Magnetic Monopoles at the LHC

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for the ATLAS and MoEDAL Collaborations

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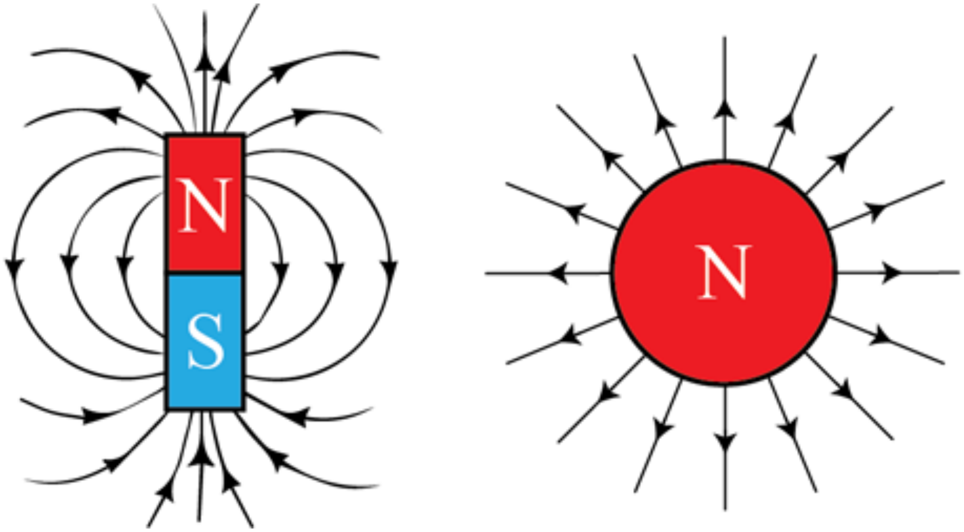
Magnetic monopoles



Tom Whyntie

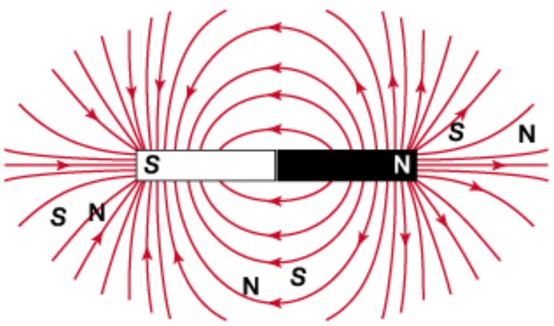
Monopoles: symmetrising Maxwell

- As no magnetic monopole had ever been seen, Maxwell kept isolated magnetic charges out from his equations – making them *asymmetric*
- A magnetic monopole restores the symmetry to Maxwell's equations

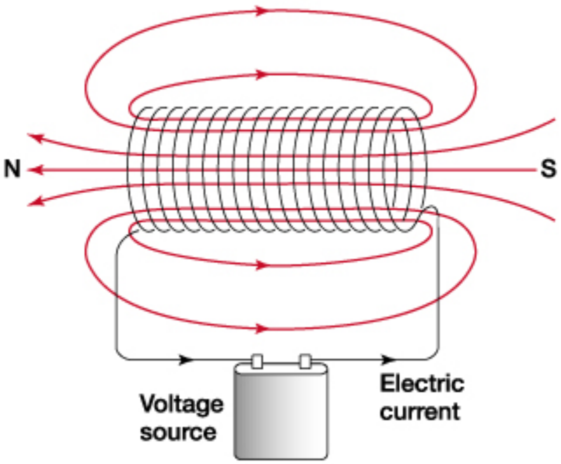
Laws	Without magnetic monopoles	With magnetic monopoles
Gauss's law	$\boldsymbol{\nabla}\cdot\mathbf{E} = 4\pi\rho_e$	$\boldsymbol{\nabla}\cdot\mathbf{E} = 4\pi\rho_e$
Gauss's law for magnetism	$\boldsymbol{\nabla}\cdot\mathbf{B} = 0$	$\boldsymbol{\nabla}\cdot\mathbf{B} = 4\pi\rho_m$
Faraday's law	$-\boldsymbol{\nabla}\times\mathbf{E} = \frac{\partial\mathbf{B}}{\partial t}$	$-\boldsymbol{\nabla}\times\mathbf{E} = \frac{\partial\mathbf{B}}{\partial t} + 4\pi\mathbf{J}_m$
Ampère's law	$\boldsymbol{\nabla}\times\mathbf{B} = \frac{\partial\mathbf{E}}{\partial t} + 4\pi\mathbf{J}_e$	$\boldsymbol{\nabla}\times\mathbf{B} = \frac{\partial\mathbf{E}}{\partial t} + 4\pi\mathbf{J}_e$

- Symmetrised Maxwell's equations invariant under rotations in (**E**, **B**) plane of the electric and magnetic field ➤ Duality
- In addition, magnetic monopole explain electric-charge quantisation

Dirac's Monopole



- Paul Dirac in 1931 hypothesised that the magnetic monopole exists
- In his conception the monopole was the end of an infinitely long and infinitely thin solenoid
- Dirac's quantisation condition:

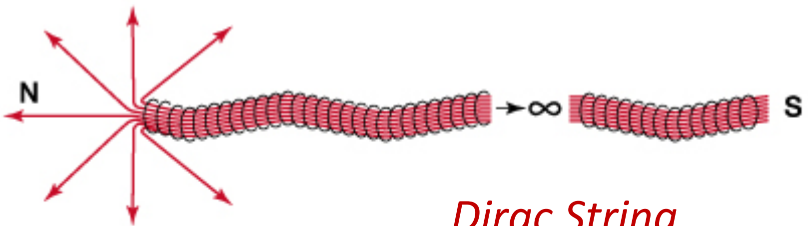


$$ge = \left[\frac{\hbar c}{2}\right] n \quad OR \quad g = \frac{n}{2\alpha} e \quad \left(from \ \frac{4\pi e g}{\hbar c} = 2\pi n \quad n = 1,2,3..\right)$$

  - where g is the "magnetic charge" and α is the fine structure constant 1/137

- This means that **g = 68.5e** (when n=1)!
- If magnetic monopole exists, then electric charge is quantised:

$$e = \left[\frac{\hbar c}{2g}\right] n$$

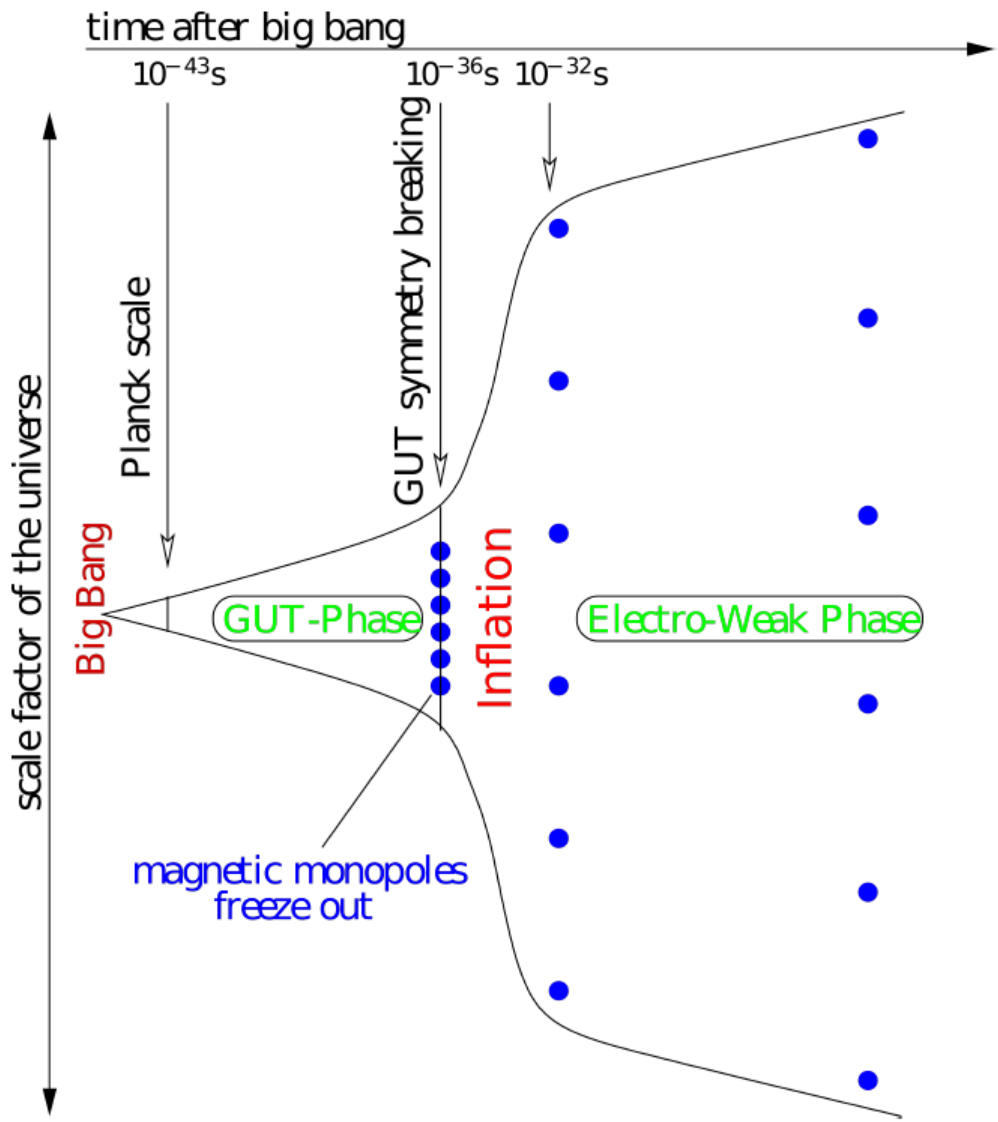


Dirac String

GUT monopoles

- ´t Hooft and Polyakov (1974) showed that monopoles are fundamental solutions to non-Abelian gauge grand unification theories (GUTs)
- **Topological solitons**: stable, non-dissipative, finite-energy solutions
- Size: **extended object**
  - radius > few femtometers
- Mass: ~ $\mathbf{10^{16} – 10^{17}}$ **GeV**

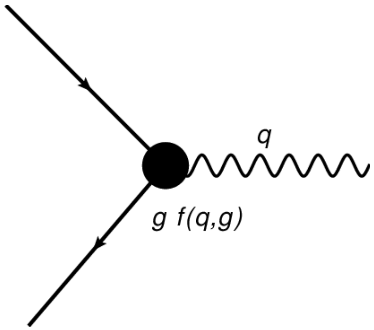
  → cannot be produced in particle accelerators



T. Glüsenkamp 10

Monopole properties in a nutshell

- Single magnetic charge (Dirac charge): $g_D = 68.5e$
  - higher charges are integer multiples of Dirac charge: $g = ng_D$, $n = 1, 2, \ldots$
  - if carries electric charge as well, is called Dyon
- Photon-monopole coupling constant
  - large: $g/\hbar c \sim 20$ (precise value depends on units)
  - following duality arguments, may be β-dependent, $\beta = \sqrt{1 - \frac{4M^2}{s}}$



- Monopoles would *accelerate* along field lines – and *not curve* as electrical charges in a magnetic field – according to the Lorentz equation

$$\vec{F} = g\left(\vec{B} - \vec{v} \times \vec{E}\right)$$

- Dirac monopole is a point-like particle; GUT monopoles are extended objects
- Monopole spin is not determined by theory → free parameter
- Monopole mass not theoretically fixed → free parameter
- Monopole interaction with matter: Cherenkov radiation, multiple scattering and **high ionisation**

