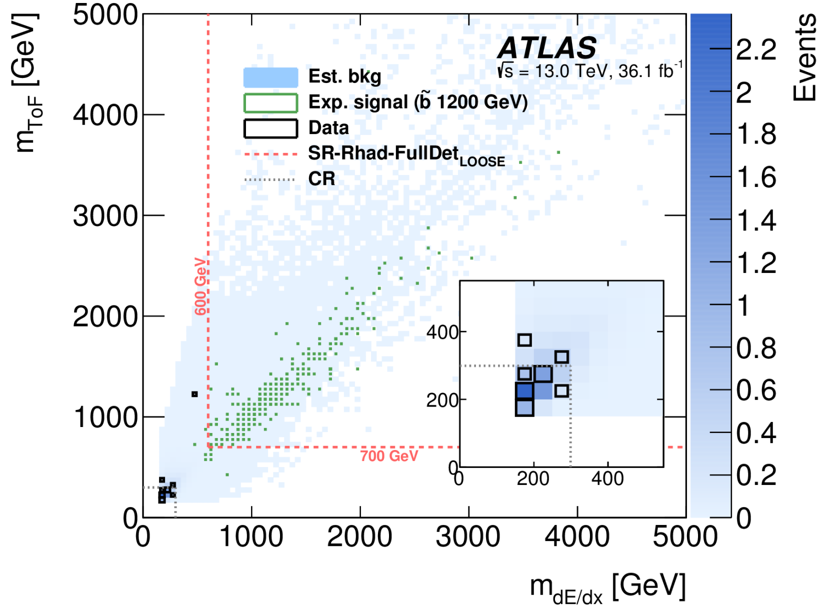
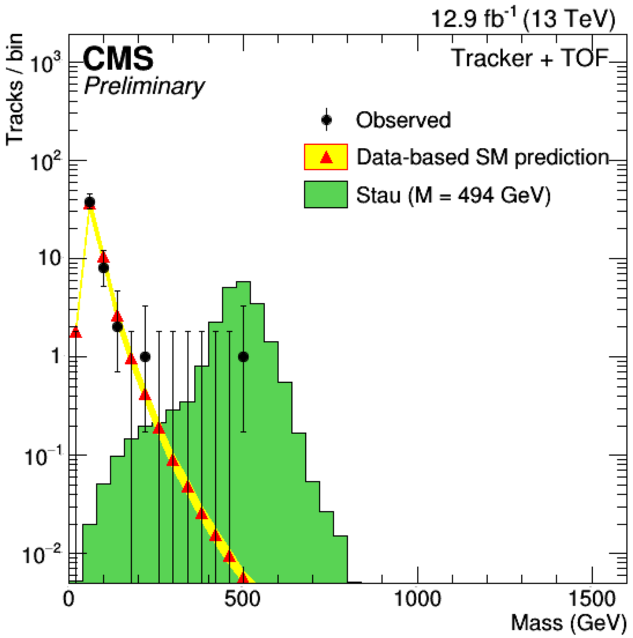


(meta-)Stable massive charged particles

- Use muon trigger
- Select candidates with large energy loss (dE/dx) in the tracker and large β from timing measurements in muon detector
- Background estimated using ABCD method, assuming β and dE/dx uncorrelated for background
- Combine measurements to estimate mass of candidates

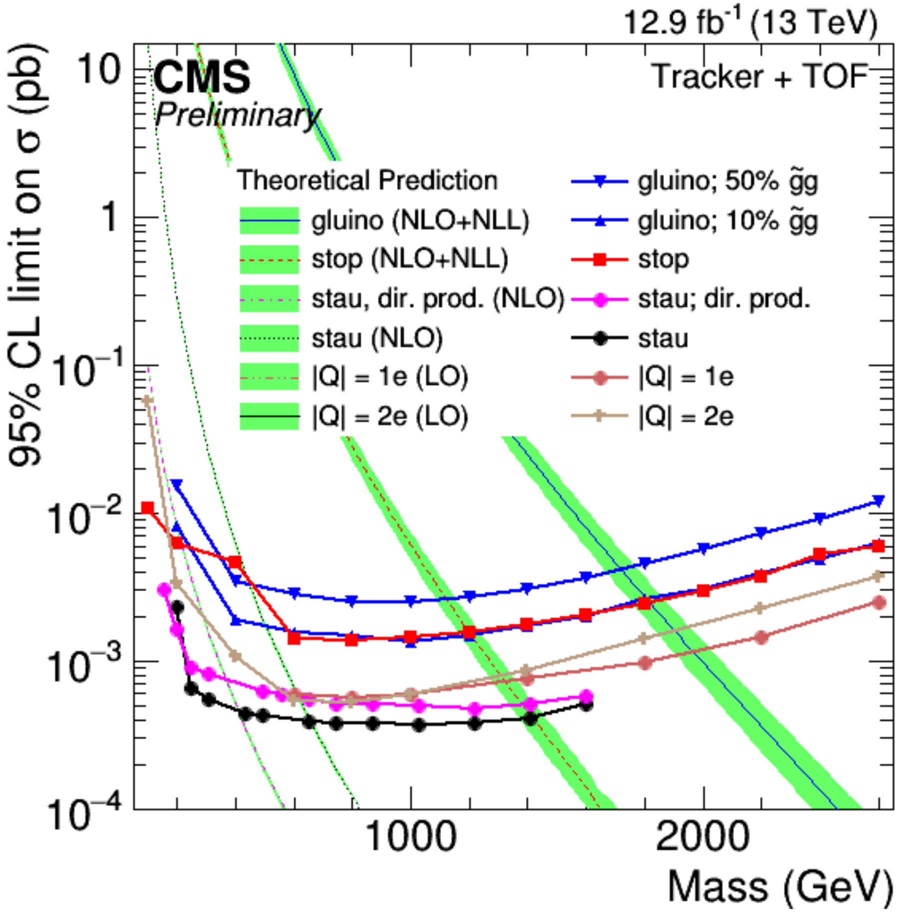




(meta-)Stable massive charged particles: Example sensitivity

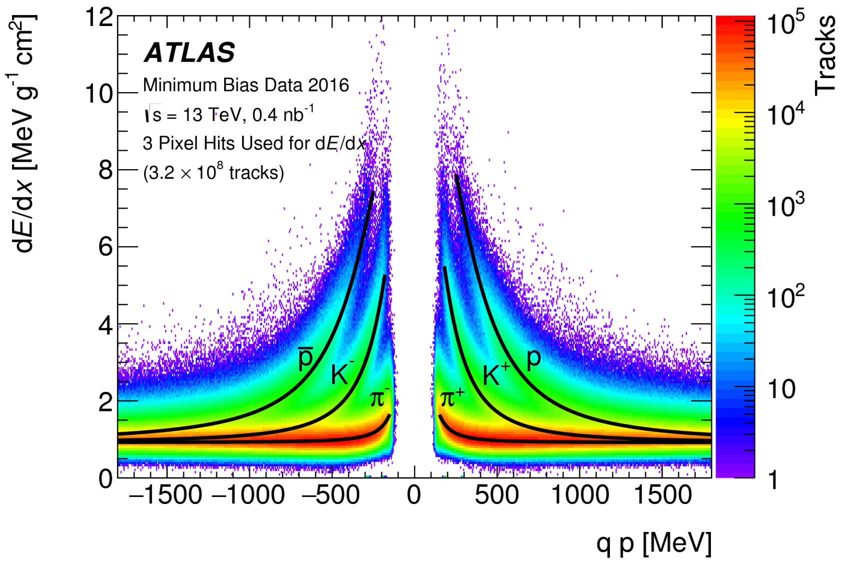
For coloured LLPs limits ~1.2 TeV (stop) - ~1.8 TeV (gluino)
For stau depends on the production model – but limits in the range 400-600 GeV

Model	Analysis	Mass Limits
Gluino $f = 0.1$	tracker-only	$M > 1850(1850)$ GeV
	tracker+TOF	$M > 1810(1810)$ GeV
Gluino $f = 0.1$ CS	tracker-only	$M > 1840(1840)$ GeV
Gluino $f = 0.5$	tracker-only	$M > 1760(1760)$ GeV
	tracker+TOF	$M > 1720(1720)$ GeV
Gluino $f = 0.5$ CS	tracker-only	$M > 1800(1800)$ GeV
Stop	tracker-only	$M > 1250(1250)$ GeV
	tracker+TOF	$M > 1200(1200)$ GeV
Stop CS	tracker-only	$M > 1220(1220)$ GeV
GMSB Stau	tracker-only	$M > 660(660)$ GeV
	tracker+TOF	$M > 660(660)$ GeV
Pair Prod. Stau	tracker-only	$M > 170(170)$ GeV
	tracker+TOF	$M > 360(360)$ GeV

