SEARCH FOR BSM PHYSICS USING CHALLENGING SIGNATURES WITH THE ATLAS DETECTOR

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on behalf of

The ATLAS Collaboration

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BSM at ATLAS

- BSM physics may produce final states which are difficult to trigger on or reconstruct, or may have complicated backgrounds
- Particles may leave atypical types of tracks in the detector, or decays anywhere in the detector, including in the calorimeters or the muon spectrometer

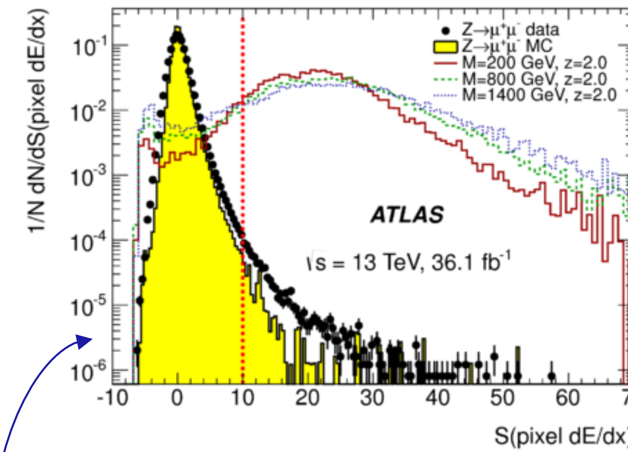
- Will discuss four recent searches performed by the ATLAS collaboration
- Multi-charged particles – https://arxiv.org/abs/1812.03673
  - Make use of dE/dx measurements in multiple subdetectors
- Displaced jets in the HCal – https://arxiv.org/abs/1811.02542 , https://arxiv.org/abs/1902.03094
  - Use jets with ratio of calorimeter energy deposits distinct from SM jets
- Displaced jets in the MS – https://arxiv.org/abs/1811.07370
  - Displaced jets in the MS use special trigger and reconstruction

Multi-charged particles

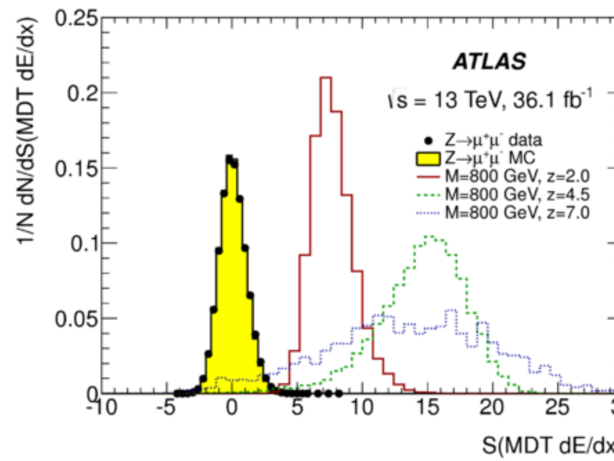
- Many theories predicting multi-charged particles (MCPs)
  - Almost-commutative leptons
  - Technibaryons
  - Doubly charged Higgs boson
- Lepton-like MCPs pair produced with a Drell-Yan production model
  - Q = ze -> (2,2.5,… 7)e
- Expect MCPs to travel through entire detector, with muon-like tracks and distinct ionization signal (dE/dx) throughout ATLAS
  - dE/dx related to charge – dE/dx ~z^2
  - dE/dx measurable in the pixel, TRT, MDT
    - $S(dE/dx) = \frac{dE/dx - \langle dE/dx \rangle_\mu}{\sigma(dE/dx)_\mu}$

★ Heavy particles (presented by B. Hooberman) – also use dE/dx in the pixel to determine mass of slow, highly ionizing particles

https://arxiv.org/abs/1812.03673



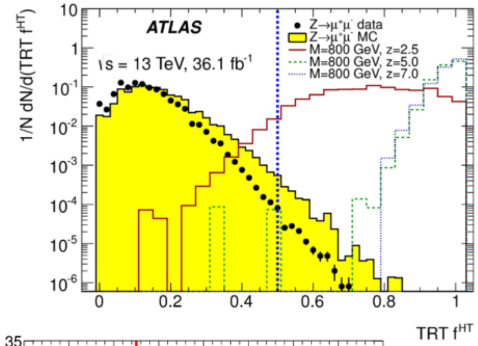
Used for tight signal selection



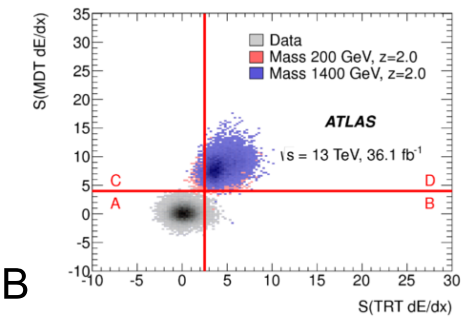
Used for final signal selection

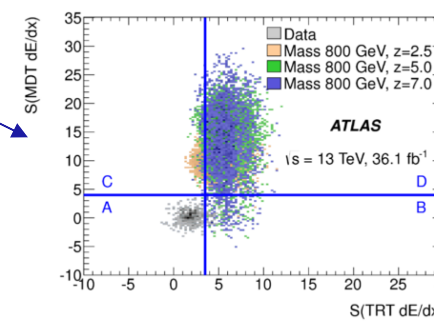
Multi-charged particles

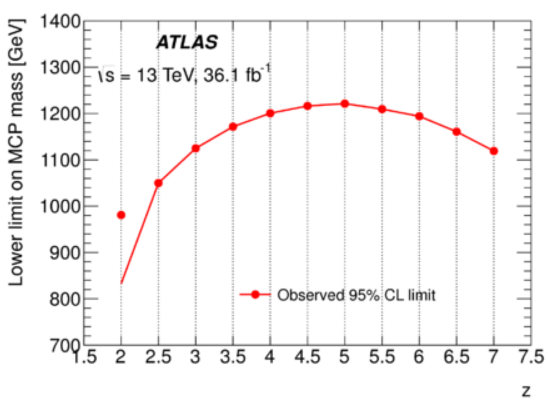
- Pixel dE/dx cannot handle z > 2, use overflow bits in the IBL and use TRT HT fraction
- Background estimation
  - S(TRT dE/dx) and S(MDT dE/dx) very useful to separate signal and background events
  - Two methods
    - Standard ABCD for z = 2
    - No background events in C – develop probability for background to pass S(MDT dE/dx) to apply to events in B
  - < 1 background events predicted, 0 observed

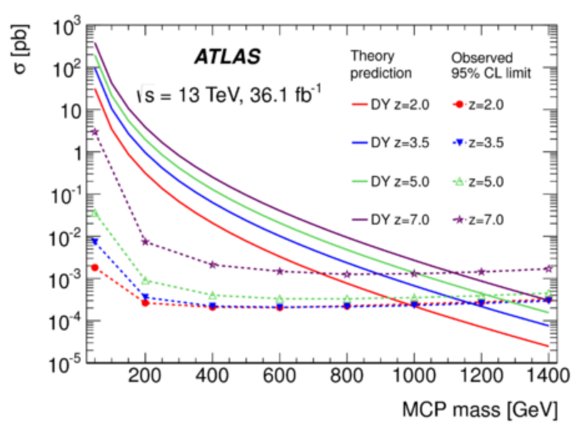


Used for tight signal selection for z > 2







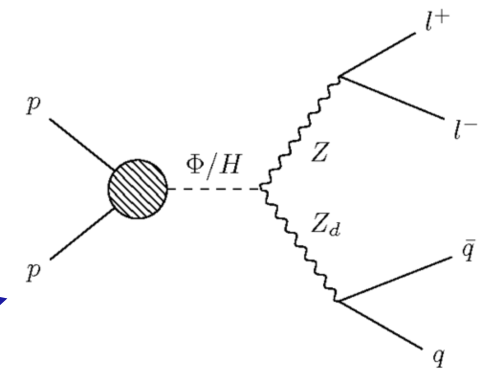


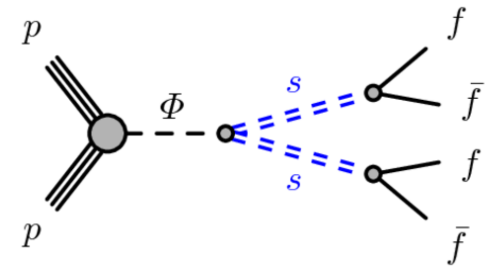
- New limits on DY MCP pairs, using 36.1 fb^{-1} of 2015-2016 data, exclude a range of masses for several z values

