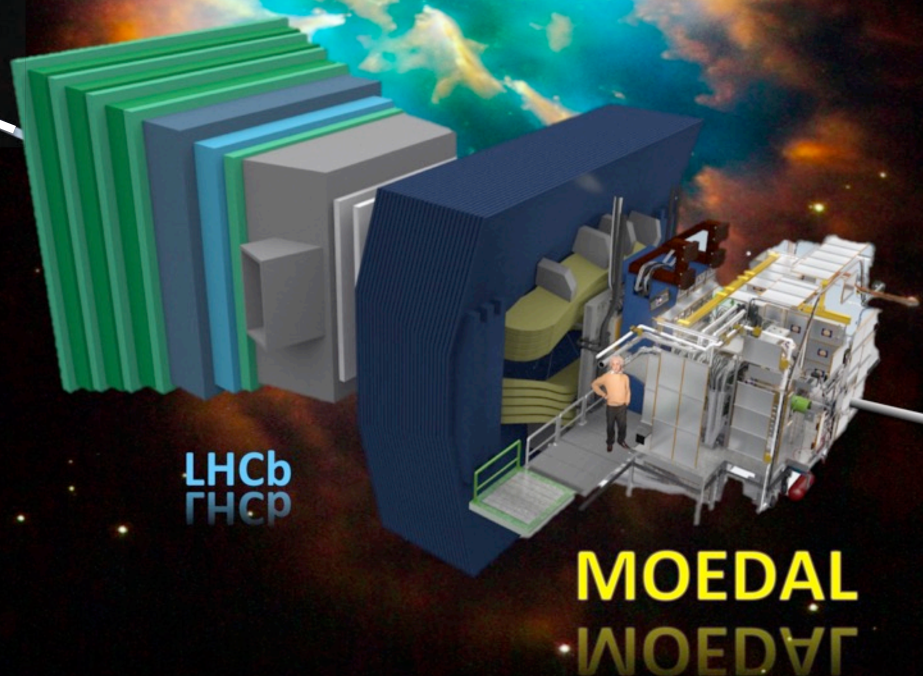
MoEDAL – A New Experiment at the LHC's Discovery Frontier

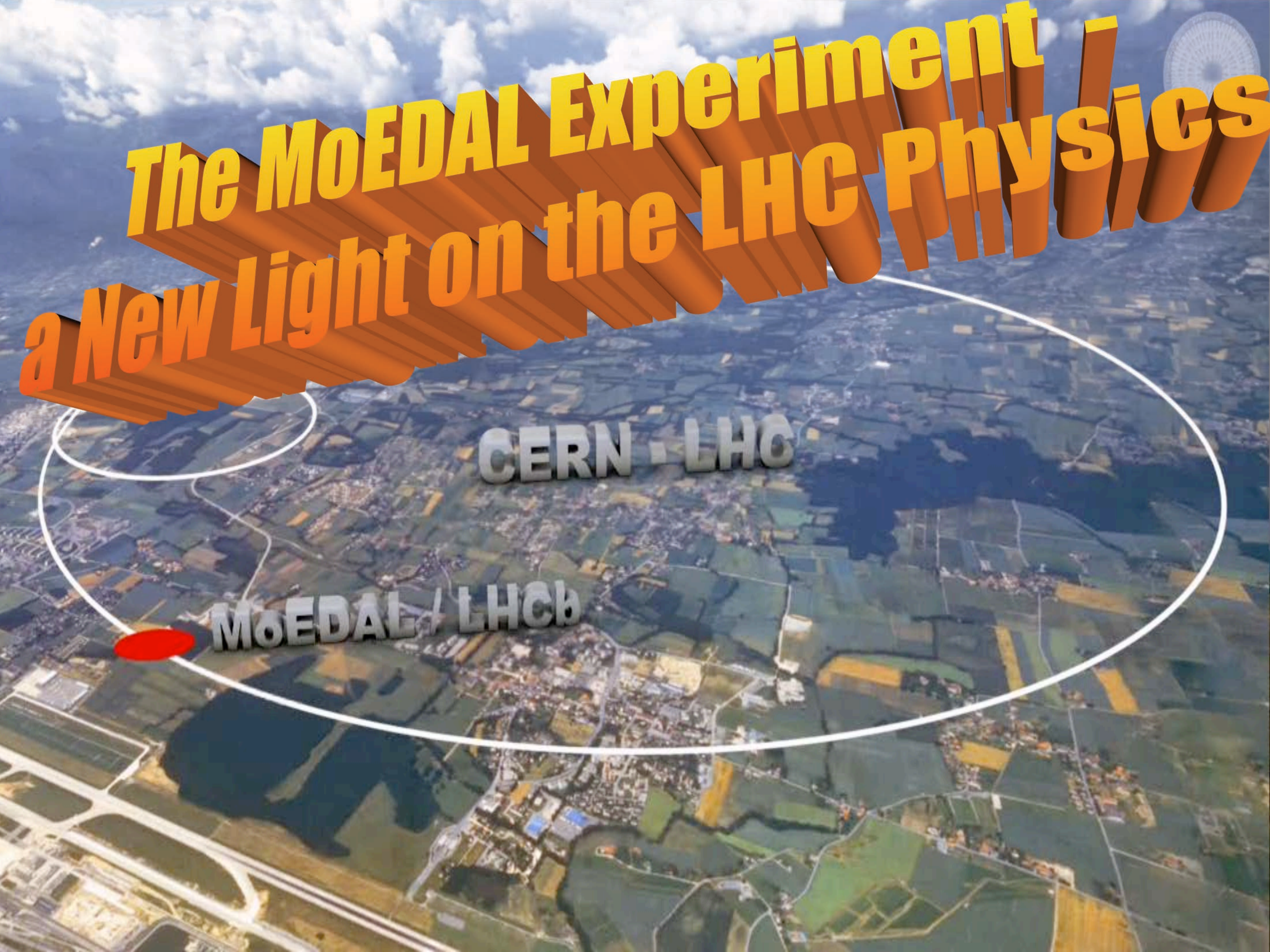
James L. Pinfold, For the MoEDAL Collaboration

ISVHECRI 2016, Moscow.



MoEDAL

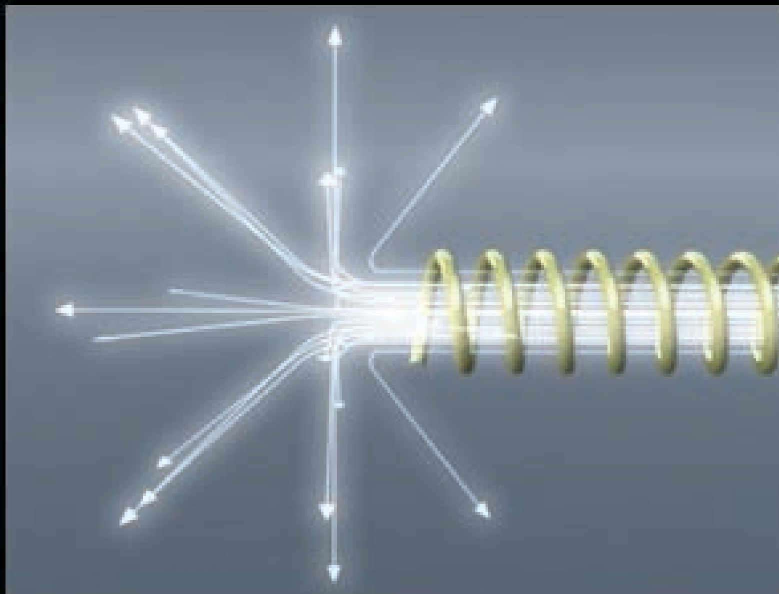
The MoEDAL Experiment – a New Light on the LHC Physics

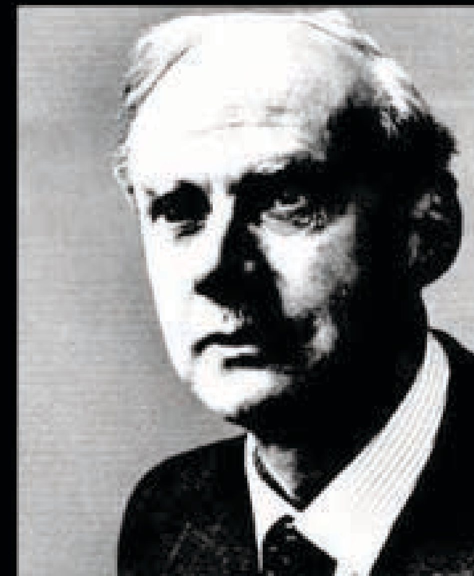


The Monopole is MoEDAL's Higgs

- *Just as the general purpose experiments ATLAS & CMS have as their prime physics purpose the discovery and elucidation of the Higgs……*
- *….Then the equivalent "benchmark" physics physics process for MoEDAL is the magnetic monopole production – thus we shall concentrate on this topic due to time constraints*
- *But ATLAS, CMS and MoEDAL can do much more!*

Dirac's Monopole

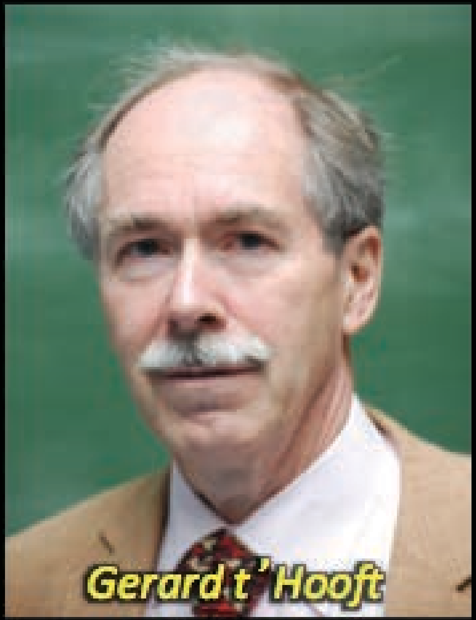


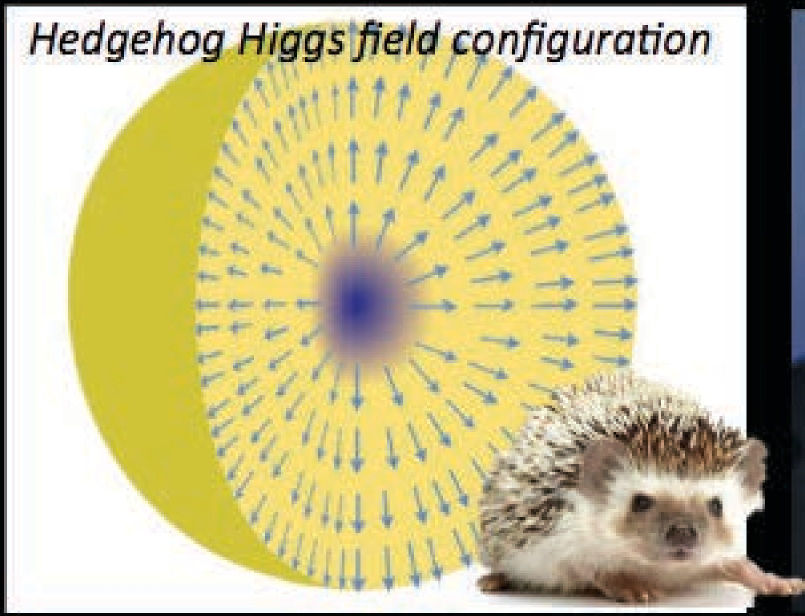


- *In 1931 Dirac hypothesized that the Monopole exists as the end of an infinitely long and thin solenoid - the "Dirac String"*
- *Requiring that the string is not seen gives us the Dirac Quantization Condition & explains the quantization of charge!*

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

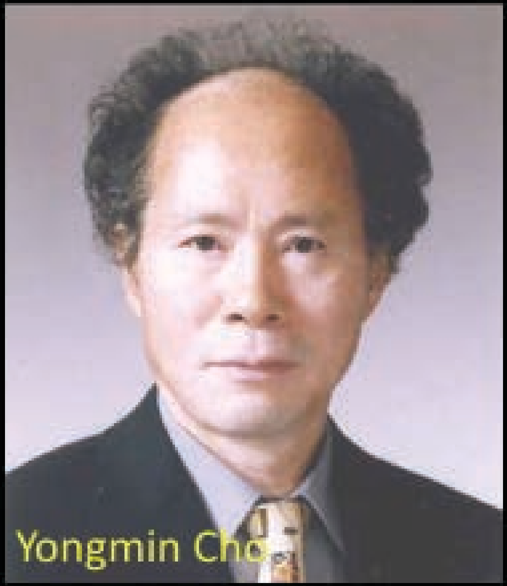
The ‘t Hooft-Polyakov Monopole





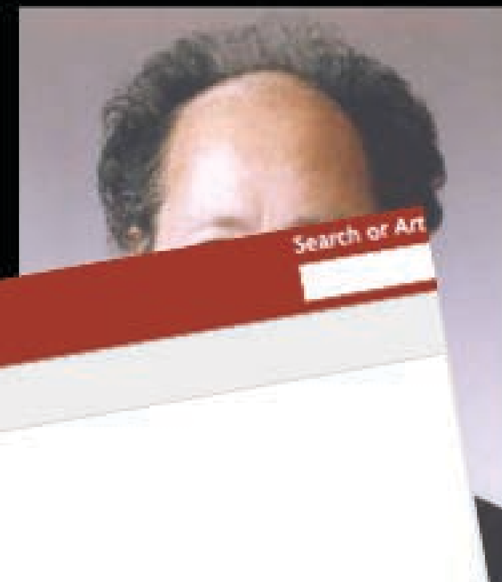
- *In 1974 ‘t Hooft and Polyakov showed that monopoles must exist with the framework the SU(5) GUT with mass around 10^{16} GeV (10 ng in SI units)*
  - *The 't Hooft and Polyakov monopole arises when the Higgs field vector points away from the origin everywhere - the “hedgehog” configuration*
  - *Such monopoles are topological solitons (stable, non dissipative, finite energy solutions) <u>- Like a knot in the Higgs field configuration</u>*

The Cho-Maison Magnetic Monopole



- *Yongmin Cho's pioneering paper in 1986 envisioned a spherically symmetric Electroweak Monopole, with:*
  - *Magnetic charge $2g_D$ & mass potentially in the range 4→7 GeV/c^2*
- *The Cho monopole is a non-trivial hybrid between the Dirac monopole & the 't Hooft-Polyakov monopole*
  - *His monopole arises from the framework of the Standard Model*
- *The Cho-Maison monopole could be detectable by MoEDAL*

The Cho-Maison Magnetic Monopole



arXiv.org > hep-ph > arXiv:1602.01745

Search or Art

High Energy Physics – Phenomenology

The Price of an Electroweak Monopole

John Ellis, Nick E. Mavromatos, Tevong You

(Submitted on 4 Feb 2016 (v1), last revised 10 Feb 2016 (this version, v2))

In a recent paper, Cho, Kim and Yoon (CKY) have proposed a version of the SU(2) × U(1) Standard Model with finite-energy monopole and dyon solutions. The CKY model postulates that the effective U(1) gauge coupling → ∞ very rapidly as the Englert-Brout-Higgs vacuum expectation value → 0, but in a way that is incompatible with LHC measurements of the Higgs boson $H \to \gamma\gamma$ decay rate. We construct generalizations of the CKY model that are compatible with the $H \to \gamma\gamma$ constraint, and calculate the corresponding values of the monopole and dyon masses. We find that the monopole mass could be < 5.5 TeV, so that it could be pair-produced at the LHC and accessible to the MoEDAL experiment.

- ... Dirac
  ... pole
- ... in the Standard Model (Weinberg-Salam)
- Th...-Maison monopole could be detectable by MoEDAL

Magnetic Monopole Properties

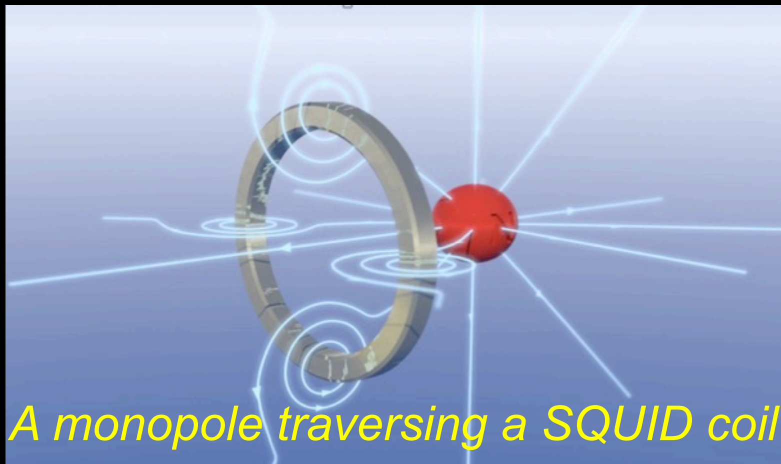
Magnetic charge = ng = n68.5e (if e→1/3e; g→3g) HIGHLY IONIZING

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

Induction Experiments - Evidence?



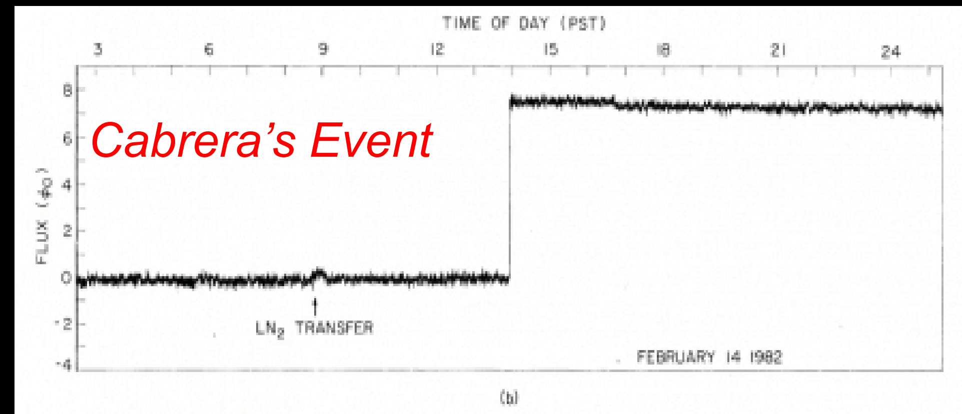
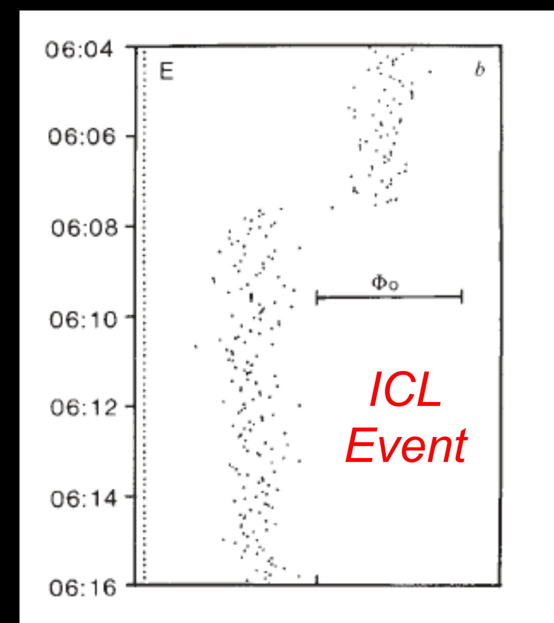
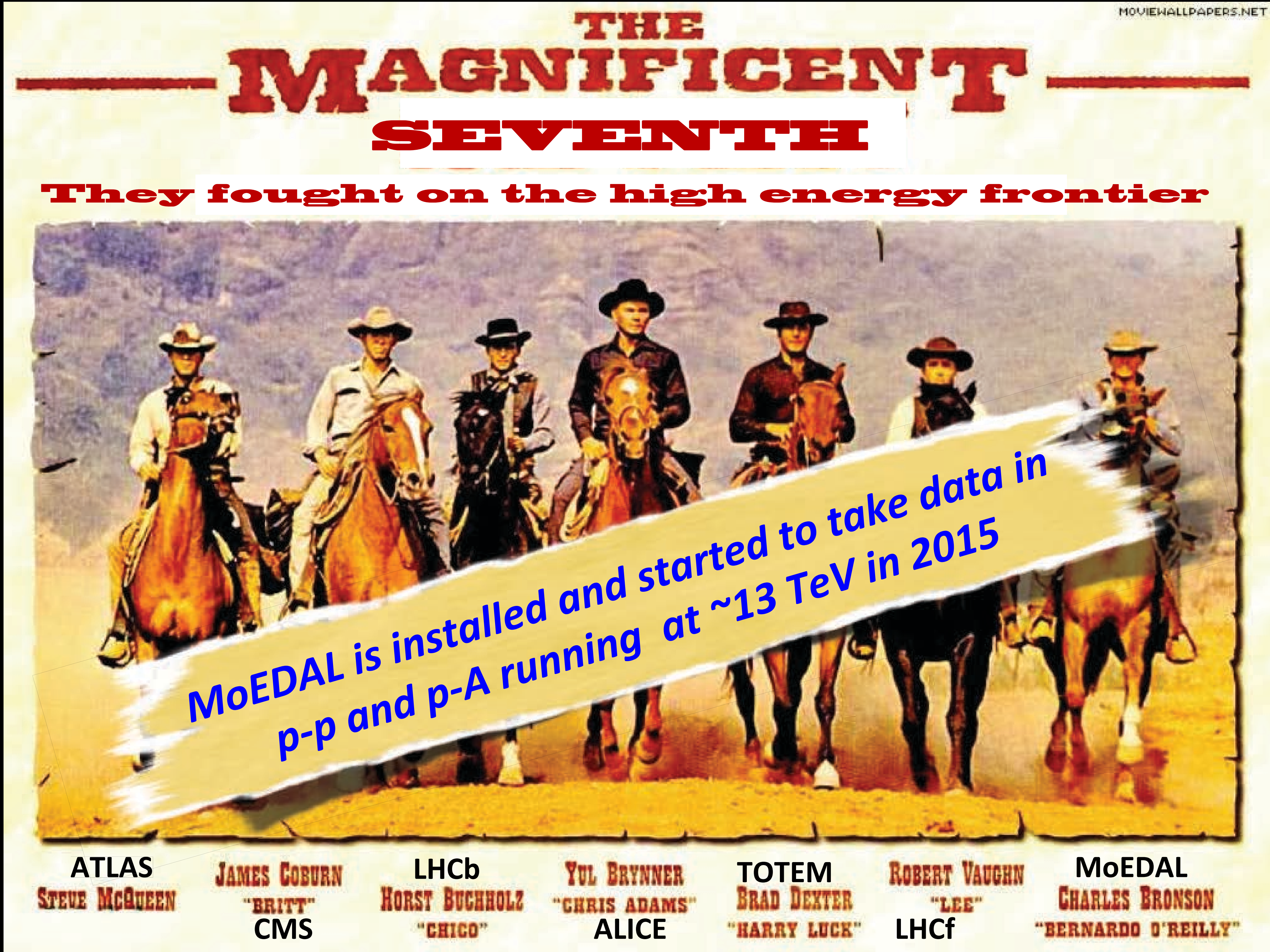


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

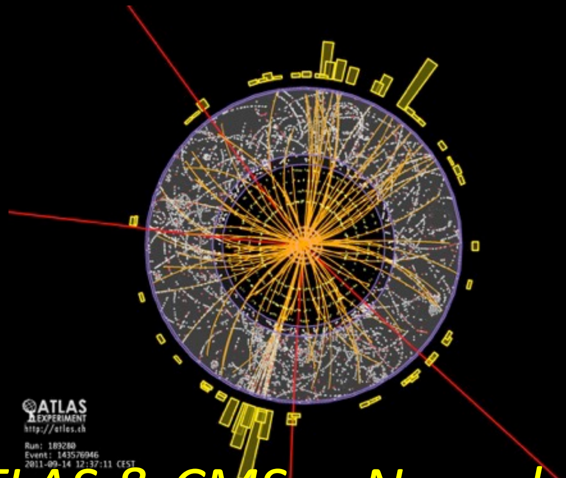
- *Data from Cabrera's apparatus taken on St Valentine's day in 1982 (A=20 cm^2).*
  - *The trace shows a jump – just before 2pm - that one would expect from a monopole traversing the coil.*
- *In August 1985 a groups at ICL reported the:"observation of an unexplained event" compatible with a monopole traversing the detector (A= 0.18 m^2*
- *SAME TECHNOLOGY IS UTILIZED BY MoEDAL*




MOVIEWALLPAPERS.NET
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"
LHCf
MoEDAL
CHARLES BRONSON
"BERNARDO O'REILLY"

Highly Ionizing Particles – Avatars of New Physics

Avatar [av-uh-tahr]: An incarnation, embodiment, or manifestation of a person or idea:



MoEDAL – Highly Ionizing Particles directly detected as messengers of new physics – no SM backgrounds

ATLAS & CMS – New physics largely reconstructed from SM particles – large SM backgrounds

The Ways to Get Anomalous Ionization

- **Electric charge** - ionization increases with increasing charge & falling velocity β (β=v/c) – use Z/β as an indicator of ionization

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

  - If Z ~ 0.001e (millicharged) we get anomalously low ionization

- **Magnetic charge** - ionization increases with magnetic charge $g = ng_d$ and decreases with velocity β – a unique signature

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

  - The velocity dependence of the Lorentz force cancels $1/\beta^2$ term
  - As g = 137e/2 = 68.5e the ionization of a rel. monopole is $4700n^2$!! (n=1) that of a MIP. But n could be larger!

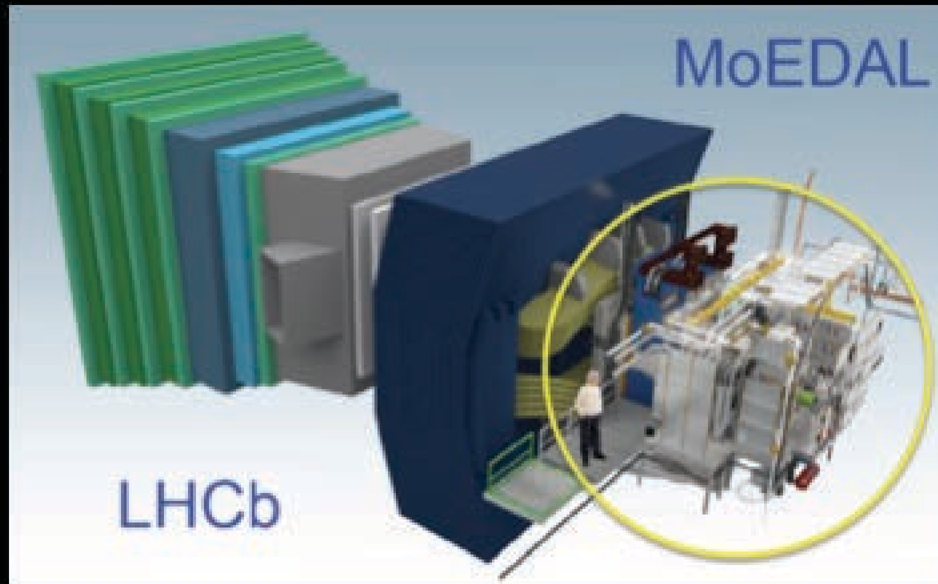
The MoEDAL Collaboration

66 physicists from 14 countries & 24 institutes. on 4 continents:

U. Alberta, UBC, INFN Bologna, U. Bologna, CAAG-Algeria, U. Cincinatti, Concordia U., CSIC Valencia, Gangneung-Wonju Nat. U., U. Geneva, U. Helsinki, IEAP/CTU Prague, IFIC Valencia, Imperial College London, ISS Bucharest, King's College London, Konkuk U., U. Montréal, MISiS Moscow, Muenster U., National Inst. Tec. (india),Northeastern U., Simon Langton School UK, Stanford University [is the latest (associate) member of MoEDAL], Tuft's.

MoEDAL – a Unique Collider Detector

Permanent Physical record of new physics



No Standard Model Physics Backgrnds

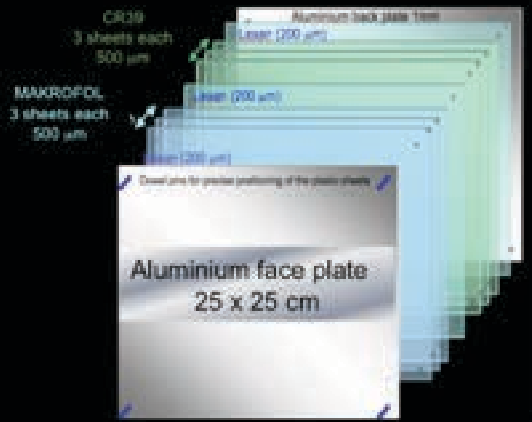
MoEDAL is largely passive made up of three detector system.

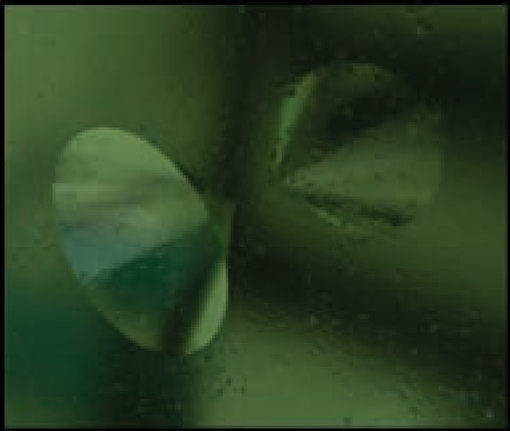
NUCLEAR TRACK DETECTOR Plastic array (~200 sqm) – Like a Giant Camera (with film)

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

TIMEPIX Array a digital Camera for real time radiation monitoring

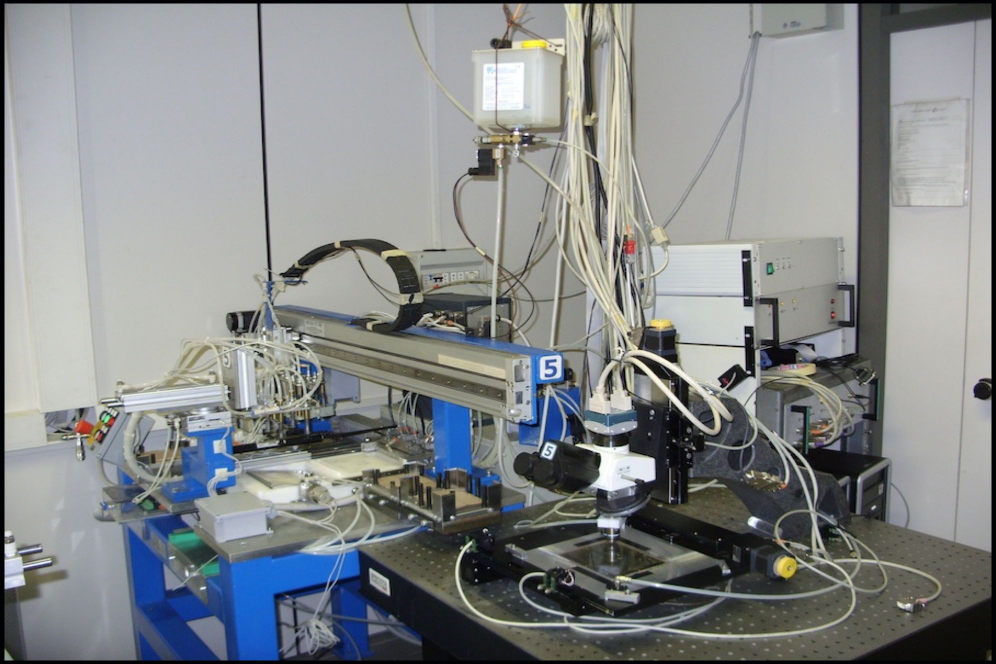
The Nuclear Track Detector System





- *Largest array (150 m² 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*

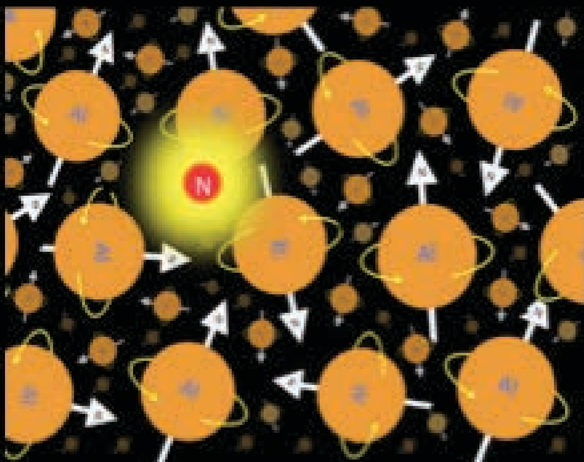
Scanning for New Physics



- *Exposed NTDs are being used to test automated high-rate optical CCD based scanning microscopes developed by MoEDAL groups at INFN Bologna and the Univ. of Muenster.*
  - *Very high scan rate 60-100 frames /sec → 100 cm^2 in 40 minutes*
  - *Specialized image enhancement/pattern recognition software*

X

The Trapping Detector System



Trapped monopole

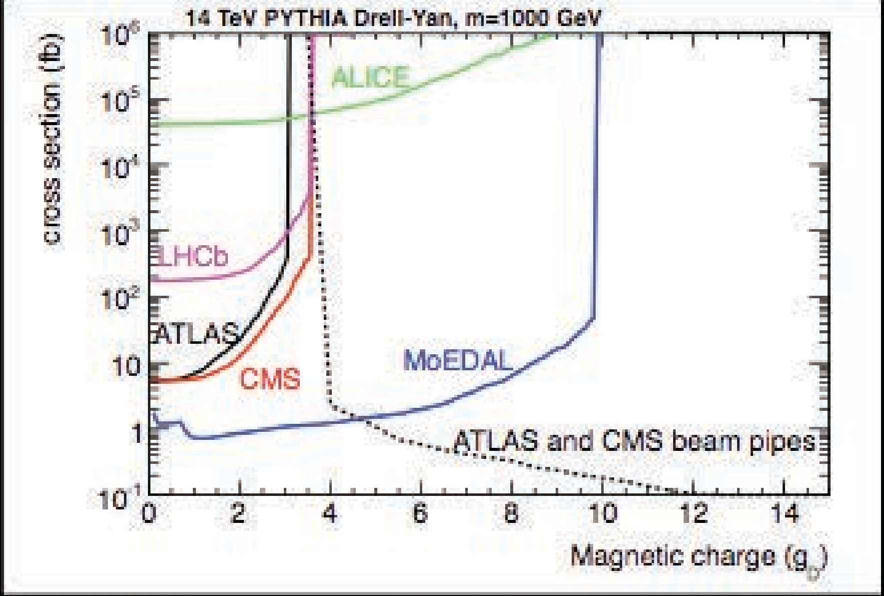
SQUID magnetometer (ETH Zurich)

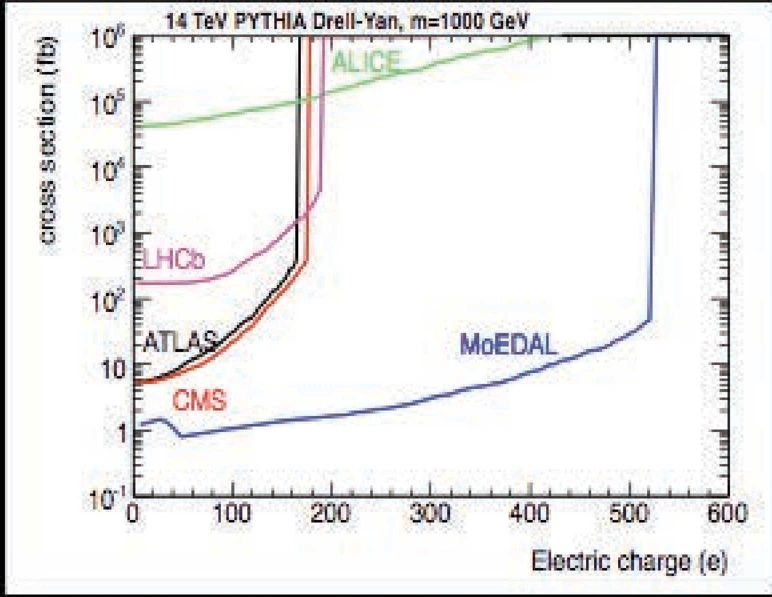
Search for trapped quasi-stable decays at SNOLAB

- *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*

MoEDAL's Sensitivity

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*

MoEDAL's Complementarity

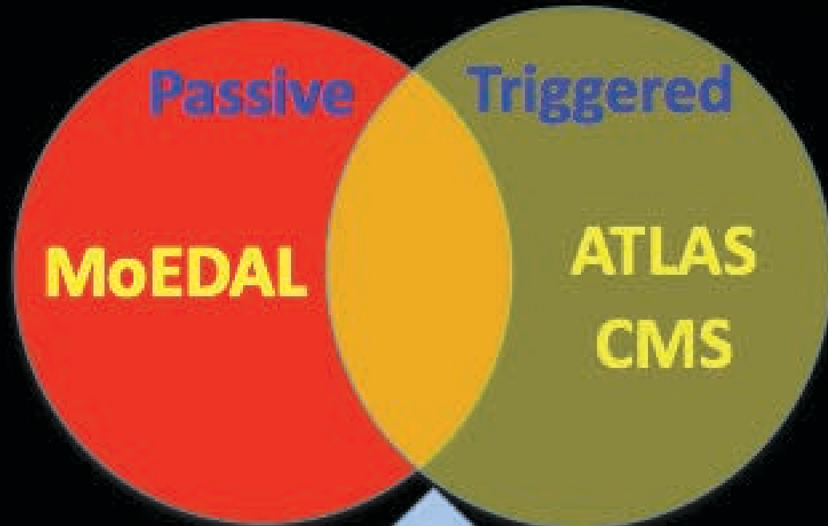
Optimized for highly ionizing particles

Insensitive to SM particles

Sensitive to very long-lived particles

Can directly detect & trap magnetic charge

Calibrated by heavy-ions



Optimized for SM relativistic MIPs & photons

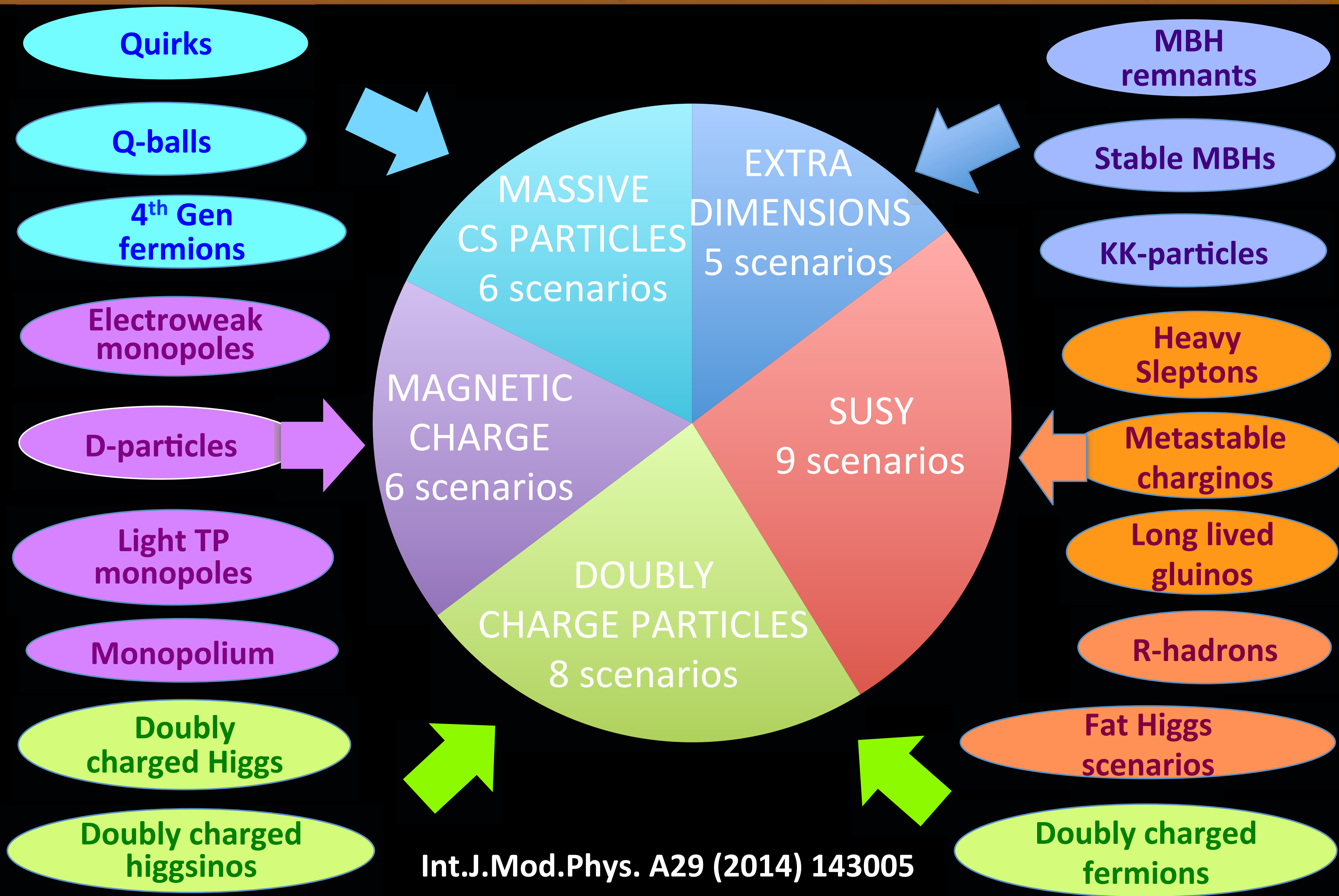
Difficult to measure very slow decays

Cannot detect magnetic charge

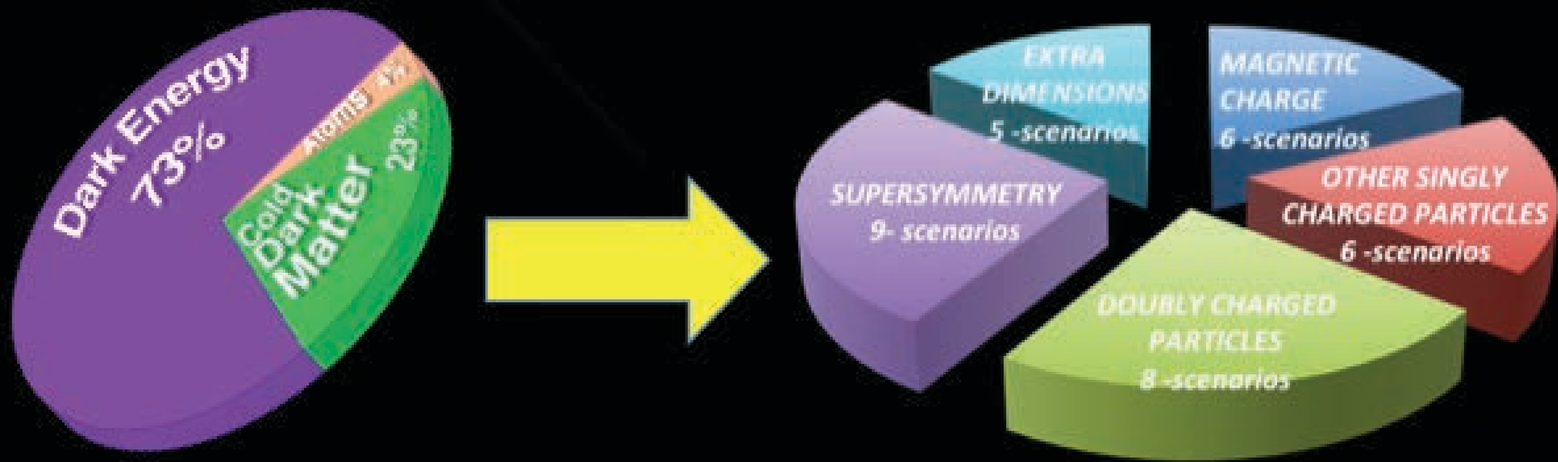
Cannot be directly calibrated for highly ionizing particles

The totally different systematics and mode of detection of MoEDAL compared to the ATLAS/CMS experiments will yield important validation of and insights into a joint observation of new physics that we hope to see starting in 2015

MoEDAL – Physics Scenarios (34+)



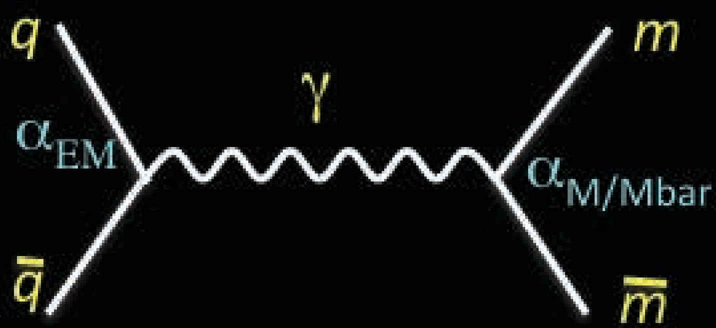
MoEDAL's Dark Matter Scenarios



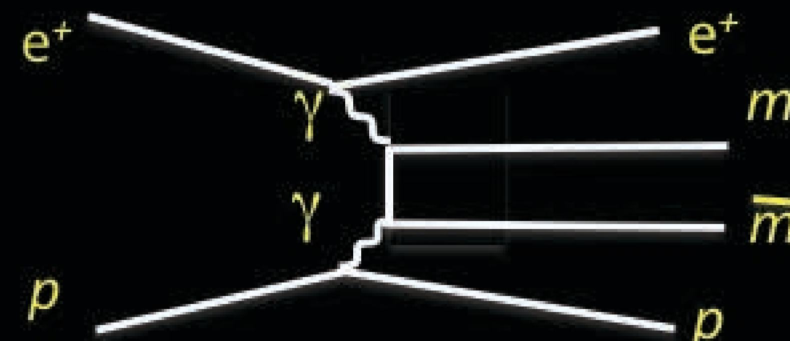
- *Most of MoEDAL's 34 physics scenarios involve new physics with well **motivated** dark matter scenarios (SUSY, extra dimensions)*
- *Several scenarios directly involve the detection of particles that could contribute to the dark matter of the universe:*
  - *Magnetic monopoles and monopolium*
  - *Stable microscopic black holes and black hole remnants*
  - *D-particles and Quirks.*
  - *Q-balls nuclearites/strangelets*
  - *Fractionally charged CHAMPs*
  - *Millicharged particles (Phase-II MoEDAL)*

Monopole Production at Colliders

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

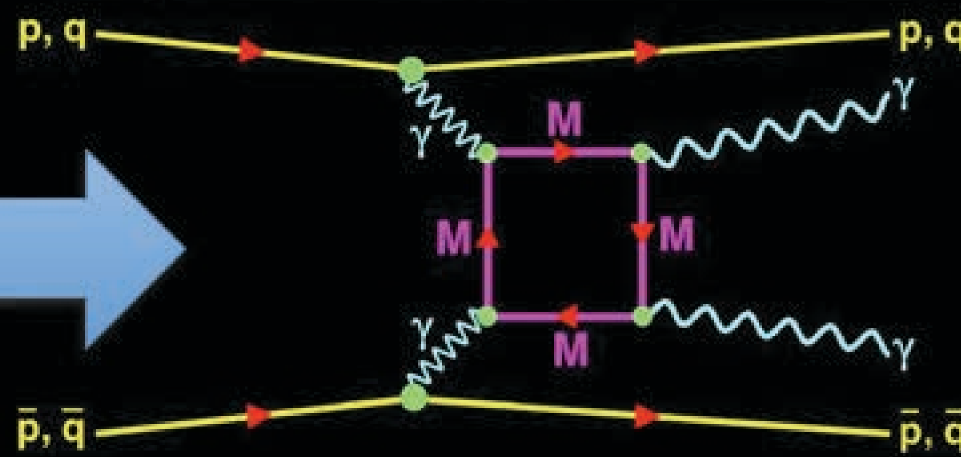


Drell-Yan Production



Two-photon production

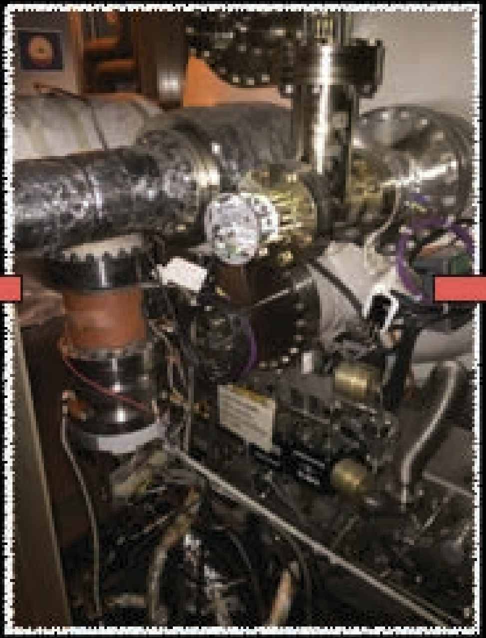
Indirect search using virtual monopole box diagrams allow – observable two high energy gammas.



The First MOEDAL Physics Result Paper

The 1st Result - Breaking News

Prototype trapping detector
160 kg



The challenge

Current deployment
270 kg /800 kg

- The MoEDAL trapping detector is the first of its kind (a purpose built detector for trapping highly ionizing particles
- Our first result is on the search for trapped magnetic charge using a SQUID to monitor for magnetic charge - future results also on trapped electric charge are in the pipeline.

The Results - Breaking News

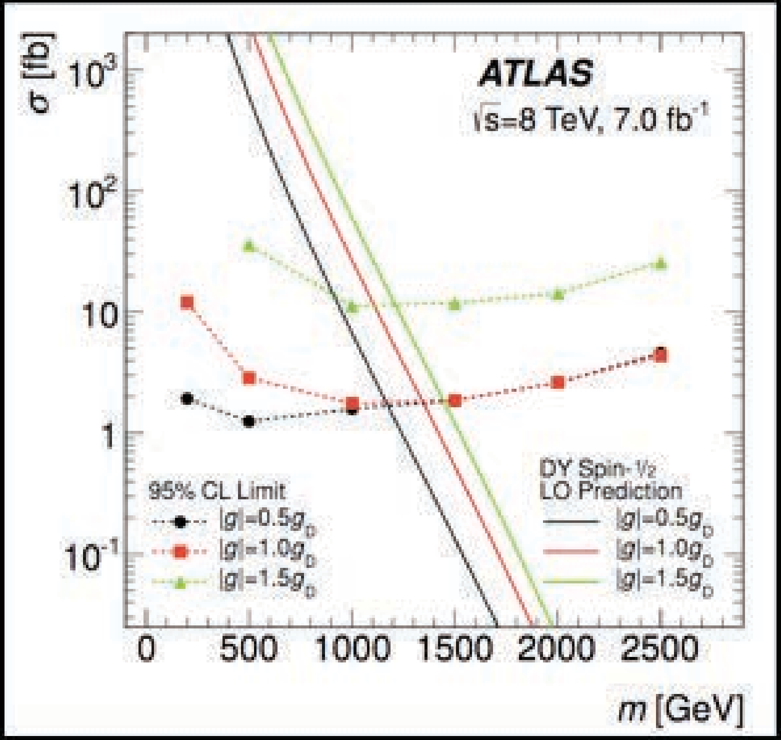
Journal of High Energy Physics
August 2016, 2016:67

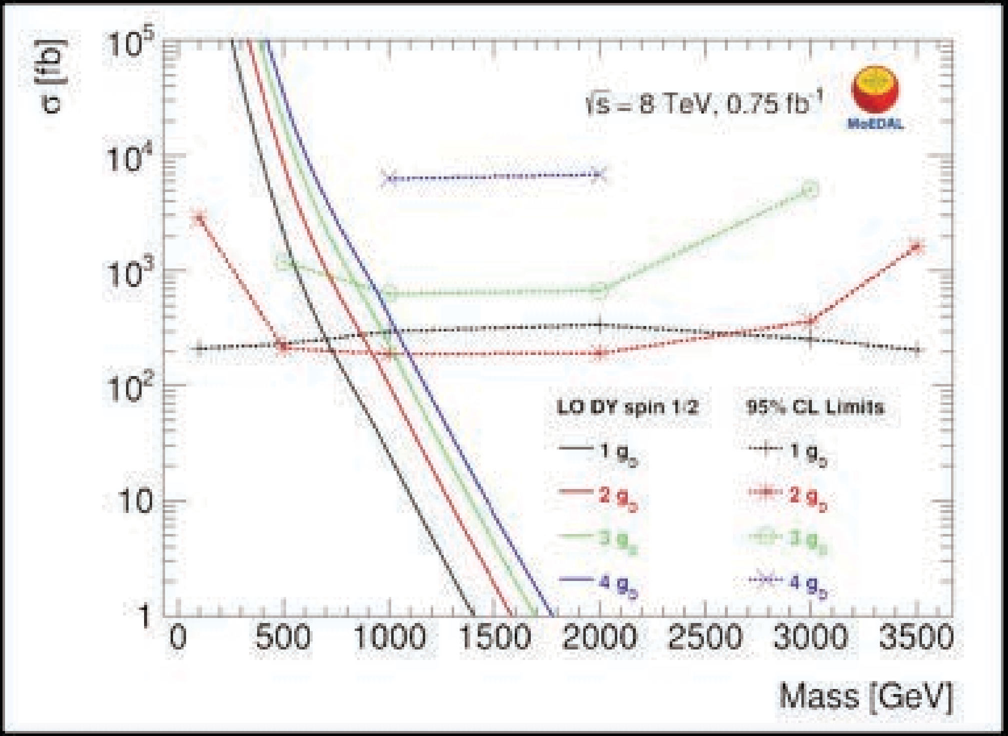
Search for magnetic monopoles with the MoEDAL prototype trapping detector in 8 TeV proton-proton collisions at the LHC

The MoEDAL collaboration, B. Acharya, J. Alexandre, K. Bendtz, P. Benes, J. Bernabéu, M. Campbell, S. Cecchini, J. Chwastowski, A. Chatterjee, M. de Montigny, D. Derendarz, A. De Roeck, J. R. Ellis, M. Fairbairn, D. Felea, M. Frank, D. Frekers, C. Garcia, G. Giacomelli, D. Hasegan, M. Kalliokoski, A. Katre, D.-W. Kim, M. G. L. King, K. Kinoshita, D.H. Lacarrère, S. C. Lee, C. Leroy, A. Lionti, A. Margiotta, N. Mauri, N. E. Mavromatos, P. Mermod, D. Milstead, V. A. Mitsou, R. Orava, B. Parker, L. Pasqualini, L. Patrizii, G. E. Păvălas, J. L. Pinfold, M. Platkevič, V. Popa, M. Pozzato, S. Pospisil, A. Rajantie, Z. Sahnoun, M. Sakellariadou, S. Sarkar, G. Semenoff, G. Sirri, K. Sliwa, R. Soluk, M. Spurio, Y. N. Srivastava, R. Staszewski, M. Suk, J. Swain, M. Tenti, V. Togo, M. Trzebinski, J. A. Tuszynski, V. Vento, O. Vives, Z. Vykydal, T. Whyntie, A. Widom, G. Willems, J. H. Yoon … *show less*

sections, mass limits are derived for $|g| = 2g_D$ and $|g| = 3g_D$ for the first time at the LHC, surpassing the results from previous collider experiments.

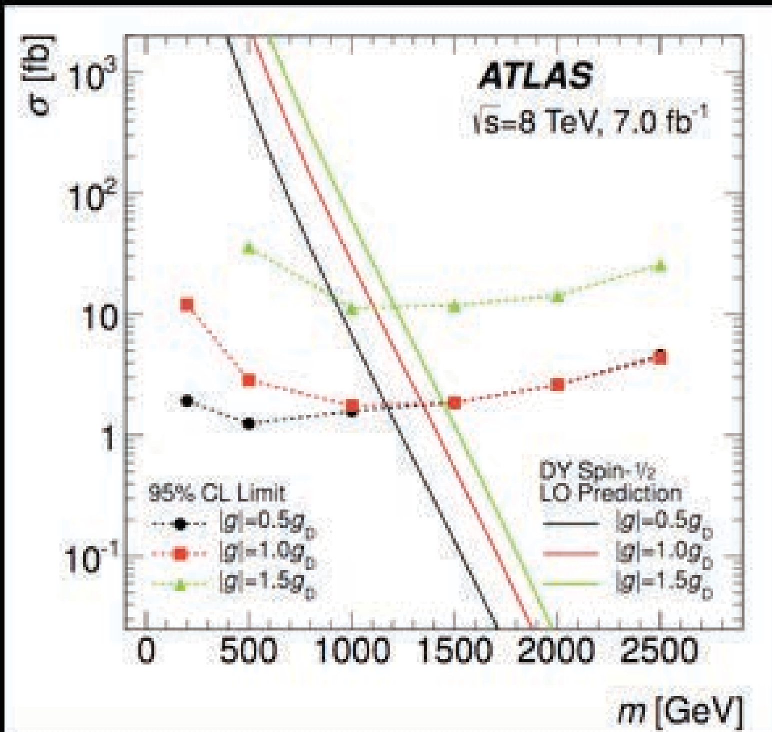
The Results - Some numbers

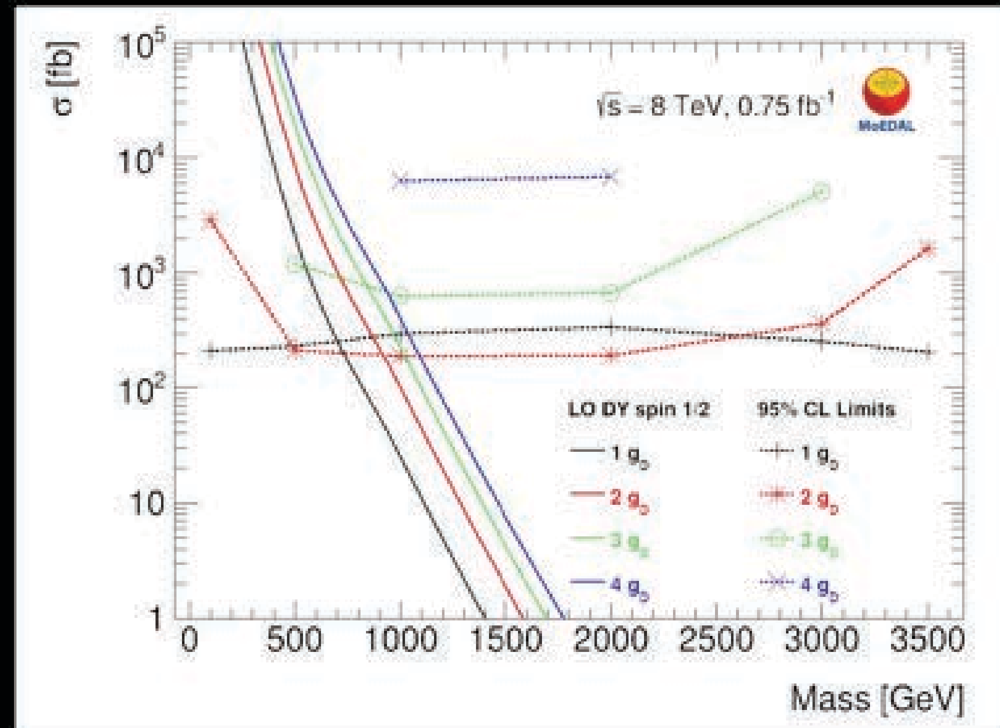




- *Even with this prototype & low lumi MoEDAL probed multiple magnetic charges which other LHC detectors find challenging*
- *Greater mass range probed by MoEDAL - 3.5 TeV (M) 2.5 Tev (A)*

The Results - Some numbers





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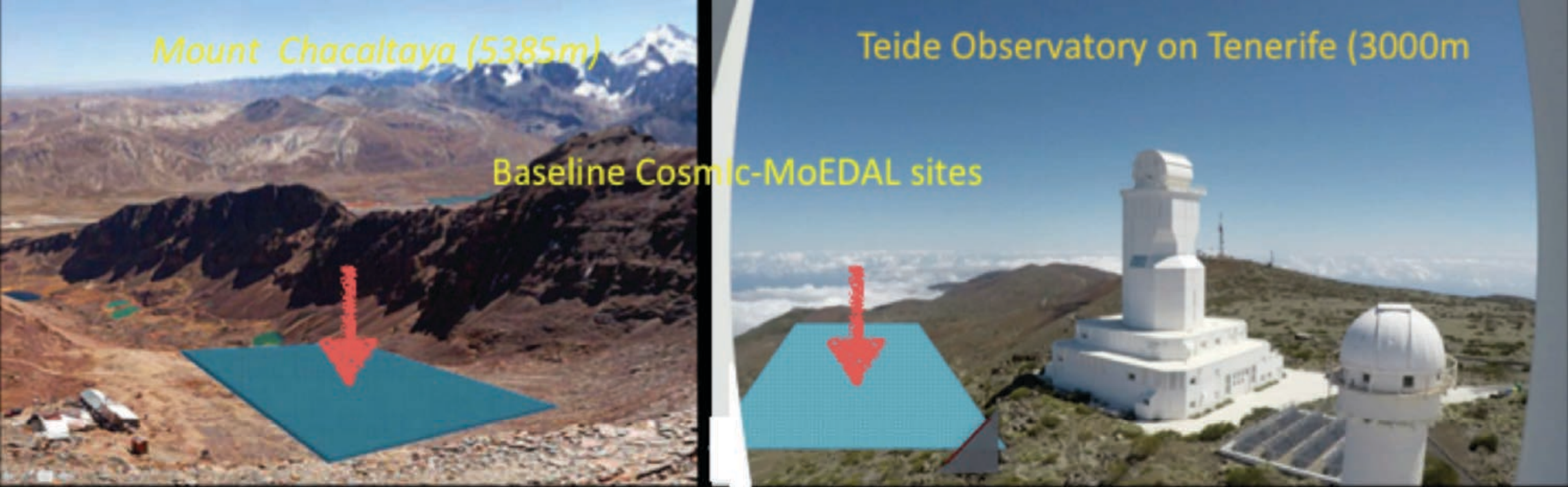
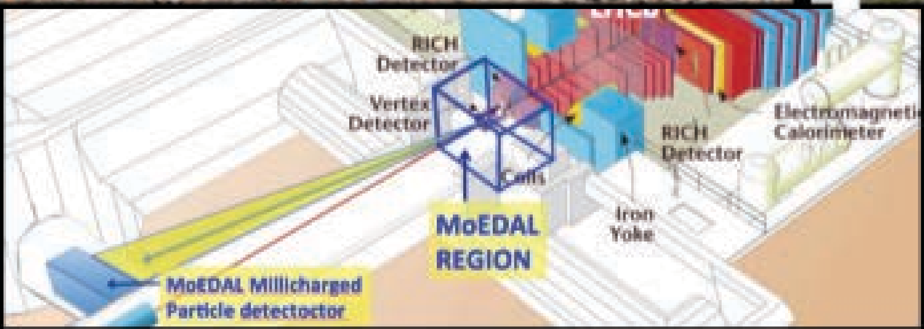
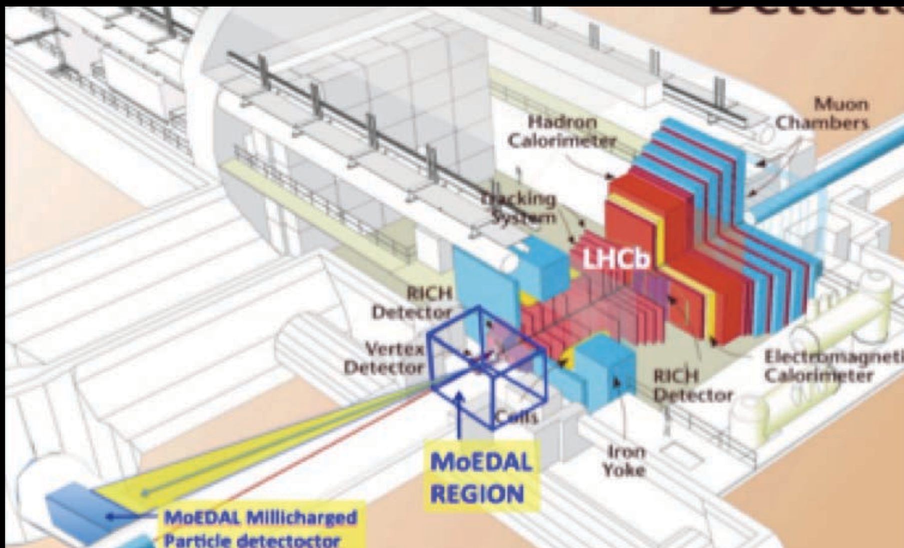




- ***MoEDAL is working on a new sub-detector to search for*** *millicharged particles (as low as $10^{-3}e$)*
    - *A location near to IP8 in front of the MoEDAL detector (protected by 20m of rock/concrete) has been identified*
- *We can also use this detector as a beam dump detector when LHCb is using SMOG (a gas fixed target beam using their VELO)*

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 charge ~0.1 (beyond the reach of the other LHC detectors)*
  - *To search for new pseudostable neutrals.*
  - *To search for anomalously pentrating particles*

Example Physics Rationale for MAPP

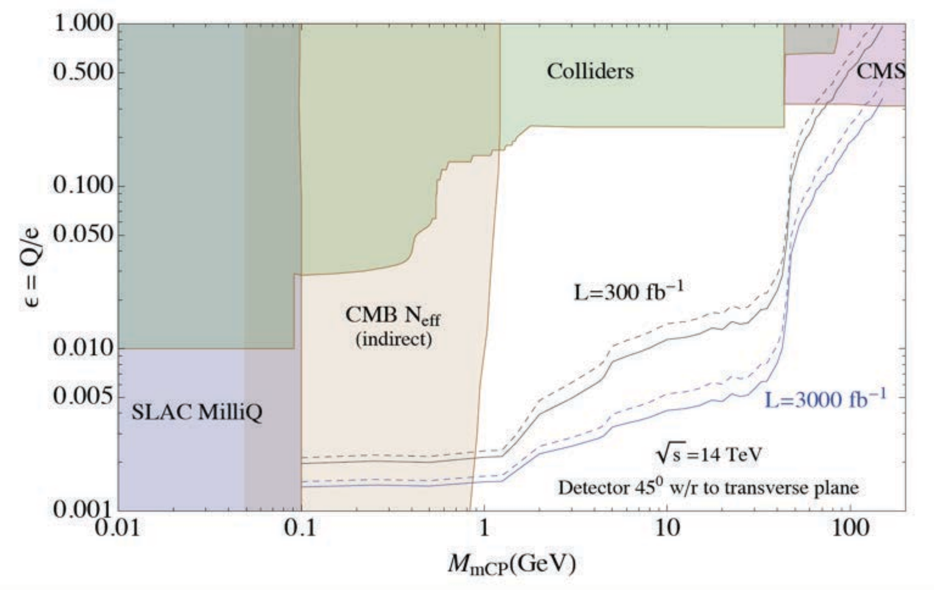
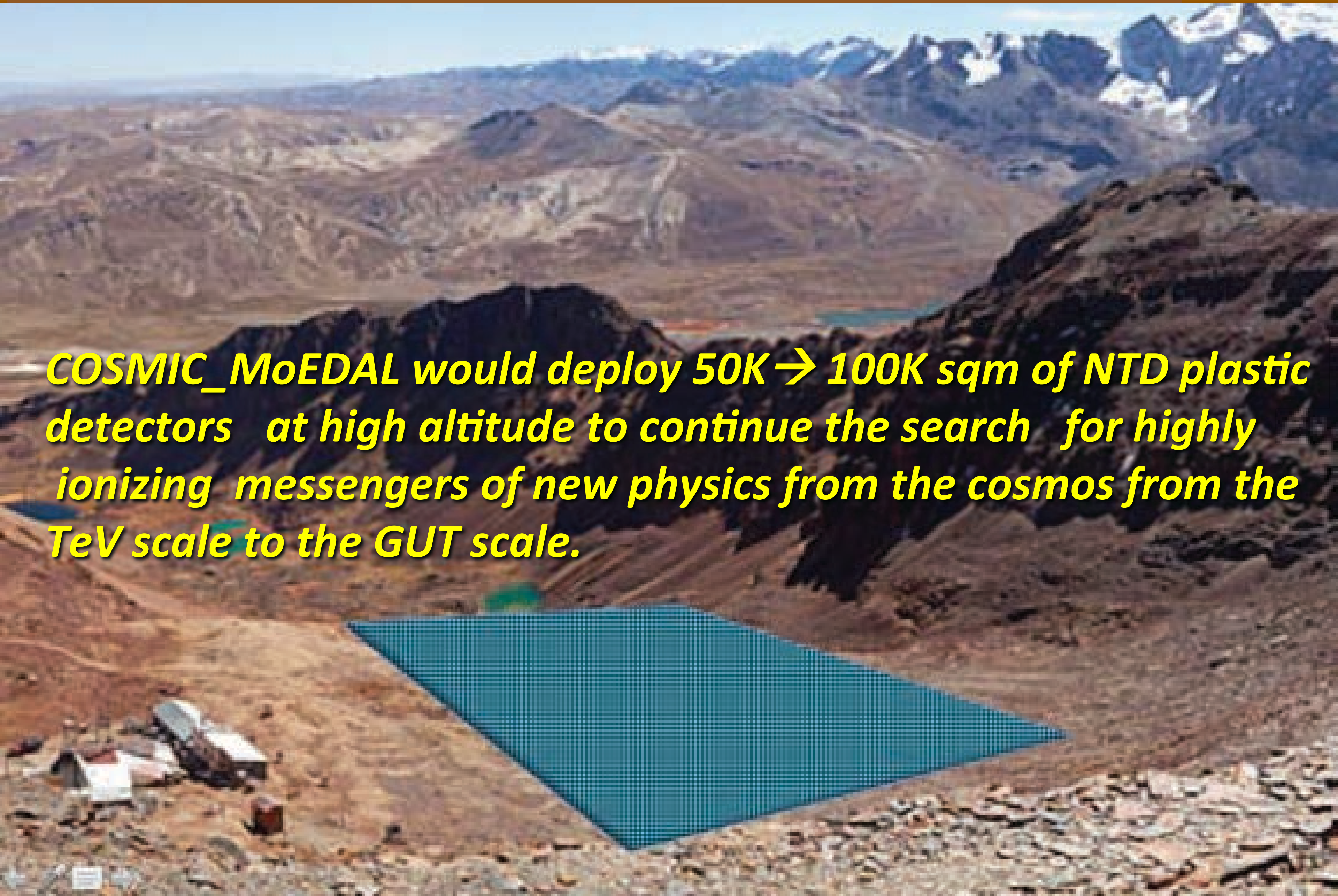


FIGURE TAKEN FROM: "Looking for milli-charged particles with a new experiment at the LHC Andrew Haas, Christopher S. Hill, Eder Izaguirre, Itay Yavin, . Oct 24, 2014. 4 pp. Phys.Lett. B746 (2015) 117-120 – Experiment is planning to run at the CMS IP.

300 fb^{-1} is the data expected to be gained in the first 10-12 years of LHC running

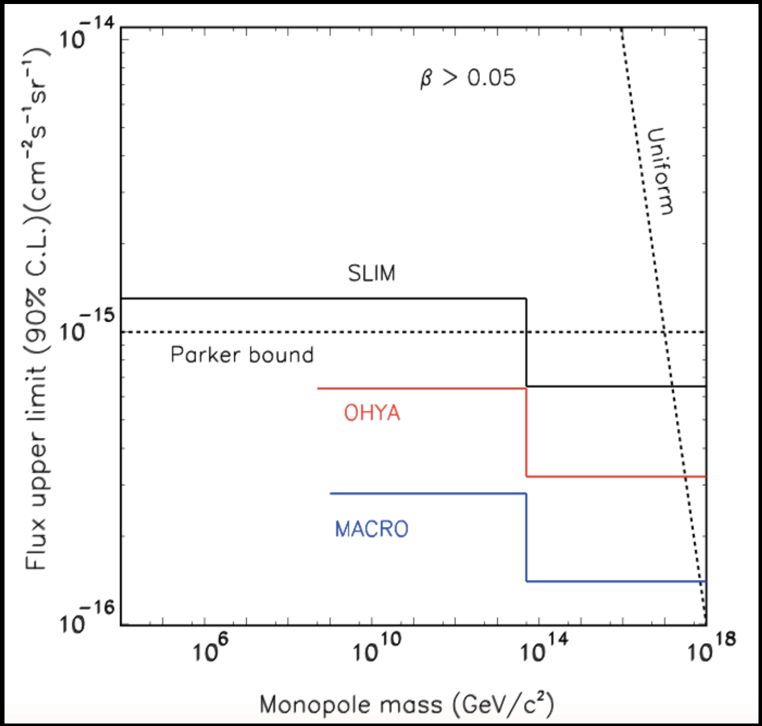
- *Search for millicharged particles – a dark matter candidate - to which the standard LHC detectors are not sensitive*
  - *New dark sectors can have new particles which appear with small fractional charge wrt the Standard Model sector*
  - *Charges typically in the range 10^{-1} to 10^{-3} e*
  - *No direct constraints above 100 MeV and Q/e <0.01*
- ***A MoEDAL millicharged detector could probe up to 100 GeV***

The Future – Cosmic MoEDAL



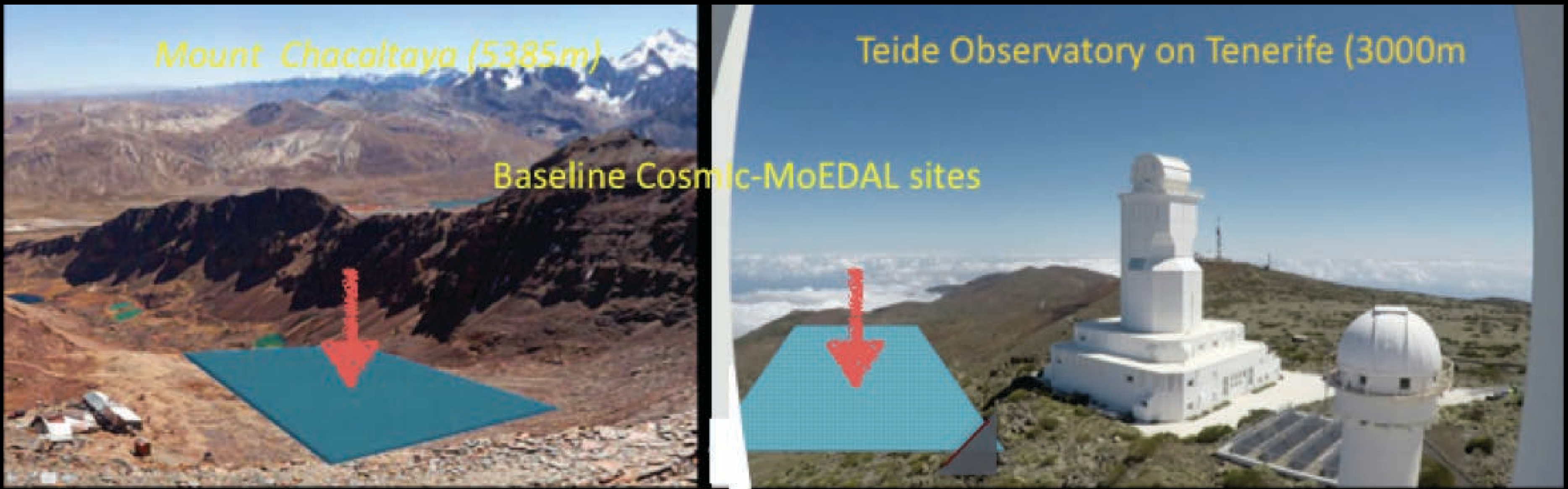
COSMIC_MoEDAL would deploy 50K→ 100K sqm of NTD plastic detectors at high altitude to continue the search for highly ionizing messengers of new physics from the cosmos from the TeV scale to the GUT scale.

The SLIM Experiment at Chacaltaya



- *SLIM was a (400 m^2) IM magnetic monopole and nuclearite deployed at high altitude. The detector consists of multiple CR39 layers and Makrofoil*
- *The RH figure shows flux (90% CL) upper limits for cosmic MMs of charge $g = g_D$ and $\beta > 0.05$ vs monopole mass.*

Cosmic MoEDAL – the Program

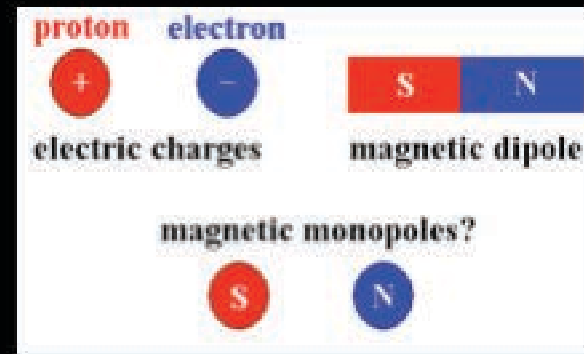


- *Possible sites under consideration: Chacaltaya, Teide (Canary Islands), Pryamid Lab. in Nepal, etc.*
- *Detect monopoles, nuclearites, strangelets, microscopic black hole remnants, etc. Particularly to push the serach for GUT monopoles to well below the Parker Bound and previous limits from MACRO.*

MoEDAL Addresses 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?

MoEDAL Addresses Fundamental Questions:

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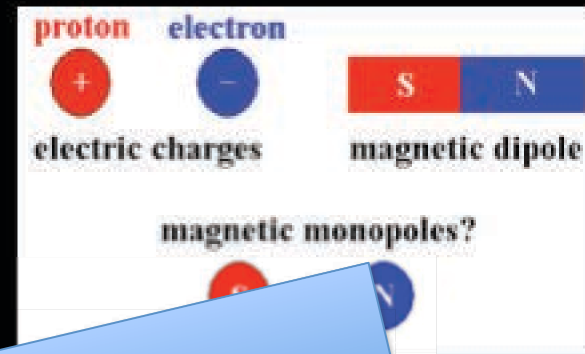
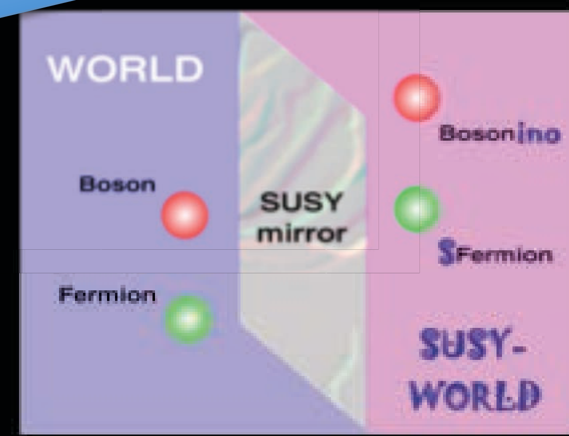


arge exist?

Stay tuned for many, potentially revolutionary, MoEDAL results to come

What is the nature of Dark matter?

What happened just after the big bang?



Are there new symmetries of nature?