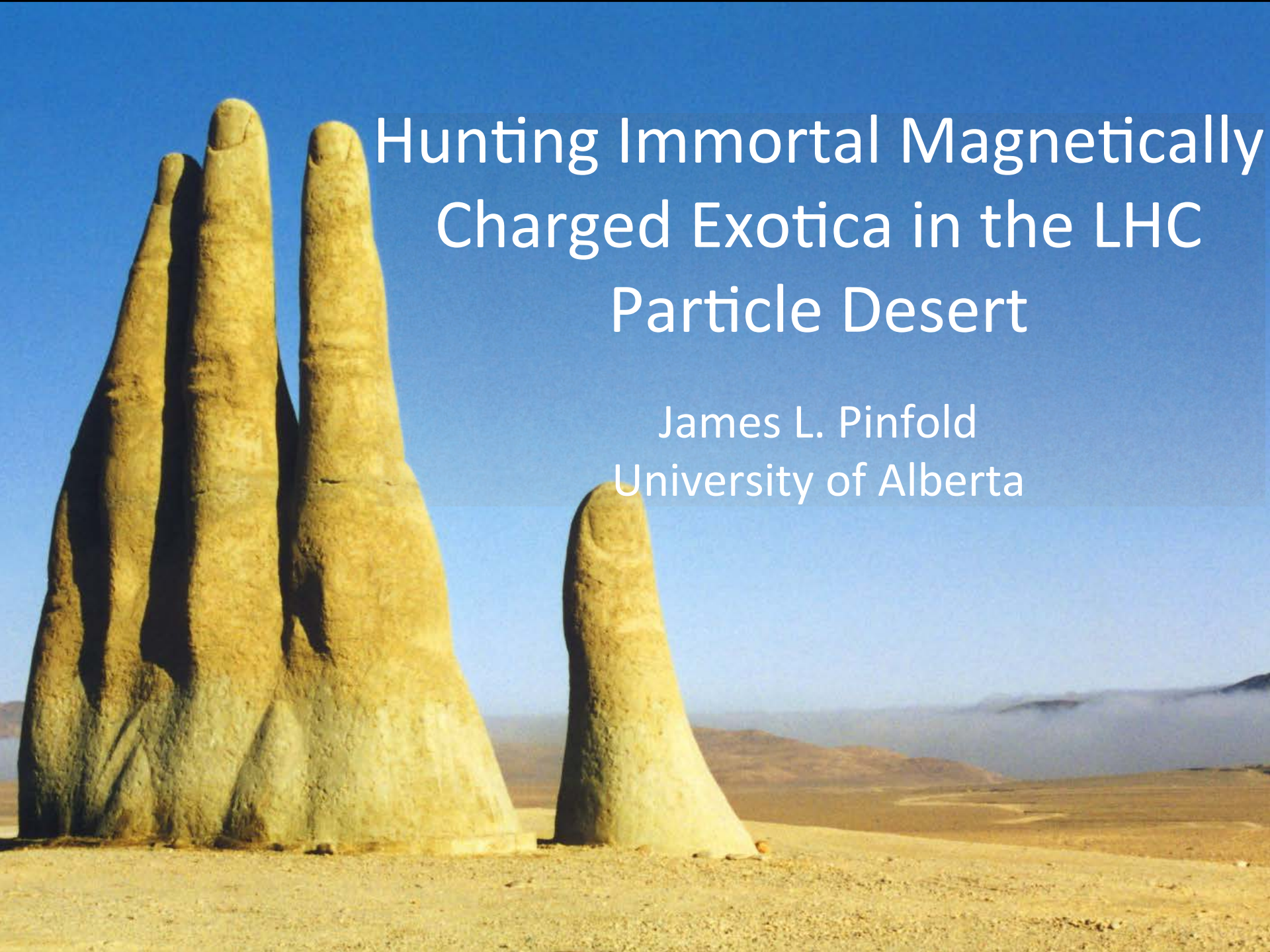


Hunting Immortal Magnetically Charged Exotica in the LHC Particle Desert

James L. Pinfold
University of Alberta

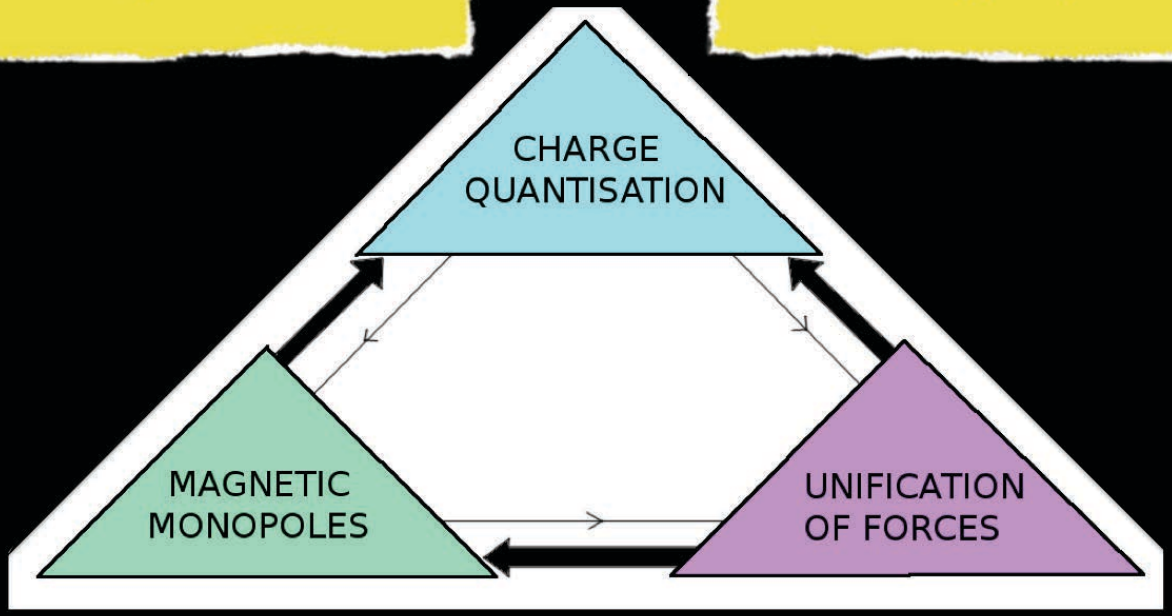
Limiting Our Exotic Prey to a 15min Hunt

- *Heavy stable charged particles with magnetic charge* ✓
- *Heavy stable charged particles with single or multiple charge* ✗
- *Stable charge particles with fractional charge* ✗
- *Heavy new particles detected by late decays,* ✗
  - *Heavy long-lived particles stopped in in the detector* ✗

