The Search for the Magnetic Monopole in the LHC Era

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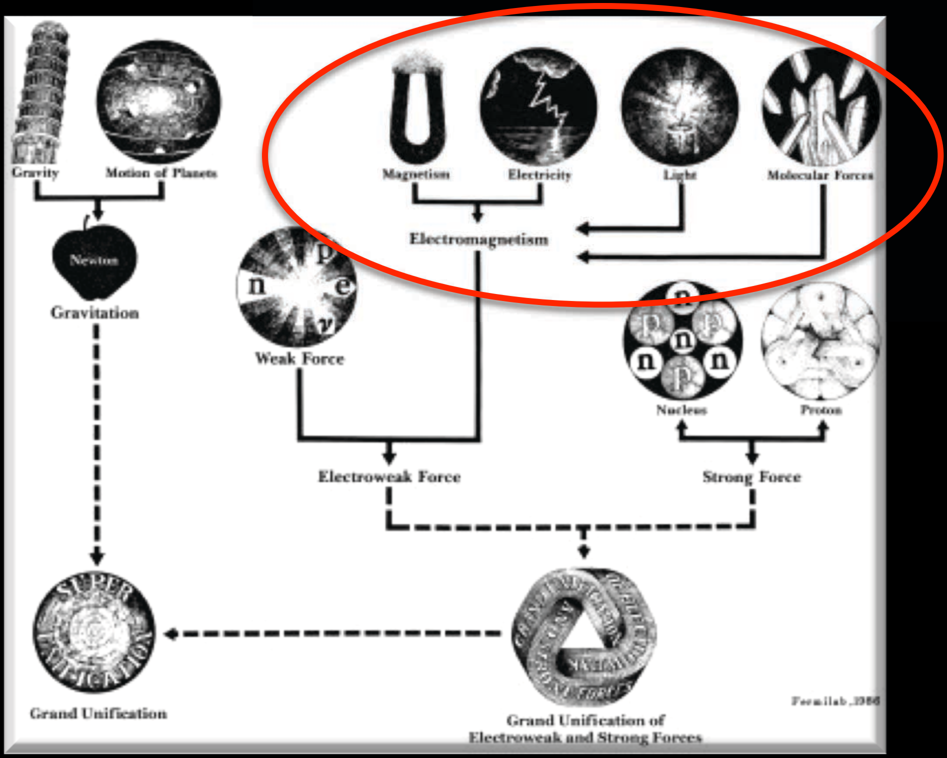
The Menu

- *A little history*
- *Dirac's Monopole*
- *t'Hooft's Monopole*
- *The Cho-Maison Monopole*
- *Collider Searches*
- *The MoEDAL experiment*
  - *Introduction*
  - *The Physics Program*
  - *The detector*
- *Last Words*

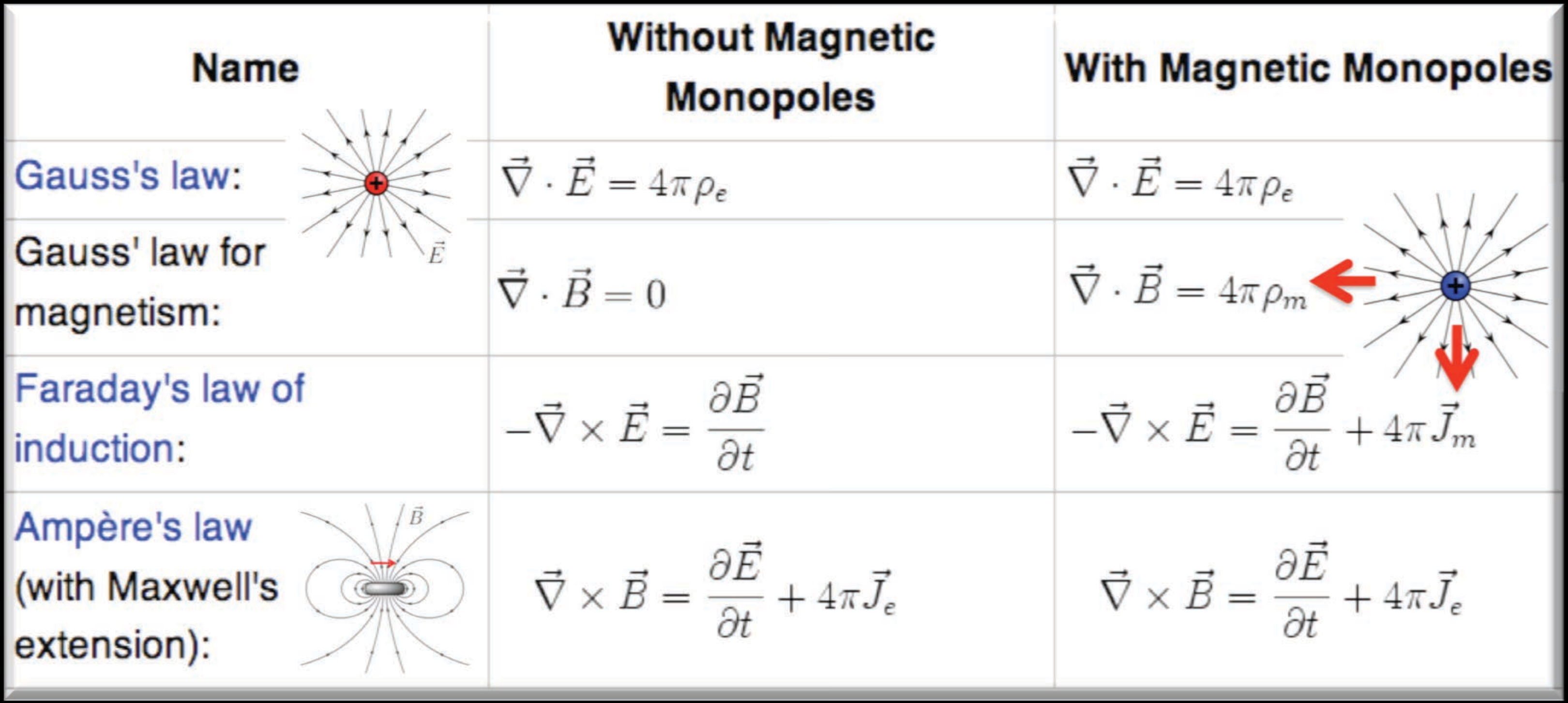
Aim of the experiment – sear
for the highly ionizing particle
avatars of new physics e.g
the Magnetic Monopole

Maxwell's Grand Unification



- *Maxwell, in 1873, makes the connection between electricity & magnetism – the Victorian Grand Unified Theory!*
- *The theoretical work that led him to this unification was mostly carried out King's College London*

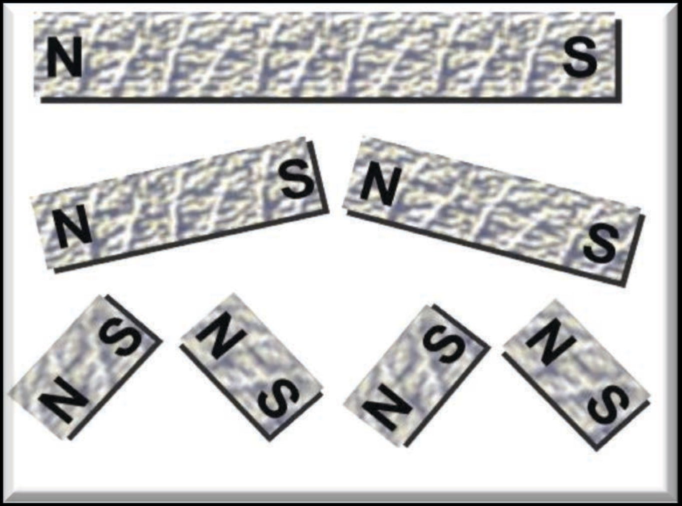
Maxwell's Asymmetric Equations



Name	Without Magnetic Monopoles	With Magnetic Monopoles
Gauss's law:	$\vec{\nabla}\cdot\vec{E} = 4\pi\rho_e$	$\vec{\nabla}\cdot\vec{E} = 4\pi\rho_e$
Gauss' law for magnetism:	$\vec{\nabla}\cdot\vec{B} = 0$	$\vec{\nabla}\cdot\vec{B} = 4\pi\rho_m$
Faraday's law of induction:	$-\vec{\nabla}\times\vec{E} = \frac{\partial\vec{B}}{\partial t}$	$-\vec{\nabla}\times\vec{E} = \frac{\partial\vec{B}}{\partial t} + 4\pi\vec{J}_m$
Ampère's law (with Maxwell's extension):	$\vec{\nabla}\times\vec{B} = \frac{\partial\vec{E}}{\partial t} + 4\pi\vec{J}_e$	$\vec{\nabla}\times\vec{B} = \frac{\partial\vec{E}}{\partial t} + 4\pi\vec{J}_e$

