

# Searches for anomalous ionizing particles, SIMPs, and monopoles at the LHC



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# Heavy long-lived multi-charged particles

## Models

- Almost-commutative (AC) leptons: pairs of SU(2) EW singlets with opposite charges
- Technibaryons from walking-technicolor model: made of 2 techniquarks and 2 anti-techniquarks with arbitrary electric charge – lightest technibaryon is stable
- Doubly charged Higgs bosons in left-right symmetric model
- Doubly charged particles that could explain positron excess in dark matter searches

## Signature

- Bethe-Bloch formula:  $dE/dx \sim z^2 \rightarrow$  characteristic ionization,  $|q| = ze$

## ATLAS analysis arXiv 1812.03673

- Particles with charges in half-integer steps considered
- $2 \leq z \leq 7$
- Production model: purely electromagnetic coupling, proportional to charge of MCP
- MCP mass range 50 to 1400 GeV
- Muon-like particles, traversing ATLAS detector without decaying
- Large  $dE/dx$  leads to slowdown  $\rightarrow$  trigger and reconstruction need to be adapted

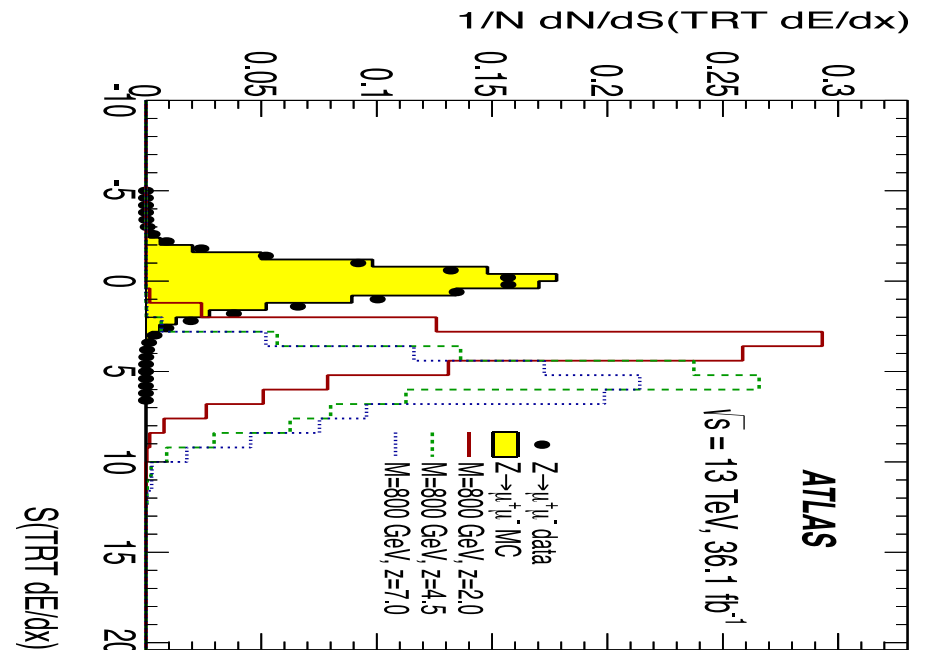
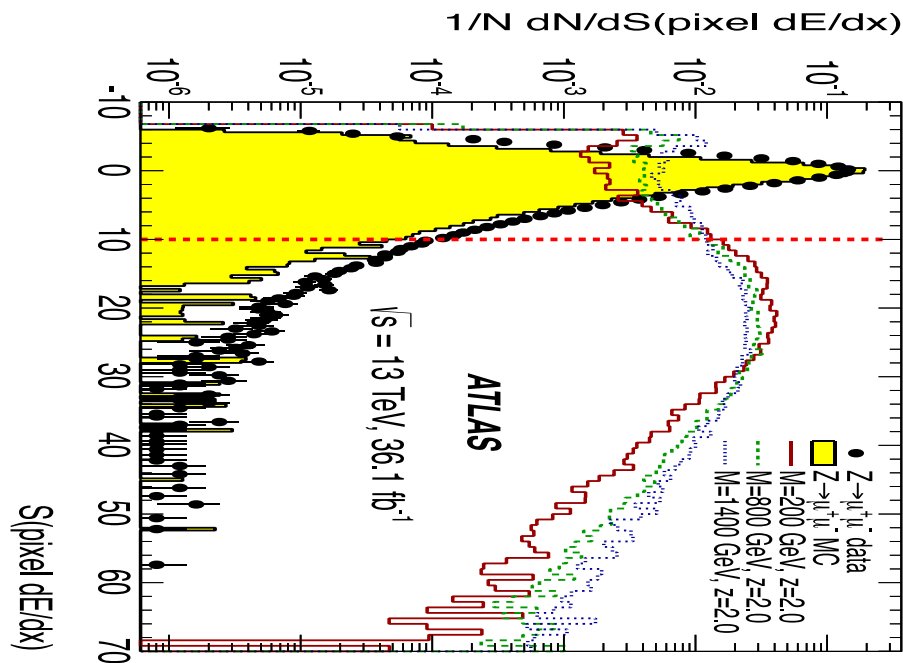
## Data sample and trigger

- $36.1 \text{ fb}^{-1}$  (2015, 2016),  $\sqrt{s} = 13 \text{ TeV}$  pp collisions
- Single-muon trigger with  $p_T/z > 50 \text{ GeV}$ ; sensitive for  $\beta > 0.6$  (timing window)
- Additional  $E_T^{\text{miss}}$  trigger (70, 90, 110 GeV);  $E_T^{\text{miss}}$  from calorimeters only; adds 20%

# Heavy long-lived multi-charged particles

## Event and candidate selections

- Ionization energy measured in pixel, TRT, MDT detectors
- Tight and final selection rely on ionization estimators
- Significance  $S(dE/dx)$  estimated by comparison with average for a highly-relativistic  $\mu$  using  $Z \rightarrow \mu\mu$  control sample



# Heavy long-lived multi-charged particles

## Background sources

- Muons with ionization randomly fluctuating to larger values due to occupancy effects
- $\delta$ -rays

