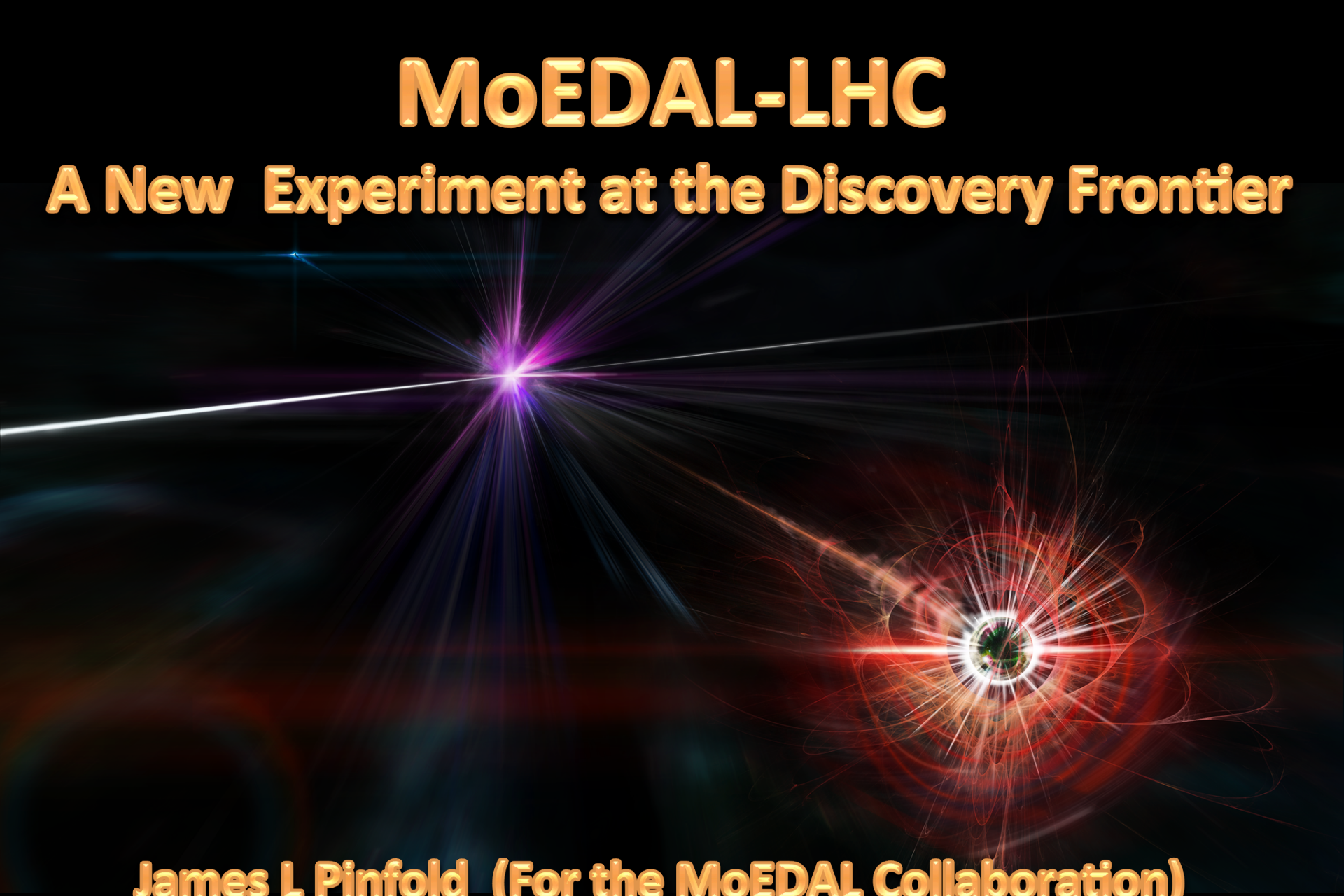
MoEDAL-LHC

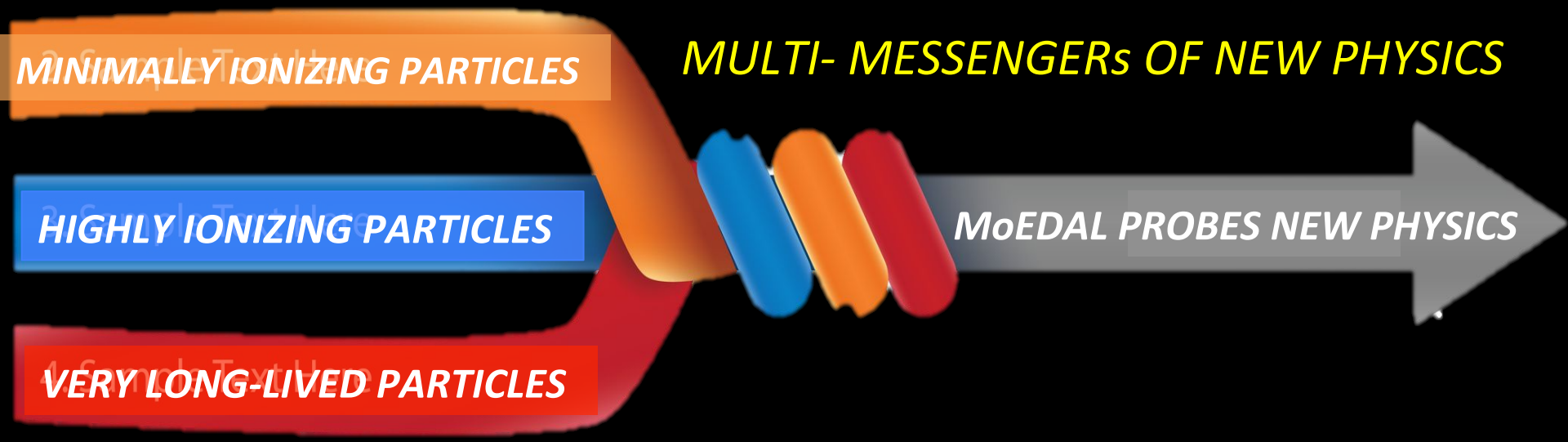
A New Experiment at the Discovery Frontier



James L Pinfold (For the MoEDAL Collaboration)
The University of Alberta

MoEDAL's PHYSICS APPROACH

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



MoEDAL COMPLEMENTS ATLAS & CMS

The Paths to Anomalous Ionization

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

ELECTRIC CHARGE (z)

VERY HIGH IONIZATION
Z↑ β(=v/c)↓

VERY LOW IONIZATION
Z(<<1) β(~1)

VERY HIGH IONIZATION

$g = n137e/2 = n\ 68.5e$

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

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

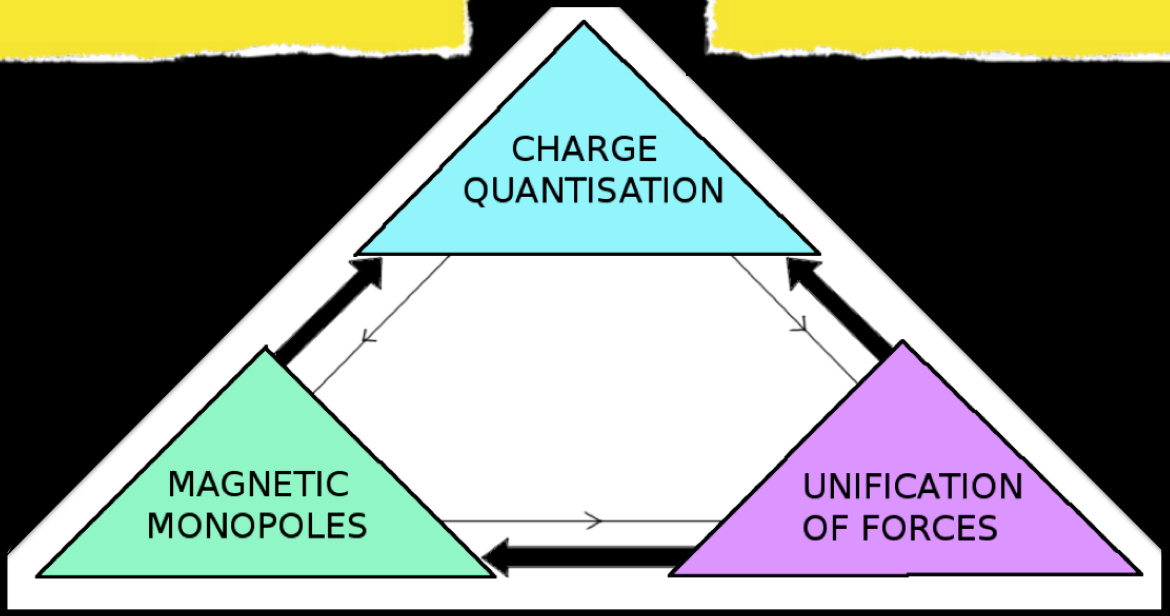
The Monopole and the Higgs Boson

- *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 Importance of the Magnetic Monopole

