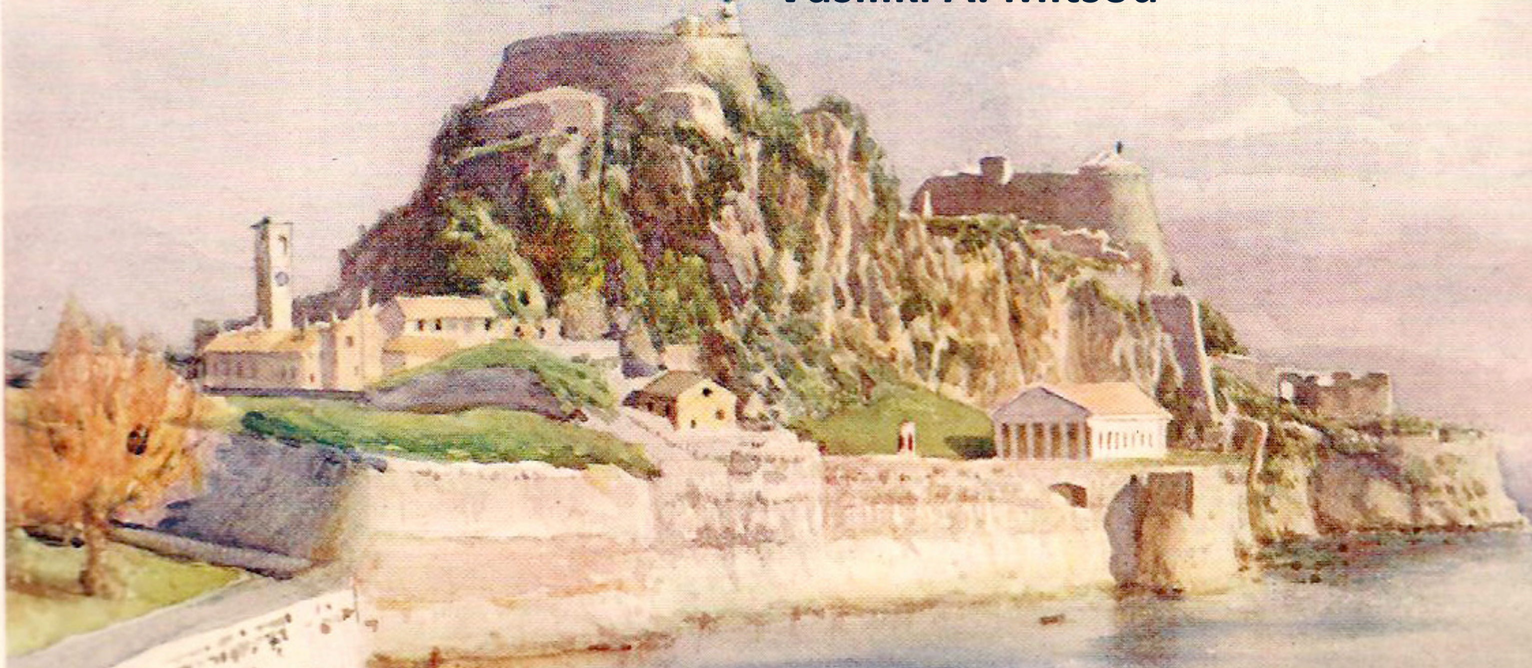
The Quest for Magnetic Monopoles
Past, Present and Future

Vasiliki A. Mitsou



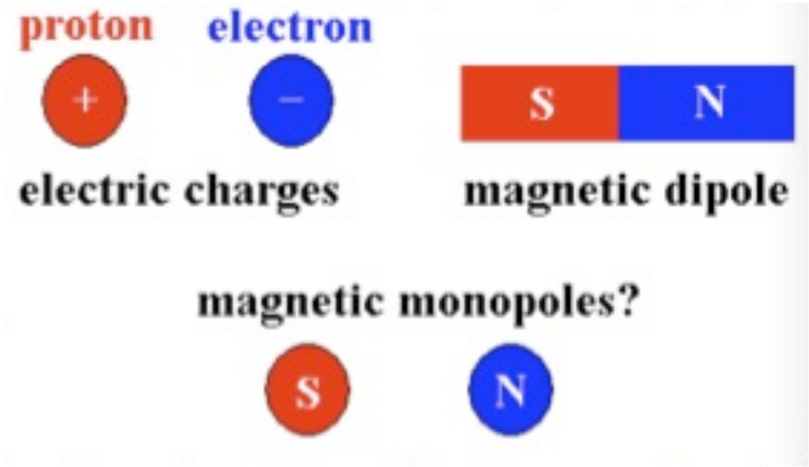
17th HELLENIC SCHOOL AND WORKSHOPS ON ELEMENTARY PARTICLE PHYSICS AND GRAVITY

Workshop on Testing Fundamental Physics Principles

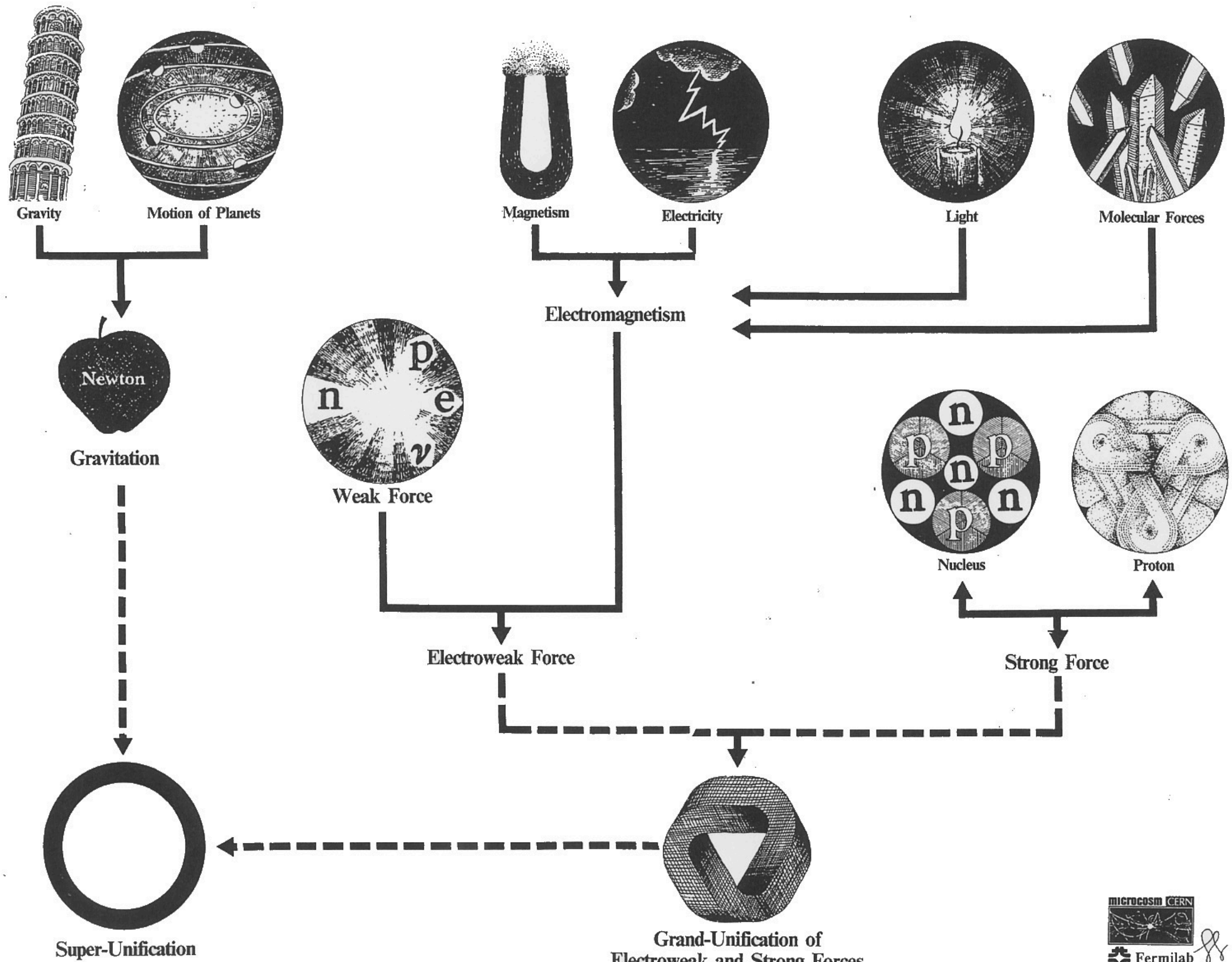
September 22 – 28, 2017, Corfu, Greece

Magnetic monopoles

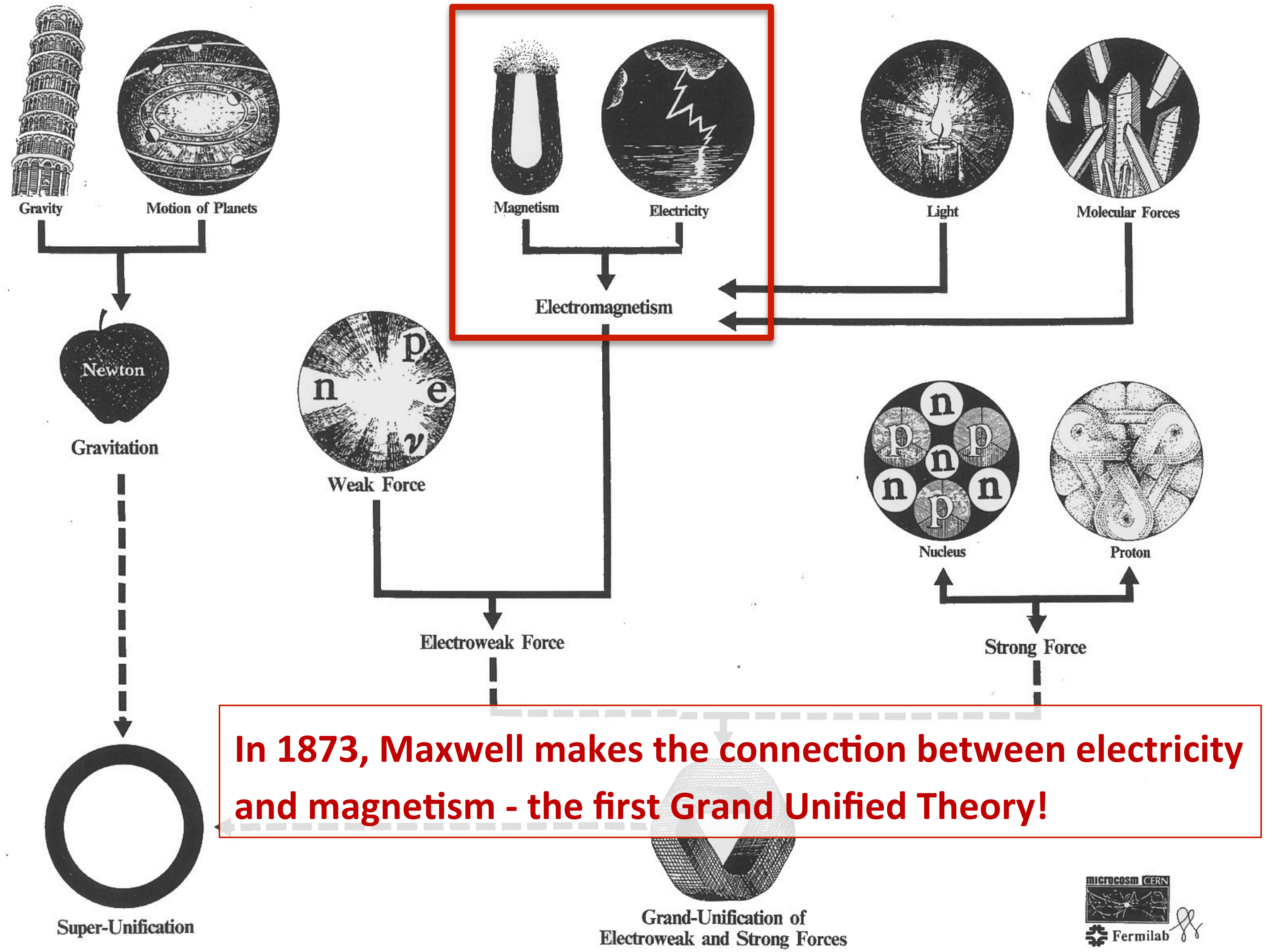
- Motivation
- Theoretical proposals



Unification of Forces



Unification of Forces



In 1873, Maxwell makes the connection between electricity and magnetism - the first Grand Unified Theory!

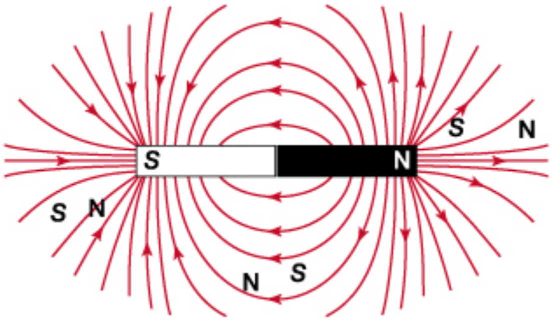
Magnetic monopoles: symmetrising Maxwell

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

Name	Without Magnetic Monopoles	With Magnetic Monopoles
Gauss's law:	$\vec{\nabla}\cdot\vec{E} = 4\pi\rho_e$	$\vec{\nabla}\cdot\vec{E} = 4\pi\rho_e$
Gauss' law for magnetism:	$\vec{\nabla}\cdot\vec{B} = 0$	$\vec{\nabla}\cdot\vec{B} = 4\pi\rho_m$
Faraday's law of induction:	$-\vec{\nabla}\times\vec{E} = \frac{\partial\vec{B}}{\partial t}$	$-\vec{\nabla}\times\vec{E} = \frac{\partial\vec{B}}{\partial t} + 4\pi\vec{J}_m$
Ampère's law (with Maxwell's extension):	$\vec{\nabla}\times\vec{B} = \frac{\partial\vec{E}}{\partial t} + 4\pi\vec{J}_e$	$\vec{\nabla}\times\vec{B} = \frac{\partial\vec{E}}{\partial t} + 4\pi\vec{J}_e$

- Symmetrised Maxwell's equations invariant under rotations in (E, B) plane of the electric and magnetic field
- Duality ➤ distinction between electric and magnetic charge becomes one of mere definition

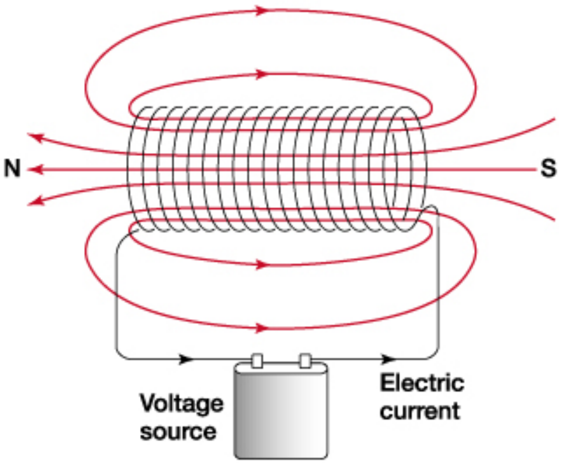
Dirac's Monopole



- Paul Dirac in 1931 hypothesized 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:

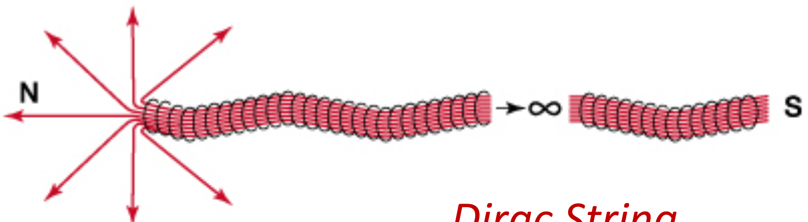
$$ge = \left[\frac{\hbar c}{2}\right] n \quad OR \quad g = \frac{n}{2\alpha} e \quad \left(from \quad \frac{4\pi e g}{\hbar c} = 2\pi n \quad n = 1,2,3..\right)$$