Searches for magnetic monopoles

- Detection techniques
- Past results
- LHC

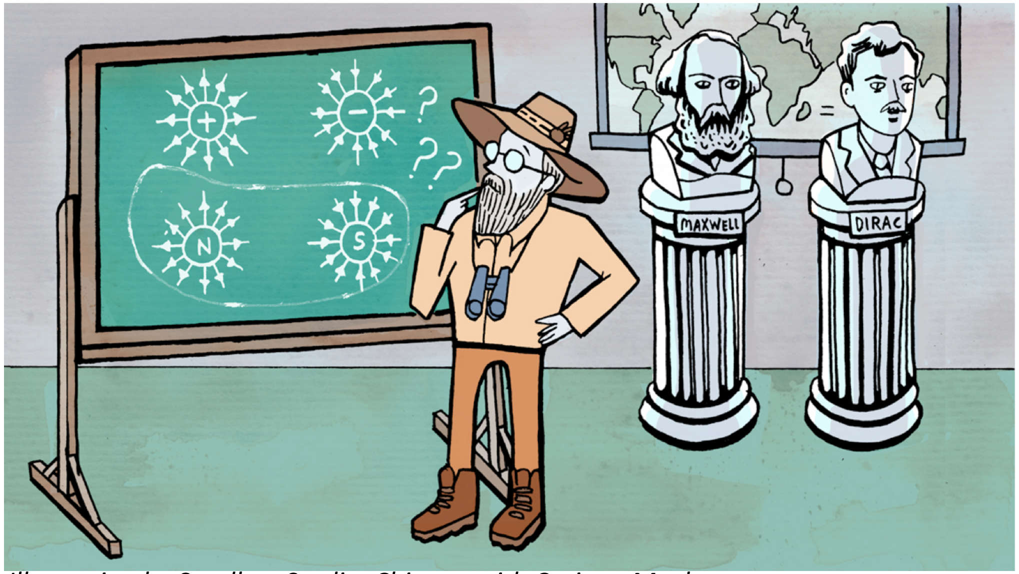


Illustration by Sandbox Studio, Chicago with Corinne Mucha

High ionisation

$$\frac{\text{charge}}{\text{velocity: } \beta = v/c} = z/\beta$$

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

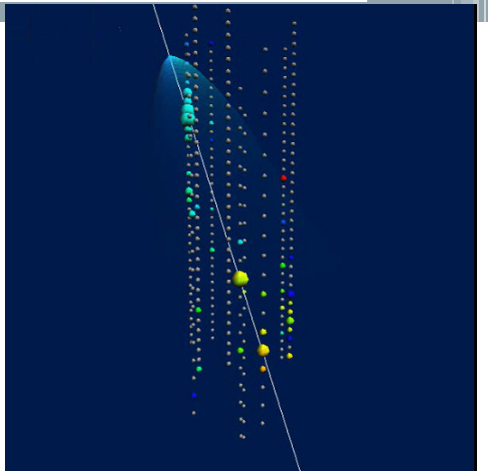
Electric charge
Bethe-Bloch formula

- Achieved, e.g., by **magnetic monopoles** due to ionisation $68.5^2 \approx 4700$ times higher than minimum ionising particle
- Actually, **any heavy, stable, electrically charged particle**, either stable or metastable, will be slow moving, so it would provide a high-ionisation signal
  - some searches for monopoles also sensitive for high electrically charged objects (HECOs)
  - multiple electric charges (H^{++}, Q-balls, black hole remnants, etc.) can also be highly ionising particles (HIPs)

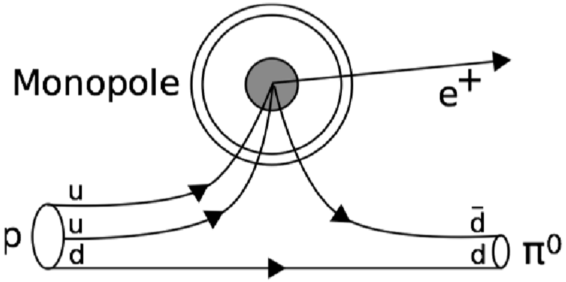
$$-\frac{dE}{dx} = K\frac{Z}{A}g^2\left\{\ln\frac{2m_e c^2\beta^2\gamma^2}{I_m} + \frac{K|g|}{2} - \frac{1}{2} - B(g)\right\}$$

Magnetic charge
Bethe-Ahlen formula

Detection techniques



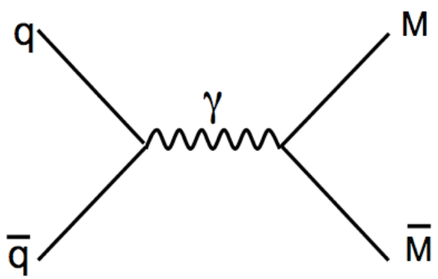
- High ionisation in gaseous detectors and scintillators
  - **Tevatron (CDF)**, MACRO, **ATLAS**, …
- Induction technique in superconductive coils *(☛ MoEDAL part)*
  - initially for cosmic MMs; not competitive with other techniques now
  - for monopoles trapped in material: rocks, **beam pipes**, **HERA (H1), MoEDAL detectors** …
- Cherenkov light in scintillators
  - deep-sea/ice experiments: ANTARES, IceCube
  - balloon-borne experiments (ANITA)
- Energy loss in nuclear track detectors *(☛ MoEDAL part)*
  - cosmic (SLIM)
  - colliders: **PETRA, CERN ISR, Tevatron (D0), LEP (MODAL, OPAL), LHC (MoEDAL)**
- Catalysis of nucleon decay
  - GUT monopoles may catalyse B-number violating decays
  - Soudan, MACRO, IMB, ν-telescopes (IceCube, Super-Kamiokande)
- Indirect searches
  - Diphotons **(D0),** air showers (Auger)



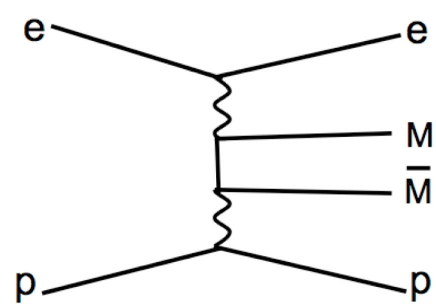
Callan-Rubakov mechanism

Monopole production at colliders

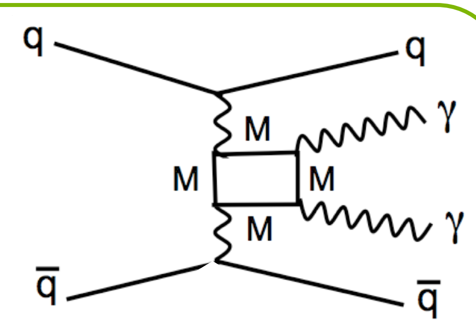
Production mechanisms in colliders



Drell Yan mechanism



Photon fusion

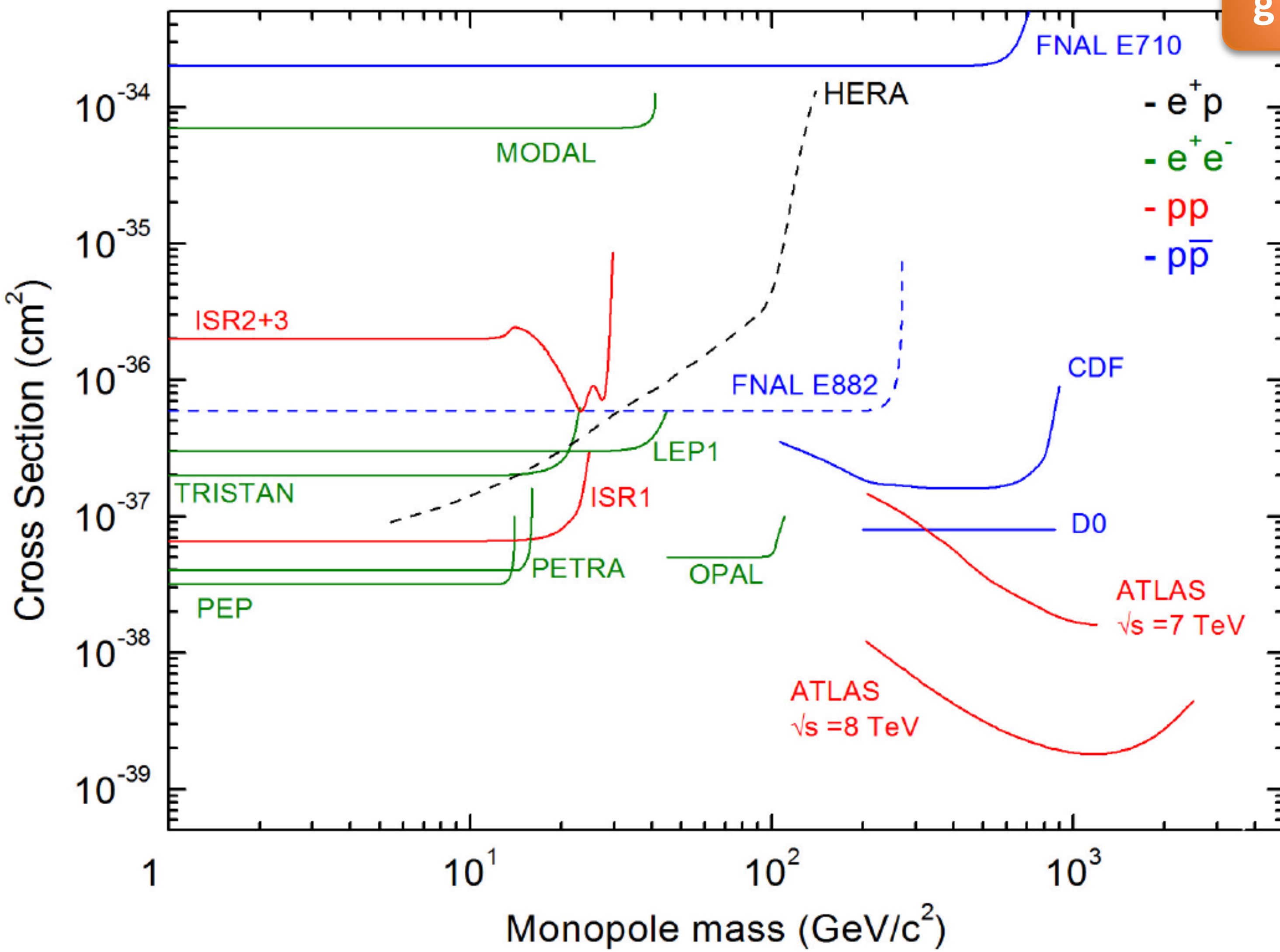


Box diagram

- Various high ionisation techniques (including NTDs) and induction (D0, CDF, HERA) have been used to search for monopoles at colliders before LHC startup
- A search for monopole-induced diphoton production with **D0 @ Tevatron** set lower 95% C.L. limits of 610, 870, or 1580 GeV on the mass of a spin 0, ½ or 1 Dirac monopole [PRL 81 (1998) 524]
- Dirac monopole production with $\sigma > 0.05$ pb at **LEP** was excluded by **OPAL** for 45 < mass < 102 GeV [PLB 663 (2008) 37]
- **CDF @ Tevatron** excluded MM pair production at the 95% CL for cross-section < 0.2 pb and monopole masses 200 < m_M < 700 GeV [PRL 96 (2006) 201801]

