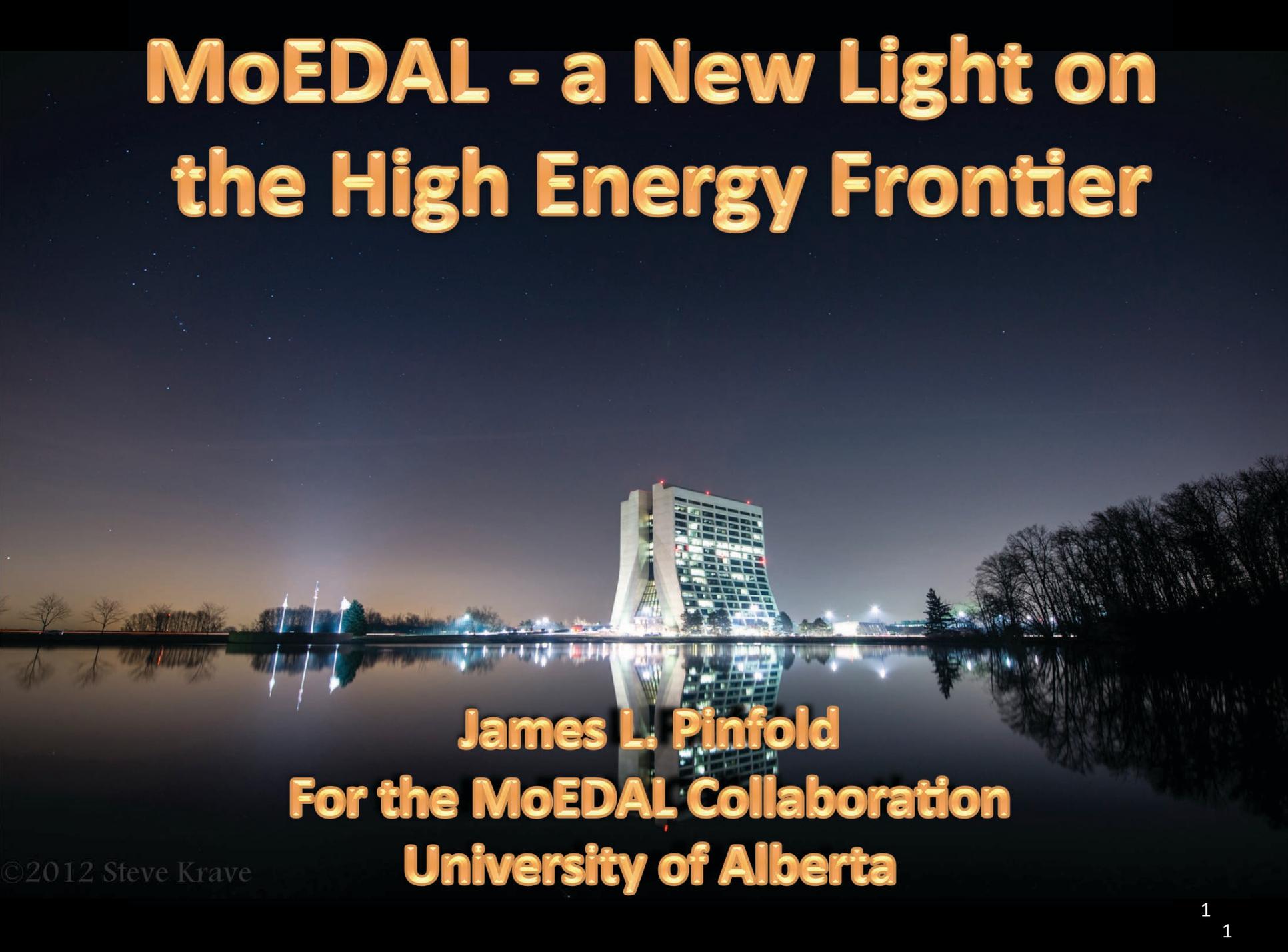


MoEDAL - a New Light on the High Energy Frontier



James L. Pinfold
For the MoEDAL Collaboration
University of Alberta



MoEDAL's PHYSICS APPROACH

DIRECTLY SEARCH FOR ANOMALOUSLY IONIZING AND VERY LONG-LIVED AVATARS OF NEW PHYSICS

MINIMALLY IONIZING PARTICLES

HIGHLY IONIZING PARTICLES

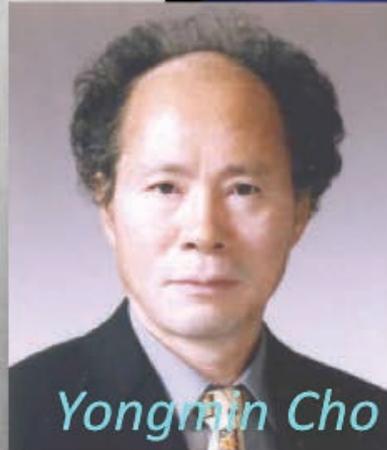
VERY LONG-LIVED PARTICLES

MULTI- MESSENGERS OF NEW PHYSICS

MoEDAL PROBES NEW PHYSICS

MoEDAL COMPLEMENTS ATLAS & CMS

The Monopole and the Higgs Boson

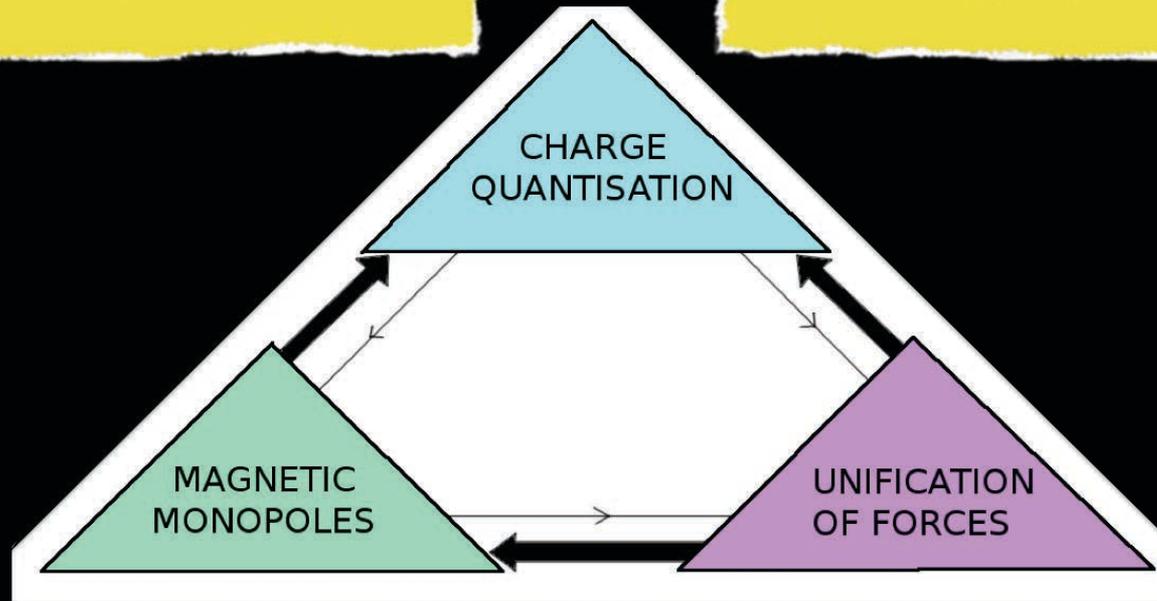


- *The general purpose experiments have as their prime physics purpose the discovery & elucidation of the Higgs boson....*
- *The corresponding “baseline” physics prpose for MoEDAL is the search for the Magnetic Charge*
- *BUT ATLAS, CMS & MOEDAL CAN DO MUCH MORE*

The Magnetic Monopole's Importance

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 $e \rightarrow 1/3e$; $g \rightarrow 3g$)
HIGHLY IONIZING

Coupling constant =
 $g/\hbar c \sim 34$. Spin $1/2$?

