Recent Results and Future Plans of the MoEDAL Experiment

FORWARD PHYSICS AND DIFFRACTION AT THE LHC, DUBLIN, 2019

James L Pinfold
University of Alberta

The MoEDAL Experiment

(Now 70 physicists Contributing)

- *MoEDAL has taken data in p-p collisions at 8 TeV and 13 TeV Collision Energy as well as in heavy-ion collisions*

The Higgs Boson & the Magnetic Monopole

Paul Dirac

Peter Higgs

- ***The main purpose of the general purpose LHC experiments ATLAS and CMS is to find and study the Higgs boson***
- ***The main purpose of the MoEDAL- LHC Experiment is to search for the magnetic monopole,***
  - ***The modern conception of the monopole is that it is a stable topological excitation (a topological soliton) of a Higgs field***
- ***But ATLAS, CMS and MoEDAL can do much more***

The Monopole's Peculiar Properties

$$\Delta I = \frac{4\pi N}{L} g_D = 2\Delta I_0$$

$2\ \Delta I_{0\varpi}$ → 1 unit quantum quantum Flux unit superconductivity

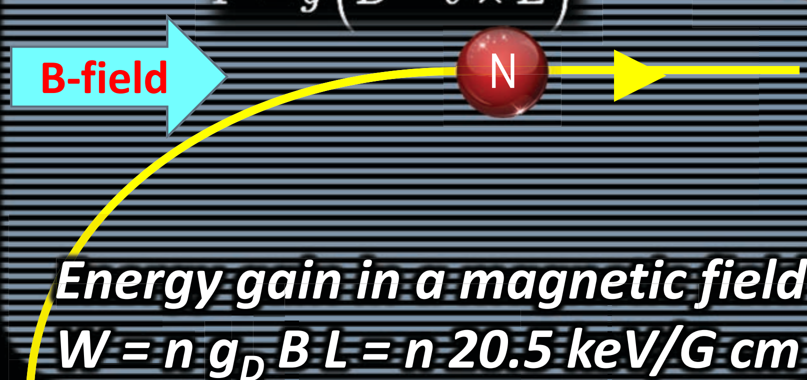
$(ze)_{equiv.} = n g_D \beta(=v/c)$: Ionizes $n^2 g_D^2$ more than a rel. proton i.e 4700 times more when n=1

Cerenkov Radiation is enhanced a factor of 8500 compared with muon yield

monopole

Strange trajectory in a B field

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



Energy gain in a magnetic field $W = n\, g_D\, B\, L = n\ 20.5$ keV/G cm

"HUGE" coupling constant $a_m = g_D^2/hc = 34$

In experimental searches the monopole's mass & spin are usually regarded as free parameters

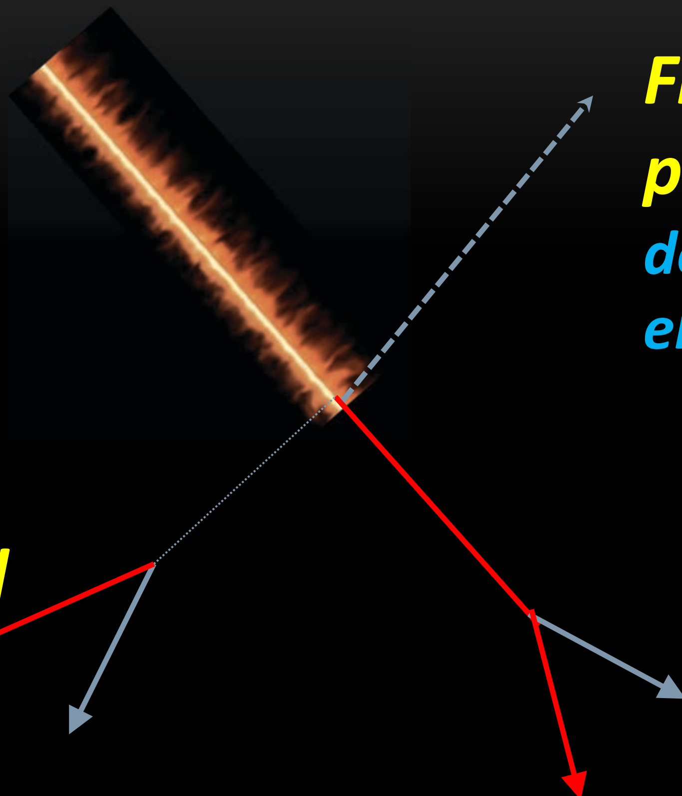
L= 1 kpc and B = 3 μG, W ≅ 1.8 x10^{21} eV

MoEDAL's Avatars of New Physics

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

Very Highly ionizing particles
(≥ 5 times that of a standard relativistic charged particle)

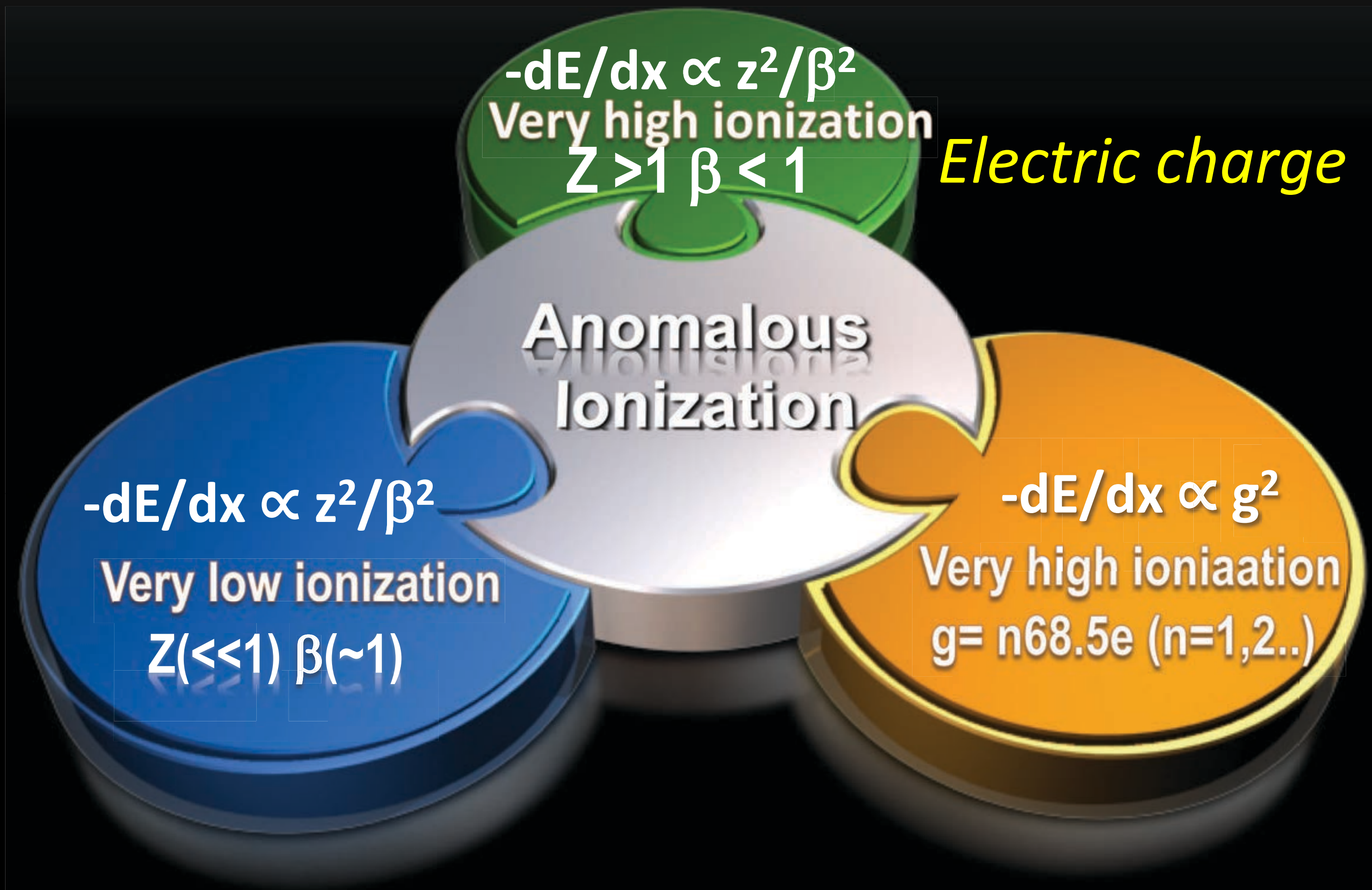
Fractionally charged particles *(with charge down to ~1/mille of the electron's charge)*



Long lived neutral particles –
($c\tau$ up to ~100m)

Very long-lived charged particles
(with lifetimes up to ~10 years)

