A search for magnetic monopoles and exotic long-lived particles with large electric charge at ATLAS

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ATLAS EXPERIMENT

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Highly ionizing particles (HIPs)

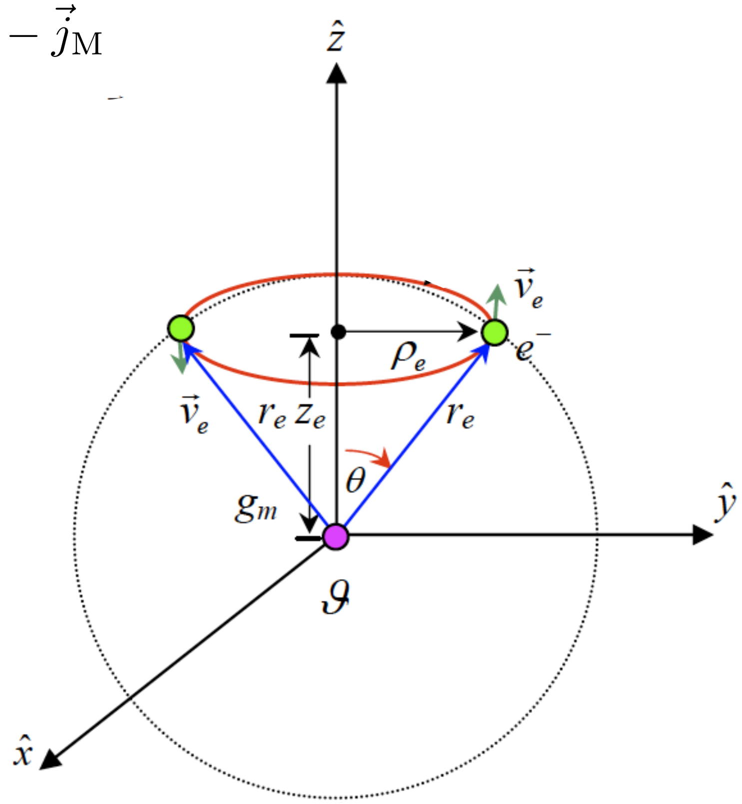
- Magnetic monopoles
  - Enforcing symmetries

$$\vec{\nabla}\cdot\vec{E}=\rho_{\mathrm{E}},\quad \vec{\nabla}\times\vec{B}=\frac{\partial\vec{E}}{\partial t}+\vec{j}_{\mathrm{E}}$$
$$\vec{\nabla}\cdot\vec{B}=0,\quad \vec{\nabla}\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}$$

$$\vec{\nabla}\cdot\vec{E}=\rho_{\mathrm{E}},\quad \vec{\nabla}\times\vec{B}=\frac{\partial\vec{E}}{\partial t}+\vec{j}_{\mathrm{E}}$$
$$\vec{\nabla}\cdot\vec{B}=\rho_{\mathrm{M}},\quad \vec{\nabla}\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}-\vec{j}_{\mathrm{M}}$$

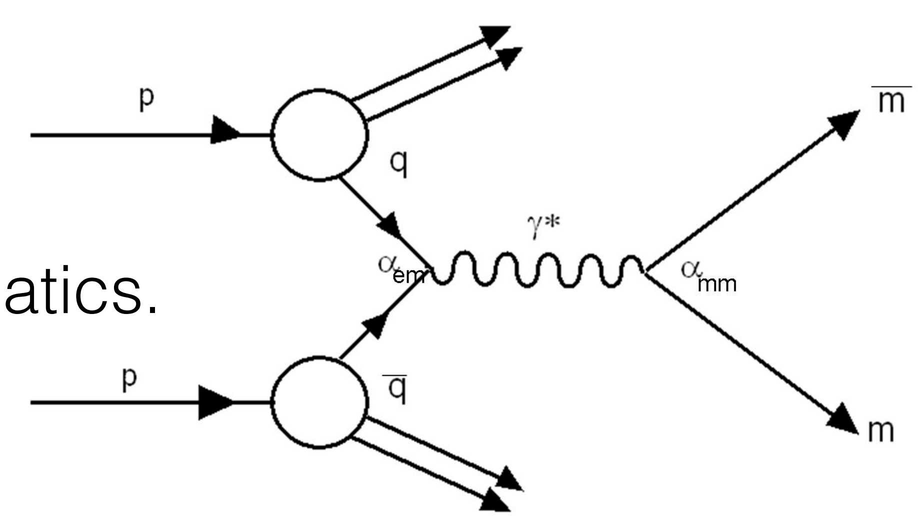
  - Understanding charge quantization (Dirac 1931)

$$\frac{q_e q_m}{\hbar c}=\frac{n}{2}\rightarrow\quad g_D=\frac{\hbar c}{2e}\rightarrow\quad \frac{g_D}{e}=\frac{1}{2\alpha_e}\approx 68.5$$



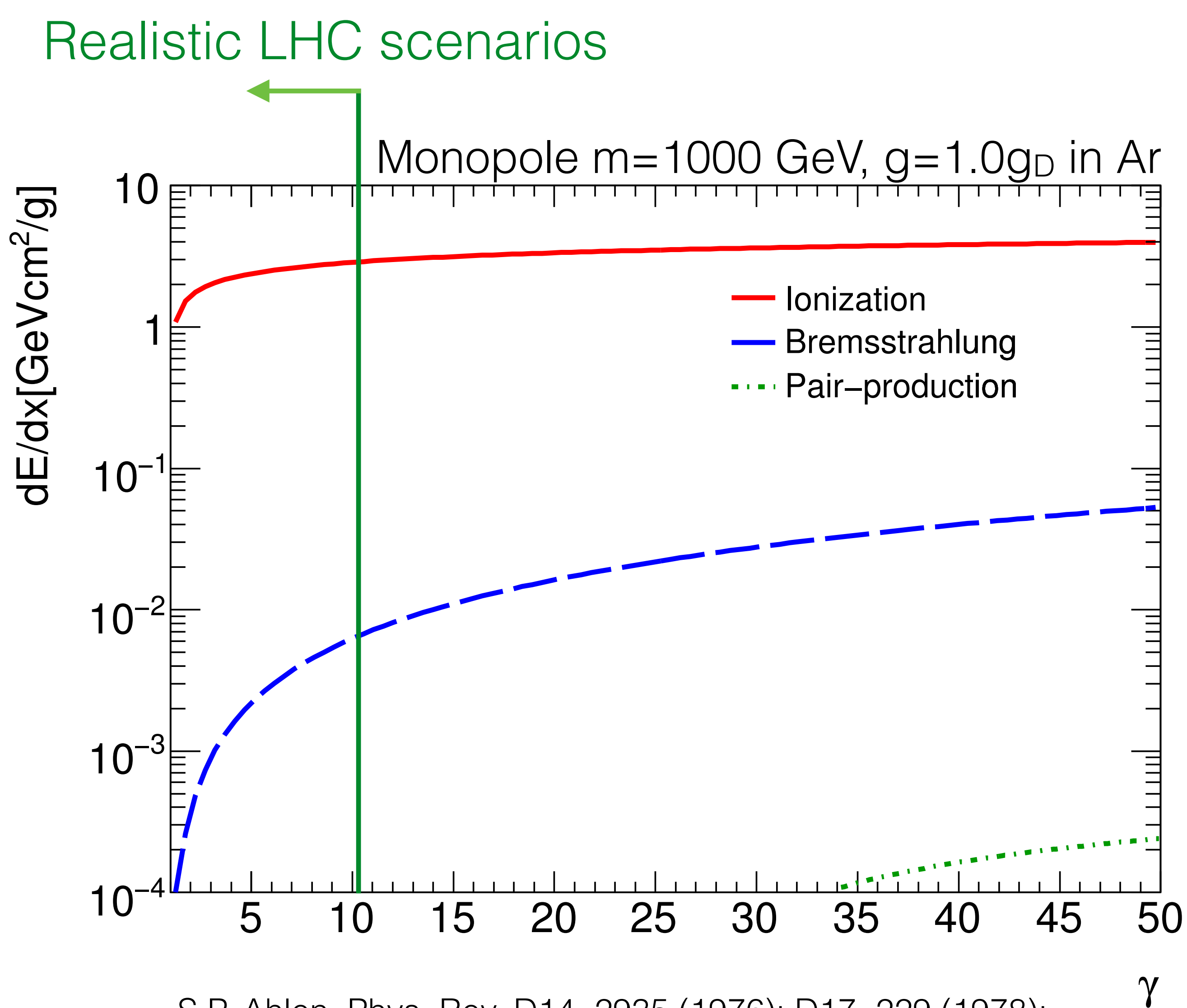
- Highly electrically charged objects (HECOs)
  - Strangelets
  - Q-balls
  - Micro black hole remnants

- Production mechanism
  - Production mechanism at LHC energies is poorly understood. Drell-Yan model gives reasonable kinematics.
  - No preference on spin of HIP.



Energy deposition by HIPs

- Ionization is the dominant mechanism of energy loss for HIPs of mass near TeV scale.
- Large number of energetic δ-electrons produced.
- Energy deposition of magnetically charged particles differs from that of electrically charged particles.



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

HECO

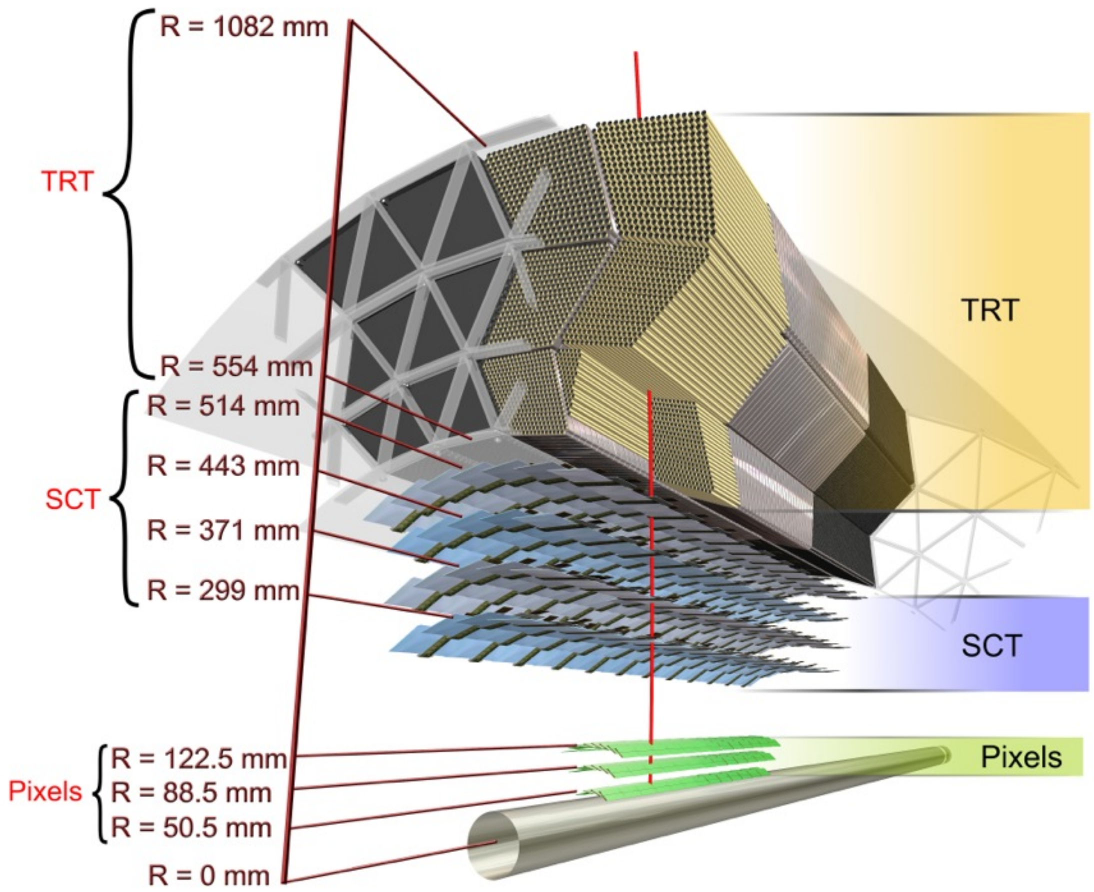
$$-\frac{dE}{dx} = K\frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I} - \beta^2 - \frac{\delta}{2}\right]$$

Monopole

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

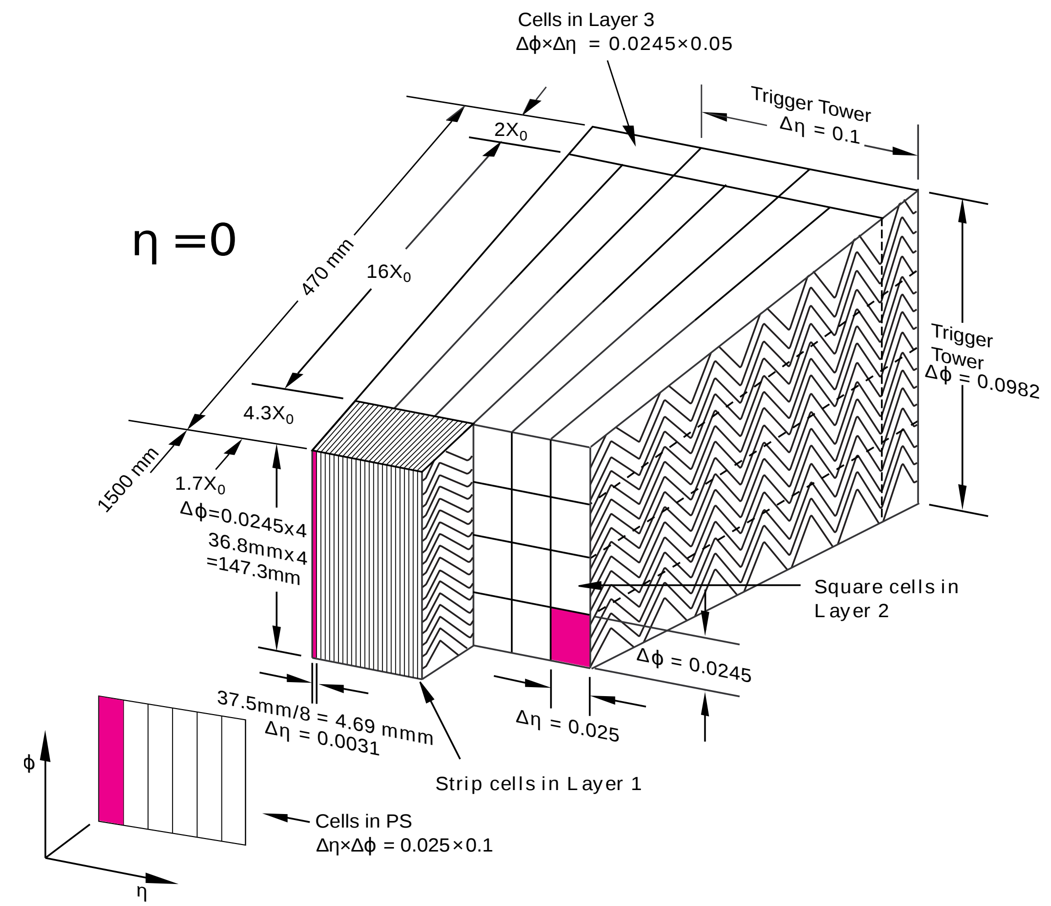
The ATLAS detector and HIP signatures

Transition Radiation Tracker (TRT)



- Two energy deposition thresholds:
  - Low threshold (LT) for tracking (200 eV)
  - High threshold (HT) for electron ID (6 keV)
- HIP ionization in the TRT exceeds the high level threshold producing HT hits.
- δ-electrons propagate in one or two straws depositing a few keV and producing TRT HT hits.