Collider searches ≤ 2015

$g = g_D$

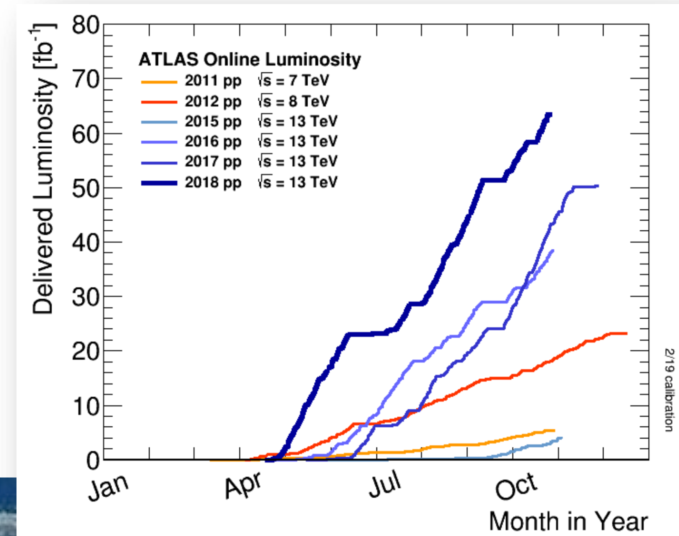


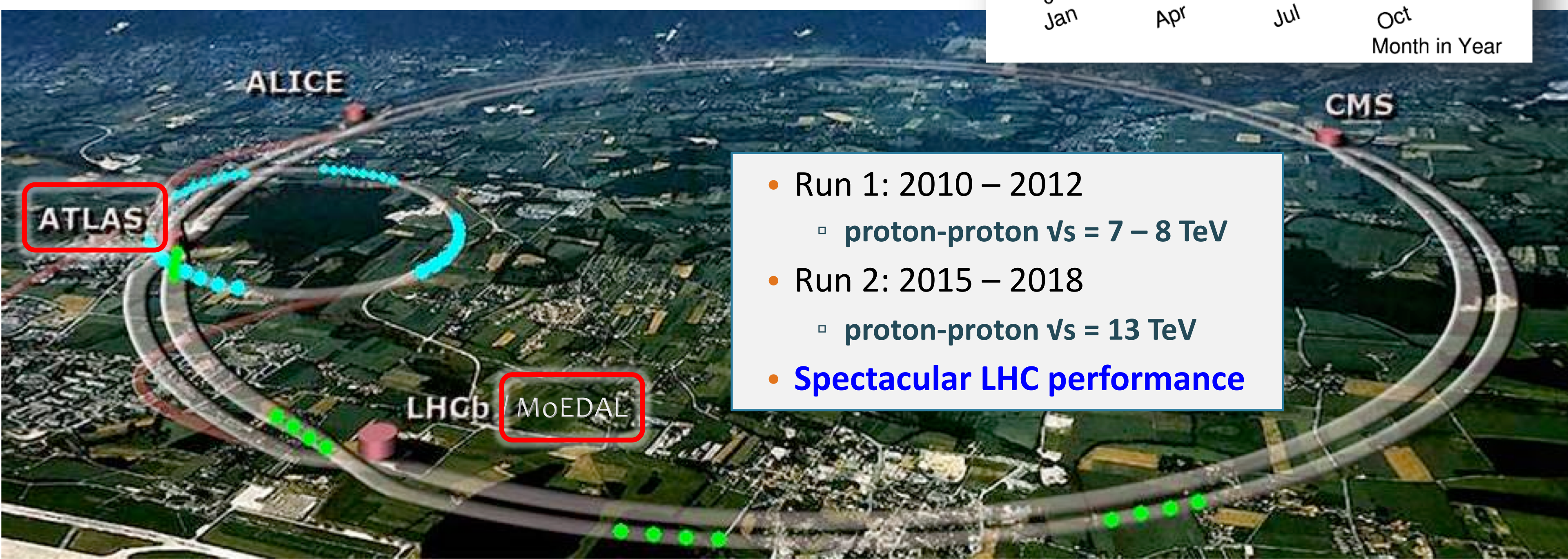
Patrizii L, Spurio M. 2015.
Annu. Rev. Nucl. Part. Sci. 65:279–302

Updated 2015

Large Hadron Collider at CERN

- ATLAS and MoEDAL have performed searches for magnetic monopoles
- MoEDAL receives ~50 times less luminosity than ATLAS
- Complementarity
  - ATLAS general-purpose; based on electronic readout
  - MoEDAL dedicated to (meta)stable particles; mostly passive detectors



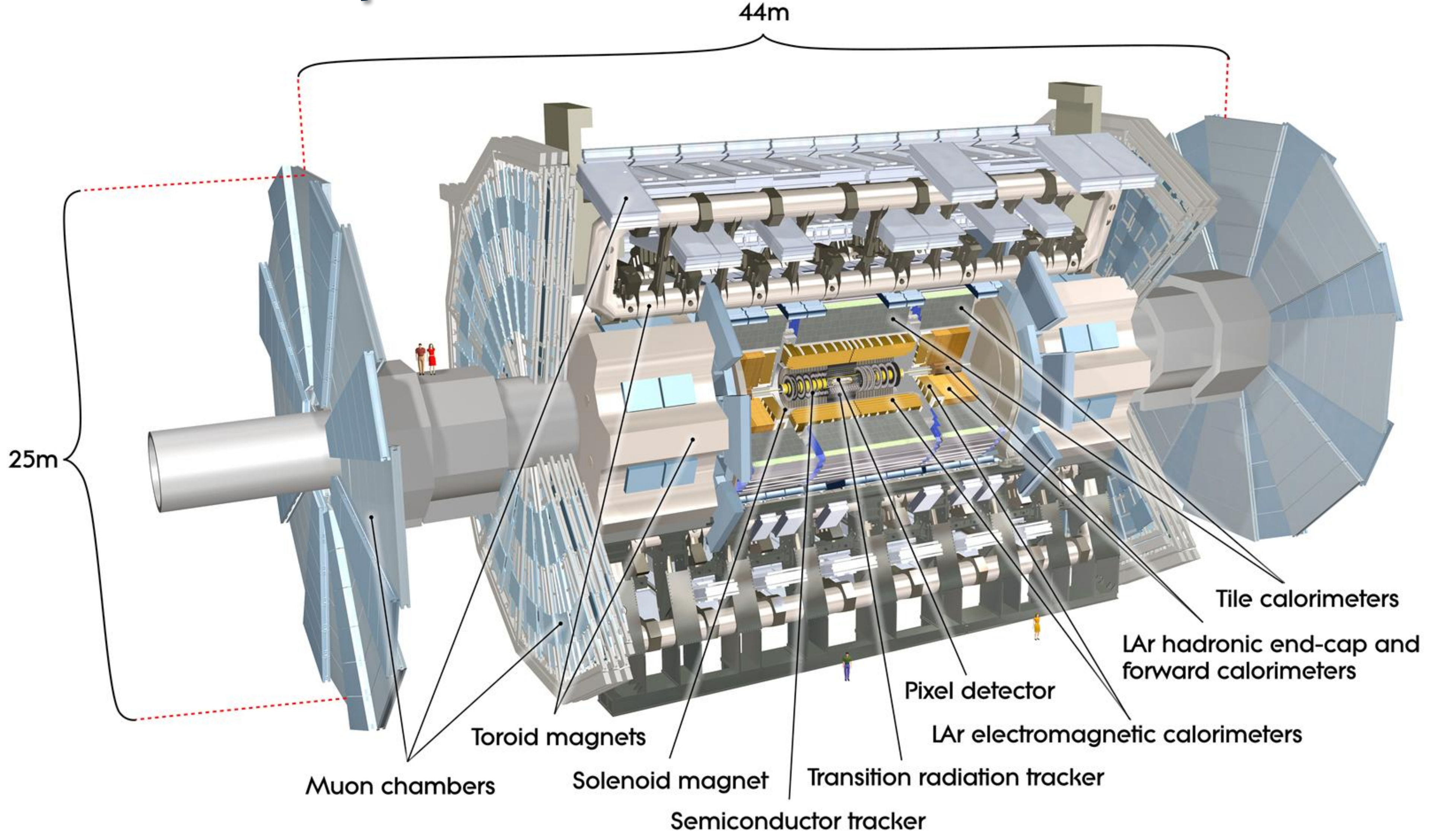


- Run 1: 2010 – 2012
  - **proton-proton √s = 7 – 8 TeV**
- Run 2: 2015 – 2018
  - **proton-proton √s = 13 TeV**
- **Spectacular LHC performance**

ATLAS search @ 13 TeV

arXiv:1905.10130, submitted to PRL

ATLAS experiment

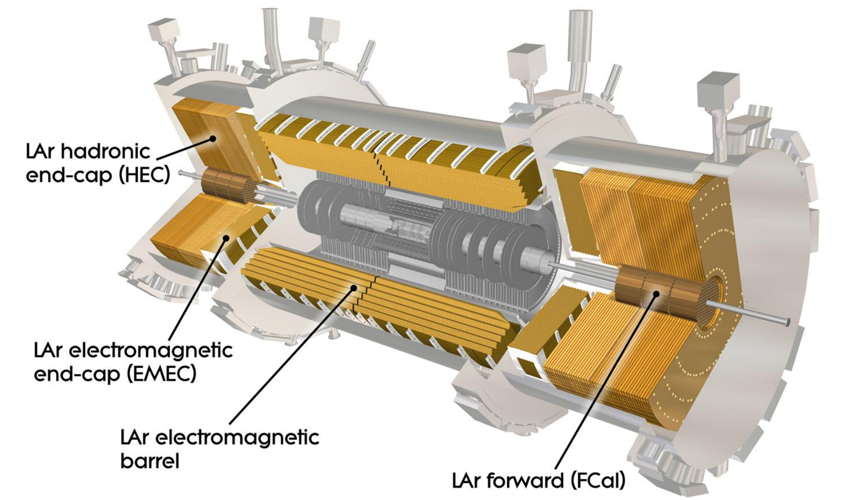


Detectors for HIP searches

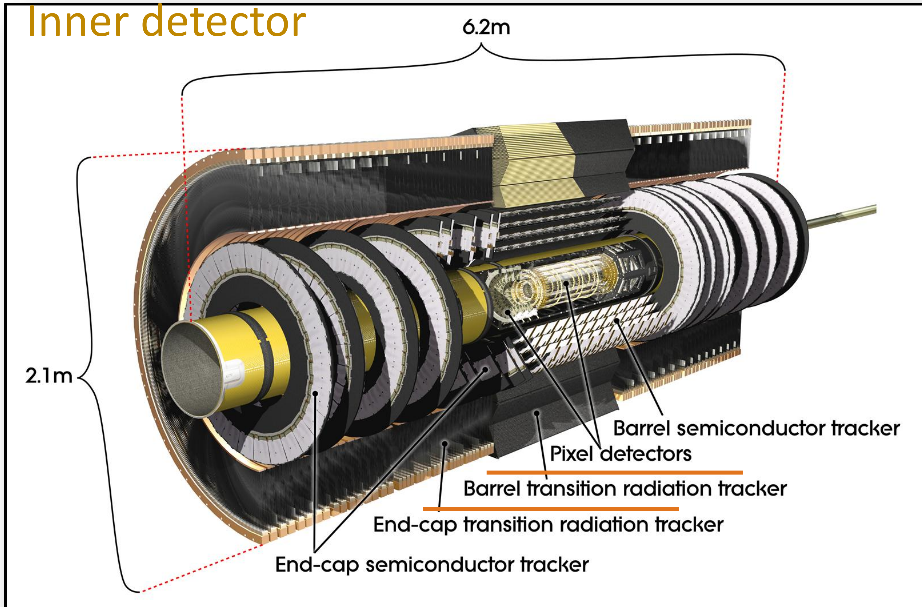
ATLAS monopole searches are based on high ionisation deposits measured in

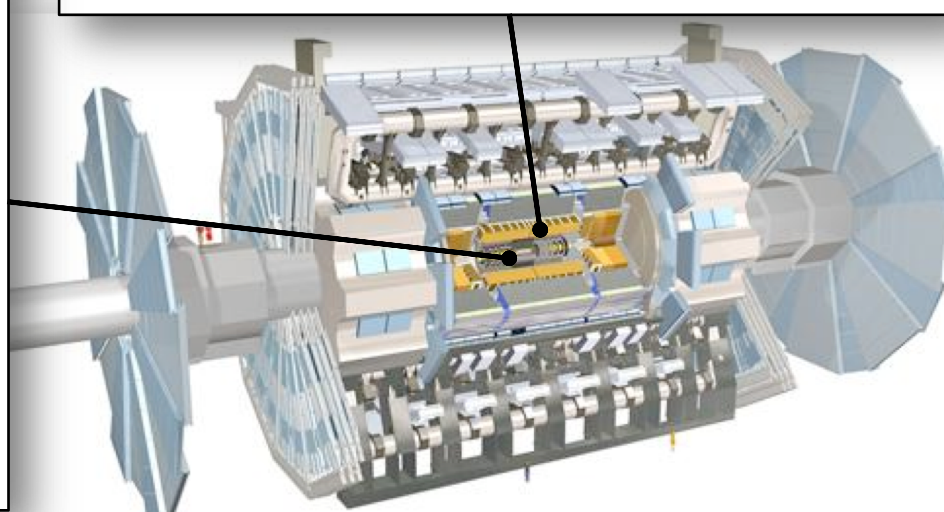
- electronic calorimeter (EM calorimeter)
  - lead–liquid Argon with accordion geometry
- transition radiation tracker (TRT)
  - Xe-filled or Ar-filled straw drift tubes
  - outermost part of the inner detector