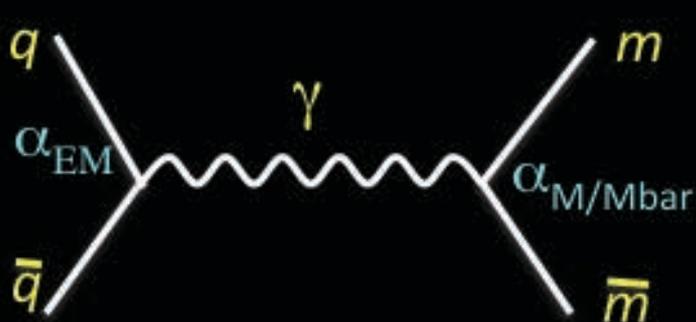


Energy acquired in
a magnetic field
 $= 2.06 \text{ MeV/gauss.m}$
 $= 2 \text{ TeV}$ in a 10m,
10T solenoidal field

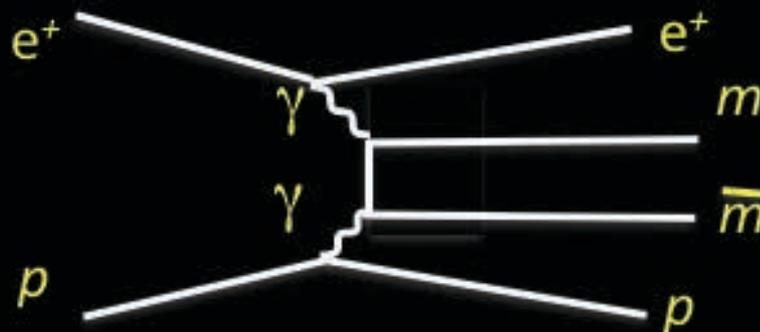
The monopole mass is
not predicted within
the Dirac's theory, \sim
4-7 TeV EW monopole

Monopole Production at Colliders

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

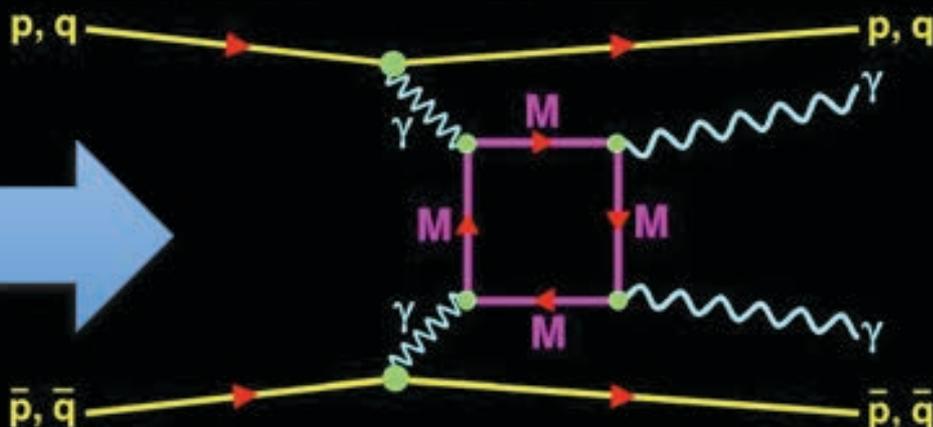


Drell-Yan Production



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**
 $z \uparrow \beta (=v/c) \downarrow$

ELECTRIC CHARGE (z)

**VERY LOW
IONIZATION**
 $z (\ll 1) \beta (\sim 1)$

**VERY HIGH
IONIZATION**
 $g = n137e/2 = n 68.5e$

IONIZATION
 $(dE/dX)_g \sim n^2 4700 (dE/dX)_{proton}$

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



MoEDAL

THE MAGNIFICENT SEVENTH

They fought on the high energy frontier



**MoEDAL is installed and started to take data in
p-p and p-A running at ~13 TeV in 2015**

ATLAS
STEVE MCQUEEN

JAMES COBURN
"BRITT"
CMS

LHCb
HORST BUCHHOLZ
"CHICO"

