Exotic signatures - Experiment

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Searches for long-lived particles at the LHC: Workshop of the LHC LLP Community
CERN
25th April 2017

UNIVERSITY of WASHINGTON

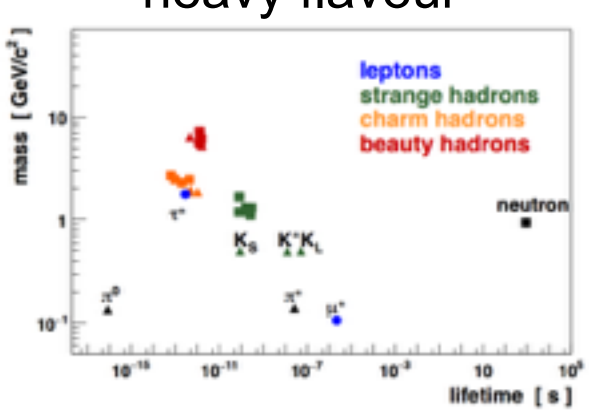
ATLAS EXPERIMENT

What's left to look for?

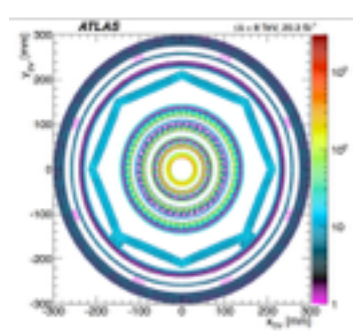
Challenges in LLP searches

- LLPs come with interesting signatures, hard to realize
- Trigger: combination of hardware + software that must decide very quickly whether to save an event or lose it forever
  - First step in every search for LLPs: make sure that interesting events are saved!
    1. In associated production, trigger on prompt particle (Eg. WH prod. trigger on muons or MET)
    2. Design and develop a new trigger. Need to keep trigger rates under control and within budget
  - new in Run-2: “including topological triggers”
- Object identification algorithms assume prompt particles. Need to adapt them
  - Dedicated reconstruction methods and search strategies
- Backgrounds: usually instrumental background has to be taken into account

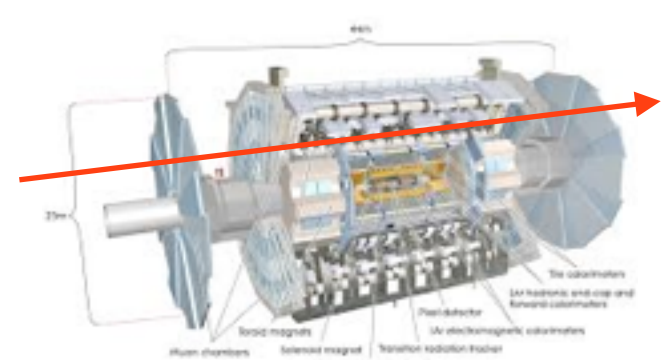
weak decays of heavy flavour



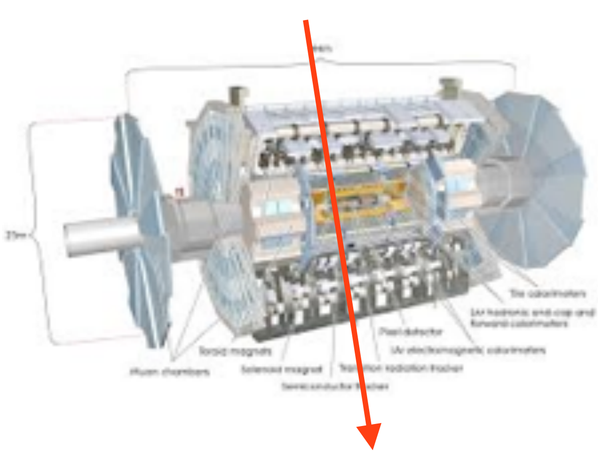
material interactions



beam halo muons

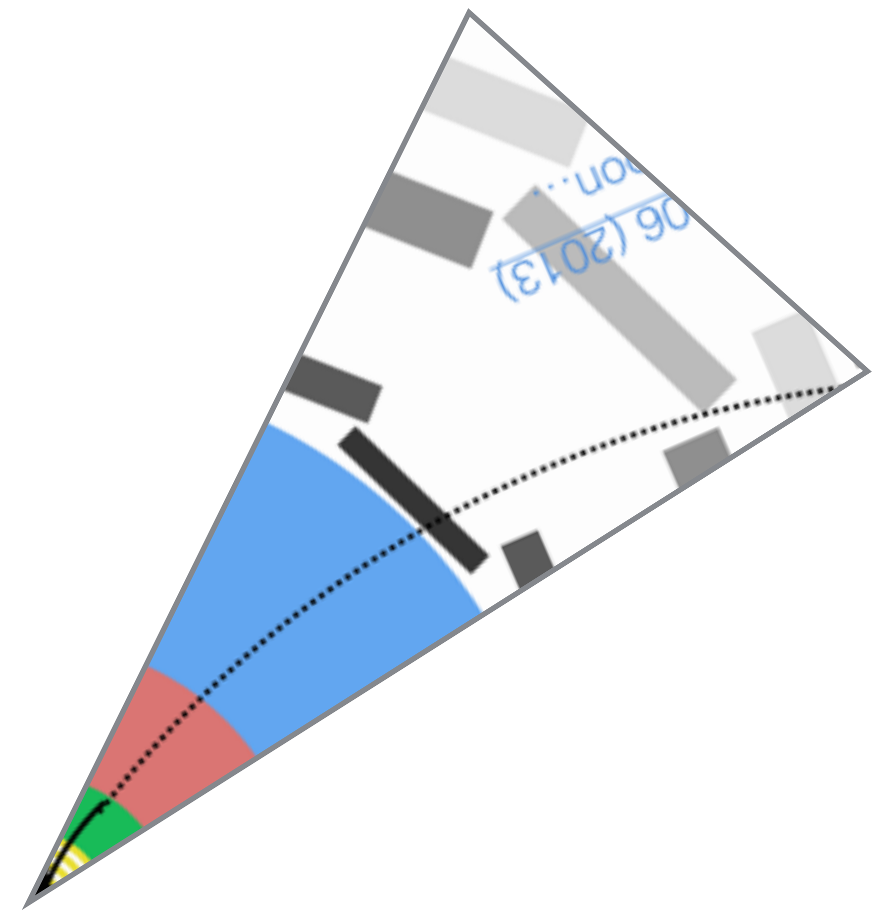


cosmic muons



- Systematic uncertainties: can’t use ATLAS recommendations for object reconstruction nor trigger

Disappearing tracks

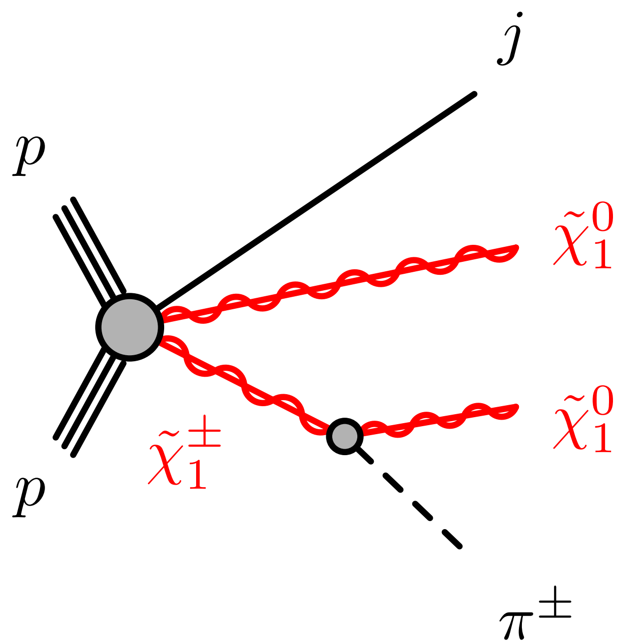


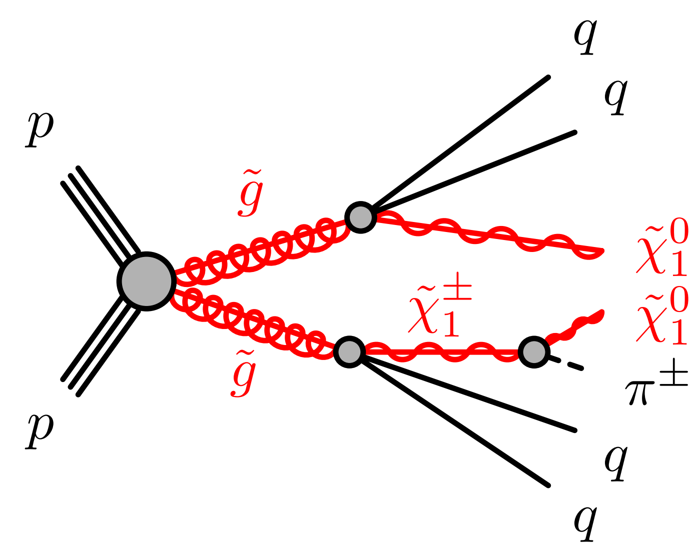
ATLAS latest result:
ATLAS-CONF-2017-017
CMS latest result:
JHEP 01 (2015) 096

Odd tracks at hadron colliders, Meade et al.
PhysRevLett.109.031801
Nice summary and motivation for odd tracks

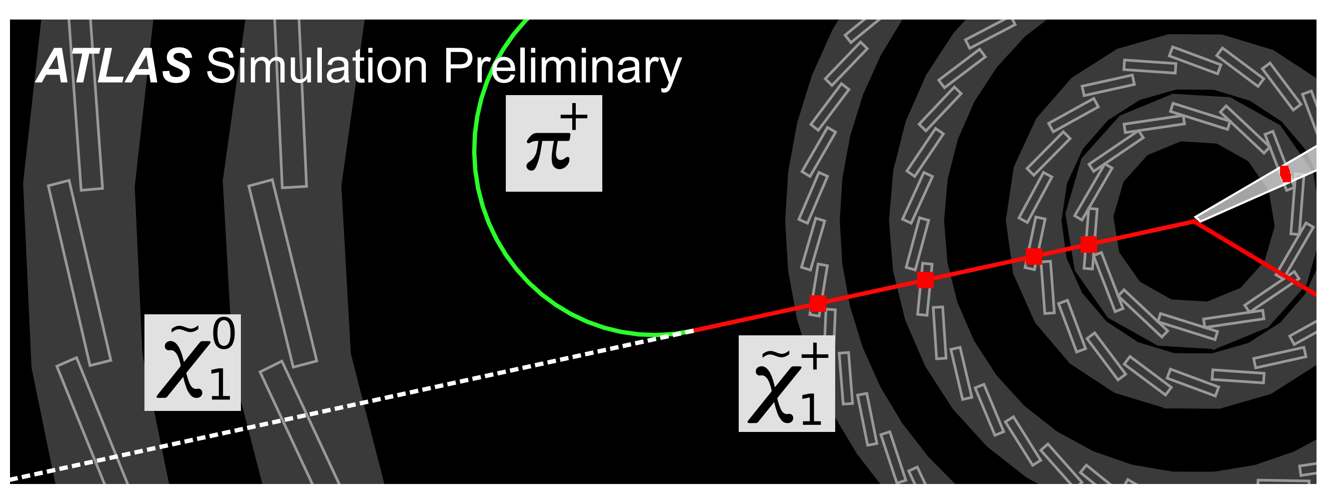
Disappearing tracks description

- Search for disappearing track + MET + jets
- AMBS model with almost degenerate neutralino and chargino (0.2 ns -> 6 cm)