  - 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 charge is quantised:

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

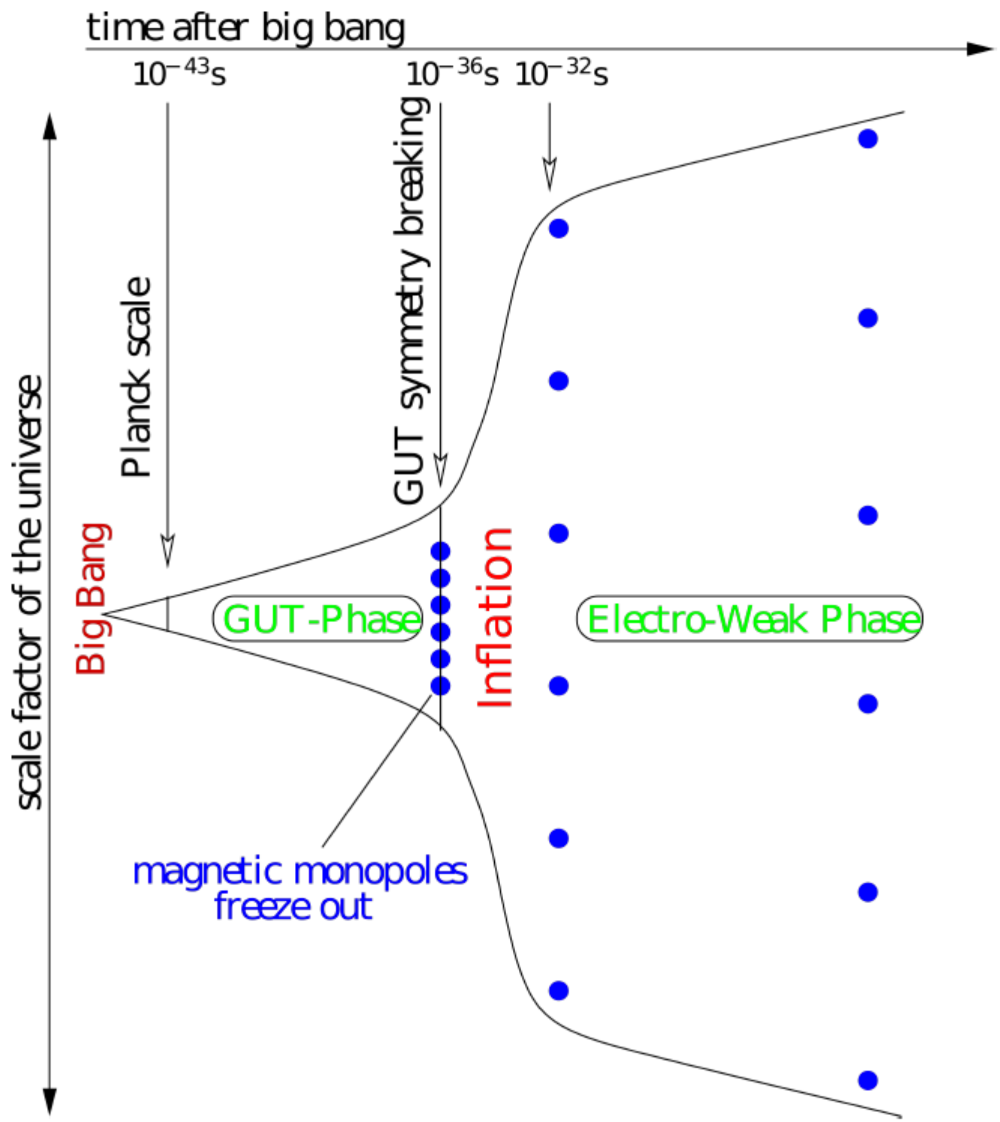


Dirac String

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
- Mass: $m(M_{GUT}) \geq m_X/G > 10^{16}$ GeV → **10^{17} GeV ~ 0.2 μg**

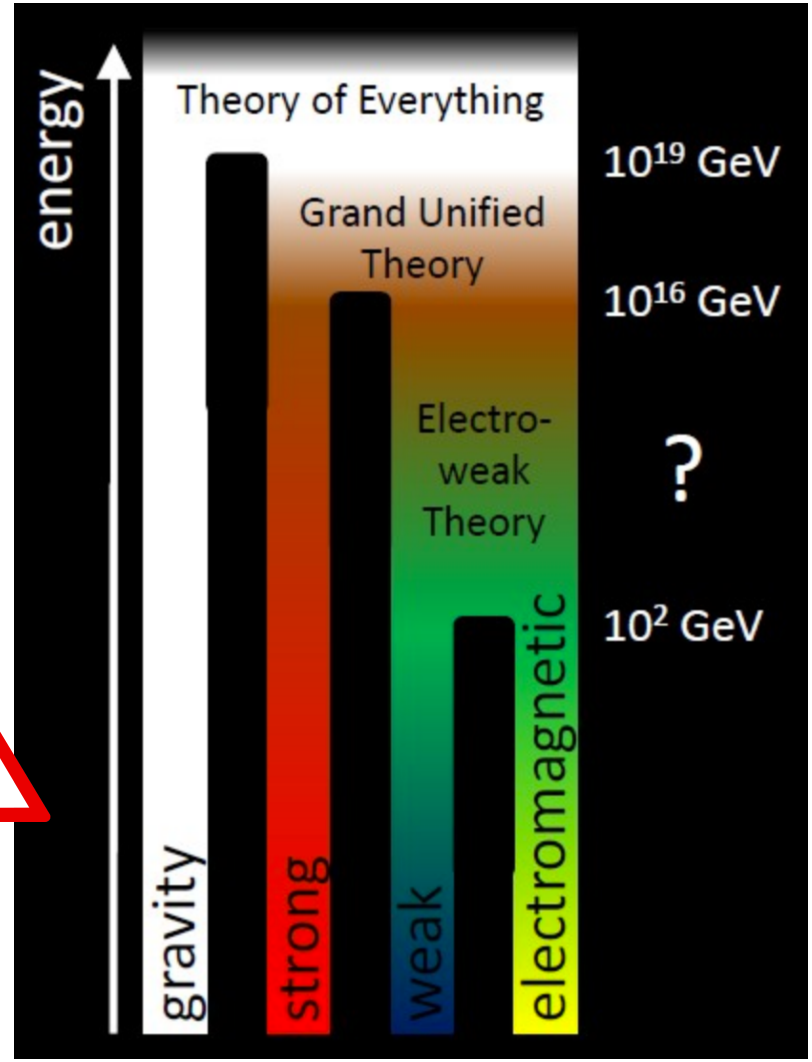
  ➜ not producible by particle accelerators
- Size: **extended object**
  - radius > few femtometers



T. Glüsenkamp 10

Electroweak monopole

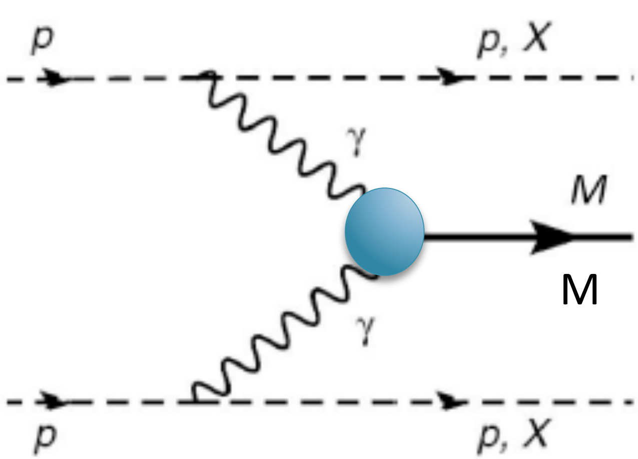
- In 1986 Cho & Maison [Phys.Lett. B391 (1997) 360], envisioned a spherically-symmetric electroweak (EW) monopole arising from the framework of the Weinberg-Salam model
- Non-trivial hybrid between the Dirac and the 't Hooft & Polyakov monopole
- Properties
  - charge $2g_D$
  - mass predicted to be ~4 ÷10 TeV
    ➜ accessible to LHC !
- *"The Price of an Electroweak Monopole"* Point-singularity makes estimate of mass classically impossible ➜ finite-energy solution needed [Ellis, Mavromatos, You, Phys.Lett. B756 (2016) 29]

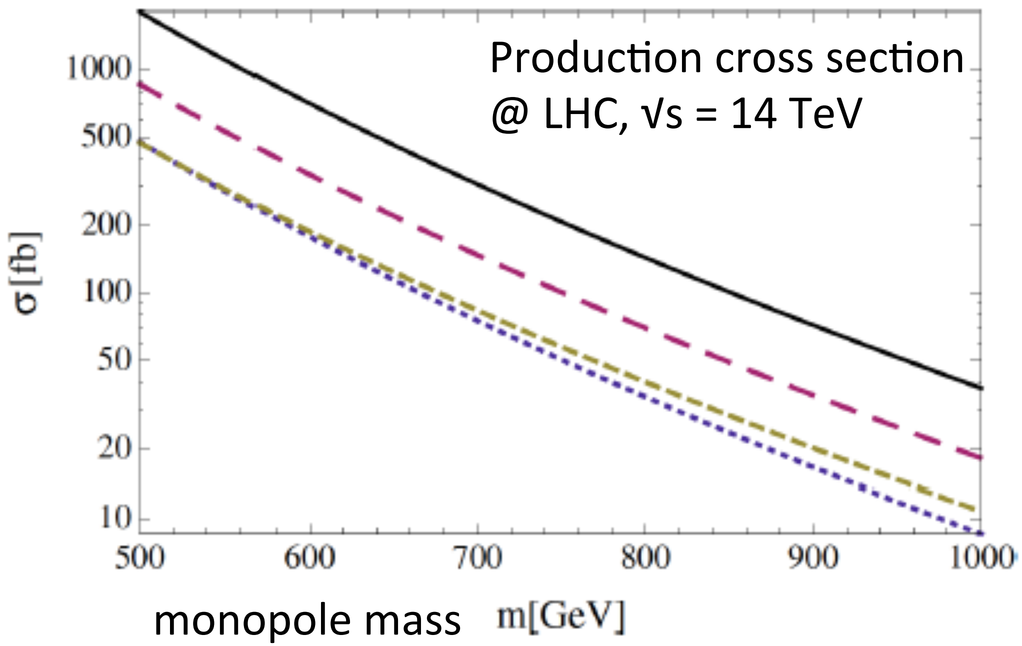


A. Rajantie

Monopolium

Dirac or other monopoles may not be free states but bound states
➜ MONOPOLIUM (MM)





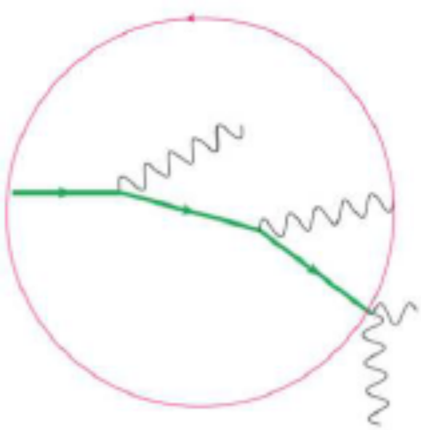
$$\sigma(2\gamma \to M) = \frac{4\pi}{E^2} \frac{M^2\, \Gamma(E)\, \Gamma_M}{(E^2 - M^2)^2 + M^2\, \Gamma_M^2}$$

Binding energy fixed = 2m/15 , e.g.
for m=750 GeV, binding energy = 100 GeV
→ monopolium mass M = 1400 GeV

Epele, Fanchiotti, Garcia-Canal, VAM, Vento, EPJ Plus 127 (2012) 60 [arXiv:1205.6120 [hep-ph]]

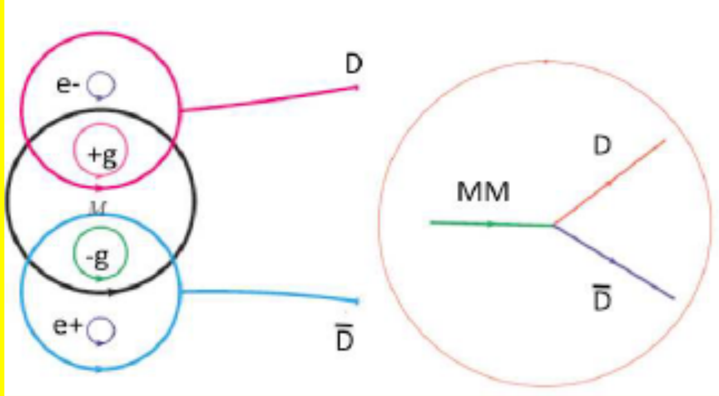
Monopolium detection

- Via its decay to **two photons** [Epele, Fanchiotti, Garcia-Canal, VAM, Vento, arXiv:1607.05592]
- Monopolium is neutral in its ground state thus, if produced in such a state, it is difficult to detect it directly
- HOWEVER… it may be produced in an excited state, which could be a magnetic multiple ➜ highly ionising



Its decay via photon emission would produce a **peculiar trajectory** in the medium, if the decaying states are also magnetic multipoles

Monopolium might break up into highly-ionising **Dyons**



In presence of magnetic fields ➤ huge polarisability

$$d \sim r_M^3 \, B \sim (\alpha \, E_{binding})^{-3} \, B$$

V. Vento, in MoEDAL Physics Review, Int.J.Mod.Phys. A29 (2014) 1430050

Magnetic monopole properties in a nutshell

- Single magnetic charge (Dirac charge): $g_D = 68.5e$
  - if carries electric charge as well, is called Dyon
- Large coupling constant: $g/\hbar c \sim 34$
- Monopoles would *accelerate* along field lines and *not curve* as electrical charges in a magnetic field - according to the Lorentz equation

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

- Energy acquired in a magnetic field: 2.06 MeV/gauss.m
  - monopoles accelerated to ~2 TeV with a 10 m × 10 T magnet!
- Dirac monopole is a point-like particle; GUT monopoles are extended objects
- Monopole spin is not determined by theory
- Monopole mass not predicted within Dirac's theory; other theories predict masses from $\mathcal{O}$(TeV) (electroweak) to $\gtrsim 10^{17}$ GeV (GUT)
- Monopoles would have anomalously high ionisation, Cherenkov radiation, transition radiation and multiple scattering

Searches for magnetic monopoles

- Types of detection
- Past results
- Currently operating experiments
- Future proposals

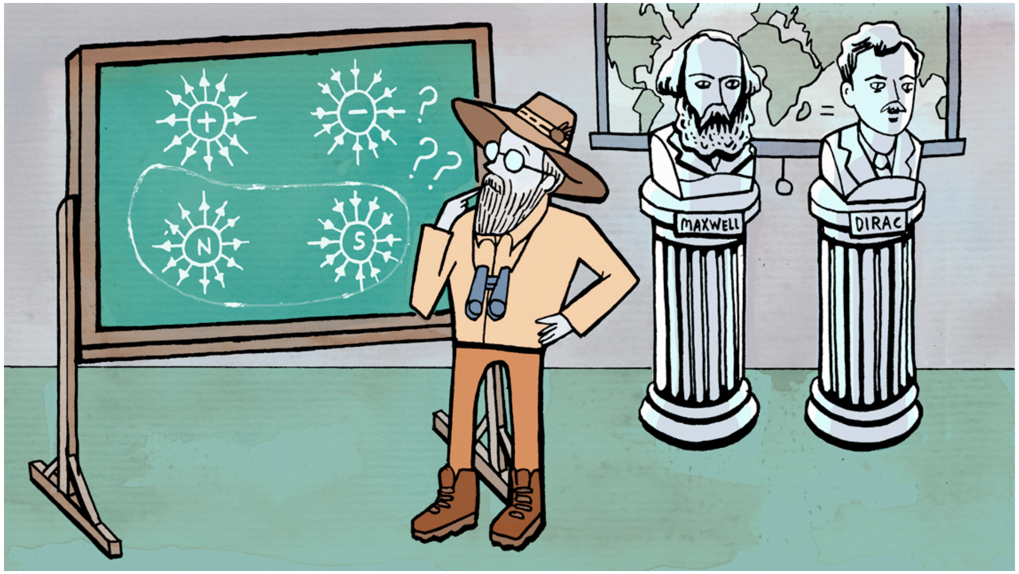


Illustration by Sandbox Studio, Chicago with Corinne Mucha

Detection techniques

- High ionization in gaseous detectors – transition radiation
  - MACRO, ATLAS, …
- Induction technique in superconductive coils (SQUID)
  - for monopoles trapped in material: rocks, beam pipes, …
- Cherenkov light in scintillators
  - cosmic monopoles
  - ice, balloon, deep-sea experiments
- Energy loss in nuclear track detectors
  - cosmic (SLIM, …)
  - colliders: LEP (MODAL, OPAL), LHC (ATLAS, MoEDAL)