- ***Maxwell**, in 1873, makes the connection between electricity and magnetism - the first Grand Unified Theory!*
- *As no magnetic monopole had ever been seen Maxwell cut isolated magnetic charges from his equations - making them asymmetric*

Monopoles Symmetrize Maxwell’s Eqns



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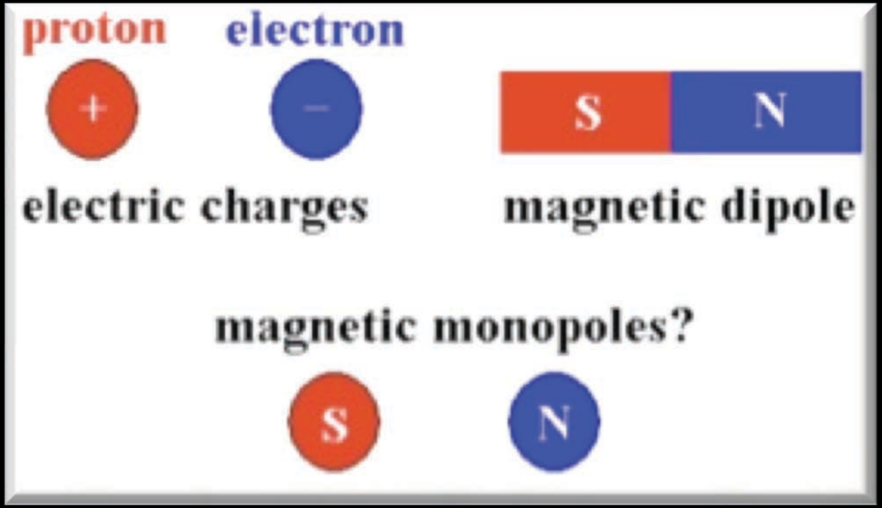
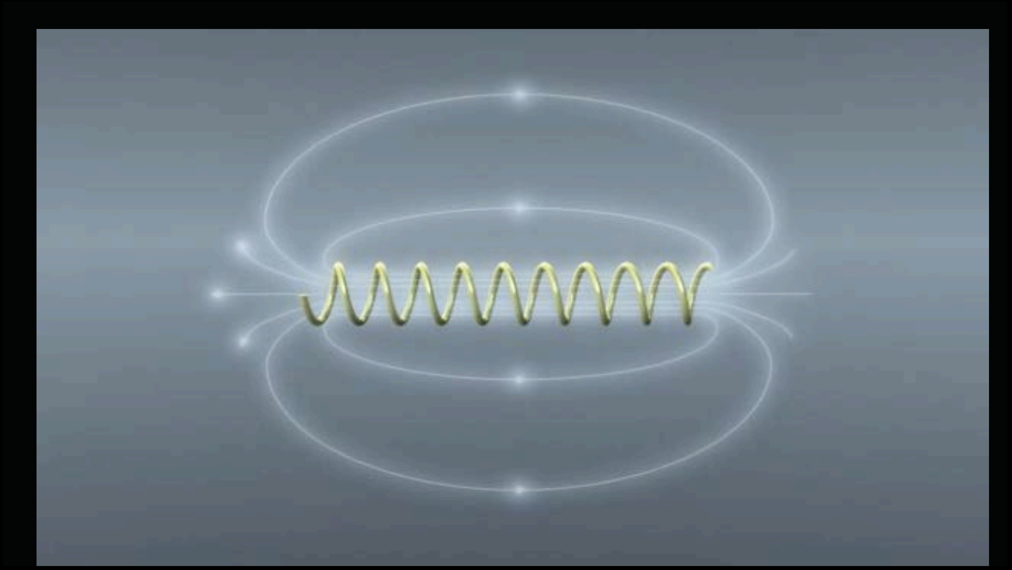


- *A magnetic monopole restores symmetry to Maxwell’s eqns*
- *The symmetrized Maxwell’s equations are invariant under rotations in the plane of the electric and magnetic field*

$$\begin{pmatrix} \vec{E}' \\ \vec{B}' \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \vec{E} \\ \vec{B} \end{pmatrix}$$

- *This symmetry is called Duality - the distinction between electric and magnetic charge is merely one of definition*

Dirac’s Monopole

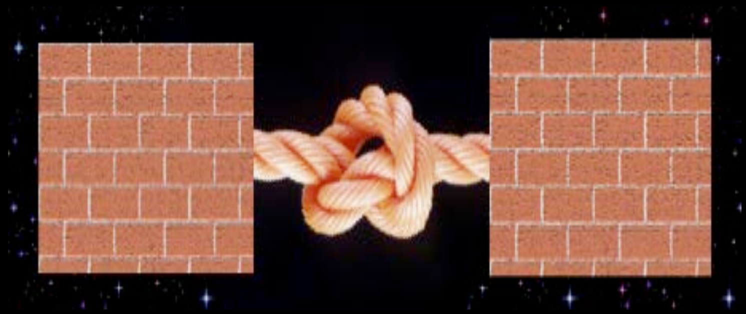


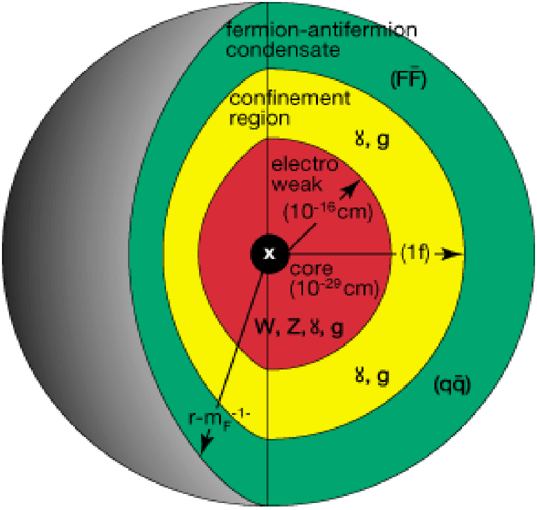
- *In 1931 Dirac hypothesized that the Monopole exists as the end of an infinitely long and thin solenoid - the “Dirac String”*
- *Requiring that the string is not seen gives us the Dirac Quantization Condition & explains the quantization of charge!*