LAr electromagnetic calorimeter



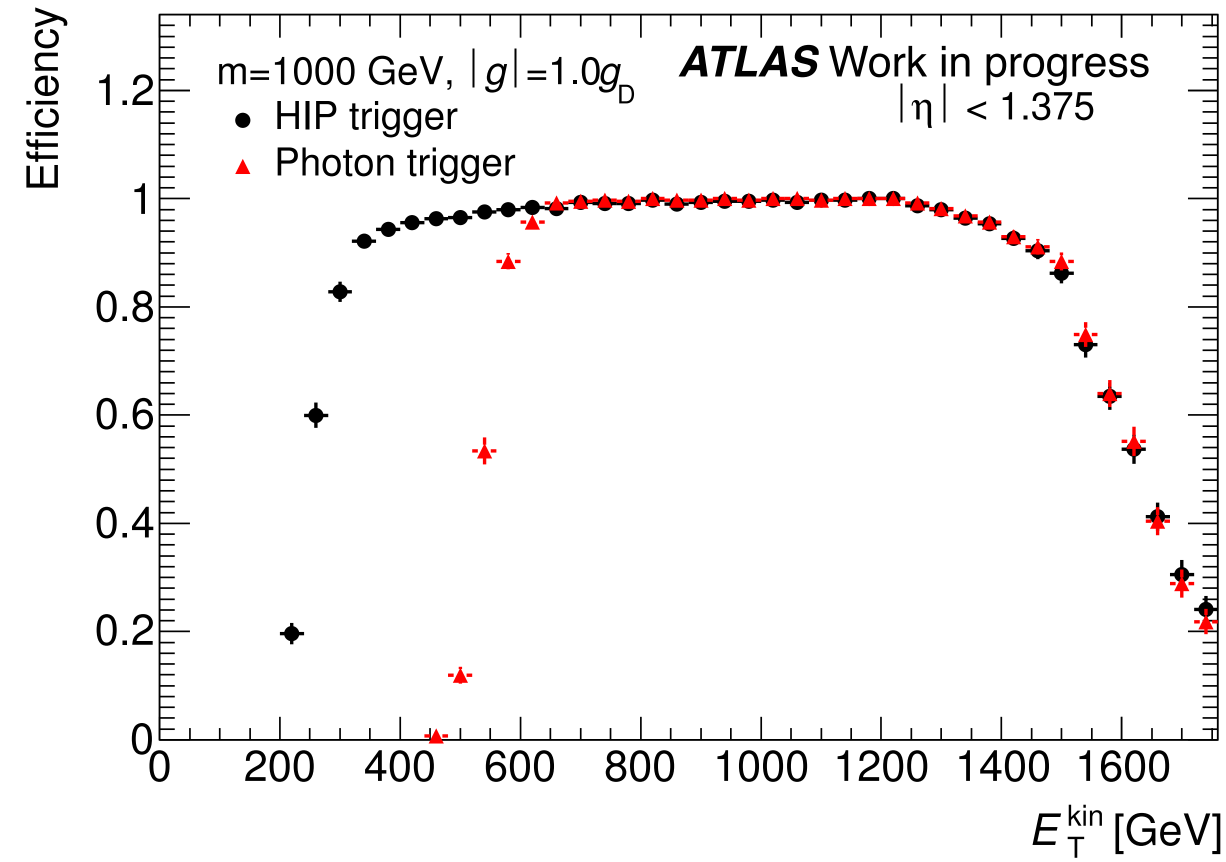
- Four layers varying in depth and granularity.
- Low lateral dispersion in calorimeter cluster due to absence of electromagnetic cascade.
- HIPs stop early in the calorimeter. Energy deposits in the presampler and EM1 of great importance to this search.

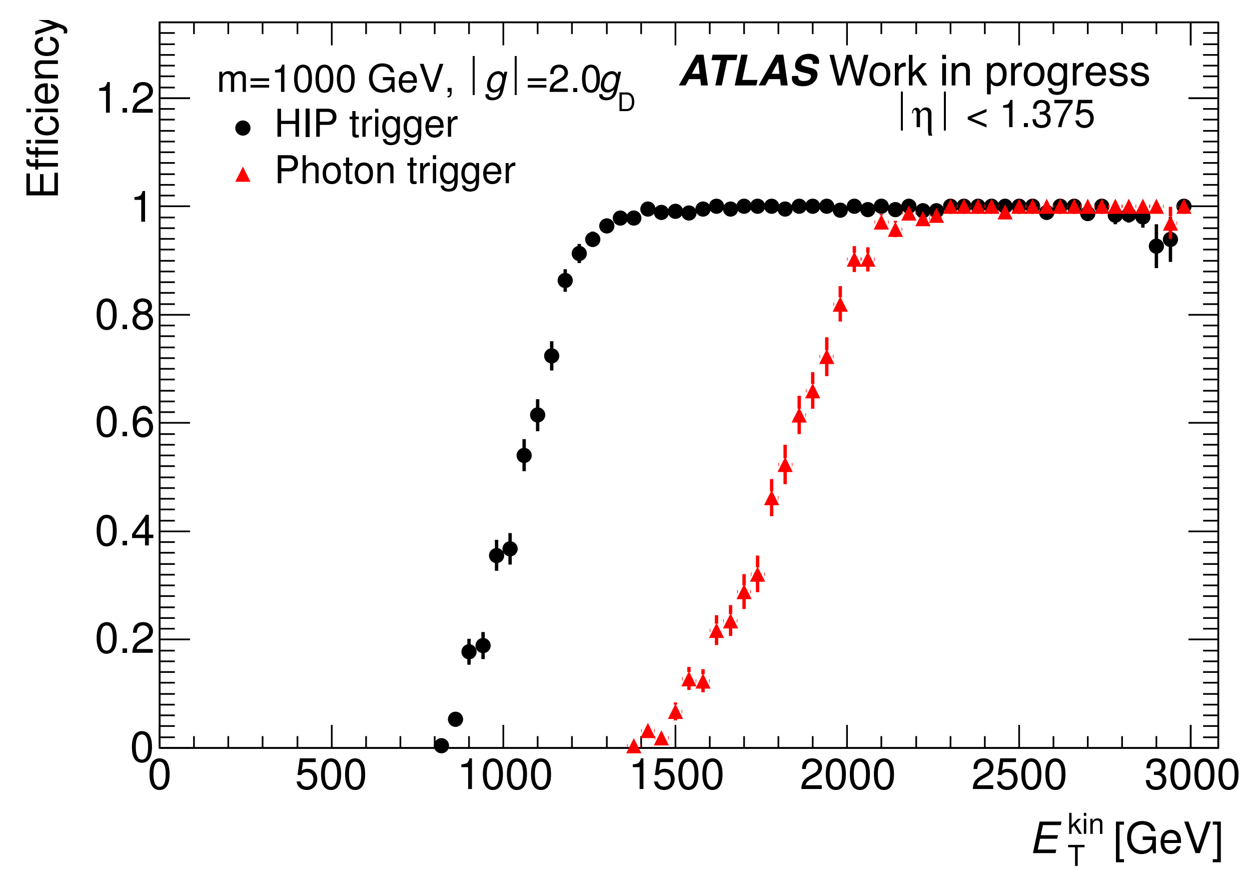
Monte Carlo signal samples

- This search includes HIPs of mass in the range 200 GeV – 2500 GeV and charge:
  - magnetic charge $0.5g_D < |g| < 2.0g_D$
  - electric charge $10 < |z| < 60$
- Fully simulated samples:
  - Single particle HECOs and monopoles.
  - Spin-½ HECOs and monopoles using Drell-Yan production model.
- Generator level 4-vectors of spin-0 HECOs and monopoles, assuming the Drell-Yan model, have been produced to extrapolate results using single particle selection efficiency maps.

HIP trigger

- ATLAS trigger system is divided in three levels.
- Level 1: requires a region with 18 GeV of energy deposition in calorimeter and less than 1 GeV in hadronic calorimeter.
- Level 2: dedicated trigger uses TRT information only.
- The number and fraction of TRT HT hits in a wedge aligned with the calorimeter region of size $\Delta\phi = \pm 0.015$ are required to be > 20 and > 0.37, respectively.
- Approximately 7 fb^{-1} of *pp* collisions data collected since late September 2012.

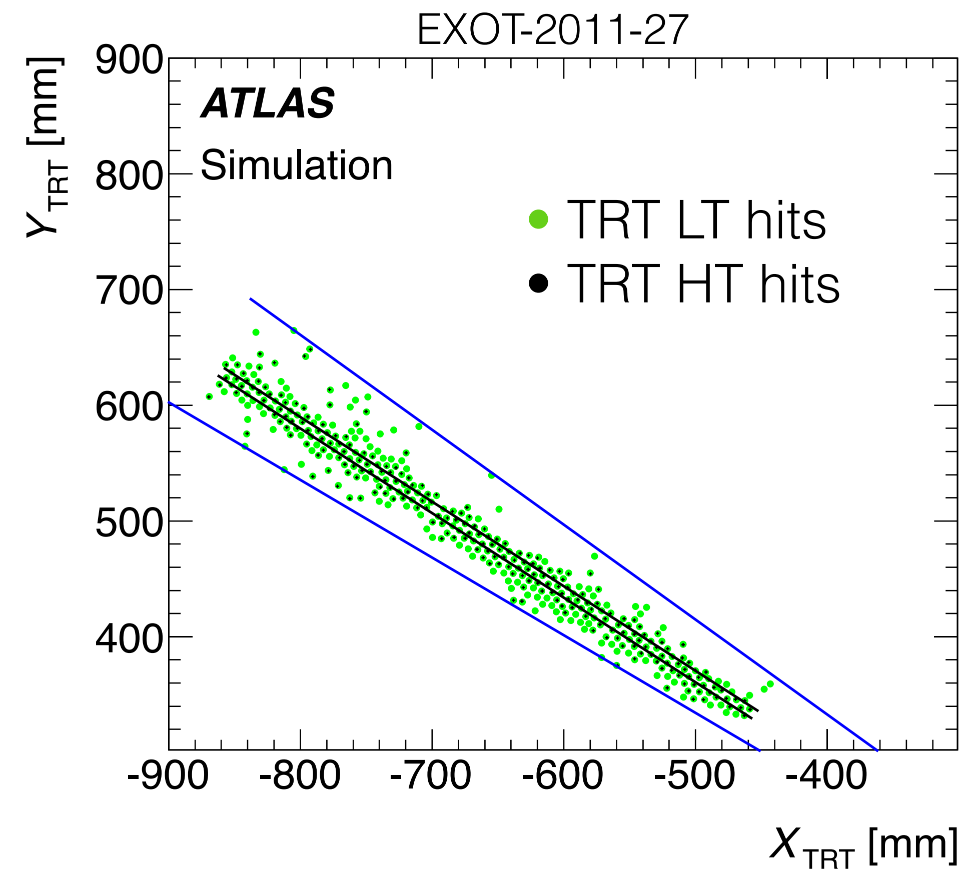




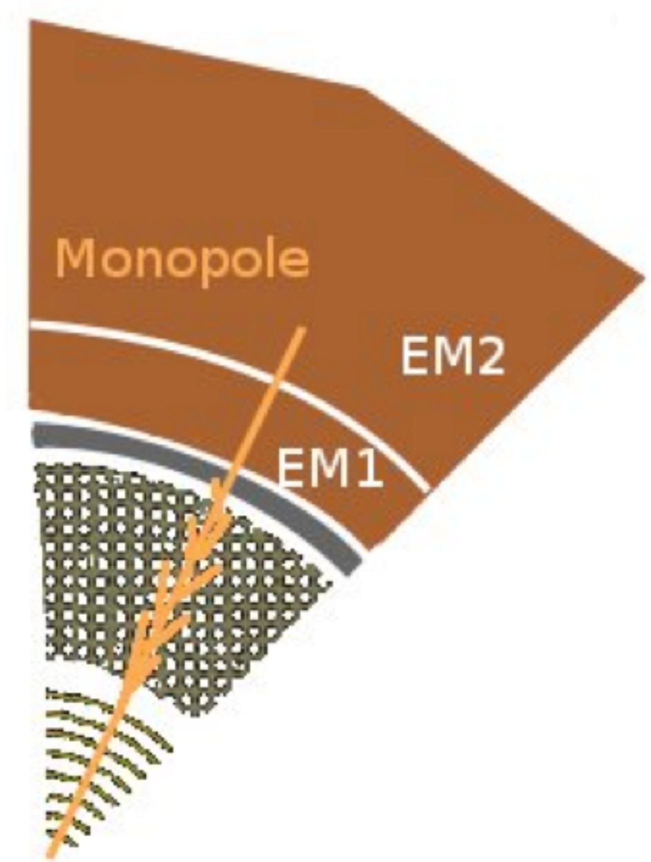
Spin-½	$\lvert z\rvert = 20$	$\lvert z\rvert = 40$	$\lvert g\rvert = 1.0 g_D$	$\lvert g\rvert = 2.0 g_D$
m=500 GeV	24.9	22.2	15.9	0.03
m=1500 GeV	28.9	10.9	23.6	0.11
m=2500 GeV	13.7	1.12	11.3	0.03

Trigger efficiencies in % for typical spin-½ Drell-Yan produced HIP samples

HIP reconstruction



- HIPs that passed the dedicated trigger are reconstructed based on a combination of TRT and LAr EM calorimeter information.
  - A HIP candidate comprises a TRT region with a high fraction of TRT HT hits and EM calorimeter cluster.
  - Only EM calorimeter clusters with transverse energy E_T > 16 GeV are considered.
  - TRT regions with a large fraction of TRT HT hits in a narrow swath aligned with a selected EM cluster are selected.
  - EM clusters and TRT regions are uniquely paired.
  - Only one candidate per event is selected.