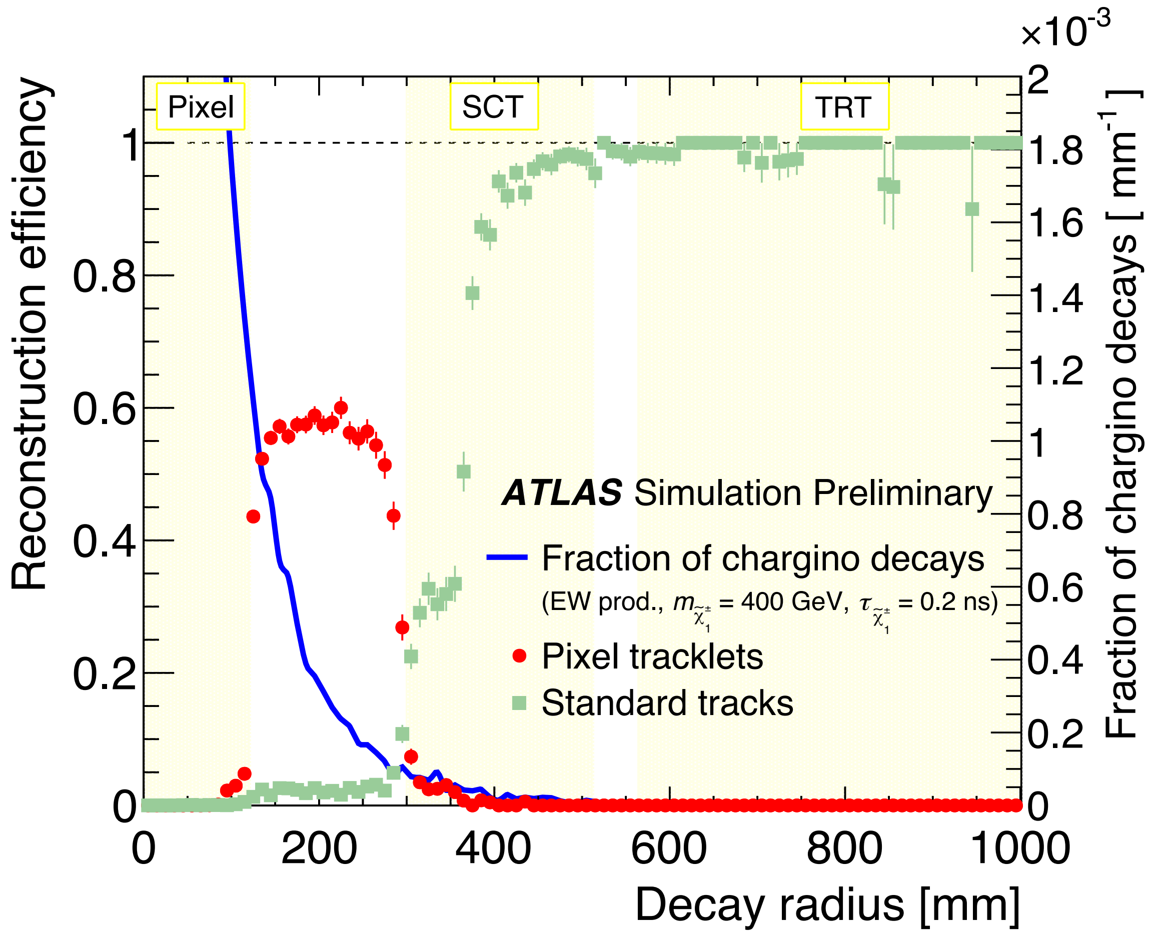


- Chargino track “disappears” when it decays, into MET
- Low momentum pion track (0.1 GeV) is lost
- Challenge to reconstruct short tracks with decent momentum resolution
- Search sensitive to LLP lifetime of 10ps to 10 ns



Disappearing track: track reconstruction

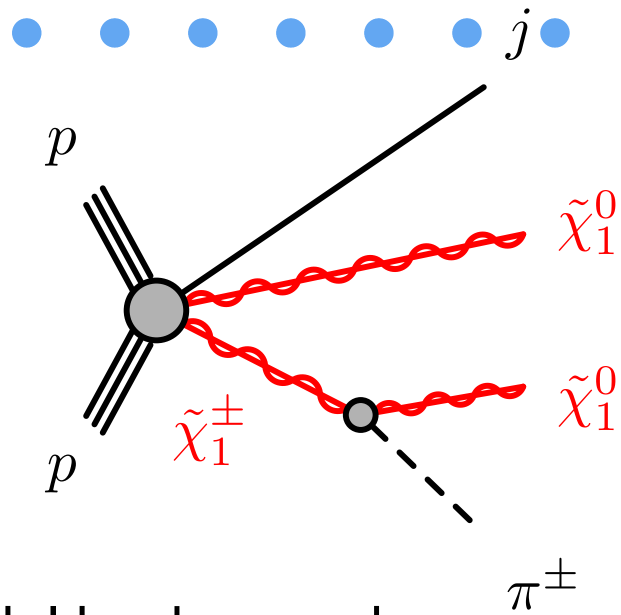
- Track reconstruction in 2 steps:
  1. standard tracking
  2. second pass using only hits not associated with tracks in 1.
     - Looser criteria, require >=4 pixel hits with hits on all four pixel layers , zero holes
     - Veto hits on SCT —> identify "pixel tracklets", disappears between the pixel and the SCT
     - Tracklets isolated from jets and MS tracks



- Inclusion of the innermost tracking layer (IBL) significantly improves the sensitivity to short chargino lifetimes

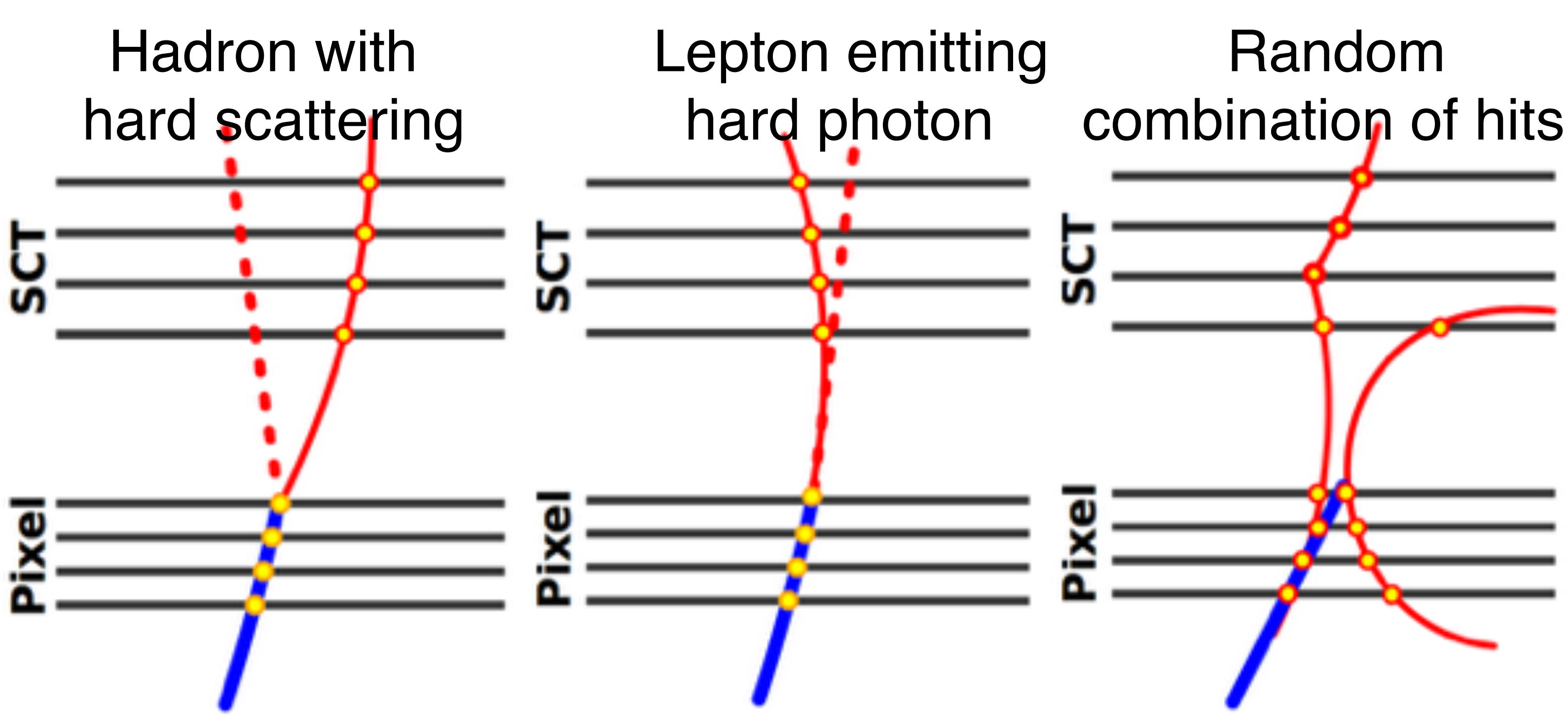
- 10x larger acceptance for 400 GeV AMSB chargino decaying before the SCT

Disappearing track Backgrounds



- Require high MET, one high pT jet, lepton veto (to suppress contributions from ttbar and *W*/*Z*+jets)

- Challenge to reject fake tracks with poor momentum resolution, and model backgrounds
- Isolation and quality requirements are mainly useful to reduce fake tracklets



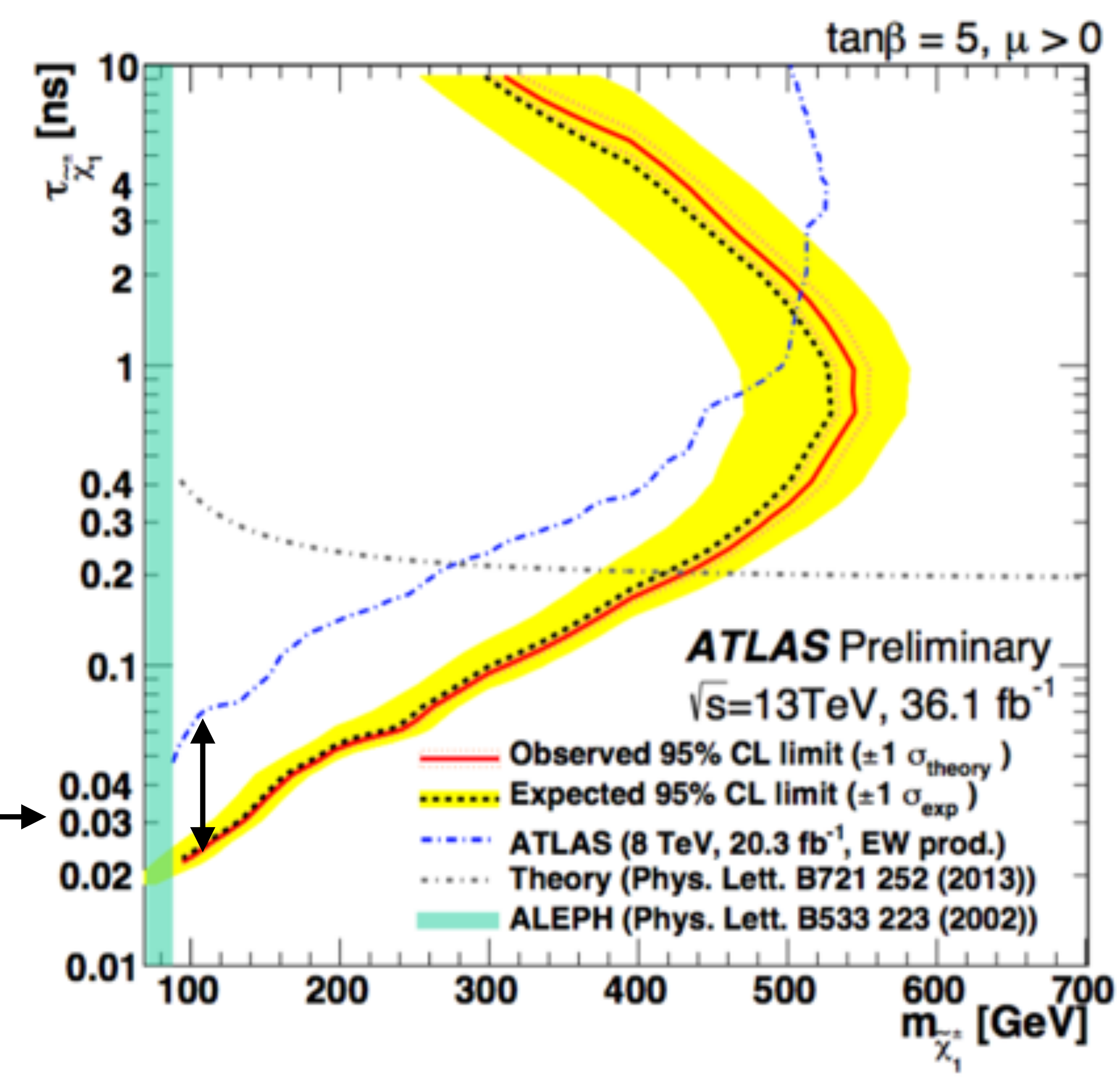
- Main background: ttbar, W+jets where e bremsstrahlungs or pion coming form tau lepton, scaters
- Random combination of unrelated particles tracks
- Templates for these background components are estimated from data.

