Searches for black holes, sphalerons and magnetic monopoles

NICK E. MAVROMATOS
KING'S COLLEGE LONDON

UK HEP FORUM:
Into the Unknown with LHC13

3-4 November 2016

The Cosener's House

Abindgon, UK

KING'S College LONDON

MoEDAL

Durham University

IP3

Science & Technology Facilities Council

OUTLINE

- **Black Holes, sphalerons & magnetic monopoles: Theory Background**
- **Experimental searches :**

  (i) in space

  (ii) @ colliders

  ((iii) as analogues in condensed matter Labs)

- **The MoEDAL LHC experiment**

  Experiment specifically designed for:

  Detection of highly ionising, long-lived massive particles predicted in a plethora of BSM models such as SUSY

  Detection of solitonic defects:

  (i) Generic Monopole-like structures if in TeV mass range, Model independent searches

  (ii) specific **Electroweak Monopoles** rather than GUT monopoles, with TeV masses

- **CONCLUSIONS & OUTLOOK**

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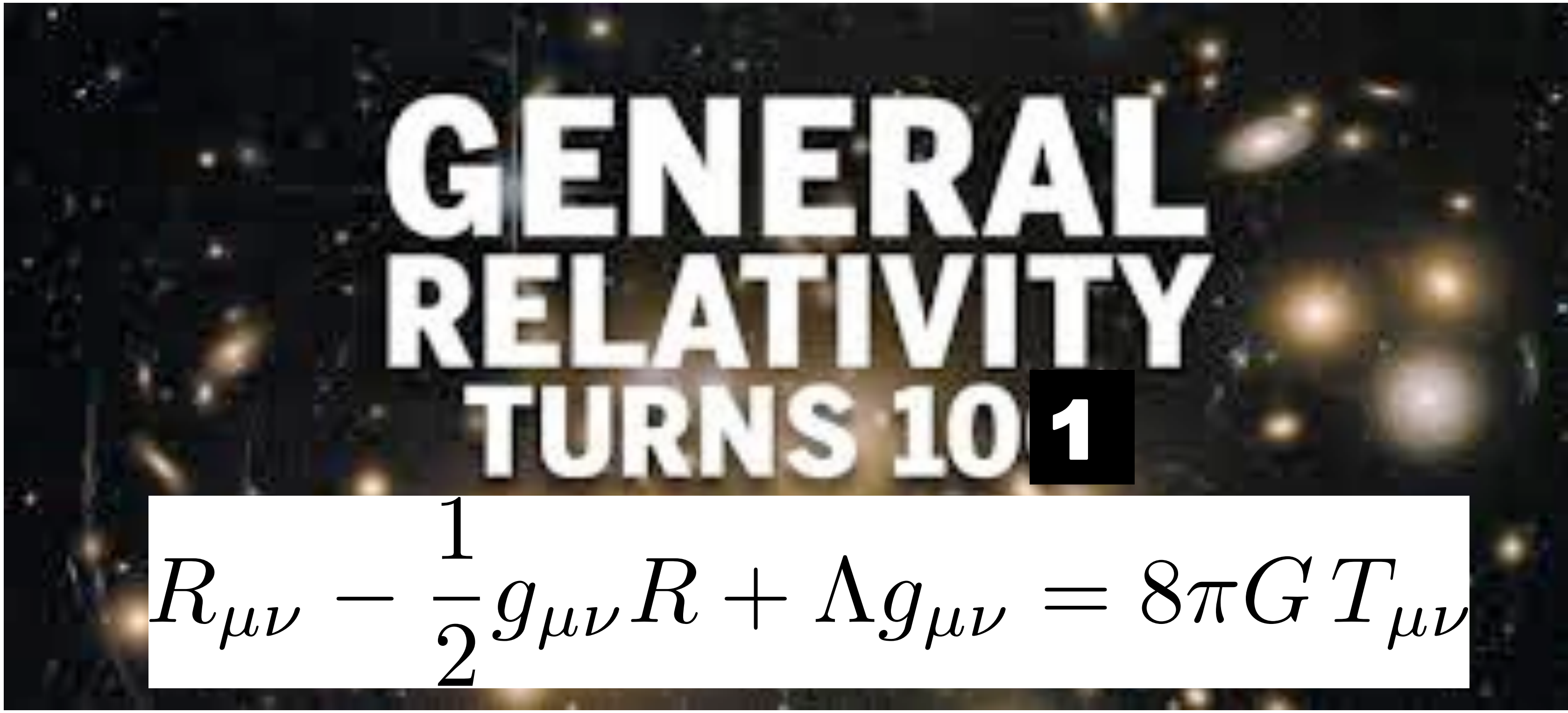
- **CONCLUSIONS & OUTLOOK**

First bounds (on masses) for monopoles with **spin-0, spin ½** and magnetic charge $q_m = g_D, \ldots, 6g_D$ from **8 TeV LHC run 2012**

Black Holes



$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

Solutions of Einstein's equations , physically arise from collapsing matter

Types of Black Holes

Schwarzschild (non rotating, mass *M*)

$$d\tau^2 = (1 - \frac{2G_N\, M}{r})dt^2 - \frac{dr^2}{1 - \frac{2G_N\, M}{r}} - r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

Reissner-Nordstrom (non-rotating, mass *M,* charged (Q))

$$d\tau^2 = (1 - \frac{2G_N\, M}{r} + \frac{G_N Q^2}{r^2})dt^2 - \frac{dr^2}{1 - \frac{2G_N\, M}{r} + \frac{G_N Q^2}{r^2}} - r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

Kerr-Newmann (rotating (angular momentum *J*), mass *M,* charged (Q))

$$d\tau^2 = -\left(\frac{dr^2}{\Delta} + d\theta^2\right)\rho^2 + \left(c\,dt - a\sin^2\theta\,d\phi\right)^2\frac{\Delta}{\rho^2} - \left(\left(r^2 + a^2\right)d\phi - ac\,dt\right)^2\frac{\sin^2\theta}{\rho^2}$$

$$a = \frac{J}{M}$$

$$\rho^2 = r^2 + a^2\cos^2\theta$$

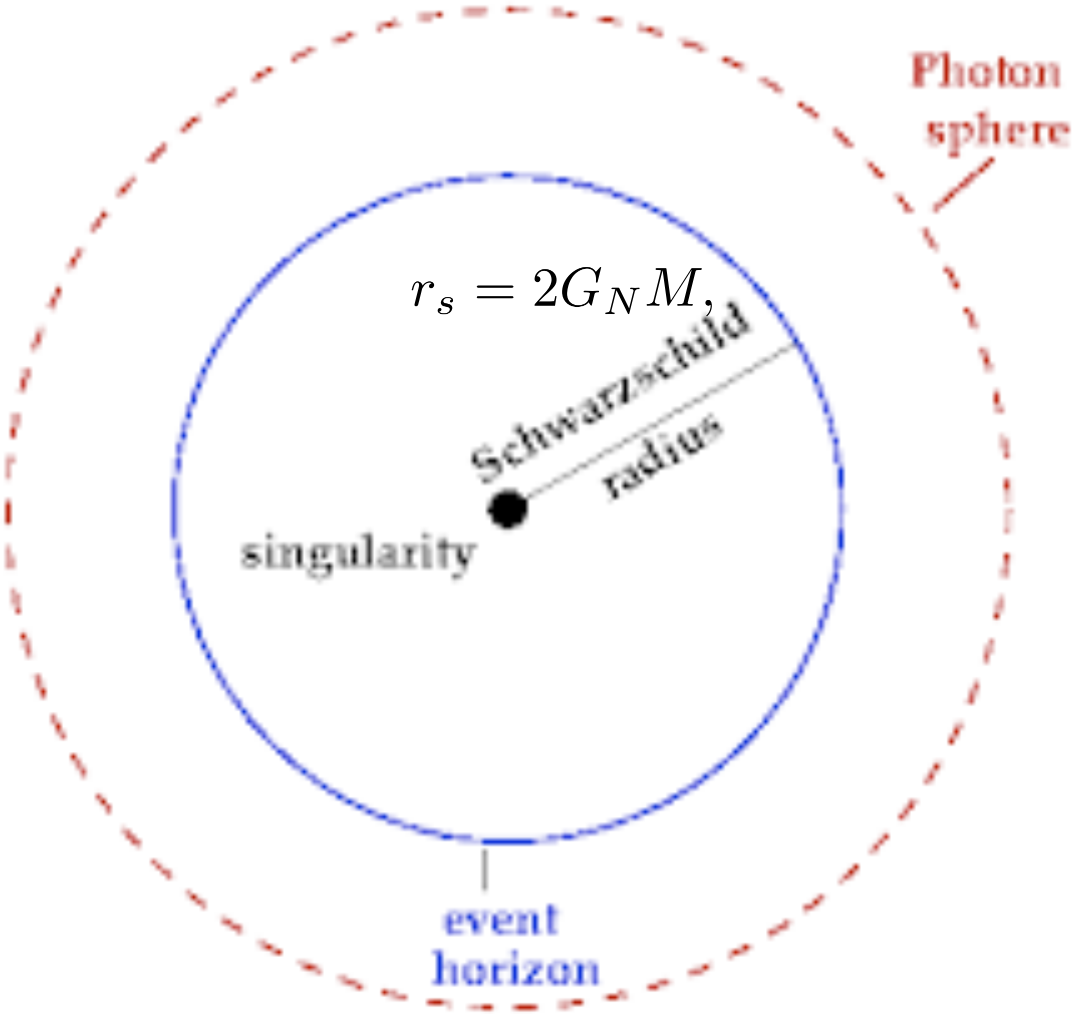
$$\Delta = r^2 - r_s r + a^2 + r_Q^2$$

$$r_s = 2G_N M,$$

$$r_Q = G_N Q^2$$

Black-Hole Geometries

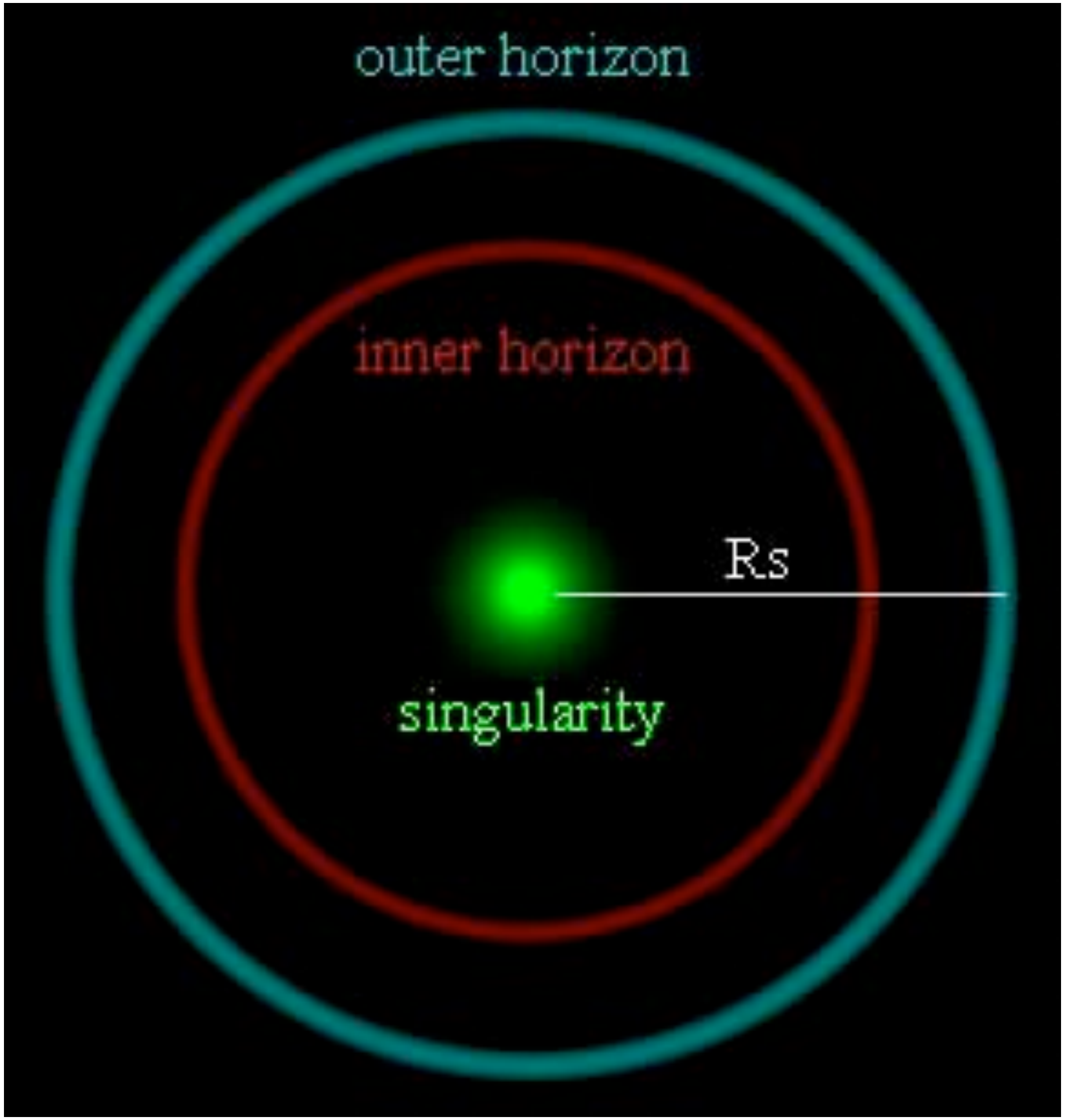
Schwarzschild (non rotating, mass *M*)



(a spherical boundary of zero thickness in which photons that move on tangents to that sphere would be trapped in a circular orbit about the black hole)

Black-Hole Geometries

Reissner-Nordstrom (non-rotating, mass *M*, charged (Q))



