The Hunt for Magnetic Monopoles

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MoEDAL

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IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

EXCELENCIA SEVERO OCHOA

OUTLINE

- **Why Monopoles? A brief history and properties**

- **Overview of Magnetic Monopole types:**
  wide range of mass: 0,02 μg (10^{16} GeV) → 10^{-15} μg (~TeV)

- ***Model independent (as much as possible) searches for TeV monopole***
  – MoEDAL results / bounds from 2012 8 TeV RUN I LHC

Novel developments in this talk:

- **The price of an electroweak Monopole**

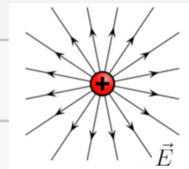
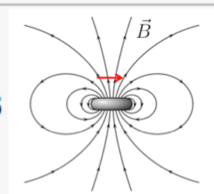
  Ellis, NEM & You
  PLB 756, 29 (2016)

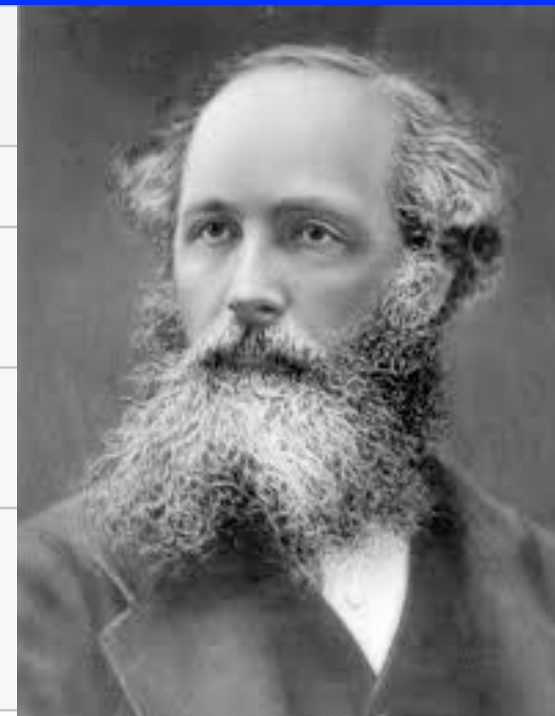
- **Global Monopoles inducing magnetic charge**

  NEM & Sarkar 2016

A Brief History of MONOPOLES

Maxwell's Asymmetric Equations

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



- ***Maxwell**, in 1873 (@ KCL), 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*

Heaviside's form in terms of E, B

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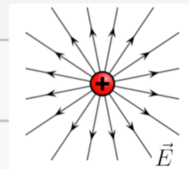
Gauss's law: 	$\vec{\nabla} \cdot \vec{E} = 4\pi\rho_e$
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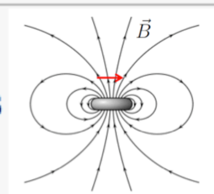
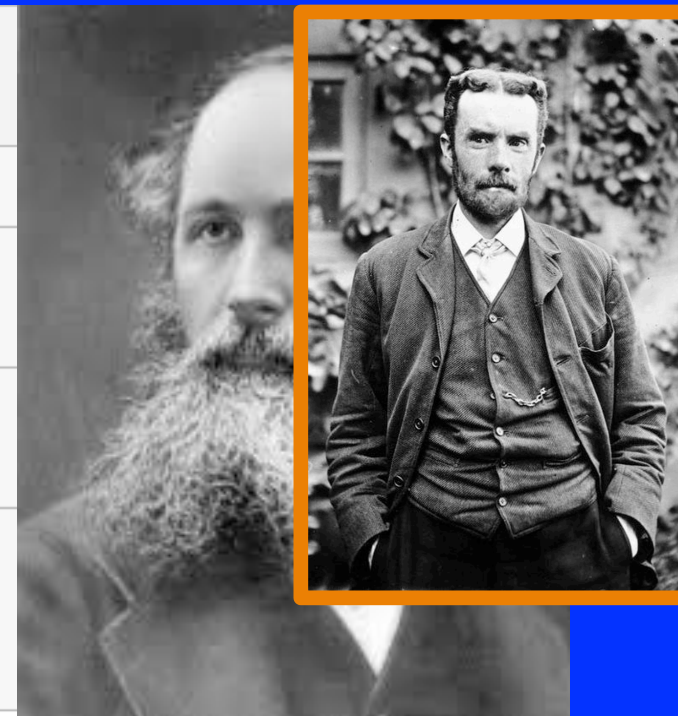
Ampère's law (with Maxwell's extension): 	$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi \vec{J}_e$



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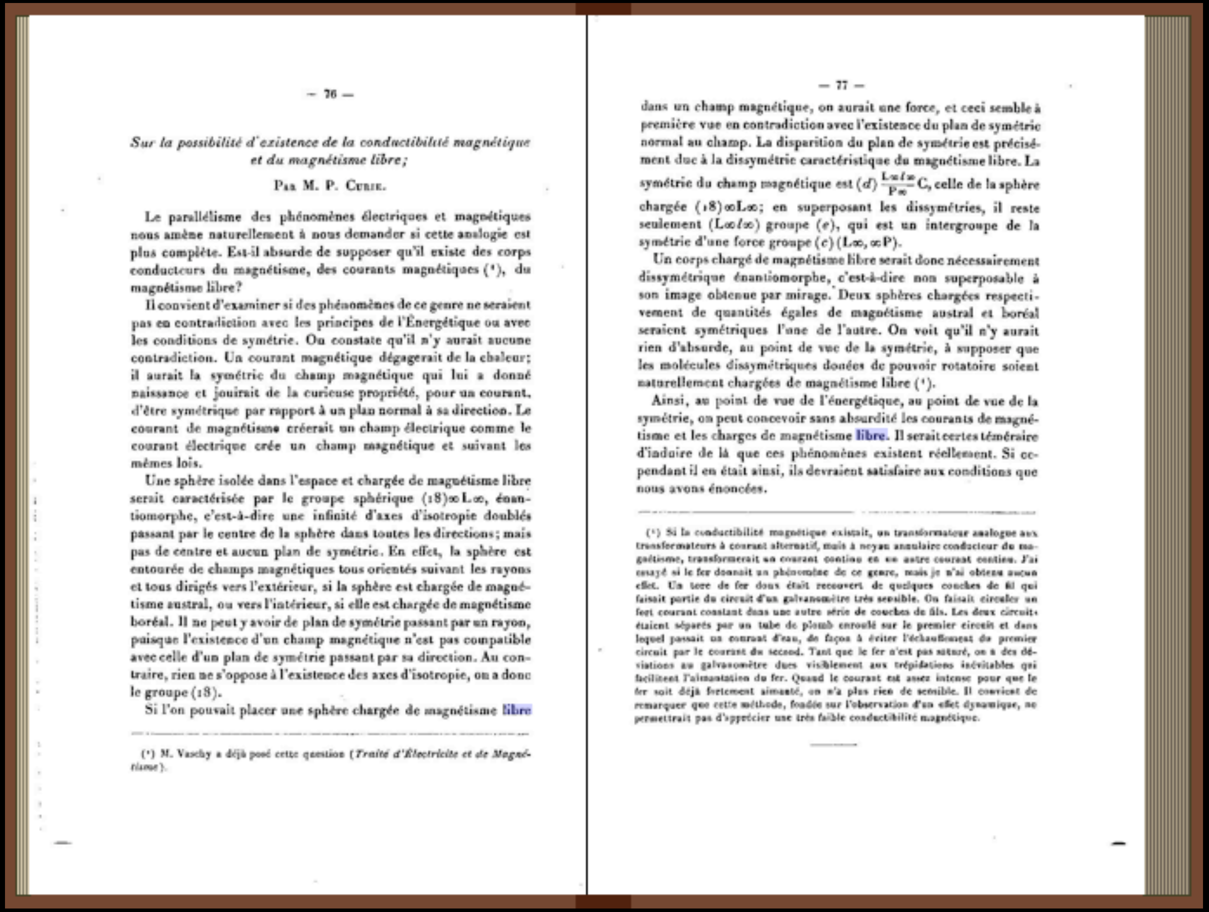
Maxwell's Asymmetric Equations



— 76 —

Sur la possibilité d'existence de la conductibilité magnétique et du magnétisme libre;

Par M. P. Curie.

Le parallélisme des phénomènes électriques et magnétiques nous amène naturellement à nous demander si cette analogie est plus complète. Est-il absurde de supposer qu'il existe des corps conducteurs du magnétisme, des courants magnétiques (¹), du magnétisme libre?

Il convient d'examiner si des phénomènes de ce genre ne seraient pas en contradiction avec les principes de l'Énergétique ou avec les conditions de symétrie. On constate qu'il n'y aurait aucune contradiction. Un courant magnétique dégagerait de la chaleur; il aurait la symétrie du champ magnétique qui lui a donné naissance et jouirait de la curieuse propriété, pour un courant, d'être symétrique par rapport à un plan normal à sa direction. Le courant de magnétisme créerait un champ électrique comme le courant électrique crée un champ magnétique et suivant les mêmes lois.

Une sphère isolée dans l'espace et chargée de magnétisme libre serait caractérisée par le groupe sphérique $(18)\infty L\infty$, énantiomorphe, c'est-à-dire une infinité d'axes d'isotropie doublés passant par le centre de la sphère dans toutes les directions; mais pas de centre et aucun plan de symétrie. En effet, la sphère est entourée de champs magnétiques tous orientés suivant les rayons et tous dirigés vers l'extérieur, si la sphère est chargée de magnétisme austral, ou vers l'intérieur, si elle est chargée de magnétisme boréal. Il ne peut y avoir de plan de symétrie passant par un rayon, puisque l'existence d'un champ magnétique n'est pas compatible avec celle d'un plan de symétrie passant par sa direction. Au contraire, rien ne s'oppose à l'existence des axes d'isotropie, on a donc le groupe (18).

Si l'on pouvait placer une sphère chargée de magnétisme libre

(¹) M. Vaschy a déjà posé cette question (*Traité d'Électricité et de Magnétisme*).

— 77 —

dans un champ magnétique, on aurait une force, et ceci semble à première vue en contradiction avec l'existence du plan de symétrie normal au champ. La disparition du plan de symétrie est précisément due à la dissymétrie caractéristique du magnétisme libre. La symétrie du champ magnétique est $(d)\ \frac{L\infty l\infty}{P\infty} C$, celle de la sphère chargée $(18)\infty L\infty$; en superposant les dissymétries, il reste seulement $(L\infty l\infty)$ groupe (e), qui est un intergroupe de la symétrie d'une force groupe (c) $(L\infty, \infty P)$.

Un corps chargé de magnétisme libre serait donc nécessairement dissymétrique énantiomorphe, c'est-à-dire non superposable à son image obtenue par mirage. Deux sphères chargées respectivement de quantités égales de magnétisme austral et boréal seraient symétriques l'une de l'autre. On voit qu'il n'y aurait rien d'absurde, au point de vue de la symétrie, à supposer que les molécules dissymétriques douées de pouvoir rotatoire soient naturellement chargées de magnétisme libre (¹).

Ainsi, au point de vue de l'énergétique, au point de vue de la symétrie, on peut concevoir sans absurdité les courants de magnétisme et les charges de magnétisme libre. Il serait certes téméraire d'induire de là que ces phénomènes existent réellement. Si cependant il en était ainsi, ils devraient satisfaire aux conditions que nous avons énoncées.

(¹) Si la conductibilité magnétique existait, un transformateur analogue aux transformateurs à courant alternatif, mais à noyau annulaire conducteur du magnétisme, transformerait un courant continu en un autre courant continu. J'ai essayé si le fer donnait un phénomène de ce genre, mais je n'ai obtenu aucun effet. Un tore de fer doux était recouvert de quelques couches de fil qui faisait partie du circuit d'un galvanomètre très sensible. On faisait circuler un fort courant constant dans une autre série de couches de fils. Les deux circuits étaient séparés par un tube de plomb enroulé sur le premier circuit et dans lequel passait un courant d'eau, de façon à éviter l'échauffement du premier circuit par le courant du second. Tant que le fer n'est pas saturé, on a des déviations au galvanomètre dues visiblement aux trépidations inévitables qui facilitent l'aimantation du fer. Quand le courant est assez intense pour que le fer soit déjà fortement aimanté, on n'a plus rien de sensible. Il convient de remarquer que cette méthode, fondée sur l'observation d'un effet dynamique, ne permettrait pas d'apprécier une très faible conductibilité magnétique.

- *Pierre Curie was the first to suggest that Magnetic Monopoles could exist (Seances, Société Française de Physique, 1894)*
- *He based his conjecture on symmetry of Maxwell 's equations!*

Maxwell's Asymmetric Equations

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Thomson's & Poincaré's Monopole

Birkeland Experiment (1896) :

Magnet in a Crook's tube induces focusing of the cathodic (electron) beam

Birkeland's arrangement

Thomson's & Poincaré's Monopole

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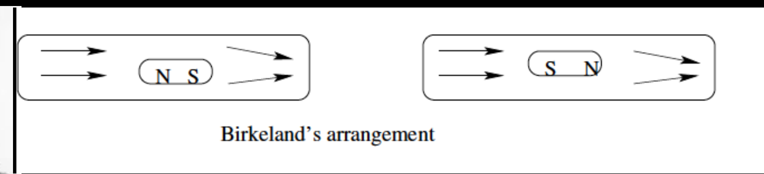
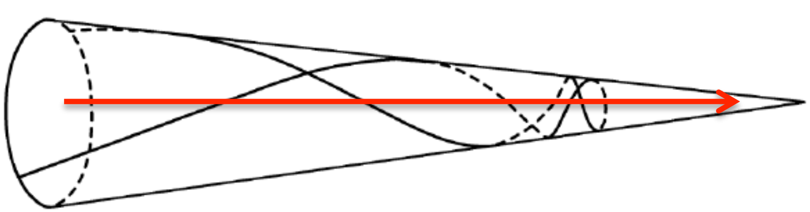


Poincaré (1896) ascribe this effect to the force of a magnetic pole at rest on a moving electric charge → path of electrons r(t) geodesic of axially symmetric (Poincaré) cone → prove focusing effect

$$\frac{d^2\mathbf{r}}{dt^2} = \lambda \frac{1}{r^3} \frac{d\mathbf{r}}{dt} \times \mathbf{r} \; ; \quad \lambda = \frac{eg}{mc}$$



g = magnetic charge
m= mass of electron

Angular momentum

$$J = mL$$

$$\mathbf{L} := \mathbf{r} \times \frac{d\mathbf{r}}{dt} + \lambda \frac{\mathbf{r}}{r}$$

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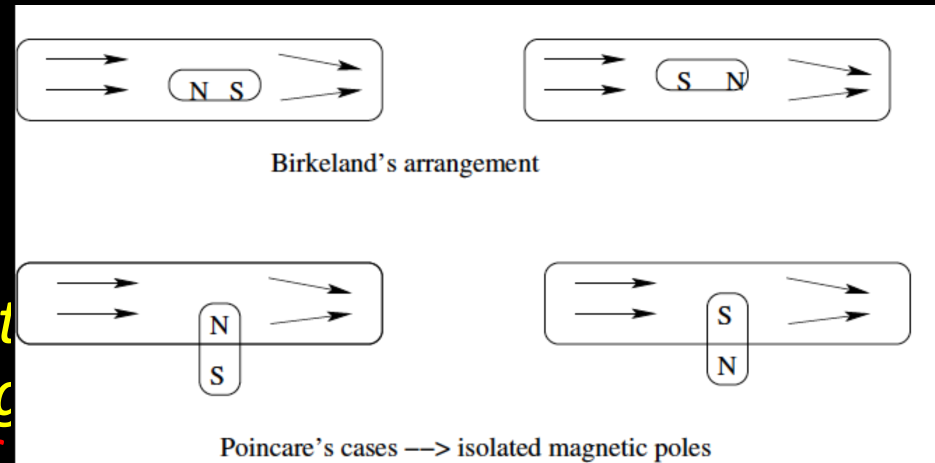

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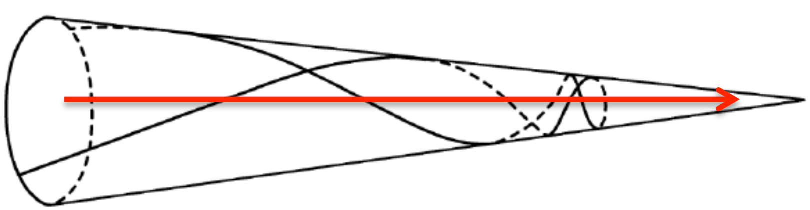

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Poincare's cases --> isolated magnetic poles

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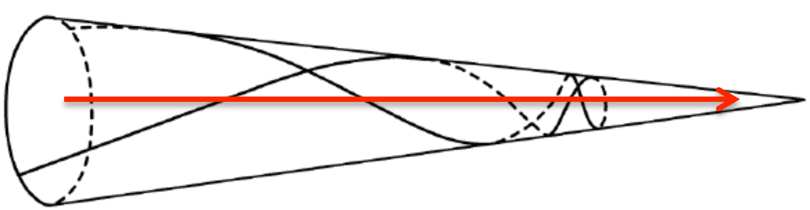

angular momentum symmetry axis

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Angular momentum

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magnetic po
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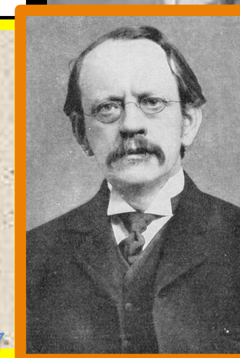
$$\frac{eg}{c}\frac{\vec{r}}{r} = \frac{1}{4\pi c}\int_{-\infty}^{+\infty} \vec{x} \times (\vec{E} \times \vec{B}) d^3x$$

Electromagnetic momentum interpretation by Thomson (1904)



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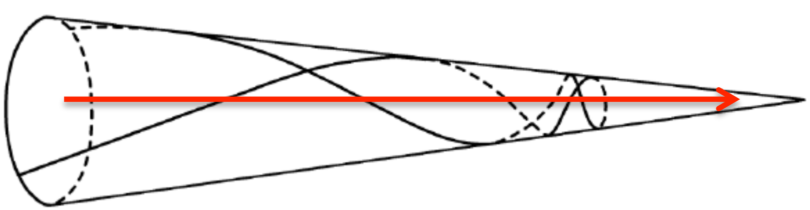

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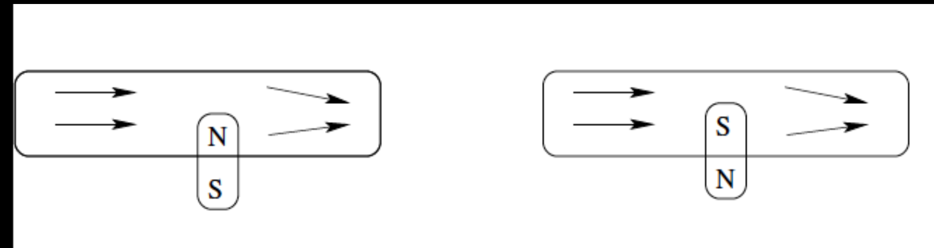

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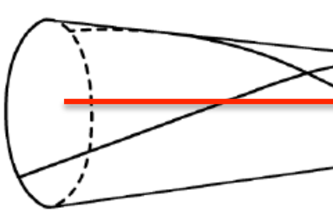
Electromagnetic momentum intepretation by Thomson (1904)

NB: 1897 Thomson demonstrated that cathodic rays were electrons (charge –e)

$$\frac{d^2\mathbf{r}}{dt^2} = \lambda\,\frac{1}{r^3}$$

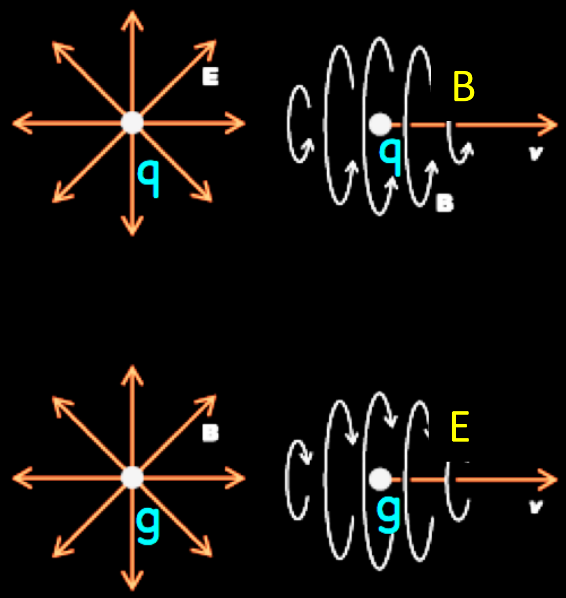


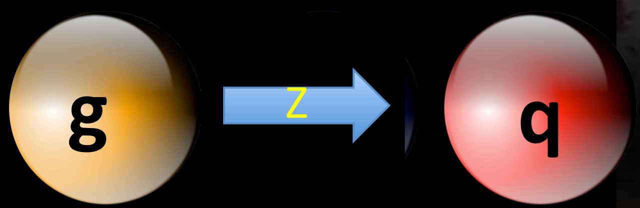
angular momentum symmetry axis

mL

$+\,\lambda\,\frac{\mathbf{r}}{r}$

Thomson's & Poincaré's Monopole

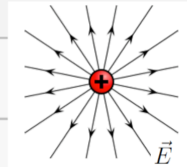
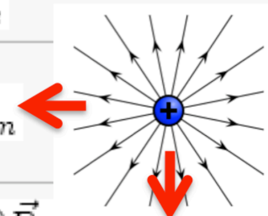




In 1904 Thomson published a paper in which he considered an electric charge (e) – magnetic monopole (g) system

- *He found the angular momentum of the EM field of this system in the direction shown $J_Z = eg/c$*
- *By invoking the quantization rule for angular momentum we can write $eg/c = n\hbar/2$ → Dirac's quantization rule!*

Monopole symmetrizes 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:	$\vec{\nabla} \cdot \vec{B} = 0$	$\vec{\nabla} \cdot \vec{B} = 4\pi\rho_m$ 
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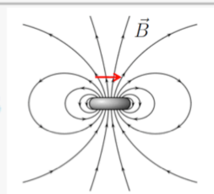
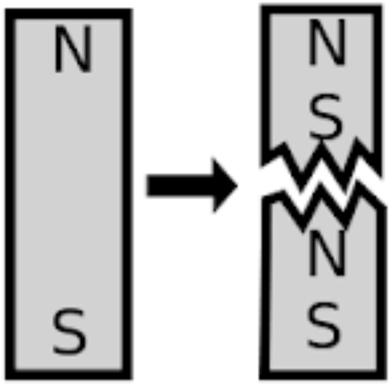
Ampère's law (with Maxwell's extension): 	$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi\vec{J}_e$	$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi\vec{J}_e$

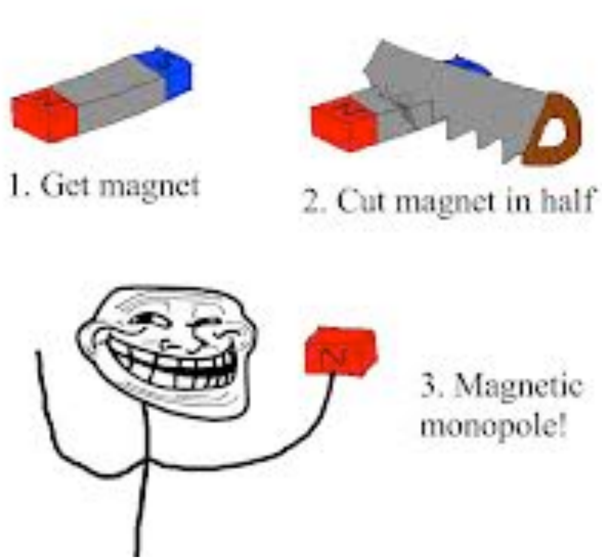
- *DUALITY symmetric equations in the presence of monopoles*

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

the distinction between electric and magnetic charge is merely one of definition



Cannot be the property of ordinary matter



If magnetic monopole exists should be a
NEW entity
elementary particle ?
or a more complicated configuration ?