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

The ‘t Hooft-Polyakov Monopole

Gerard t’Hooft

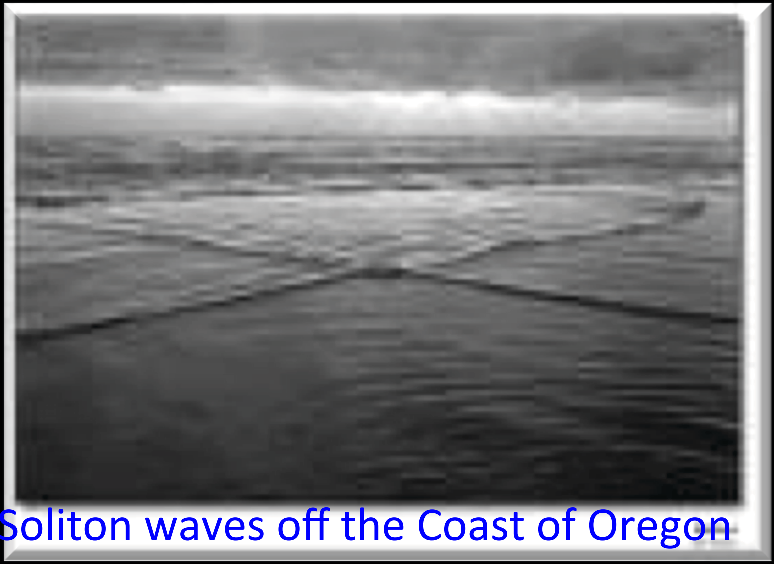




- *In 1974 ‘t Hooft and Polyakov found that many (non-Abelian) Grand Unified gauge theories predict Monopoles*
  - *Such monopoles are topological solitons(stable, non dissipative, finite energy solutions) with a topological charge*
  - *The topology of the soliton’s field configuration gives stability EG a knot in a rope fixed at the ends (boundary conditions)*
- *Produced in the early Universe at G.U.T. phase transition a GUM is a tiny replica of the Big Bang with mass ~ 0.02 μg*

Solitons in Our Everyday World

The Grand Union Canal



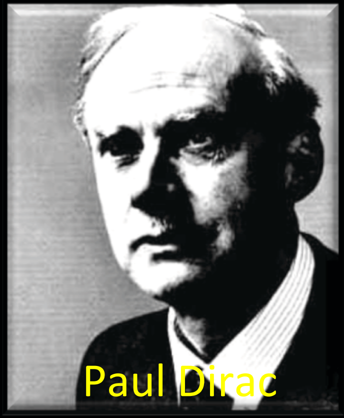
Soliton waves off the Coast of Oregon

- *The first reported instanton phenomenon was described by John Russell in 1834*
  - *He saw a canal barge create a wave as it pushed its way along the Union Canal near Edinburgh.*
  - *The soliton was seen as a wave that moved down the canal without dissipating until it was out of sight.*

The Cho-Maison Magnetic Monopole


Gerard ‘t Hooft


Yongmin Cho


Paul Dirac

- *Yongmin Cho produced a pioneering paper in 1986 in which he envisioned a new type of spherically symmetric Electroweak Standard Model Monopole, with:*
  - *Magnetic charge $2g_D$ - ionization ~19,000 x MIP!*
  - *Mass in the range 4→7 GeV/c^2*
- *The Cho monopole is a non-trivial hybrid between the abelian Dirac monopole and the non-abelian ‘t Hooft-Polyakov monopole*
- *Cho-Maison monopole would be detected by MoEDAL*

Magnetic Monopole Properties

Magnetic charge $g = n68.5e$
highly Ionizing. If the
fundamental charge is 1/3
$g = 3n68.5e$

Coupling constant =
g/Ћc ~ 34 for n=1
Spin ½?

Energy acquired in
a magnetic field
=2.06MeV/gauss.m
= 2TeV in a 10m,
10T LHC magnet

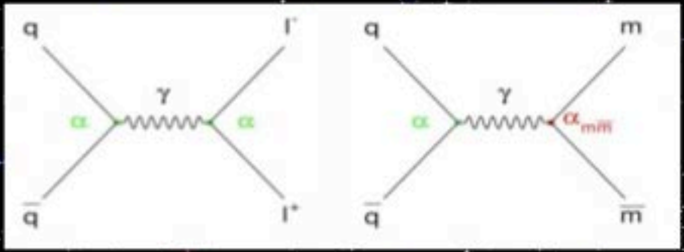
The monopole mass is
not predicted within
the Dirac's theory.

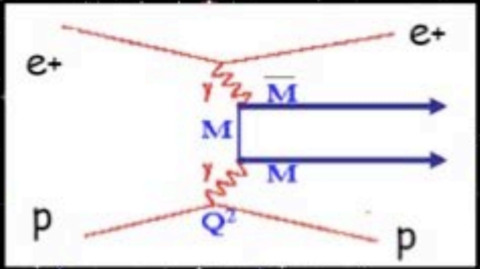
Collider Searches

Monopole Production at Colliders

$$e^+e^- \rightarrow M\,M\,,\quad \overline{p}p \rightarrow M\,\overline{M}\,,\quad pp \rightarrow pp\,M\,\overline{M}$$

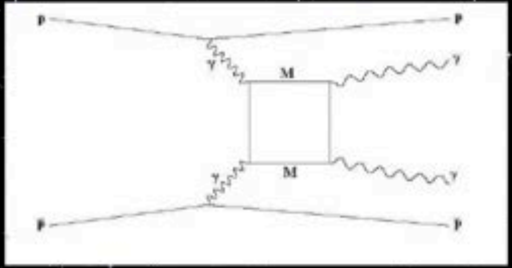
Drell-Yan mechanism (Direct)





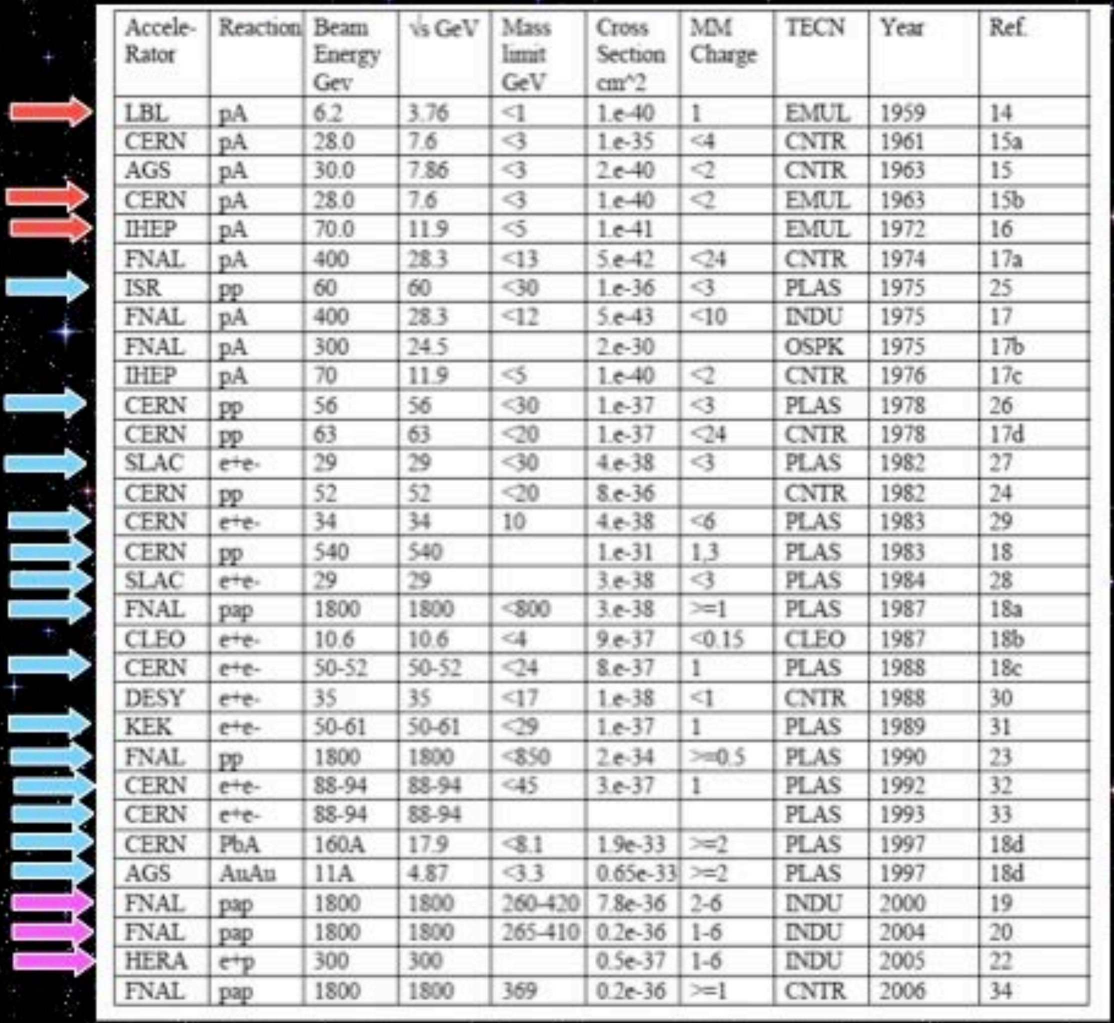
Two-photon interactions (Direct)