https://arxiv.org/abs/1812.03673

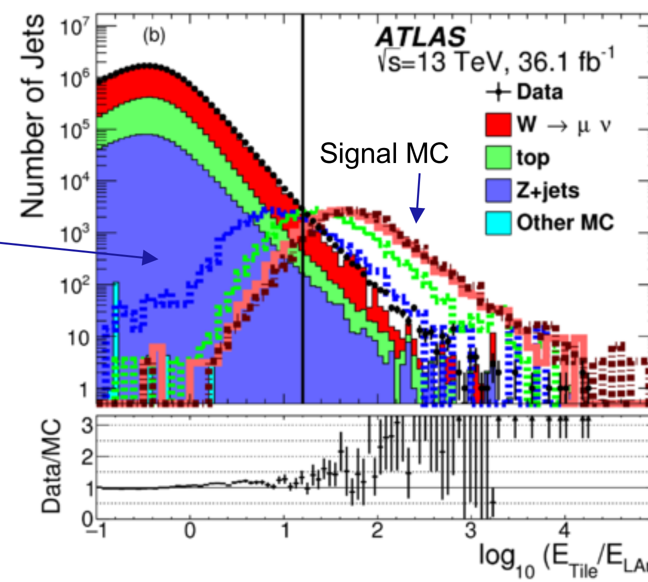
Displaced jets in the HCal

- Two different searches using a H/Φ mediator
  - H/Φ → Z→l^+l^- + Z_D→ $q\bar{q}$
    - Prompt leptons and one displaced jet
    - https://arxiv.org/abs/1811.02542
  - H/Φ → s s → $f\bar{f}f\bar{f}$
    - Two displaced jets
    - https://arxiv.org/abs/1902.03094 (just released!)



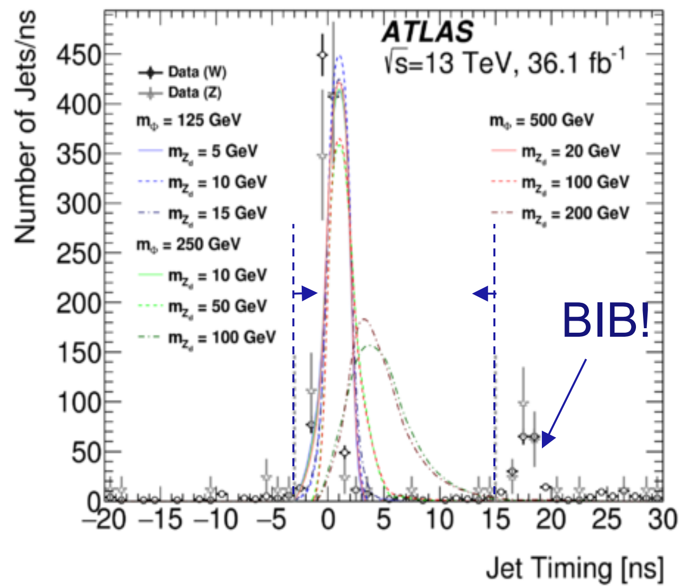


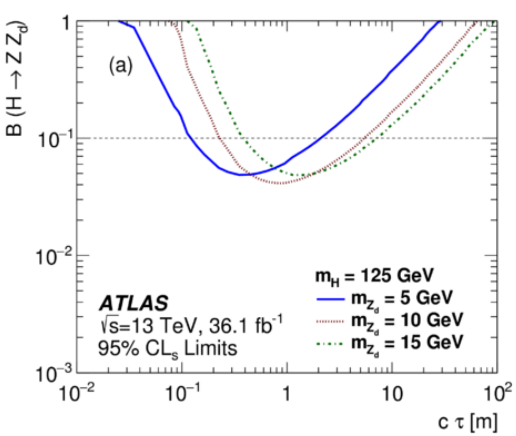
- Properties of jets decaying in the HCal
  - Very little energy left in the ECal
    - CalRatio - $\frac{E\_HCAL}{E\_ECAL}$ - greater than most SM jets
  - Jets appear narrower than those from prompt decays
  - Very few tracks point to ATLAS primary vertex
    - Unlike most SM process which come from PV

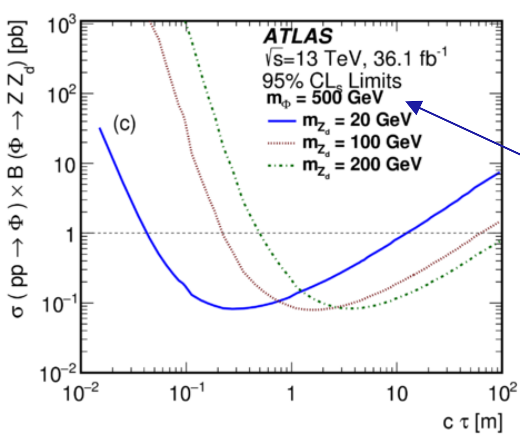


Displaced jets in the HCal – H/Φ → $Z \rightarrow l^+l^- + Z_D \rightarrow q\bar{q}$

- Prompt leptons in the event
  - Useful for trigger, event selection
- SM backgrounds (Z/W+jets, top)
  - Discriminate using cuts on tracks per jet and calRatio
- Other backgrounds (Out-of-time pileup, BIB)
  - Discriminate against using jet timing
- Background estimation
  - $f_{CR} = N_{CR\text{-}jet}/N_{jet}$ in W->lν data





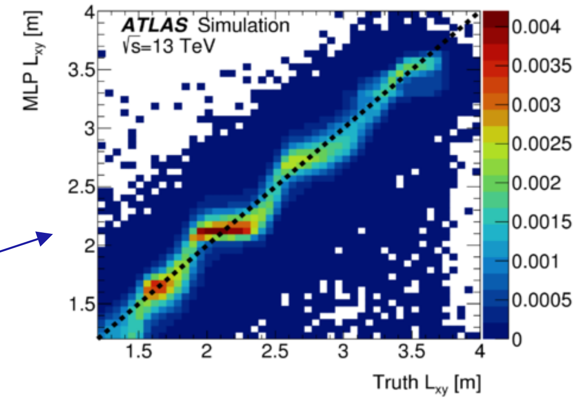


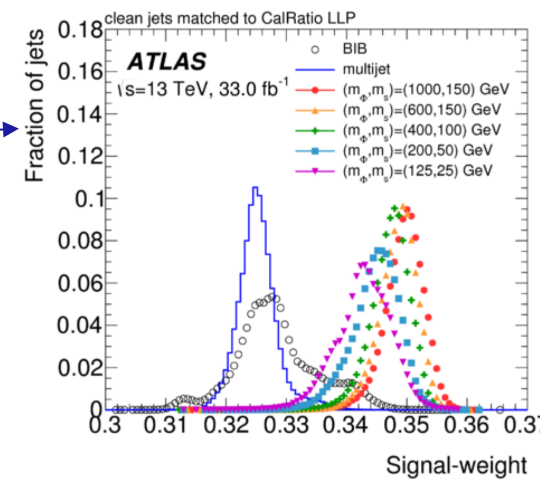
- Limits set using 36.1 fb^{-1} of 2015+2016 data
- Expand previous search with addition of higher mass Φ

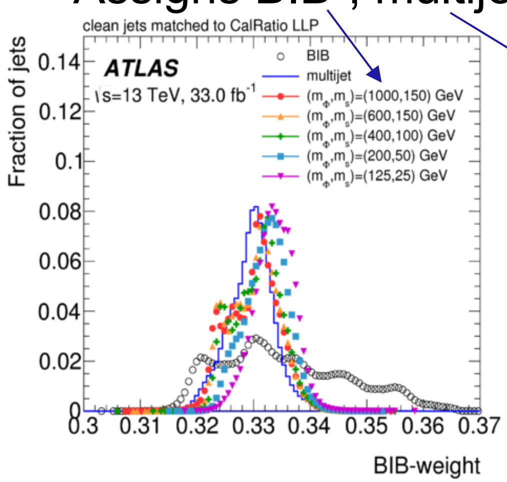
https://arxiv.org/abs/1811.02542

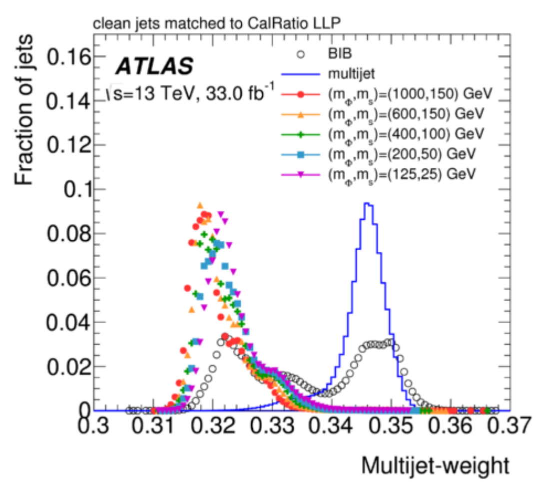
Displaced jets in the HCal – H/Φ → s s → $f\bar{f}f\bar{f}$