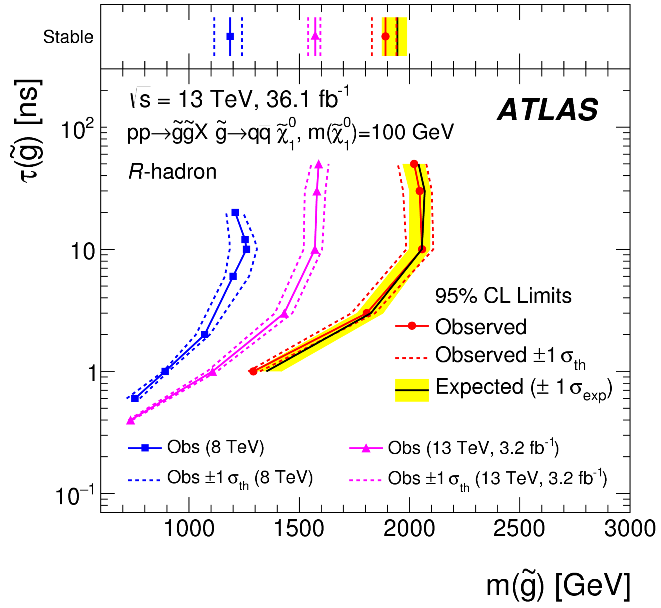


(meta-)Stable massive charged particles: Extensions

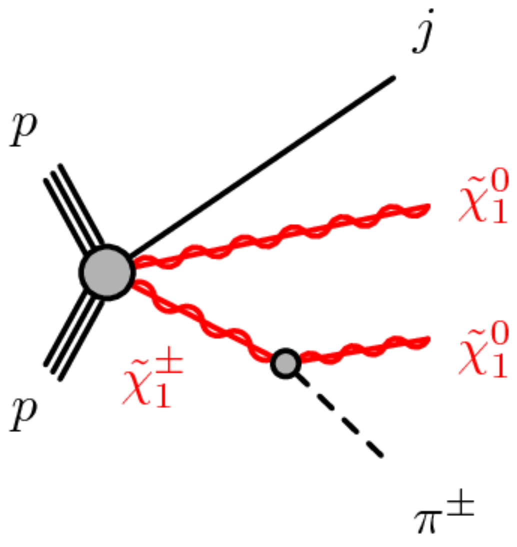
- Coloured LLPs (hadronizing to form R-hadrons) can change electric charge during propagation through detector due to interactions with detector material
  - Use calorimeter timing instead of muon timing to search for candidates which start off charged but become neutral in the detector
  - Change to MET trigger
- Increase sensitivity to lower lifetimes by just using dE/dx measurements (background estimation becomes more difficult)
  - Push to lowest lifetimes using dE/dx of tracklets with only a few pixel hits on them
    - Radius of first few tracker layers sets accessible lifetime range



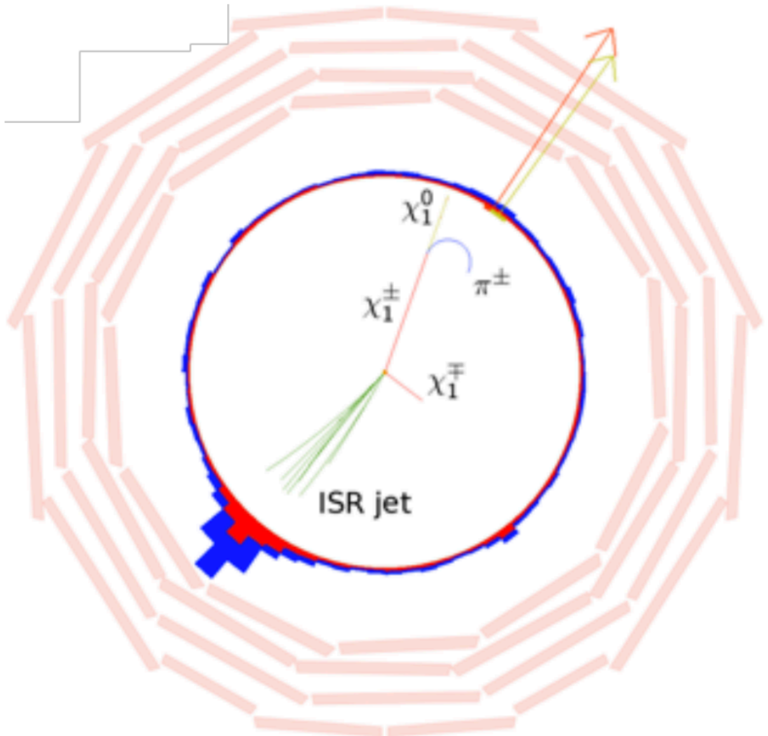
dE/dx calibrated at <1 GeV scale. Searching for new particles at the TeV level.