Key feature: **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

High ionisation (HI) possible when:

- multiple electric charge (H^{++}, Q-balls, etc.) = n × e
- very low velocity & electric charge
- magnetic charge (monopoles, dyons) = ng_D = n × 68.5 × e
  - a singly charged relativistic monopole has ionisation ~4700 times MIP!!
- any combination of the above

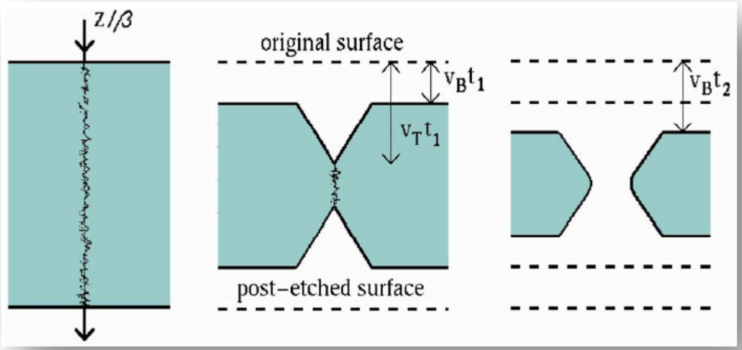
$$-\frac{dE}{dx} = K \frac{Z}{A} g^2 \left[\ln\frac{2m_e c^2 \beta^2 \gamma^2}{I_m} + \frac{K|g|}{2} - \frac{1}{2} - B(g)\right]$$

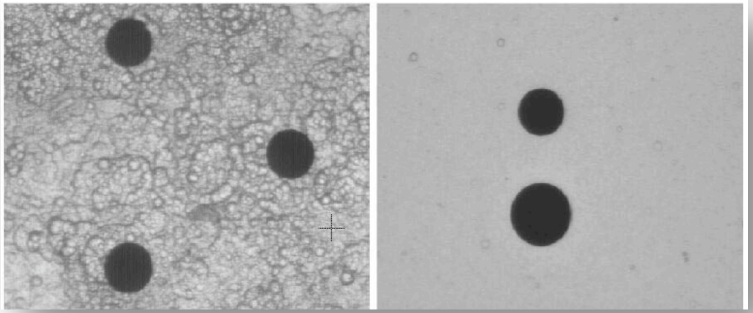
Magnetic charge

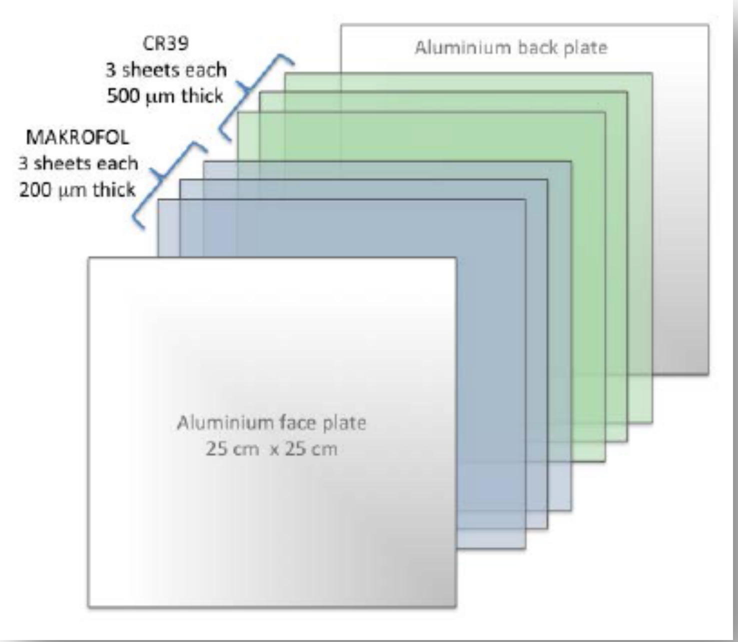
Ahlen formula

HI particle detection in NTDs

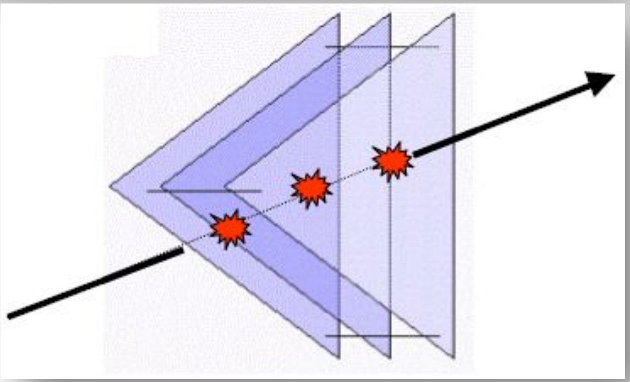
- Passage of a highly ionising particle through the plastic NTD marked by an invisible damage zone (**“latent track”**) along the trajectory
- The damage zone is revealed as a **cone-shaped etch-pit** when the plastic sheet is chemically **etched**
- Plastic sheets are later **scanned** to detect etch-pits



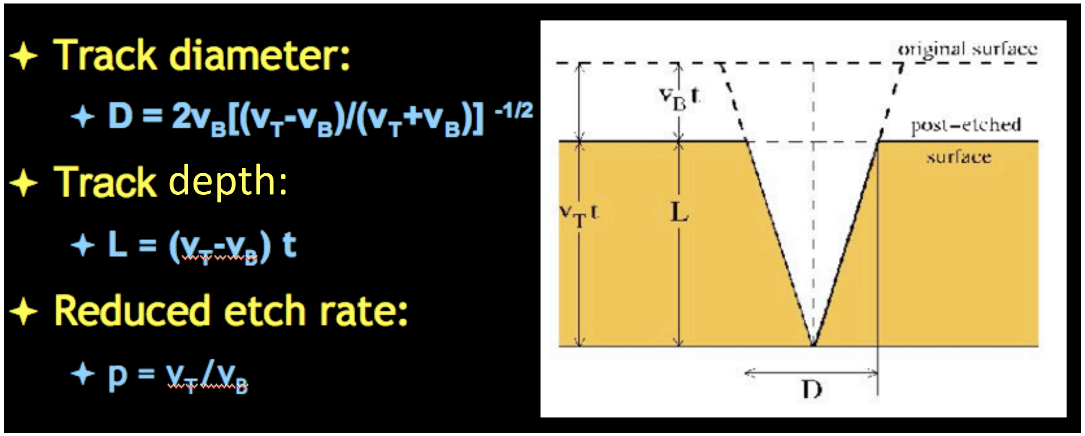


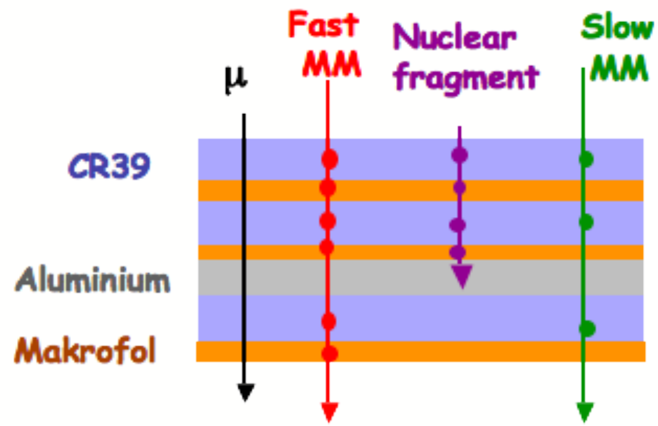


Looking for aligned etch pits in multiple sheets



Analysis procedure

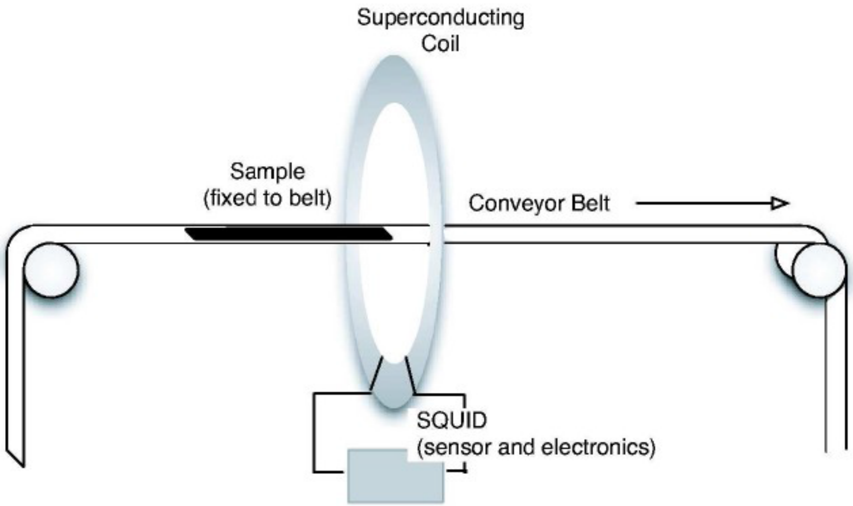


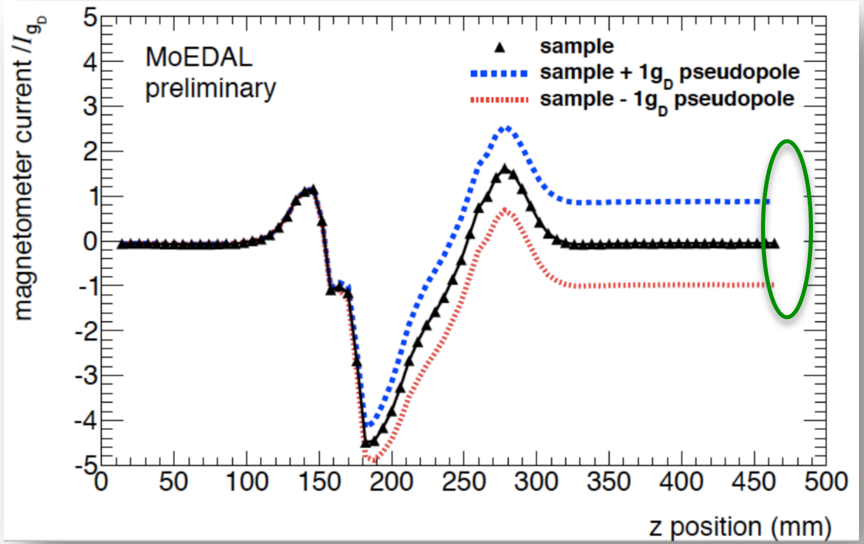


- Electrically-charged particle: $dE/dx \sim \beta^{-2}$ ➔ slows down appreciably within NTD ➔ opening angle of etch-pit cone becomes **smaller**
- Magnetic monopole: $dE/dx \sim \ln\beta$
  - slow MM: slows down within an NTD stack ➔ its ionisation falls ➔ opening angle of the etch pits would become **larger**
  - relativistic MM: dE/dx essentially constant ➔ trail of equal diameter etch-pit pairs
- The reduced etch rate is simply related to the *restricted energy loss* REL = $(dE/dx)_{\text{10nm from track}}$

Induction technique

- Binding energy of monopoles in nuclei with finite magnetic dipole moments → $\mathcal{O}$(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
  - if other than zero → *monopole signature*





Typical sample & pseudo-monopole curves

Induction – evidence?

- Data from Cabrera's apparatus taken on St. Valentine's day in 1982 (A=20 cm^2)
  - the trace shows a jump consistent with a monopole traversing the coil
- In August 1985 a group at Imperial College London reported the "observation of an unexpected event" also compatible with a monopole traversing the detector (A=0.18 m^2)
  - however their analysis conclude that "it is increasingly likely that Cabrera's original candidate event was spurious"

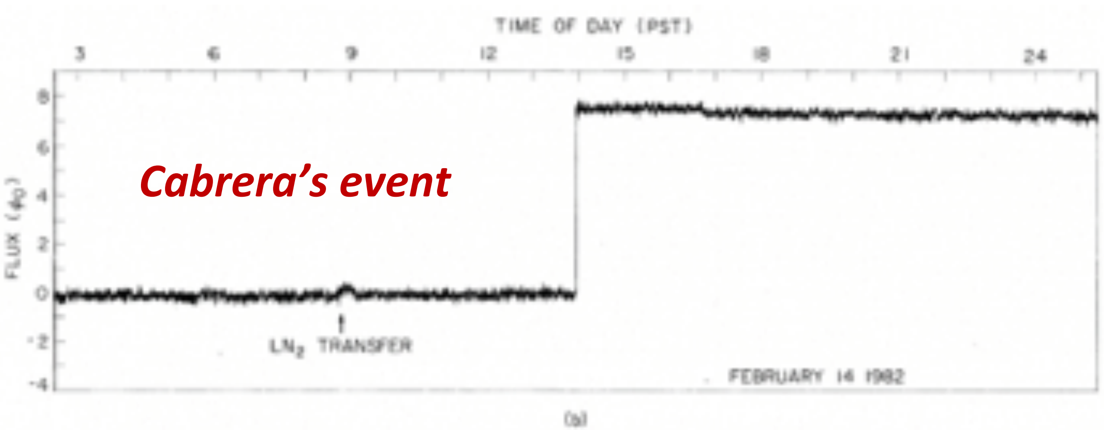
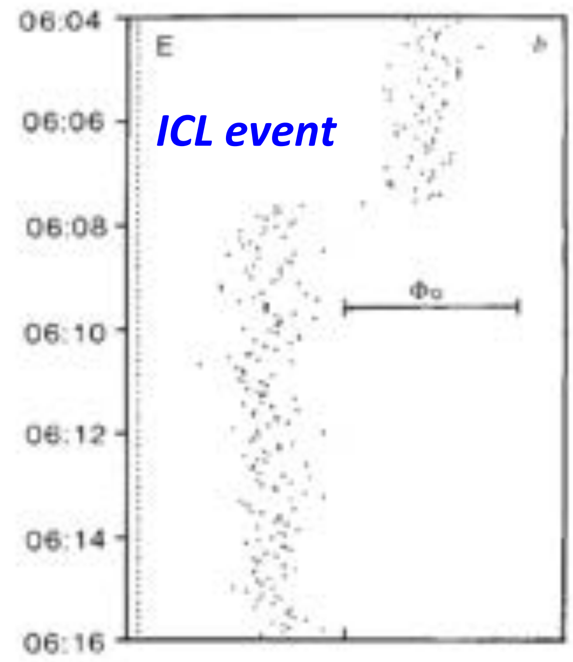


