Dark/Hidden Sector Searches @ ATLAS

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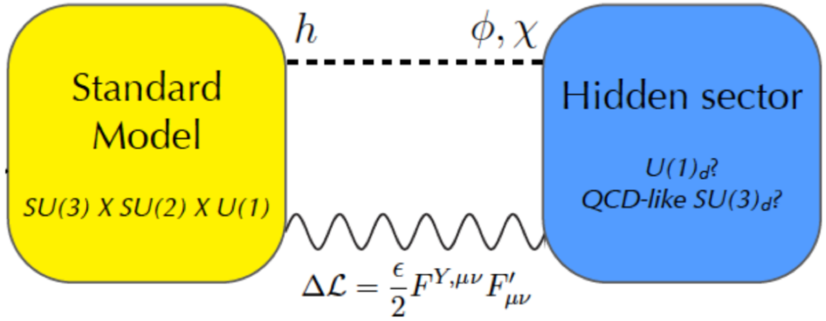
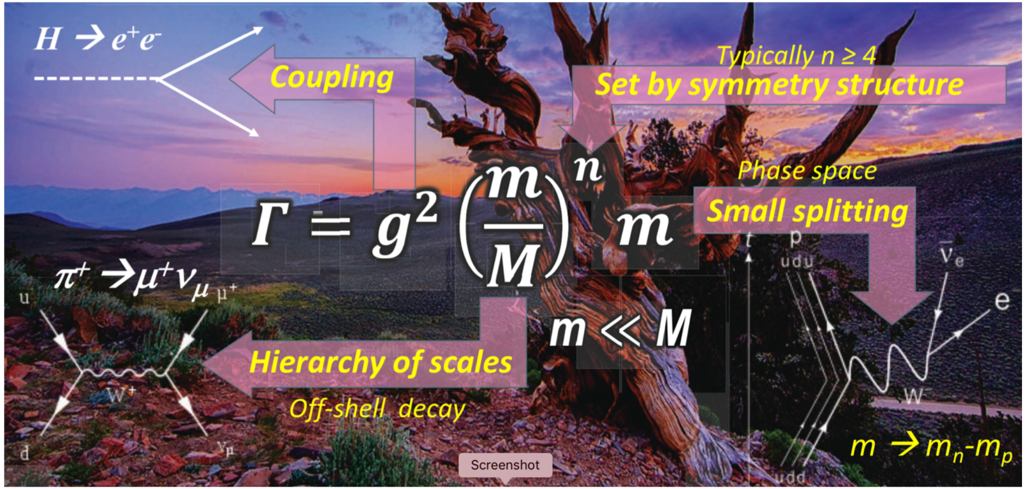
Dark/Hidden Sector

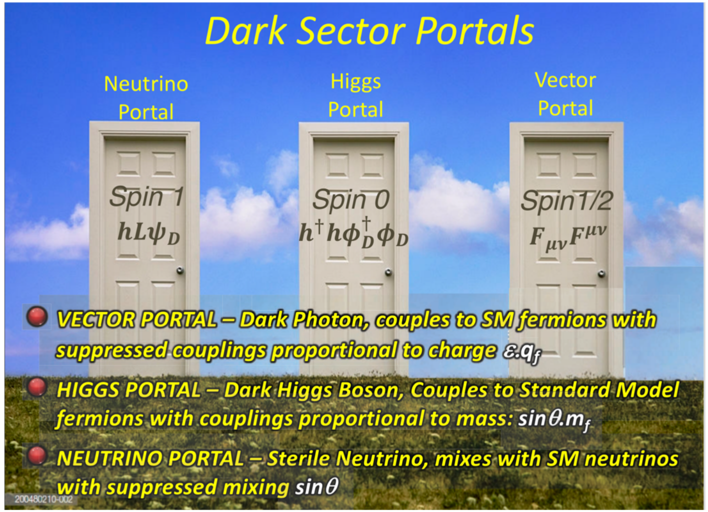
- Extend the SM with a new ‘sector’ only weakly coupled to the SM
- Dark sector can be simple (e.g., a single $U(1)_d$) or more complicated, involving dark QCD sector / dark hadronization, dark matter candidates, etc.



Dark/Hidden Sector

- Weak coupling to SM leads to long-lived particles and un-conventional signatures in ATLAS. Need at least one of
  - Small phase-space (nearly degenerate masses)
  - Small coupling
  - Highly virtual intermediate particles
- Need un-conventional reconstruction and background estimation
  - So experimentally a lot of fun!

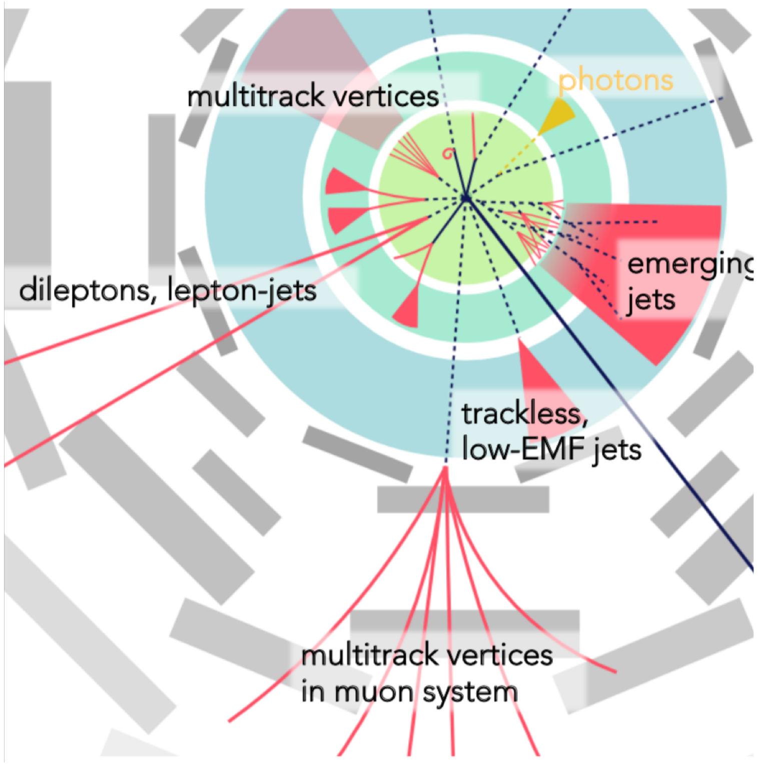




Our Approach: Signature Based

- Displaced decays
  - Displaced multitrack vertices
  - Displaced photons
  - Displaced jets
  - Emerging jets
  - Trackless jets with low EM energy fraction
  - Displaced dileptons and lepton-jets