Disappearing track signature

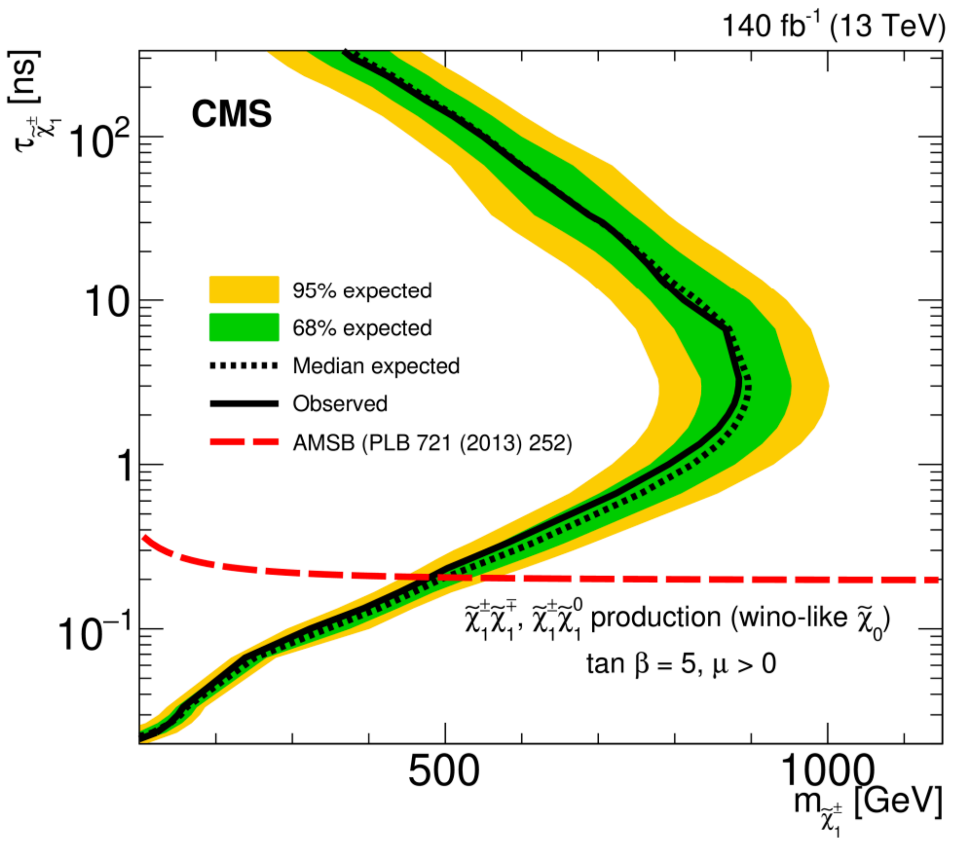


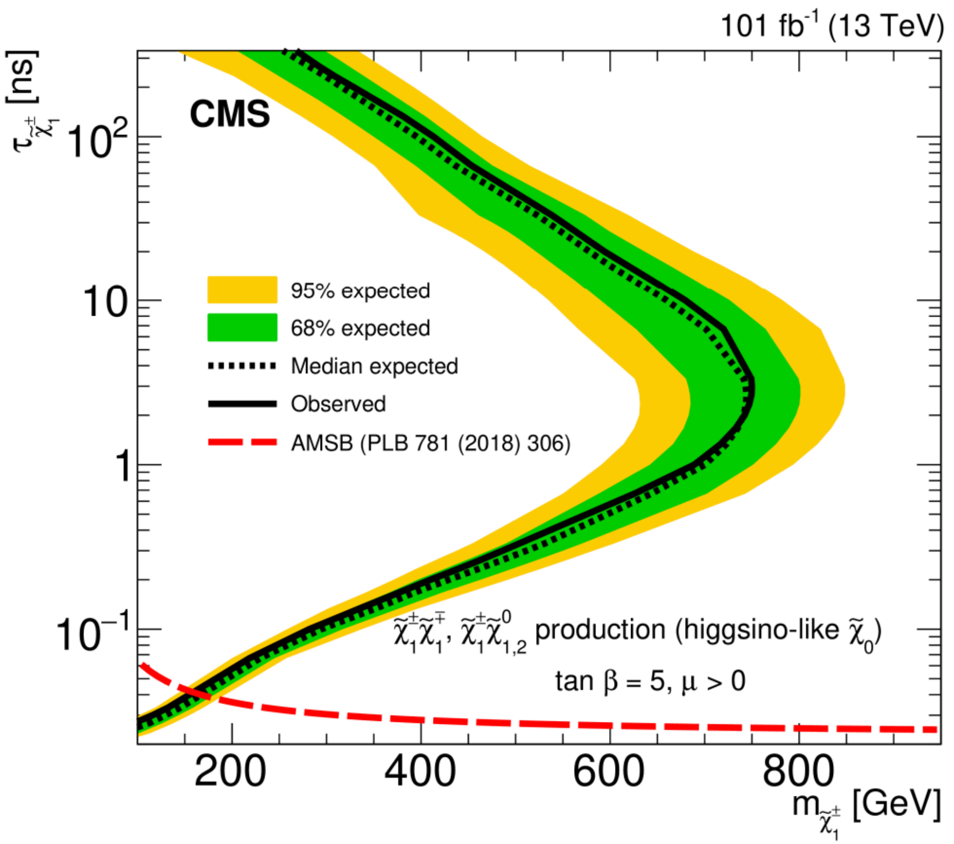
- In SUSY the lightest electroweakino states can be nearly degenerate
  - E.g. for wino or higgsino like LSPs
  - Small mass splitting supressed decay rate of lightest chargino ($\tilde{\chi}_1^+$) and leads to non-prompt decay
  - Can be searched for by looking for a short charged particle track that disappears with the decay $\tilde{\chi}_1^+ \rightarrow \pi^+ \tilde{\chi}_1^0$ (where the pion is too soft to be detected)
- The analysis:
  - Trigger on an ISR jet +MET
  - Select events with a high p_T high quality short track
  - Reject tracks associated to reconstructed leptons or with associated energy in the calorimeter
  - Backgrounds estimated in data control regions (e.g. Tag&Probe for disappearing lepton tracks that fail veto)



Disappearing track signature

Only 2017/8 data included here.
New CMS pixel detector installed for 2017 running, with extra barrel layer, and closer inner radius allows shorter liftime charginos to be probed.





In AMSB SUSY scenarios excludes winos LSPs with masses below and higgsino LSPs with masses below.
Since light higgsinos well motivated by naturalness big interest in pushing sensitivity to shorter lifetimes to increase higgsino exclusion.

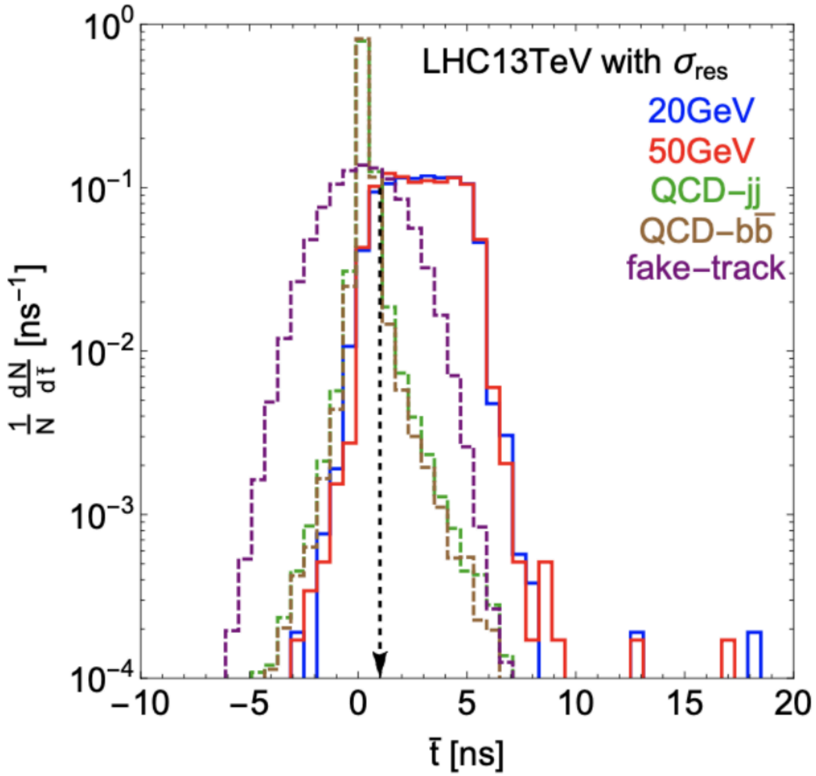
New ideas for improving triggering on LLPs

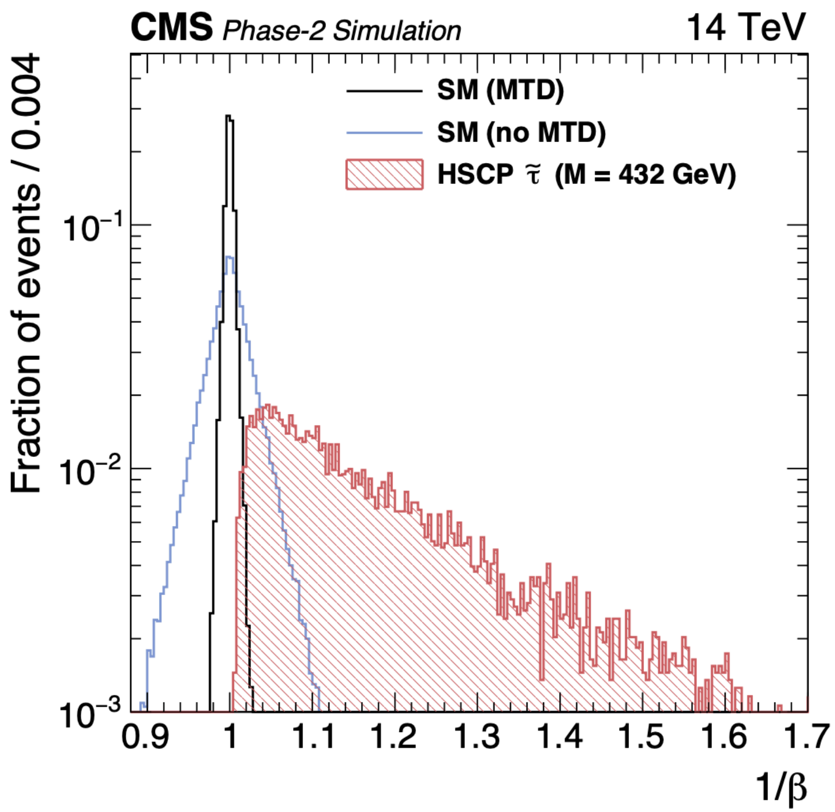
In many cases the L1 trigger limits LLP search sensitivity
Makes searches more model dependent since often requires additional object in event to trigger on.
New ideas to take into account improvements in trigger hardware introduced for Phase-1 (LS2) and Phase-2 (LS3) upgrades.
Some examples:

- Use timing information in trigger (trigger on slow particles reaching calorimeter of dedicated timing detector)
- Trigger on large-d_0 tracks seen in L1 track trigger (as a trigger for displaced vertex analyses)
- Use trigger information from consecutive bunch crossings to improve sensitivity for very slow particles reaching muon detectors

New ideas for improving triggering on LLPs: Timing at L1

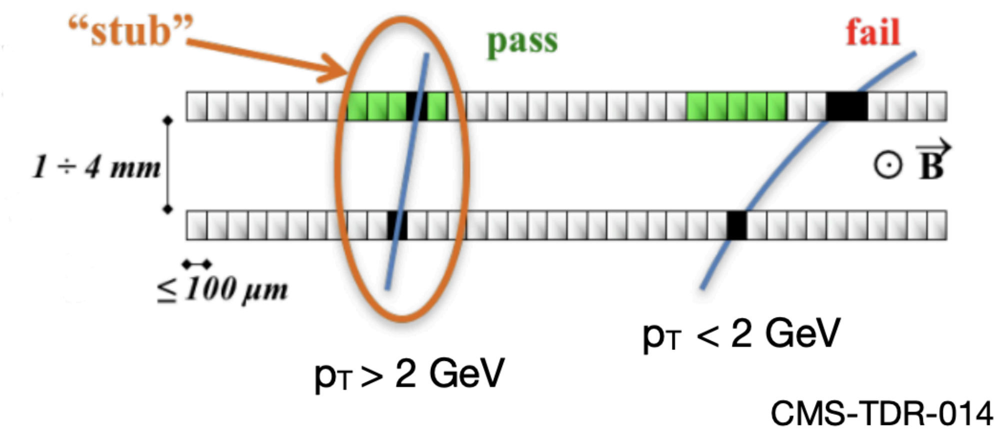
Understanding how this will be used for LLP trigges at L1 is still work in progress.
But time resolution of 30ps for the CMS MIP Timing Detector, and 25ps for the High Granularity Calorimeter can offer excellent discrimination between a LLP signal and background – with the information in principle available in the L1 trigger. (HGCal information can also provide calorimeter cluster 'pointing' information which can be used at L1).