The Importance of the Magnetic Monopole

They restore symmetry to Maxwell's Equations

They explain electric charge quantization



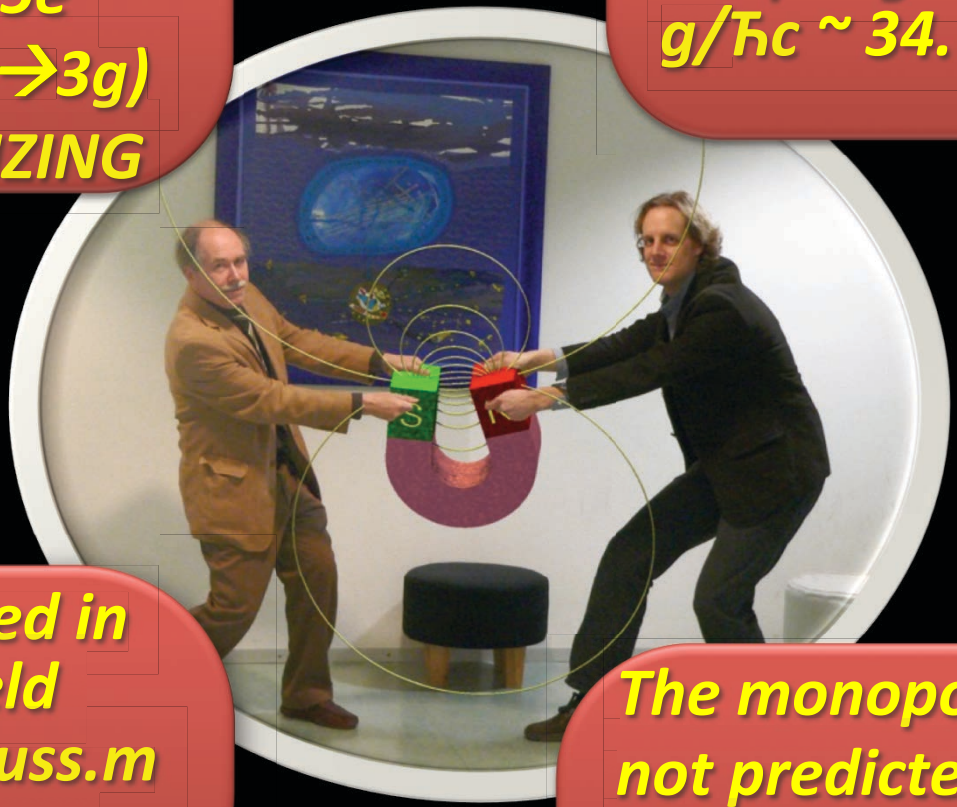
GUT & EW monopoles are excitations of the Higgs field

They are required by GUTs string theory & M-theory

Magnetic Monopole Properties

Magnetic charge = ng = n68.5e (if e→1/3e; g→3g) HIGHLY IONIZING

Coupling constant = g/ħc ~ 34. Spin ½?

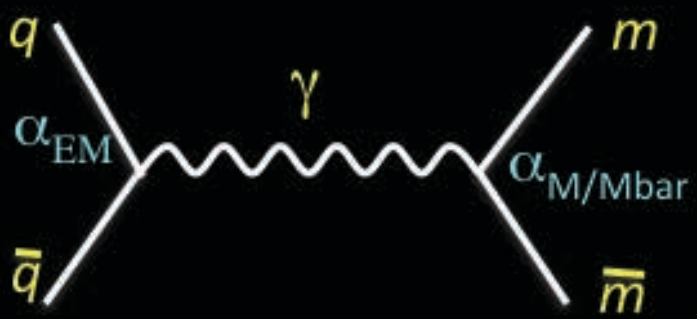


Energy acquired in a magnetic field =2.06MeV/gauss.m = 2TeV in a 10m, 10T solenidal field

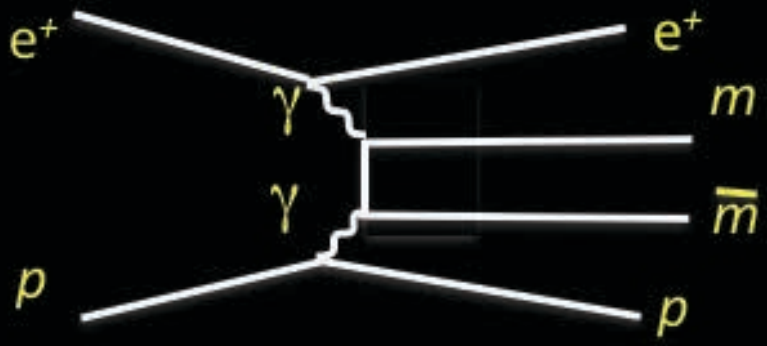
The monopole mass is not predicted within the Dirac's theory, ~ 4-7 TeV EW monopole

Monopole Production at Colliders

$e^+e^- \to M\bar{M}$, $pp \to M\bar{M}$, $e^+p \to e^+pM\bar{M}$, etc.

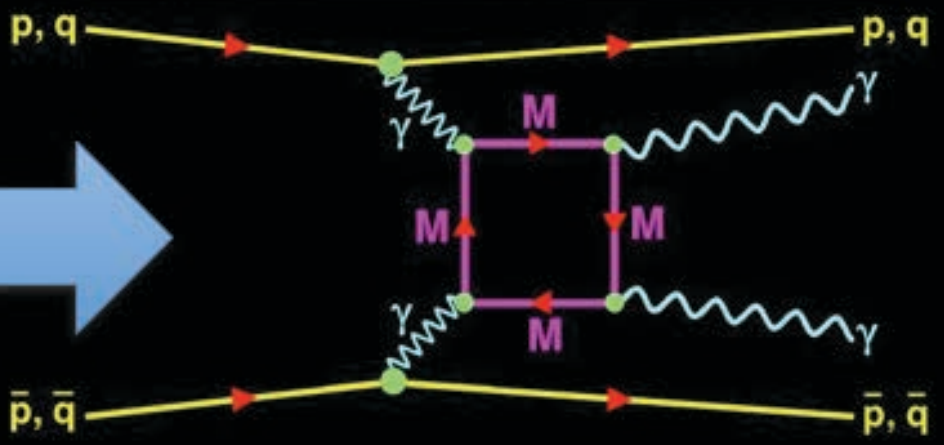


Drell-Yan Production



Two-photon production

Indirect search using virtual monopole box diagrams allow – observable two high energy gammas.