## Two methods of background estimation

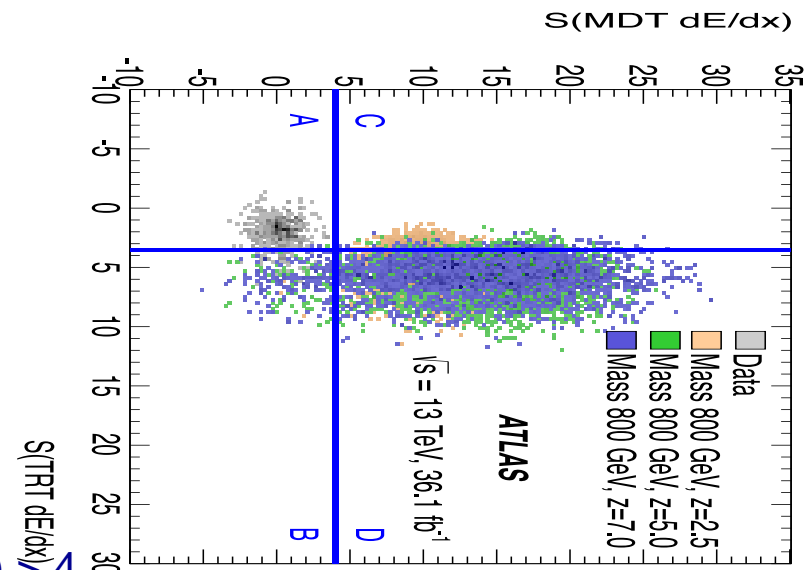
- $z = 2$ : ABCD method
- Plane  $S$  (TRT  $dE/dx$ ) –  $S$  (MDT  $dE/dx$ ) divided in 4 regions, using final selection cuts
- Expected number of background events in signal region D estimated from observed data events in regions A, B, C

$$N_{\text{data}}^{\text{D expected}} = \frac{N_{\text{data}}^{\text{B observed}} \times N_{\text{data}}^{\text{C observed}}}{N_{\text{data}}^{\text{A observed}}}$$

- $z > 2$ : sideband method

$$N_{\text{data}}^{\text{D expected}} = N_{\text{data}}^{\text{B observed}} \times f$$

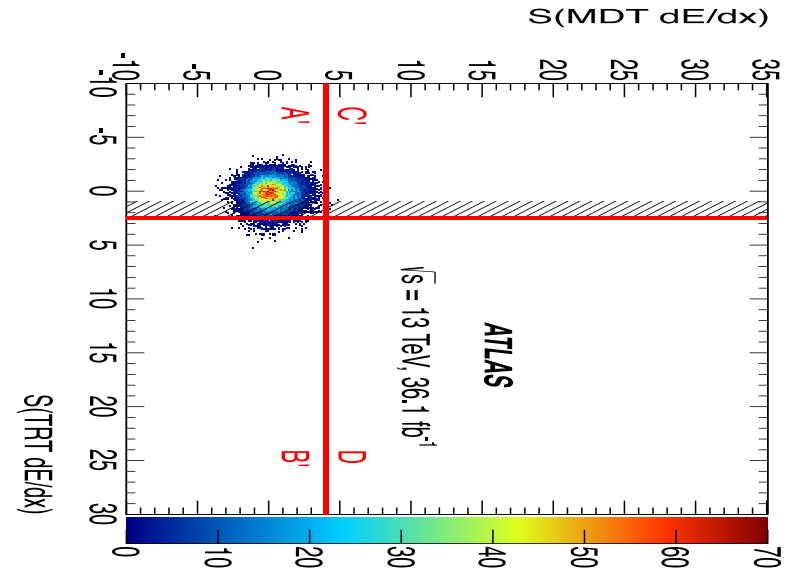
- $f$ : probability to find particle with  $S$  (MDT  $dE/dx$ )  $> 4$
- derived from cumulative  $S$  (MDT  $dE/dx$ ) distribution with anti-tight selection applied



# Heavy long-lived multi-charged particles

## Uncertainties

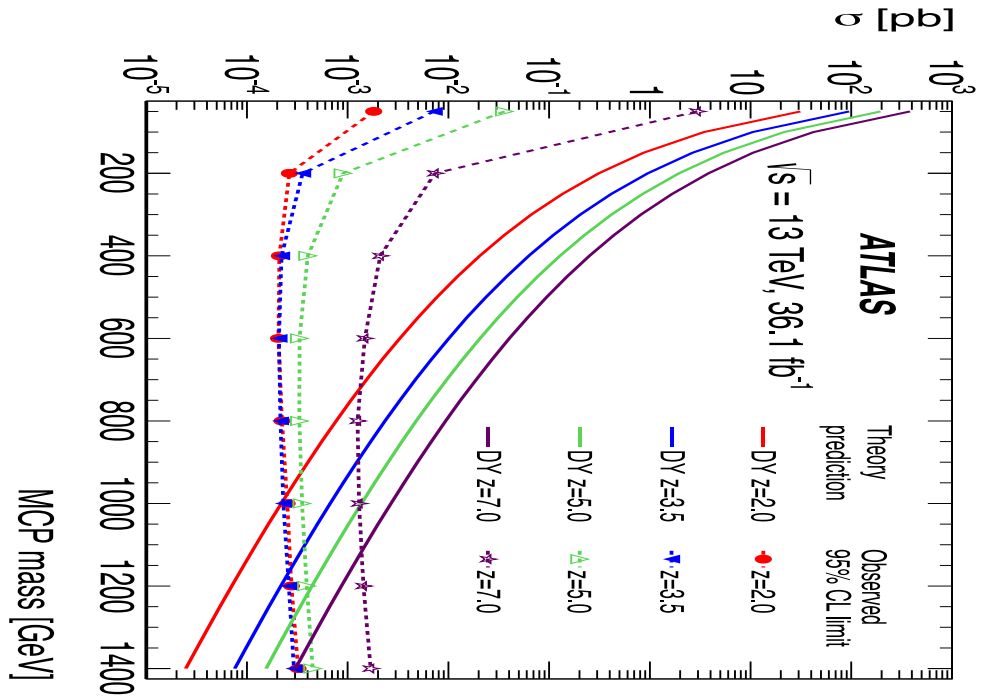
- Background estimation uncertainty
  - dead regions introduced (see example, shaded grey), to check possible correlations between 2 variables constructing the ABCD plane
  - Final systematic uncertainties in background estimation:  
67% for  $z = 2$ ; 75% for  $z > 2$
- Integrated luminosity: 2.1%
- Signal selection efficiency