Electromagnetic calorimeter



Inner detector





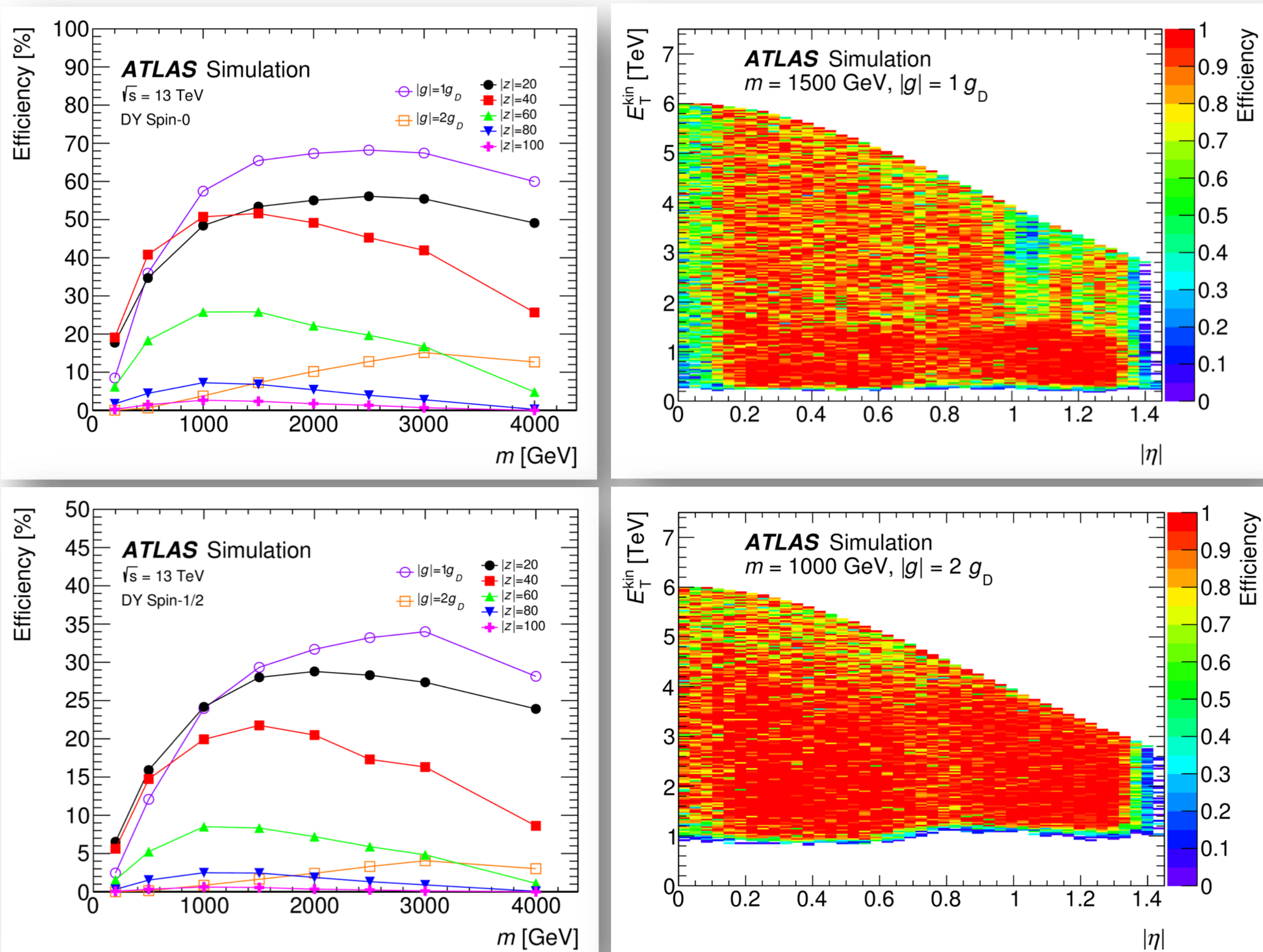
High ionisation signals

arXiv:1905.10130

- Two different signals in
  - TRT: large high-threshold (HT) hit fraction, f_{HT}, due to HIP & associated δ-electrons
  - EM calorimeter: HIPs slow down (and usually stop) there, leaving a pencil-shape energy deposit, unlike extensive showers from (much lighter) electron
    - *w*: energy-dispersion variable; expresses the fraction of EM cluster energy contained in the most energetic cells in the EM presampler, EM1 and EM2 layers, when energy is well above cluster-level noise
- **Trigger** based on number and fraction of TRT HT hits in a narrow region around the EM calorimeter region of interest
  - hadronic calorimeter veto applied
- **Offline selection** enhanced using combination of f_{HT} and energy dispersion of the EM cluster ***w***
- Background from
  - overlapping charged particles and noise in TRT straws
  - high-energy electrons and noise in EM calorimeter cells
- Data-driven background estimation based on ABCD method in the (w, f_{HT}) plane

Signal efficiency

ATLAS EXPERIMENT



Signal loss due to

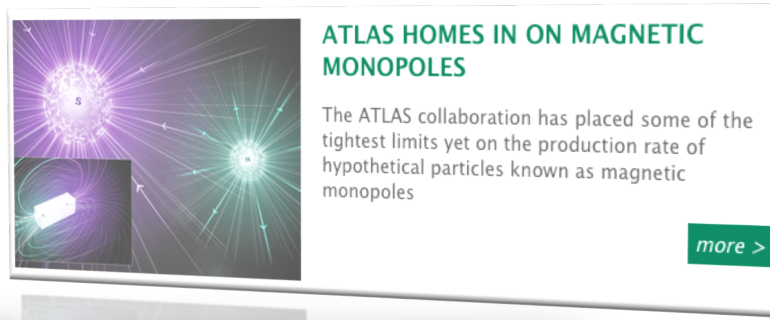
- high HIP charge: stop before EM calorimeter
- low HIP charge: too little energy deposied in EM calorimeter, or penetrate reaching hadronic calorimeter, invoking veto

arXiv:1905.10130

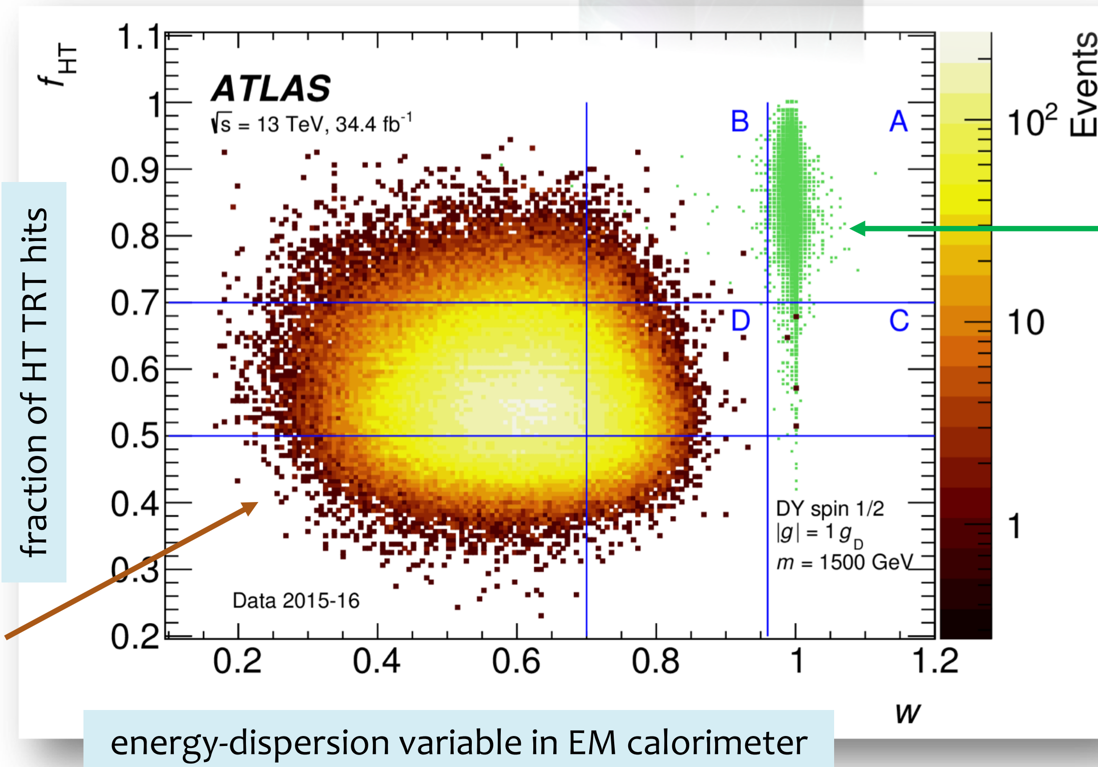
Selection efficiency = fraction of MC events surviving the trigger and offline selection criteria

Results

- Results based on 2015+2016 data (34.4 fb^{-1})
  - ☛ first ATLAS monopole search at $\sqrt{s}$ = 13 TeV !
- No events observed in signal region A



0.20 ± 0.11 (stat) ± 0.40 (sys) background events expected, estimated as $N_A^{exp} = N_B N_C / N_D$



monopole signal

data / background

arXiv:1905.10130

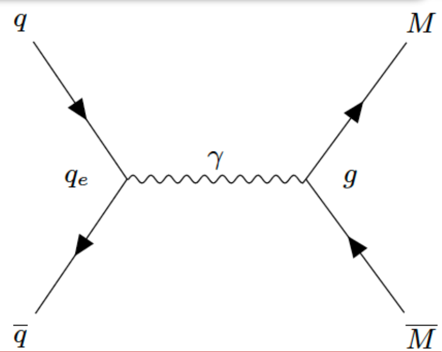
Interpretation

- Magnetic charges probed: $1 < |g| < 2.0\ g_D$
  - extending previous 8 TeV results $\leq 1.5\ g_D$
- Upper limits on production cross section set, assuming Drell-Yan (DY) spin-0 and spin-½ kinematics, as a function of monopole mass
- Lower limits on mass set for Dirac monopoles for DY production & β-independent γ-M coupling

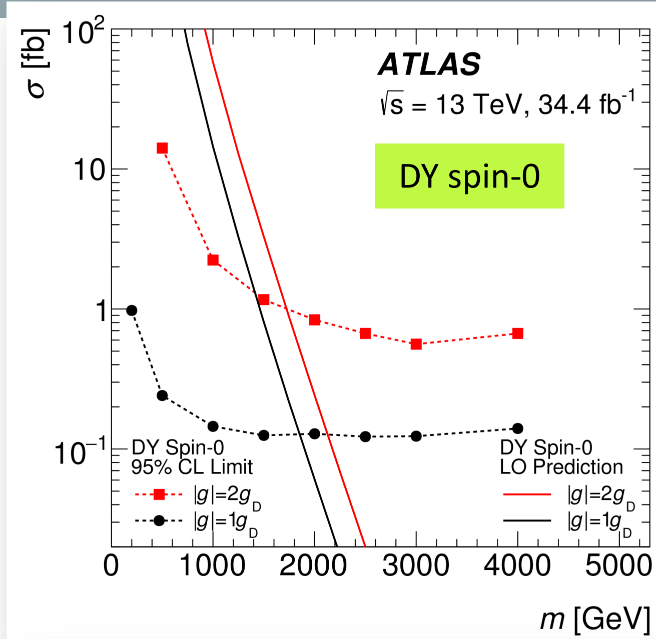
Strongest limits on monopoles of charge 1-2 g_D !

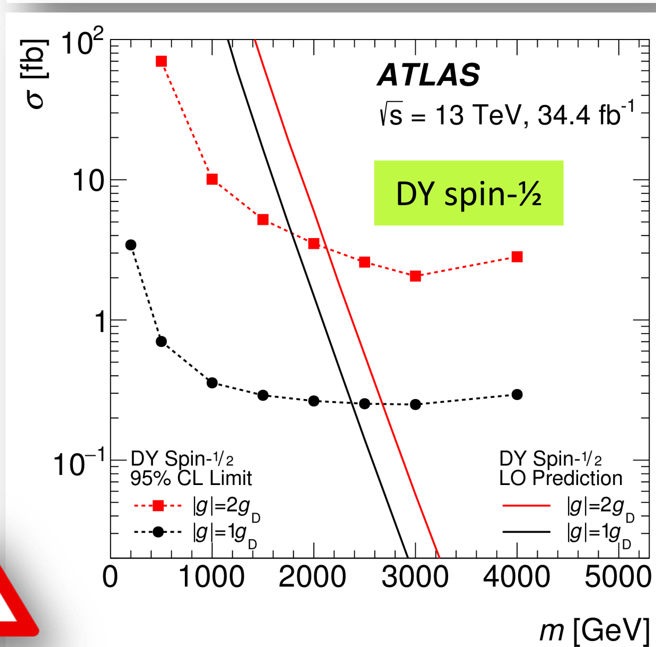
Drell–Yan lower mass limits [GeV]		
	$g = 1g_D$	$g = 2g_D$
spin-0	1850	1725
spin ½	2370	2125

arXiv:1905.10130



Mass limits based on Feynman-*like* diagrams, where perturbative calculations are impossible due to large γ-monopole coupling. They *only* serve to facilitate comparisons.