Event selection

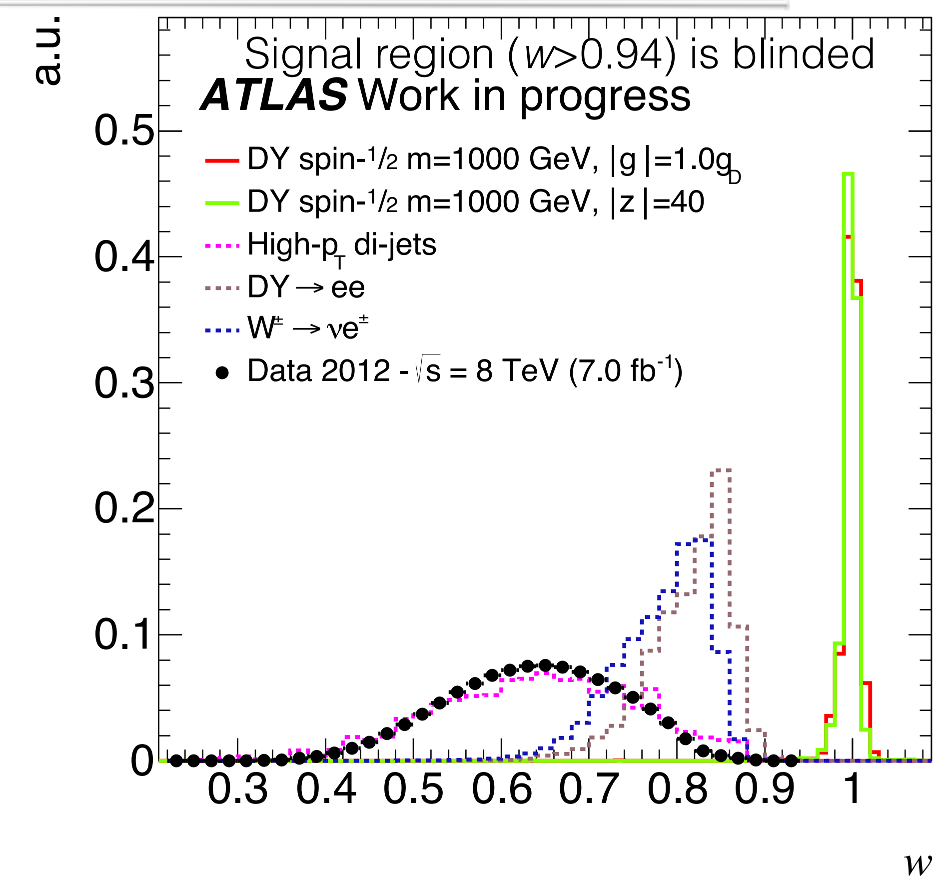
- The *w* variable measures the lateral dispersion of the energy deposition in the calorimeter:
  - Defined as the average of w_0, w_1 and w_2, where

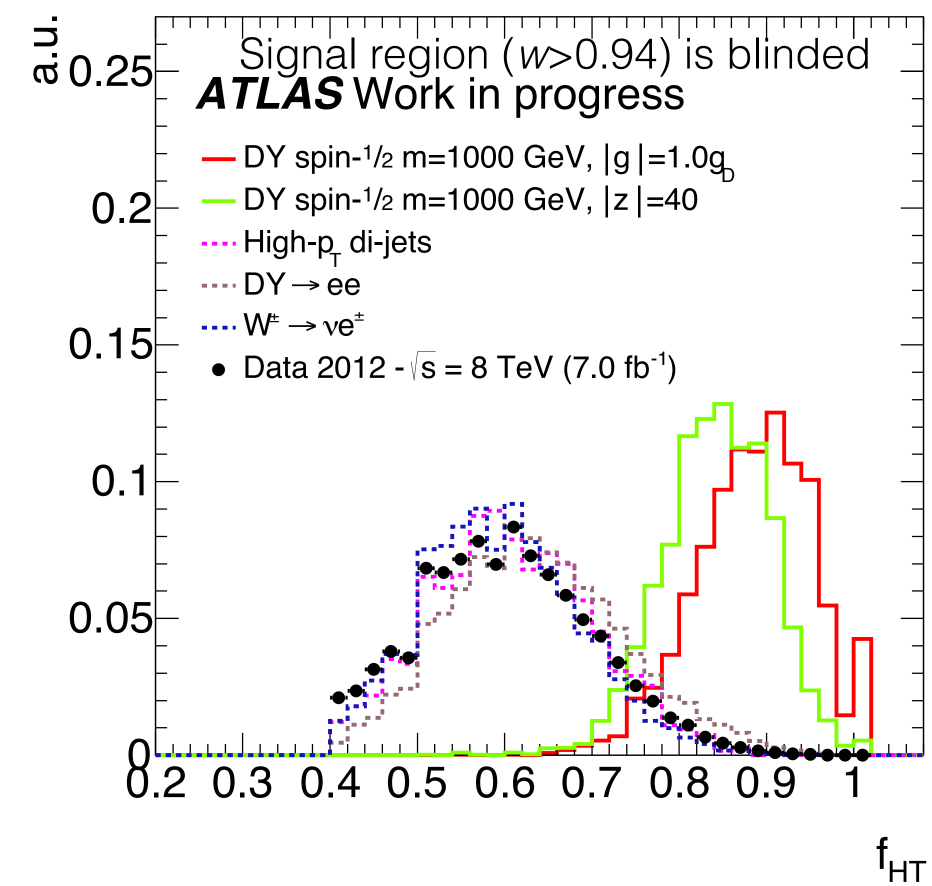
$$w_i = \frac{\sum_n^N E_{n,i}}{E_i},$$

  E_n the nth highest energy cell in layer *i*, and N=2, 4 and 5 for presampler, EM1 and EM2, respectively, with the N optimized to account for the changing granularity.

- The f_{HT} variable offers good discriminating power, specially for higher charge samples.
  - Defined as the ratio of TRT HT hits over all hits in a rectangular road (wedge) of ±4mm (Δϕ=0.006) in the barrel (end-cap).
  - Originally designed for monopoles of charge $|g|=1.0g_D$ and HECOs of charge $|z|\geq40$.

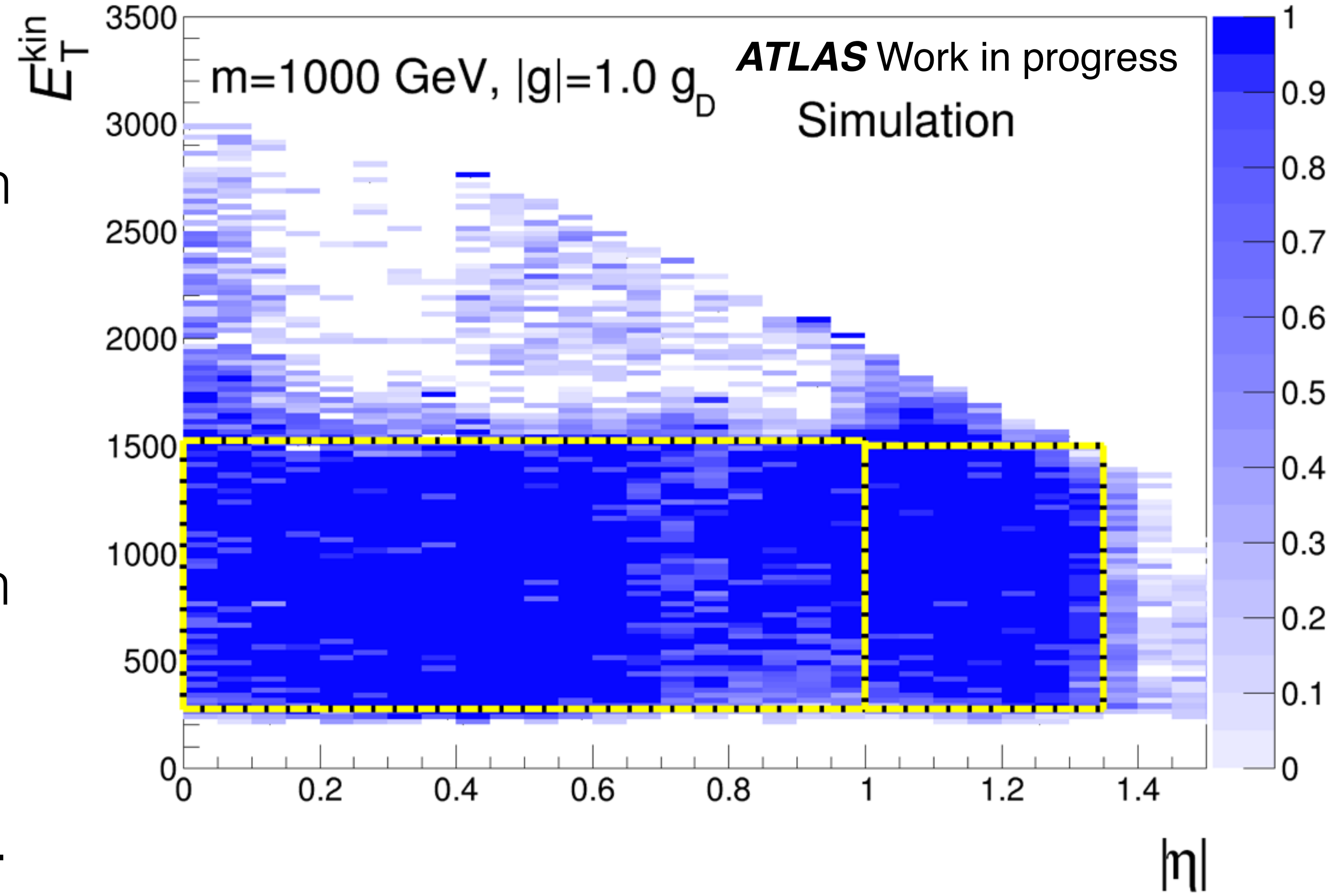
Signal region defined as $w > 0.94$ and $f_{HT} > 0.7$





Event selection efficiency

- Efficiency maps have been obtained using single particle HIPs for definition of fiducial regions of high and uniform event selection efficiency.
  - Average efficiency: $\varepsilon_{avg} > 0.9$
  - Standard deviation: $\sigma(\varepsilon) < 0.125$
- Level 1 trigger acceptance is the main source of inefficiencies.
- The selection criteria is highly efficient for HIP signals that passed the trigger.



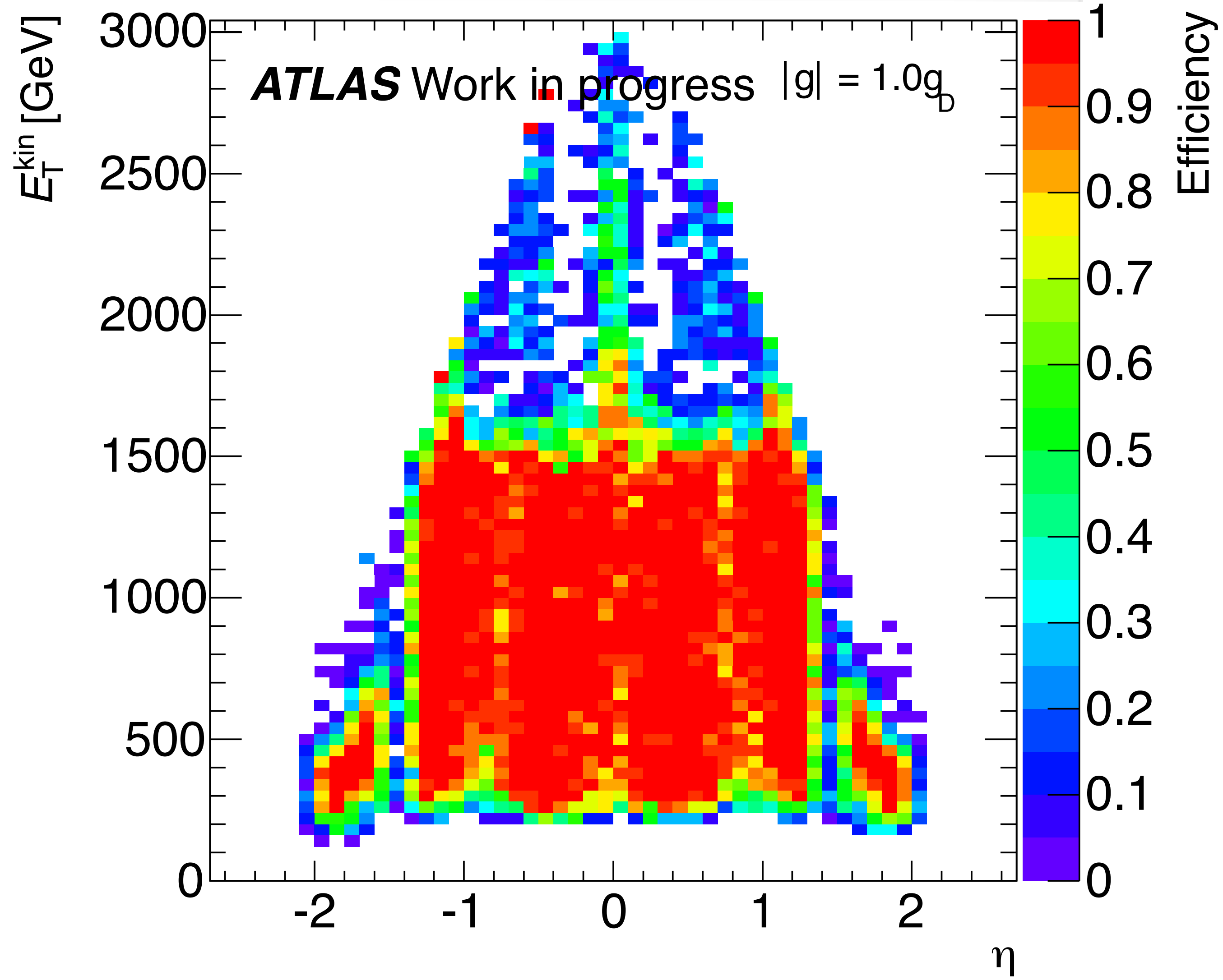
	DY Spin-½ Monopole Selection Efficiencies [%]			
	Magnetic Charge			
Mass [GeV]	$\|g\| = 0.5\ g_D$	$\|g\| = 1.0\ g_D$	$\|g\| = 1.5\ g_D$	$\|g\| = 2.0\ g_D$
200	22.32 ± 0.29	3.51 ± 0.13	0.14 ± 0.03	0.001 ± 0.004
500	33.53 ± 0.33	14.86 ± 0.25	1.16 ± 0.09	0.02 ± 0.02
1000	27.83 ± 0.32	23.37 ± 0.30	3.65 ± 0.13	0.055 ± 0.028
1500	23.66 ± 0.30	22.15 ± 0.29	3.53 ± 0.13	0.099 ± 0.033
2000	16.69 ± 0.26	16.53 ± 0.26	2.79 ± 0.12	0.055 ± 0.024
2500	9.796 ± 0.210	9.759 ± 0.216	1.61 ± 0.09	0.02 ± 0.01