"Monopole-box" diagram (Indirect)



- *CDF excluded MM pair production at the 95% CL for cross-section < 0.2 pb and monopole masses 200 < m_M < 700 GeV/c^2*

A History of Accelerator Searches



Accele-Rator	Reaction	Beam Energy Gev	$\sqrt{s}$ GeV	Mass limit GeV	Cross Section cm^2	MM Charge	TECN	Year	Ref.
LBL	pA	6.2	3.76	<1	1.e-40	1	EMUL	1959	14
CERN	pA	28.0	7.6	<3	1.e-35	<4	CNTR	1961	15a
AGS	pA	30.0	7.86	<3	2.e-40	<2	CNTR	1963	15
CERN	pA	28.0	7.6	<3	1.e-40	<2	EMUL	1963	15b
IHEP	pA	70.0	11.9	<5	1.e-41		EMUL	1972	16
FNAL	pA	400	28.3	<13	5.e-42	<24	CNTR	1974	17a
ISR	pp	60	60	<30	1.e-36	<3	PLAS	1975	25
FNAL	pA	400	28.3	<12	5.e-43	<10	INDU	1975	17
FNAL	pA	300	24.5		2.e-30		OSPK	1975	17b
IHEP	pA	70	11.9	<5	1.e-40	<2	CNTR	1976	17c
CERN	pp	56	56	<30	1.e-37	<3	PLAS	1978	26
CERN	pp	63	63	<20	1.e-37	<24	CNTR	1978	17d
SLAC	e+e-	29	29	<30	4.e-38	<3	PLAS	1982	27
CERN	pp	52	52	<20	8.e-36		CNTR	1982	24
CERN	e+e-	34	34	10	4.e-38	<6	PLAS	1983	29
CERN	pp	540	540		1.e-31	1,3	PLAS	1983	18
SLAC	e+e-	29	29		3.e-38	<3	PLAS	1984	28
FNAL	pap	1800	1800	<800	3.e-38	>=1	PLAS	1987	18a
CLEO	e+e-	10.6	10.6	<4	9.e-37	<0.15	CLEO	1987	18b
CERN	e+e-	50-52	50-52	<24	8.e-37	1	PLAS	1988	18c
DESY	e+e-	35	35	<17	1.e-38	<1	CNTR	1988	30
KEK	e+e-	50-61	50-61	<29	1.e-37	1	PLAS	1989	31
FNAL	pp	1800	1800	<850	2.e-34	>=0.5	PLAS	1990	23
CERN	e+e-	88-94	88-94	<45	3.e-37	1	PLAS	1992	32
CERN	e+e-	88-94	88-94				PLAS	1993	33
CERN	PbA	160A	17.9	<8.1	1.9e-33	>=2	PLAS	1997	18d
AGS	AuAu	11A	4.87	<3.3	0.65e-33	>=2	PLAS	1997	18d
FNAL	pap	1800	1800	260-420	7.8e-36	2-6	INDU	2000	19
FNAL	pap	1800	1800	265-410	0.2e-36	1-6	INDU	2004	20
HERA	e+p	300	300		0.5e-37	1-6	INDU	2005	22
FNAL	pap	1800	1800	369	0.2e-36	>=1	CNTR	2006	34

31 searches

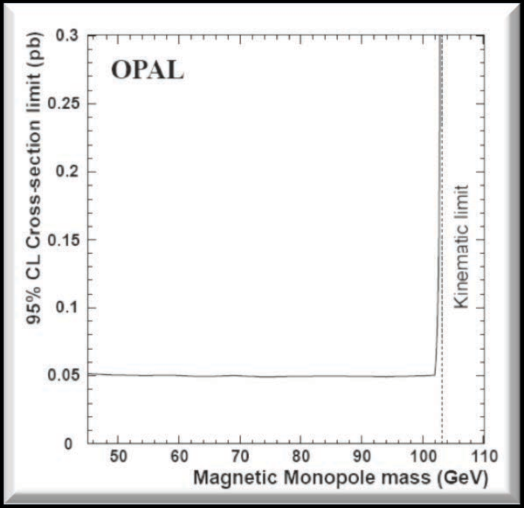
14 using Plastic NTDs

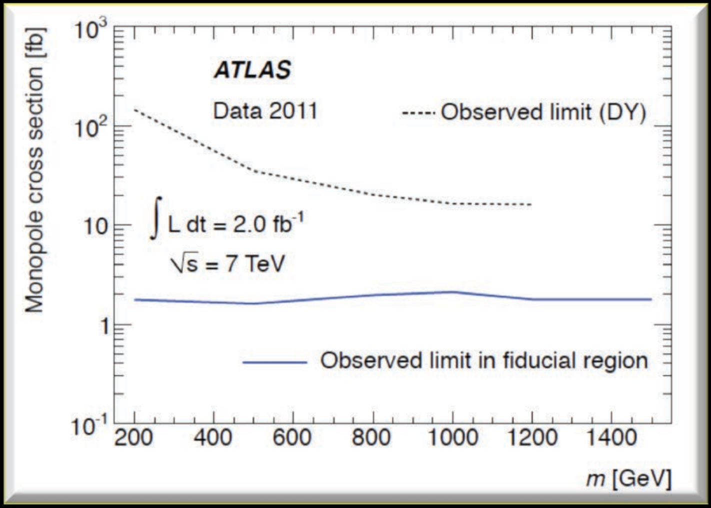
3 using emulsions

3 using induction

11 using counters

Recent Direct Searches (last 5 years)