Dirac's Monopole

Name	With Magnetic Monopoles
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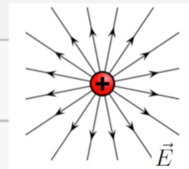
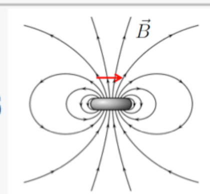
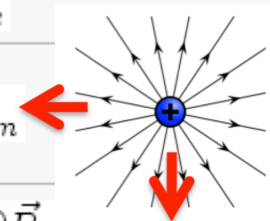






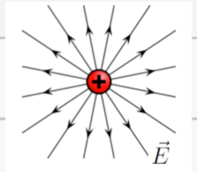
- ***Dirac**, in 1931 postulates the existence of magnetic monopoles* – ***first quantum field theory formulation***
- *DUALITY symmetric equations in the presence of monopoles*

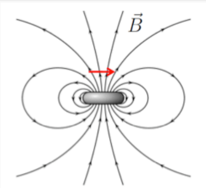
$$\begin{pmatrix} \vec{E}' \\ \vec{B}' \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \vec{E} \\ \vec{B} \end{pmatrix}$$

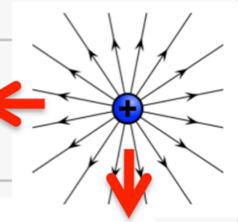
the distinction between electric and magnetic charge is merely one of definition

Dirac's Monopole symmetrizes 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):	$\vec{\nabla}\times\vec{B} = \frac{\partial\vec{E}}{\partial t} + 4\pi\vec{J}_e$	$\vec{\nabla}\times\vec{B} = \frac{\partial\vec{E}}{\partial t} + 4\pi\vec{J}_e$
Lorentz force law	$\mathbf{F} = q_e\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)$	$\mathbf{F} = q_e\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right) + q_m\left(\mathbf{B} - \frac{\mathbf{v}}{c}\times\mathbf{E}\right)$



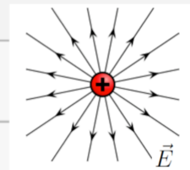
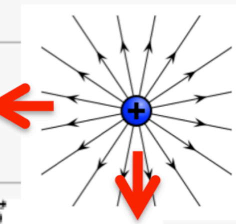
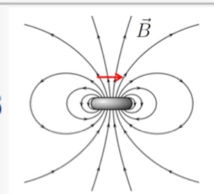




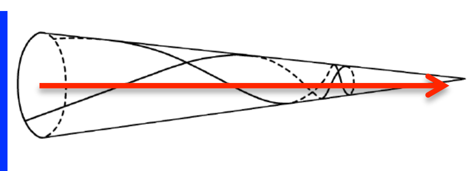
For Dirac monopole

$$\mathbf{E} = 0, \qquad \mathbf{B} = g\frac{\mathbf{r}}{r^3}$$

Dirac's Monopole

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): 	$\vec{\nabla}\times\vec{B}=\frac{\partial\vec{E}}{\partial t}+4\pi\vec{J}_e$	$\vec{\nabla}\times\vec{B}=\frac{\partial\vec{E}}{\partial t}+4\pi\vec{J}_e$
Lorentz force law	$\mathbf{F}=q_e\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right)$	$\mathbf{F}=q_e\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right)+q_m\left(\mathbf{B}-\frac{\mathbf{v}}{c}\times\mathbf{E}\right)$

$$\frac{d^2\mathbf{r}}{dt^2}=\lambda\frac{1}{r^3}\frac{d\mathbf{r}}{dt}\times\mathbf{r}\;;\quad\lambda=\frac{eg}{mc}$$

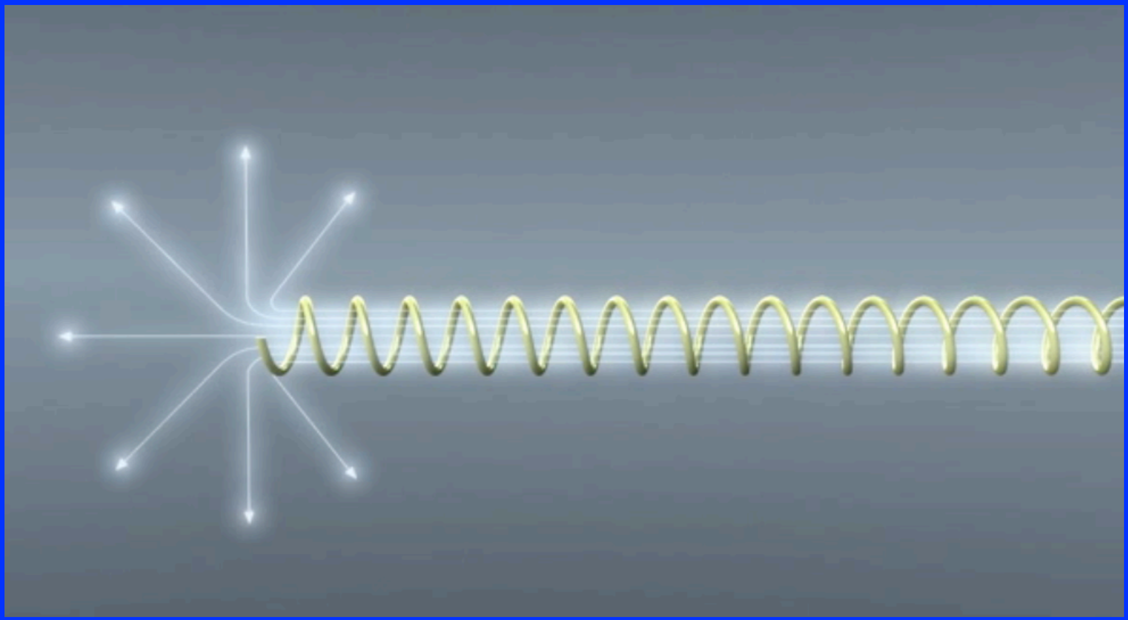


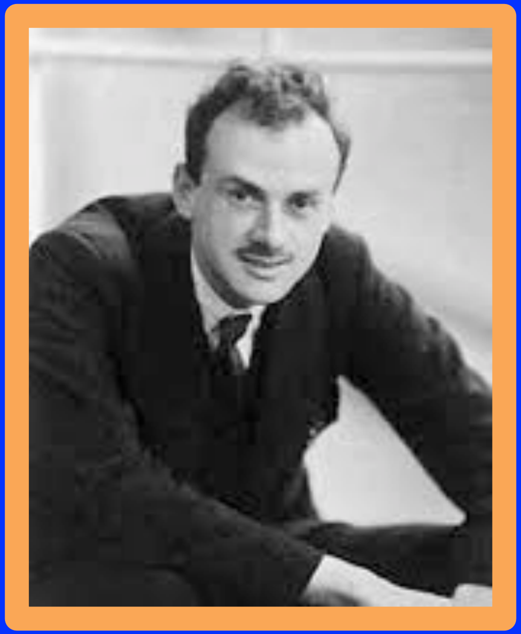
Poincaré Eq.

For Dirac monopole

$$\mathbf{E}=0,\qquad\mathbf{B}=g\frac{\mathbf{r}}{r^3}$$

Dirac's Monopole

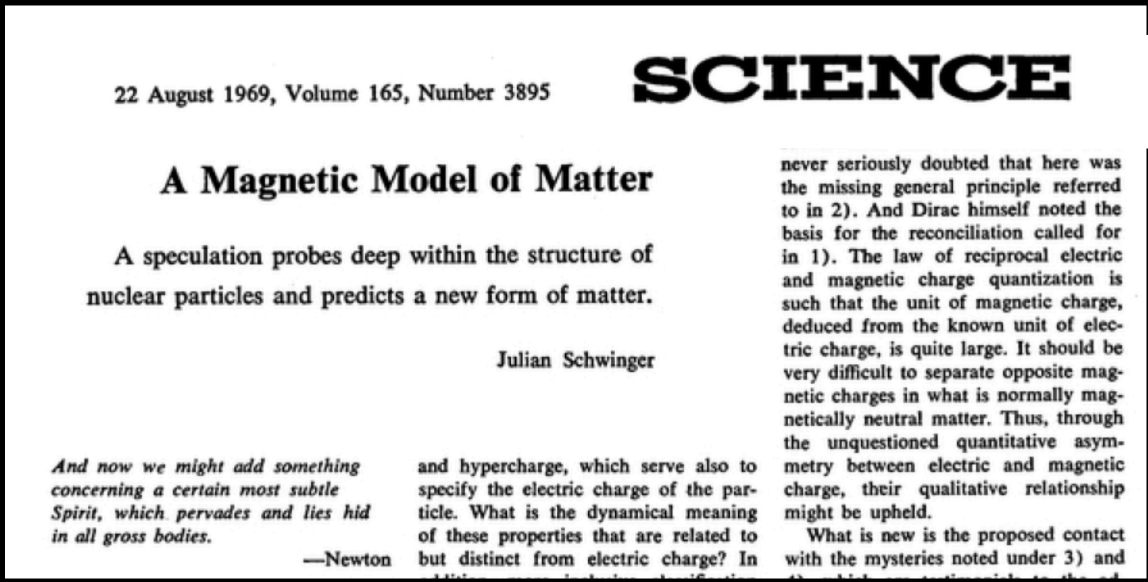




- *In 1931 Dirac hypothesized that the Monopole exists as the end of an infinitely long and thin solenoid - the "Dirac String"*
- *Requiring that the string is not seen gives us the Dirac Quantization Condition & explains the quantization of charge!*

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

Schwinger's Dyon



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

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.

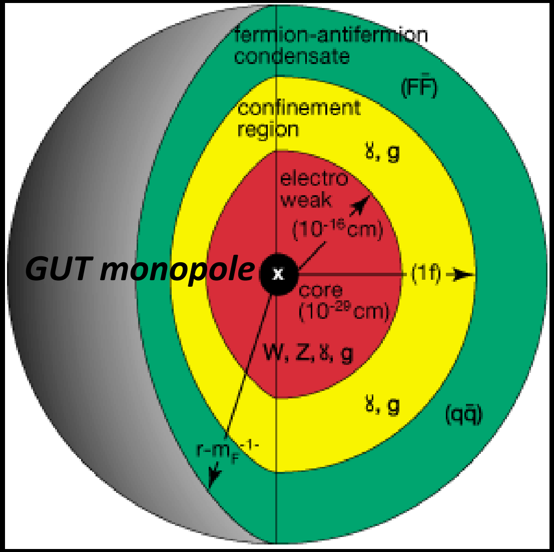
What is new is the proposed contact with the mysteries noted under 3) and

- *Postulated a "dyon" that carries electric & magnetic charge*
- *Quantisation of angular momentum with two dyons (q_{e1},q_{m1}) and (q_{e2},q_{m2}) yields*

$$(q_{e1},q_{m1}) - (q_{e2},q_{m2}) = 2nh/m_0 \quad (\text{ n is an integer})$$

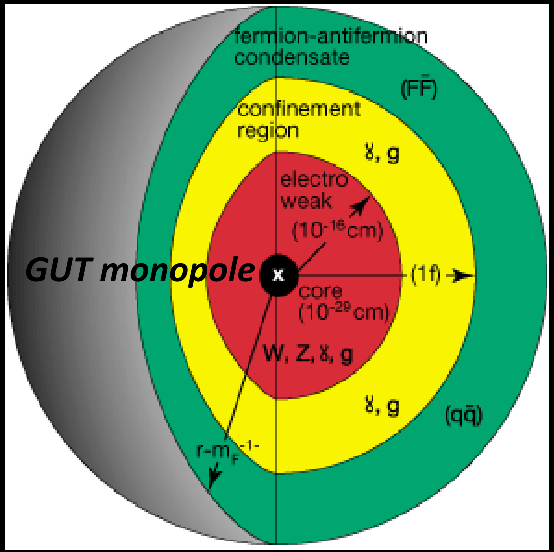
- *Fundamental magnetic charge is now $2g_D$ (g_D = Dirac's magn. charge)*
  - *If the fundamental charge is 1/3 (d-quark) as the fundamental electric charge then the fundamental magnetic charge becomes $6g_D$*

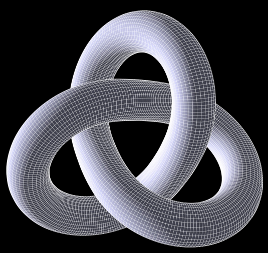
The 't Hooft-Polyakov Monopole



- *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 e.g. a trefoil 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*

The ‘t Hooft-Polyakov Monopole





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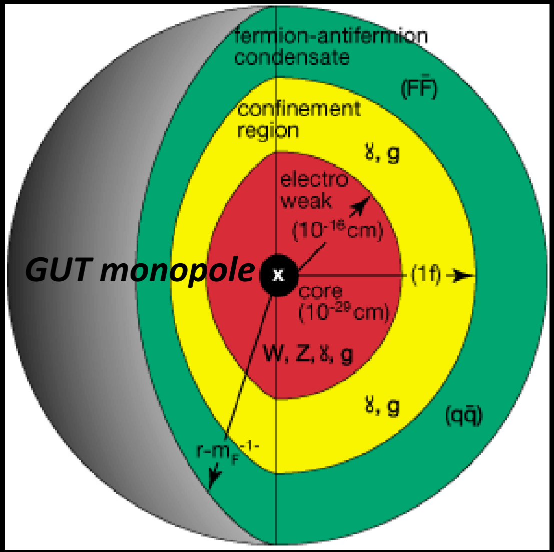

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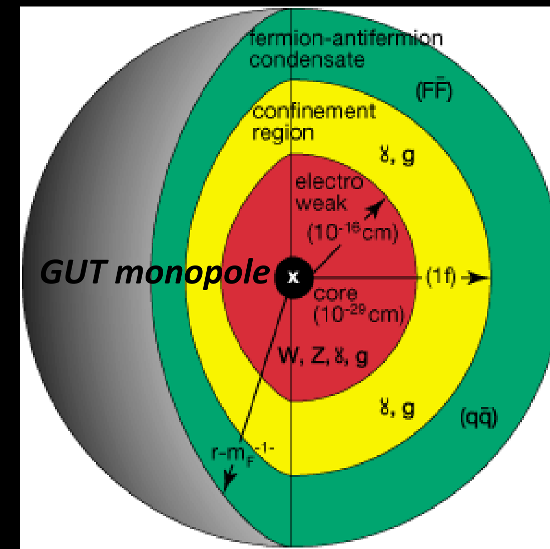
The 't Hooft-Polyakov Monopole



Equivalent to an energy of **10^{16} GeV** (GUT scale)

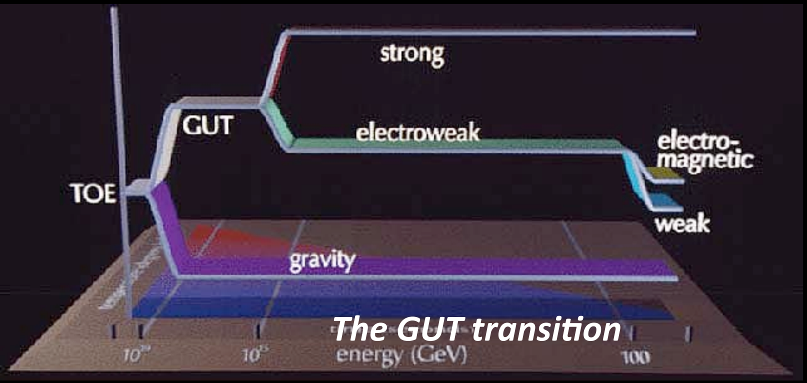
i.e. inflation would wash them out cosmically

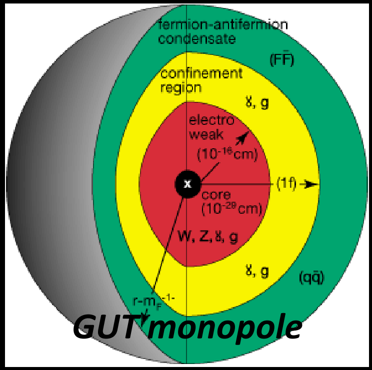
Moreover, cannot be produced at LHC energies

Bounds on fluxes and mass placed by Expts

- *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*

The GUT Monopole (GUM)





- *A symmetry-breaking phase transition caused the creation of topological defects as the universe froze out at the GUT trans.*
  - *The GUM is a tiny replica of the Big Bang with mass ~ 0.02 μg (10^{16} GeV*
  - *GUT monopoles should comprise 10^{11} x $\rho_{critical}$ of the Universe !!*
  - *Guth introduced the inflationary scenario to dilute the monopoles to an acceptable level and also solve the horizon and flatness problems.*
- *Lighter "Intermediate Mass Monopoles" can be produced at later Phase Transitions – mass 10^{10} GeV or lower*

$$SO(10) \underset{10^{-35}\,s}{\overset{10^{15}\ GeV}{\longrightarrow}} SU(4) \times SU(2) \times SU(2) \underset{10^{-23}\,s}{\overset{10^{9}\ GeV}{\longrightarrow}} SU(3) \times SU(2) \times U(1)$$

GUT Monopole Catalysis of p-Decay

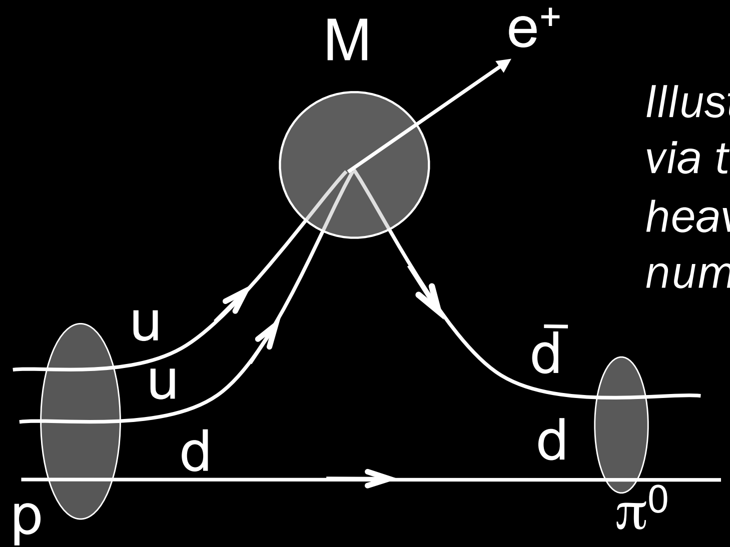


Illustration of monopole catalysis of proton decay via the Rubakov-Callan Mechanism via super heavy gauge bosons that mediate baryon number violation

- *The central core of the GUT retains the original symmetry containing the field of the superheavy "X" all quarks and leptons are here essentially indistinguishable*
  - *Protons can be induced to decay with x-section ofo $\sigma_B\beta \sim 10^{-27}$ cm^2- giving a line of catalyzed proton decays on the trail of the monopole*
- *One can search for non relativistic monopoles at water/ice detectors (IceCube, KamioKande, etc.) using catalysis*

But… GUT monopoles not alone in market

Other monopole states predicted in
theories beyond the standard model,
like strings (Wen & Witten) may have sufficiently
low-masses (if string scale is low @ TeV)
to be falsifiable at LHC energies

Electroweak Magnetic Monopole?

Y.M. Cho and D. Maison,
Phys. Lett. B391, 360 (1997).

- *Cho – Maison in 1997 envisioned a new type of spherically symmetric Electroweak Standard Model dyon, with:*
  - *Magnetic charge $2g_D$*
  - *Mass in the range 4→7 GeV/c^2 → Cho et al. arXiv: 1212.3885 [hep-ph]*
- *This monopole is a non-trivial hybrid between the abelian Dirac monopole and the non-abelian 't Hooft-Polyakov monopole*
- *Cho-Maison monopole would be produced → detected/ falsified @ LHC if its mass lies in the predicted range*

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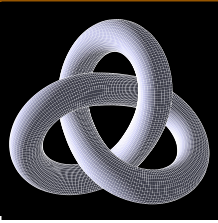

Important role of $U_Y(1)$ for SM admitting monopole solutions

$SU(2) \times U_Y(1) / U_{em}(1)$ → CP^1 structure

→ $\pi_2(CP^1) = Z$, Higgs doublet as CP^1 field
→ **non trivial topology (knot - like soliton)**

- *Cho – Maison in 1997 envis... symmetric Electroweak Stan... with:*
  - *Magnetic charge $2g_D$*
  - *Mass in the range 4→7 GeV/c^2 → Cho et al. arXiv: 1212.3885 [hep-ph]*
- *This 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/falsified by MoEDAL if its mass lies in the predicted range*

The Cho-Maison Magnetic Monopole

Y.M. Cho and D. Maison, Phys. Lett. B391, 360 (1997).

The Standard Model provides naturally the non-trivial topological framework for the existence of a ``monopole-like'' state

$$\mathcal{L} = -\frac{1}{4}\vec{F}^2_{\mu\nu} - \frac{1}{4}G^2_{\mu\nu} - |D_\mu\phi|^2 - \frac{\lambda}{2}\left(|\phi|^2 - \frac{\mu^2}{\lambda}\right)^2,$$

$$D_\mu\phi = \left(\partial_\mu - i\frac{g}{2}\vec{\tau}\cdot\vec{A}_\mu - i\frac{g'}{2}B_\mu\right)\phi,$$

NB: incorrect conjectures in the past that E/W model does not have monopoles

SOLUTION

$$\phi = \frac{1}{\sqrt{2}}\rho(r)\xi(\theta,\varphi), \quad \xi = i\begin{pmatrix} \sin(\theta/2)\ e^{-i\varphi} \\ -\cos(\theta/2) \end{pmatrix},$$

$$\hat{\phi} = \xi^\dagger\vec{\tau}\xi = -\hat{r},$$

$$\vec{A}_\mu = \frac{1}{g}A(r)\partial_\mu t\ \hat{r} + \frac{1}{g}(f(r)-1)\ \hat{r}\times\partial_\mu\hat{r},$$

$$B_\mu = \frac{1}{g'}B(r)\partial_\mu t - \frac{1}{g'}(1-\cos\theta)\partial_\mu\varphi.$$

NB: apparent string-like singularity in ξ, *B* is gauge artefact, can be removed by making U(1) non-trivial → e/w Dyon

The Cho-Maison Magnetic Monopole

Y.M. Cho and D. Mais... Phys. Lett. B391 ...).