- Delayed decays and trapped stable particles
  - Particles stopped in the detector
  - Particles trapped in the detector (magnetic monopoles)
  - Decays not during LHC beam crossing (out-of-time detection)



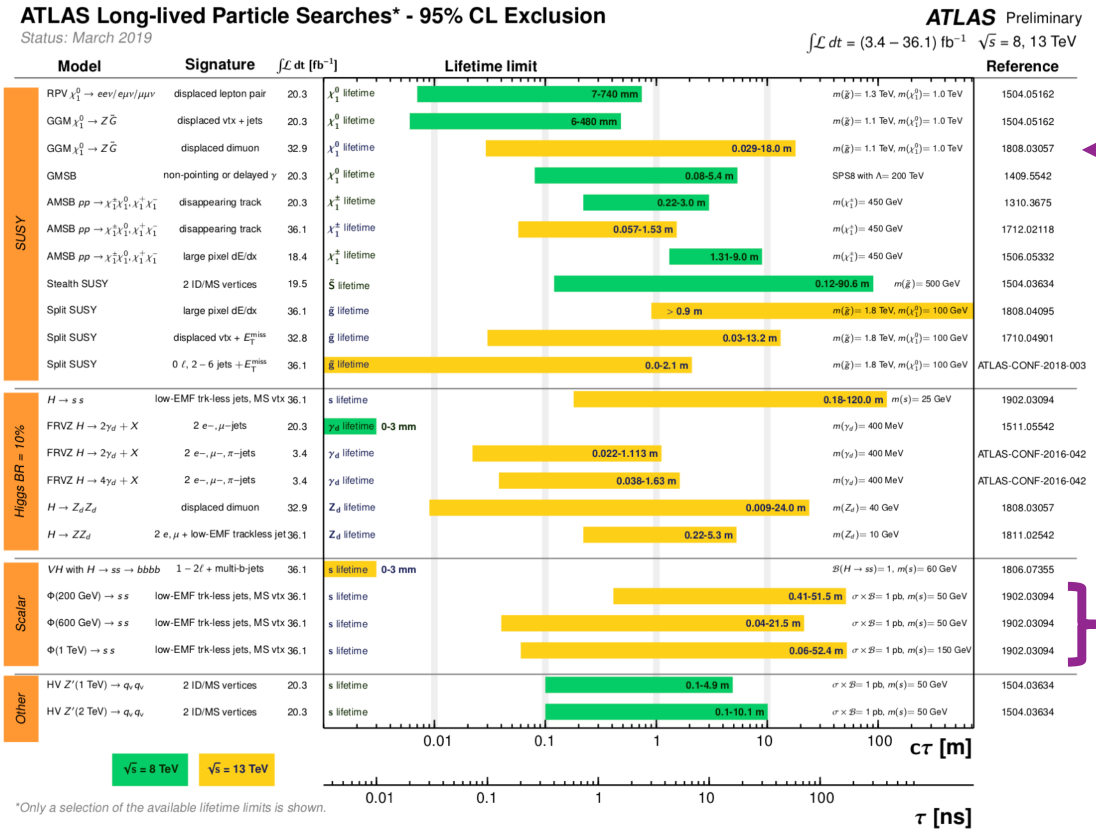
Experimental Challenges

- Different shower shapes in calorimeters e.g. unusual fractions of EM/hadronic Energy
- Decays not from the primary vertex
  - Non-standard track reconstruction ('large radius tracking') *(ATL-PHYS-PUB-2017-014)*
  - Secondary vertex finding algorithms *(ATL-PHYS-PUB-2019-013)*
  - Jets appearing in muon system
- Timing information useful but not available for all detectors
- Non-standard trigger requirements
- Cannot process all data in these 'non-standard ways': need to be selective
- Simulation samples not readily available (MC)
- Unusual backgrounds
  - Pile-up, beam induced backgrounds, cosmic rays,…
  - Long-lived SM hadrons
  - Material interactions (mostly in tracker)
  - Electronic noise
- Often dealing with very small number of events

Experimental Challenges: Solutions

- Simple trigger requirements while keeping bandwidth low
  - Often rely on prompt particles in associated production
  - Trigger during abort gaps or in ‘bunch after’ something happens
  - Use timing information or calorimeter layer information in non-standard ways
- Reconstruction
  - Track reconstruction optimized for prompt particles -> needs different algorithms that take time
    - e.g. Only use un-used hits from first ‘pass’ at reconstruction
  - Displaced vertex identification
    - Build on b-tagging knowledge but not always appropriate
  - Calorimeter noise spikes more concerning
- Background
  - Obtain as much as possible from data
  - Use control regions to validate and/or constrain

What we cover: Long-Lived Particles



+ 'bonus' brand new heavy neutrino search

Trackless Jets (CalRatio)