- Custom trigger
  - Relies on calRatio, trackless jet features of displaced jets
  - Two triggers for low and high E_T regions
- Multilayer perceptron (MLP)
  - TMVA trained on signal MC samples
  - Used to predict displaced jet decay position
- Per-jet BDT
  - Uses MLP, track, jet properties as input
  - Trained on signal MC, multi-jet MC, BIB data
  - Assigns BIB-, multijet-, signal- weights to jets





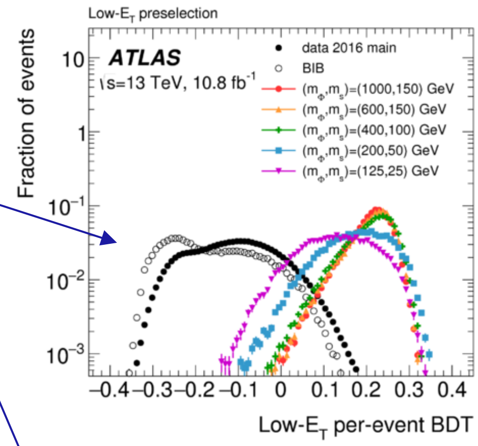


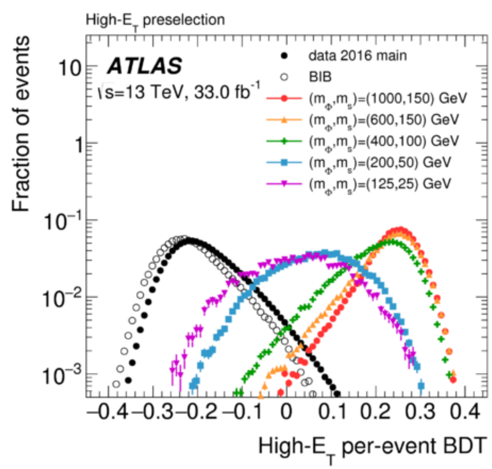


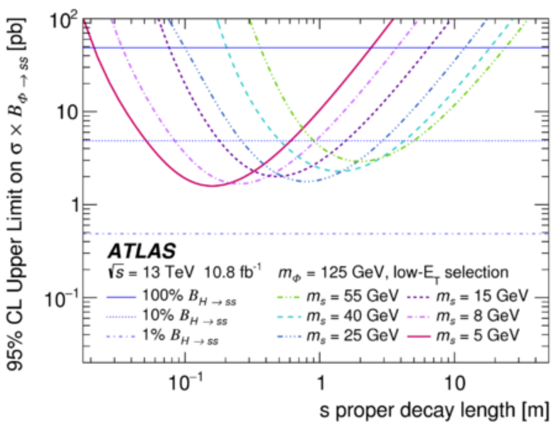
https://arxiv.org/abs/1902.03094

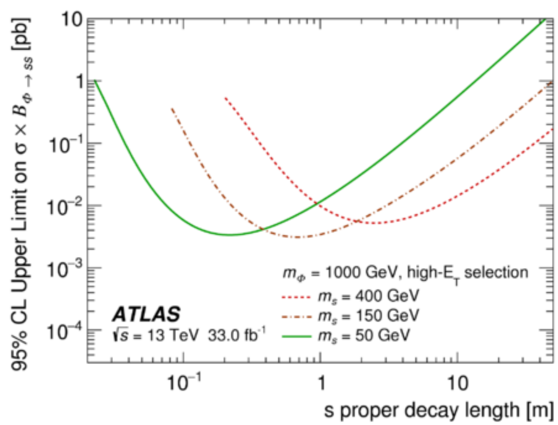
Displaced jets in the HCal – H/Φ → s s → $f\bar{f}f\bar{f}$

- Per-event BDTs
  - Use per-jet BDT, other event level variables
  - Trained on signal MC and BIB data
  - Purpose to distinguish BIB events from signal events
  - Event cleaning including BDT output – removes BIB
- Data driven ABCD method
  - Use per-event BDT and $\sum \Delta R_{min}(jet, tracks)$
- Limits set
  - Using 10.8 fb^{-1} of 2016 data for low E_T
  - Using 33.0 fb^{-1} of 2016 data for high E_T







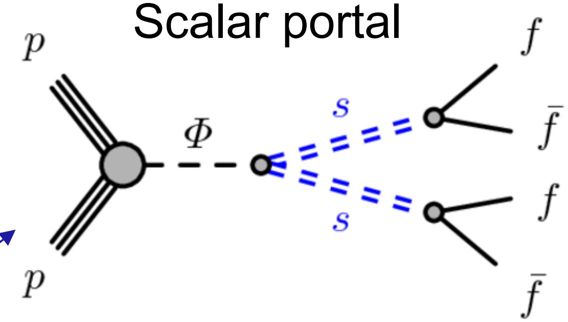


https://arxiv.org/abs/1902.03094

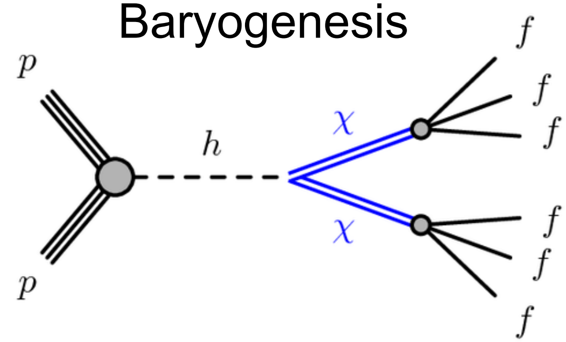
Displaced MS jets

- Many signatures can result in displaced hadronic jets decaying after the last layer of the HCal
  - Scalar bosons decaying to fermion pairs
    - 2MSVx
    - 1MSVx + E_T^{miss}
  - Baryogenesis models
    - 2MSVx
    - 1MSVx + E_T^{miss}
  - Stealth SUSY models
    - 2MSVx
    - 1MSVx + Jets

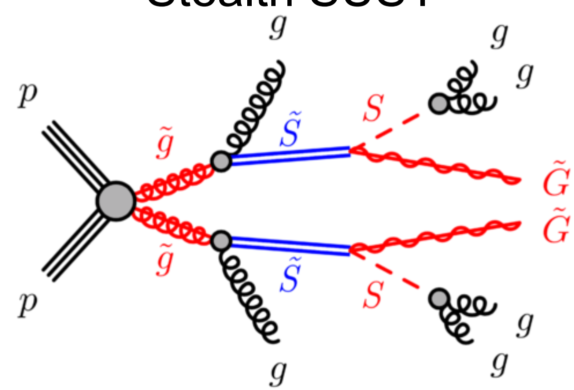
Scalar portal



Baryogenesis



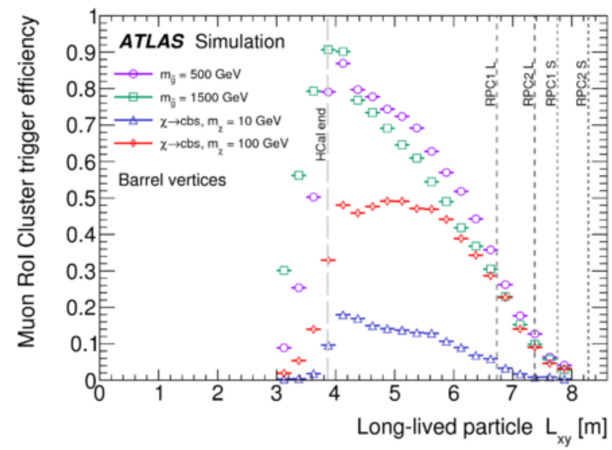
Stealth SUSY

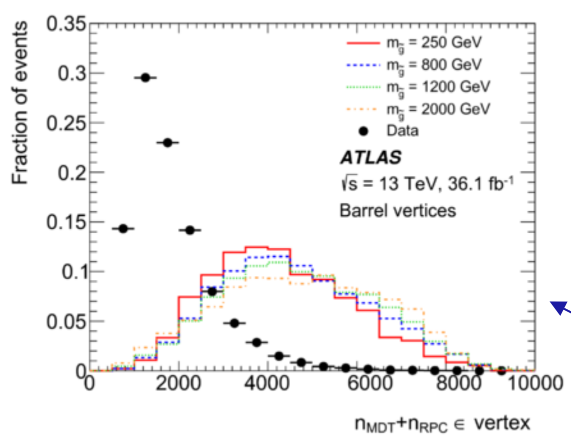


https://arxiv.org/abs/1811.07370

Displaced MS jets

- Hadronic vertices in the MS – large numbers of low p_T, charged particles
  - Quite different from tracks of muons in the MS
- Specialized muon trigger
  https://arxiv.org/abs/1305.2284
  - Based on a dimuon trigger at L1
  - Requires clusters of 3 (4) muon regions of interest in $\Delta R < 0.4$ cone in the barrel (endcap)
  - Trigger efficiency impacted by LLP decay position – earlier decays are more spatially separated