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$$D_\mu\phi = \Big(\partial_\mu - i\frac{g}{2}\vec{\tau}\cdot\vec{A} \ldots$$

...poles

...$\varphi), \quad \xi = i\big(\ldots$,

$$\hat{\phi} = \xi^\dagger\vec{\tau}\xi = \ldots$$

$$\vec{A}_\mu = \frac{1}{g}A(r)\partial_\mu t\,\hat{r} + \frac{1}{g}(f(r)-1)\,\hat{r}\times\partial_\mu\hat{r},$$

$$B_\mu = \frac{1}{g'}B(r)\partial_\mu t - \frac{1}{g'}(1-\cos\theta)\partial_\mu\varphi.$$

... U(1)

...e/w Dyon

But...POINT-SINGULARITY OF CHO-MAISON MONOPOLE MAKES ESTIMATE OF MASS CLASSICALLY IMPOSSIBLE → Need to find FINITE-ENERGY Solutions

Recent Model of Cho for finite dyons

Cho, Kim, Yoon , arXiv:1305.12.1699
Eur.Phys.J. C75 (2015) 2, 67

Finiteness is obtained if one **modifies $U_Y(1)$-part of SM lagrangian**:

$$\mathcal{L}_{\text{eff}} = -|\mathcal{D}_\mu \phi|^2 - \frac{\lambda}{2}\left(\phi^2 - \frac{\mu^2}{\lambda}\right)^2 - \frac{1}{4}\vec{F}_{\mu\nu}^2 - \frac{1}{4}\epsilon(|\phi|^2) G_{\mu\nu}^2,$$

weak interactions gauge bosons

hypercharge ``photon''

Recent Model of Cho for finite dyons

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Assume Higgs field affects dielectric constant of vacuum e.g. due to quantum (loop) corrections

$\varepsilon(|\varphi|^2) \to 1$
$r \to \infty$

$U(1)_Y$ gauge coupling → ``running''

$$g' \to \bar{g}' = g'/\sqrt{\epsilon}.$$

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Cho, Kim, Yoon , arXiv:1305.12.1699
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$$\mathcal{L}_{\rm eff} = -|\mathcal{D}_\mu \phi|^2 - \frac{\lambda}{2}\left(\phi^2 - \frac{\mu^2}{\lambda}\right)^2 - \frac{1}{4}\vec{F}_{\mu\nu}^2 - \frac{1}{4}\epsilon(|\phi|^2) G_{\mu\nu}^2,$$

For finite energy of Cho-Maison Dyon we need

$$\epsilon \simeq \left(\frac{\rho}{\rho_0}\right)^n, \quad n > 4 + 2\sqrt{3} \simeq 7.46.$$

$$\phi = \frac{1}{\sqrt{2}}\rho\, \xi, \quad (\xi^\dagger \xi = 1),$$

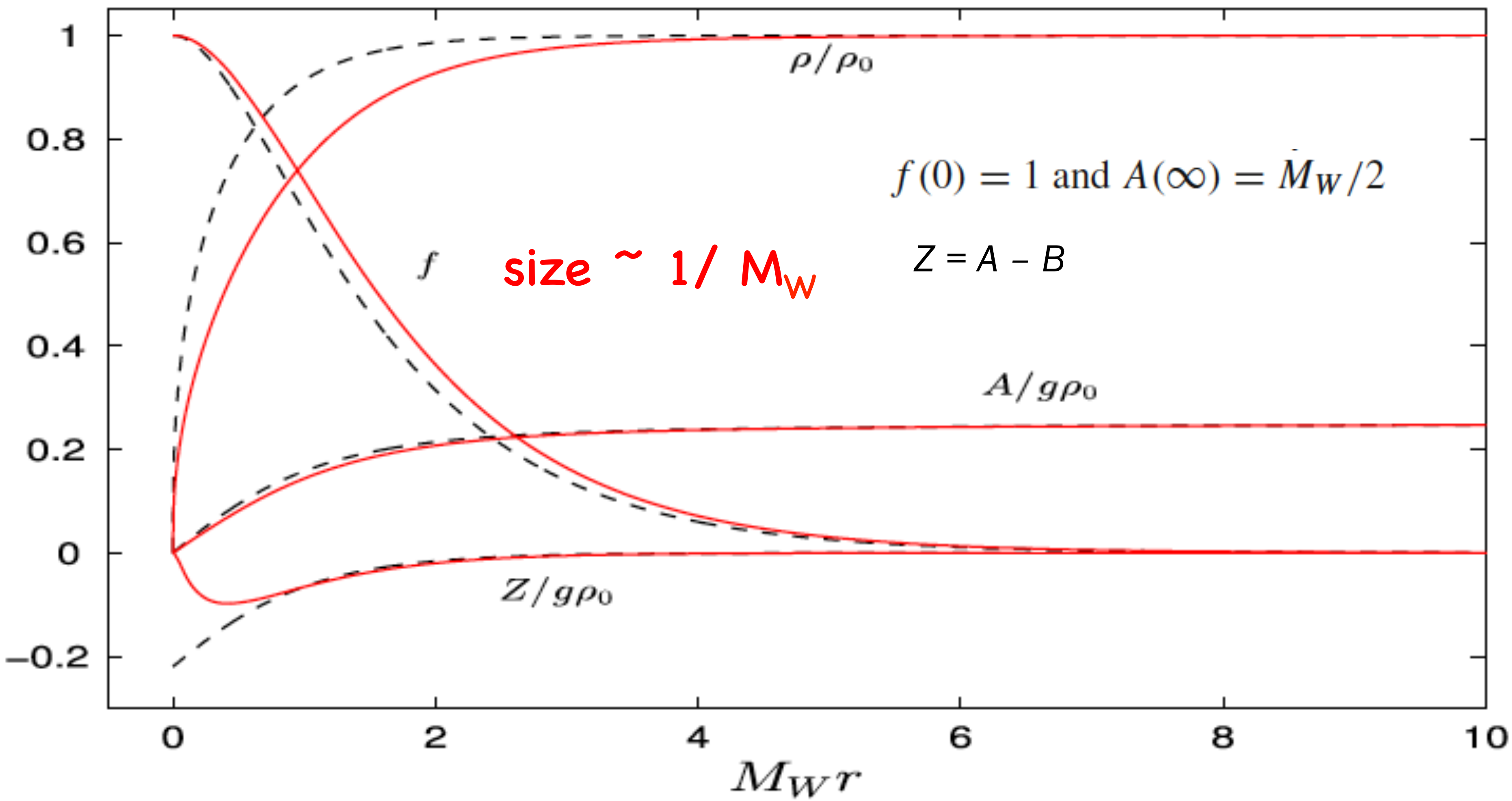
With $n = 8$ we have

$$\rho(r) \simeq r^{\delta}, \quad \delta = \frac{\sqrt{3}-1}{2},$$

Cho, Kim, Yoon , arXiv:1305.12.1699
Eur.Phys.J. C75 (2015) 2, 67

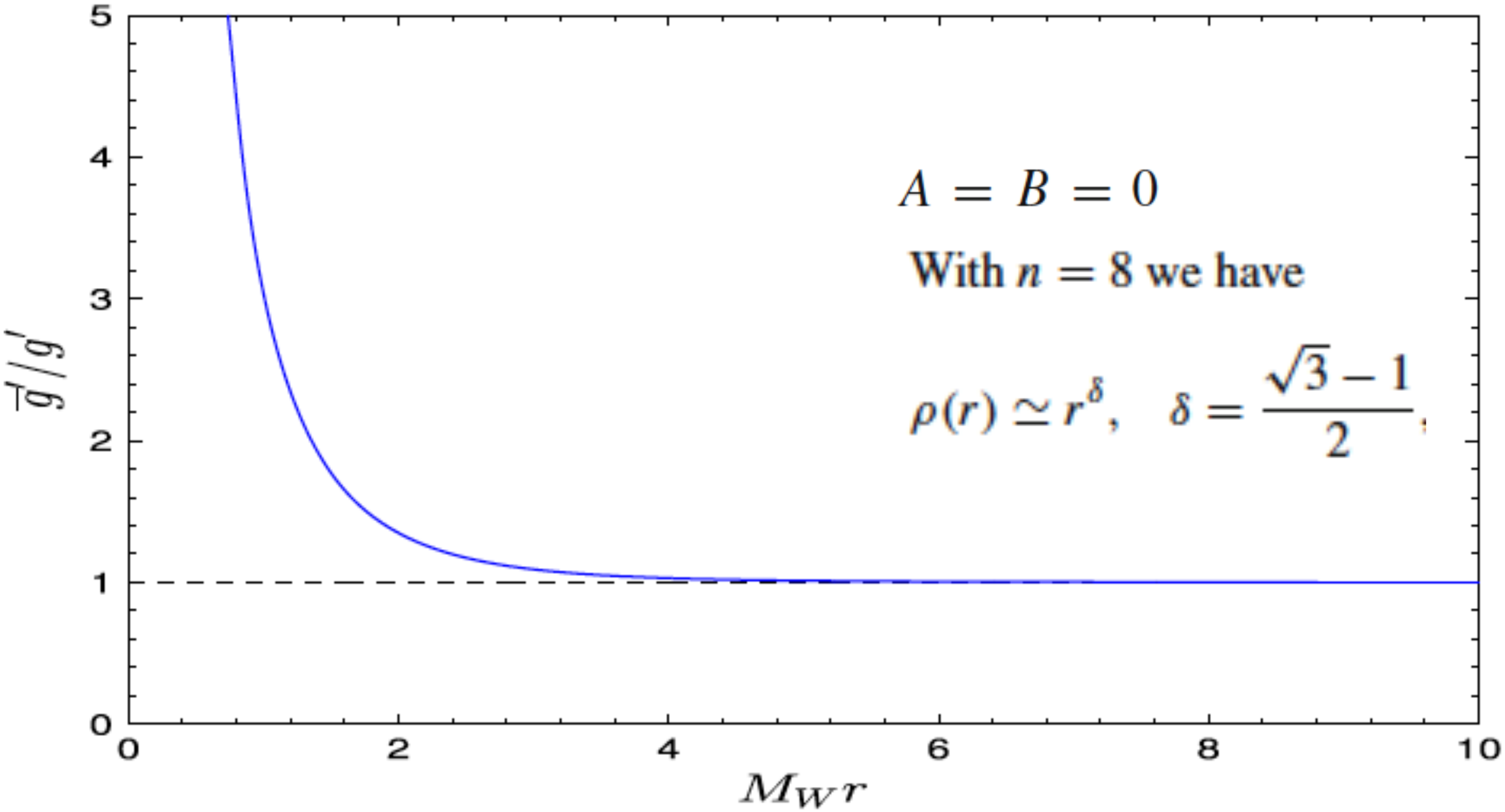
- - - - Cho-Maison dyon

——— FINITE ENERGY dyon



Finite-Energy Dyon:
Running $U_Y(1)$ coupling

Cho, Kim, Yoon , arXiv:1305.12.1699
Eur.Phys.J. C75 (2015) 2, 67



Finite energy for the dyon

$$E \simeq 0.65 \times \frac{4\pi}{e^2} M_W \simeq 7.19 \text{ TeV}.$$

$$\epsilon \simeq \left(\rho/\rho_0\right)^n \propto \left(\frac{\phi\,\phi^\dagger}{\rho_0^2}\right)^{n/2}$$

$$n > 4 + 2\sqrt{3} \simeq 7.46$$

Theoretical requirement for finiteness of energy

NB1: Regularised models may also be obtained by embedding the $U_Y(1)$ onto larger groups, e.g. $SU_Y(2)$ as in left-right symmetric GUT SO(10) models, → at present no realistic models have been examined

Cho, Kim, Yoon , arXiv:1305.12.1699
Eur.Phys.J. C75 (2015) 2, 67

NB2: Regularised Model falls into category of models of defects with non-canonical kinetic terms → also constraints from early Universe physics should be investigated

E. BABICHEV,
PHYSICAL REVIEW D 74, 085004 (2006)

$$\epsilon \simeq \left(\rho/\rho_0\right)^n \propto \left(\frac{\phi\,\phi^\dagger}{\rho_0^2}\right)^{n/2}$$

$$n > 4 + 2\sqrt{3} \simeq 7.46$$

Theoretical requirement for finiteness of energy

NB3: Embedding the Cho-Maison solution to Gravity (self-gravitating) **reduces** the mass

Cho, Kim, Yoon , arXiv:1605.08129

$$ds^2 = -N^2(r)A(r)dt^2 + \frac{dr^2}{A(r)} + r^2(d^2\theta + \sin^2\theta d\varphi^2)$$

$$A(r) = 1 - \frac{2Gm(r)}{r}.$$

$$S = \int \left[\frac{1}{4\pi}\dot{m} - AK - U\right] N dr \qquad K = \frac{\dot{f}^2}{g^2} + \frac{r^2}{2}\dot{\rho}^2$$

$$\dot{a} \equiv da/dr$$

$$U = \frac{(1-f^2)^2}{2g^2r^2} + \frac{\lambda}{8}r^2(\rho^2 - \rho_0^2)^2 + \frac{\epsilon(\rho)}{2g'^2r^2} + \frac{1}{4}f^2\rho^2$$

$$\dot{m} = 4\pi(AK + U)$$

$$\epsilon \simeq \left(\rho/\rho_0\right)^n \propto \left(\frac{\phi\,\phi^\dagger}{\rho_0^2}\right)^{n/2}$$

$$n > 4 + 2\sqrt{3} \simeq 7.46$$

Theoretical requirement for finiteness of energy

NB3: Embedding the Cho-Maison solution to Gravity (self-gravitating) **reduces** the mass

Cho, Kim, Yoon , arXiv:1605.08129

$$m(r) = 4\pi e^{P(r)} \int_0^r (K+U) e^{-P(r')} dr',$$

$$P(r) = 8\pi G \int_r^\infty \frac{K}{r'} dr'.$$

size ~ 1/ M_W

$$\alpha = \sqrt{G}\rho_0 = \rho_0/M_p$$

$$\rho(r) = h_1 \rho_0 x^{\delta_1} + \ldots, \quad (\delta_1 = \frac{\sqrt{3}-1}{2})$$

$$\beta = M_H/M_W$$

$$m(r) = \frac{2\pi\alpha^2 h_1^2 \delta_1^2}{G M_W \delta_2} x^{\delta_2} + \ldots, \quad (\delta_2 = \sqrt{3}),$$

$$x = M_W r$$

NB3: Embedding the Cho-Maison solution to Gravity (self-gravitating) **reduces** the mass

Cho, Kim, Yoon , arXiv:1605.08129

α	$\mathcal{M}$
0 (non-gravitating)	7.19 TeV
0.10	7.15 TeV
0.20	6.97 TeV
0.38	6.34 TeV
$\alpha_{max} \simeq 0.39$	black hole

$$\beta = \frac{M_H}{M_W} = 1.55$$

$$\alpha = \sqrt{G}\rho_0 = \rho_0 / M_p$$

$$\epsilon = (\rho/\rho_0)^8$$

$$\epsilon \simeq \left(\rho/\rho_0\right)^n \propto \left(\frac{\phi\,\phi^\dagger}{\rho_0^2}\right)^{n/2}$$

$$n > 4 + 2\sqrt{3} \simeq 7.46$$

Theoretical requirement for finiteness of energy

OPEN ISSUES: Examine potential effects of Higgs-dependent `dielectric constant' modification ε(*φ*) of $U_Y(1)$ vacuum in **electroweak data**

→ **Bounds on n**

Ellis, NEM, You PLB 756, 25 (2016)

The price of a finite energy electroweak monopole (dyon)

The price of a finite energy electroweak monopole (dyon)

Ellis, NEM, You PLB 756, 25 (2016)

Phenomenological constraint from $H \to \gamma\gamma$ decay

$$\epsilon = (\rho/\rho_0)^8$$

Cho *et al.* 2015

The price of a finite energy electroweak monopole (dyon)

Ellis, NEM, You PLB 756, 25 (2016)

Phenomenological constraint from $H \to \gamma\gamma$ decay

$$\epsilon = (\rho/\rho_0)^8$$

→ **Excluded by LHC data on $H \to \gamma\ \gamma$**

Cho *et al.* 2015

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Dim 6 operators
complete EFT analysis

Ellis, Sanz, You JHEP 1503 (2015)

$$\frac{c_\gamma}{\Lambda^2}\mathcal{O}_\gamma \equiv \frac{\bar{c}_\gamma}{M_W^2} g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$

$$\bar{c}_\gamma \equiv c_\gamma M_W^2/\Lambda^2$$

Global fit to LHC data

$$\bar{c}_\gamma = O(10^{-3}) < 0$$

Expand around the Higgs v.e.v

$\rho = \rho_0 + \tilde{\rho}, \qquad \tilde{\rho}/\rho_0 \ll 1 \qquad\qquad \rho_0 \equiv \sqrt{2}\mu/\sqrt{\lambda}$

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$$\mathcal{L}_{\text{eff}} = -|\mathcal{D}_\mu \phi|^2 - \frac{\lambda}{2}\left(\phi^2 - \frac{\mu^2}{\lambda}\right)^2 - \frac{1}{4}\vec{F}_{\mu\nu}^2$$
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$$n \geq 8 \Rightarrow \bar{c}_\gamma \lesssim -0.8$$

observed

$$\bar{c}_\gamma \gtrsim 10^{-3}$$

Implementing the $H \to \gamma\gamma$ constraint

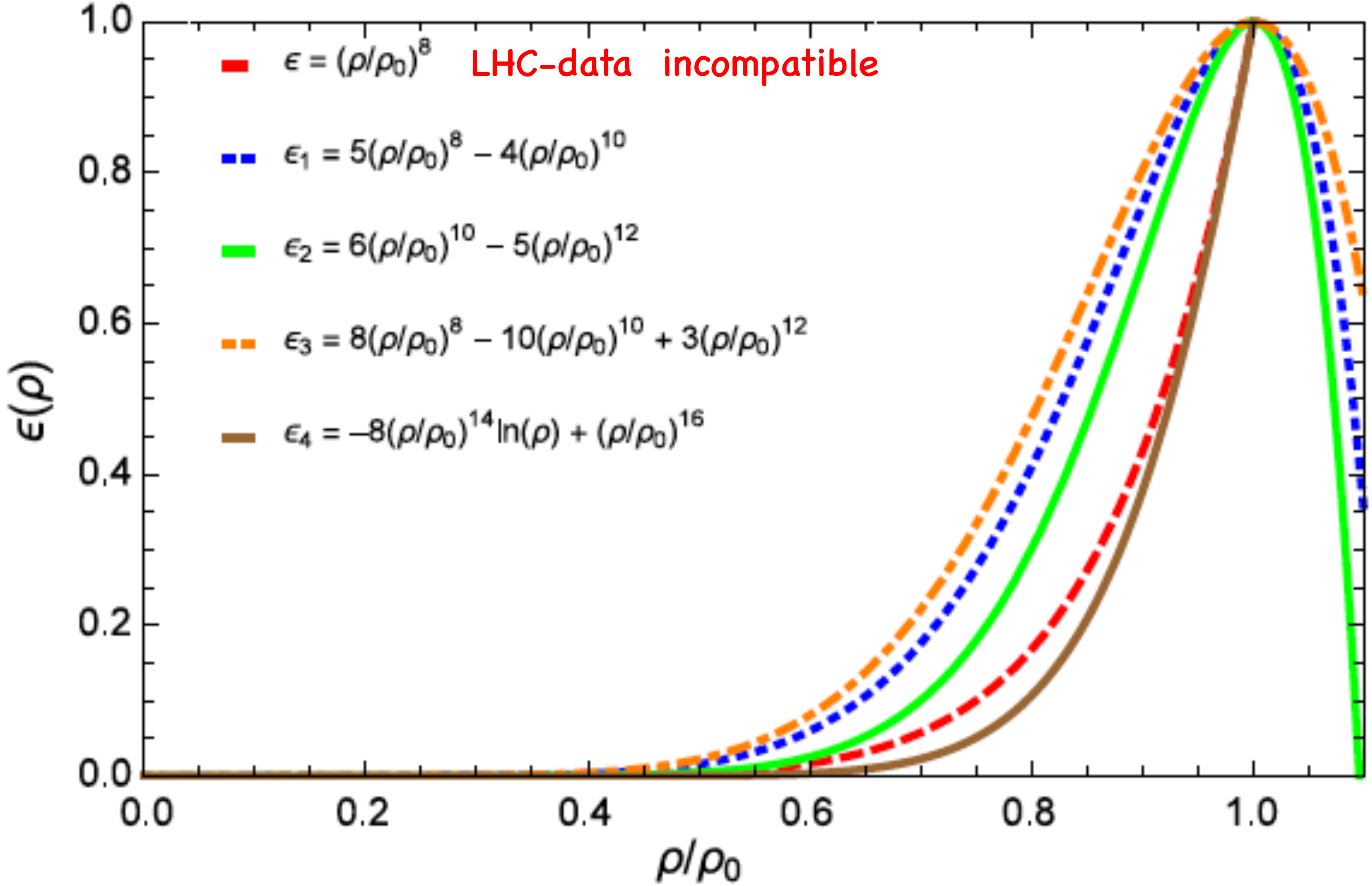
Try more general (phenomenological) function of $\varepsilon(\phi \phi^+)$

$$\text{e.g.} \quad \epsilon_n(\rho) = \sum_{n \in Z^+} C_n \left(\frac{\rho}{\rho_0}\right)^{8+2n}$$

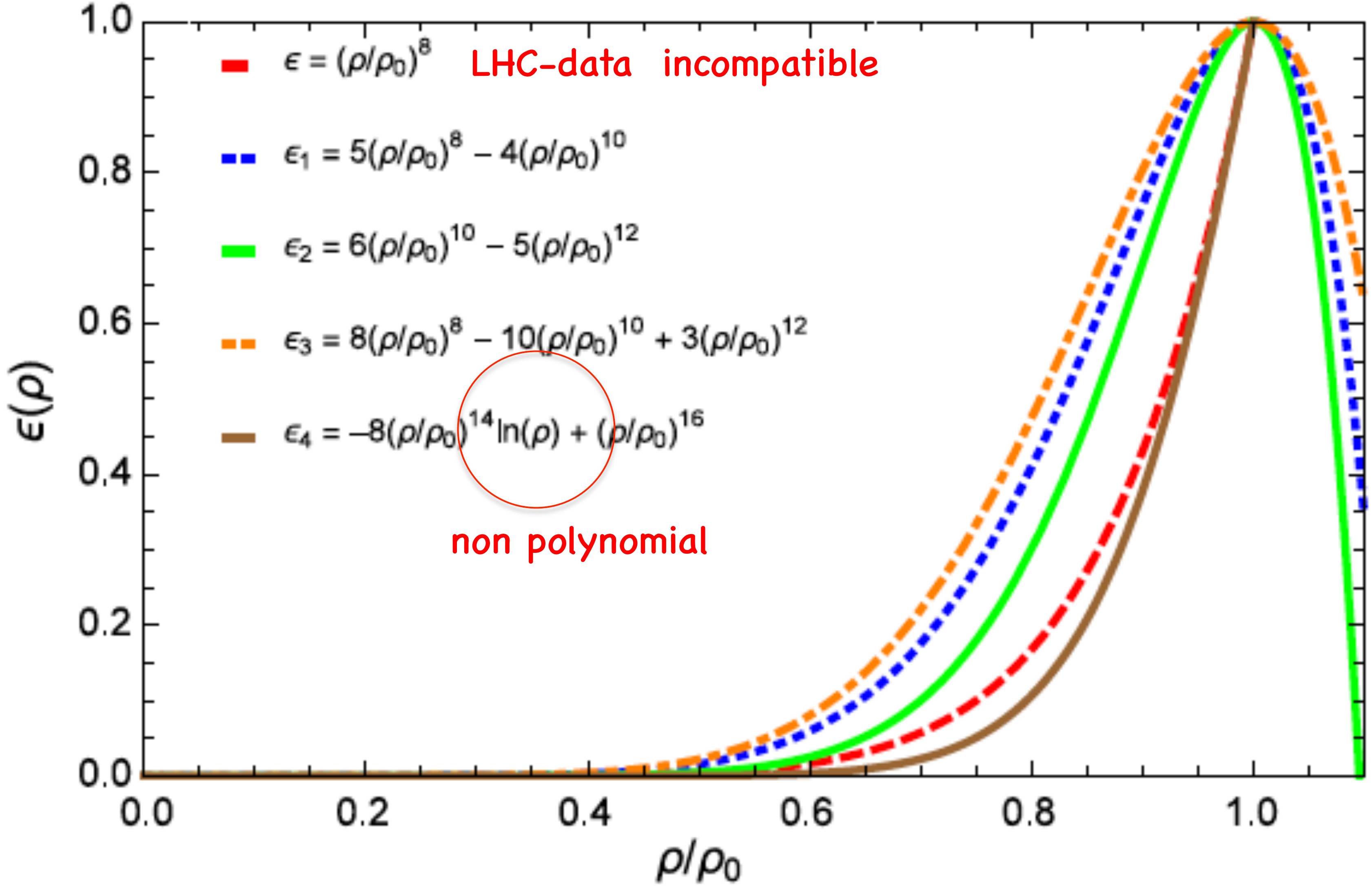
Require Maximal Entropy

$$S = -\int_0^1 dx \epsilon(x) \ln(\epsilon(x)), \quad x \equiv \frac{\rho}{\rho_0}$$