- Assume a simplified hidden sector with a heavy neutral scalar decaying to two ‘dark’ scalars
- Focus on decays in (or just before) the calorimeter
- Sensitivity
  - 125 GeV < m_Φ < 1 TeV
  - 5 GeV < m_s < 400 GeV
  - 2 different analysis optimisations for ‘high mass’ and ‘low mass’ Φ
- Dataset and trigger
  - 2016 data only
  - High-E_T CalRatio trigger (33 fb^{-1})
    - Low efficiency for m_Φ <200 GeV
    - L1: narrow jets (0.2x0.2) E_T>60 GeV
  - Low-E_T CalRatio trigger (10.8 fb^{-1}, from Sept 2016)
    - L1 topological trigger: largest energy deposit in HCal E_T > 30 GeV && no ECal with E_T>2 GeV within dR=0.2
  - HLT same for both
    - ≥ 1 jet with: E_T > 30 GeV && $|\eta|$ < 2.5 && $\log_{10}(E_H/E_{EM})$ > 1.2
    - No tracks with p_T>2 GeV within ΔR=0.2 of that jet axis
    - BIB removal cut (cell timing and position)
  - Dedicated background triggers: BIB, cosmics

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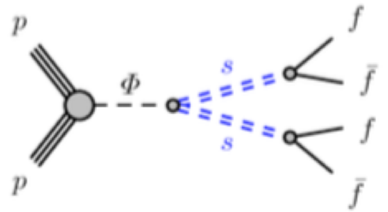
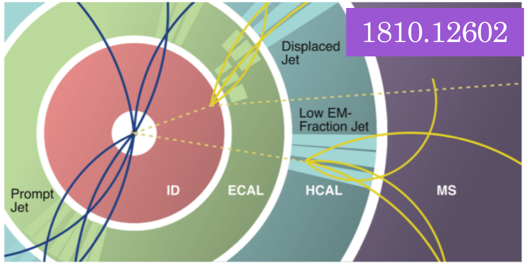
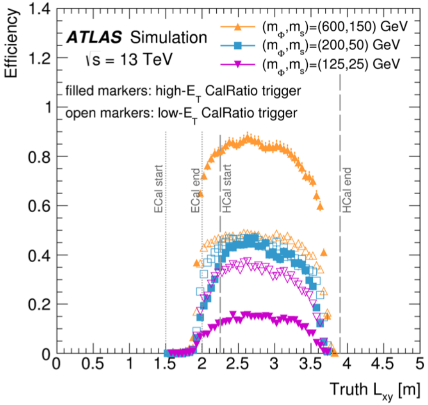




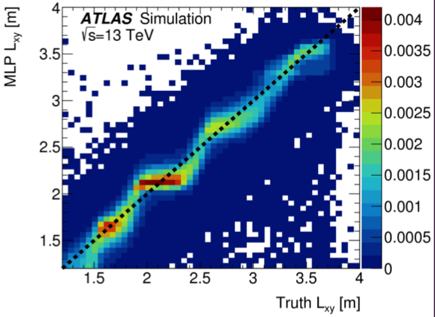
Simulated trigger efficiency in barrel



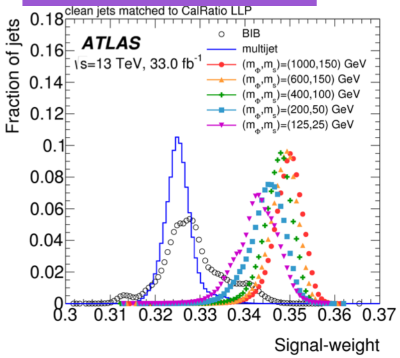
Trackless Jets (CalRatio)

Event selection and reconstruction

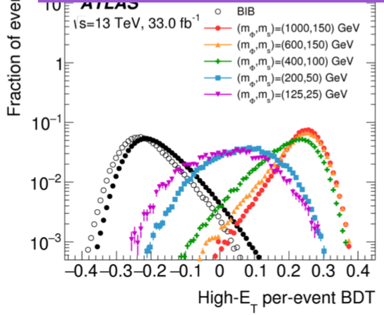
- At least 2 trackless and low-EM fraction jets (CalRatio)
- Multi-layer perceptron (MLP) to determine radial and longitudinal decay positions (L_{xy} and L_z)
- Per-jet BDT
  - 3 classes: Signal, QCD, Beam Induced background (BIB)
  - Inputs: MLP L_{xy} and L_z, track variables, and jet properties
  - Flatten p_T spectrum for training
- Event-level BDTs
  - Separate training for low and high masses
  - Further reduce BIB
  - Inputs: 2 highest per-jet BDT weight for signal and BIB, vector over scalar sum of jet E_T, jet E_T s, ΔR*(highest 2 signal BDT weight jets)*



Per-jet BDT score (signal)

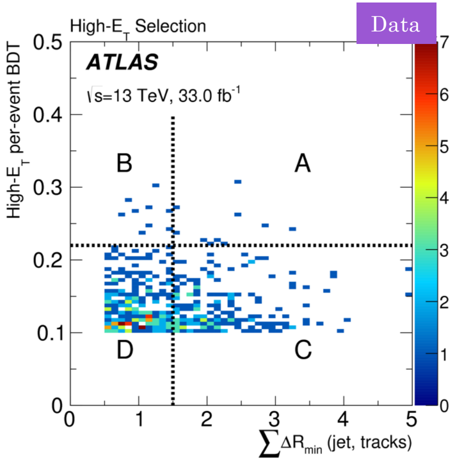


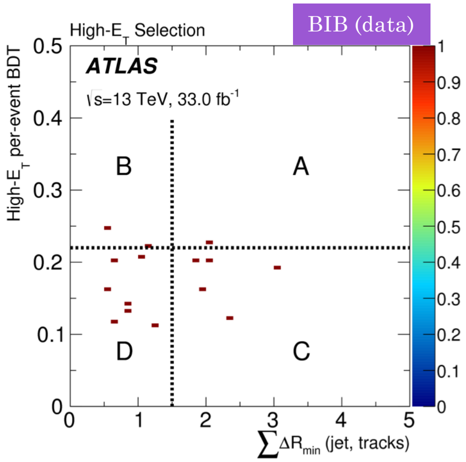
Per event BDT score (high mass)