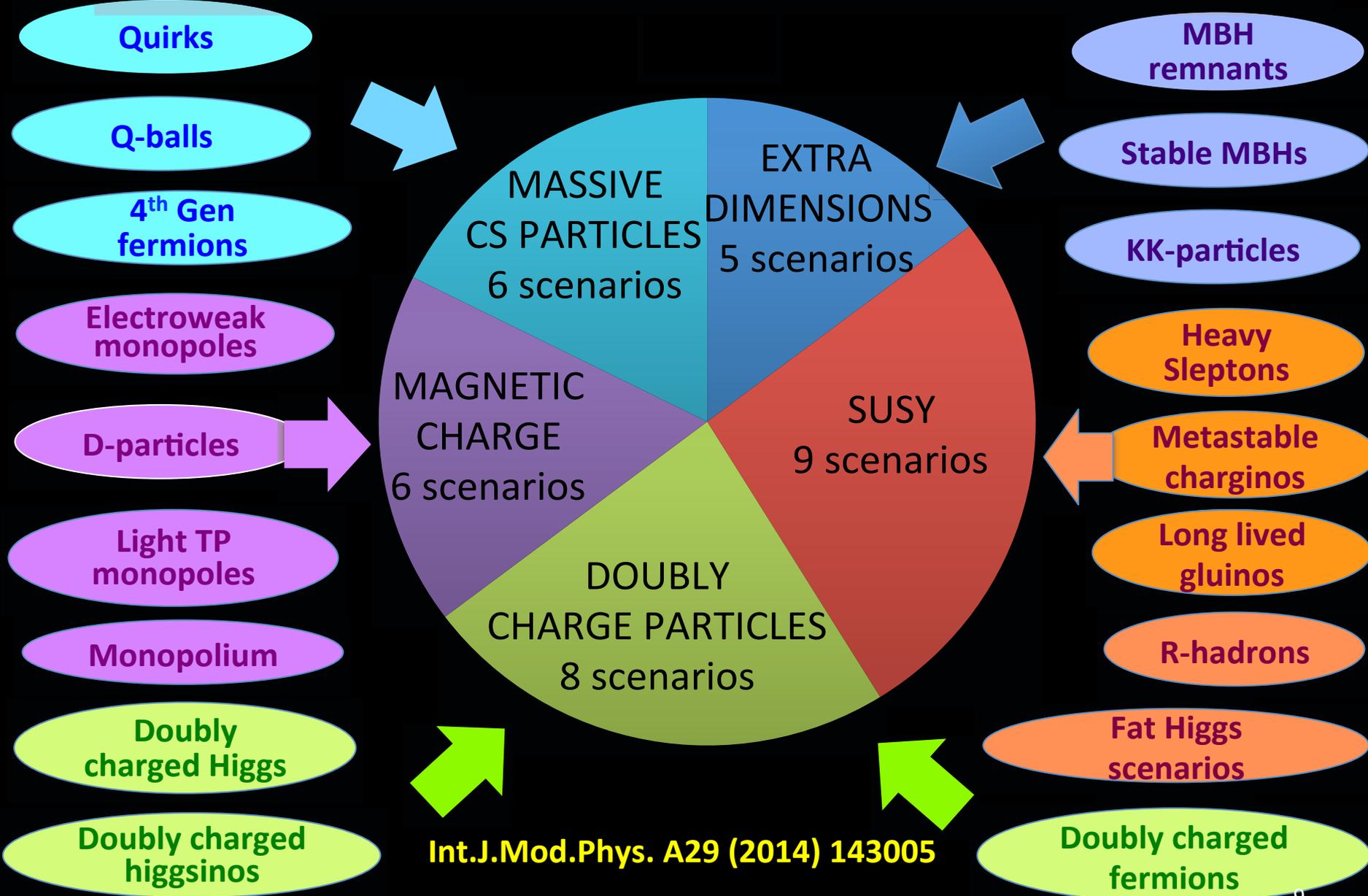
YUL BRYNNER
"CHRIS ADAMS"
ALICE

TOTEM
BRAD DEXTER
"HARRY LUCK"

ROBERT VAUGHN
"LEE"
ICE

MoEDAL
CHARLES BRONSON
"BERNARDO O'REILLY"

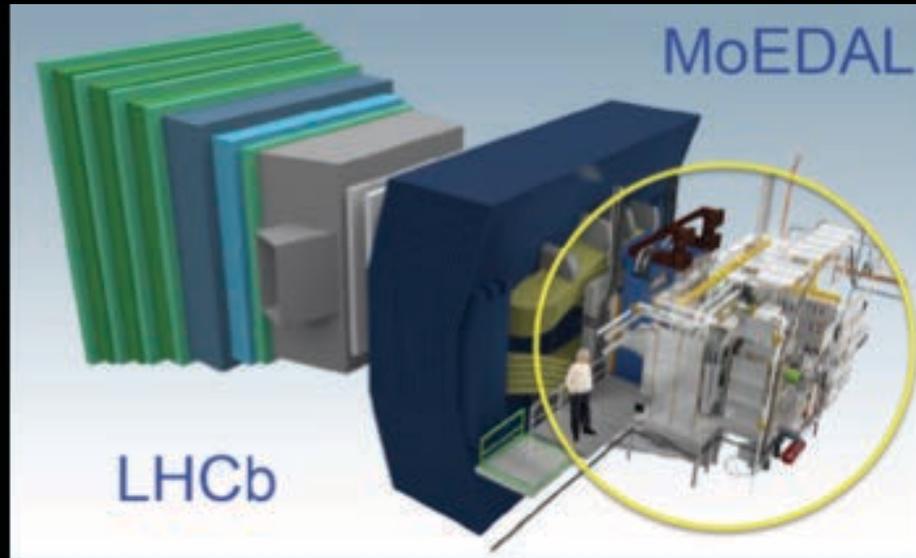
MoEDAL – Physics Scenarios (34+)