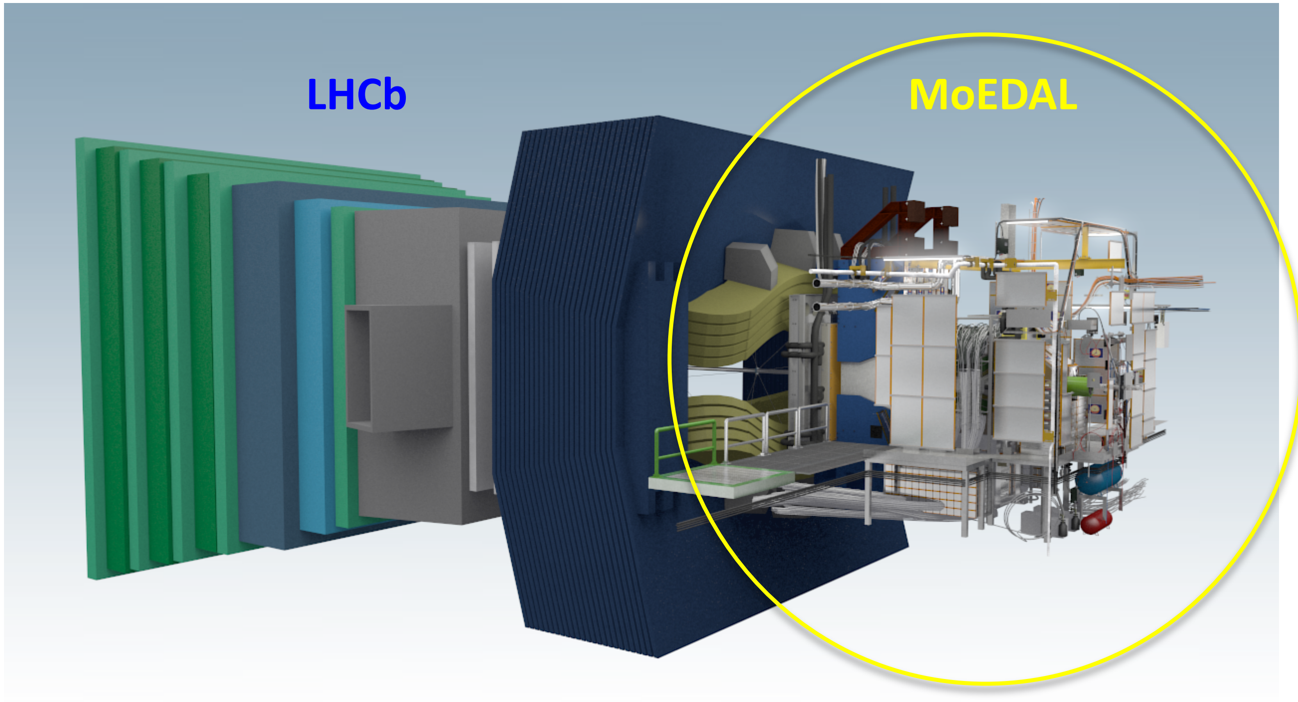




MoEDAL results

PRL *to appear* [arXiv:1903.08491]

MoEDAL detector



DETECTOR SYSTEMS

① Low-threshold NTD (**LT-NTD**) array
- $z/\beta >$ ~5-10

② Very High Charge Catcher NTD (**HCC-NTD**) array
- $z/\beta >$ ~50

③ **TimePix** radiation background monitor

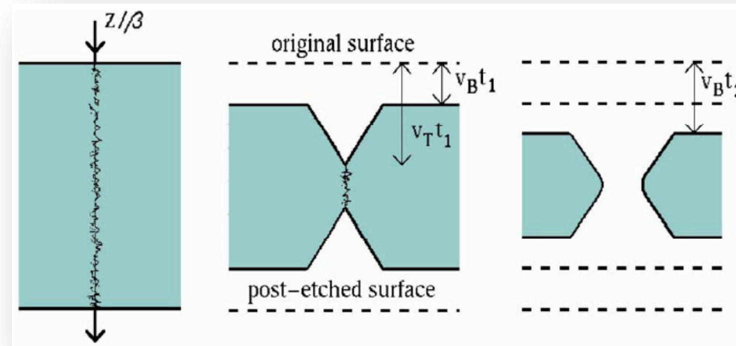
④ Monopole Trapping detector (**MMT**)

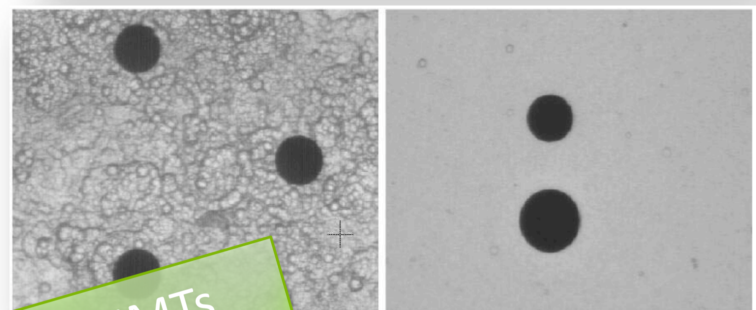
- Mostly **passive detectors**; no trigger; no readout
- Largest deployment of passive **Nuclear Track Detectors (NTDs)** at an accelerator
- First time that **trapping detectors** are deployed as a detector

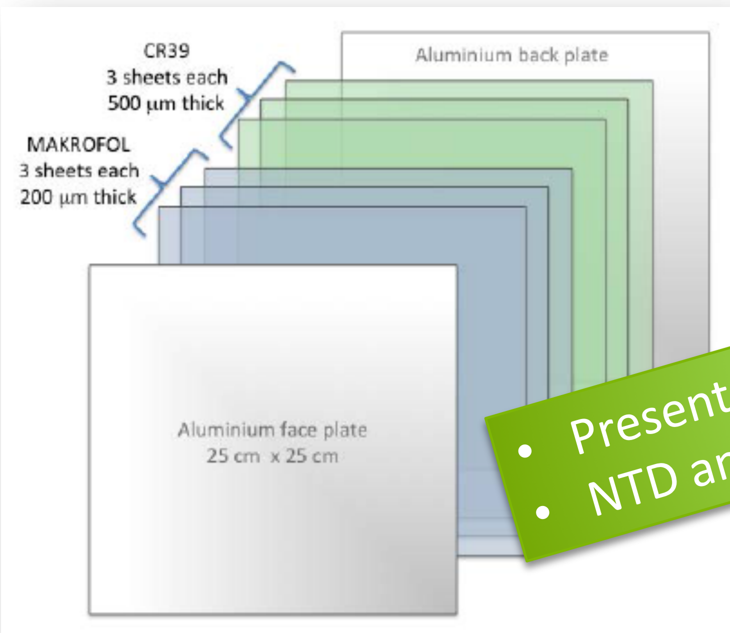
MoEDAL physics program
Int. J. Mod. Phys. A29 (2014) 1430050

Nuclear Track Detectors (NTDs)

- Passage of a highly ionising particle through the plastic NTD marked by an invisible damage zone (**"latent track"**) along the trajectory
- The damage zone is revealed as a **cone-shaped etch-pit** when the plastic sheet is chemically **etched**
- Plastic sheets are later **scanned** to detect etch-pits

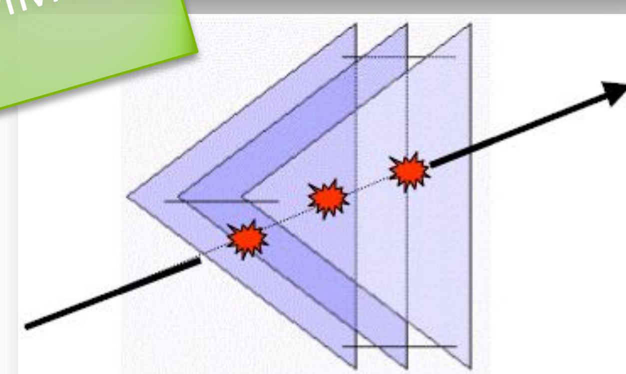






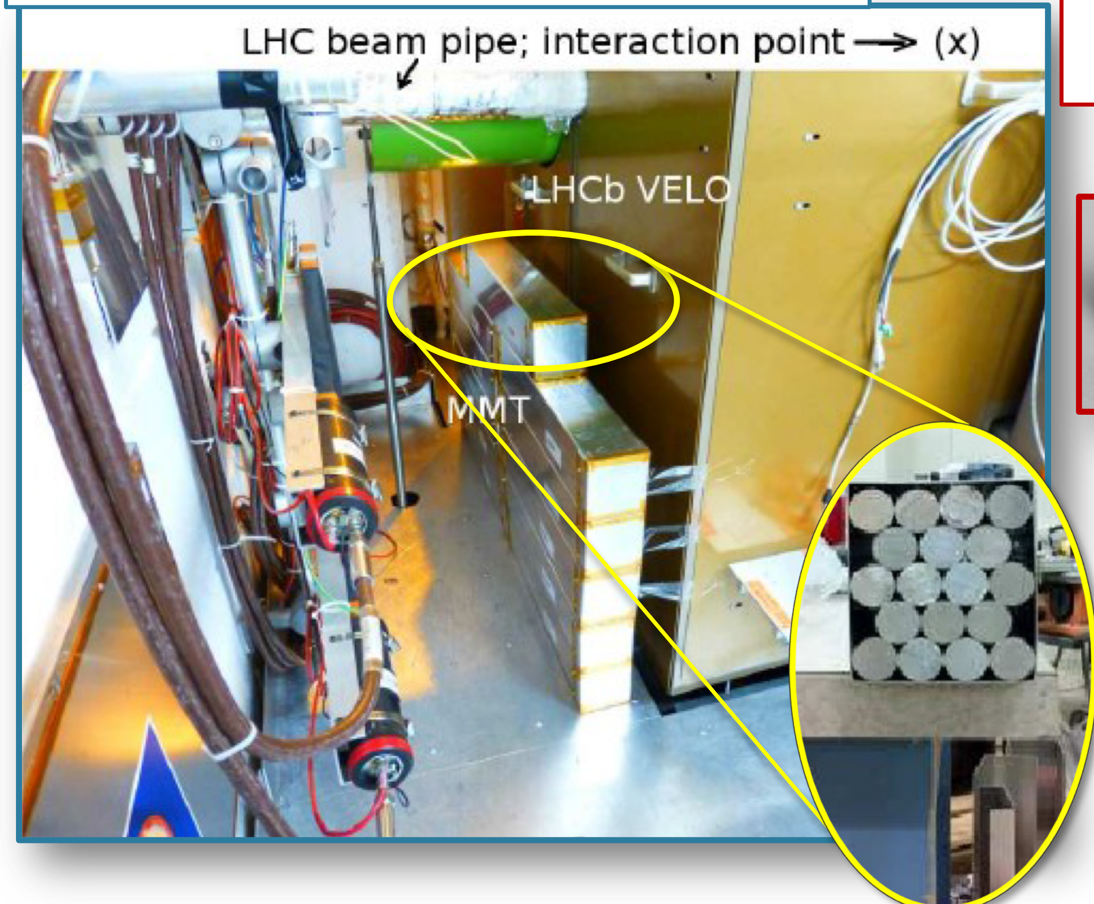
- Presented results based on MMTs
- NTD analysis in progress