	DY Spin-½ HECO Selection Efficiencies [%]			
	Electric Charge			
Mass [GeV]	$\|z\| = 10$	$\|z\| = 20$	$\|z\| = 40$	$\|z\| = 60$
200	3.79 ± 0.13	9.66 ± 0.21	11.89 ± 0.23	3.14 ± 0.12
500	6.714 ± 0.177	19.03 ± 0.28	20.00 ± 0.28	6.169 ± 0.170
1000	10.74 ± 0.22	24.61 ± 0.30	16.85 ± 0.26	3.80 ± 0.13
1500	13.83 ± 0.24	22.47 ± 0.30	9.966 ± 0.212	1.43 ± 0.09
2000	15.51 ± 0.26	17.47 ± 0.27	3.68 ± 0.13	0.24 ± 0.03
2500	12.25 ± 0.23	10.24 ± 0.21	1.05 ± 0.07	0.009 ± 0.007

Points excluded from the search due to low acceptance

Extrapolation to spin-0

- Efficiencies for spin-0 particles are determined based on single particle event selection efficiency maps.
- Only 4-vectors from MC generator are necessary.
- DY spin-0 selection efficiencies higher than DY spin-½ due to harder spectra.
- Systematic uncertainty associated to this method is determined from comparing extrapolated DY spin-½ with fully simulated DY spin-½ samples.



	DY Spin-0 Monopole Selection Efficiencies [%]			
	Magnetic Charge			
Mass [GeV]	$\|g\| = 0.5\ g_D$	$\|g\| = 1.0\ g_D$	$\|g\| = 1.5\ g_D$	$\|g\| = 2.0\ g_D$
200	42.5 ± 0.3	10.0 ± 0.2	0.40 ± 0.04	0.01 ± 0.01
500	53.8 ± 0.3	34.8 ± 0.3	4.1 ± 0.1	0.11 ± 0.02
1000	44.3 ± 0.3	51.1 ± 0.3	11.4 ± 0.2	0.39 ± 0.04
1500	36.5 ± 0.3	49.7 ± 0.3	13.8 ± 0.2	0.43 ± 0.04
2000	30.9 ± 0.3	41.6 ± 0.3	10.9 ± 0.2	0.32 ± 0.04
2500	22.9 ± 0.3	30.8 ± 0.3	6.9 ± 0.2	0.12 ± 0.02

	DY Spin-0 HECO Selection Efficiencies [%]			
	Electric Charge			
Mass [GeV]	$\|z\| = 10$	$\|z\| = 20$	$\|z\| = 40$	$\|z\| = 60$
200	5.9 ± 0.2	28.0 ± 0.3	27.6 ± 0.3	8.2 ± 0.2
500	9.8 ± 0.2	35.3 ± 0.3	42.1 ± 0.3	15.1 ± 0.2
1000	15.1 ± 0.2	45.7 ± 0.3	37.5 ± 0.3	11.4 ± 0.2
1500	19.9 ± 0.3	47.7 ± 0.3	26.7 ± 0.3	4.8 ± 0.1
2000	25.5 ± 0.3	43.6 ± 0.3	13.2 ± 0.2	1.15 ± 0.07
2500	26.9 ± 0.3	31.7 ± 0.3	4.3 ± 0.1	0.18 ± 0.03

Points excluded from the search due to low acceptance

Systematics uncertainties on selection efficiency

- Main systematic uncertainties:
  - TRT occupancy: accuracy of pileup description affects the TRT occupancy. (~3%).
  - HIP correction to Birks' law for recombination effects: uncertainties in the experimental heavy ion data limit the precision of the correction. (~10%).
  - Cross-Talk in LAr EM calorimeter: cross-talk in ϕ is not implemented in ATLAS simulation. It is considered to be 1.8%. (~1%).
  - δ-ray production model: the model has a 3% associated uncertainty. Delta ray production is suppressed by this amount. (~5%).
  - GEANT4 range cut: low energy δ-rays are not simulated explicitly. The ID range cut is decreased to 25 μm from 50 μm. (~1%).
  - Detector material density: ATLAS geometry with increased ID material including Pixel and SCT services is used. (5% – 15%).
  - Luminosity: uncertainty due to the luminosity measurement: 2.8%
  - Spin-0 extrapolation: uncertainty due to use of efficiency maps instead of full simulation. (~8%).

Background estimate

- Background estimation performed using a data-driven approach.

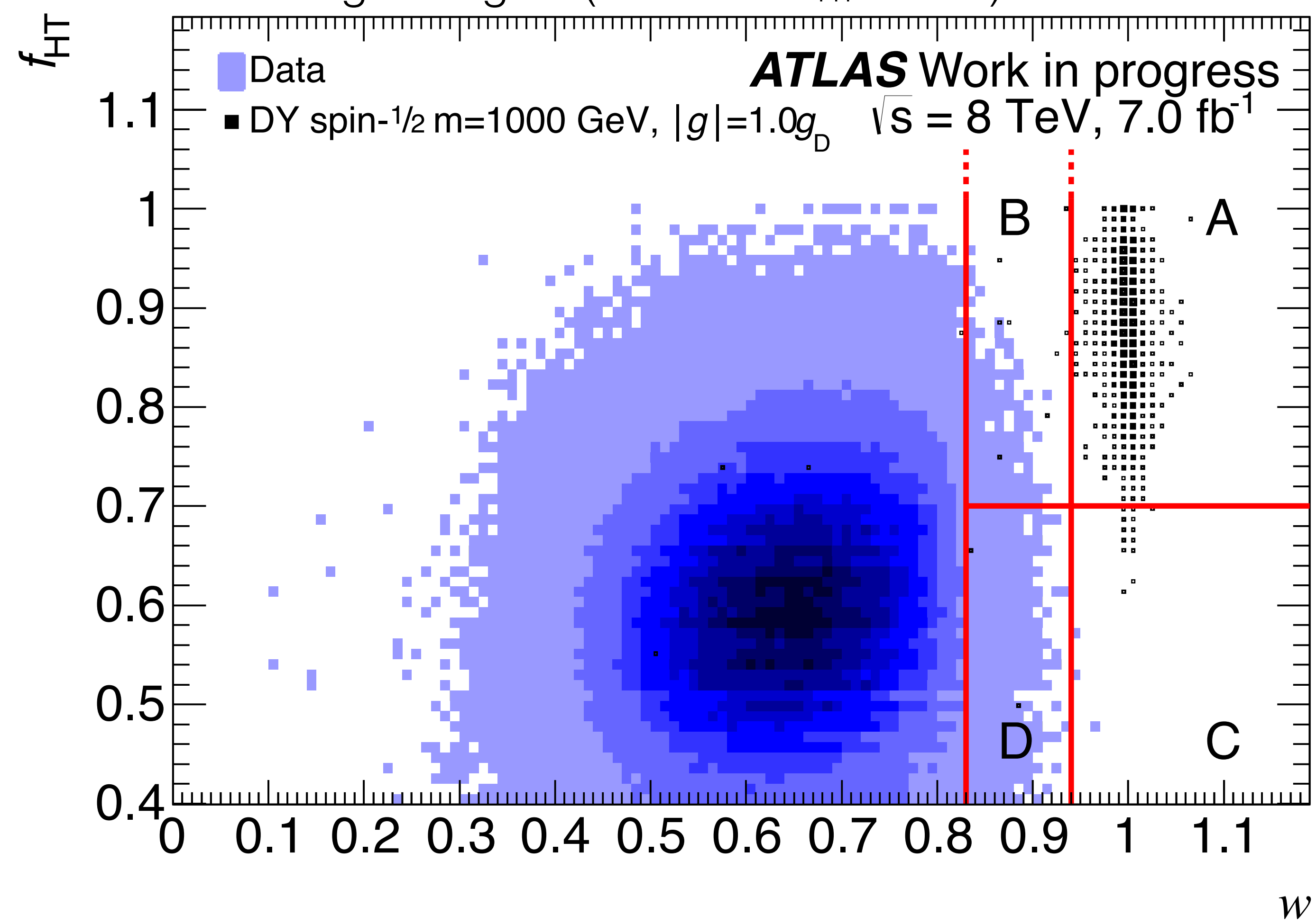
- ABCD method is used:

A_{est} = BC/D = 0.41 ± 0.24(stat.) ± 0.16(sys.)

- Signal leakages are taken into account individually for each sample in the limit setting procedure using a likelihood.

$$
\begin{aligned}
\mu_A &= \mathrm{eff}_{sig} \cdot \mu + \mu^U, \\
\mu_B &= \mathrm{eff}_{sig} \cdot b\mu + \mu^U \tau_B, \\
\mu_C &= \mathrm{eff}_{sig} \cdot c\mu + \mu^U \tau_C, \\
\mu_D &= \mathrm{eff}_{sig} \cdot d\mu + \mu^U \tau_B \tau_C
\end{aligned}
$$