Anomalously Ionizing Signatures of New Physics

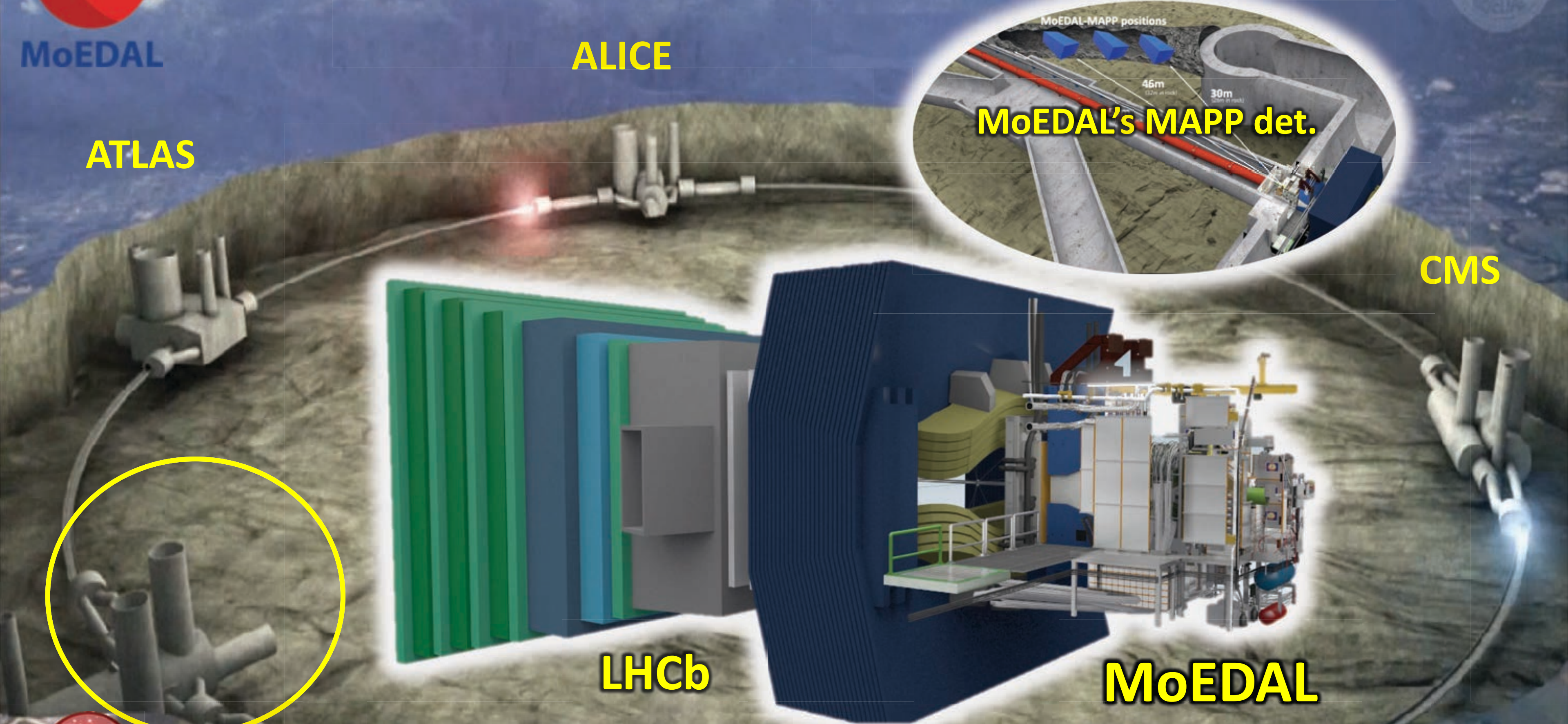


Fractional electric charge

Magnetic charge

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

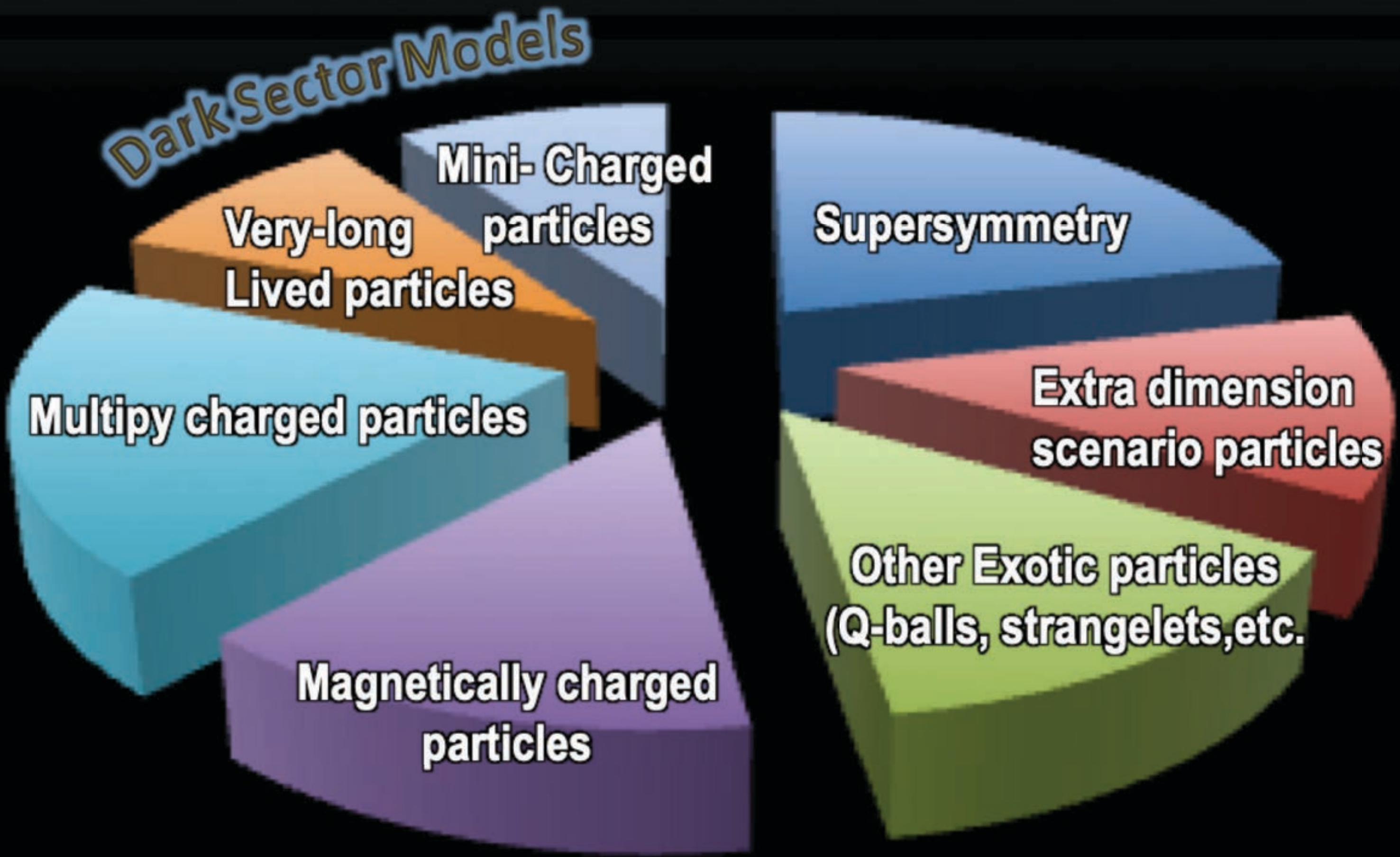
The MoEDAL Detector



- MoEDAL is a passive detector sensitive to new physics only.
  - It can track (with a permanent record) and trap highly ionizing avatars of new physics such as magnetic monopoles
  - MoEDAL's (proposed) Apparatus for Penetrating Particles (MAPP) will extend our reach to mini-charged particles & long-lived neutrals

MoEDAL Physics Program

Sensitive to over 40 new physics scenarios



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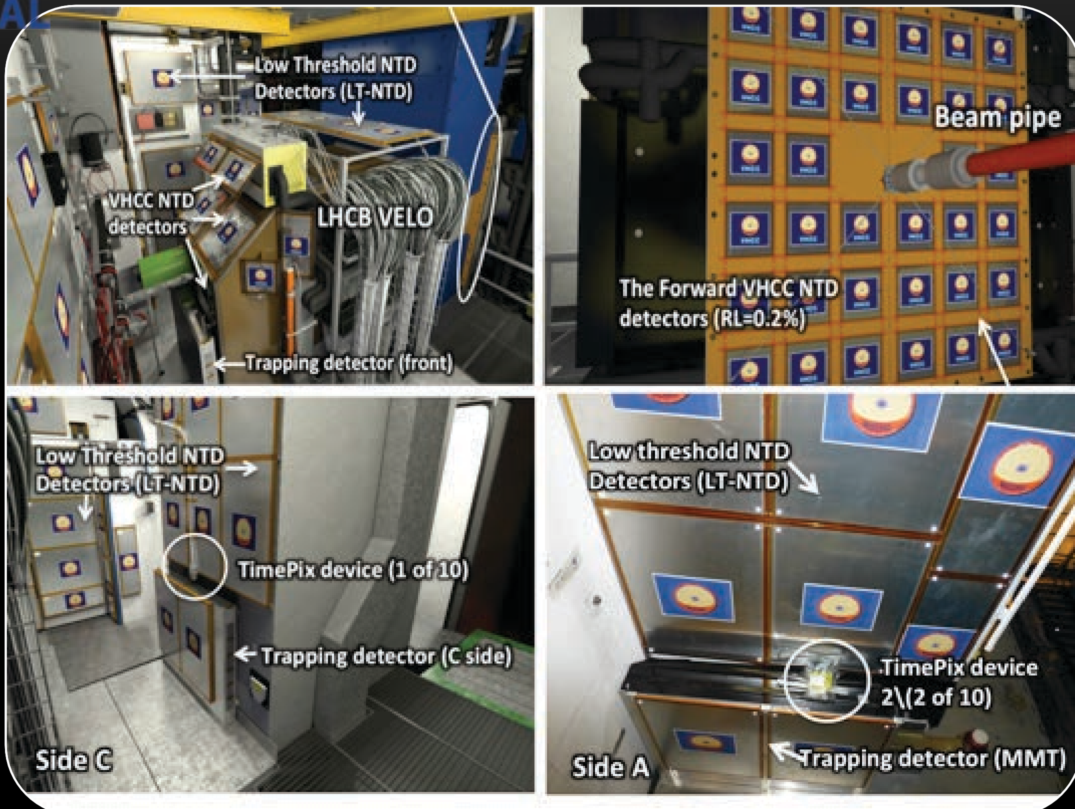
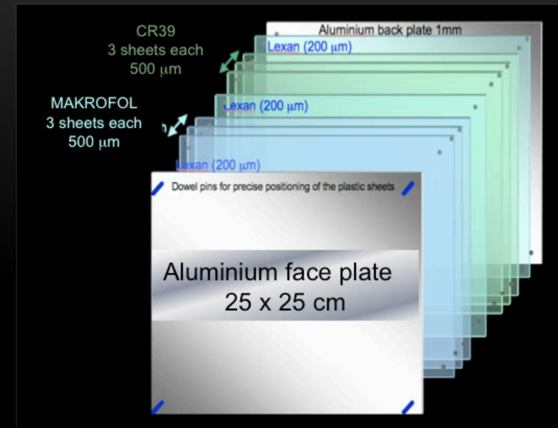
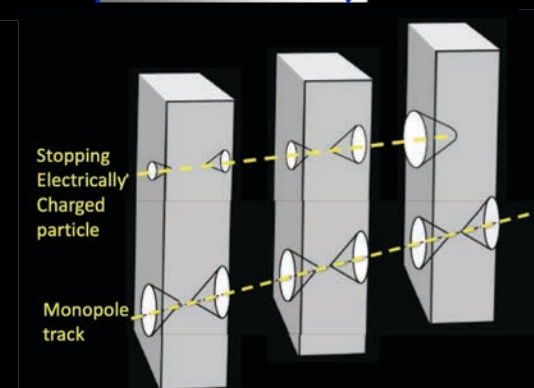
Tracking Monopoles



