Search for BSM physics using challenging signatures with the ATLAS detector

Emma Torró (on behalf of the ATLAS Collaboration)
University of Washington - Seattle

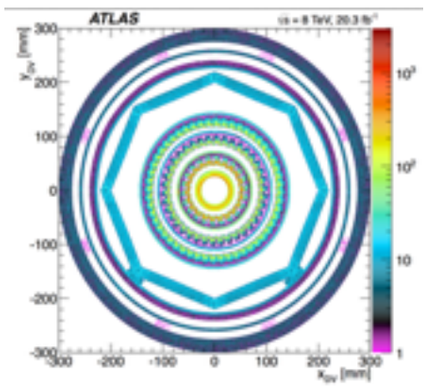
EPS-HEP Conference
Ghent
10 - 17 July 2019

Search for New Physics. Where should we look?

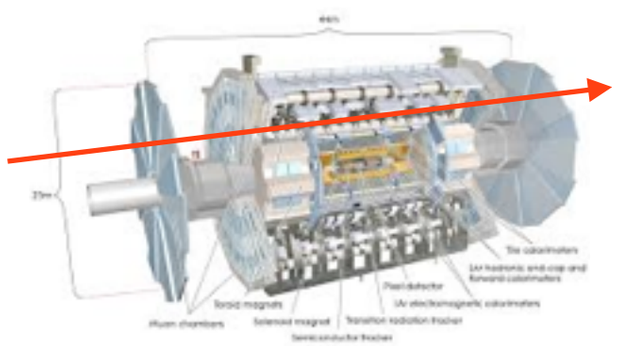
- A large number of Beyond the Standard Model (SM) scenarios exist to cover the limitations of the SM
- New particles will either be
  - Prompt decaying
  - Semi-stable Long-Lived Particles (LLPs), decay in the detector ← we need to make sure we have sensitivity to these too!
  - Detector-stable, decay outside the detector
  - Stable

- ATLAS is designed to optimize object identification for prompt particles
- Searches for LLPs present several challenges
  - Trigger: First step in every search for LLPs: make sure that interesting events are saved!
    - If LLP not associated with prompt activity, need to design dedicated triggers
  - Object identification algorithms assume prompt particles. Need to adapt them
  - Backgrounds: usually instrumental background and non-collision backgrounds

