SEARCH FOR THE MAGNETIC MONOPOLE AT ATLAS

Sergey Burdin
The University of Liverpool
HEP Seminar @ University of Birmingham
Oct 2, 2013

Outline

- Motivation
- Past searches
- Monopole interactions with matter
- Search at ATLAS
- Prospects

History

- One of the longest searches in physics
- "Epistola de Magnete" by Petrus Peregrinus
  - Characterization of magnets
  - Magnets have two poles

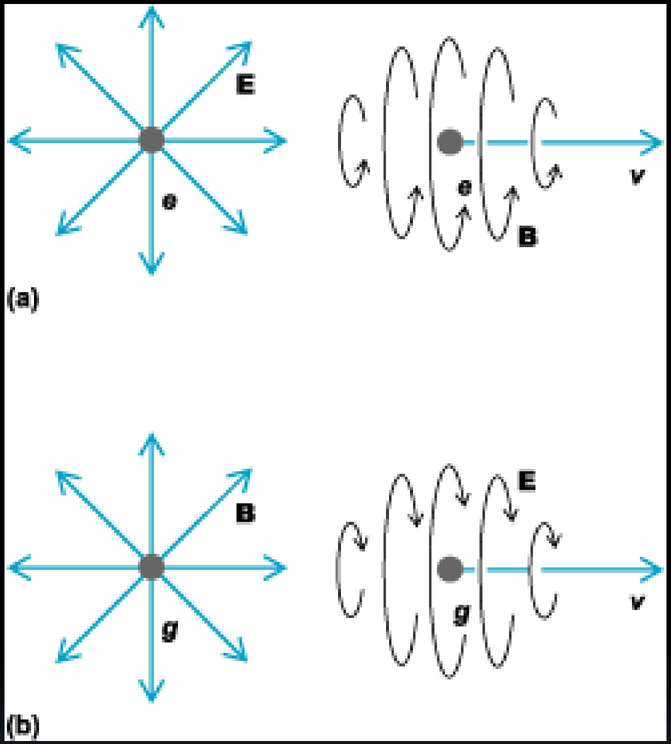
THE LETTER OF
PETRUS
PEREGRINUS
ON THE MAGNET, A.D. 1269

TRANSLATED BY
BROTHER ARNOLD, M.Sc.

so that the two make but one by nature. In the case of this wonderful lodestone this may be shown in the following manner: Take a lodestone which you may call *A D*, in which *A* is the north pole and *D* the south; cut this stone into two parts, so that you may have two distinct stones; place the stone having the pole *A* so that it may float on water and you will observe that *A* turns towards the north as before; the breaking did not destroy the properties of the parts of the stone, since it is homogeneous; hence it follows that the part of the stone at the point of fracture, which may be marked *B*, must be a south pole; this broken part of which we are now speaking may be called *A B*. The

Maxwell's Equations

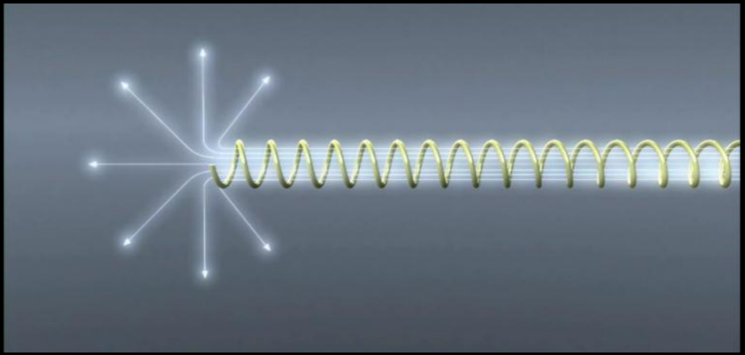
$$\vec{\nabla} \cdot \vec{E} = \rho_{\mathrm{E}}$$
$$\vec{\nabla} \cdot \vec{B} = \rho_{\mathrm{M}}$$
$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} - \vec{j}_{\mathrm{M}}$$
$$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + \vec{j}_{\mathrm{E}}$$



Duality: $\vec{E} \leftrightarrow \vec{B}$

Charge quantization

- The existence of even one magnetic monopole would explain charge quantization (Dirac 1931)
- A static system of an electric and a magnetic monopoles separated by a distance *r* possesses angular momentum
- Quantization of angular momentum ➔charge quantization



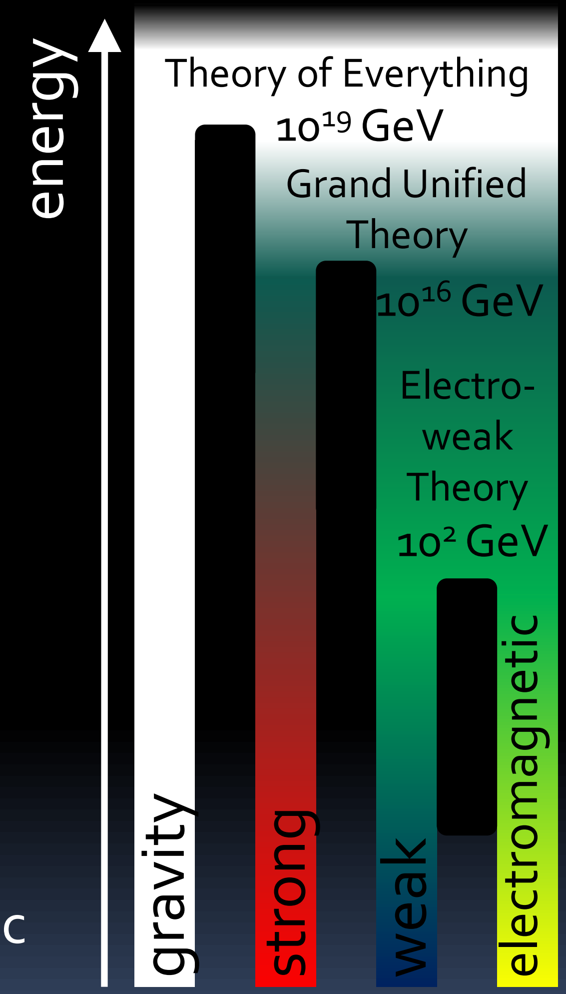
$$\frac{ge}{\hbar c} = \frac{n}{2}; \quad n = 1,2,\ldots$$

$$g = ng_D \Rightarrow \frac{g_D}{e} = \frac{\hbar c}{2e^2} = \frac{1}{2\alpha} \approx 68.5$$

If the free electric charge is $e/3$, g_D is larger

Magnetic Monopoles in theory

- In GUTs, monopoles are the solitons of the GUT broken symmetries (‘t Hooft & Polyakov)
  - Monopole mass ~ scale of GUT breaking
- Fermionic and bosonic monopoles predicted in the breaking of supersymmetric theories (Argyres & Douglas, Seiberg & Witten)
  - Monopole mass ~ scale of SUSY breaking
- Monopole condensation has been proposed for EWSB (Csaki & Shirman & Terning) $\Rightarrow$ origin of mass
  - Monopoles are the solitons of a new magnetic force
  - Monopole mass ~ monopole condensation scale ~electroweak scale



Past searches for magnetic monopoles

- Magnetic monopoles trapped in beampipes
  - HERA, CDF/DØ beam-pipe
- Direct collider searches for monopole-antimonopole pairs
  - LEP: OPAL, MODAL
  - Tevatron: CDF (DØ)
- GUT magnetic monopoles
  - MACRO, SLIM, RICE, AMANDA, Baikal, etc.
- Polar rocks - *Bendtz et al. PRL 110 (2013) 121803*

First Results from a Superconductive Detector for Moving Magnetic Monopoles

Blas Cabrera
Physics Department, Stanford University, Stanford, California 94305

(Received 5 April 1982)

