Searches for monopoles and other exotic particles using LHC data at the ATLAS experiment

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ATLAS EXPERIMENT

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Introduction

- Observation of particles with |z|>1 or magnetic charge would be a signature for physics beyond the SM, answering fundamental open questions as:
  - the nature of dark matter
  - quantization of charge
- Searches for such particles are based on anomalous ionization in ATLAS
- Ionization is the main energy loss mechanism
  - absence of electromagnetic cascade

Electrically charged particles

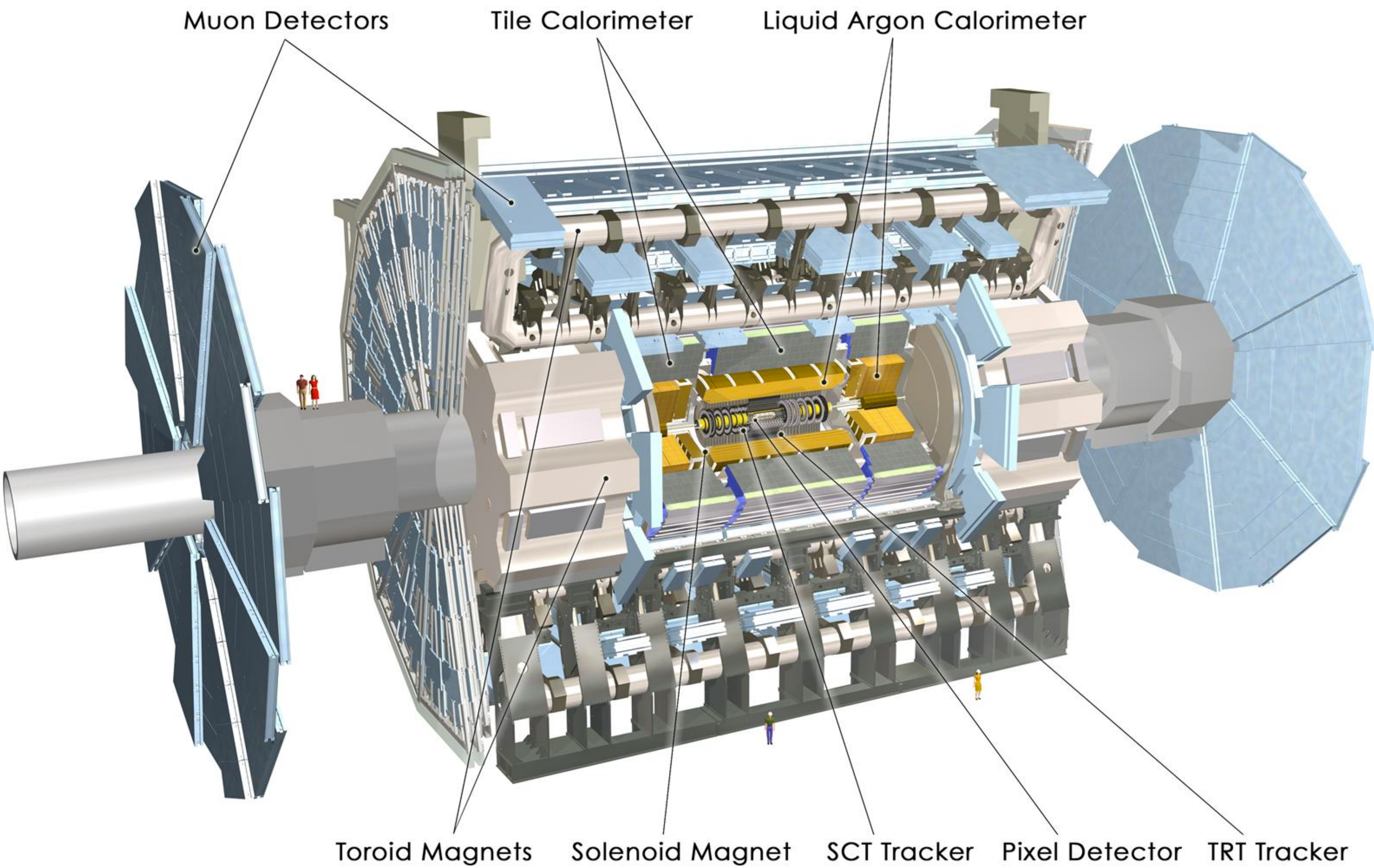
$$-\frac{dE}{dx} = K\frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I} - \beta^2 - \frac{\delta}{2}\right]$$

Magnetic monopole

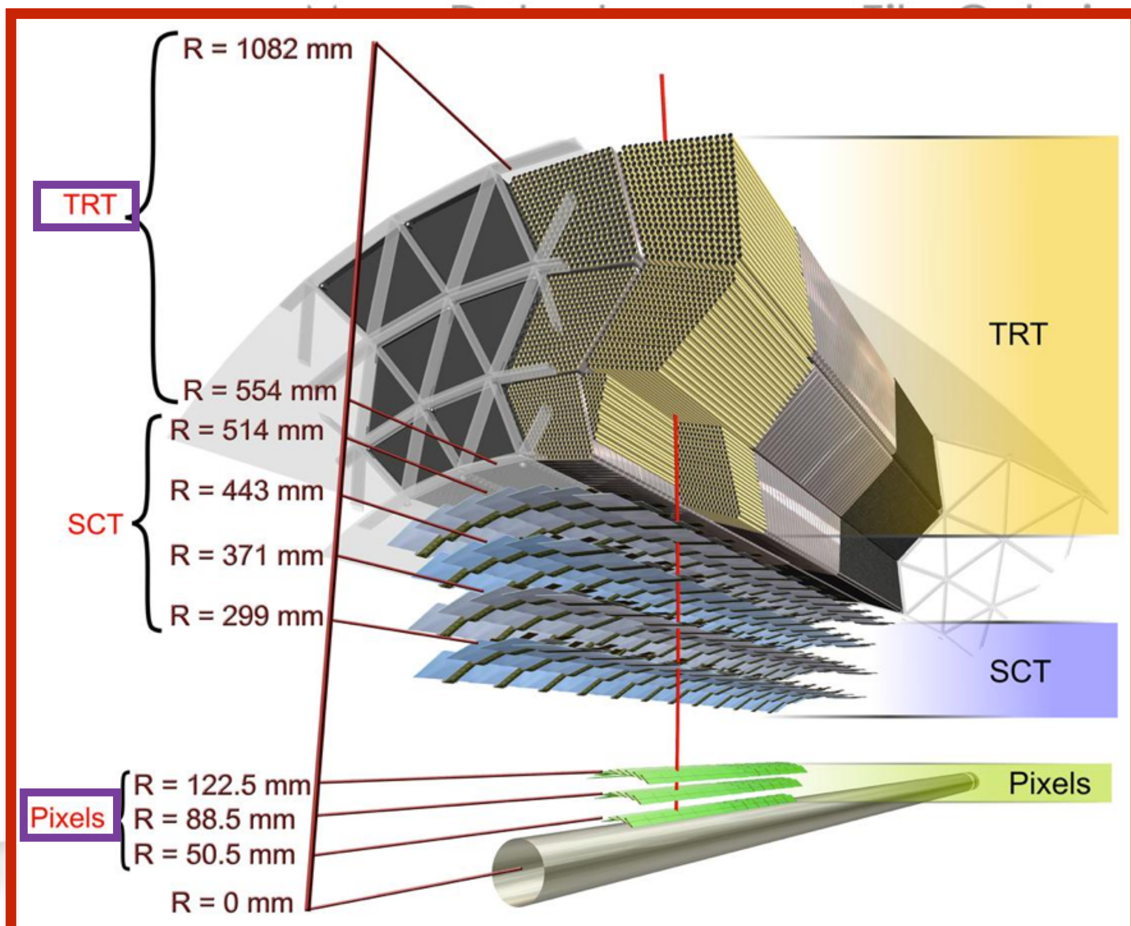
$$-\frac{dE}{dx} = K\frac{Z}{A}g^2\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I} + \frac{k(|g|)}{2} - \frac{1}{2} - \frac{\delta}{2} - B(|n|)\right]$$

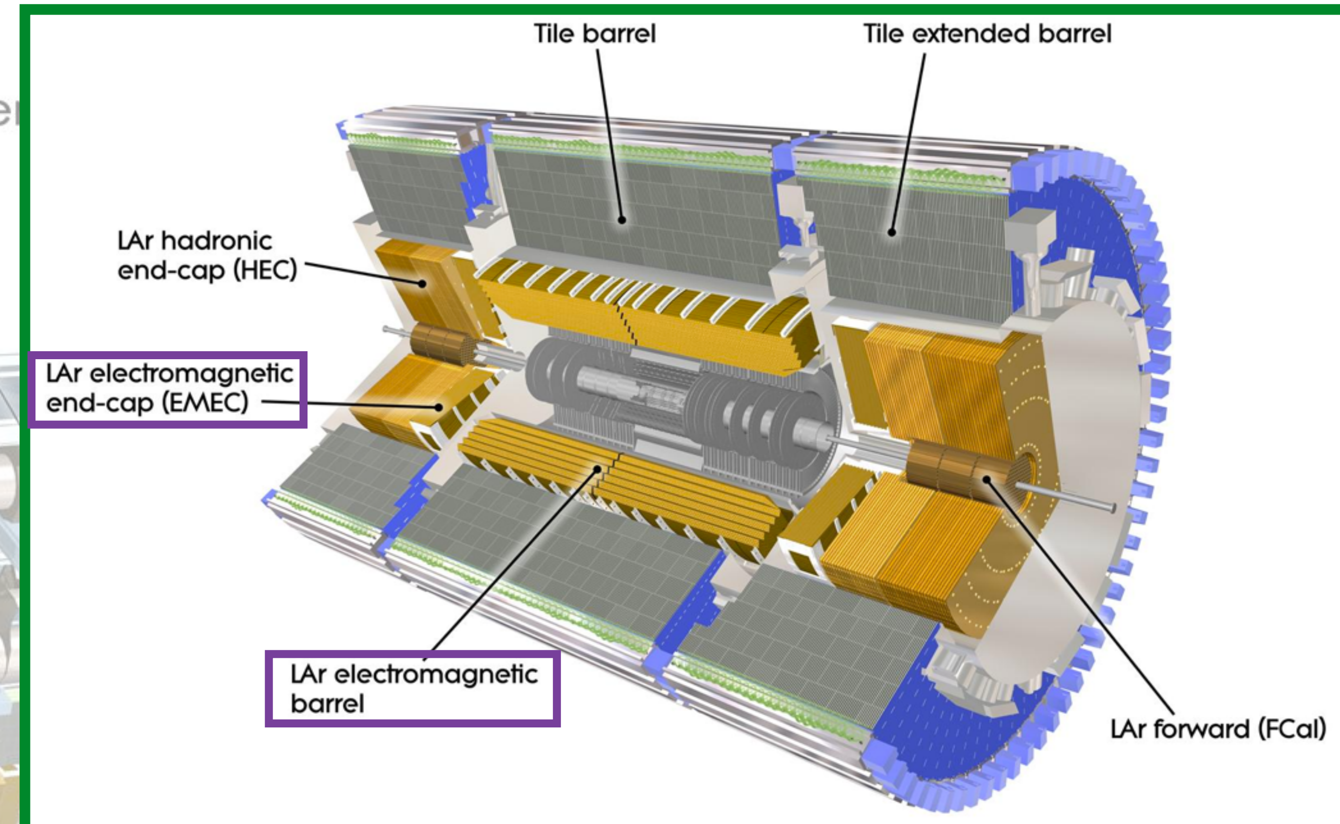
- Latest results using 8 TeV data are presented here