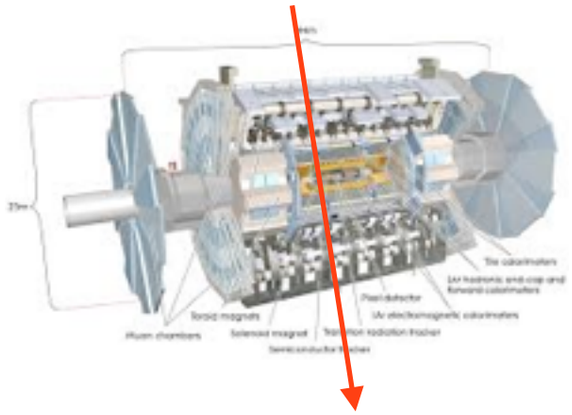
material interactions



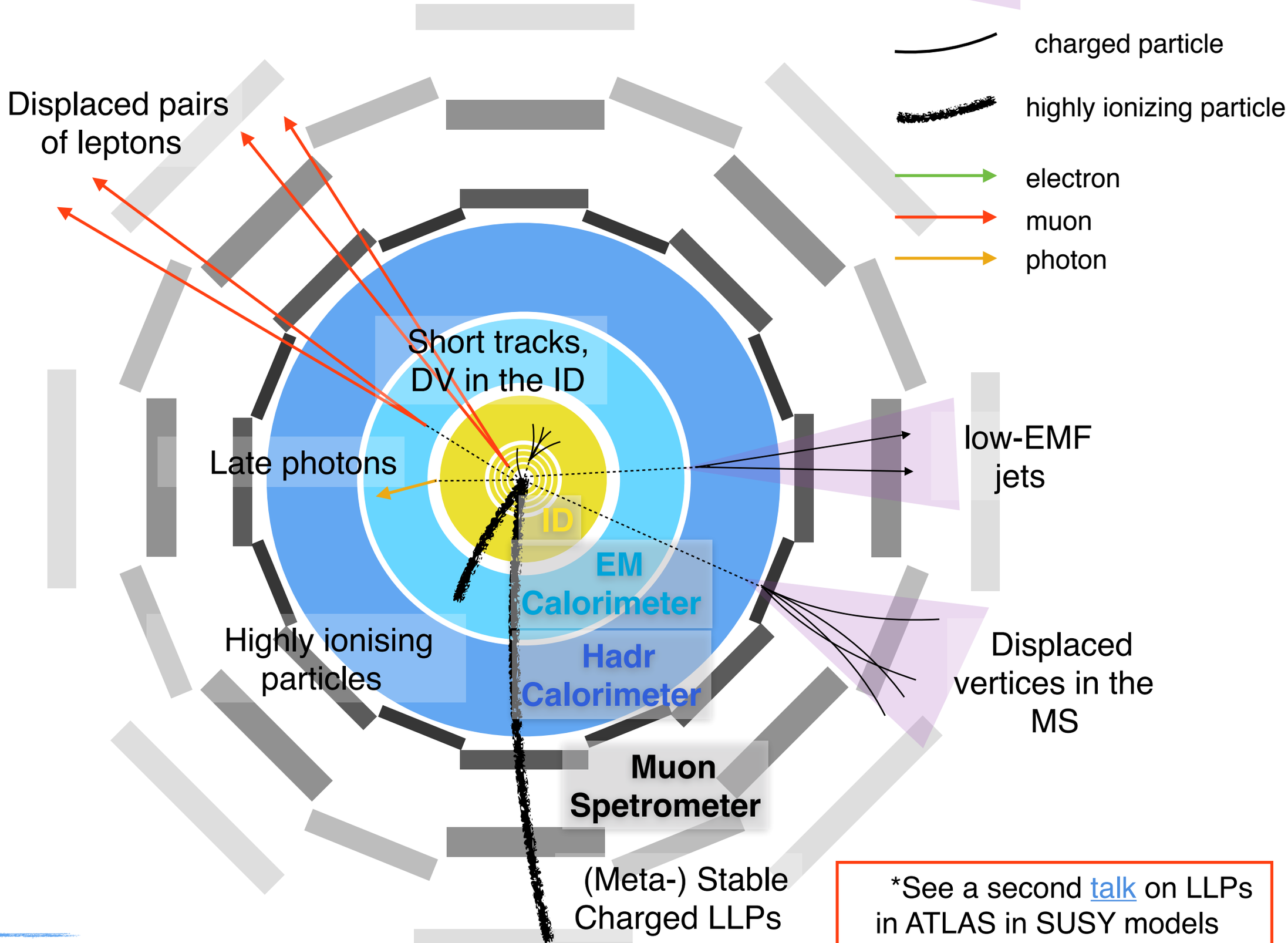
beam halo muons



cosmic muons



- Strategy: organize searches according to unconventional signature

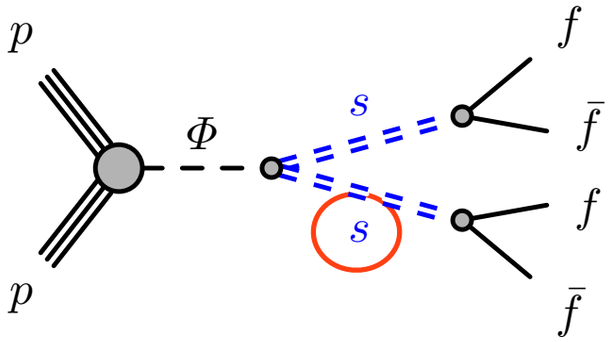


*See a second talk on LLPs in ATLAS in SUSY models
C. Ohm, Friday evening

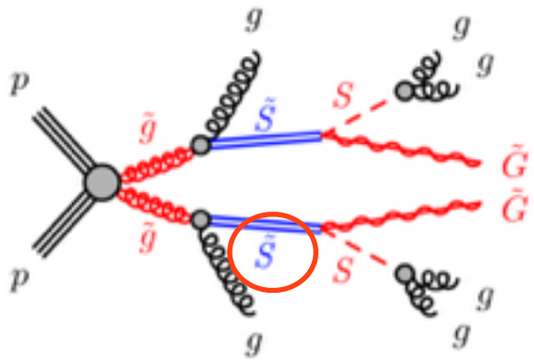
Displaced jets (DJ) - Description

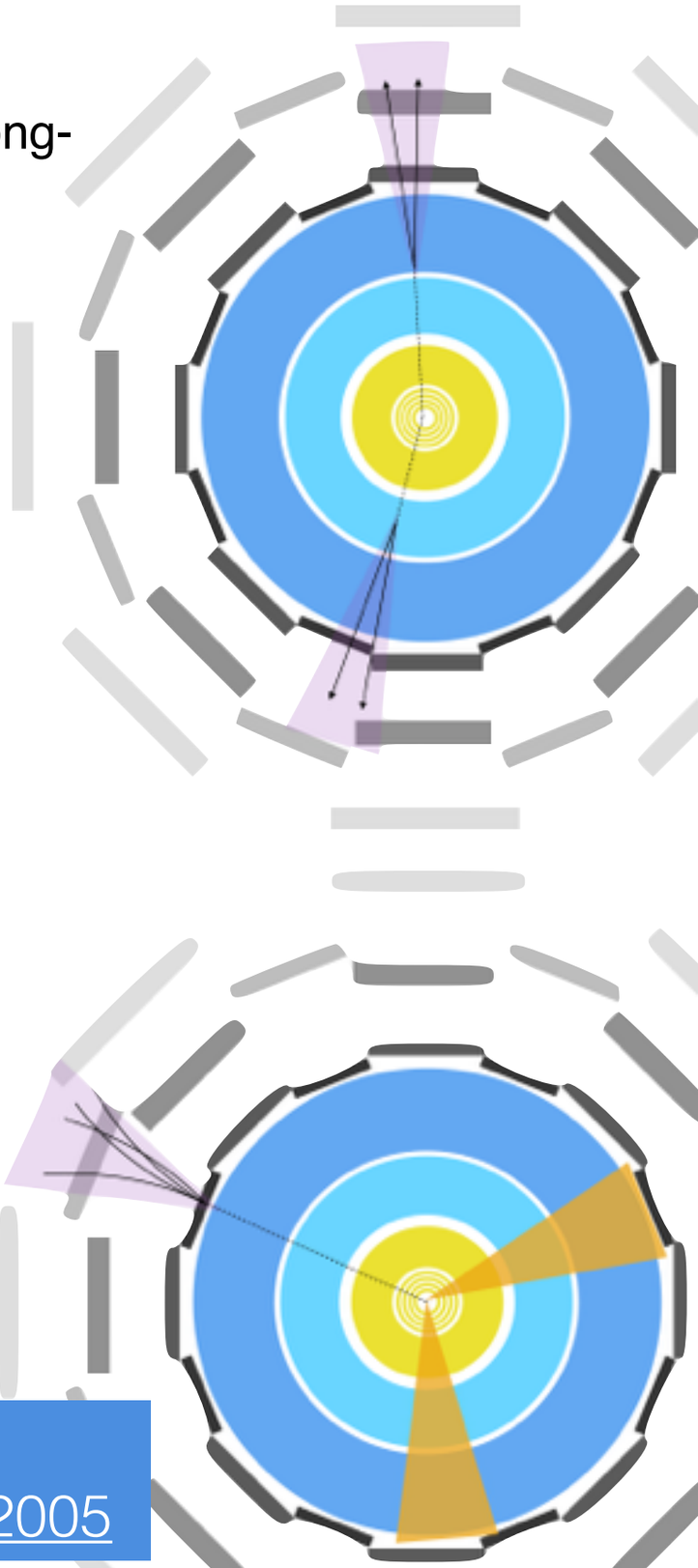
- Search for pairs of neutral long-lived particles decaying to SM fermions in the Hadronic Calorimeter (HCal) or in the Muon Spectrometer (MS)

- Target model: Hidden sector with a heavy neutral boson, ϕ, decaying to two long-lived neutral scalars, s, that decay to pairs of SM fermions.



- Stealth SUSY





  - m_ϕ = 125 to 1000 GeV
  - m_s = 5 to 400 GeV

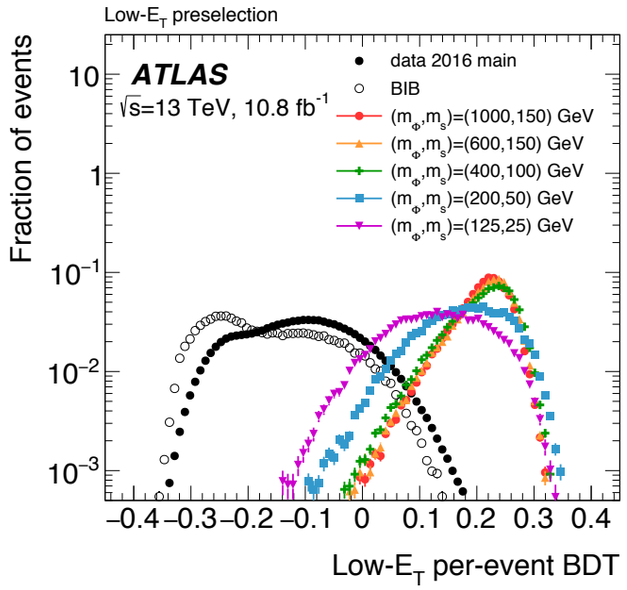
- Signatures:
  - 2 displaced jets (DJ) in the Calorimeter:
    - no ID tracks, low electro-magnetic fraction (EMF)
  - DJ in the MS:
    - reconstruct displaced vertex in the MS
    - 2DJ in the MS
    - 1DJ in the MS + prompt jets or MET

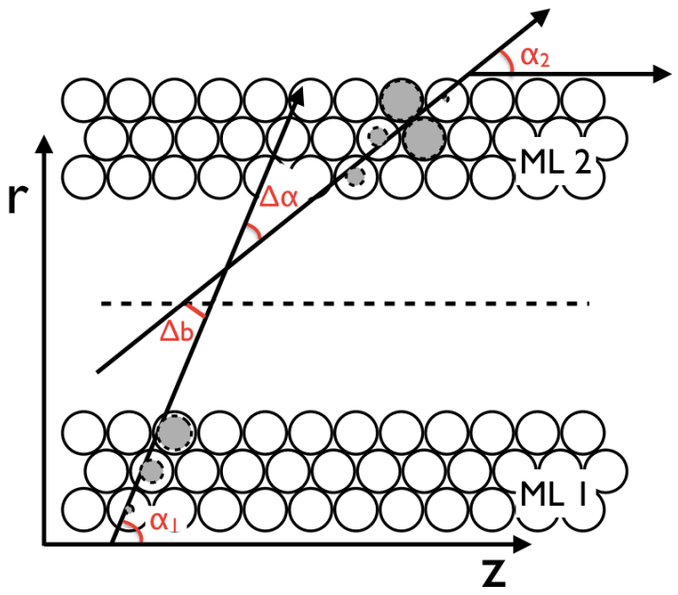
- Dedicated triggers:
  - HCal: select trackless jets with low EMF
  - MS: select clusters of muons in the MS

arxiv 1902.03094
Phys Rev D.99 (2019) 052005

DJs - identification and backgrounds

- DJs in the HCal identification done using 3 nested MVA techniques
  - 1) regression to identify LLP decay position
  - 2) per-jet BDT in classification mode for signal-, beam halo- or QCD-like jets
  - 3) per-event BDT to classify events as signal or background (QCD + beam halo)



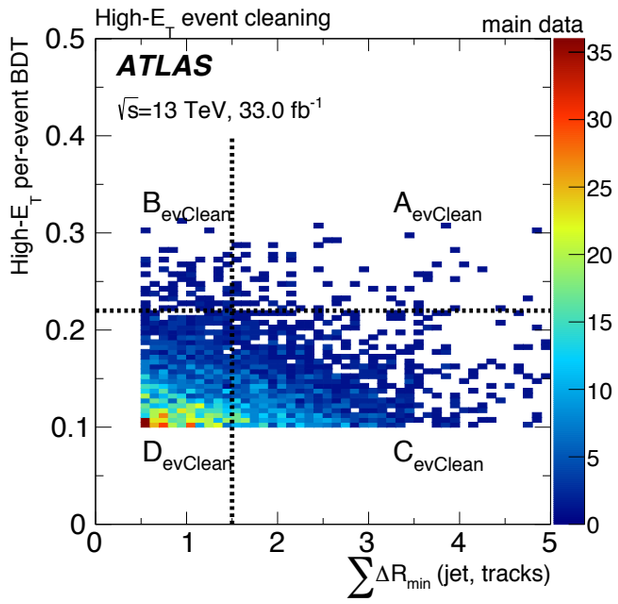


- MS vertex reconstruction algorithm:
  - Reconstruct segments in each muon system multilayer
  - Form tracklets by matching segments in multilayers 1 and 2
  - Form vertices merging tracklets
  - Vertex isolation criteria from ID tracks and from high EMF jets

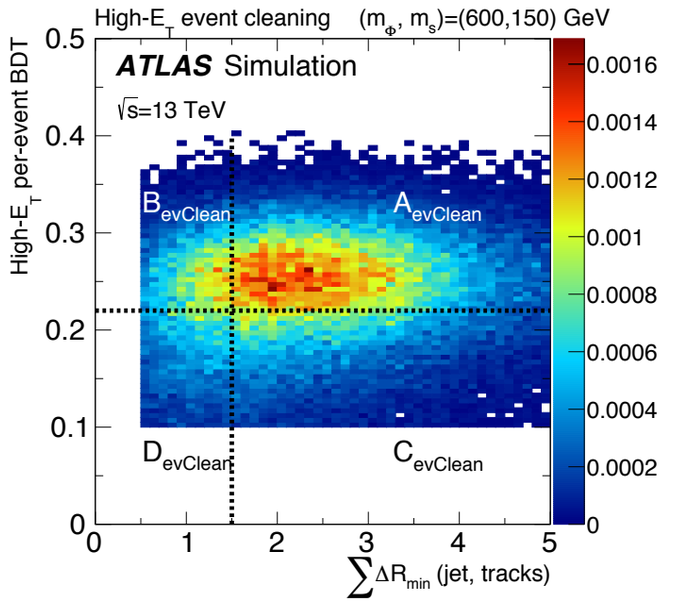
- Background contributions mainly from:
  - QCD: jets produced from neutral hadrons (neutrons)
  - Non-collision backgrounds:
    - beam-induced background (BIB)
    - cosmic muons
  - Estimated using data in CRs:

$$N_A = \frac{N_B \times N_C}{N_D}$$

Data

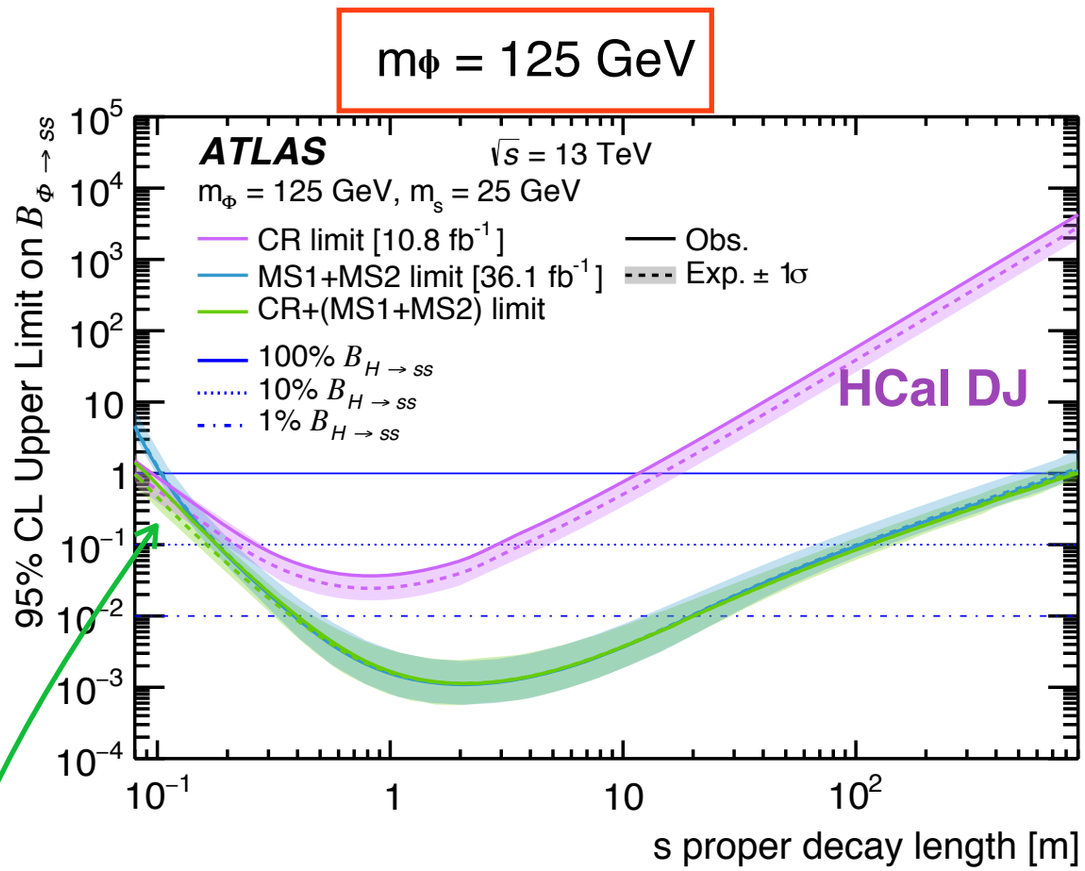


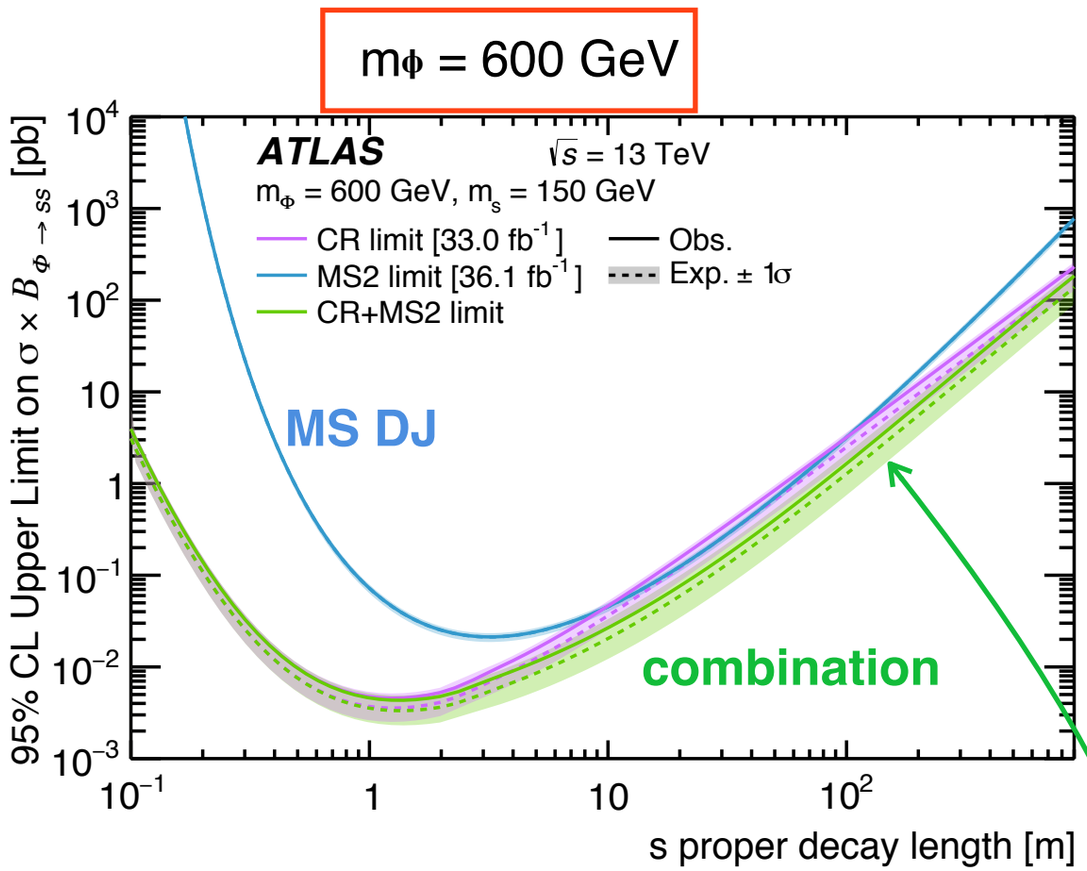
Signal



MS + Calorimeter DJs combination

- No excess observed in neither of these two searches
- Limits are calculated using a simultaneous fit on regions ABCD
- The two searches are complementary. Their limits have been combined for the $\phi \rightarrow ss$ model





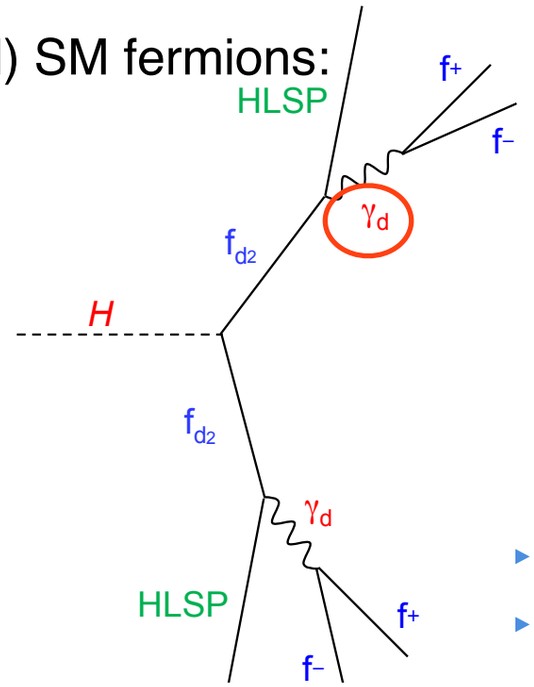
- MS search more sensitive for low masses (soft pT)
- Some complementarity at short lifetimes

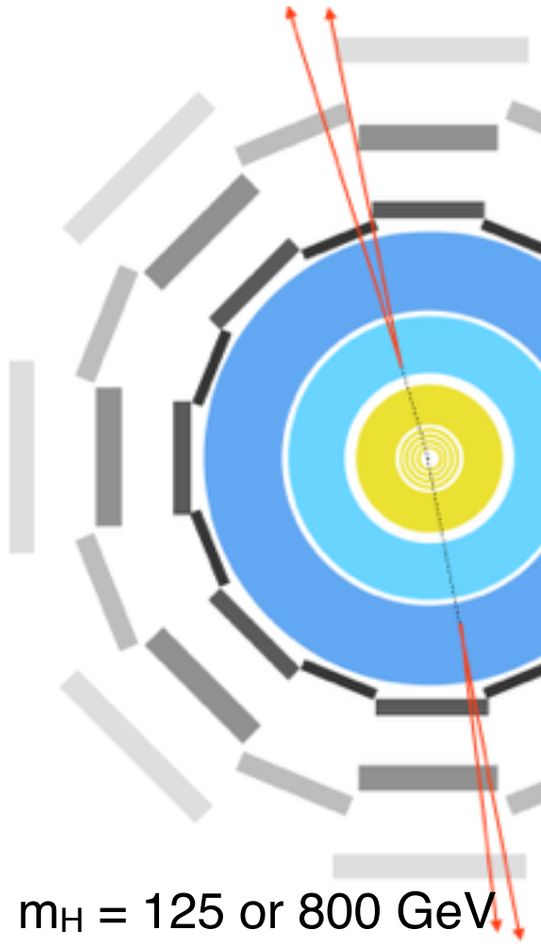
- CR search more sensitive for low masses (high pT)
- Some complementarity at large lifetimes

Displaced dark photon jets - Description

- Search for pairs of neutral long-lived particles decaying to collimated pairs of SM fermions after the ID

- Target model: Hidden sector communicating with the SM through the Higgs portal
  - FRVZ model: Dark fermion fd2 decaying to Hidden LSP (HLPS) and long-lived dark photon.
  - Dark photons with large boost decay to pairs of (collimated) SM fermions: Dark Photon Jets (DPJ)