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

Phys.Rev.Lett. 48 (1982) 1378

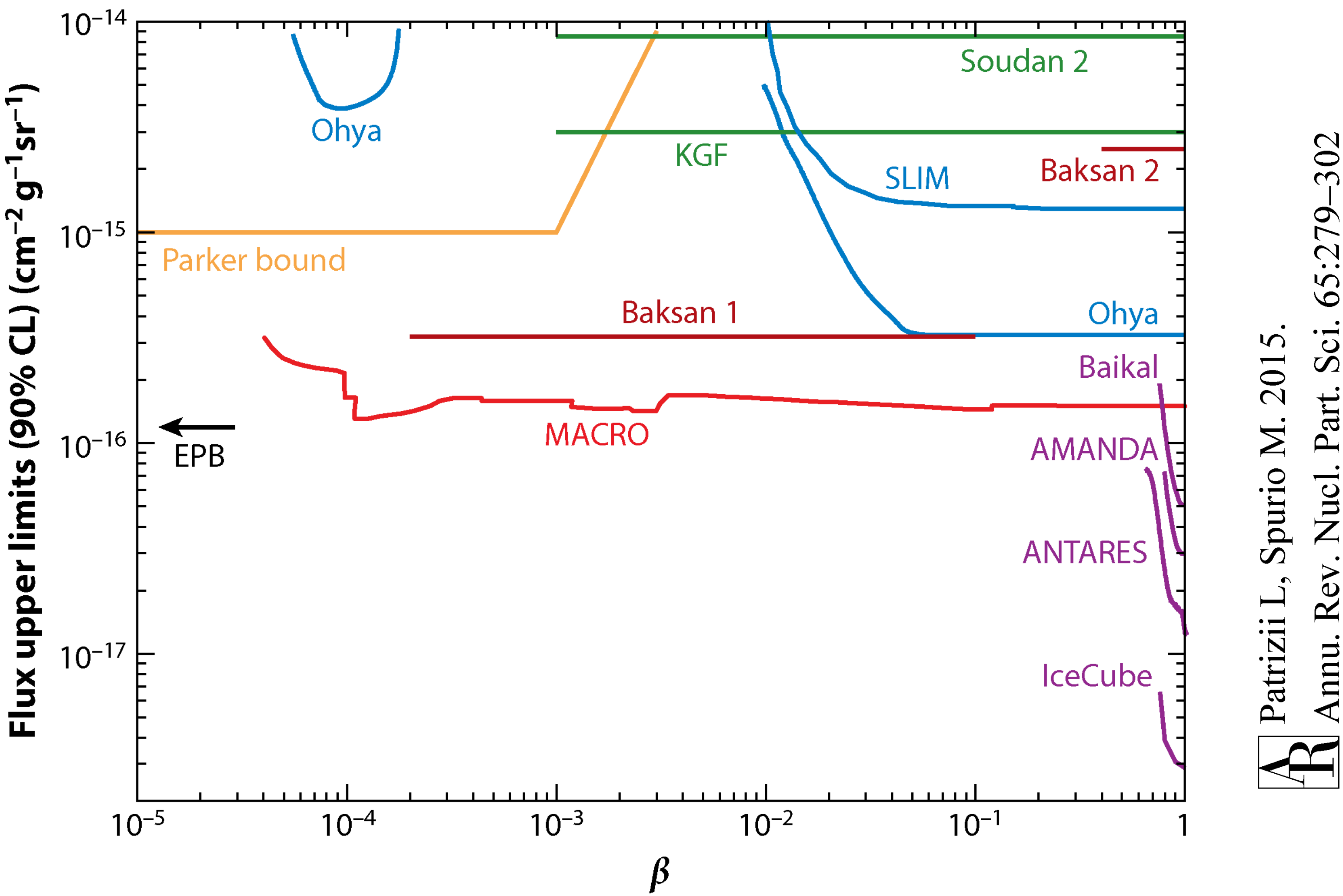


Nature 317 (1985) 234

Indirect detection

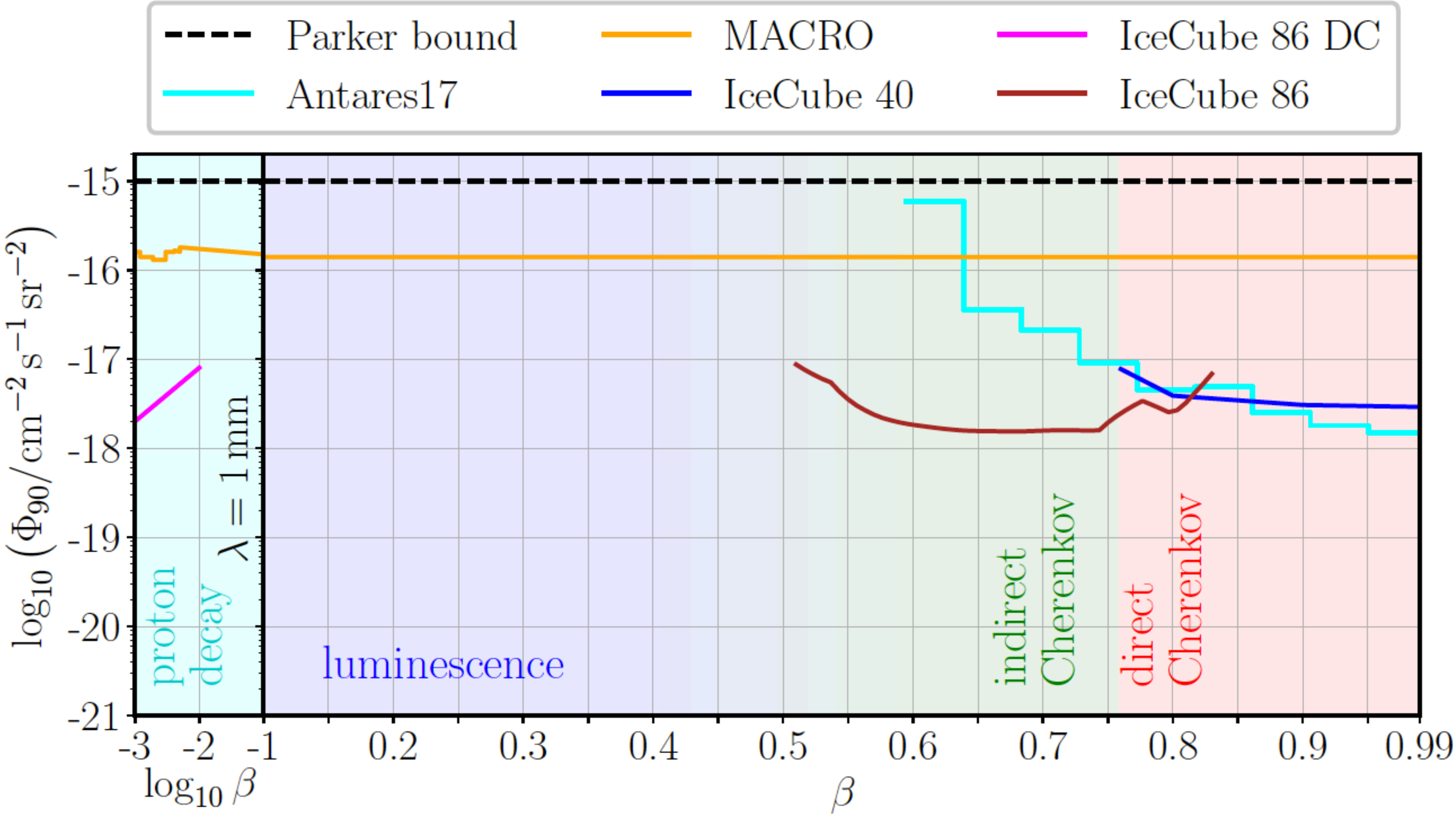
- Searches in bulk matter
  - terrestrial magnetic materials
  - meteorites
  - moon rocks: One of the first scientific experiments with moon rocks was to search for a concentration of magnetic monopoles
- Searches in cosmic rays
  - with counters
  - with passive detectors

Cosmic monopole searches



tracking calorimeter | scintillators | NTDs | ν-telescopes

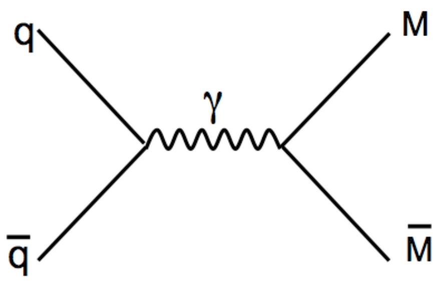
Focus on "fast" (β>0.1) monopoles



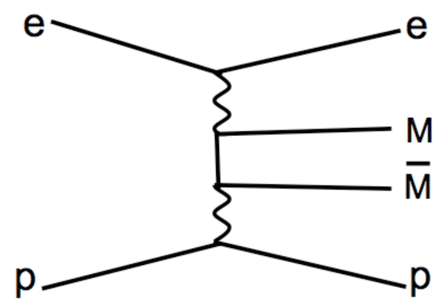
F. Lauber, ICNFP2017

Monopole production at colliders

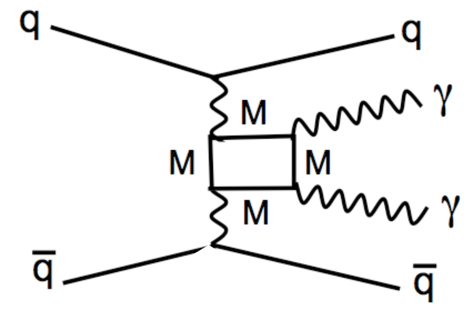
Production mechanisms in colliders



Drell Yan mechanism



Photon fusion

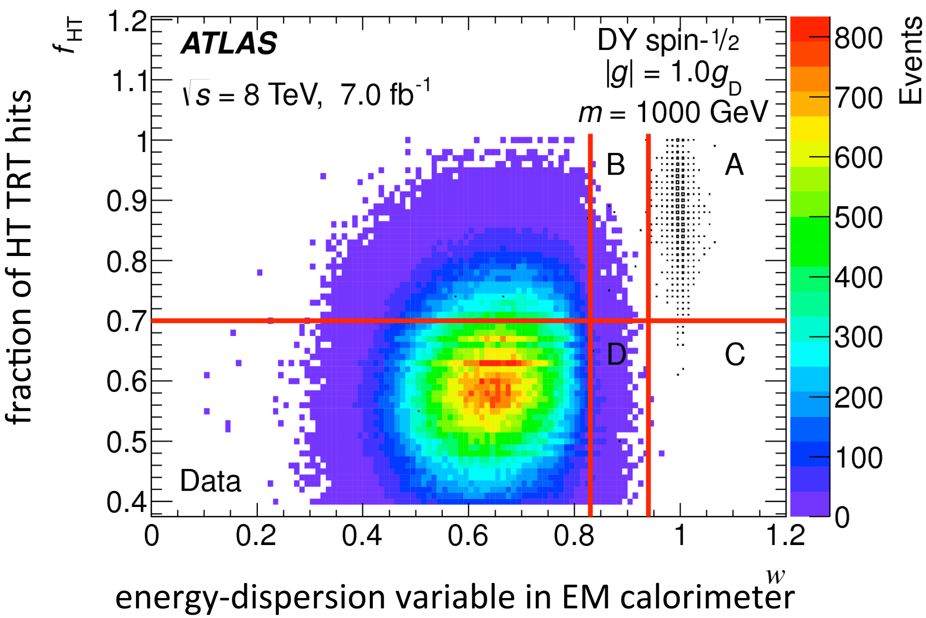


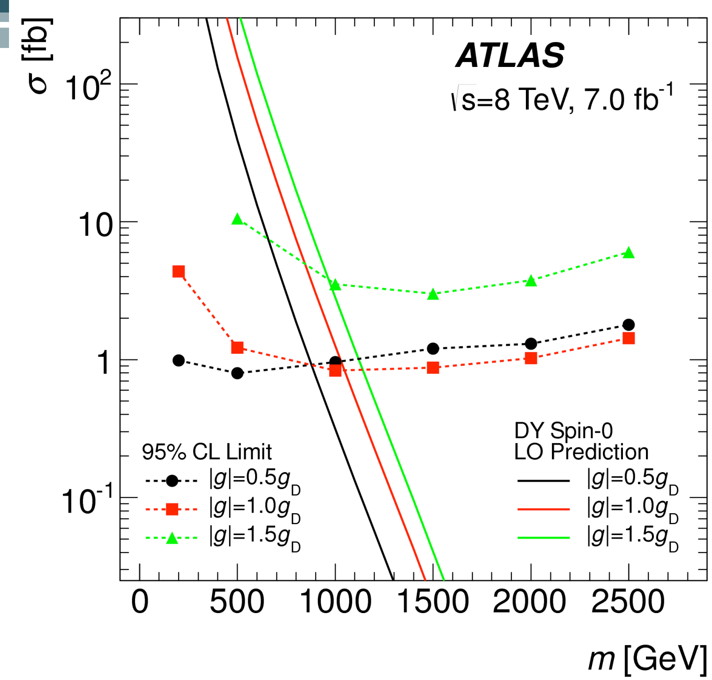
Box diagram

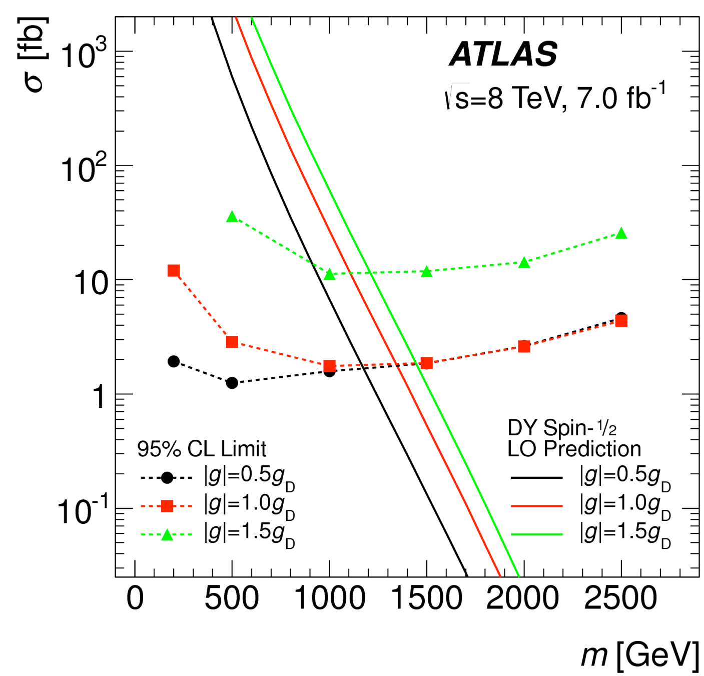
- Various high ionisation techniques (including NTDs) and induction (D0, CDF, HERA) have been used to search for monopoles at colliders
- Dirac monopole production with $\sigma > 0.05$ pb at **LEP** was excluded by OPAL for $45 < \text{mass} < 102$ GeV [Phys.Lett. B663 (2008) 37]
- CDF @ **Tevatron** excluded MM pair production at the 95% CL for cross-section < 0.2 pb and monopole masses $200 < m_M < 700$ GeV [Phys.Rev.Lett. 96 (2006) 201801]

ATLAS @ LHC

- Exploit distinct signals in Transition Radiation Tracker (high-threshold hit) and EM calorimeter (large localized energy deposit)
- Upper cross-section limits set for Dirac monopoles of mass of 200 – 2500 GeV
- Magnetic charges probed: $0.5 < |g| < 2.0\ g_D$



