Searches for long-lived and highly-ionizing particles at the CMS and ATLAS experiments

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

DFG

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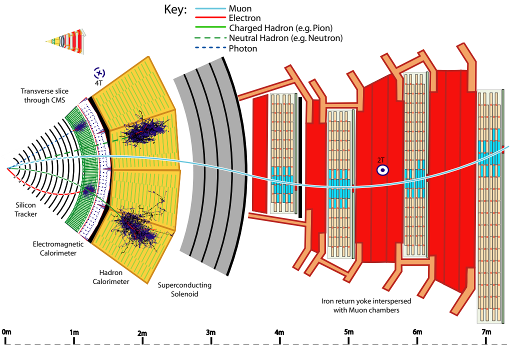
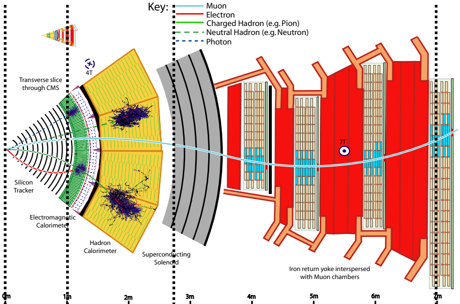
Introduction

- Long-lived particles are contained in many extensions of the SM
  - Supersymmetric models (AMSB, split supersymmetry, ...);
  - Universal extra dimensions;
  - Technicolor; ...
- Long-lived particles can enter/pass through the detector



A variety of long-lived searches at CMS and ATLAS

Particles can be neutral or charged or change their charge through interactions.



(Displaced) jets	CMS: Phys.Rev.D 91, 012007 (2015) ATLAS: Phys.Lett.B 743,15 (2015)
Lepton jets	ATLAS: JHEP 11,088 (2014)
Displaced leptons	CMS: CMS-PAS-EXO-14-012 CMS: Phys.Rev.Lett. 114, 061801 (2015)
Displaced vertices	ATLAS: Phys.Rev.D 92, 072004 (2015)
Displaced / delayed photons	ATLAS: Phys.Rev.D 90, 112005 (2014)
Stopped particles	ATLAS: Phys.Rev.D 88, 112003 (2013) CMS: EPJ C 75, 4 (2015)
Disappearing tracks	ATLAS: Phys.Rev.D 88, 112006 (2013) CMS: JHEP 01 (2015) 096
Heavy stable charged particles	CMS: CMS-PAS-EXO-15-010 ATLAS: Submitted to PRD
Multi-charged particles	ATLAS: EPJC 75 (2015) 362
Monopoles/highly charged particles	ATLAS: PRD 93, 052009 (2016)

A variety of long-lived searches at CMS and ATLAS

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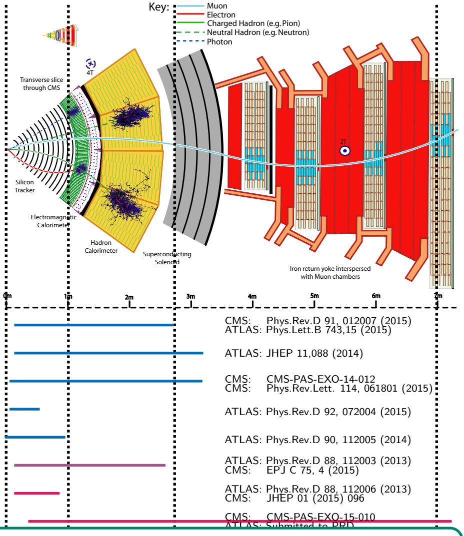

(Displaced) jets
Lepton jets
Displaced leptons
Displaced vertices
Displaced / delayed photons
Stopped particles
Disappearing tracks
Heavy stable charged particles
Multi-charged particles
Monopoles/highly charged particles

Exploit heaviness of new particles using dE/dx

Energy loss per path length - dE/dx

- Mean energy loss described by Bethe formula

$$\langle \frac{dE}{dx} \rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} [\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}]$$

Energy loss per path length - dE/dx

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Energy loss per path length - dE/dx