Disappearing track Results

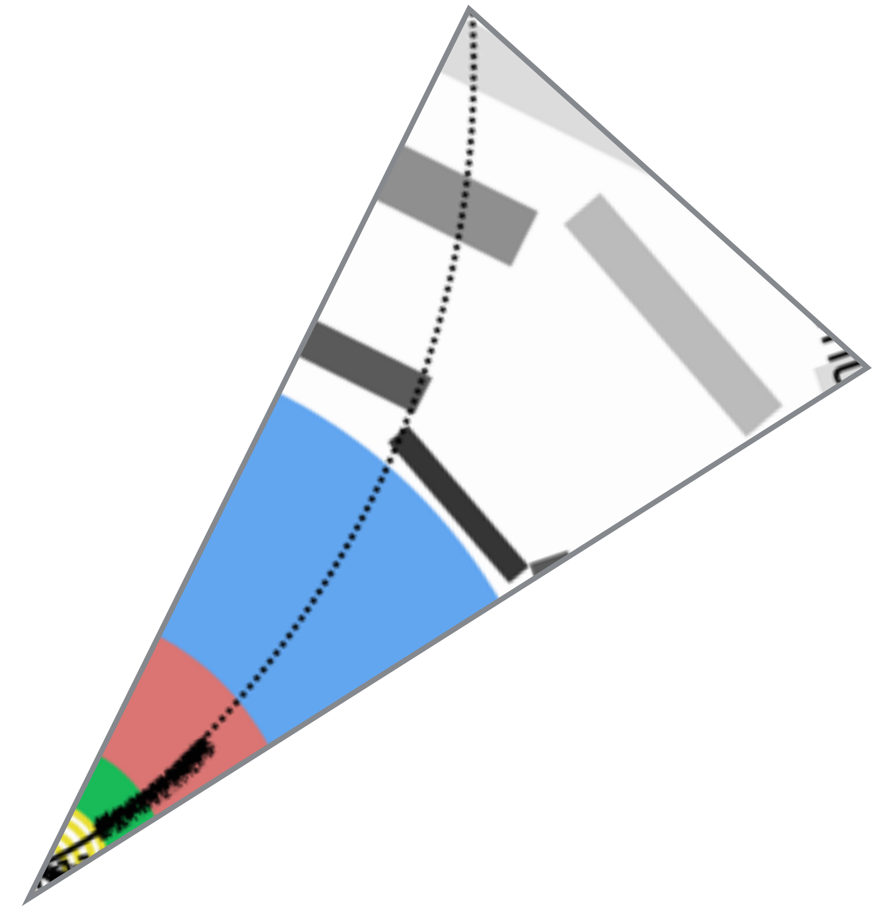
- Background prediction agrees with data observation

High E_T^{miss} region	Electroweak channel	Strong channel
	$(m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm})$ =(400 GeV, 0.2 ns)	$(m_{\tilde{g}}, m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm})$ =(1600 GeV, 500 GeV, 0.2 ns)
Observed	9	2
Total background	11.8 ± 3.1	2.1 ± 0.9
Expected signal	10.4 ± 1.7	4.1 ± 0.5

- Extended limits to lower lifetimes



HIP/monopole



ATLAS latest result
PRD 93, 052009 (2016)

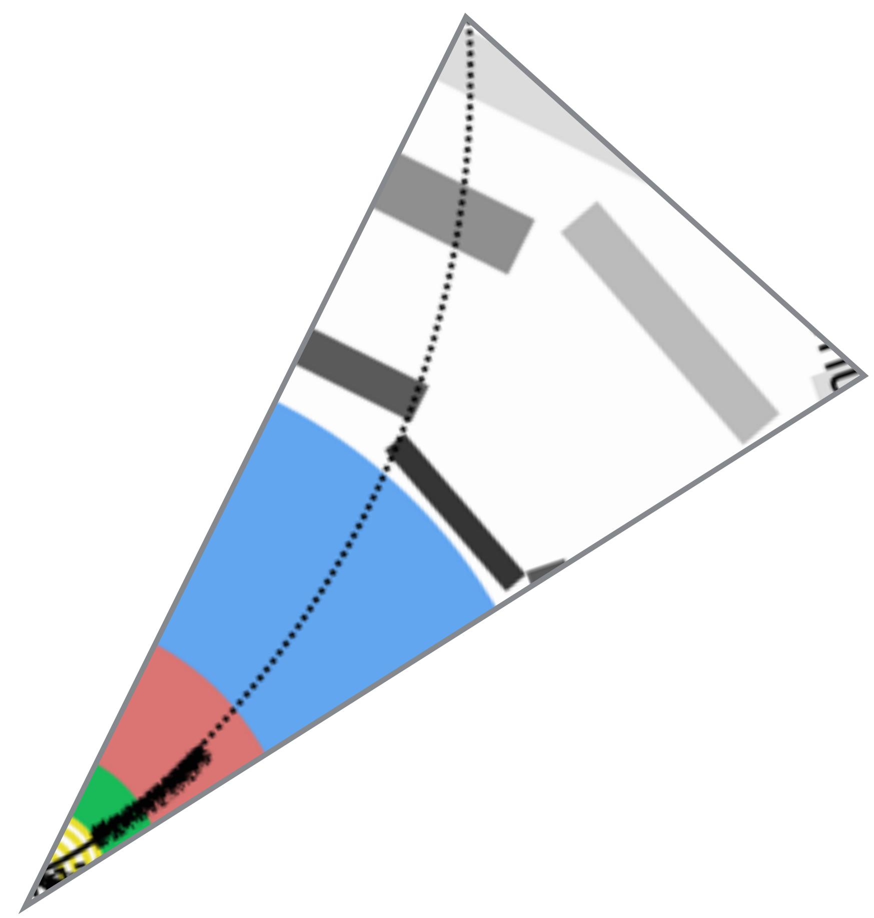
HIP/monopole

- Long-lived Highly Ionizing Particles (HIP) are predicted in several theories:
  - strange quark matter
  - Q-balls,
  - Stable microscopic black-hole remnants
  - Theories of magnetic monopoles:
    - lightest magnetic monopole would be stable and carry a charge multiple of the Dirac charge:

$$\frac{g_D}{e} = \frac{1}{2\alpha_e} \approx 68.5$$

- In terms of ionization energy loss corresponds to an electrically charged particle of |z| = 68.5

- Signature:
  - region of high ionization density in the TRT
  - stopping in the EMCal
  - very narrow EM showers (Bremsstrahlung and ee pairs negligible)



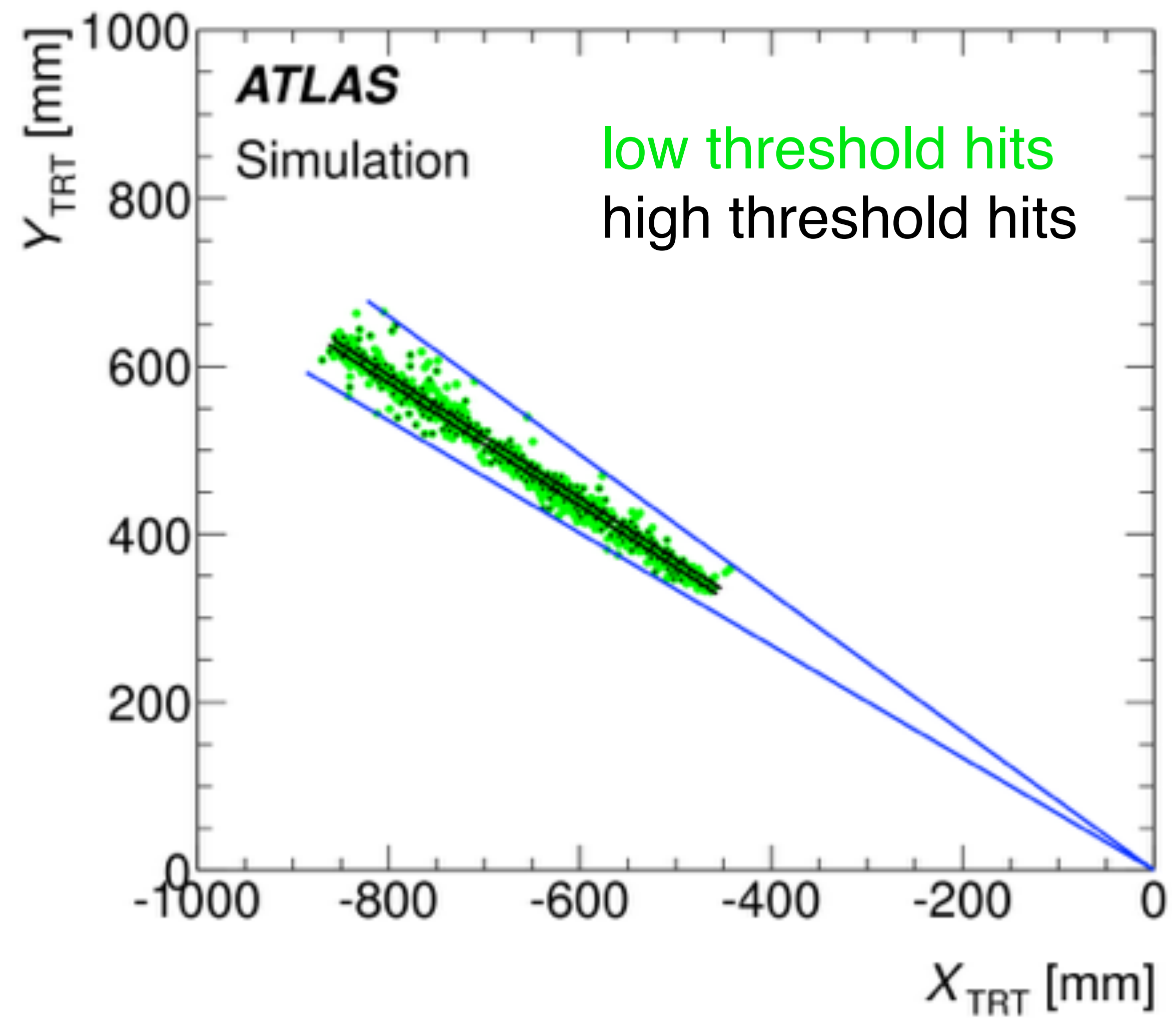
HIP/monopole Trigger

- Standard electron triggers require energy in all layers of the EM calorimeter
  - Not efficient if the HIP stops before
- Standard photon triggers have high pt thresholds
  - Not efficient for lower masses

- New trigger developed for 2012 data taking:
- Seeded by EM deposit but no requirement on layers
- No energy in the HCal (< 1 GeV —> eff drops for high pt jets. It's been improved in run2)

- TRT hits requirements:
  - large number of high threshold (HT) hits along the object track: $N_{HT} > 20$
  - large fraction of high threshold hits as compared to low threshold: $f_{HT} > 0.37$

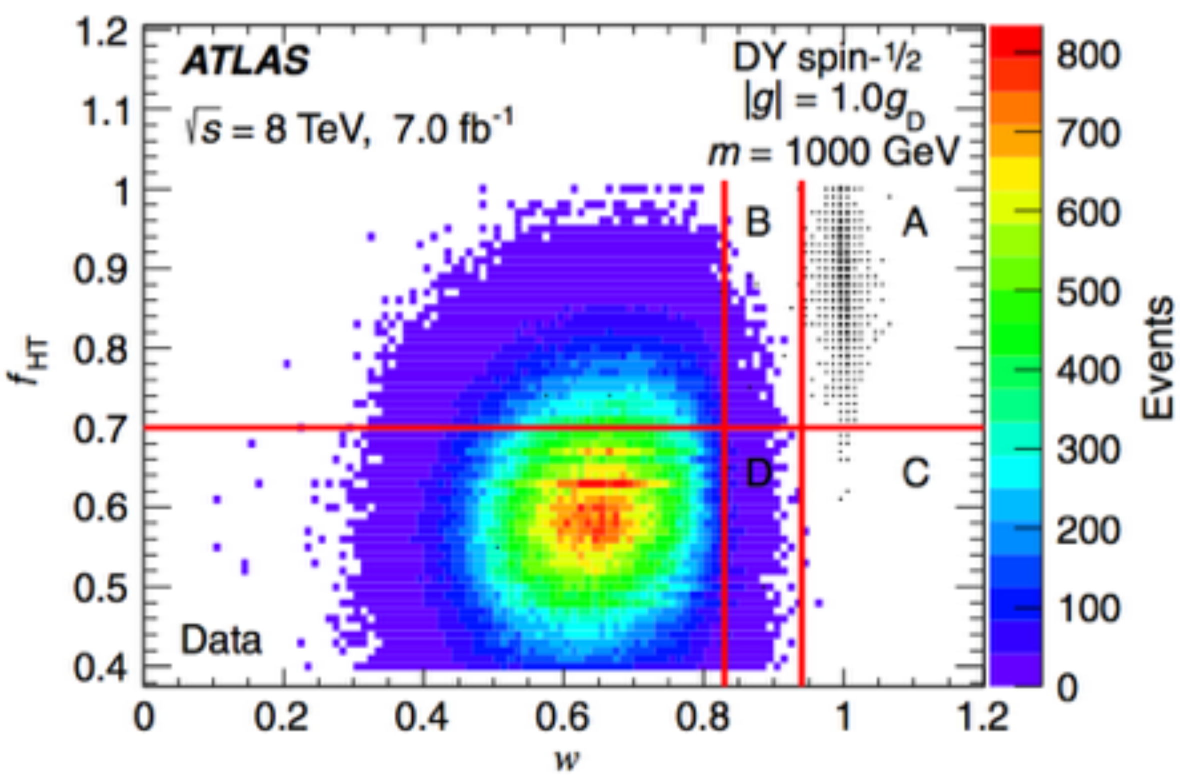
- Trigger developed at the end of 2012: $7 fb^{-1}$
- Pileup dependence



HIP/monopole Event selection

- Backgrounds:
  - Multijets where several jets overlap by chance giving high numbers of HT hits + EM shower misreconstructed to be very narrow + all jet components very collimated sharing TRT track)
  - Electrons from W and Z production
  - Electronic noise (negligible after offline selection: no TRT tracks matched)