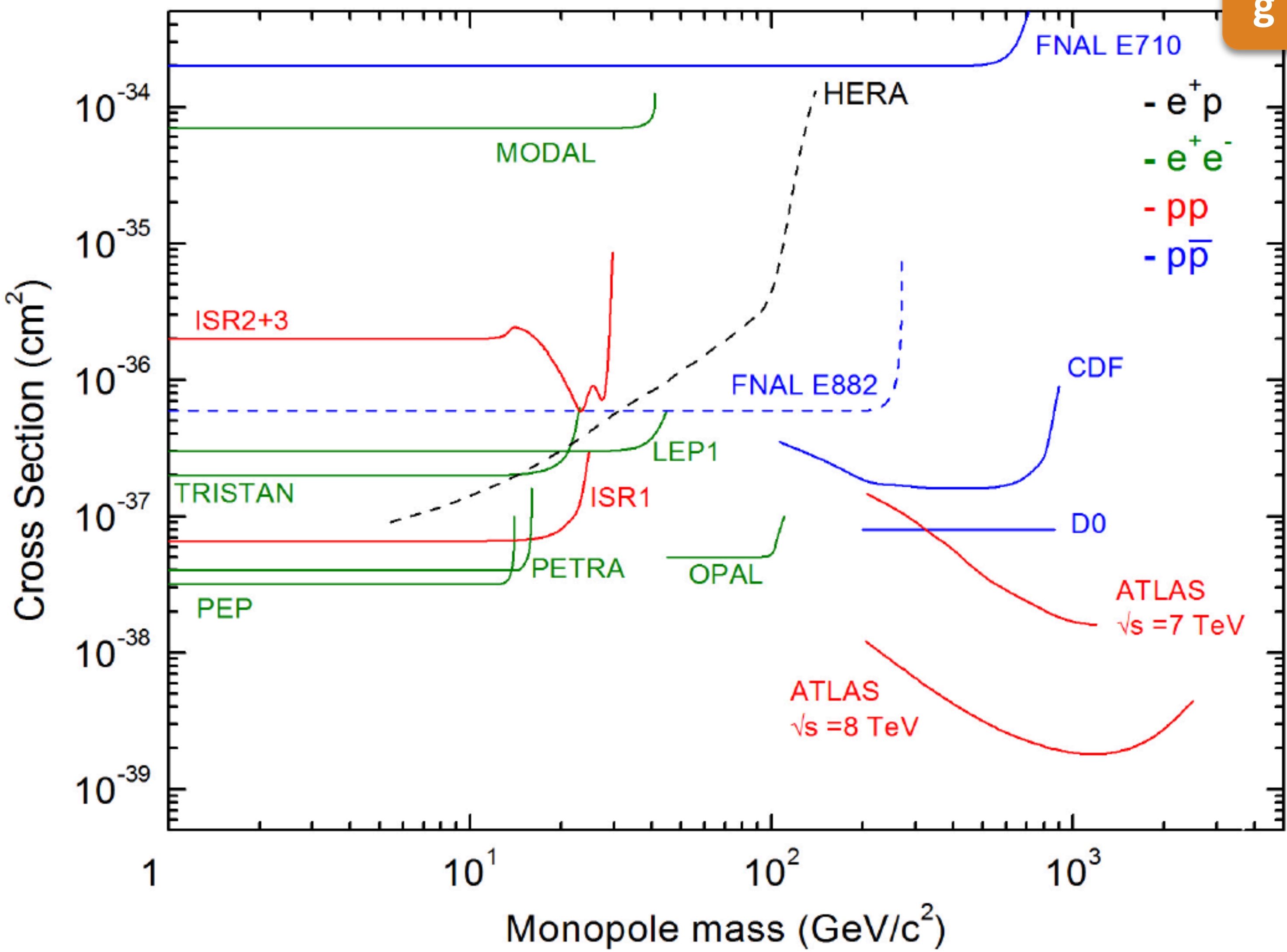




ATLAS, Phys. Rev. D 93, 052009 (2016)

Collider searches ≤ 2015

g = g_D



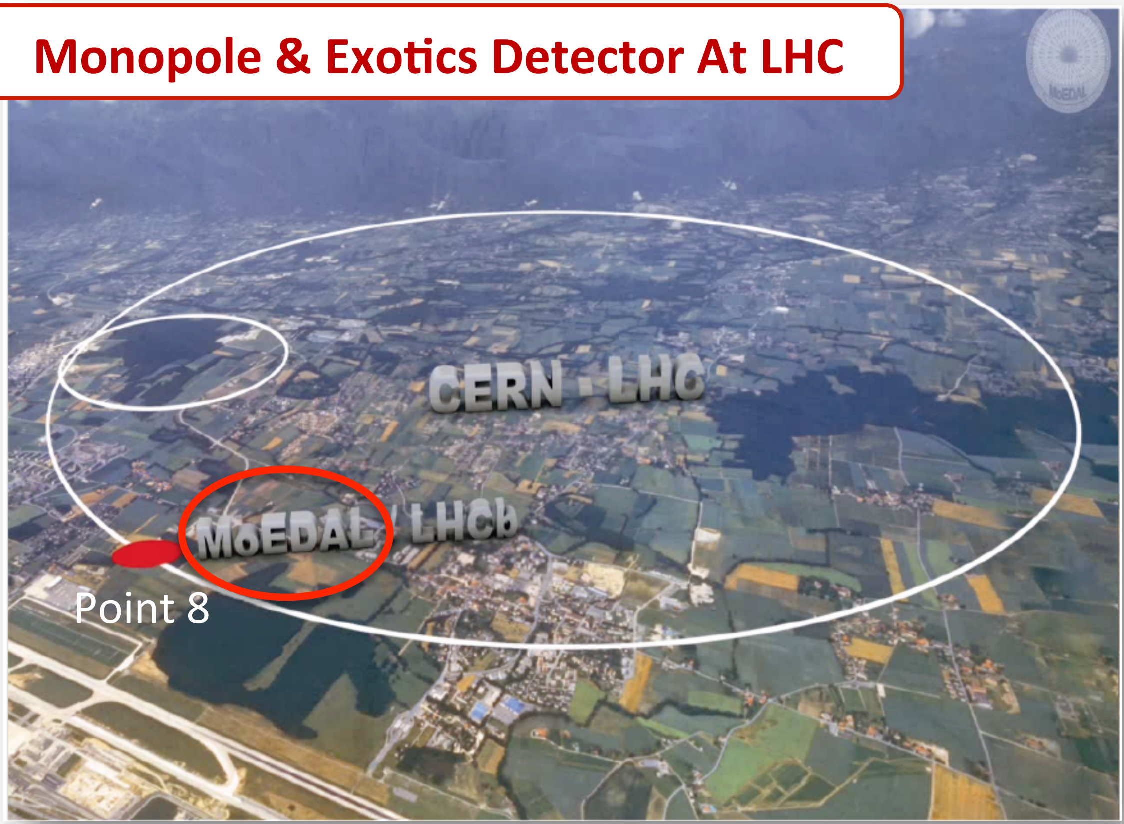
Patrizii L, Spurio M. 2015.
Annu. Rev. Nucl. Part. Sci. 65:279–302

Updated 2015

MoEDAL experiment at LHC

MoEDAL

Monopole & Exotics Detector At LHC

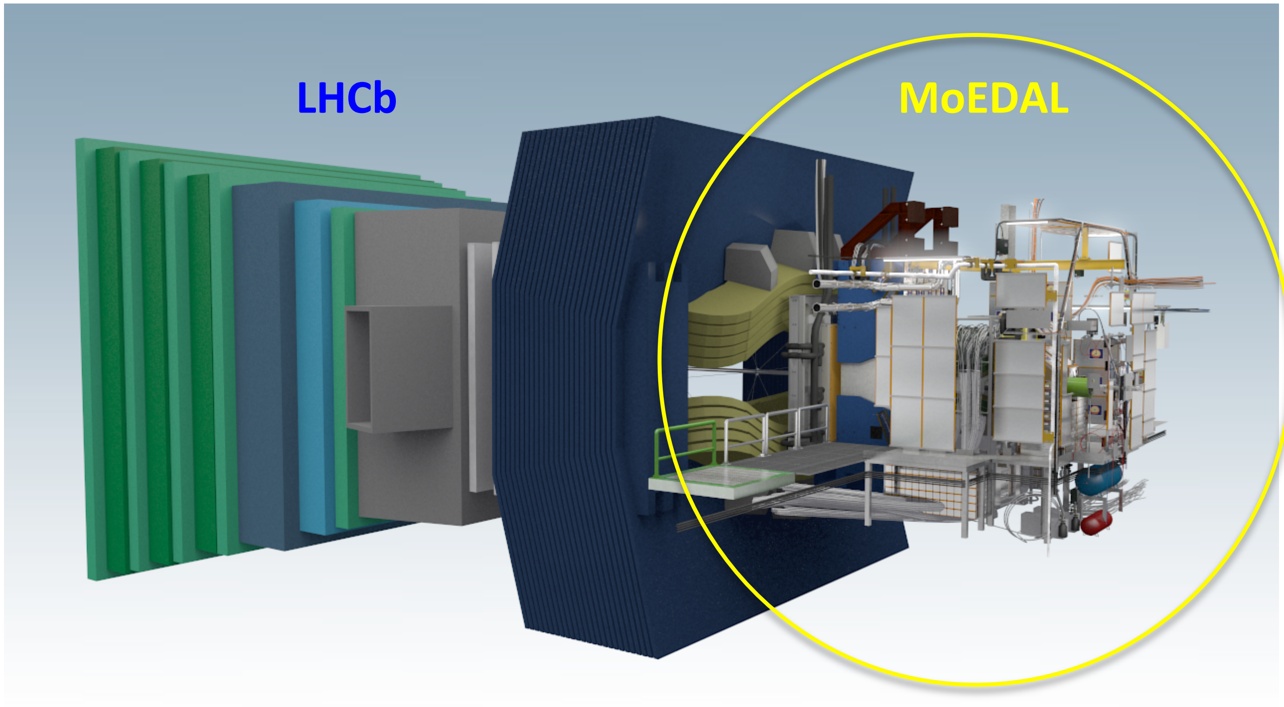


International collaboration
~70 physicists from
~20 participating institutions

UNIVERSITY OF ALABAMA
UNIVERSITY OF ALBERTA
INFN & UNIVERSITY OF BOLOGNA
UNIVERSITY OF BRITISH COLUMBIA
CERN
UNIVERSITY OF CINCINNATI
CONCORDIA UNIVERSITY
GANGNEUNG-WONJU NATIONAL UNIVERSITY
UNIVERSITÉ DE GENÈVE
UNIVERSITY OF HELSINKI
IMPERIAL COLLEGE LONDON
KING'S COLLEGE LONDON
KONKUK UNIVERSITY
UNIVERSITY OF MÜNSTER
MOSCOW INSTITUTE OF PHYSICS AND TECHNOLOGY
NORTHEASTERN UNIVERSITY
TECHNICAL UNIVERSITY IN PRAGUE
QUEEN MARY UNIVERSITY OF LONDON
INSTITUTE FOR SPACE SCIENCES, ROMANIA
STAR INSTITUTE, SIMON LANGTON SCHOOL
TUFT'S UNIVERSITY
IFIC VALENCIA

MoEDAL detector

MoEDAL



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 Monopole Trapping detector (**MMT**)

④ TimePix radiation background monitor

MoEDAL is unlike any other LHC experiment:

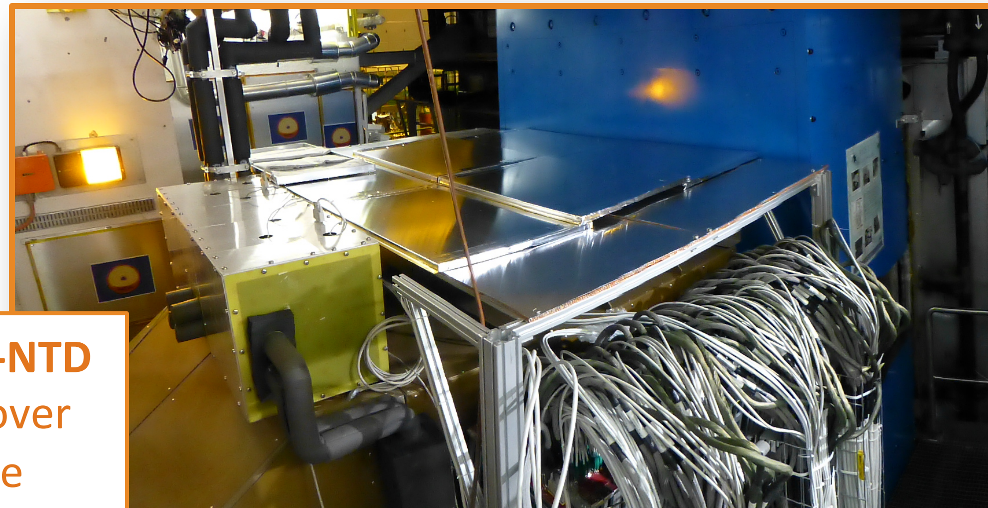
- mostly **passive detectors**; no trigger; no readout
- the largest deployment of passive **Nuclear Track Detectors (NTDs)** at an accelerator
- the 1st time **trapping detectors** are deployed as a detector

MoEDAL physics program
Int. J. Mod. Phys. A29 (2014) 1430050
[arXiv:1405.7662]

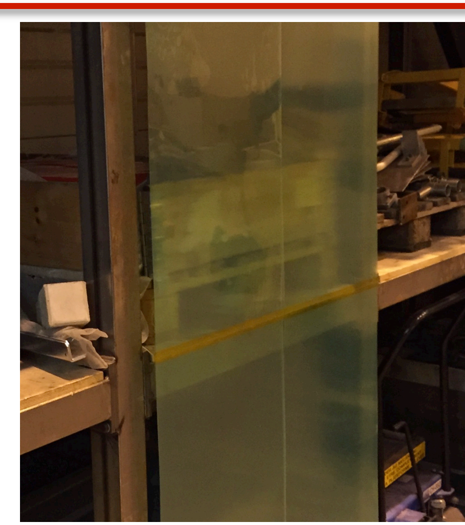
1 & 2 NTDs deployment

MoEDAL

2012: LT-NTD
NTDs sheets kept in boxes mounted onto LHCb VELO cavern walls



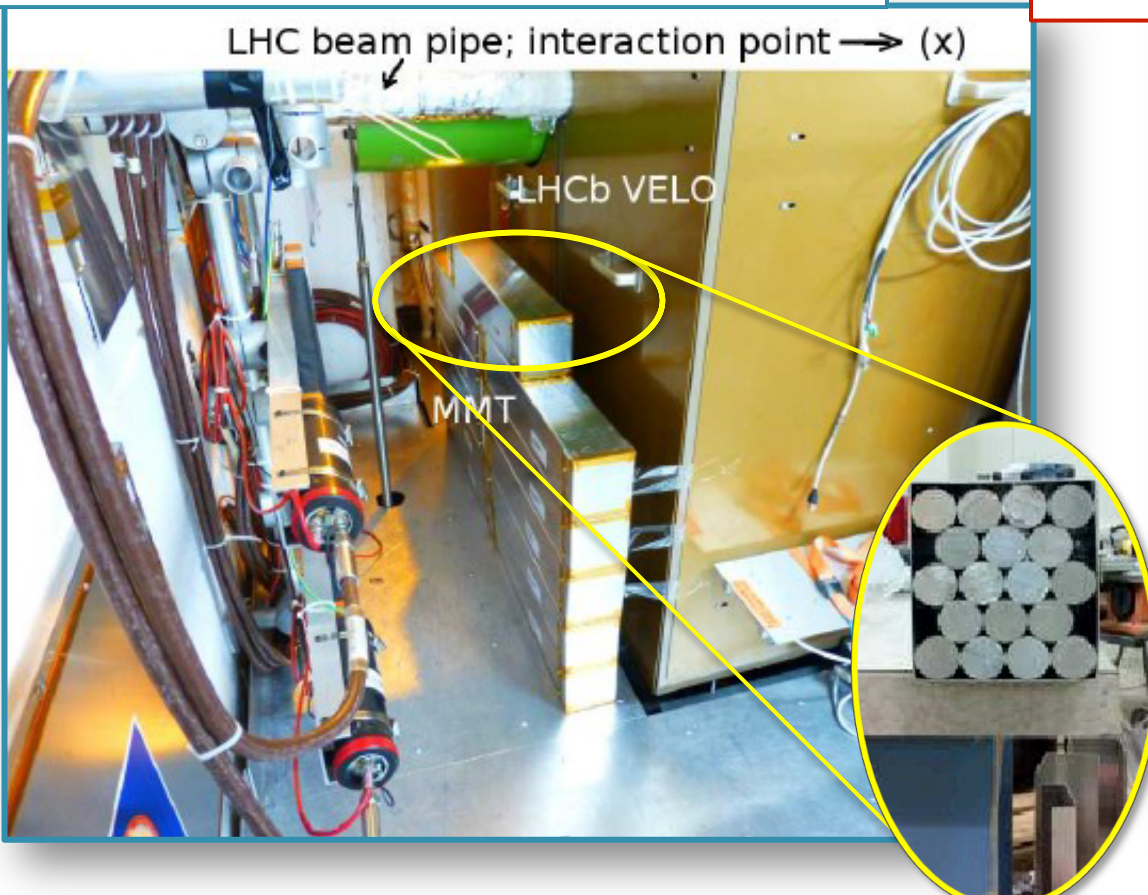
2015-2016: LT-NTD
Top of VELO cover
Closest possible location to IP