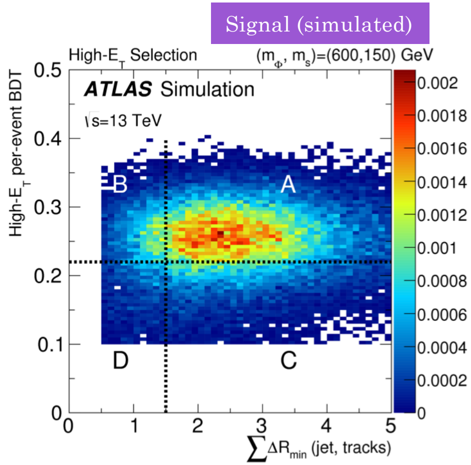


Trackless Jets (CalRatio)

- Background
  - From ABCD method in simultaneous likelihood
  - Within each region: count events





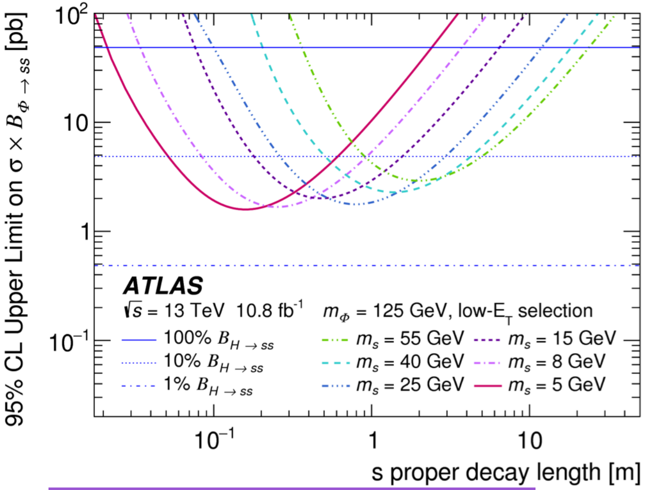


Main selections	B	C	D	Estim. A (*a priori*)	A	Estim. A (*a posteriori*)
High-E_T selection	9	187	253	$6.7^{+3.2}_{-2.3}$	10	$8.5^{+2.3}_{-2.0}$
Low-E_T selection	2	70	57	$2.5^{+2.5}_{-1.4}$	7	$5.3^{+2.1}_{-1.6}$

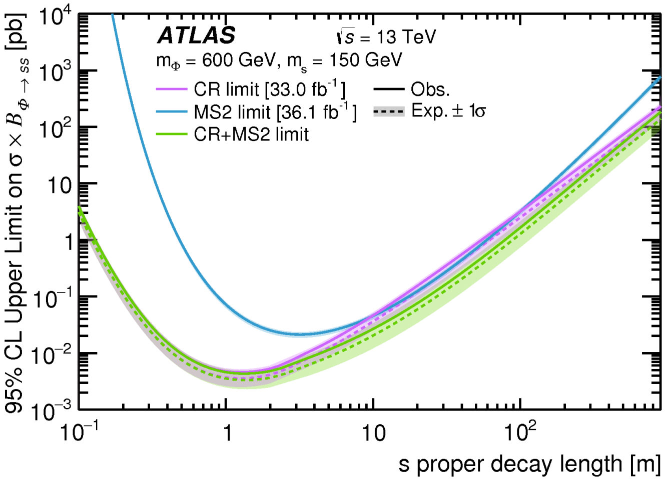
Trackless Jets (CalRatio)

- No excess of events observed
- Include combination with analysis looking for displa jets appearing in muon spectrometer

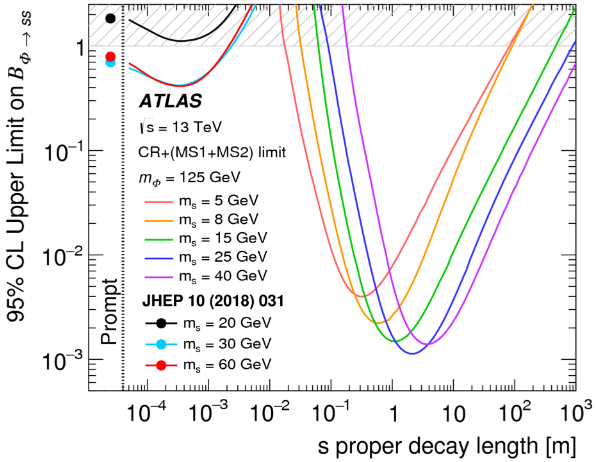
Scalar mass 125 GeV



Scalar mass 600 GeV (combined with MS)