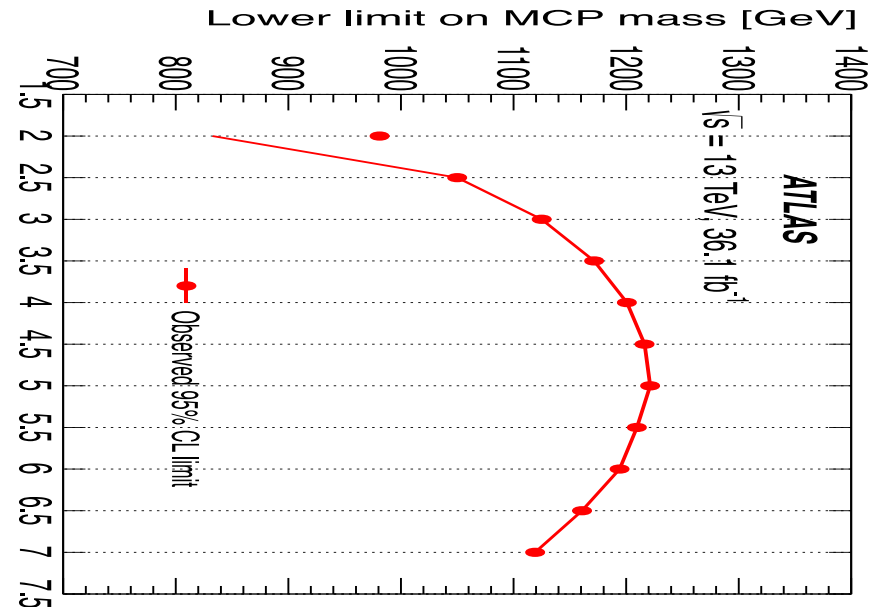
## Most significant contributions to overall systematic uncertainties in signal selection efficiency

Signal benchmark point		Data-simulation comparison [%]	Trigger efficiency [%]	PDF parameterization [%]	Selection efficiency overall uncertainty [%]
$z$	Mass [GeV]				
2.0	200	12	0.9	6.5	14
	800	7.2	3.6	10	13
	1400	6.1	5.0	17	19
4.5	200	8.9	1.4	6.9	12
	800	5.7	2.4	11	12
	1400	5.9	10.2	17	21
7.0	200	9.3	3.1	7.2	14
	800	6.6	8.2	11	16
	1400	6.7	5.6	18	21

# Heavy long-lived multi-charged particles



Observed 95% CL lower mass limits of lepton-like MCPs with Drell–Yan pair production model



Lepton-like multi-charged particles with masses between **50 GeV** and **980 – 1220 GeV** excluded for  $2 \leq z \leq 7$





# Strongly interacting massive particles (SIMPs)

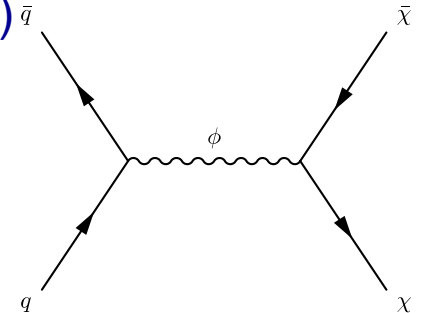
## Motivation

- Dark matter searches targeted WIMPs in the past
- Phase space for WIMPs in minimal models now quite reduced
- Large interaction cross sections with nucleons of SIMPs ( $\chi$ )

## Simplified model

- Interaction through scalar or vector low-mass mediator  $\phi$

$$\mathcal{L}_{int} = -g_\chi \Phi \bar{\chi} \chi - g_q \Phi \bar{q} q$$



- Purely repulsive SIMP-nucleon interaction to avoid bound states
- SIMPs hadronize only through production of quarks via mediator radiated by a SIMP

## Experimental signature: trackless jets

- Pairs of jets in calorimeters
- No tracks from charged particles in tracker

## CMS analysis [arXiv 2105.09178](#)

- Different phase space than in ATLAS analysis using principally only HCAL

[arXiv 1902.03094](#)



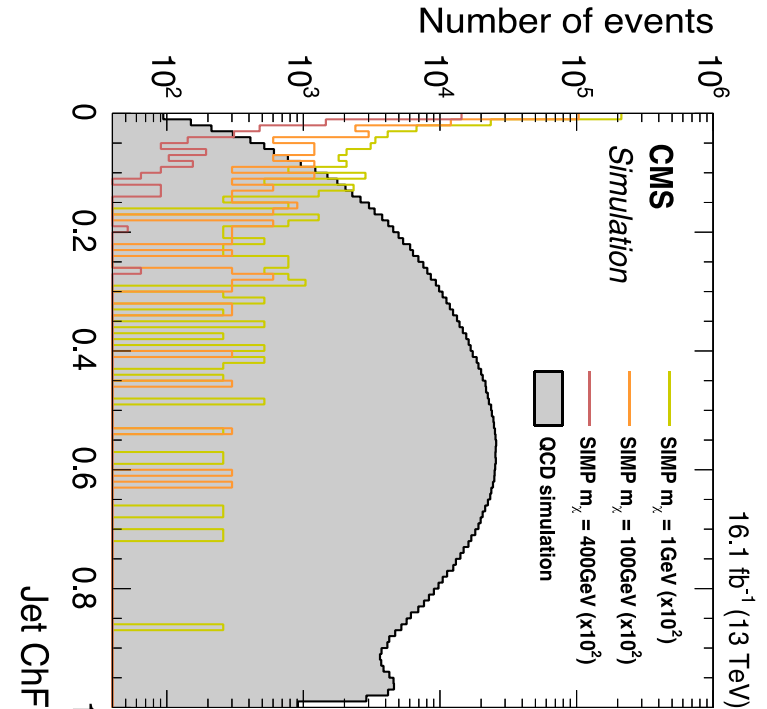
# Strongly interacting massive particles (SIMPs)