Anomalous Ionization Signature

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

VERY HIGH IONIZATION
Z↑ β(=v/c)↓

ELECTRIC CHARGE (z)

VERY LOW IONIZATION
Z(<<1) β(~1)

VERY HIGH

g = n137e/2 =n 68.5e

IONIZATION

$(dE/dX)_g$ ~$n^2$4700 $(dE/dX)_{proton}$

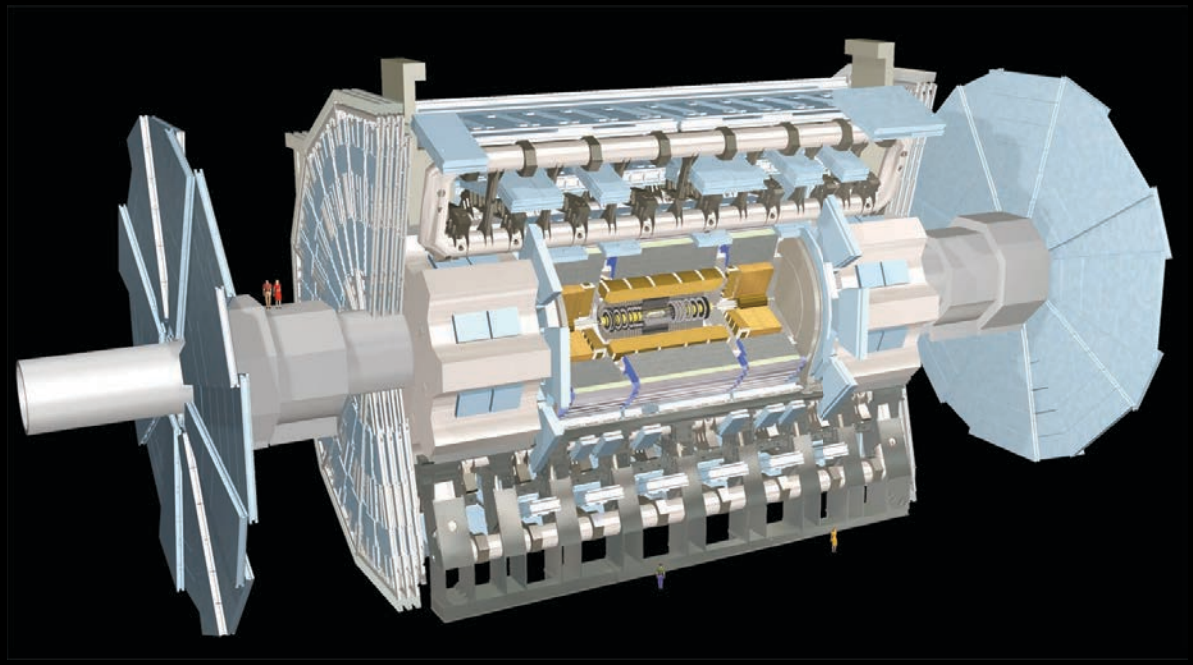
MAGNETIC CHARGE (g)

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

The velocity dependence of the Lorentz force cancels $1/\beta^2$ term

The LHC Detectors with Results - ATLAS

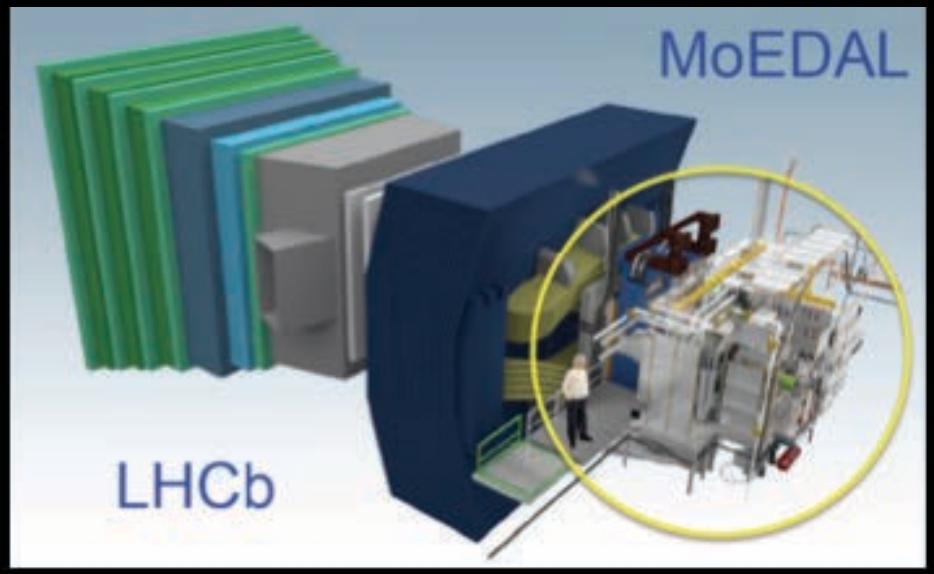
ATLAS Detector 7000 tonnes & 46m x 25m



- *The two general purpose LHC detectors ATLAS and CMS*
  - *Standard collider electronic detectors with magnetic field comprised of: Inner Tracker; EM calorimeter, Hadronic Calorimeter and Muon detectors*
  - *Multi level trigger is required.*