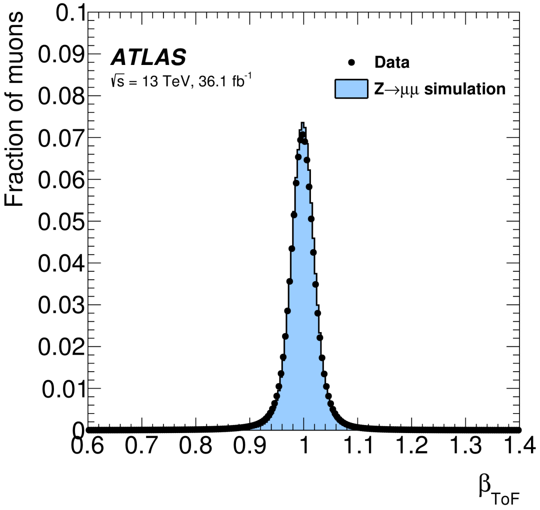


Comparison to Exotic Higgs search

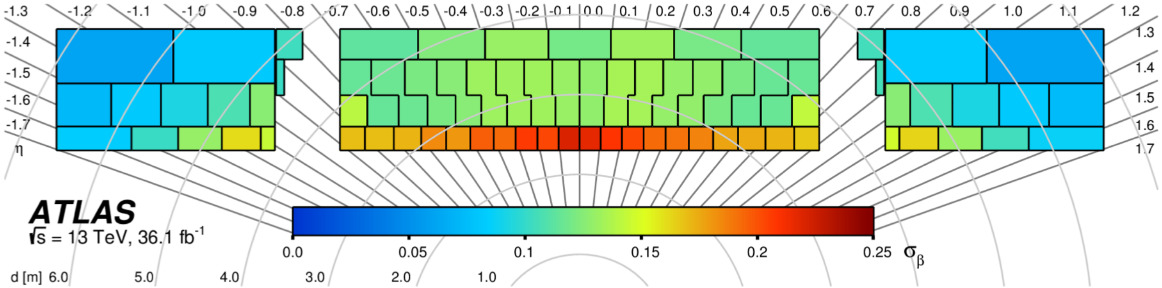


Heavy Charged LLP

- Charged particles but heavy
  - Similar signatures to 'normal' searches but the timing is different
- Show R-hadron, stau or chargino interpretation
- Dataset and selection
  - Up to 35 fb^{-1}
  - Triggers: Single muon && Missing ET
  - Observables
    - dE/dx estimate in pixel detector
    - Time-of-flight (ToF) in Tile Cal, and muon chambers (RPCs and MDTs)
  - Need dedicated calibration of dE/dX and ToF



Resolution (σ_β) of β^{tof}_{tile}



EXOT-2016-032
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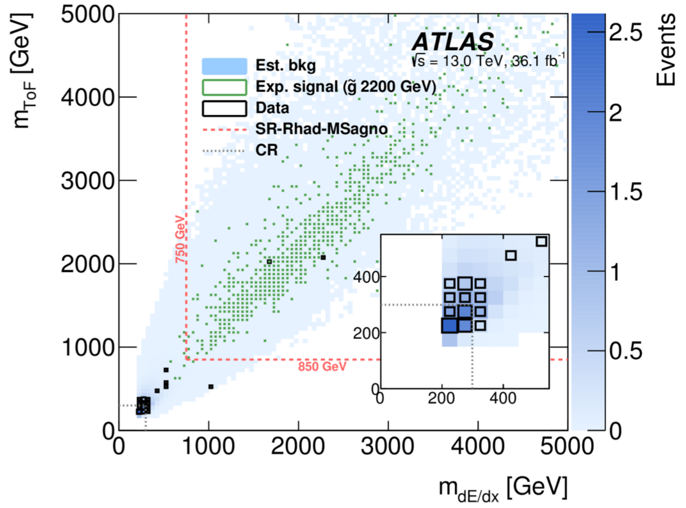
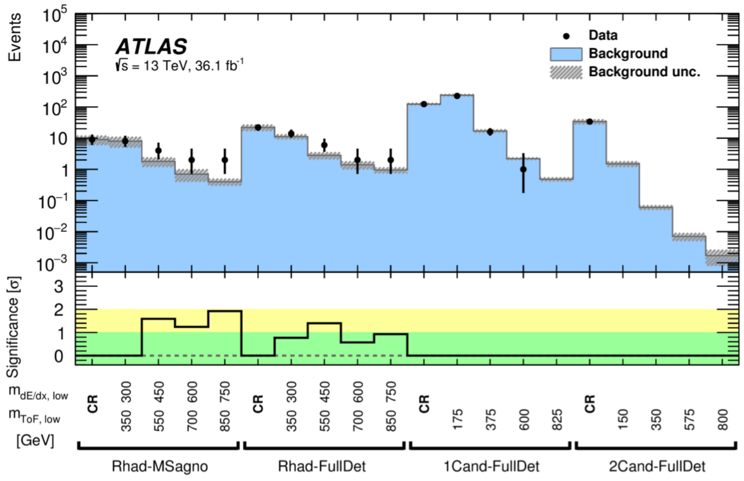
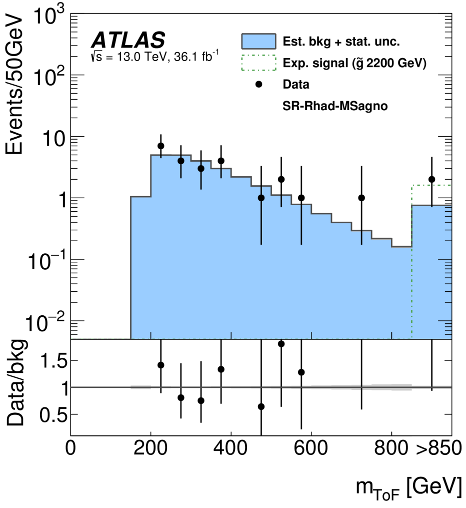
Heavy Charged LLP

- Background estimation
  - Invert cuts to get shapes
  - Normalisation from control regions
    - Side-bands to SR
- Final fit
  - CR and 16 SR
- No excess of events observed