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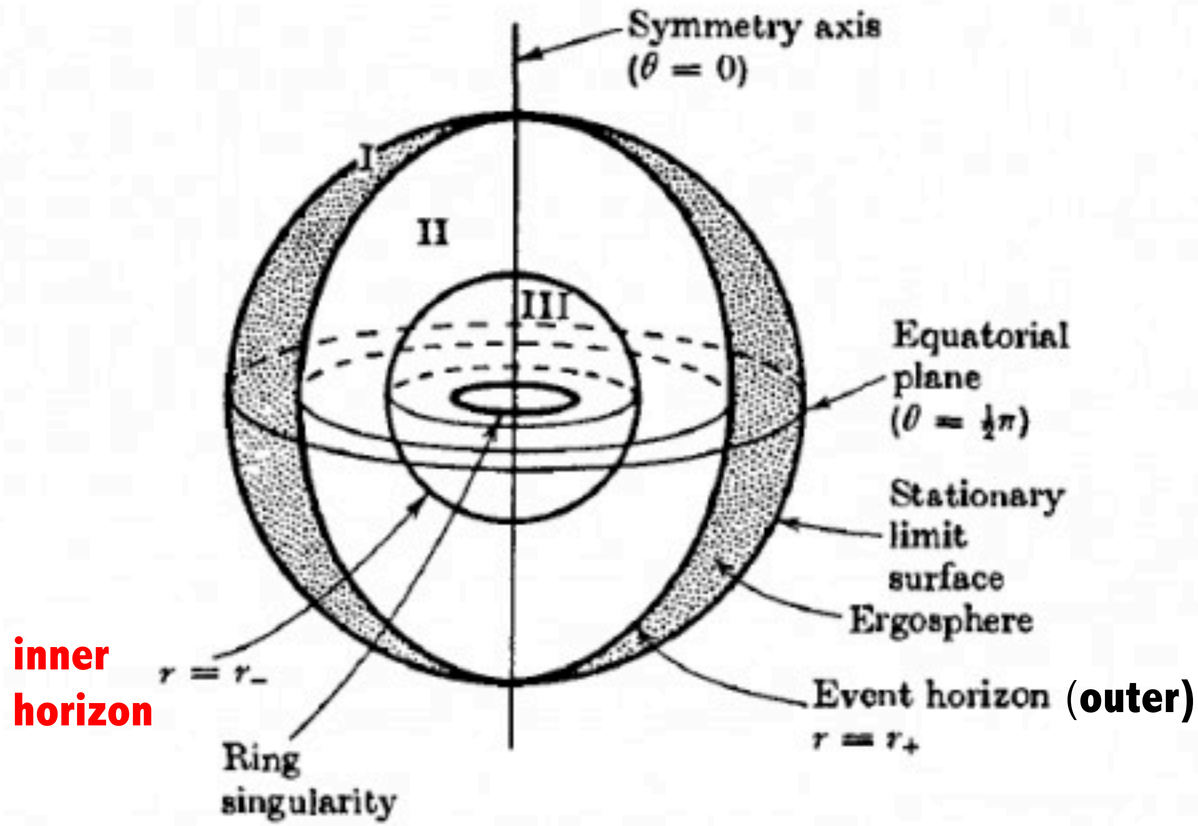


FIGURE 29. In the Kerr solution with $0 < a^2 < m^2$, the ergosphere lies between the stationary limit surface and the horizon at $r = r_+$. Particles can escape to infinity from region I (outside the event horizon $r = r_+$) but not from region II (between $r = r_+$ and $r = r_-$) and region III ($r < r_-$; this region contains the ring singularity).

Black Hole with some Hair

No hair conjecture/theorem : Black holes can only be characterised by their **mass**, **angular momentum** and **charge**.

Evasion of no-hair theorem (violation of its assumptions) :
Black Holes with scalar hair

Einstein Yang-Mills –Higgs systems

String-inspired GR with higher-curvature (Gauss Bonnet) terms & dilatons

Einstein-Maxwell-axion systems

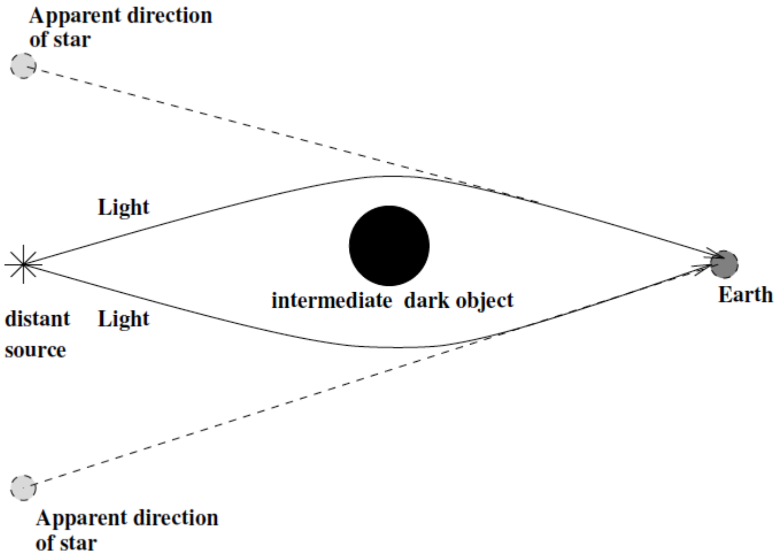
Modified Gravity models

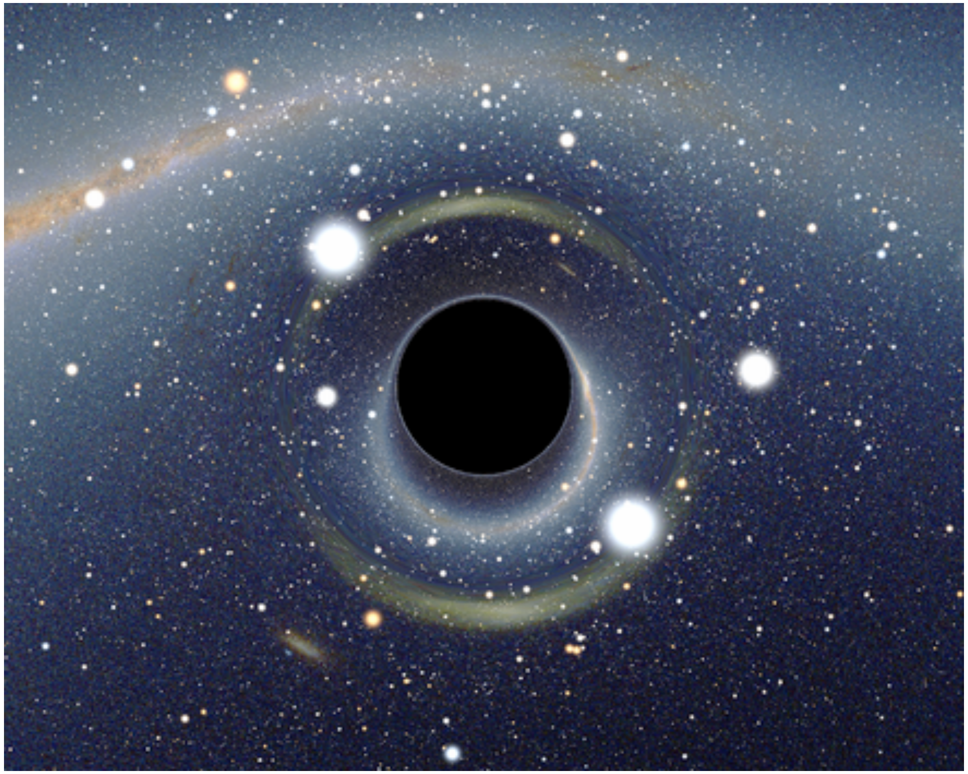
....

Hair may be **secondary** i.e. non trivial scalar fields outside horison but **corresponding charge** may be a **function** of **primary hair** eg mass

Astrophysical Detection

Gravitational lensing





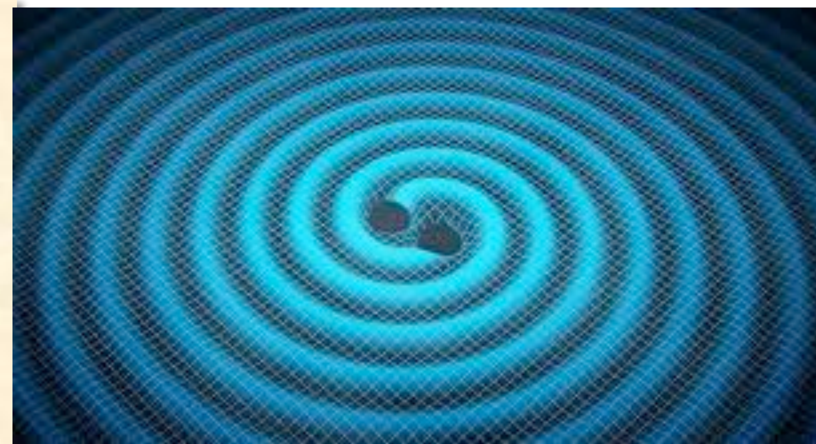
Simulated view of a black hole in front of the **Large Magellanic Cloud**. Note the **gravitational lensing effec**t, which produces two **enlarged but highly distorted views of the Cloud**. Across the top, the Milky Way disk appears distorted into an arc.

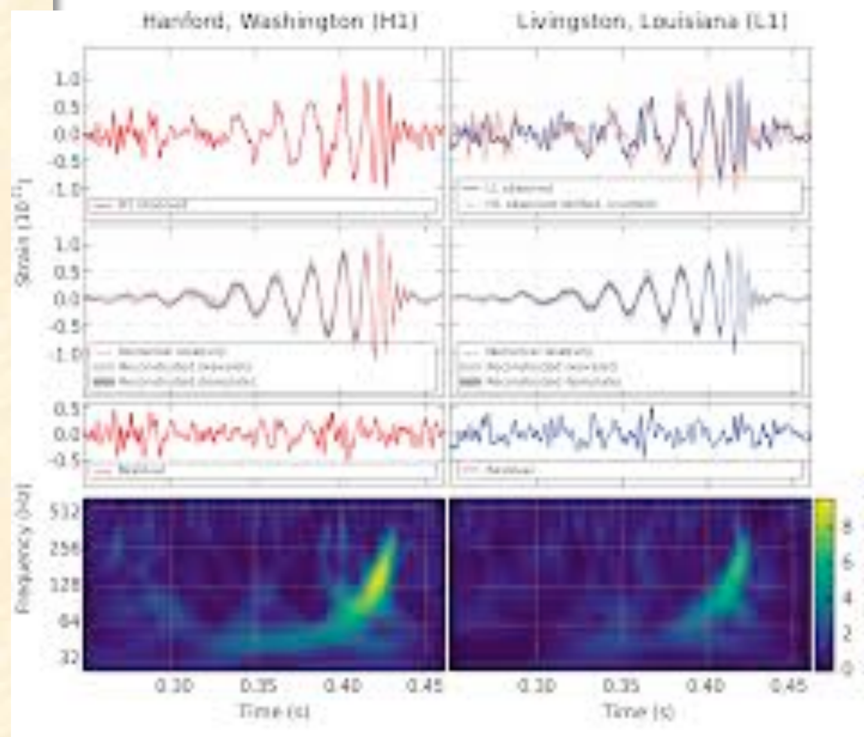
in 2016:

DETECTION
OF Gravitational Waves
(GR IMPORTANT PREDICTION)
ARE ANNOUNCED BY
VIRGO-LIGO Colls

(signal GW150914 in 2015 & GW151226)

Signals interpreted/fitted very well by assumption that GW were produced during merging of two spiralling black holes onto a larger black hole



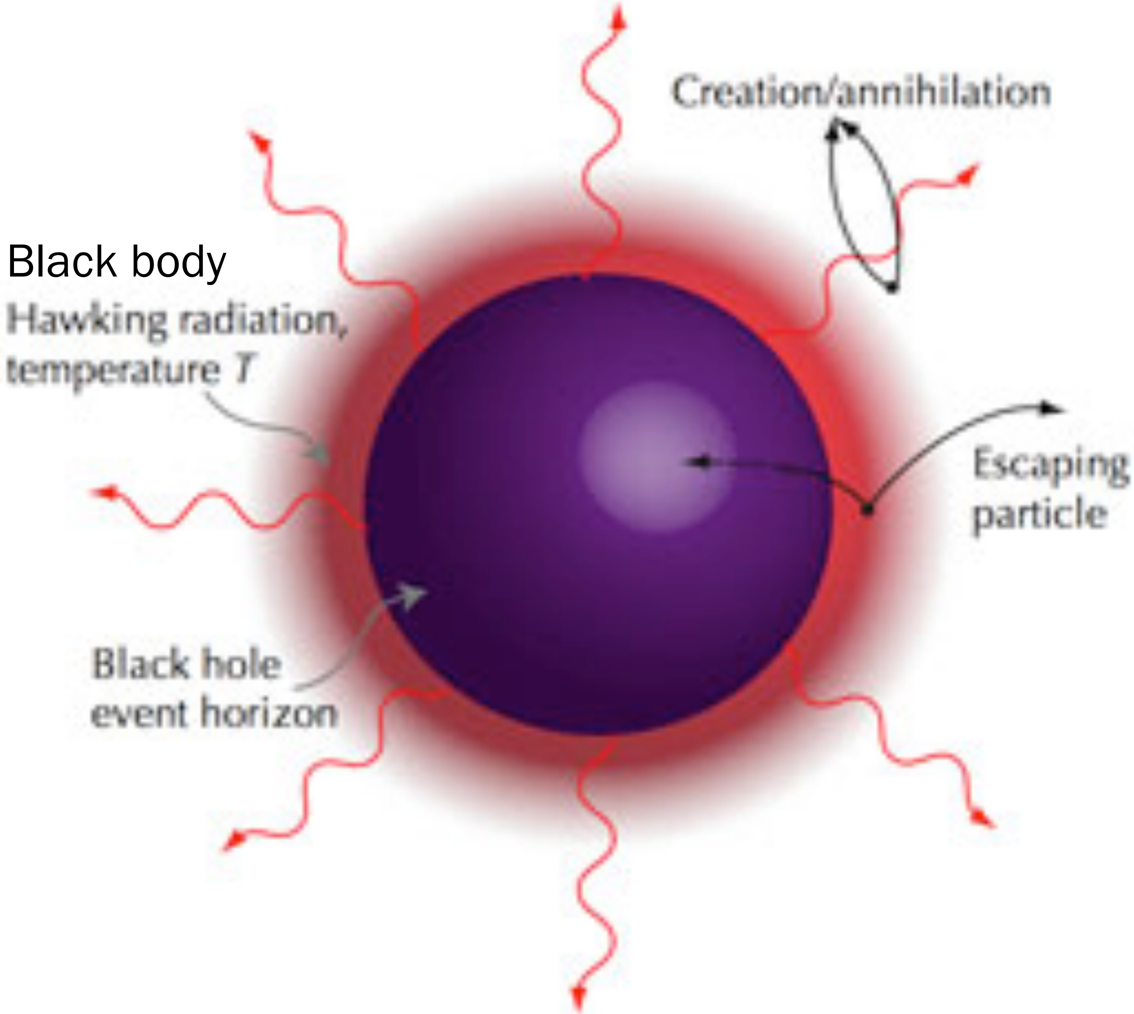


(Quantum) Black Hole Evaporation & Information Loss ``paradox''

start from pure QM state → end up in ``thermal'' states described by density matrix ?

for observers asymptotically far from BH horizon

Black body



...still debatable despite holographic AdS-CFT correspodence ...etc

Image credit: The Extreme Light Infrastructure European Project.