Int.J.Mod.Phys. A29 (2014) 143005

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*

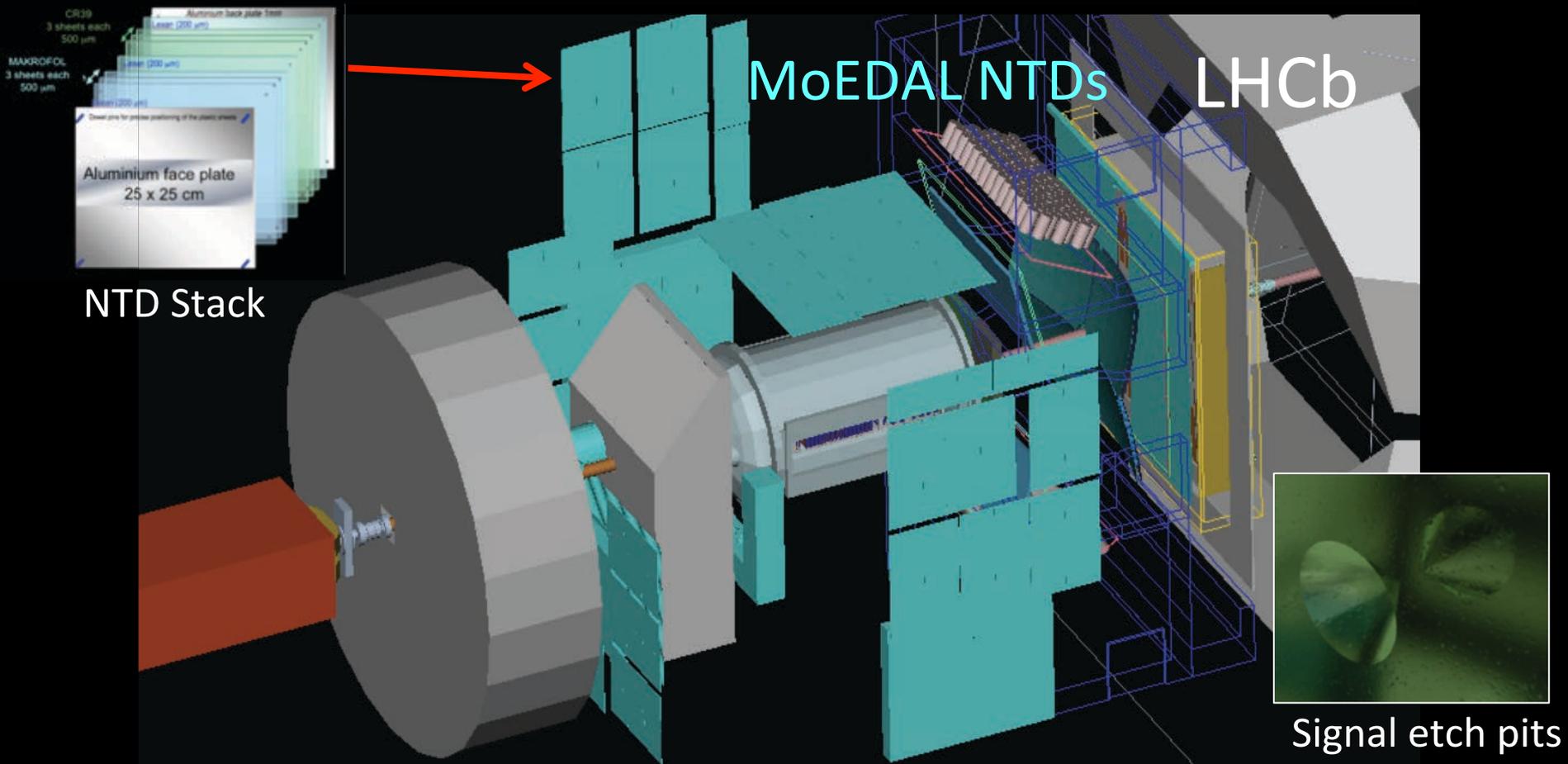


TRAPPING DETECTOR ARRAY
*A tonne of Al to trap Highly
Ionizing Particles for analysis*



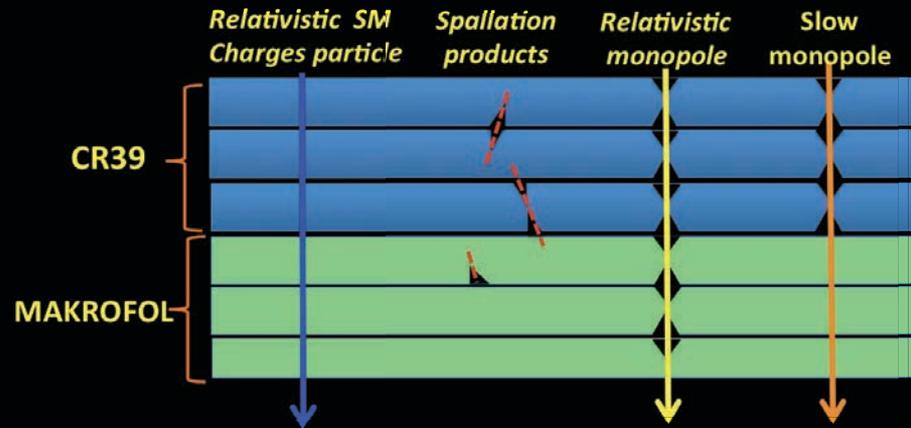
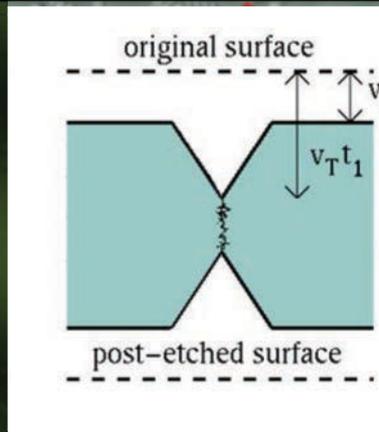
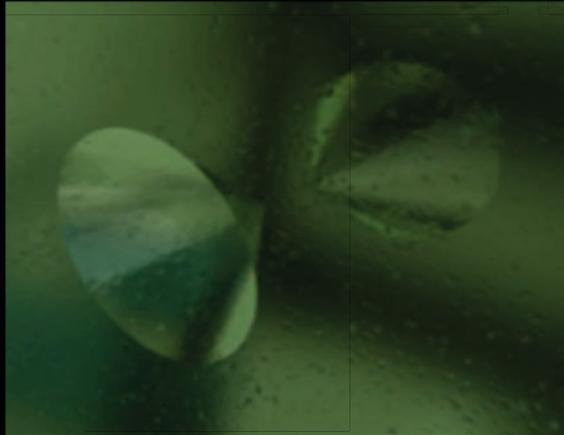
TIMEPIX Array *a digital
Camera for real time
radiation monitoring*

Full NTD Deployment in 2015/16



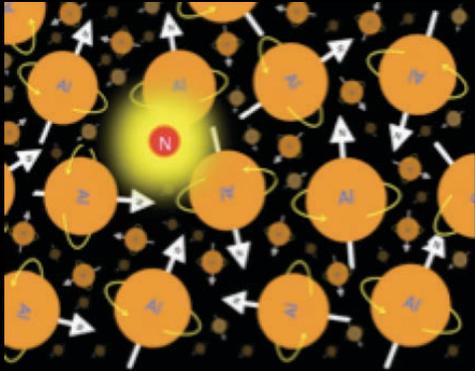
- Acceptance for at least one monopole from monopole pair production to hit NTDs $\sim 70\%$ (over 150 m² of plastic)

The Signal in the NTDS



- **Largest NTD array (150m^2 tot) ever deployed at an accelerator**
 - NTD tacks consist of CR39 (Thr. 5 mip) & Makrofol (Thr. 50 mip)
 - Damage revealed by controlled etching - etch pits are formed
 - Charge resolution is $\sim |0.1|e$, where $|e|$ is the electron charge
 - Precision of each track measurement ~ 20 -20 microns
- **NTDs are calibrated at heavy-ion beams at NSRL & NA61**
- **ATLAS and CMS cannot calibrate for highly ionizing plastic**