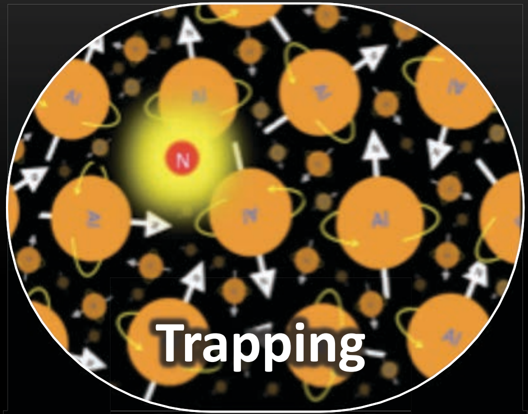


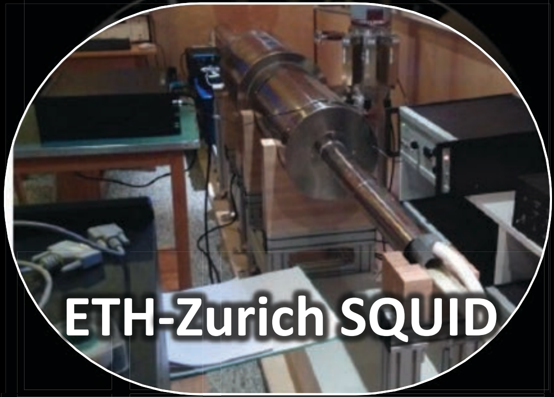


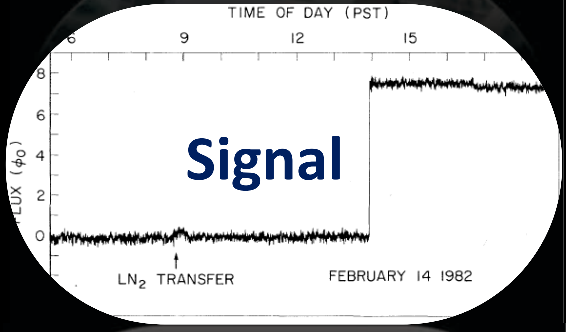
Etch pit sizes ~30μm

- ***The Nuclear Track Detector (NTD)system is comprised of 20m² surface area of stacks → 120m² of plastic in total***
  - *Threshold for detection 5/50 that of a MIP for CR39/Makrofol*
  - *Passage of a highly ionizing particle revealed as etch-pits by chemical etching*
  - *Scanning & measurement with AI enhanced optical scanning microscopes*

Trapping Monopoles

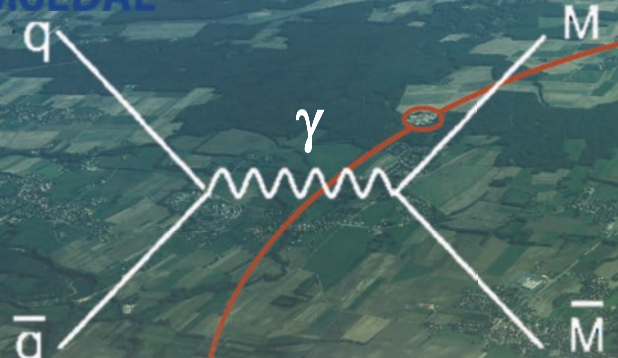






- *Trapping detectors (~1 tonne) in capture HIPS. Volumes comprised of ~ 2400 Al bars (2.5x2.5 x10 cm³)*
  - *Exposed trapping volumes are passed through a SQUID magnetometer to detect trapped monopoles*
  - *Trapped monopoles can be released for further study*

Accelerator Searches for Monopoles

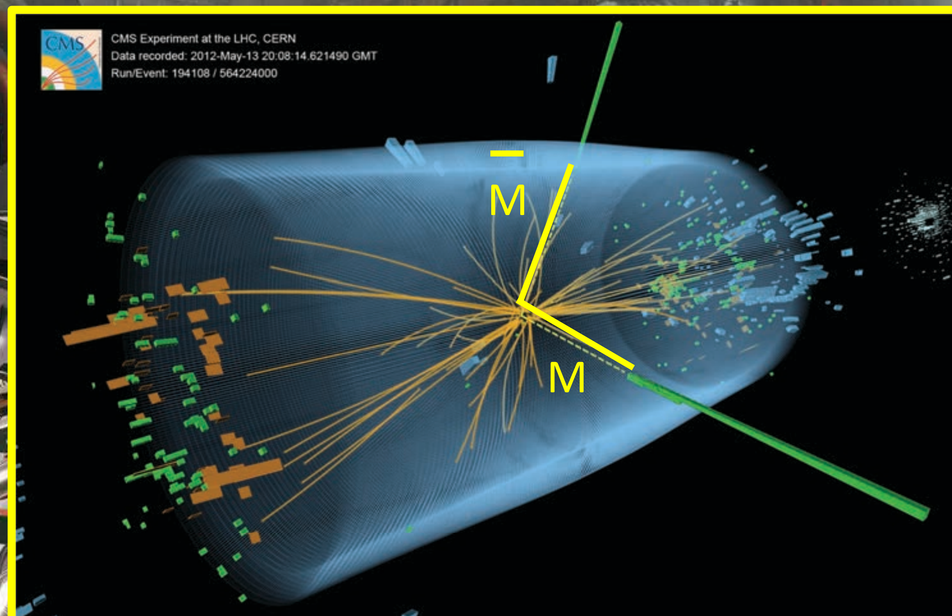


Drell Yan mechanism

Photon fusion

Monopole box

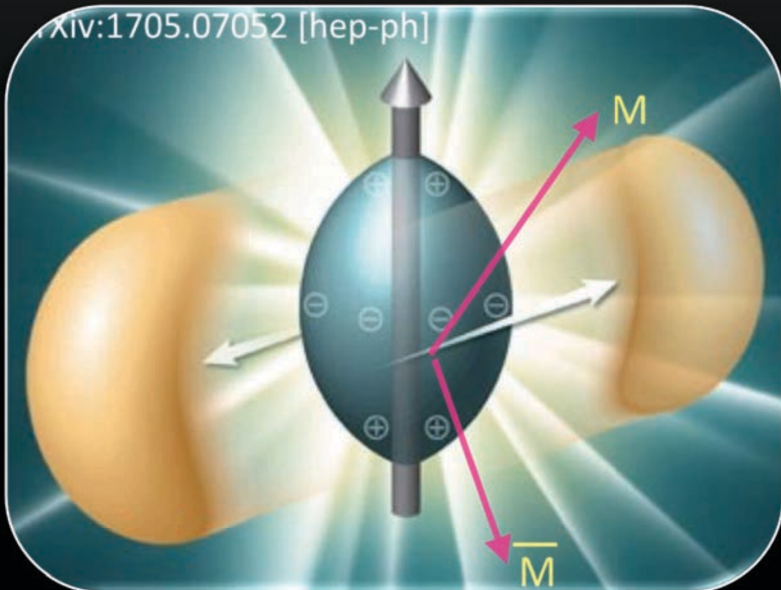
- ***Monopole pairs can be directly produced in particle interactions at accelerator experiments***
- ***Detection mechanisms, :***
  - ***a) High Ionization***
  - ***b) Anomalous trajectory***
  - ***c) Magnetic induction***

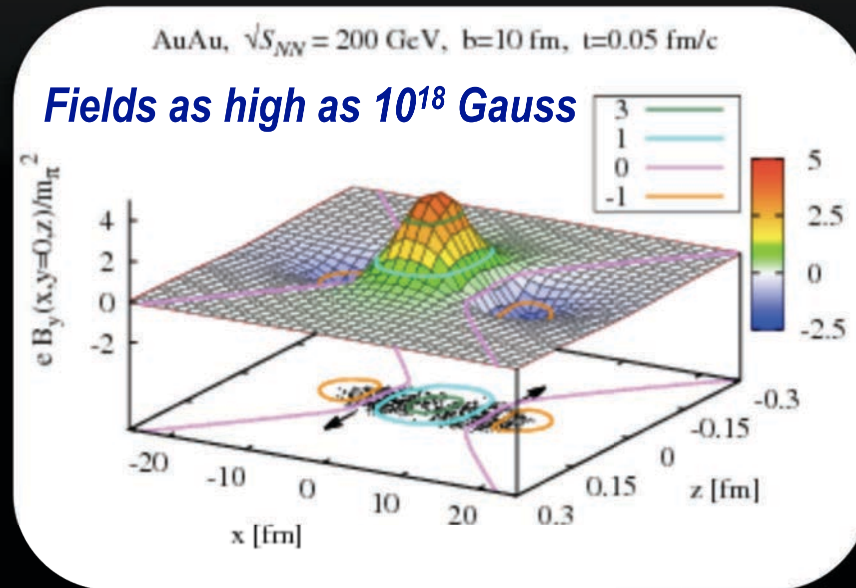


MoEDAL

Monopole From Heavy-ion Collisions

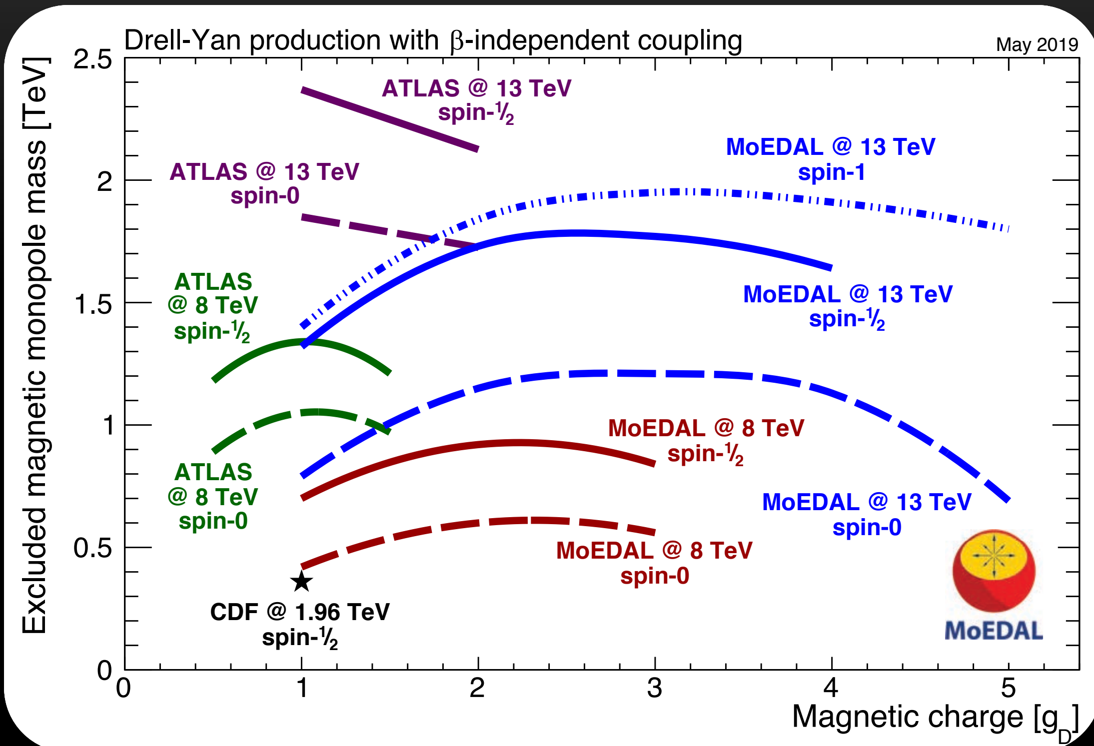
via the Thermal Schwinger Mechanism





- **Probability of producing a monopole pair $\sigma_{MM} = \sigma_{Inl} V_{ST}\, \Gamma_T$** *(where V_{st} is the space-time volume of the field, Γ_T is the rate/unit volume & σ_{inl} is the inelastic nuclear cross-section)*
- ***Important benefits:***
  - *No exponential suppression for finite sized monopoles*
  - *Cross-section calculation does not suffer from non-perturbative nature of coupling as in Drell-Yan production*