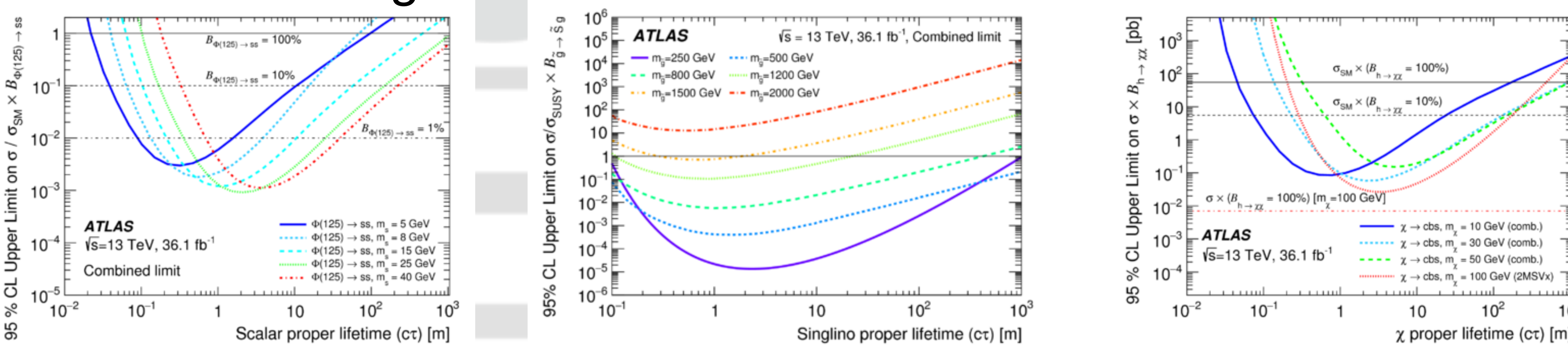


- Specialized MSVx reconstruction
  https://arxiv.org/pdf/1311.7070.pdf
  - Takes advantage of MDT chamber structure to form tracklets
  - Tracklets used to reconstruct vertices
  - Slightly different algorithms for MSVxs in the barrel vs endcaps
    - Differences in B-field
  - High hit multiplicity and isolation of MSVx required to separate true displaced decays from background

https://arxiv.org/abs/1811.07370

Displaced MS jets

- Two different background determination methods, for 2MSVx or 1MSVx + X
  - For 2MSVx strategy background calculated using counting method with zero bias data
    - -> $N_{2Vx} = N^{1Cl} \times P^{Vx}_{noMStrig}$
  - For the 1MSVx + X, ABCD methods were used with two different planes
    - 1MSVx + jets – Isolation criteria vs nMDT + (nRPC,nTGC) hits in MSVx
    - 1MSVx + E_T^{miss} – Isolation criteria vs $\Delta\varphi$ between MSVx and E_T^{miss} vector
- Limits set using 36.1 fb^{-1} of 2015+2016 data on σ×BR



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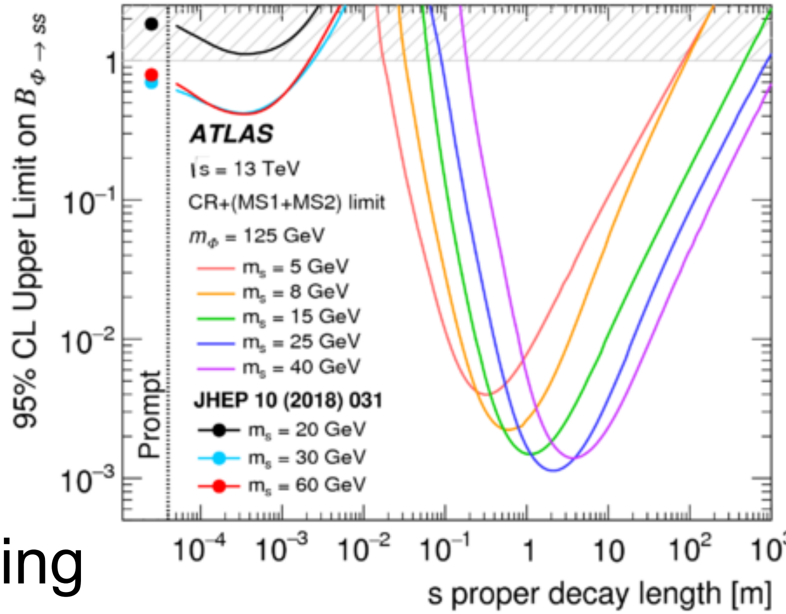
Conclusions

- Bonus – hot off the presses, new combined limits using results from displaced HCal and MS jets searches



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2017-25/

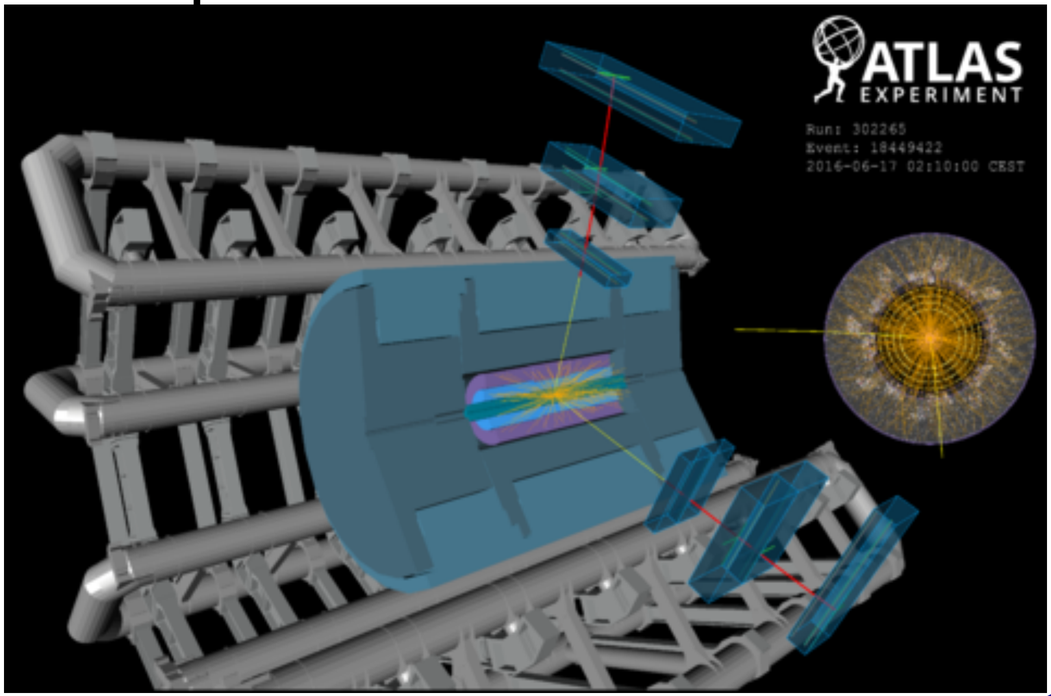
- Many interesting searches happening at the ATLAS experiment right now (including slightly older searches I didn't have time to mention)

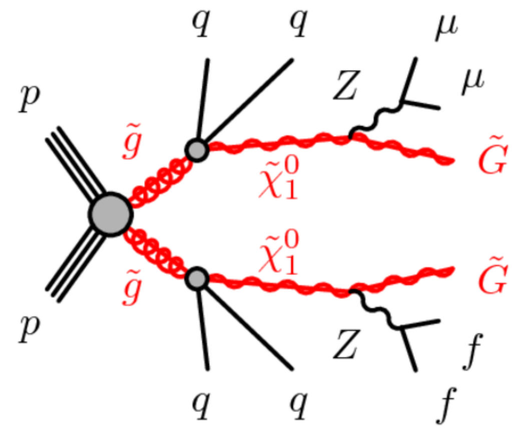
https://journals.aps.org/prd/pdf/10.1103/PhysRevD.99.012001

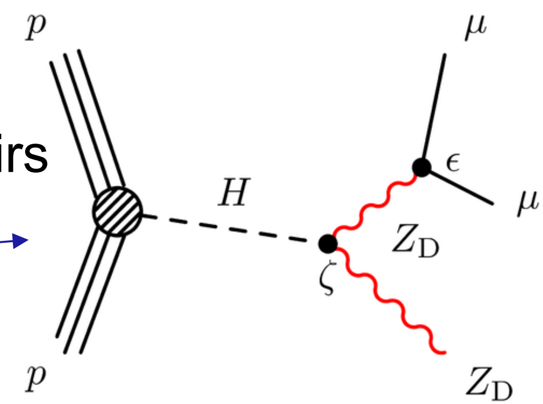
- Challenging signatures take time and creativity but are necessary to cover all the available phase space
- Many more analyses in the pipeline
- Thanks for listening!