- Estimated with ABCD method, tested in VRs

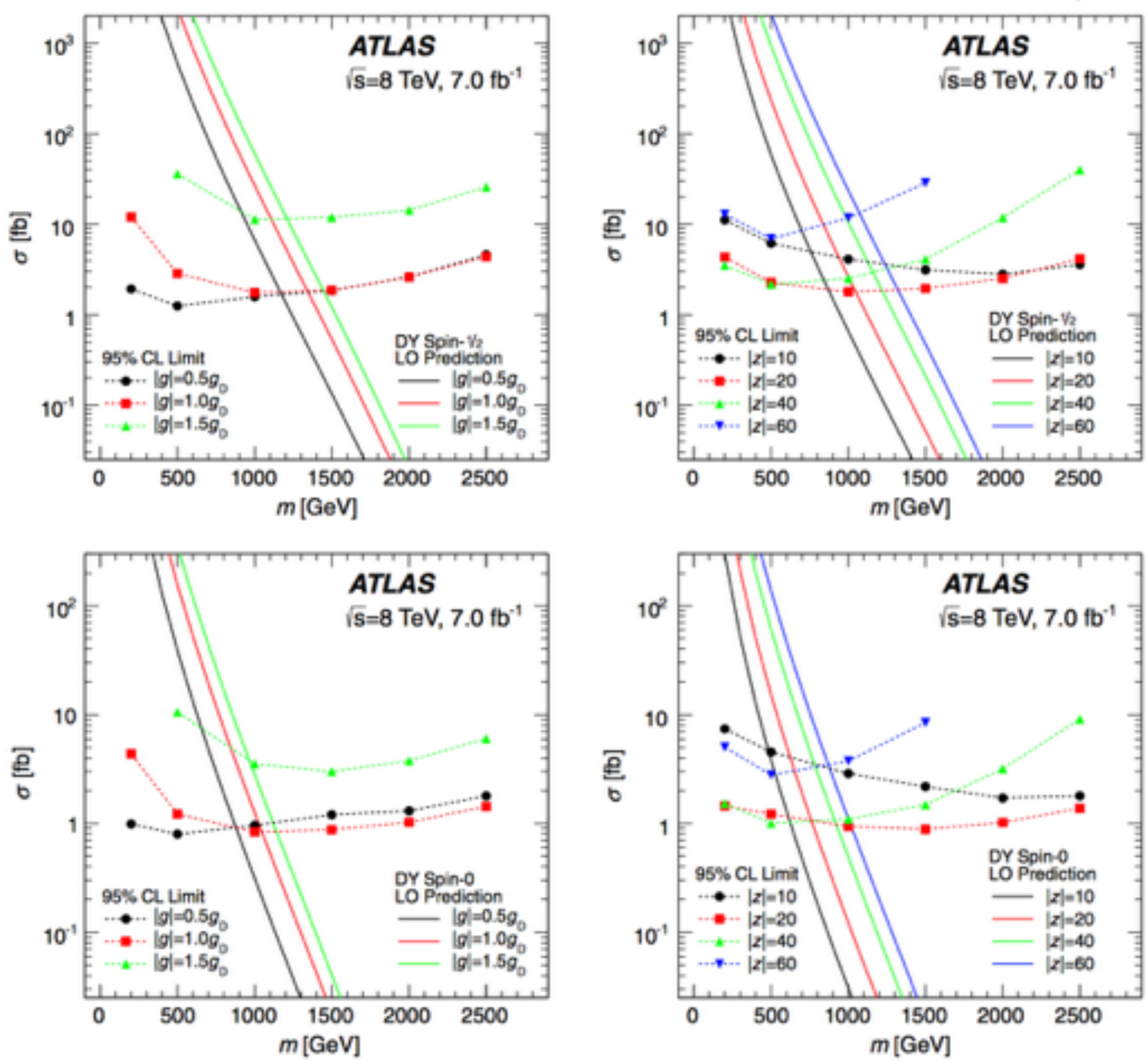


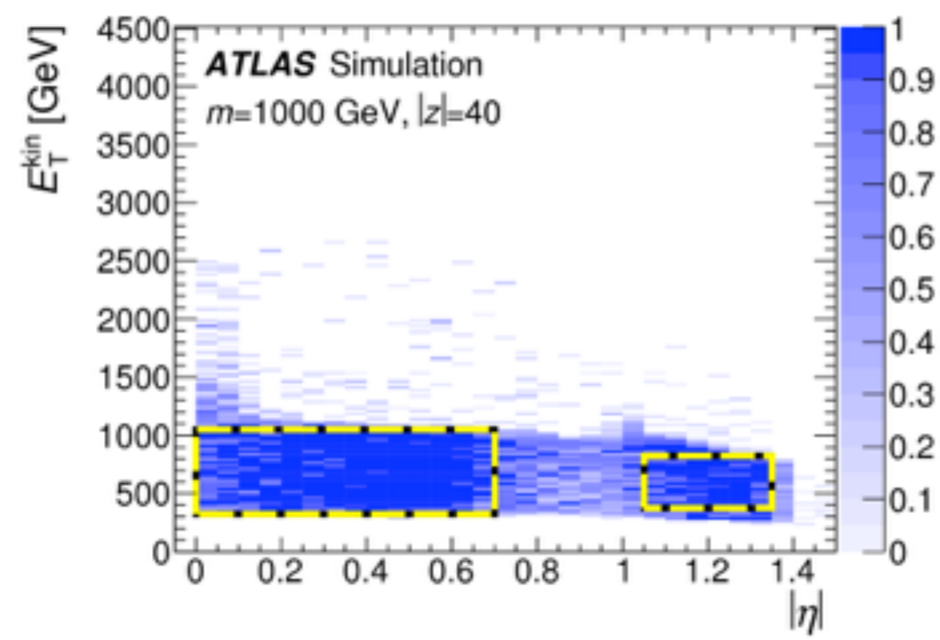
- w: related to the number of cells containing a high fraction of the energy
- large fraction of HT hits: f_{HT}

HIP/monopole Results

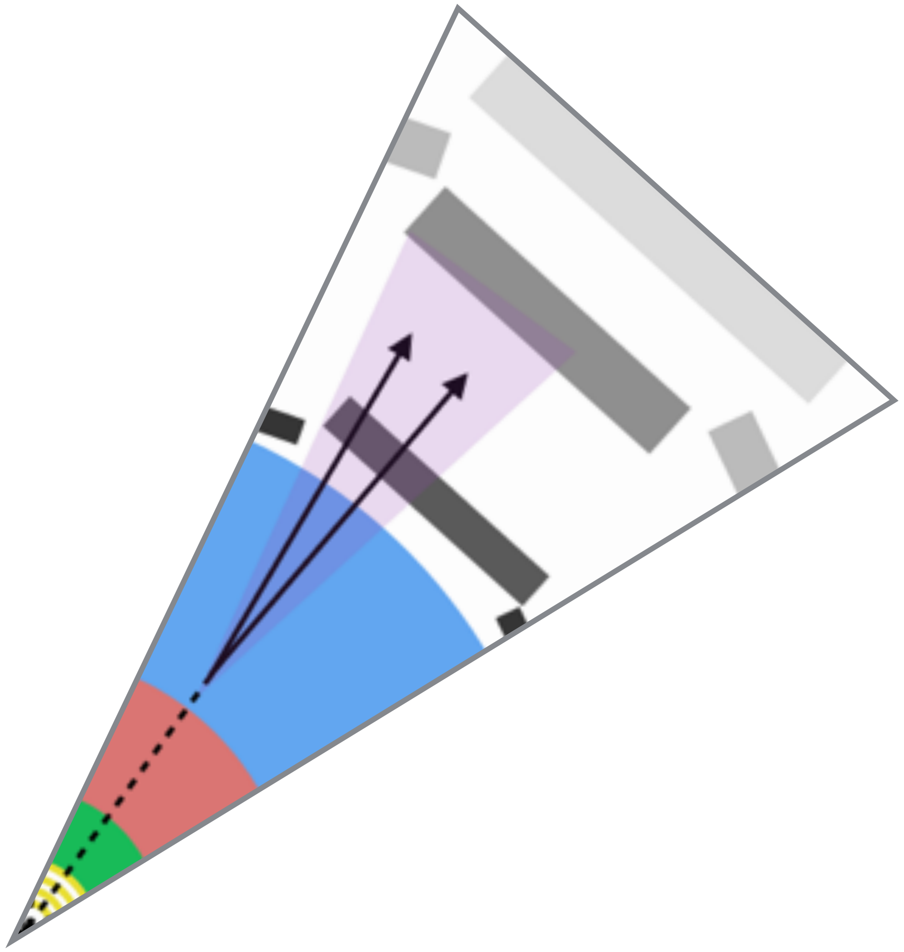
- Different efficiency maps are created for several fiducial regions where the selection efficiency is approximately constant

For DY samples, apply efficiency maps to the simulated particles —> get cross-sec limits





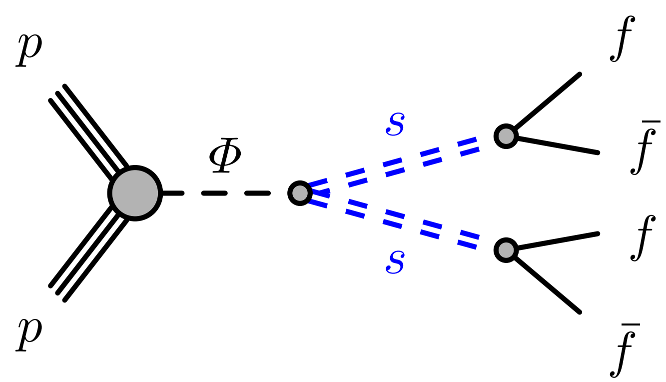
Displaced jets in the Hadronic Calorimeter

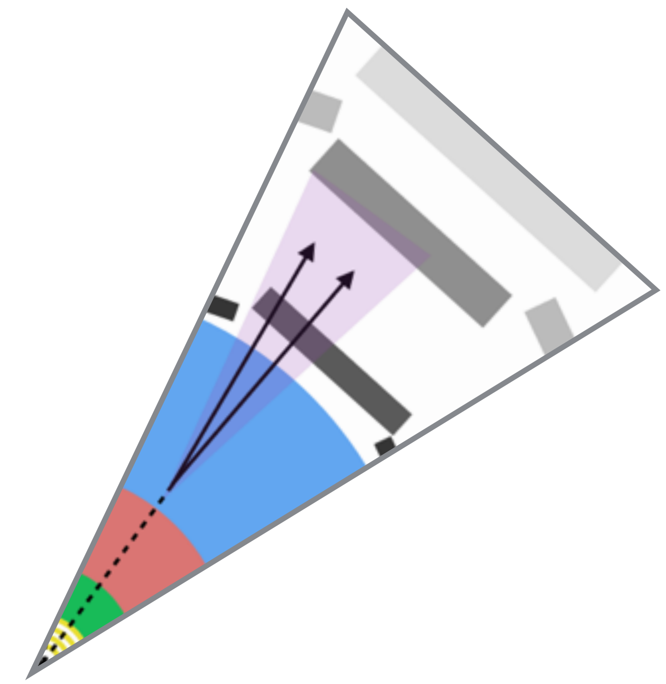


ATLAS latest result
ATLAS-CONF-2016-103
CMS latest result
CMS-PAS-EXO-16-003

Displaced hadronic jets in the Hadronic Calorimeter

- Search for neutral long-lived particles decaying to SM fermions in the detector. Decays can occur in the ID, in the calorimeter (HCal), in the MS
- Hidden sector with a heavy neutral boson phi as the communicator, decaying to two long-lived neutral scalars, s, that will eventually decay to pairs of SM fermions





- Signature: 2 displaced jets in the Calorimeter
- Idea to combine 1 displaced jet in the ID or MS + 1 displaced jet in the calorimeter in the future
- Dedicated CalRatio (Calorimeter Ratio: E_H/E_{EM}) trigger selecting jets with unusual features