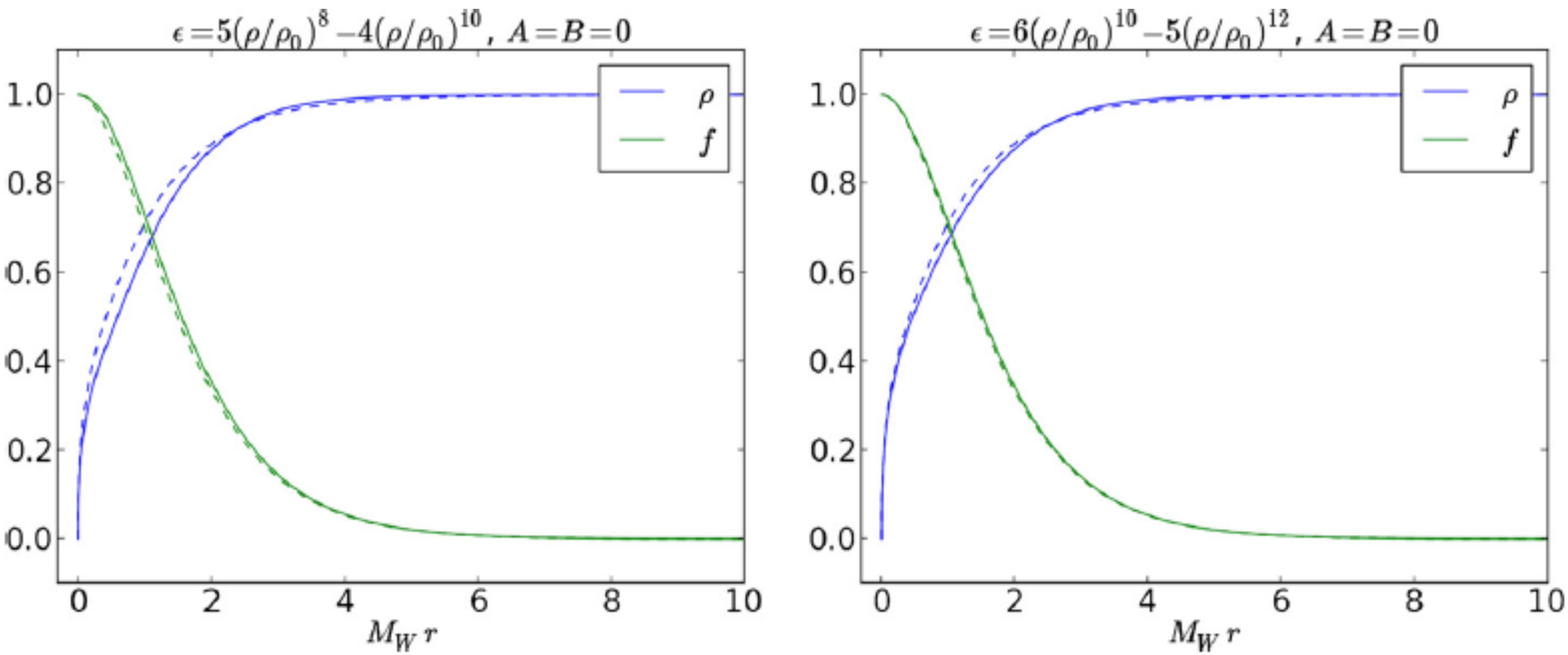
Implementing the $H \to \gamma\gamma$ constraint



Implementing the $H \to \gamma\gamma$ constraint

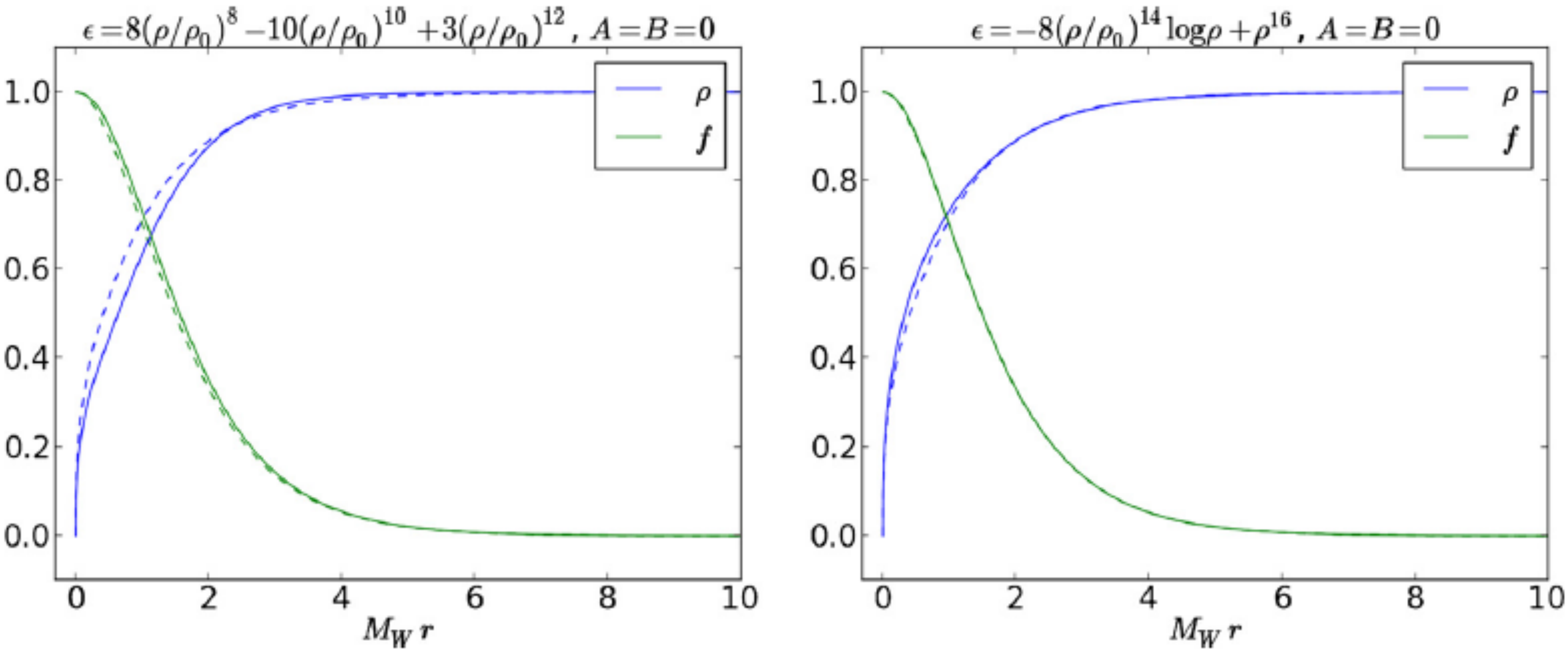


Ellis, NEM, You PLB 756, 25 (2016)



Modified Finite-Energy Electroweak Monopole

Ellis, NEM, You PLB 756, 25 (2016)



Modified Finite-Energy Electroweak Monopole

Modified Monopole Masses

ϵ regularisation	M [TeV]
$\left(\frac{\rho}{\rho_0}\right)^8$	5.7
$\left(\frac{\rho}{\rho_0}\right)^8$ $(A, B \neq 0)$	10.8
$5\left(\frac{\rho}{\rho_0}\right)^8 - 4\left(\frac{\rho}{\rho_0}\right)^{10}$	6.6
$6\left(\frac{\rho}{\rho_0}\right)^{10} - 5\left(\frac{\rho}{\rho_0}\right)^{12}$	6.2
$8\left(\frac{\rho}{\rho_0}\right)^8 - 10\left(\frac{\rho}{\rho_0}\right)^{10} + 3\left(\frac{\rho}{\rho_0}\right)^{12}$	6.8
$8\left(\frac{\rho}{\rho_0}\right)^{14} - 7\left(\frac{\rho}{\rho_0}\right)^{16}$	5.7
$-8\left(\frac{\rho}{\rho_0}\right)^{14} \log(\rho) + \left(\frac{\rho}{\rho_0}\right)^{16}$	5.4

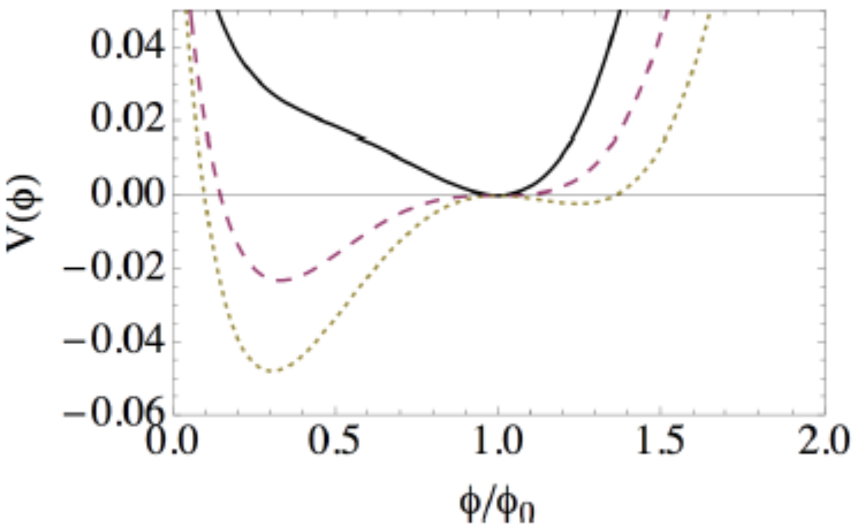
Ellis, NEM, You PLB 756, 25 (2016)

Gravitation can reduce the mass further

Vacuum instabilities & light GUT monopoles?

MOeDAL review : ArXiv:1406.7662

A. Rajantie Contemp.Phys. 53 (2012) 195-211; arXiv:1204.3073

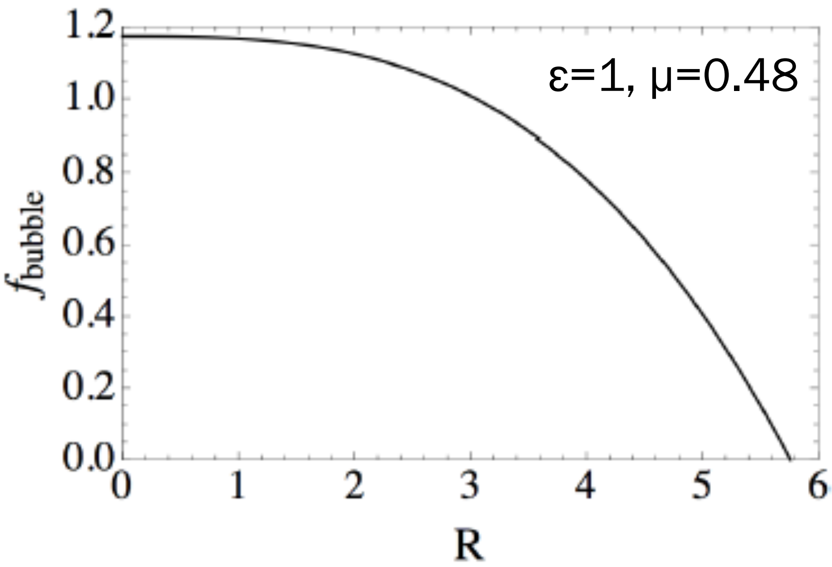


Monopole Energy density

$$E(\epsilon,\mu) = \frac{M_W}{\alpha_{em}} f(\epsilon,\mu),$$

@ GUT scales

Original Higgs vacuum decays to a new true vacuum via bubble formation : true vacuum inside bubble of radius R (new scale) containing monopole, bubble surrnounded by false vacua. Monopole decays



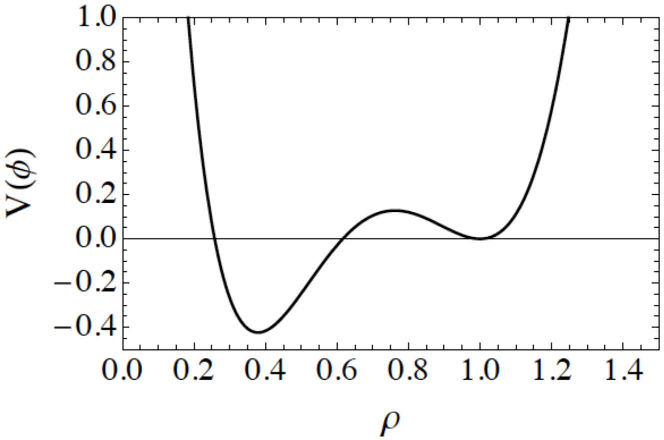
vacuum bubble radius

Vacuum instabilities & light GUT monopoles?

Courtesy: Vicente Vento (Valencia)

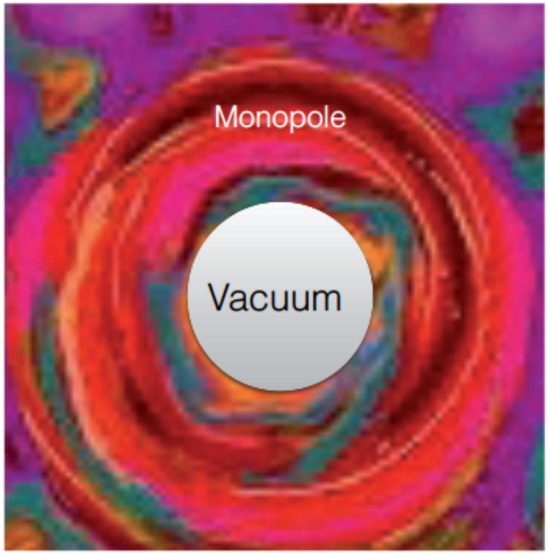
Work in progress on description of monopole structure & study of possible consequences.

Modifications of Georgi-Glashow (MGG) model
→ towards **smaller** monopole masses **BUT ALSO stable monopoles**
→ **relevance to MoEDAL**



Monopole structure in MGG model:
Bag model: **core:** true quasi empty vacuum
outside: a monopole tail

The bigger the core the smaller the mass



But ...there may already be...
several, light monopoles in the ...air

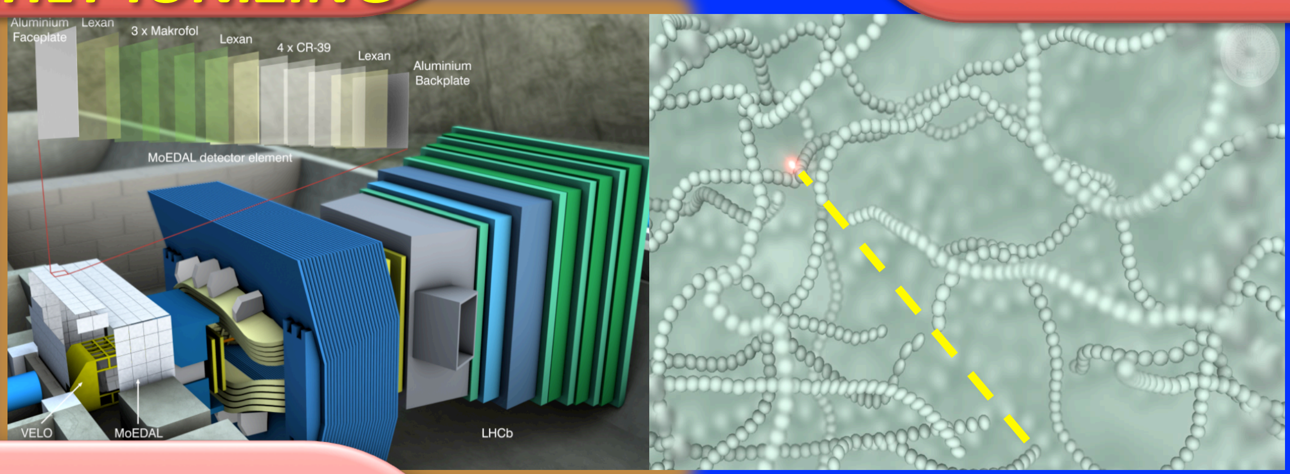
Magnetic Monopole Properties

– behaviour in matter

Magnetic Monopole Properties

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

Coupling constant = $g/\hbar c \sim 34$. Spin ½?



Breaks chemical bonds eg in Plastics of Nuclear Track detectors

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.

Magnetic Monopole Properties

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

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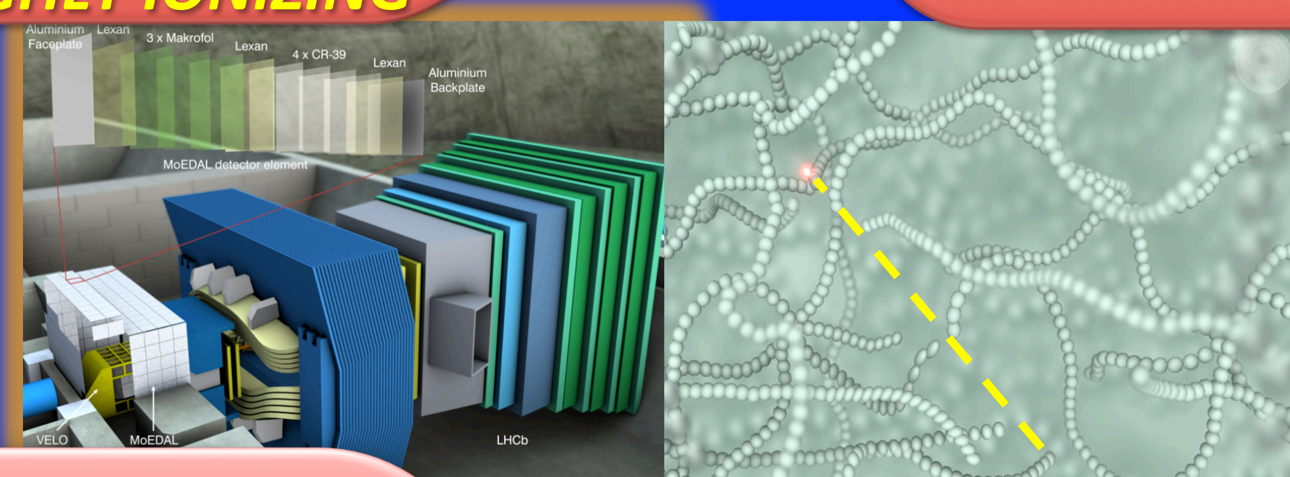


Energy acquired in a magnetic field =2.06MeV/gauss.m = 2TeV in a 10m, 10T LHC magnet

Dirac Monopole is singular
Mass cannot be predicted classically
needs regularization

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

The Ways to get High Ionization

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

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

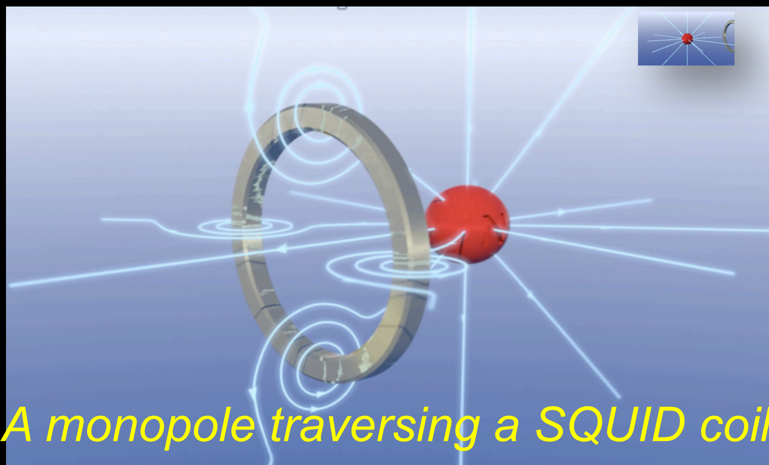
- **Magnetic charge** - *ionization increases with magnetic charge and decreases with velocity β – a unique signature*

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

  - *The velocity dependence of the Lorentz force cancels $1/\beta^2$ term*

- *The ionization of a relativistic monopole is $(ng)^2$ times that of a relativistic proton i.e $4700n^2$!! (n=1,2,3...)*

Induction Experiments



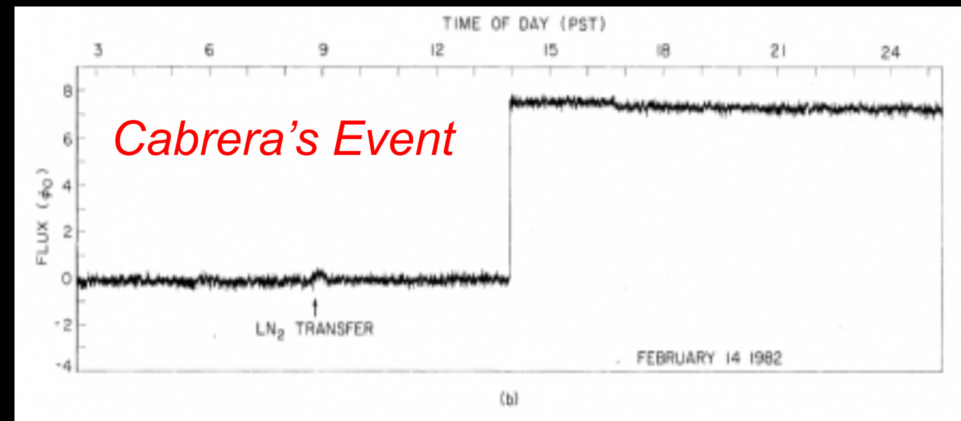
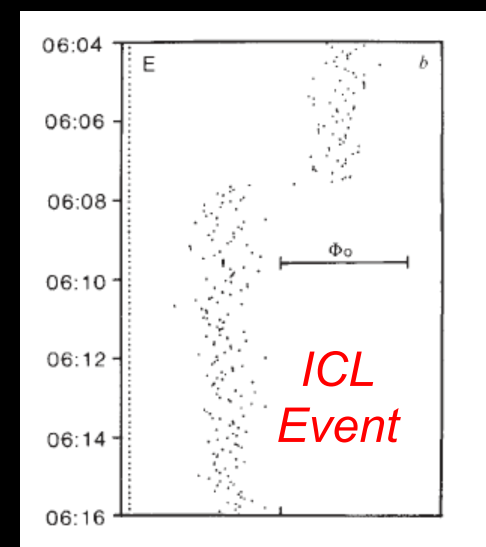
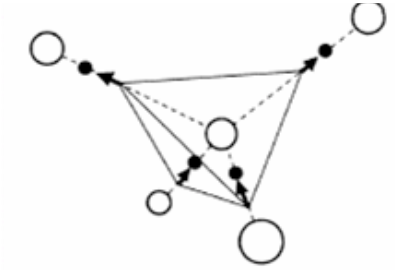


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

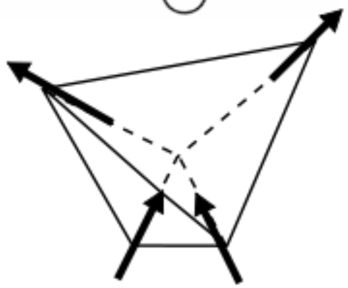
- *Data from Cabrera's apparatus taken on St Valentine's day in 1982 (A=20 cm²).*
  - *The trace shows a jump – just before 2pm - that one would expect from a monopole traversing the coil.*
- *In August 1985 a groups at ICL reported the:"observation of an unexplained event" compatible with a monopole traversing the detector (A= 0.18 m²)*
- *SAME TECHNOLOGY IS UTILIZED BY MoEDAL*



Spin Ice Monopole-like Quasiparticles



The arrangement of hydrogen atoms (black circles) about oxygen atoms (open circles) in **ice**

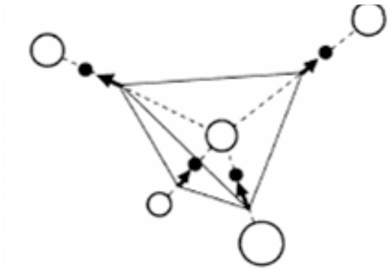


The arrangement of spins (black arrows) in a **spin ice – material tetrahedra of ions with non-zero spin**

Monopole-like quasiparticles (excitations):

C. Castelnovo, R. Moessner, S. L. Sondhi
Nature 451, 42-45 (2008)

Spin Ice Monopole-like Quasiparticles



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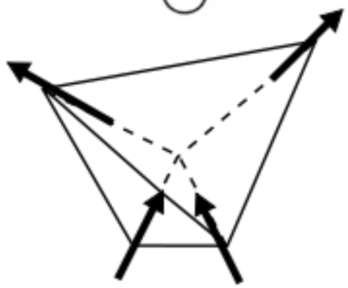
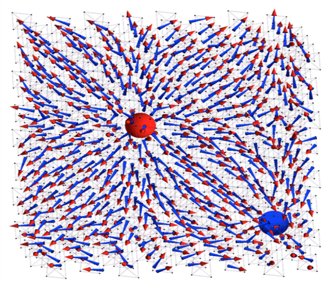


The arrangement of spins (black arrows) in a **spin ice – material tetrahedra of ions with non-zero spin**

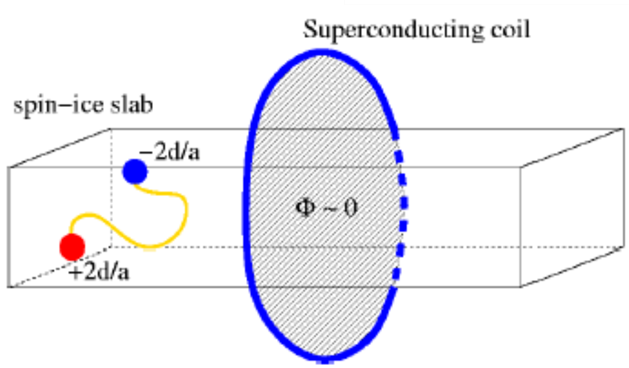
Monopole-like quasiparticles (excitations):

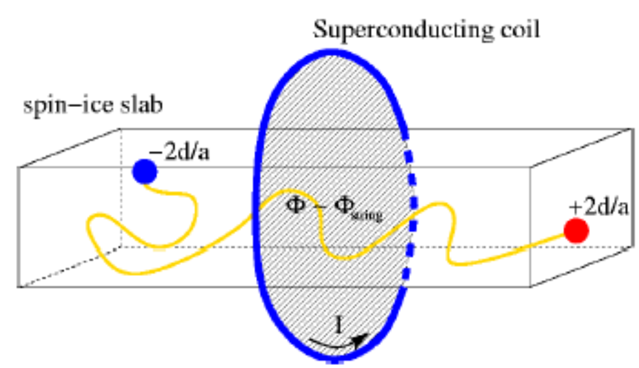
These excitations are **NOT** describing a fundamental particle unlike the real monopole.