## Data sample, trigger, and event selection

- $16.1 \text{ fb}^{-1}$  (2016),  $\sqrt{s} = 13 \text{ TeV}$  pp collisions
- Search for jet-like objects with very small energy fraction carried by charged particles (ChF)
- Online trigger: jet with  $p_T > 450 \text{ GeV}$
- Offline selection: 2 jets with  $p_T > 550 \text{ GeV}$  in  $|\eta| < 2$  (tracker volume), separated in azimuth by  $\Delta\phi > 2$ , as well as photon veto within  $\Delta R < 0.1$
- Reject events with other jets with  $p_T > 30 \text{ GeV}$  and  $|\eta| < 5$

## Background

- $\gamma$  + jets background negligible
- QCD multijet background estimated from data
- Control region: baseline selection above, with  $\geq 1$  leading jet with  $\text{ChF} > 0.25$
- ChF requirement applied only to jets from primary vertex
- Selection efficiency measured by selecting 1 jet with  $\text{ChF} > 0.25$ , the other with  $\text{ChF} < 0.05$  (signal selection), in bins of  $p_T$  and  $\eta$
- Number of QCD events in signal region estimated from number of dijet events passing baseline selection, applying selection efficiencies on the 2 leading jets (2-leg)
- Alternatively, events with 1 jet with  $\text{ChF} < 0.05$  were used, with efficiencies applied to other jet (1-leg)



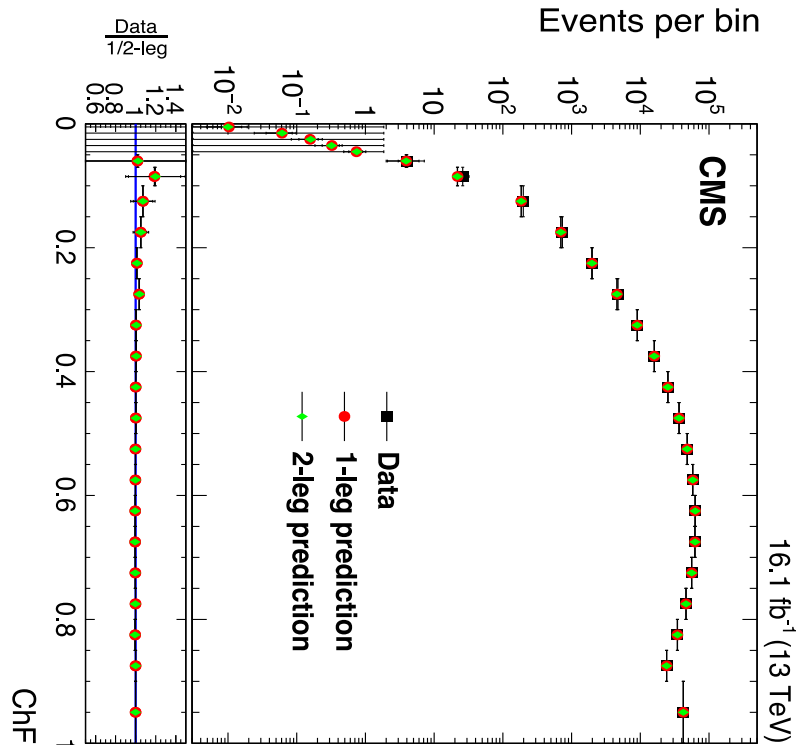




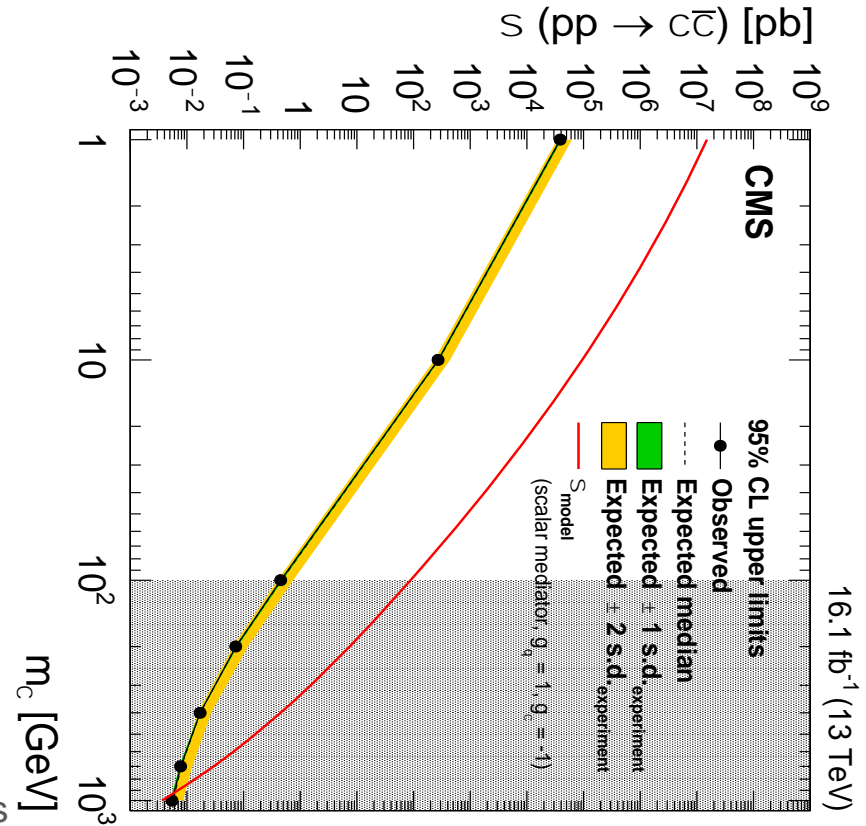
# Strongly interacting massive particles (SIMPs)

Signal region:  $\text{ChF} < 0.05$

- SIMP interaction in detector is assumed as neutron-like

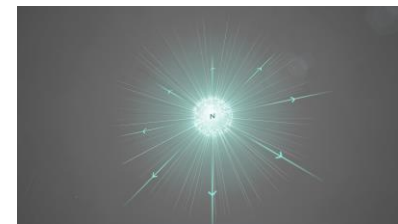


Nr. of background events from predictions derived from data, and data, in ChF bins where either the leading or subleading jet has a ChF within the bin edges, and both have a ChF below the upper bin threshold.