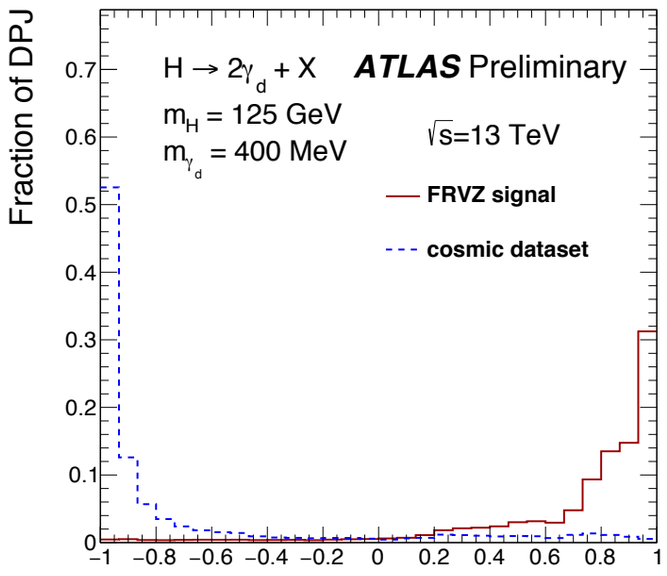


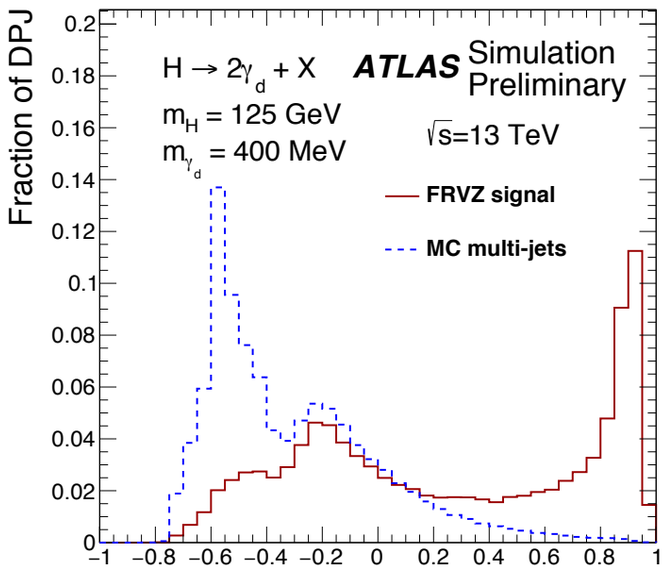


- Signature: 2 displaced jets of collimated ee / $\pi\pi$ or μμ (dDPJ)
- Two types of dDPJs, depending on their components:
  - $\gamma_d \rightarrow \mu\mu$ (muonic)
  - $\gamma_d \rightarrow ee$ / $\pi\pi$ (hadronic)

- m_H = 125 or 800 GeV
- m_{γ_d} = 400 MeV

- Dedicated triggers:
  - hadronic: select trackless jets with low EMF
  - muonic: narrow scan triggers select pairs of displaced, collimated muons

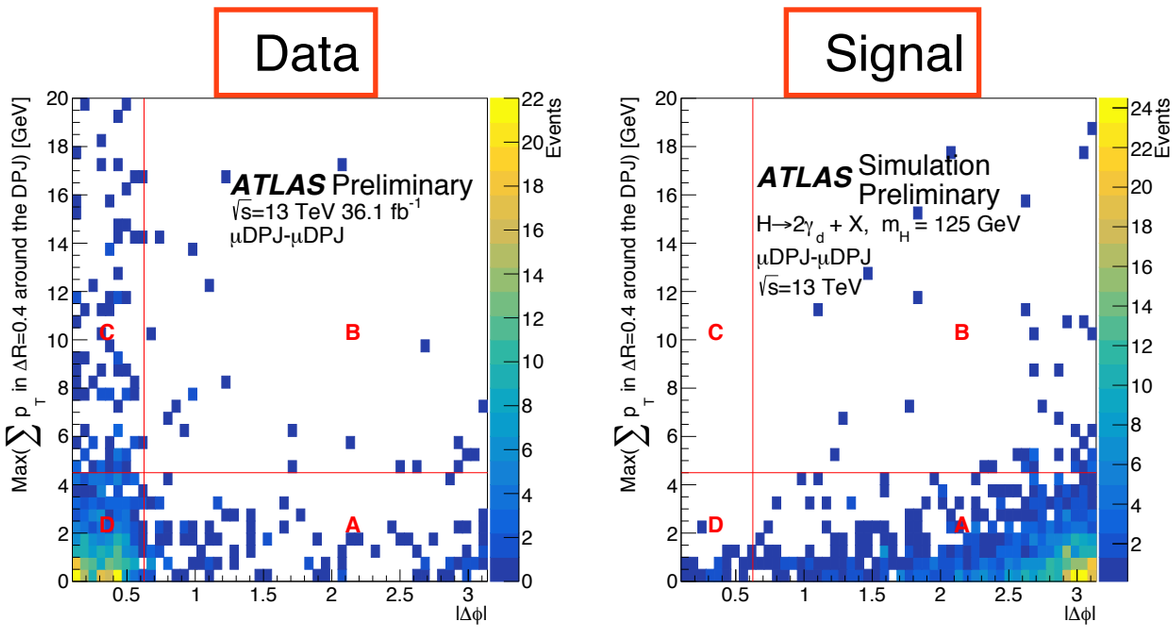




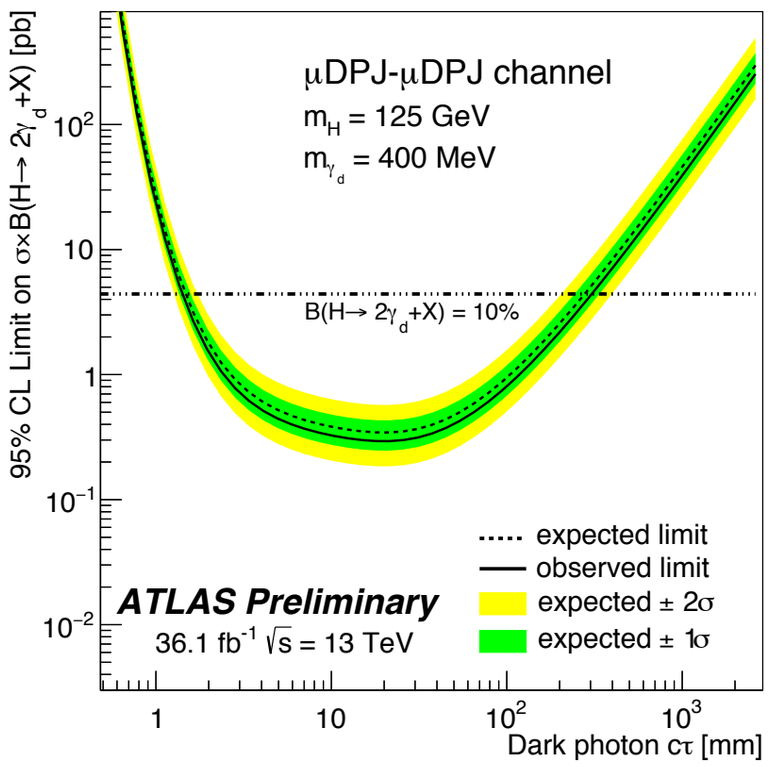
- identification done using BDT, separated for muon and e/pi channels

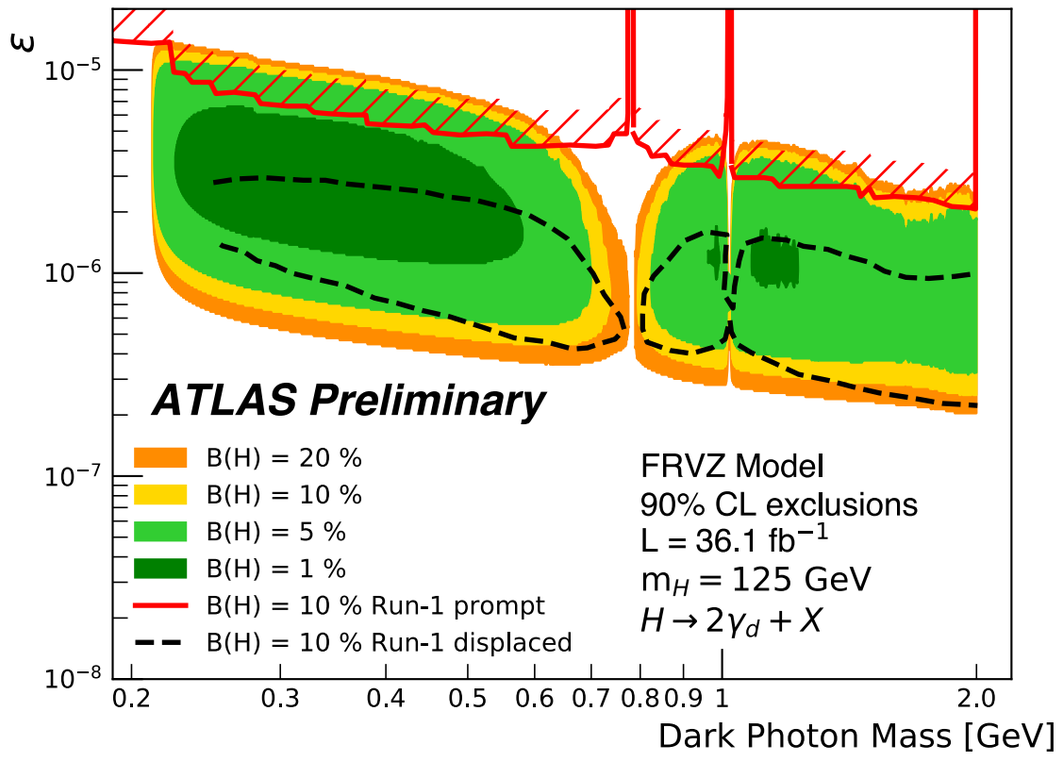
Displaced dark photon jets - backgrounds and results

- Background contributions mainly from:
  - mu-dDPJ: cosmics and jets punch-through
  - e/pi-dDPJ: QCD jets produced from neutral hadrons (neutrons)
  - Non-collision backgrounds:
    - beam-induced background (BIB)
    - cosmic muons
  - Estimated using data in CRs: $N_A = \frac{N_B \times N_C}{N_D}$