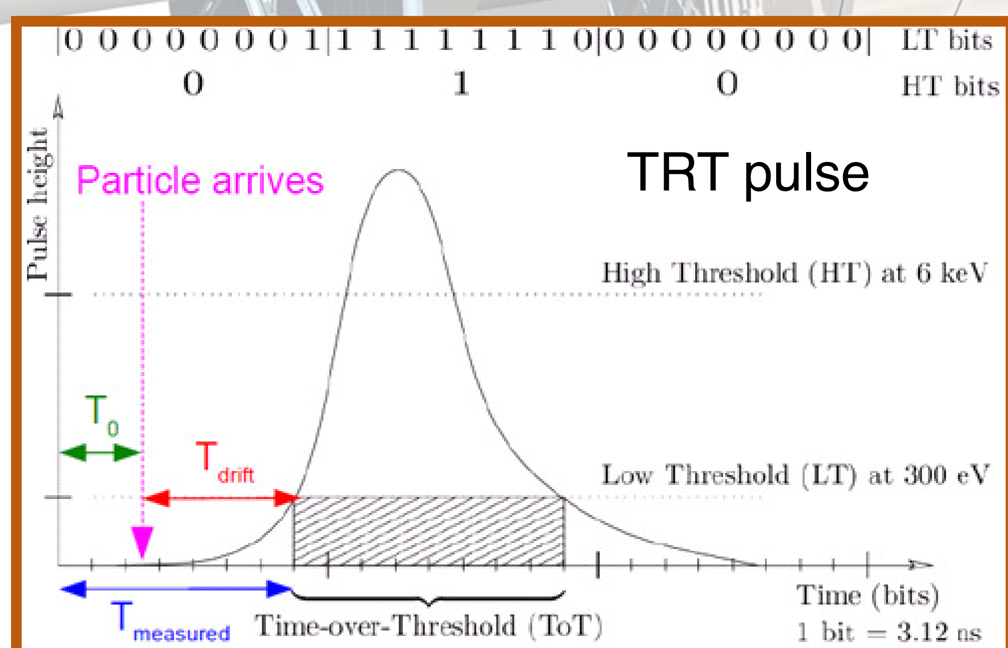
The ATLAS detector

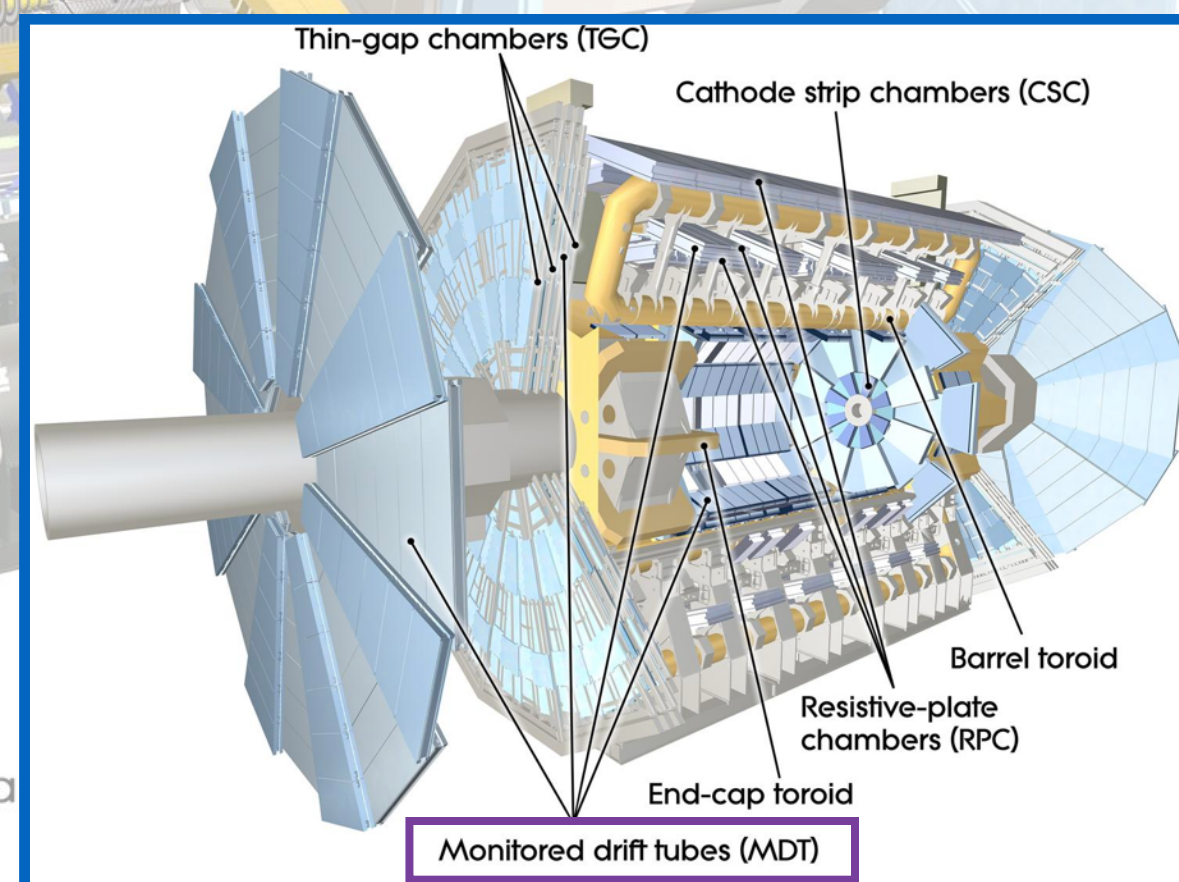


The ATLAS detector









Long-lived multi-charged particles

arXiv:1504.04188 [hep-ex] accepted by EPJ C

- Long-lived multi-charged particles of spin-½ with electric charge in the range
  - $2 < |z| < 6$
- Predicted by:
  - Almost-commutative model [1]:
    - Two extra heavy fermions with $|z| \geq 1$ and expected mass > 100 GeV
  - Walking technicolor model [2]:
    - Three technibaryons with charge z+1, z, z-1
  - Left-right symmetric model [3]:
    - Right-handed version of weak interaction. Requires doubly charged Higgs
- Observation of particles with even charge $|z|=2n$ are of special interest for cosmological models of composite dark matter [4]

[1] J.Phys. A **39** 9657 (2006), arXiv:hep-th/0509213

[2] Phys. Rev. D **71** 0151901 (2005), arXiv:hep-th/0405209

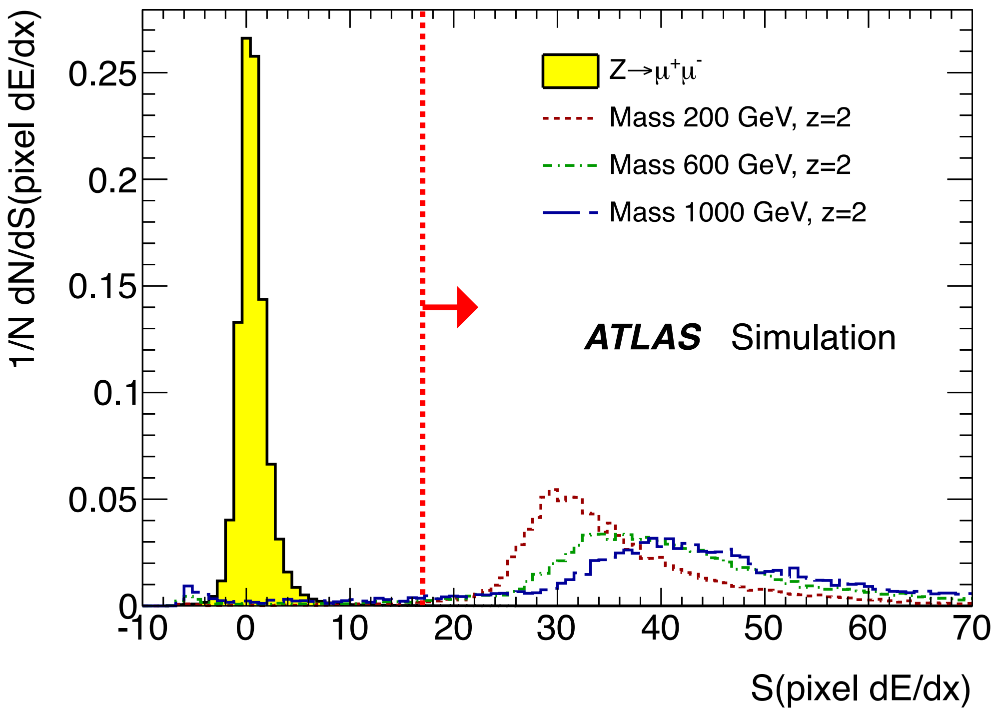
[3] J Phys. Rev. D **11** 566 (1975)