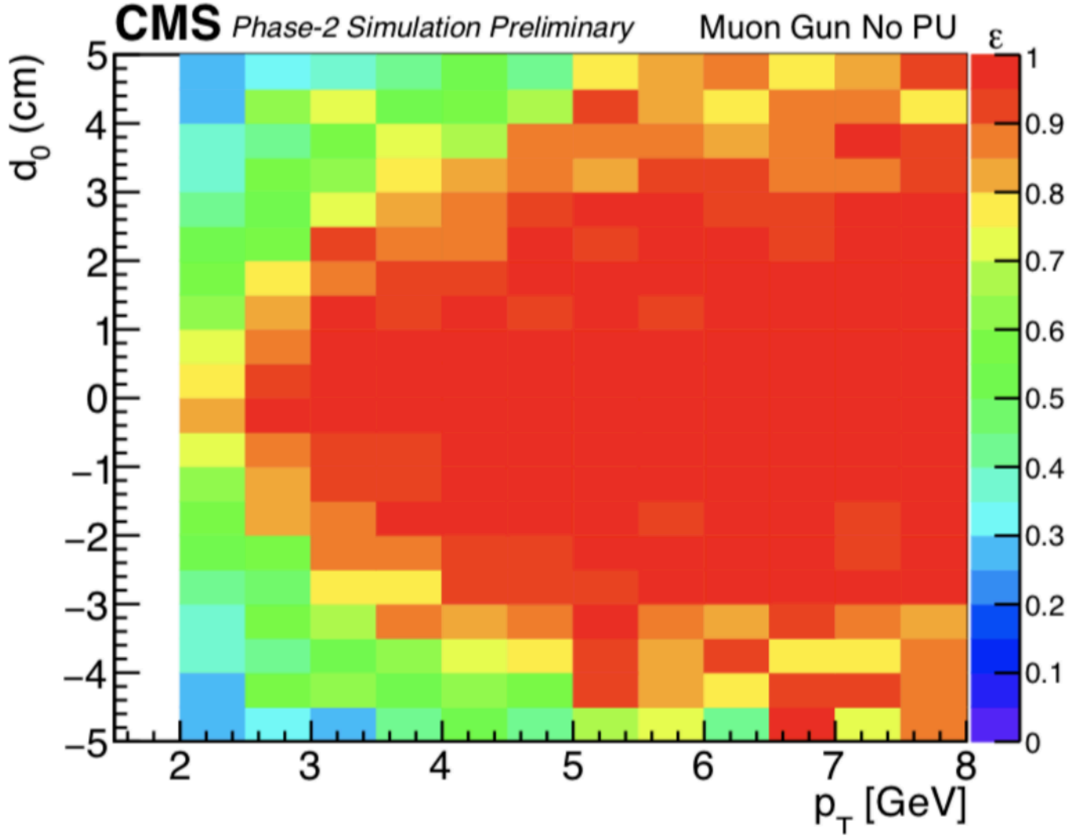




New ideas for improving triggering on LLPs: Large d0 tracks at L1

The L1 track trigger in the CMS Phase-2 upgrade makes track stubs corresponding to tracks from the collision point with p_T>2 GeV.
Depending on the available resources, the trigger can have good acceptance for displaced tracks with d_0 upto >5cm which could then be used to seed later triggers looking for displaced vertcies in the tracker.

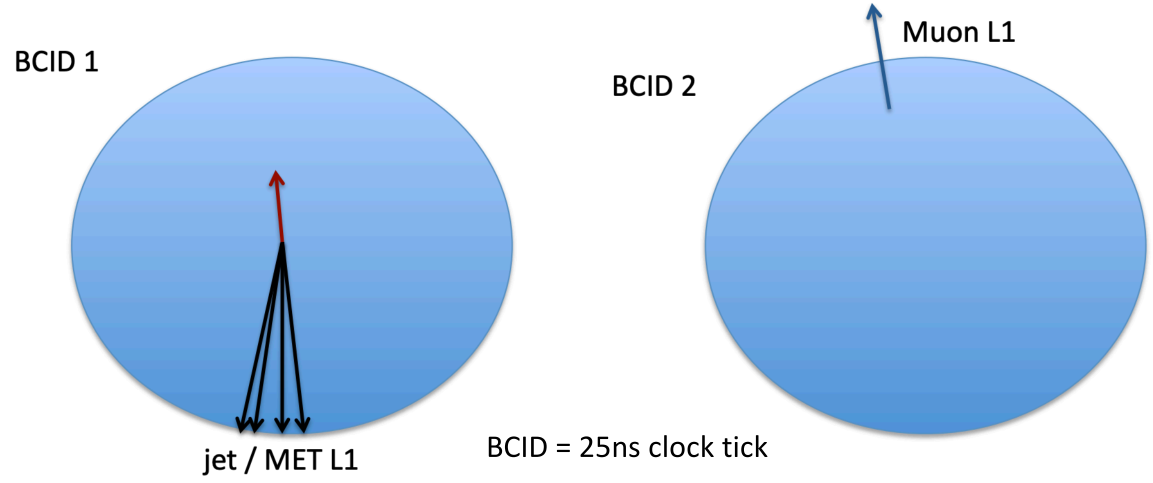


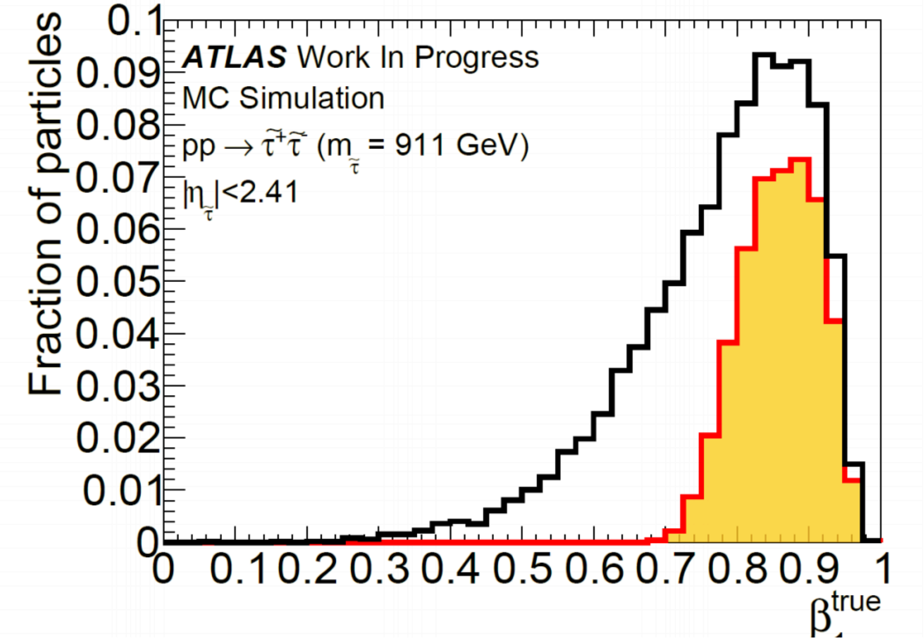


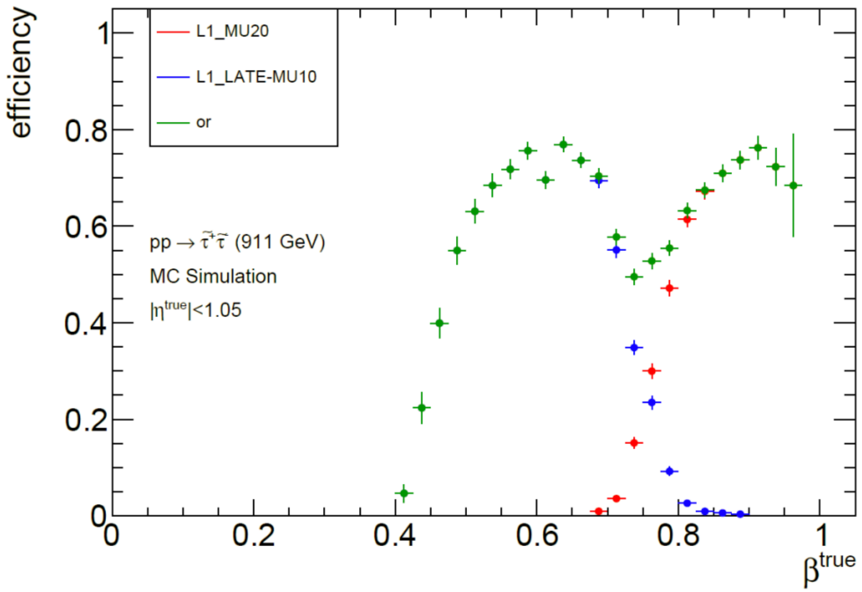
There will be significant background from material interactions giving displaced tracks - to be studied further.