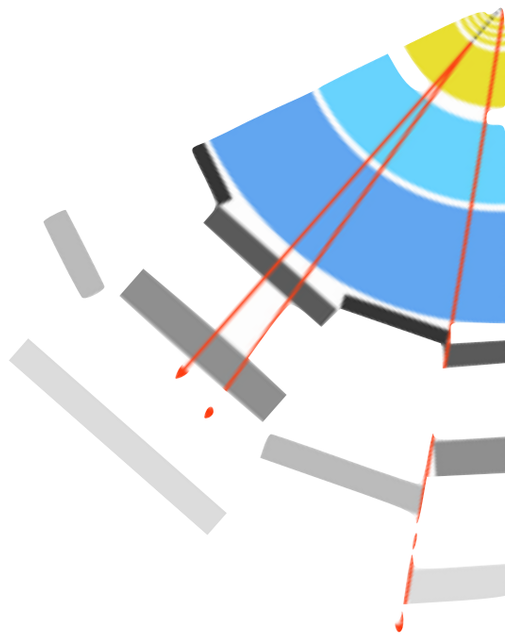
- No excess observed
- Limits are calculated using 3 separate simultaneous fit on regions ABCD for combination of channels:
  - mu mu; mu-had; had- had



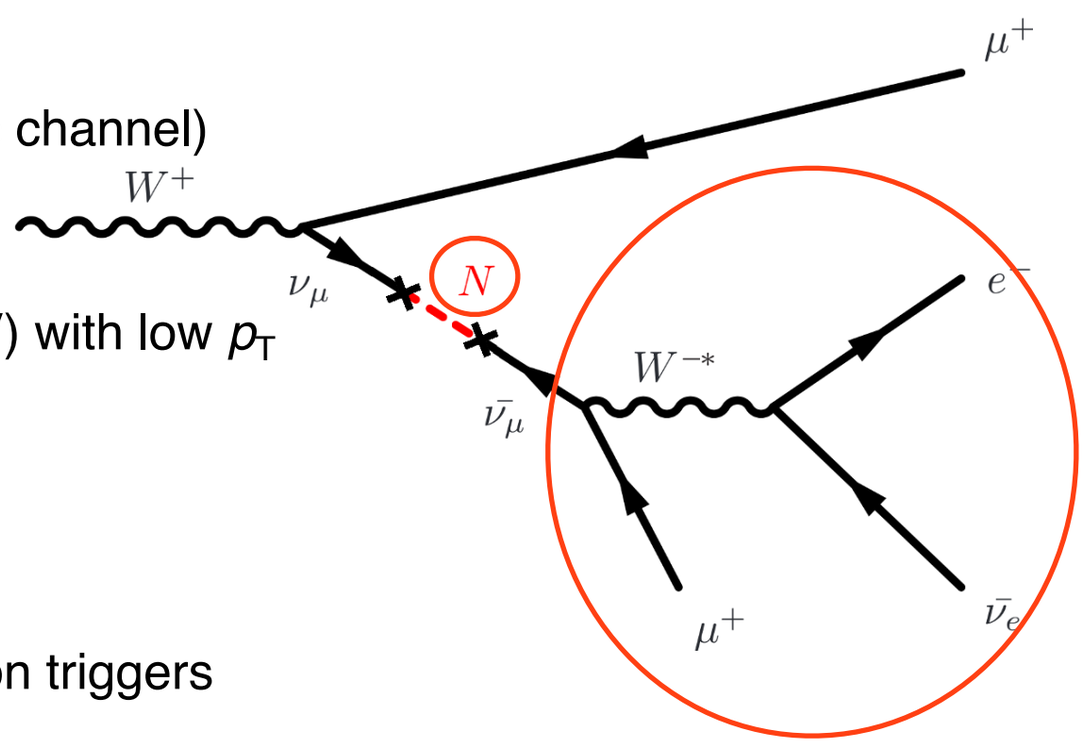


Heavy neutral leptons (HNL) - Description

- Search for prompt HNL (e and μ channels) or displaced HNL (μ channel)
- Target model: HNL
  - HNL lifetime has strong dependence on coupling strength $|U|^2$ and m_N
  - If lepton number violation (LNV) is allowed, twice as many decay channels are allowed, and τ_N is reduced by a factor of 2



- Signature:
  - Prompt: lepton ID track can be reconstructed
    - Same-charge, same-flavour leptons (LNV):
    - $W^{\pm} \rightarrow \mu^{\pm}\mu^{\pm}e^{\mp}\nu_e$ (μ channel) and $W^{\pm} \rightarrow e^{\pm}e^{\pm}\mu^{\mp}\nu_\mu$ (e channel)
  - Displaced: $m_N < 20$GeV
    - prompt muon from the W boson + displaced vertex (DV) with low p_T tracks, among which there are two belonging to leptons.
    - ~0 background search, allows to for LNC

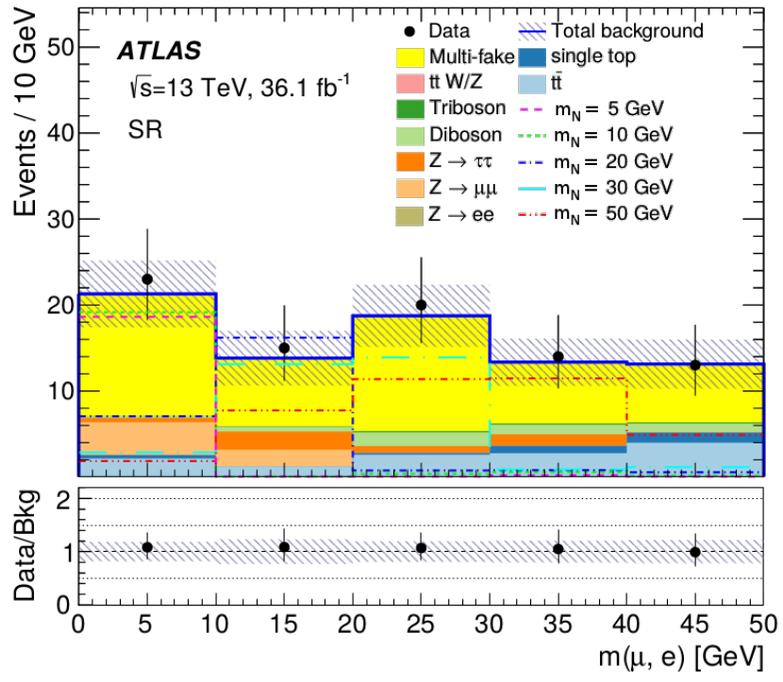


- Triggers:
  - in both analysis, standard prompt single-lepton and di-lepton triggers

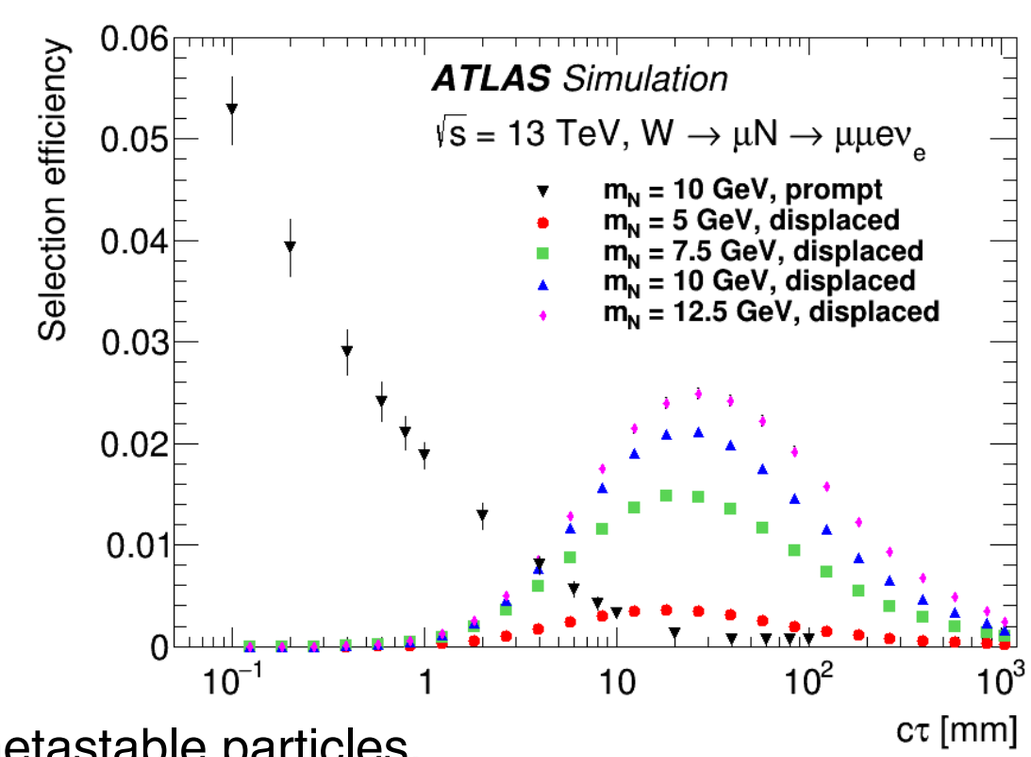
arxiv 1905.09787

HNL - Reconstruction and backgrounds

- Prompt:
  - Backgrounds:
    - irreducible (exactly three leptons): negligible (small X-sec)
    - Reducible (fake leptons): simultaneous binned maximum-likelihood fit in three CR and the SR.
    - Normalisation factors are obtained for dominant background $t\bar{t}$ and the multi-fake background