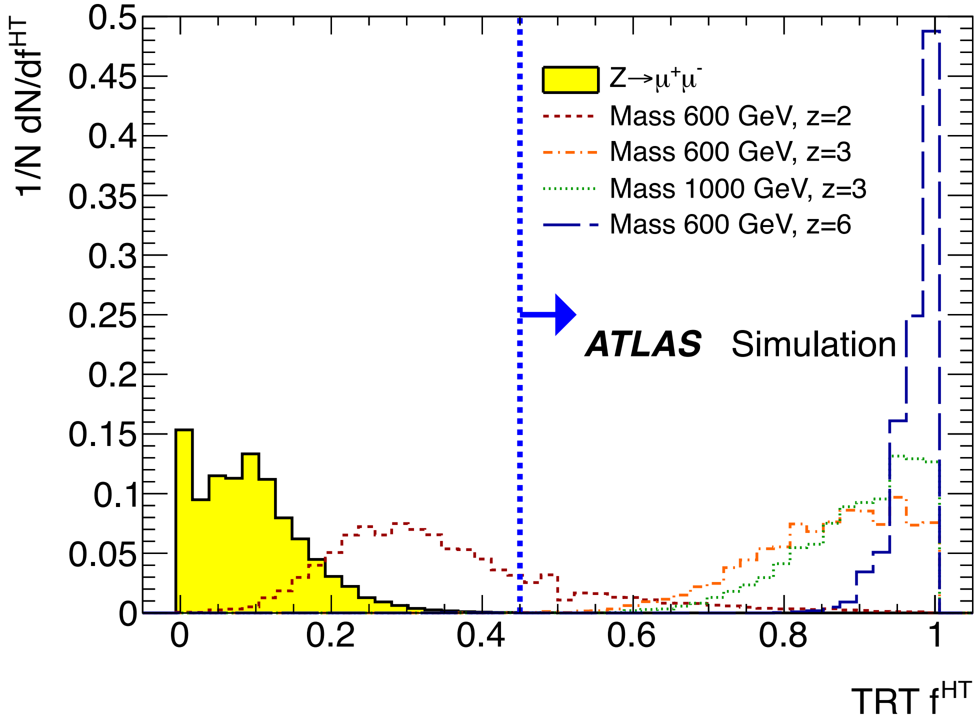
[4] Mod.Phys.Lett. **A26** 2823 (2011), arXiv:1111.2838

Long-lived multi-charged particles

- Search for particles with charge $2 \leq |z| \leq 6$ and mass 50 — 1000 GeV
- Long-lived particles with muon-like signature with anomalous dE/dx
- Events selected with two triggers:
  - Single-muon with $p_T/z > 36$ GeV: sensitive to particles with $\beta > 0.6$
  - Missing $E_T > 80$ GeV: recovers 10% of events missed by single-muon trigger
- Analysis based on dE/dx measurements in Pixel, TRT and MDT, and fraction of TRT high-threshold hits f^{HT} on track
- Selection of candidate tracks:
  - For $|z|=2$, high dE/dx significance in pixel S(pixel dE/dx) is required
  - For $|z|>2$, large fraction f^{HT} is required

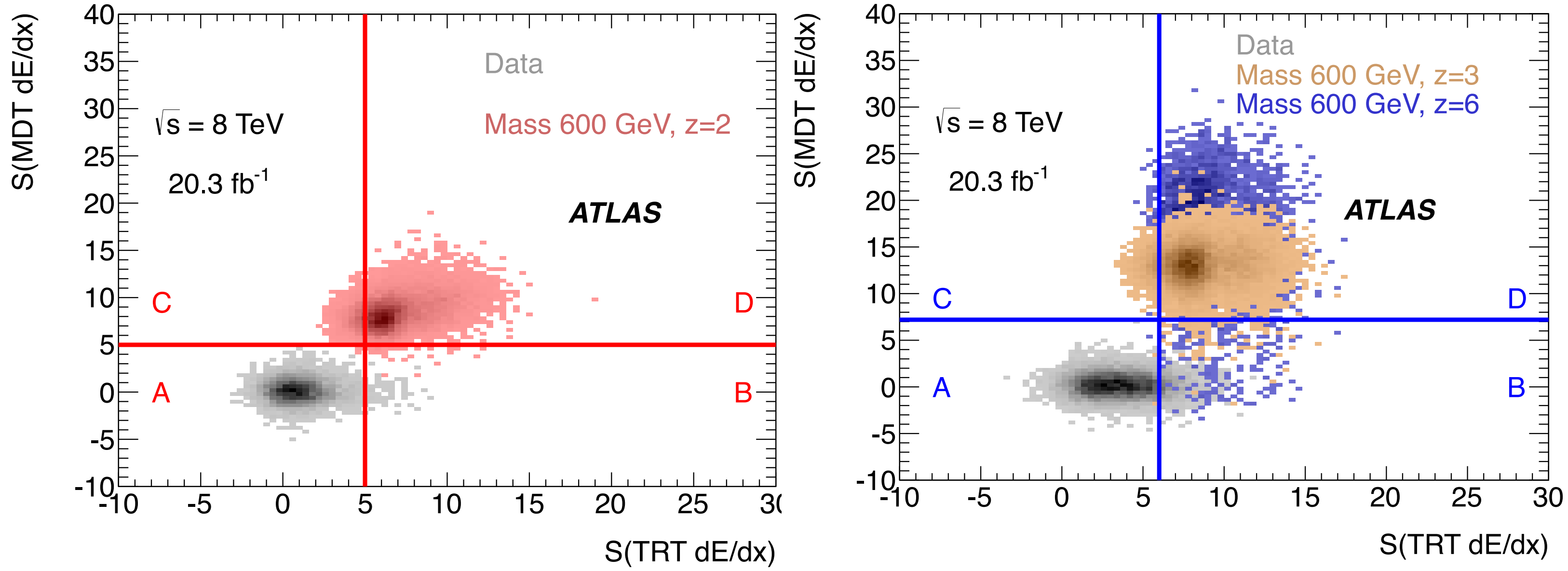
$$S(\mathrm{d}E/\mathrm{d}x) = \frac{\mathrm{d}E/\mathrm{d}x_{\mathrm{track}} - \langle \mathrm{d}E/\mathrm{d}x_{\mu} \rangle}{\sigma(\mathrm{d}E/\mathrm{d}x_{\mu})}$$

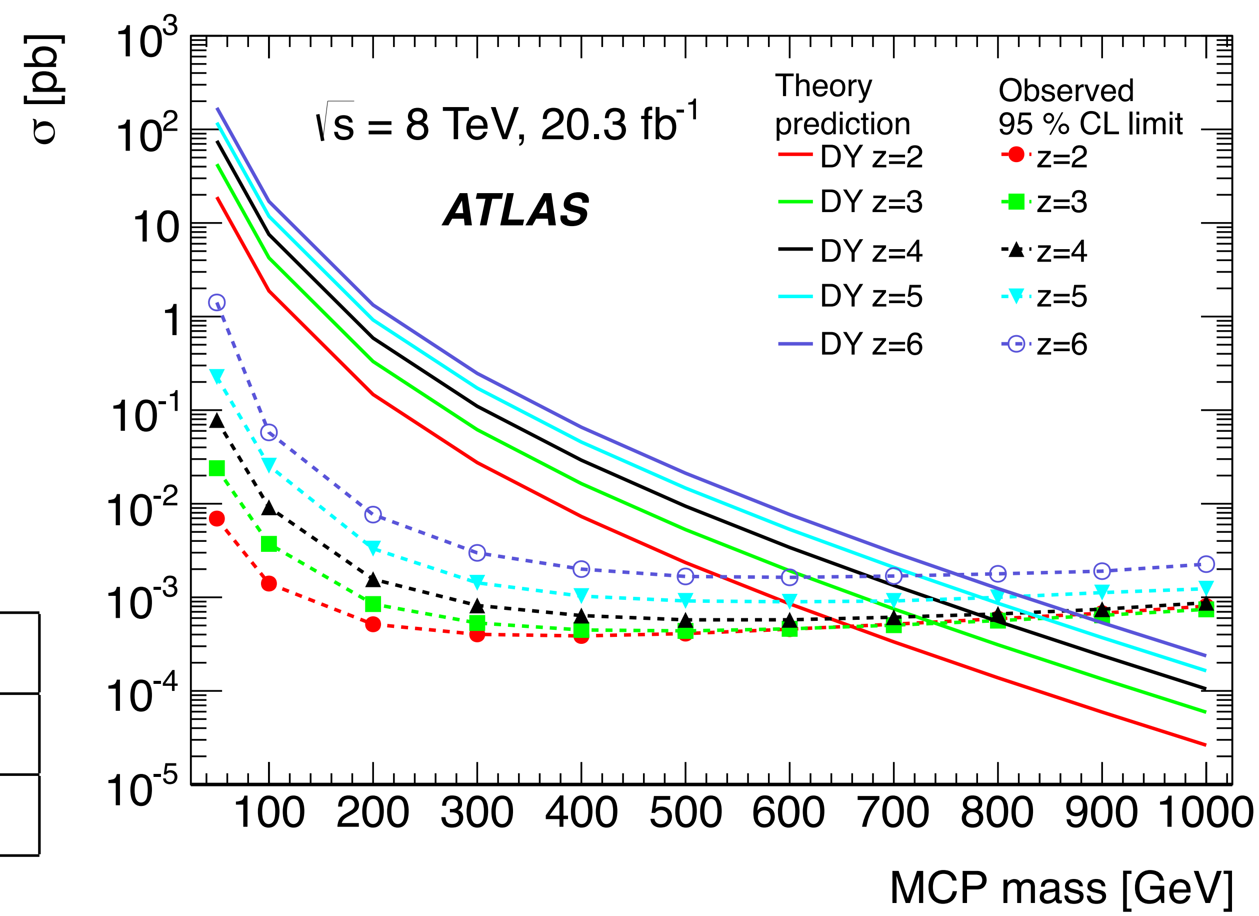




Long-lived multi-charged particles

- Final selection based on dE/dx significance in TRT and MDT
- Data-driven background estimate using ABCD method
- No candidate events observed in signal region
- Upper cross section limits set at 95% confidence level assuming pair production using CLs method*
- Mass exclusion regions obtained for wide ranges of tested masses