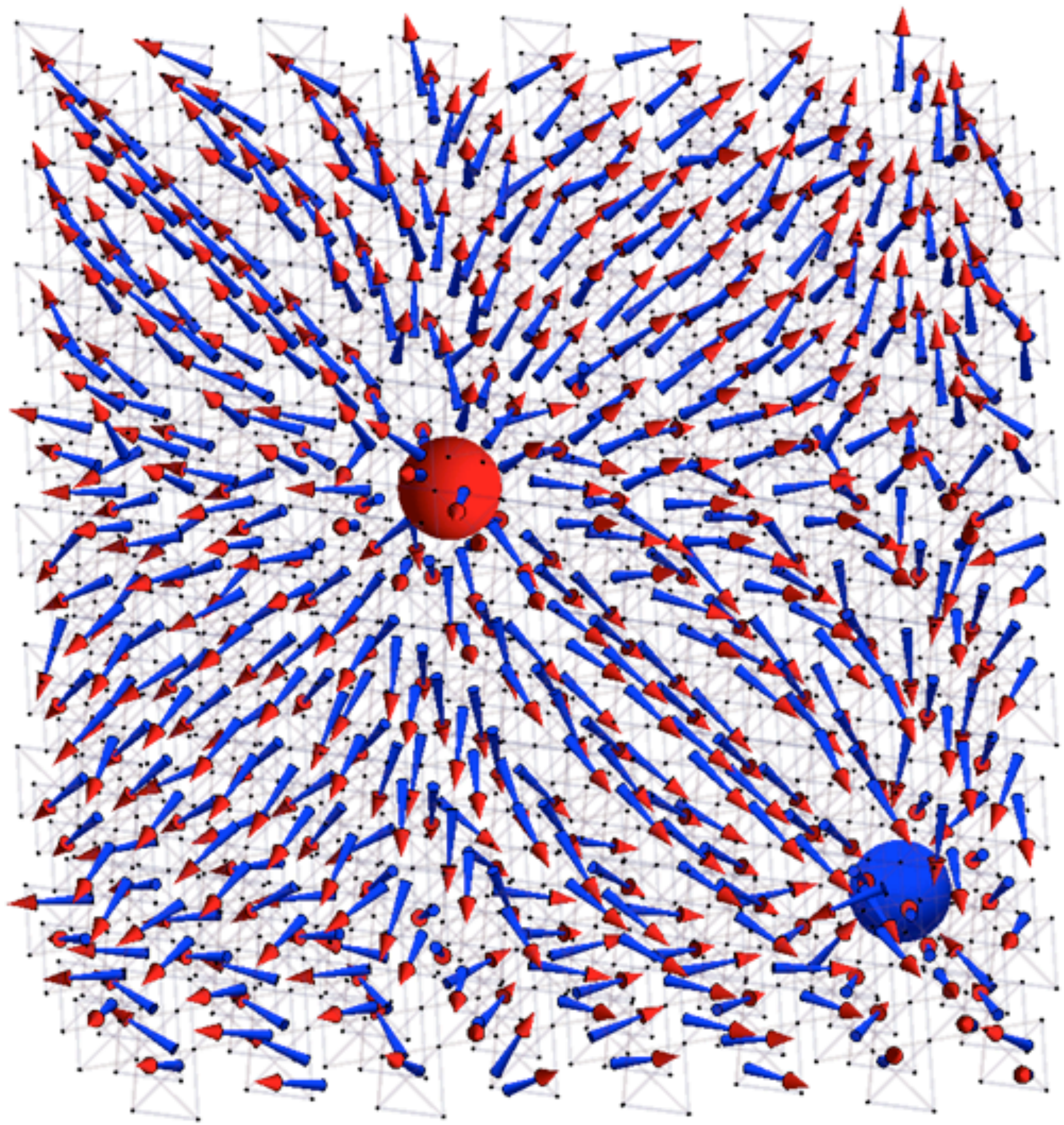


C. Castelnovo, R. Moessner, S. L. Sondhi
Nature 451, 42-45 (2008)

They account for phase transition of spin ice in a magnetic field



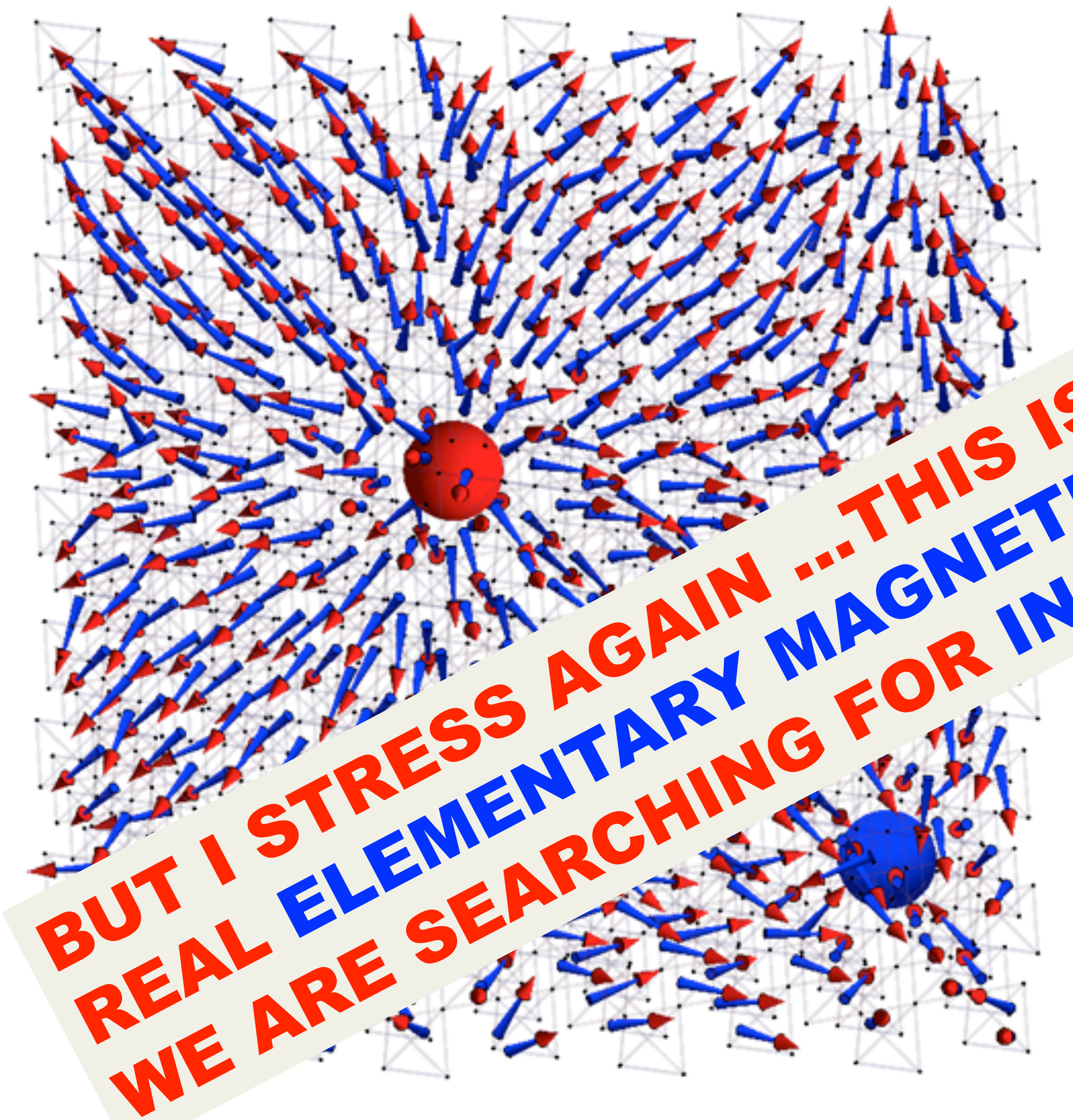




Dr C Castelonovo
https://www.royalholloway.ac.uk/cmt/research/frustratedmagnetism.aspx

Magnetic frustration leads to ``monopole-like'' quasiparticle excitations in spin ice :
sp[in d.o.f. magnetic dipoles fractionalise into decpnfined pairs of magntic monopole-like configurations

The magnetic moments were shown to align in the spin ice into interwoven tube-like bundles resembling Dirac strings.
At the defect formed by the end of each tube, the magnetic field looks like that of a monopole.
Use of applied magnetic field (break the symmetry of the system) can control the density and orientation of these strings



BUT I STRESS AGAIN ...THIS IS NOT THE REAL ELEMENTARY MAGNETIC MONOPOLE WE ARE SEARCHING FOR IN PARTICLE PHYSICS

Magnetic frustration
leads to ``monopole-lik
quasiparticle excit
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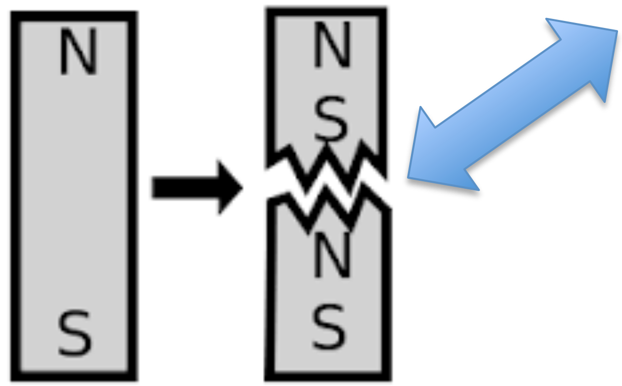


Cannot be the property of ordinary matter

If magnetic monopole exists should be a NEW elementary particle !

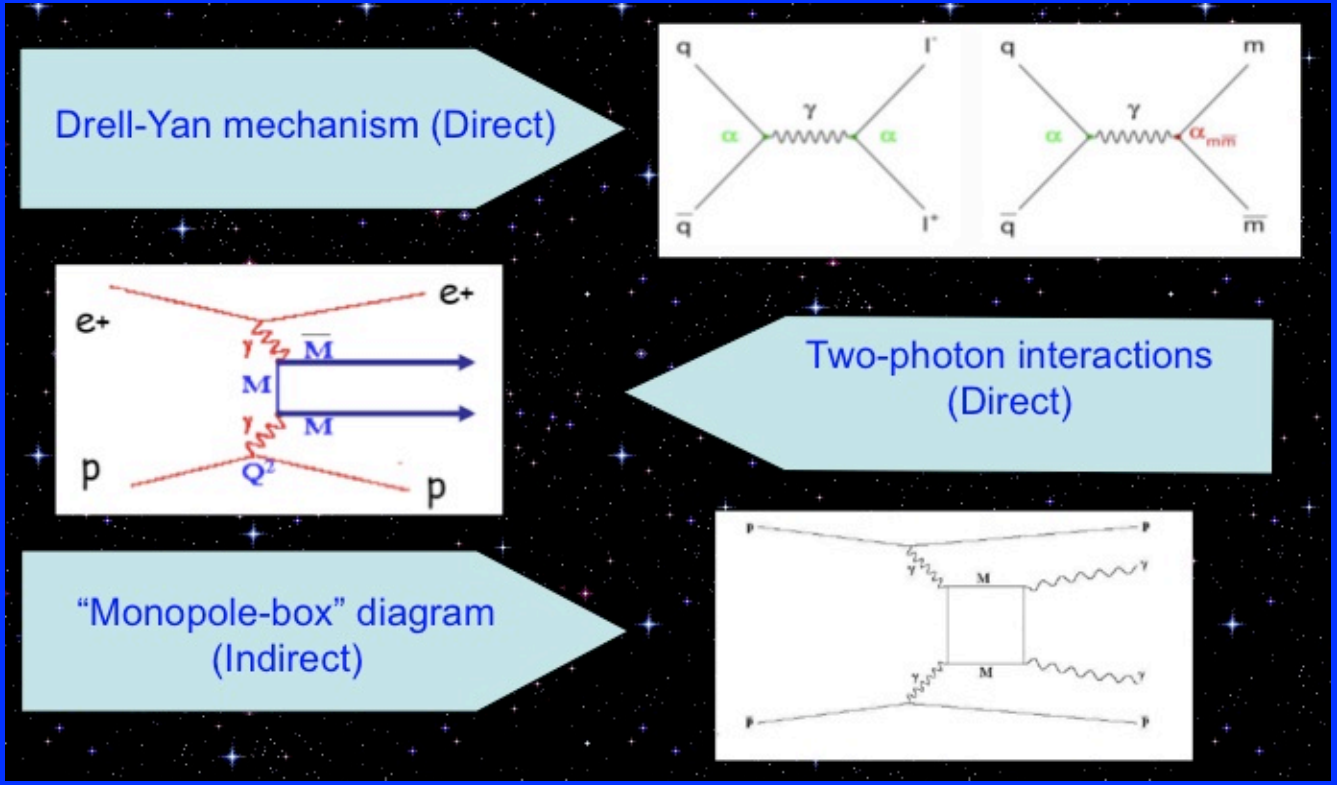
This is what Particle Physics Experiments at LHC such as MoeDAL are currently searching

U. Alberta-IC-KCL-Langdon School Collaboration

Searching for Low Mass (O(10 TeV)) Magnetic Monopoles @ LHC

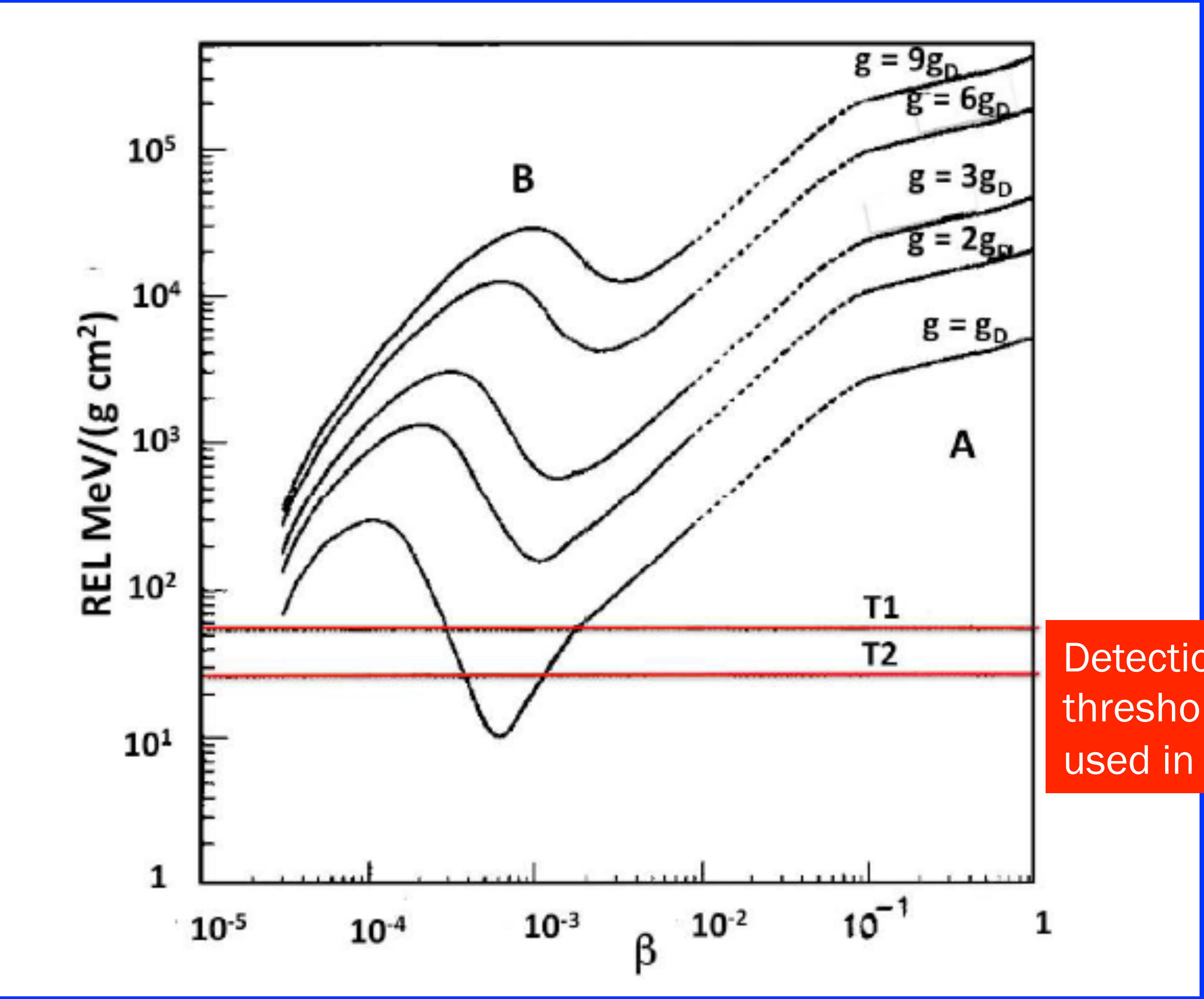
Monopole Production at Colliders

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



- 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

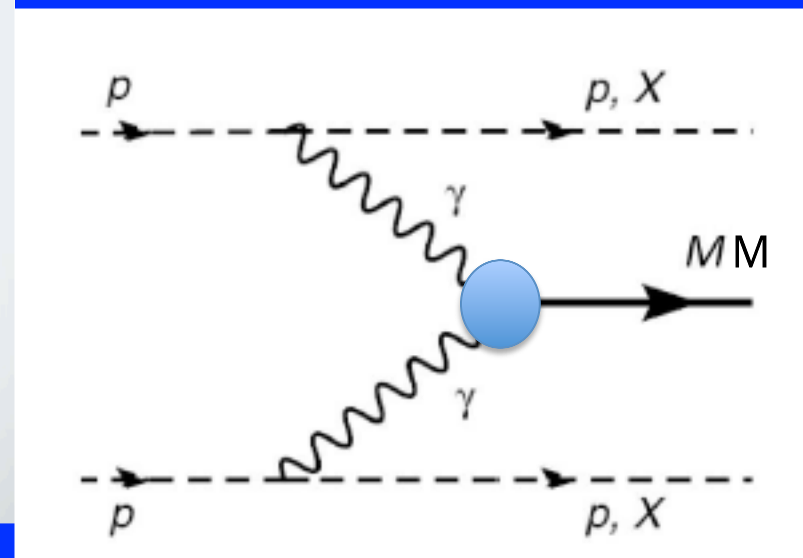
Monopole Energy Losses in plastic Nuclear Track Detectors (NTD)



Detection thresholds of CR39 used in MACRO Expt

THE SEARCH FOR MONOPOLIA

Dirac or other monopoles (e.g. Cho-Maison monopole) may not be free states but BOUND states → MONOPOLIUM (MM) → produced at colliders?