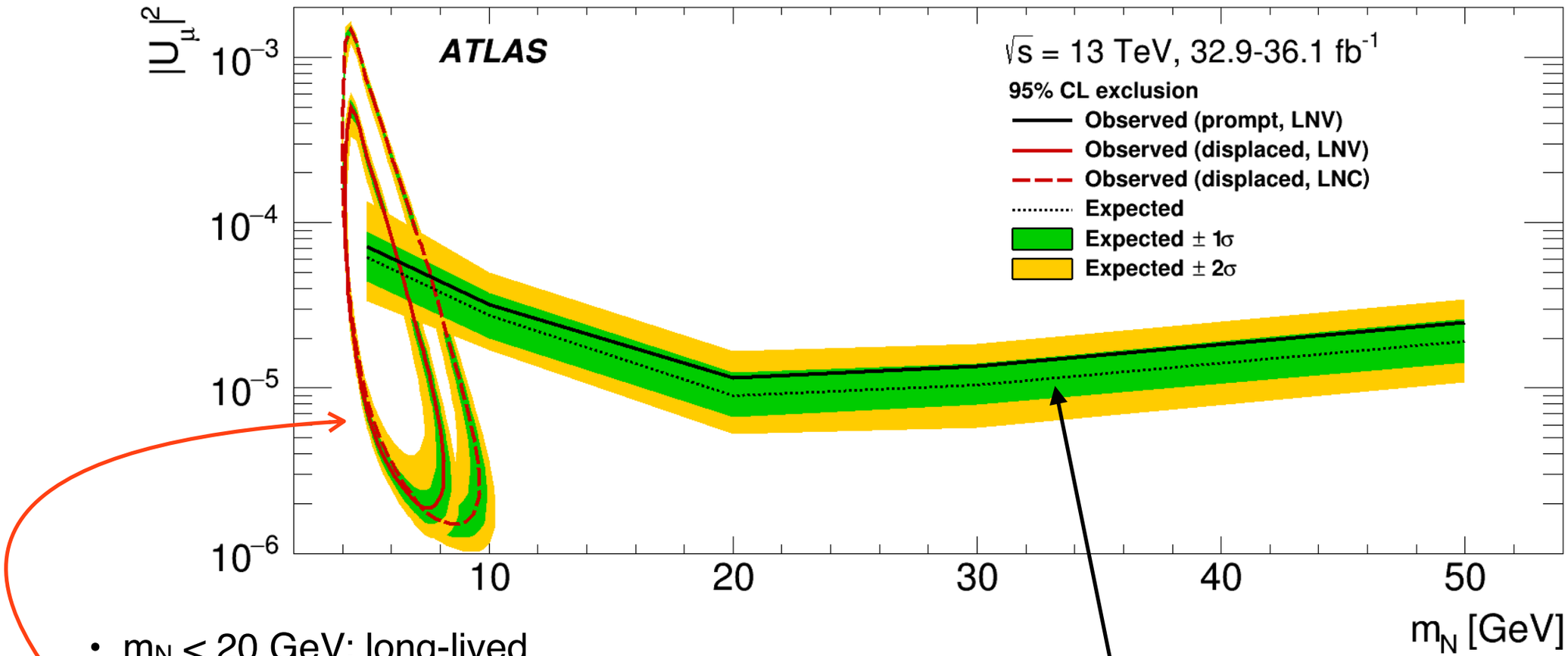
- Displaced:
  - DV reconstruction:
    - large-radius tracking to get tracks with large d_0
    - Using all tracks, displaced vertex reconstruction:
      - **exactly two tracks with opposite charges**
      - $4 < r_{DV} < 300$ mm
      - cosmic-ray veto
      - **at least one tight muon and an additional tight lepton (e or μ)**
      - $m_{DV} > 4$ GeV (reject material interactions)



- Backgrounds:
  - SM backgrounds mostly eliminated with DV
    - Remaining multijets and W+jets estimated with data
  - Instrumental: hadronic interactions in material, decays of metastable particles, accidental crossings of charged particles and cosmic-ray muons

HNL - Results

Observations in the signal regions are consistent with background expectations in both the prompt and displaced signatures

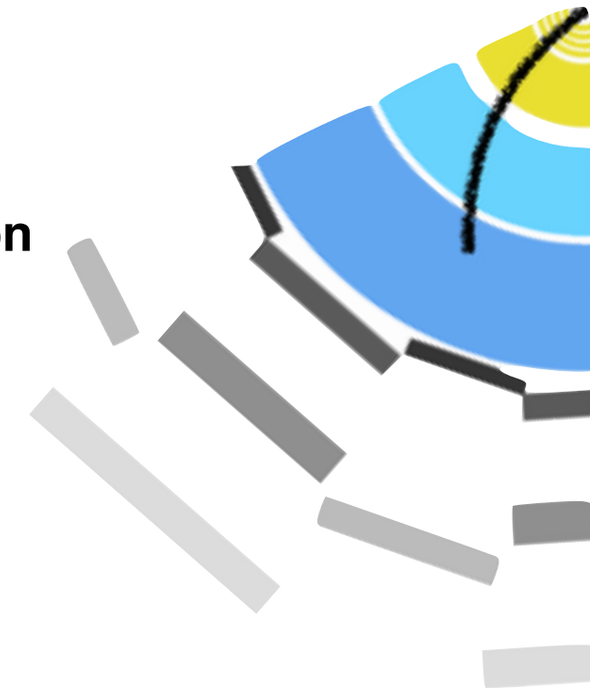


- $m_N < 20$ GeV: long-lived
- Limits from displaced search: range in coupling strength
- great sensitivity for long decays

- Limits from prompt search: single value in coupling strength per mass point, wide range in m_N

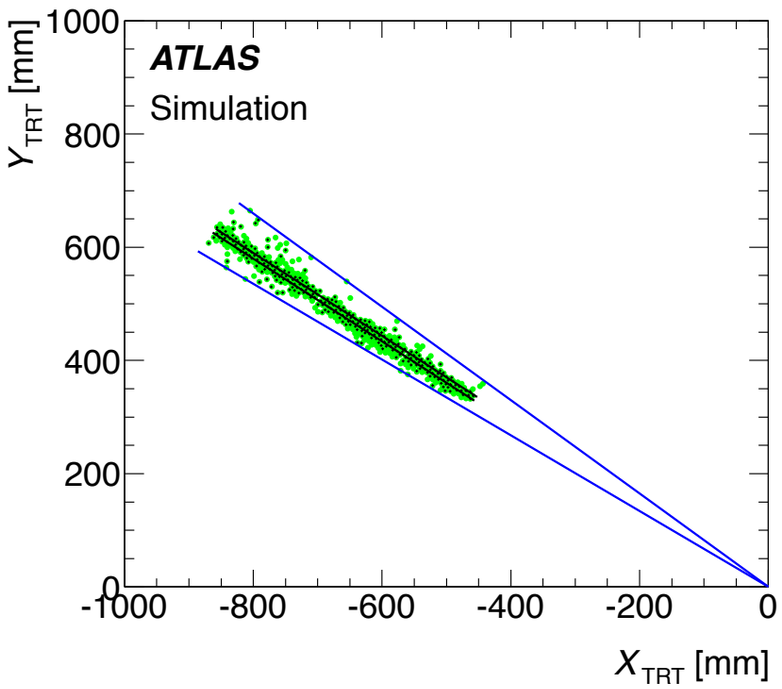
Highly ionizing particles - Description

- Search for monopoles and exotic stable high-electric-charge objects (HECOs)



- Target model: magnetic monopoles
  - formulated by Dirac in 1931 provides explanation for **electric charge quantization**
  - spin and mass of a monopole are not constrained theoretically
- Signature: high-ionization signatures stopped in the calorimeters:
  - energy loss $\propto q_m^2$: monopole with |g| = g_D = 68.5e would deposit 4700 times more energy by ionization than a proton
  - large dE/dx in the ID
  - monopoles: |g| = $1g_D$, $2g_D$
  - HECOs: $20 \leq |z| \leq 100$

- Dedicated Trigger:
- looks for tracks with high number and fraction of TRT high threshold (HT) hits in a narrow region

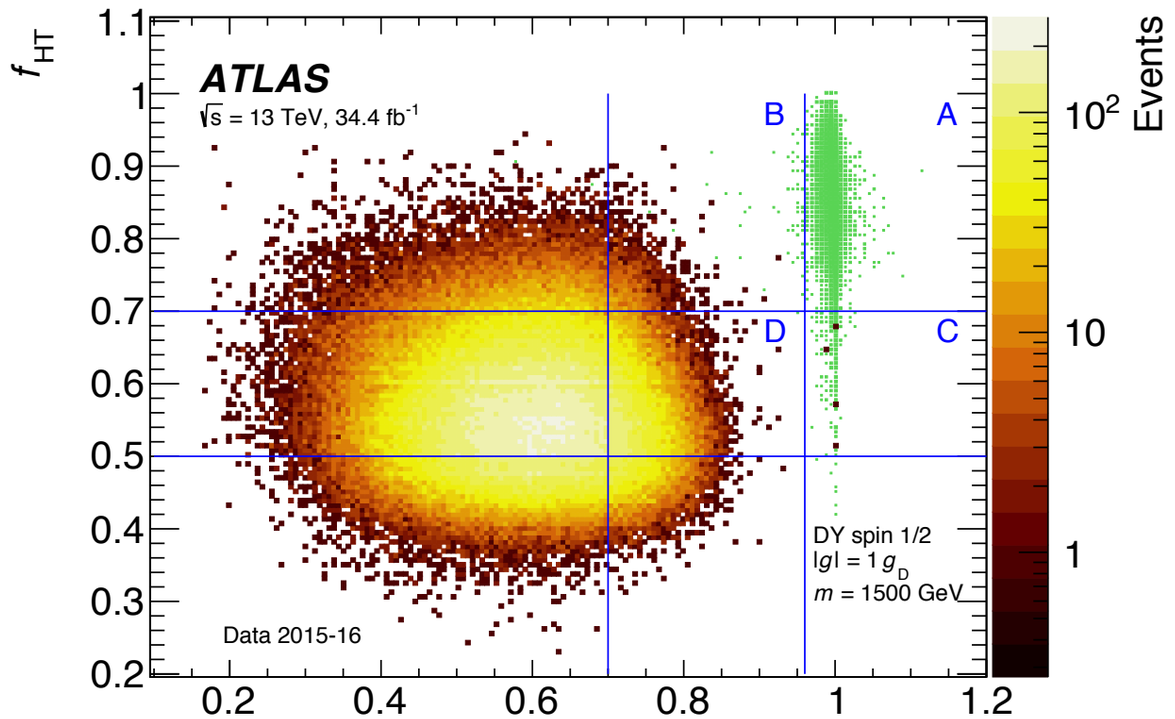


- Backgrounds:
  - calorimeter noise (cleaning)
  - random combinations of rare processes:
    - overlapping tracks from charged particles and noise
  - estimated from data in CRs.