2015-2016: HCC-NTD
Installed in LHCb acceptance between RICH1 and TT

3 MMTs deployment

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



2015-2016
- Installed in additional locations: sides A & C, too
- Approximately **800 kg** of Al
- Total 2400 aluminum bars

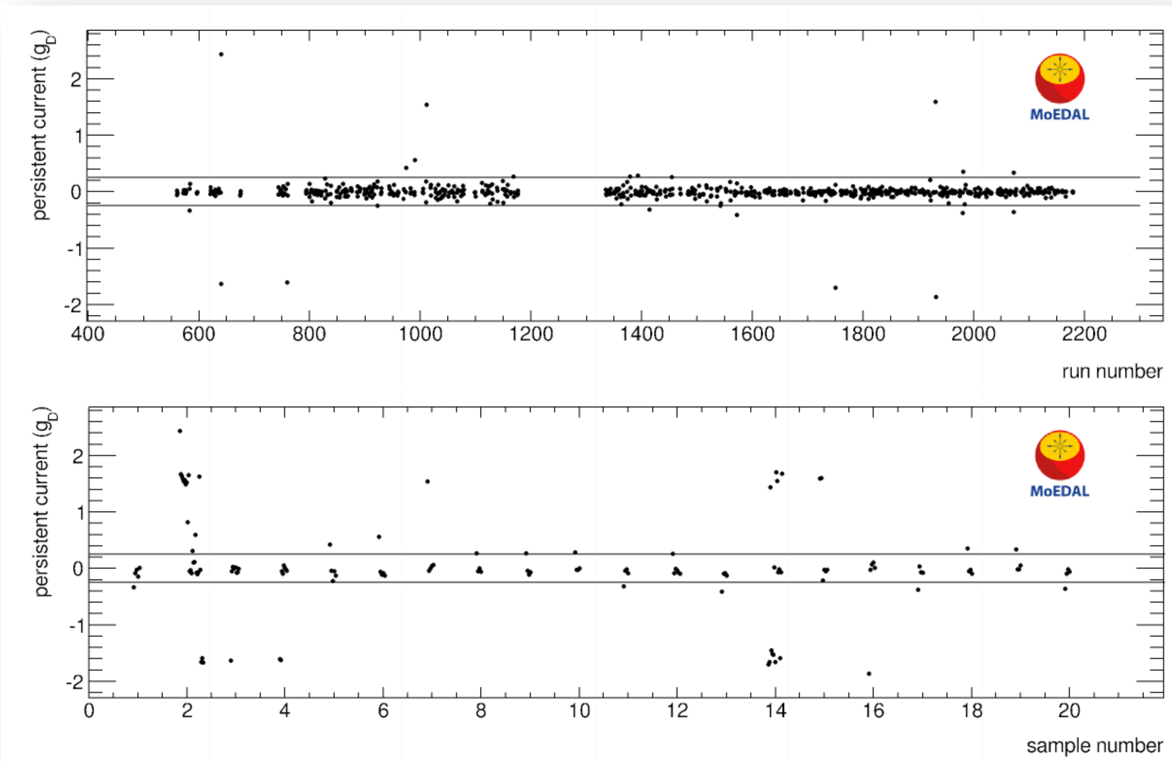
MoEDAL

MoEDAL MMT2015 scanning

Detector: prototype of **222 kg** of aluminium bars

Exposure: **0.371 fb^{-1}** of **13 TeV** *pp* collisions during 2015

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



Persistent current after first passage for all samples

MoEDAL

Persistent current for multiple measurements of candidates

PRL 118 (2017) 061801
[arXiv:1611.06817]

No monopole with charge > 0.5 g_D observed in MMT samples at 99.5% CL

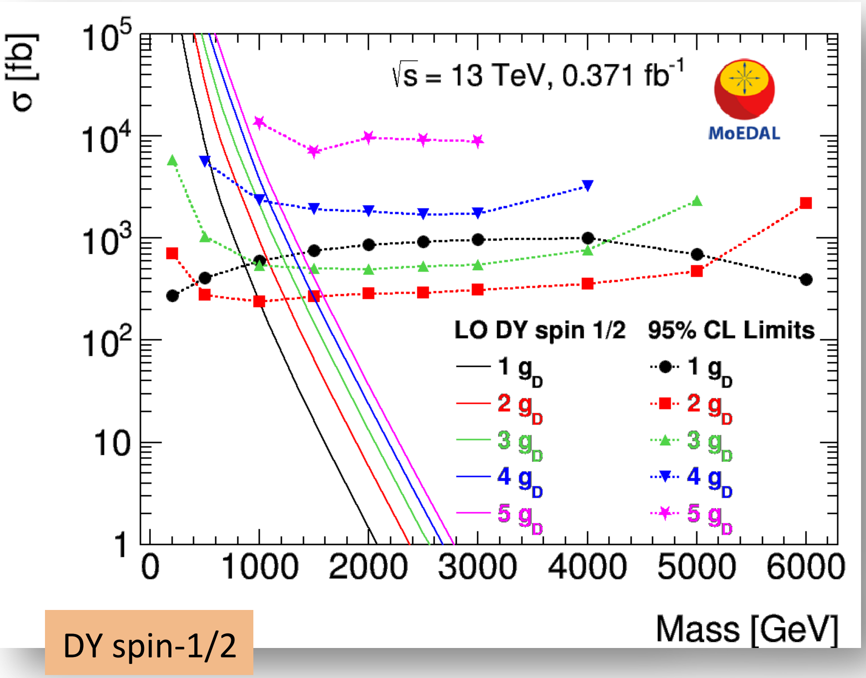
MoEDAL MMT2015 results

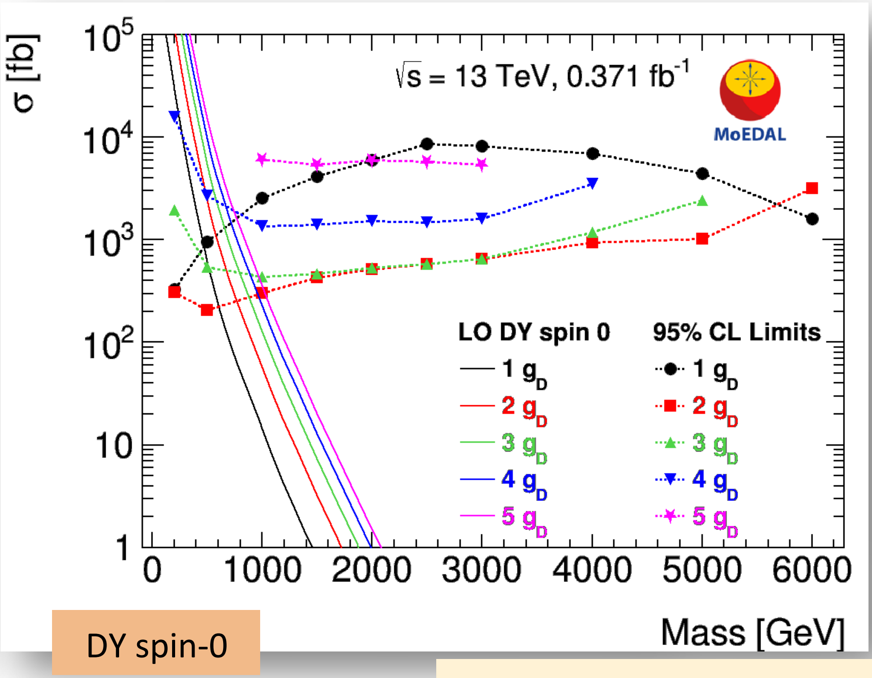
MoEDAL

Detector: prototype of **222 kg** of aluminium bars

Exposure: **0.371 fb^{-1}** of **13 TeV** *pp* collisions during 2015

☞ see also **JHEP 1608 (2016) 067** [arXiv:1604.06645] for results **@ 8 TeV**

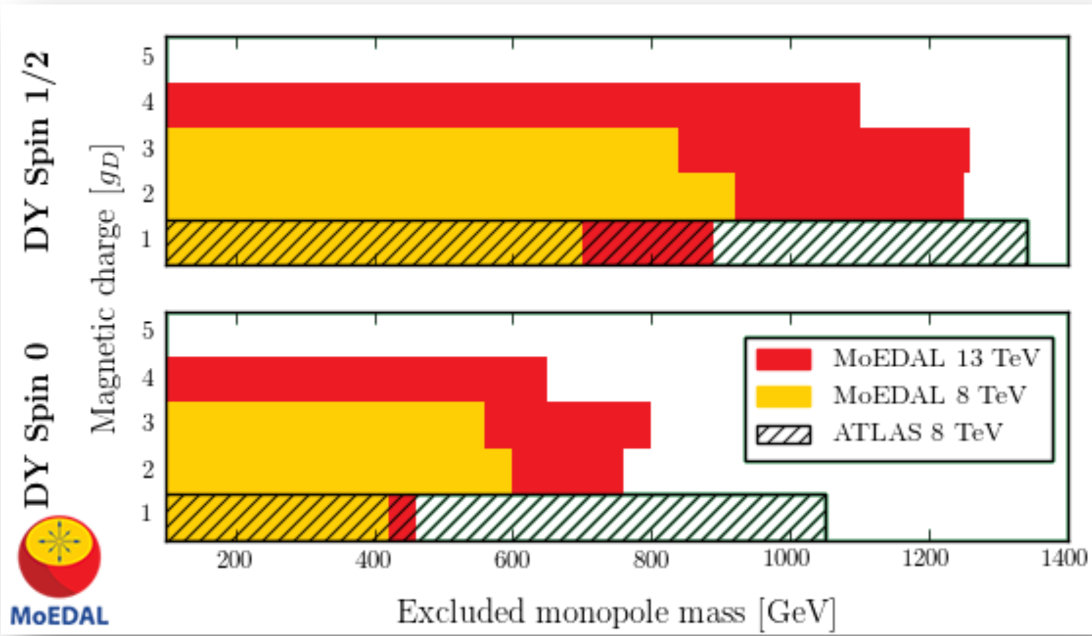




PRL 118 (2017) 061801
[arXiv:1611.06817]

- First monopole searches at **13 TeV** at LHC
- First limits for magnetic charge of **5 g_D** and masses **> 3.5 TeV**

LHC monopole mass limits



DY lower mass limits [GeV]		$\lvert g \rvert = g_D$	$\lvert g \rvert = 2g_D$	$\lvert g \rvert = 3g_D$	$\lvert g \rvert = 4g_D$
MoEDAL 13 TeV	spin ½	890	1250	1260	1100
	spin 0	460	760	800	650
MoEDAL 8 TeV	spin ½	700	920	840	—
	spin 0	420	600	560	—
ATLAS 8 TeV	spin ½	1340	—	—	—
	spin 0	1050	—	—	—

MoEDAL

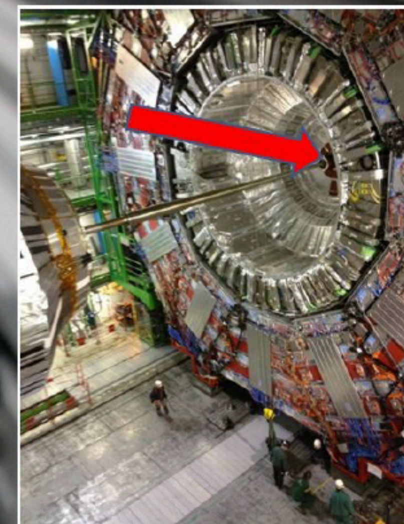
- Mass limits are *highly model-dependent*
  - Drell-Yan production does *not* take into account non-perturbative nature of the large monopole-photon coupling
- Exclude low masses for **$\lvert g \rvert = 4g_D$** for the first time at LHC
- World-best collider limits for **$\lvert g \rvert \geq 2\ g_D$**

PRL 118 (2017) 061801
[arXiv:1611.06817]

MoEDAL

Beampipe Searches for Very Highly Ionizing Particles – Now in Play

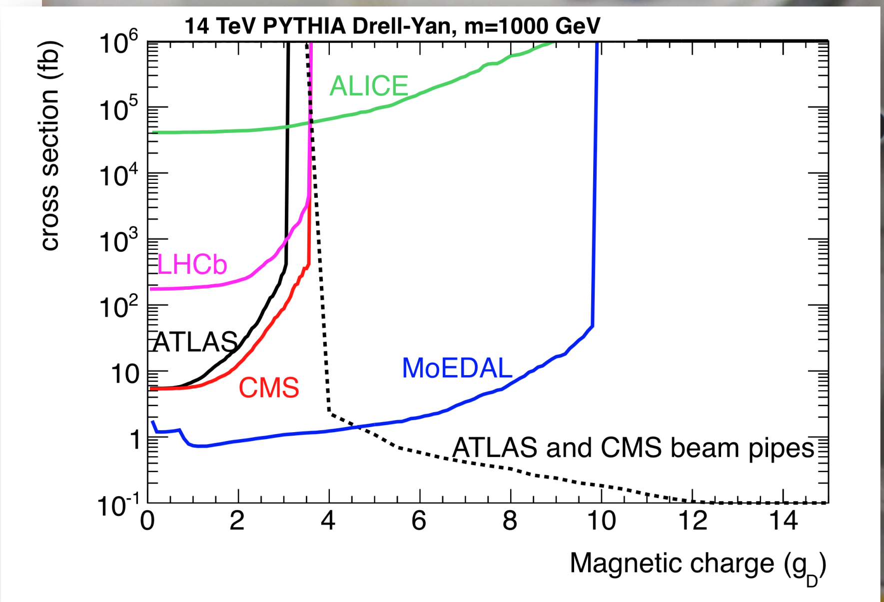
ATLAS/CMS Beryllium beampipes ?

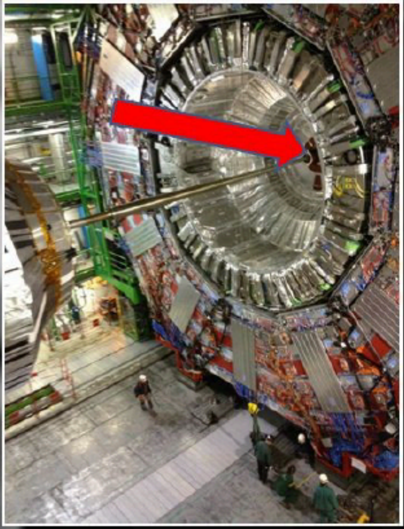


MoEDAL- Beampipe Consortium have submitted a proposal to ATLAS & CMS to utilize their replaced surplus-to-requirement beam pipes in order to scan them for the presence of very highly ionizing monopoles trapped in the beam pipe walls

J. Pinfold, LHC LLP Workshop, Apr 2017

Beampipe Searches for Very Highly Ionizing Particles – Now in Play





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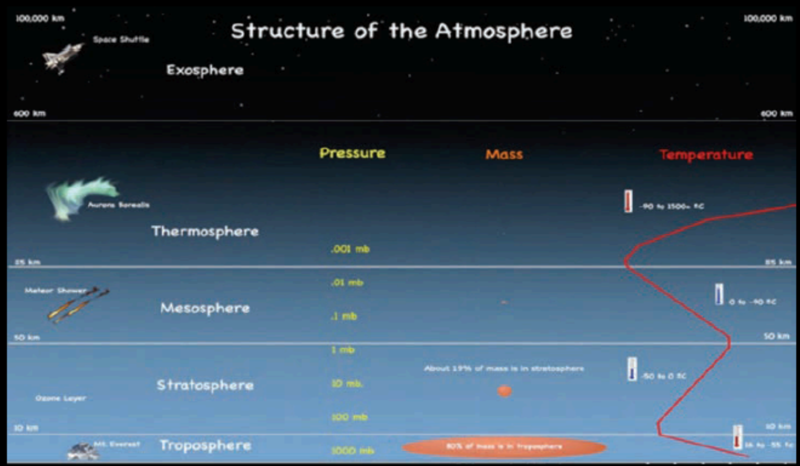
J. Pinfold, LHC LLP Workshop, Apr 2017

The Future - Cosmic-MoEDAL?