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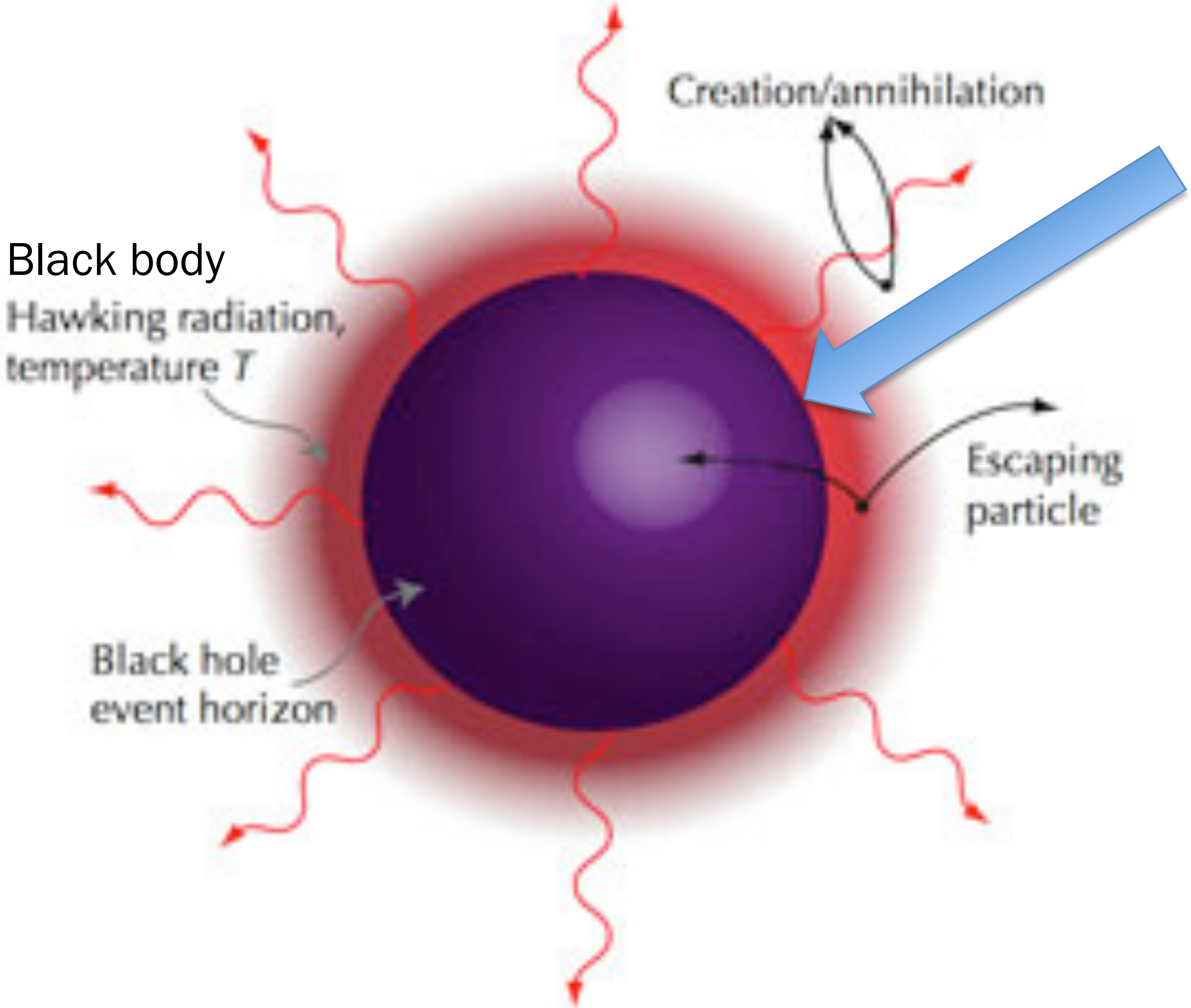

Image credit: The Extreme Light Infrastructure European Project.

Hawking radiation @ Horizon of BHs:
Effective two-dimensional field theory with **phase-space area-preserving**

Bonora *et al.*

W_∞ symmetries → particle in such near BH horizon geometry is described by **completely integrable field theory**

+ in string theory :
W - gauge symmetries
→ infinite dimensional gauge hair →
→ **information retention?**

Ellis, NEM, Nanopoulos

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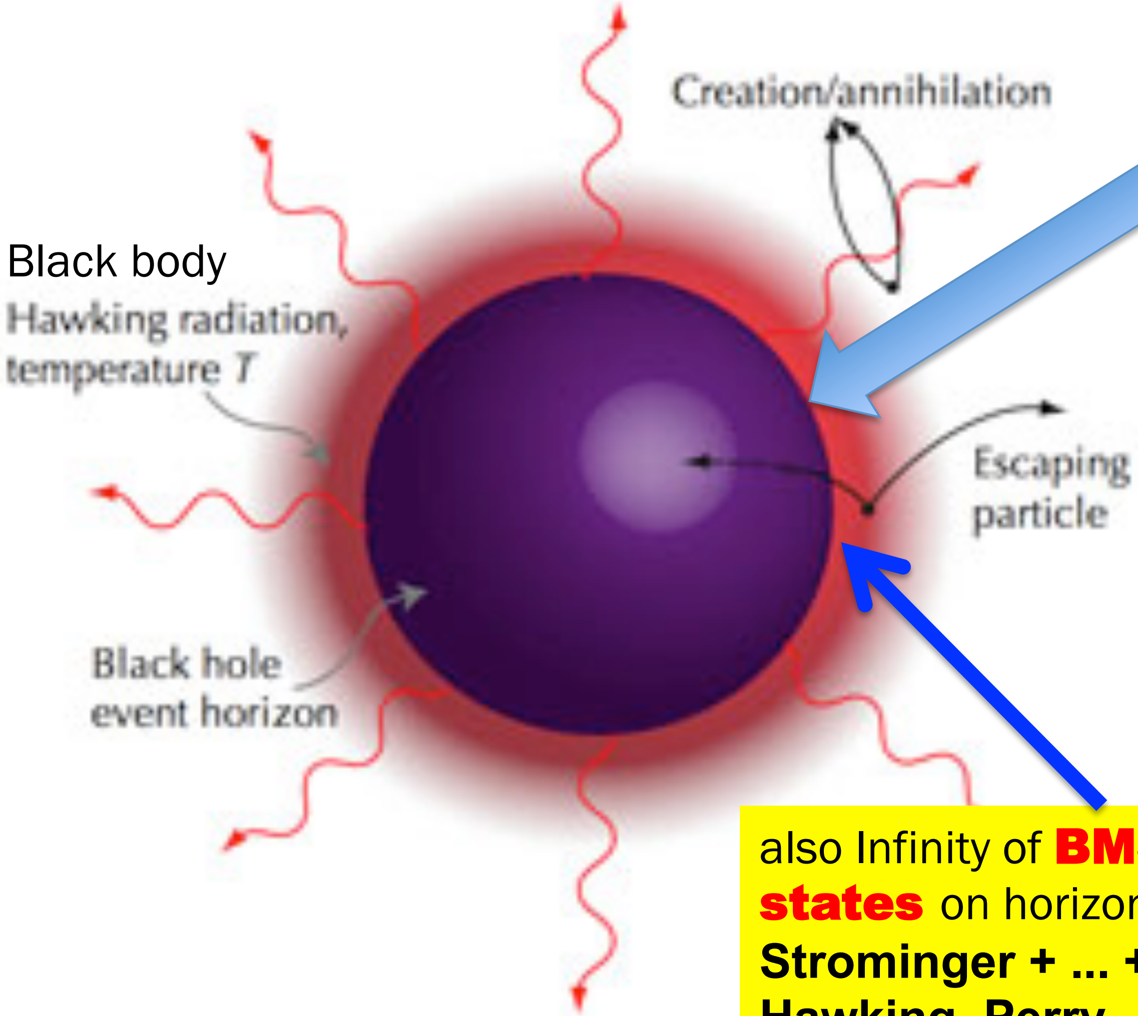
for observers asymptotically far from BH horizon



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also Infinity of **BMS states** on horizon **Strominger + … + Hawking, Perry** **not relevant to coherence?**

TeV Black Holes in Large Extra Dimensional Models

In standard GR, the Planck scale M_P is the scale at which quantum gravity phenomena are expected to set in

In String theory with extra space dimensions, the quantum gravity scale is the string scale **$M_s = 1/\sqrt{\alpha'} = 1/$ (minimal string length)**. This is disconnected from the Planck scale, as there is the following relation

$$M_P^2 = M_s^{D-2} V^{D-4}$$

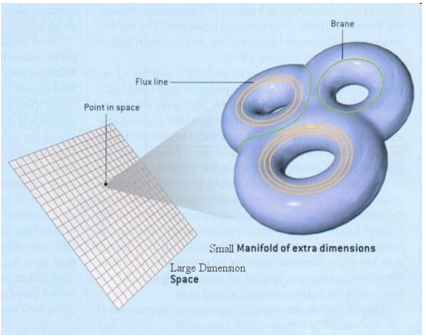
where V is the compactification volume and D number of space-time dimensions. Depending on the size of V one may have

$$M_s = O(\text{TeV}) << M_P$$

This has implications in having **Black Hole solutions in string theory** with mass of order of the string scale $M_s << M_P$, **producable at** colliders such as **LHC**.

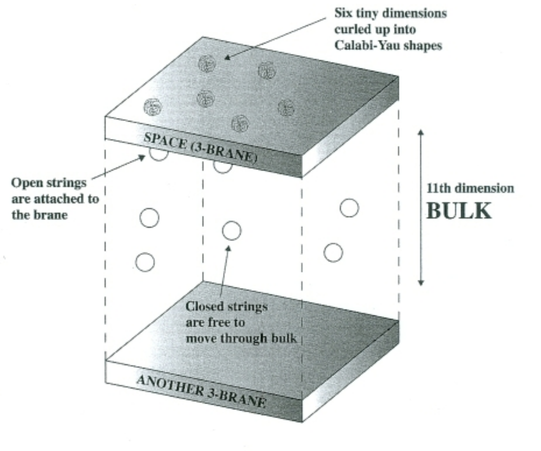
Large Extra dimension models motivated by string theory

Arkani-Hamed
Dimopoulos, Dvali
(string models)



Both relevant
for providing
resolution of
the hierarchy
problem
in field theory

Randall Sundrum
(brane models)



Stringy effects @ low
scales (TeV) possible

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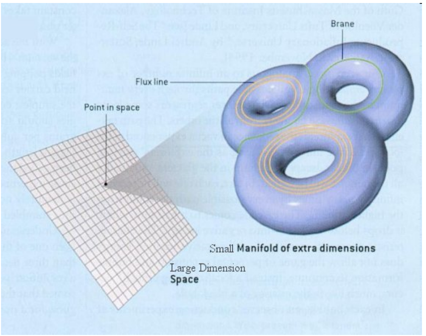

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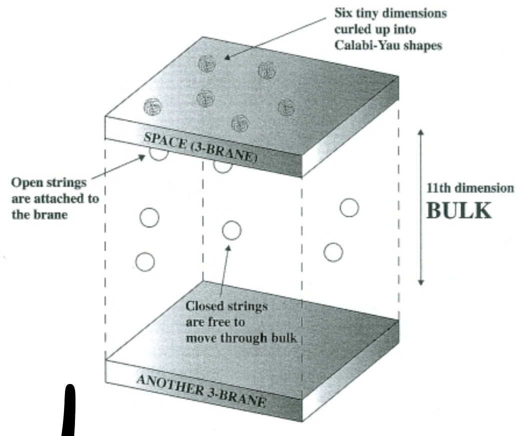

gravitons
propagate
in bulk
as well as
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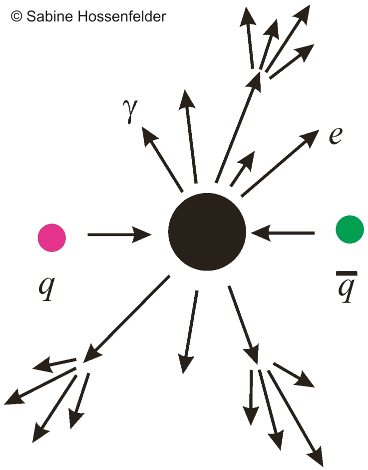