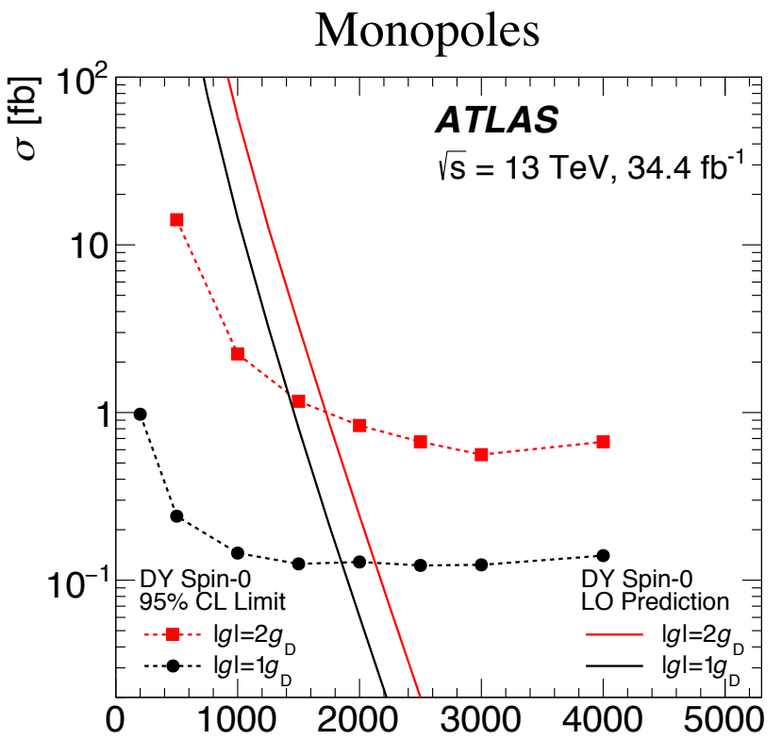
arxiv 1905.10130

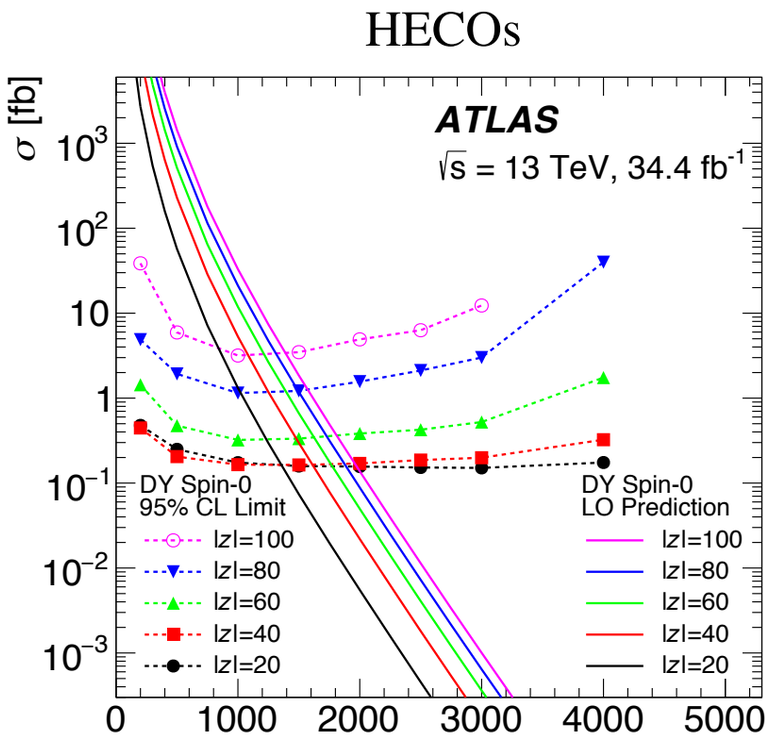
HIP - Reconstruction and backgrounds

- Reconstruction based on “stopping power”:
- Two variables using high dE/dx to identify them:
  - w: average of fraction of energy in the most energetic cells in every EM layer
    - gives a measure of the energy dispersion of the EM cluster candidate
  - f_{HT}: fraction of TRT high threshold hits



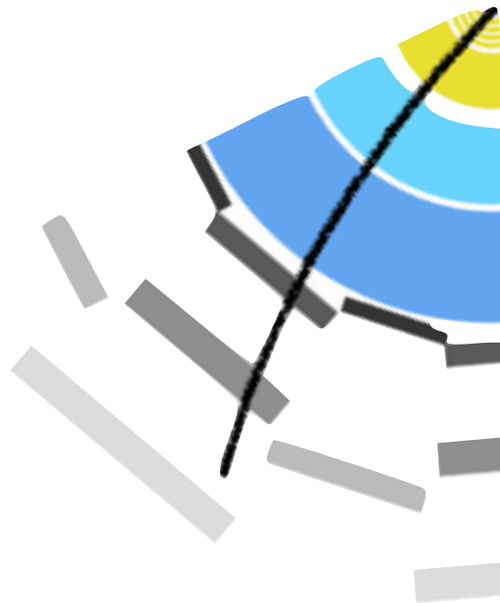
No event was observed in the signal region A





Multicharged particles - Description

- Search for heavy long-lived (detector-stable) multicharged particles (MCPs)

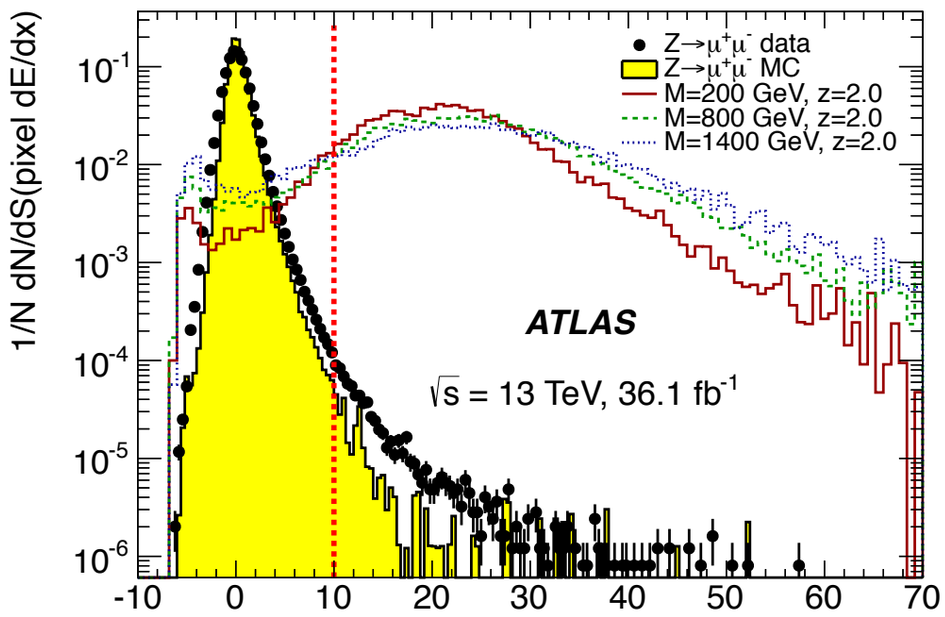


- Target model: multicharged (mch) particles predicted in many models:
  - almost-commutative-leptons: pairs of SU(2) electro-weak singlets with opposite em charges and no other gauge charges of the SM, which makes them behave as heavy stable charged leptons.
  - Technibaryons: predicted by the walking-technicolor model
  - Doubly charged Higgs bosons

- Signature: high-ionization signatures, muon like tracks with high dE/dx in several sub-detectors.
  - energy loss $\propto q^2$
  - **detector-stable!** signature seen along the whole detector: **muon-like** signature
  - large dE/dx in the ID and in MS
  - significant slow-down

- m_{mch} = 50 to 1400 GeV
- |q|= ze, $2 \leq z \leq 7$

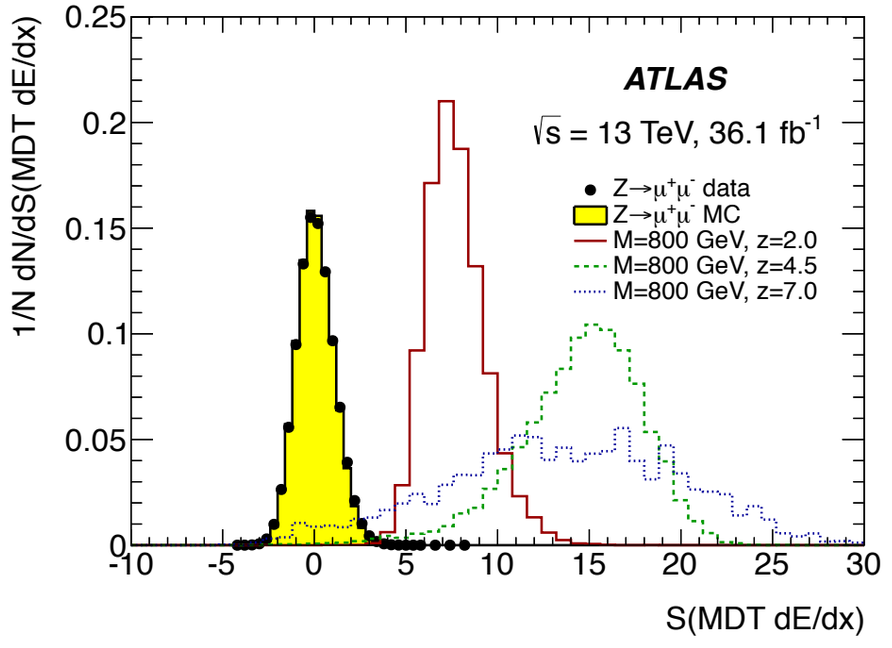
- Selection:
  - "combined" muon (ID+MS), $p_T > 50$ GeV
  - Large dE/dx in the pixel, TRT, and MDT subdetector systems.