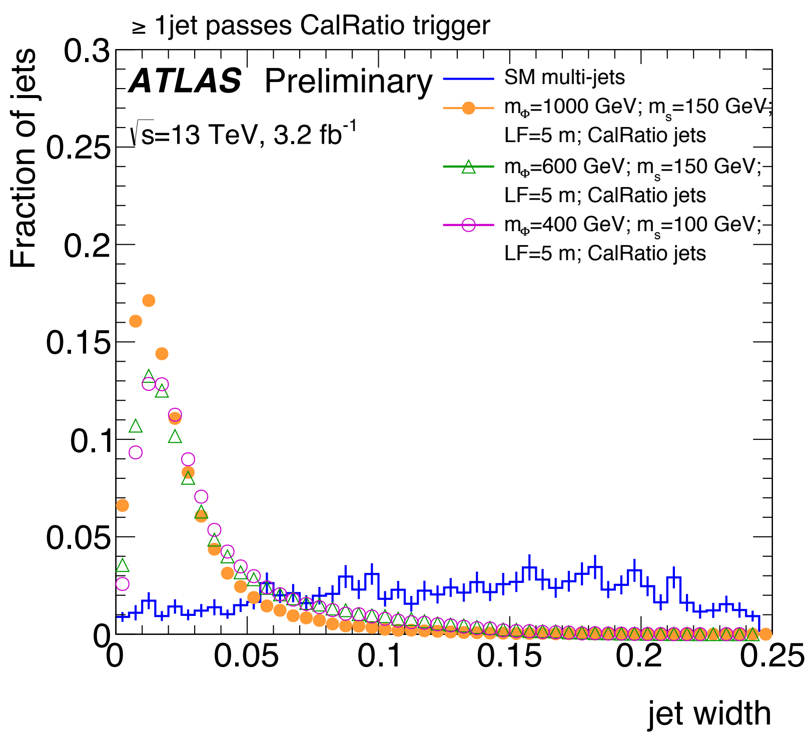
CalRatio Trigger

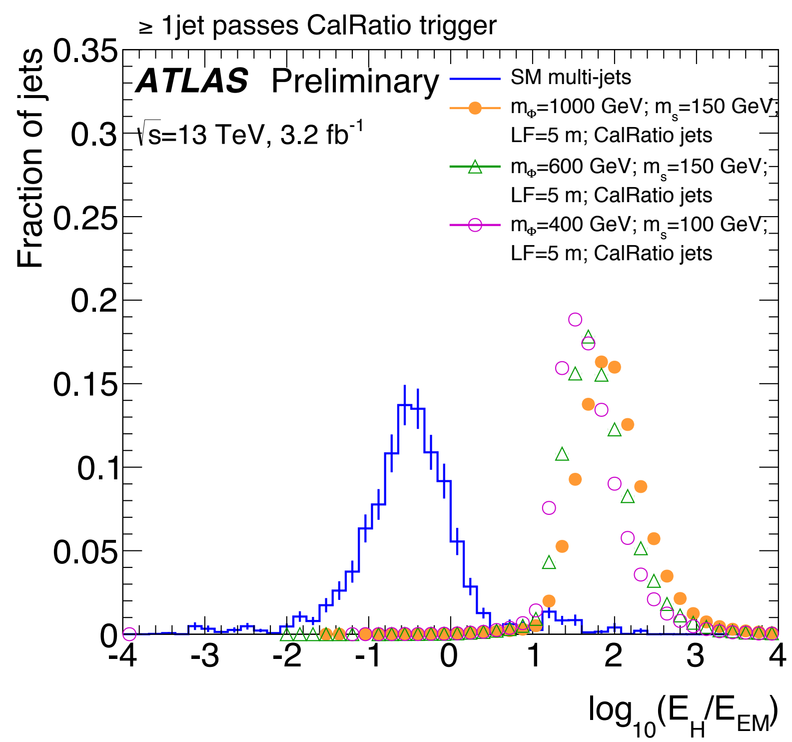
- Scalars decaying in the HCal produce jets with unusual features compared to SM jets:

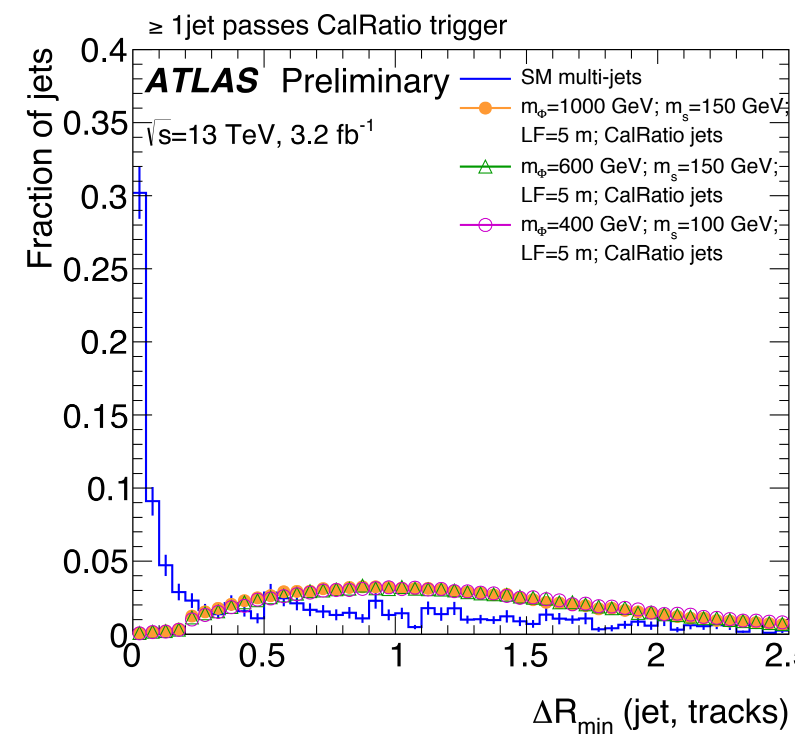
Narrow jets

high ratio of energy deposited in the HCal to the energy in the ECal

lack of tracks in the jet cone





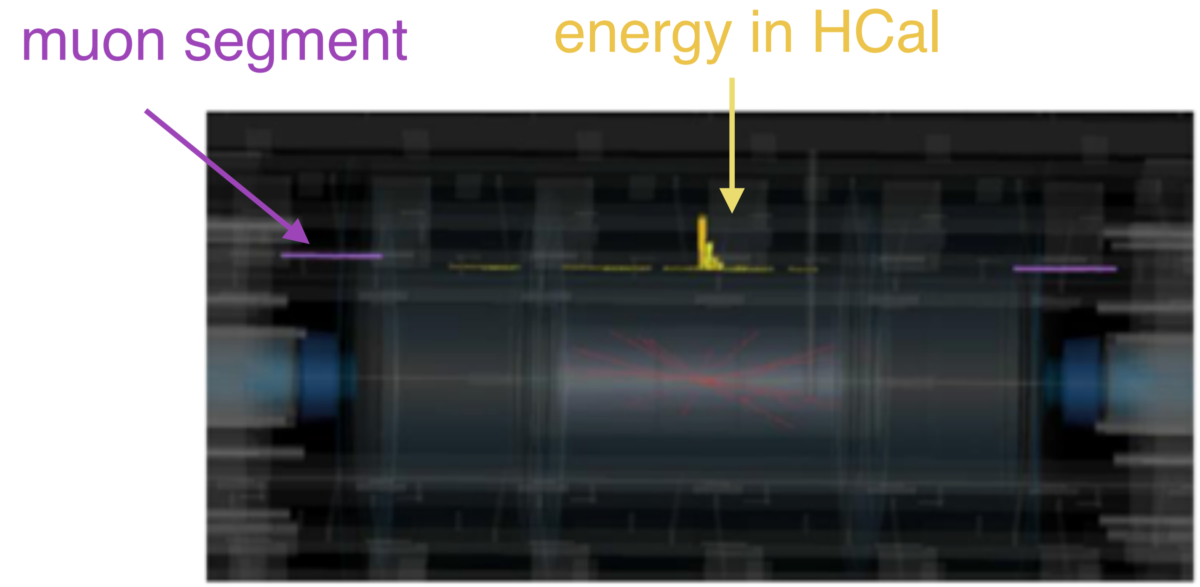


- Standard jet triggers apply a cleaning requirement on CalRatio (E_H/E_{EM}) that would kill all the signal

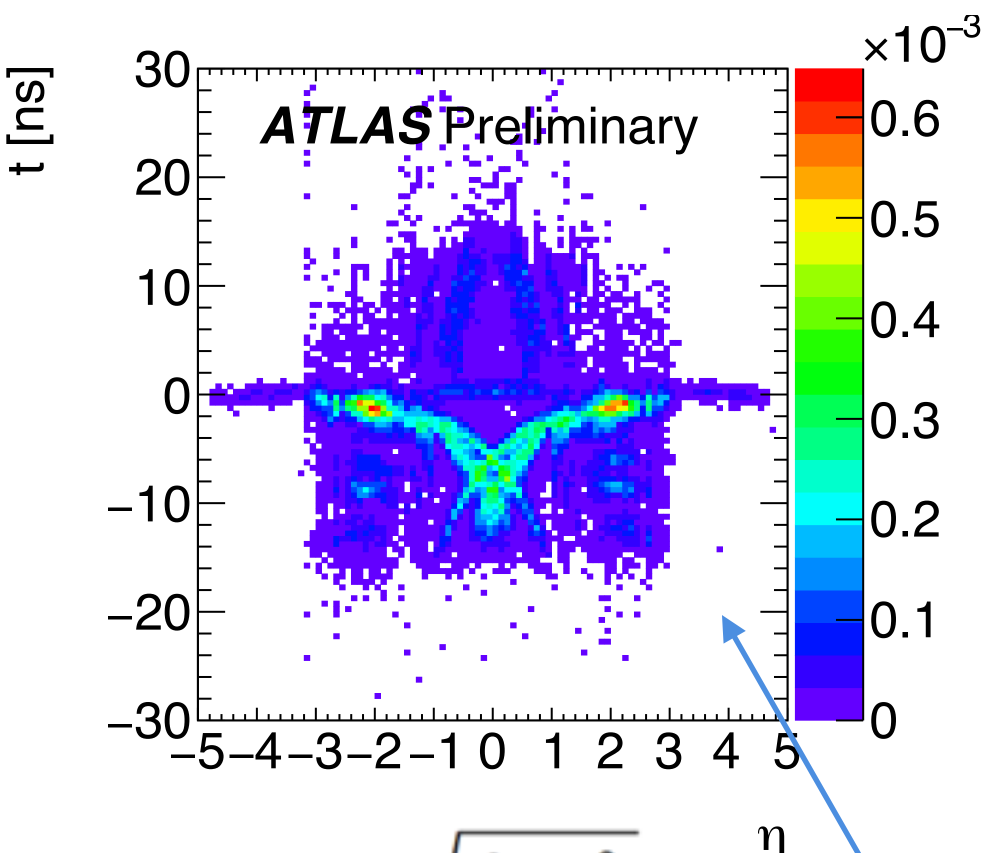
- Trigger developed taking into account:
  - Narrow cone: because decay is in the calorimeter the jet cone is smaller
  - high CalRatio: defining variable for this analysis
  - lack of ID tracks

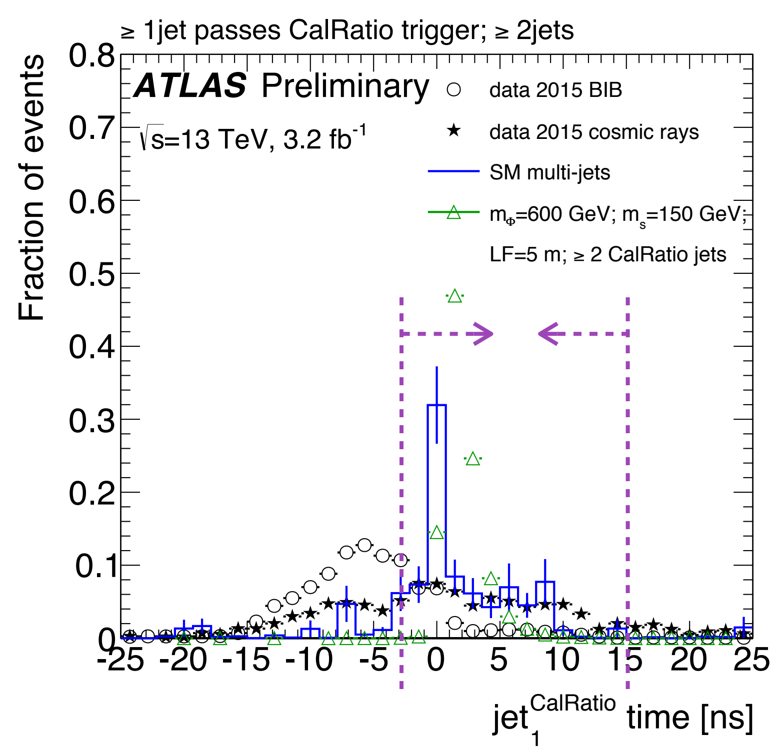
CalRatio Non-collision Backgrounds

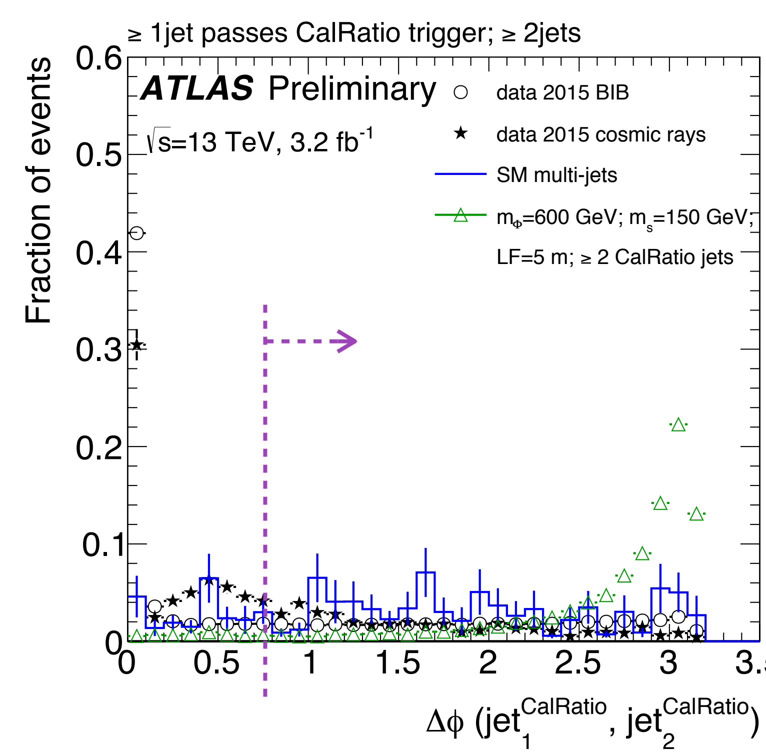
- cosmic ray muons
- Beam-Induced background (BIB):
  - muons produced by proton interactions with collimators or gasses,
  - travel parallel to the beampipe through the calorimeter
  - leave energy deposits