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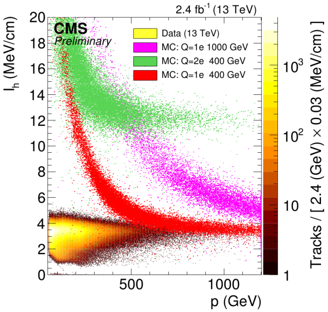
- Large dE/dx for
  - Low velocities (high masses)
  - Multiple charges

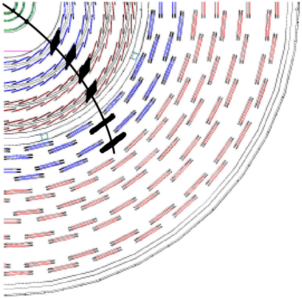


High-momentum Standard Model particles are minimally ionizing (MIPs)

$\longrightarrow$

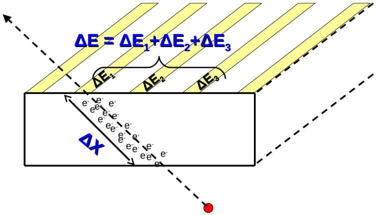
Good discrimination power using dE/dx

dE/dx measurement at CMS



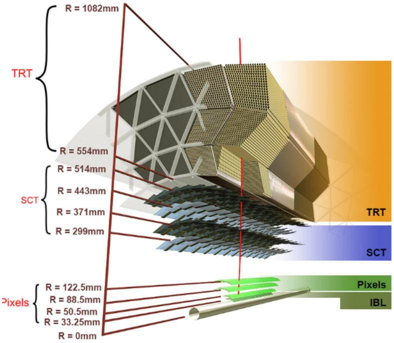
- CMS tracker fully silicon based
- Inside a 3.8T solenoid
- Coverage up to $|\eta| = 2.5$
- $R = 4.4\,\text{cm} - 1.1\,\text{m}$
- Typically around 17 hits

ΔE/Δx measurements ⟶ **dE/dx estimator (discriminator)**



- Harmonic-2 estimator
  $I_{\mathrm{h}} = \left(\frac{1}{N}\sum_{i=1}^{N}(\Delta E_i/\Delta x_i)^{-2}\right)^{-1/2}$
- Likelihood discriminator
  - Built from hypothesis distribution of MIPs

dE/dx measurement at ATLAS



- Mixture of silicon tracker and transition radiation tracker (TRT)
- Inside a 2T solenoid
- Coverage up to $|\eta| = 2.5$
- New pixel layer at 13 TeV
- $R = 3.3\,\text{cm} - 1.1\,\text{m}$

Silicon pixel tracker

- Typically around four measurements
- Estimation of mean/most probable energy loss
- Estimation of dE/dx significance

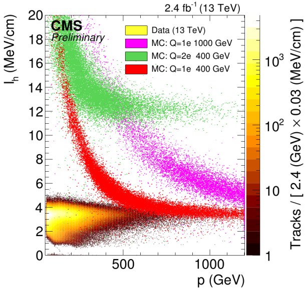
Transition radiation tracker

- Typically around 32 straw hits
- Estimation of dE/dx significance
- Comparison of high-threshold to low-threshold hits

Heavy stable charged ($Q = e$) particles - CMS

CMS-PAS-EXO-15-010

- Search for new particles by exploiting low velocity ($\beta < 1$)
  - Large ionization losses (dE/dx)
  - Long time-of-flight (TOF)



Selection ("tracker-only" analysis)

- Trigger:
  - Muon ($p_T^\mu > 50$ GeV) OR
  - MET ($E_T^{miss} > 170$ GeV)
- Candidate track with:
  - $p_T > 55$ GeV
  - High-quality track
  - Cluster cleaning
  - Track isolation: $\Sigma p_T < 50$ GeV
  - Calorimeter isolation: $E/p < 0.3$

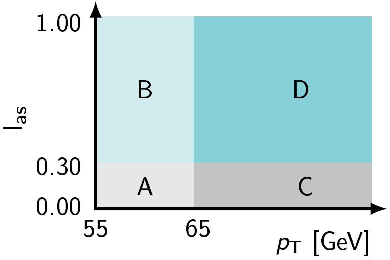
Background arising from tails in the dE/dx distribution of MIPs

Heavy stable charged ($Q = e$) particles - CMS 13 TeV

CMS-PAS-EXO-15-010

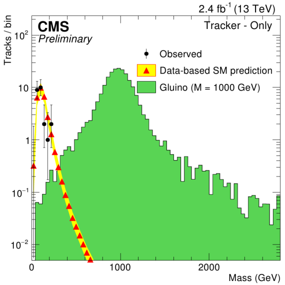
Background estimation:

- ABCD method using dE/dx likelihood discriminator I_{as} and p_T
- SM particles: p_T and I_{as} uncorrelated



Mass reconstruction with:

- $I_h = K \frac{m^2}{p^2} + C$
- K and C determined from low-momentum protons in data
- Binned probability of I_h (p) from control regions B (C) $\rightarrow$ prediction of mass spectrum in region D

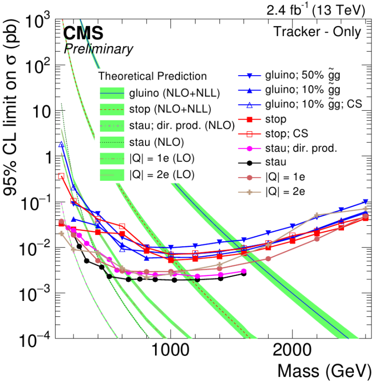


Heavy stable charged ($Q = e$) particles - CMS 13 TeV

CMS-PAS-EXO-15-010

Interpreted in:

- Split supersymmetry
- mGMSB models



Limits up to
$m = 1590\,\text{GeV}$ for long-lived gluinos
$m = 1020\,\text{GeV}$ for long-lived stops
$m = 480\,\text{GeV}$ for long-lived staus

Heavy long-lived charged particles - ATLAS

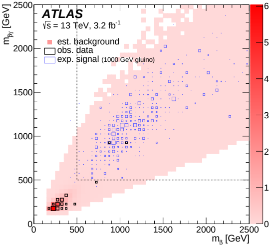
13 TeV

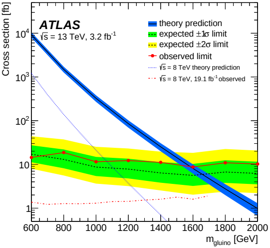
arXiv:1606.05129

- Search using pixel dE/dx + time-of-flight
- Similar to CMS analysis

Mass reconstruction from dE/dx and time-of-flight

Interpretation:
Long-lived R-hadrons:
gluinos, stops, sbottoms

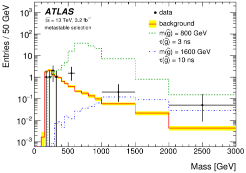




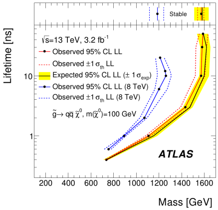
Limits up to
$m = 1580$ GeV for gluinos
$m = 890$ GeV for stops
$m = 805$ GeV for sbottoms

arXiv:1604.04520

- Pixel dE/dx only search



Interpreted in:
- Mini-split supersymmetry
- AMSB models

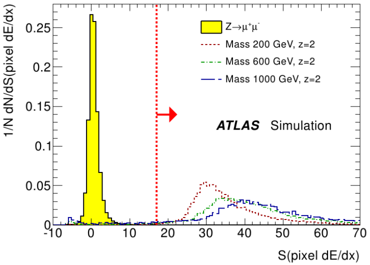


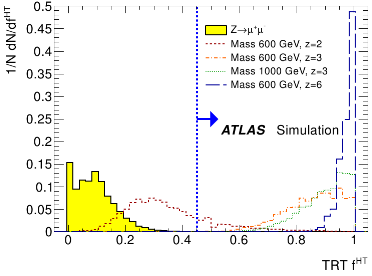
See talk from Jordan Tucker in SUSY (Parallel-2) session

Search for multi-charged particles - ATLAS 8 TeV

Eur.Phys.J. C75 (2015) 362

- dE/dx measurements in pixel tracker, TRT and monitored drift tube (MDT) chambers
- dE/dx estimators:
  - Pixel, TRT, MDT: $S(\mathrm{dE/dx}) = \frac{dE/dx_{\mathrm{track}} - \langle dE/dx_{\mu} \rangle}{\sigma(dE/dx_{\mu})}$
  - TRT: Fraction of hits passing high threshold f^{HT}
- Initial selection with muon system ($>$ 7 MDT hits)
- Candidate track selection (high quality, $p_{\mathrm{T}} > 30/40$ GeV, isolated, ...)
- Tight selection based on $S_{\mathrm{pixel}}(\mathrm{dE/dx})$ and f^{HT}