The LHC Detectors with Results - MoEDAL

Permanent Physical record of new physics



No Standard Model Physics Backgrnds

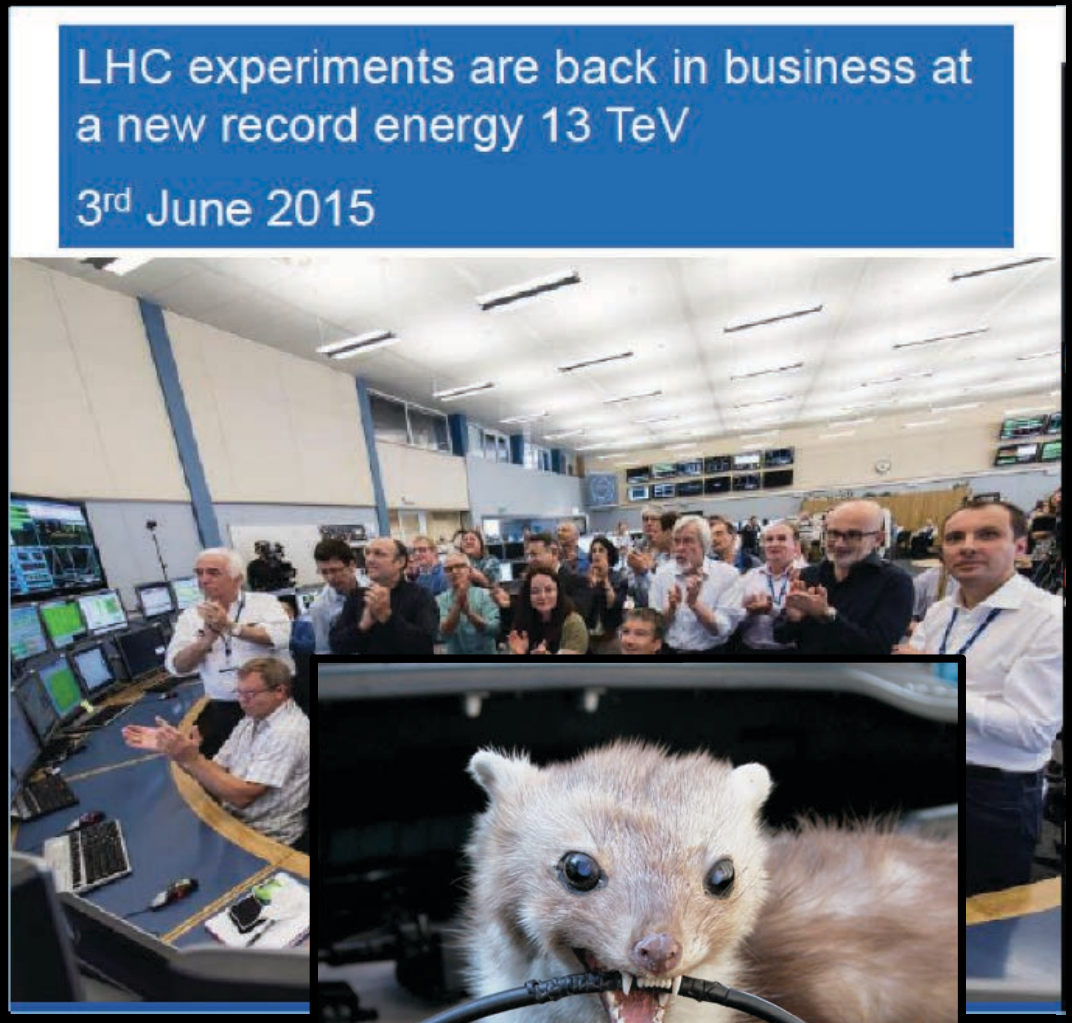
MoEDAL is largely passive and made up of three detector systems

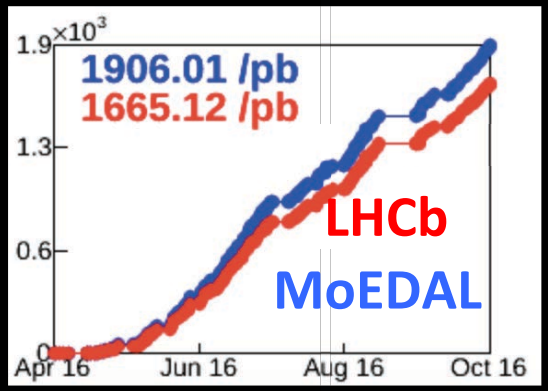
NUCLEAR TRACK DETECTOR
Plastic array (~200 sqm)
– Like a Giant Camera

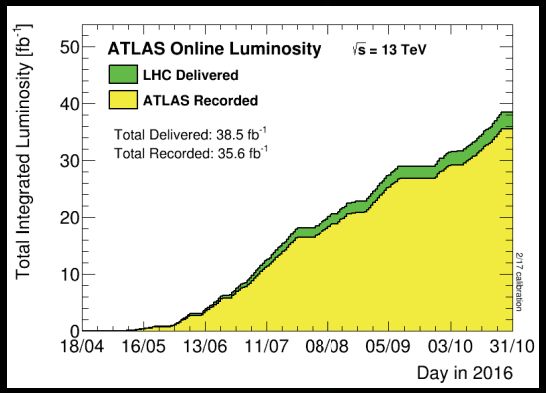
TRAPPING DETECTOR ARRAY
A tonne of Al to trap Highly Ionizing Particles for analysis

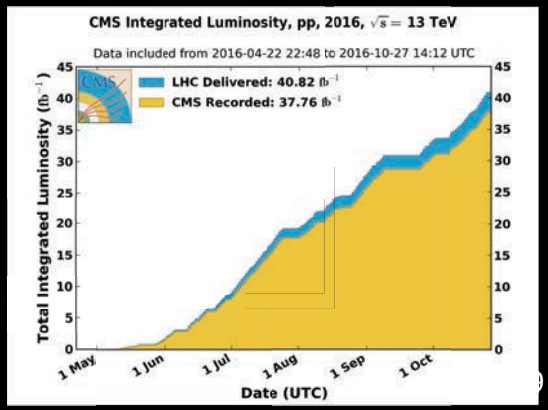
TIMEPIX Array a digital Camera for real time radiation monitoring