- Several well known characteristics can be used to eliminate both:





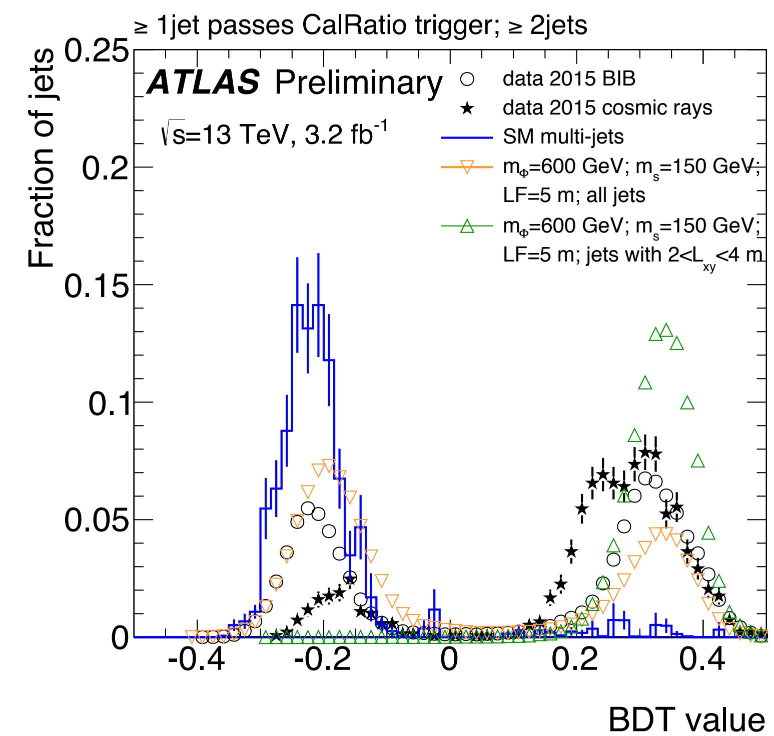


$$t_{\mathrm{BIB}} = \frac{\pm z - \sqrt{z^2 + L_{xy}^2}}{c}$$

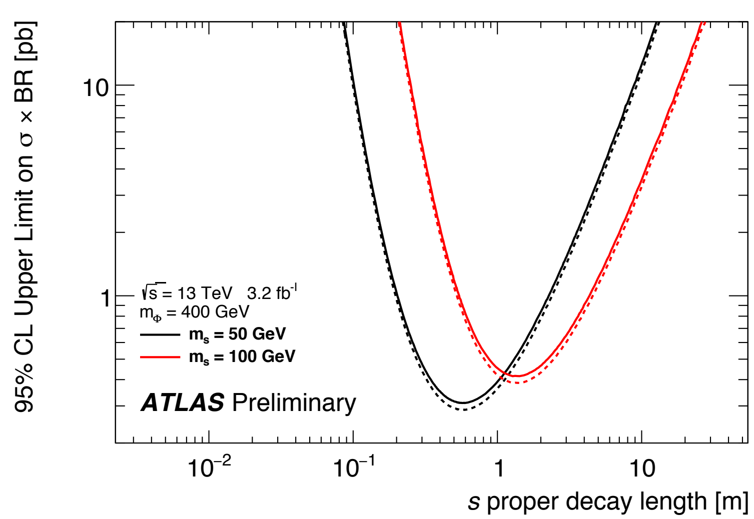
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/NonCollisionBackgroundPublicResults

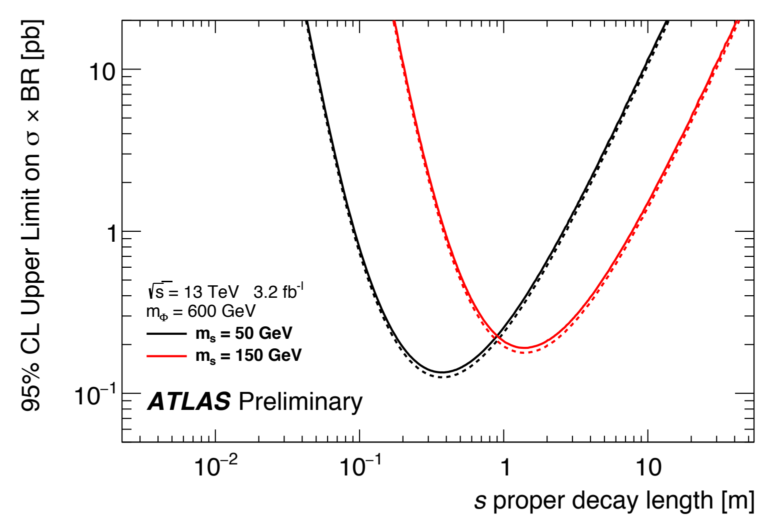
CalRatio multijet Background, result

- Main source of background: SM multijets
  - Jets formed predominantly by neutral particles can be trackless and deposit most of their energy in the HCal
  - Train a per-jet Boosted-decision-tree (BDT) to identify signal-like jets
  - Final estimation done with data-driven methods

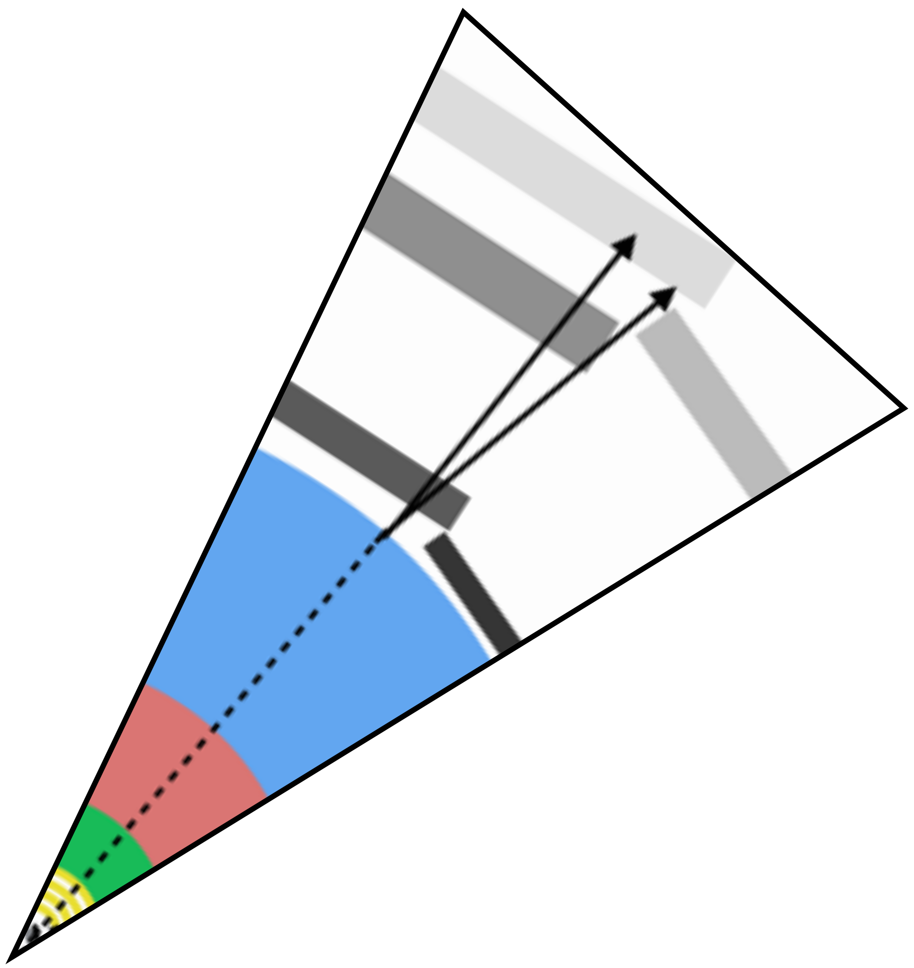


- The final number of events estimated in SR is 18.4 ± 6.3(stat) ± 6.6(syst) is in agreement with the 24 observed events
- Limits are set in the cross-section x BR as a function of the LLP lifetime





Displaced jets in the Muon System (MS) or in the Inner Detector (ID)



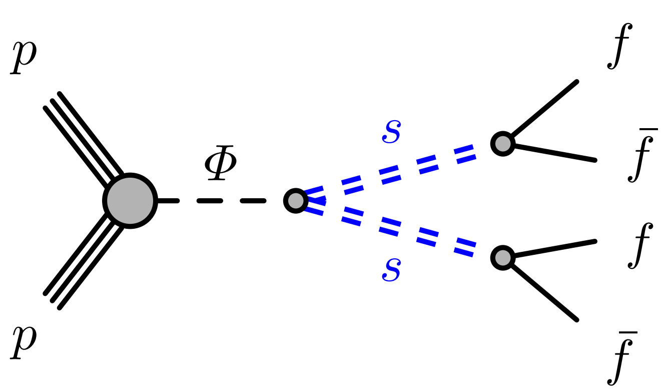
ATLAS latest result
[PRD 92, 012010 (2015)](PRD 92, 012010 (2015))

Displaced jets MS-ID

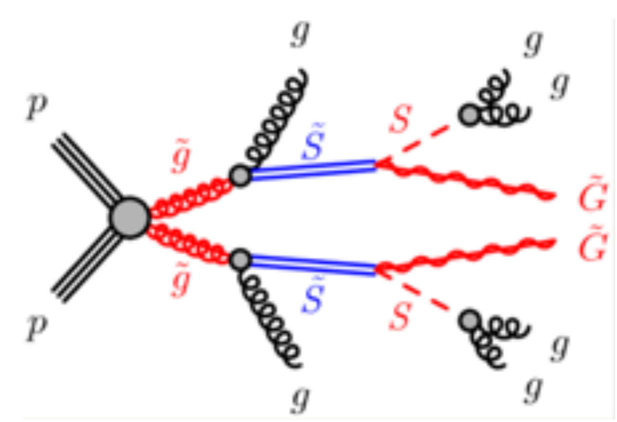
- Search for neutral long-lived particles decaying to SM fermions in the detector. Decays can occur in the ID, in the calorimeter, in the MS

- 3 benchmark models involving Hidden sectors:

- heavy neutral boson phi as the communicator
- Signature: 2 displaced jets in the MS



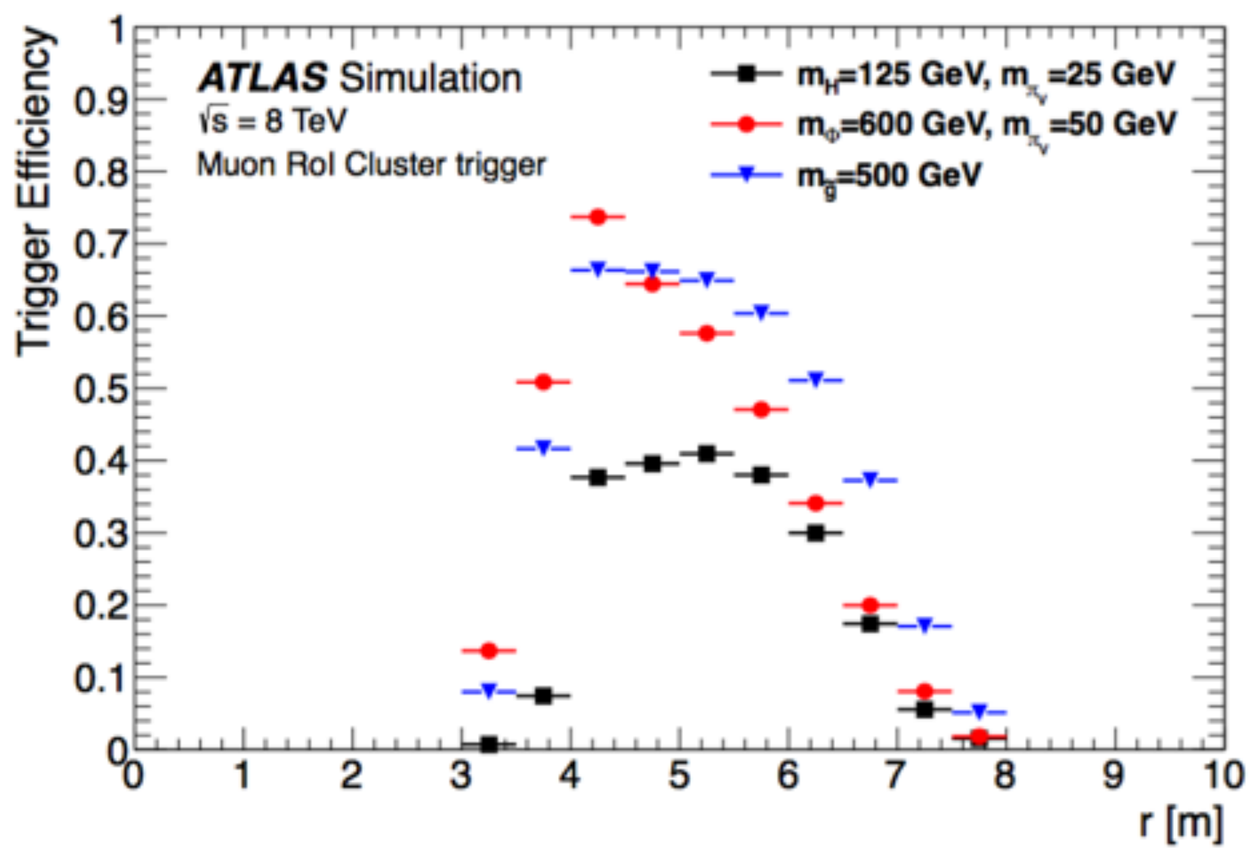
- Stealth SUSY
- hidden singlet superfield weakly coupled to the MSSM
- Signature:
  - 2 displaced jets in the MS
  - 1 displaced jet + 2 prompt jets