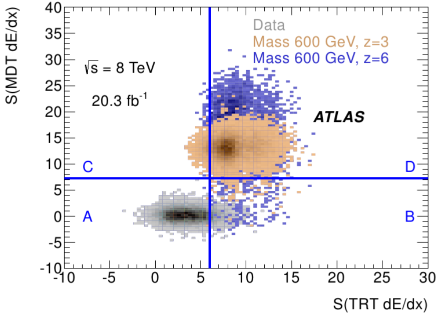


Eur.Phys.J. C75 (2015) 362

Background estimation

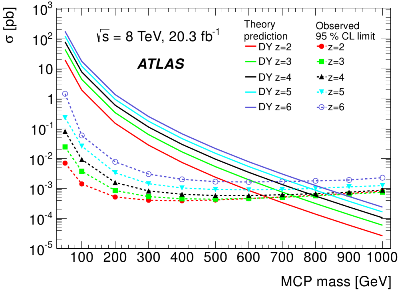
- ABCD with $S_{\mathrm{TRT}}(\mathrm{dE/dx})$ and $S_{\mathrm{MDT}}(\mathrm{dE/dx})$
- $N^{D}_{\mathrm{exp}} = N^{B}_{\mathrm{obs}} \cdot f^{C/A}_{\mathrm{preselection}}$

	$N^{\mathrm{B}}_{\mathrm{obs}}$	f	$N^{\mathrm{D}}_{\mathrm{exp}}$	$N^{\mathrm{D}}_{\mathrm{obs}}$
$z = 2$	76	1.8×10^{-4}	0.013 ± 0.002	0
$z \geq 3$	1251	2.1×10^{-5}	0.026 ± 0.003	0



Interpreted in:

- DY production model with pure electromagnetic coupling



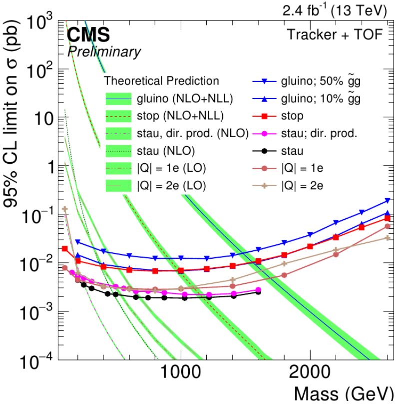
Search for multiple-charged (Q=2) particles - CMS 13 TeV

CMS-PAS-EXO-15-010

- Optimized selection for multiple-charged particles only at 8 TeV
  - Harder selection cut in dE/dx
  - No cluster cleaning
  - No E/p selection requirement

Interpreted in:

- DY production model with pure electromagnetic coupling



Limit at $\sqrt{s} = 13\,\text{TeV}$: $M = 650\,\text{GeV}$
Limit at $\sqrt{s} = 8\,\text{TeV}$: $M = 730\,\text{GeV}$
because of optimized selection

Search for magnetic monopoles - ATLAS

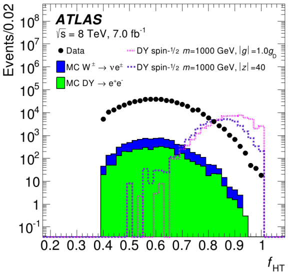
8 TeV

Phys.Rev.D 93, 052009 (2016)

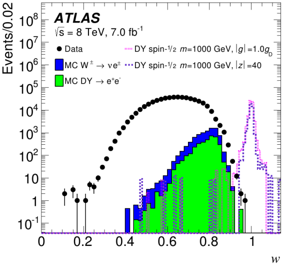
- Dirac argument: Magnetic monopoles
- Magnetic charge (g_D) corresponds to electric charge via:

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

→ Huge ionization losses!