LHC Run 2 Is a Big Success





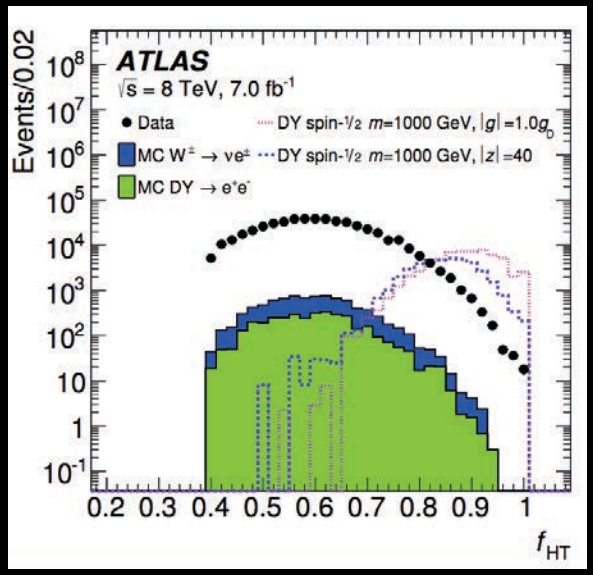


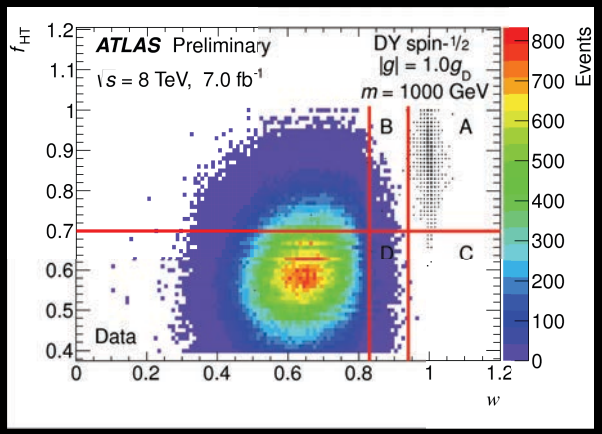


Despite "Sparky" the Beech Marten – LHC is on track

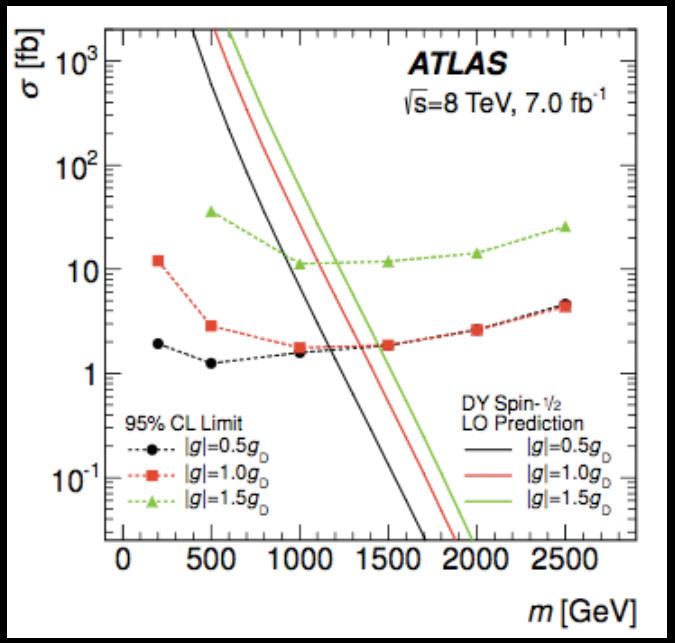
The ATLAS Search for Monopoles & Stable Highly Charged Particles (Phys Rev. D 93 052009 2016)

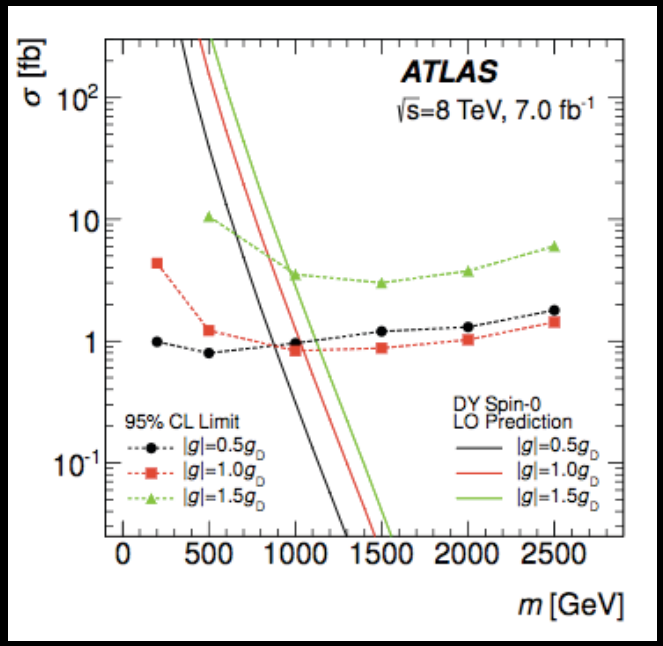
- *ATLAS event selection*
  - *Level-1: Hardware triggers select events with **E**T > 18 → 20 GeV in the EM calo (ECAL) and **E**T < 1 GeV in hadronic calo*
  - *Level-2: ECAL associated hits in a wedge of = ±0.015 rad in ϕ;*
  - *Discriminants: fraction & # HT TRT hits ($N^{trig}_{HT} > 20$ & $f^{trig}_{HT} > 0.37$)*
  - *EM energy deposit dispersion (fraction of EM energy contained in most energetic cells, w)*
  - *Background determined from data using ABCD regions*





The ATLAS √s =8TeV Monopole Search Results





Drell-Yan Lower Mass Limits (GeV)

	$\|g\| = 0.5g_D$	$\|g\| = 1.0g_D$	$\|g\| = 1.5g_D$
spin-1/2	1180	1340	1210
spin-0	890	1050	970

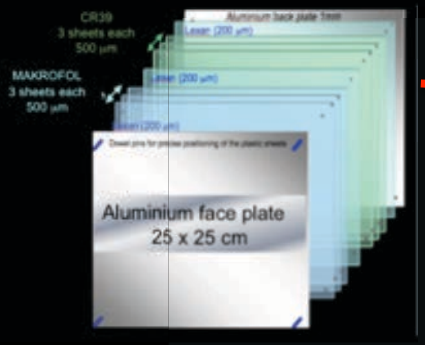
- *Limits on integer magnetic charge g_D=1*