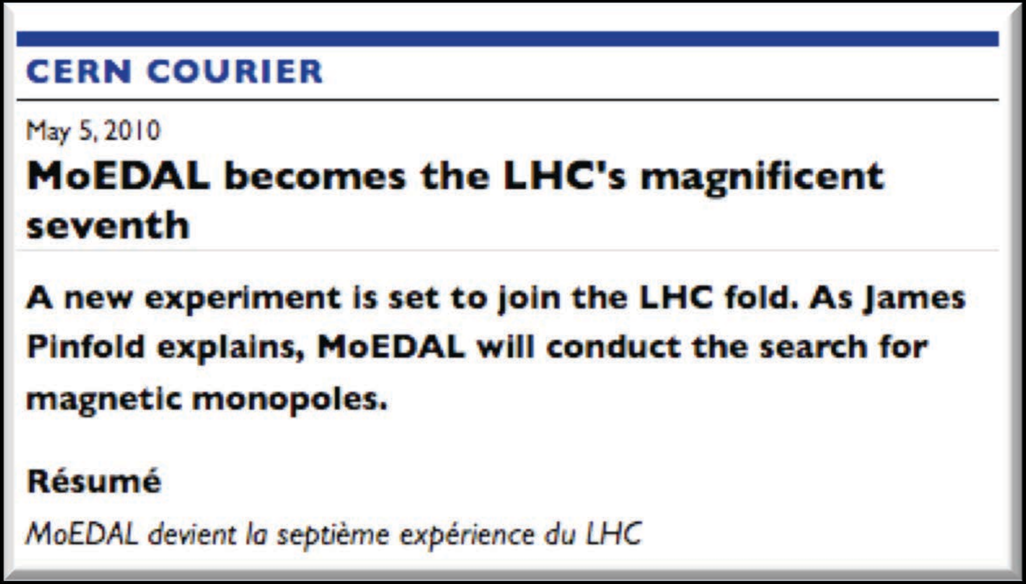




- *OPAL (2008) searched for MM pairs at* **$\sqrt{}$***s = 206.3 GeV in 62.7 pb^{-1} based on the mom. & E_{loss} in the OPAL tracking chamber*
  - *The 95% CL cross section upper limit for the production of monopoles with 45 GeV/c^2 < m_M < 104 GeV/c^2 was 0.05 pb*
- *ATLAS(2012) searched for MM pairs at* **$\sqrt{}$***s = 7 TeV in 2 fb^{-1} based on the momentum & E_{loss} in the OPAL tracking chamber*
  - *The 95% CL cross section upper limit for the production of monopoles with 200 GeV/c^2 < m_M < 1500 GeV/c^2 was 2 pb*

The MoEDAL Detector
Future Search
for the Monopole
at the LHC

MoEDAL the 7th LHC Experiment



CERN COURIER

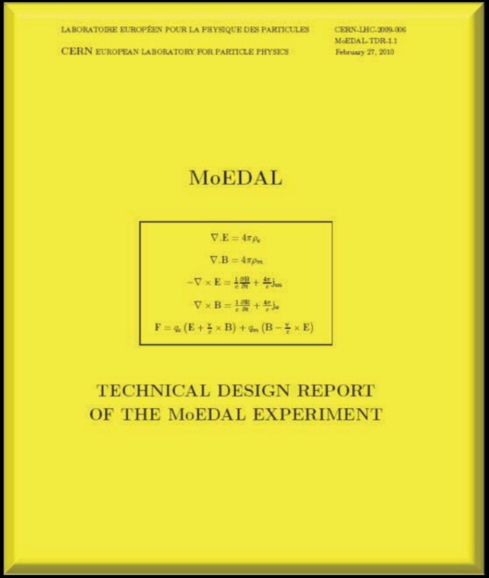
May 5, 2010

MoEDAL becomes the LHC's magnificent seventh

A new experiment is set to join the LHC fold. As James Pinfold explains, MoEDAL will conduct the search for magnetic monopoles.

Résumé

MoEDAL devient la septième expérience du LHC



LABORATOIRE EUROPÉEN POUR LA PHYSIQUE DES PARTICULES

CERN EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN-LHC-2009-006
MoEDAL-TDR-1.1
February 27, 2010

MoEDAL

$$\boxed{\begin{gathered}\nabla.\mathbf{E} = 4\pi\rho_e \\ \nabla.\mathbf{B} = 4\pi\rho_m \\ -\nabla\times\mathbf{E} = \frac{1}{c}\frac{\partial\mathbf{B}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_m \\ \nabla\times\mathbf{B} = \frac{1}{c}\frac{\partial\mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_e \\ \mathbf{F} = q_e\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right) + q_m\left(\mathbf{B} - \frac{\mathbf{v}}{c}\times\mathbf{E}\right)\end{gathered}}$$

TECHNICAL DESIGN REPORT
OF THE MoEDAL EXPERIMENT

- *The MoEDAL experiment the 7th LHC experiment was officially approved by the CERN Research Board on March 3rd 2010*
- *MoEDAL shares the 8th LHC IP with the LHCb experiment*
- *MoEDAL is an array of passive Nuclear Track-Etch Detectors & Trapping Detectors - with a MediPix chip online radiation monitor system*

The MoEDAL Collaboration

- *42 Physicists from:*
  - *19 Institutes: University of Alberta, UBC, CERN, Concordia, Cincinnati, CTU Prague, Geneva, Helsinki, Imperial College London, INFN Bologna, ISC Bucharest**,** King’s College London**,** Konkuk University, University of Muenster, Northeastern, Tuft’s University, Valencia, York*
  - *11 Countries: Canada, Czech Republic, Finland, Germany, Italy, Korea, Romania, Spain, Switzerland**,** **UK**, USA*

Where is the MoEDAL Experiment?

MoEDAL shares intersection point 8 on the LHC ring with LHCb

The MoEDAL Experiment Revealed

The MoEDAL Detector – a Tour

DETECTOR SYSTEMS

1)The TDR NTD array $(Z/\beta > \sim 5)$

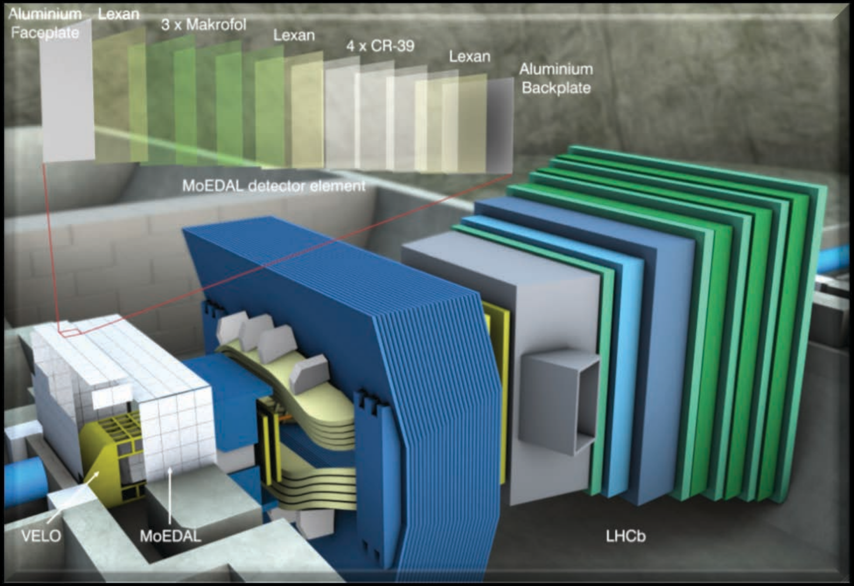
2)The Very High Charge Catcher NTD array $(Z/\beta > \sim 50)$

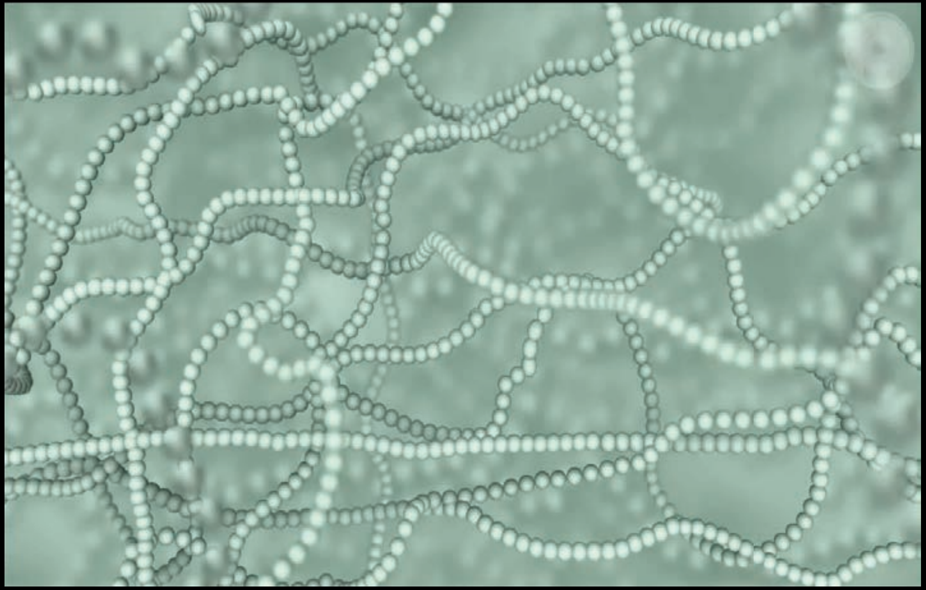
3)The Monopole Trapping detector

4)The TimePix radiation background monitor

- *MoEDAL is unlike any other LHC experiment:*
  - *The largest deployment of passive Nuclear Track Detectors (NTDs) at an accelerator*
  - *The 1st time trapping detectors will be deployed as a detector*