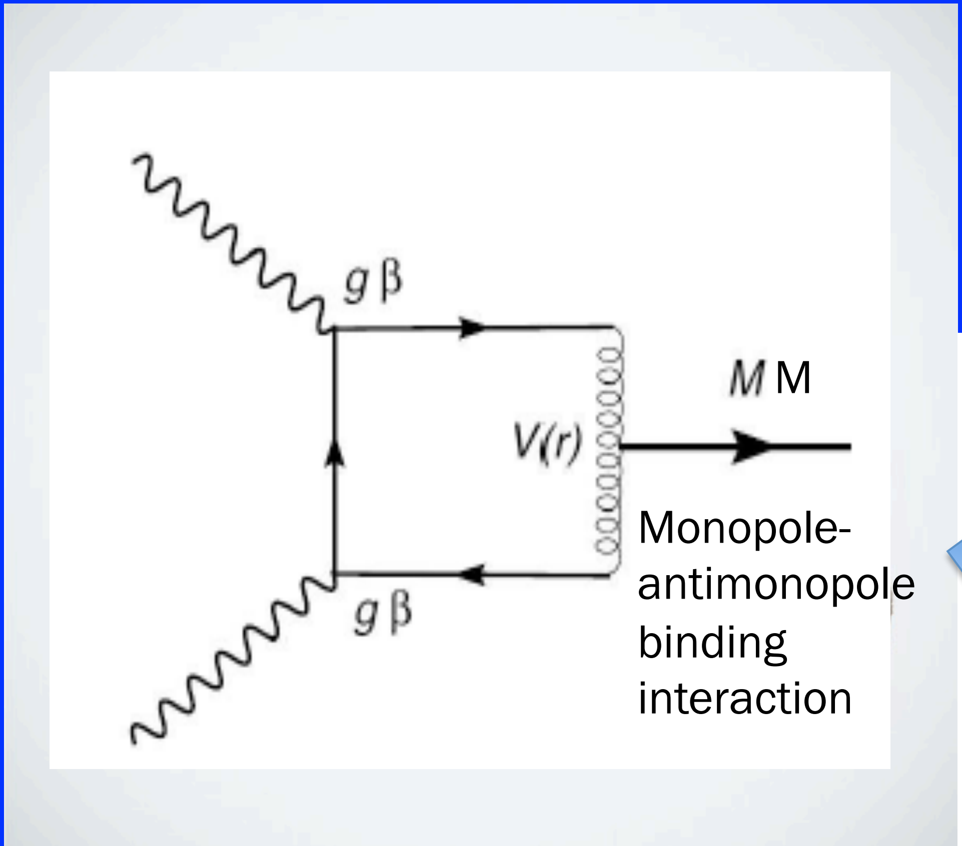


Epele, Fanchiotti, Garcia-Canal, Mitsou, Vento,
EPJPlus 127 (2012), 60

$$\sigma(2\gamma \to MM) = \frac{4\pi}{E^2} \frac{M^2\Gamma(E)\Gamma(MM)}{(E^2 - M^2)^2 + M^2\Gamma^2_{MM}}$$

$$\Gamma(M) = 0.$$

THE SEARCH FOR MONOPOLIA



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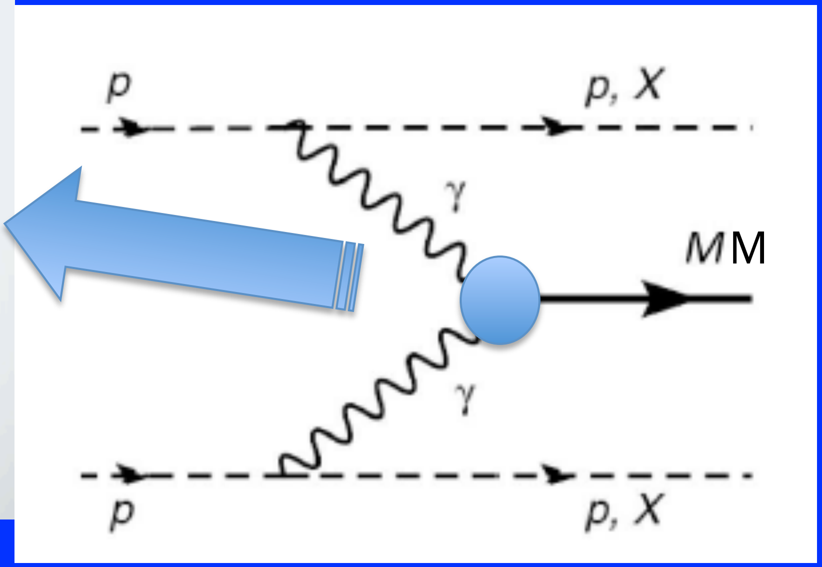

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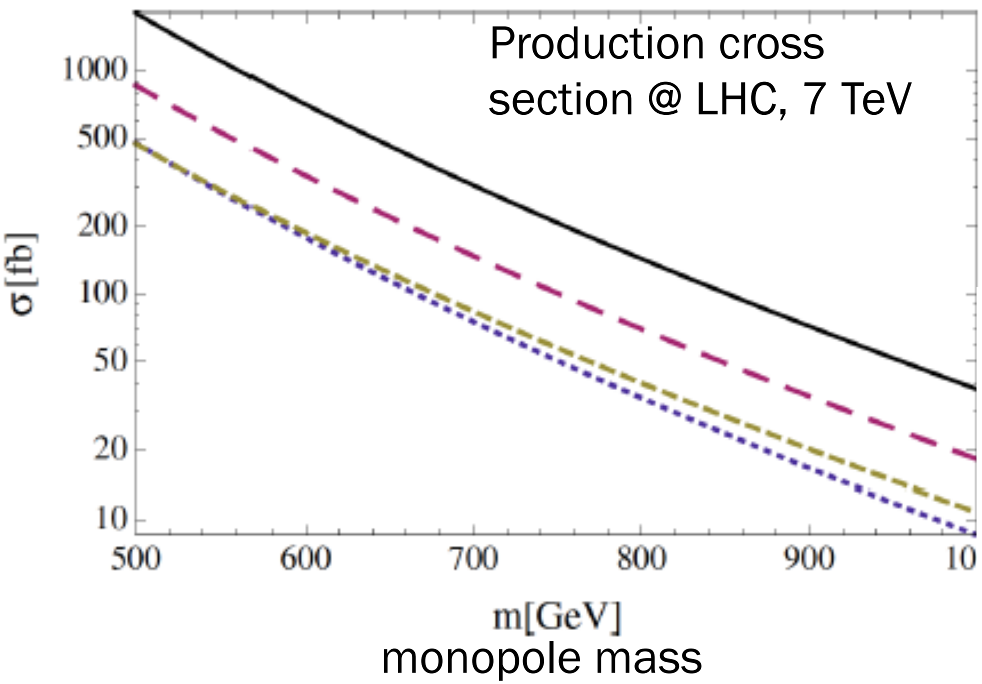
THE SEARCH FOR MONOPOLIA



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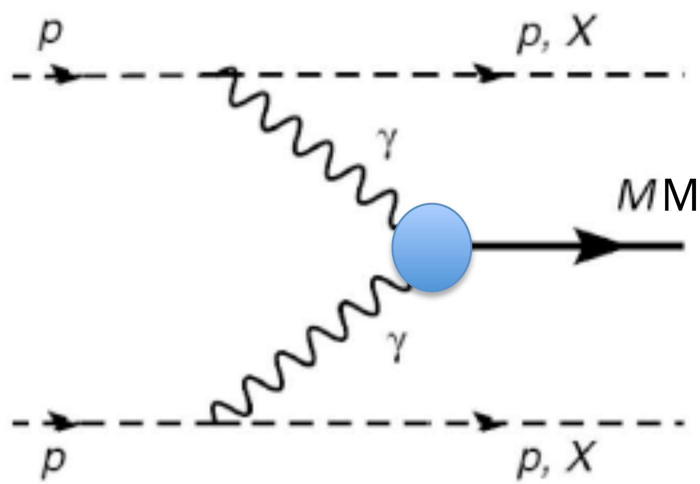


Binding energy fixed BE = 2m/15 , e.g.
for m=750 GeV, binding energy = 100 GeV
→ monopolium mass M= 1400 geV

V. Vento

in MOeDAL Physics Review

arXiv:1405.7662

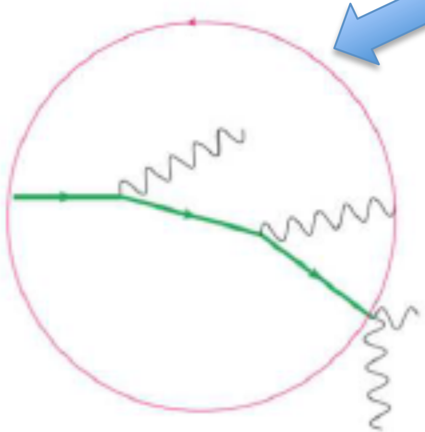
$$\sigma(2\gamma \to MM) = \frac{4\pi}{E^2} \frac{M^2\Gamma(E)\Gamma(MM)}{(E^2 - M^2)^2 + M^2\Gamma^2_{MM}}$$

$$\Gamma(E) \propto \beta^4 \;\to\; \Gamma(M) = 0.$$

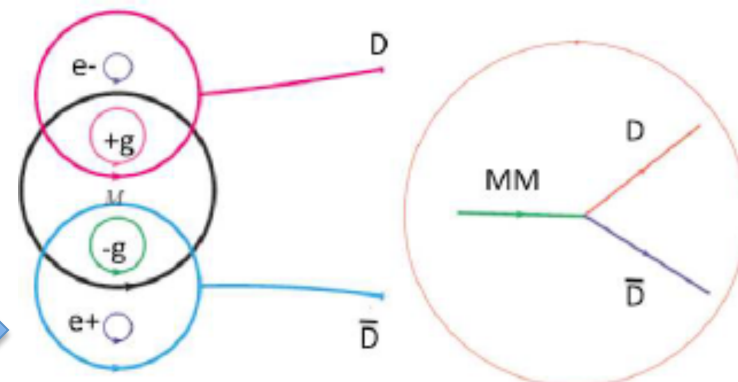
Relevance to LHC & MoEDAL Expts

Monopolium is neutral in its ground state & thus if produced in such a state is difficult, probably impossible, to detect in LHC (ATLAS, CMS) or MoeDAL (since damage to plastics from SM background could be higher)

BUT...it may be produced in an excited state, which could be a magnetic multiple → highly ionizing. Its decay via photon emission will produce a **peculiar trajectory,** if the decaying states are also magnetic multipoles, the process will generate a peculiar trajectory in the medium.



Monopolium might break up in the medium of MoEDAL into highly-ionizing Dyons



V. Vento

in MOeDAL Physics Review

arXiv:1405.7662

Moreover, In presence of magnetic fields huge polarizability

$$d \sim r_M^3\, B \sim (\alpha\, E_{binding})^{-3}\, B$$

The MoEDAL-LHC Experiment first Physics paper on MM searches

MoEDAL

MOEDAL

The 7th LHC Experiment

DESIGNED TO SEARCH FOR HIGHLY-IONIZING PARTICLES PRODUCED IN P-P COLLISONS AT THE LHC. SUCH PARTICLES ARE HARBINGERS OF REVOLUTIONARY NEW PHYSICS

MoEDAL

International Collaboration
> 65 Physicists from
21 Participating Institutions

UNIVERSITY OF ALBERTA

INFN & UNIVERSITY OF BOLOGNA

UNIVERSITY OF BRITISH COLUMBIA

CERN

UNIVERSITY OF CINCINNATI

INPPS CRACOW

CONCORDIA UNIVERSITY

CZECH TECHNICAL UNIVERSITY IN PRAGUE

UNIVERSITÉ DE GENÈVE

GANGNEUNG-WONJU NATIONAL UNIVERSITY

DESY

HELSINKI UNIVERSITY

IMPERIAL COLLEGE LONDON

KING'S COLLEGE LONDON

KONKUK UNIVERSITY

UNIVERSITY OF MÜNSTER

NORTHEASTERN UNIVERSITY

NATIONAL UNIVERSITY OF SCIENCE & TECHONOLOGY (MISiS) MOSCOW

INSTITUTE FOR SPACE SCIENCES, ROMANIA

TUFT'S UNIVERSITY

IFIC VALÈNCIA

Magnetic Monopole Trapper (MMT)-Why aluminium

- Aluminium is a good choice for the trapping volume material for three important reasons:
- First, the anomalously large magnetic moment of aluminium nucleus means that it will strongly bind a trapped monopole.
- Second, aluminium does not present a problem with respect to activation.
- Lastly, aluminium allows a cost effective approach to the construction of the MMT detector.

Complementarity of MoEDAL

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

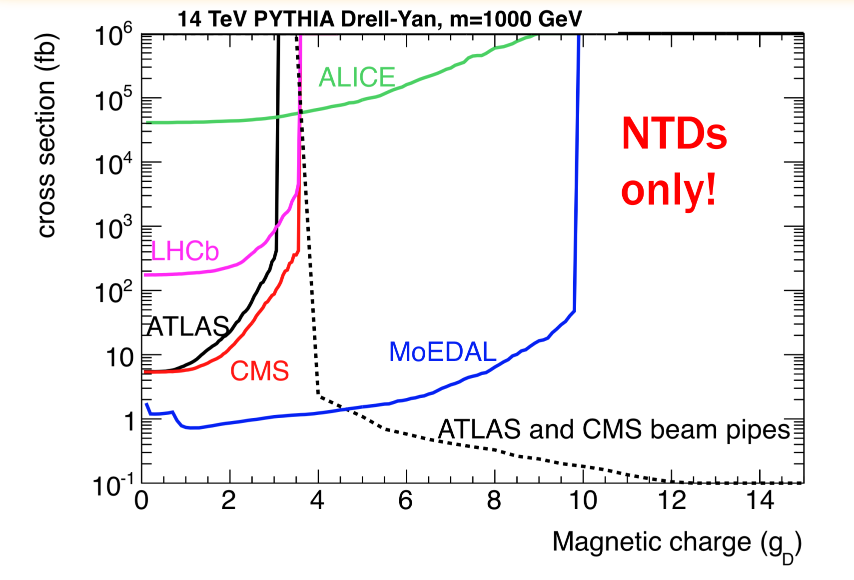
MoEDAL

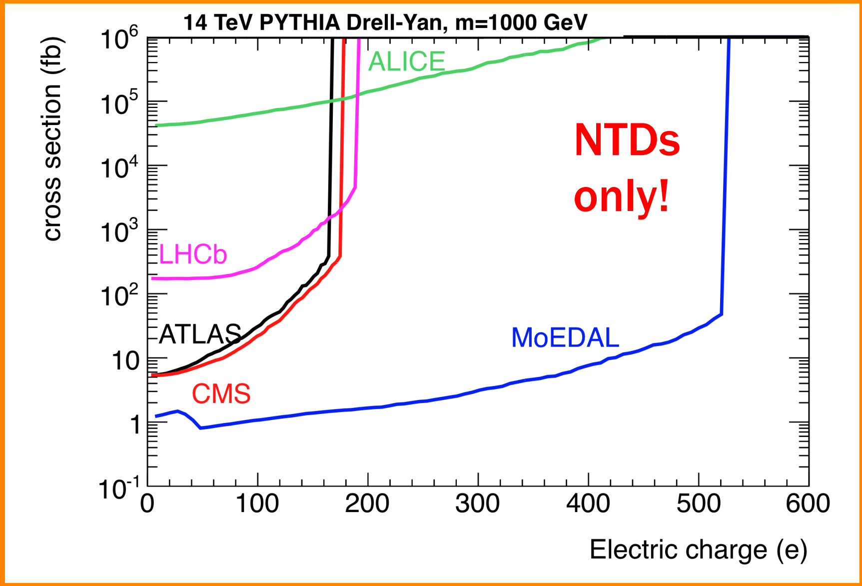
- MoEDAL is designed to detect charged particles, with effective or actual $Z/\beta > 5$.
- As it has no trigger/ electronics slowly moving ($\beta <$ ~5) particles are no problem
- One candidate event is enough to establish the signal (no Standard Model backgrounds)

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*

@ 20 fb^{-1} (assumed)

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 for the year long shutdown in Winter 2014.*
- *In spring 2015 commenced first ``official'' run to be continued until we reach an integrated luminosity*

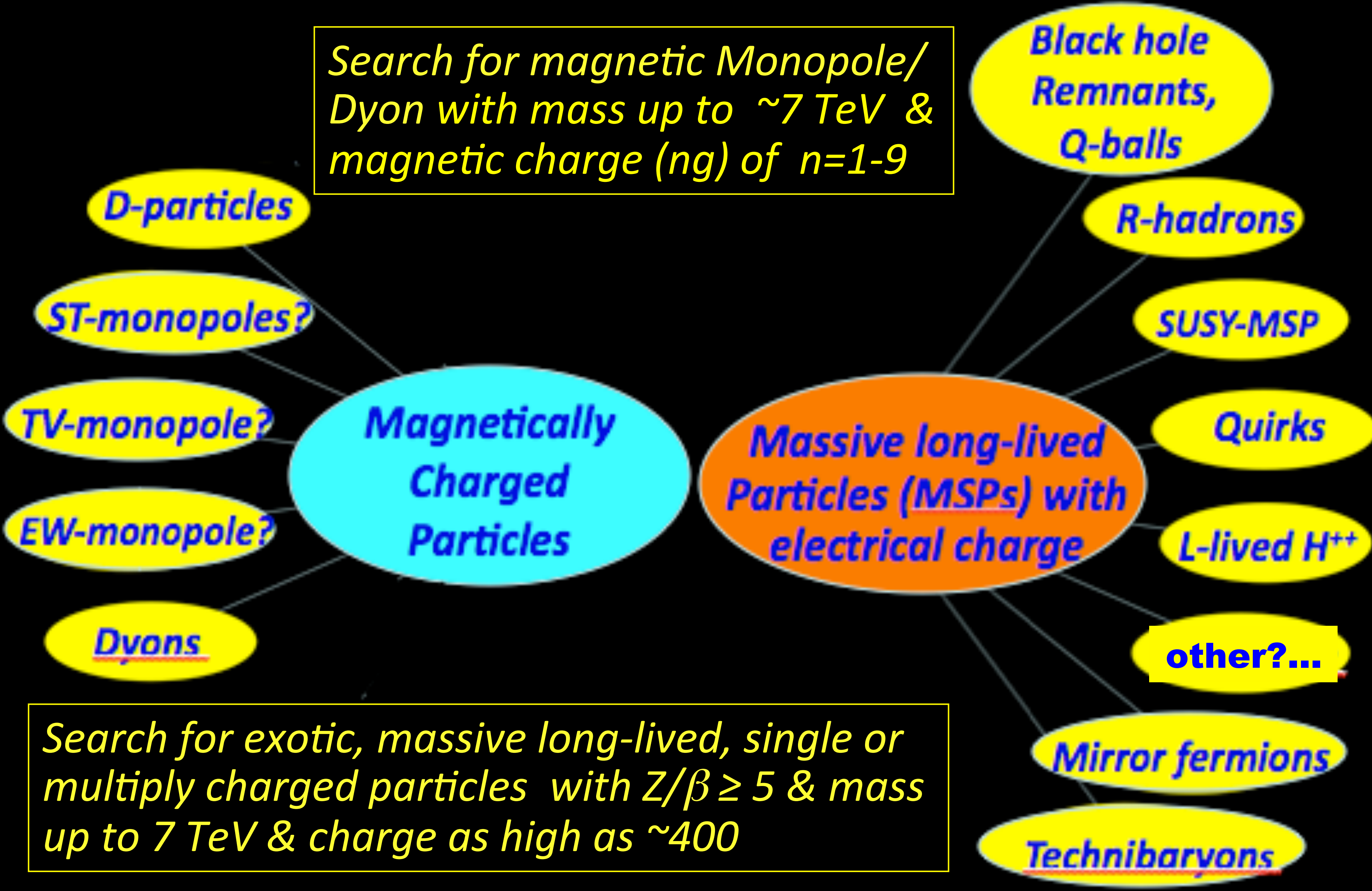
  $\int L \geq \sim 10\ fb^{-1}$ *at 14 TeV.*

THE PHYSICS of MoEDAL

Review paper: the Physics of MoEDAL
arXiv: 1405.7662 - Int.J.Mod.Phys. A29 (2014) 1430050

The MoEDAL Physics Program

Search for magnetic Monopole/ Dyon with mass up to ~7 TeV & magnetic charge (ng) of n=1-9



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

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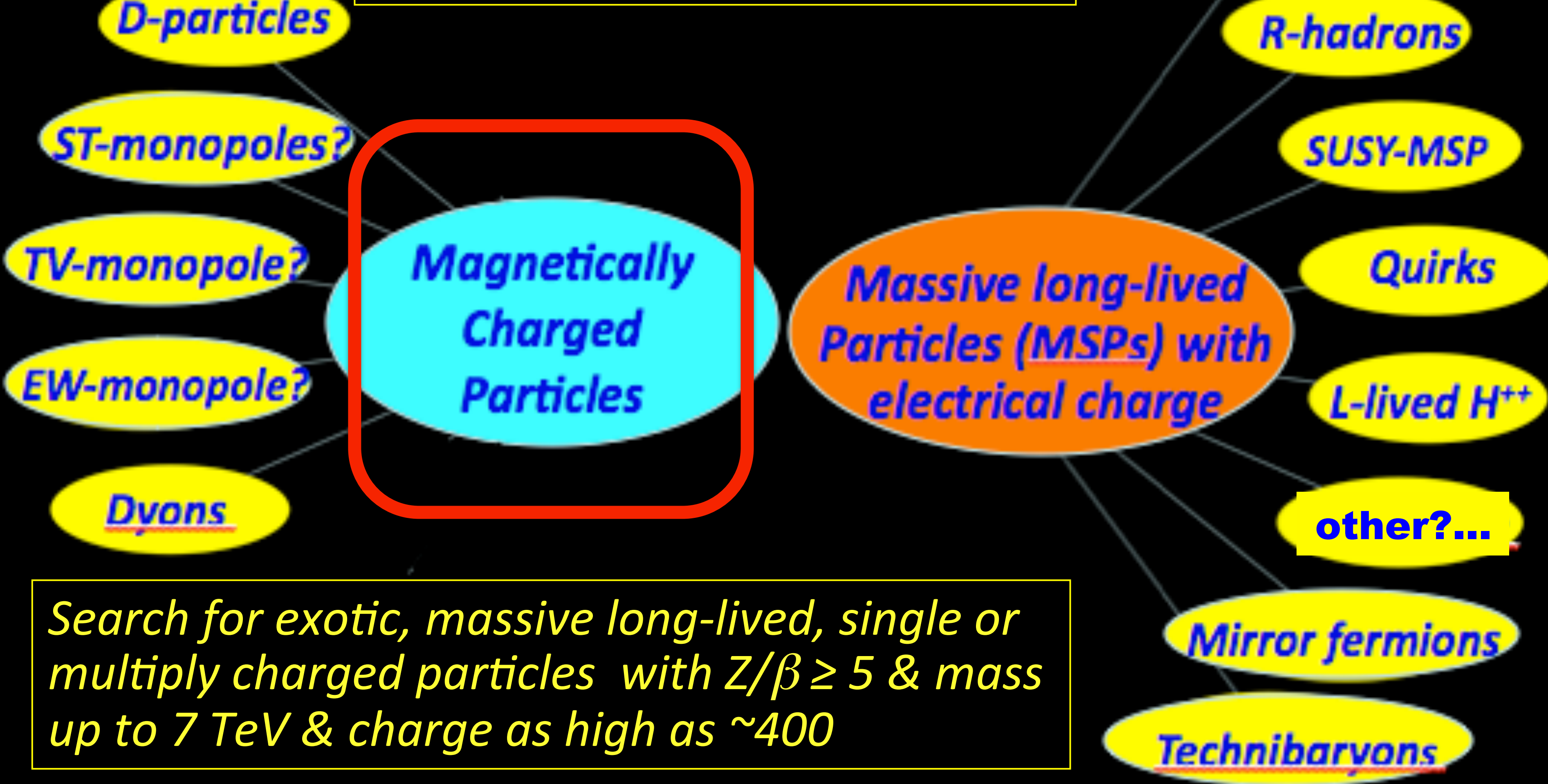

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First MoEDAL Monopole Searches in 2012 @ 8 TeV LHC Energies, and $\int L = 0.75\ \mathrm{fb}^{-1}$

THE PHYSICS of MoEDAL

B. Acharya et al. [MoeDAL Coll]
arXiv:1604.06645, JHEP in press

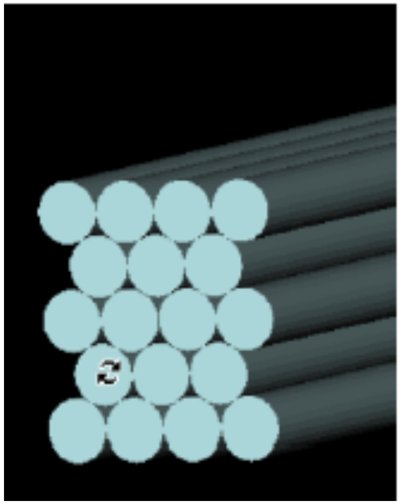
FIRST PAPER ON BOUNDS OF MONOPOLE MASSES FOR THE
2012 LHC RUN @ 8 TeV, in integrated luminosity 0.75 $fb^{-1,}$

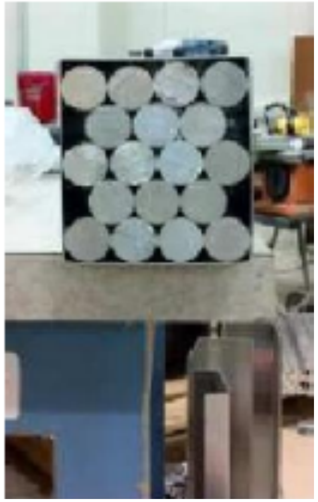
No magnetic charge (> 0.5 g_D) is detected in any of the samples and the results are interpreted for monopoles in the mass range 100 GeV ≤ m ≤3500 GeV and in the charge range $1g_D \leq |g| \leq 6g_D$, where g_D is the Dirac charge in quantization condition

$$\frac{q_m}{e} = \frac{n}{2\alpha_e} = n \cdot g_D \approx n \cdot 68.5$$

MoEDAL First Monopole Searches @ 8 TeV, $\int L = 0.75\ \text{fb}^{-1}$

Test Monopole Trapping Detector (MTD)





The MoEDAL Coll, arXiv:1604.06645

The 2012 MoEDAL trapping detector prototype was an aluminium volume comprising 11 boxes each containing 18 cylindrical rods of 60 cm length and 2.5 cm diameter.