SIMP masses less than **100 GeV** are excluded.  
Upper limit on fiducial cross section at 95% CL:  
**0.18 fb**

# Monopoles and high-electric-charge objects



## Theoretical considerations

- Dirac monopole: spin and mass not constrained
- Electroweak monopoles with masses as low as 4 TeV predicted by some models
- Fundamental magnetic charge:  $q_m = N g_D$  ec; Dirac charge:  $g_D = 1/2\alpha = 68.5$
- Implies that high-velocity Dirac monopole of magnetic charge  $g_D$  interacts with matter like ion with electric charge  $z = 68.5$
- Energy deposit 4700 times higher than for proton, and many  $\delta$ -rays
- High-ionization signature also for stable high-electric-charge (HECO) objects (aggregates of ud- or s-quark matter, Q-balls, micro-black-hole remnants)

arXiv 1905.10130

## ATLAS analysis

- Search for highly-ionizing particles (HIPs), requiring at least one HIP
- Sensitivity for monopoles up to  $|g| = 2g_D$  (complementary to MoEDAL)
- Results interpreted for models with spin-0 and spin- $1/2$  Drell–Yan production of stable particles with 1 or 2 Dirac magnetic charges or an electric charge within  $20 \leq z \leq 100$  and masses between 200 and 4000 GeV

# Monopoles and high-electric-charge objects

## Data sample, signature, trigger

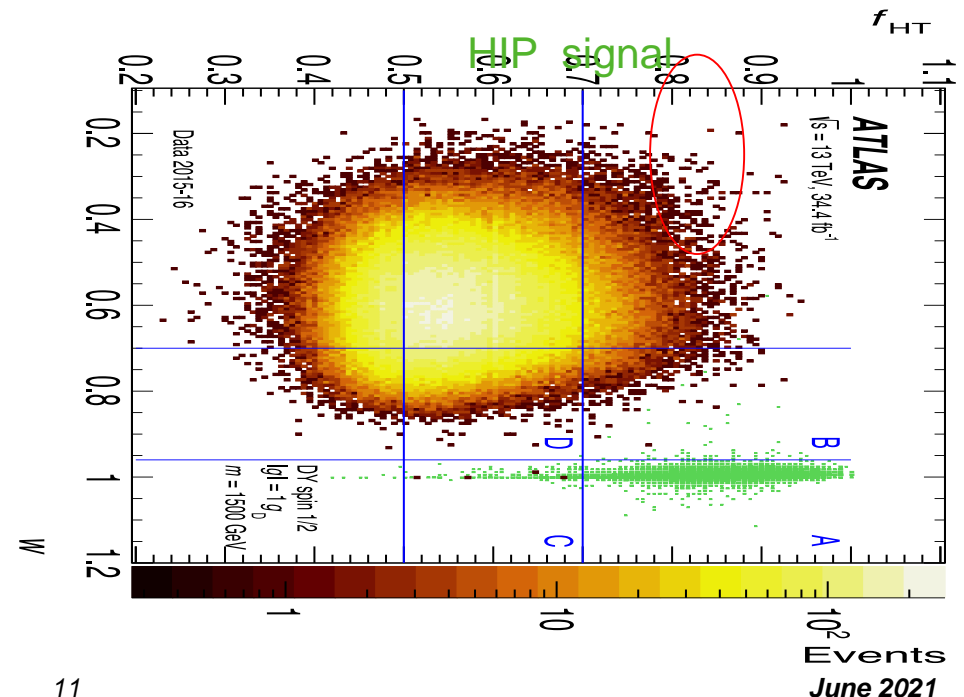
- 34.4 fb<sup>-1</sup> (2015, 2016),  $\sqrt{s} = 13$  TeV pp collisions
- Single HIP in Transition Radiation Tracker (TRT) and pencil-shaped deposit in ECAL (no shower, since much heavier than electrons)
- Dedicated trigger, different from muon trigger used for lower-charge HECOs
- High-threshold (HT) hits in TRT required
- Software-based trigger on number ( $N_{\text{HTtrig}} > 30$ ) and fraction ( $f_{\text{HTtrig}} > 0.5$ ) of TRT hits in narrow RoI (10 mrad r- $\phi$  wedge)