Displaced jets MS Triggers

- For decays in the MS, dedicated Muon RoI Cluster trigger to find clusters of muon RoIs with no ID tracks and no jets associated

- Place cuts on number of MDT hits
- Primary background is punch-through jets

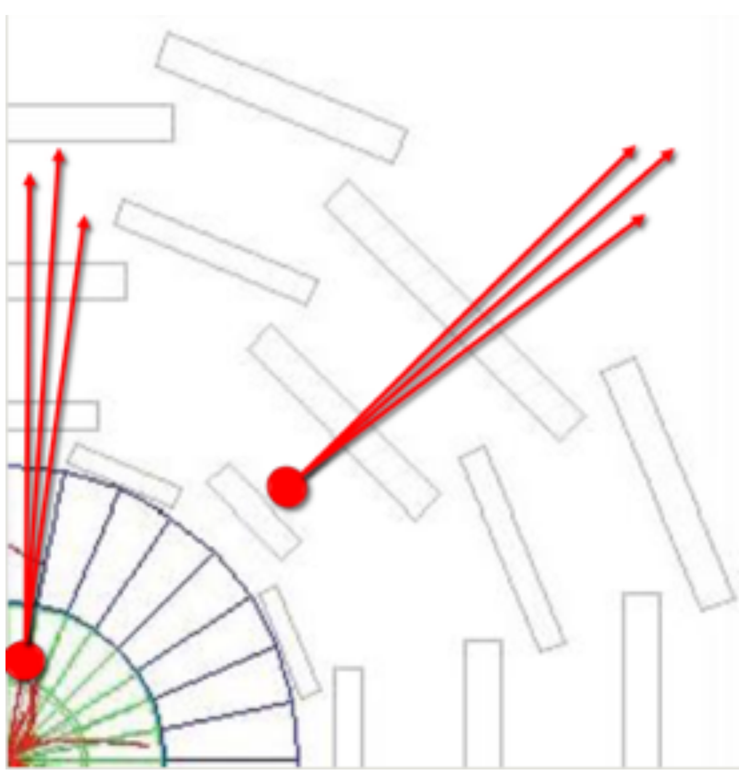


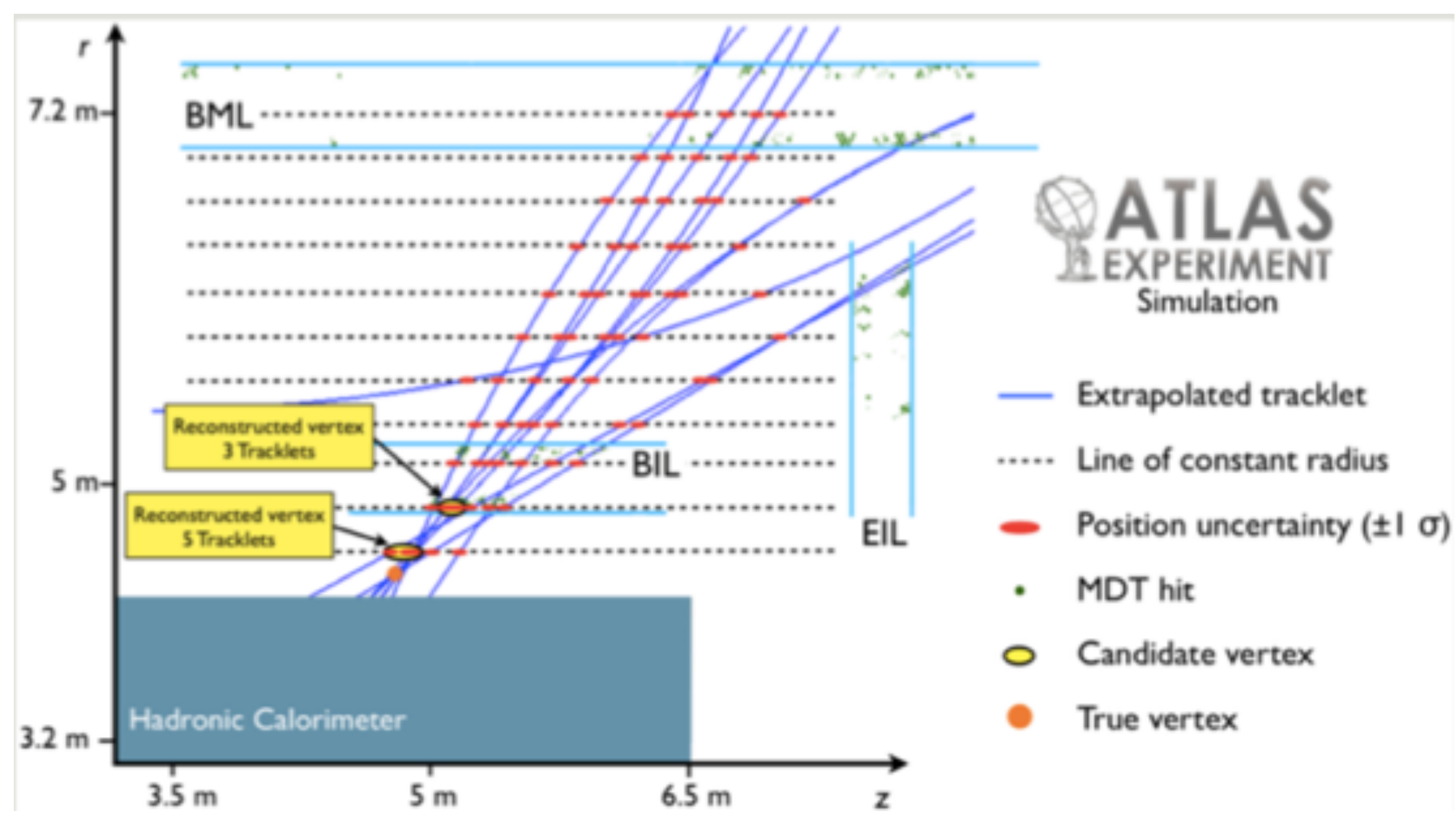
MS vertex reconstruction

- MS vertices from displaced jets: high MDT hits multiplicity, no ID tracks, no jets

- Background rejection:
- SM muons are composed by an ID track matched to an MS track
  - Track isolation rejects SM muons
- High-pt SM jets can “punch-through” the calorimeters and make many MDT hits
  - Jet isolation

MS vertex reconstructed by combining “tracklets”



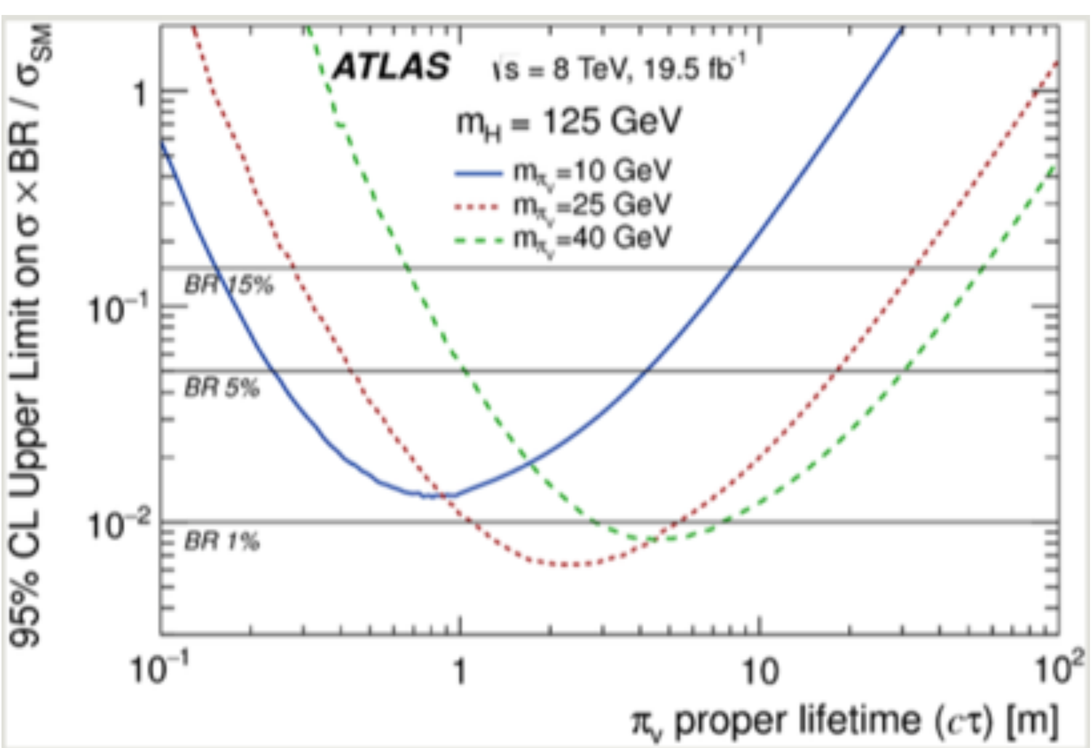


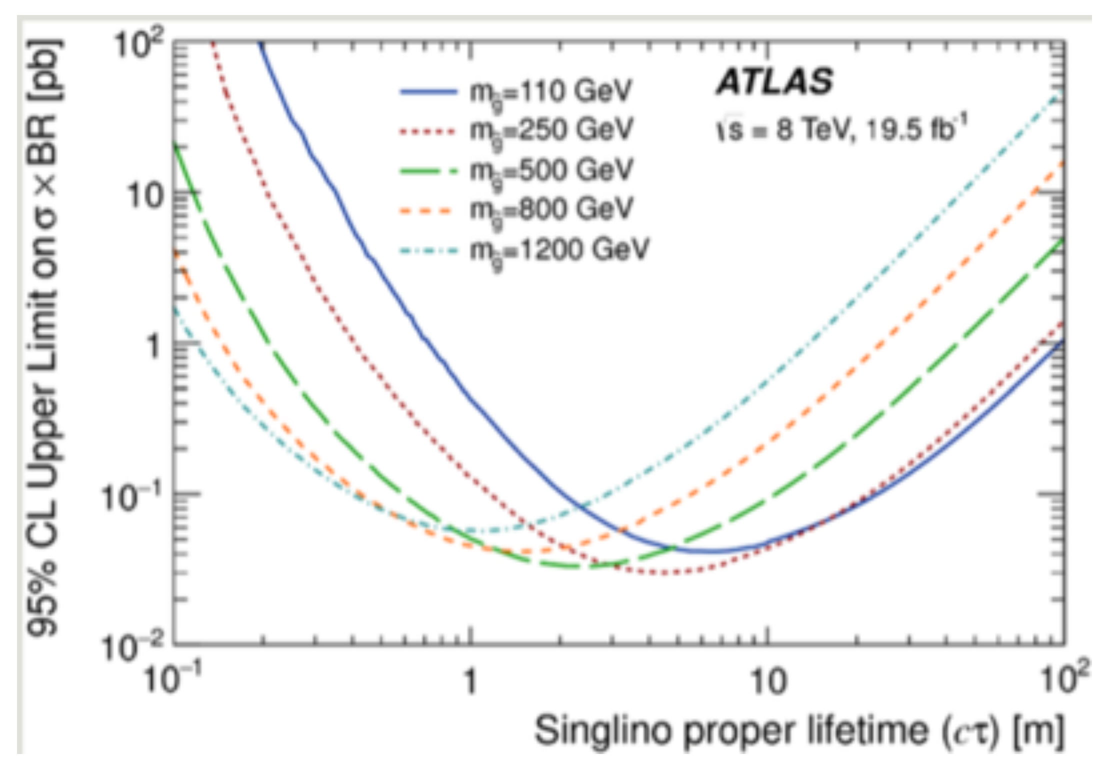
Displaced jets MS-ID results

- Backgrounds estimated using combination of probabilities of a single fake object (data-driven)
- Results given in 3 possible combinations: 2 ID; ID + MS, 2 MS