They restore symmetry to Maxwell's Equations

They explain electric charge quantization



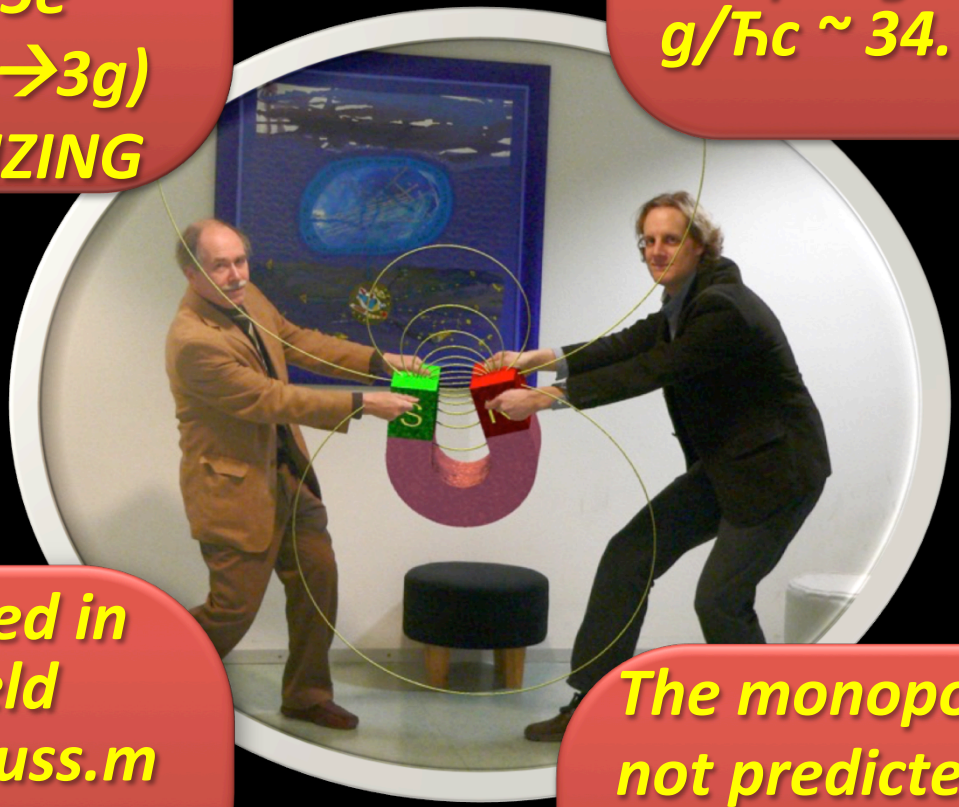
GUT & EW monopoles are excitations of the Higgs field

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

The Detector

MoEDAL

THE MAGNIFICENT SEVENTH

They fought on the high energy frontier

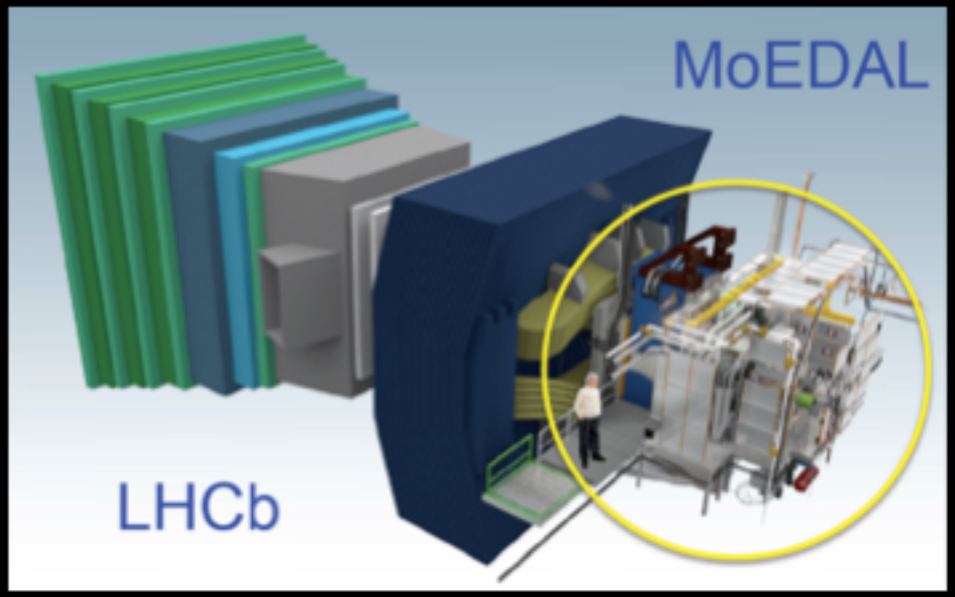
The MoEDAL Collaboration

66 physicists from 14 countries & 26 institutes. on 4 continents:

1) U. Alberta, 2) U. Alabama,3) UBC, 4) INFN Bologna, 5) U. Bologna,6) CAAG-Algeria, 7) U. Cincinatti, 8) Concordia U., 9) CSIC Valencia,10) Gangneung-Wonju Nat. U.,11) 12) U. Geneva, 13) U. Helsinki, 14) IEAP/CTU Prague, 15) IFIC Valencia, 16) Imperial College London, 17) ISS Bucharest,18) King's College London, 19) Konkuk U., 20) U. Montréal,21) MISiS Moscow, 22) Muenster U., 23) National Inst. Tec. (india), 24) Northeastern U., 25) Queen Mary College UK, 25) IRIS/Simon Langton School UK, 26) Tuft's.

MoEDAL – a Unique Collider Detector

Permanent Physical record of new physics



No Standard Model Physics Backgrnds

MoEDAL is largely passive made up of three detector system.

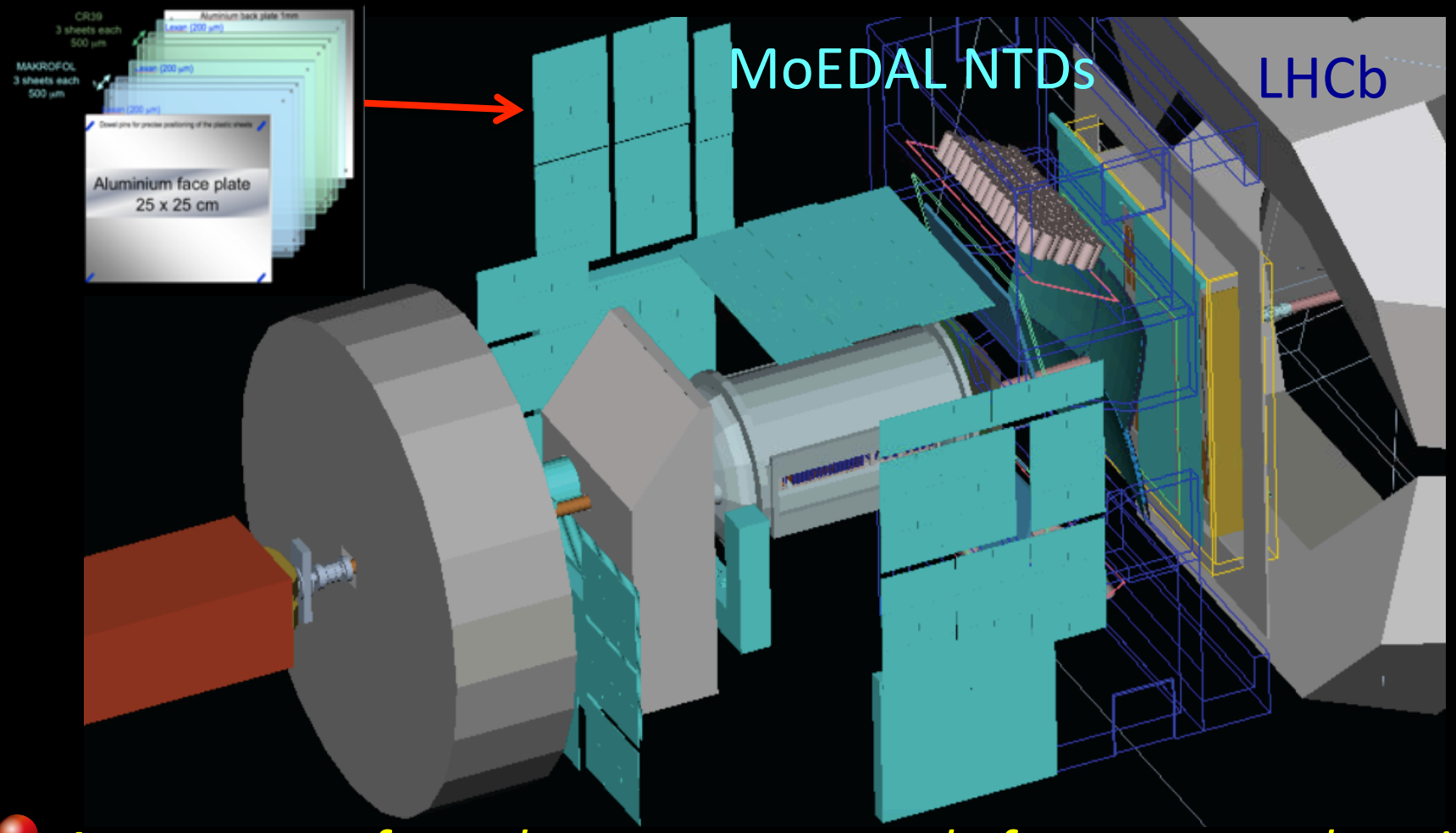
NUCLEAR TRACK DETECTOR
Plastic array (~200 sqm)
– Like a Giant Camera (with film)

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

TIMEPIX Array a digital Camera for real time radiation monitoring

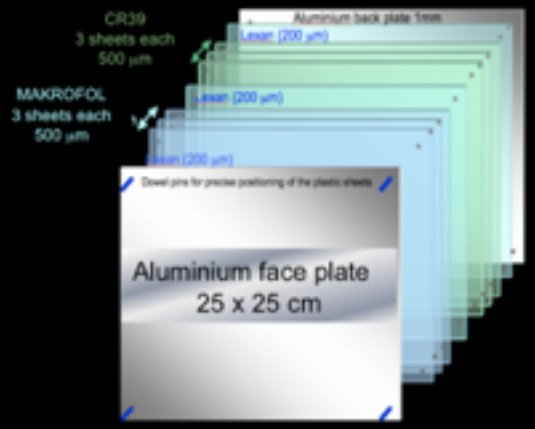
24

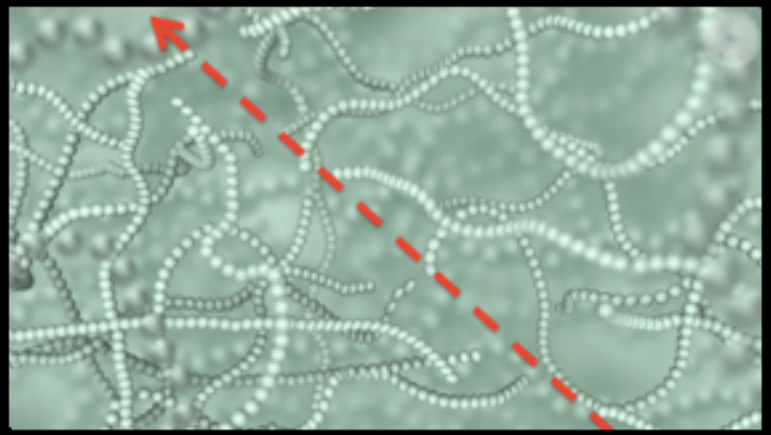
Full NTD Deployment in 2015/16

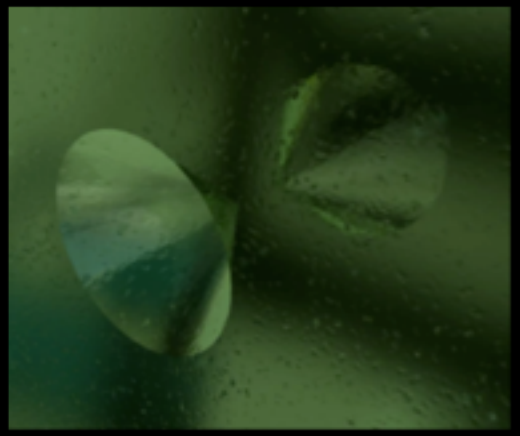


- *Accceptance for at least one monopole from monopole pair production to hit NTDs ~70%*
  - *Detection efficiency of traversing track essentially 100%*
  - *Detection threshold $Z/\beta \geq 5$ (CR39) and 50 (MAKROFOL)*

The Nuclear Track Detector System

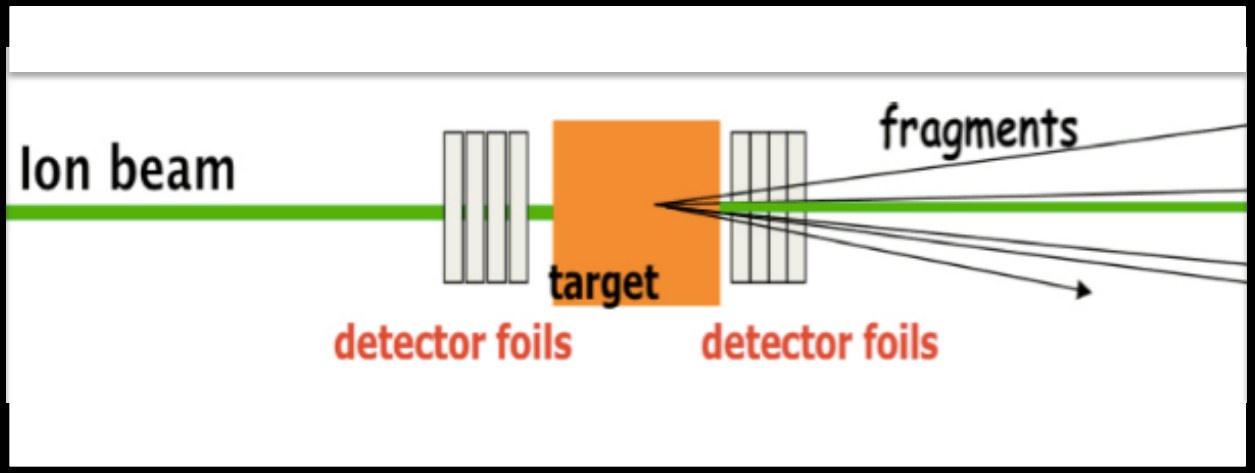


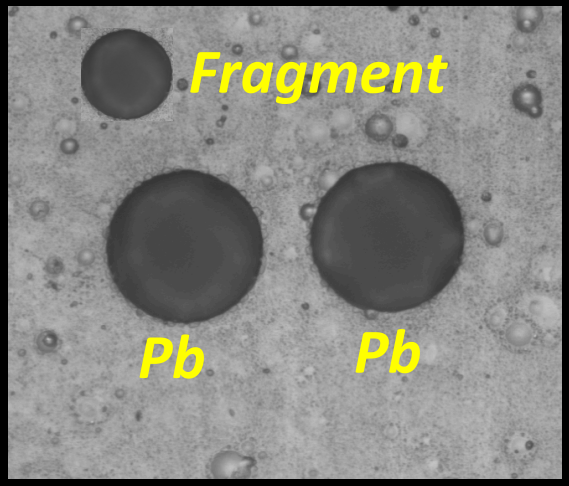




- *Largest array (150 m^2 of NTDs every deployed at an accelerator*
  - *Plastic NTD stacks consist of CR39 (threshold 5 MiPs) and Makrofol (50 MiPs) – that are "damaged" by the highly ionizing particle*
  - *The damage is revealed by controlled etching in a hot Sodium Hydroxide solution – etch pits are formed*
  - *Charge resolution is ~0.1|e|, where |e|is the electron charge*
- *NTD system acts like a giant camera that is only sensitive to new physics - no known SM backgrounds*

NTDs are Calibrated with Heavy Ions

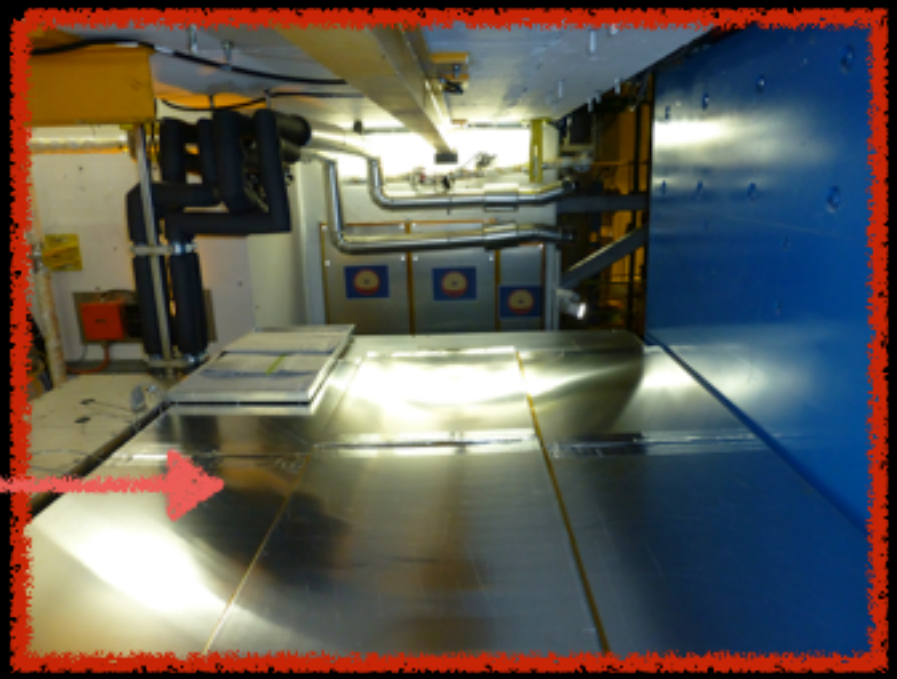


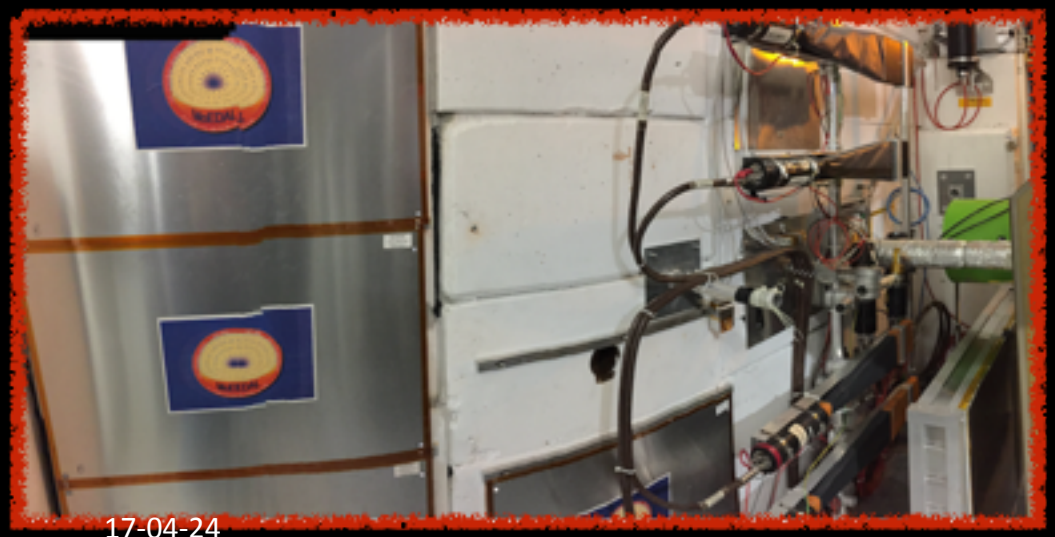


Pb on Makrofol foils already exposed to 13 TeV LHC Collisions at IP8

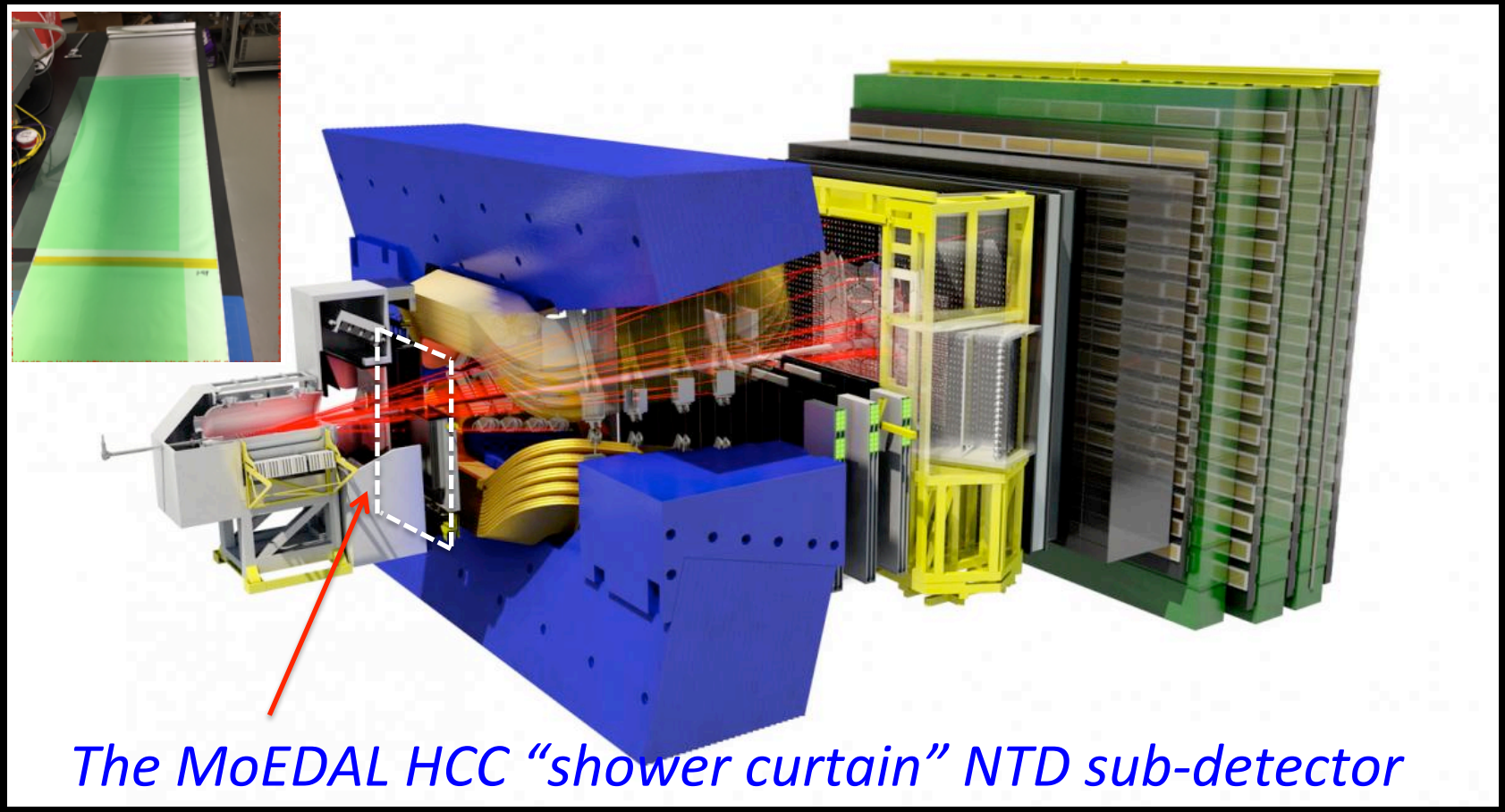
- ***Currently use the NASA Space Radiation facility EG:***
  - *Fe^{26} 1.5 GeV/nucleon (max.),) Xe^{132} 0.35 GeV/nucleon (max), O^{16} 1.5 GeV/nucleon, C^{12} 1.5 GeV/nucleon (max)*
- *NA61 (CERN) Various EG*
  - *Pb 30 GeV/nucleon, Ar upto 150 GeV/nucleon, etc.*
- *Properly calibrated the charge can be measured to 0.1e*

NTD Deployment





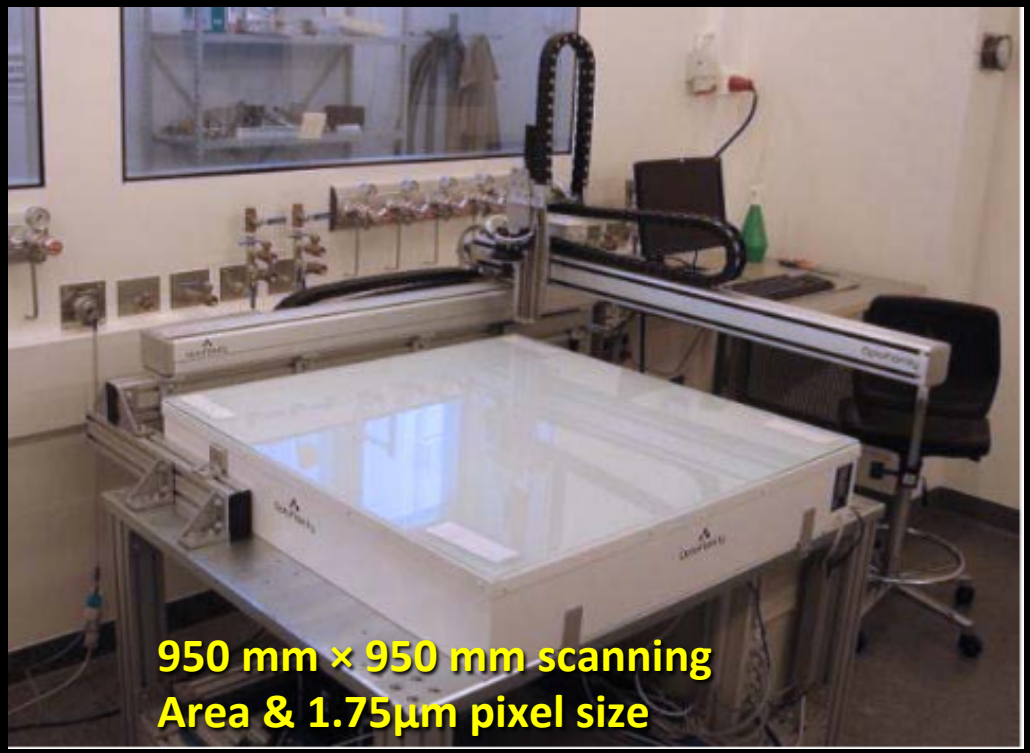
NTD Deployment in LHCb's Acceptance

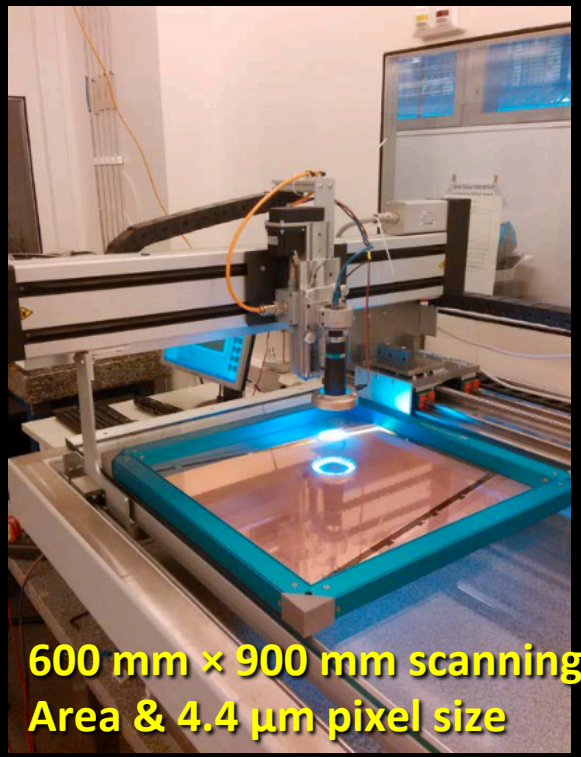


The MoEDAL HCC "shower curtain" NTD sub-detector

- *High charge catcher (HCC) within LHCB acceptance between RICH and TT1*
- *Threshold Z/β ~50 , installed in the Winter of 2015*

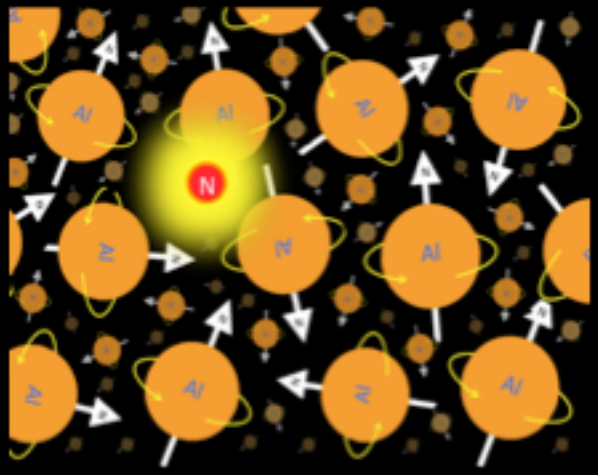
Scanning for New Physics



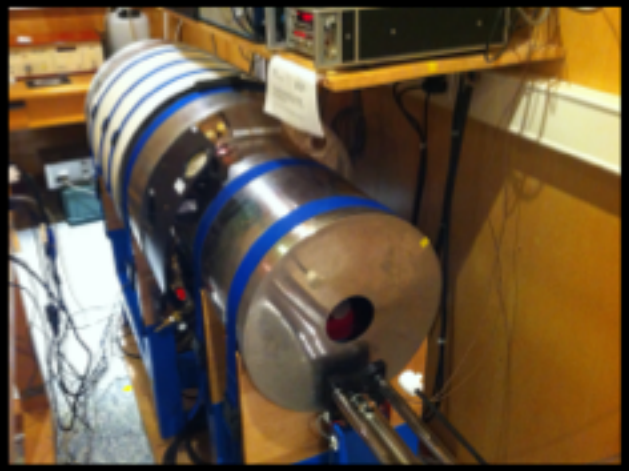


- *Exposed NTDs will be scanned using automated high rate CCD based scanning microscope developed by groups at Bologna, Muenster and Helsinki*
  - *Specialized image enhancement/ pattern recognition software*
  - *Helsinki scanner can scan 100 cm^2 in 20 minutes*

The Trapping Detector System



Trapped monopole

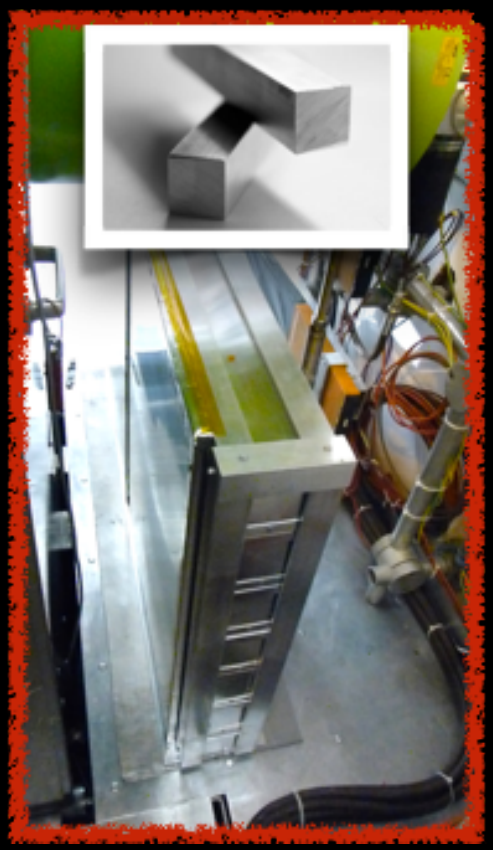


SQUID magnetometer (ETH Zurich)

Search for trapped quasi-stable decays at SNOLAB

- We will deploy trapping volumes (~1 tonne) in the MoEDAL/ VELO Cavern to trap highly ionizing particles
  - The binding energies of monopoles in nuclei with finite magnetic dipole moments are estimated to be hundreds of keV
- After exposure the traps are removed and sent to:
  - The SQUID magnetometer at ETH Zurich for Monopole detection
  - Underground lab to detect decays of MSPs

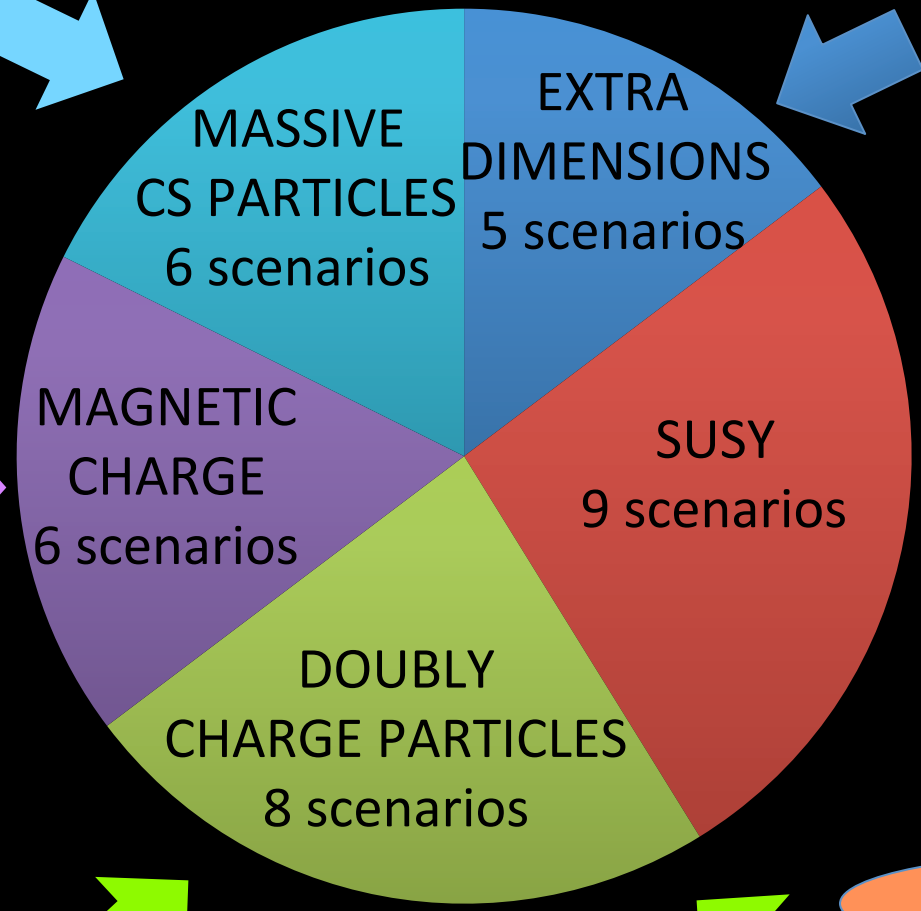
Full MMT Deployment in 2015/16



- *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*
  - *After scanning for monopoles Al will be monitored underground for very slow decays,*

Physics Program and Initial Results

MoEDAL – Physics Scenarios (34+)

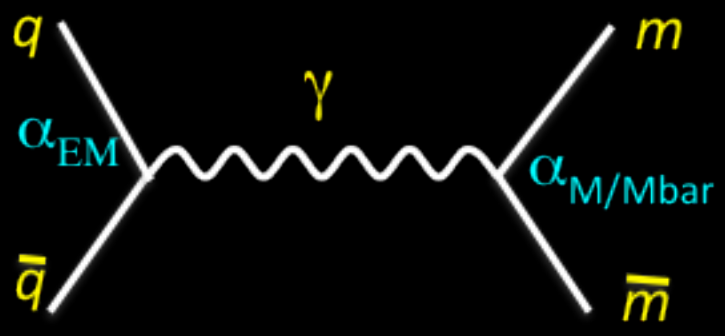


- Quirks
- Q-balls
- 4th Gen fermions
- Electroweak monopoles
- D-particles
- Light TP monopoles
- Monopolium
- Doubly charged Higgs
- Doubly charged higgsinos
- MBH remnants
- Stable MBHs
- KK-particles
- Heavy Sleptons
- Metastable charginos
- Long lived gluinos
- R-hadrons
- Fat Higgs scenarios
- Doubly charged fermions

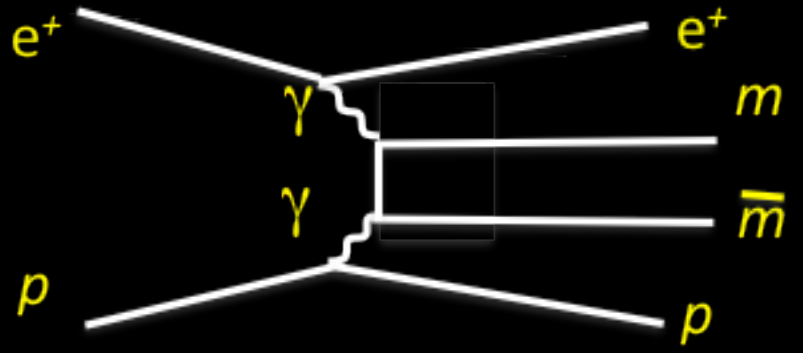
Int.J.Mod.Phys. A29 (2014) 143005

Monopole Production at Colliders

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

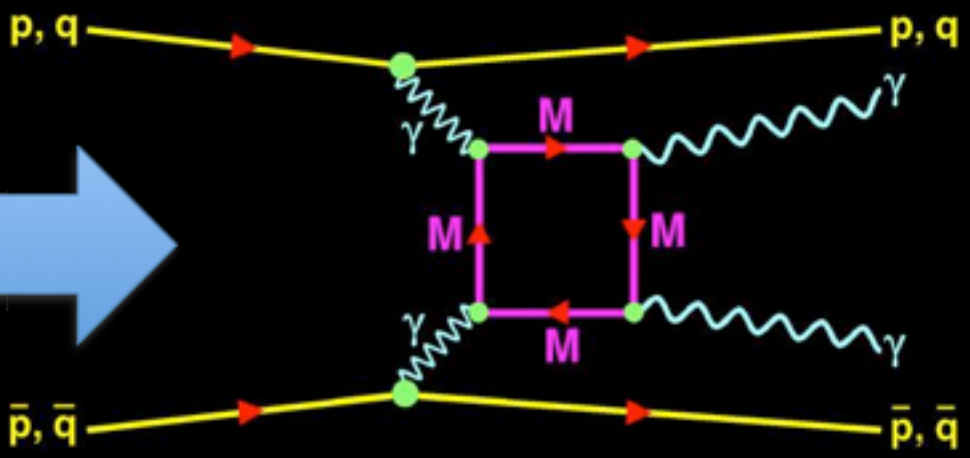


Drell-Yan Production



Two-photon production

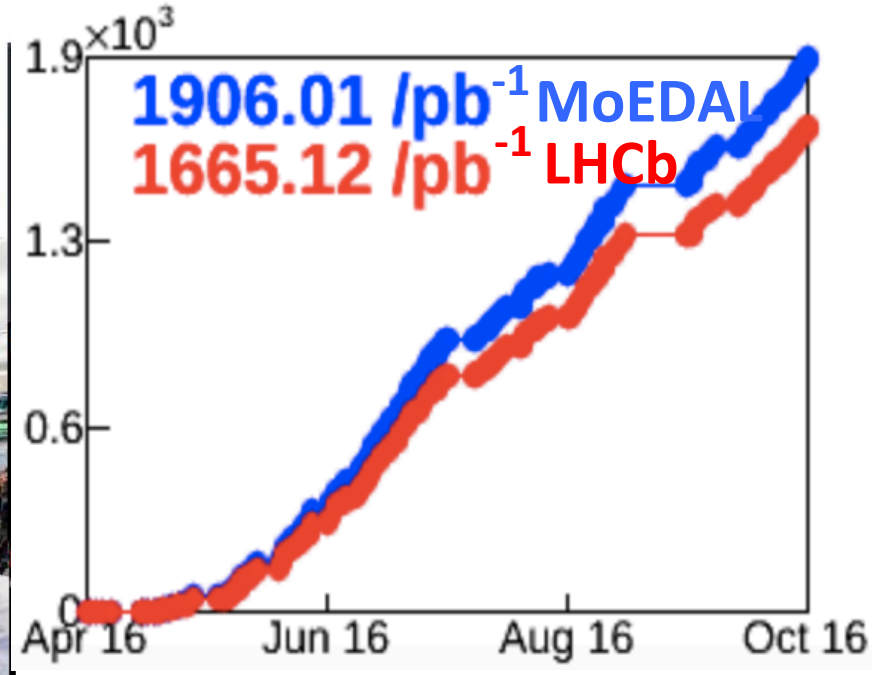
Indirect search using virtual monopole box diagrams allow – observable two high energy gammas.



MoEDAL in Run 2

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

3rd June 2015

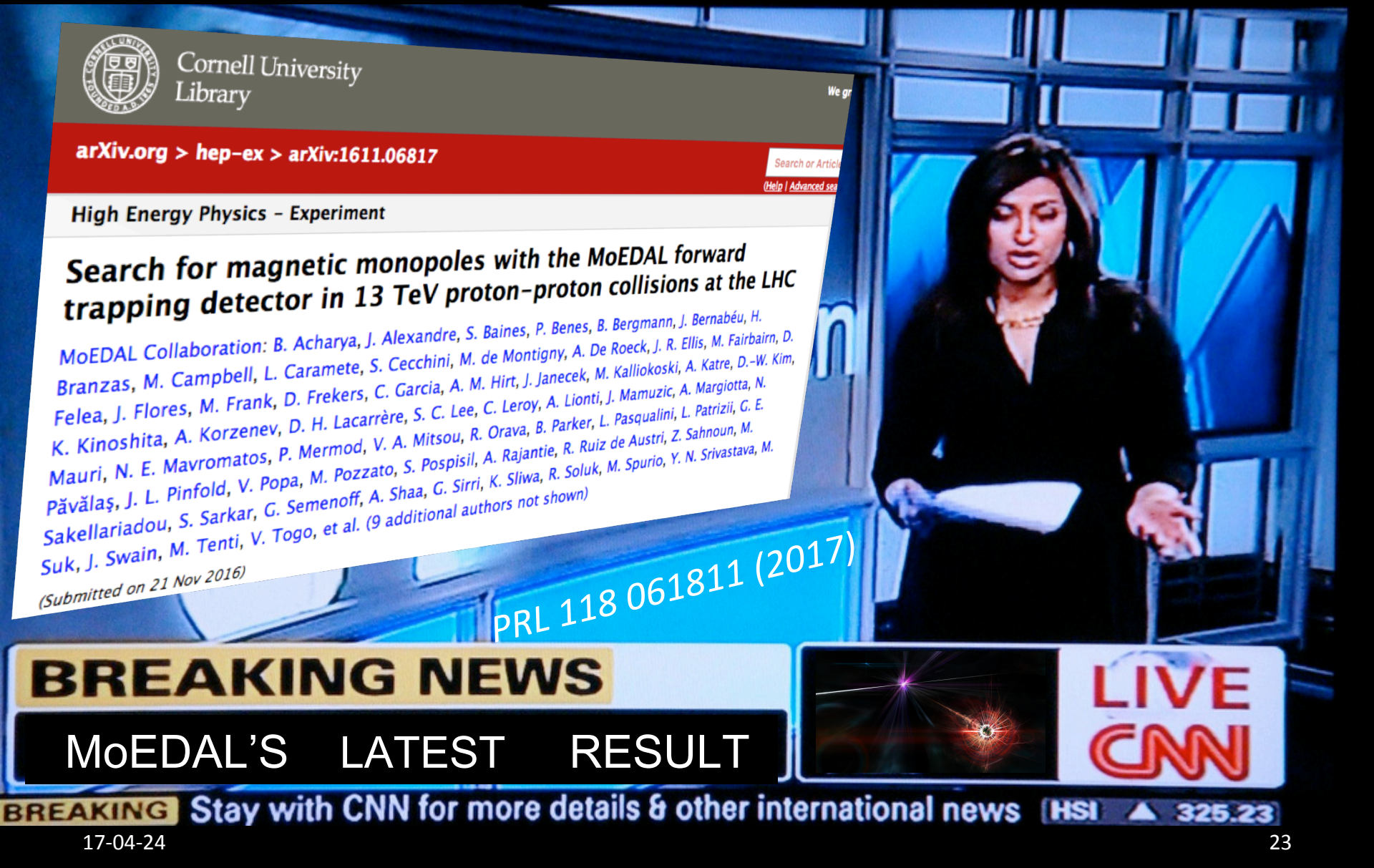


Recorded Luminosity

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

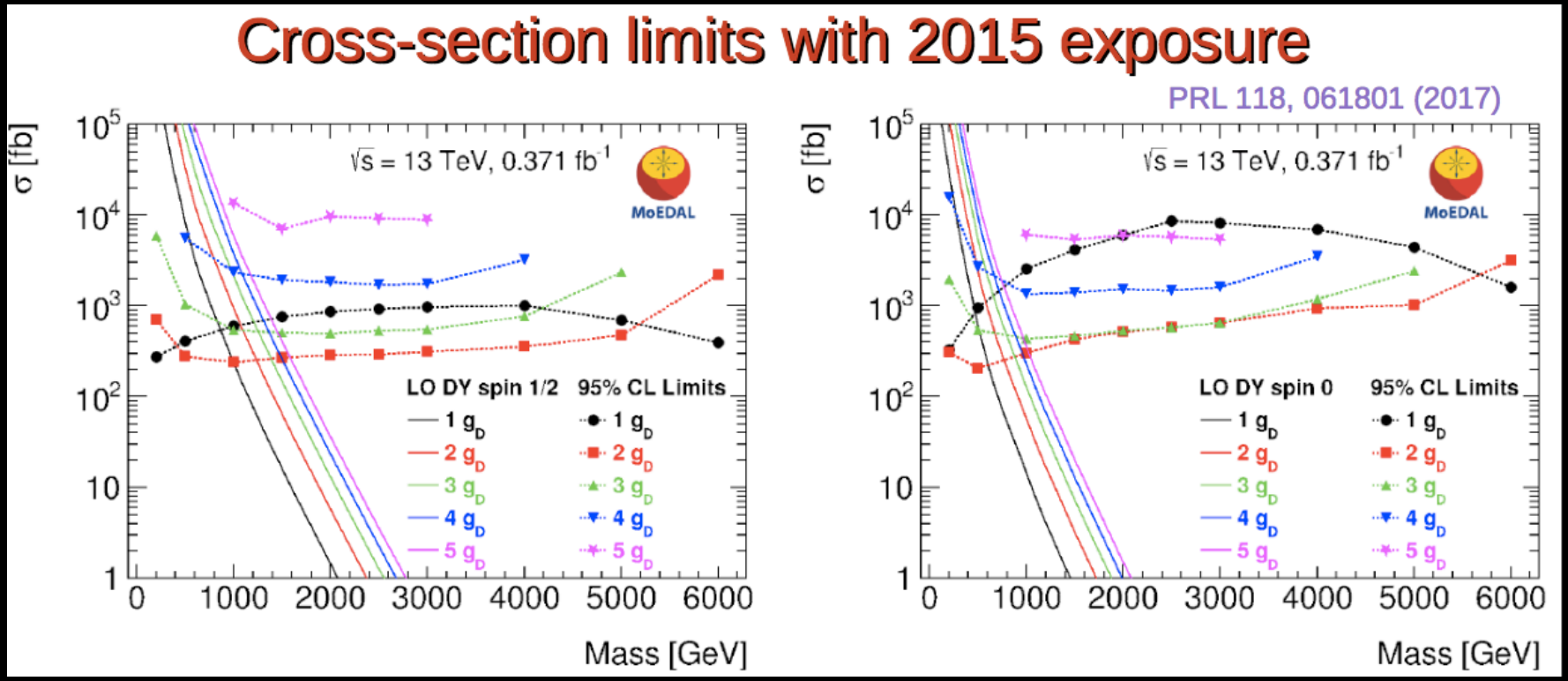
Despite "Sparky" the Beech Marten – LHC is now on track

1st MoEDAL Result at 13 TeV (2015 exp.)



MoEDAL Results - 2015 Exposure

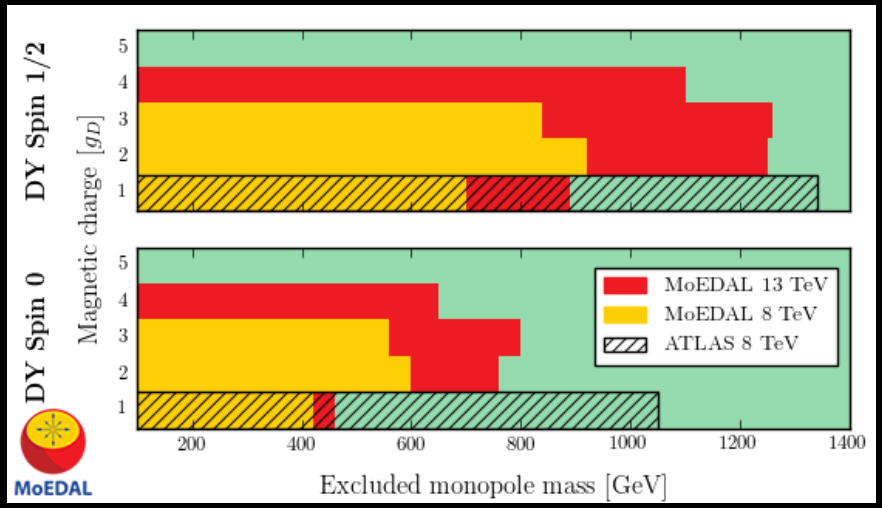
Cross-section limits with 2015 exposure



- *First monopole constraints in 13 TeV pp collisions*
- *Best Collider results with $|g| > g_D$*
- *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*

MoEDAL Results in 2017

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	–	–	–



PRL 118 061811 (2017)

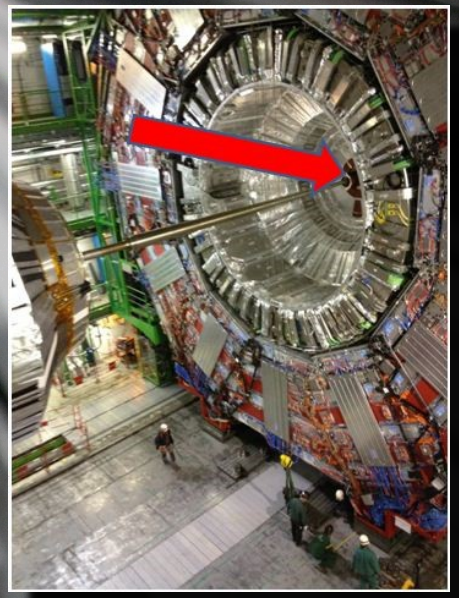
- *Exclude monopole with $|g| = 4g_D$ for the 1st time at the LHC*

IN THE PIPELINE:

- *MMT Trapping search at √s =13 TeV with 5-6 time more lumi*
- *First results using the NTD detectors at √s =7→8 TeV*
- *Expansion of the monopole physics discussion:*
  - *From spin 0 and ½ monopoles to include spin-1 monopoles*
  - *Include dyon-pair production and $\gamma\gamma$ → monopole- anti-monopole*

Beampipe Searches for Very Highly Ionizing Particles – Now in Play

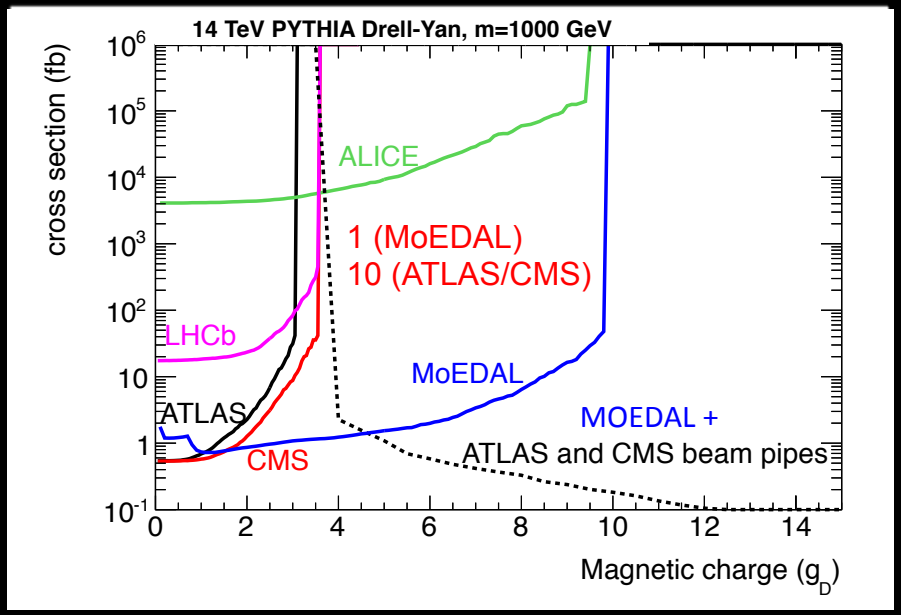
ATLAS/CMS Beryllium beampipes ?

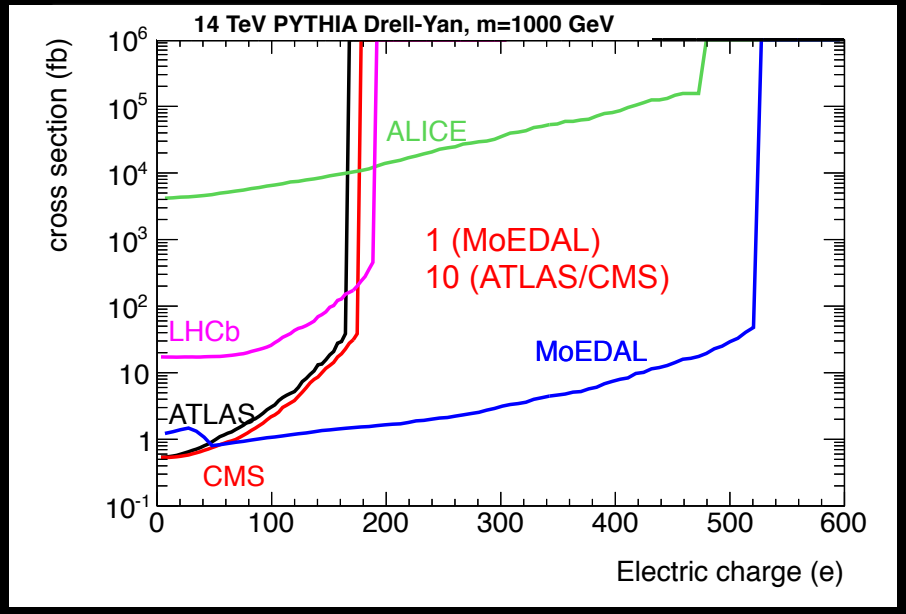


MoEDAL- Beampipe Consortium have submitted a proposal to ATLAS & CMS to utilize their replaced surplus-to-requirement beam pipes in order to scan them for the presence of very highly ionizing monopoles trapped in the beam pipe walls

MoEDAL+BEAM-PIPE - COMPLEMENTARITY

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 ✔

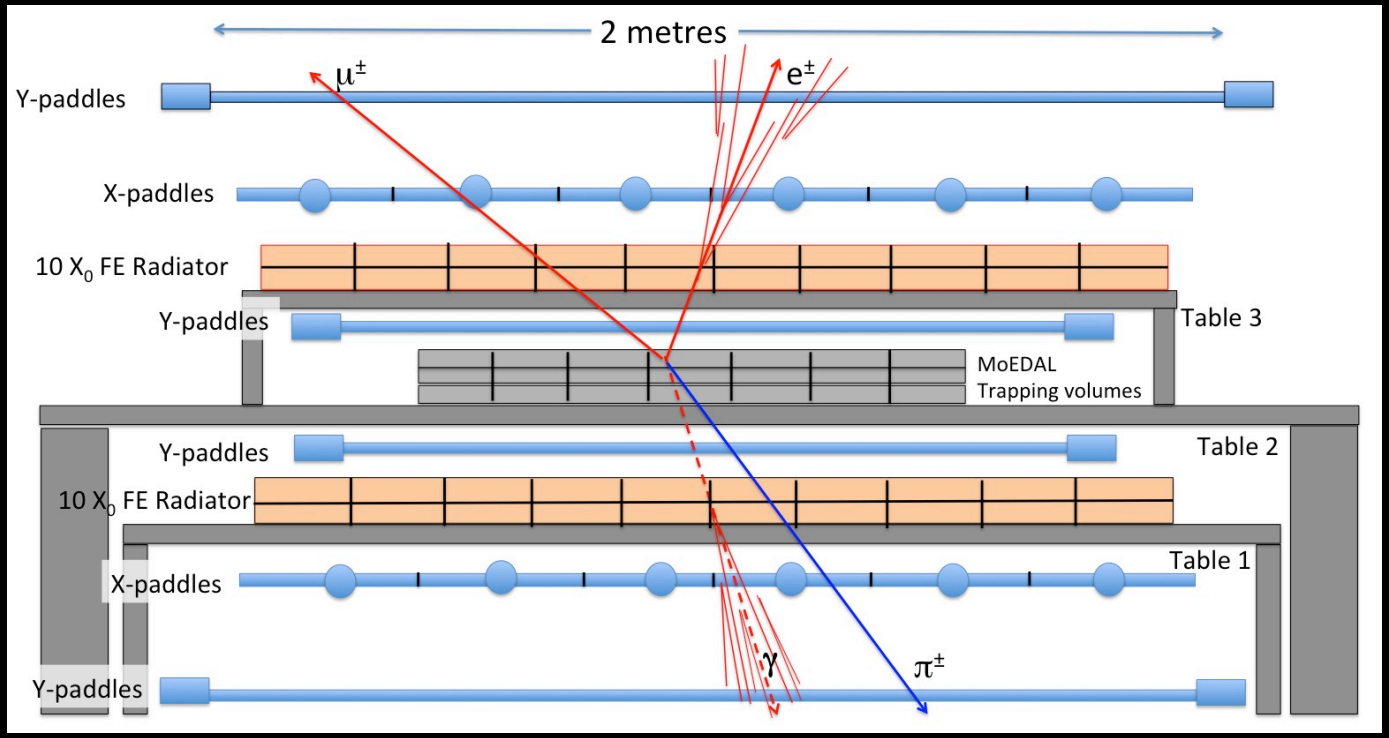




- *Cross-section limits for magnetic (LEFT) and electric charge (RIGHT) (from **arXiv:1112.2999V2** [hep-ph])*
- *MoEDAL COMPLEMENTS the physics reach of the existing LHC experiments*

Planned Detector Upgrades

The Search for the Decays of Very Long Lived Highly Ionizing Particles(1)

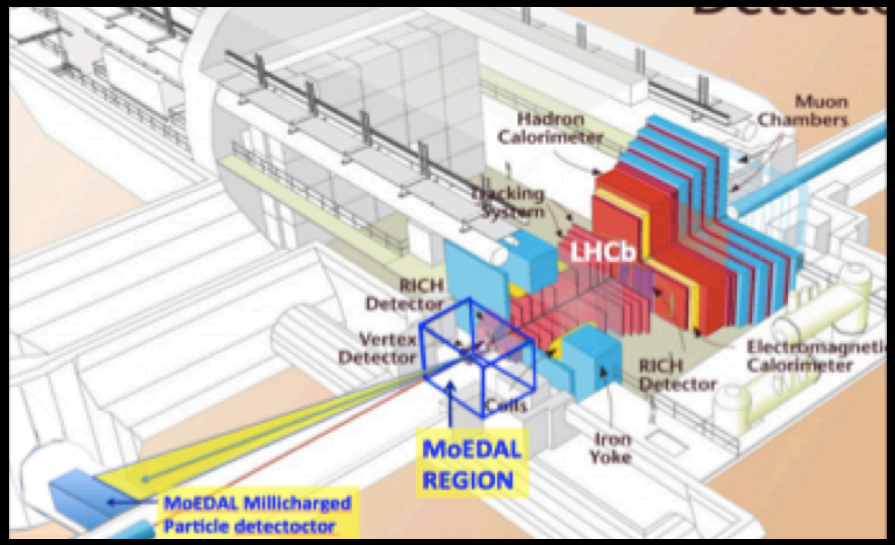


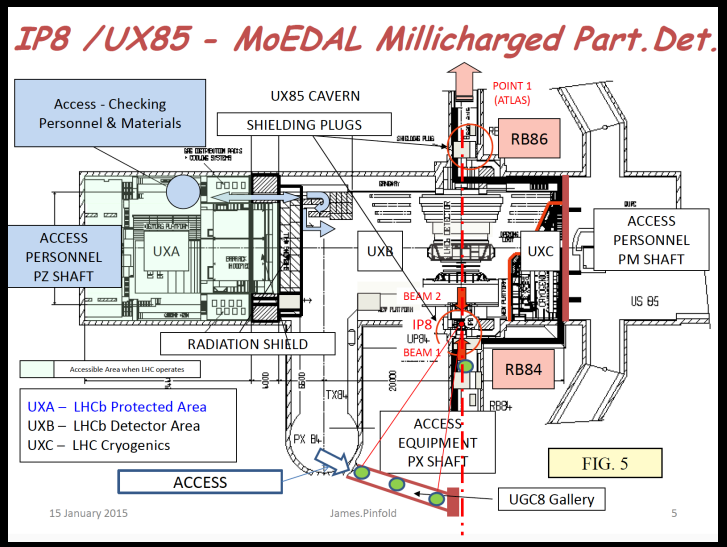
- *After exposure trapping volumes will be monitored underground for the decays of trapped very long-lived particles using the scintillator detector sketched above.*
  - *The planned detector has a low threshold (eg ~1 GeV muons) and is sensitive to electrons, muons, hadrons and photons.*

The Search for the Decays of Very Long Lived Highly Ionizing Particles(2)

- *Monitoring detector will be deployed underground (baseline location SNOLAB ~ 2 km rock overburden.*
  - *Electronics is designed to differentiate between upward going and downward going particles (electronics designed and prototyped)*
  - *Low threshold (~1 GeV), essentially background-less operation is sensitive to decaying particles with lifetimes as high as 10^9 seconds*

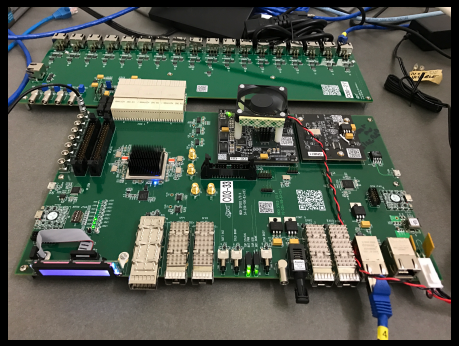
MoEDAL Apparatus for Penetrating Particles (MAPP)



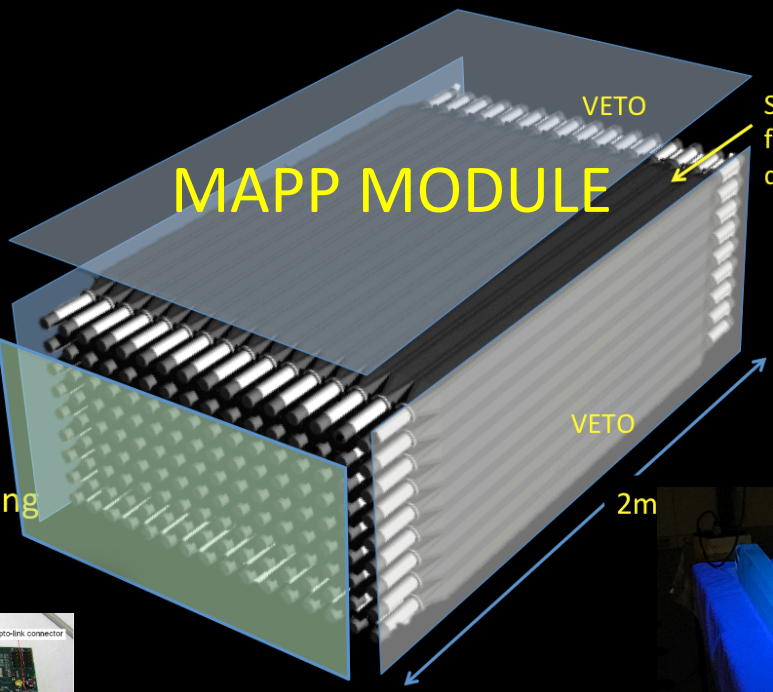


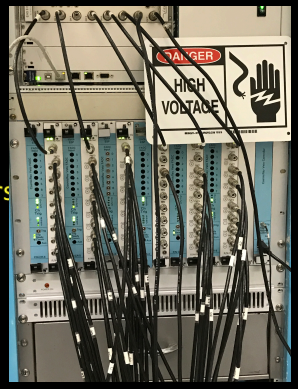
- *MAPP will be able to take data in p-p, p-A,A-A and also fixed target interactions using SMOG (an internal gas target in LHCb)*
- *MAPP has three motivations*
  - *To search for particles with charges <<1e (beyond the reach of the other LHC detectors) – from, say, new dark sectors*
  - *To search for new pseudo-stable neutrals with long lifetime.*
  - *To search for anomalously penetrating particles (eg from SUSY models, HV models of dark matter, neutral naturalness, etc.)*

MAPP Is Coming Together

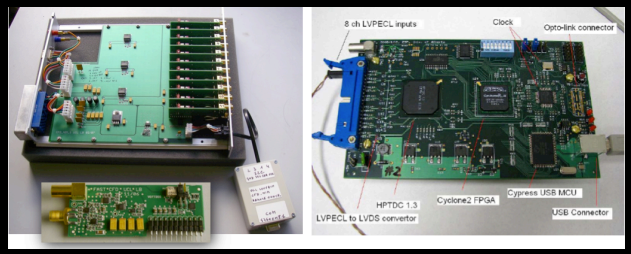


RCE – Connecting to the LHC





The VETO & readout system



Precision ToF with resolution ~15ps

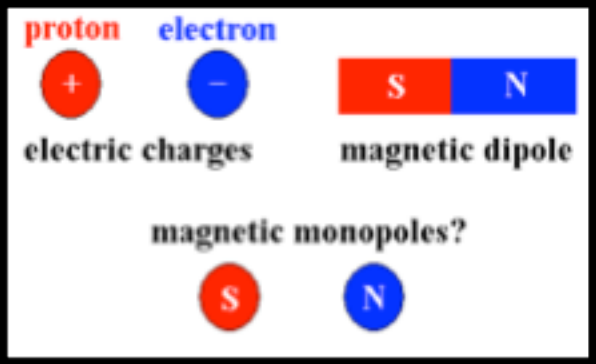
The scintillator under test

- A MAPP prototype will be installed at IP8 in Sept. 2017

MoEDAL Can Address Fundamental Questions

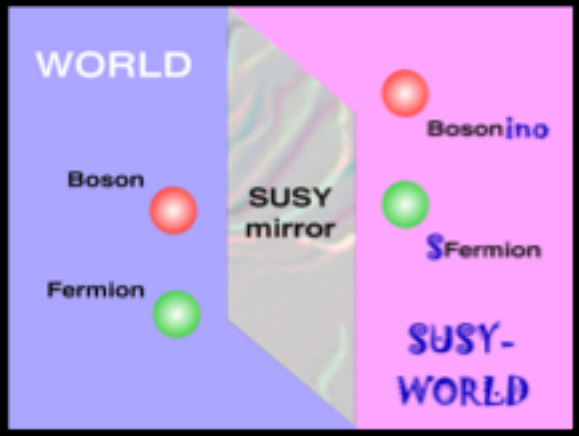
Are there extra dimensions?

What happened just after the big bang?



Does magnetic charge exist?

What is the nature of *Dark matter?*



Are there new symmetries of nature?