Mass exclusion regions [GeV]				
$\|z\| = 2$	$\|z\| = 3$	$\|z\| = 4$	$\|z\| = 5$	$\|z\| = 6$
50–660	50–740	50–780	50–785	50–760

*J. Phys. G: Nucl. Part. Phys. **28** (2002) 2693

Monopoles and objects with large electric charge

To be submitted to PRD (EXOT-2014-16)

- Magnetic monopoles are stable particles
  - Explain charge quantization [1]:
    - Dirac's condition $g = \frac{ne}{2\alpha}$
    - From Dirac's quantization condition: $g = ng_{\mathrm{D}}, \quad g_{\mathrm{D}} = \frac{e}{2\alpha} \approx 68.5e$
  - Predicted by GUT theories and some EW models [2]:
    - GUT: Mass 10^{11} — 10^{13} TeV
    - EW : Mass 4 — 7 TeV, $g=2g_{\mathrm{D}}$
- Scenarios with objects with large electric charge [3]:
  - Strange quark matter
  - Q-balls
  - Micro black hole remnants
- No spin preference: search includes both spin-0 and spin-½ particles

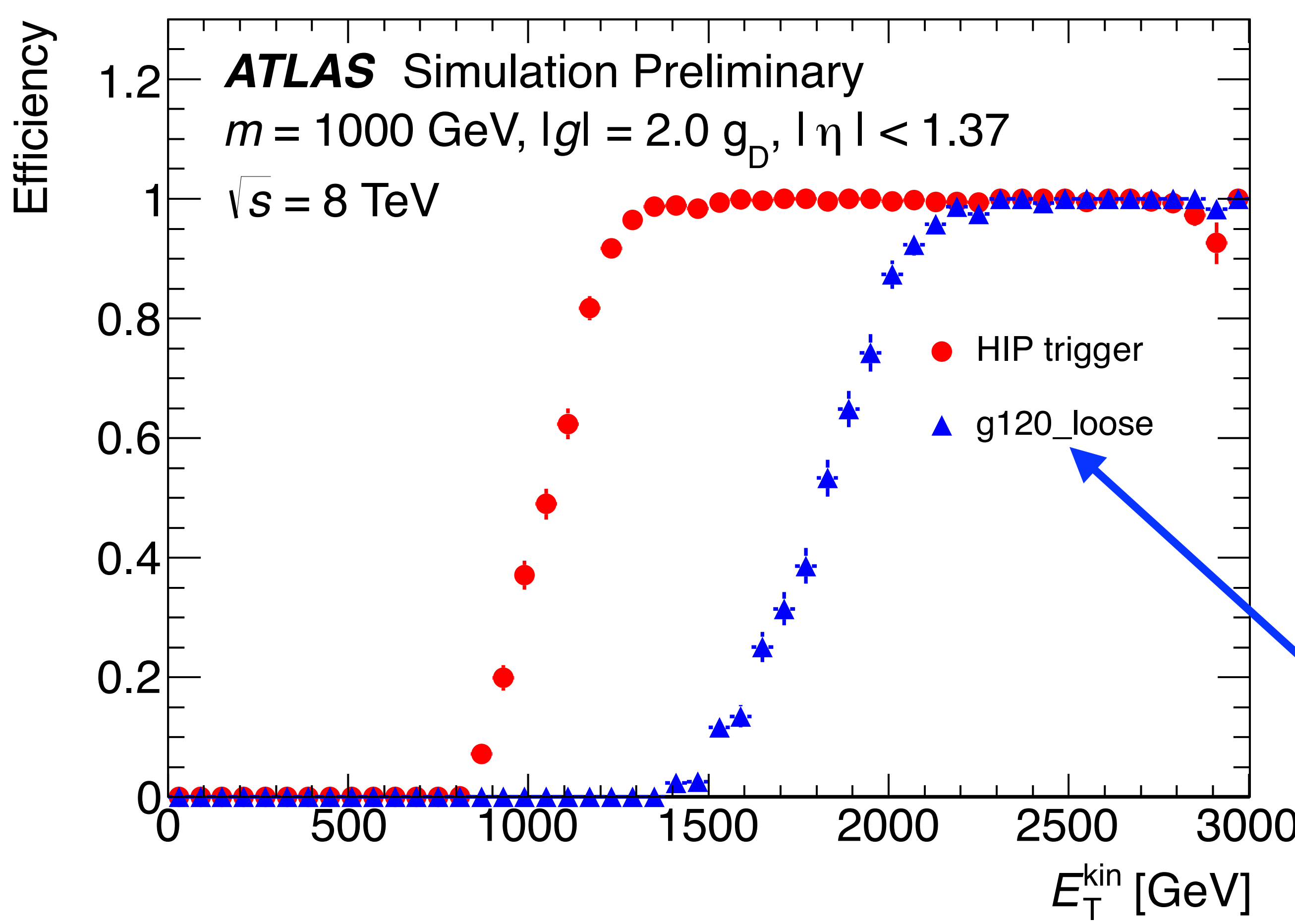
[1] Proc. Roy. Soc. A **133** 60 (1931)

[2] arXiv:1212.3885v6 [hep-ph]

[3] Phys. Rept. **438** 1 (2007), arXiv:0611040 [hep-ph]

Highly ionizing particle (HIP) trigger

- ATLAS trigger system is divided in three levels
  - Level-1: hardware based, uses calorimeter energy deposits and muon spectrometer hits
  - Level-2: reconstruction of regions of interest selected at Level-1
  - Level-3: full event reconstruction

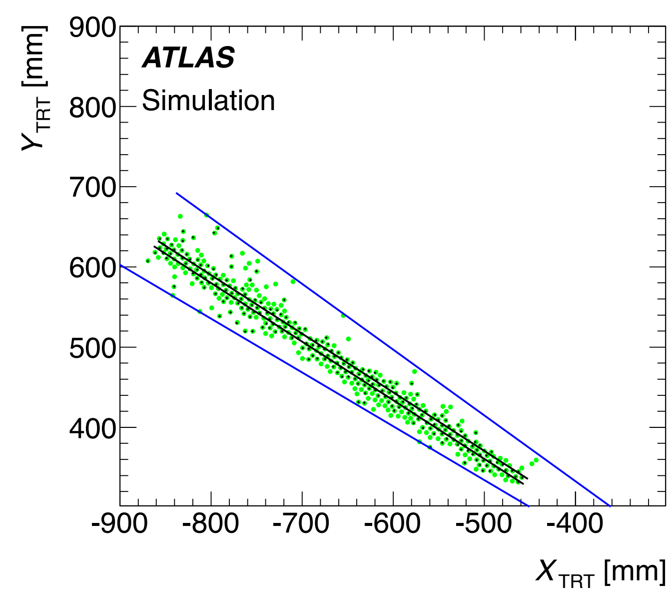


120 GeV photon trigger

- A dedicated Level-2 trigger for HIPs was developed
  - Level-1: $E_T \geq 18$ GeV in LAr EM calorimeter and less than 1 GeV in hadronic calorimeter
  - **Level-2: TRT information in a wedge of size $\Delta\phi = \pm 0.015$ is required**
  - **Requirements on the number and fraction of TRT HT hits are applied**
  - Collected luminosity: 7.0 fb^{-1}
  - Trigger efficiency turn-on determined by Level-1 trigger acceptance
  - Monopoles with $|g| > 1.0 g_D$ accessible for the first time at ATLAS

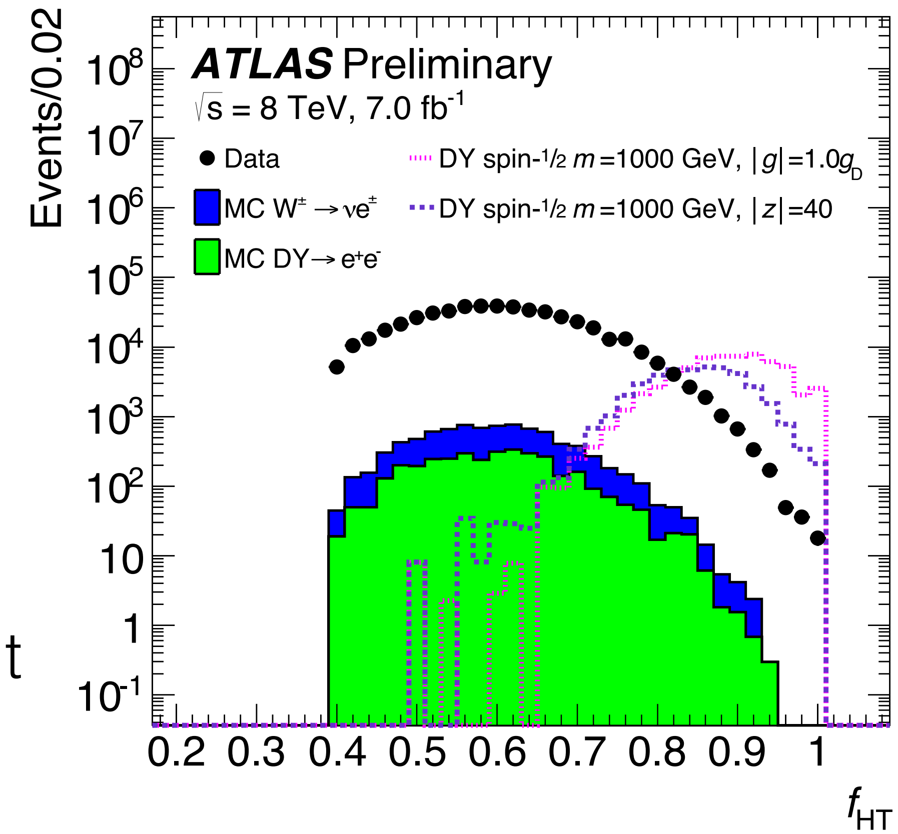
Monopoles and objects with large electric charge