Mass Limits on Multiply Charge Monopoles



JHEP 1608 (2016) 067

Phys.Rev.Lett. 118 (2017) 061801

Phys.Lett. B782 (2018) 510

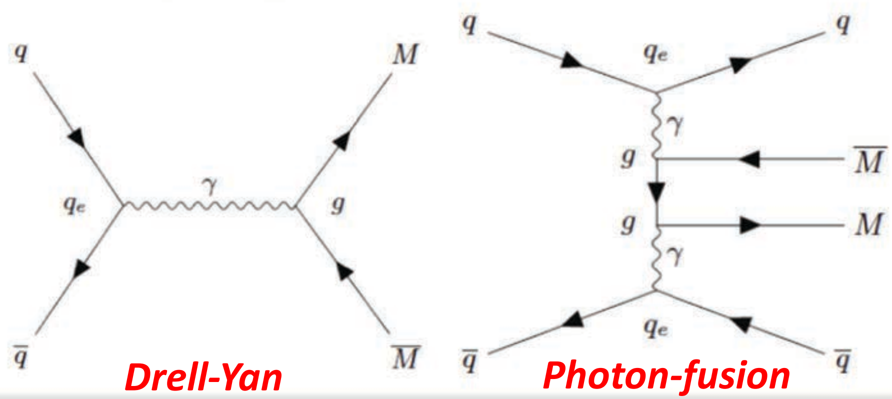
Phys.Rev.Lett. June (2019) 510

- *MoEDAL has placed the world's best published limits on multiply charge monopoles and the first limits ever on Spin-1 monopoles*
- *This measurement is based on detection of the magnetic charge and would clearly identify the monopole*
  - *Uncalibrated Ionization measurements are not enough to identify a monopole*

MoEDAL's Latest Monopole Mass Limits

Magnetic monopole search with the full MoEDAL trapping detector in 13 TeV *pp* collisions interpreted in photon-fusion and Drell-Yan production

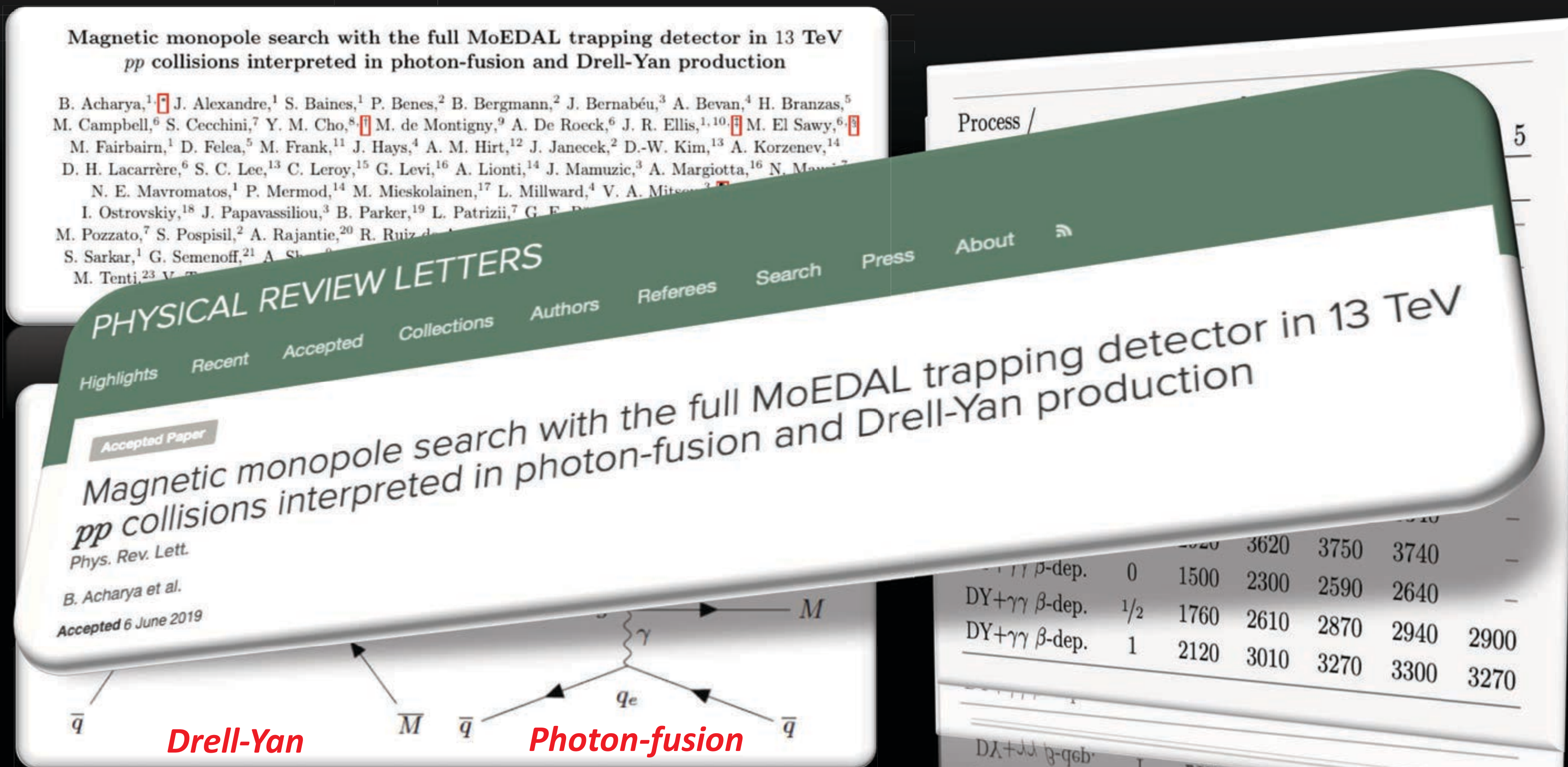
B. Acharya,[1,*] J. Alexandre,[1] S. Baines,[1] P. Benes,[2] B. Bergmann,[2] J. Bernabéu,[3] A. Bevan,[4] H. Branzas,[5] M. Campbell,[6] S. Cecchini,[7] Y. M. Cho,[8,†] M. de Montigny,[9] A. De Roeck,[6] J. R. Ellis,[1,10,‡] M. El Sawy,[6,§] M. Fairbairn,[1] D. Felea,[5] M. Frank,[11] J. Hays,[4] A. M. Hirt,[12] J. Janecek,[2] D.-W. Kim,[13] A. Korzenev,[14] D. H. Lacarrère,[6] S. C. Lee,[13] C. Leroy,[15] G. Levi,[16] A. Lionti,[14] J. Mamuzic,[3] A. Margiotta,[16] N. Mauri,[7] N. E. Mavromatos,[1] P. Mermod,[14] M. Mieskolainen,[17] L. Millward,[4] V. A. Mitsou,[3,¶] R. Orava,[17] I. Ostrovskiy,[18] J. Papavassiliou,[3] B. Parker,[19] L. Patrizii,[7] G. E. Păvălaş,[5] J. L. Pinfold,[9] V. Popa,[5] M. Pozzato,[7] S. Pospisil,[2] A. Rajantie,[20] R. Ruiz de Austri,[3] Z. Sahnoun,[7,**] M. Sakellariadou,[1] A. Santra,[3] S. Sarkar,[1] G. Semenoff,[21] A. Shaa,[9] G. Sirri,[7] K. Sliwa,[22] R. Soluk,[9] M. Spurio,[16] M. Staelens,[9] M. Suk,[2] M. Tenti,[23] V. Togo,[7] J. A. Tuszyński,[9] V. Vento,[3] O. Vives,[3] Z. Vykydal,[2] A. Wall,[18] and I. S. Zgura[5]
(THE MoEDAL COLLABORATION)



Process / coupling	Spin	Magnetic charge [g_D] 1	2	3	4	5
		95% CL mass limits [GeV]				
DY	0	790	1150	1210	1130	–
DY	½	1320	1730	1770	1640	–
DY	1	1400	1840	1950	1910	1800
DY β-dep.	0	670	1010	1080	1040	900
DY β-dep.	½	1050	1450	1530	1450	–
DY β-dep.	1	1220	1680	1790	1780	1710
DY+γγ	0	2190	2930	3120	3090	–
DY+γγ	½	2420	3180	3360	3340	–
DY+γγ	1	2920	3620	3750	3740	–
DY+γγ β-dep.	0	1500	2300	2590	2640	–
DY+γγ β-dep.	½	1760	2610	2870	2940	–
DY+γγ β-dep.	1	2120	3010	3270	3300	3270

- *MoEDAL has now improved its monopole production limits and placed the LHC's 1st limits on monopole production via γ-fusion.*

MoEDAL's Latest Monopole Mass Limits

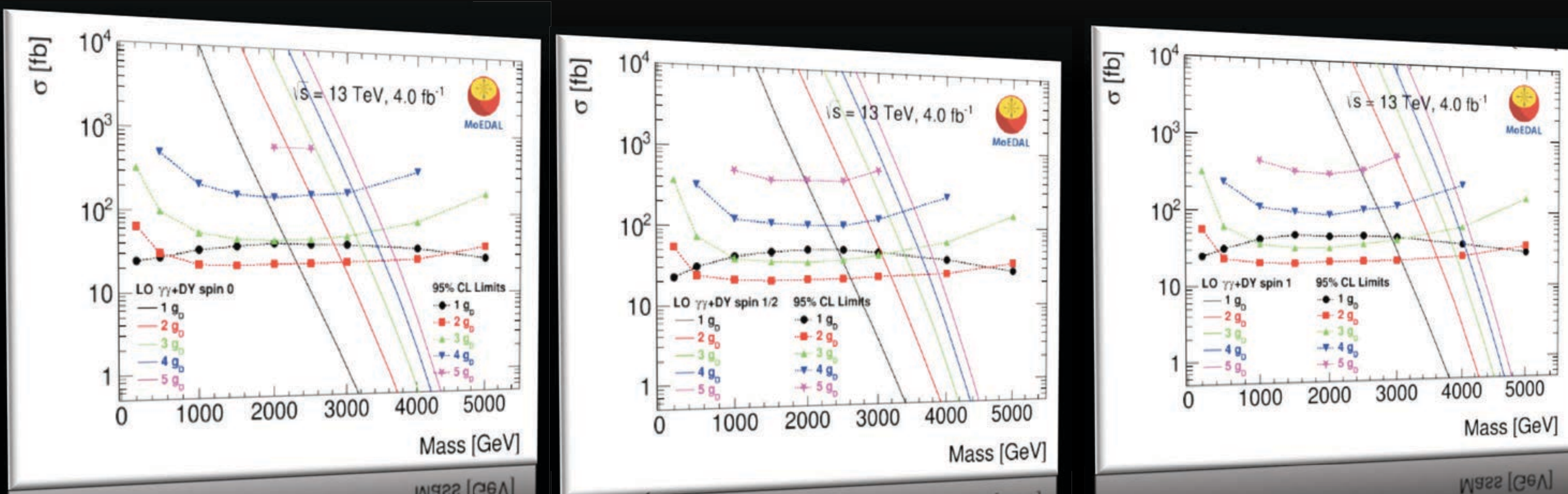


- *MoEDAL has now improved its monopole production limits and placed the LHC's 1st limits on monopole production via γ-fusion.*