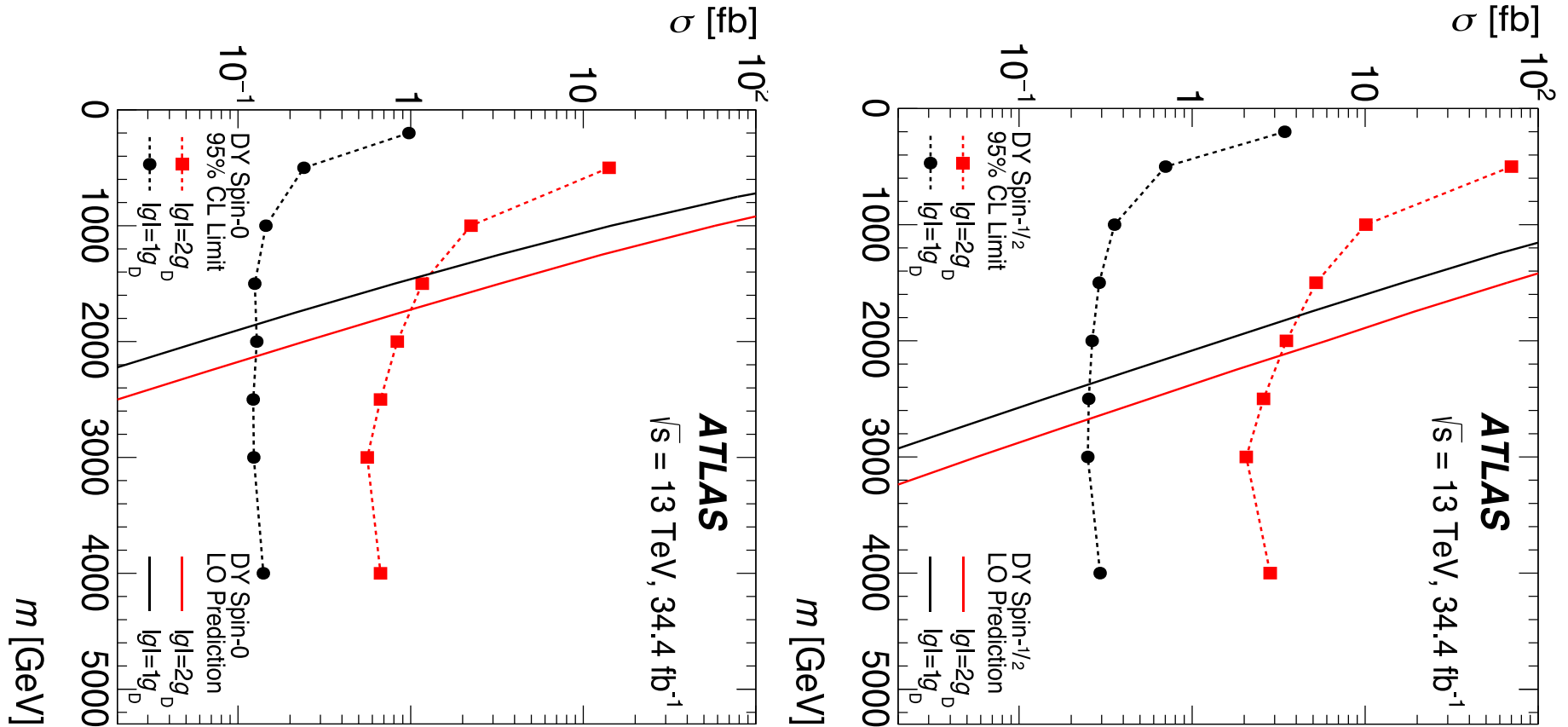
## Event selection

- Topical cluster of ECAL cells with  $E_T > 18$  GeV
- Cut on powerful variables:  $f_{\text{HT}}$  (similar to  $f_{\text{HTtrig}}$ ) and  $w$  (lateral energy dispersion)

## Backgrounds (from data)

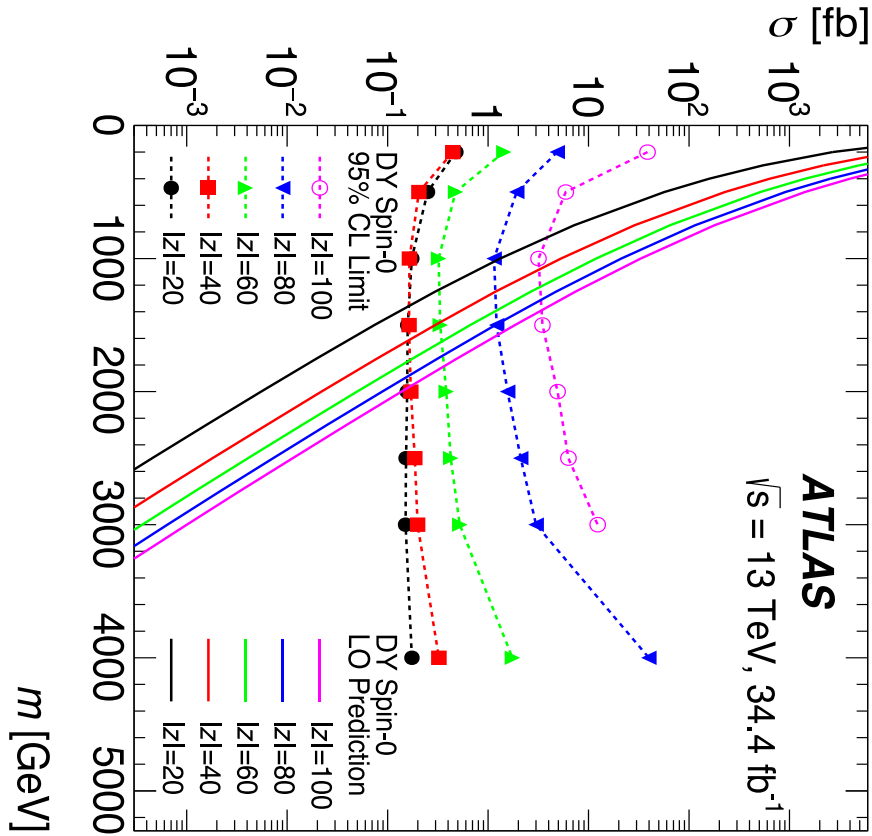
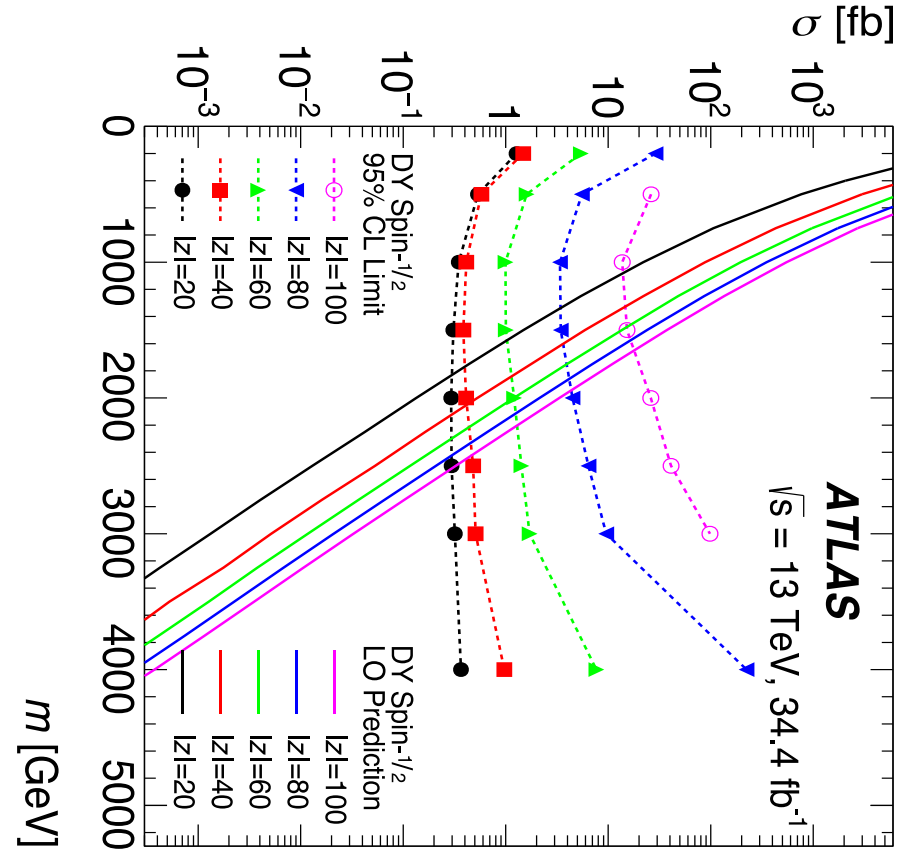
- TRT: overlapping charged particles
- High-energy electrons in ECAL
- Noise in TRT straws and ECAL