Signal in the MMT & SQUID Detectors



Monopole trapped by aluminium nuclei



The MoEDAL trapping detectors at IP8



THE Zurich DC-SQUID magnetometer

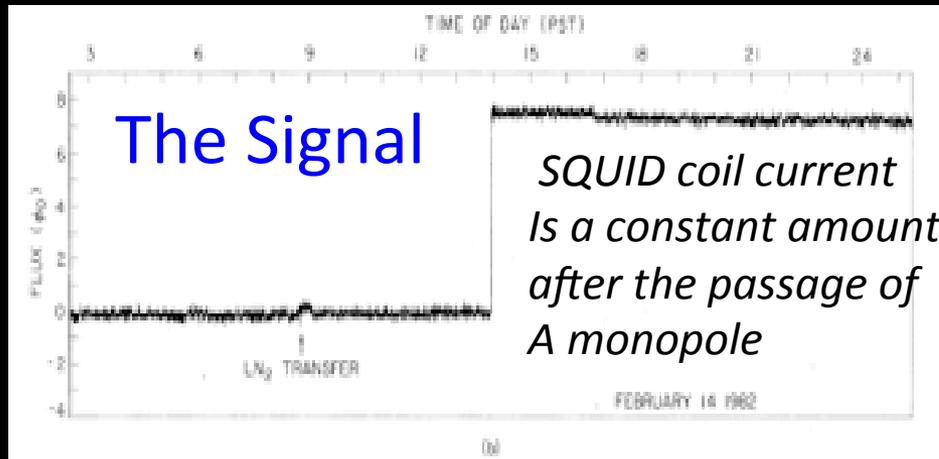
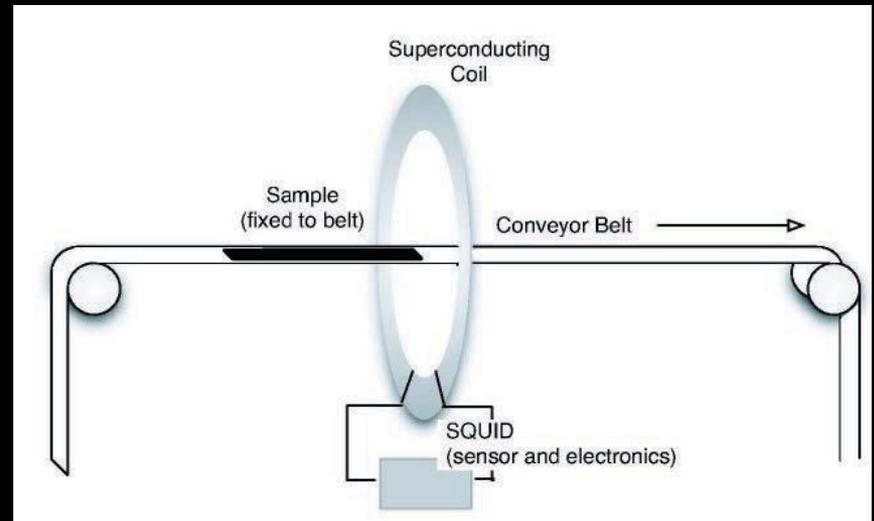
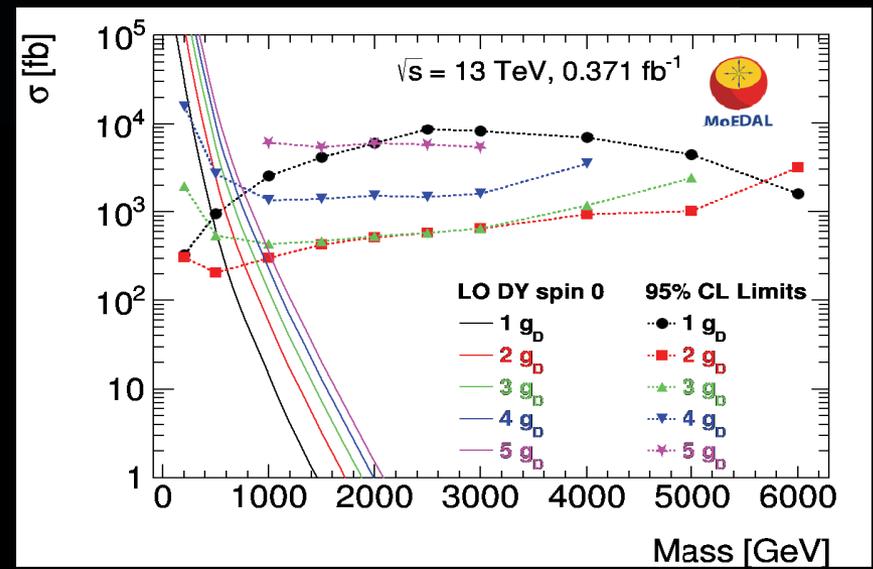
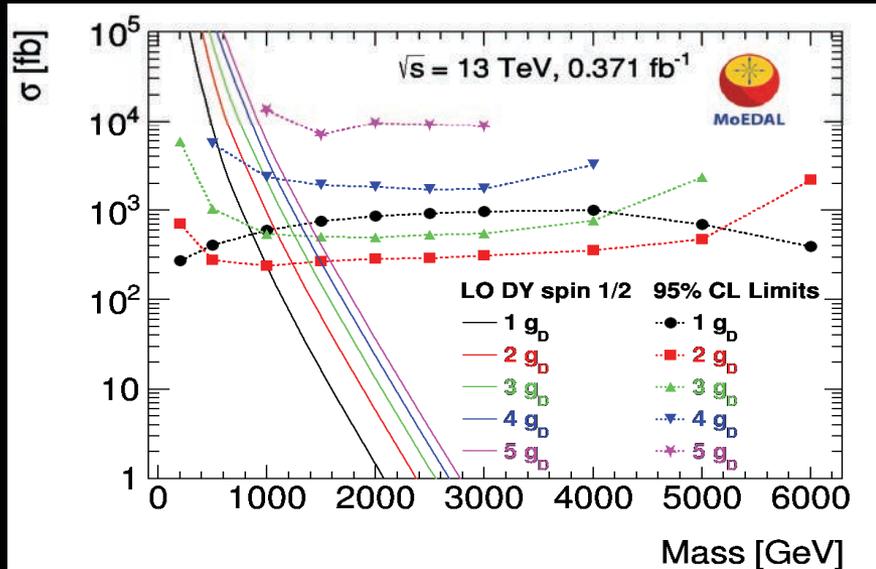


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.