MoEDAL Cross-section Limits (DY +$\gamma\gamma$)

Spin-1 limits for the first time

(β-dependent results below)



- **S = 0 ➔ Scalar Quantum Electrodynamics**

  Monopole as a scalar field obeying a U(1) gauged KG equation

- **S = ½ ➔ Dirac Quantum Electrodynamics**

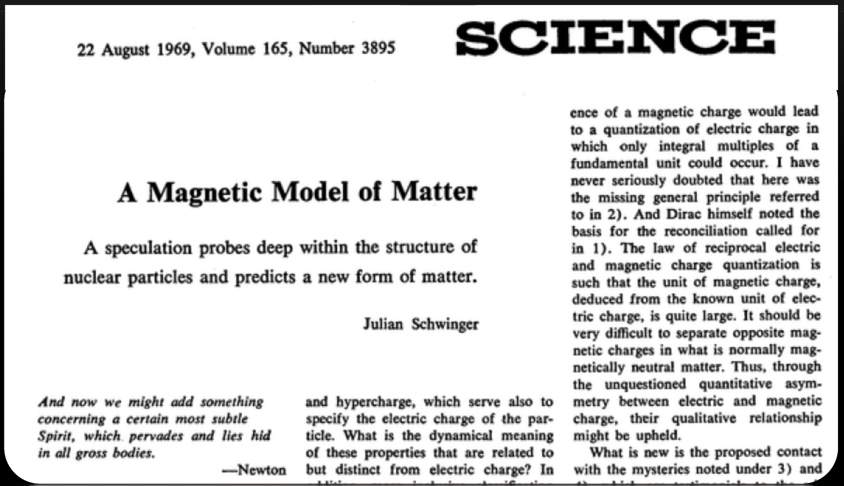
  Monopole as a spinor field obeying a U(1) gauged Dirac equation

- **S = 1 ➔ Lee-Yang Field Theory**

  Monopole as a vector equation obeying a gauged KG equation

Analyses in Progress – the Search for:

1) Schwinger's Dyon & 2) Highly Electrically Charged Objects



22 August 1969, Volume 165, Number 3895 **SCIENCE**

A Magnetic Model of Matter

A speculation probes deep within the structure of nuclear particles and predicts a new form of matter.

Julian Schwinger

And now we might add something concerning a certain most subtle Spirit, which pervades and lies hid in all gross bodies.

—Newton

and hypercharge, which serve also to specify the electric charge of the particle. What is the dynamical meaning of these properties that are related to but distinct from electric charge? In

ence of a magnetic charge would lead to a quantization of electric charge in which only integral multiples of a fundamental unit could occur. I have never seriously doubted that here was the missing general principle referred to in 2). And Dirac himself noted the basis for the reconciliation called for in 1). The law of reciprocal electric and magnetic charge quantization is such that the unit of magnetic charge, deduced from the known unit of electric charge, is quite large. It should be very difficult to separate opposite magnetic charges in what is normally magnetically neutral matter. Thus, through the unquestioned quantitative asymmetry between electric and magnetic charge, their qualitative relationship might be upheld.

What is new is the proposed contact with the mysteries noted under 3) and

- Postulated a "dyon" that carries electric & magnetic charge ($2g_D$)
  - Quantisation of angular mom. with two dyons (q_{e1},q_{m1}) & (q_{e2},q_{m2}) yields
- $$(q_{e1}, q_{m1}) - (q_{e2}, q_{m2}) = 2nh/m_0 \quad (\text{ n is an integer})$$
  - Using the MoEDAL's MMT detector we cover a wide range of electric and magnetic charge combinations serach RUN-2 data
- MoEDAL's Search for Highly Electrically Charged Objects (HECOs) uses the NTD system for the first time

CMS Beam-Pipe Dreams

MONOPOLES

CMS beam pipe to be mined for monopoles

On 18 February the CMS and MoEDAL collaborations at CERN signed an agree-ment that will see a 6 m-long section of the CMS beam pipe cut into pieces and fed into a SQUID in the name of fundamental research. The 4 cm diameter beryllium tube – which was in place (right) from 2008 until its replacement by a new beampipe for LHC Run 2 in 2013 – is now

CERN-PHOTO-201611-288-4

Pipe dreams
The original CMS beampipe, in use during LHC Run 1.

- *The old CMS beampipe arrived at the University of Alberta this week (May 2019)*
- *At the UofA the Beryllium beampipe will be cut into pieces small enough to be scanned at MoEDAL's SQUID magnetometer at ETH Zurich*
- *This will allow us to search for monopoles with magnetic charge above $5g_d$*

6m long

MoEDAL – Desperately Seeking SUSY

MoEDAL

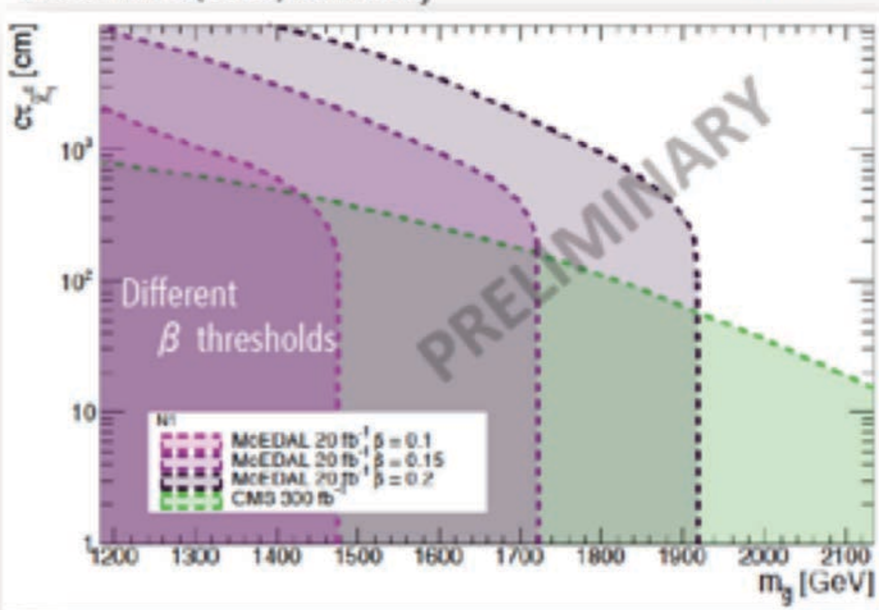
Results for $\tilde{g}\tilde{g}$, $\tilde{g} \to jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to \tau^{\pm}\tilde{\tau}_1$

$\tilde{\chi}_1^0$ long-lived despite large mass split between $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ ➜ decays in tracker

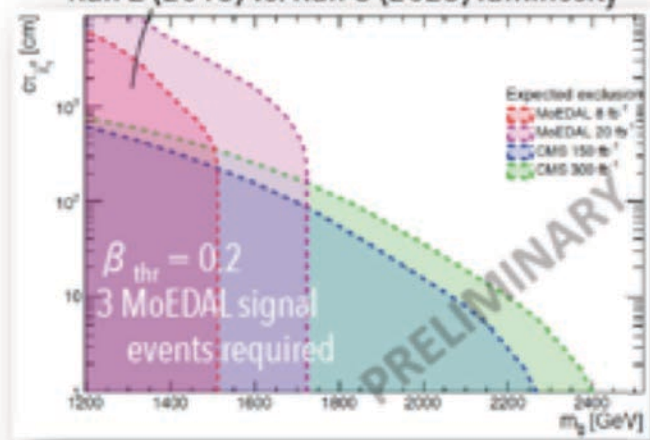
(massive) $\tau^{\pm}$ produces a kink between $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ tracks ⇒ large impact parameter d_{xy}, d_z

$\tilde{\tau}_1$ metastable, e.g. gravitino LSP ➜ detected by MoEDAL

End-of-run-3 (2023) luminosity



Run 2 (2018) vs. Run-3 (2023) luminosity



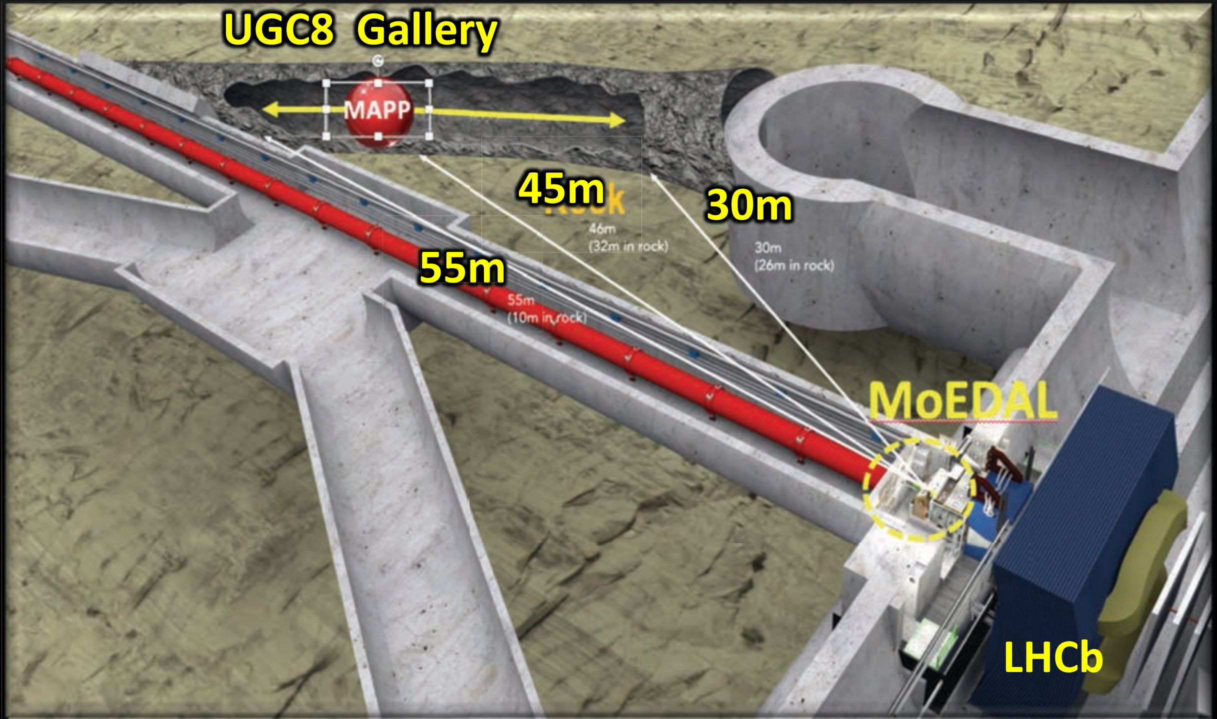
- CMS suffers twice:
  - a) no pixel hit
  - b) too large impact parameters

- MoEDAL can cover long-lifetime region inaccessible by ATLAS/CMS even with a *moderate* NTD performance **z/β > 10**

⚠ Comparison of CMS exclusion with MoEDAL discovery potential requiring 1 event

MAPP – MoEDAL Upgrade for RUN-3

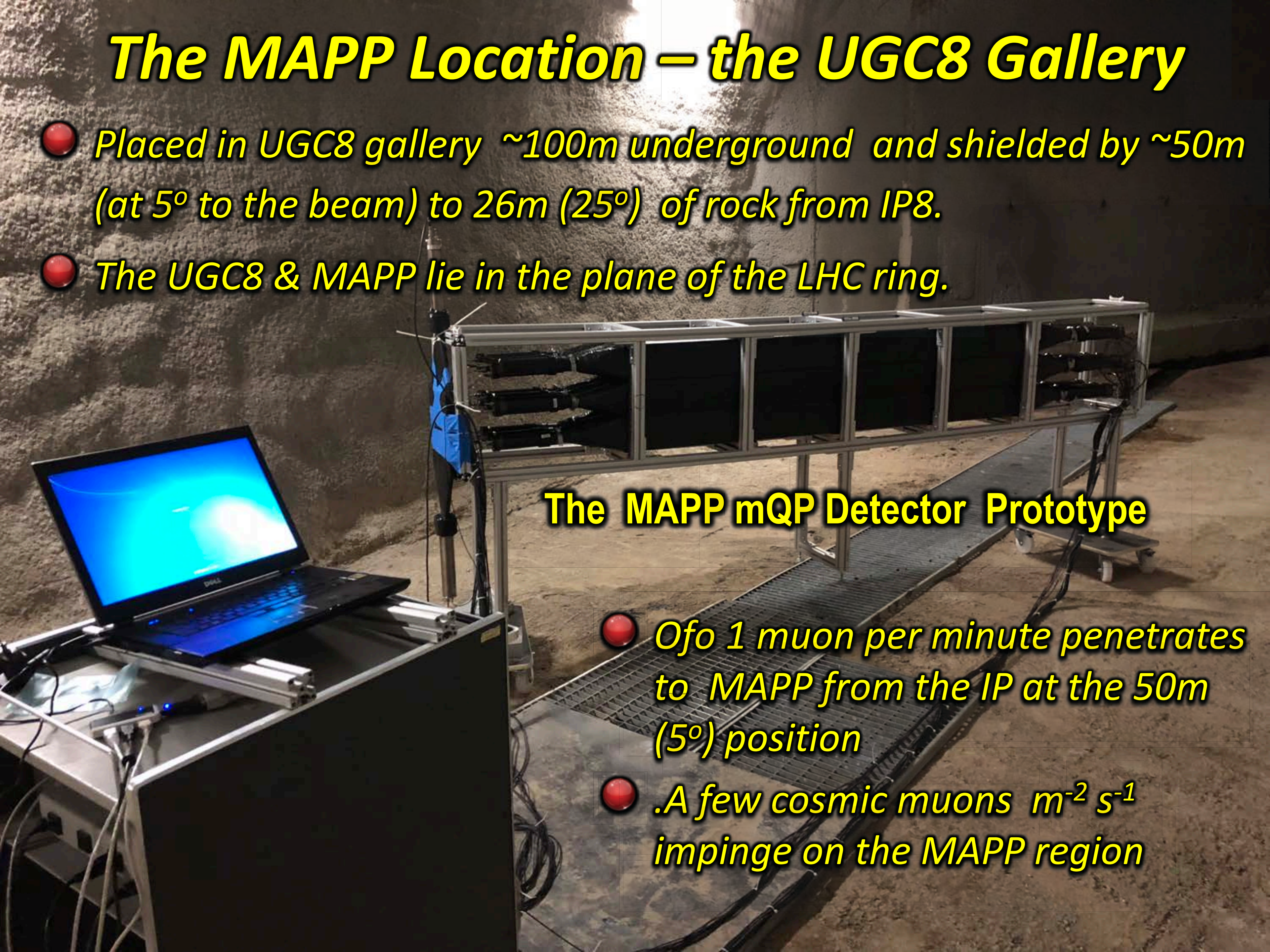
(MoEDAL Apparatus for Penetrating Particles



- *MAPP (to be installed for Run-3 of the LHC) has 3 motivations*
  - *To search for particles with charges <<1e (ATLAS & CMS limited to searches with particles of charge around e ≥ 1/3)*
  - *To search for new pseudo-stable neutrals with long lifetime*
  - *To search for other anomalously penetrating particles*

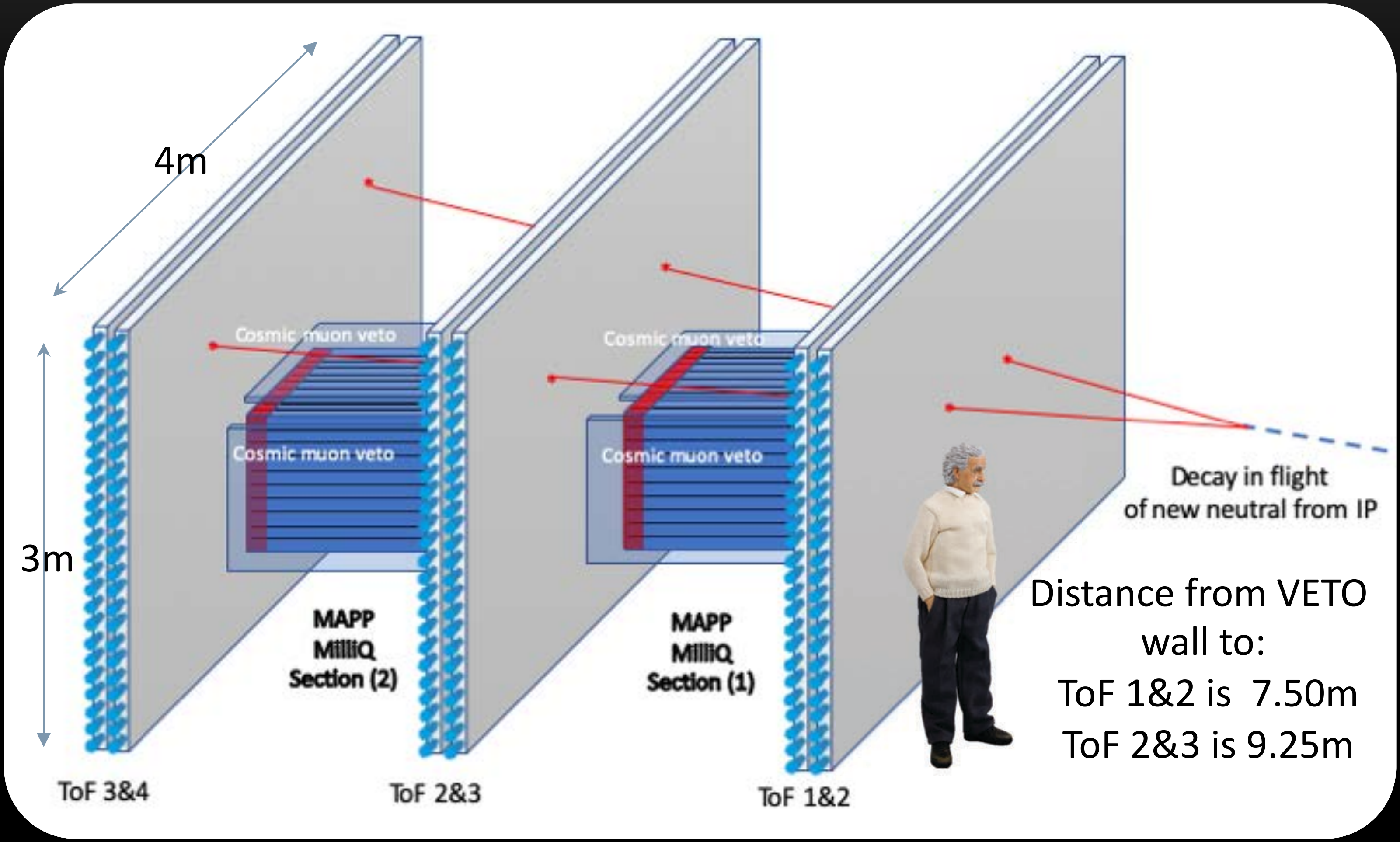
The MAPP Location – the UGC8 Gallery

- *Placed in UGC8 gallery ~100m underground and shielded by ~50m (at 5^{o} to the beam) to 26m (25^{o}) of rock from IP8.*
- *The UGC8 & MAPP lie in the plane of the LHC ring.*



- *Ofo 1 muon per minute penetrates to MAPP from the IP at the 50m (5^{o}) position*
- *.A few cosmic muons m^{-2} s^{-1} impinge on the MAPP region*