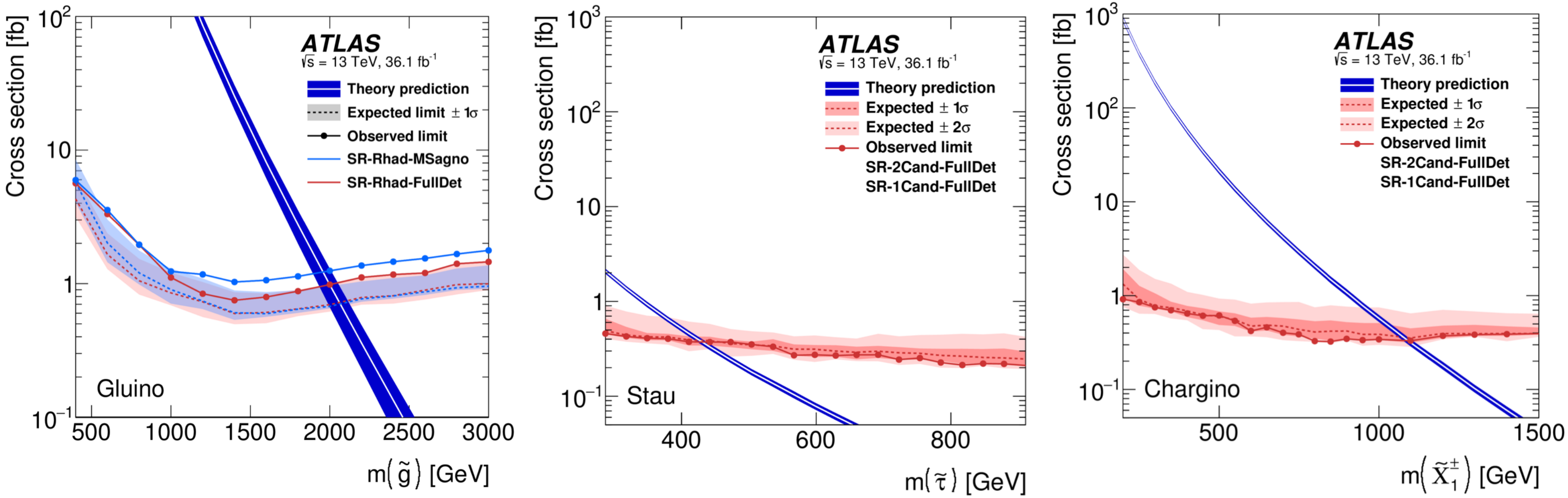






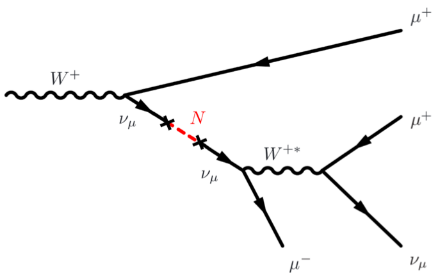
Heavy Charged LLP

- Results interpreted under various hypothesis of what is the LLP
  - Gluino: m<2000 GeV
  - Sbottom: m < 1250 GeV
  - Stop: m<1340 GeV
  - Stau: m<430 GeV
  - Charginos: m<1090 GeV

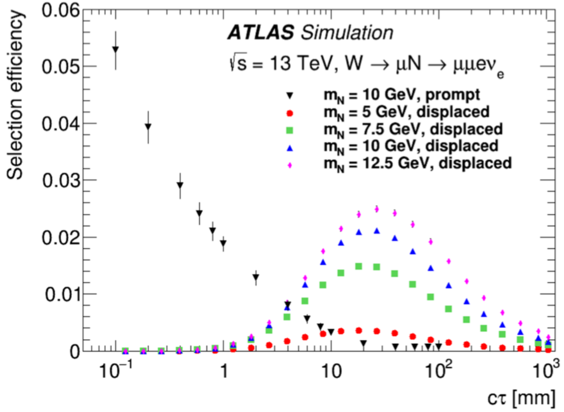


Heavy Neutral Leptons (HNL)

- Motivation / benchmark model
  - Right-handed neutrinos with Majorana masses below the EWK scale
  - Produced through mixing with muon or electron neutrinos
  - SM neutrinos acquire mass inversely proportional to HNL Majorana mass, providing natural explanation for neutrino masses and why they are so small
  - Heavy Neutral Leptons with O(keV) mass could be a valid dark-matter candidate
  - Assume a new heavy neutrino that weakly couples to SM neutrinos, W and leptons



- Data and event selection
  - 2 targeted signatures: prompt and displaced
  - 36 fb^{-1} (32.9 fb^{-1}) 13 TeV
  - Prompt
    - 1e or 2mu trigger
    - 3 leptons (2/1μ + 1/2e), veto same flavor opposite-sign, m_{lll} 40-90 GeV
  - Displaced
    - Targeting $m_N < 20$ GeV
    - 1 μ trigger
    - 1 prompt μ
    - Displaced di-muon vertex (4-400mm)



EXOT-2017-026
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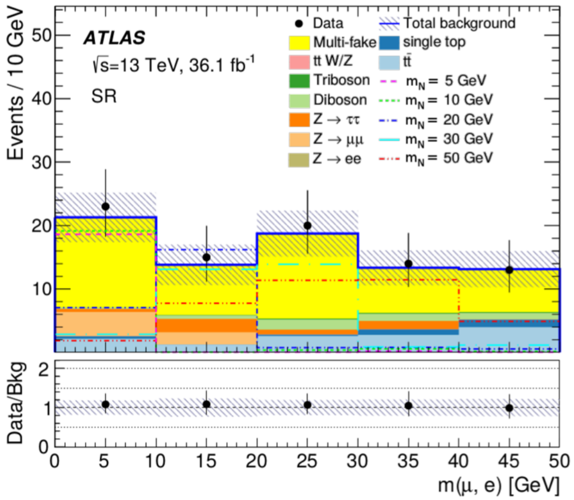
Heavy Neutral Leptons

- Prompt background estimate
  - Simultaneous binned maximum-likelihood fit in p_T^{3l} in three control regions (CR) and the signal region (SR)
    - Normalisation factors for dominant MC background: ttbar and fake-lepton background
- Displaced background estimate
  - Fully data-driven using control regions
  - Background: hadronic interactions in material, metastable particles (*b*- and *s*-hadrons), accidental crossings tracks, cosmic-ray muons + prompt.
    - Prompt mu: Reduced by > 1 order of magnitude
    - 'Tight' selection criteria to remove all but cosmics
  - Cosmics are entirely rejected by cosmic veto