Observed 95% CL upper limits on Drell–Yan spin-0 and spin-1/2 monopole production cross sections

# High-electric-charge objects



Observed 95% CL upper limits on Drell–Yan HECO production cross sections

# Bibliography

## ATLAS

**<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>**

- Search for long-lived neutral particles in pp collisions at  $\sqrt{s} = 13$  TeV that decay into displaced hadronic jets in the ATLAS calorimeter: EPJC 79 (2019) 481, arXiv 1902.03094, hepdata 1719200, EXOT-2017-25
- Search for heavy long-lived multi-charged particles in proton-proton collisions at  $\sqrt{s} = 13$  TeV using the ATLAS detector: PRD 99 (2019) 031802, arXiv 1812.03673, hepdata 1707957, EXOT-2017-13
- Search for magnetic monopoles and stable high-electric-charge objects in proton-proton collisions with the ATLAS detector: PRL 124 (2020) 052003, arXiv 1905.10130, hepdata 1736730, EXOT-2017-20

## CMS

**<https://cms-results.web.cern.ch/cms-results/public-results/publications>**

- Search for strongly interacting particles generating trackless jets in proton-proton collisions at  $\sqrt{s} = 13$  TeV: submitted to EPJC, arXiv 2105.09178, hepdata 1864485, EXO-17-010



- Lepton-like multi-charged particles with masses between 50 GeV and 980 – 1220 GeV are excluded for  $2 \leq z \leq 7$
- SIMP masses less than 100 GeV are excluded for scalar mediator and couplings  $g_q = 1$ ,  $g_\chi = -1$
- Improvement by factor 5 of the constraints on direct production of magnetic monopoles with 1 or 2 magnetic Dirac charges and stable objects with electric charge in  $20 \leq z \leq 60$ , and charge range extended to  $60 \leq z \leq 100$

Thank you for your attention!



# Trackless jets - scalars decaying in calorimeters

## Models and dataset

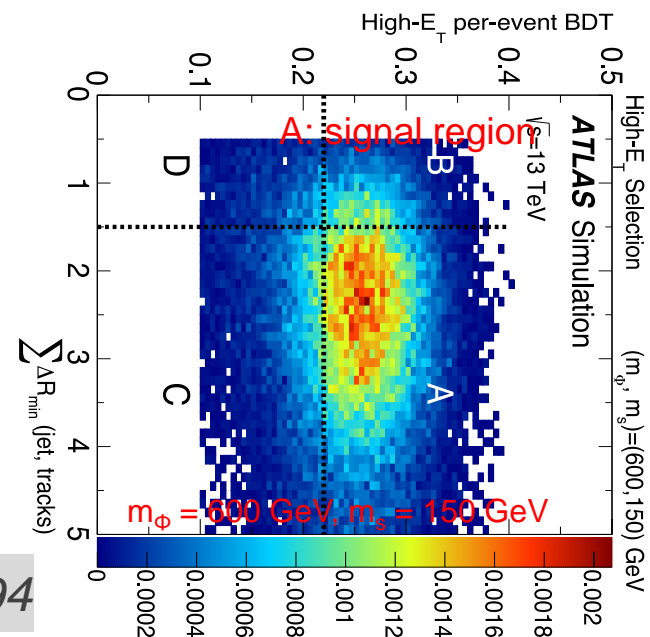
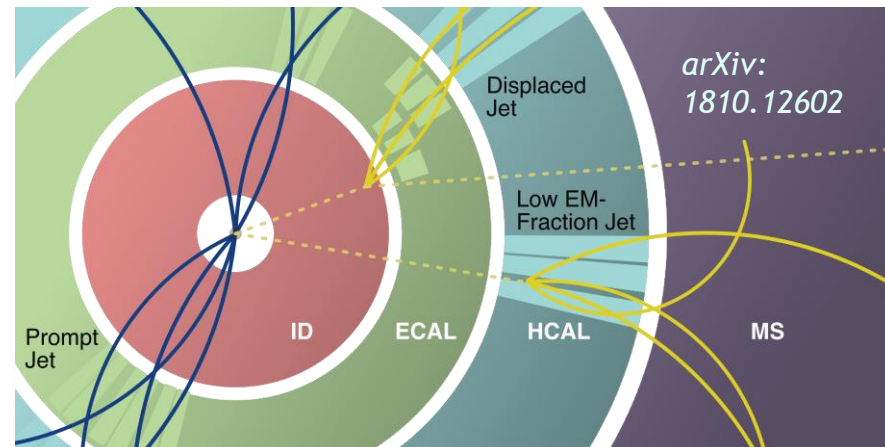
- Hidden-sector models
- $10.8 \text{ fb}^{-1}$  and  $33.0 \text{ fb}^{-1}$  at  $\sqrt{s} = 13 \text{ TeV}$
- $c\tau$  range few cm to tens of m