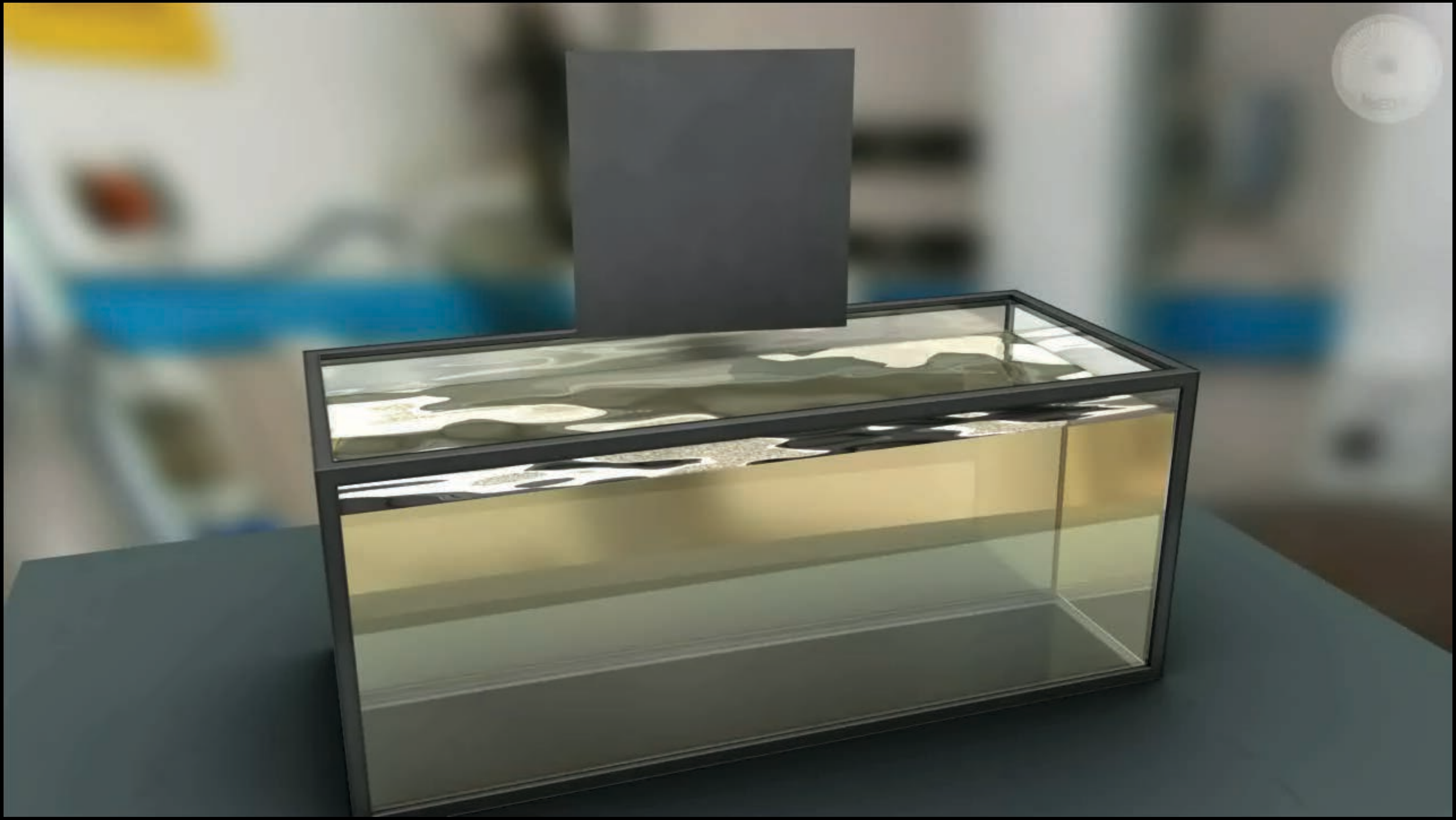
MoEDAL NTDs- How They Work





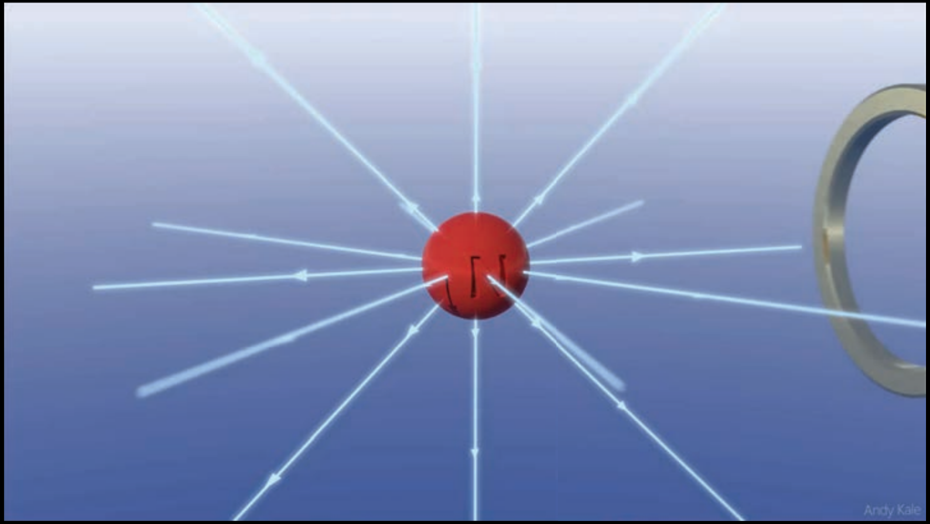
- *The highly ionizing particle leaves a cylindrical trail of damage in the plastic track etch detectors*
- *NTDs are passive detectors that don't need extensive support structures or HV, gas, electronic readout or trigger & are insensitive to relativistic SM particles*

The Etching Process



- *Tracks are revealed as conical etch pits by controlled etching of the NTD with charge resolution ~0.05e and spatial resolution ~ 10 microns/pit – pointing to the IP*

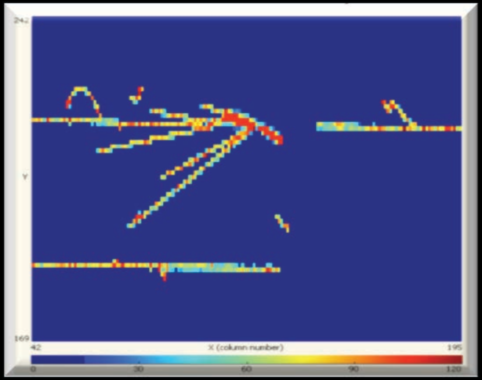
The Trapping Detector (MMT)