Dimopoulos, Landsberg

Formation of TeV Black Holes (BH) by high energy SM particle Collisions

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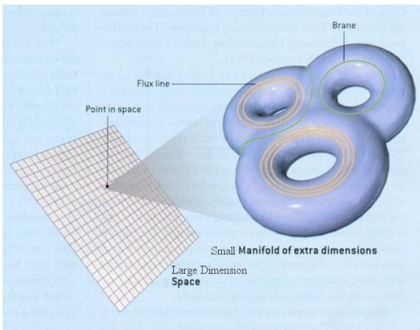

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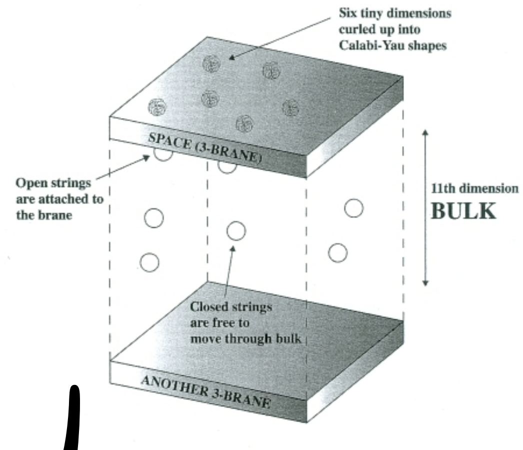

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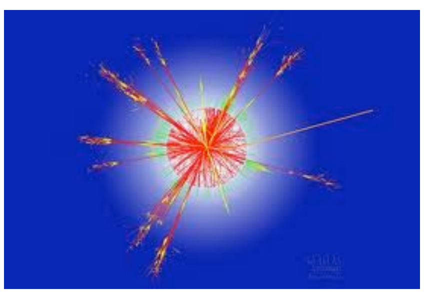


Dimopoulos, Landsberg

Formation of TeV Black Holes (BH) by high energy SM particle Collisions

BH produced in proton-proton collisions can carry **electric charge**

Charged BH Hawking evaporate but not completely → certain fraction of final
BH **remnants** carry charge ($BH^{\pm}$)

Collider Production of TeV Black Holes

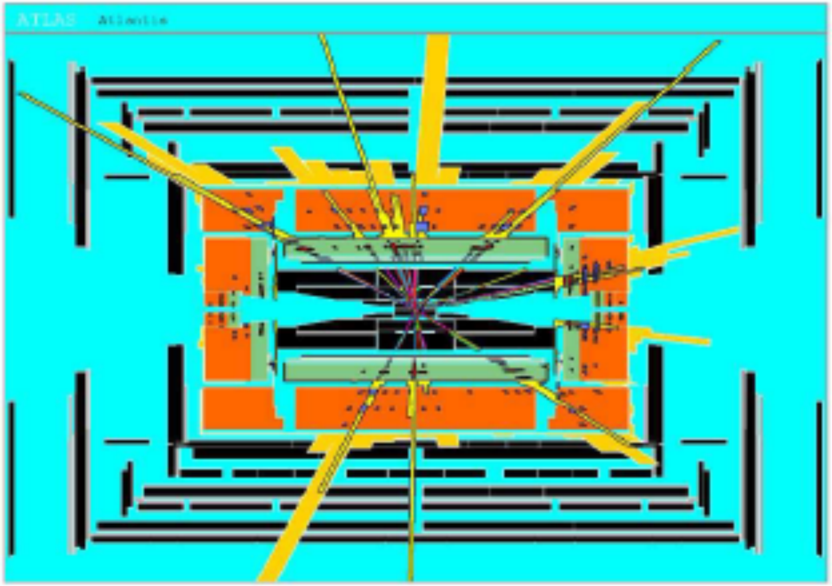
If colliding particles with TeV energies @ LHC are closer than Schwarzschild radius of (quantum) TeV black holes → formation of (**unstable**) black holes → Hawking (**thermal**) evaporation , spectacular signal @ LHC of emission of particles

mini BH life time

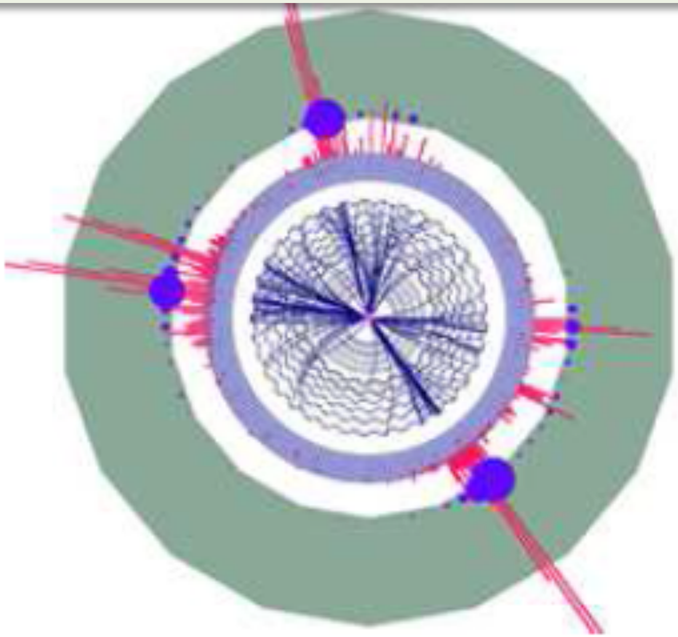
$$\tau \sim \frac{1}{M_D}\left(\frac{M_{\rm BH}}{M_D}\right)^{\frac{n+3}{n+1}}$$

n= number of extra dims

→ **$\tau < 10^{-26}$ s**



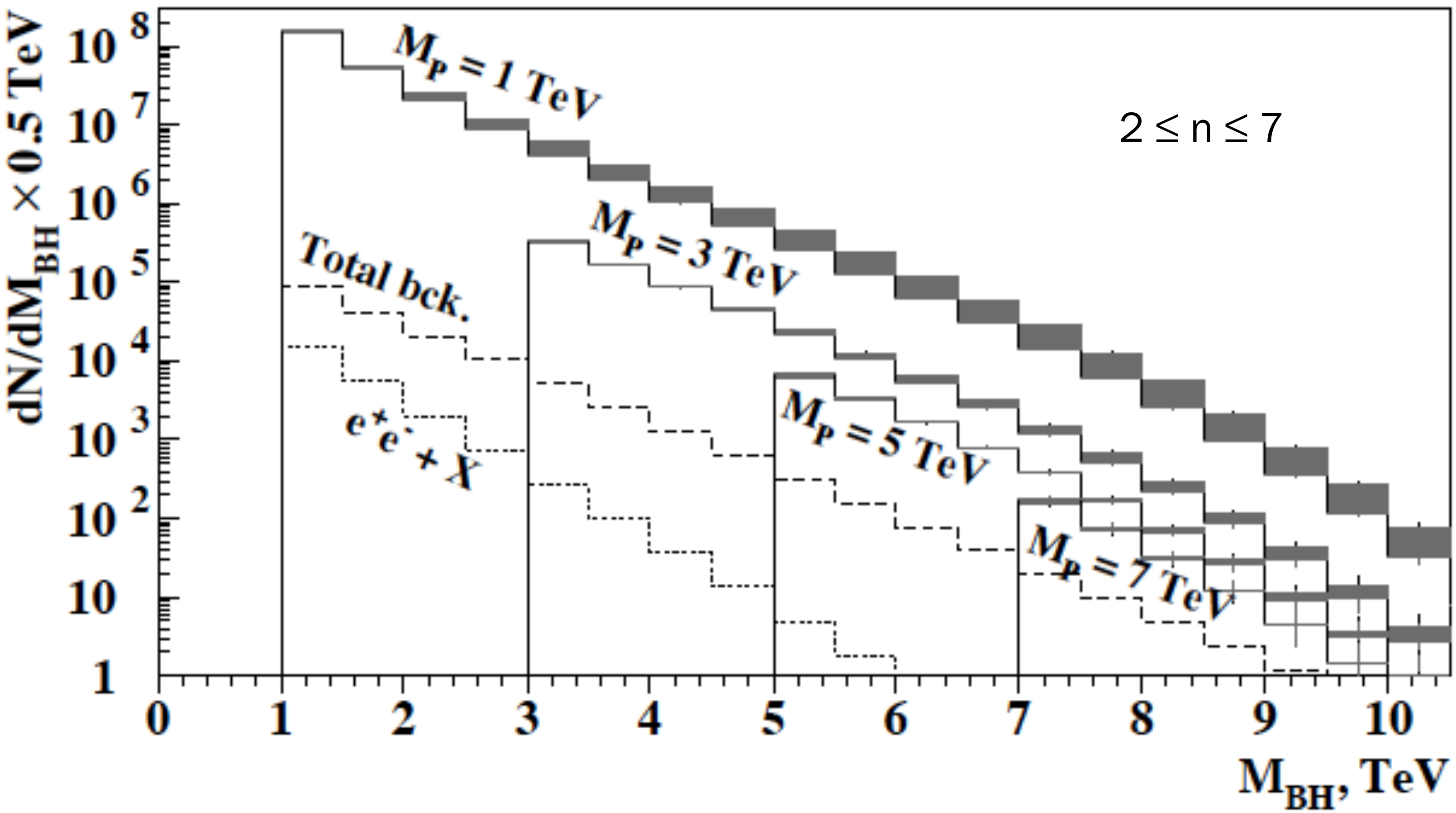
Event as would be seen by **ATLAS**
CHARYBDIS generator



Event as would be seen by **CMS**
TRUENOIR gemerator

Theoretical predictions in electron or photon channels with 100 fb^{-1} $\int L$

Landsberg arXiv:0607297



Multiplicity of emitted particles of given spin depends on gray body factors – detailed studies in higher dimensional GR

Theoretical predictions in electron or photon channels with 100 fb^{-1} $\int L$

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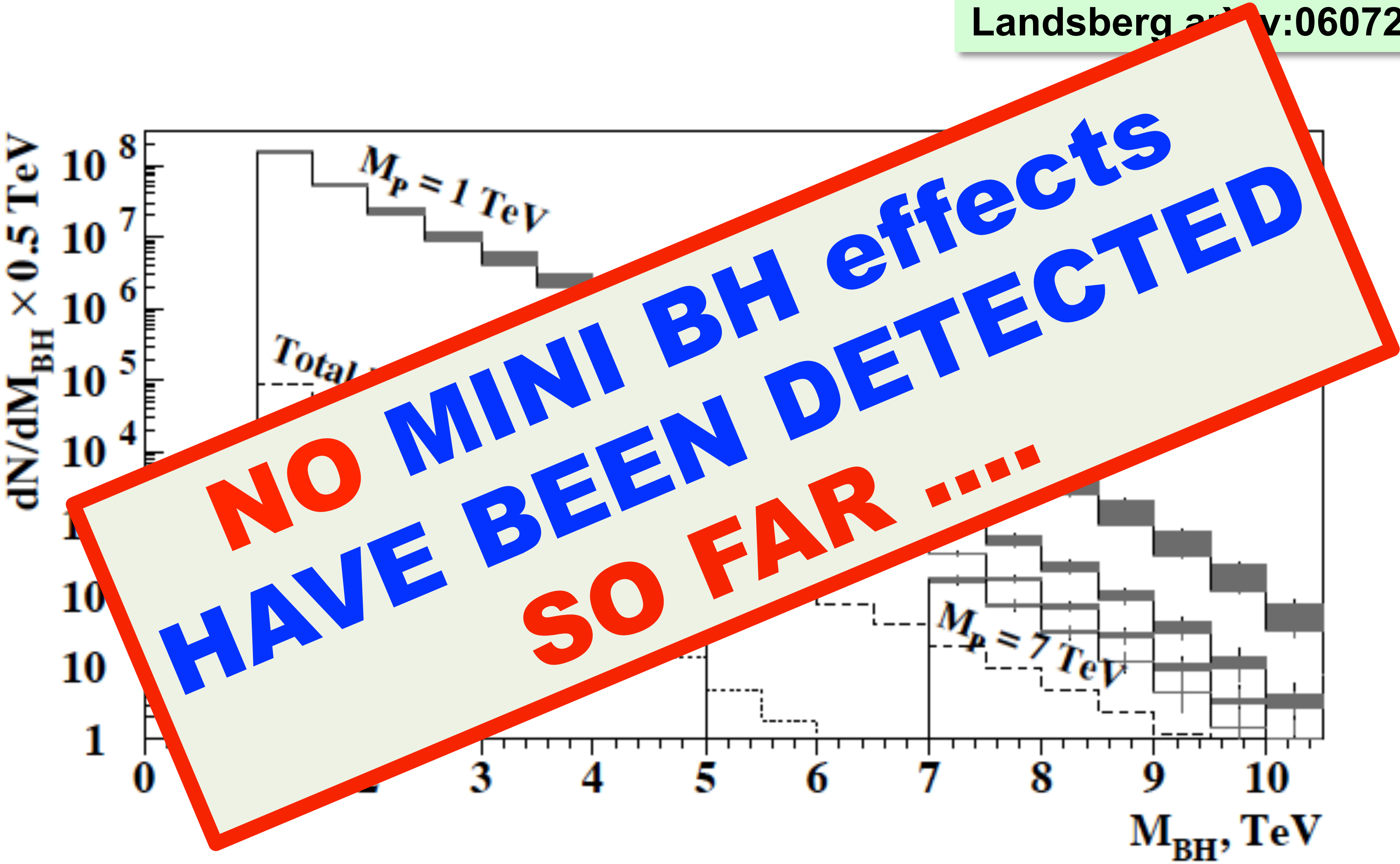