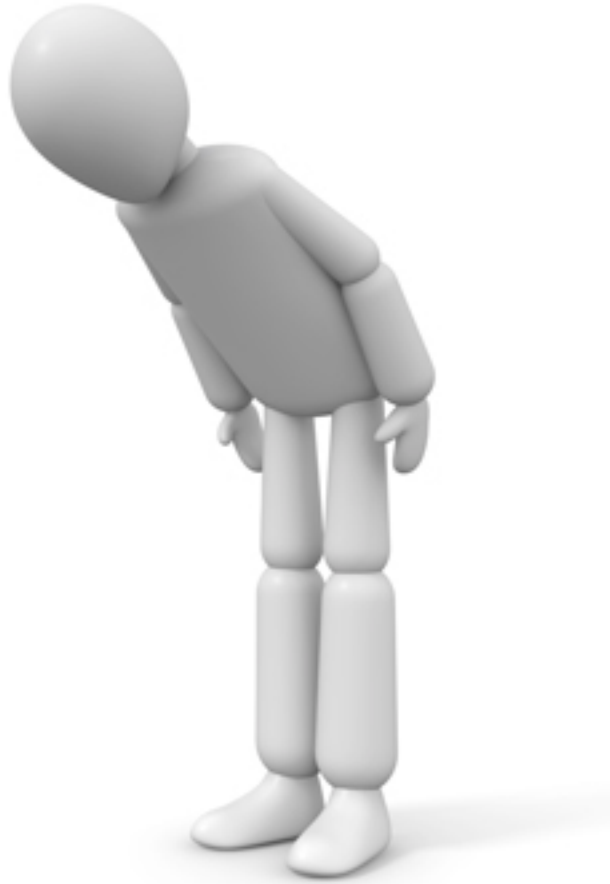
- *Cosmic-MoEDAL envisage deployment of ~50K m^2 of NTDs at high altitude - 50/125 times larger than MACRO/SLIM*
  - *To detect remnants from the early universe: EW monopoles and monopoles from late phase transition & GUT scenarios with mass from ~10^4 to 10^{18} GeV, as well as strangelets, nuclearites, etc*
  - *We can also look for monopoles and massive (pseudo)-stable charged particles particles produced in very high energy air showers.*
- *Sites under consideration: Chacaltaya (5km); Tenerife -Tiede (3km); IceCube (3km); Jeju Island (2km)*

J. Pinfold, MoEDAL collab. meeting, Bologna, 2017

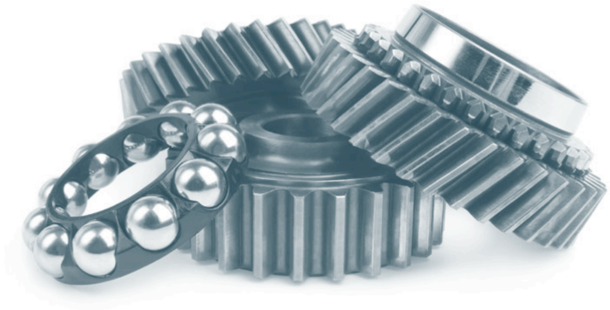
Outlook

- Monopoles continue to excite interest and have been the subject of numerous experimental searches
- The MoEDAL experiment at the LHC is one of the key players in this quest
  - design *optimised* for such searches
  - combining various detector technologies
  - also searching for other **(meta)stable highly ionising particles**
- **Stay tuned for upcoming results !**

Thank you for your attention!

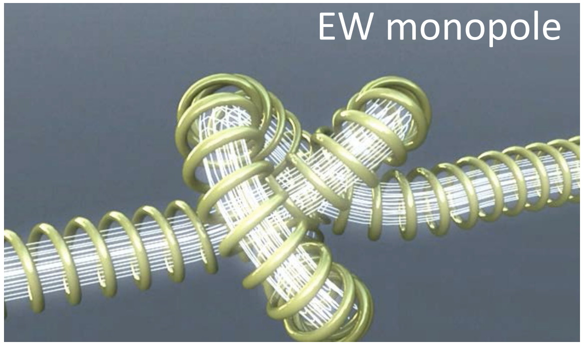


Spares



Magnetic monopole mass

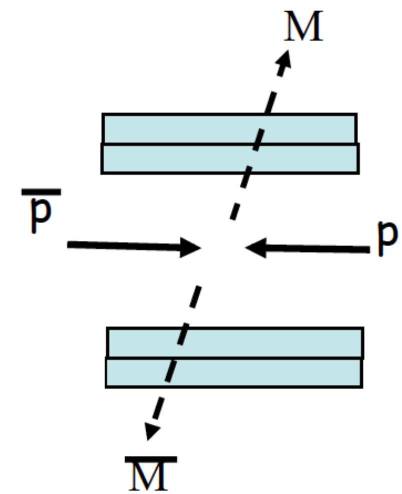
- No real prediction for classical Dirac monopole mass
  - if monopole radius ~ electron radius ⇒ $m_{monopole} \approx n \times (2.4\ \text{GeV})$
- There are other models where monopoles could appear in a mass range accessible to the LHC. e.g.:
  - the electroweak Cho-Maison monopole [PLB 391 (1997) 360]
  - the Troost-Vinciarelli monopole had a matter field: 50-100 GeV [PLB 63 (1976) 453]

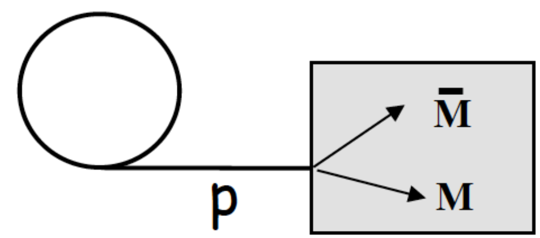


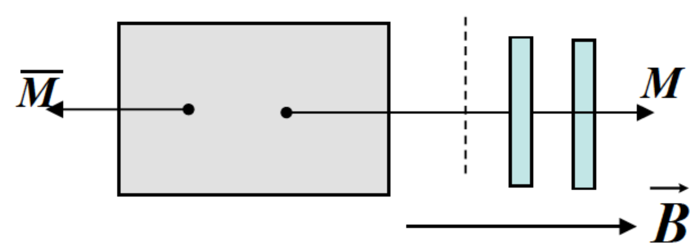
- GUT monopoles
  - 't Hooft and Polyakov (1974) showed that monopoles are fundamental solutions to non-Abelian gauge "GUT" theories – in any theory with an unbroken U(1) factor embedded
  - $m(M_{GUT}) \geq m_X/G > 10^{16}$ GeV ⟶ 10^{17} GeV ~ 0.02 μg - not producible by particle accelerators
- We consider the magnetic monopole mass a free parameter

Monopole origin

- Direct detection (immediately after production in high-energy collisions)
  - e.g. thin plastic sheets surround interaction regions
- Indirect searches (monopoles are searched for a long time after their production)
  - monopoles produced ➤ stopped ➤ trapped
  - later: accelerated ➤ extracted ➤ detected



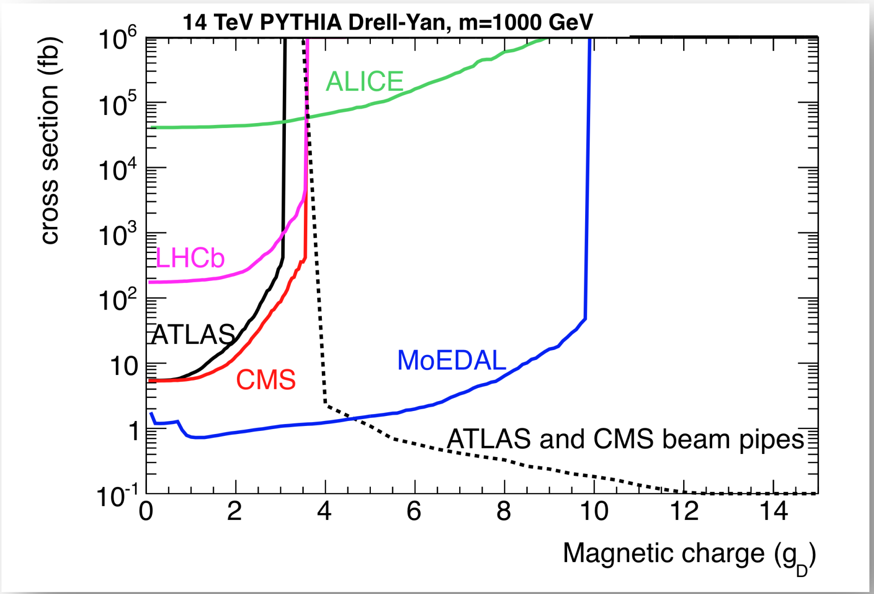


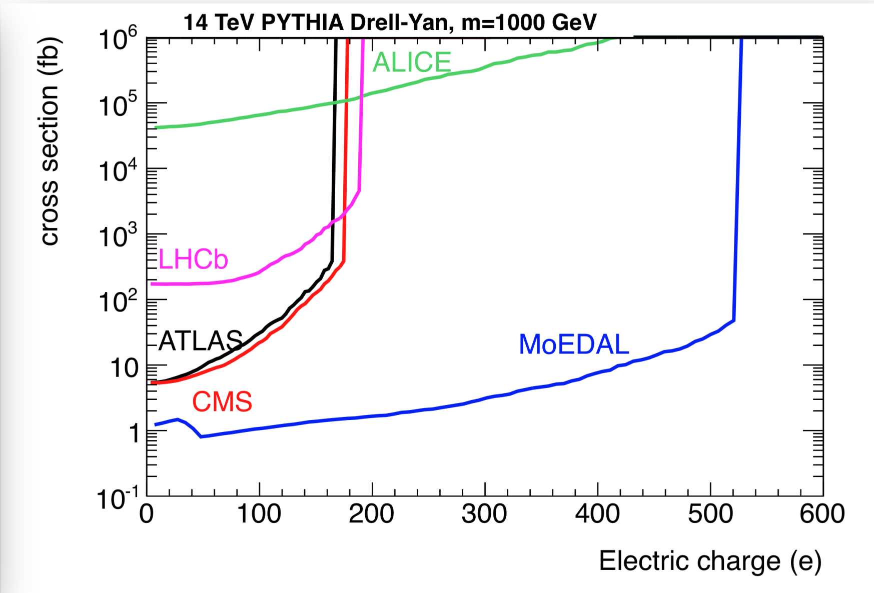


MoEDAL sensitivity

Cross-section limits for magnetic and electric charge assuming that:

- ~ one MoEDAL event is required for discovery and ~100 events in the other LHC detectors
- integrated luminosities correspond to about two years of 14 TeV run



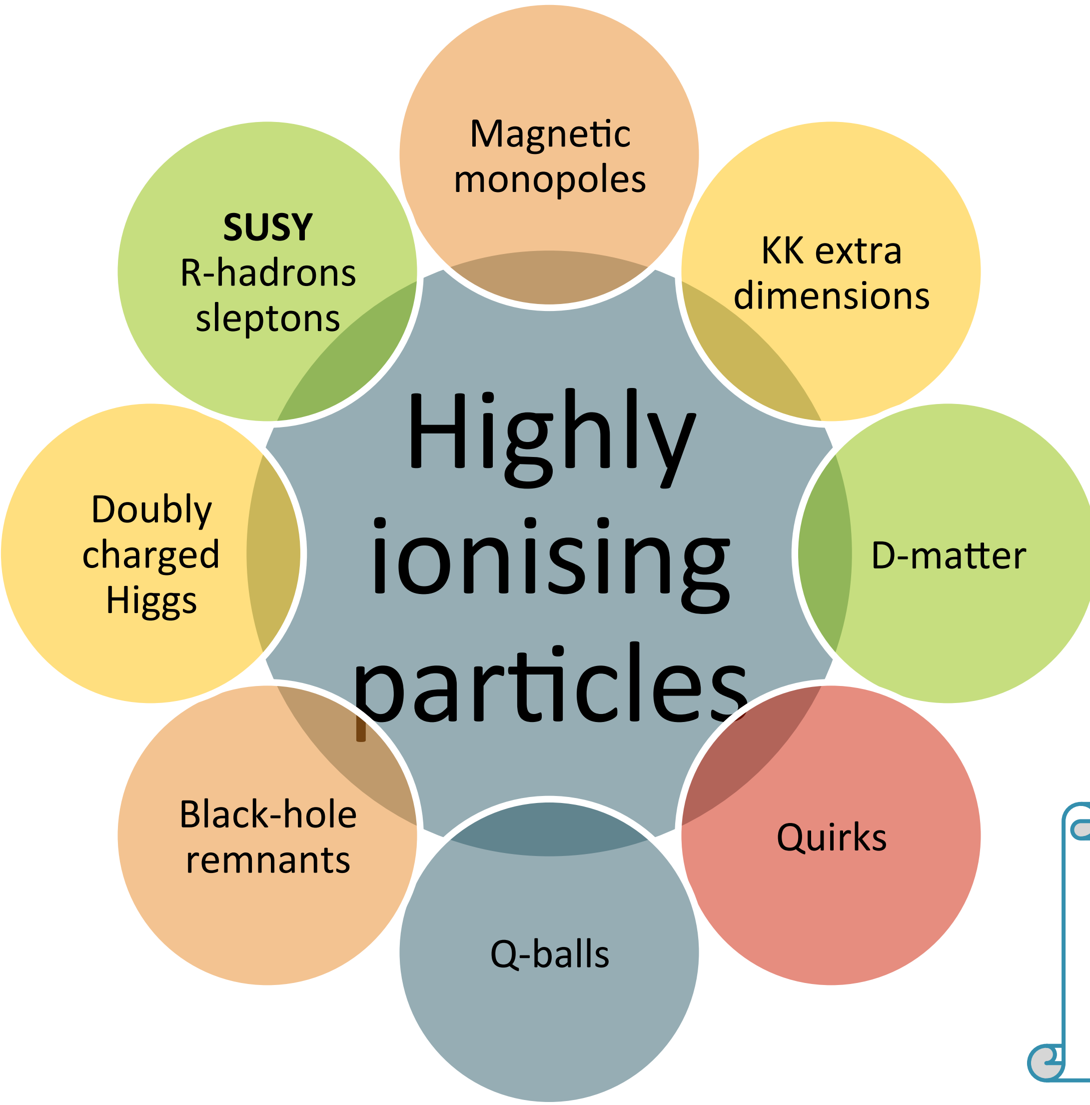


De Roeck, Katre, Mermod, Milstead, Sloan, EPJC72 (2012) 1985 [arXiv:1112.2999]

MoEDAL offers robustness against timing and well-estimated signal efficiency

MoEDAL physics programme

MoEDAL



Searching for *massive*, *long-lived* & *highly ionising* particles

MoEDAL physics program
Int. J. Mod. Phys. A29 (2014) 1430050
[arXiv:1405.7662]

Complementarity of MoEDAL & other LHC exps

MoEDAL

ATLAS+CMS

- Optimised for *singly* electrically charged particles ($z/\beta \sim 1$)
- LHC timing/trigger restricts sensitivity to (nearly) *relativistic* particles ($\beta \approx 1$)
- Typically a largish statistical sample is needed to establish a signal
- ATLAS & CMS cannot be calibrated for highly ionising objects
- Magnetic charge detection via its trajectory in non-bend plane → calibration introduces large systematics

MoEDAL

- Designed to detect charged particles, with effective or actual $z/\beta > 5$
- No trigger/electronics → slowly moving ($\beta < \sim 0.5$) particles are no problem
- One candidate event should be enough to establish a signal (no SM bkg)
- MoEDAL NTDs are calibrated using heavy ion beams
- Magnetic-charge sensitivity directly calibrated in a clear way

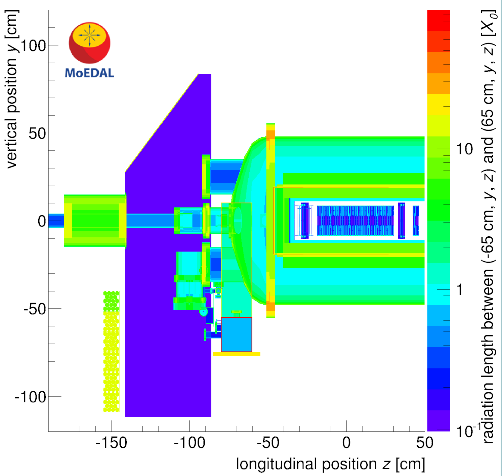
MoEDAL strengthens & expands the physics reach of LHC

MoEDAL

MoEDAL analysis

Geometry

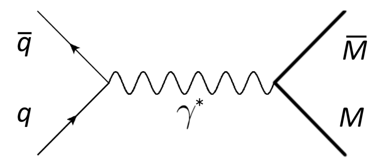
Material description between IP & detector

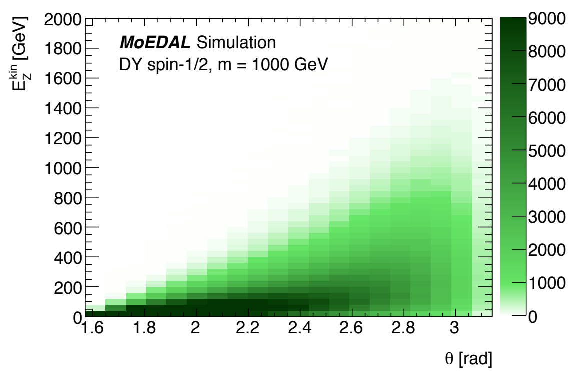


Kinematics

Event generation of Drell Yan production

coupling ≫ 1 ⇒ non-perturbative!