Looking for aligned etch pits in multiple sheets



MMTs deployment

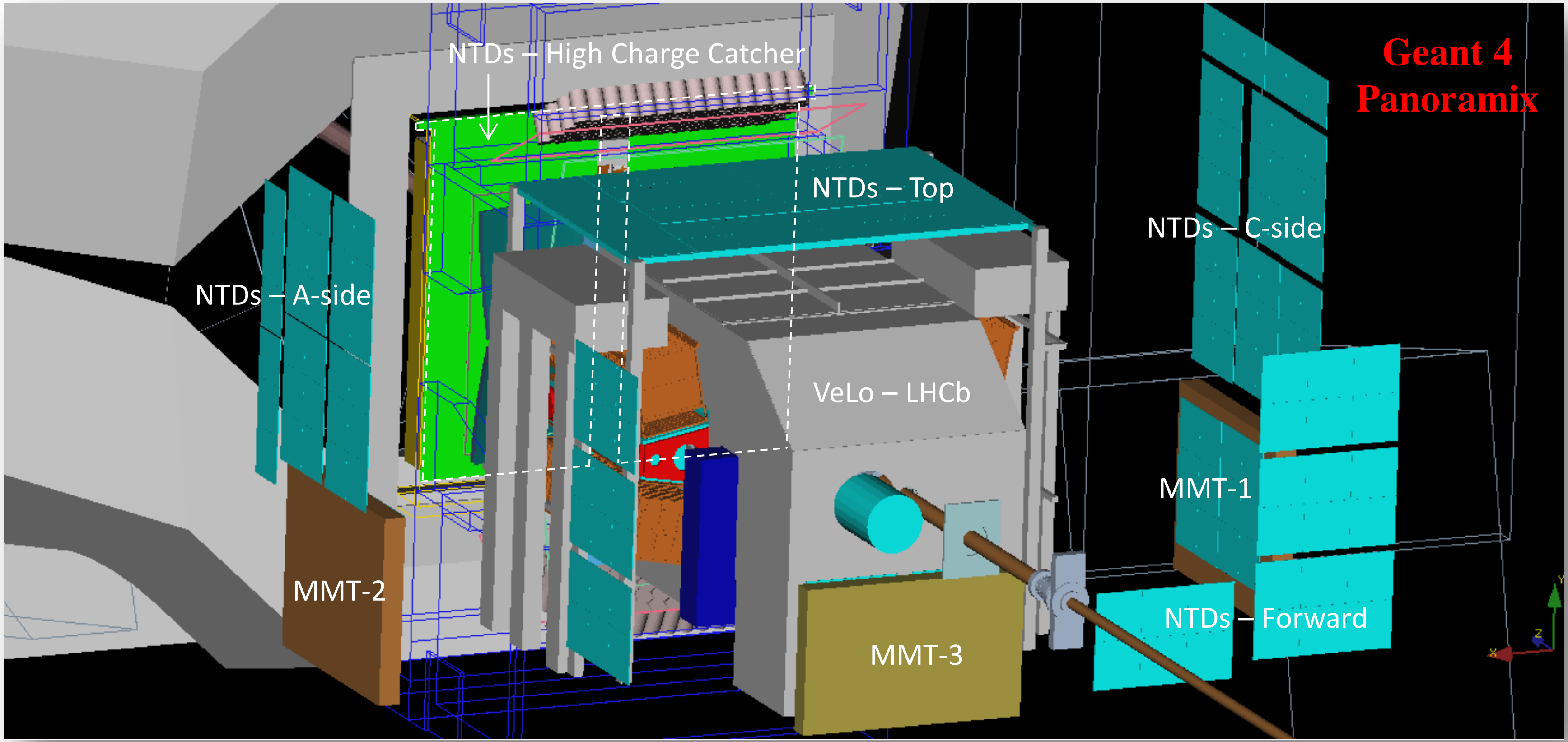
2012
11 boxes each containing 18 Al rods of 60 cm length and 2.54 cm diameter (**160 kg**)



2015-2018
- Installed in forward region under beam pipe & in **sides A & C**
- Approximately **800 kg** of aluminium
- Total 2400 aluminum bars

Detector position in Run 2

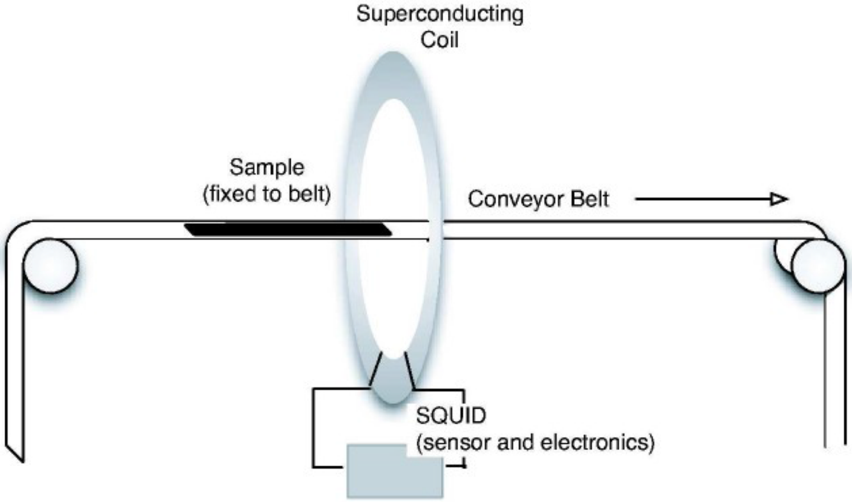
- Latest analysis is based on data extracted from all three MMT components
- MMT-1 and MMT-2 (sides) are newly added with respect to previous MoEDAL analyses

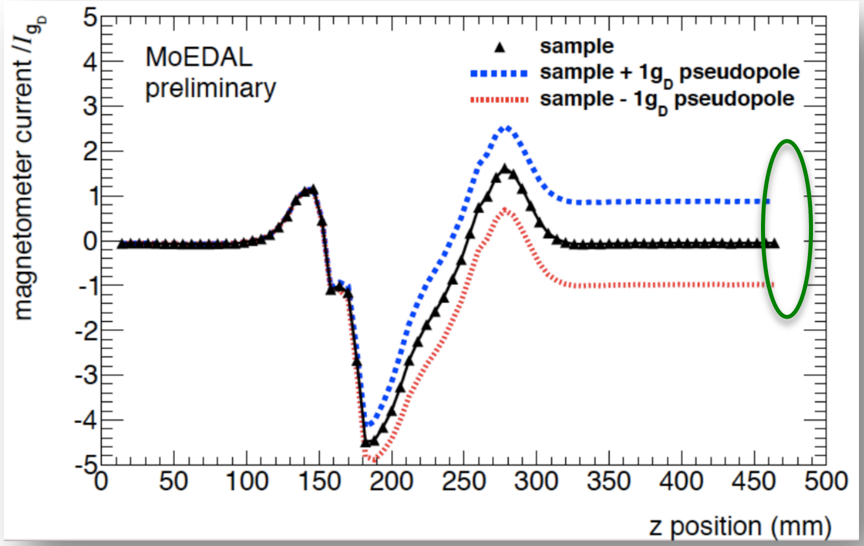


PRL, *to appear* [arXiv:1903.08491]

Induction technique

- Monopoles can bind to nuclei
  - large binding energy ~ $\mathcal{O}$(100 keV)
- Monopole trapping volumes analysed with superconducting quantum interference device (SQUID)
- **Persistent current:** difference between resulting current after and before
  - first subtract current measurement for empty holder
  - calibration constant P = 32.4 g_D / A
  - if other than zero → *monopole signature*





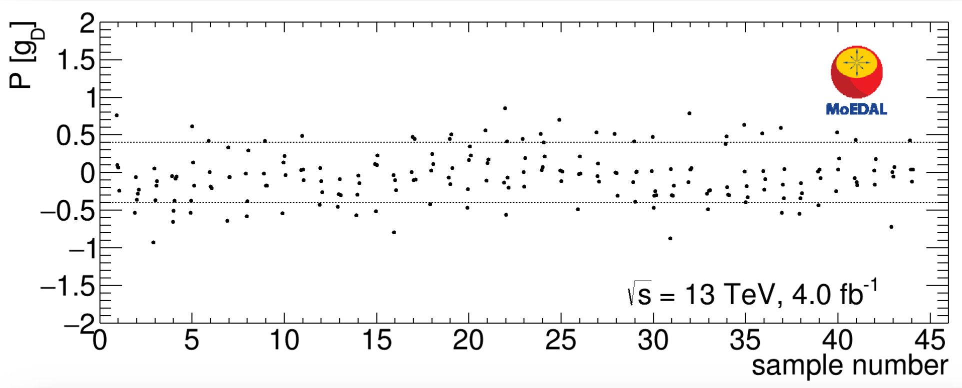
Typical sample & pseudo-monopole curves

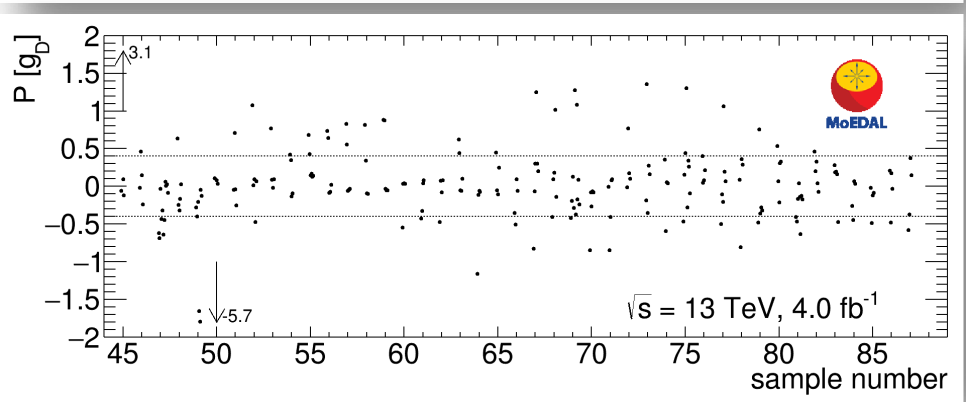
MMT 2015-2017 scanning

- Analysed with SQUID at ETH Zürich
- Excellent charge resolution (< 0.1 g_D)

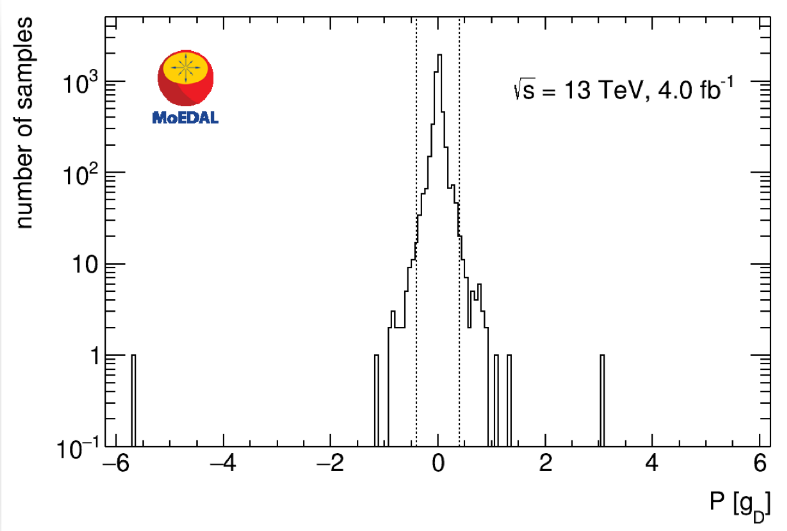
Detector: **794 kg** of aluminium bars

Exposure: **4.0 fb^{-1}** of **13 TeV** *pp* collisions during 2015-2017





Persistent current after first two passages for all samples

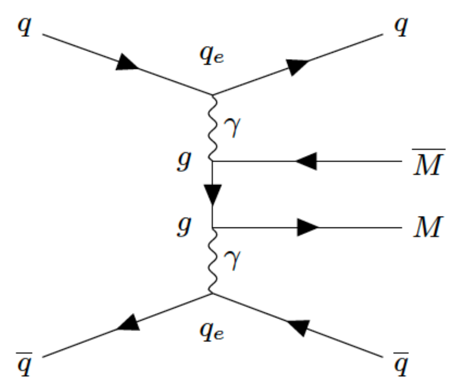


PRL, *to appear* [arXiv:1903.08491]