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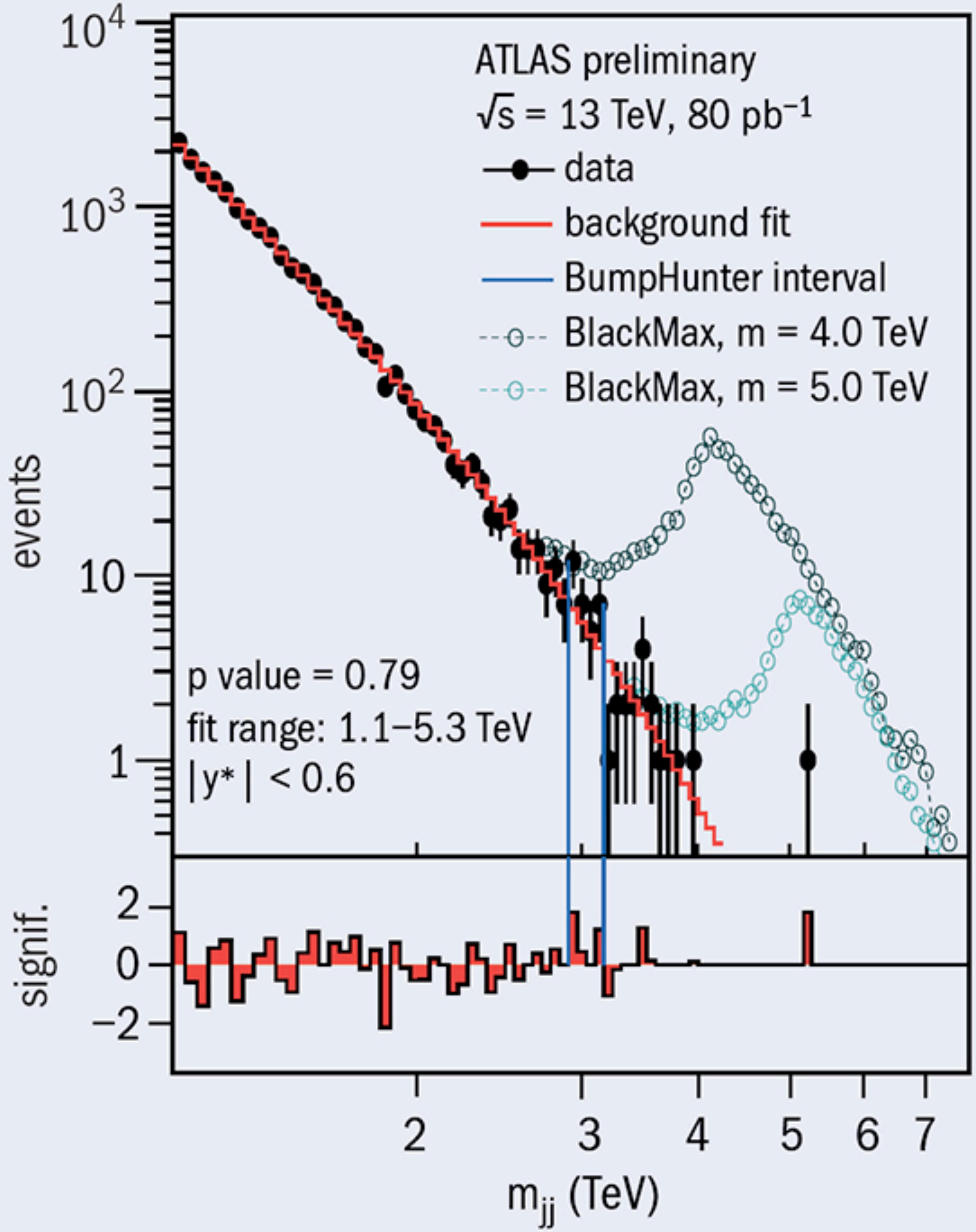
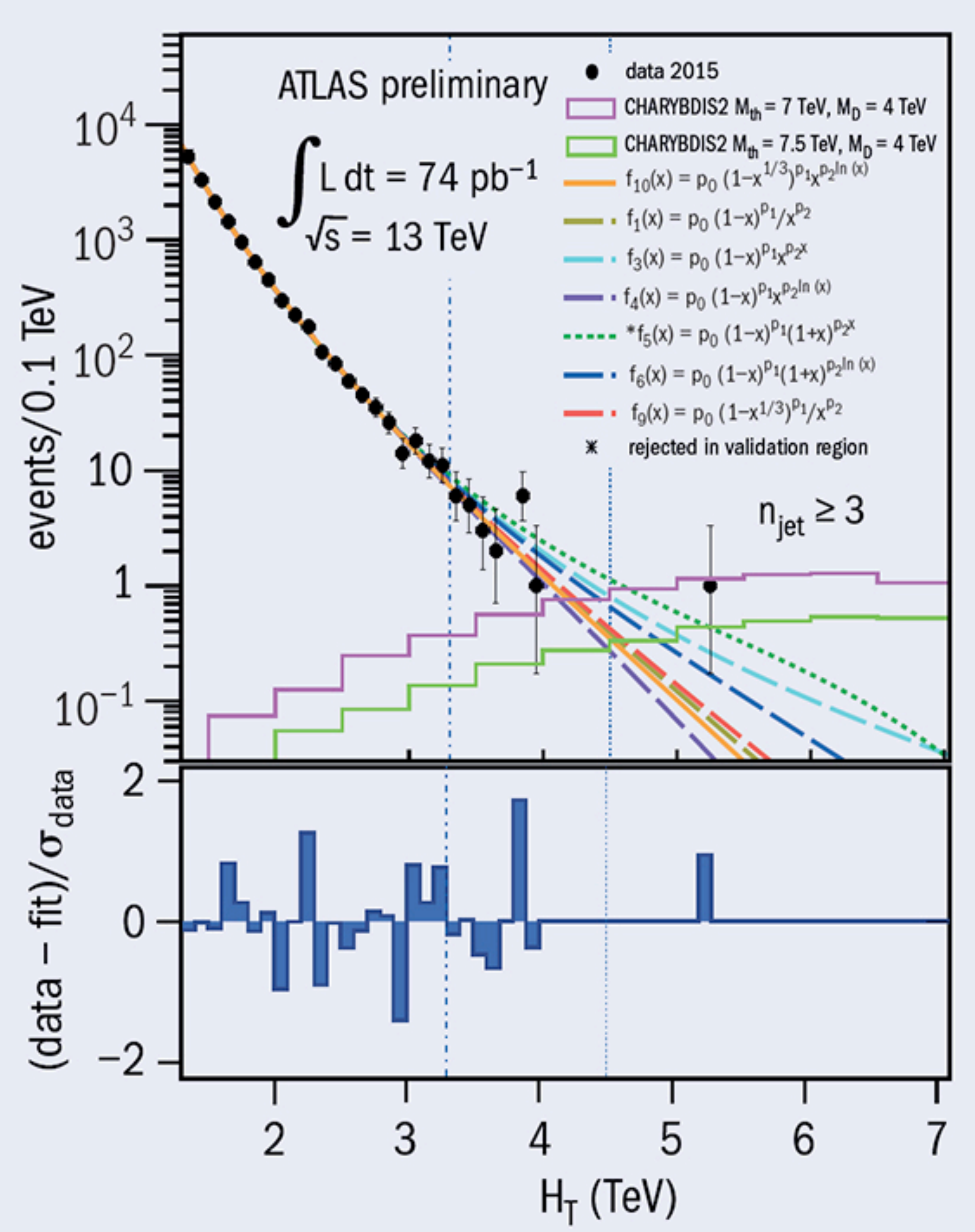


The dijet mass distribution (filled points) for selected events, together with predictions from BlackMax for two quantum-black-hole signals, normalized to the predicted cross-section.
The bottom panel shows the bin-by-bin significance of the difference between data and fit, considering statistical uncertainties only.

CERN Courier 2015/9

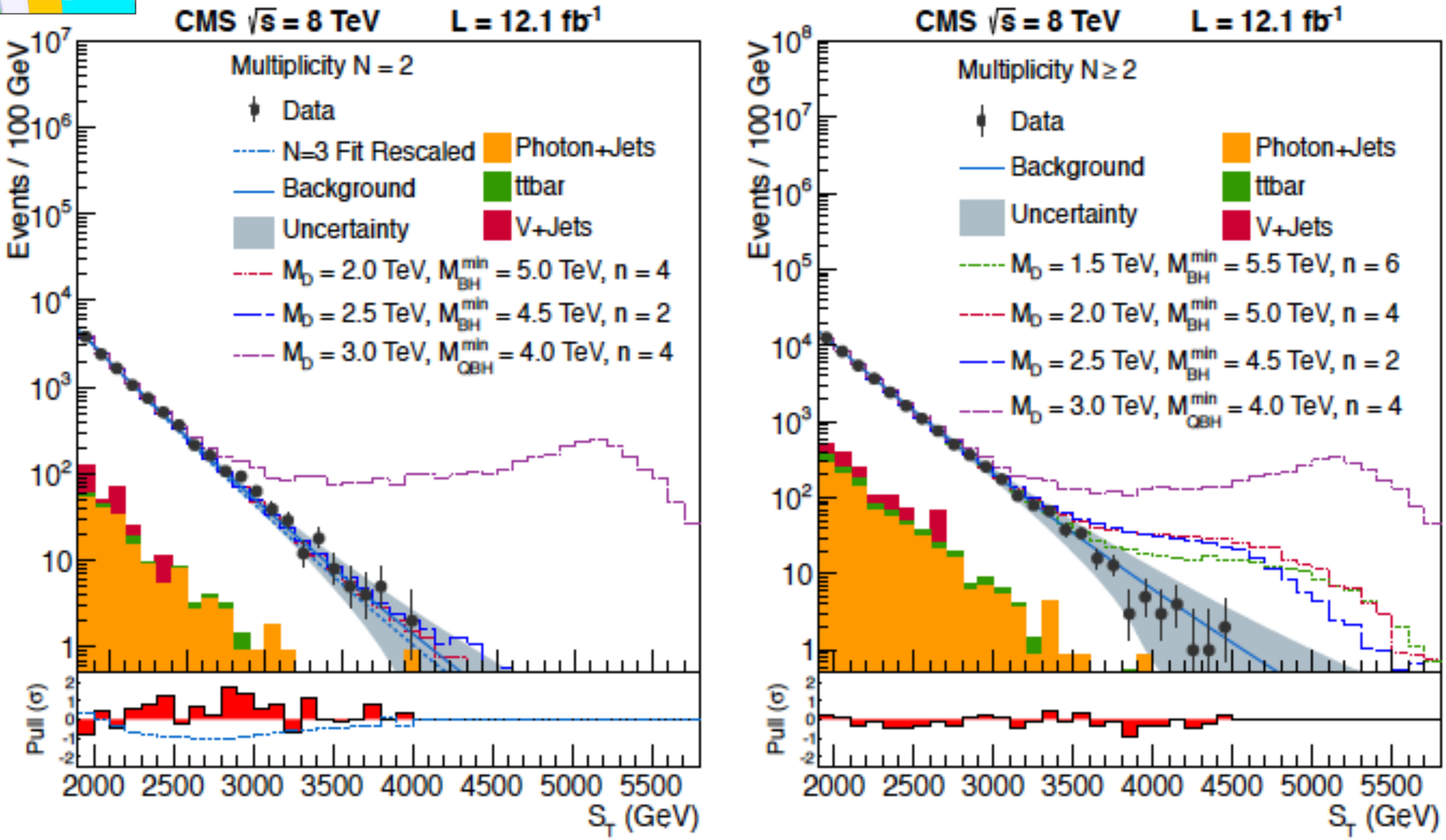


If micro BH exist will Hawking decay to a large number of SM particles

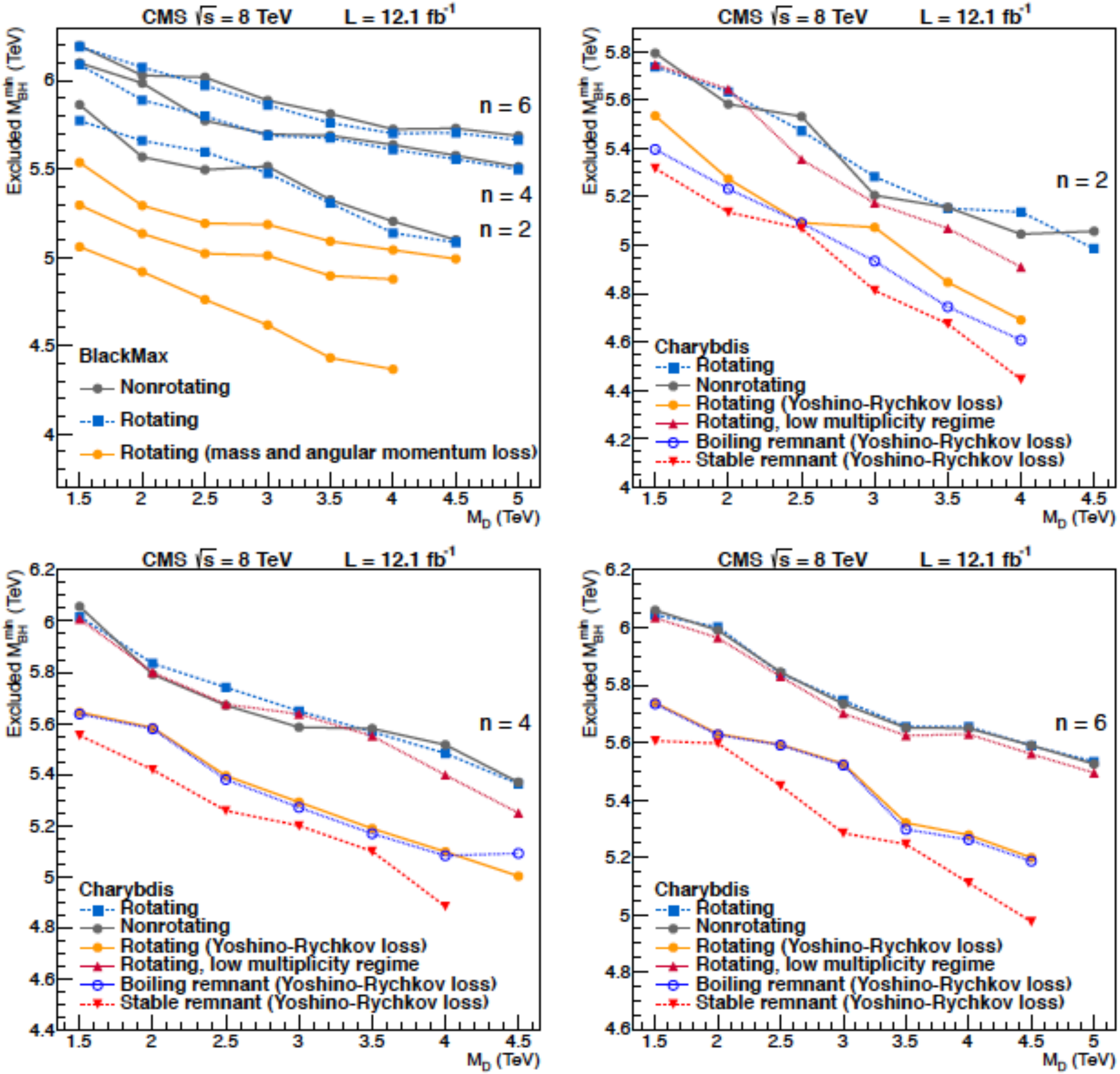
Scalar sum of jet transverse momenta (HT) in high-multiplicity events fitted by the baseline function (solid line) and six alternatives (dashed lines). Examples of simulated signals are also shown. The bottom panel shows the bin-by-bin significance of the difference between the data and the fit, where the fit prediction is taken from the baseline function.