BACKUP

Displaced dimuon vertices





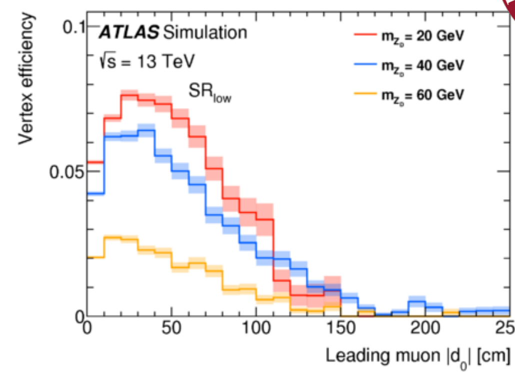


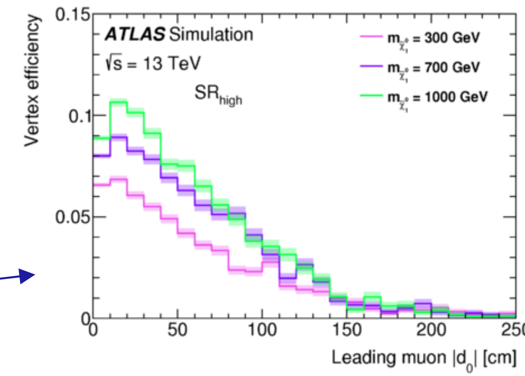
- Different models can produce displaced muon pairs
  - General gauge mediated SUSY
  - Dark sector gauge boson models
- $\mu^+\mu^-$ from a vertex at least several cm from IP
- Use MS standalone tracks
- Vertex position – half way between points of closest approach (to the IP) of the two muons

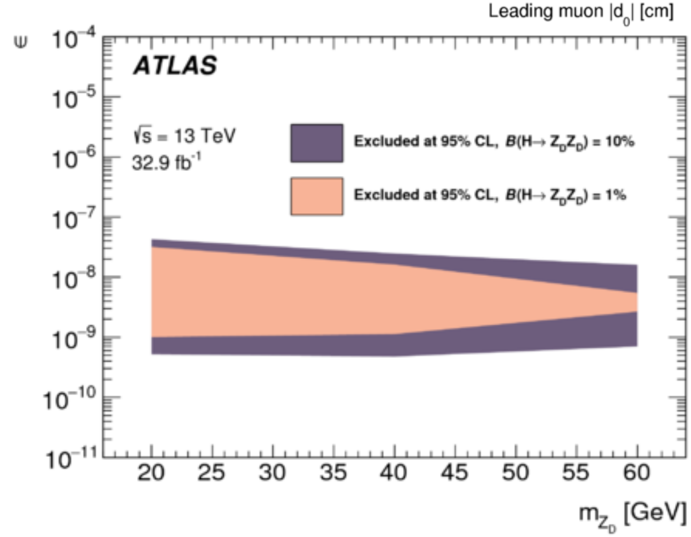
https://journals.aps.org/prd/pdf/10.1103/PhysRevD.99.012001

Displaced dimuon vertices

- Many backgrounds to consider including BIB, cosmic muons, fakes, and prompt muons from several SM processes
- Isolation of muon candidates required from ID tracks and jet activity
  - Impacts efficiency for signal muons at low d_0, in addition to limits at high d_0
- Limits set with 32.9 fb^{-1} of 2016 data
  - Lifetime ranges excluded for each mass point in GGM and dark sector models
  - Values of coupling parameter ε excluded for 20 < m_{ZD} < 60 GeV



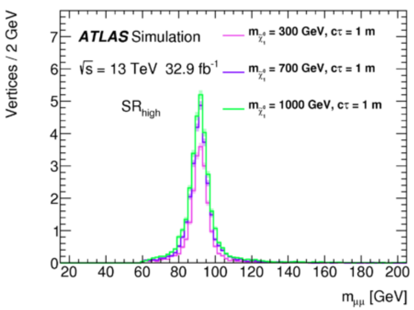


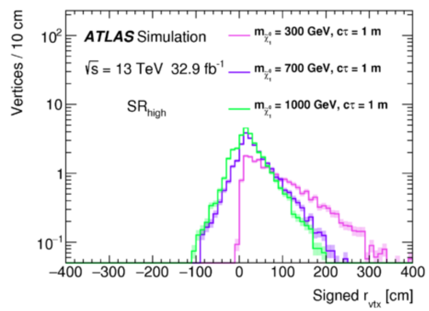


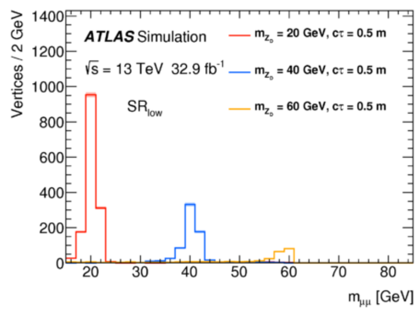
https://journals.aps.org/prd/pdf/10.1103/PhysRevD.99.012001

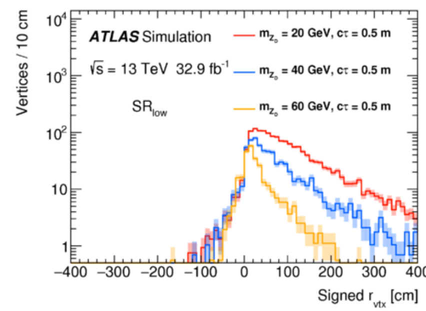
Backup for displaced dimuon vertices

- The distributions of dimuon invariant mass and r_{vtx} (the projection of the vertex position into the xy-plane)
  - For GGM   for dark-sector

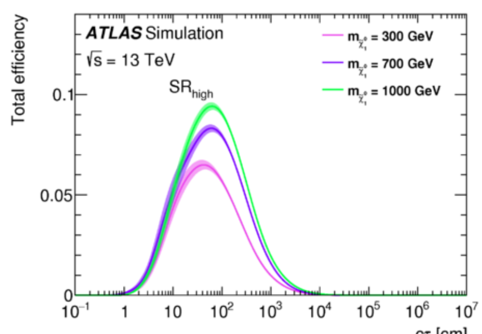


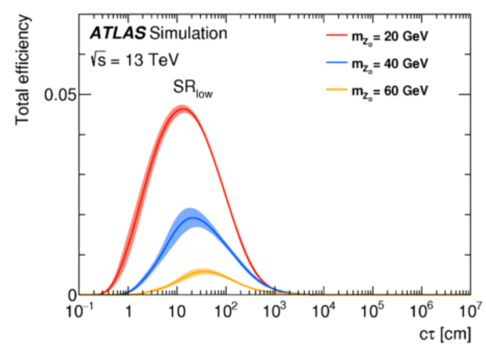






- Overall event-level efficiencies after full signal region selection for GGM and dark-sector