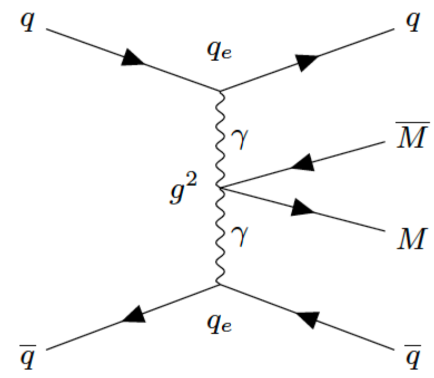
No monopole with charge > 0.5 g_D observed in MMT samples

Drell-Yan & γ-fusion

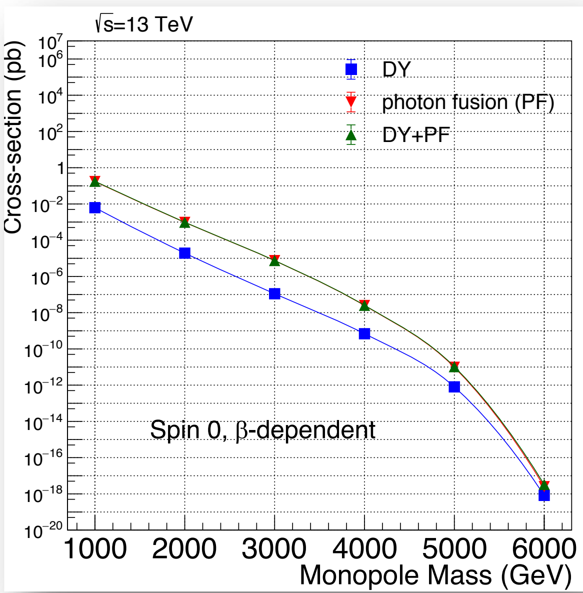
- Photon fusion most abundant than DY for almost whole mass range at LHC energies
- No interference effects between Drell-Yan and γγ processes
  - → total cross section = sum DY + γγ

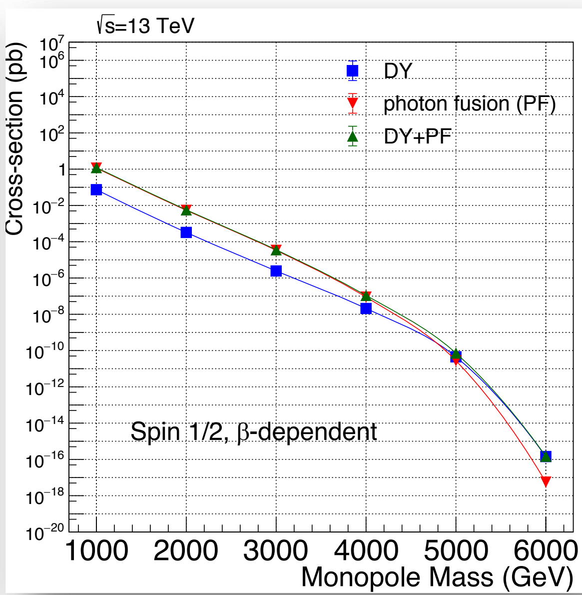


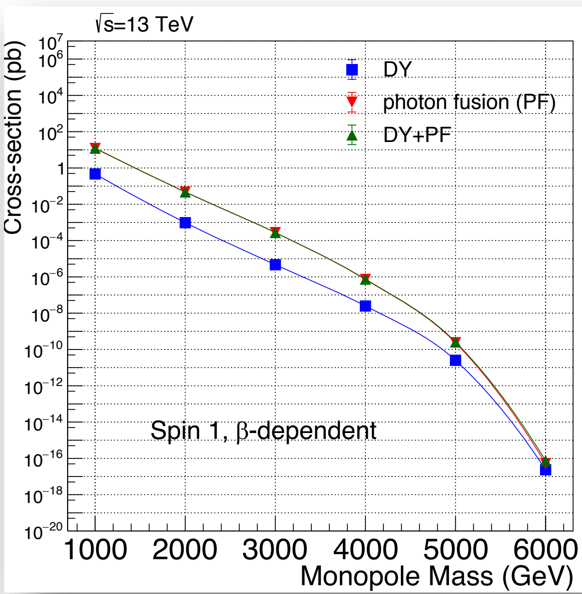
(c) Three-vertex PF process.



(d) Four-vertex PF process.



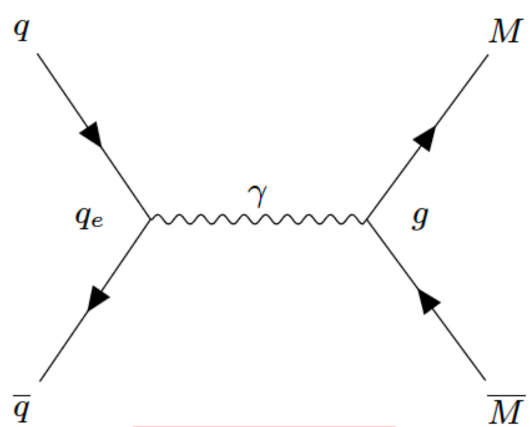




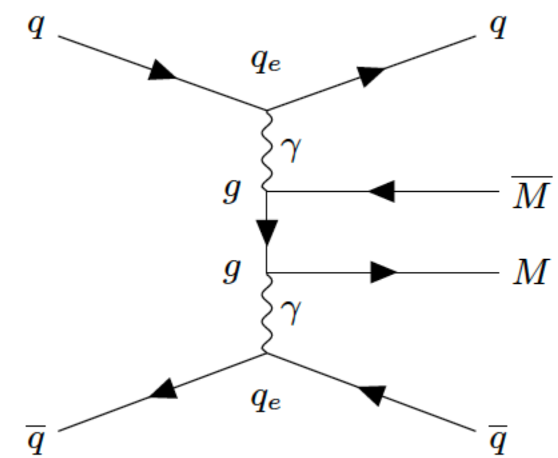
Baines, Mavromatos, VAM, Pinfold, Santra, Eur.Phys.J. C78 (2018) 966

Analysis

- Both β-independent and β-dependent $\gamma M\bar{M}$ coupling is assumed
- Spin-1 monopoles are considered in addition to spin-0 and spin-½
- Both Drell-Yan and γ-fusion production mechanisms assumed
  - only H1 in HERA has considered γ-fusion before [Eur.Phys.J. C41 (2005) 133]
- Kinematics differ between DY and γγ production mechanisms; differences depend on spin
- In comparison with previous results
  - full MMT detector ~4 times more volume
  - ~2 times more integrated luminosity



Drell-Yan

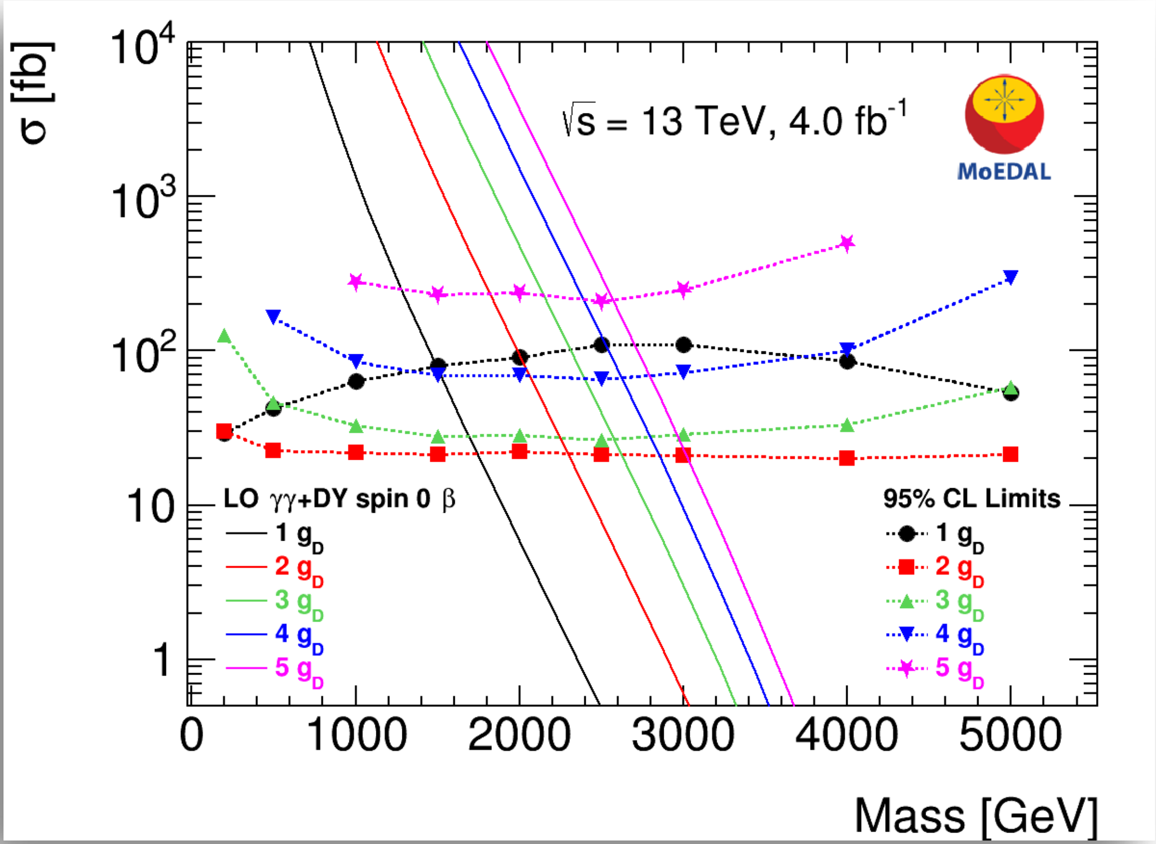


γ fusion

PRL, *to appear* [arXiv:1903.08491]

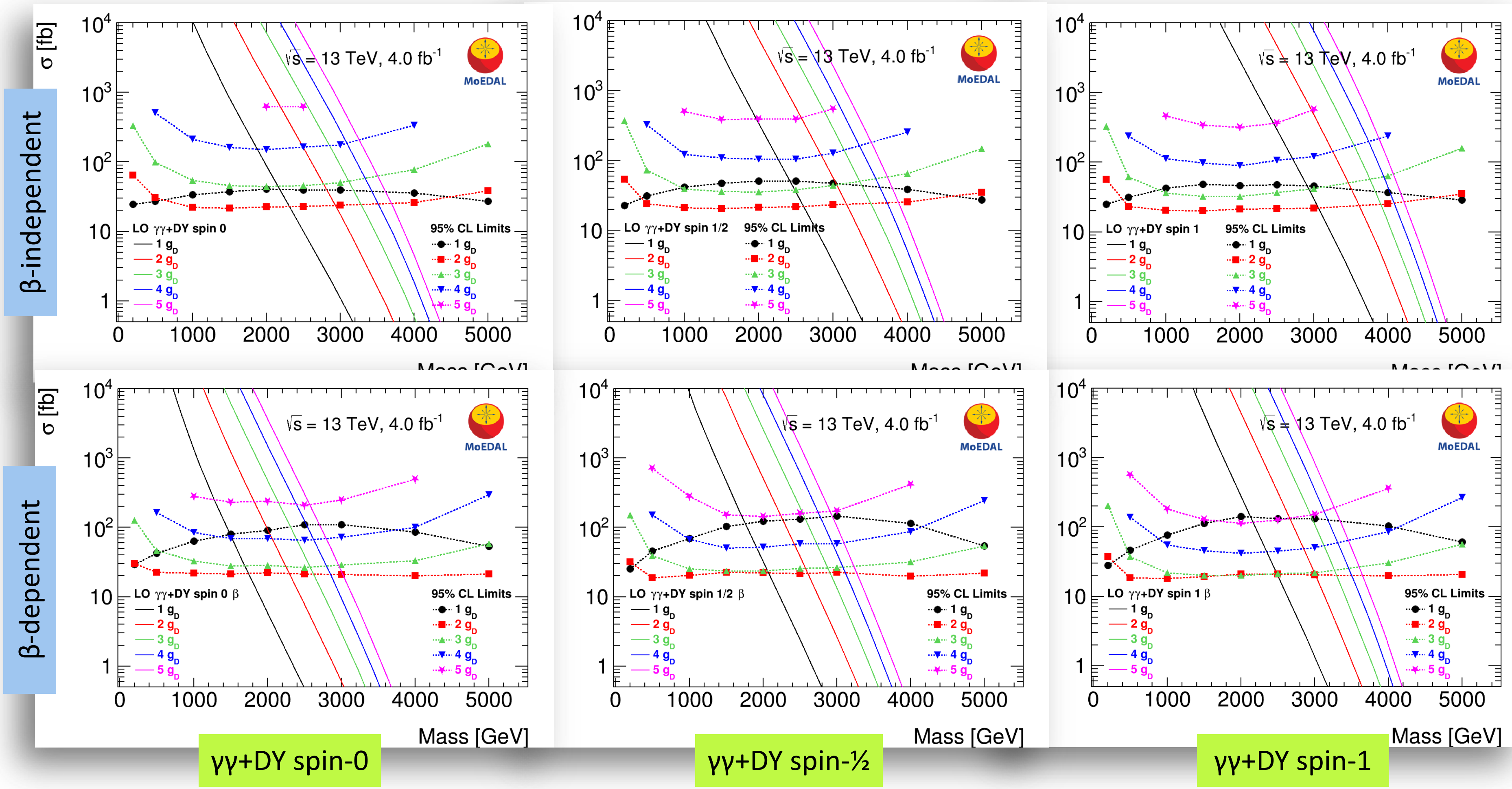
Results 1

- Acceptance losses
  - $|g| = g_D$: predominantly from punching through the trapping volume,
  - $|g| > g_D$: stopping in the material upstream of the trapping volume
- Acceptance < 0.1% for monopoles of $6g_D$ or higher
  - insufficient energy to traverse upstream material