CERN Courier 2015/9

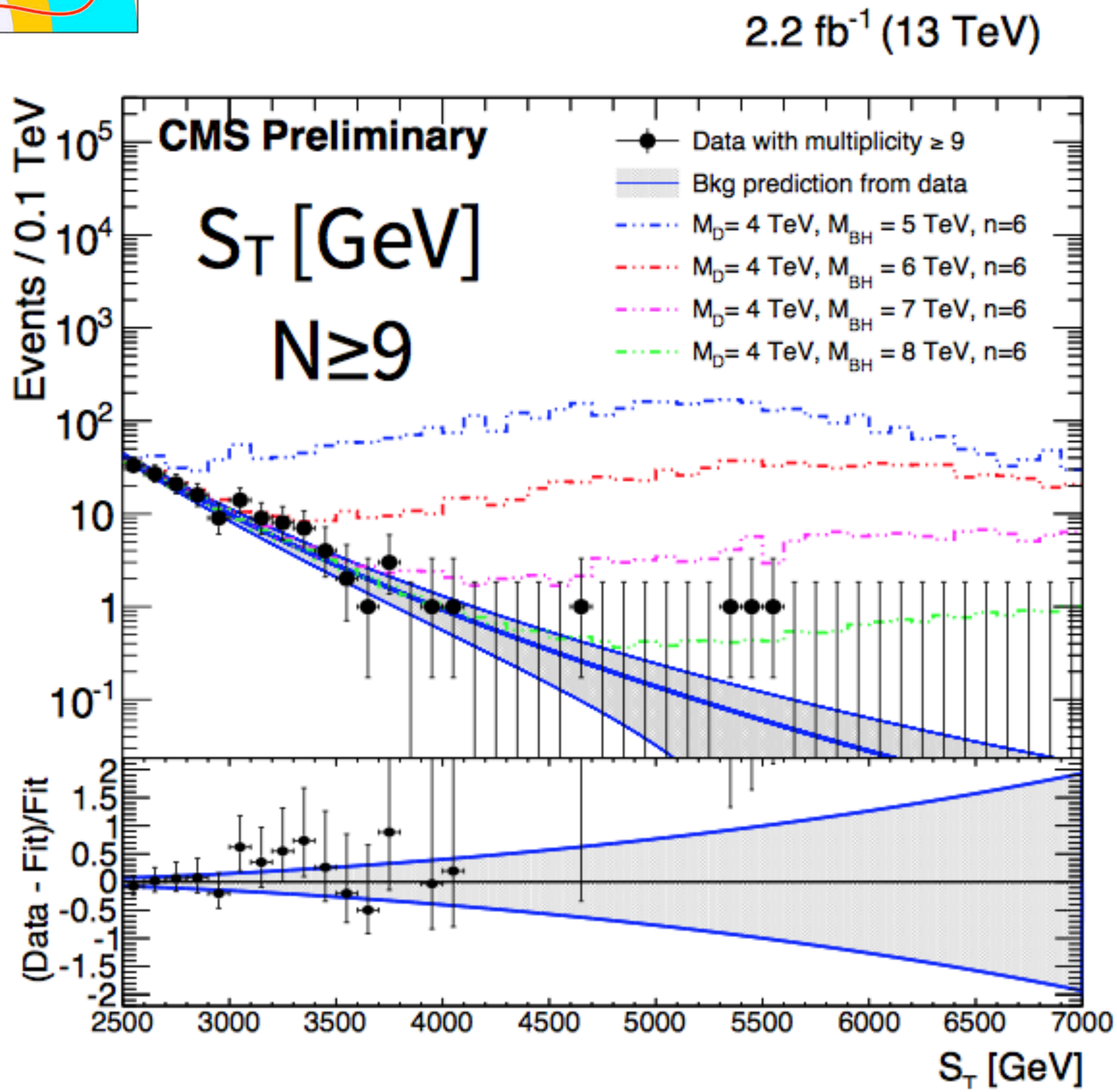
CMS Coll: 1303.5338



Distribution of the scalar sum of transverse energy, S_T, for events with multiplicity: N



area below a curve excluded



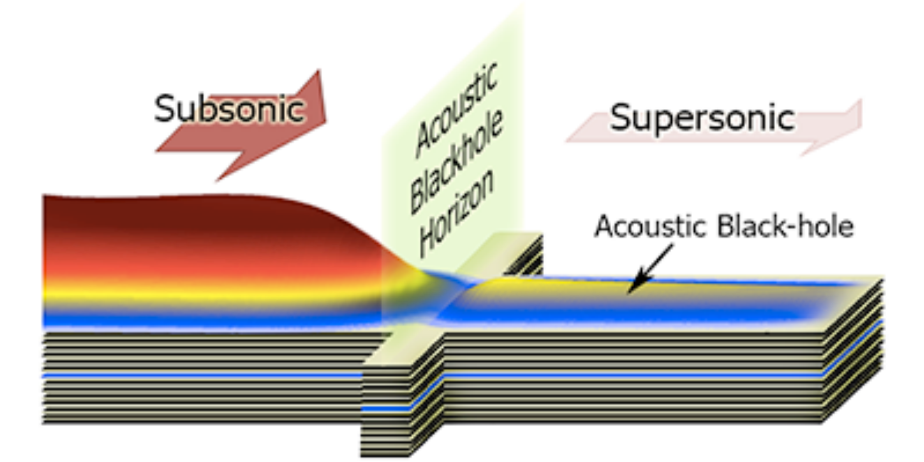
Black Hole Masses < 8-9 TeV excluded, depending on models and assumptions

A de Roeck
SUGRA @ 40 (2016)

Analogue (Sonic or Acoustic) Black Holes in Condensed matter

Phonons (sound perturbations) unable to escape from a fluid flowing faster than the speed of sound → analogies with light trapped in BH horizons: surface of sonic black hole at which the flow speed changes from being greater than the sound speed to being less than then sound speed is called the Horizon analogue (frequency of phonons approaches zero). **Phononic version of Hawking radiation at the horizon** → useful analogues for drawing conclusions on astrophysical black holes?

First predicted by Unruh in 1981 , elaborated further by Visser 1997, demonstrating the existence of Hawking radiation phononic analogue.

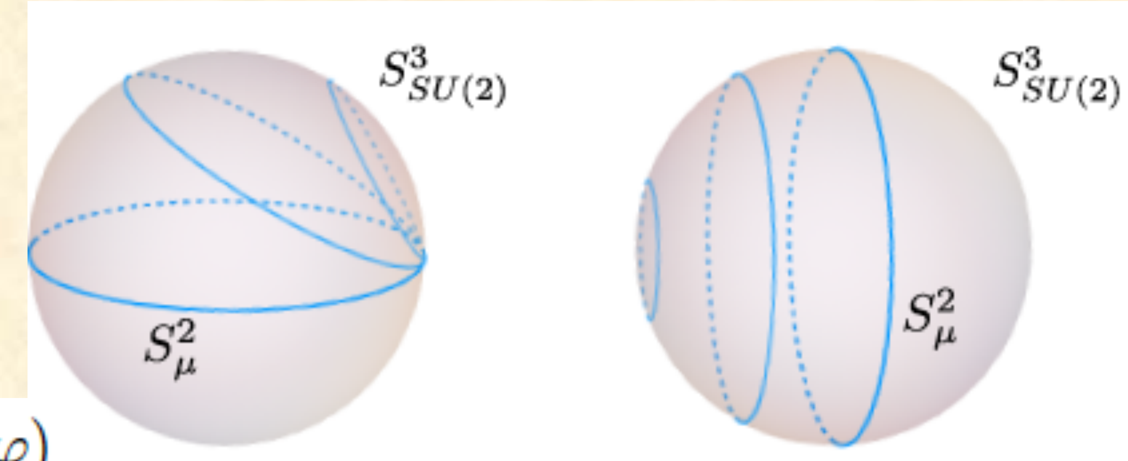


First experimental demonstration in **rubidium Bose-Einstein condensate** in 2009
O. Lahav, A. Itah, A. Blumkin, C. Gordon & J. Steinhauer, arXiv:0906.1337 (2009).
First Self-amplifying phononic Hawking radiation (analogue BH laser) observed in 2014
J. Steinhauer, Nat Phys doi:10.1038/nphys3104 (2014).

SPHALERONS

SPHALERONS:

Static unstable solutions of **Electroweak theory** playing an important role for **Baryo/Leptogenesis**



Euclidean instanton solutions imply SU(2) Vacua labelled by n → Minkowski gauge & scalar fields

$A_i(\mu, r, \theta, \varphi)$ $\Phi(\mu, r, \theta, \varphi)$

$0 \leq \mu < \pi$

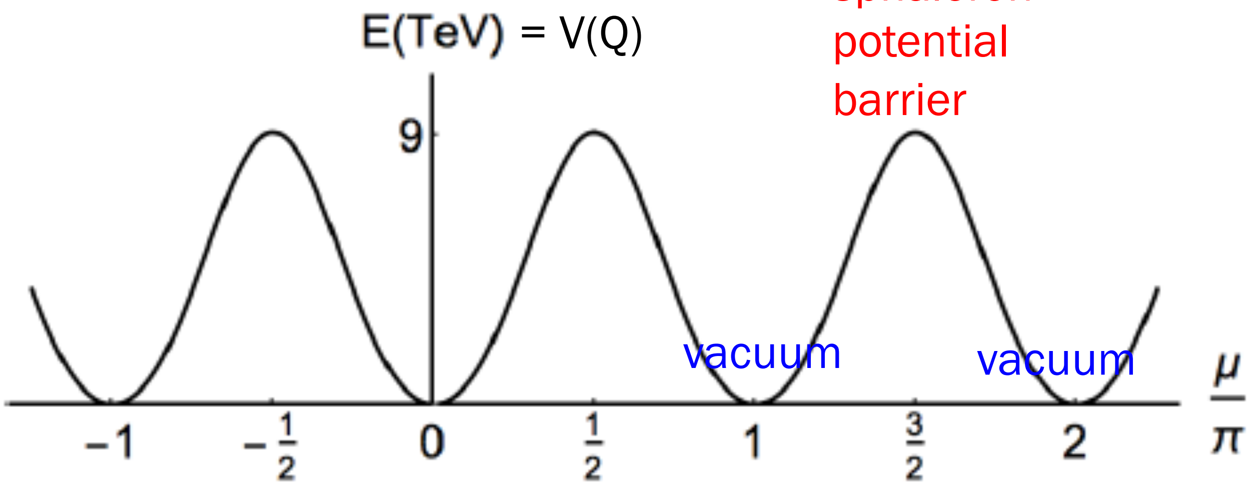
$$\pi_3\left(SU(2)\right) = \pi_3\left(S^3\right) = \mathbb{Z}.$$

S^2 maximum size at μ=π/2 (**sphaleron-unstable**), S^2 shrinks → 0 @ μ=0, π

A sphaleron may convert baryon to antileptons and antibaryons t leptons → (i) wipe out any baryon asymmetry generated before the electroweak symmetry breaking (when sphalerons were abundant) (ii) a baryon net excess can be created during the EW breaking but it can be preserved if the breaking is **first order**

They also **preserve B-L** so they can communicate Lepton number violation to Baryonic sector in some theories of Leptogenesis, which is then transformed to Baryogenesis

Manton (1983)



periodic sphaleron potential in EW theory

$$\left(-\frac{1}{2m}\frac{\partial^2}{\partial Q^2} + V(Q)\right)\Psi(Q) = E\Psi(Q)$$

$$Q = \mu/m_W$$

Effective one-dim Schroedinger eq.