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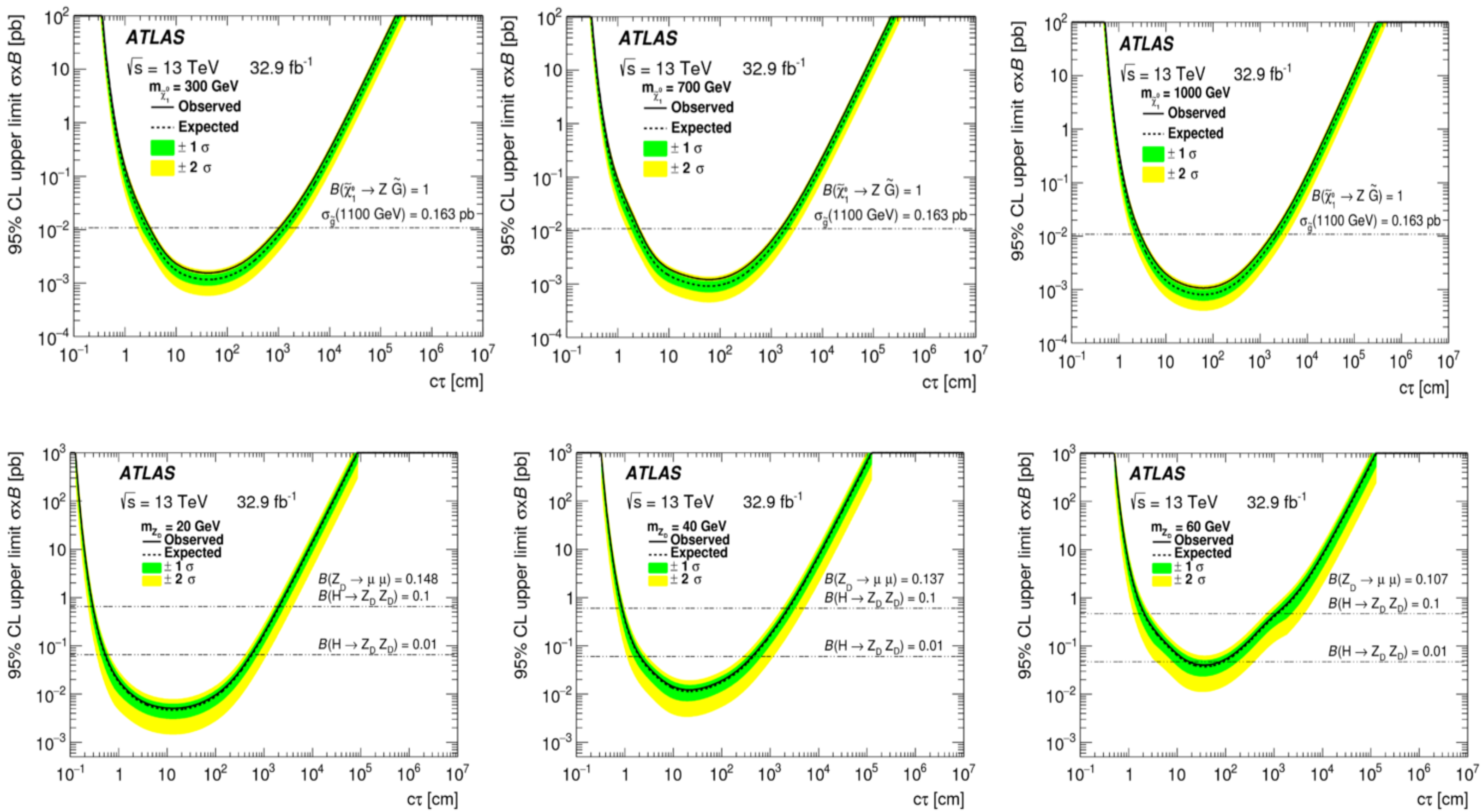
Backup for displaced dimuon vertices – more limit plots



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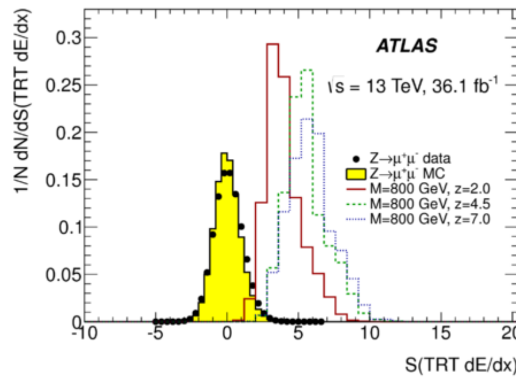
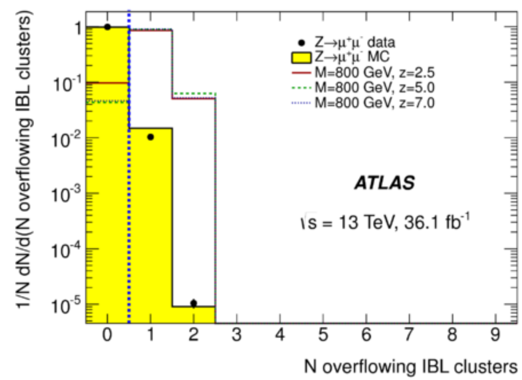
Backup for multi-charged particles

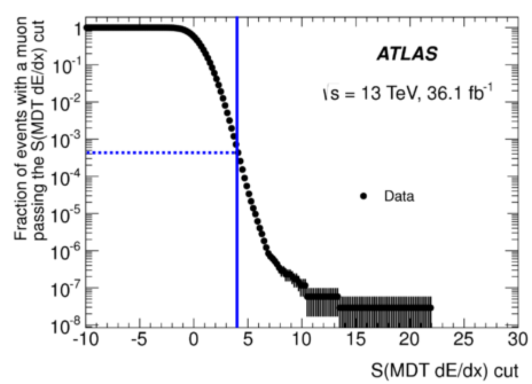
- S(TRT dE/dx) used in ABCD plane/extra background discrimination



- Number of overflow IBL clusters used for z > 2
  - Pixel saturates at ~8.5*MIP, IBL at ~1.5*MIP
  - IBL has an overflow bit, the rest of the pixel layers do not



- Factor f used for calculation of background for z > 2 for which ABCD plane has no events in 'C'
  - Set using 'anti-tight' selection, reversing either TRT HT fraction or IBL overflow cluster cut



https://arxiv.org/abs/1812.03673

Backup for multi-charged particles

https://arxiv.org/abs/1812.03673

- Selection and background estimation for multi-charged particles

		Candidate track preselection	Tight selection	Final Selection
Reqs	z = 2	Combined muon with: "medium" identification criteria $p_T^{\mu}/z > 50$ GeV $\|\eta\| < 2.0$ no other tracks with p_T/z > 0.5 GeV within ΔR < 0.01	Preselection + S(pixel dE/dx) > 10	Tight selection + S(TRT dE/dx) > 2.5 S(MDT dE/dx) > 4
	z > 2		Preselection + ≥ 1 overflowing IBL cluster, $f^{HT} > 0.5$	Tight selection + S(TRT dE/dx) > 3.5 S(MDT dE/dx) > 4

z = 2

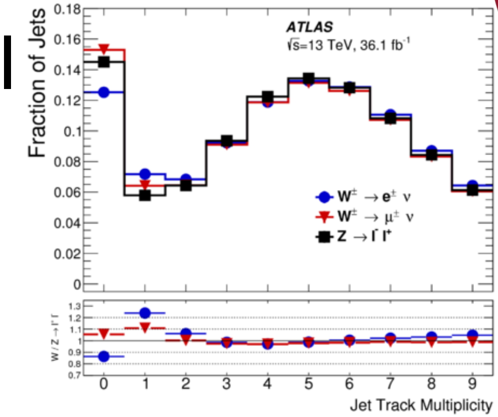
$N_{data}^{A\ obs}$	$N_{data}^{B\ obs}$	$N_{data}^{C\ obs}$	$N_{data}^{D\ exp}$	$N_{data}^{D\ obs}$
22117	379	9	0.15 +/- 0.05 +/- 0.10	0

z > 2

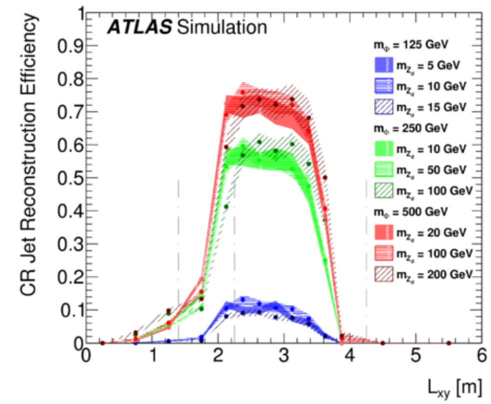
$N_{data}^{B\ obs}$	f	$N_{data}^{D\ exp}$	$N_{data}^{D\ obs}$
66	4.3×10^{-9}	$(2.9 +/- 0.4 +/- 2.2)\times10^{-2}$	0

Backup for displaced jets in the HCal – H/Φ → Z→ll + Z_D→qq

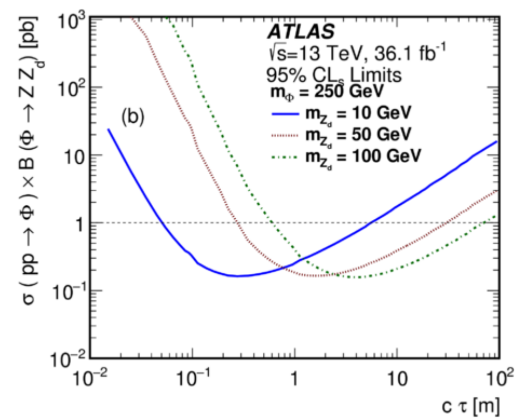
- Jet track multiplicity for SM jets in data
  - Some difference between different decay modes, W->ev looks less like Z, thus it was used for systematics instead of the background estimate