- Dedicated software trigger for highly-ionizing particles
  - # of high-threshold (HT) hits: $N_{\mathrm{TRT}}^{\mathrm{HT}}$
  - Fraction of HT hits: $f_{\mathrm{TRT}}^{\mathrm{HT}}$
- Discriminating variables: $f_{\mathrm{TRT}}^{\mathrm{HT}}$, E, energy dispersion in the electromagnetic calorimeter (w)

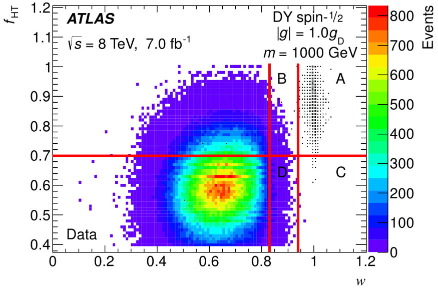


Search for magnetic monopoles - ATLAS 8 TeV

Phys.Rev.D 93, 052009 (2016)

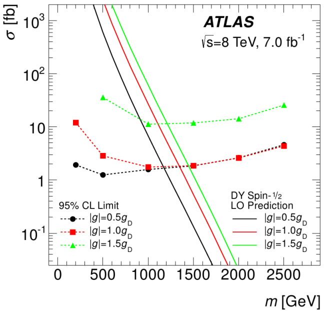
Background estimation:

- Background arising from QCD-multijet and W+jet events
- ABCD with $f_{\mathrm{TRT}}^{\mathrm{HT}}$ and w
- Increasing correlations between w and $f_{\mathrm{TRT}}^{\mathrm{HT}}$ for decreasing w



Interpreted in:

- DY production model
- Model-independent, single-particle production



Model-independent cross section upper limit of 0.5 fb.

Conclusion

Searches for long-lived and highly-ionizing particles
at the CMS and ATLAS experiments

- Long-lived searches sensitive to a variety of models (not only SUSY ...)
- New 13 TeV results available at CMS and ATLAS
- Many new results are expected!

- Typically very low backgrounds
- "data-driven" background estimations
- Good understanding of detector is crucial

- So far, no evidence for physics beyond the Standard Model
- Still, many different scenarios and models need to be tested
- Long-lived particle searches can fill up the gap not covered by conventional searches (e.g. mass-degenerate scenarios, ...)

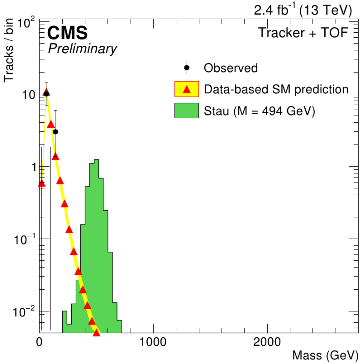
Thank you

Backup

Number of predicted and observed events

	Selection cuts				Number of events $\sqrt{s} = 13$ TeV	
	p_T (GeV)	I_{as}	$1/\beta$	Mass (GeV)	Pred.	Obs.
Trk-only	> 65	> 0.3	-	> 0	28.8 ± 6.1	24
				> 100	17.8 ± 3.8	13
				> 200	2.6 ± 0.6	2
				> 300	0.53 ± 0.12	0
				> 400	0.16 ± 0.035	0
Trk+TOF	> 65	> 0.175	> 1.250	> 0	17.9 ± 3.6	13
				> 100	4.1 ± 0.8	3
				> 200	0.60 ± 0.12	0
				> 300	0.12 ± 0.024	0

Reconstructed mass (tracker+TOF)

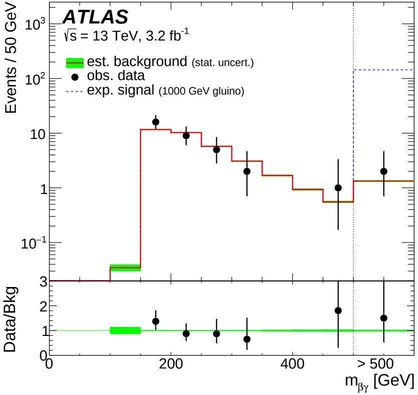


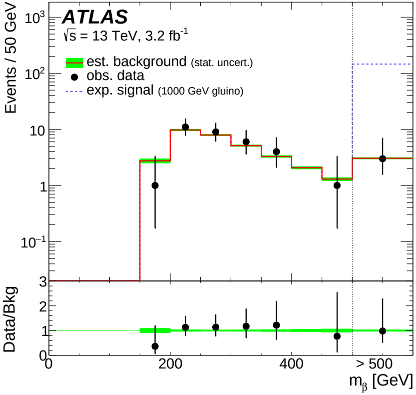
Systematic uncertainties

Source of Systematic Uncertainties	Relative Uncertainty (%)	
Signal acceptance	Trk-only	Trk+TOF
- Trigger efficiency	13	13
- Track momentum scale	< 20	< 20
- Track reconstruction	< 2	< 2
- Ionization energy loss	< 15	< 15
- HIP background	< 25	< 30
- Time-of-flight	-	< 5
- Muon reconstruction	-	2
- Pileup	< 1	< 1
Total uncertainty on signal acceptance	< 35	< 50
Background uncertainty	20	20
Luminosity uncertainty	4.6	