Signal region (w>0.94 & f_{HT}>0.70) is blinded

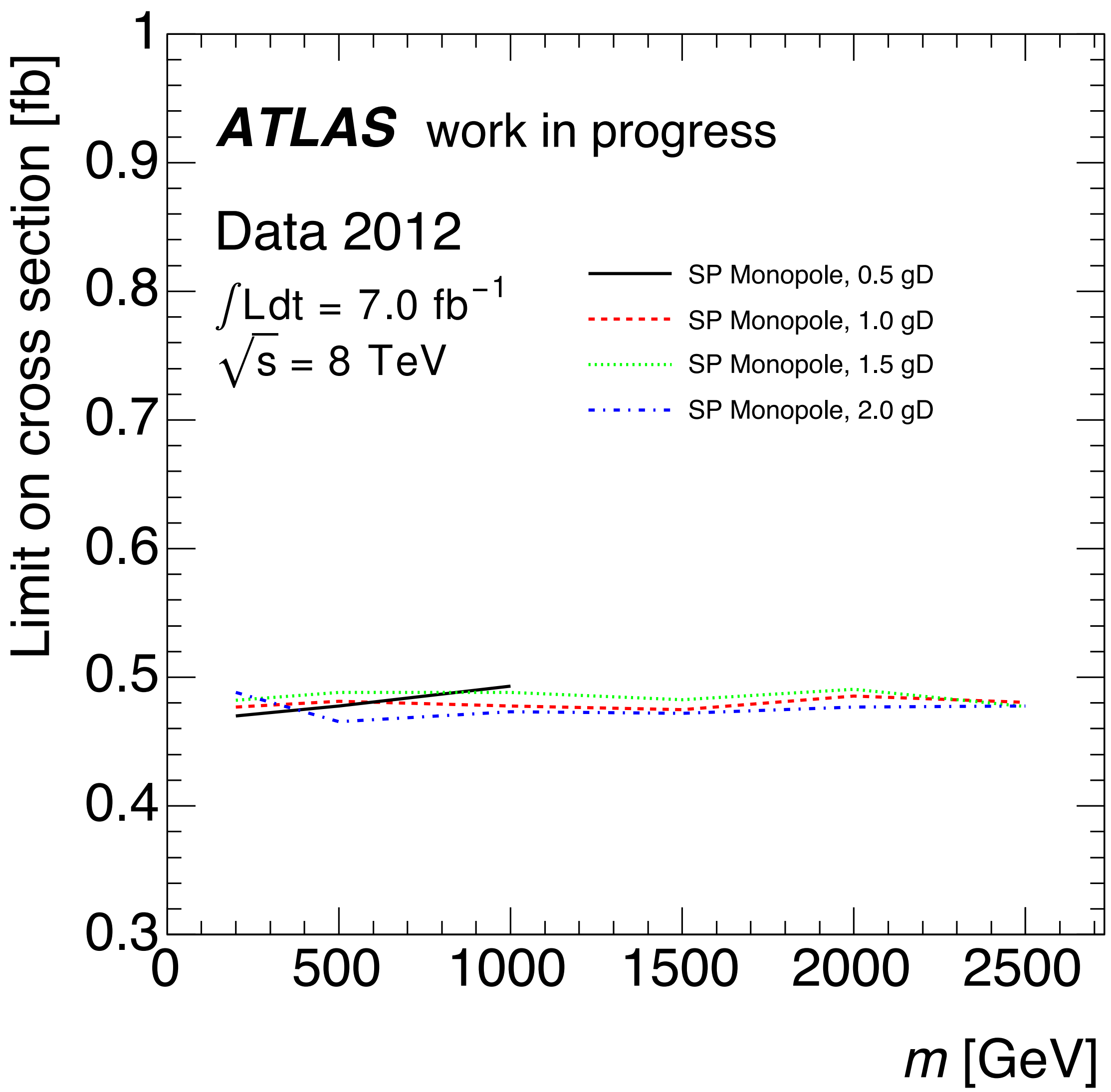


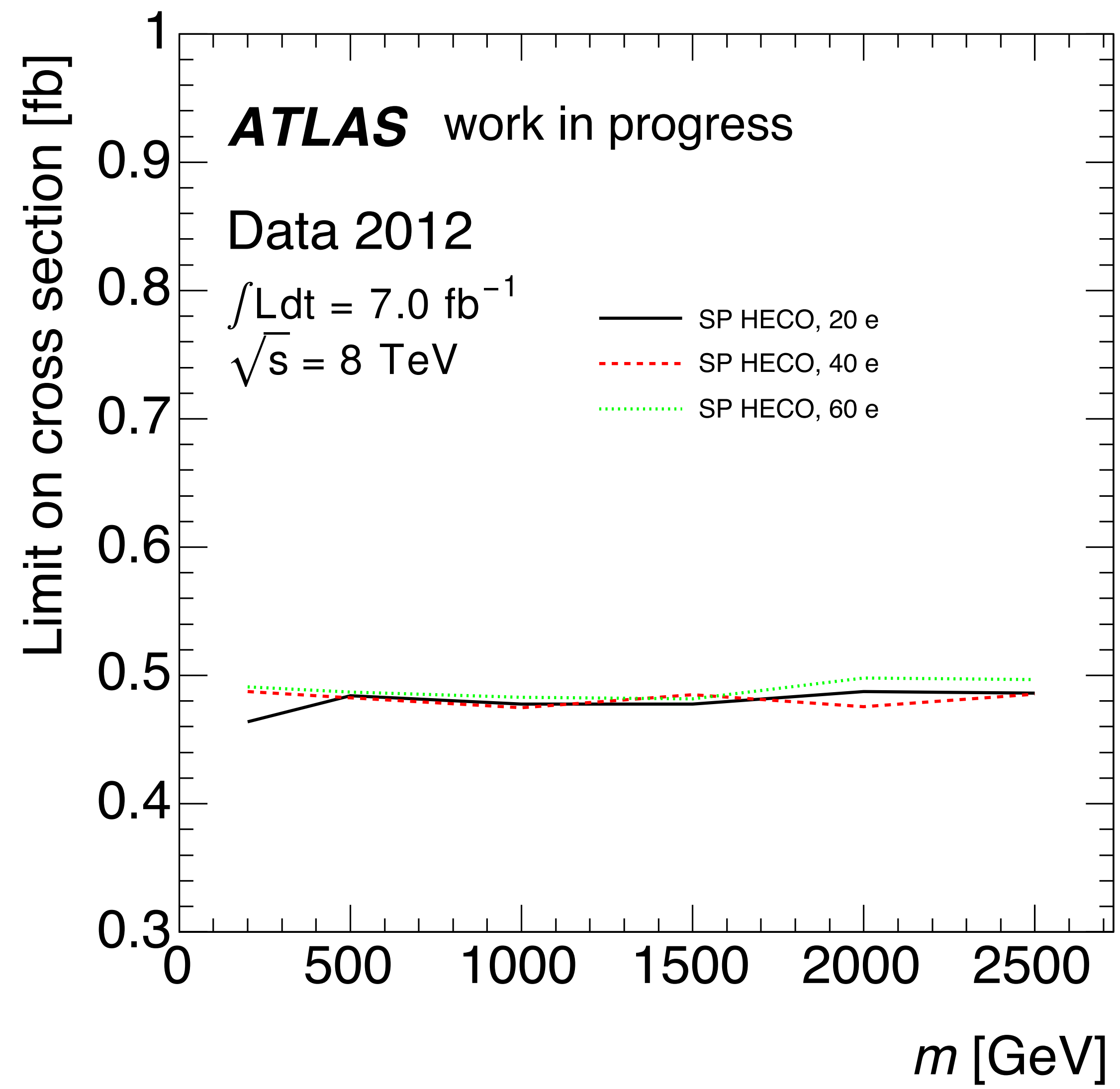
Region	A	B	C	D
Events	blinded	618	3	4539

Number of events in 7 fb^{-1} of √s=8 TeV *pp* data

Model independent expected limits

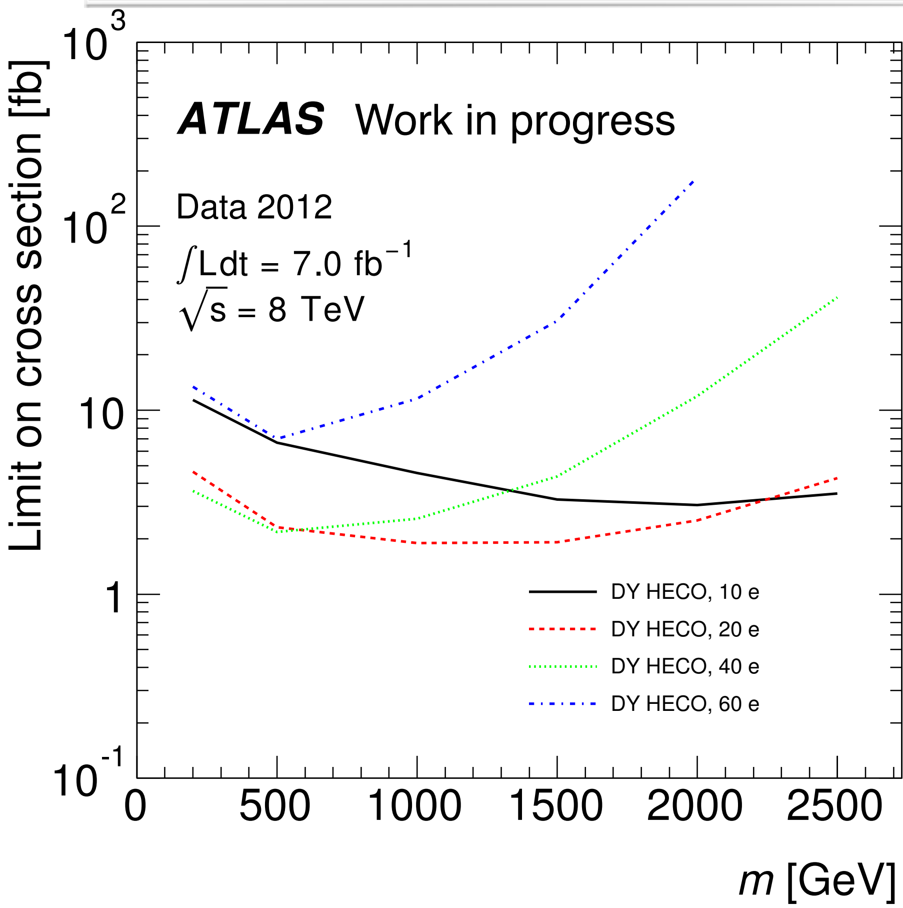
- Expected limits are set using the CLs method at 95% CL assuming zero observed events.
- An upper limit on the production cross section of ~**0.5 fb** is expected for single HIPs in fiducial regions.

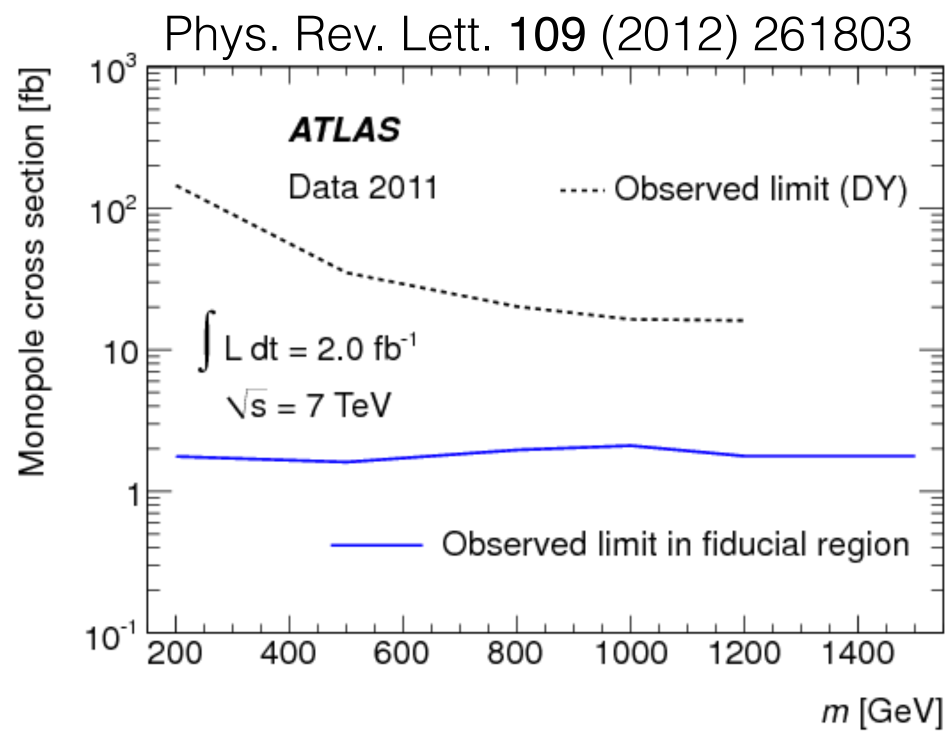




Drell-Yan production model expected results

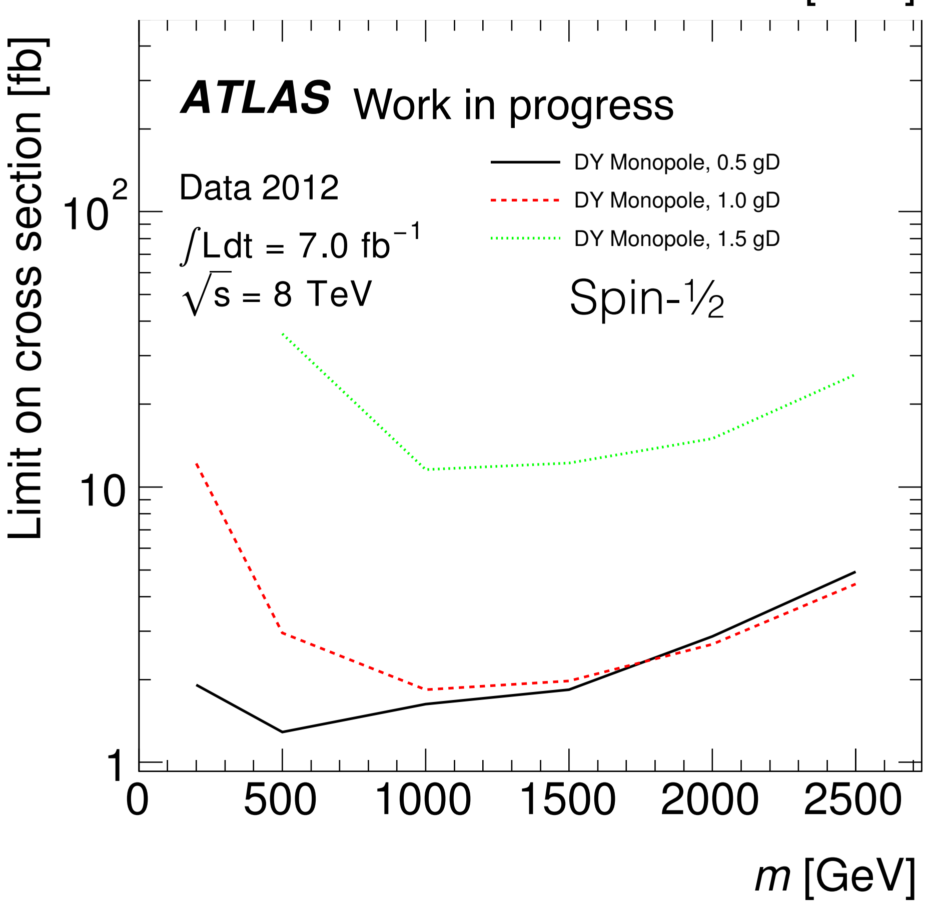
HECO

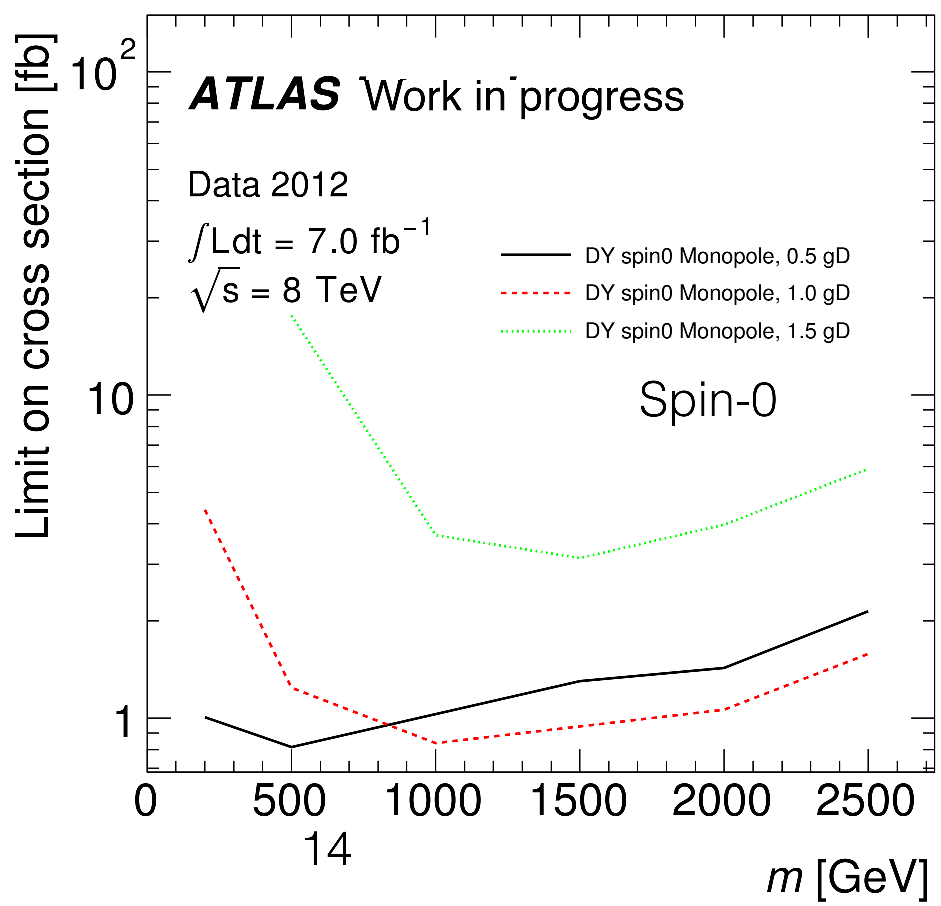




- Pair production of spin-0 and spin-½ HIPs using the Drell-Yan model.
- Expected upper limits on production cross section are set assuming zero observed events.
- Improvement with respect to 2011 results is expected.