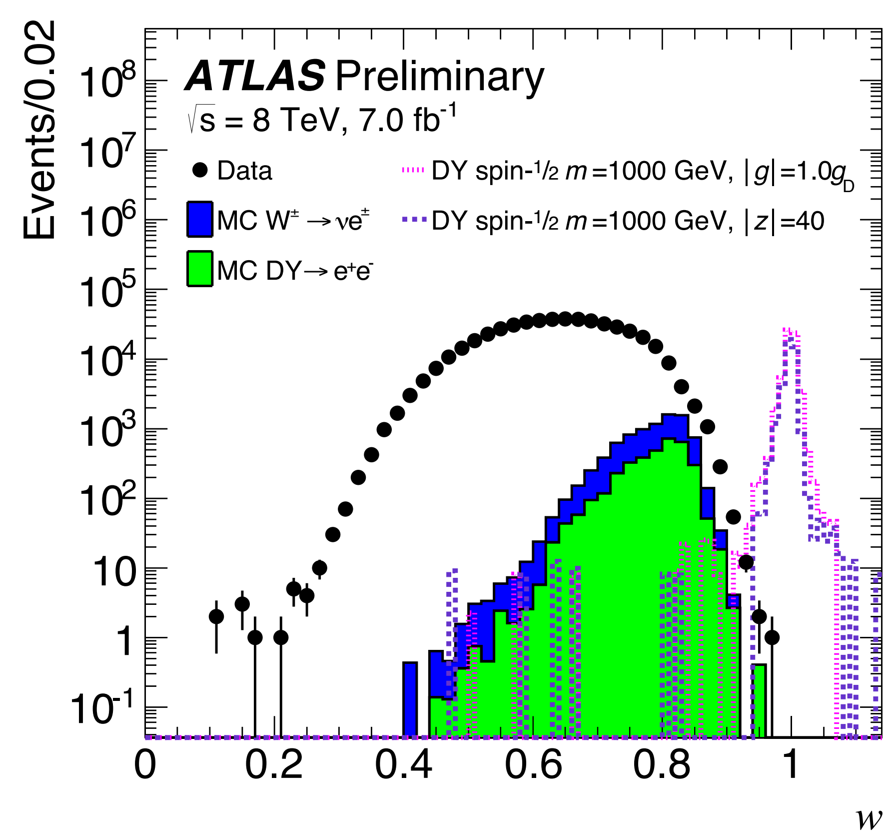
- Search for HIPs in mass range 200 — 2500 GeV
  - $10 \leq |z| \leq 60$
  - $0.5g_D \leq |g| \leq 2.0g_D$
- HIP signatures in ATLAS:
  - Region of high ionization density in TRT
  - Low lateral dispersion in LAr calorimeter energy deposit
- Events must have passed the HIP trigger
- High fraction of TRT HT hits f_{HT} in a narrow region



- Lateral dispersion $w = \frac{\sum_{\text{layers}} w_i}{N_{\text{layers}}}$

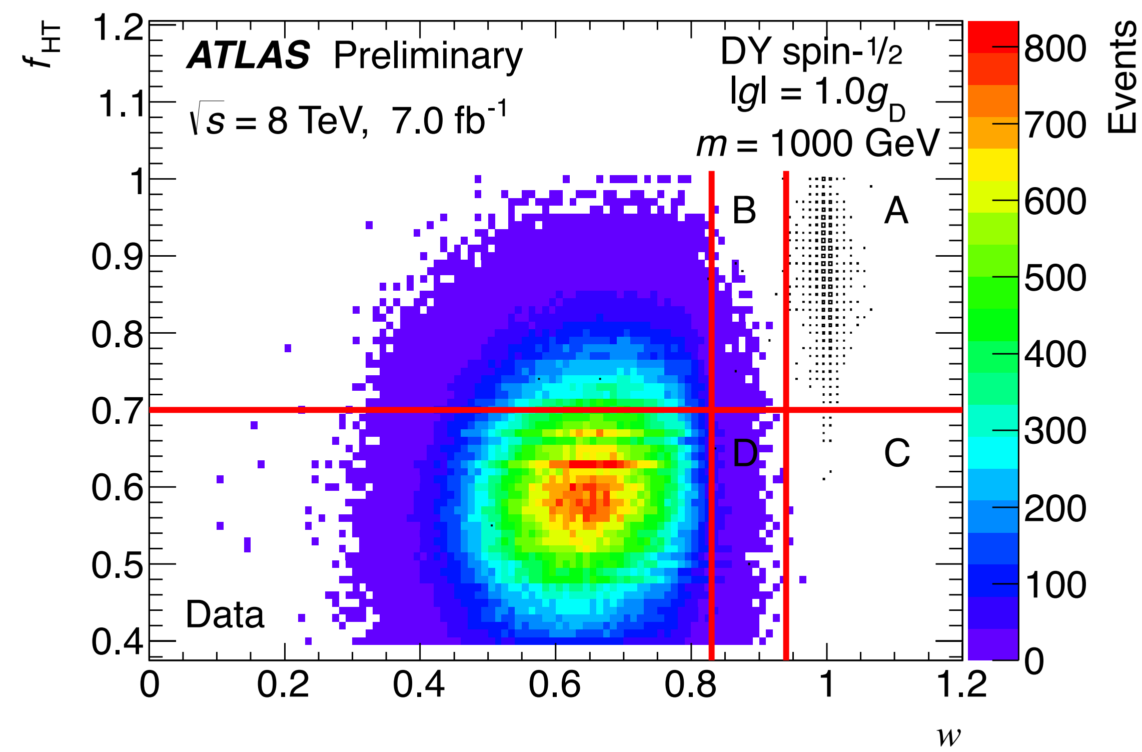
$$w_i = \frac{\sum_{\text{cells in layer } i} E_j}{E_i^{\text{total}}}$$



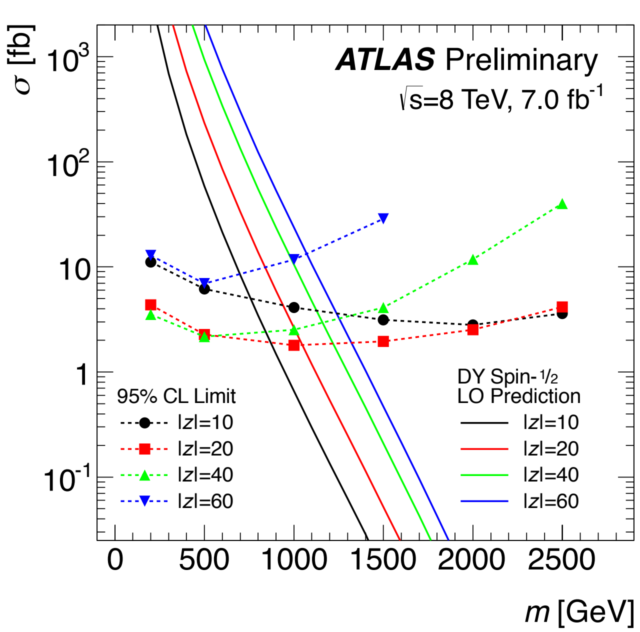


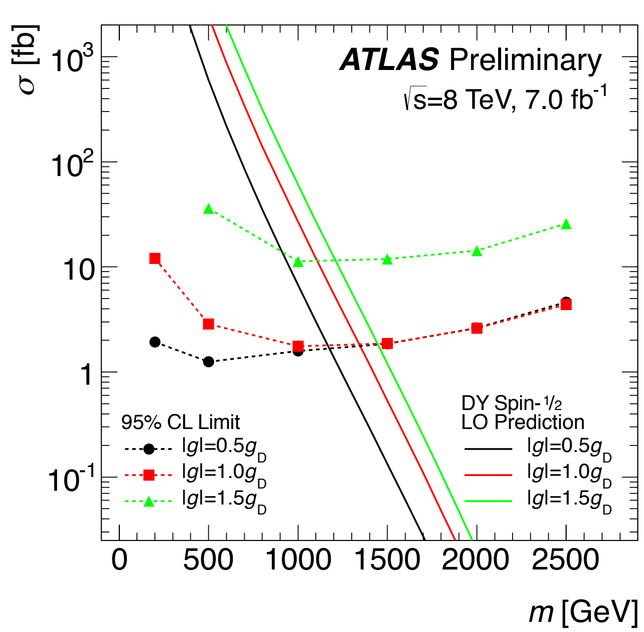
Monopoles and objects with large electric charge

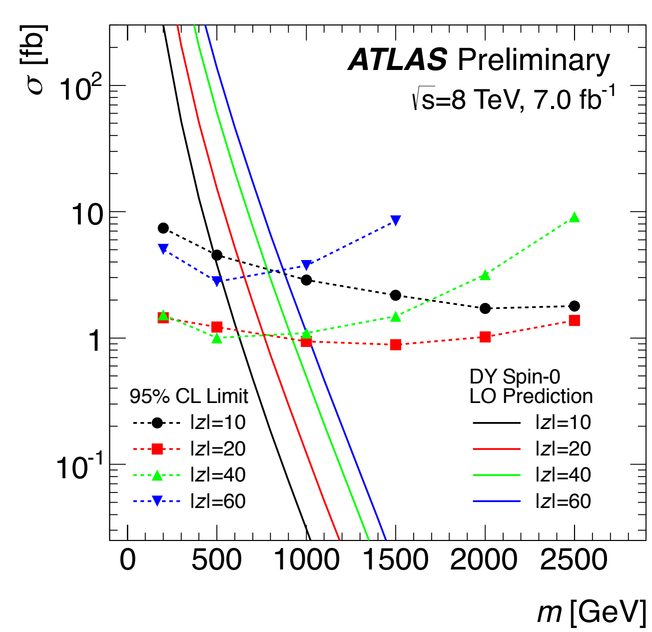
- Data-driven background estimate using ABCD method
- No candidate events observed in signal region
- Model-independent upper cross section limits set to **0.5 fb** for HIPs in fiducial regions of high and uniform event selection efficiency
- Upper cross section limits and lower mass limits set assuming pair production model at 95% confidence level with CLs method
- Results from spin-1/2 extrapolated to spin-0