The physics principle of Monopole Detection: if monopole is present in MTD then **persistent current** exist: difference (jump) in current before and after passage of the sample through sensing coil

Candidate events: if persistent current is different from zero by more than 0.25 g_D

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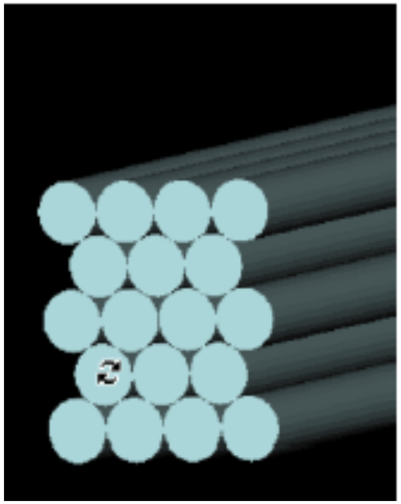
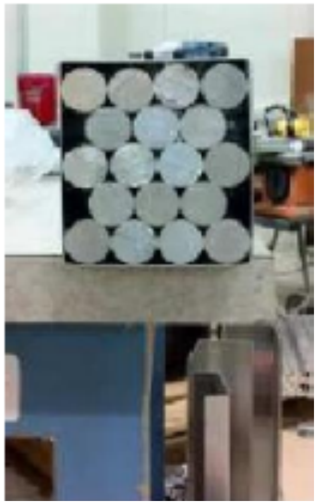

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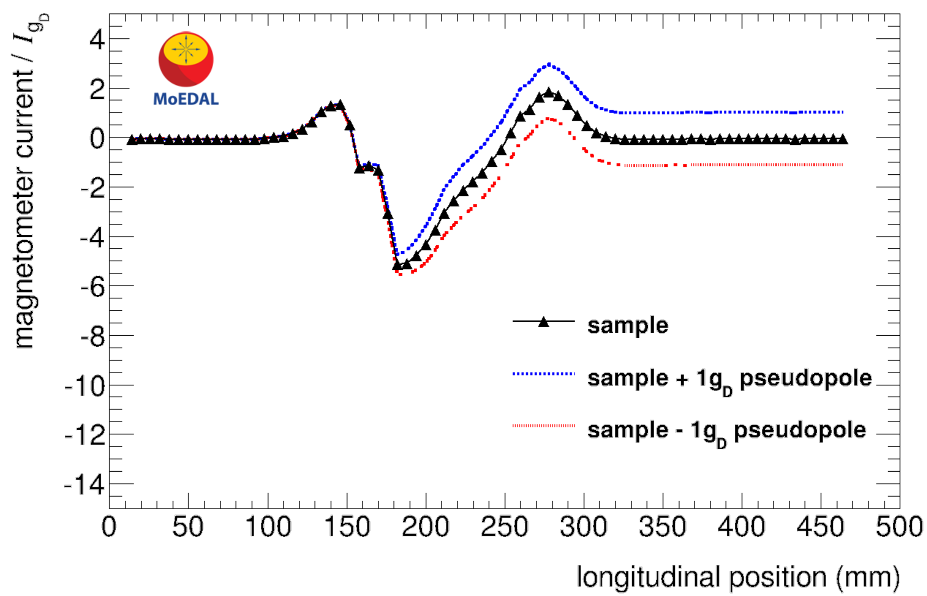

Magnetometer response profile for a typical aluminium sample of the MTD

The physics principle of Monopole Detection: if monopole is present in MTD then **persistent current** exist: difference (jump) in current before and after passage of the sample through sensing coil

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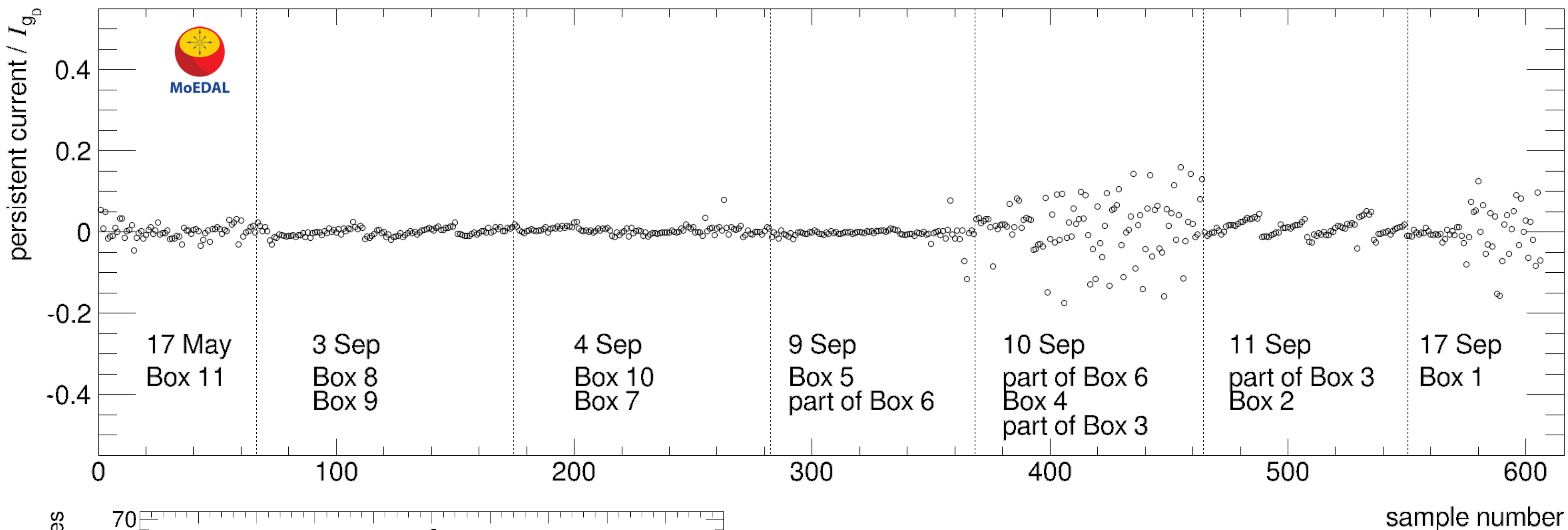
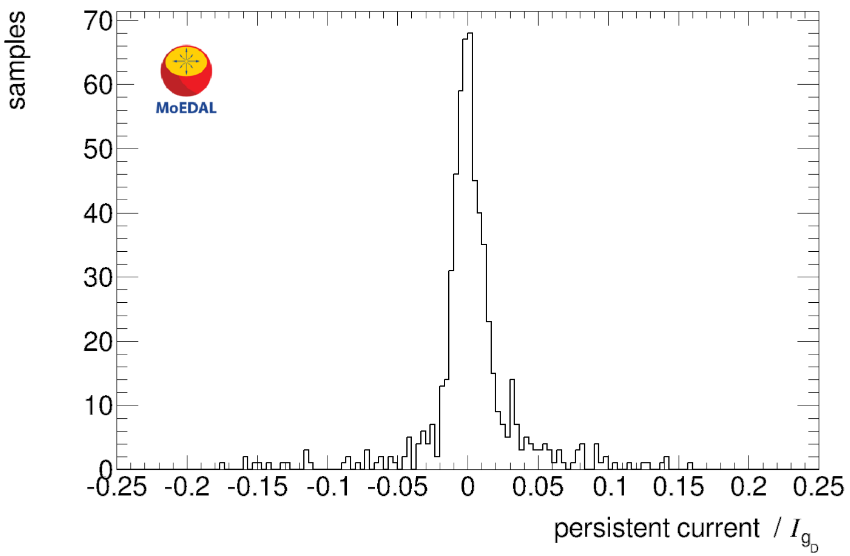




No non-trivial result for the 2012 Measurements in the 2012 MTD

The MoEDAL Coll, arXiv:1604.06645

The MoEDAL Coll, arXiv:1604.06645

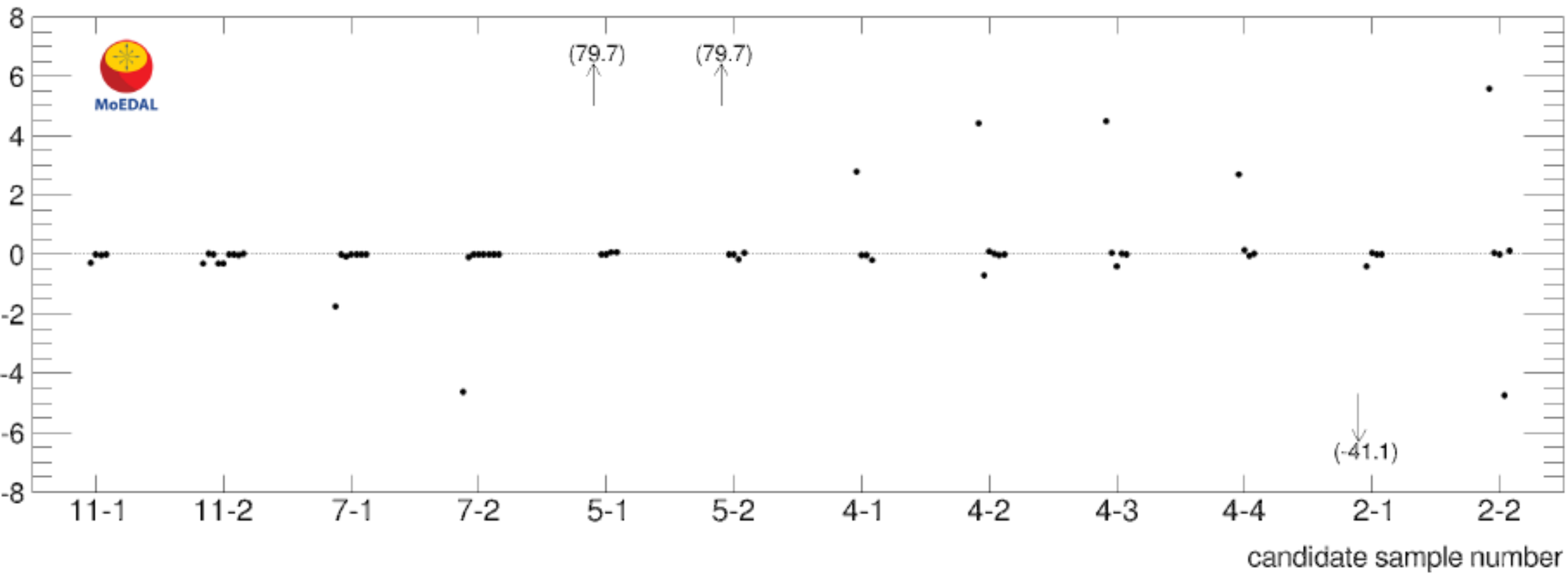
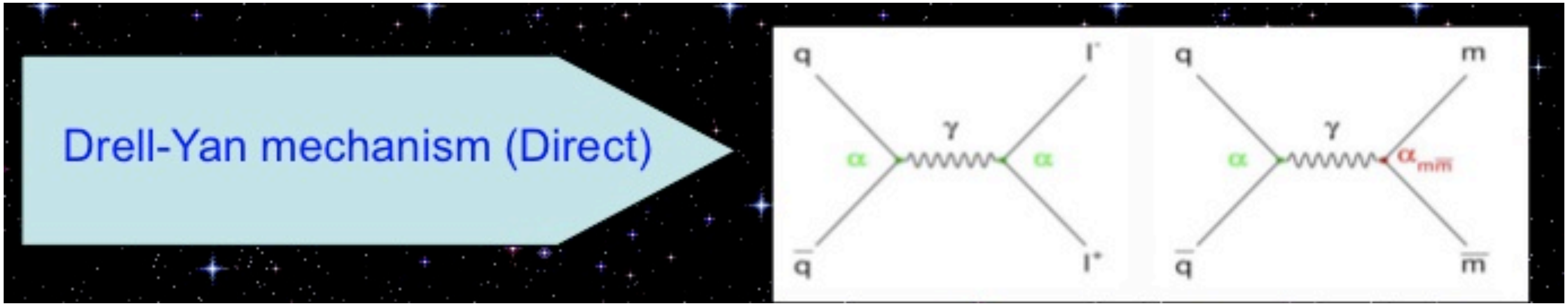


Figure 3. Results of multiple persistent current measurements (in units of the Dirac charge) for the 12 samples which yielded large ($|g| > 0.25\ g_D$) values for the first measurement.

Interpretation of Results-Monopole Simulations

The MoEDAL Coll, arXiv:1604.06645

Model-dependent and model-independent interpretation of results require magnetic monopole simulation using Drell-Yan & single monopole production
Leading DY process: pp → q –anti q → virtual photon → Monopole antimonopole Pairs
Use MADGRAPH5 MONTE CARLO EVENT GENERASTOR for spin ½, and spin 0 monopoles



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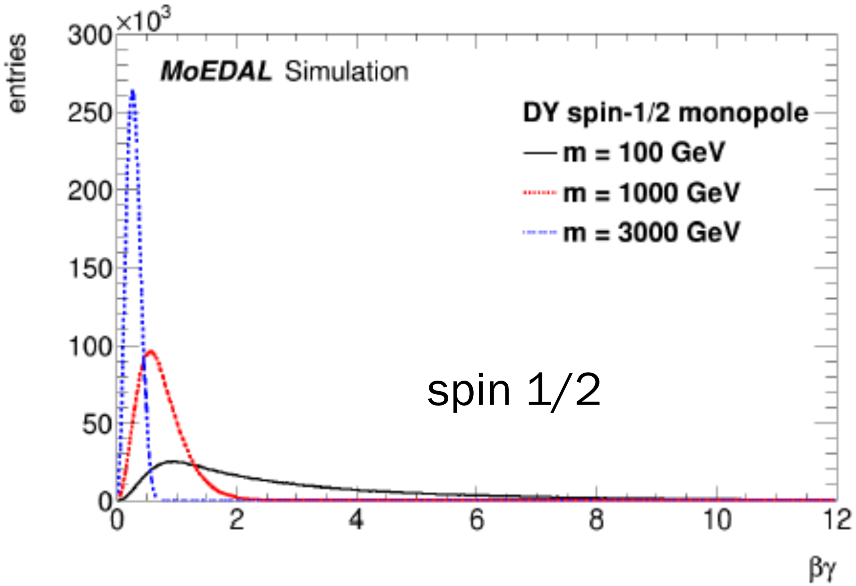

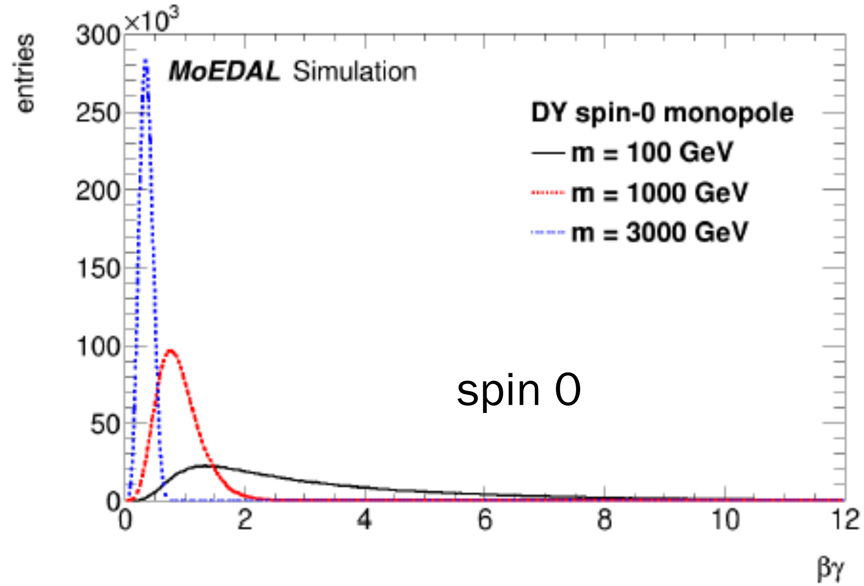

Independent of monopole charge

Use GEANT4 tool kit for the simulations of Monopole energy losses & the Geometry of MTD

Interpretation of Results-Monopole Simulations

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$$-\frac{\mathrm{d}E}{\mathrm{d}x} = C\frac{Z}{A}g^2\left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I} + \frac{K(|g|)}{2} - \frac{1}{2} - B(|g|) - \frac{\delta}{2}\right]$$

Use GEANT4 tool kit for the simulations of Monopole energy losses & the Geometry of MTD

Energy losses

The MoEDAL Coll, arXiv:1604.06645

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X Can be ignored

$$C = \frac{e^4}{m_u 4\pi\epsilon_0^2 m_e c^2} = 0.307\ \mathrm{MeV\ g^{-1}cm^2},$$

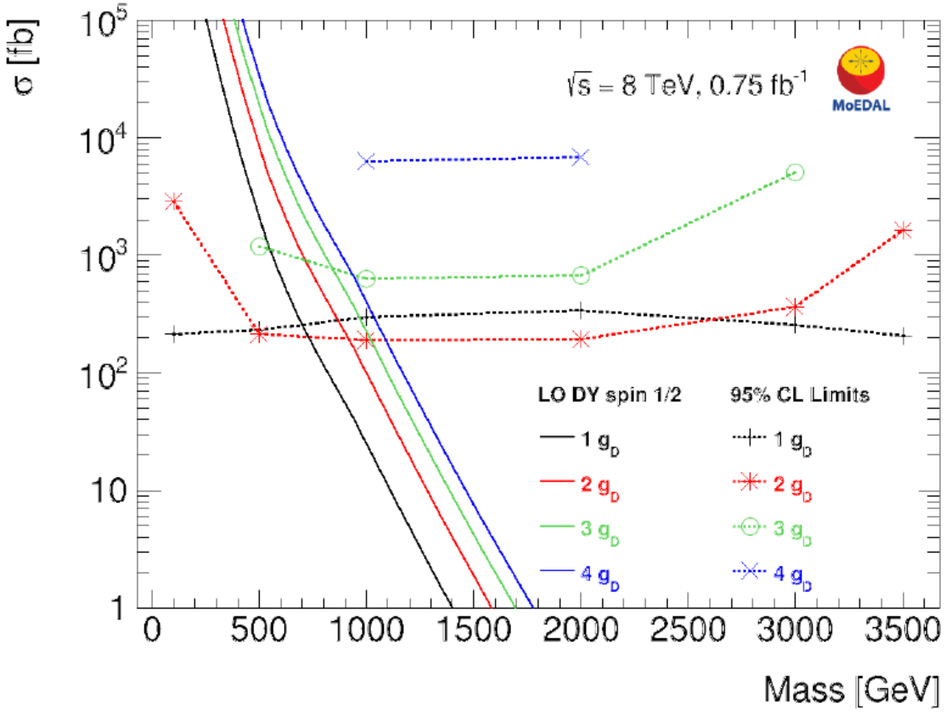
Delicate dependence on β

$10^{-4} < \beta < 0.01$ — **assume medium as degenerate e gas**

$0.01 < \beta < 0.1$ — **linear interpolation**

Use GEANT4 tool kit for the simulations of Monopole energy losses & the Geometry of MTD

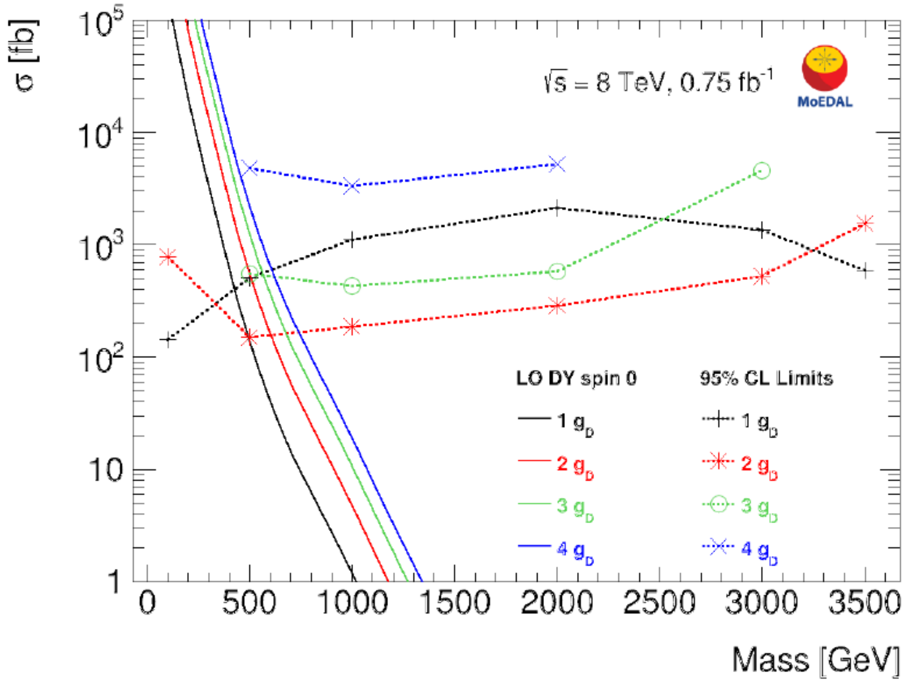
MoEDAL Limits on Monopole Production



The MoEDAL Coll, arXiv:1604.06645

spin ½

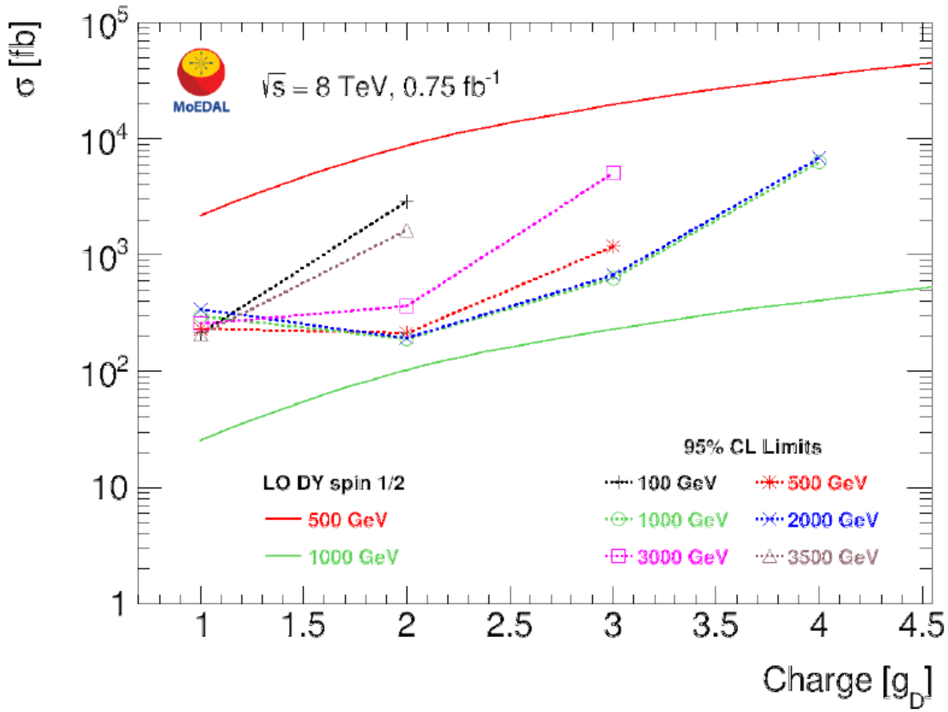
spin 0



Cross section upper limits @ 95% C.L. for DY processes

MoEDAL Limits on Monopole Production

The MoEDAL Coll, arXiv:1604.06645



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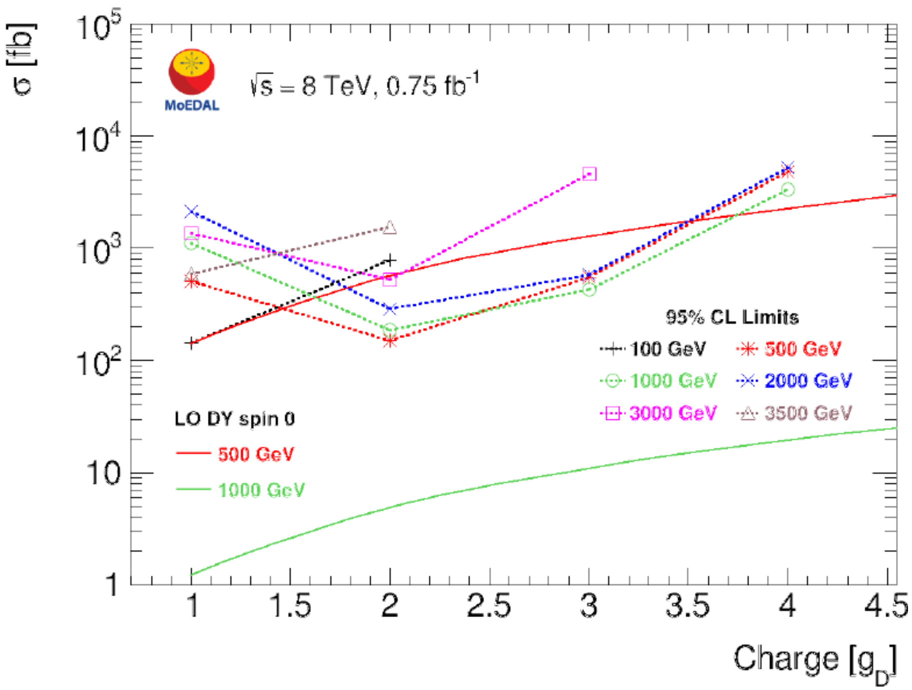

Cross section upper limits @ 95% C.L. for DY processes

The MoEDAL Coll, arXiv:1604.06645

LOWER BOUNDS ON MONOPOLE MASSES

FROM MoEDAL @ 8 TeV LHC , $\int L = 0.75\ fb^{-1}$

DY Lower Mass Limits [GeV]	$\lvert g \rvert = g_D$	$\lvert g \rvert = 2g_D$	$\lvert g \rvert = 3g_D$
spin-1/2	700	920	840
spin-0	420	600	560

NB: DY processes not reliable perturbatively

MoEDAL

The MoEDAL Coll, arXiv:1604.06645

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For the first time @ LHC , surpass previous collider results

MoEDAL

Is it worthy the effort?