Prompt



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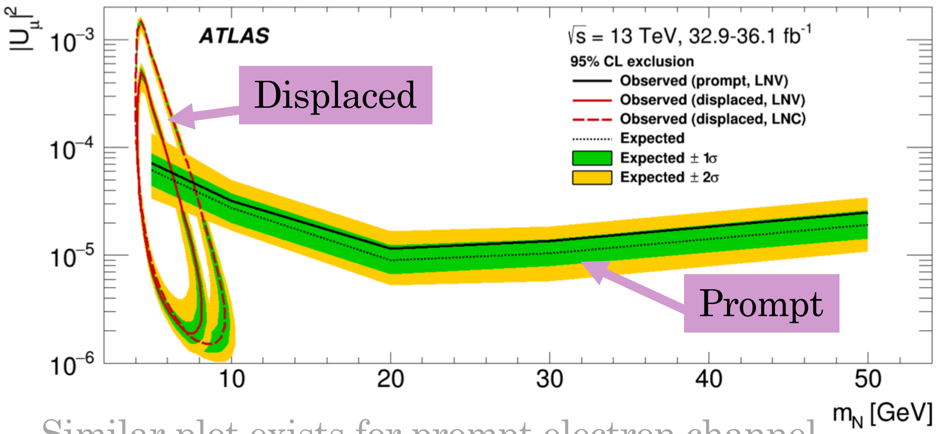
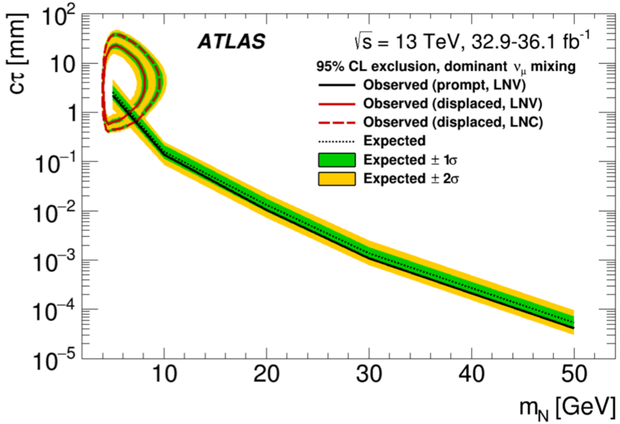
Heavy Neutral Leptons

- Displaced analysis: 0 events observed
- Results interpreted in context of a single right-handed Majorana neutrino N produced in leptonic W boson decays, with just two parameters: mass (m_N) and coupling strength ($|U|^2$)
- Displaced signature: mass range 4.5–10 GeV, $|U_\mu|^2$ down to ~2×10^{-6} (1.5×10^{-6}) assuming Lepton Number Violation (LNV) (or LN Conservation)
  - LNV has weaker limits: for given coupling strength, lifetime reduced by factor of two



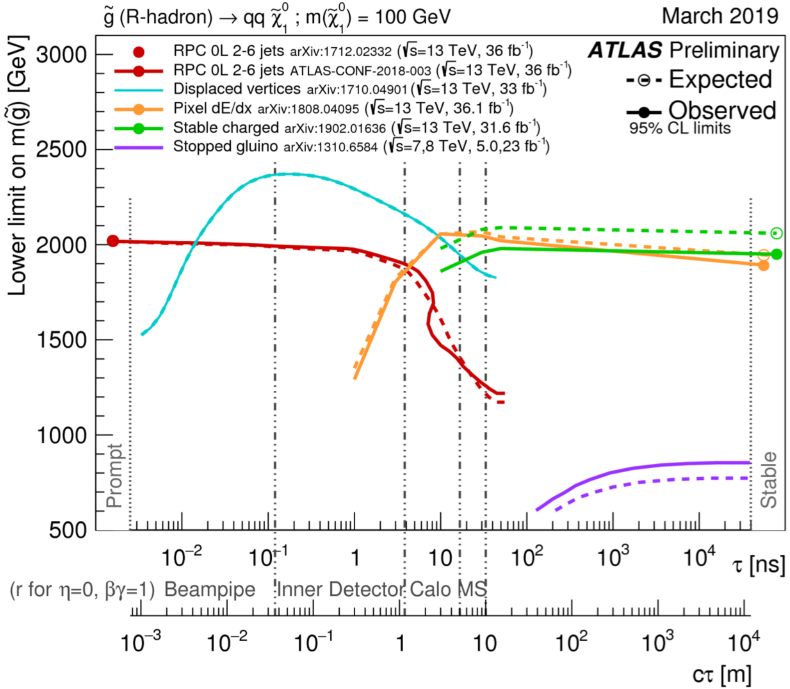
Similar plot exists for prompt electron channel

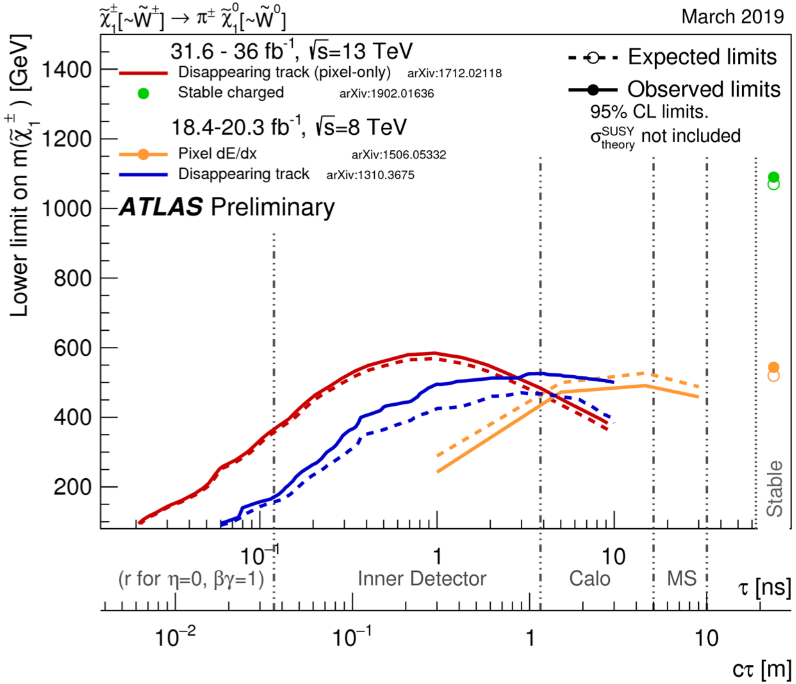
Shown as a function of lifetime



Putting it all together

- Summary plots only available for SUSY interpretations (for now)





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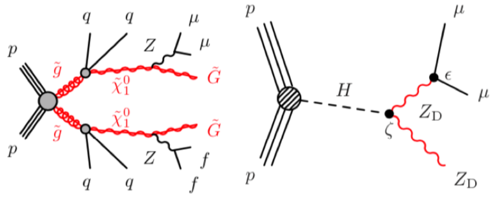
Conclusions

- Searches for Dark Sector mediators really in its infancy
  - Still lots of potential for improvement in experimental techniques and analysis optimisation
  - Still un-explored regions of phase-space that are accessible in principle

- Difficult analyses
  - Non-standard triggers and reconstruction
  - Non-standard backgrounds: most need to be data-driven
  - Small number of events
  - Who said LHC analyses were becoming ‘routine’?!