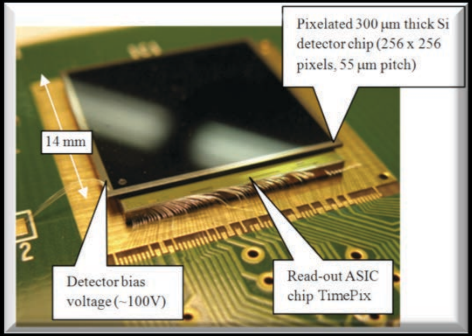


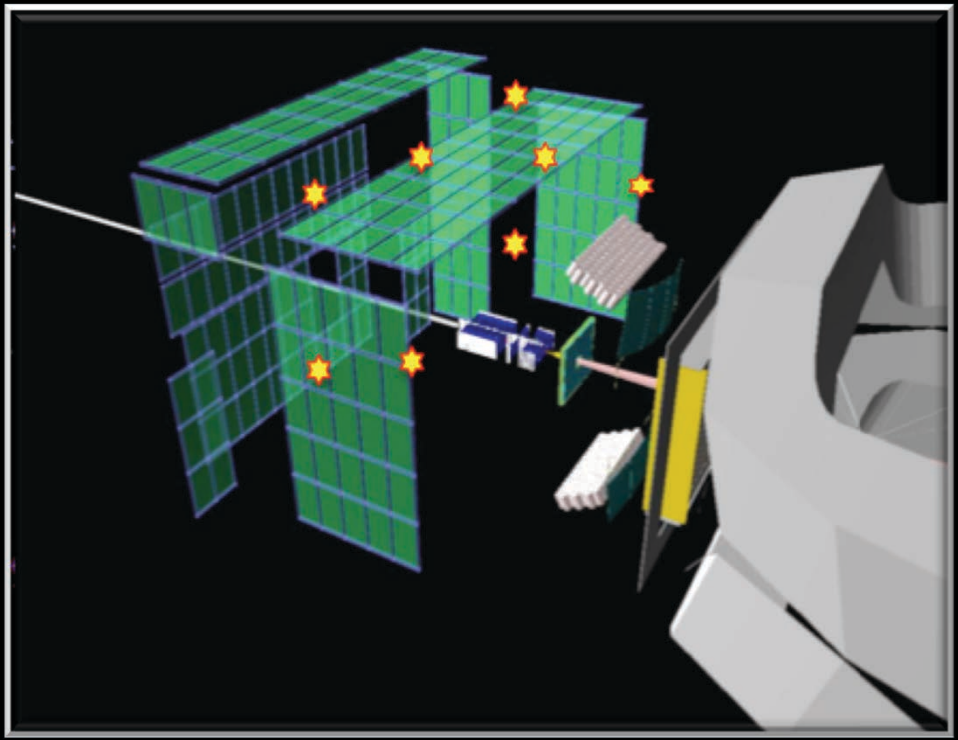
SQUID magnetometer (Southhampton)

- *We will deploy trapping volumes 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 we can measure a magnetic field corresponding to* $\geq 0.1\ g_D$
  - *SNOLAB (2km underground) to detect decays of MSPs*

The TimePix Radiation Monitor



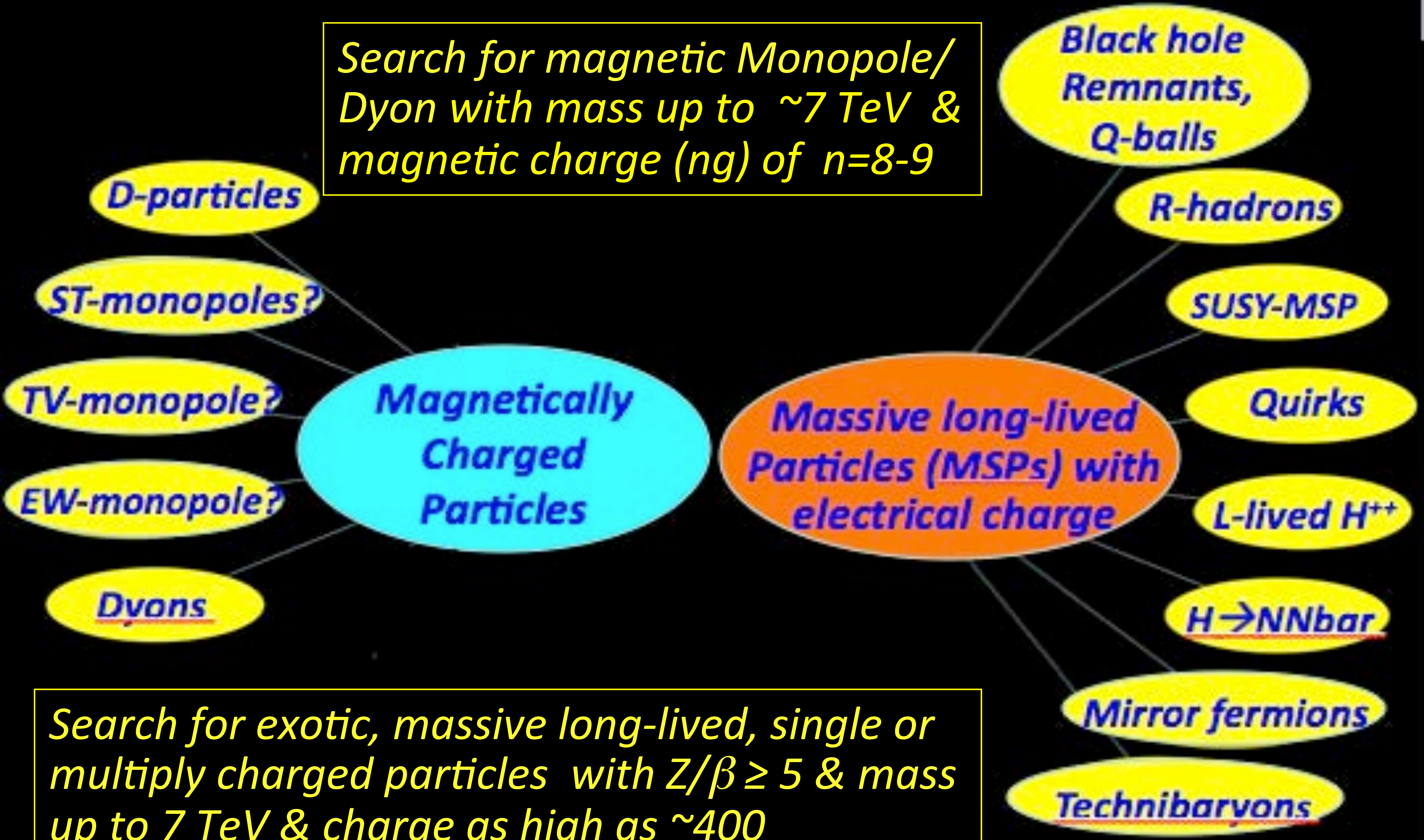




- *Timepix (MediPix) chips are used to measure online the radiation field + measure the spallation product background*
- *The Timepix chip pixels are instrumented with an amplifier + comparator + counter + timer (allows TOT energy measurement)*
- *The TimePix chip is essentially an electronic bubble chamber*

The MoEDAL Physics Program

Search for magnetic Monopole/ Dyon with mass up to ~7 TeV & magnetic charge (ng) of n=8-9



Magnetically Charged Particles

- D-particles
- ST-monopoles?
- TV-monopole?
- EW-monopole?
- Dyons

Massive long-lived Particles (MSPs) with electrical charge

- Black hole Remnants, Q-balls
- R-hadrons
- SUSY-MSP
- Quirks
- L-lived H^{++}
- H→NNbar
- Mirror fermions
- Technibaryons

Search for exotic, massive long-lived, single or multiply charged particles with $Z/\beta \geq 5$ & mass up to 7 TeV & charge as high as ~400

MoEDAL Complements ATLAS & CMS

ATLAS+CMS

- *The main LHC detectors are optimized for the detection of singly (electrically) charged (or neutral) particles (Z/β~1) moving near to the speed of light ($\beta > 0.5$)*
- *Typically a largish statistical sample is needed to establish a signal*