Monopole





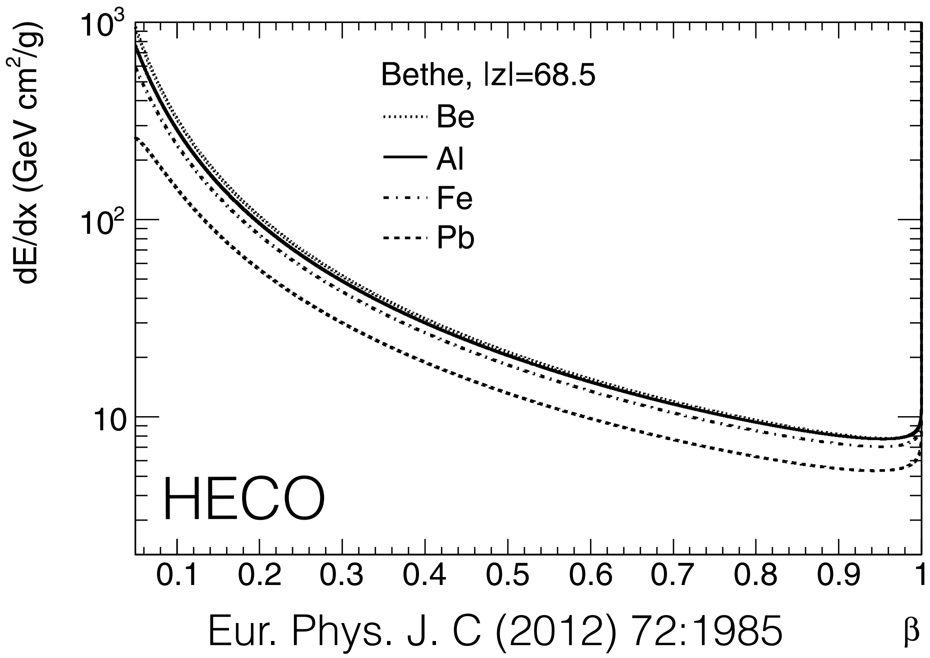
Conclusion

- Improved limits with respect to search on 2011 data on production cross section and mass for monopoles of charge $1.0g_D$ are expected.
- Run 2 search for HIPs:
  - Improved HIP dedicated trigger: integrates TRT ±4mm rectangular road.
  - Accumulated knowledge from searches for HIPs in run 1 data.
  - Possibility of including dyons (electrically and magnetically charged particles).
  - Extrapolation method allows study of any production model.

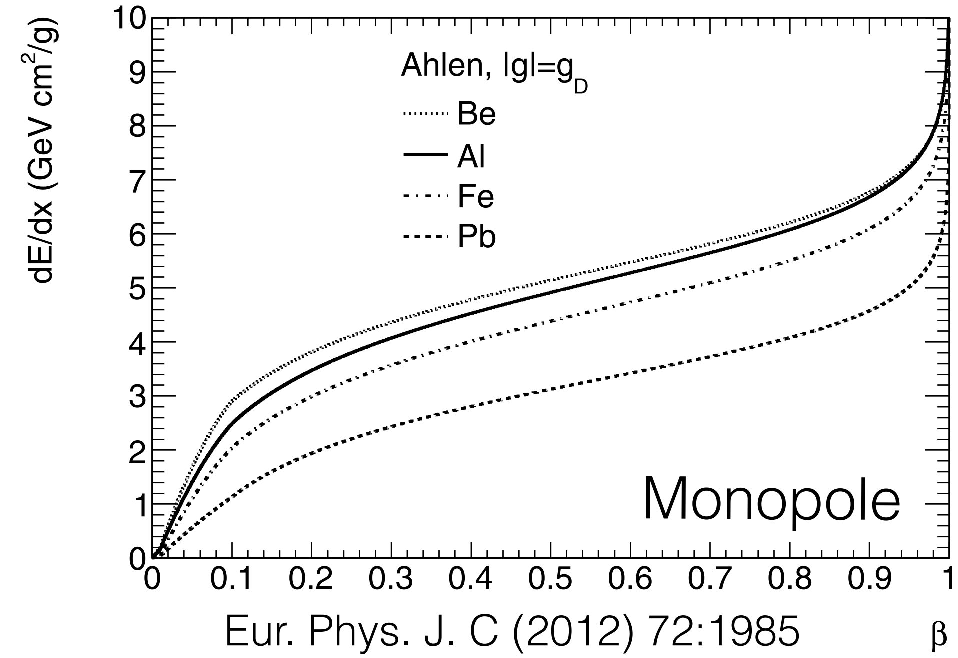
Backup

Energy deposition by HIPs

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

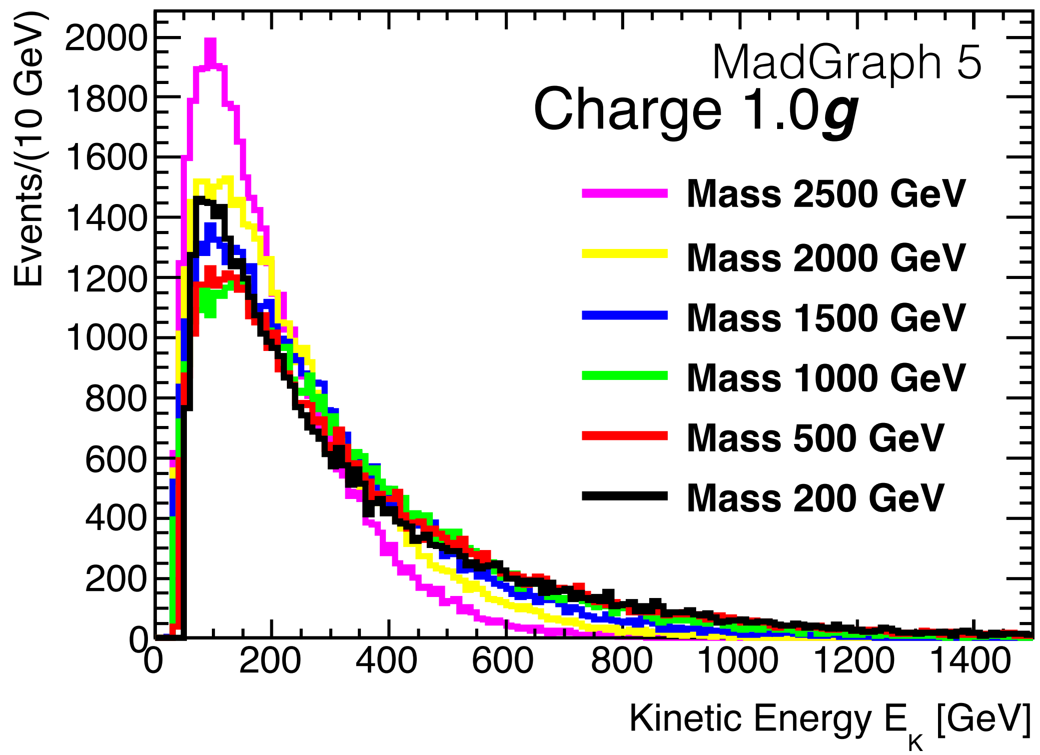


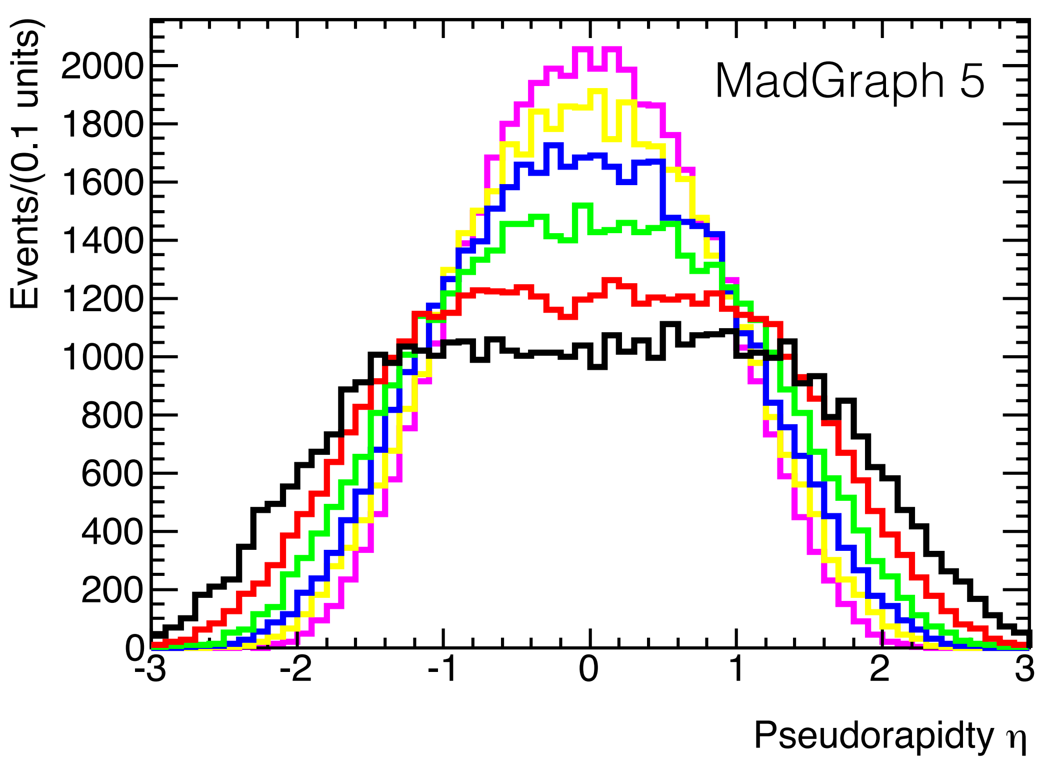
$$-\frac{dE}{dx} = K\frac{Z}{A}g^2\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I} + \frac{k(|g|)}{2} - \frac{1}{2} - \frac{\delta}{2} - B(|n|)\right]$$