MoEDAL

THE MAGNIFICENT SEVENTH

They fought on the high energy frontier

Full NTD Deployment in 2015/16



NTD Stack

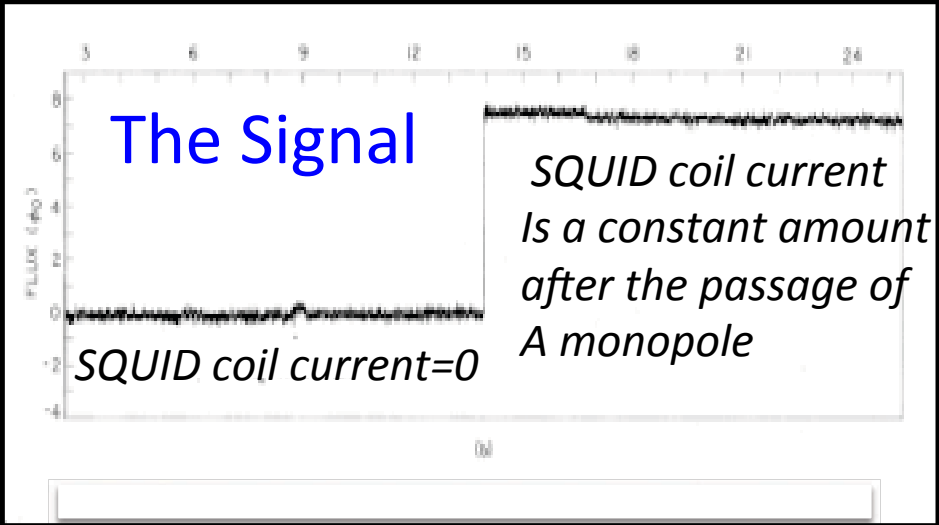
Signal etch pits

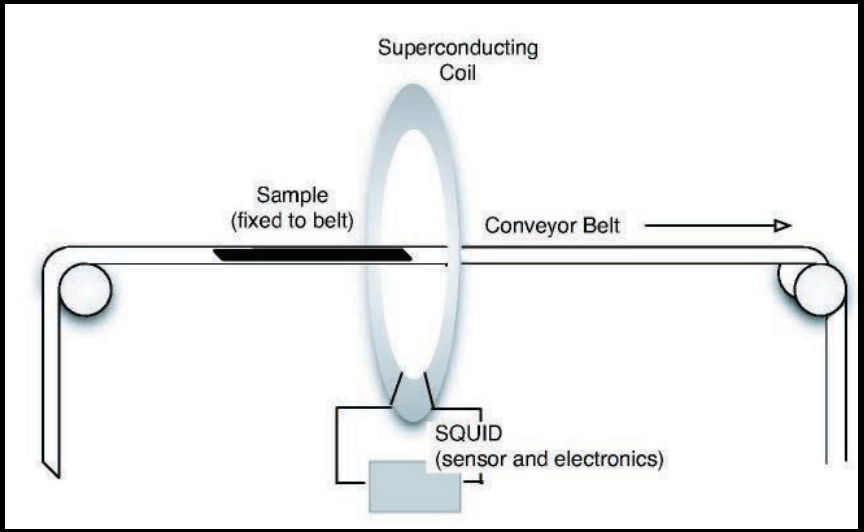
- *Accceptance for at least one monopole from monopole pair production to hit NTDs ~70% (over 150 m^2 of plastic)*
  - *Detection efficiency ~100% ($\theta > 45^O$) + measurement accuracy of 0.1e*
  - *Detection threshold $Z/\beta \geq 5$ (CR39) and 50 (MAKROFOL)*

The MoEDAL Trapping Detector System

- *Only 1/3 of the trapping array used for √s=13 TeV search*
  - *The full sensitivity includes results from all of the trapping and NTD detectors – so much impoved results in the future*
- *Total mass of trapping detectors ~ 800 kg of Al (~2400 bars)*
  - *Read out by a SQUID magnetometer calibrated with special solenoids*
  - *First time a purpose built trapping detector has ever been deployed*

The SQUID Detector



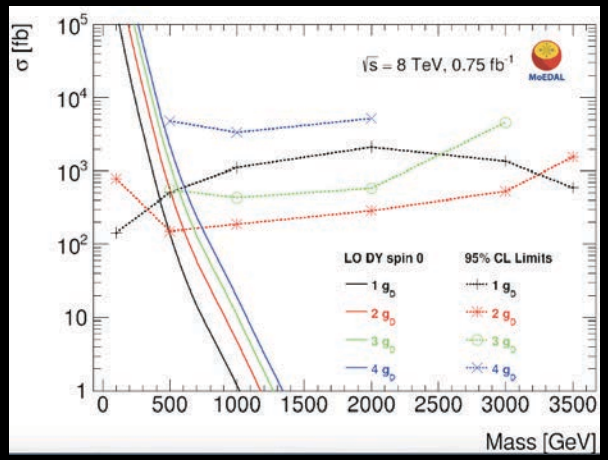


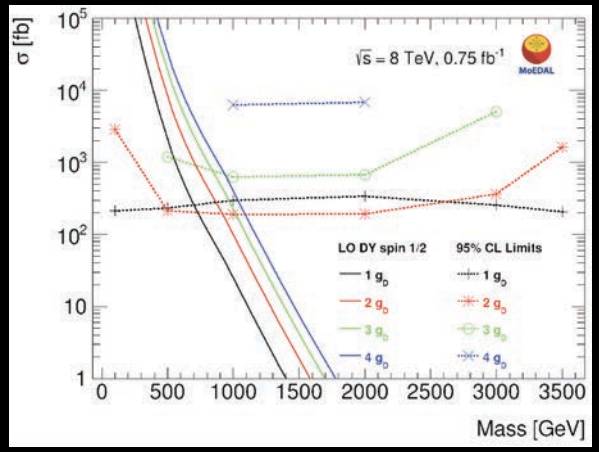
Laboratory of Natural Magnetism, ETH Zurich

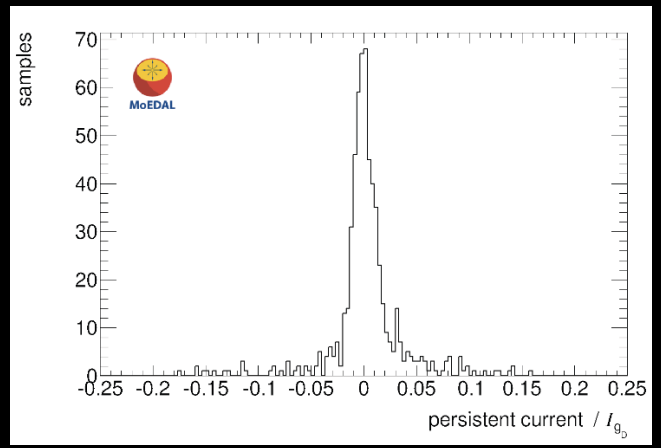
Magnetically shielded room

DC-SQUID magnetometer

The MoEDAL Monopole Search at $\sqrt{s} = 8$ TeV - JHEP 1608 (2016) 067







DY Lower Mass Limits [GeV]	$\|g\| = g_D$	$\|g\| = 2g_D$	$\|g\| = 3g_D$
spin-1/2	700	920	840
spin-0	420	600	560