- Calo jet reconstruction efficiency vs L_{xy} of the jet



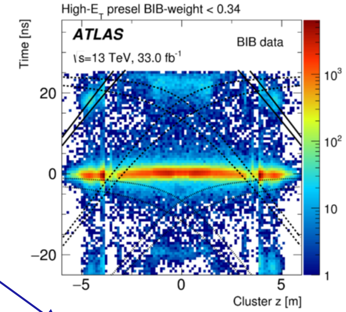
- Limits for m_Φ = 250 GeV
  - Extra scalar mass since previous iteration in addition to 500 GeV

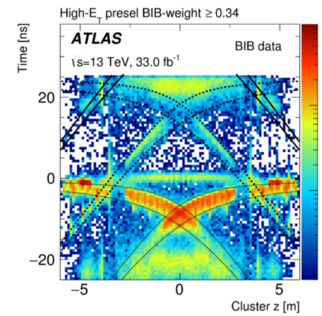


https://arxiv.org/abs/1811.02542

Backup for displaced jets in the HCal – H/Φ → s s → ffff

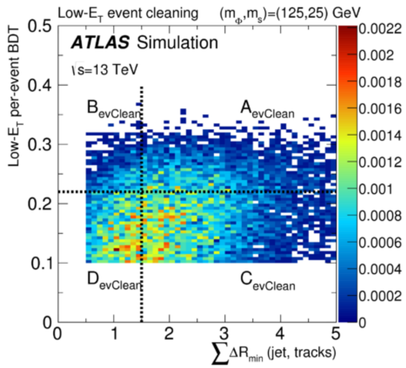
- Bib jet identification ability of per-jet BDT

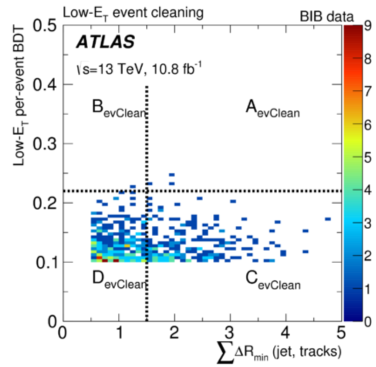


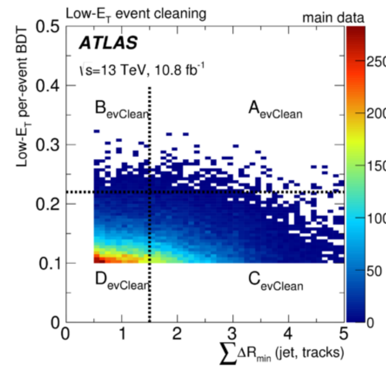


- Low E_T ABCD planes for signal, BIB data, and main data

Low E_T – H/Φ 125,200 GeV

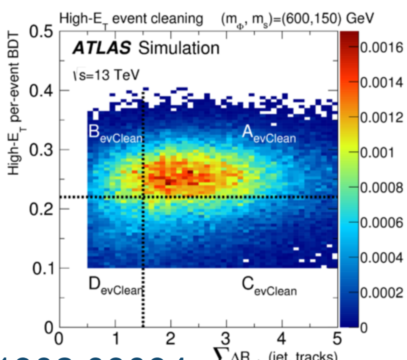


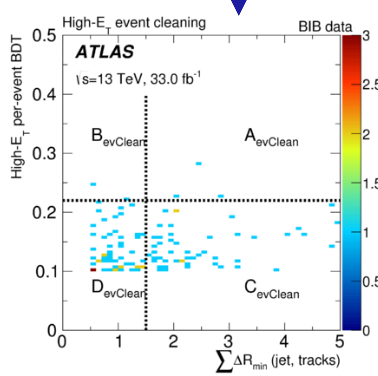


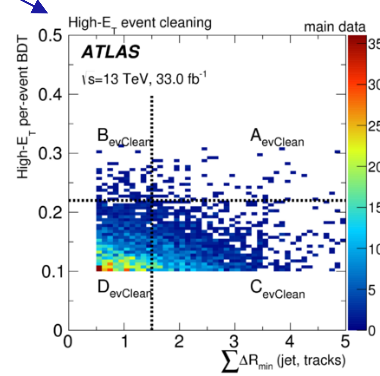


- High E_T ABCD planes for signal, BIB data, and main data

High E_T – Φ 400, 600, 1000 GeV



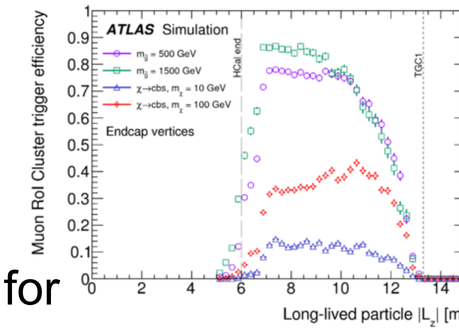




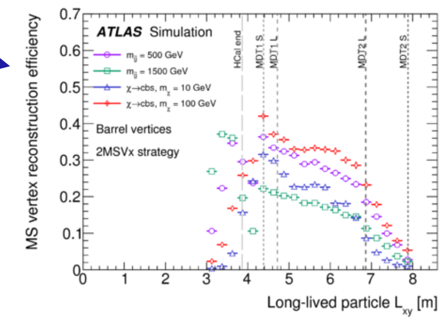
https://arxiv.org/abs/1902.03094

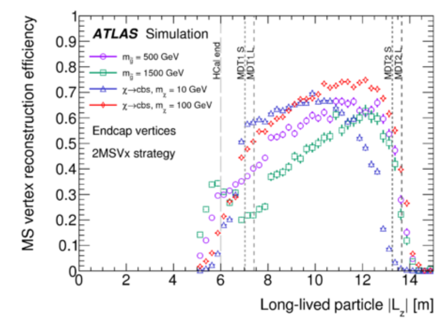
Backup for displaced MS jets

- Trigger efficiency vs MSVx L_z

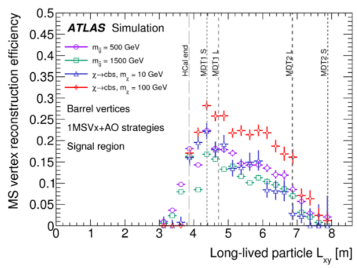


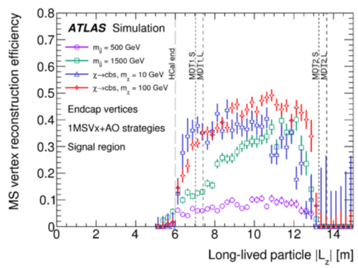
- Vertex reco efficiency for barrel and endcap vertices for 2MSVx strategy



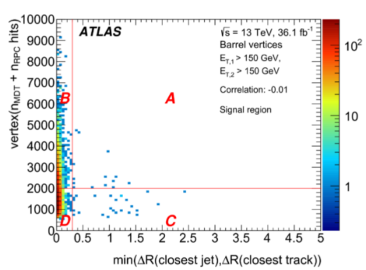


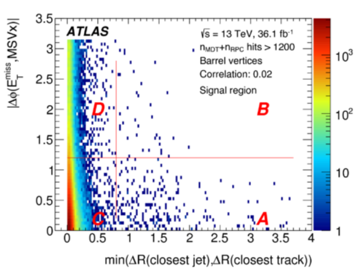
- Vertex reco efficiency for barrel and endcap vertices for 1MSVx + X





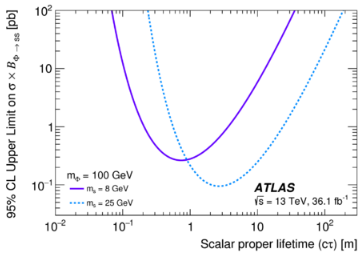
- ABCD planes for 1MSVx + X

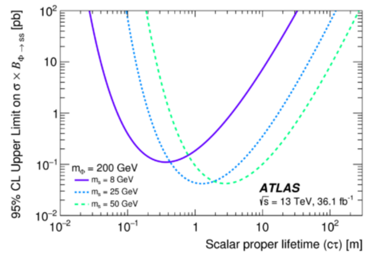


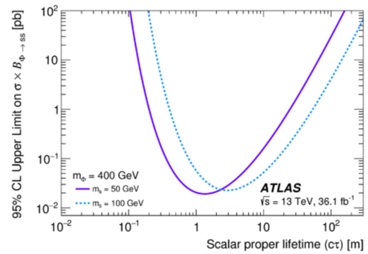


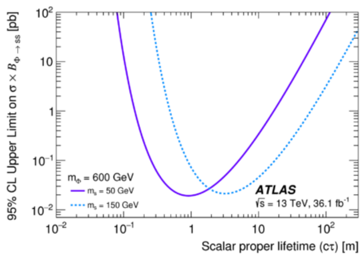
https://arxiv.org/abs/1811.07370

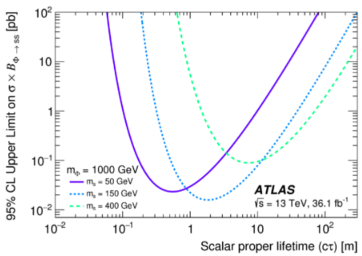
Backup for displaced MS jets – more limit plots