For SM values $E_{sph} = \max[V(Q)] = V\left(\frac{\pi}{2m_W}\right) = 9.11 \text{ TeV}$

Tye & Wong (2015) Solution for the Bloch wave function → **baryon-lepton number violating** processes can occur **without tunnelling suppression**

Interesting Phenomenology @ colliders: B+L violating processes

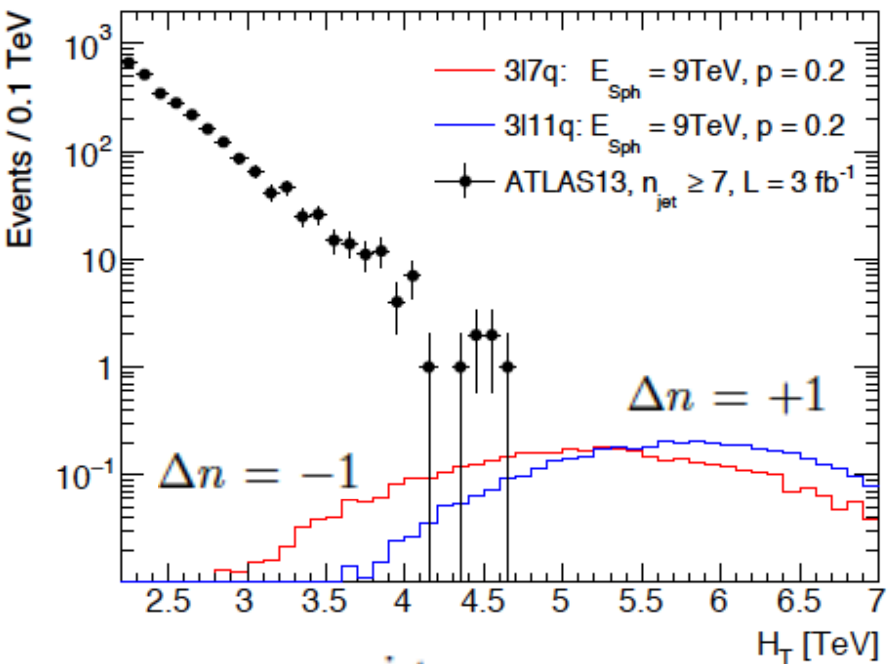
$$q_L + q_L \rightarrow \bar{l}_e \bar{l}_\mu \bar{l}_\tau \bar{q}\bar{q}\bar{q}\bar{q}\bar{q}\bar{q} + X$$ ← any number of $W^{\pm}$, Z

$$q_L + q_L \rightarrow e^- \mu^- \tau^- bbbcccdddu u + X$$

$E_1 + E_2 \geq E_{sph}$ NO SUPPRESSION

Searches @ LHC

Ellis, Sakurai 1601.03654



$$H_T \equiv \sum p_T^{\text{jet}}$$

DATA POINTS :number of events with $n_{jet} \geq 3$
RED histogram: Δn=-1 sphaleron process
(3 antileptons, 7 antiquarks in final state)
BLUE histogram: Δn=+1 process
(3 leptons, 11 quarks in final state)

parametrize cross section of parton-parton collisions

$$\sigma(\Delta n = \pm 1) \ = \ \frac{p}{m_W^2} \sum_{ab} \int dE \frac{d\mathcal{L}_{ab}}{dE} \exp\left(c \frac{4\pi}{\alpha_W} S(E)\right)$$

parton luminosity function of colliding quarks a and b

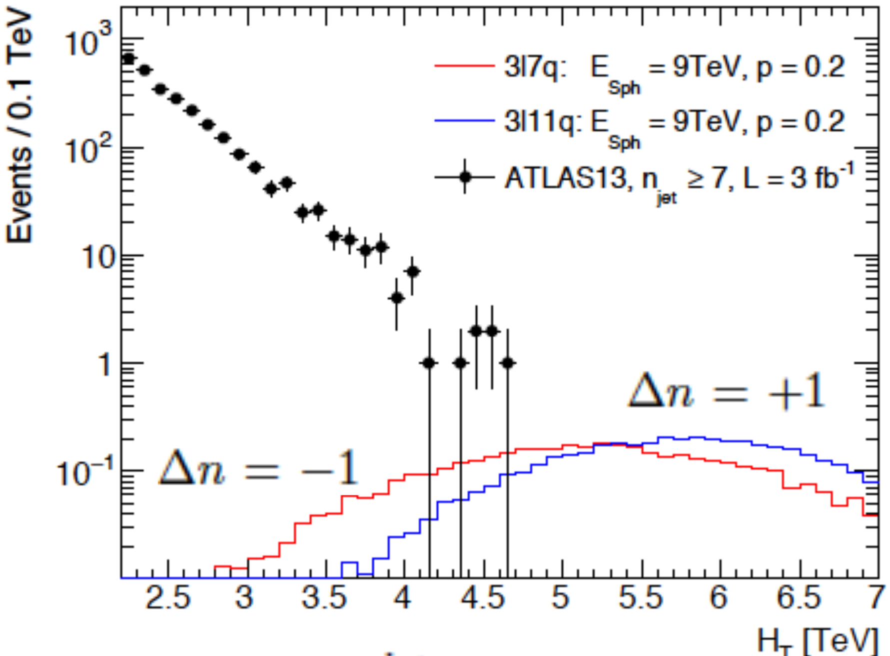
$$\frac{d\mathcal{L}_{ab}}{dE} = \frac{2E}{E_{\rm CM}^2} \int_{\ln\sqrt{\tau}}^{-\ln\sqrt{\tau}} dy f_a(\sqrt{\tau}e^y) f_b(\sqrt{\tau}e^{-y}),$$

$$\tau = E^2/E_{\rm CM}^2.$$

centre of mass energy of pp collision

Searches @ LHC

Ellis, Sakurai



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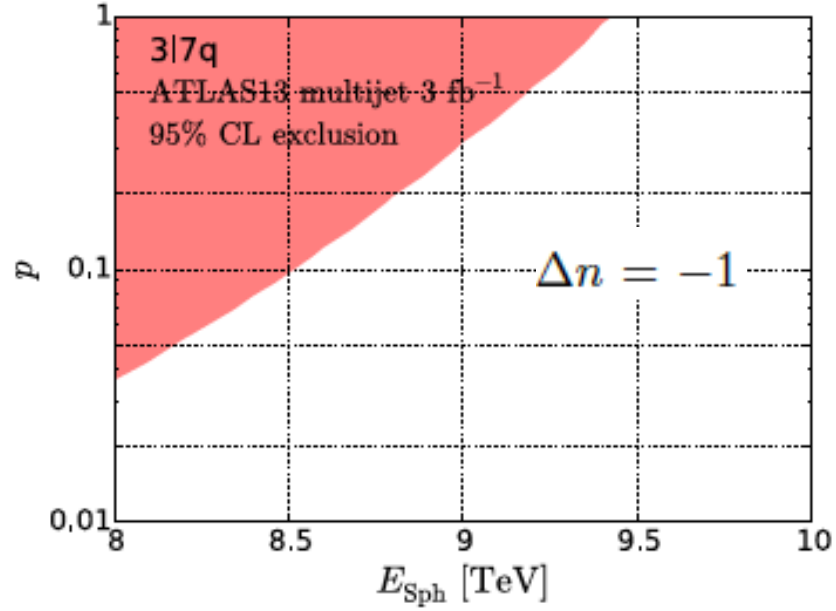
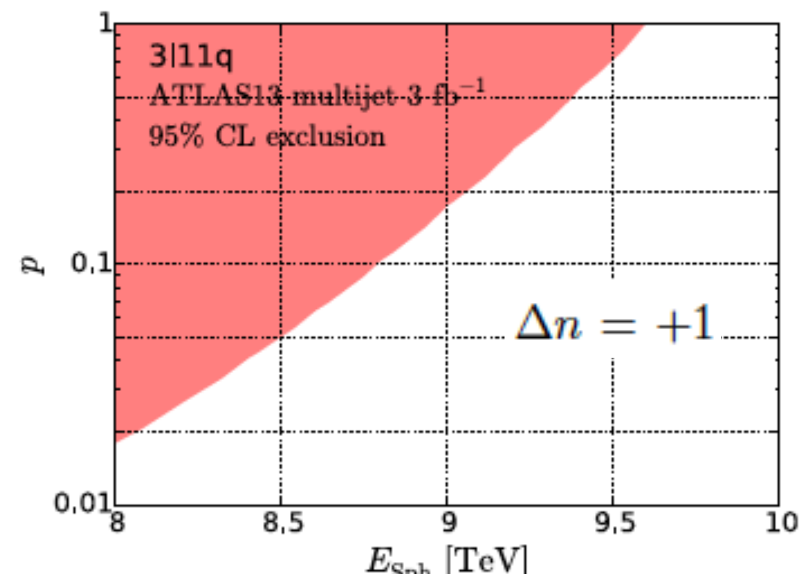
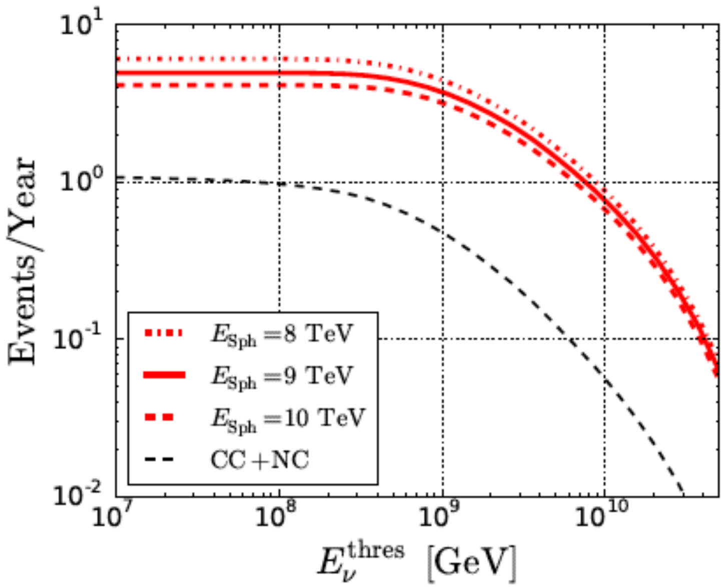




exclusion region: recast 13 TeV ATLAS data for microscopic BH at 3 fb^{-1}

Searches in ICECUBE

Ellis, Sakurai, Spannowsky
1603.06573



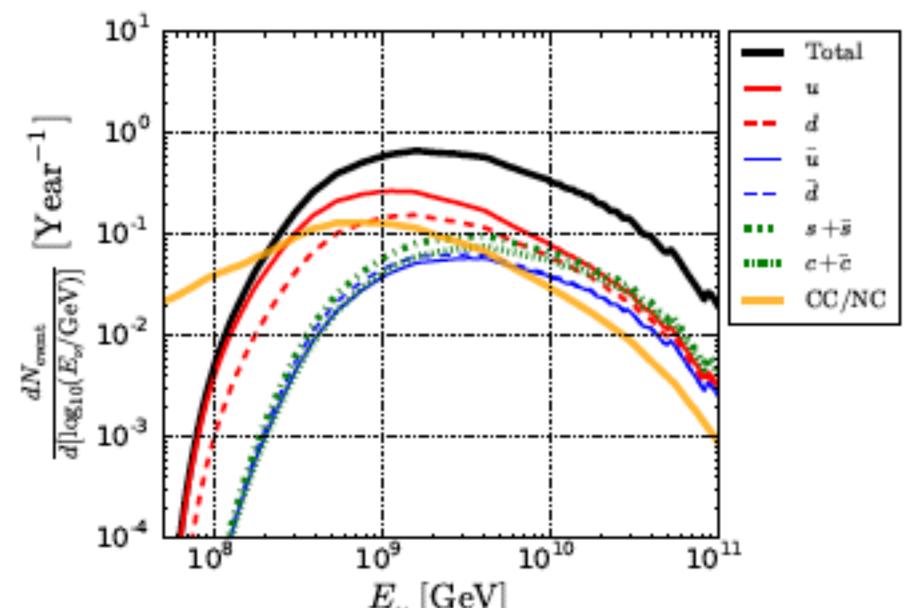
parametrize sphaleron-induced neutrino-quark collision

$$\hat{\sigma}_{q\nu}(\hat{s}) = \frac{p}{m_W^2}$$

$$\sigma_{\nu N}(E_\nu) = \sum_q \int_0^1 dx\, f_q(x,\mu)\hat{\sigma}_{q\nu}(2xm_N E_\nu)$$

sphaleron-event rate in ICECUBE

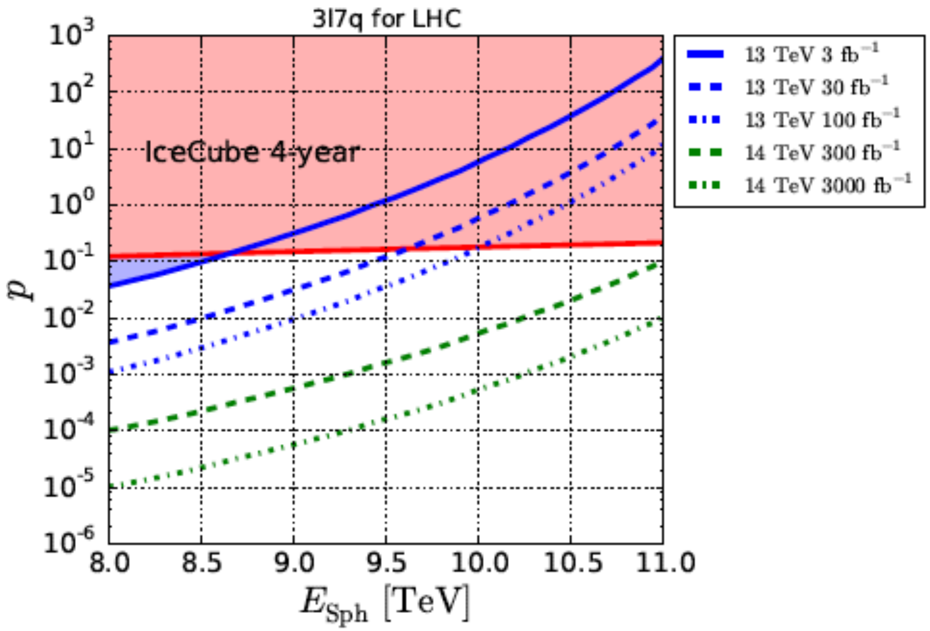
$$\frac{dN_{\rm Sph}}{dt} = \int_{E_\nu^{\rm thres}} dE_\nu \int d\Omega \frac{\sigma_{\nu N}^{\rm Sph}(E_\nu)}{\sigma_{\nu N}^{\rm CC/NC}(E_\nu)} A_{\rm eff}(E_\nu) \frac{d^2\Phi}{dE_\nu dt d\Omega}$$