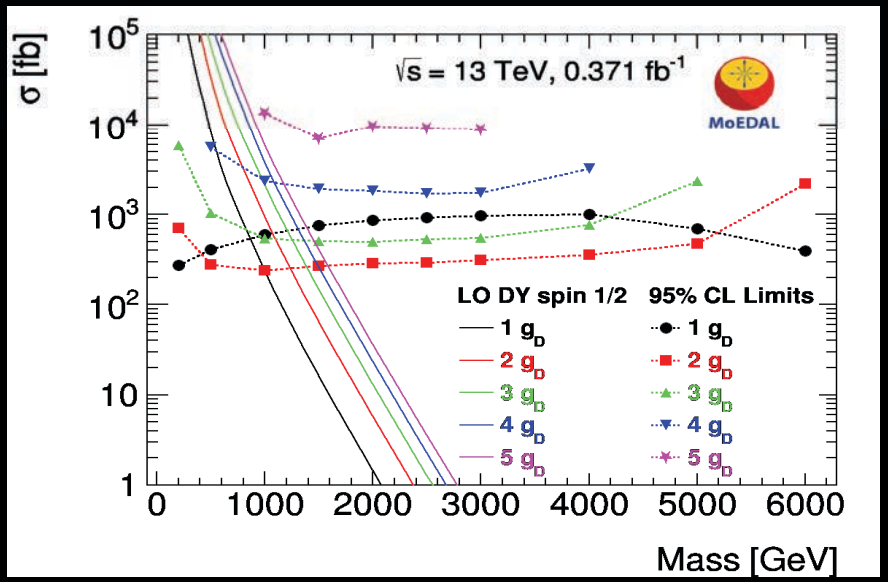
MoEDAL

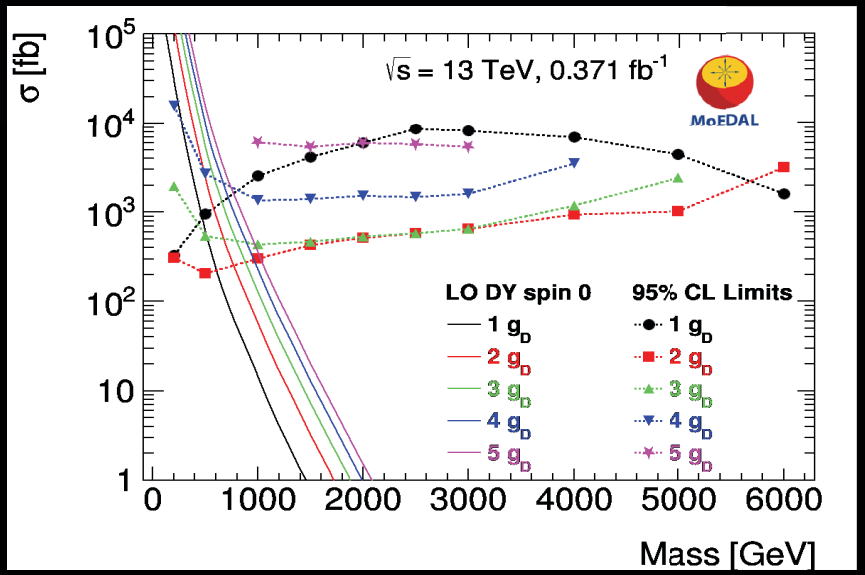
$\|g\| = g_D$
1340
1050

ATLAS

World best limits for $|g| > g_D$
(previously ~400 GeV at the Tevatron)

MoEDAL Monopole Search Results at- √s =13 TeV - PRL 118 061811 (2017)



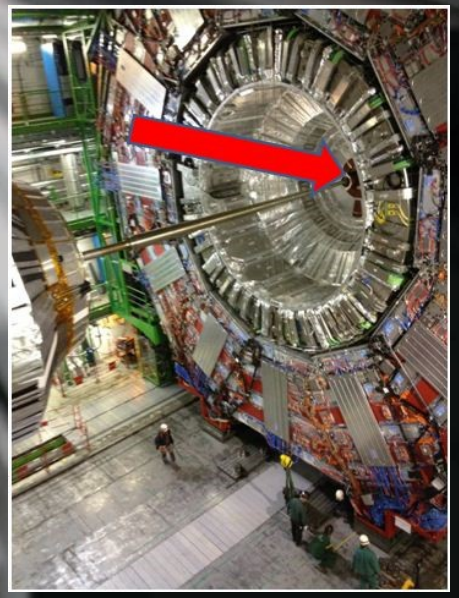


- *First monopole constraints in 13 TeV pp collisions*
  - *Probe TeV masses for up to $5g_D$ for the 1st time at the LHC*
  - *Exclude monopole with $|g|=4g_D$ for the 1st time at the LHC*

mass limits [GeV]	$1g_D$	$2g_D$	$3g_D$	$4g_D$
MoEDAL 13 TeV (this result)				
DY spin-1/2	890	1250	1260	1100
DY spin-0	460	760	800	650
MoEDAL 8 TeV				
DY spin-1/2	700	920	840	–
DY spin-0	420	600	560	–
ATLAS 8 TeV				
DY spin-1/2	1340	–	–	–
DY spin-0	1050	–	–	–