New ideas for improving triggering on LLPs: Triggering across bunch crossings

The ATLAS L1 muon trigger loses efficiency for heavy particles with **β**<0.8 since the signals start to come in the next bunch crossing.
A new trigger has been developed that uses L1 trigger objects in 2 consecutive bunch crossings: The first has a Jet or MET trigger (from ISR) and the second see's the signal of the heavy particle in the Muon detector.
As can be seen in the plots below – this can provide a boost in the trigger efficiency for e.g. heavy stau's.



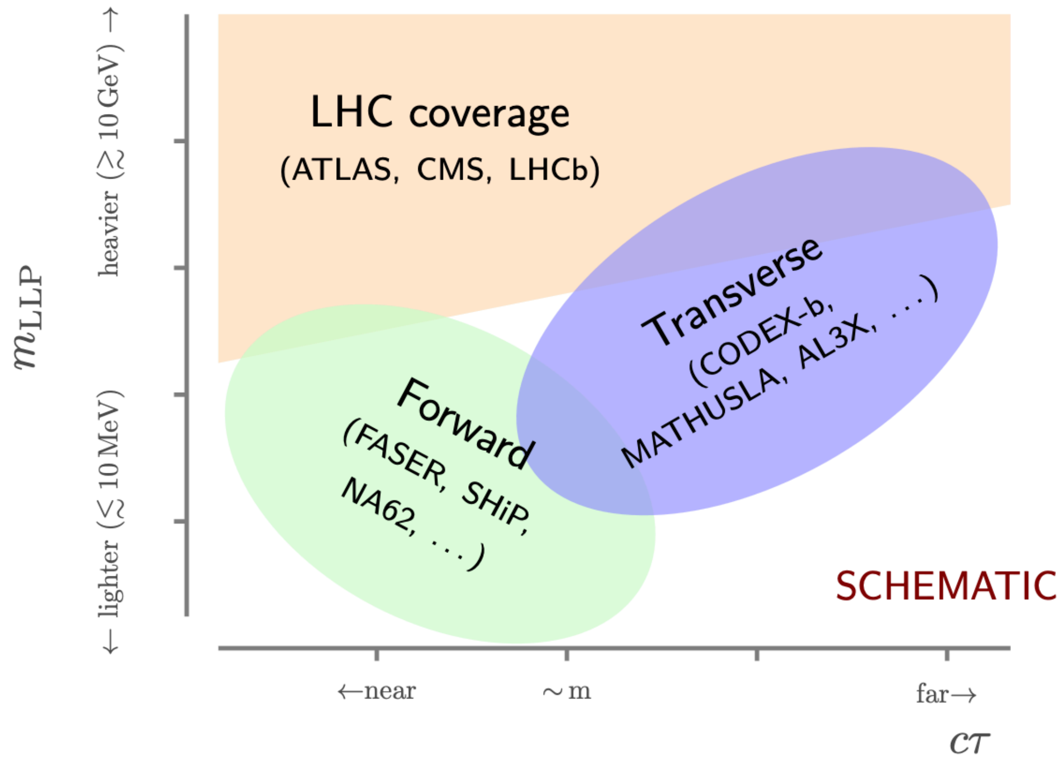


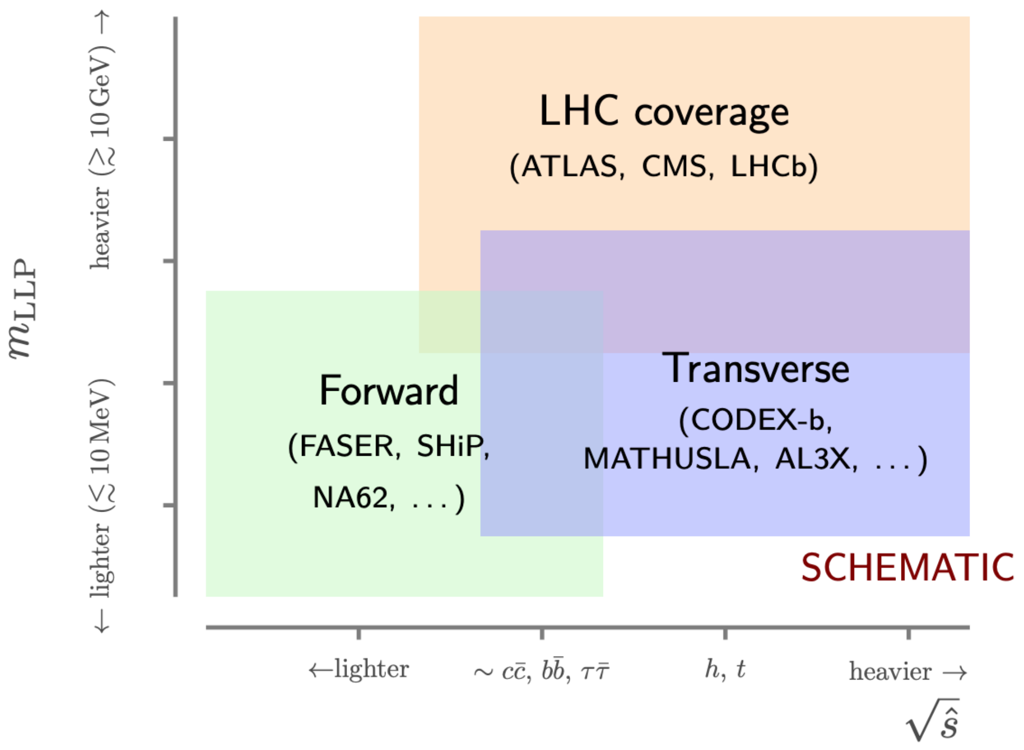


These plots are not approved by ATLAS. Please treat as such!

Proposed new LLP experiments at the LHC

From Codex-b physics case paper: 1911.00481



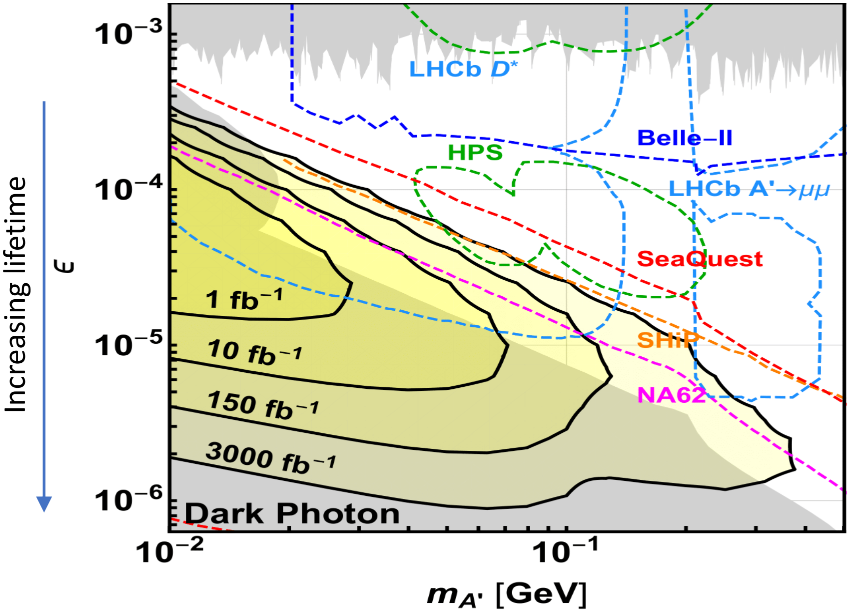


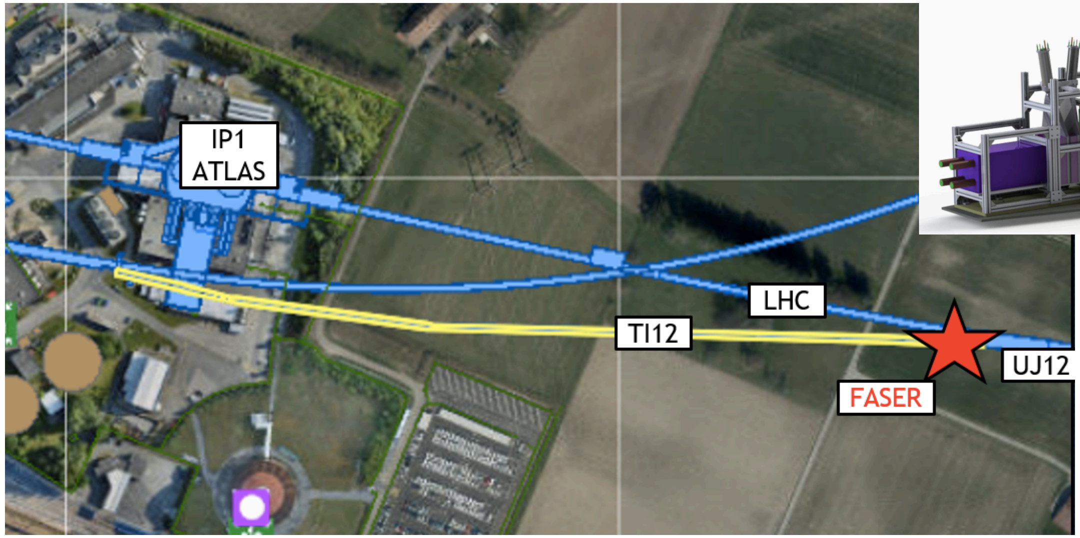
In recent years there have been a number of proposals for new dedicated LLP experiments to be installed at the LHC.
Spanning different regions of forward/transverse space, and very different detector sizes and costs.
Some are being realized now, some in discussion over funding and approval…