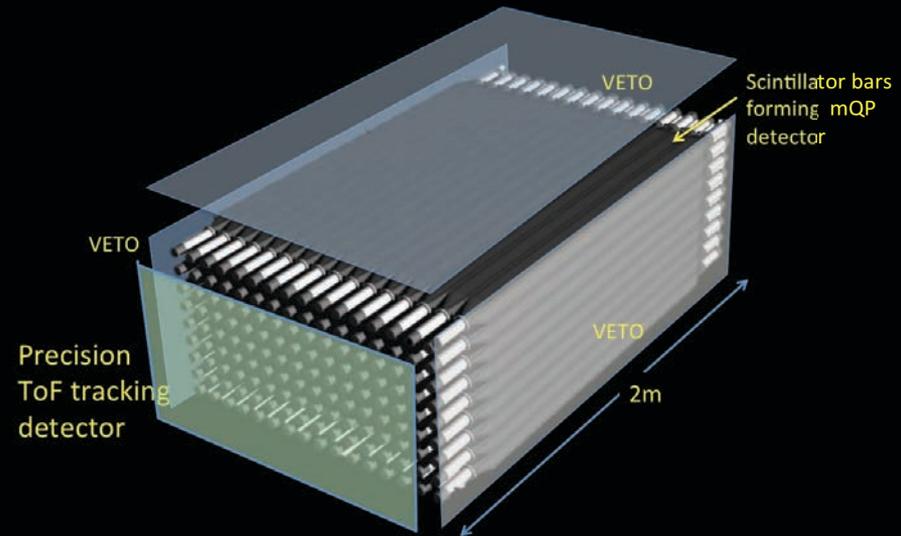
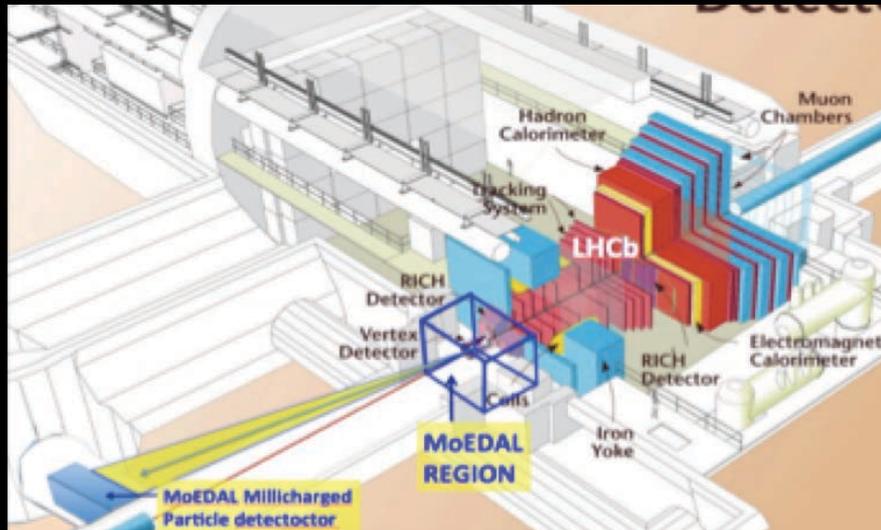
MoEDAL Monopole Search Results at- $\sqrt{s} = 13$ TeV - PRL 118 061811 (2017)



- **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	—	—	—

MoEDAL Apparatus for Penetrating Particles (MAPP)



- *MAPP will be able to take data in p - p , p - A , A - A and also fixed target interactions using SMOG (an internal gas target in LHCb)*
- *MAPP has three motivations*
 - *To search for particles with charges $\ll 1e$ (ATLAS & CMS limited to searches with particles of charge $e \geq 1/3$)*
 - *To search for new pseudo-stable neutrals with long lifetime and anomalously penetrating particles*

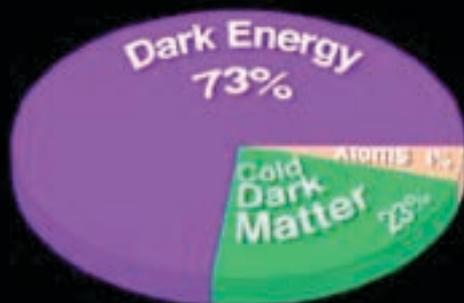
MoEDAL Addresses Fundamental Questions:



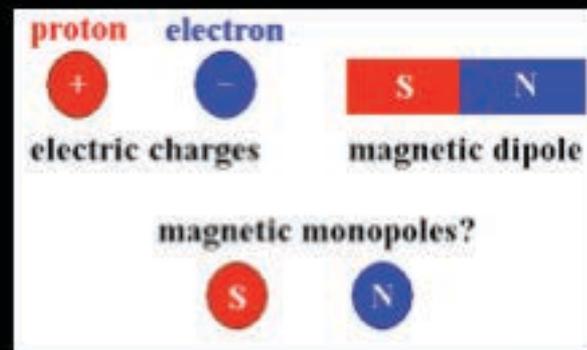
Are there extra dimensions?



What happened just after the big bang?



What is the nature of Dark matter?



Does magnetic charge exist?

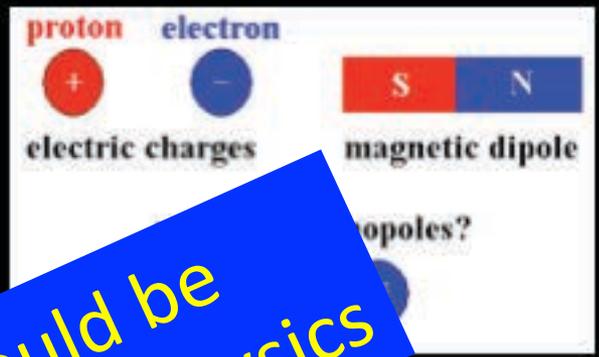


Are there new symmetries of nature?

MoEDAL Addresses Fundamental Questions:



Are there extra dimensions?



Can magnetic charge exist?

STAYED TUNED - The LHC could be poised on the threshold of new physics



What is the nature of Dark matter?



What happened just after the big bang?



Are there new symmetries of nature?