Beampipe Searches for Very Highly Ionizing Particles – Now in Play

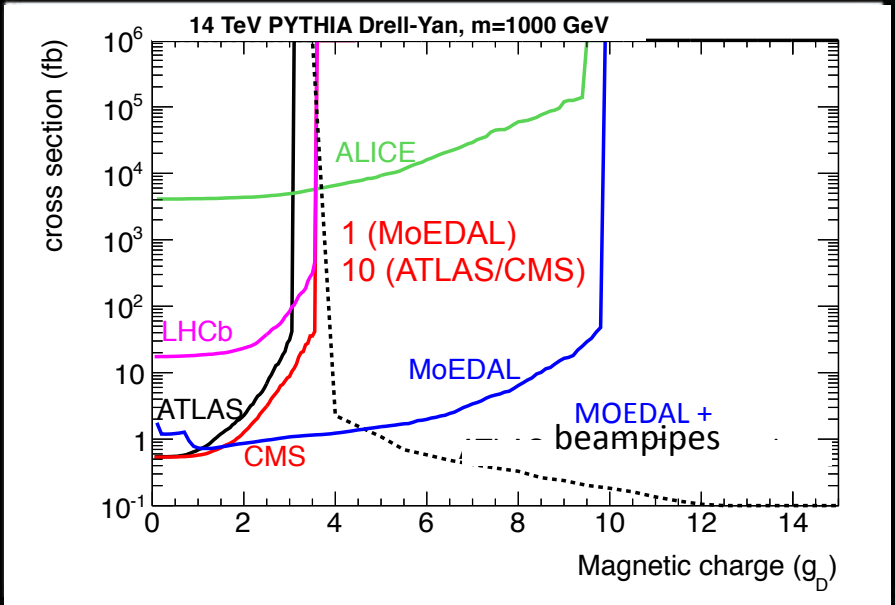
CMS Beryllium beampipe

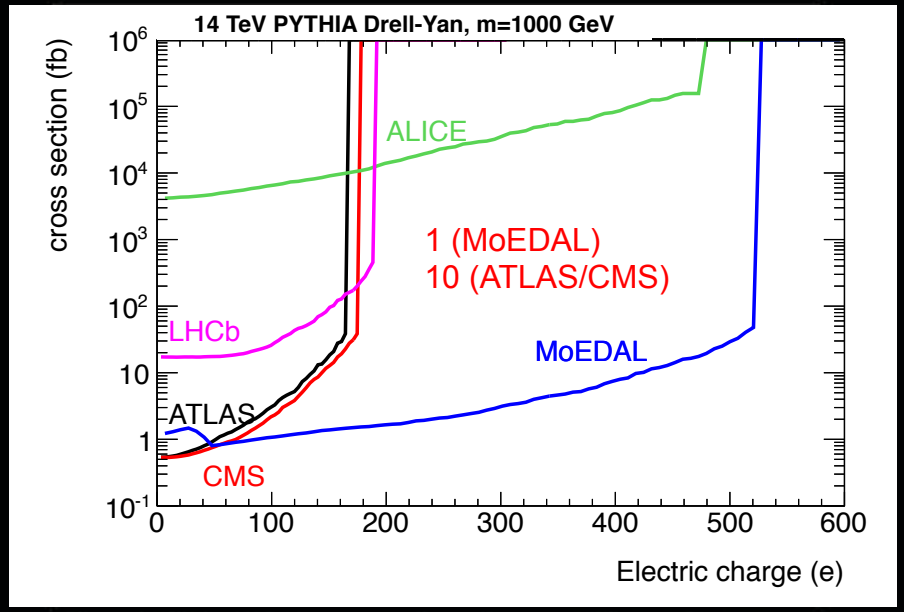


MoEDAL- Beampipe Consortium have submitted a proposal to CMS to utilize their replaced surplus-to-requirement IP region beam pipe in order to scan them for the presence of very highly ionizing monopoles trapped in the beam pipe walls

LHC Sensitivity to Monopoles

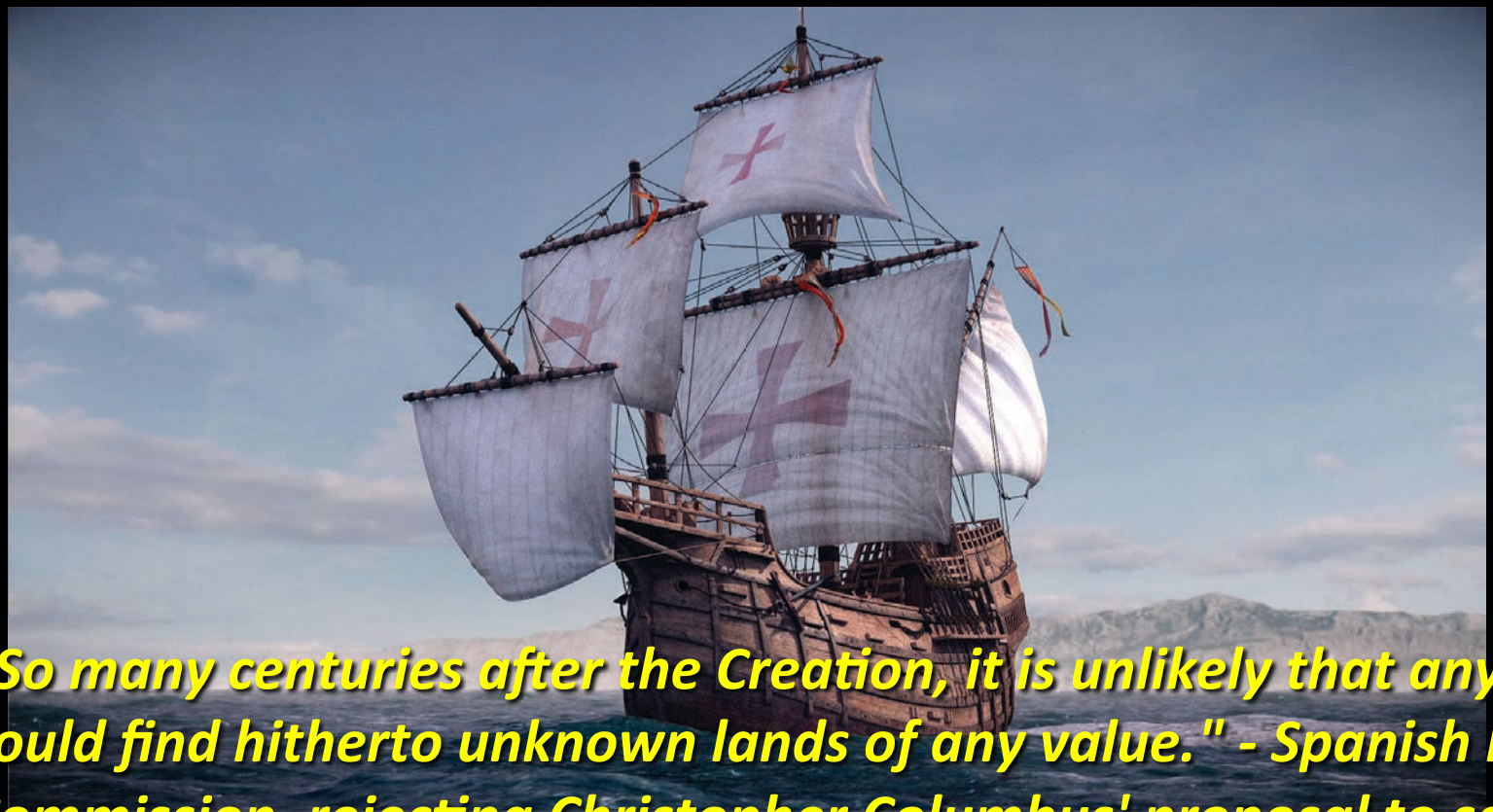
detector	energy threshold	angular coverage	luminosity	robust against timing	robust efficiency
ATLAS	medium	central	high	no	no
CMS	relatively low	central	high	no	no
ALICE	very low	very central	low	yes	no
LHCb	medium ✔	forward	medium	no	no
MoEDAL	low	full ✔	medium ✔	yes ✔	yes ✔





- *Cross-section limits for magnetic (LEFT) and electric charge (RIGHT) (from **arXiv:1112.2999V2** [hep-ph])*
- *MoEDAL COMPLEMENTS the physics reach of the existing LHC experiments*

The LHC's Voyage of Discovery



"So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value." - Spanish Royal Commission, rejecting Christopher Columbus' proposal to sail west.

In 2015 the LHC experiments – now including MoEDAL - set sail out on a voyage of discovery at the new LHC high energy frontier of 13TeV - ***stay tuned for the report of new worlds***