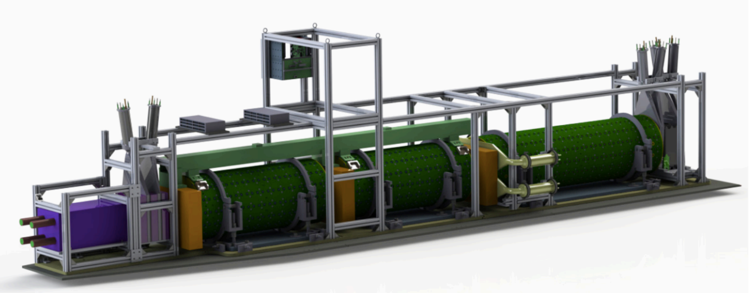
https://arxiv.org/abs/1812.09139

FASER

- FASER is a small experiment (5m x R=0.1m) to search for long lived, light particles produced in meson decay in the very forward region of LHC collisions ($|\eta|>9.1$)
- It sits in an unused tunnel TI12, ~500m from the ATLAS collision point, and directly aligned with the beam collision axis
- Covering only (2×10^{-6})% of the solid angle, 2% of π^0's (with E>10GeV) are produced in the FASER angular acceptance
  - 10^{15} pi0s in LHC Run-3
- For dark sector particles produced very rarely in π^0 decays (e.g. BF ~ $O(10^{-10})$) FASER can still detect a significant number of signal events







https://arxiv.org/abs/1812.09139

FASER

FASER being constructed and installed in LS2 to take data in Run 3. Installation to be completed by Feb 2021.

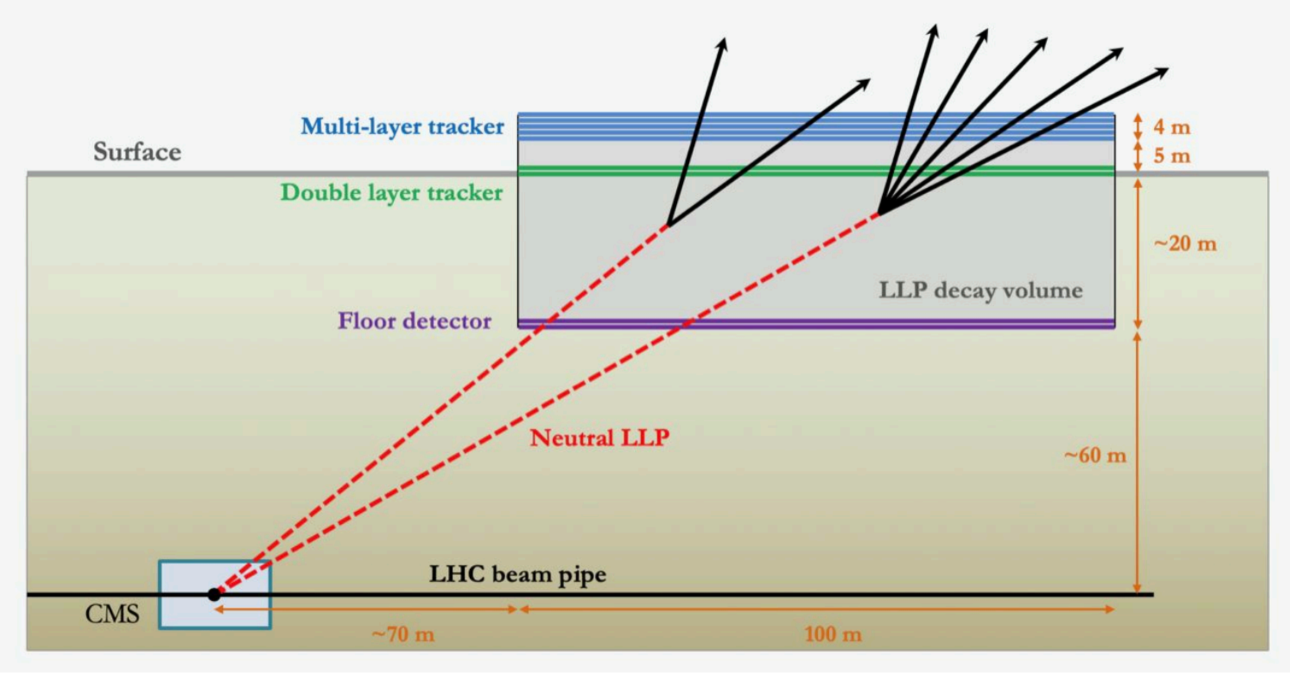
FASER location in 2018

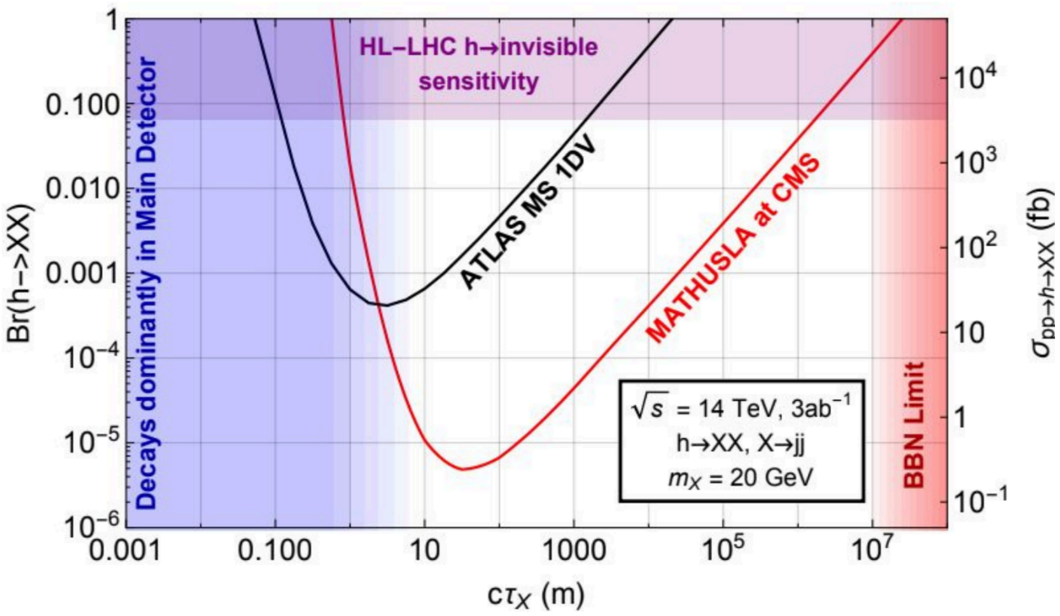
FASER location in today

https://arxiv.org/pdf/1901.04040

MATHUSLA

- MATHUSLA is a proposed large detector to sit close to the surface above CMS to search for LLP
  - 100m x 100m x 25m (O(5%) of solid angle)
- Search for neutral LLP decaying to charged particles in a 20m long decay volume
  - Sensitive to particles with very long lifetimes due to the distance from the IP
- Current design uses scintillating bars for the tracking detector
  - Very low backgrounds due to shielding from IP, and tracker time measurements
- Current status:
  - Small teststand (2.5 x 2.5 x 6.5m) running above ATLAS
  - LOI submitted to LHCC
  - May be able to combine data with CMS to allow more complete picture of LLP production, and to help with background rejection