ADDITIONAL SLIDES

Beampipe Searches for Very Highly Ionizing Particles – Now in Play

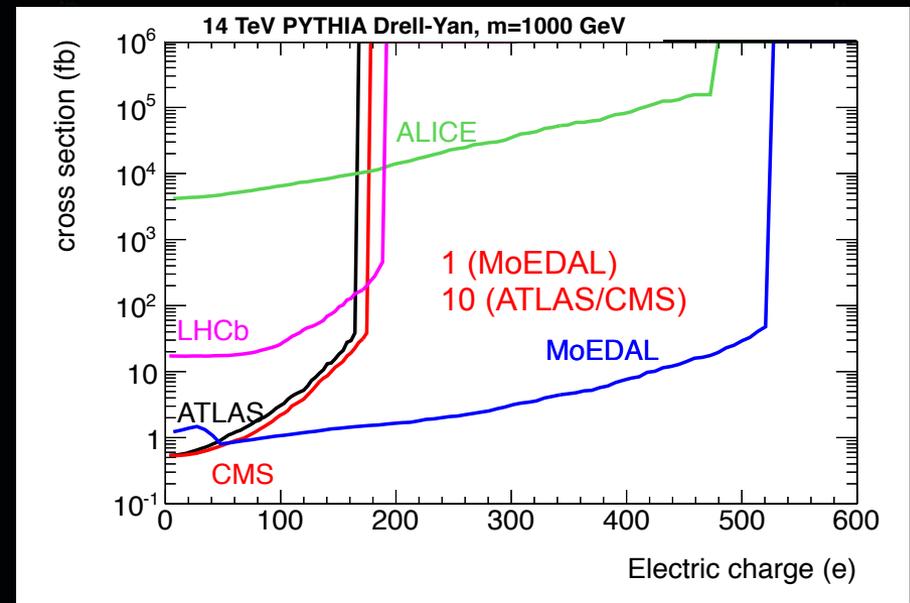
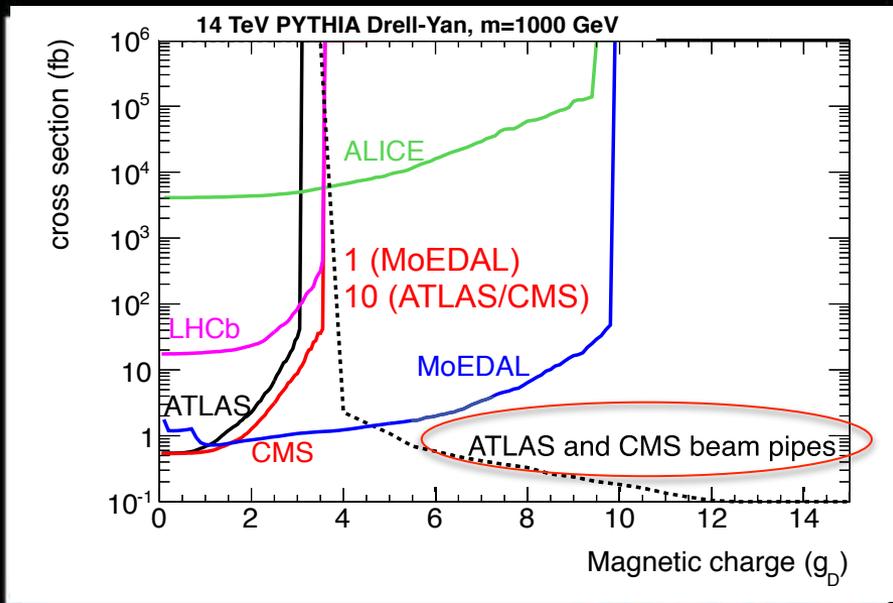
CMS Beryllium beampipe



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](https://arxiv.org/abs/1112.2999v2) [hep-ph])
- MoEDAL COMPLEMENTS the physics reach of the existing LHC experiments

The MoEDAL Trapping Detector System



- *Only 1/3 of the trapping array used for $\sqrt{s}=13$ TeV search*
 - *The full sensitivity includes results from all of the trapping and NTD detectors – so much improved 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*