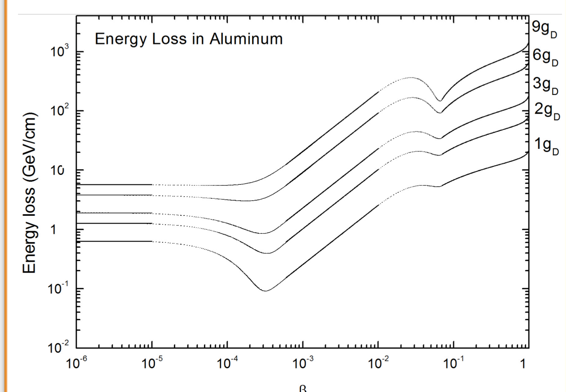




JHEP 1608 (2016) 067

Propagation in matter

- Ahlen formula
- Monopole energy loss
- Stopping range



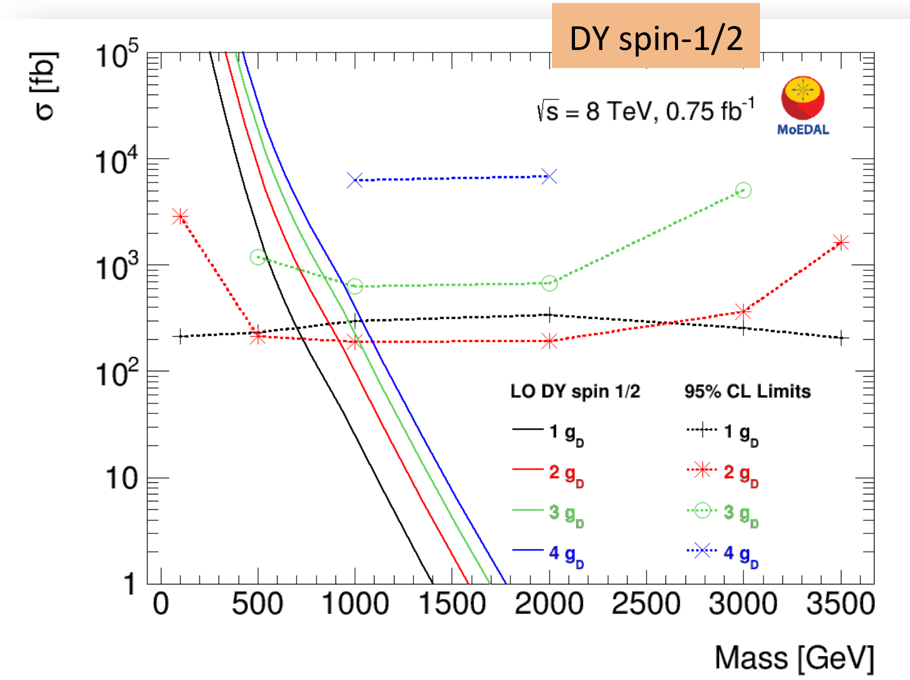
arXiv:1606.01220

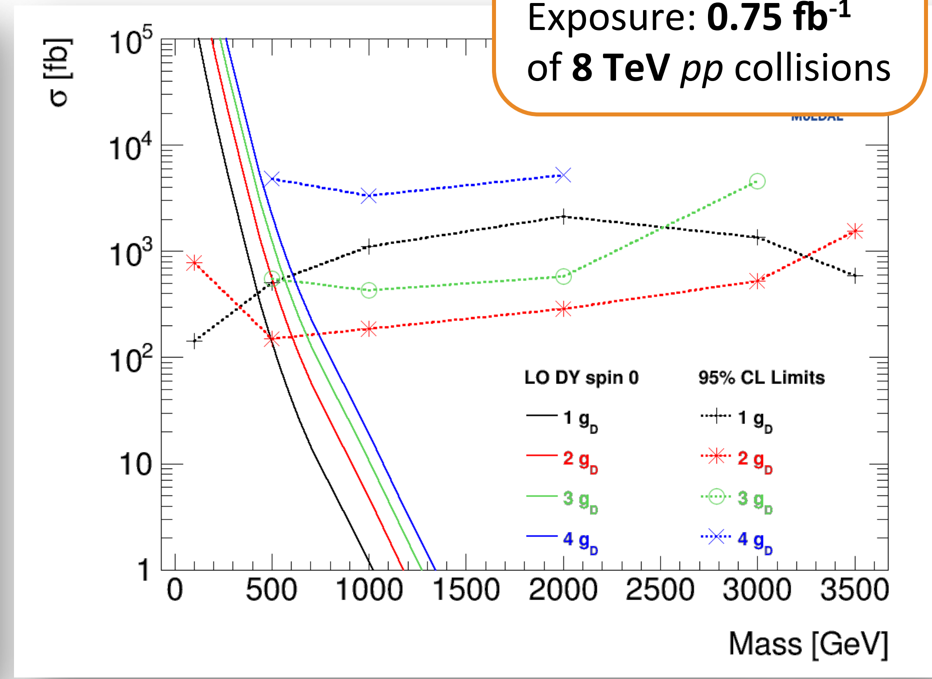
Cross section limits versus mass

Detector: prototype of **160 kg** of Al rods

Exposure: **0.75 fb^{-1}** of **8 TeV** *pp* collisions

DY spin-1/2





Limits extend up to masses **> 2500 GeV** for the first time at the LHC

- reminder: shown (tiny) LO DY cross sections are not reliable
  ⇒ makes sense to probe and constrain very high masses

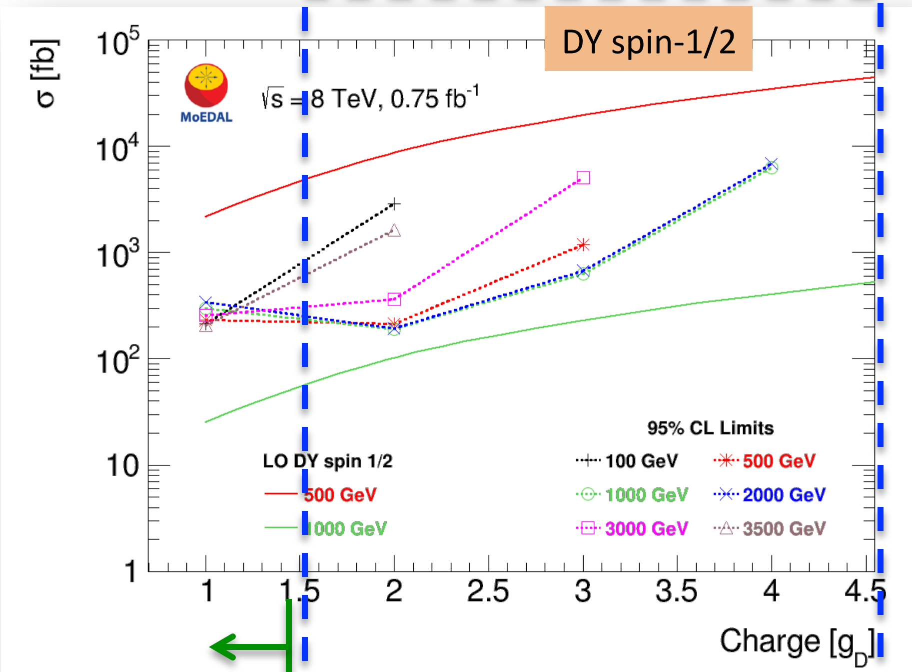
JHEP 1608 (2016) 067 [arXiv:1604.06645]

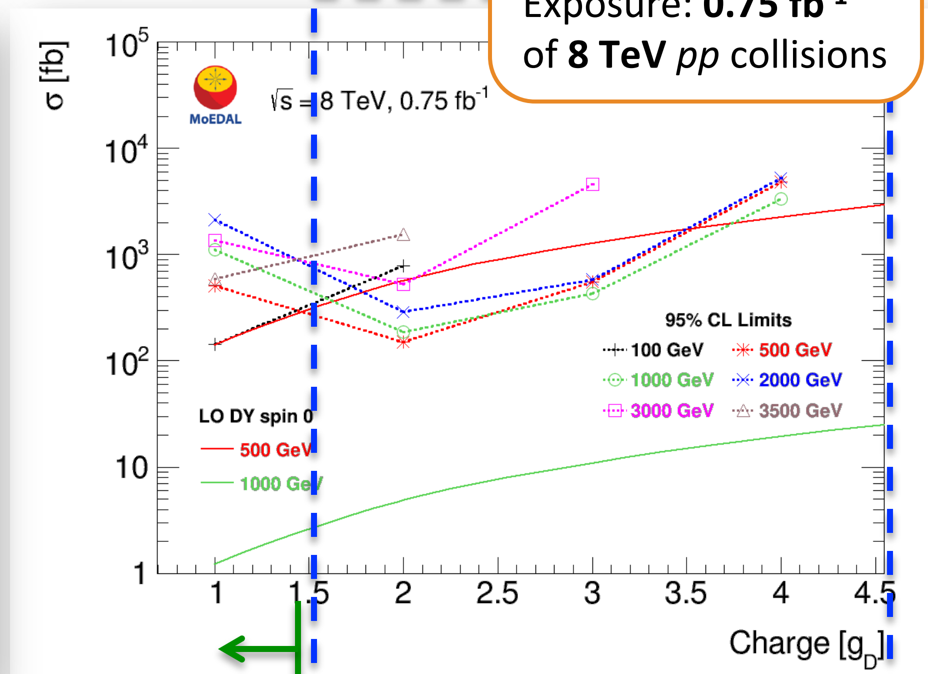
MoEDAL

Cross section limits versus charge

Detector: prototype of **160 kg** of Al rods

Exposure: **0.75 fb^{-1}** of **8 TeV** *pp* collisions





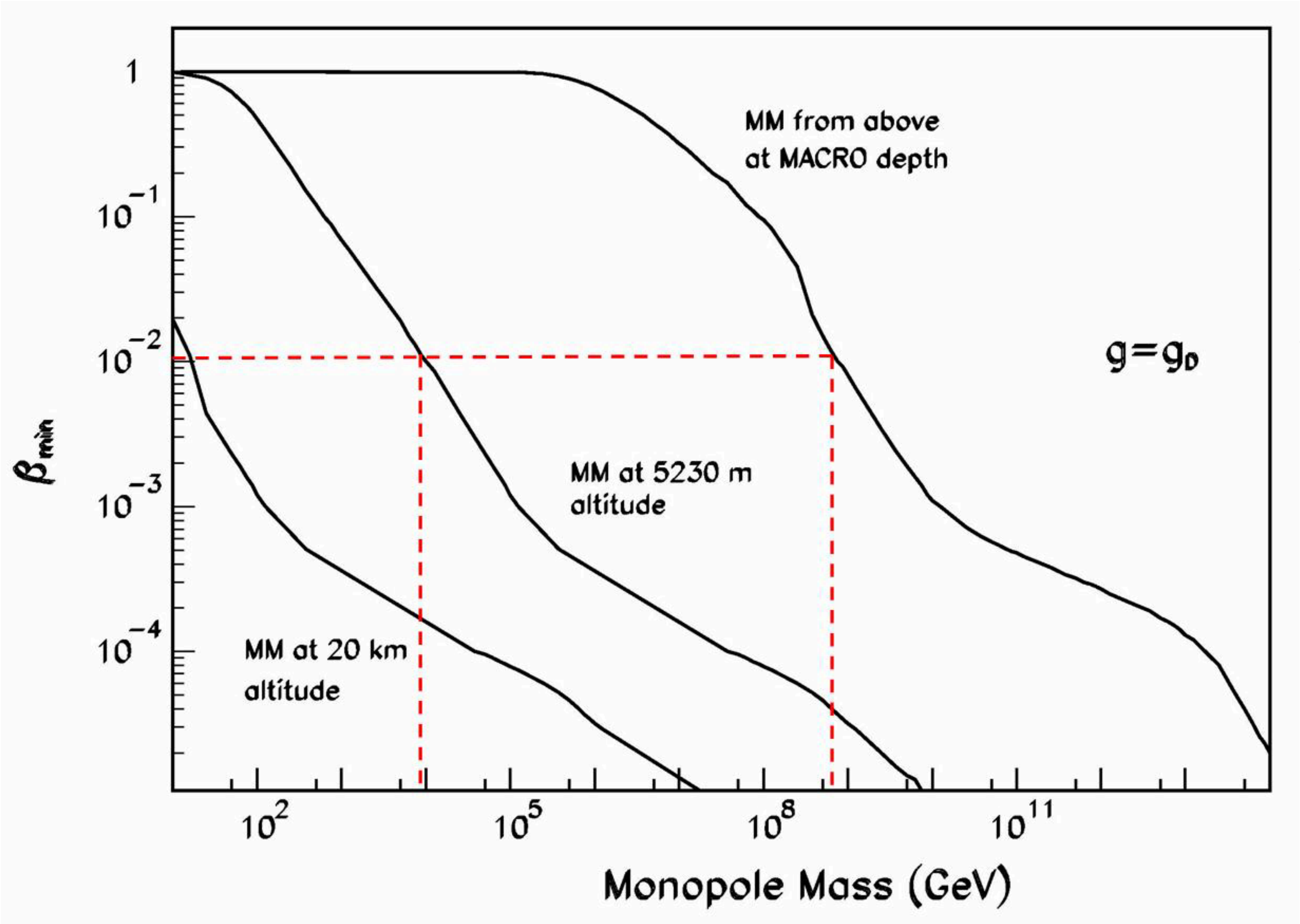
also covered by ATLAS search

World-best limits for |g| > 1.5 g$_D$

- previously ~400 GeV at Tevatron [e.g. CDF hep-ex/0509015]
- **first time at the LHC**

JHEP 1608 (2016) 067
[arXiv:1604.06645]

Cosmic monopoles



SLIM Collab, Eur.Phys.J. C55 (2008) 57