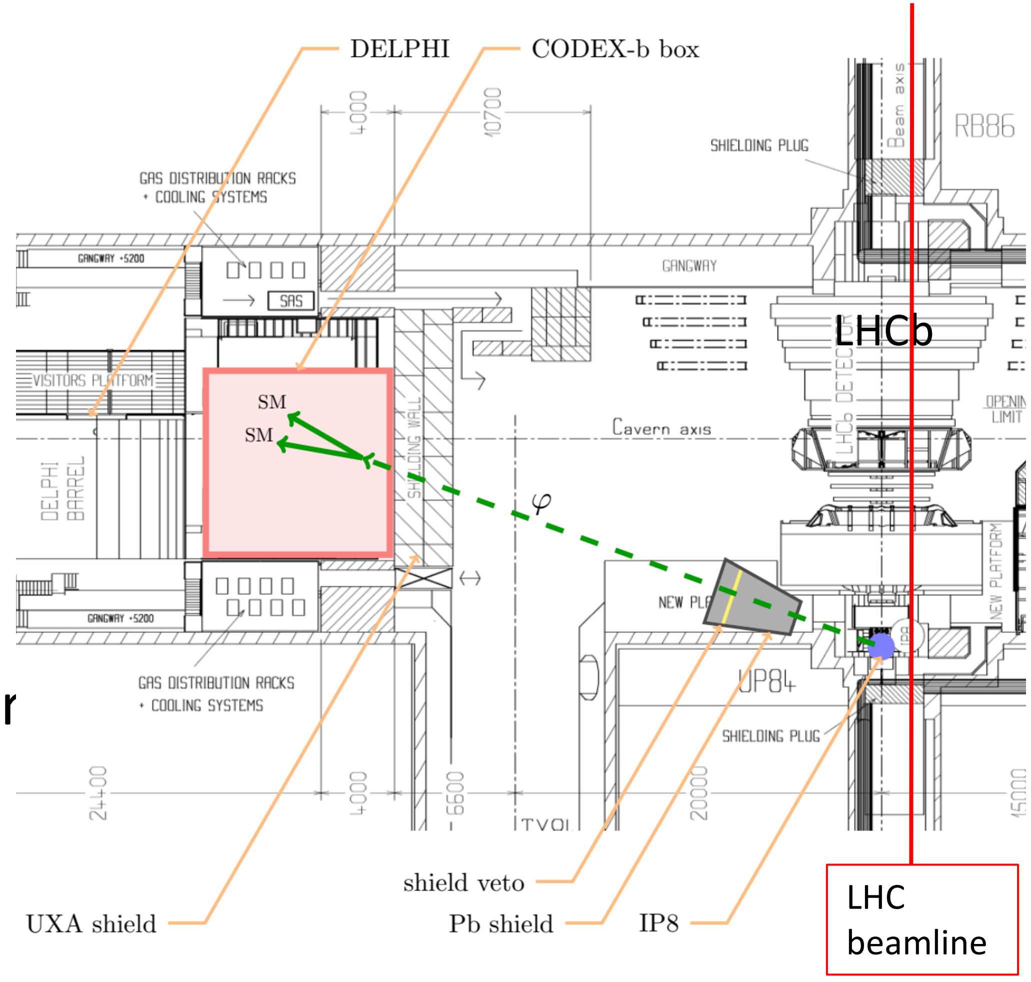


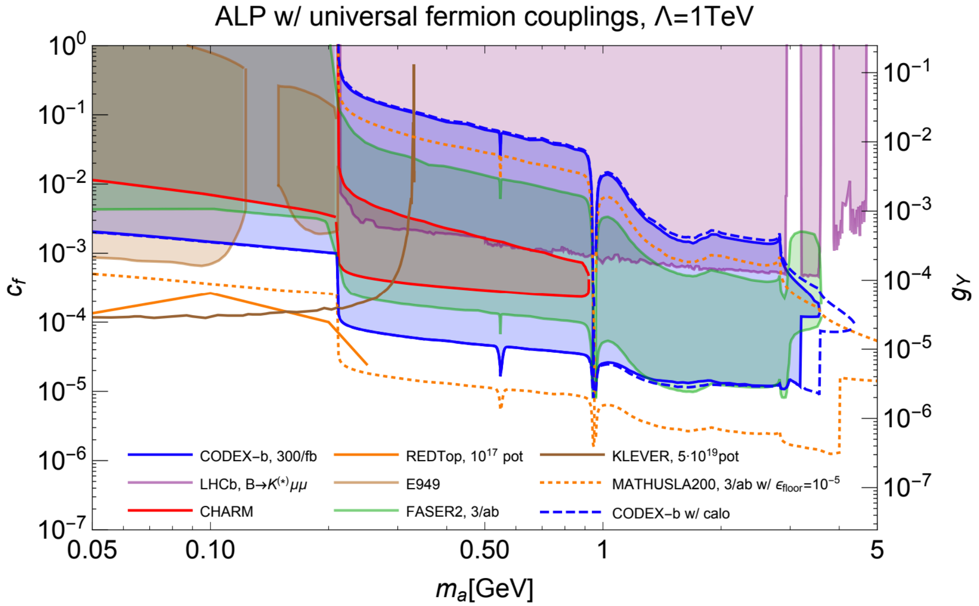


https://arxiv.org/pdf/1911.00481

CODEX-b

- Proposed medium sized experiment to be situated close to LHCb
  - ~25m from LHCb IP (behind active and passive shielding)
  - Detector size 10m x 10m x 10m
- Baseline design uses RPCs for tracking with good (100ps) timing resolution for background rejection
- Construction of a small (2m x 2m x 2m) demonstrator CODEX-**β** under consideration





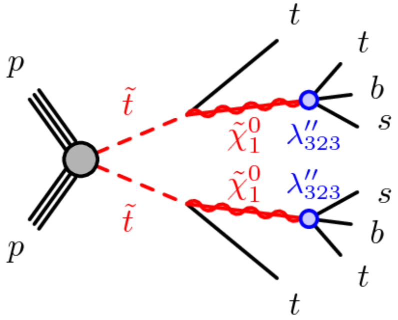
Summary

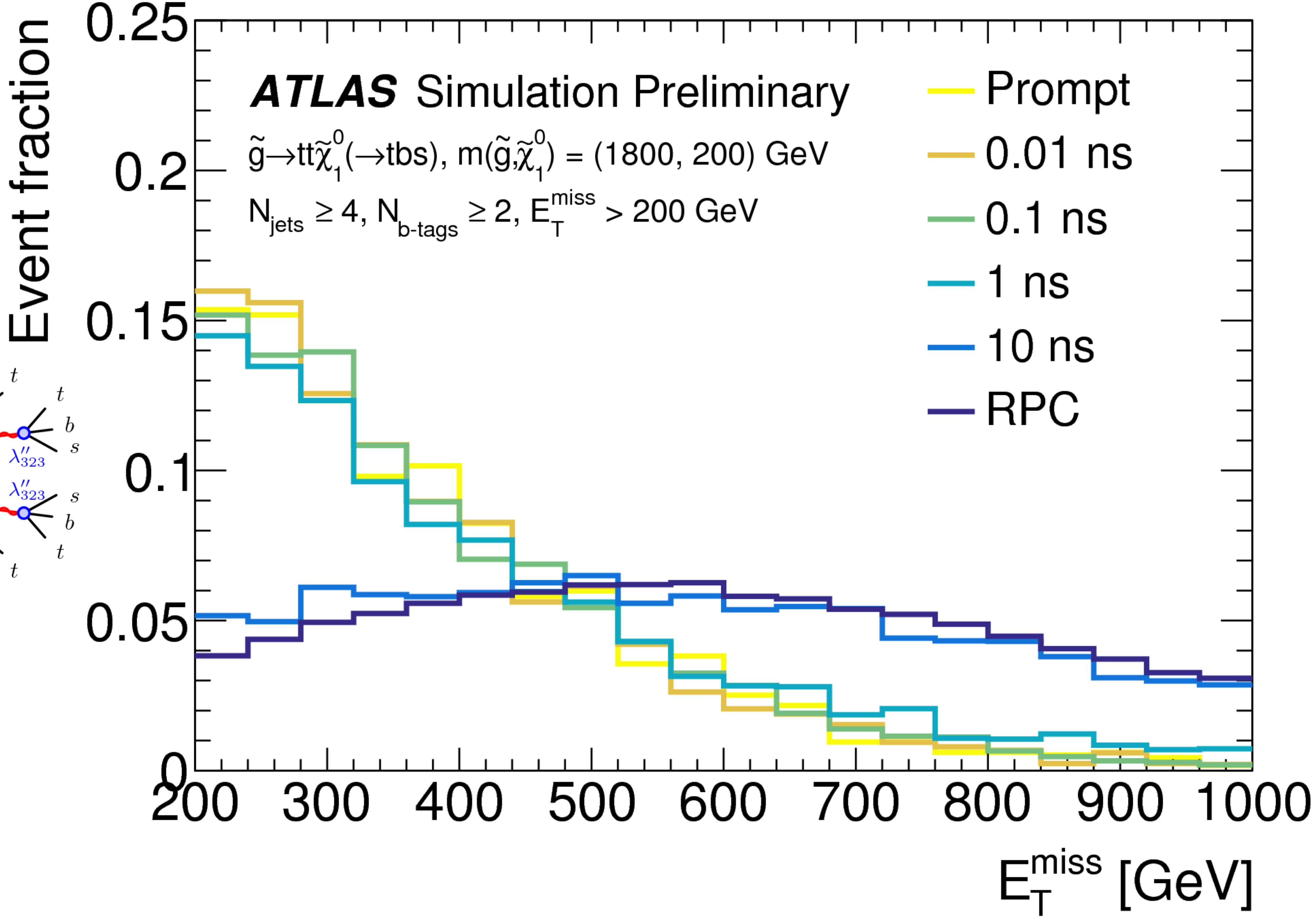
- A number of well motivated new physics models predict LLPs
- Leads to many searches for LLPs at the LHC
  - Rapidly expanding field
  - Analyses continually pushing the sensitvity in both the short and long lifetime limits as well as trying to reduce the model dependence of the results
- Analyses usually quite different from prompt searches
  - Non-standard reconstruction
  - Different backgrounds
  - Hard to validate the signal efficiency estimate
- Biggest challenge is often the L1 trigger
  - Improvements expected with new functionailty in Phase-1 and Pase-2 upgrades
- A number of new dedicated LLP experiments for the LHC have been proposed
  - Covering different scenarios and lifetimes
  - Aim to maximize the physics output of the LHC machine in the HL-LHC era