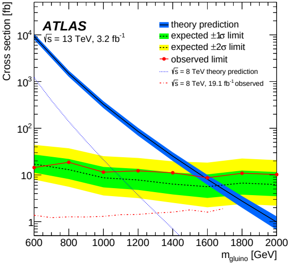
Mass measurement with dE/dx

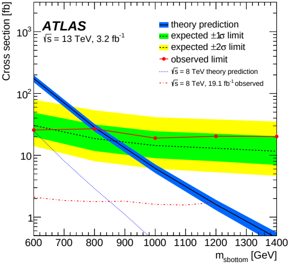
- $\mathrm{MPV}_{dE/dx} = \frac{p_1}{\beta^{p_3}} \ln\left(1 + (|p_2|\beta\gamma)^{p_5}\right) - p_4$
- Mass estimate: $m_{\beta\gamma} = p/\beta\gamma$





Limits


ATLAS
√s = 13 TeV, 3.2 fb-1
theory prediction
expected ±1σ limit
expected ±2σ limit
observed limit
√s = 8 TeV theory prediction
√s = 8 TeV, 19.1 fb-1 observed
Cross section [fb]
m_gluino [GeV]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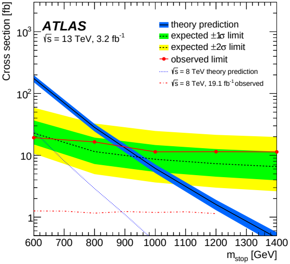
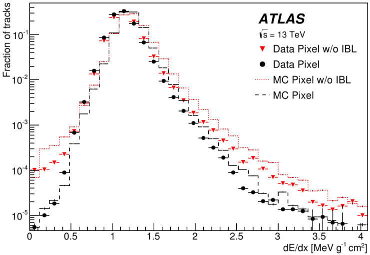
√s = 13 TeV, 3.2 fb-1
theory prediction
expected ±1σ limit
expected ±2σ limit
observed limit
√s = 8 TeV theory prediction
√s = 8 TeV, 19.1 fb-1 observed
Cross section [fb]
m_sbottom [GeV]


ATLAS
√s = 13 TeV, 3.2 fb-1
theory prediction
expected ±1σ limit
expected ±2σ limit
observed limit
√s = 8 TeV theory prediction
√s = 8 TeV, 19.1 fb-1 observed
Cross section [fb]
m_stop [GeV]

Metastable heavy charged particles - ATLAS 13 TeV

Impact of fourth pixel layer



Result table

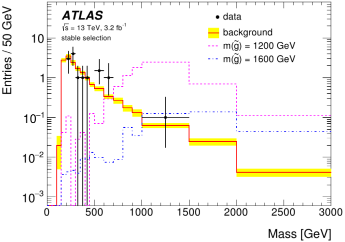
- Two different selections:
  - Metastable R-hadron selection (veto reconstructed muons)
  - Stable R-hadron selection (no muon veto)

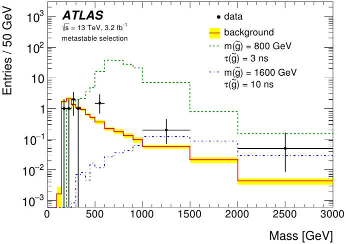
Selection region	Background exp.	Data
Metastable R-hadron	11.1 ± 1.7 ± 0.7	11
Stable R-hadron	17.2 ± 2.6 ± 1.2	16