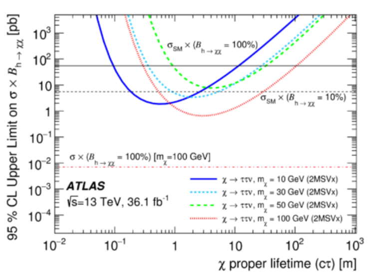


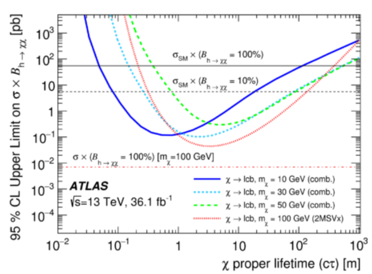


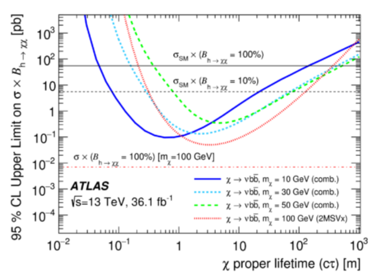








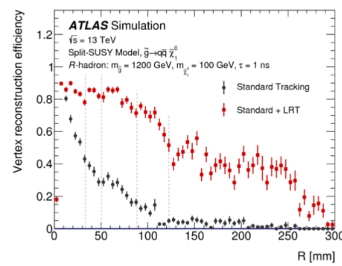


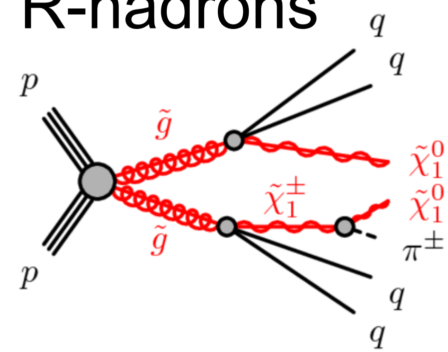


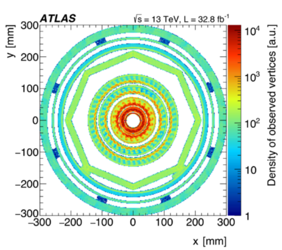
https://arxiv.org/abs/1811.07370

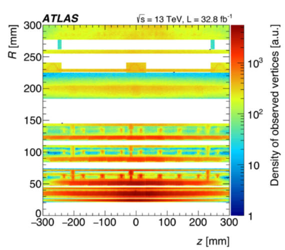
Older interesting searches – Displaced vertex + MET

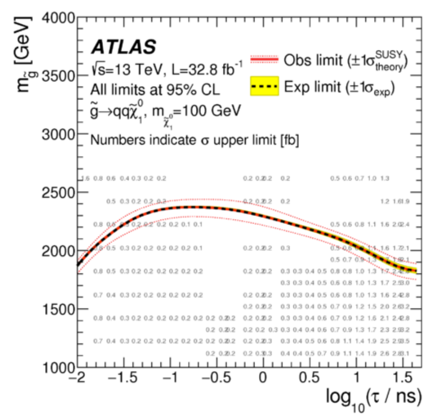
- Displaced ID vertices with missing transverse momentum
- Split SUSY scenarios – large squark mass -> R-hadrons which are long lived
- Vertices in the ID far from the IP
  - Uses specialized displaced tracking
  - Special secondary vertexing
  - Main source of background – hadronic vertices from material interactions



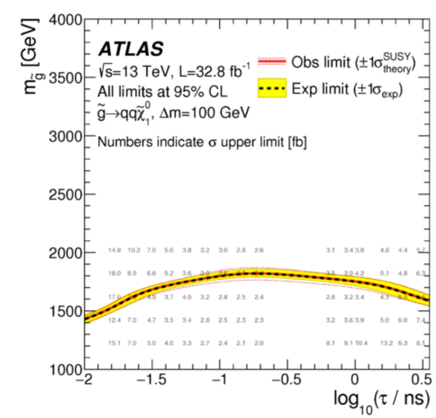






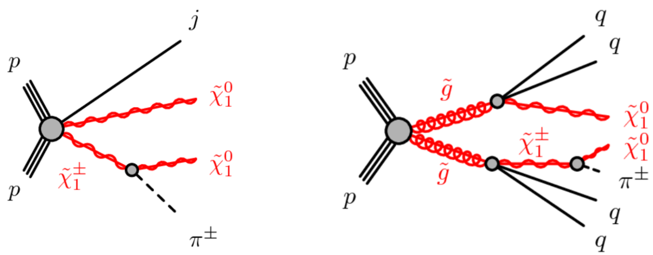


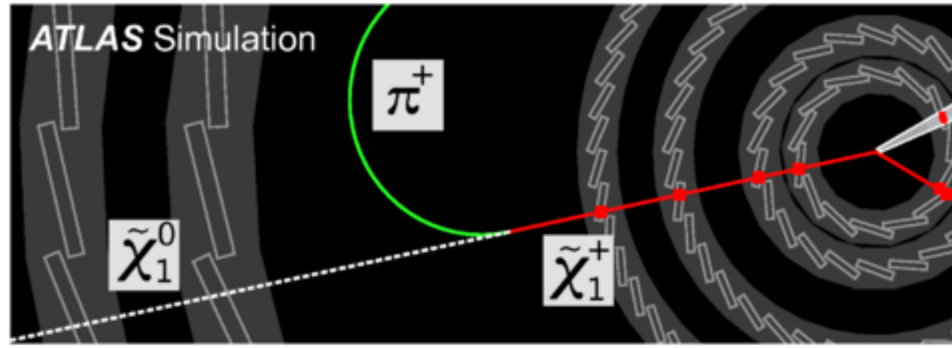
- Limits set using 32.8 fb^{-1} of LHC data



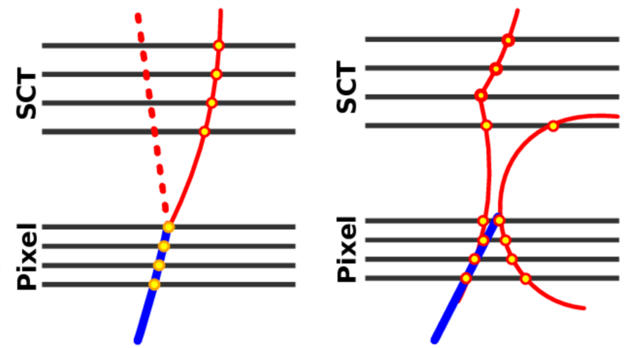
https://arxiv.org/abs/1710.04901

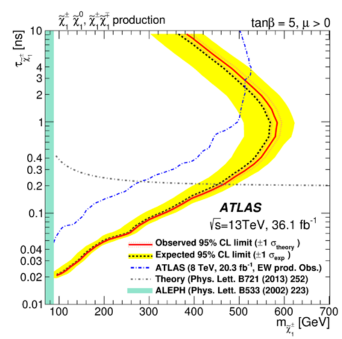
Older interesting searches – Long lived charginos with disappearing tracks

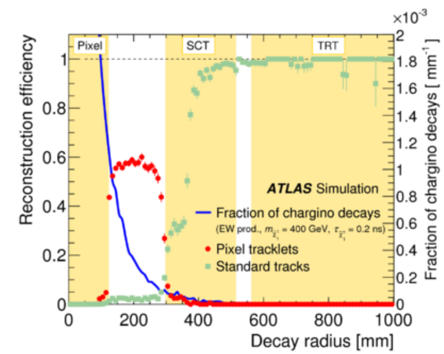




- Chargino may decay in such a way that the track is only briefly visible to the ATLAS detector
- Having such short tracklets creates unique challenges for reconstruction and background rejection
- Extra quality criteria must be applied to tracklets such as narrow geometrical acceptance, isolation, zero pixel holes, and no SCT hits
- Limits were set with 36.1 fb^{-1} of 2015+ 2016 data







https://arxiv.org/abs/1712.02118