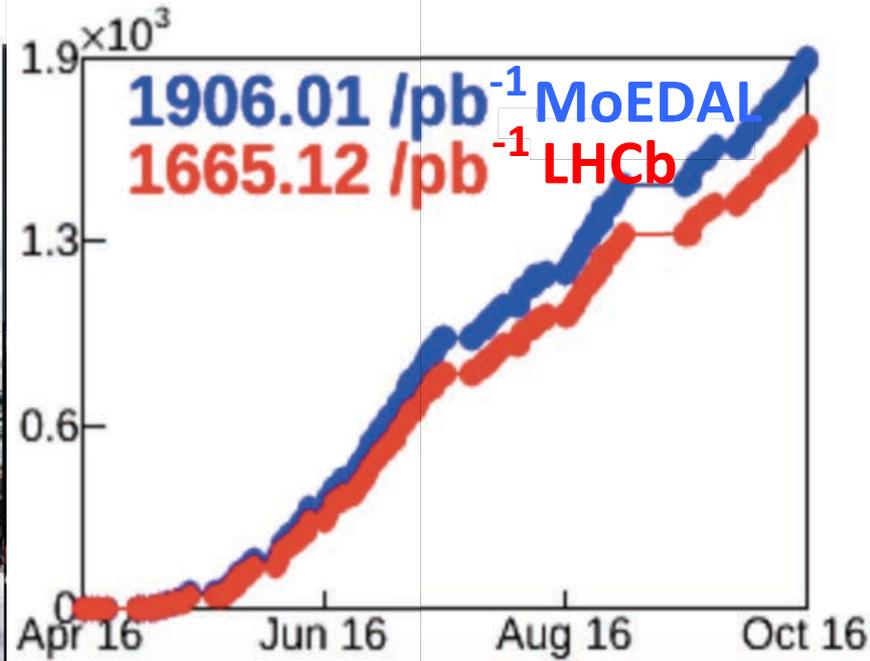


MoEDAL

MoEDAL in Run 2

LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015

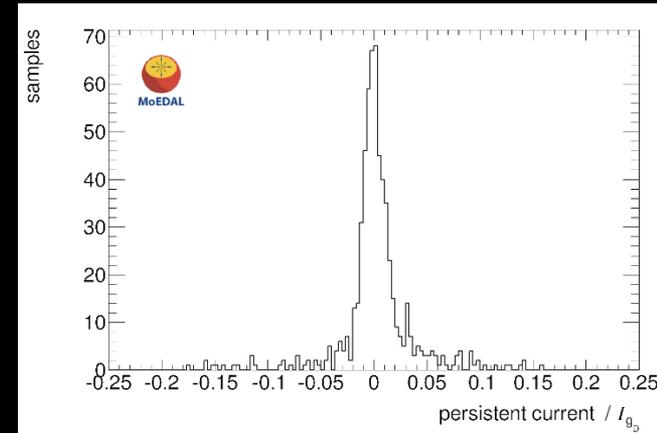
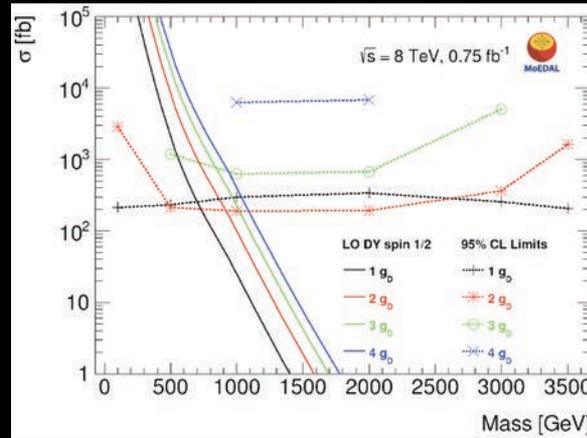
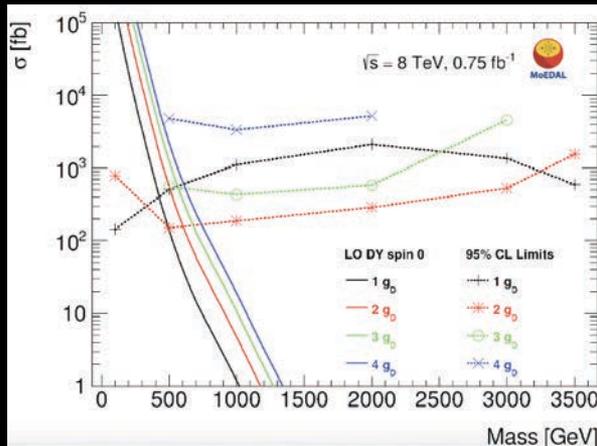


Recorded Luminosity

The luminosity delivered to MoEDAL in 2015 was 366 pb^{-1}

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

The MoEDAL Monopole Search at $s = 8 \text{ TeV}$ - 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

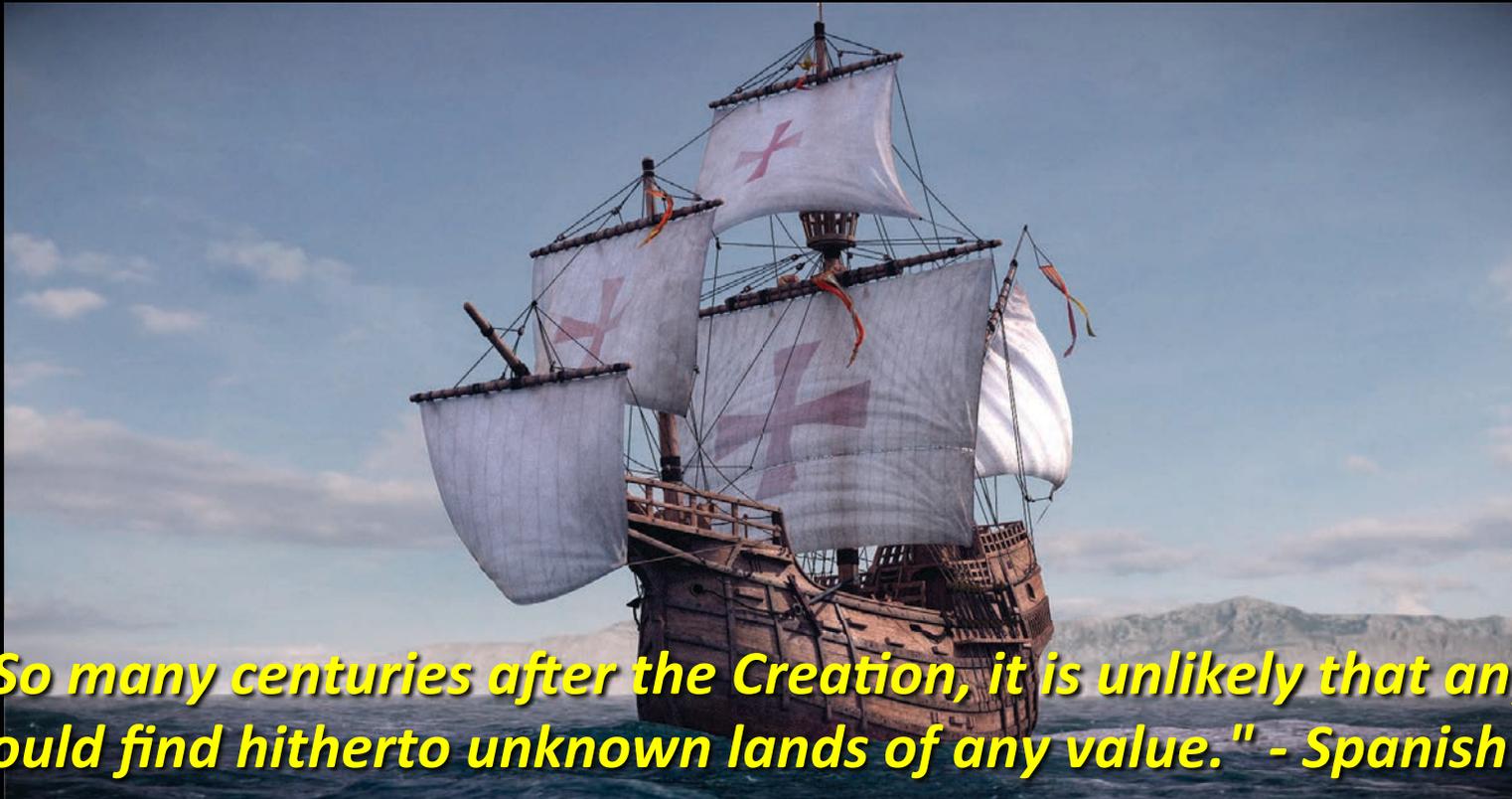
$ g = g_D$
1340
1050

MoEDAL

ATLAS

World best limits for $|g| > g_D$
(previously $\sim 400 \text{ GeV}$ at the Tevatron)

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