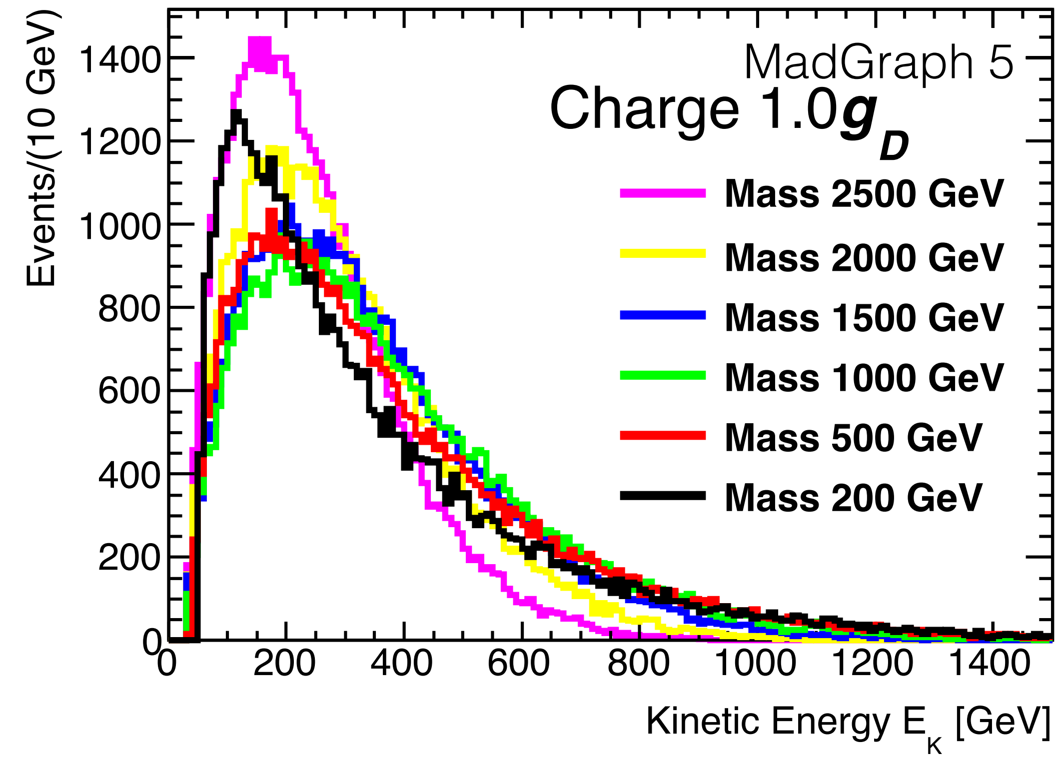
Spin-0 vs. spin-½

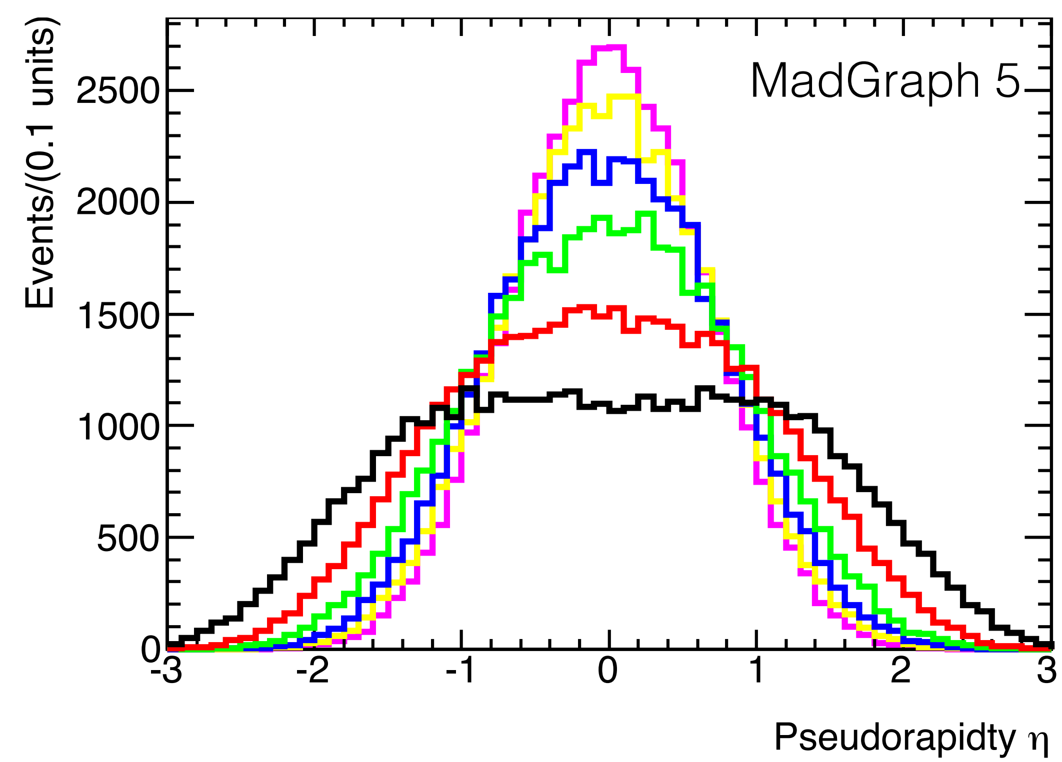
Spin-½



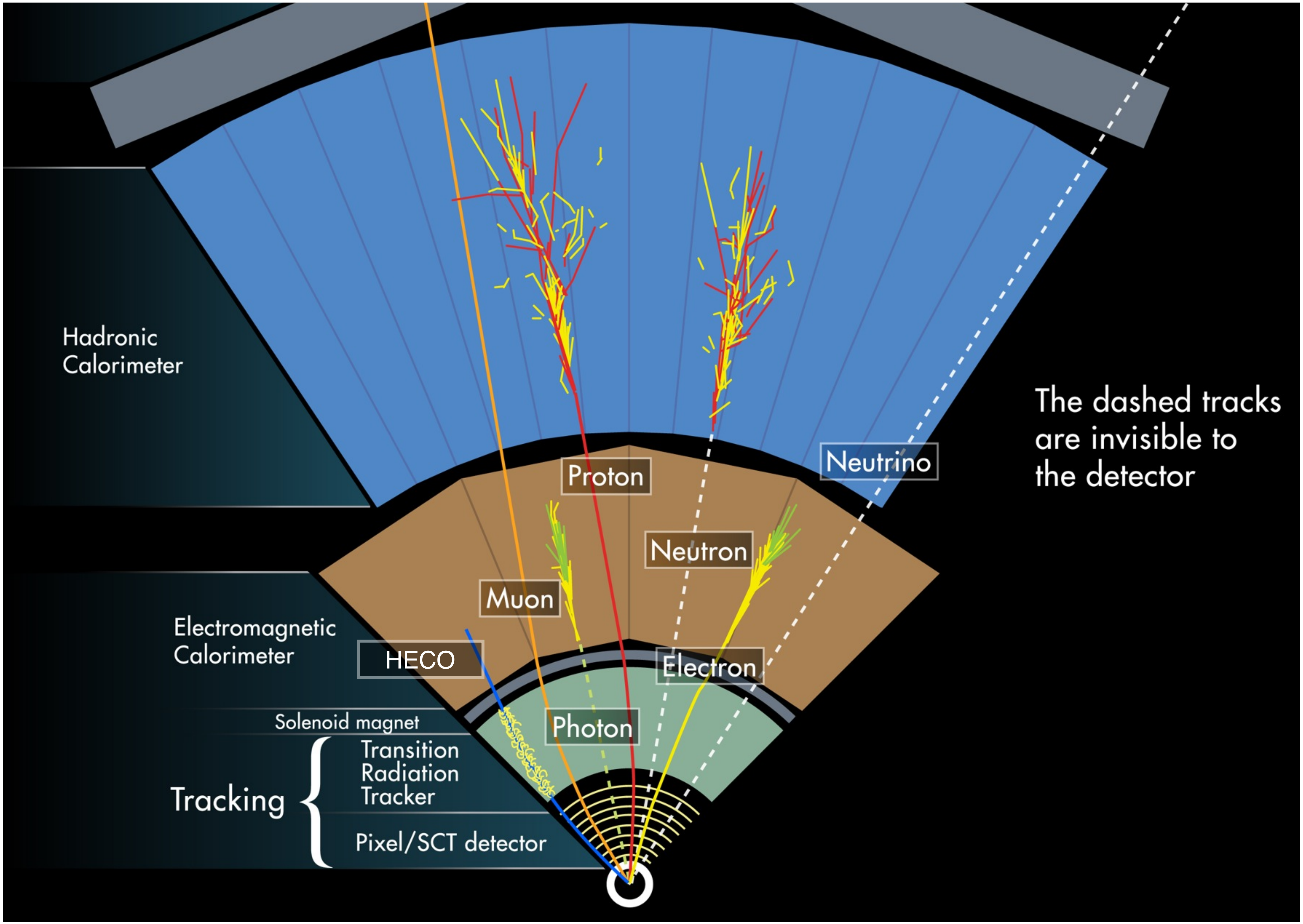


Spin-0

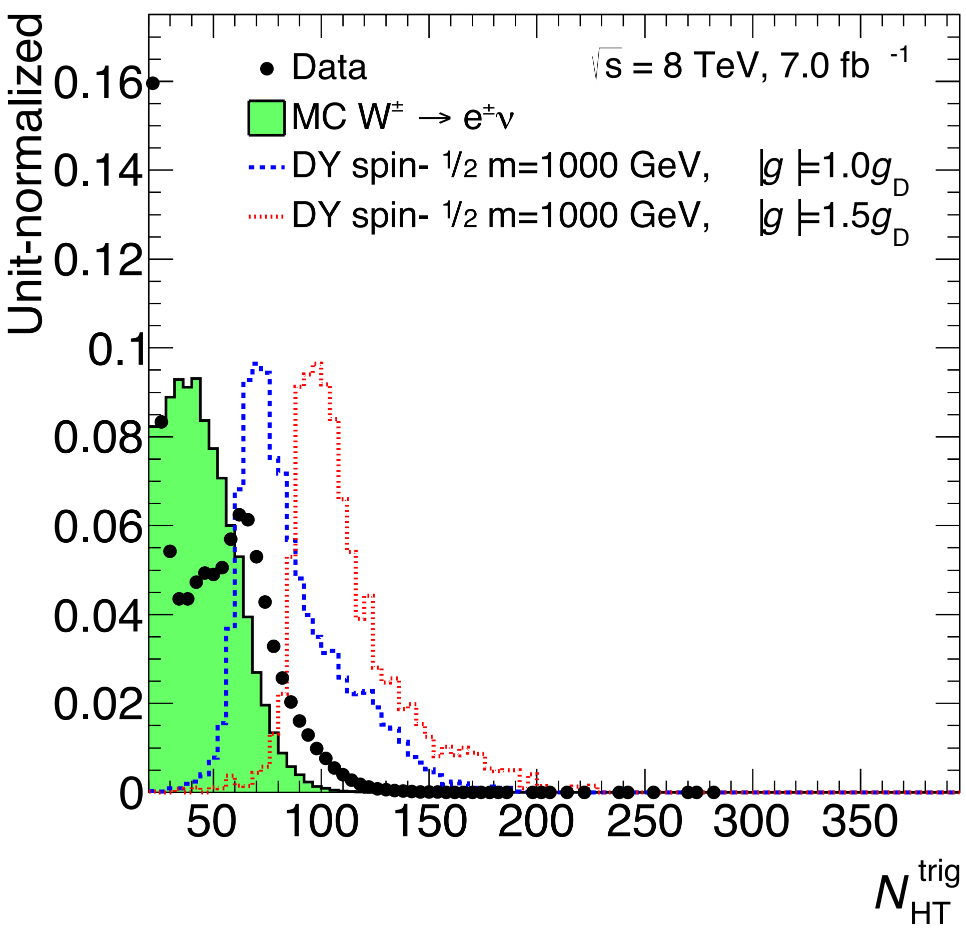




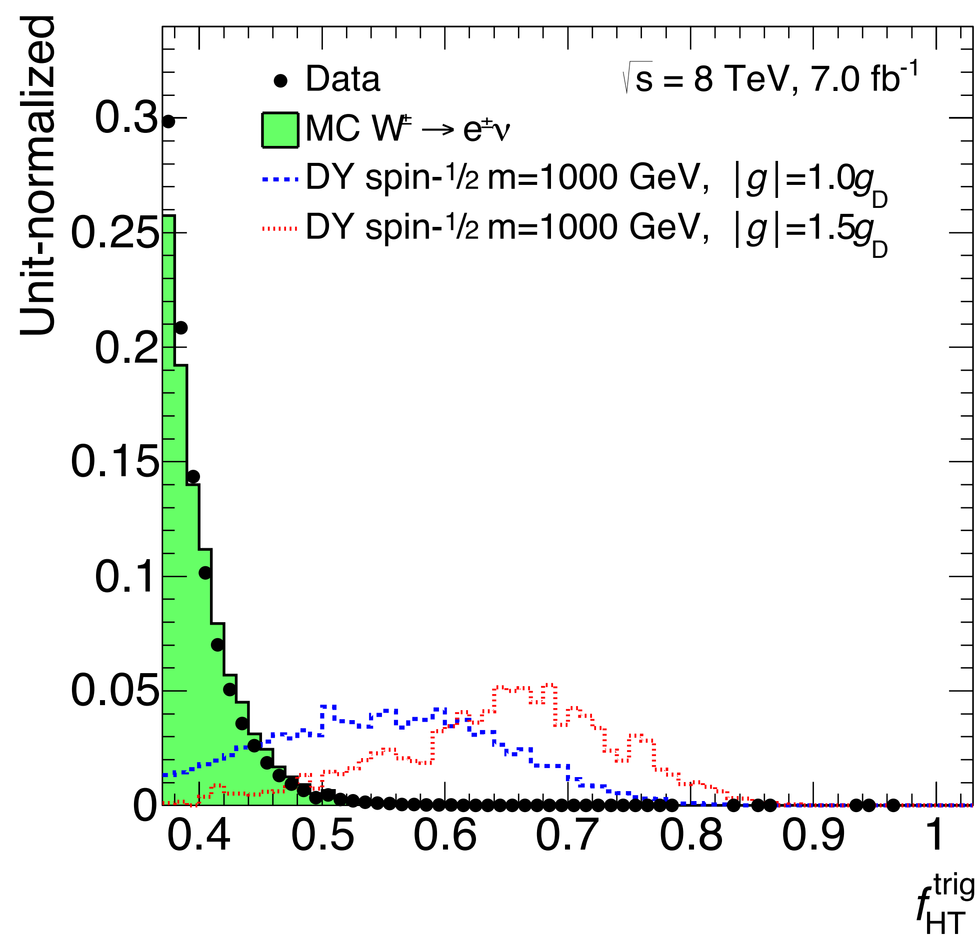
Signatures in ATLAS



HIP trigger



Unit-normalized
Data
$\sqrt{s}$ = 8 TeV, 7.0 fb^{-1}
MC $W^{\pm} \rightarrow e^{\pm}\nu$
DY spin- 1/2 m=1000 GeV, $|g|$=1.0g_D
DY spin- 1/2 m=1000 GeV, $|g|$=1.5g_D
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
50
100
150
200
250
300
350
N_{HT}^{trig}



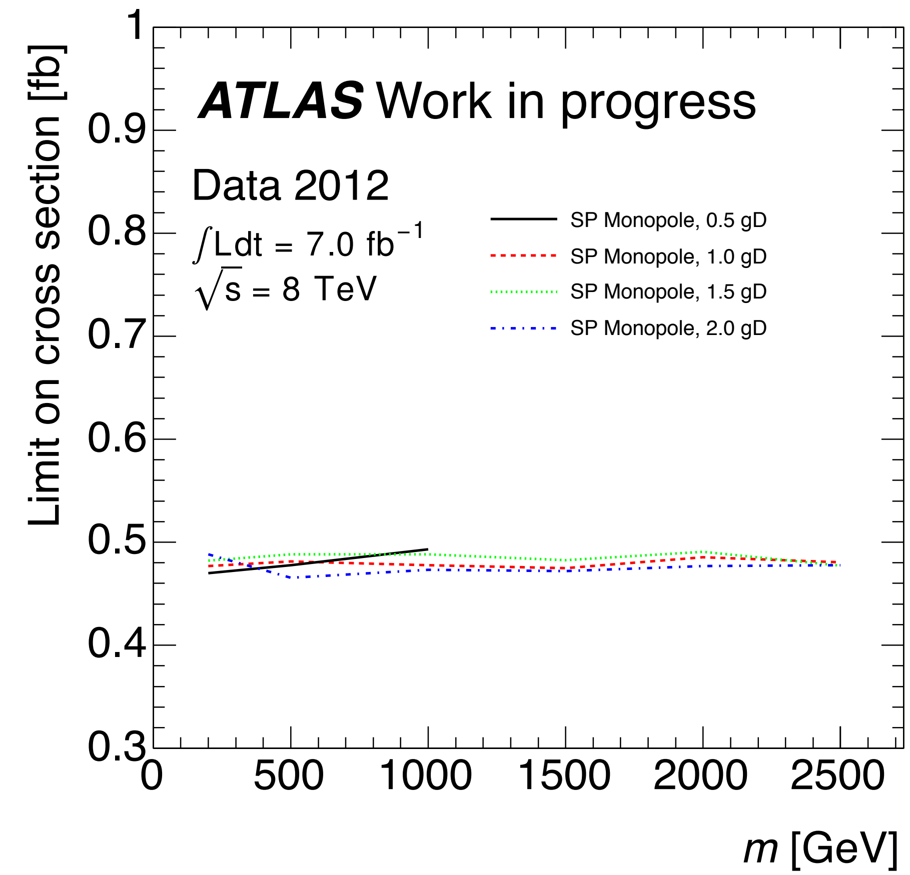
Unit-normalized
Data
$\sqrt{s}$ = 8 TeV, 7.0 fb^{-1}
MC $W^{\pm} \rightarrow e^{\pm}\nu$
DY spin-1/2 m=1000 GeV, $|g|$=1.0g_D
DY spin-1/2 m=1000 GeV, $|g|$=1.5g_D
0.3
0.25
0.2
0.15
0.1
0.05
0
0.4
0.5
0.6
0.7
0.8
0.9
1
f_{HT}^{trig}