## Signature and trigger

- Displaced jets in HCAL or outer edge of ECAL
- At least 2 trackless and low-EMF jets - CalRatio (CR) jets
- dedicated low- and high- $E_T$  triggers

## Analysis strategy and background

- Machine learning techniques (neural network to determine jet origin, BDT classifier for jets)
- Backgrounds: mainly multijet and beam-induced, estimated with ABCD method



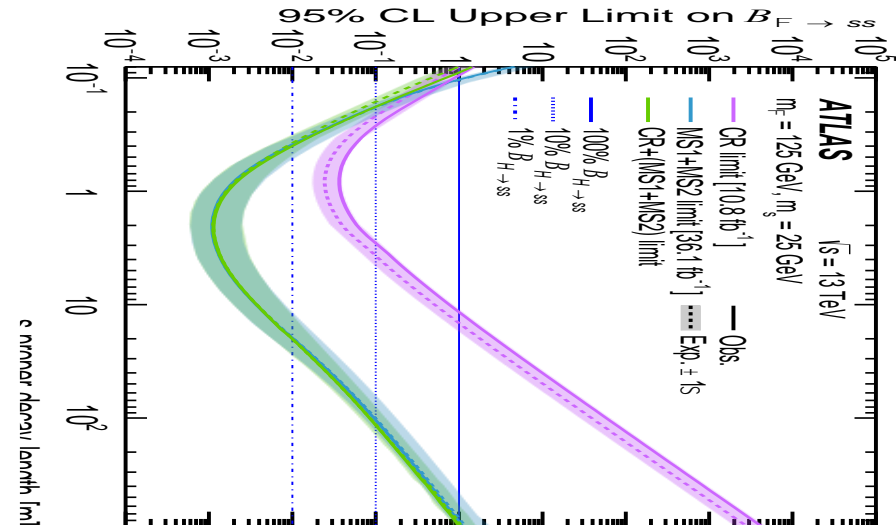
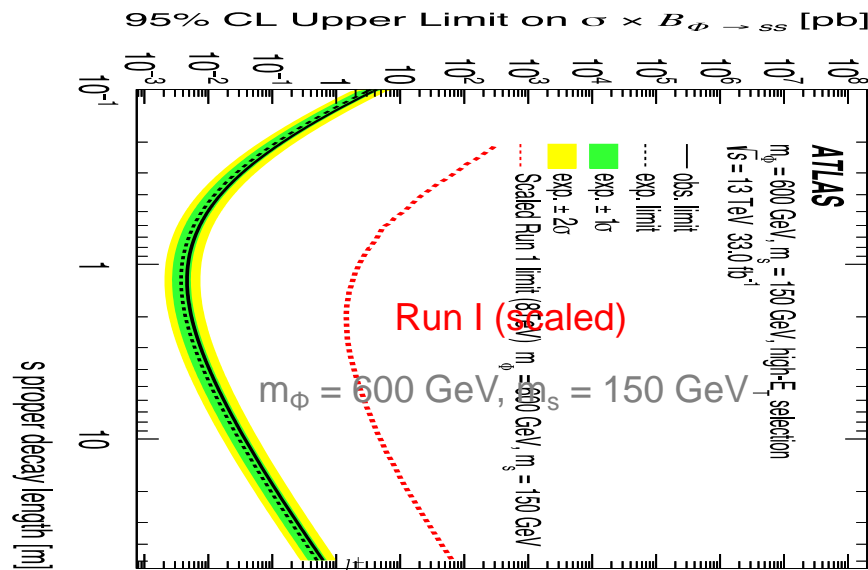
EXOT-2017-025, arXiv 1902.03094

# Trackless jets - scalars decaying in calorimeters

## 95% CL limits set on $\sigma(\phi) \times B(\phi \rightarrow ss)$

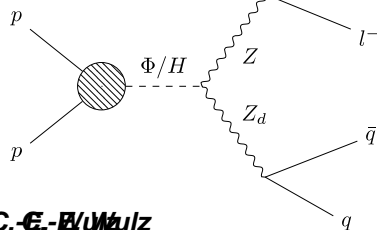
Mediator  $\phi$  with  $m_\phi = 125$  GeV:  $m_s$  between 5 and 55 GeV excluded for  $\tau$  between 5 cm and 5m, for  $B(\phi \rightarrow ss) = 10\%$

For  $m_\phi = 400$  GeV,  $m_\phi = 600$  GeV, and  $m_\phi = 1000$  GeV,  $\sigma(\phi) \times B(\phi \rightarrow ss)$  values  $> 0.1$  pb excluded between 12 cm and 9 m, 7 cm and 20 m, and 4 cm and 35 m respectively, depending on  $m_s$



Combination with displaced jet analysis in muon system  
 arXiv 1811.07370

Related analysis with CR jet and Z: arXiv 1811.02542



# Heavy long-lived multi-charged particles

## Selection criteria

		Candidate track preselection	Tight selection	Final selection
Requirements	$z = 2$	Combined muon with:  “medium” identification criteria,  $p_T^\mu/z > 50 \text{ GeV}$ ,  $ \eta  < 2.0$ ,  no other tracks with $p_T/z > 0.5 \text{ GeV}$ within $\Delta R < 0.01$	Preselected candidate with:  $S(\text{pixel } dE/dx) > 10$	Tightly selected candidate with:  $S(\text{TRT } dE/dx) > 2.5$ , $S(\text{MDT } dE/dx) > 4$
	$z > 2$		Preselected candidate with:  $\geq 1$ overflowing IBL cluster, $f^{\text{HT}} > 0.5$	Tightly selected candidate with:  $S(\text{TRT } dE/dx) > 3.5$ , $S(\text{MDT } dE/dx) > 4$

# Monopoles and high-electric-charge objects

## Lower mass limits

Lower limits on the mass of Drell–Yan magnetic monopoles and HECOs [GeV]

	$ g  = 1g_D$	$ g  = 2g_D$	$ z  = 20$	$ z  = 40$	$ z  = 60$	$ z  = 80$	$ z  = 100$
Spin-0	1850	1725	1355	1615	1625	1495	1390
Spin-1/2	2370	2125	1830	2050	2000	1860	1650