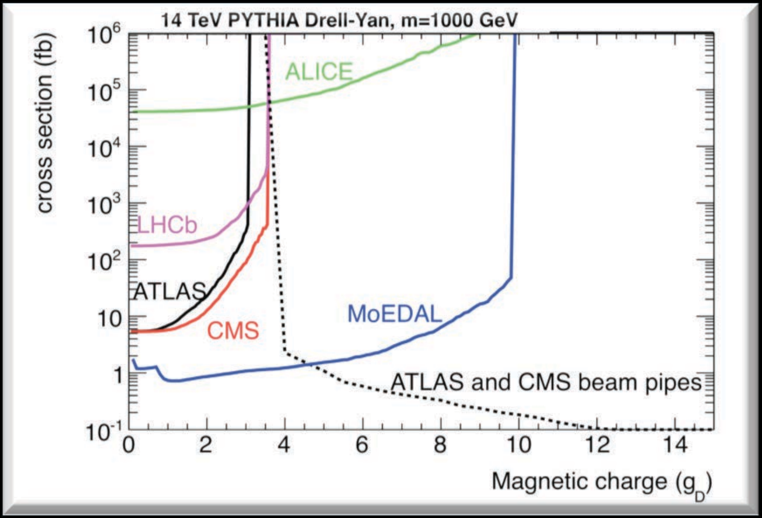
MoEDAL

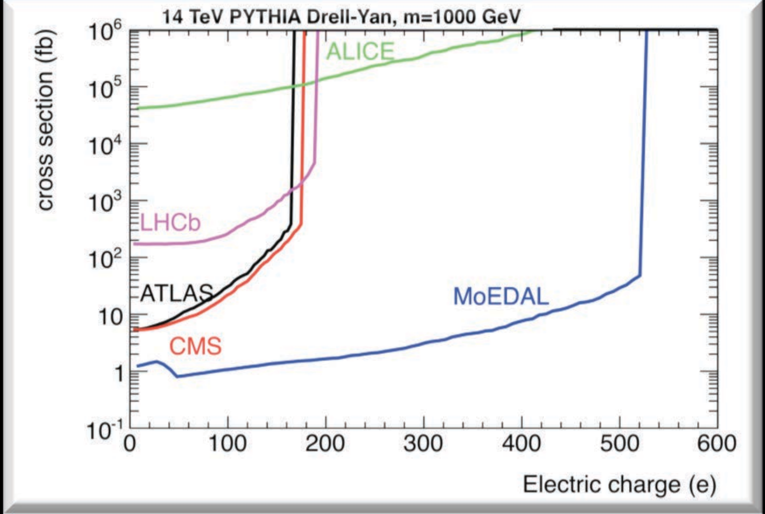
- *MoEDAL is designed to detect charged particles, with effective or actual $Z/\beta > 5$.*
- *As it has no trigger/ electronics slowly moving ($\beta <$ ~5) particles are no problem*
- *One candidate event is enough to establish the signal (no Standard Model backgrounds)*

MoEDAL is complementary to the main LHC experiments and expands the physics reach of LHC

MoEDAL 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 ✓

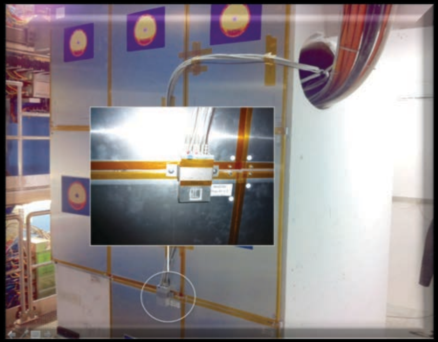




- *Cross-section limits for magnetic (L) and electric charge (R) (from **arXiv:1112.2999V2** [hep-ph]) assuming:*
  - *Only one MoEDAL event is required for discovery and ~100 events in the other (active) LHC detectors*

The MoEDAL Timescale

- *First detectors (10 sqm of plastic) deployed in Nov. 2009)*
- *We deployed a larger area of plastic (~80 m^2) in Jan. 2011*
- *Test deployment of TimePix detectors in Feb. 2012*
- *Test Deployment of MMT sub-detector in Sept. 2012*
- *Full deployment is planned for the year long shutdown starting in 2013/2014.*
- *In 2015 expect to have our first "official" run to be continued until we reach a ΣL of $\geq$ ~10fb^{-1} at 14 TeV.*



Last Words

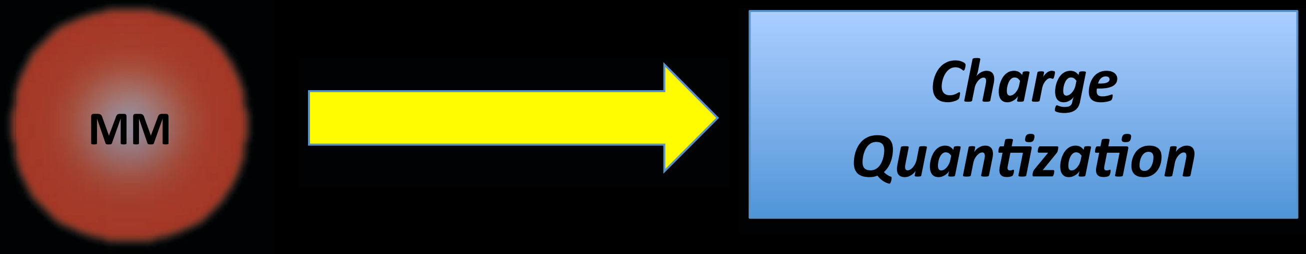
On the Existence of the Monopole

- ***Dirac** felt that he "would be surprised if Nature had made no use of it". It, being the Magnetic Monopole.*

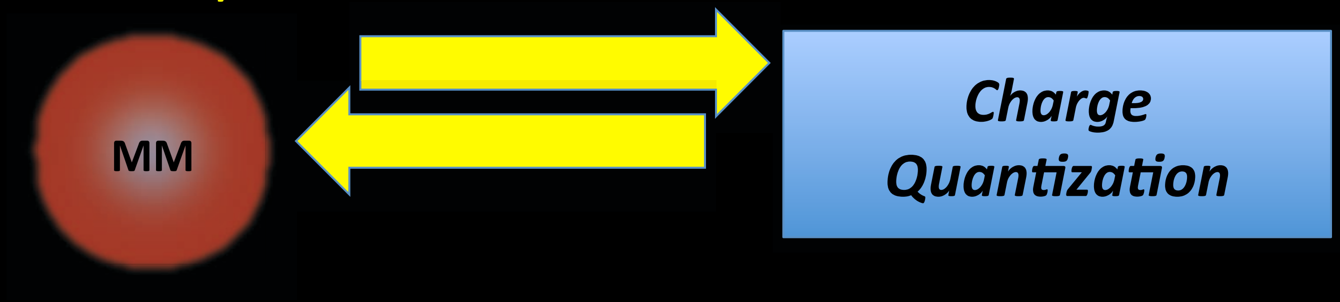
- ***Ed Witten** once asserted in his Loeb Lecture at Harvard, "almost all theoretical physicists believe in the existence of magnetic monopoles, or at least hope that there is one."*

The Polchinski Conjecture

- *Dirac showed that the existence of at least one magnetic monopole would explain charge quantization*



- *Thus, the leading string theorist Joseph Polchinski conjectured, any theory requiring charge quantization must have a monopole*



- *He also maintains that in any fully unified theory, for every gauge field there will exist electric and magnetic sources.*

The Polchinski Conjecture

I would like to express my strong support for the MoEDAL experiment. Although monopoles do not get as much press as dark energy and other hot topics, in fact they are the most certain prediction of theory beyond the Standard Model - more so than supersymmetry, strings, extra dimensions, modified gravity, or many other widely discussed ideas. As I have discussed in my Dirac Centenary Talk, their existence seems inevitable in any framework that explains the quantization of electric charge. Of course their mass scale and abundance are highly uncertain, but the same can be said for almost any other form of new physics