Jet+ME_T Trigger	Displaced Trigger	Topology	Expected	Observed
Yes	-	2 ID	$(1.8 \pm 0.4) \times 10^{-4}$	0
Yes	MS	ID + MS	2.0 ± 0.4	0
Yes	MS	2 MS	$0.4^{+0.3}_{-0.2}$	2

- Final limits only calculated with the combination of the 3
- Number of expected events is compatible with the background prediction
- Place limits on cross-section x BR as a function of the LLP lifetime



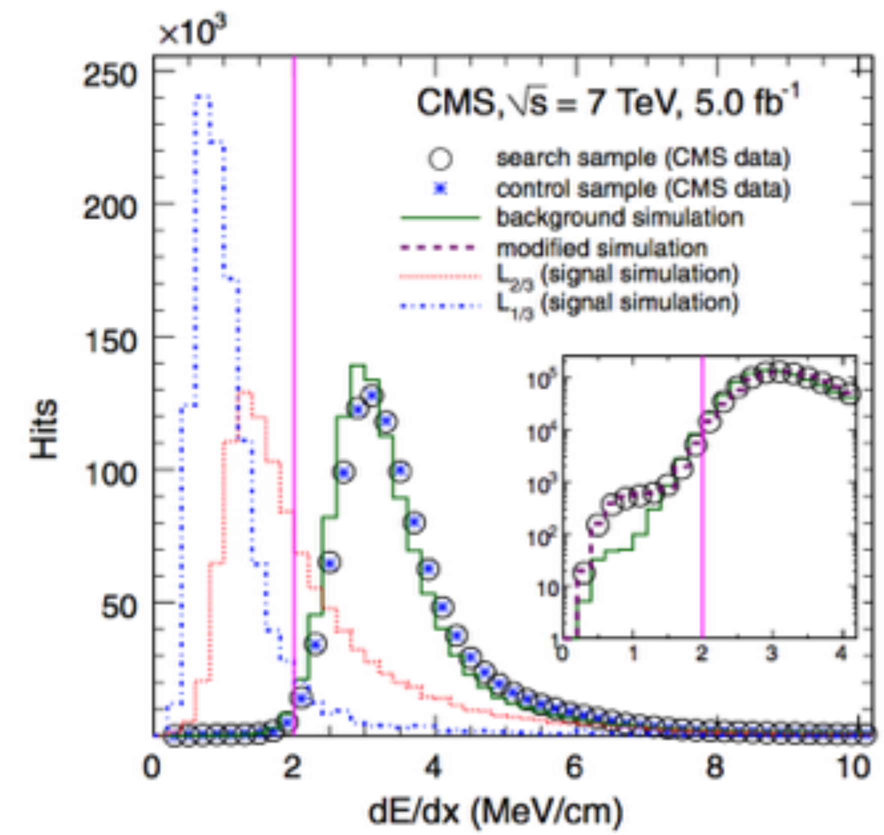


Fractional charge particles

CMS latest result
PhysRevD.87.092008

- Search for long-lived fractionally charged fermions, Lq
- Fractionally charged particles are common in some theoretical scenarios (e.g. superstrings)

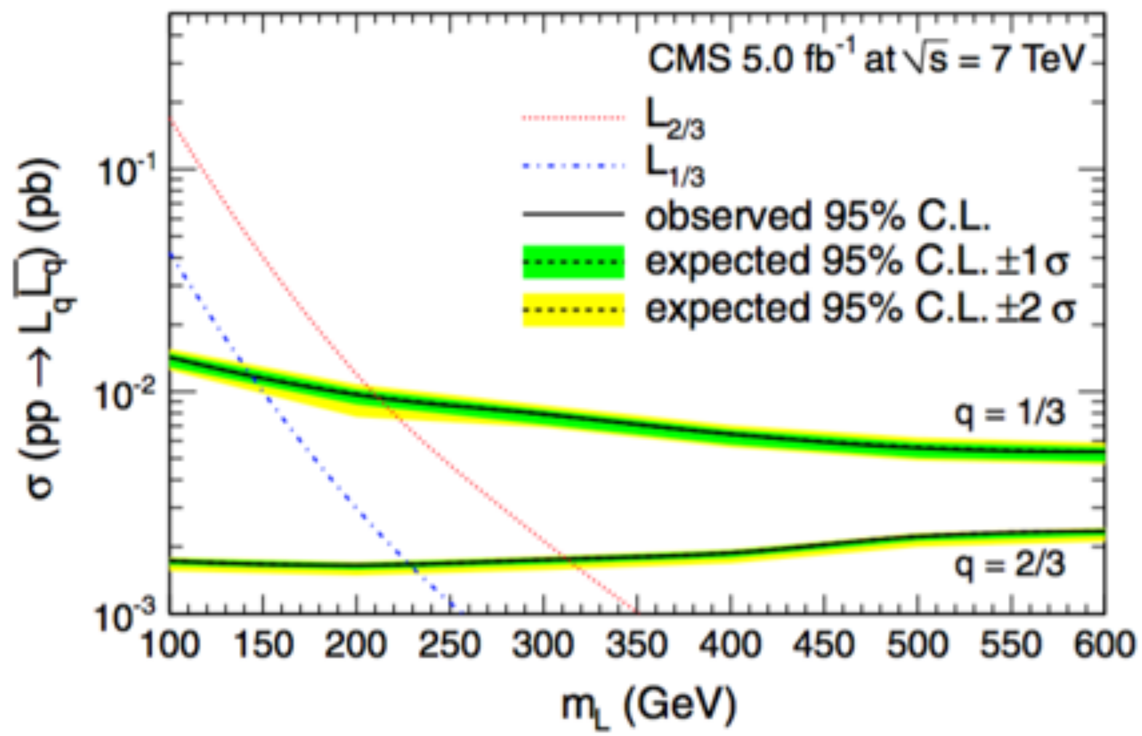
- Trigger on muons and use information from pixel dE/dx to discriminate from background:
  - look for ID track matched to MS track
  - identify fractionally charged particle candidates by their anomalous ionization energy loss in the inner tracker:
    - lower rate of energy loss in the detector since dE/dx ∝ q^2
  - require at least six dE/dx measurements from the tracker
  - track is isolated



- Backgrounds from cosmics and collisions estimated with data-driven methods
- MC-data agree within stats uncertainites

Fractional charge particles

- No data events observed
- Set limits on the fractional charge particle pair production cross section as a function of its mass

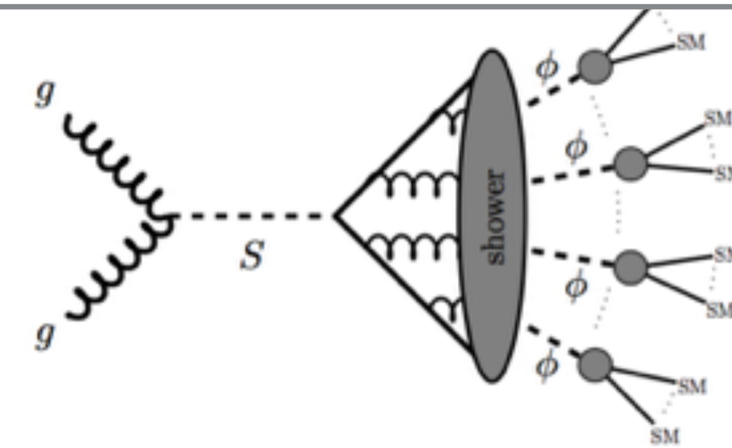


Cosmic rays	0.007 ± 0.006
pp collisions	0.005 ± 0.004
Total background	0.012 ± 0.007
Observed events	0

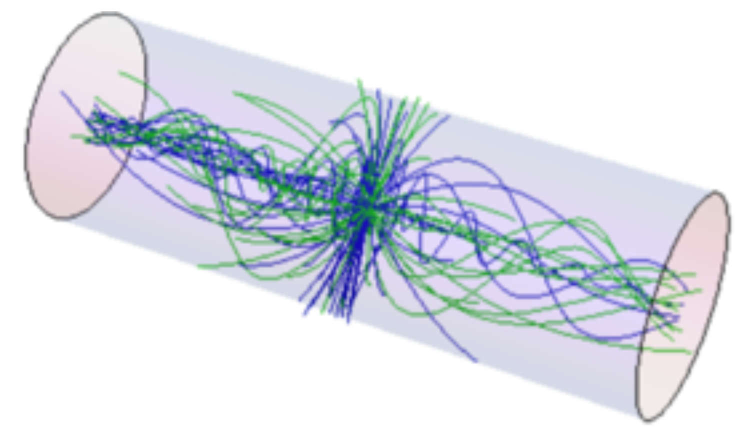
SUEP (soft, unclustered energy patterns, soft particle clouds?)

Knapen et al. 2016
[arXiv:1612.00850v1 [hep-ph]]

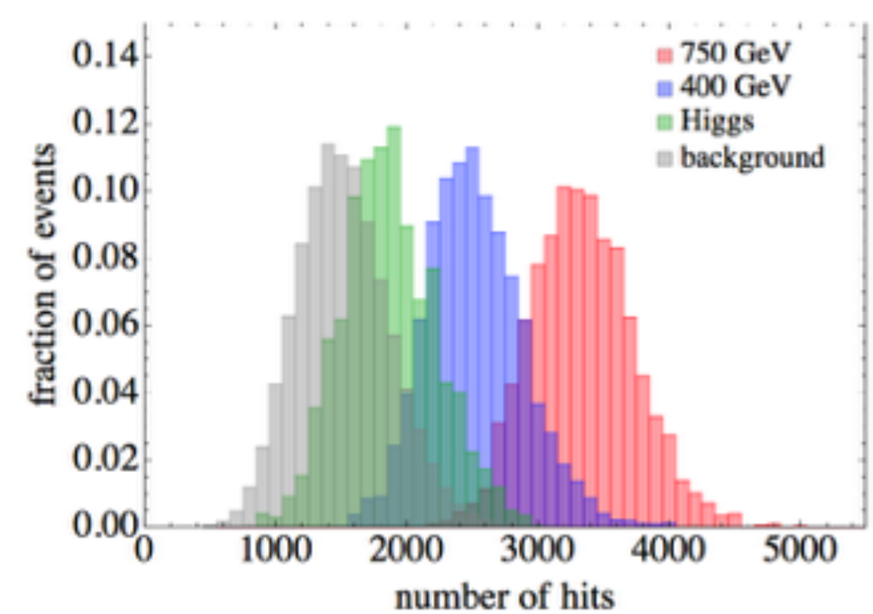
- Very high multiplicity, spherically-symmetric distributions of soft particles
- May be a signature of strongly-coupled hidden valleys



- Signature: anomalously large multiplicity of soft particles.
  - That looks like Pileup!!
  - But very concentrated, ring-shaped overdensity of hits: 'belt of fire'



- Effort to develop a trigger for SUEPs
- Main idea: use overdensity of hits on the inner layers of ID
  - L1 trigger: SUEP recoiling against a hard object. Triggers are based on jet, multijet and MET
  - HLT: full track reconstruction not possible. Instead use the distribution of the hits on the tracker surfaces to discriminate signal from background .
  - Offline: enhance background rejection via requirements on track multiplicities.



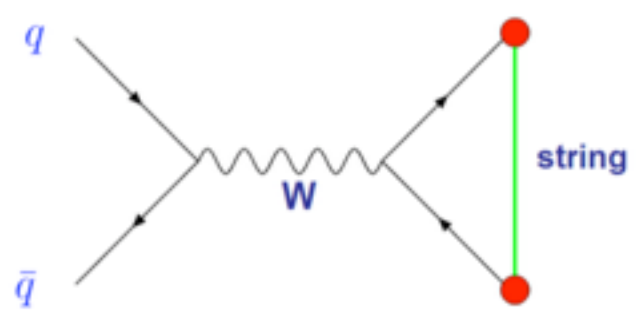
Conclusions

- Lacking any evidence for New Physics in any of the searched finalized so far, long-lived particle signatures are gaining in popularity
- Wide variety of searches
- Very challenging, pushing the detectors for searches they were not designed to perform
- Many analysis working on improvements with the full13 TeV dataset and beyond
- All new ideas should be considered so that we don’t miss a signal

Backup

Quirks

- Particular case of Fractionally charged particles:
- If charged under a new asymptotically free gauge group SU(N) —> quirks
- Characterized by
  - the mass of the new fermions (quirks),Q
  - the strength of the gauge coupling, Λ
  - consider $\Lambda << M_Q$, and M_Q = 0.1 – 1 TeV: Breaking of new symmetry suppressed, $Q\bar{Q}$ pair produced in $p\bar{p}$ collisions will not hadronize
- quirks in the pair will stay connected, the two tracks will not be resolved by the tracking system



- Strategy: requires an isolated track and a high pT jet back to back, used as trigger
- characteristic radiation and non-trivial tracking patterns