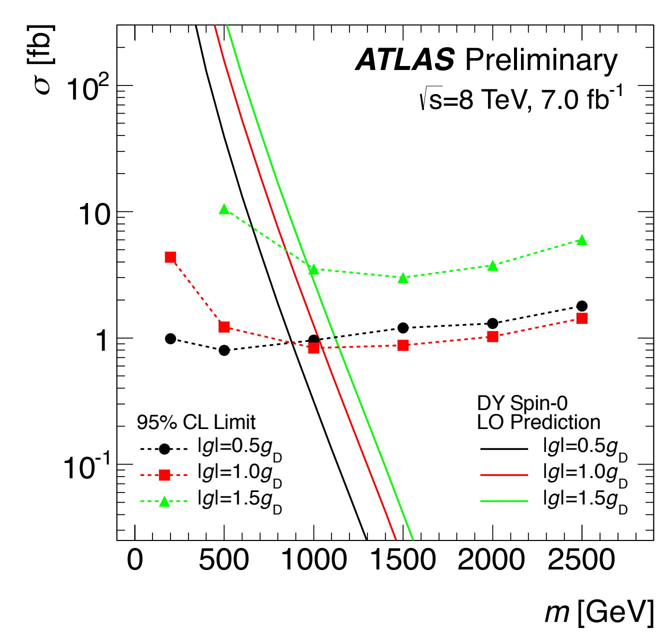


	Drell-Yan Lower Mass Limits [GeV]						
	$\lvert g\rvert = 0.5g_D$	$\lvert g\rvert = 1.0g_D$	$\lvert g\rvert = 1.5g_D$	$\lvert z\rvert = 10$	$\lvert z\rvert = 20$	$\lvert z\rvert = 40$	$\lvert z\rvert = 60$
spin-1/2	1180	1340	1210	780	1050	1160	1070
spin-0	890	1050	970	490	780	920	880









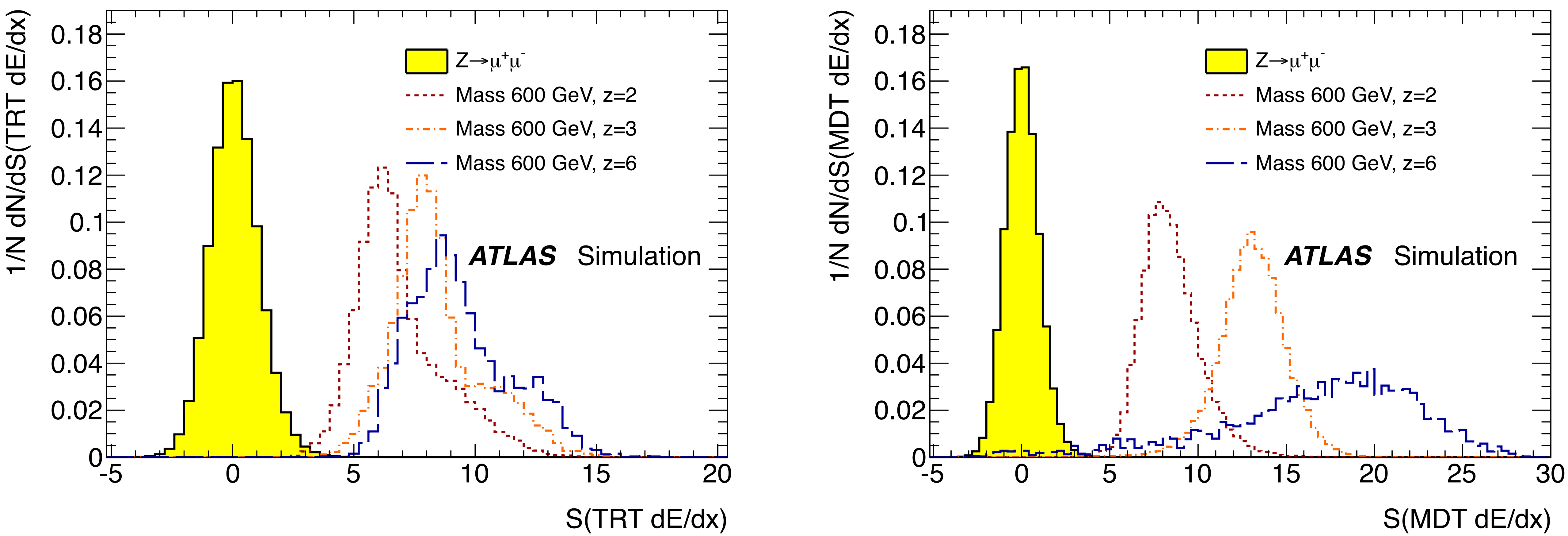
Summary

- Searches for magnetic monopoles and particles with |z|>1 have been performed using LHC *pp* collision data from Run 1.
- Analysis techniques exploit anomalous ionization from monopoles and particles with |z|>1.
- No evidence of such particles has been observed.
- Limits on production cross section have been set assuming simplified Drell-Yan production models. Mass exclusion regions have been obtained.
- Magnetic monopoles and particles with |z|>1 may be the answer (or at least part of it) to fundamental questions:
  - charge quantization
  - the nature of dark matter

Backup slides

Long-lived multi-charged particles

dE/dx significance



$$S(\mathrm{d}E/\mathrm{d}x) = \frac{\mathrm{d}E/\mathrm{d}x_{\mathrm{track}} - \langle \mathrm{d}E/\mathrm{d}x_{\mu} \rangle}{\sigma(\mathrm{d}E/\mathrm{d}x_{\mu})}$$

Long-lived multi-charged particles

Event selection criteria

<table>
<tr><th></th><th></th><th>Trigger and event selection</th><th>Candidate track selection</th><th>Tight and final selections ($z = 2$)</th><th>Tight and final selections ($z \geq 3$)</th></tr>
<tr><td rowspan="2">Requirements</td><td>Single-muon trigger case</td><td>≥ 1 trigger tight muon with $p_T/z > 36$ GeV

≥ 1 reconstructed muon with $p_T/z > 75$ GeV</td><td>Any muon with:

$N_{\text{MDT hits}} \geq 7$
$p_T/z > 40$ GeV
$|\eta| < 2.0$
$N_{\text{SCT hits}} \geq 6$
$N_{\text{TRT hits}} \geq 10$
$|d_0| < 1.5$ mm
$|z_0 \sin\theta| < 1.5$ mm
no other tracks within $\Delta R < 0.01$</td><td rowspan="2">Event passing preselection having a muon with:

$S(\text{pixel } dE/dx) > 17$
$S(\text{MDT } dE/dx) > 5$
$S(\text{TRT } dE/dx) > 5$</td><td rowspan="2">Event passing preselection having a muon with:

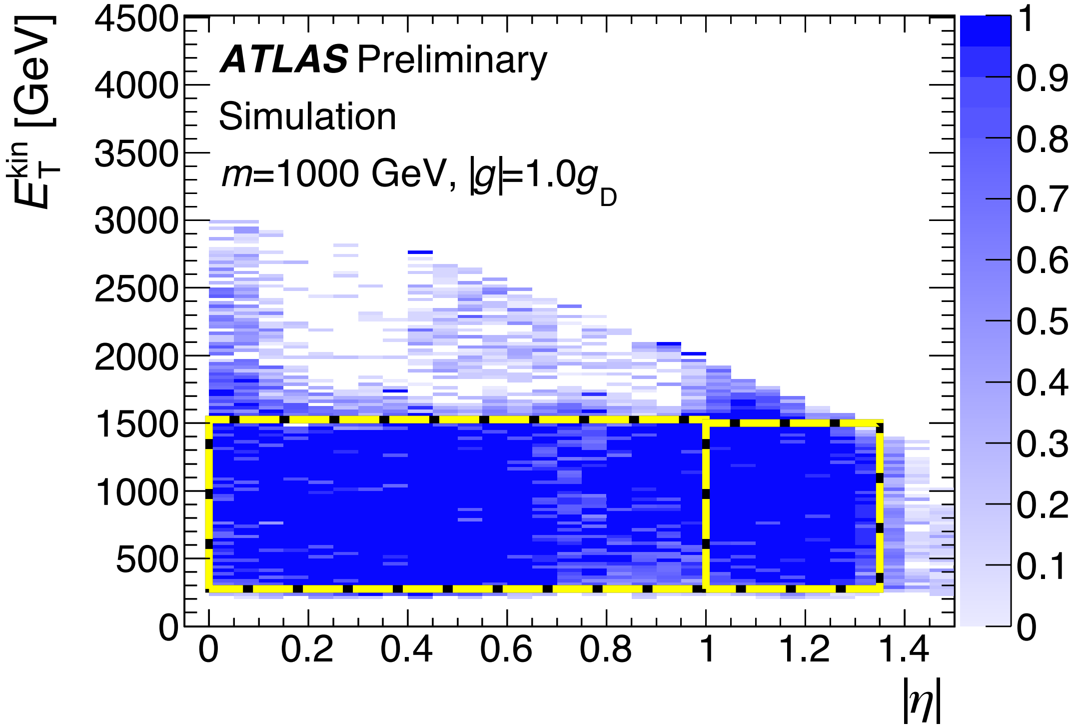
$f^{\text{HT}} > 0.45$
$S(\text{MDT } dE/dx) > 7.2$
$S(\text{TRT } dE/dx) > 6$</td></tr>
<tr><td>E_T^{miss} trigger case</td><td>trigger $E_T^{\text{miss}} > 80$ GeV