We believe so !!! ...

1) because MoEDAL is sensitive to generic monopoles beyond any theoretical details in the TeV mass range

2) modern developments on (theory arguments on) the determination of the mass of microscopic models of (hybrid) E/W monopoles @ O(10) TeV

Such theoretical arguments can be falsified or verified directly by Experimentt !!

Global Monopoles

Manuel Barriola and Alexander Vilenkin
Phys. Rev. Lett. 63, 341 (1989)

What are they?

Singular configurations of Goldstone-like triplet scalar fields, **breaking spontaneously O(3) symmetry**

$$L = \frac{1}{2}\partial_\mu \phi^a \partial^\mu \phi^a - \frac{1}{4}\lambda(\phi^a\phi^a - \eta^2)^2$$

$$\boxed{\phi^a = \eta f(r) x^a/r} \qquad a = 1,2,3. \quad x^a x^a = r^2.$$

Size of monopole core (in flat space) $\delta \sim \lambda^{-1/2}\eta^{-1}$.

Monopole core mass ≈ total Mass $\boxed{M \sim M_{\rm core} \sim \lambda\eta^4\delta^3 \sim \lambda^{-1/2}\eta\,.}$

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Monopole core mass ≈ total Mass $M \sim M_{\rm core} \sim \lambda\eta^4\delta^3 \sim \lambda^{-1/2}\eta\,.$

Monopoles distort space-time, in such a way that far away from the monopole core it is Minkowski but with a **deficit angle** (``conical-like singularity'')

$$ds^2 = dt^2 - dr^2 - (1 - 8\pi G\eta^2) r^2 (d\theta^2 + \sin^2\theta\, d\phi^2)$$

Surface $\theta = \pi/2$ has geometry of a cone with deficit angle $\Delta = 8\pi^2 G\eta^2$

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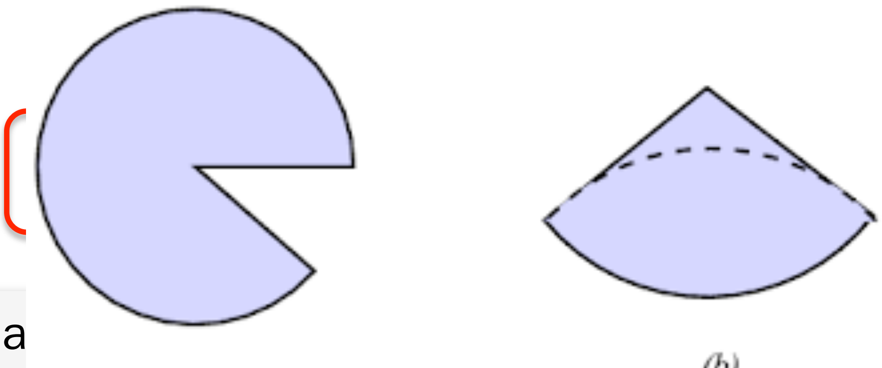
Size of monopole core (in flat space)

Monopole core mass ≈ total Mass



(a) (b)

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Scattering of Particles in the space-time of a Global Monopole - Relevance to MoEDAL

P. Mazur & J. Papavassiliou, PRD44 (1991), 1317;
H. Ren, Phys. Lett. B325 (1994), 149;
E.R. Berzera de Mello & C. Furtado, PRD56 (1997), 13.

Use quantum mechanics (partial wave analysis) to describe scattering of fermions and bosons (including light) in the deficit space time → scattering amplitudes

$$f(\theta)=\frac{1}{2ik}\sum_{l=0}^{\infty}(2l+1)[\exp(2i\delta_l)-1]P_l(\cos\theta)$$

$$\delta_l^{(1)}=\frac{\pi}{2}(l-\lambda_l)\simeq\frac{\pi}{2}\left[z_l(1-\alpha^{-1})+\frac{a^2}{2\alpha z_l}+O\left(\frac{a^4}{z_l^3}\right)\right]$$

$$z_l=l+1/2$$

$$a^2=(1-\alpha^2)/4=\Delta/4$$

$$f(\theta)=f_s(\theta)+f_0(\theta)$$

$$f_0(\theta)=\frac{i}{k}\delta(1-\cos\theta),$$

$$\alpha^2=1-8\pi Gv^2$$

$$f_s(\theta)=\frac{\alpha^{-2i\eta}}{ik}F_s(\theta)$$

$$F_s(\theta)=\sum_{l=0}z_l\exp(i\omega z_l)\left[1+\frac{i\pi a^2}{2\alpha z_l}+2i\eta\ln z_l+\cdots\right]\times P_l(\cos\theta),$$

$$\omega=\pi(1-\alpha^{-1})$$

$$\eta=K\sqrt{\frac{M}{2E\hbar^2\alpha^2}}$$

M = **mass of particle**

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$\theta=\omega$

``**singular**'' at angles = deficit angle

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$\alpha^2=1-8\pi G v^2$

$$f(\theta)=f_s(\theta)+f_0(\theta)$$

$$f_0(\theta)=\frac{i}{k}\delta(1-\cos\theta),$$

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$$F_s(\theta)=\sum_{l=0}z_l\exp(i\omega z_l)\left[1+\frac{i\pi a^2}{2\alpha z_l}+2i\eta\ln z_l+\cdots\right]\times P_l(\cos\theta),$$

$\omega=\pi(1-\alpha^{-1})$

$$\eta=K\sqrt{\frac{M}{2E\hbar^2\alpha^2}}$$

M = **mass of particle**

$\alpha\approx 1$

Scattering of Particles in the space-time of a Global Monopole - Relevance to MoEDAL

E.R. Berzera de Mello & C. Furtado, PRD56 (1997), 13.

For charged particles → additional self-interaction contributions

$$f(\theta)=f_s(\theta)+f_0(\theta)$$

$$f_0(\theta)=\frac{i}{k}\delta(1-\cos\,\theta),$$

$$f_s(\theta)=\frac{\alpha^{-2i\eta}}{ik}F_s(\theta)$$

$$F_s(\theta)=\sum_{l=0}^{\infty} z_l\,\exp(i\omega z_l)\left[1+\frac{i\pi a^2}{2\alpha z_l}+2i\eta\ln z_l+\cdots\right]\times P_l(\cos\,\theta),$$

$+\ \bar{F}_s(\theta)$

$$\bar{F}_s(\theta)=2i\eta\sum_{l=0}^{\infty} z_l \ln z\, e^{i\omega z_l}P_l(\cos\,\theta) = \frac{2\eta\,\sin\,\omega}{[2(\cos\,\omega-\cos\,\theta)]^{3/2}}\Theta_\omega(\theta)$$

$$\Theta_\omega(\theta)=\int_0^\infty dx f_\omega(x,\theta)$$

well-defined finite for $\theta\neq\omega$

also ``singular'' at $\theta=\omega$ angles = deficit angle

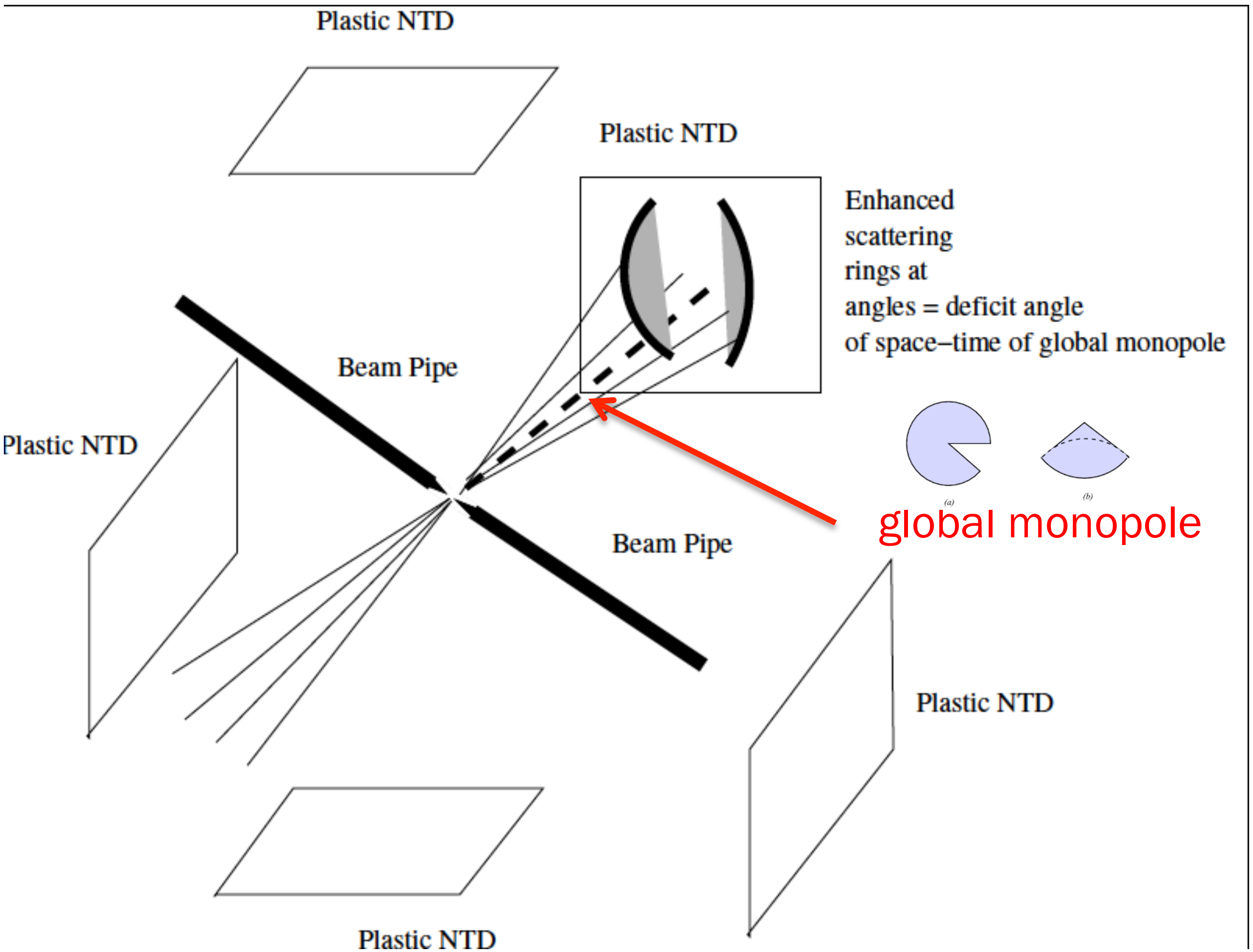
Scattering of Particles in the space-time of a Global Monopole
Relevance to MoEDAL

P. Mazur & J. Papavassiliou, PRD44 (1991), 1317;
H. Ren, Phys. Lett. B325 (1994), 149;
E.R. Berzera de Mello & C. Furtado, PRD56 (1997), 13.

Optical theorem, total cross section

$$\sigma = \frac{4\pi}{k}\,\mathrm{Im}\, f(0)$$

$$\theta = \omega$$



``**singular**'' at such (small) angles (smoothened out by higher l-multiple terms in scattering)
→ for practical purposes:

ENHANCED RING PATTERNS

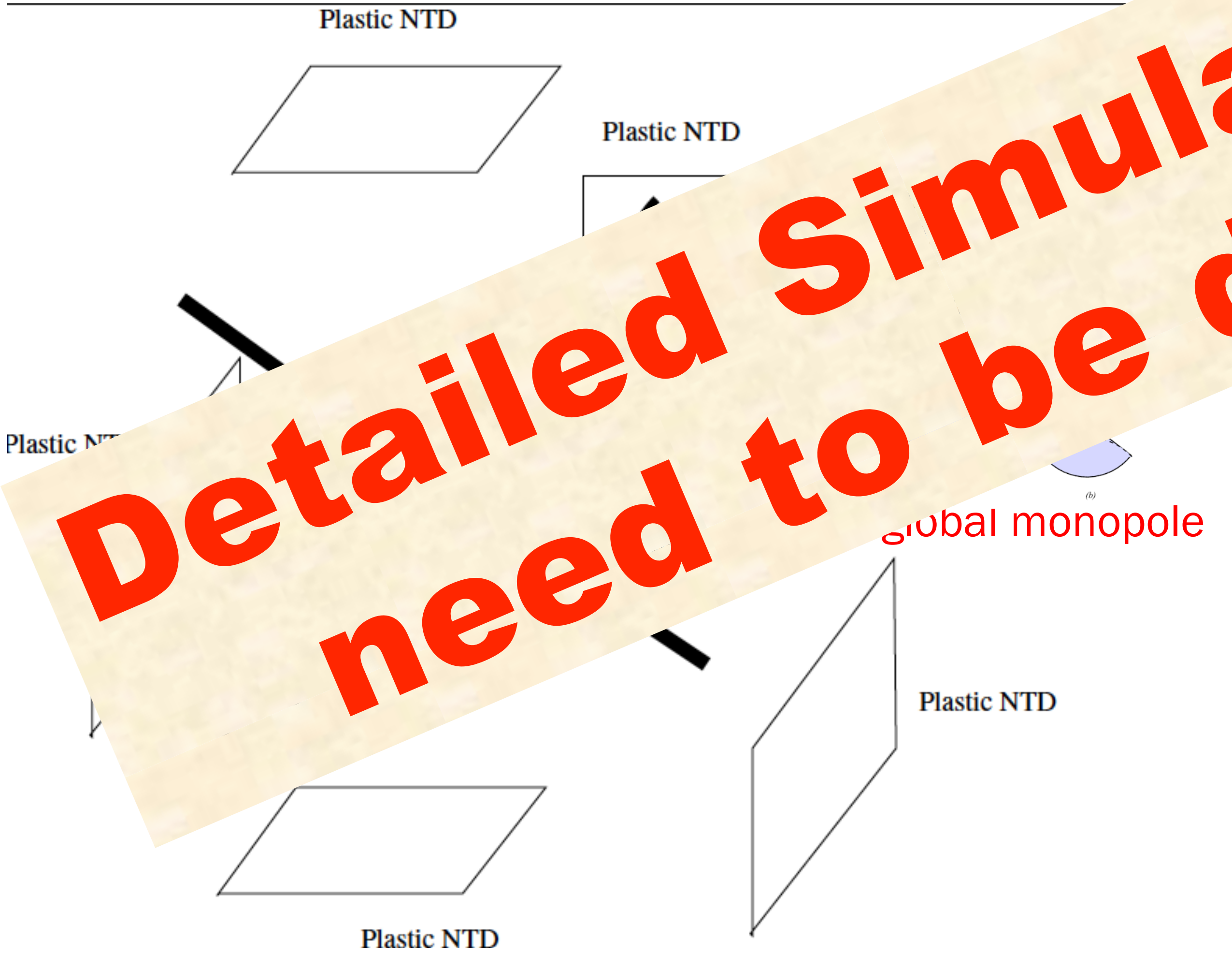
Scattering of Particles in the space-time of a Global Monopole

Relevance to MoEDAL

P. Mazur & J. Papavassiliou, PRD44 (1991), 1317;
H. Ren, Phys. Lett. B325 (1994), 149;
E.R. Berzera de Mello & C. Furtado, PRD56 (1997), 13.

Optical theorem, total cross section

$$\sigma = \frac{4\pi}{k}\,\mathrm{Im}\, f(0)$$



singular'' at such (small) angles (smoothened out by higher l-multiple terms in scattering)

→ for practical purposes:

ENHANCED RING PATTERNS

Detailed Simulations need to be done

Global Monopoles inducing magnetic charge

NEM & Sarben Sarkar (2016)

Self-gravitating Global Monopoles in the presence of U(1) Maxwell field and Kalb-Ramond Antisymmetric tensor (spin 1) gauge field

NEM & Sarben Sarkar (2016)

$$L = (-g)^{1/2}\left\{\frac{1}{2}\partial_\mu\chi^a\partial^\mu\chi^a - \frac{\lambda}{4}\left(\chi^a\chi^a - \eta^2\right)^2 + R - \frac{1}{12}H_{\rho\mu\nu}H^{\varrho\mu\nu} - \frac{1}{4}f_{\mu\nu}f^{\mu\nu}\right\}$$

$$H_{\mu\nu\rho} = \partial_{[\mu}B_{\nu\rho]}$$

spin-one
Kalb-Ramond field
antisymmetric tensor

scalars
associated with
spontaneous
breaking of
Global O(3)

electromagnetic
U(1) Maxwell
tensor

Abelian Gauge Symmetry

$$B_{\nu\rho} \to B_{\mu\nu} + \partial_{[\mu}\Theta_{\nu]}$$

Monopole Solutions of Model equations of Motion

$$g_{\mu\nu} = \begin{pmatrix} B(r) & & & \\ & -A(r) & & \\ & & -r^2 & \\ & & & -r^2\sin^2\theta \end{pmatrix} \qquad f_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2r\sin\theta\, W(r) \\ 0 & 0 & -2r\sin\theta\, W(r) & 0 \end{pmatrix}.$$

Magnetic Field

$$\mathcal{B}^r = \epsilon^{r\theta\phi} f_{\theta\phi} = \frac{1}{\sqrt{-g}}\eta^{r\theta\phi} f_{\theta\phi} = 2\,\frac{W(r)}{r}$$

$$H_{\mu\nu\lambda} = \epsilon_{\mu\nu\lambda}{}^{\sigma}\partial_\sigma b.$$

b(x) = pseudoscalar Kalb-Ramond axion

$$\chi^a = \eta f(r)\,\frac{x^a}{r}$$

v.e.v.

$$B(r) = A^{-1}(r)$$

Study solutions asymptotically for r → 0 and r → ∞

Natural units

$$W \to \frac{W}{\sqrt{g_N}}, \quad r \to \sqrt{g_N}\, r, \quad b \to \frac{b}{\sqrt{g_N}}, \quad \eta \to \frac{\eta}{\sqrt{g_N}}.$$

$g_N = 8\pi G_N$

Small r << 1

$$B(r) = A^{-1}(r) = \frac{p_0}{r^2}.$$

$$W^2(r) \sim \frac{p_0}{2r^2}.$$

$$b'(r) = \frac{\varsigma}{r^2}\sqrt{\frac{A(r)}{B(r)}}$$

$$f(r) \sim f_0 r.$$

large r >> 1

$$B(r) \sim 1 + \beta_1 + \frac{\beta_2}{r} + \frac{\beta_3}{r^2}$$

$$A(r) = B^{-1}(r)$$

$$f(r) = 1 - \frac{\alpha_1}{r^2} + \epsilon(r) \quad \alpha_1 = \frac{1}{\lambda\eta^2}$$

$$\beta_1 = -\eta^2 \qquad \beta_3 = \frac{\varsigma^2}{4(-1+\eta^2)} - \frac{1}{\lambda}.$$

deficit angle

$$\epsilon(r) = \frac{\exp\left(-\eta\sqrt{\frac{2\lambda}{1-\eta^2}}\,r\right)}{r}$$

$$W^2(r) \sim \frac{\varsigma^2}{8(1-\eta^2)\,r^2}.$$

Match $p_0/2 = \frac{\varsigma^2}{8(1-\eta^2)}$

β_2 (mass of monopole) not determined asymptotically

An estimate of the magnetic monopole mass

From the stress energy tensor integral

$$\mathcal{M} = \int \sqrt{-g}\, d^3r \left[\frac{2\,W^2}{B\,r^2} + \frac{(b')^2}{4\,BA} + \eta^2 \left(\frac{f^2}{Br^2} + \frac{(f')^2}{2BA}\right) + \frac{\lambda\,\eta^4}{4B}\,(f^2-1)^2\right].$$

$$\sim 4\pi\,\frac{\eta^2}{1-\eta^2}\int_0^L dr \sim 4\pi\,\eta^2\,L$$

Assume mass concentrate inside the core of *size L*

$$L = \xi\,\lambda^{-1/2}\,\eta^{-1}, \quad \xi \gg 1$$

Outside the core

f ≈ 1 → $\chi^\alpha \chi^\alpha$ → η^2

V → 0 (non trivial minimum)

$$\mathcal{M} \sim 4\pi\,\xi\,\lambda^{-1/2}\,\eta\,, \quad \xi \gg 1$$

to be bounded phenomenologically

Magnetic Charge Quantization and Discrete Torsion

Torsion induces monopole-like magnetic field with magnetic charge

$$\mathrm{B} = \frac{\varsigma}{\sqrt{2}} \frac{\mathbf{r}}{r^3}$$

$$g = \frac{\varsigma}{\sqrt{2}}$$

torsion charge

$$b'(r) = \frac{\varsigma}{r^2} \sqrt{\frac{A(r)}{B(r)}}$$

Torsion charge induces magnetic field monopole

$$\varsigma e = \frac{n}{\sqrt{2}}, \quad n \in Z .$$

Constraining parameters of model depends heavily on its details
Production mechanism of global monopoles at colliders *etc*

Science is the belief in the ignorance of the experts
(Richard Feynman)

Thank You !