Background estimation

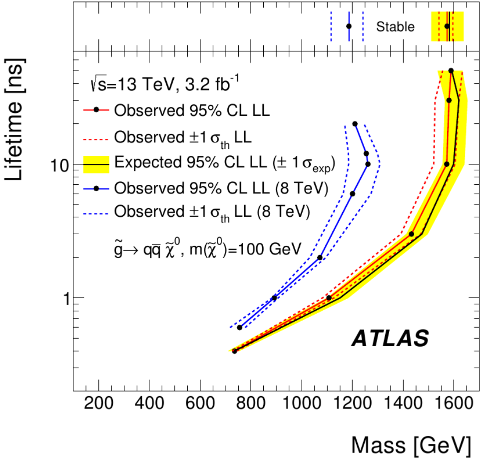
- Data-driven
- Distributions of key-variables from control regions (inverting E_T^{miss} or dE/dx)

Reconstructed mass for both selections

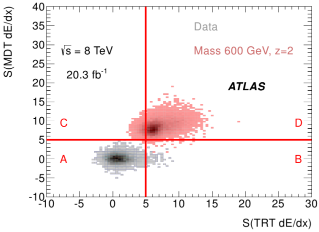


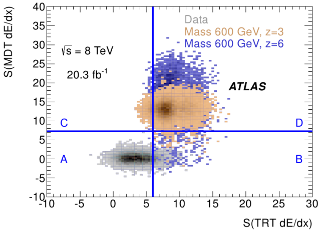


Limit in lifetime vs. mass plane

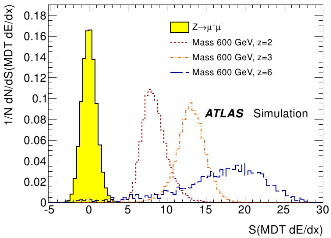


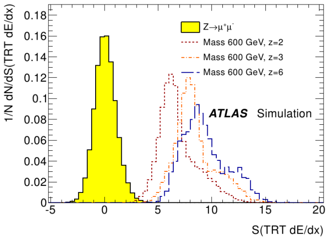
ABCD regions for $z = 2$ and $z \geq 3$ selection





dE/dx significance for TRT and MDT

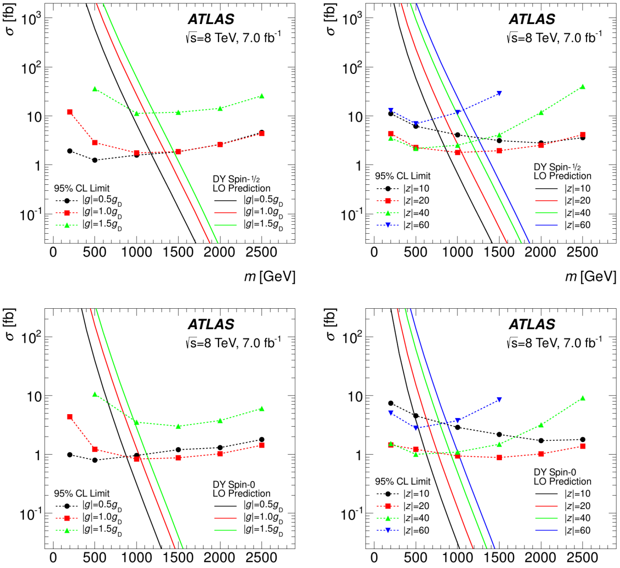




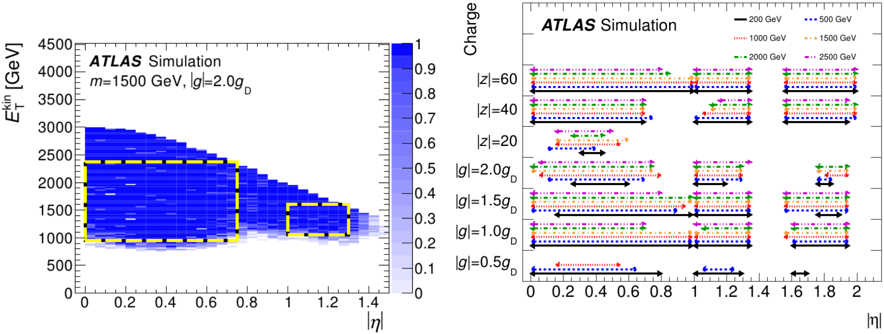
Search for magnetic monopoles - ATLAS

8 TeV

All limits



Definition of fiducial regions



- 90% selection efficiency with standard deviation $< 12.5\%$