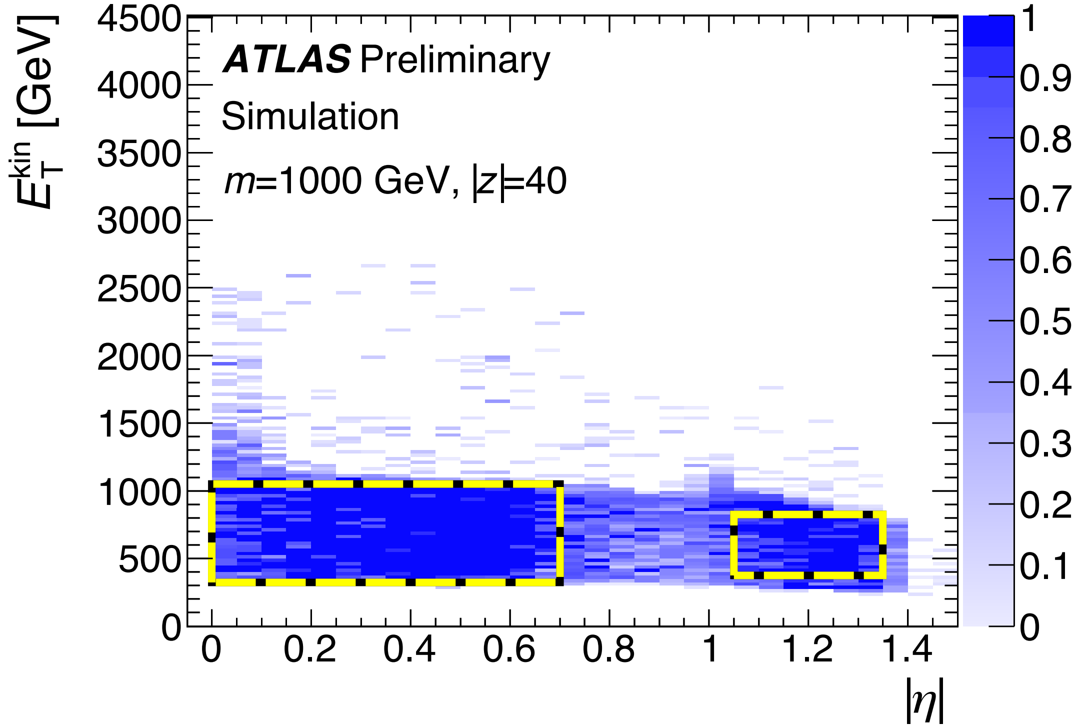
≥ 1 reconstructed muon with $p_T/z > 60$ GeV</td><td>Any muon with:

$N_{\text{MDT hits}} \geq 7$
$p_T/z > 30$ GeV
$|\eta| < 2.0$
$N_{\text{SCT hits}} \geq 6$
$N_{\text{TRT hits}} \geq 10$
$|d_0| < 1.5$ mm
$|z_0 \sin\theta| < 1.5$ mm
no other tracks within $\Delta R < 0.01$</td></tr>
</table>

Monopoles and objects with large electric charge

Fiducial regions

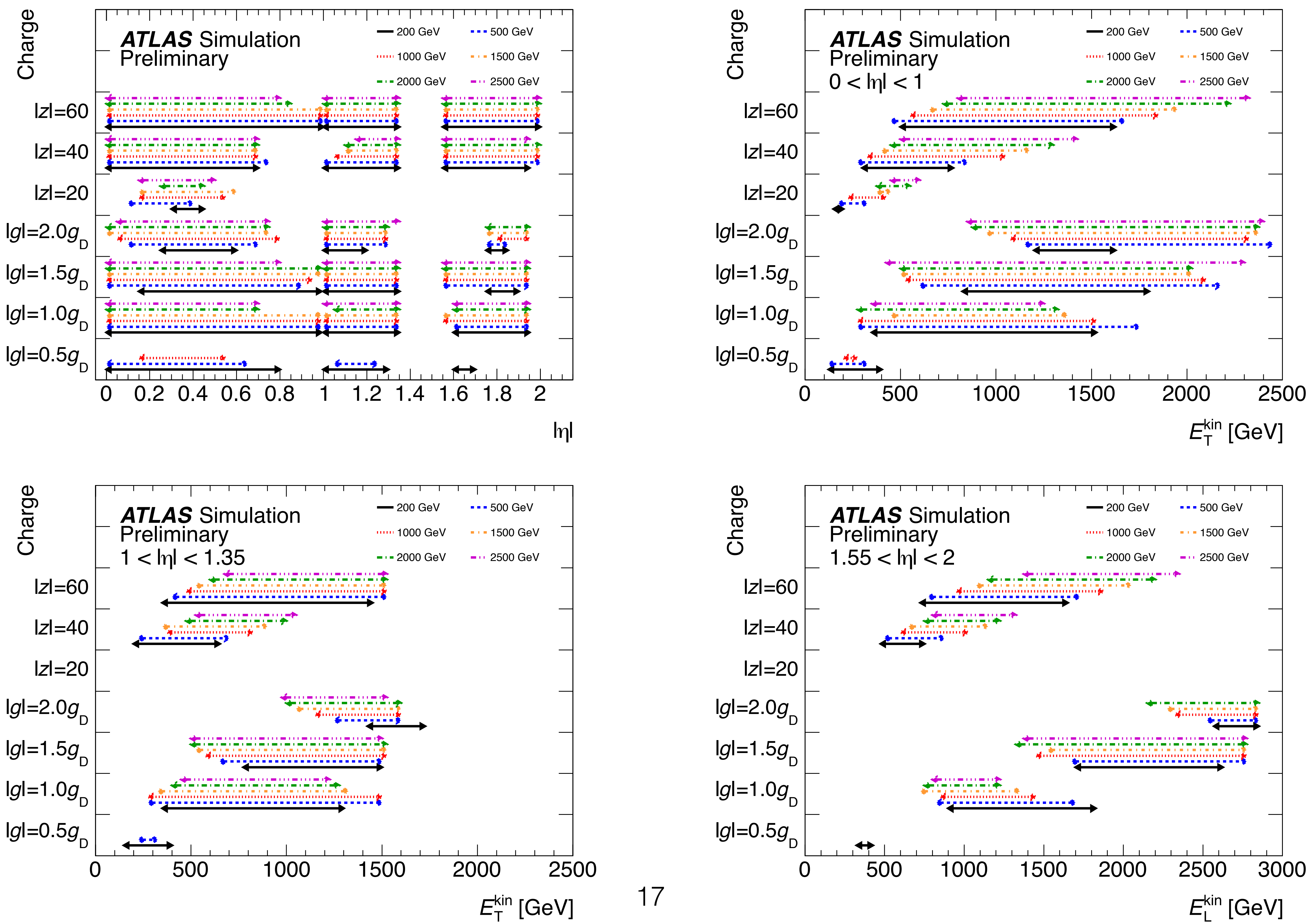




- Defined as regions of high and uniform event selection efficiency in E^{kin} vs. |η|
- Obtained using single particle samples.
- Largest rectangle with
  - average selection efficiency > 90%
  - standard deviation < 12.5%
- To account for detector geometry, three fiducial regions are defined in |η|: |η|<1, 1< |η|<1.35 and 1.55< |η|<2