PRL, *to appear* [arXiv:1903.08491]

Results II



PRL, *to appear* [arXiv:1903.08491]

Results

- First results for monopole production via γ-fusion at LHC !
- Strongest limits for magnetic charges ≥ 3 g_D

Process / coupling	Spin	Magnetic charge [g_D] 1	2	3	4	5
		95% CL mass limits [GeV]				
DY	0	790	1150	1210	1130	–
DY	1/2	1320	1730	1770	1640	–
DY	1	1400	1840	1950	1910	1800
DY β-dep.	0	670	1010	1080	1040	900
DY β-dep.	1/2	1050	1450	1530	1450	–
DY β-dep.	1	1220	1680	1790	1780	1710
DY+$\gamma\gamma$	0	2190	2930	3120	3090	–
DY+$\gamma\gamma$	1/2	2420	3180	3360	3340	–
DY+$\gamma\gamma$	1	2920	3620	3750	3740	–
DY+$\gamma\gamma$ β-dep.	0	1500	2300	2590	2640	–
DY+$\gamma\gamma$ β-dep.	1/2	1760	2610	2870	2940	2900
DY+$\gamma\gamma$ β-dep.	1	2120	3010	3270	3300	3270

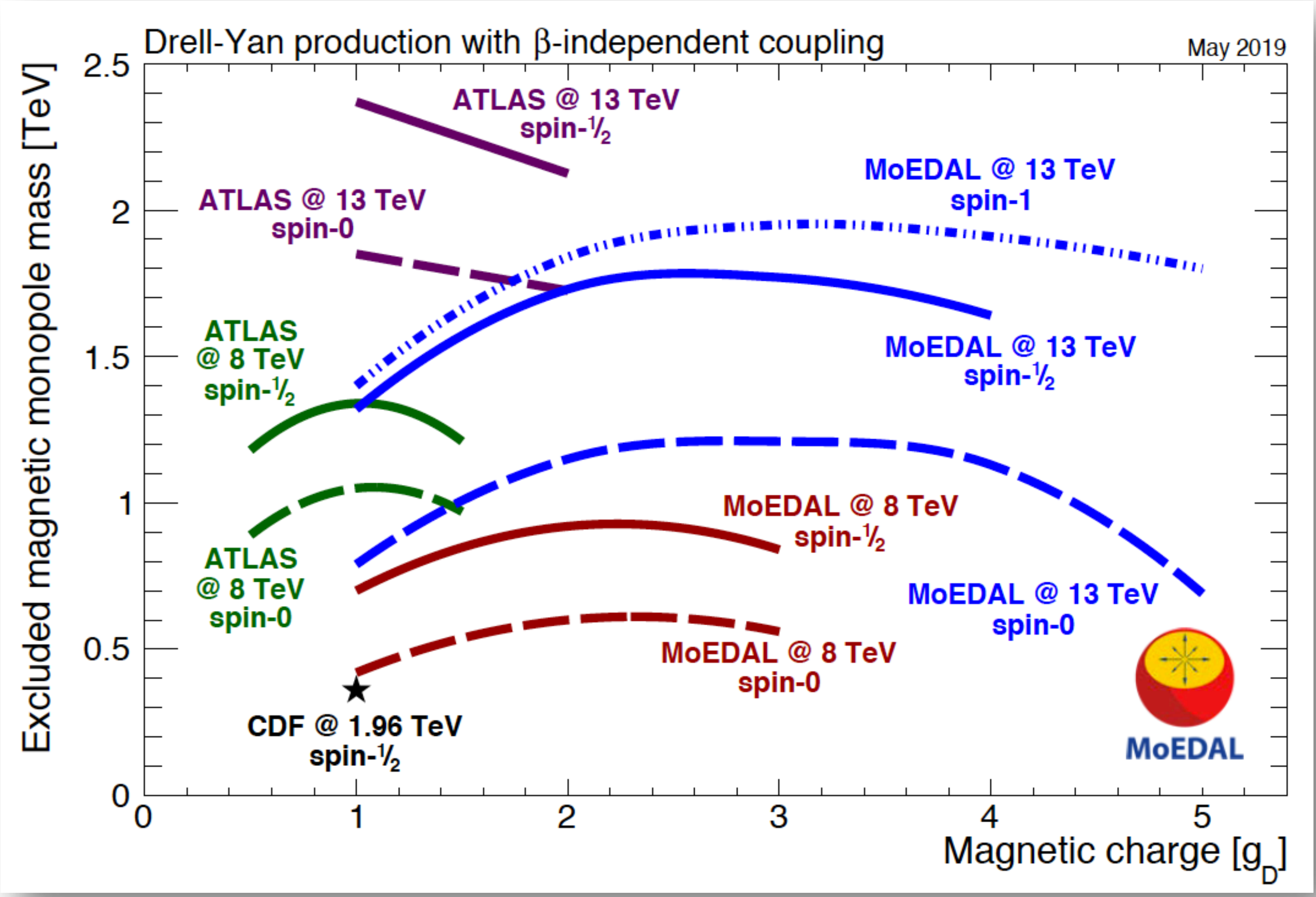
Possible solutions to *perturbative* treatment of monopole production in colliders

1. thermal Schwinger production in heavy-ion collisions [Gould & Rajantie, Phys.Rev.Lett. 119 (2017) 241601]
   - e.g. Pb-Pb run in November 2018
2. photon fusion: [Eur.Phys.J. C78 (2018) 966] perturbative coupling can be achieved for
   - very slow monopoles, β → 0, AND
   - very large magnetic-moment parameter, κ → ∞

$$\beta = \sqrt{1 - \frac{4M^2}{s}}$$

Mass limits based on Feynman-*like* diagrams, where perturbative calculations are impossible due to large γ-monopole coupling. They *only* serve to facilitate comparisons.

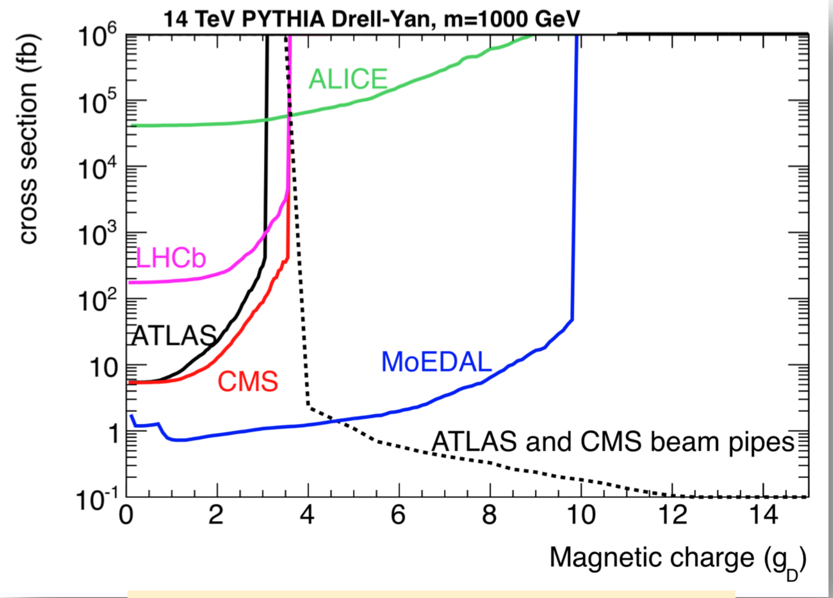
Monopole searches summary



CMS beam pipe

Beam pipe

- most directly exposed piece of material of the experiment
- covers very high magnetic charges



De Roeck et al, EPJC72 (2012) 1985

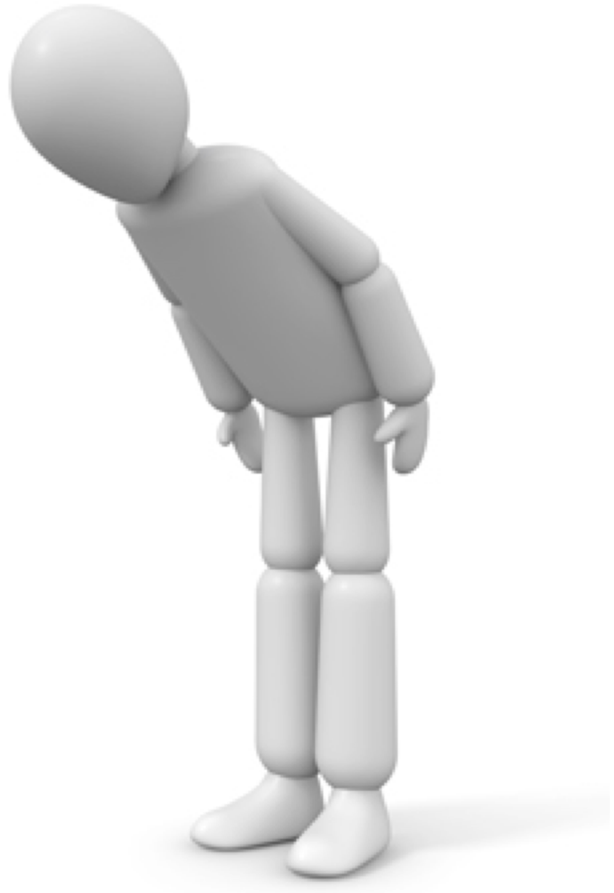
- **1990's:** materials from CDF, D0 (Tevatron) and H1 (HERA) subjected to SQUID scans for trapped monopoles
- **2012:** first pieces of CMS beam pipe tested [EPJC72 (2012) 2212]; far from collision point
- **Feb 2019:** CMS and MoEDAL collaborations signed agreement transferring ownership of the Run-1 CMS beam pipe to MoEDAL
  - beryllium (highly toxic); 6 m long; Ø 4 cm
- Status & plans
  - beam pipe cut into small pieces at Univ. Alberta, Canada
  - to be scanned in SQUID at ETH Zurich

CERN Courier, Mar-Apr 2019

Summary & outlook

- Monopoles continue to excite interest and have been the subject of numerous experimental searches
- General-purpose experiments (**ATLAS**) and dedicated detectors (**MoEDAL**) provide *complementary* constraints in the quest for monopoles
  - ATLAS dominates low magnetic charges
    - higher luminosity than MoEDAL
  - MoEDAL is stronger in high charges
    - can also identify a monopole and measure its charge
    - NTD results expected to improve sensitivity
- Much higher charges can be probed by looking for trapped monopoles in beam pipes, e.g. CMS run 1 beam pipe
- **Stay tuned for upcoming results !**

Thank you for your attention!



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