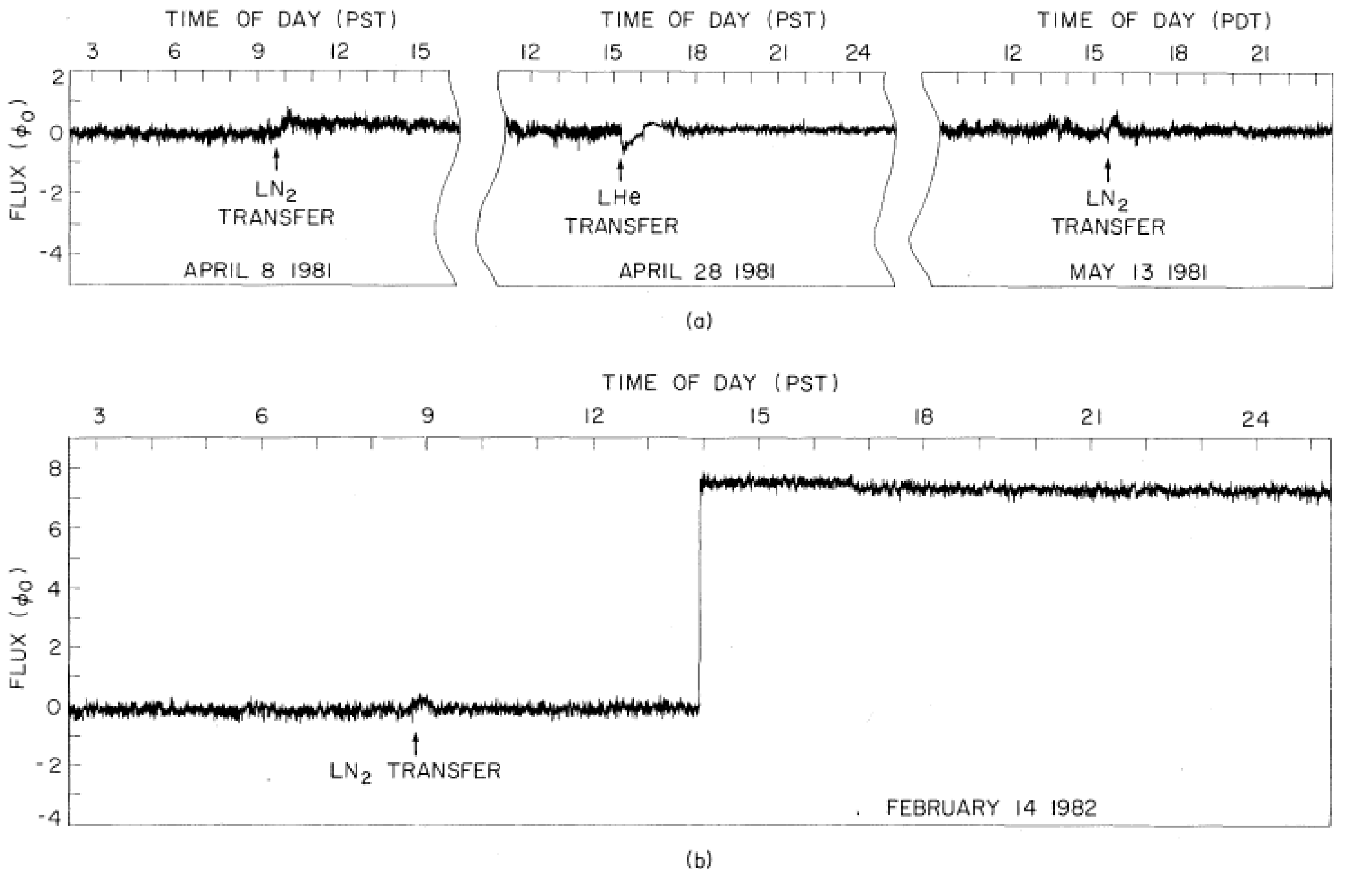


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

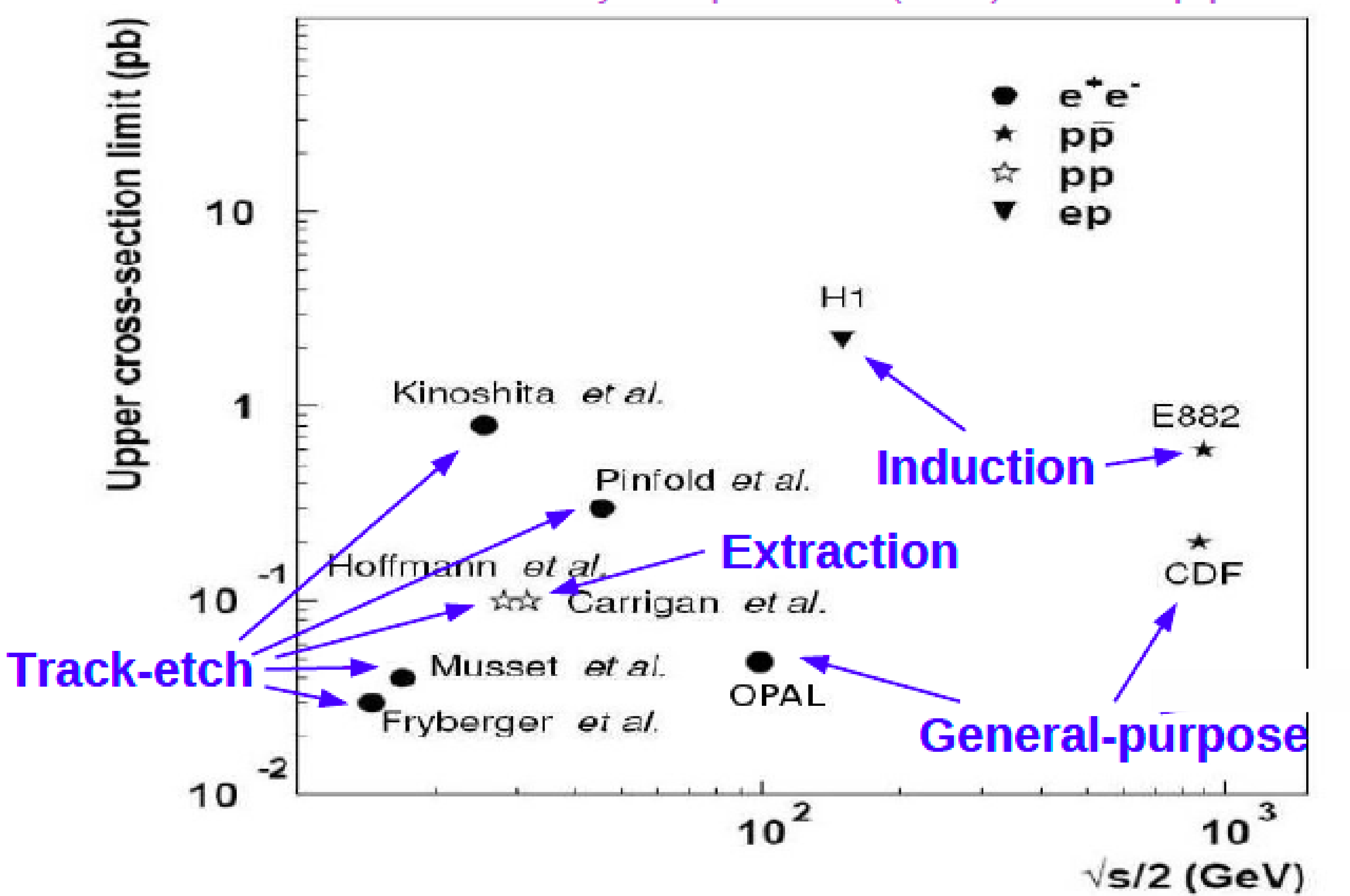
VOLUME 48, NUMBER 20 PHYSICAL REVIEW LETTERS 17 MAY 1982

Summary of past astrophysical searches

Experiment	Mass Range (GeV/c^2)	β range	Flux Upper Limit (cm^{-2} s^{-1} sr^{-1})	Detection Technique
AMANDA II Upgoing [26]	$10^{11} - 10^{14}$	$0.76 - 1$	$8.8 - 0.38 \times 10^{-16}$	Ice Cherenkov
AMANDA II Downgoing [26]	$10^{8} - 10^{14}$	$0.8 - 1$	$17 - 2.9 \times 10^{-16}$	Ice Cherenkov
AMANDA II (catalysis) [27]	$> 10^{11}$	$\simeq 10^{-3}$	5×10^{-17}	Ice Cherenkov
Baikal [28]	$10^{7} - 10^{14}$	$0.8 - 1$	$1.83 - 0.46 \times 10^{-16}$	Water Cherenkov
Baikal (catalysis) [29]	5×10^{13}	$\simeq 10^{-5}$	6×10^{-17}	Water Cherenkov
ANTARES [30]	$10^{7} - 10^{14}$	$0.65 - 1$	$9.1 - 1.3 \times 10^{-17}$	Water Cherenkov
Super-Kamiokande (catalysis) [31]	$> 10^{17}$	$10^{-5} - 10^{-2}$	$8 \times 10^{-27} - 3 \times 10^{-22}$	Water Cherenkov
MACRO [32]	$5 \times 10^{8} - 5 \times 10^{13}$	$> 5 \times 10^{-2}$	3×10^{-16}	Scint.+Stream.+NTDs
MACRO [32]	$> 5 \times 10^{13}$	$> 4 \times 10^{-5}$	1.4×10^{-16}	Scint.+Stream.+NTDs
MACRO (catalysis) [33]	5×10^{13}	$> 4 \times 10^{-5}$	$3 - 8 \times 10^{-16}$	Sctreamer tube
OHYA [34]	$5 \times 10^{7} - 5 \times 10^{13}$	$> 5 \times 10^{-2}$	6.4×10^{-16}	Plastic NTDs
OHYA [34]	$> 5 \times 10^{13}$	$> 3 \times 10^{-2}$	3.2×10^{-16}	Plastic NTDs
SLIM [20]	$10^{5} - 5 \times 10^{13}$	$> 3 \times 10^{-2}$	1.3×10^{-15}	Plastic NTDs
SLIM [20]	$> 5 \times 10^{13}$	$> 4 \times 10^{-5}$	0.65×10^{-15}	Plastic NTDs
MICA [35]	–	$10^{-4} - 10^{-3}$	$\sim 10^{-17}$	NTD
INDU Combined [9, 18]	$> 10^{5}$	–	2×10^{-14}	Induction

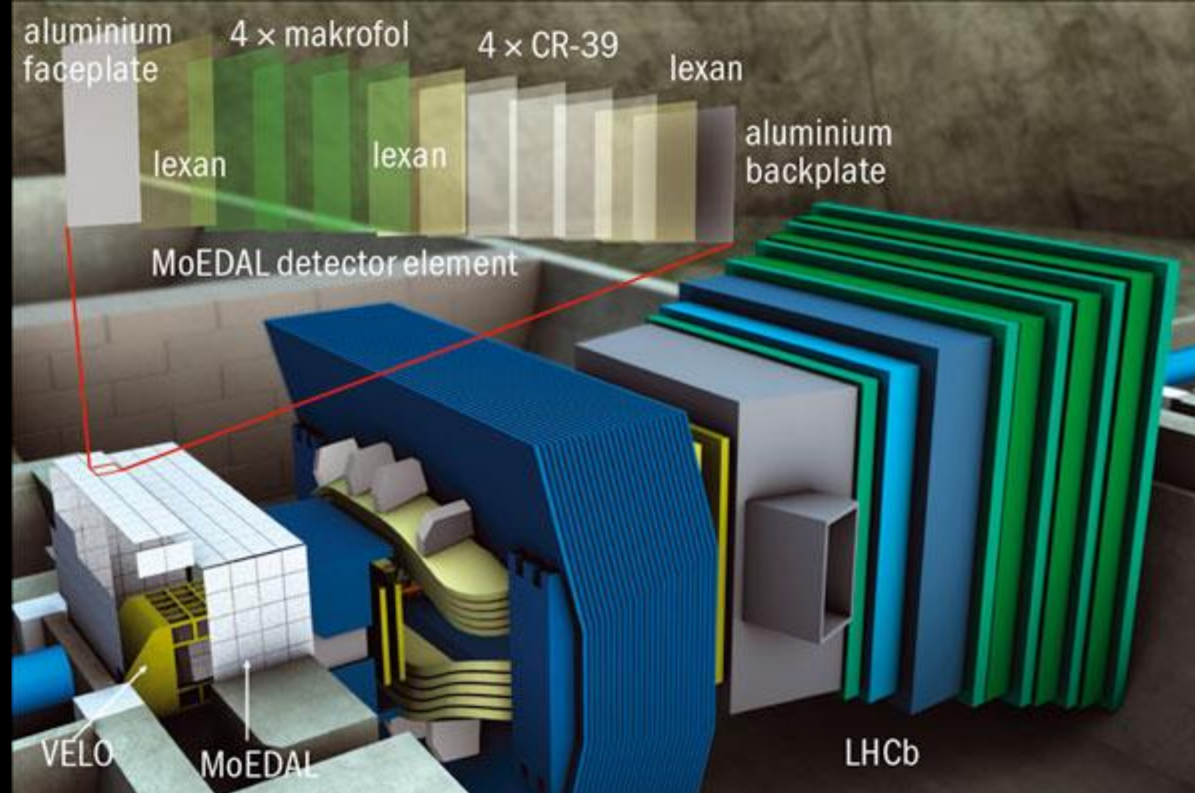
Summary of past Collider searches

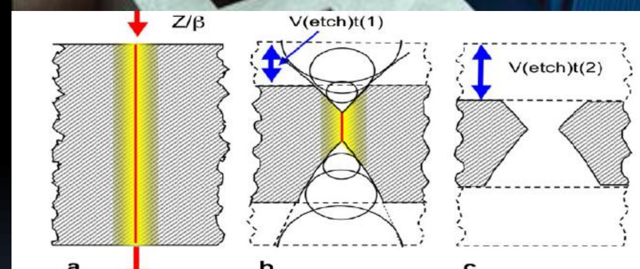
M. Fairbairn *et al.*, Phys. Rept. 438, 1 (2007), arXiv:hep-ph/0611040

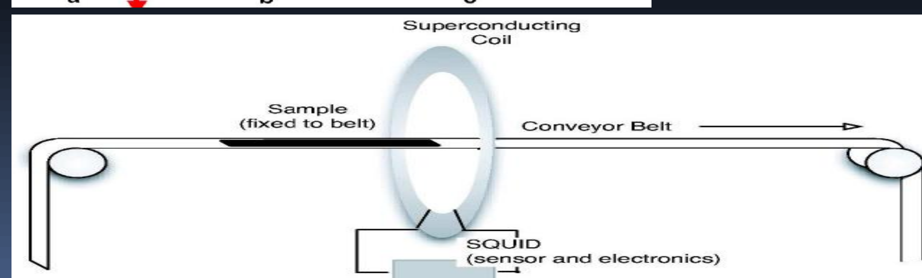


MoEDAL

- New experiment at CERN starts taking data in 2015
- Passive detectors around LHCb collision point
  - Nuclear Track Detectors
    - Thin plastic foils
    - Track-etch technique
  - Trapping Detectors
- Also sensitive to massive charged particles Z/β>~5







Classic dirac monopoles

- Point-like particle
  - Assume spin ½
- Magnetic charge

$$g = ng_D \Rightarrow \frac{g_D}{e} = \frac{\hbar c}{2e^2} = \frac{1}{2\alpha} \approx 68.5$$

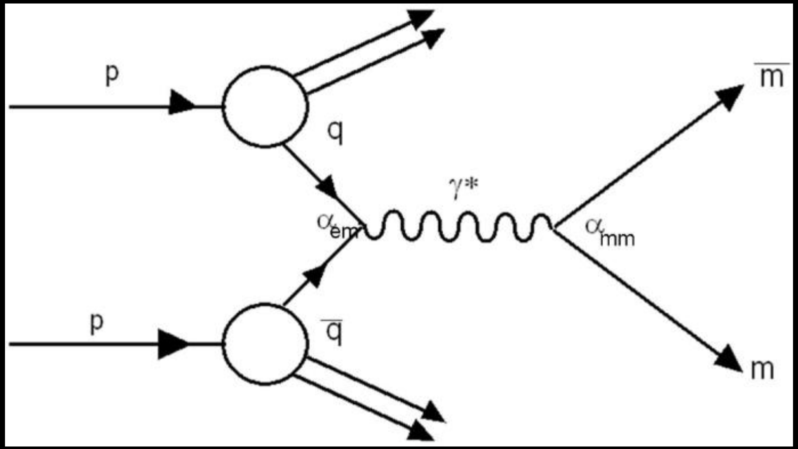
- Magnetic coupling

$$\alpha_{mm} = \frac{(g\beta)^2}{\hbar c} = \frac{1}{4\alpha}\beta^2 \sim 34.25$$

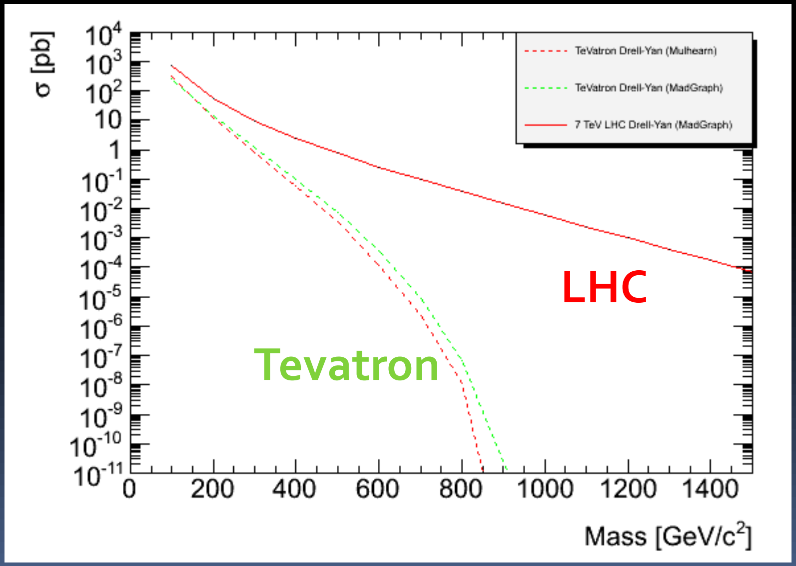
- Magnetic charge is conserved like electric charge → lowest mass magnetic monopole should be stable

Monopole Production Mechanism

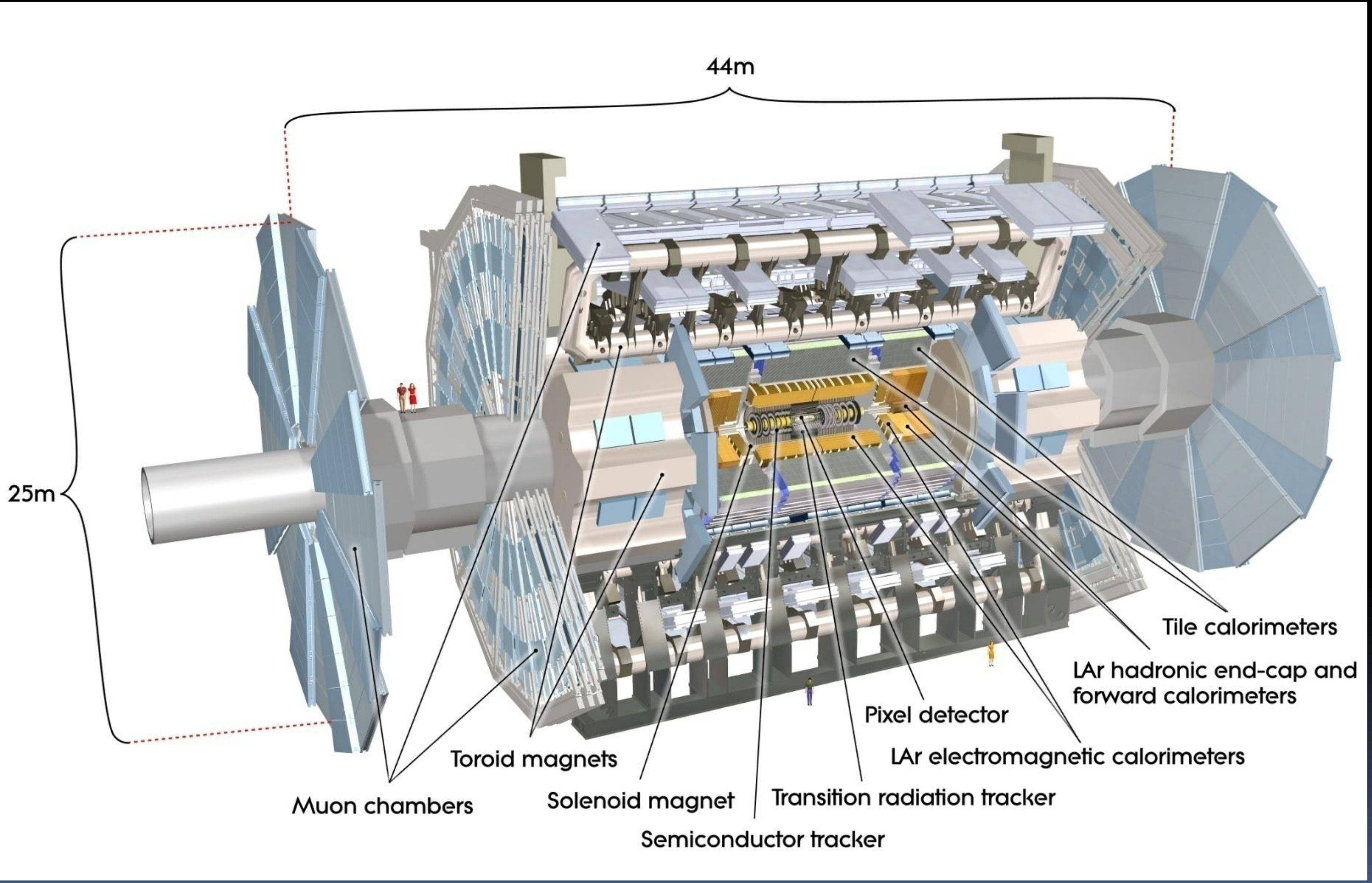
- Coupling constant α_{mm}~34 $\Rightarrow$ no perturbative expansion
- Often modelled by Drell-Yan pair production



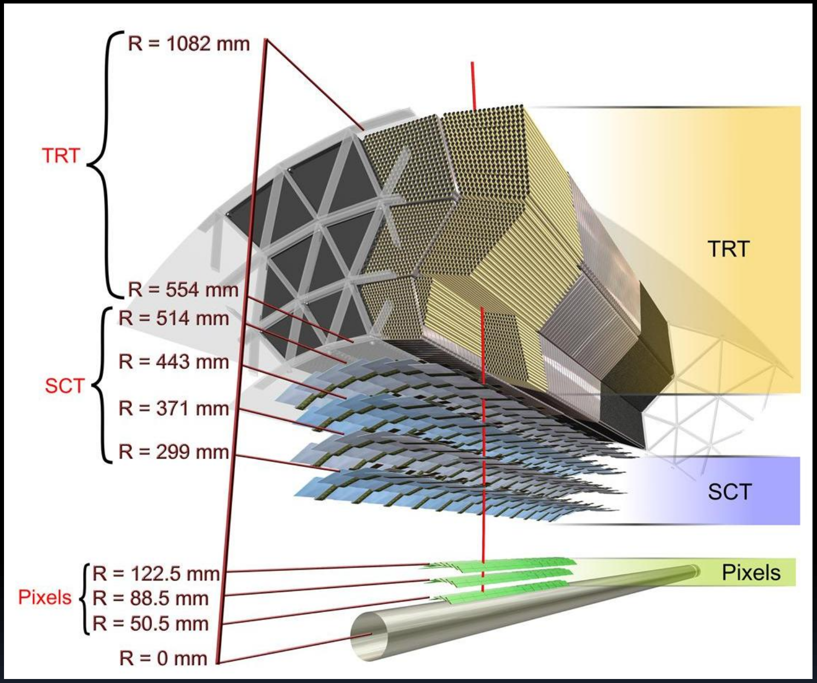
  - Calculation of cross-section derived from electron-electron scattering using naïve substitution e→gβ (cf. Milton, Schwinger, Kurochkin *et al.*)
  - Theoretical uncertainties are large, with no prospect of significant improvement

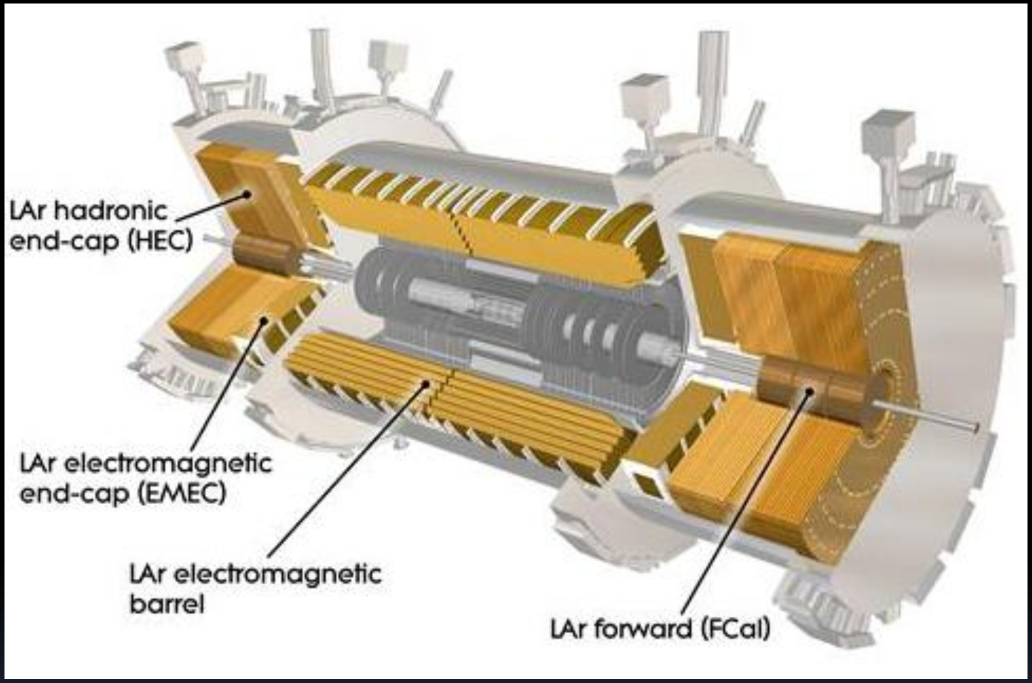


ATLAS Detector



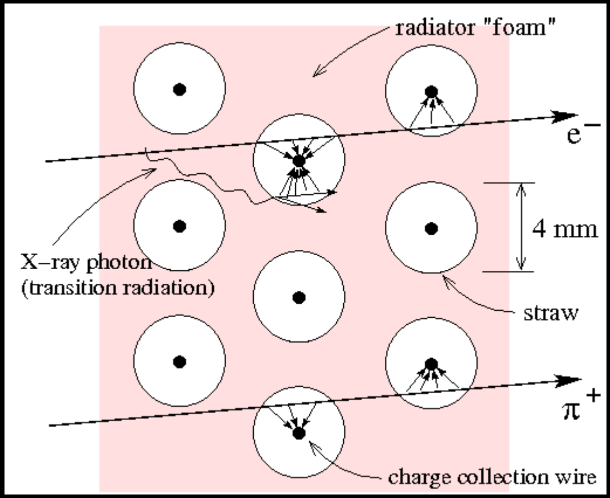
Transition Radiation Tracker and LAr Calorimeter

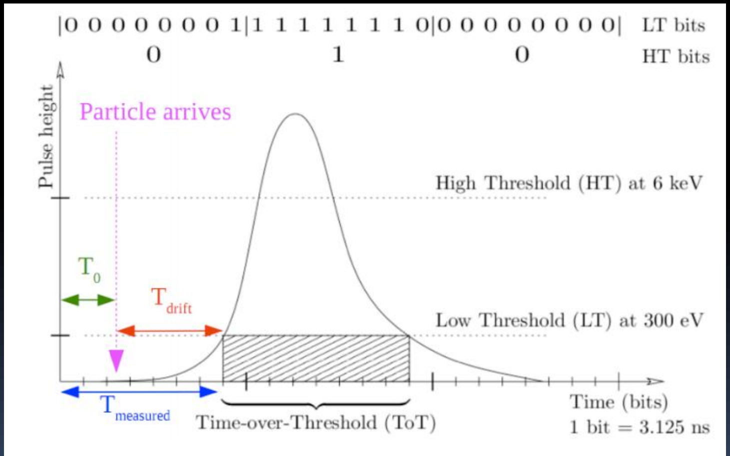




Transition Radiation Tracker (TRT)

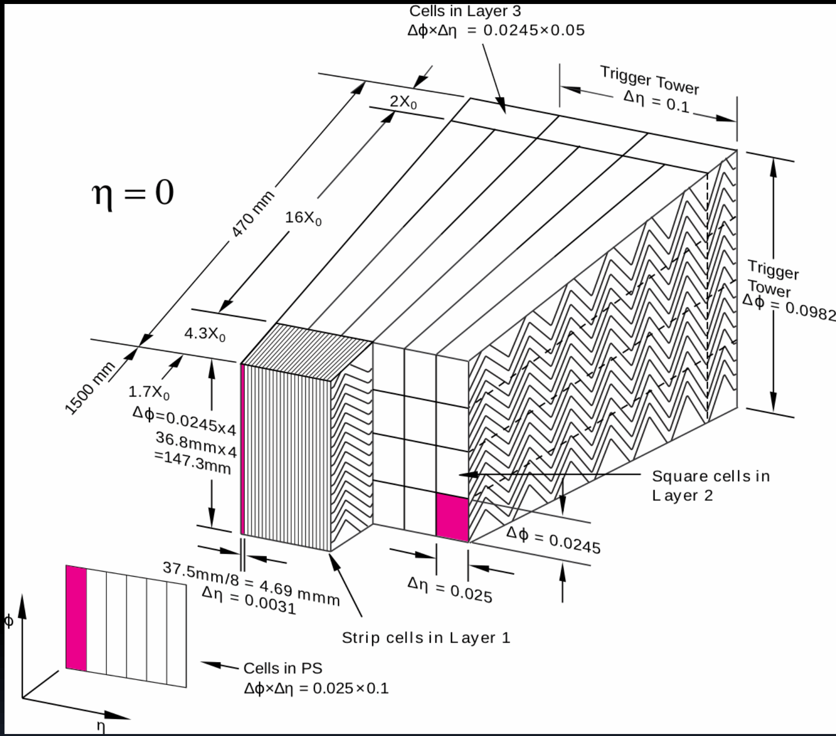
- Drift-tube straws filled with Xe gas
- Surrounded by radiator foils
  - Transition radiation photons deposit additional energy
- Two readout thresholds
  1. Low threshold (LT) for tracking
  2. High threshold (HT) for electron identification
- Large energy deposits from monopole and multiple δ-rays yield HT TRT hits





LAr Electromagnetic Calorimeter

- Second of three layers has best spatial resolution
- Ionizing particles in liquid argon create electron-ion pairs
- The electric field E_D = 10 kV/cm is applied to collect ionization electrons
  - Scale charge appropriately to determine energy deposited



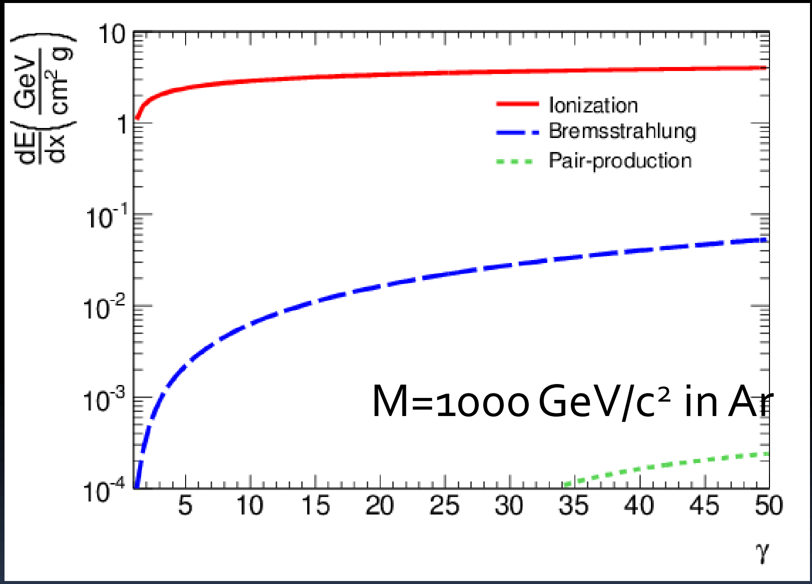
Monopole Energy loss

$$-\frac{dE}{dx} = \frac{4\pi e^2 g^2}{m_e c^2} N_e \left[\ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{I}\right) + \frac{K(|n|)}{2} - \frac{1}{2} - \frac{\delta}{2} - B(|n|) \right]$$

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

- Ionization dominates: $(ze_{eq})^2 = (g\beta)^2$
- For β=1 :

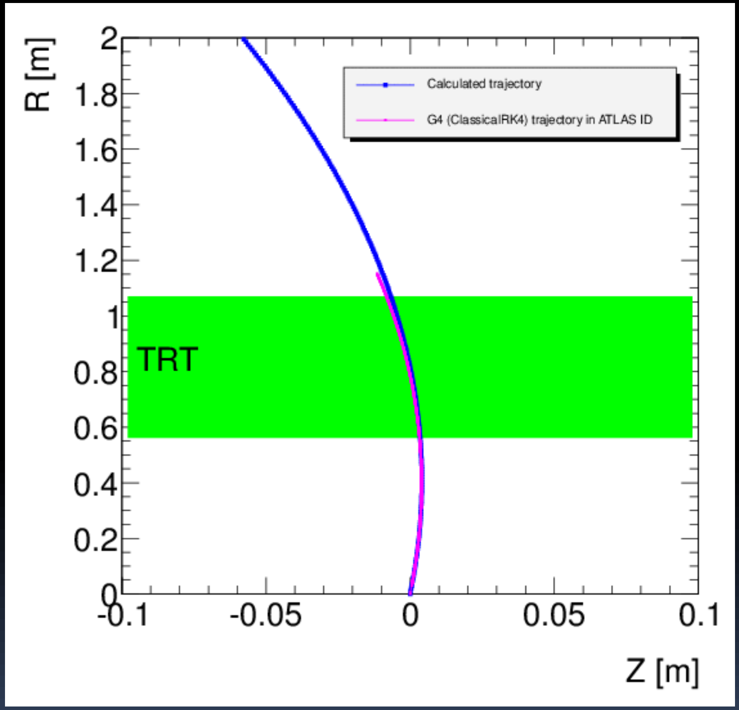
  $(dE/dx)_{mm} = 4700\ (dE/dx)_{m.i.p.}$
- Highly Ionizing Particle (HIP)
  - Narrow high-energy deposits
  - Lots of δ-rays near trajectory

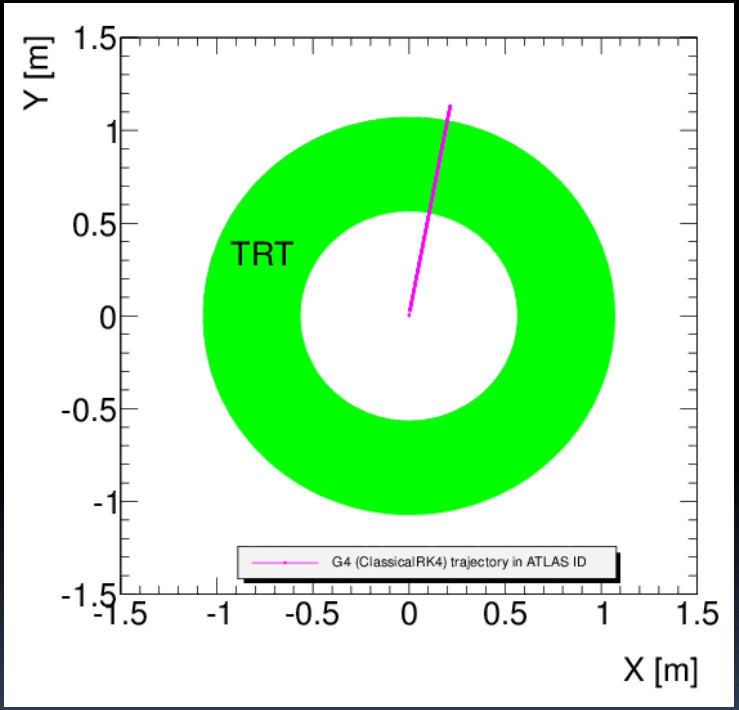


Equations of Motion

$$\frac{d\vec{p}}{dt} = g\vec{B}$$

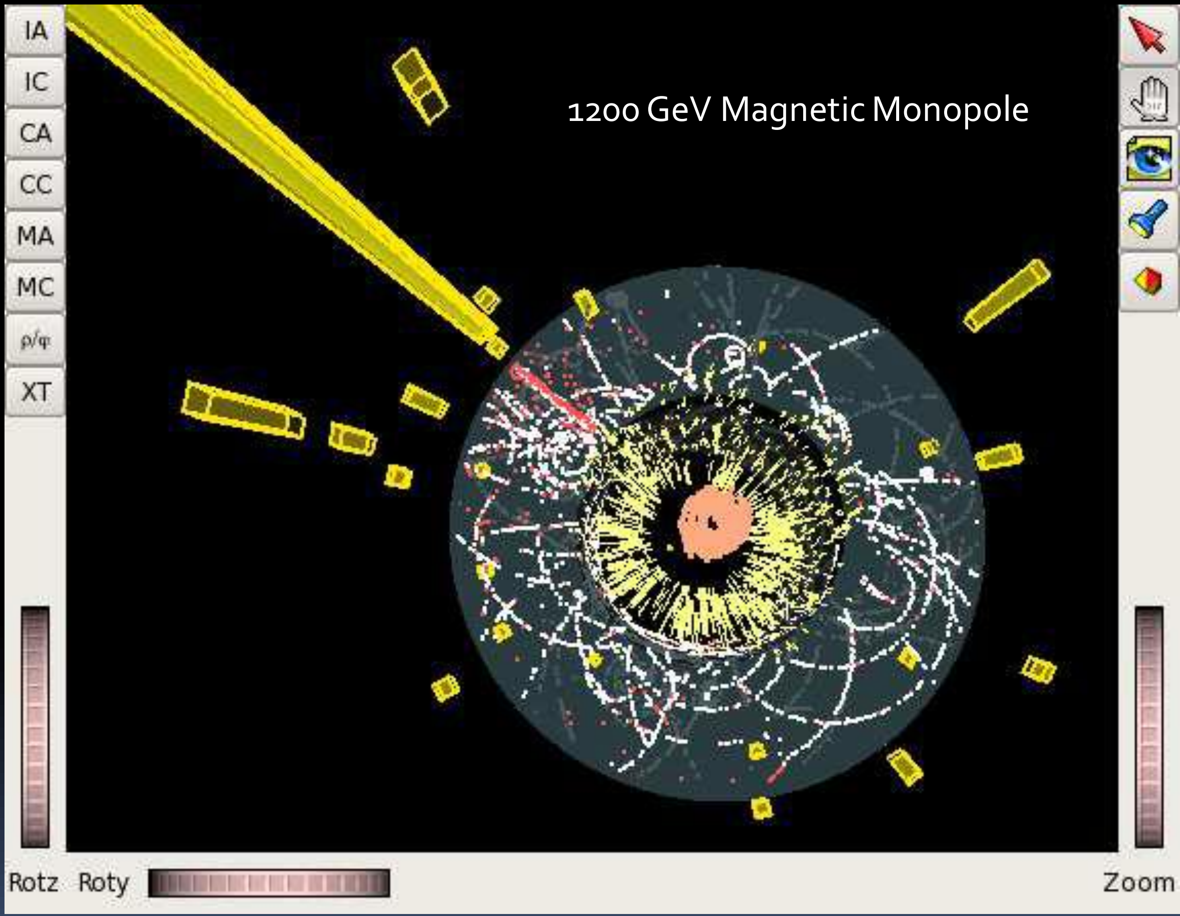
- Monopoles accelerated by magnetic field ⇒ bend in r-z plane but is straight in r-ϕ





Monopole Signature

- Straight r-ϕ track in the tracker
- Monopoles are highly ionizing
- Presence of many δ-rays
  - → lots of TRT high threshold hits
- Ionization dominates dE/dx
  - → No LAr calorimeter shower
  - → Narrow energy deposit



Analysis Strategy

- Search for straight r-ϕ track in the tracker
  - Many hits from δ-rays confuse standard tracking algorithm
    - Too many tracks are found
  - Use special reconstruction algorithm
    - Take only TRT hits for simplicity
  - Prove that hits from low energy δ-rays are understood
- Search for narrow cluster in the LAr calorimeter
  - Calibrate the LAr calorimeter recombination correction for highly ionizing particles using published heavy ion data
- Derive data-driven background estimate using ABCD method

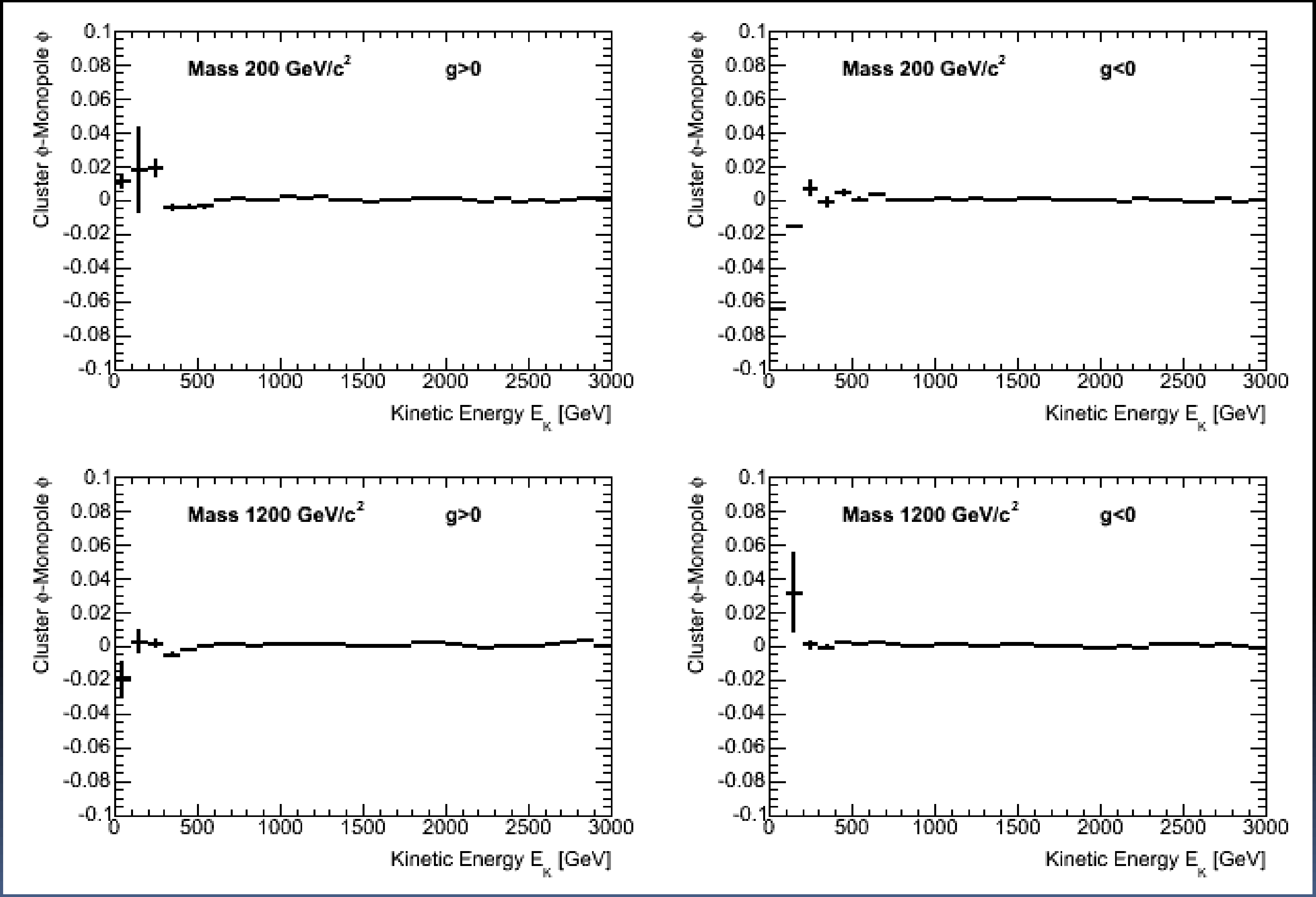
Analysis Strategy

- Want model-independent result as much as is possible
  - Use single-particle Monte Carlo (MC) samples to get E_K vs η efficiency maps
  - Extract a cross-section limit for monopoles produced in a given $E_K \sin\theta$ vs η range (*fiducial region*) where efficiency is high
- To set a mass limit and compare to CDF result [PRL96, 201801(2006)]
  - Assume Drell-Yan pair-production
  - Efficiency determined by kinematics
  - Cross-section prediction (with large uncertainties)

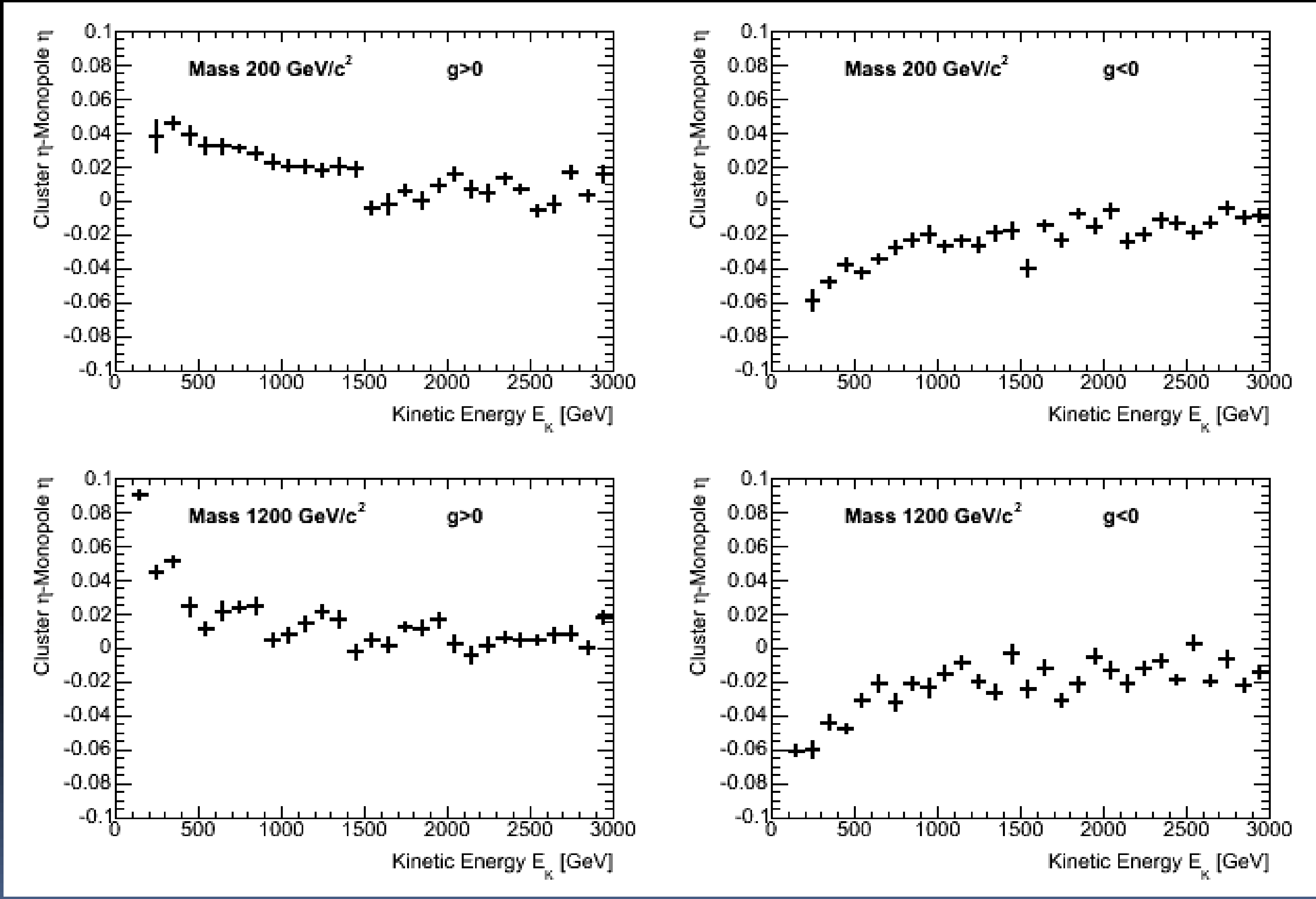
Monopole Monte Carlo Simulation

- Implement full GEANT4 simulation of magnetic monopoles
  - Equations of motion
  - Ionization
  - δ-ray production
  - LAr recombination correction for highly ionizing particles

No Bending in r-φ Plane



Bending as Expected in r-z Plane



Recombination in LAr Calorimeter

- Some electron-ion pairs may recombine
  - Electrons that have recombined will not be collected by electrodes ⇒ ionization signal is reduced and energy deposition is underestimated
- Birks' Law describes electron-ion recombination effects

$$E_{vis} = E_0 \frac{1}{1 + k/(E_D \rho_{LAr})\ dE/dx}$$

J. B. Birks, Proc. Phys. Soc A64 (1951) 874.

- Default Birks' constant measured with ICARUS LAr Time Projection Chamber using cosmic ray muons and protons

$$k = 0.0486 \pm 0.0006 (\mathrm{kV/cm})(\mathrm{g/cm^2})/\mathrm{MeV}$$

S. Amoruso *et al.*, NIM A523, 275 (2004).

→ over-suppresses signal at high dE/dx

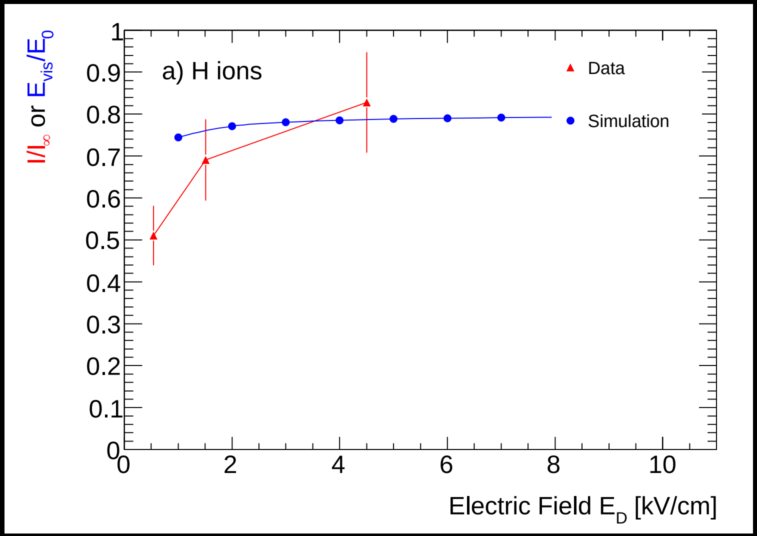
Extending Birks' Law to HIPs

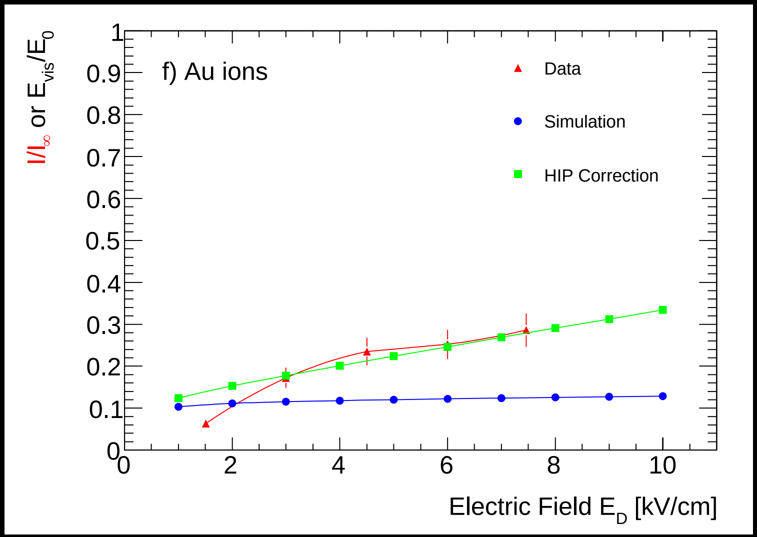
- Used GEANT4 to simulate heavy ion beams traversing a box of LAr
- Compared simulation to published experimental heavy ion results

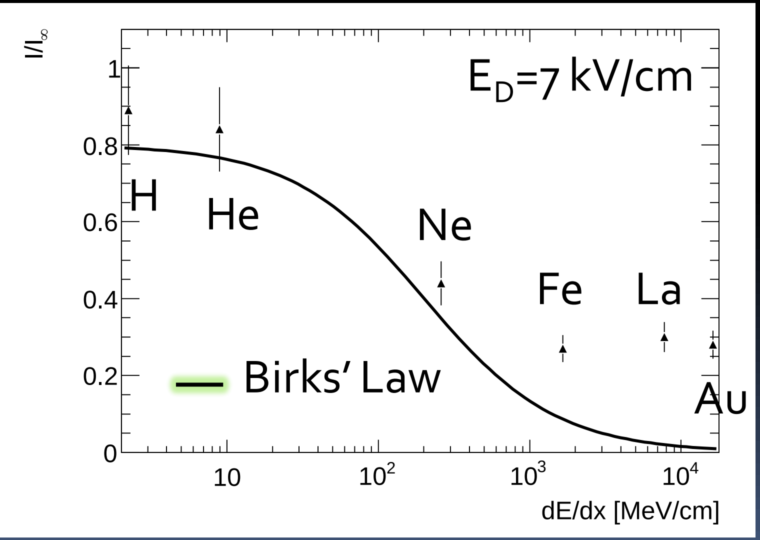
Ion property	H	He	Ne	Fe	La	Au
Charge ($\|e\|$)	1	2	10	26	57	79
Mass (GeV/c^2)	0.93885	3.7284	18.797	52.019	129.390	183.473
Kinetic energy (GeV)	1.048	4.1627	12.370	39.371	169.46	171.36
dE/dx (MeV/cm)	2.235	8.95	259.26	1655	7750	16 200
dE/dx (MeV/cm) (our simulation)	1.895	7.42	223.28	1470	6218	13 141

1. E. Shibamura *et al.*, Nucl. Instrum. Meth. A260, 437 (1987).
2. T. Doke *et al.*, Nucl. Instrum. Meth. A235, 136 (1985).
3. H.J. Crawford *et al.*, Nucl. Instrum. Meth. A256, 47 (1987).

Heavy ion Data-Simulation Comparison



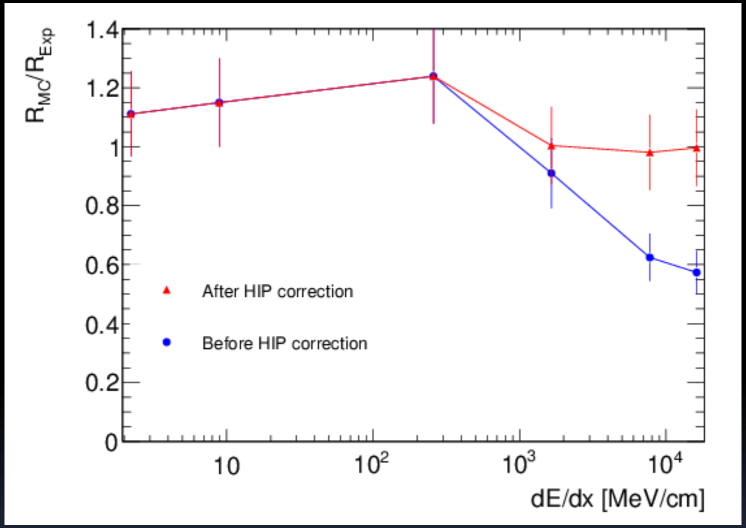




- MC significantly underestimates visible energy for high dE/dx
- Parameterize this discrepancy for HIP visible energy correction

HIP Correction to Birks' LAW IN LAR

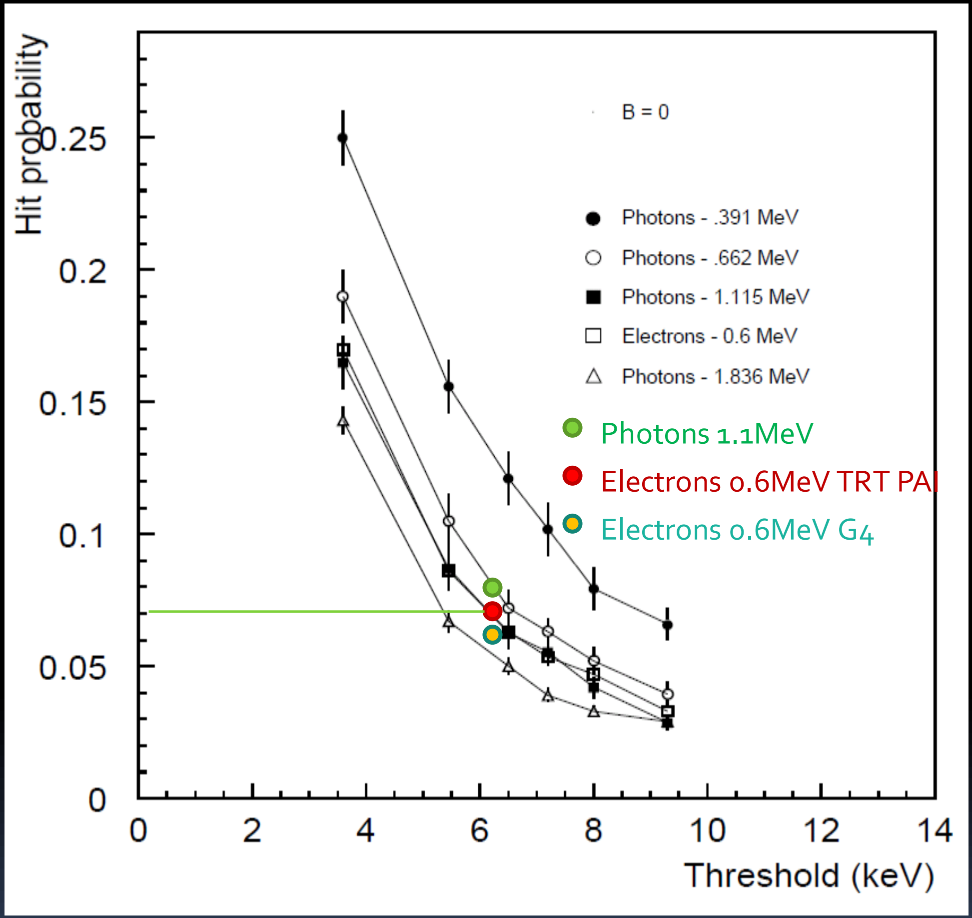
- Birks' Law describes electron-ion recombination effects in LAr ⇒ over-suppresses signal at high dE/dx
- Use published heavy ion data in LAr to derive HIP correction



- Burdin, Horbatsch & Taylor, Nucl. Instrum. Meth. A664 (2012) 111.

δ-Rays in the TRT

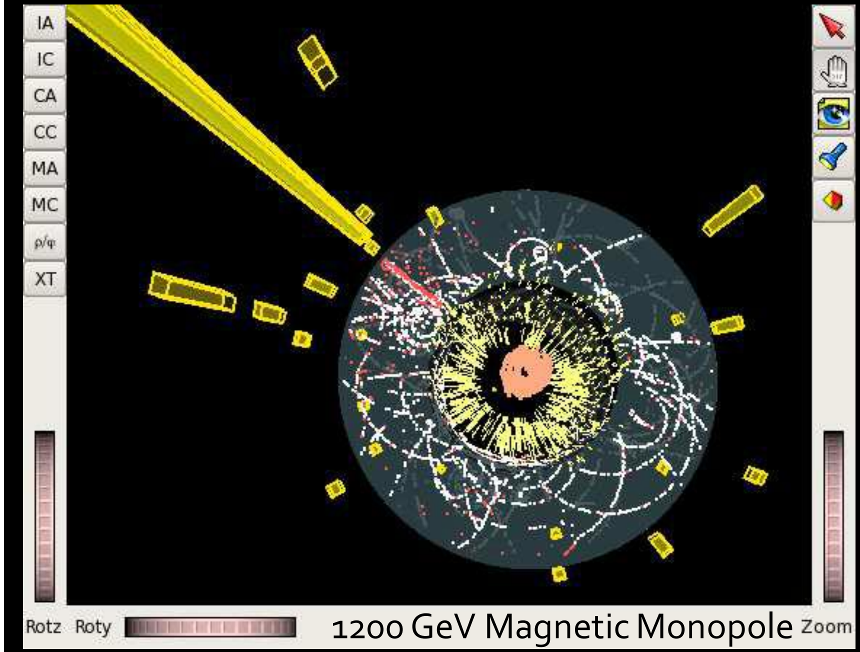
- Propagation and dE/dx of low energy δ-electrons in TRT simulation have been validated by comparison of the simulation to teststand measurements done by A.Romaniouk in 1995

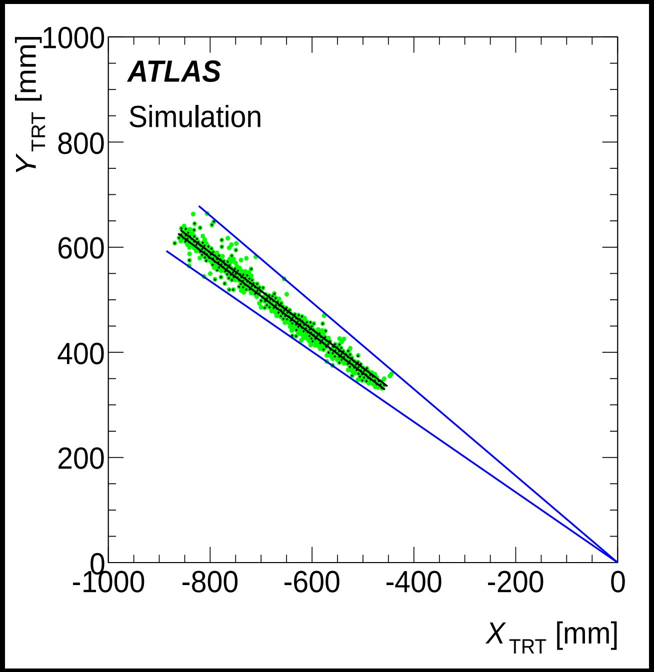


Monte-Carlo Samples

- Signal samples
  - Single particle samples for m=200-1500 GeV/c^2
  - MadGraph Drell-Yan samples for m=200-1200 GeV/c^2
- Background samples
  - Dijet events of various transverse momentum ranges
  - $Z \rightarrow ee$, $W \rightarrow e\nu$
  - γ+jets
  - t-tbar

Monopole Reconstruction





- Use electron trigger of 60 GeV threshold
- Look for narrow cluster in LAr calorimeter
- Count number of TRT hits in window around cluster
  - Select events where the number of TRT hits and the fraction of HT hits are above some threshold

Final Selection Variables

- EM cluster size σ_R

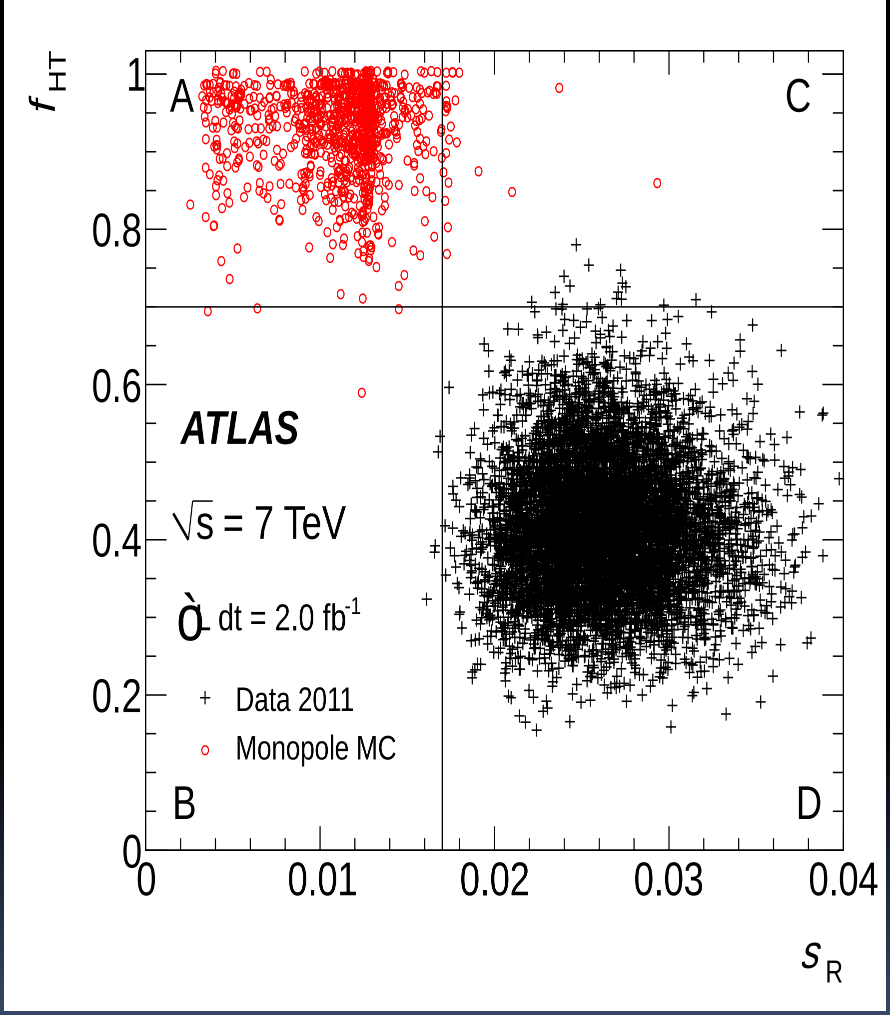
$$\sigma_\phi^2 = \sum (E_i \delta\phi_i^2) / \sum E_i - \left[\sum (E_i \delta\phi_i) / \sum E_i\right]^2$$

$$\sigma_\eta^2 = \sum (E_i \delta\eta_i^2) / \sum E_i - \left[\sum (E_i \delta\eta_i) / \sum E_i\right]^2$$

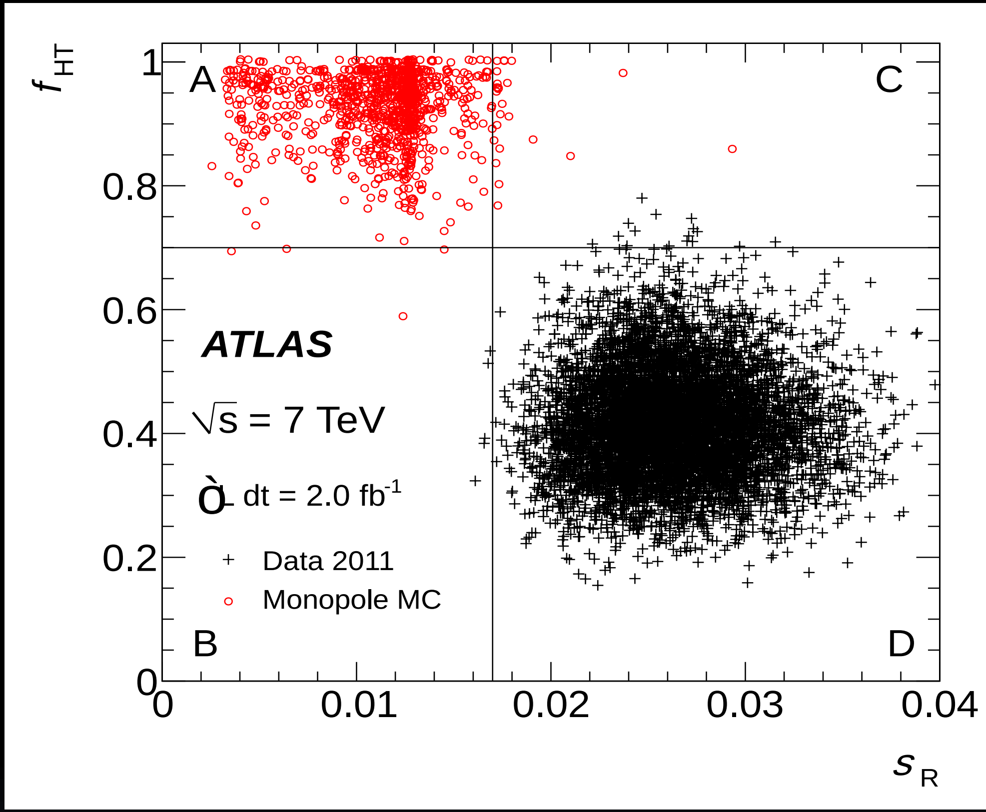
$$\sigma_R = \sqrt{\sigma_\phi^2 + \sigma_\eta^2}$$

- High-threshold TRT hit fraction

f_{HT}=nHTTRT/nTRT

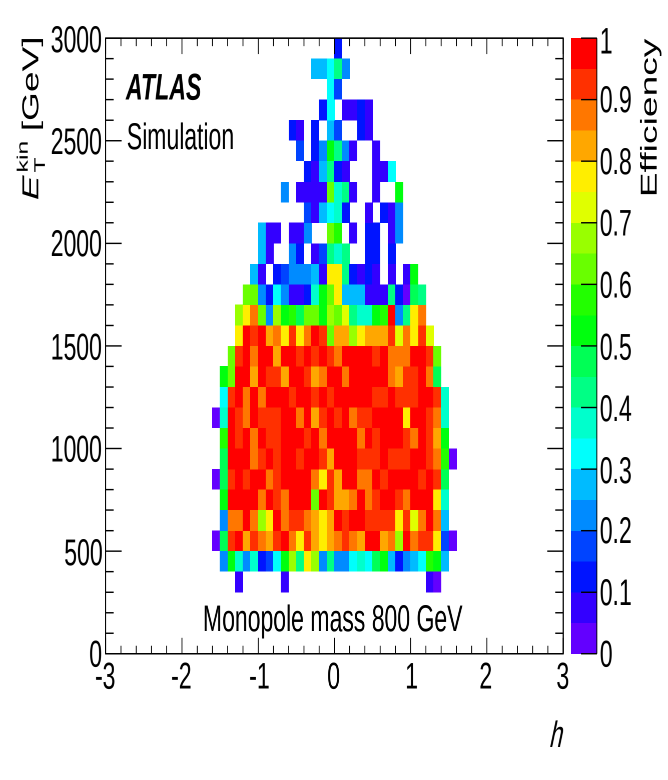


No events in the signal region



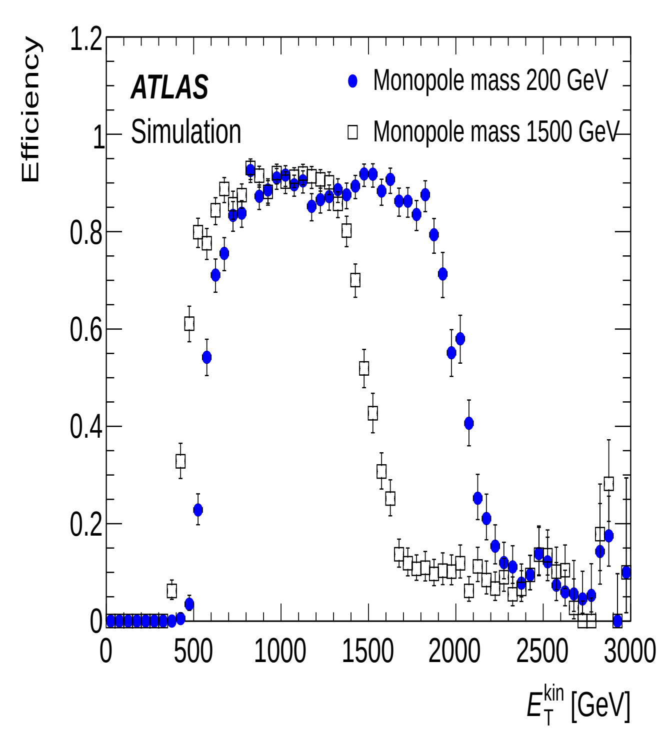
- No events observed in 2 fb^{-1}
  $\rightarrow n_A=0,\ n_B=5,\ n_C=16,\ n_D=7001$
- Expected background in the signal region A: $\mu_{bkg}=0.022\pm0.018$

Efficiencies (Includes ACCEPTANCE)



Single-particle events

$|\eta|<1.37$

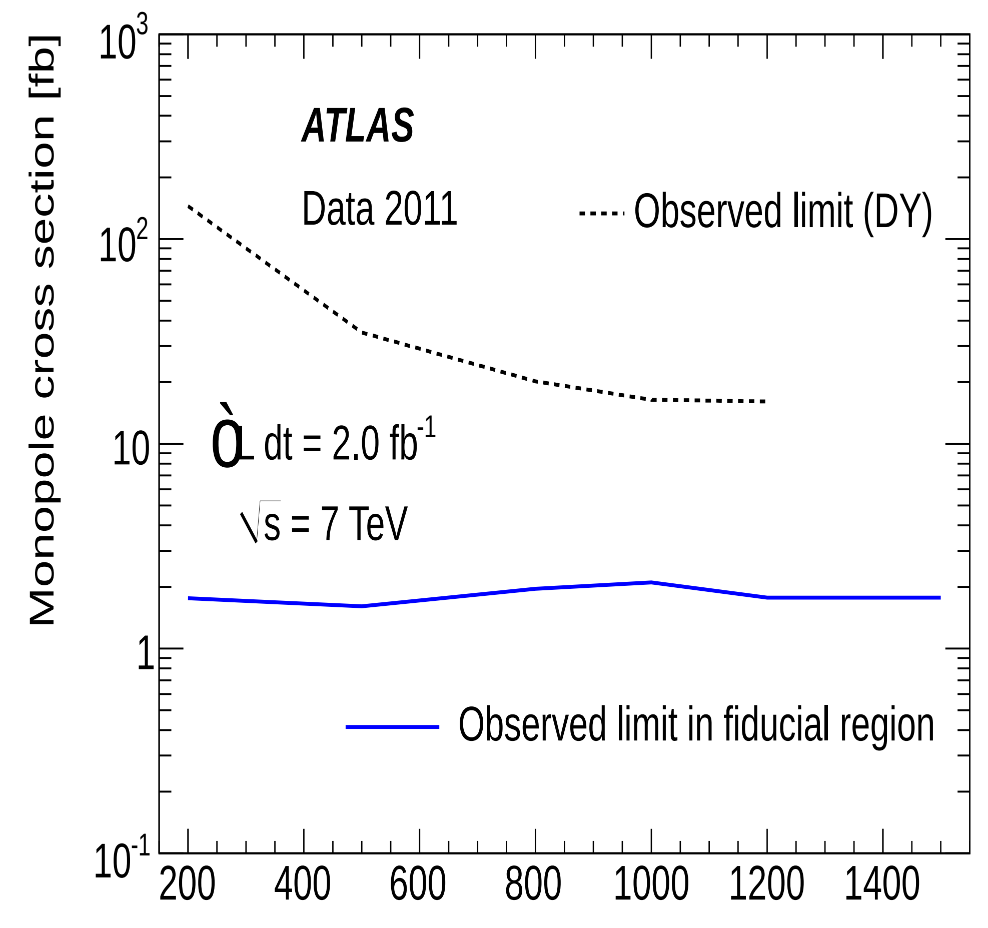


Drell-Yan events

Mass (GeV)	200	500	800	1000	1200
Efficiency	0.011	0.048	0.081	0.095	0.095
Relative uncertainty					
Upper (%)	+32	+24	+22	+23	+20
Lower (%)	−36	−23	−22	−25	−25

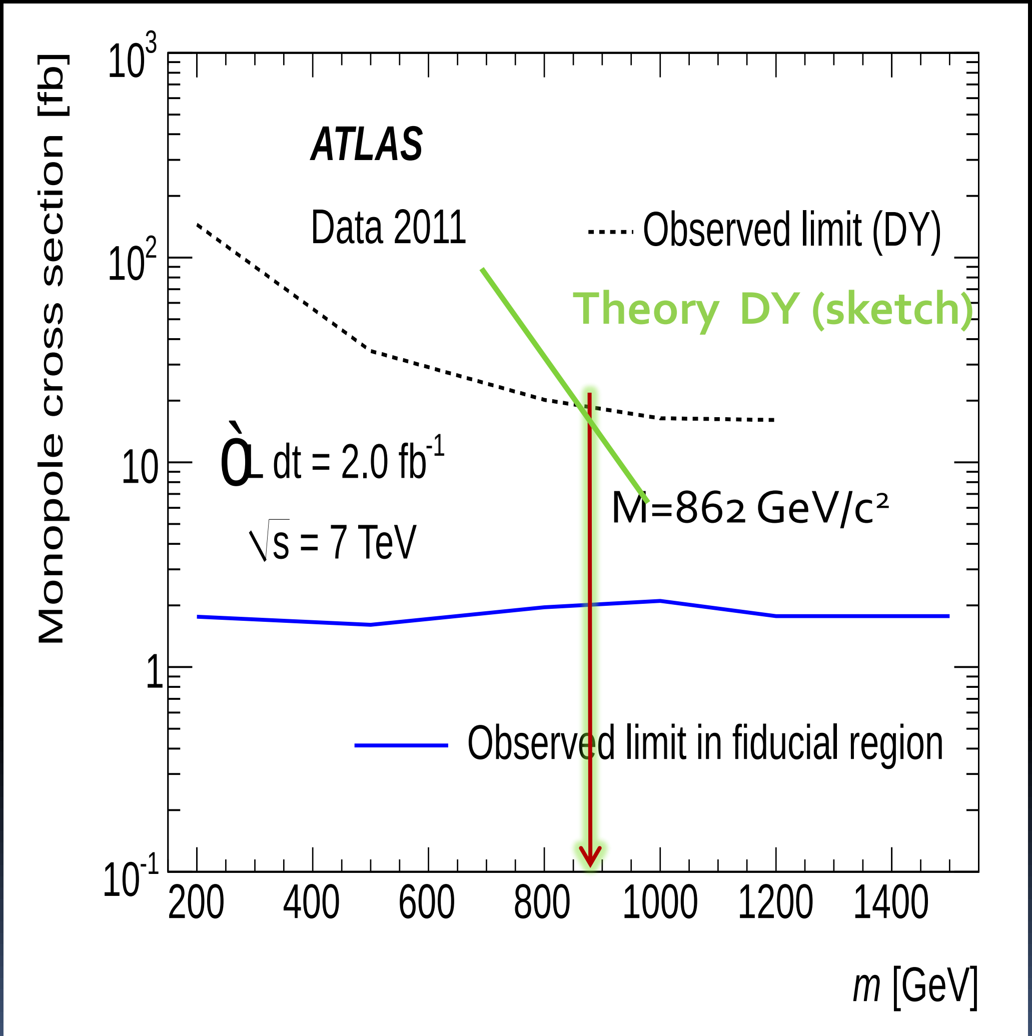
Results

- Given no data events observed in the signal region the CLs method yields 95% CL limits for different monopole masses distributed around 3 events
  - Converted to cross-sections using either number of expected signal events in case of the DY production mechanism or directly using efficiency (80%) and luminosity in the case of the model-independent production mechanism



G. Aad et al., PRL **109**, 261803 (2012).

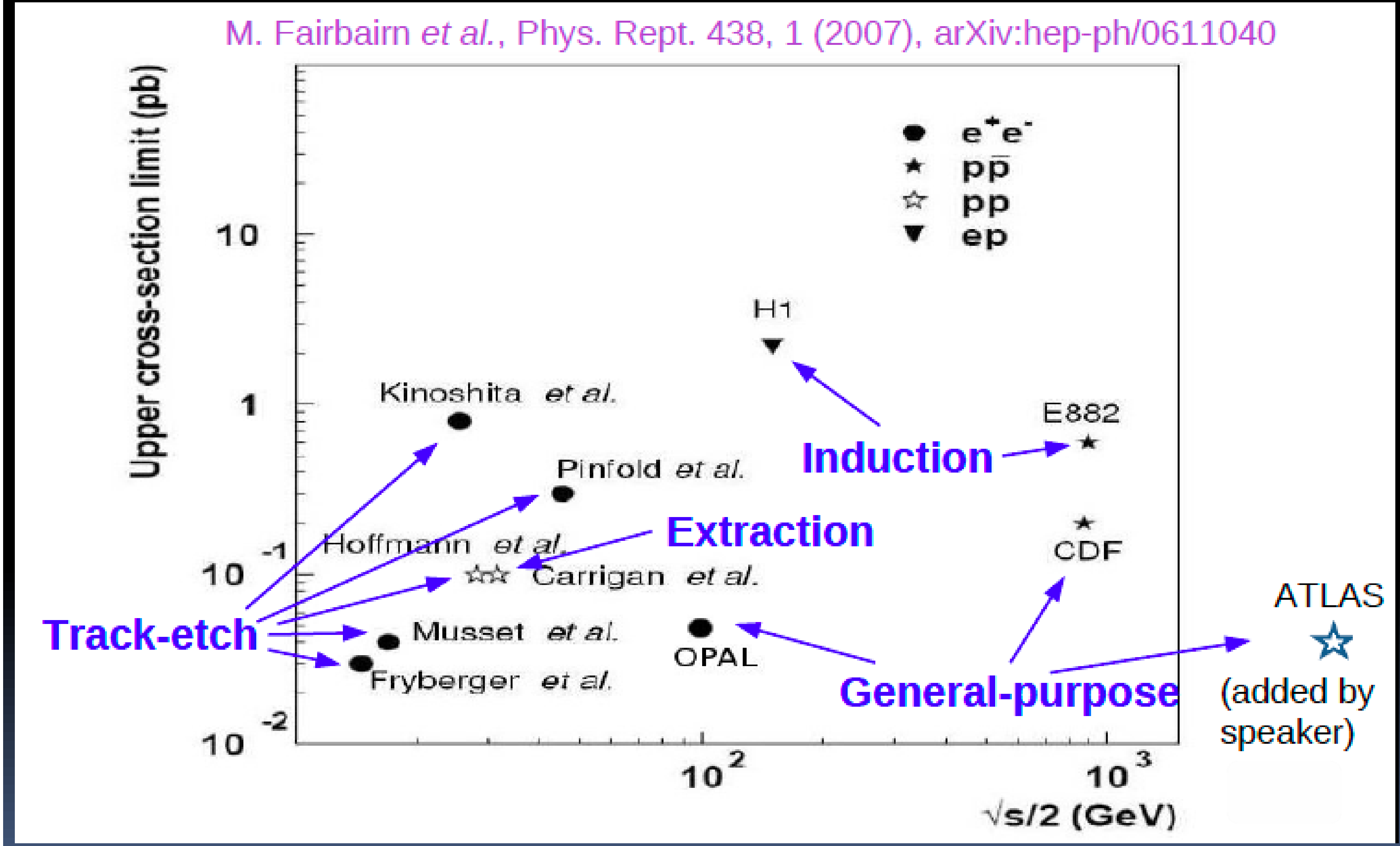
Drell-Yan mass limit



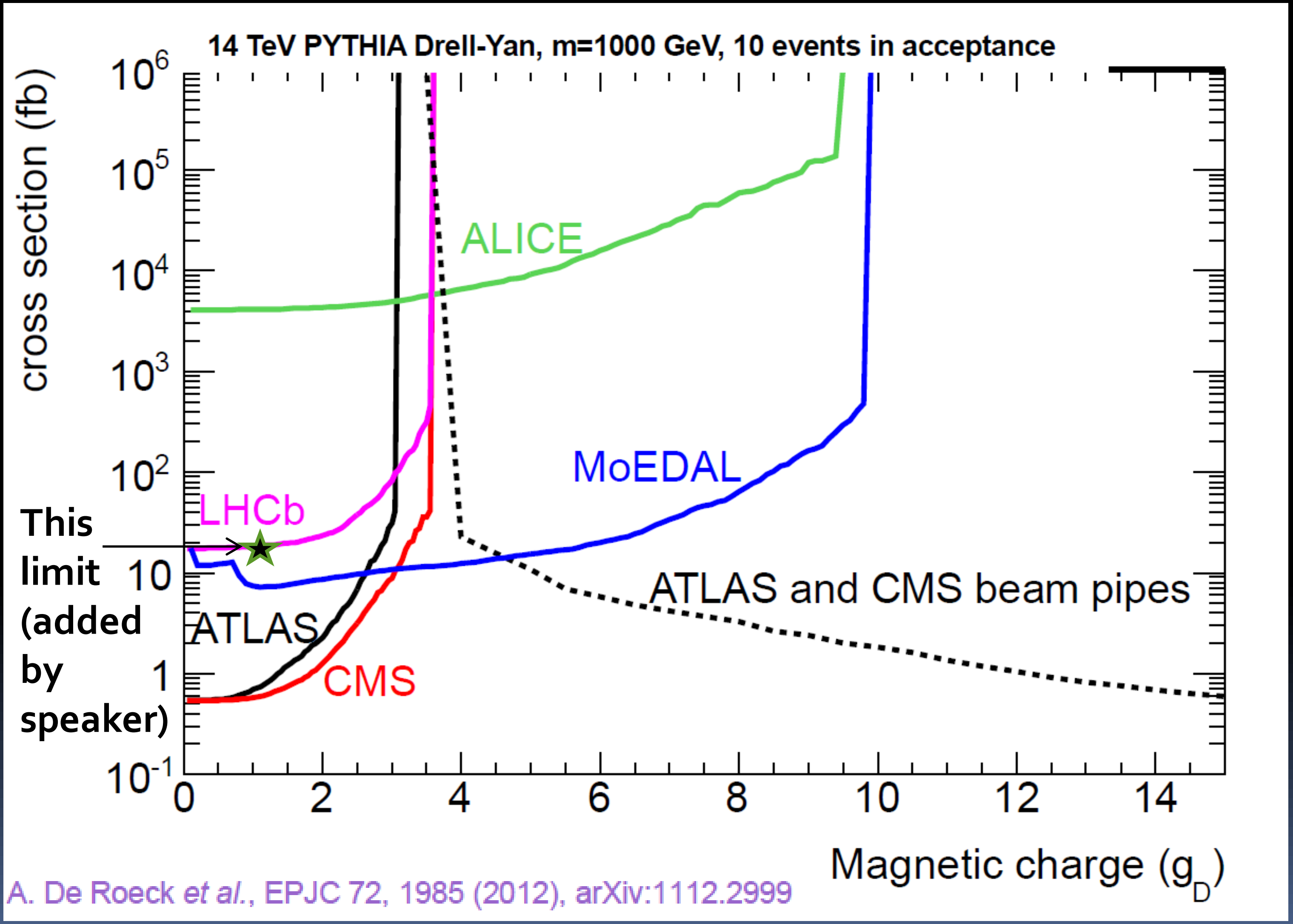
Future monopole searches at ATLAS

- A new trigger was introduced in September 2012 to select magnetic monopoles
  - Uses a reconstruction algorithm similar to 2011 analysis
  - L1 EM threshold is reduced to 18 GeV → better efficiency for lower energy monopoles
- Extend search to higher magnetic charges, dyons, spin-O
- A proposal for a TRT-based L1 hardware trigger is being prepared

Collider cross-section limits

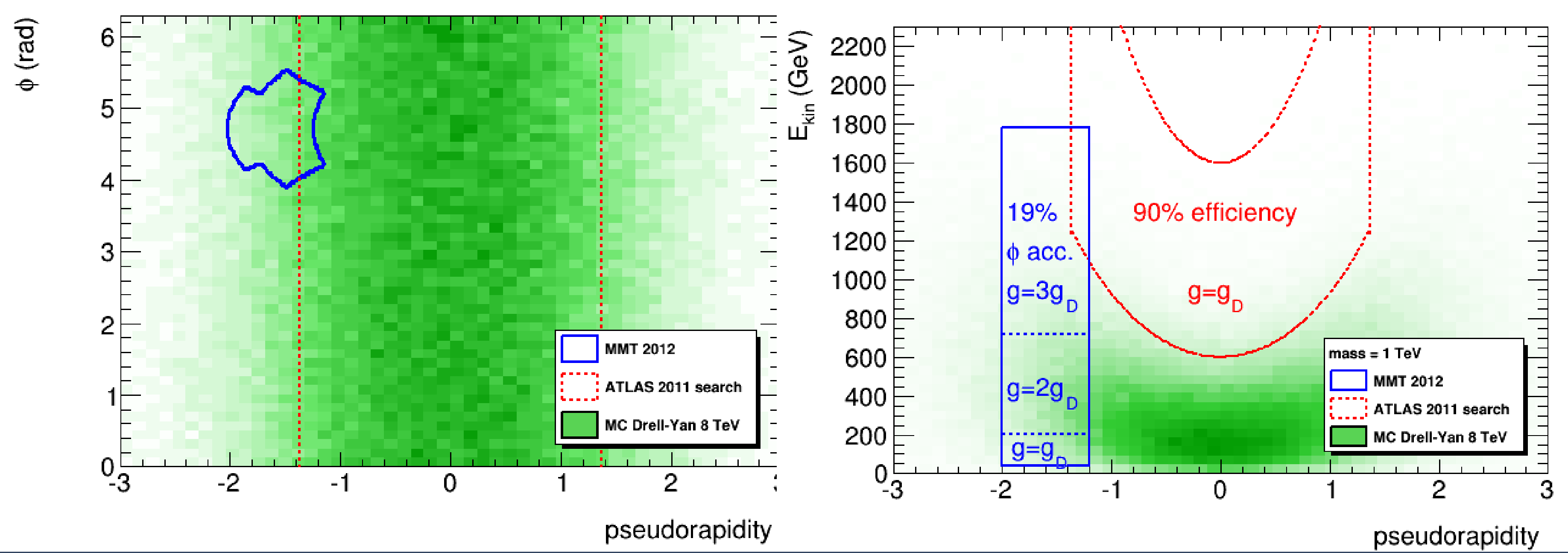


Prospects for LHC searches (after ~2 years @14TeV)



Comparison to the first results from MoEDAL

- First results from MoEDAL Magnetic Monopole Trapper were presented by Philippe Mermod (University of Geneva) at the EPS2013



Conclusion

- First LHC search for monopole has been published (**PRL 109 261803 (2012)**)
  - We set the reference
- No magnetic monopole yet but
- "one would be surprised if Nature had made no use of it." (Dirac, 1931)