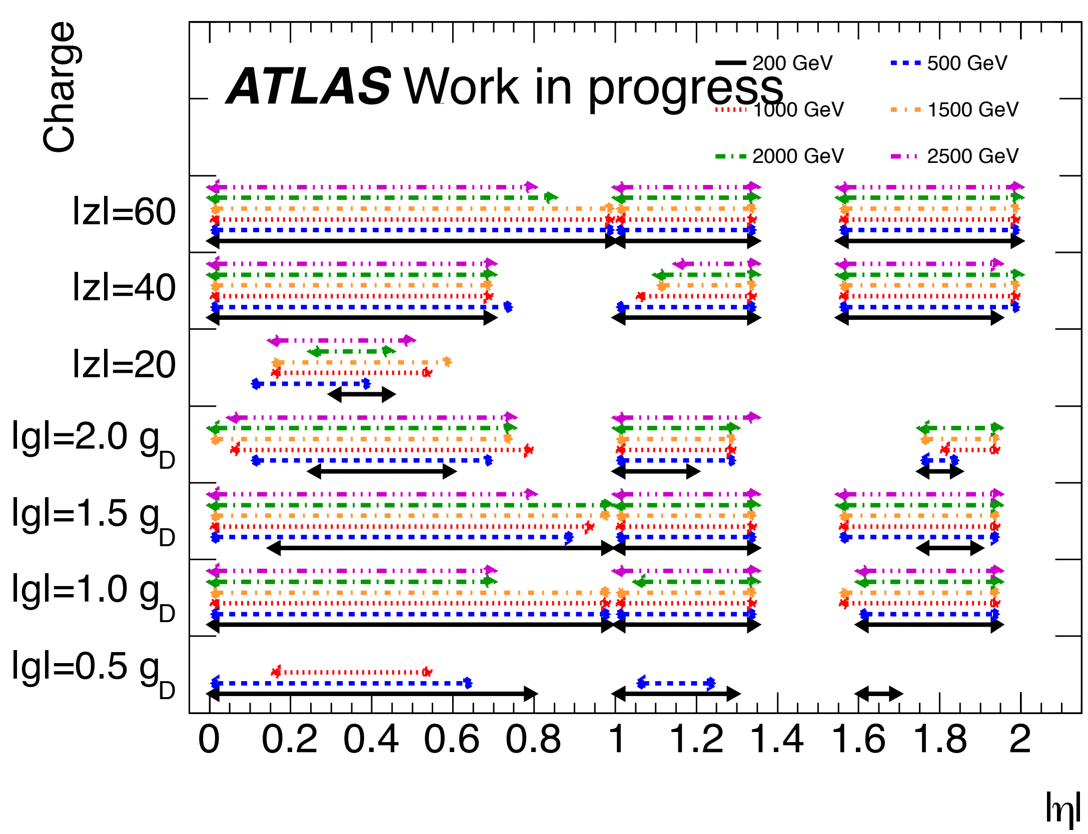
Offline selection

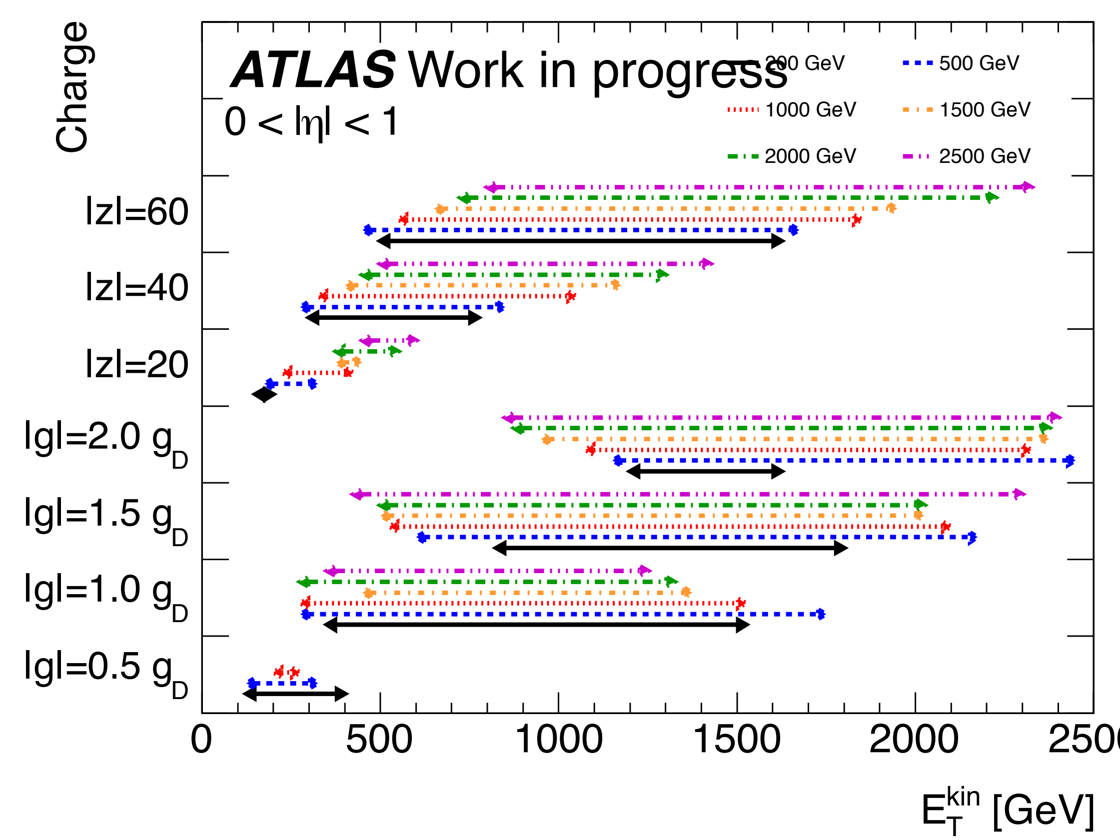
- HIP TRT trigger
- CaloCalTopoCluster
- E_T^{EM} > 16 GeV
- E_{pre}>5 GeV OR E_{EM1}> 5 GeV
- E_{Had}<1 GeV
- $|\eta|$ < 1.375 OR 1.52 < $|\eta|$ <2
- w > 0.94
- f_{HT} > 0.7

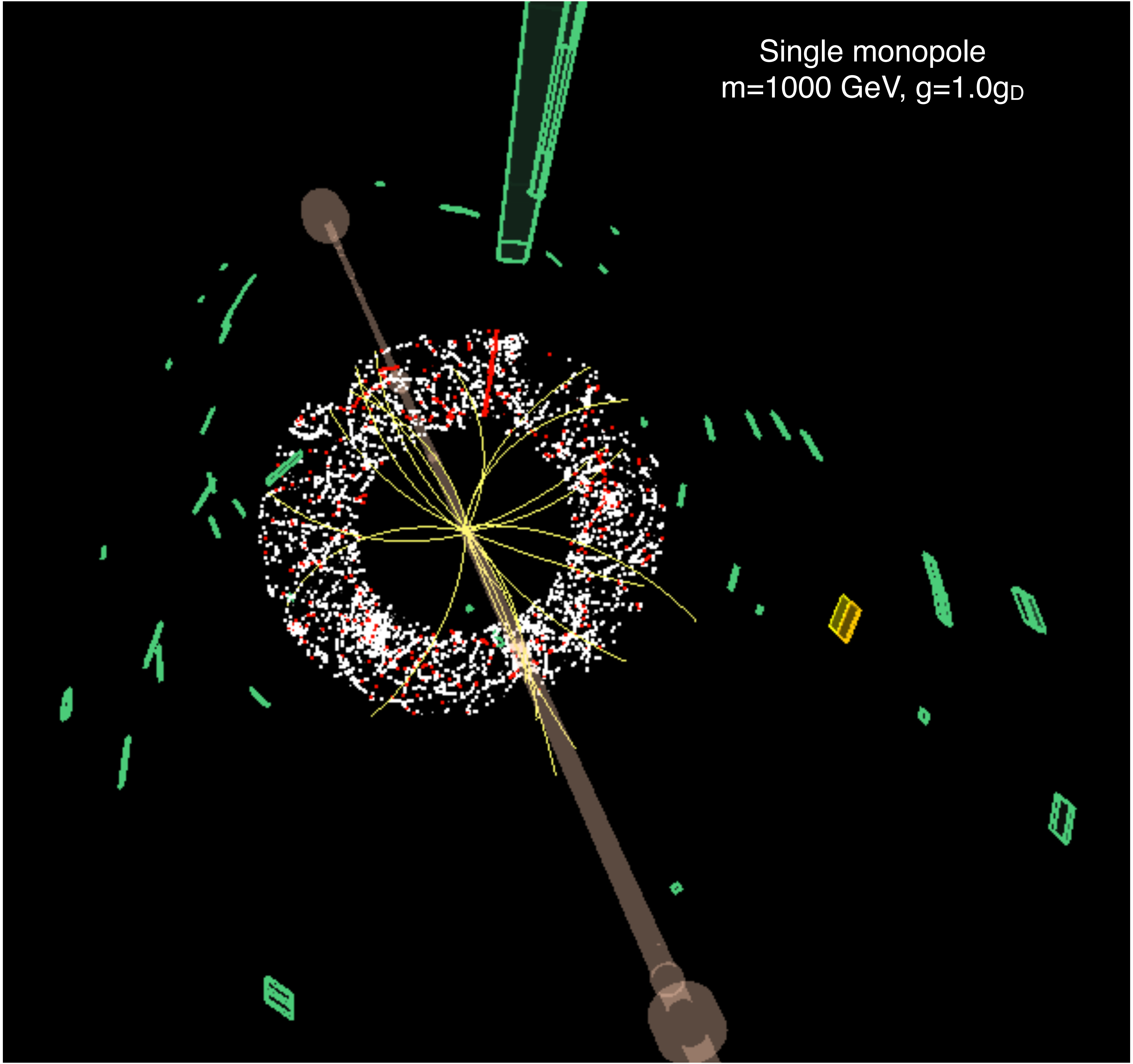
Model independent results

- Limits are set using the CLs method at 95% CL.
- An upper limit on the production cross section of ~**0.5 fb** has been obtained for single HIPs in fiducial regions.



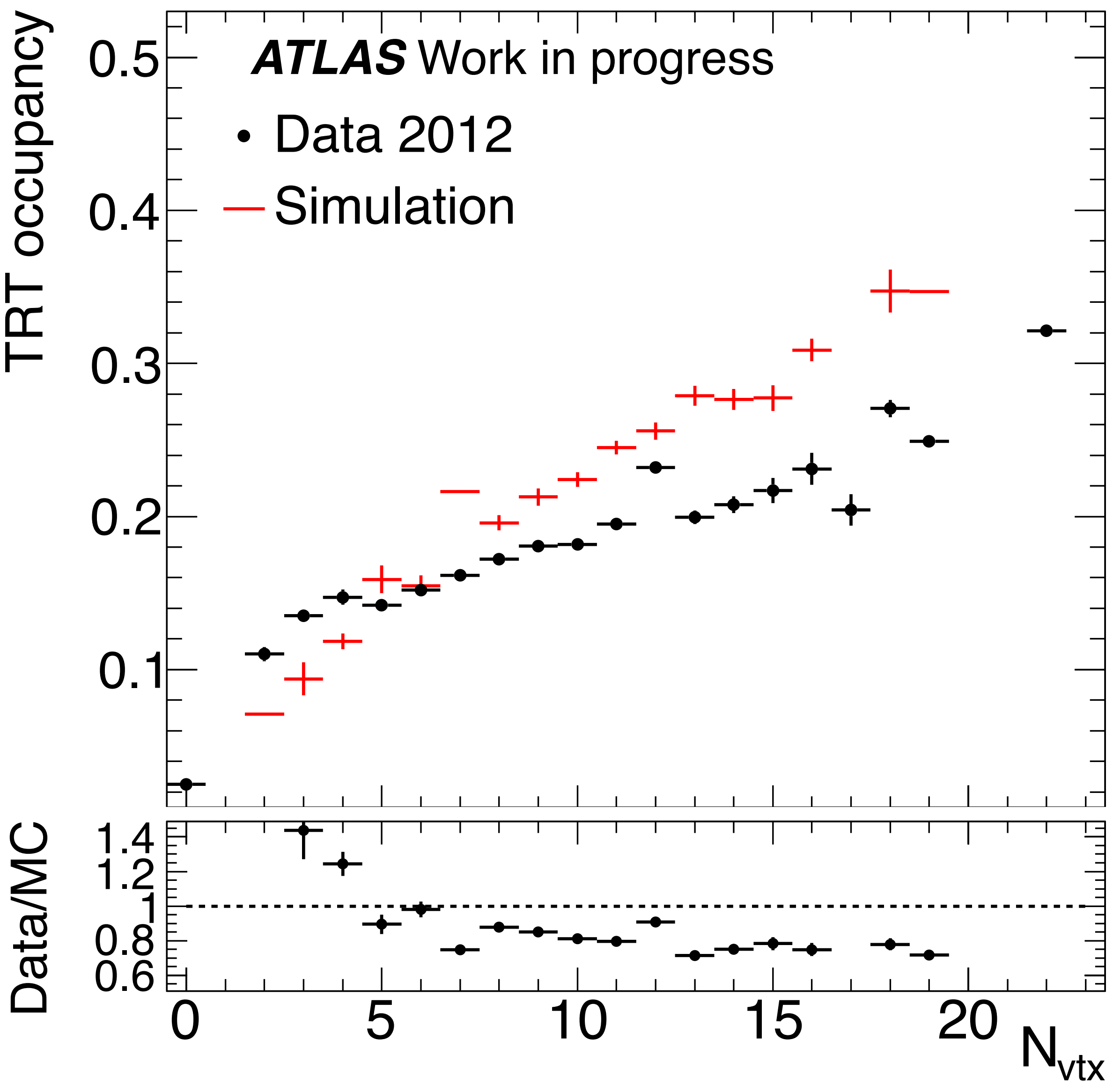





Single monopole
m=1000 GeV, g=1.0gD

Systematics uncertainties

- **TRT occupancy:** accuracy of pileup description affects the TRT occupancy. **(~3%).**
- **Cross-Talk in LAr EM calorimeter:** cross-talk in ϕ is not implemented in ATLAS simulation. It is considered to be 1.8%. **(~1%).**
- **δ-ray production model:** the model has a 3% associated uncertainty. Delta ray production is suppressed by this amount. **(~5%).**
- **Detector material density:** ATLAS geometry with increased ID material including Pixel and SCT services. **(5% – 15%).**



Systematics uncertainties

- **HIP correction to Birks' law:** uncertainties in the experimental heavy ion data limit the precision of the correction. **(~10%).**
- **GEANT4 range cut:** low energy δ-rays are not simulated explicitly. The ID range cut is decreased to 25 μm from 50 μm. **(~1%).**
- **Luminosity:** uncertainty due to the luminosity measurement: **2.8%**
- **Spin-0 extrapolation:** uncertainty due to use of single particle efficiency maps instead of full simulation. (~8%).

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