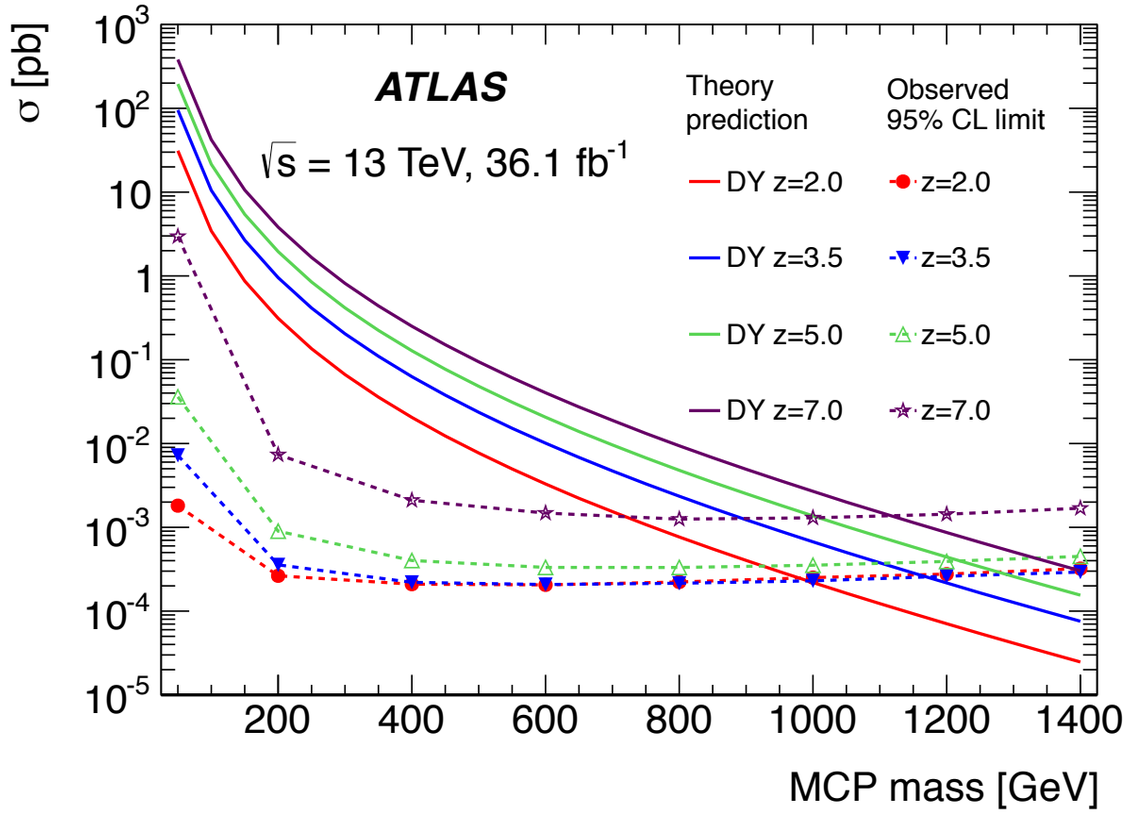
Phys Rev D.99 (2019) 052003

MCP - Reconstruction and backgrounds

- Backgrounds from the SM processes: high-p_T muons.
- Estimated from data using:
  - Significance of the dE/dx: compare observed signal dE/dx, with the average value for a highly relativistic muon
  - number of IBL clusters with at least one hit in overflow
  - fraction of HT TRT hits (f_{HT})



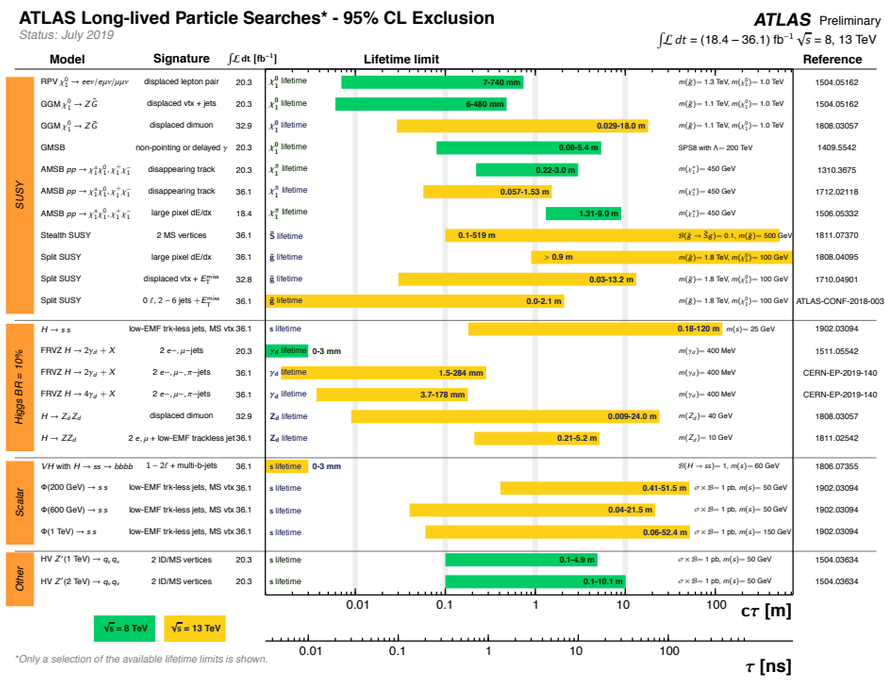
No event was observed in the signal region A

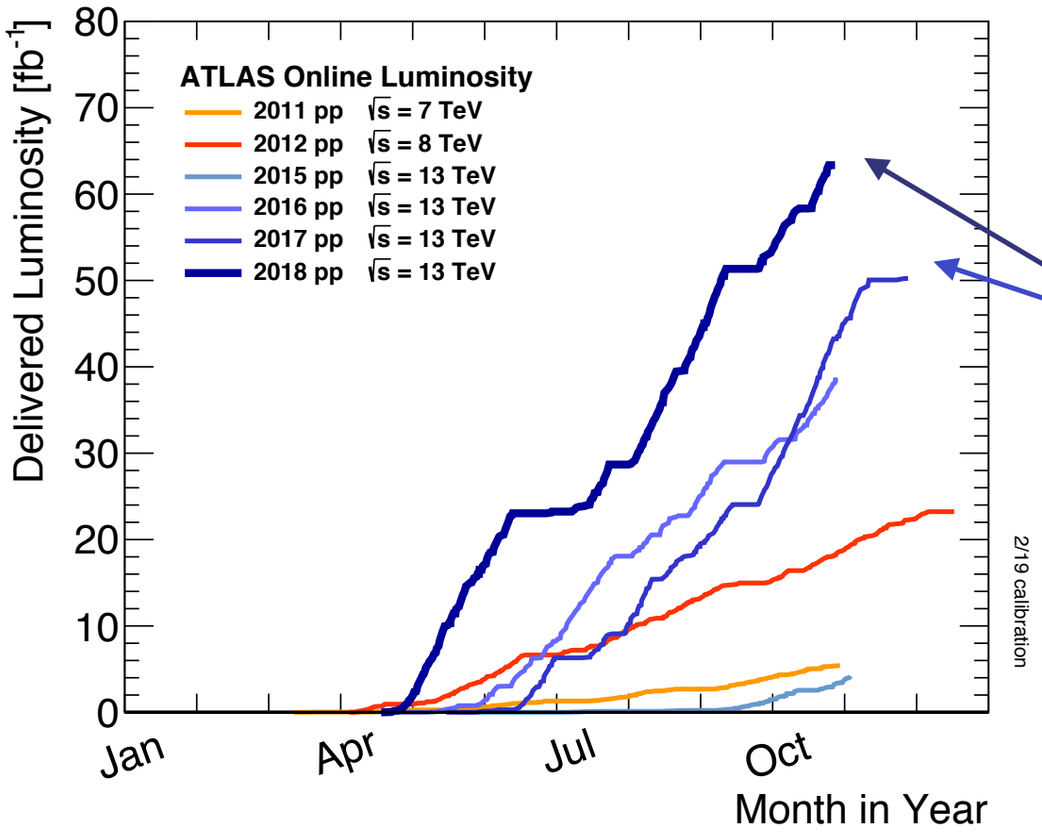


Conclusions

- Lacking any evidence for New Physics in any of the searched finalized so far, unconventional signatures are gaining in popularity

- ATLAS has a complete program to search for long-lived particles in many different signatures
  - Wide variety of searches (neutral and charged LLPs)
  - Very challenging, pushing the detector for searches it was not designed to perform





- No discovery so far but…
- 2017-2018 dataset to be studied yet!
- Lots of work being done to develop new techniques for LLP identification in uncovered phase-space
- Looking forward to seeing first significant deviations from the SM predictions!!

Backup

ATLAS public results

- All ATLAS public results:
- https:/twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome

- EXOTICS specific results:
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults