Recent Results and Future Plans of the MoEDAL Experiment – Expanding the LHC's Discovery Frontier

Rencontres du Vietnam
New Physics with Exotic and Long-Lived Particles.

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*

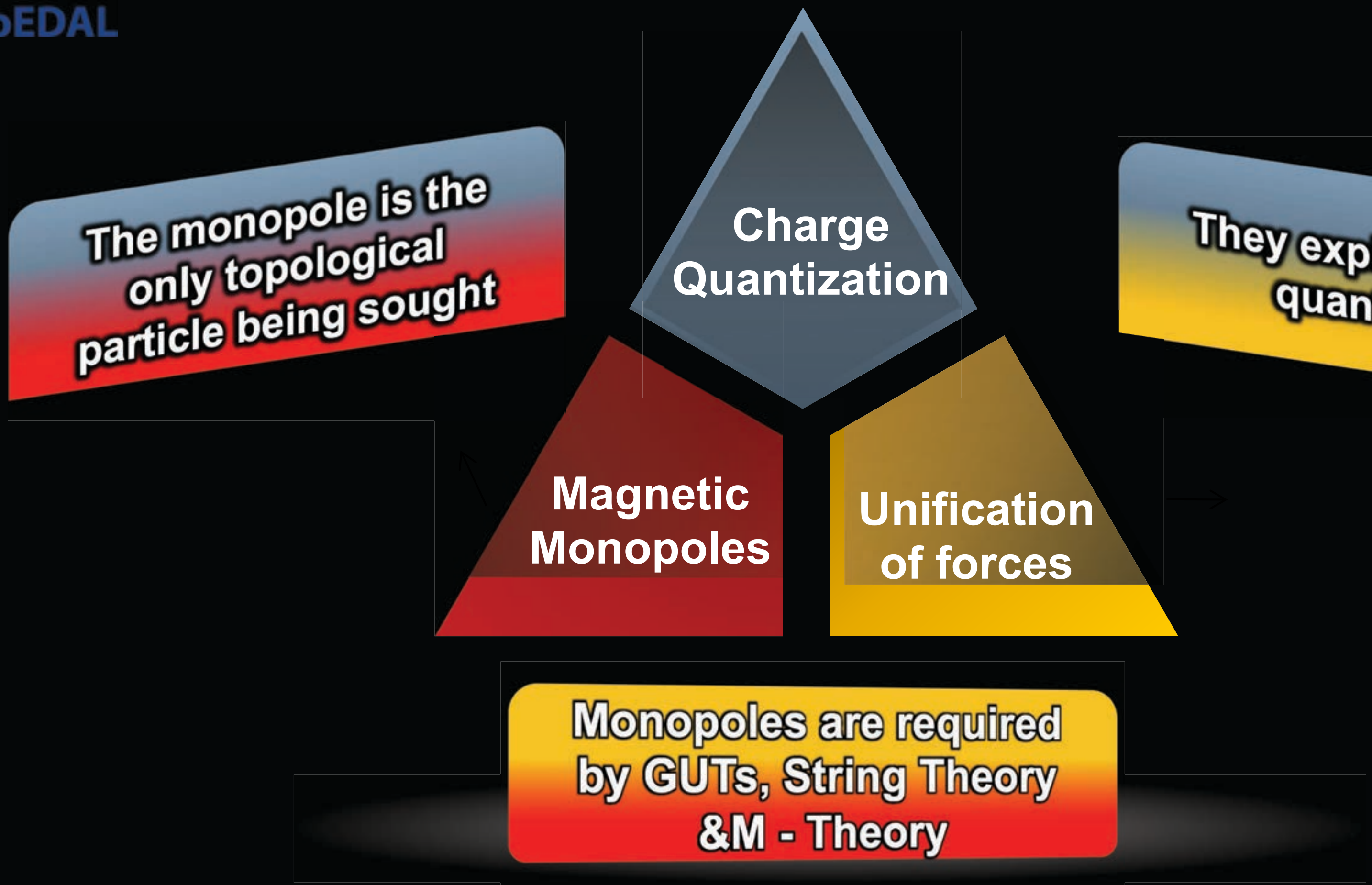
The Higgs Boson & the Magnetic Monopole

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 Role of the Magnetic Monopole



"...the existence of magnetic monopoles seems like one of the safest bets that one can make about physics not yet seen." Joseph Polchinksi (1954-2018)

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 flux unit superconductivity

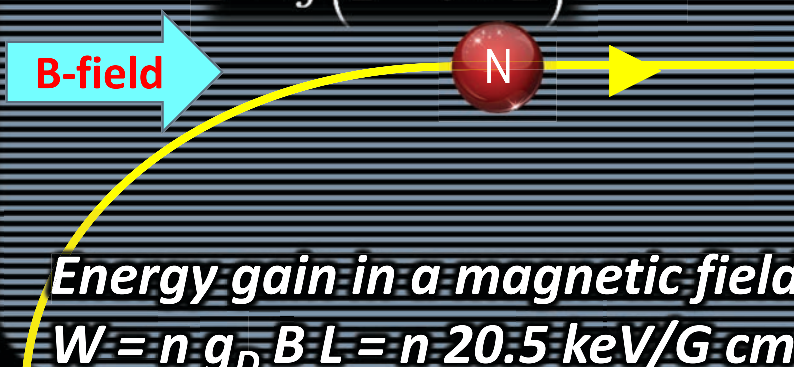
$(ze)_{equiv.} = n g_D \beta (=v/c)$: Ionizes $n^2 g_D^2$ more than a rel. proton i.e 4700 times more when n=1

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 $a_m \sim 21$

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

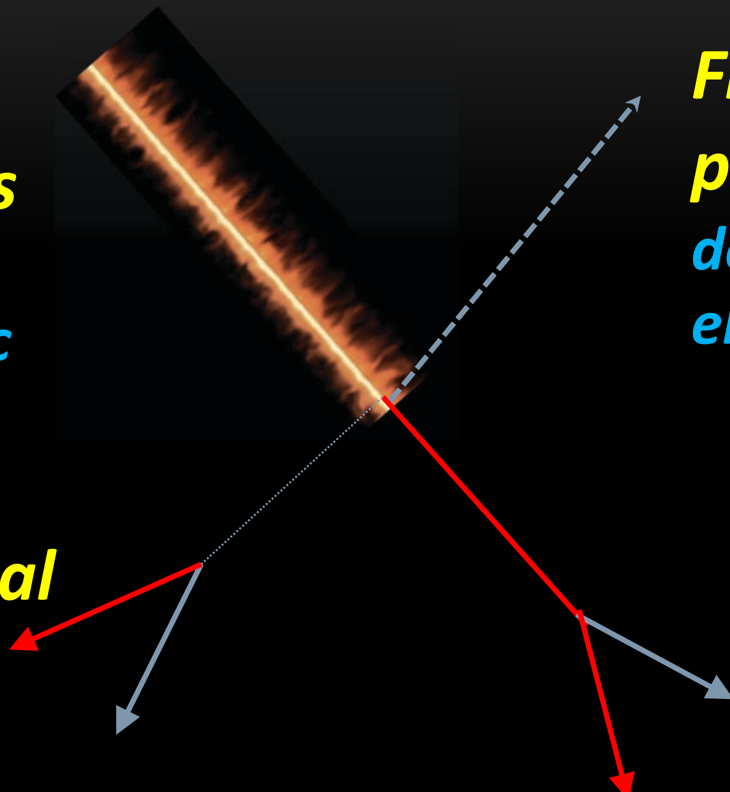
L= 1 kpc and B = 3 μG, W ≅ 1.8 x10^{21} eV

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)

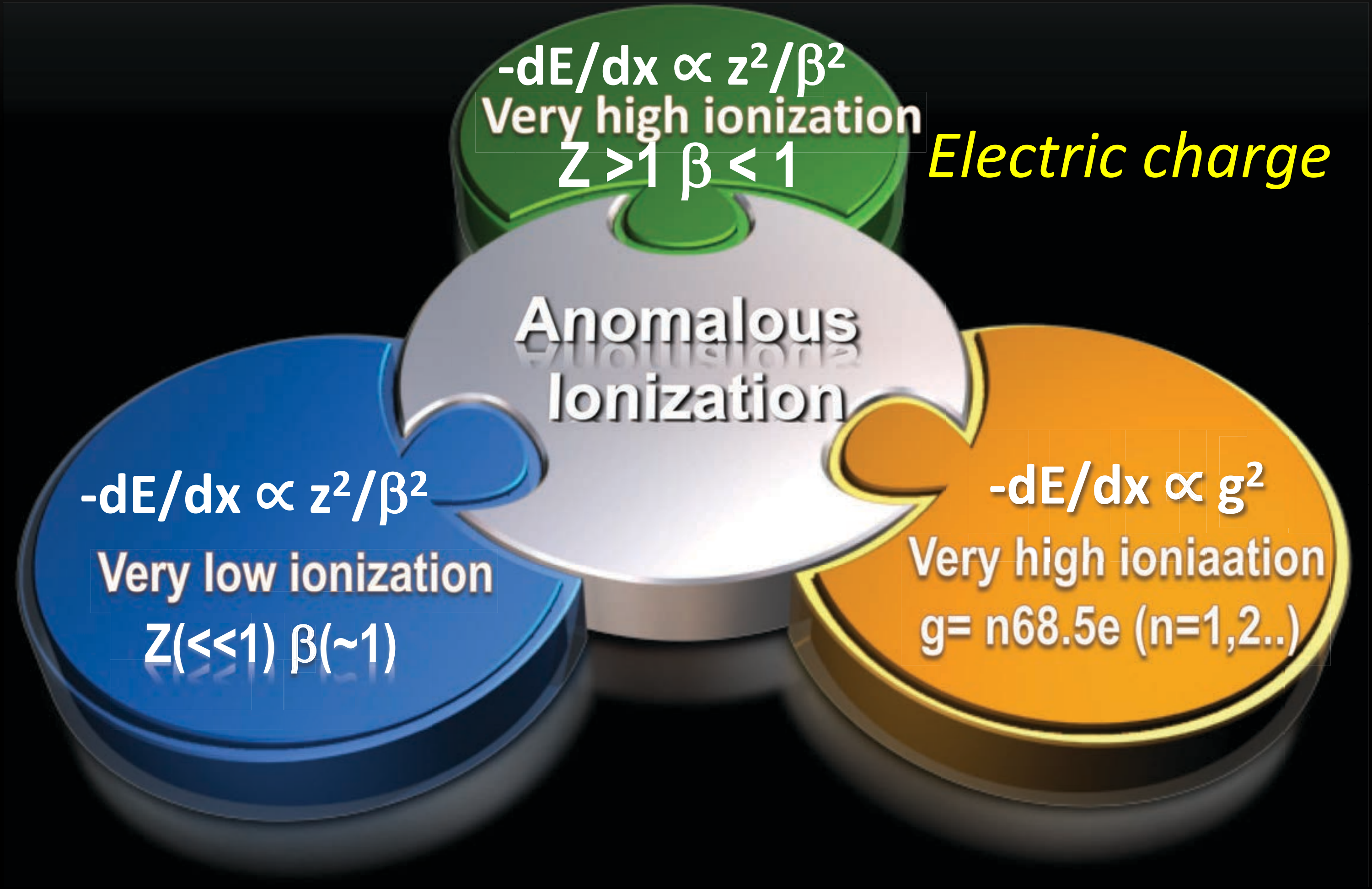
Fractionally charged particles *(with charge down to ~1/mille of the electron's charge)*



Long lived neutral particles –
($c\tau$ > ~1m)

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

Anomalously Ionizing Signatures of New Physics



Electric charge

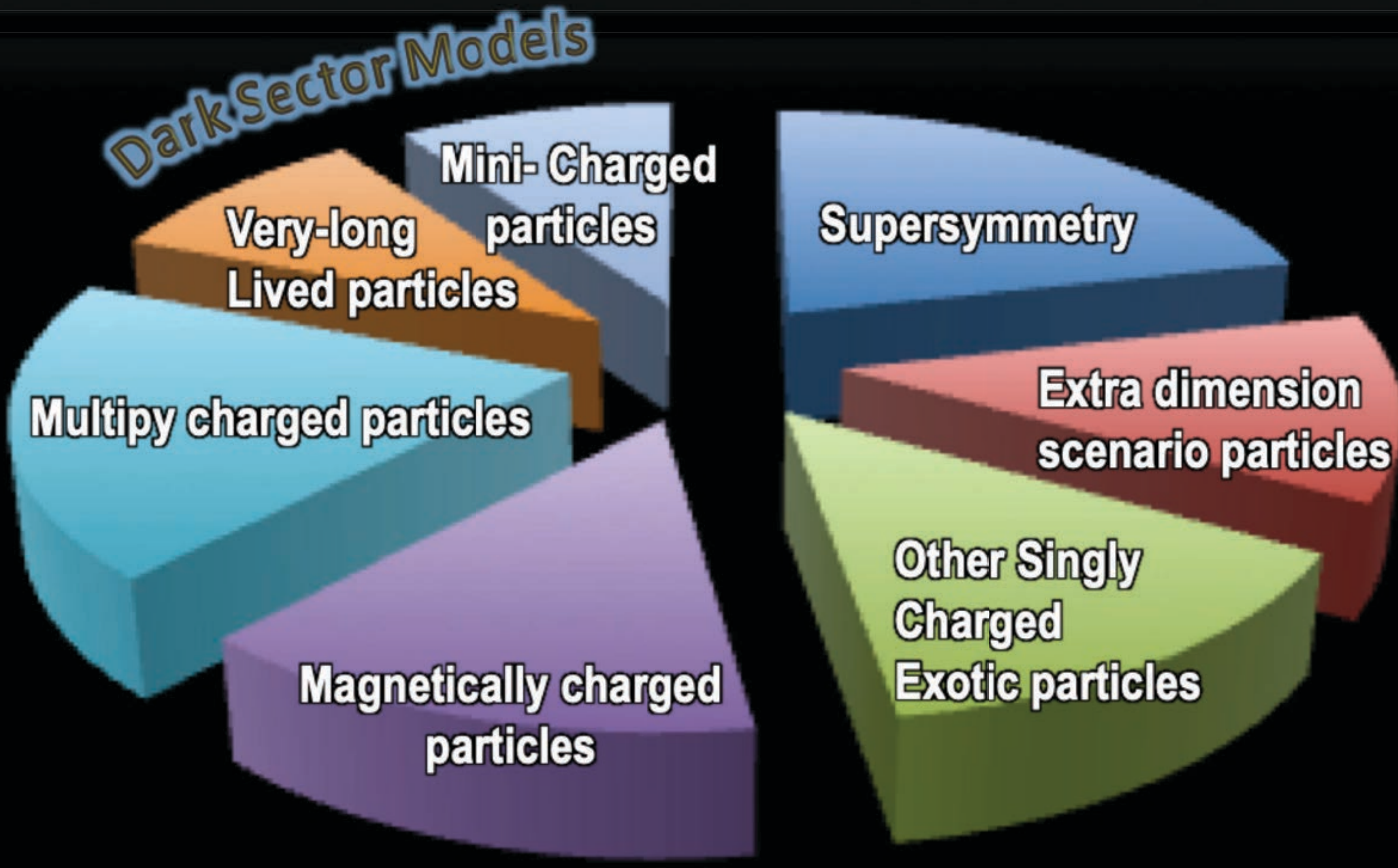
Fractional electric charge

Magnetic charge

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

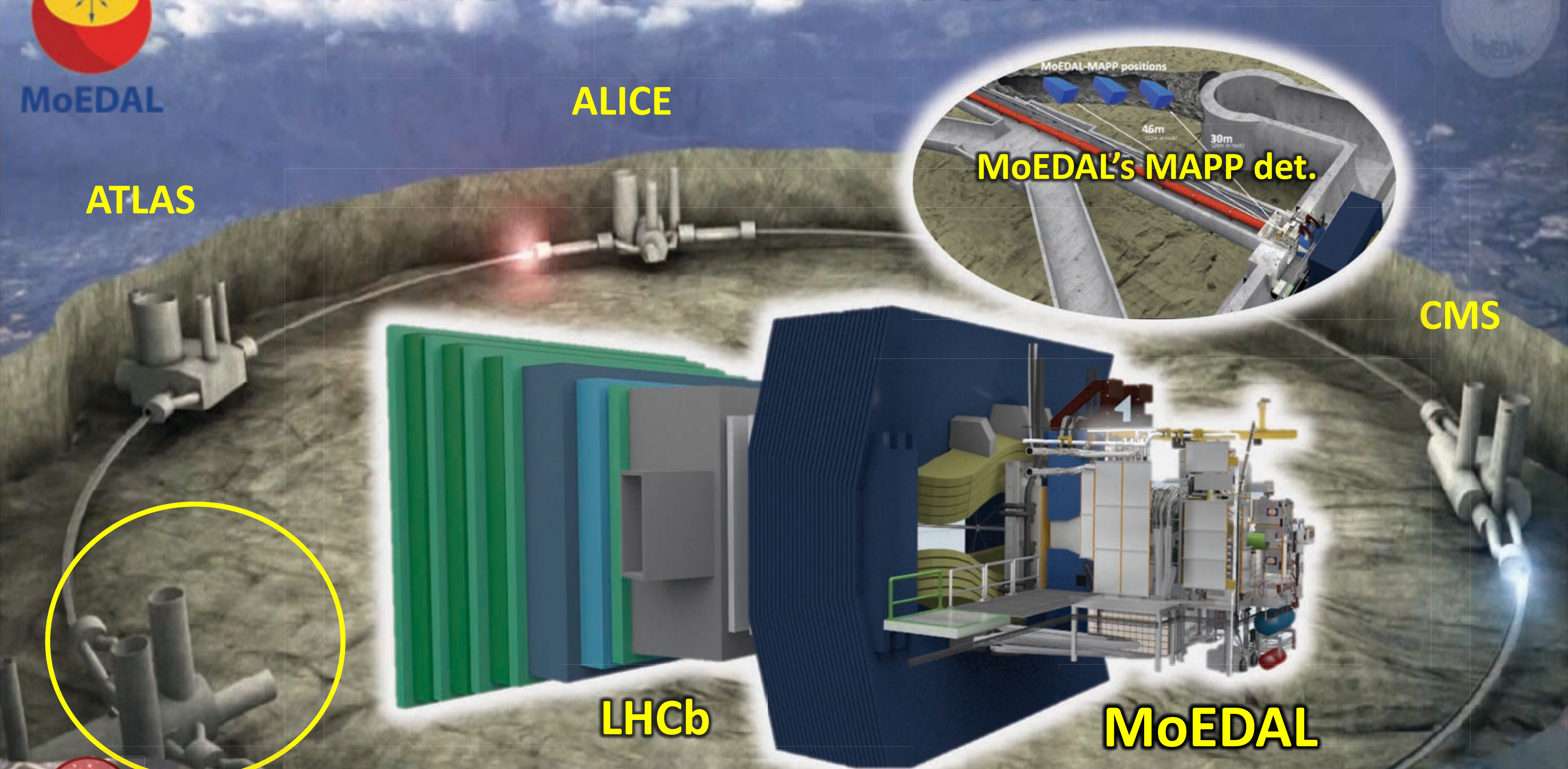
MoEDAL Physics Program

Sensitive to over 40 new physics scenarios



International Journal of Modern Physics A, September 2014, Vol. 29, No. 23

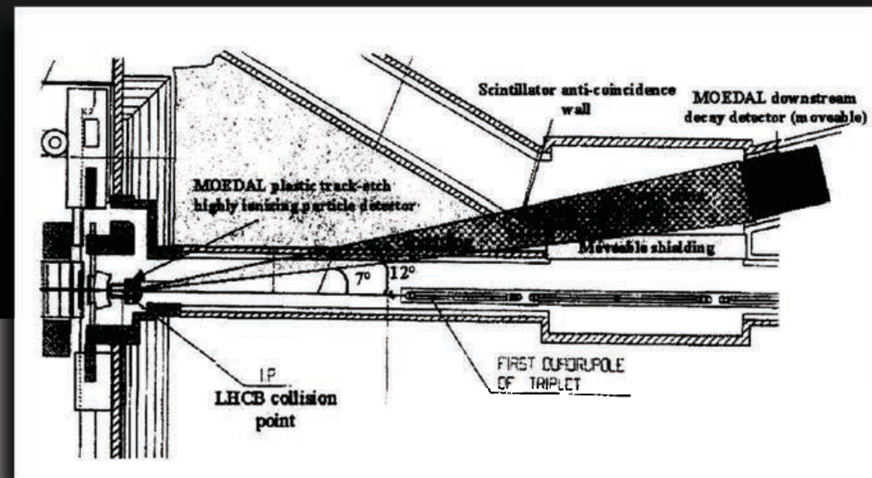
The MoEDAL Detector



- *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's 1st LoI to the LHCC in 1999

*Originally, MoEDAL was proposed to search for Highly Ionizing Particles **and** new long-lived particles*



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Nuclear Physics B (Proc. Suppl.) 78 (1999) 52–57

www.elsevier.nl/locate/npe

Searching for Exotic Particles at the LHC with Dedicated Detectors.

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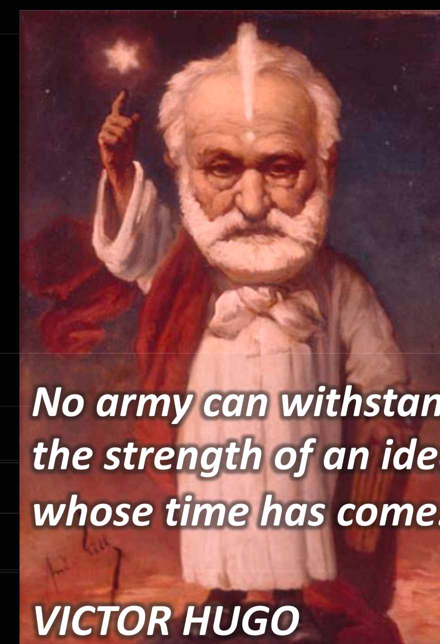
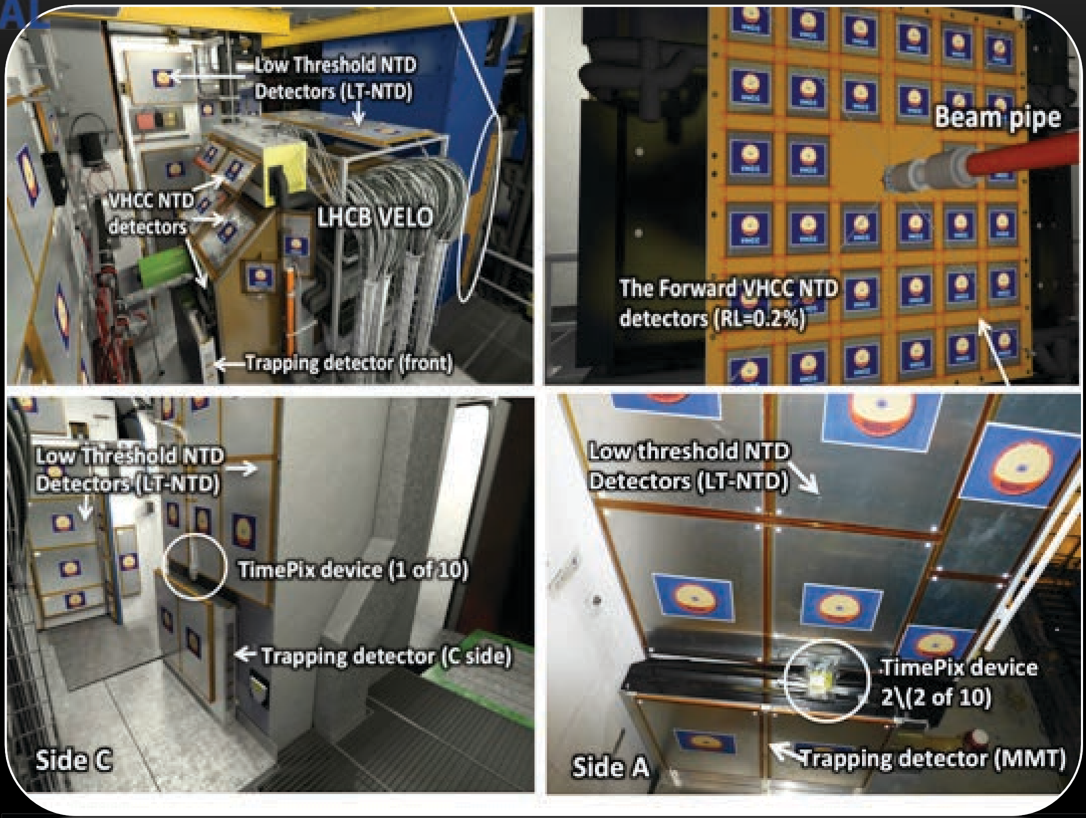
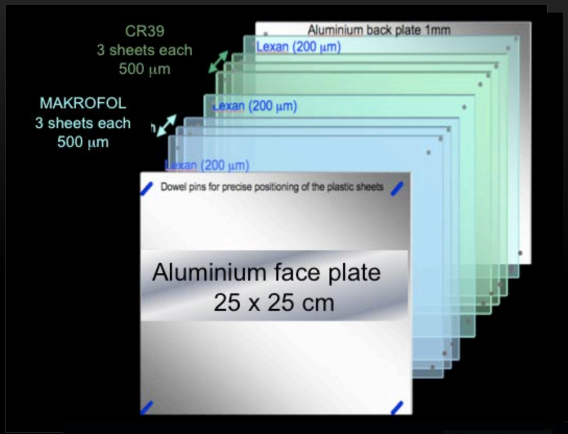
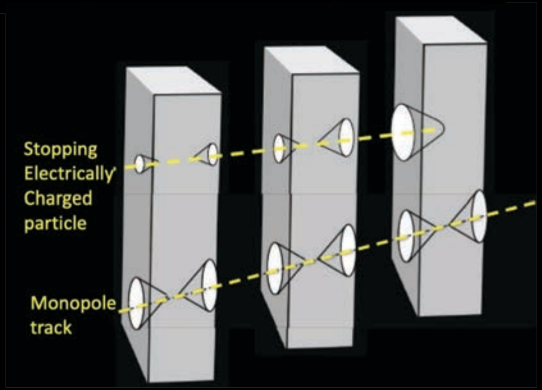
The LHC will open up a new energy regime where it may be possible to observe physics beyond the Standard Model. Therefore the search for exotic phenomena, such as: magnetic monopoles, massive stable particles; slowly decaying exotic particles; highly penetrating particles; and, free quarks and gluons, will be an important part of the LHC physics program. We propose that the search strategy for exotics planned for the main LHC detectors be extended with modest dedicated experiments designed to enhance the physics reach of the LHC. We shall use two examples to illustrate this thesis. First, a passive, plastic track-etch detector "ball" designed to detect highly ionizing particles and measure their Z/β. Such a detector is currently the subject of a Letter of Intent to the LHCC from the MOEDAL collaboration. Another (active) small acceptance detector – protected by shielding and monitoring an extended decay zone – specifically designed to detect massive stable particles and detect slowly decaying particles, is described. The use of such a detector at the LHC, has recently been proposed.



Tracking Monopoles





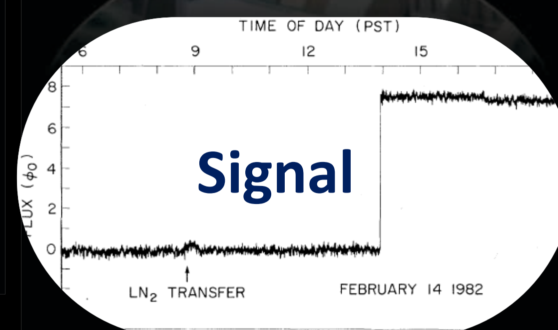


Etch pit sizes ~30μm

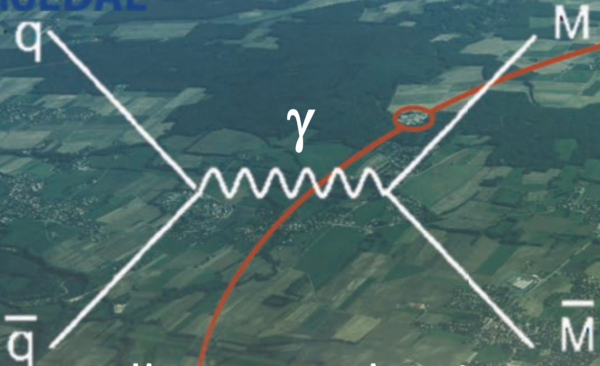
- *The Nuclear Track Detector (NTD)system is comprised of 20m² surface area of stacks → 120m² of plastic in total*
  - *Threshold for detection 5/50 that of a MIP for CR39/Makrofol*
  - *Passage of a highly ionizing particle revealed as etch-pits by chemical etching*
  - *Scanning & measurement with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

Trapping Monopoles

- *Trapping detectors (~1 tonne) in capture HIPS. Volumes comprised of ~ 2400 Al bars (2.5x2.5 x10 cm^3)*
  - *Exposed trapping volumes are passed through a SQUID magnetometer to detect trapped monopoles*
  - *Trapped monopoles can be released for further study*

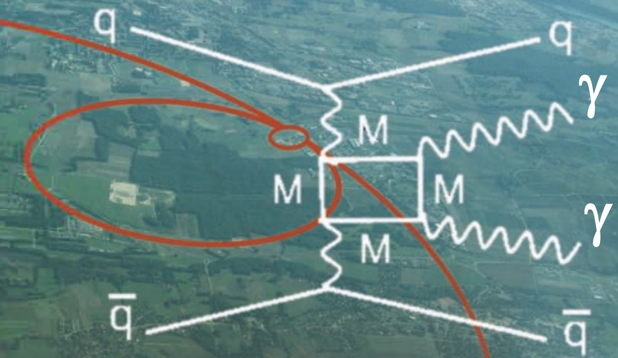


Accelerator Searches for Monopoles



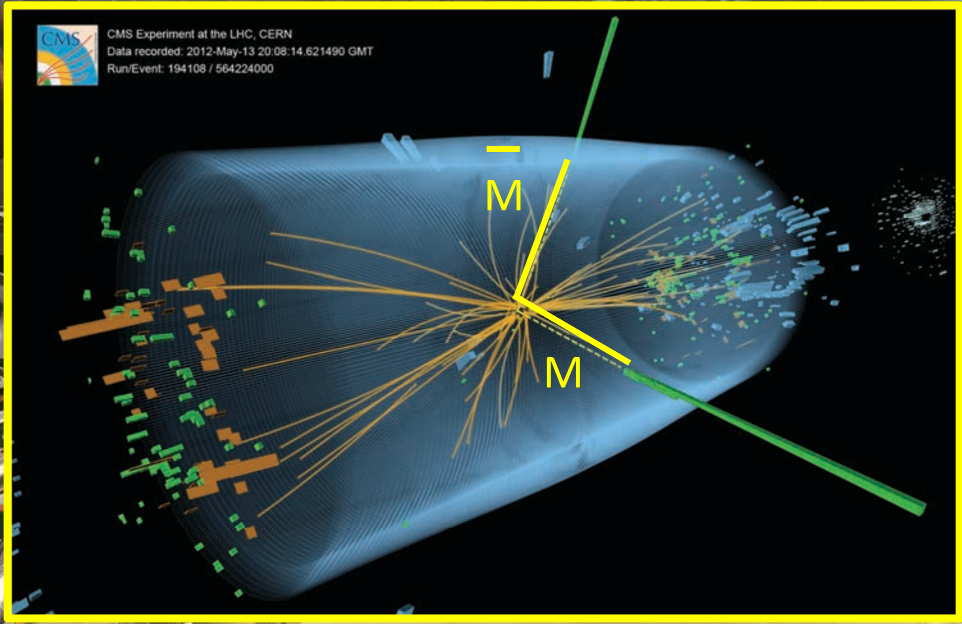
Drell Yan mechanism

Photon fusion

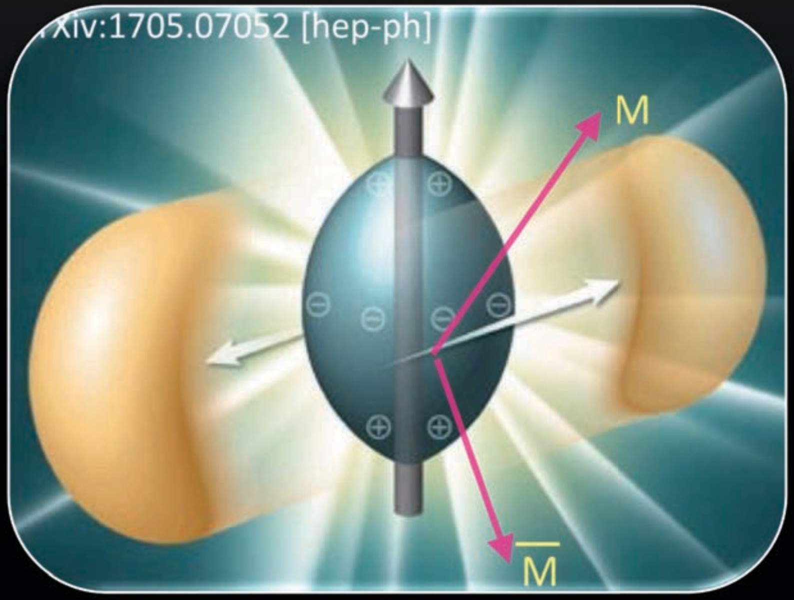


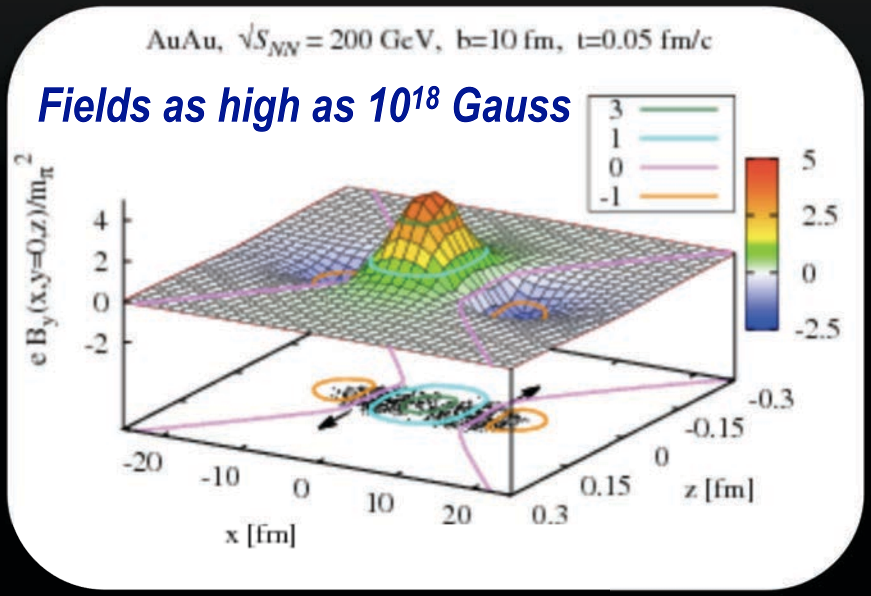
Monopole box

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



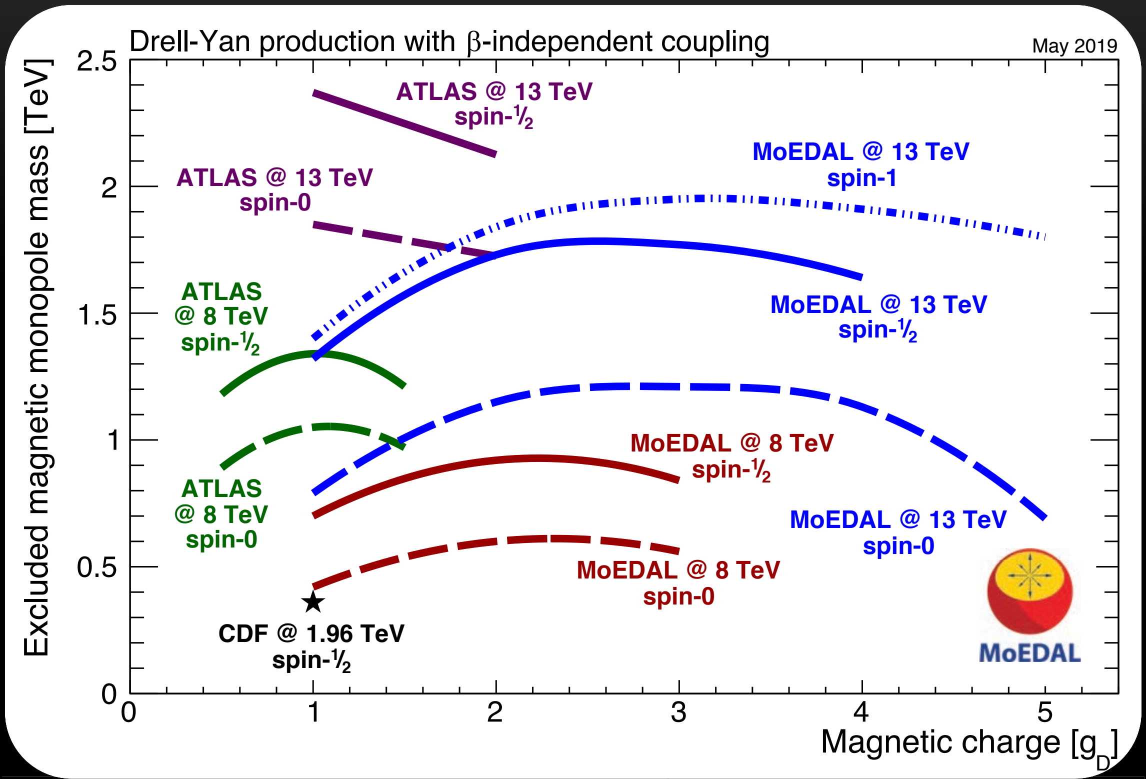
Monopole From Heavy-ion Collisions
via the Thermal Schwinger Mechanism





- *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*

LHC Mass Limits on Monopoles



JHEP 1608 (2016) 067 Phys.Rev.Lett. 118 (2017) no.6, 061801 Phys.Lett. B782 (2018) 510-516

- *ATLAS measures only the ionization signal - measurement not calibrated for highly ionizing particles*
  - *Uncalibrated Ionization measurements not enough to identify a monopole*
- *MoEDAL directly identifies the monopole magnetic charge*

MoEDAL's Latest Monopole Mass Limits

Submitted to PRL in April 2019

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

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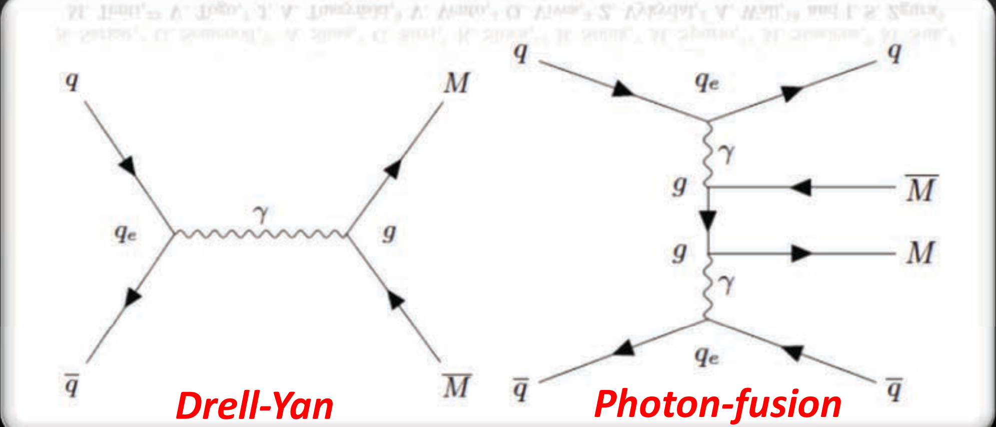
(THE MoEDAL COLLABORATION)



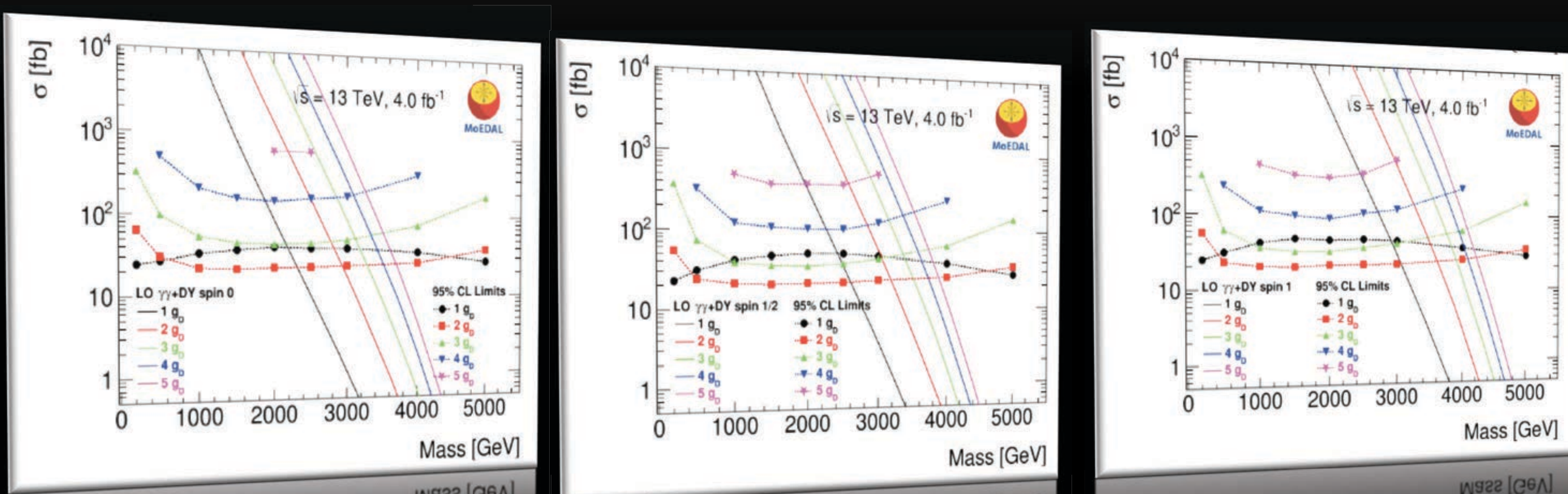
Process / coupling	Spin	Magnetic charge [g_D] 1	2	3	4	5
		95% CL mass limits [GeV]				
DY	0	790	1150	1210	1130	–
DY	½	1320	1730	1770	1640	–
DY	1	1400	1840	1950	1910	1800
DY β-dep.	0	670	1010	1080	1040	900
DY β-dep.	½	1050	1450	1530	1450	–
DY β-dep.	1	1220	1680	1790	1780	1710
DY+$\gamma\gamma$	0	2190	2930	3120	3090	–
DY+$\gamma\gamma$	½	2420	3180	3360	3340	–
DY+$\gamma\gamma$	1	2920	3620	3750	3740	–
DY+$\gamma\gamma$ β-dep.	0	1500	2300	2590	2640	–
DY+$\gamma\gamma$ β-dep.	½	1760	2610	2870	2940	2900
DY+$\gamma\gamma$ 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 Cross-section Limits (DY +$\gamma\gamma$)

Spin-1 limits for the first time

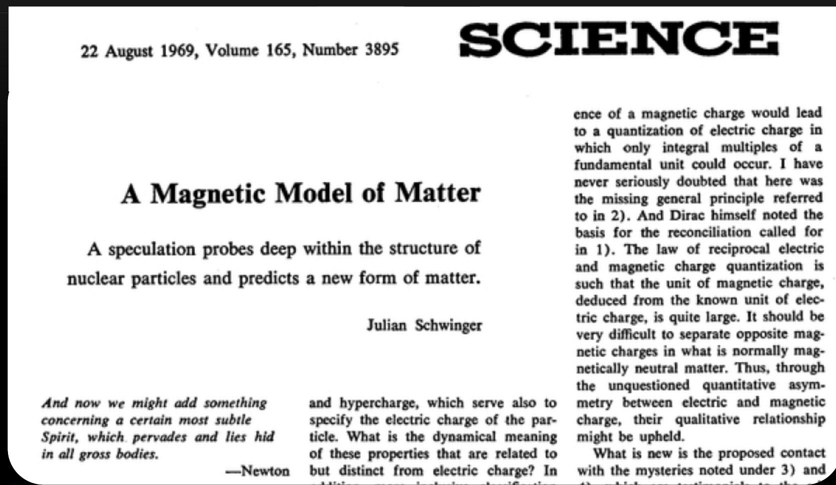
(β-dependent results below)



- **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 detectector we cover a wide range of electric and magnetic charge combinations in the search for Dyons using 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 agreement 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 in May 2019*
- *The Beryllium beampipe has been cut into small pieces and shipped to MoEDAL's SQUID magnetometer at ETH Zurich*
- *This will allow us to search for monopoles with magnetic charge 5 → 12 g_d*

6m long

MoEDAL – Desperately Seeking SUSY

ICNFP 2017 V.A. Mitsou

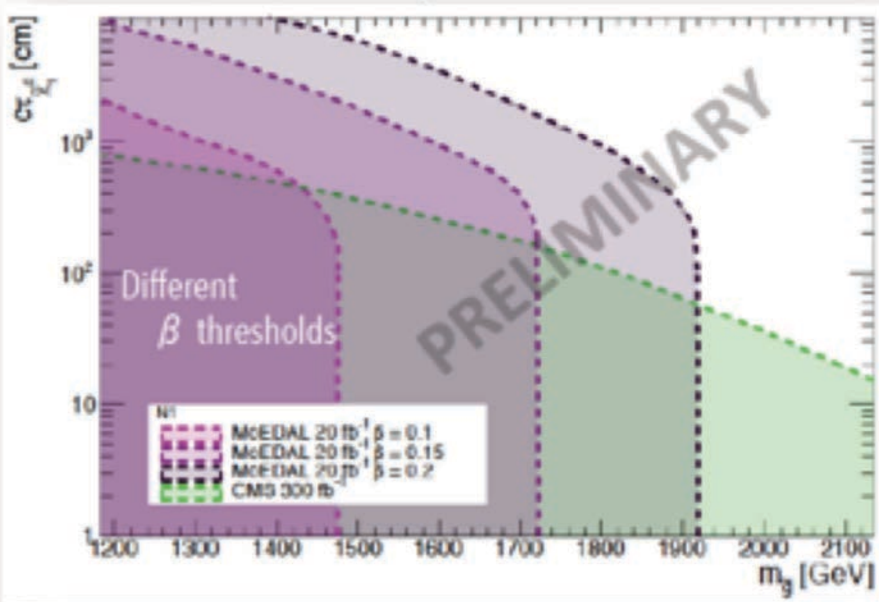
Results for $\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\tau^{\pm}\tilde{\tau}_1$

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

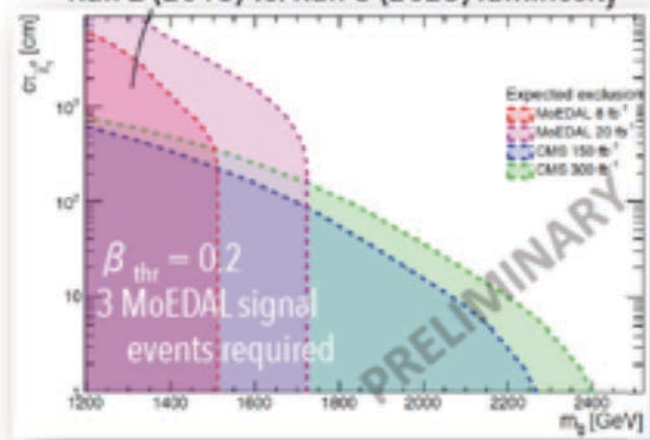
(massive) $\tau^{\pm}$ produces a kink between $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ tracks ⇒ large impact parameter d_{xy}, d_z

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

End-of-run-3 (2023) luminosity



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



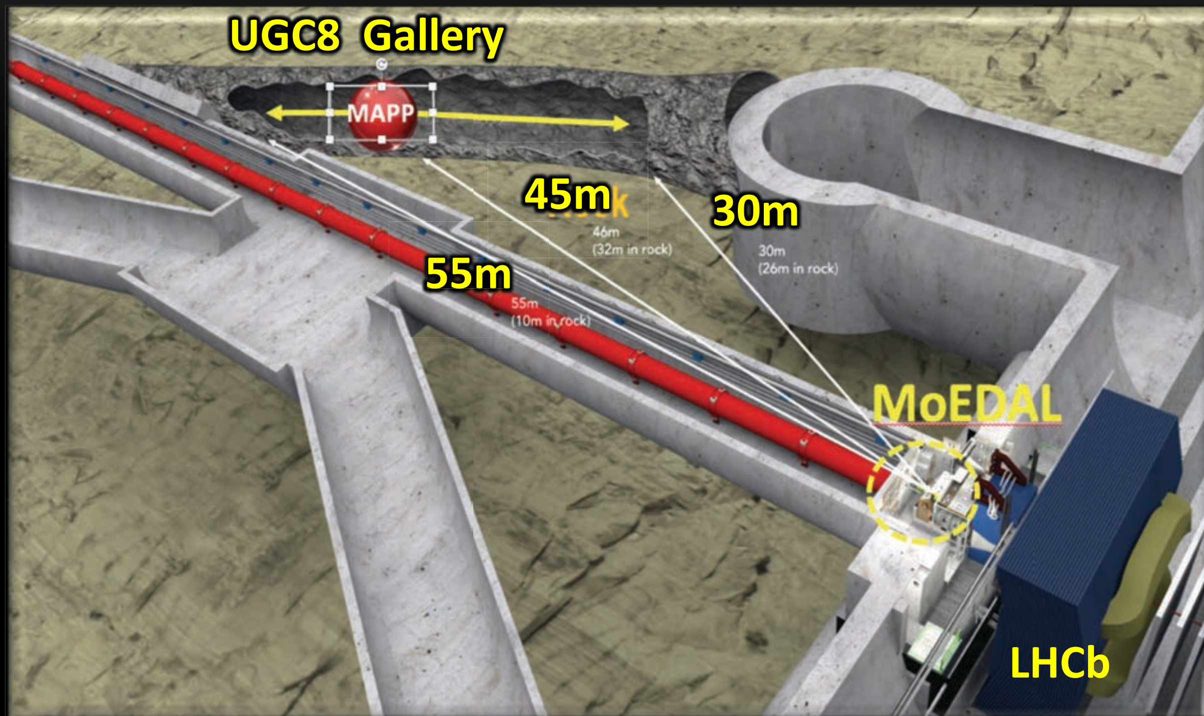
- CMS suffers twice:
  - a) no pixel hit
  - b) too large impact parameters

- 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

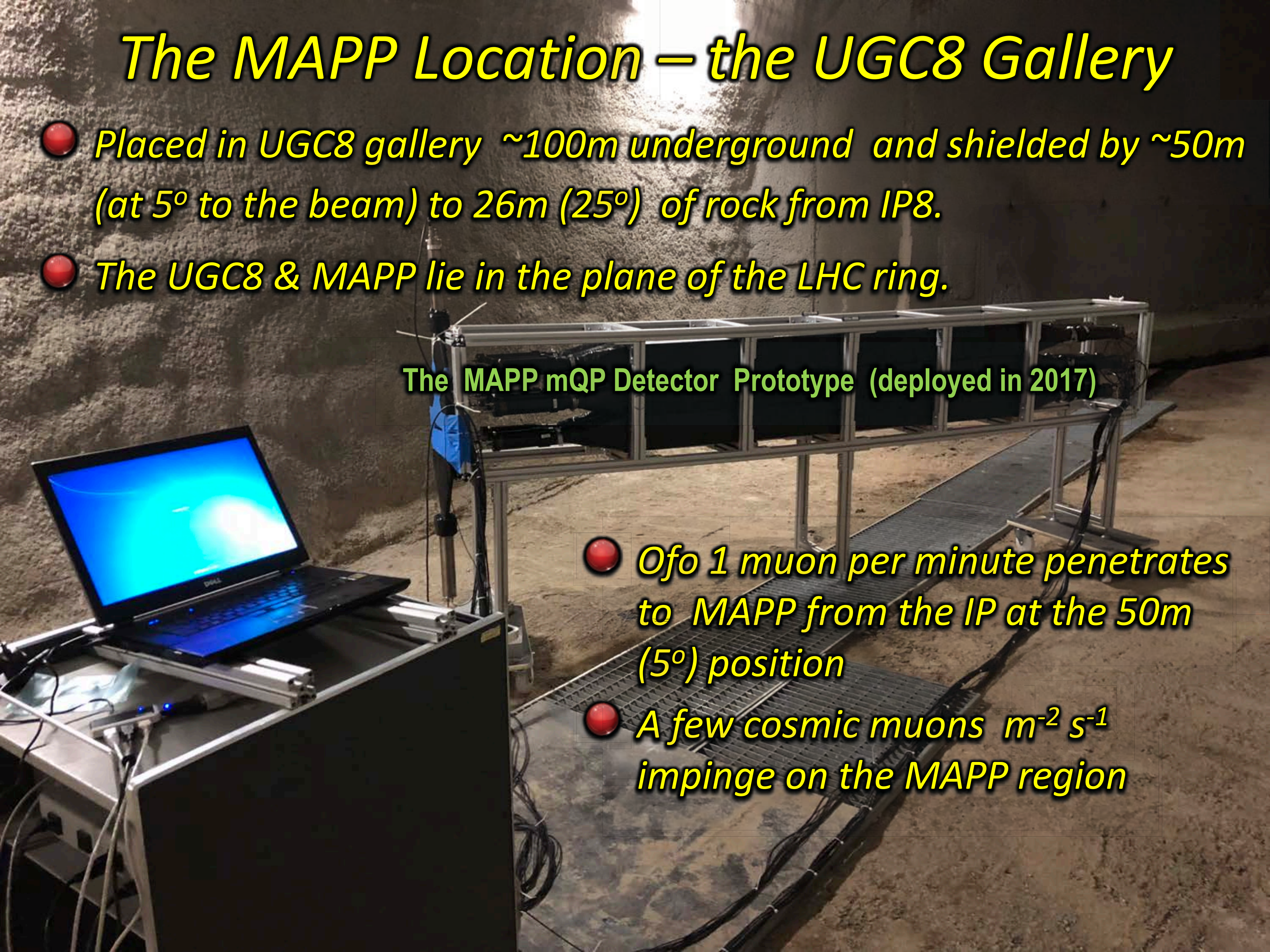
(MoEDAL Apparatus for Penetrating Particles)



- 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 weakly interacting neutrals with long lifetime
  - To search for other anomalously penetrating particles

The MAPP Location – the UGC8 Gallery

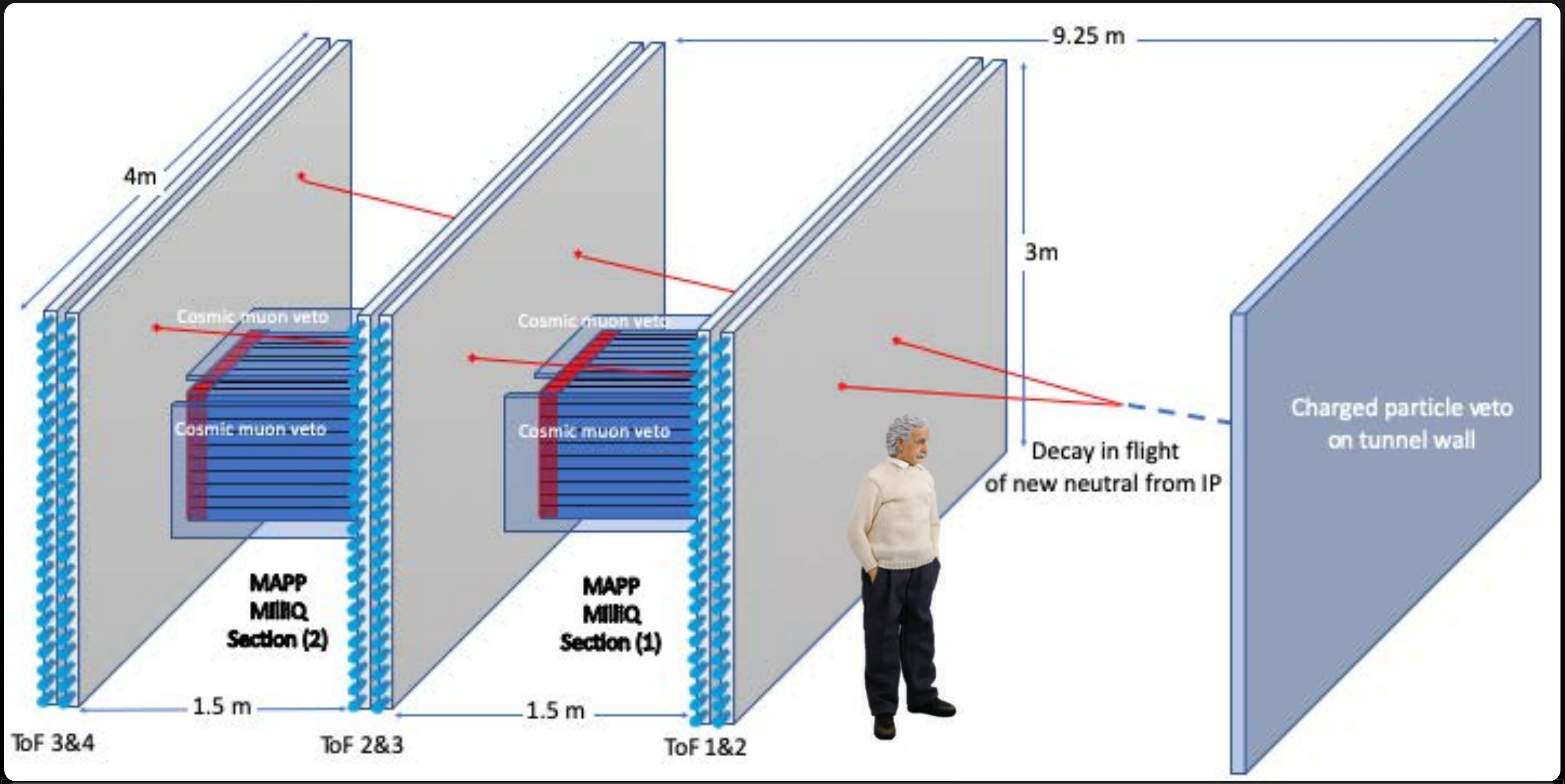
- *Placed in UGC8 gallery ~100m underground and shielded by ~50m (at 5^o to the beam) to 26m (25^o) of rock from IP8.*
- *The UGC8 & MAPP lie in the plane of the LHC ring.*



The MAPP mQP Detector Prototype (deployed in 2017)

- *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*

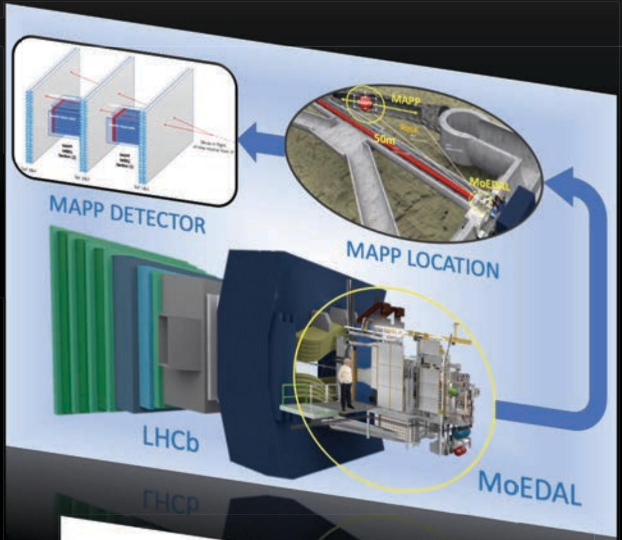
The MAPP Detector

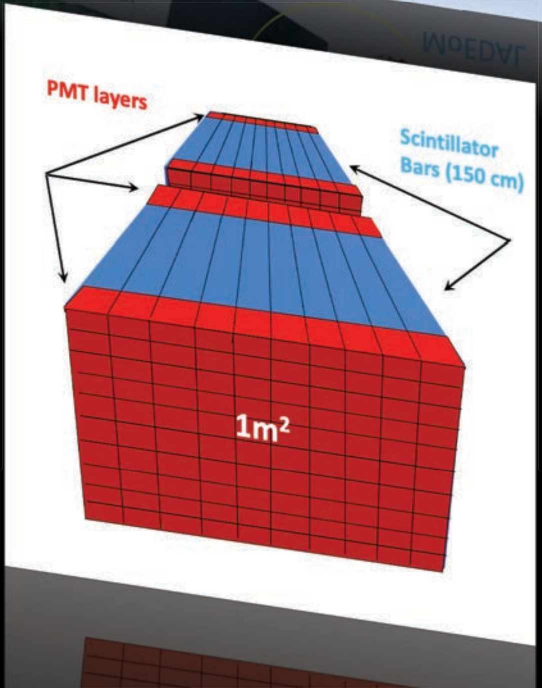


- *The MAPP (MoEDAL Apparatus for Penetrating Particles)*

MAPP: Mini-Charged Particle Detector

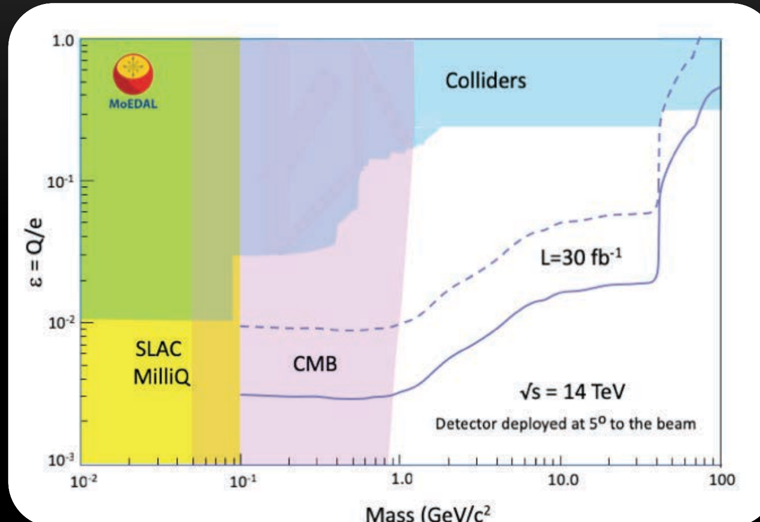
- *The Mini-charged particle (mQP) detector is a 1m x 1m x (2 x 1.5m) scintillator array, pointing to IP, in well shielded area of LHC Point 8 (LHCb)*
  - *Deployed from 5^o to the beam (at 55m) to 25^o to the beam (at 26 m)*
  - *Uses quadruple coincidence between the two scintillator bars) sections (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*

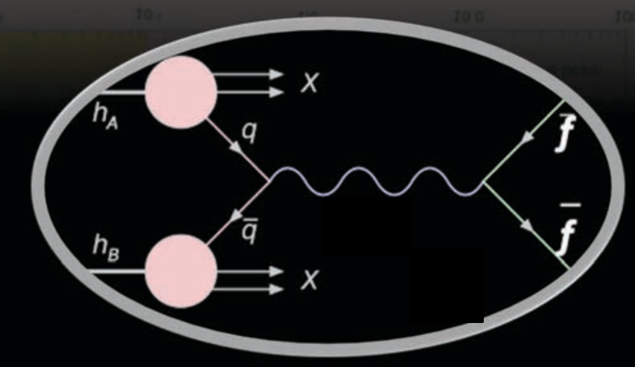




Example of MAPP Sensitivity for mQP

- MAPP will enable the search for particles with charge as low as ~10^{-3}e & masses above ~100 MeV. Simulations indicate that with 30 fb^{-1}:
  - We will have sensitivity to a charge of $\mathcal{O}(10^{-3})$ - $\mathcal{O}(10^{-3})$e for mass of $\mathcal{O}$(1) GeV & charge $\mathcal{O}(10^{-2})$ e for mass of $\mathcal{O}$(10) GeV.
- MoEDAL is competitive with other more centrally placed new 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 (5^o to the beam) enhances the acceptance of MAPP for "forward-backward" biased physics

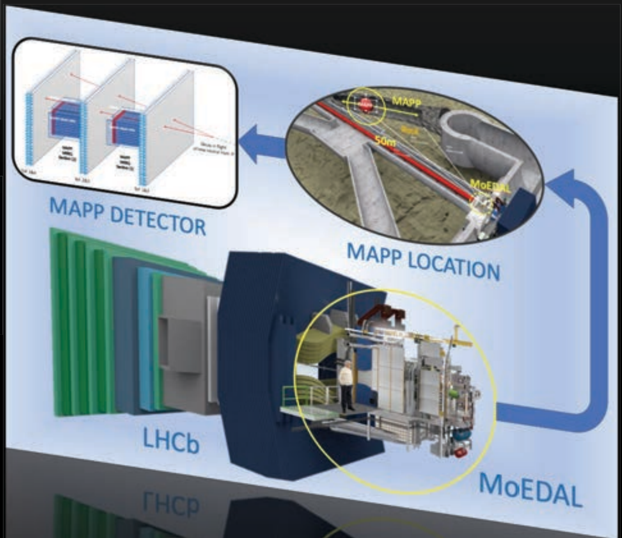


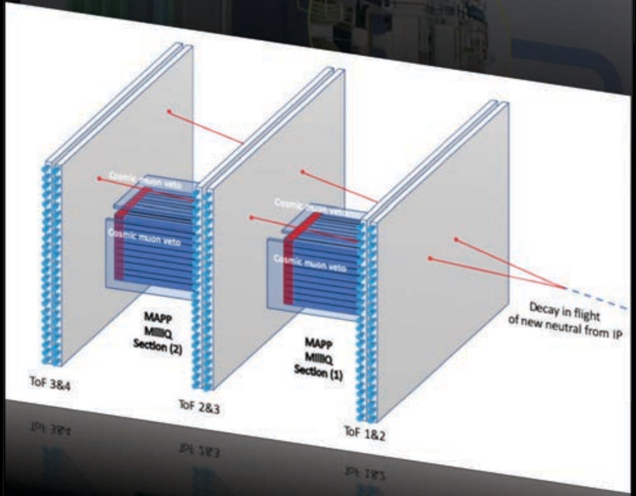


The direct and indirect bounds on mQPs for models with a massless dark photon qnd the max. projected reach of MAPP for RUN-3 (---line 10% overall MAPP eff.)

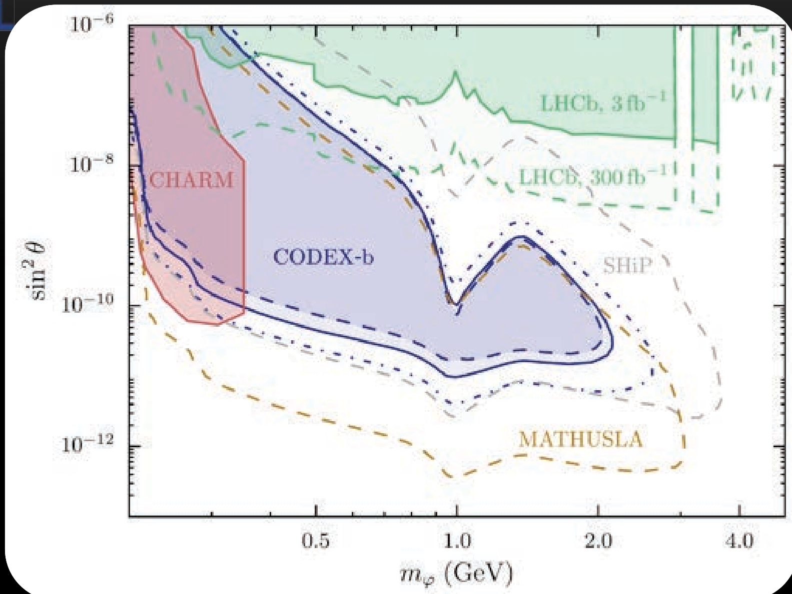
MAPP – Long Lived Particle Detector

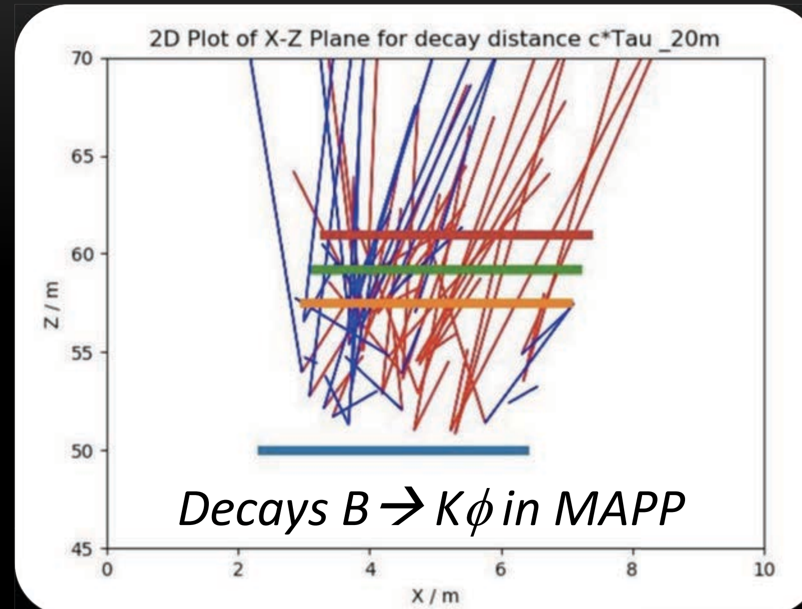
- The Long Lived Particle (LLP) detector is formed from 3 pairs of 3m x 4m scintillator hodoscopes, pointing to IP
- RPCs are also being investigated as a an alternative to scintillator
  - Deployed from 5^o to the beam (at 55m) to 25^o to the beam (at 26 m)
  - 7-10m decay zones in front of first plane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





Example of MAPP Sensitivity for LLPs





- *We envisage the full MAPP detector will operate in RUN-3 (30fb^{-1} 2021 -24)*
  - *Our max. fid. eff. for $B \rightarrow X_s\phi$ is a few x 10^{-4} (similar to full CODEX-b detector)*
    - *A Higgs mixing portal admits exotic inclusive $B \rightarrow Xs\phi$ decays, in which φ is a light CP-even scalar that mixes with the Higgs, with mixing angle $\vartheta \ll 1$.*
  - *Our limit curve for $B \rightarrow X_c\phi$ is in the process of being “blessed” but we expect it to be very competitive with that obtained with CODEX-b’s full detector that will deploy for HL-LHC (from 2026)*

Concluding Remarks

"So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value."

Spanish Royal Commission, rejecting Columbus' proposal to sail west.

With the good ships "highly ionizing particles", "fractionally charged particles" "new long-lived particles" MoEDAL will during RUN-3 explore far beyond the shores of the Terra Firma of the Standard Model hopefully to explore the "Terra Incogniito" of the next Standard Model