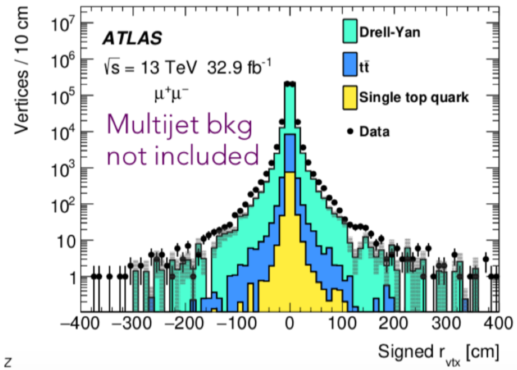
Backup

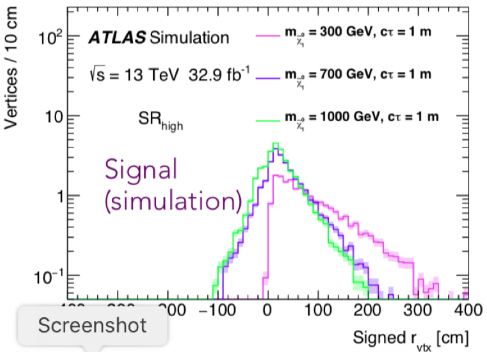
Displaced dimuons



- Target: Long-lived neutralinos in GMSB scenario
  - Long-lived dark photons Z_D from Higgs decay
  - High-mass ($Z \rightarrow \mu^+\mu^-$) and low-mass ($Z_D \rightarrow \mu^+\mu^-$)
  - $m(\chi_1^0)$ = 300-1100 GeV, $m(Z_D)$ = 20-60 GeV
- Signature: 2 opposite-sign μ in muon system with vertex up to 4m from interaction point
  - 1μ trigger efficiency 70% at IP, 10% at 4m
  - Include also MET trigger to compensate

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

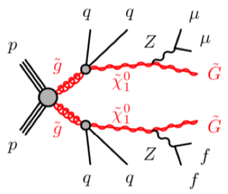
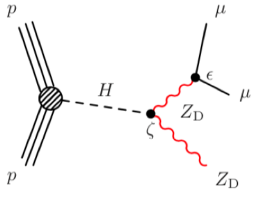




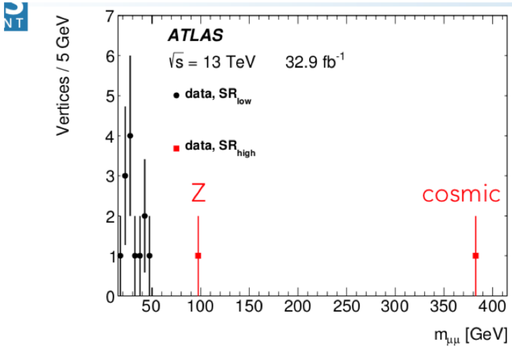
Screenshot

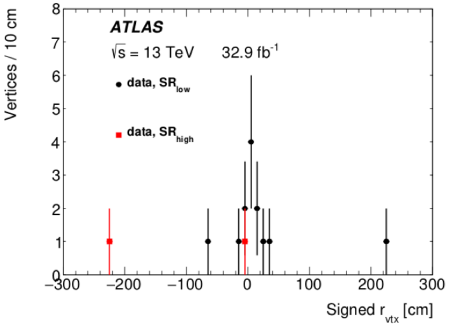
arXiV: 1808.03057
PRD 99 (2019) 012001

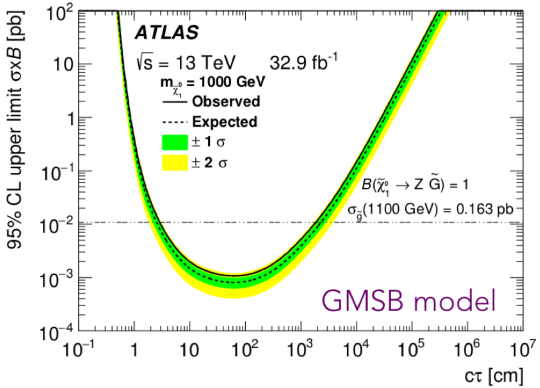
Displaced dimuons

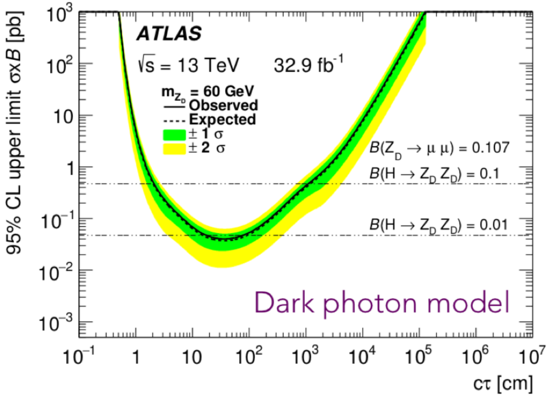



- No significant excess
- Lower and upper lifetimes from 0.3 to 2400cm depending on model parameters









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