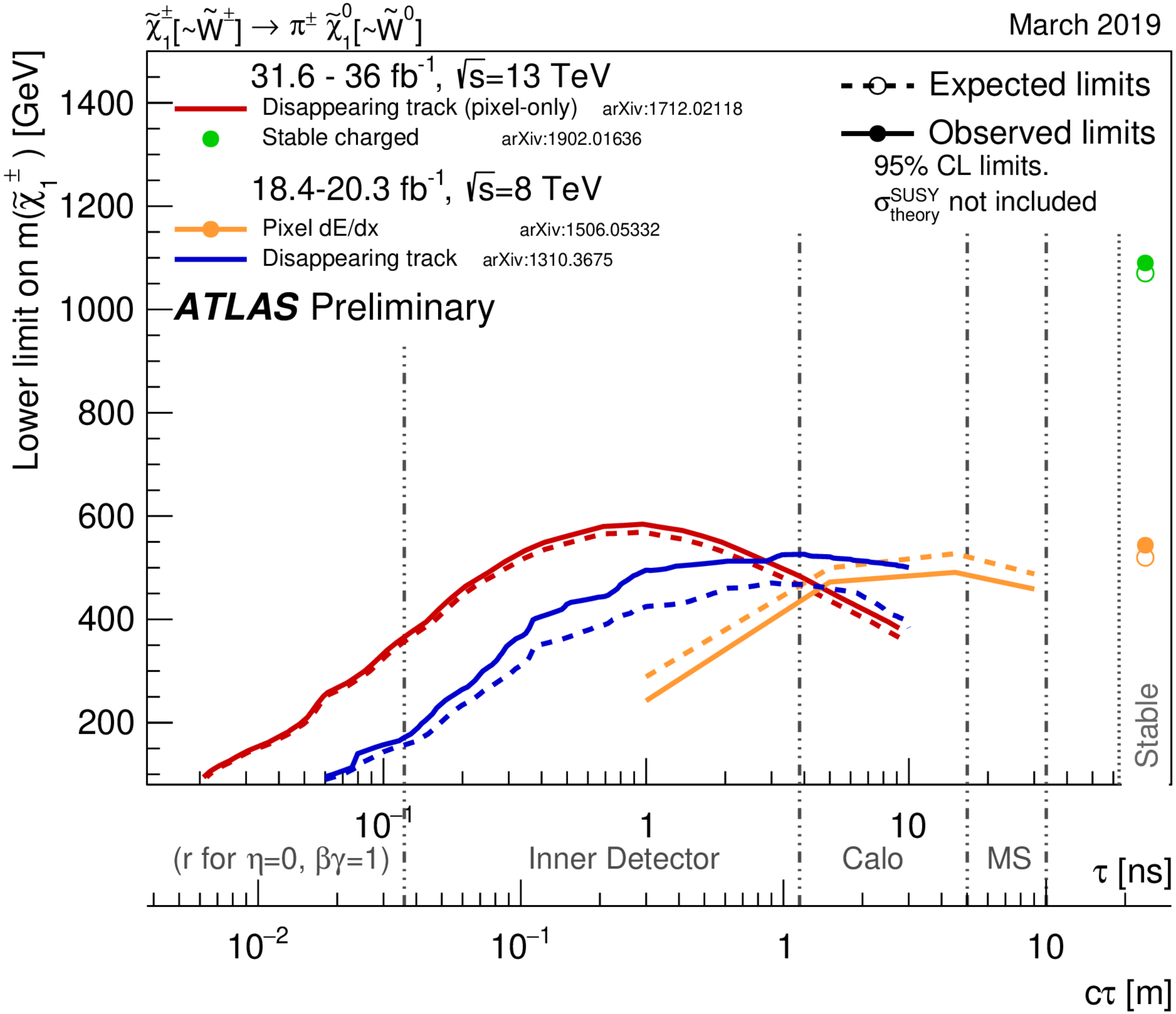
Some useful references…

- The LHC LLP Community white paper:
  - https://arxiv.org/abs/1903.04497
- ATLAS public result page:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic
- CMS public results page:
  - http://cms-results.web.cern.ch/cms-results/public-results/publications/
- LLP at the LHC workshop next week:
  - https://indico.cern.ch/event/922632/

Backup…


p
p
t̃
t̃
t
t
t
t
b
s
s
b
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
λ''_{323}
λ''_{323}


ATLAS Simulation Preliminary
$\tilde{g}\rightarrow tt\tilde{\chi}_1^0(\rightarrow tbs)$, $m(\tilde{g},\tilde{\chi}_1^0)$ = (1800, 200) GeV
$N_{jets} \geq 4$, $N_{b\text{-}tags} \geq 2$, E_T^{miss} > 200 GeV
Prompt
0.01 ns
0.1 ns
1 ns
10 ns
RPC
Event fraction
E_T^{miss} [GeV]
0
0.05
0.1
0.15
0.2
0.25
200
300
400
500
600
700
800
900
1000

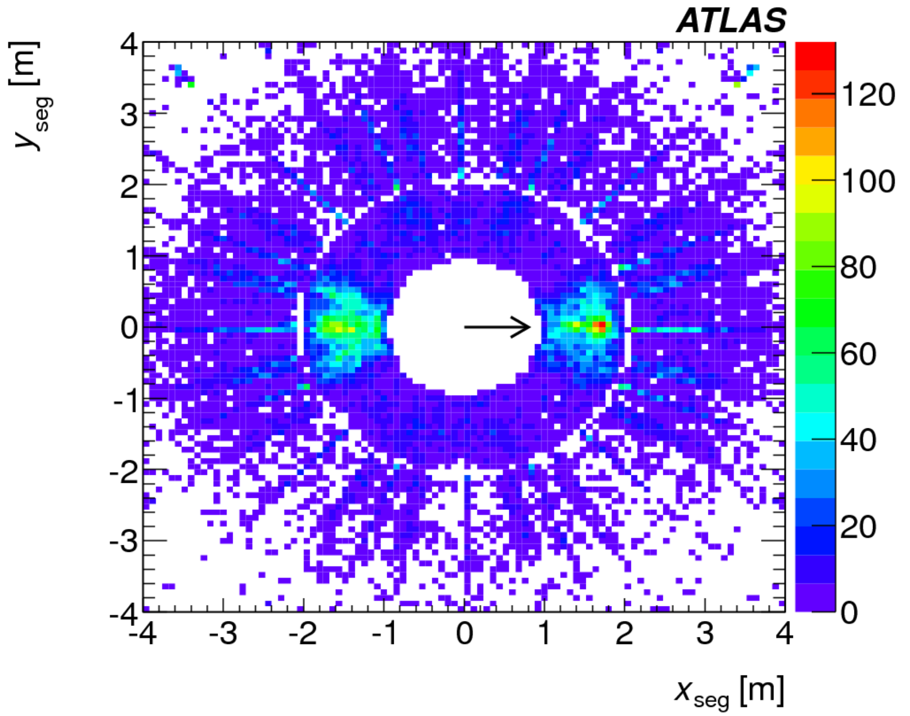


$\tilde{\chi}_1^{\pm}[\sim\tilde{W}^{\pm}] \rightarrow \pi^{\pm}\,\tilde{\chi}_1^0[\sim\tilde{W}^0]$
March 2019
31.6 - 36 fb^{-1}, $\sqrt{s}$=13 TeV
Disappearing track (pixel-only) arXiv:1712.02118
Stable charged arXiv:1902.01636
18.4-20.3 fb^{-1}, $\sqrt{s}$=8 TeV
Pixel dE/dx arXiv:1506.05332
Disappearing track arXiv:1310.3675
ATLAS Preliminary
Expected limits
Observed limits
95% CL limits.
σ_{theory}^{SUSY} not included
Lower limit on $m(\tilde{\chi}_1^{\pm})$ [GeV]
1400
1200
1000
800
600
400
200
Stable
10^{-1}
1
10
(r for η=0, βγ=1)
Inner Detector
Calo
MS
τ [ns]
10^{-2}
10^{-1}
1
10
cτ [m]

Beam background

- Beam background can be an important background for LLP searches
- Beam background events can be identified by timing, pointing and location of the hits (mostly in muon system of calorimeter)

Location of muon hits from beam background



Timing / position of reconstructed jets from beam background in calorimeter