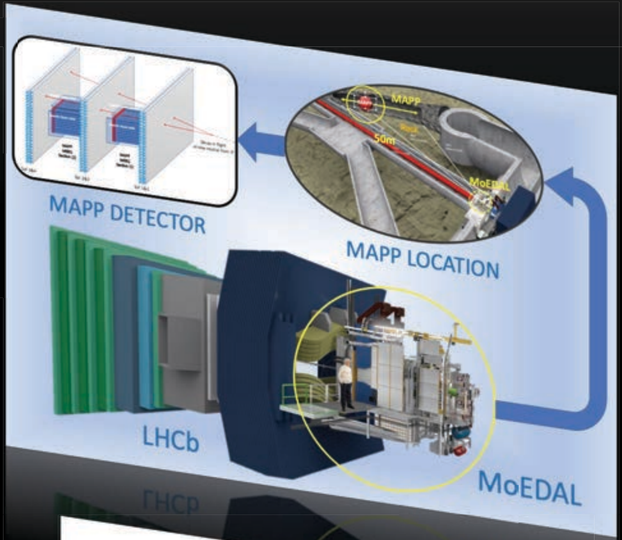
The MAPP Detector

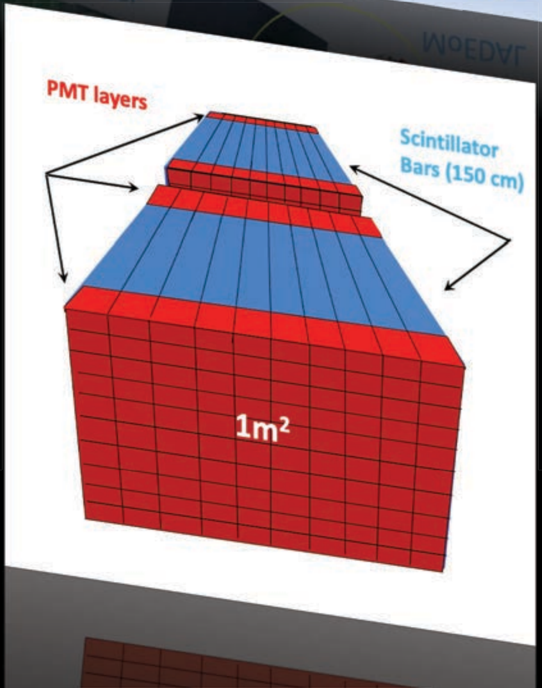


- *The MAPP (MoEDAL Apparatus for Penetrating Particles)*

MAPP: Mini-Charged Particle Detector

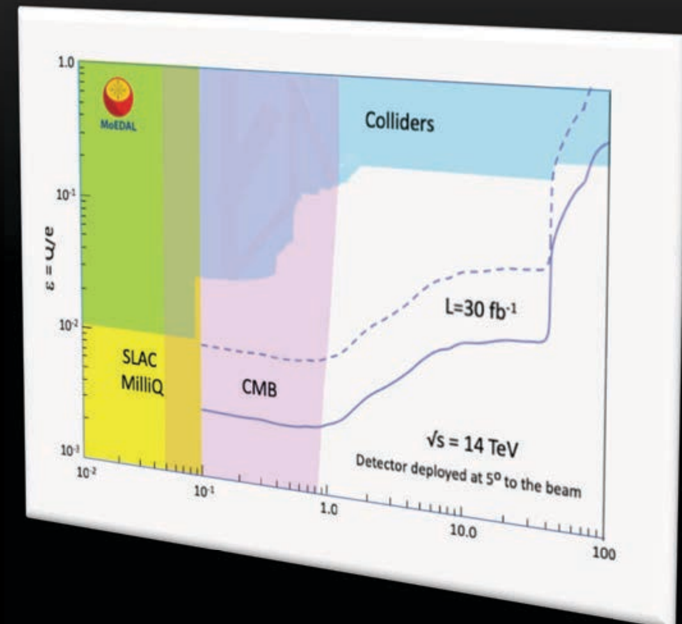
- The mini-charged particle (mQP) detector is a 1m x 1m x (2 x 1.5m) scintillator array, pointing to IP, in well shielded area of LHC Point 8 (LHCb)
  - Deployed from 5^{o} to the beam (at 55m) to 25^{o} to the beam (at 26 m)
  - Uses quadruple coincidence between the two scintillator bars) sections (2 PMTs / bar)
  - Active veto against showers in rock
  - LED pulser & cosmics + neutral density filter calibration
- Under construction during current shutdown
- Due to start data taking in LHC's RUN-3

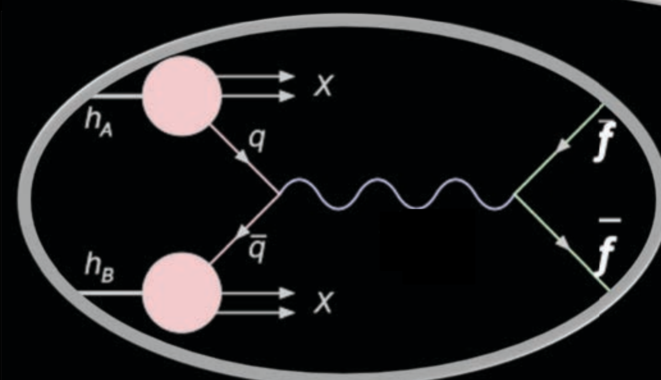




MAPP Sensitivity to mQP

- MAPP will enable the search for particles with charge as low as ~.001e and masses above ~100 MeV. Simulations indicate that with 30 fb^{-1}:
  - We will have sensitivity to a charge of $\mathcal{O}(10^{-3})$ e to $\mathcal{O}(10^{-3})$ can be achieved for masses of $\mathcal{O}$ (1) GeV, and charge $\mathcal{O}(10^{-2})$ e for masses of $\mathcal{O}(10)$ GeV.
- MoEDAL is competitive with other more centrally placed dedicated detectors planned for RUN-3, for two reasons:
  - For RUN-3 lumi delivered to MoEDAL (& LHCb) will rise by a factor of ~5
  - The forward stance of MAPP (at 5° to the beam) enhances the acceptance of MAPP for "forward-backward" biased physics



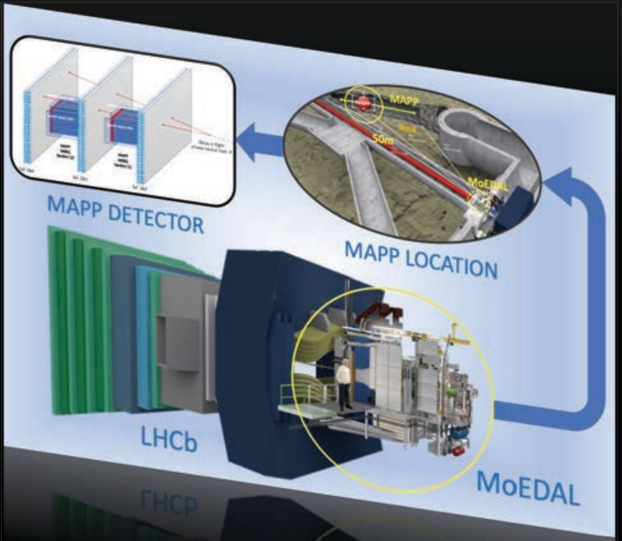


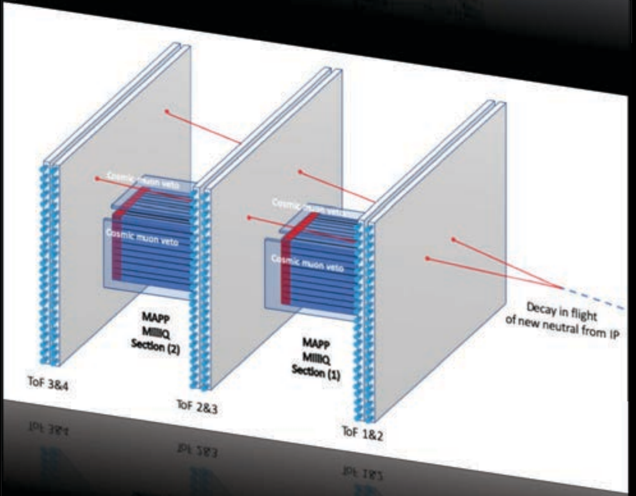
The direct and indirect bounds on mQPs for models with a massless dark photon qnd the projected reach of MAPP for RUN-3 (---line 10% overall MAPP eff.)

MoEDAL

MAPP – Long Lived Particle Detector

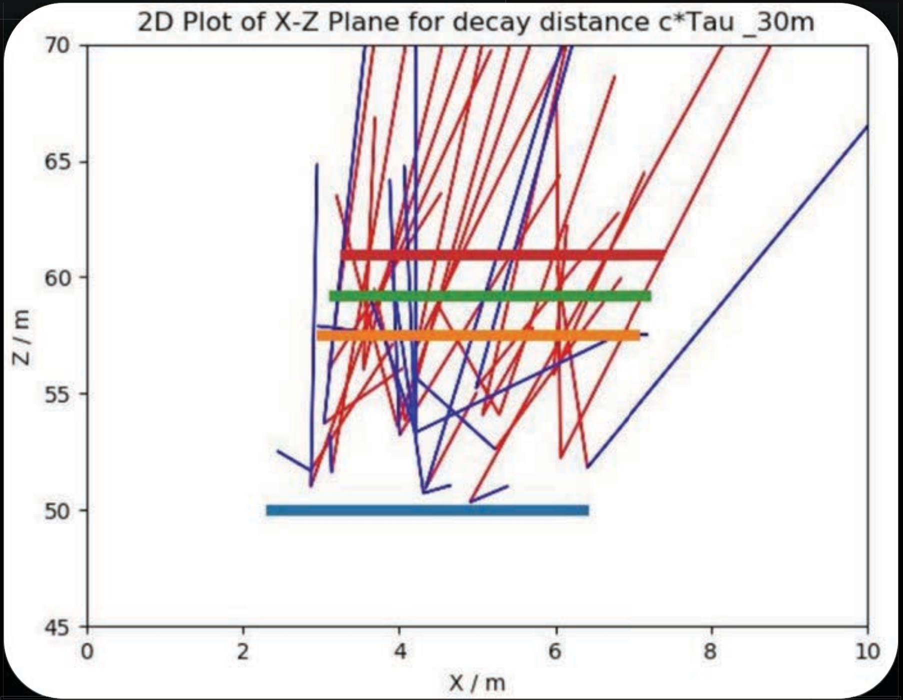
- The Long Lived Particle (LLP) detector is formed from 3 pairs of 3m x 4m scintillator hodoscopes, pointing to IP
- RPCs are also being investigated as an alternative to scintillator
  - Deployed from 5^{o} to the beam (at 55m) to 25^{o} to the beam (at 26 m)
  - 7-10m decay zones in front of first plane
  - Veto detector on tunnel face defining decay zone
- Under construction during the current LHC shutdown
- Due to start data taking in LHC's RUN-3





MAPP – Fiducial Efficiency Preliminary Result

Decay Distance / m	MAPP Decays	MAPP Fiducial Efficiency
10	435	4.35E-04
20	322	3.22E-04
30	258	2.58E-04
40	186	1.86E-04
50	192	1.92E-04
60	150	1.50E-04
70	148	1.48E-04
80	124	1.24E-04
90	119	1.19E-04
100	113	1.13E-04



- *Fiducial Efficiency ~10^{-4} for $c\tau$ up to 100m and beyond*
  - *A Higgs mixing portal admits exotic inclusive $B \rightarrow X_s\varphi$ decays where ϕ is a light CP-even scalar that mixes with the Higgs, with mixing angle $\vartheta \ll 1$.*
  - *Fiducial efficiency determined using as a benchmark $B \rightarrow K\phi$ decays.*

Concluding Remarks

We now have the prospect of a promising renewed MoEDAL detector that has sensitivity to the three clear signatures for new physics: anomalously small and high ionization as well as very long lifetime.