Monopoles and objects with large electric charge

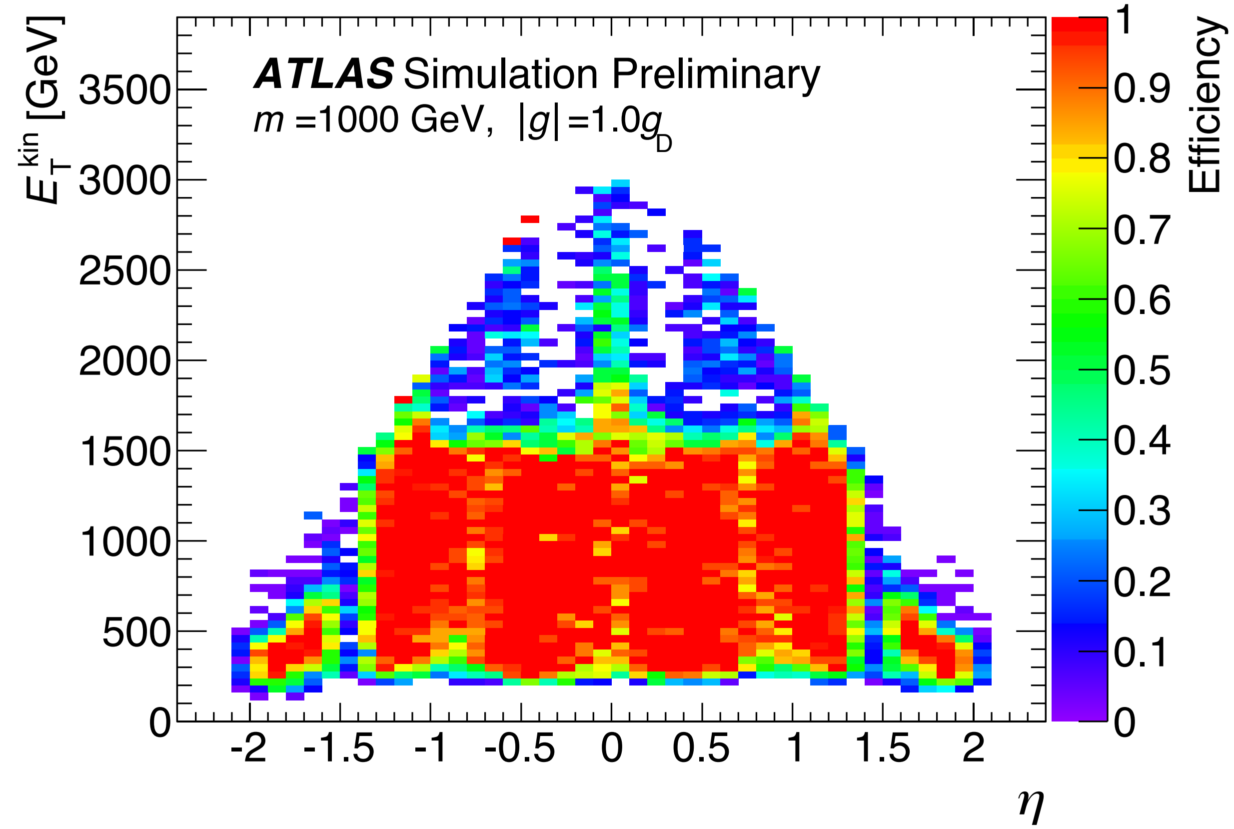
Fiducial regions



Monopoles and objects with large electric charge

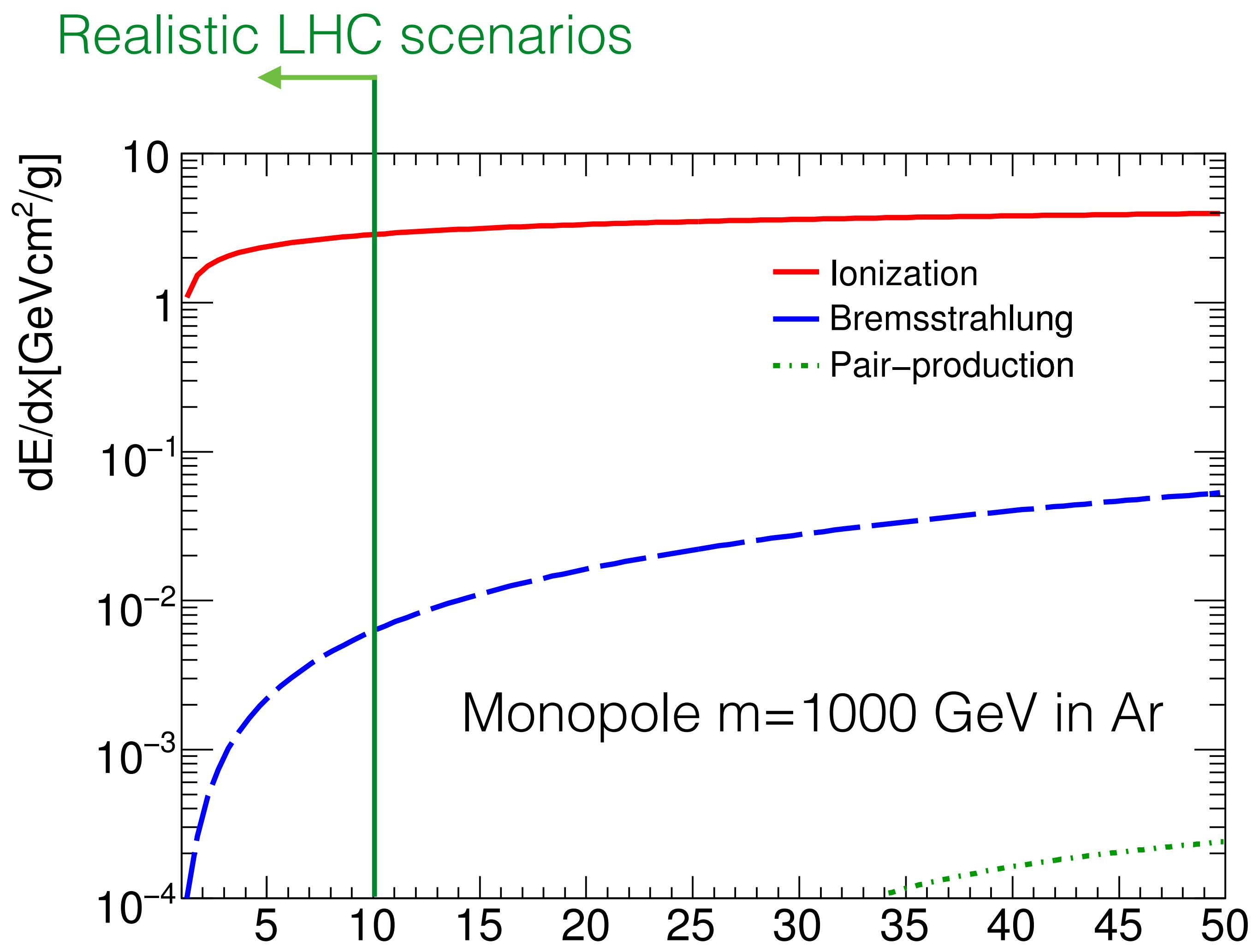
Extrapolation to spin-0

- Based on event selection efficiency maps in E_T^{kin} vs. η space
- Only 4-vectors of spin-0 HIPs produced with Drell-Yan model are needed
- A systematic uncertainty is assessed to account for the use of the extrapolation method instead of full ATLAS simulation of spin-0 HIPs



Energy losses by monopoles

- Energy losses dominated by ionization.
- Large numbers of energetic δ-rays are produced.
- Bremsstrahlung and pair production can be safely ignored in the simulation.



S.P. Ahlen, Phys. Rev. D14, 2935 (1976); D17, 229 (1978); Rev. Mod. Phys. 52, 121 (1980).

$$\frac{dE_{\rm rad}}{dx} = \frac{16}{3}\frac{Z^2}{137}\frac{z^4e^4}{M_{\rm mp}} \longrightarrow \frac{dE_{\rm rad}}{dE_{\rm coll}} = \frac{4}{3\pi}\frac{Zz^2}{137}\frac{m_e}{M_{\rm mp}}\frac{1}{\ln[\cdots]}, \qquad \beta \ll 1$$

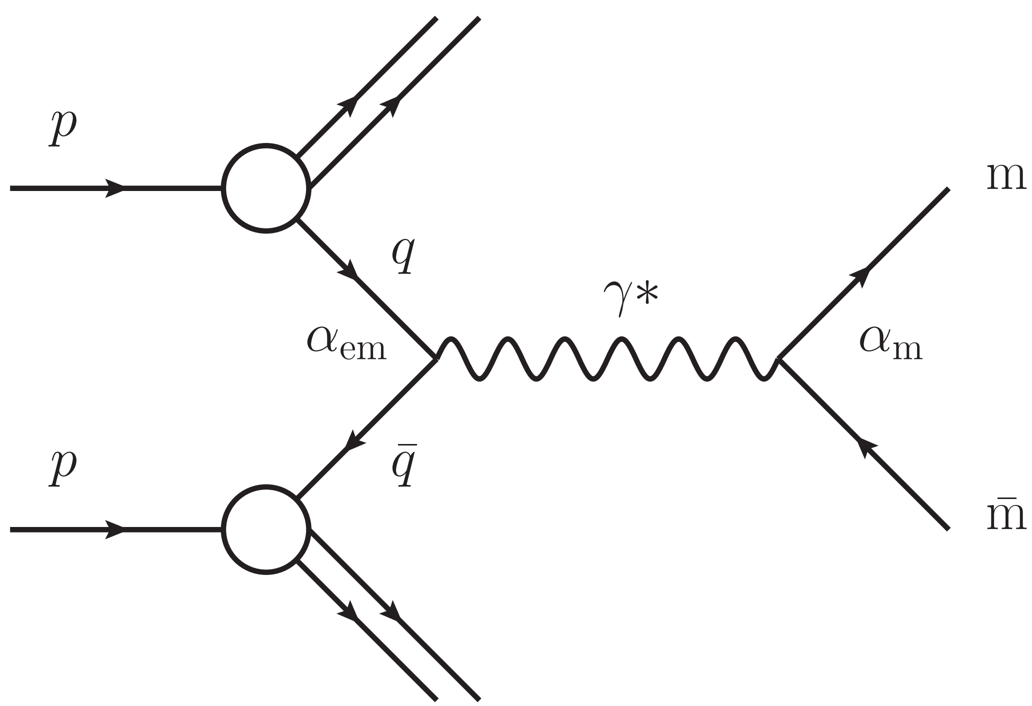
$$\frac{dE_{\rm rad}}{dx} = \frac{16}{3}\frac{Z^2}{137}\frac{z^4e^4}{M_{\rm mp}}\gamma\ln\left(\frac{233M_{\rm mp}}{Z^{1/3}m_e}\right) \longrightarrow \frac{dE_{\rm rad}}{dE_{\rm coll}} = \frac{4}{3\pi}\frac{Zz^2}{137}\frac{m_e}{M_{\rm mp}}\gamma\ln\left(\frac{233M_{\rm mp}}{Z^{1/3}m_e}\right), \qquad \gamma \gg 1$$

$g_D = 68.5e$!

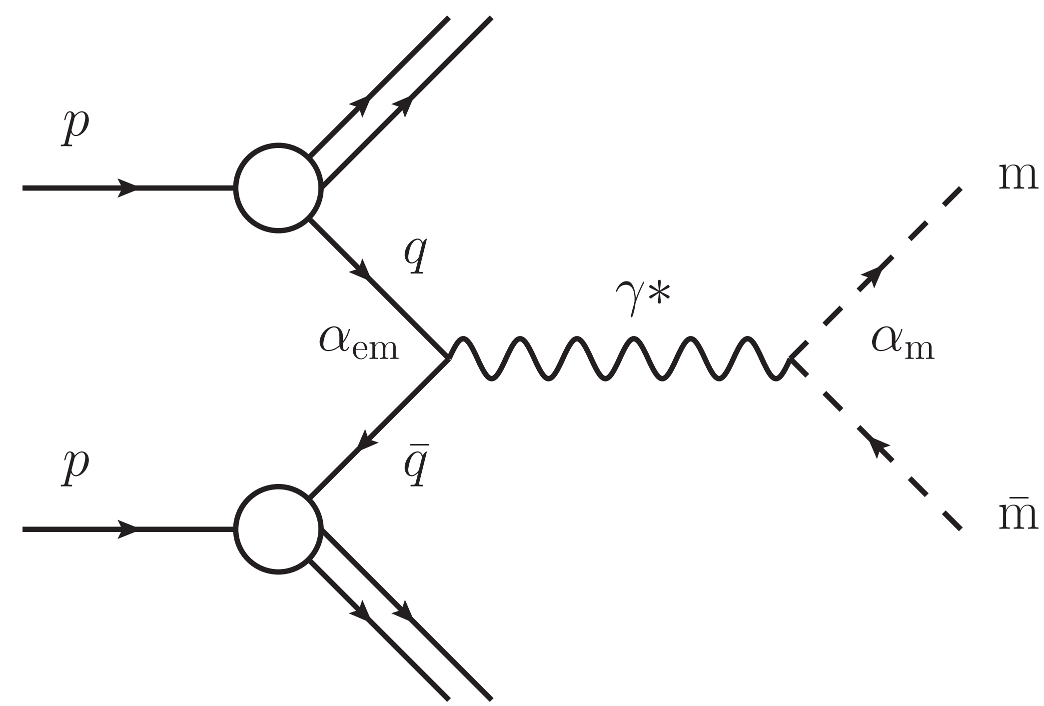
Monopoles and objects with large electric charge

Drell-Yan production

Spin-1/2



Spin-0



- Magnetic coupling: in analogy to electric coupling

$$\alpha = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c} \longrightarrow \alpha_{\mathrm{m}} = \frac{\mu_0}{4\pi}\frac{g^2}{\hbar c}$$

$$\alpha_{\mathrm{m}} = \frac{\mu_0}{4\pi}\frac{g^2}{\hbar c} \approx 34.24 > 1$$ (for n=1)