With this new tool we will to shed a complementary new light on the discovery frontier that we hope will reveal physics beyond the SM illumination

EXTRA SLIDES

MENU

1) Introduction

2) The MoEDAL Detector

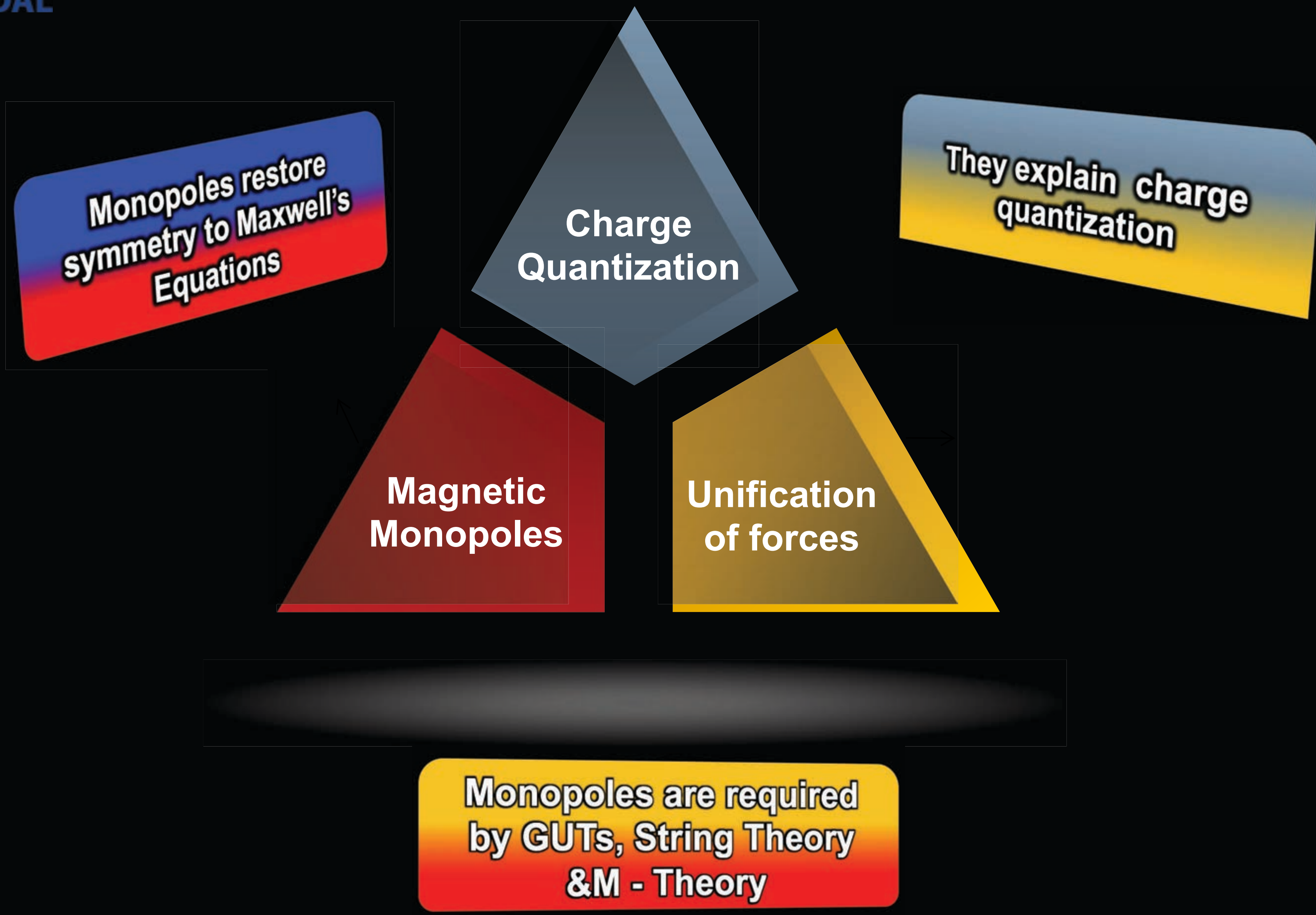
3) MoEDAL Results and Results in Progress

4) The MAPP Upgrade to the MoEDAL Detector

5) The MALL Upgrade to the MoEDAL Detector

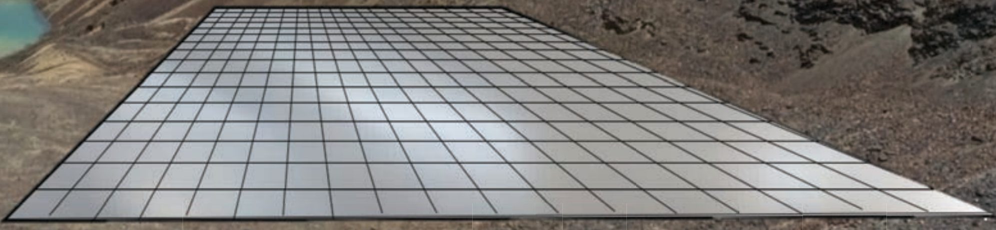
6) COSMIC MoEDAL – the Path to the GUT Scale

The Role of the Magnetic Monopole



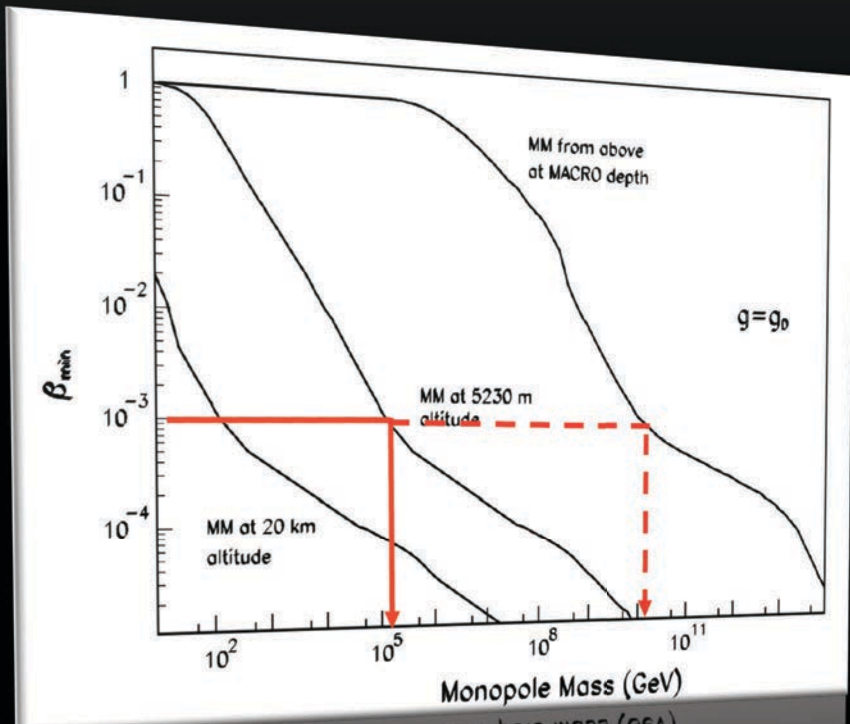
The Next Step? Cosmic-MoEDAL

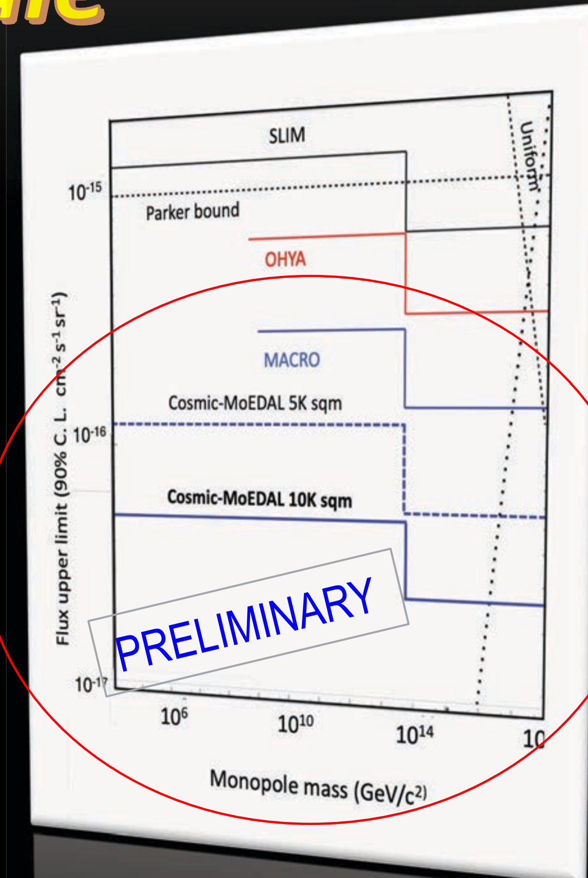
- *To continue the search for monopoles from the LHC to the GUT Scale a group of MoEDAL Collaborators are proposing Cosmic-MoEDAL: ~10K m^2 array of plastic NTD detectors*
- *Detectors would be deployed at high altitude (like SLIM) to give sensitivity to light, intermediate and GUT mass monopoles*
- *This is 10 times the plan-area of MACRO which has placed the best overall limits in this arena to date*



Candidate sites are Mt Chacaltaya,Bolivia; the Canary Islands (Tiede); and, the Pryamid Lab. in Nepal

Searching from the TeV to the GUT Scale

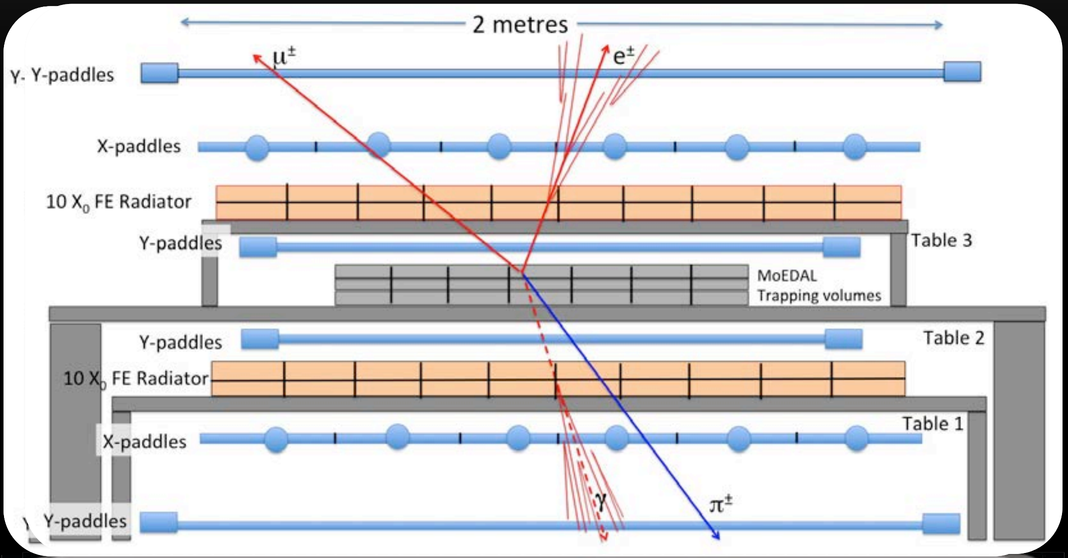




- *GUT Monopoles ~10^{18} GeV*
- *Intermediate mass monopoles produced in later phase transitions: $10^5 < M_m < 10^{12}$ GeV*
- *Electroweak Monopoles mass estimates a few to 100 TeV*

MALL

(MoEDAL Apparatus for extremely Long Lived Particles)
A project in the development stage



- *Search for massive long-lived charged particles using the MoEDAL trapping detecetor (MMT) and the MALL detector*
  - *After exposure trapping volumes will be monitored deep underground for the decays of trapped very long-lived massive charged particles with lifetime of a ~ amonth to over 10 years.*
  - *The planned scintillator has a low threshold (eg ~1 GeV muons) and is sensitive to electrons, muons, hadrons and photons.*

MAPP Deployment

- *It is envisaged that MALL will be installed deep (2km) underground at SNOLAB in Canada where cosmic backgrounds are minimised to one muon per 0.27 m^2/day*
- *Background is further reduced by the ability to determine if a detected track originated within the monitored volume and also by energy cuts on deposited signals*