COMPARISON ICECUBE-LHC

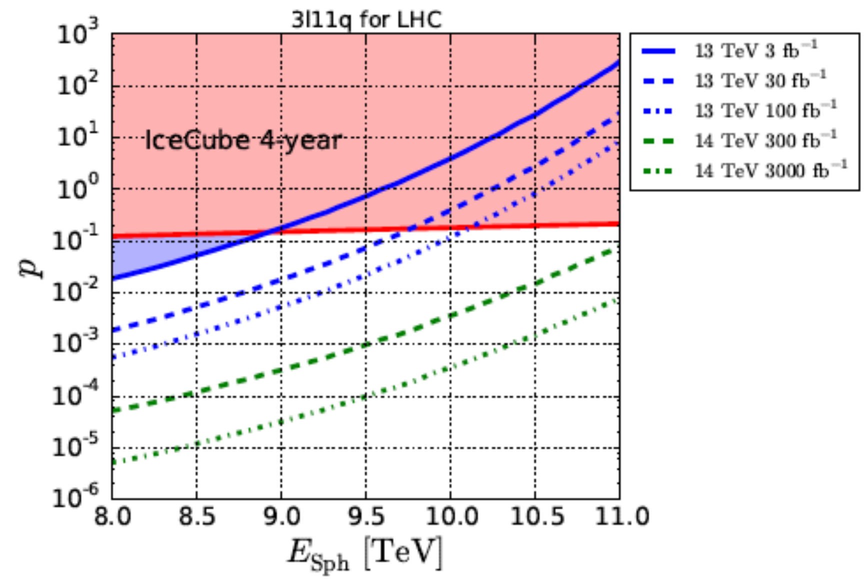
Ellis, Sakurai, Spannowsky
1603.06573

solid blue: recast of an ATLAS search for microscopic Back holes at 3 fb^{-1}



$\Delta n = -1$ *sphaleron transitions*

$\Delta n = +1$ *transitions*



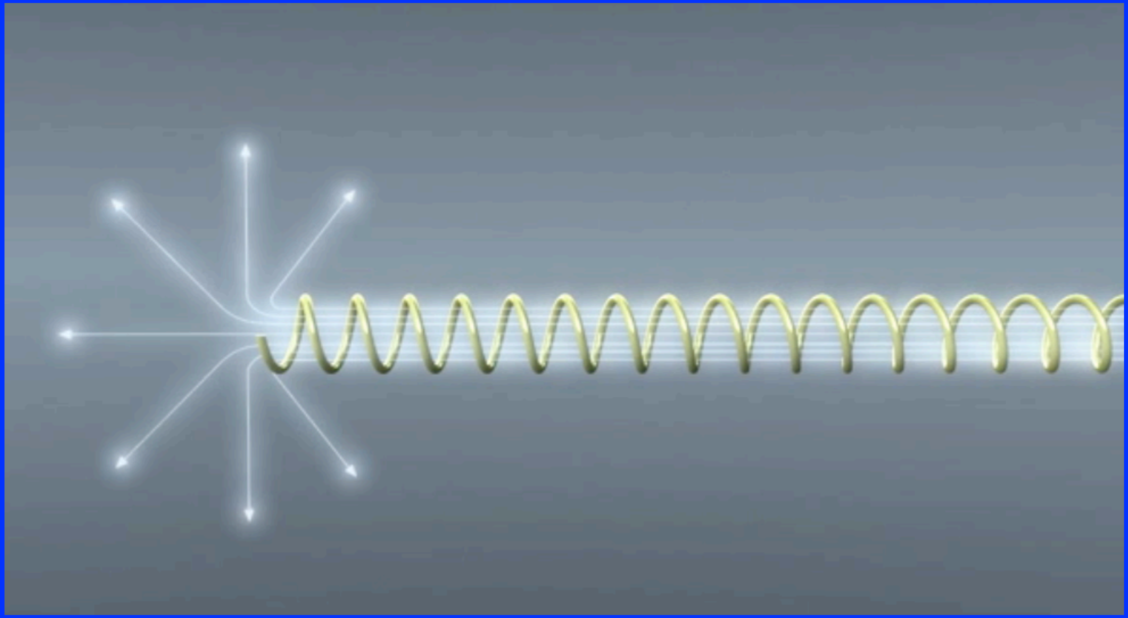
Conclusion: ICECUBE advantageous for **high** sphaleron energies $\mathbf{E_{sph}}$,

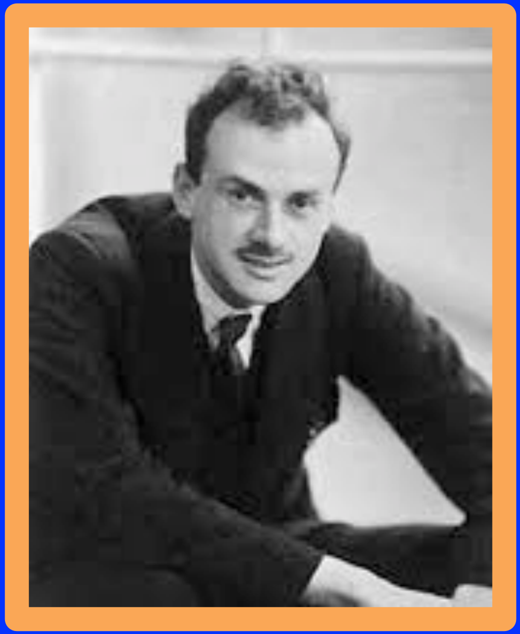
LHC for **small** $\mathbf{E_{sph}}$

MONO

POLES

Dirac's Monopole

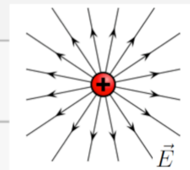
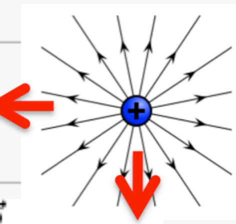
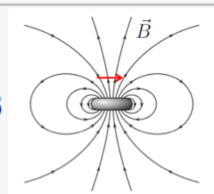




- *In 1931 Dirac hypothesized that the Monopole exists as the end of an infinitely long and thin solenoid - the "Dirac String"*
- *Requiring that the string is not seen gives us the Dirac Quantization Condition & explains the quantization of charge!*

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

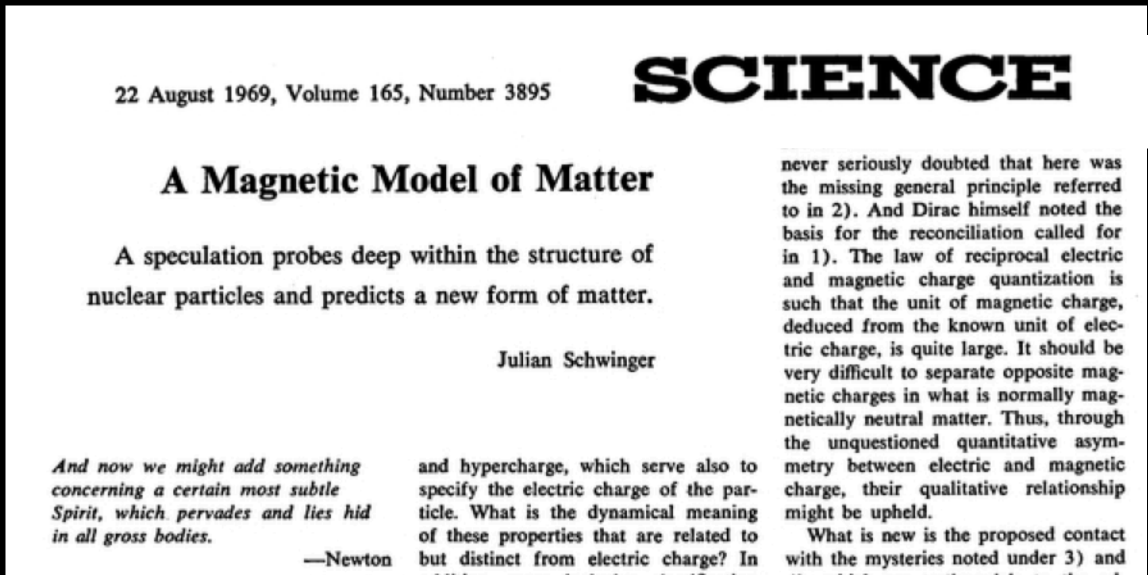
Dirac's Monopole symmetrizes Equations

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

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

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.

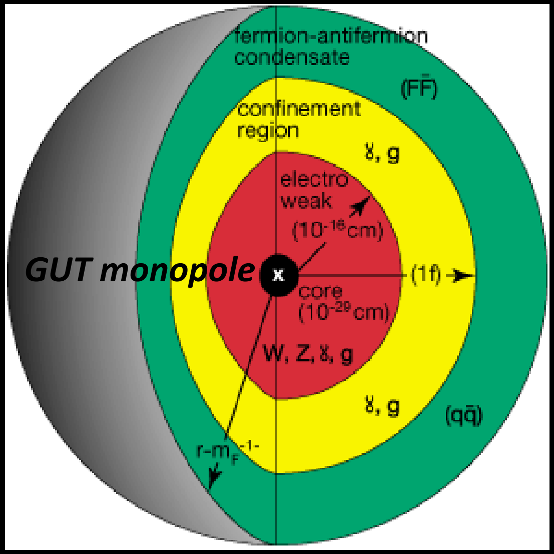
What is new is the proposed contact with the mysteries noted under 3) and

- *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*

Important Connection of `t Hooft-Polyakov Monopole with spontaneous symmetry breaking → **Higgs-like excitations**

$$\mathscr{L}(t,\vec{x}) = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \frac{1}{2}(D_\mu\phi^a)(D^\mu\phi^a) - \frac{1}{4}\lambda\left(\phi^a\phi^a - \eta^2\right)^2$$

Assume appropriate GUT non-abelian group (eg SU(5)) admitting monopoles → spontaneously broken

$\varphi = \eta \neq 0$ (*r* → ∞) symmetry broken

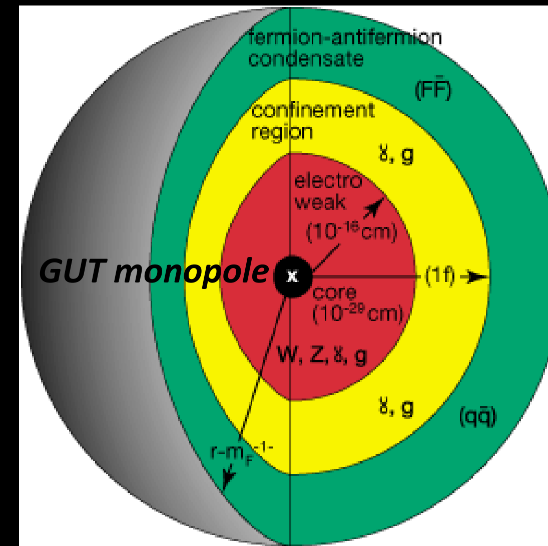
Assume mass concentrate inside the core of *size L*

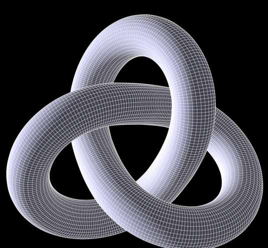
Outside the core

$f \approx 1 \rightarrow \chi^\alpha \chi^\alpha \rightarrow \eta^2$

V → 0 (non trivial minimum)

The ‘t Hooft-Polyakov Monopole





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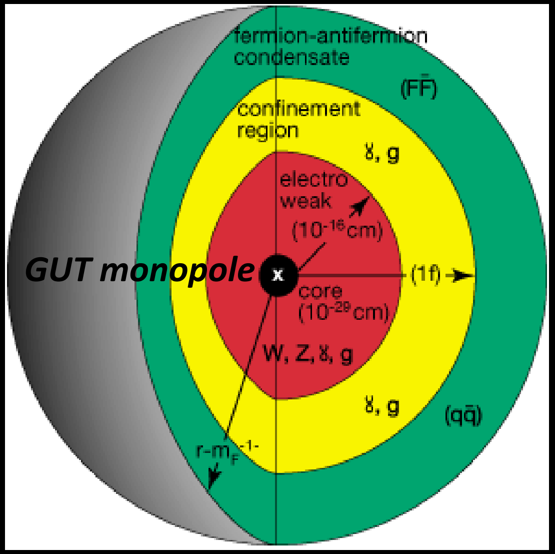
The ‘t Hooft-Polyakov Monopole



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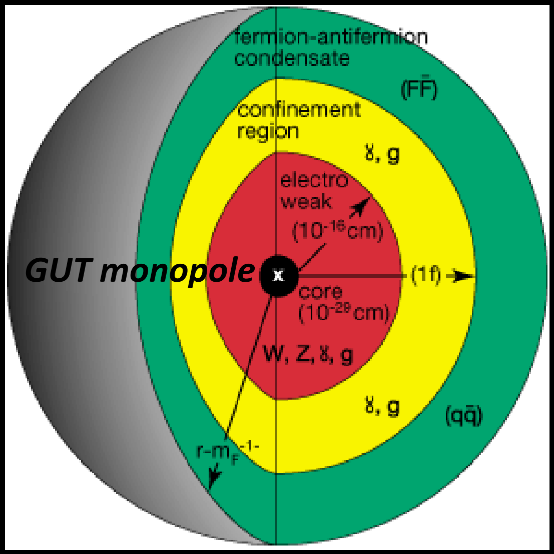

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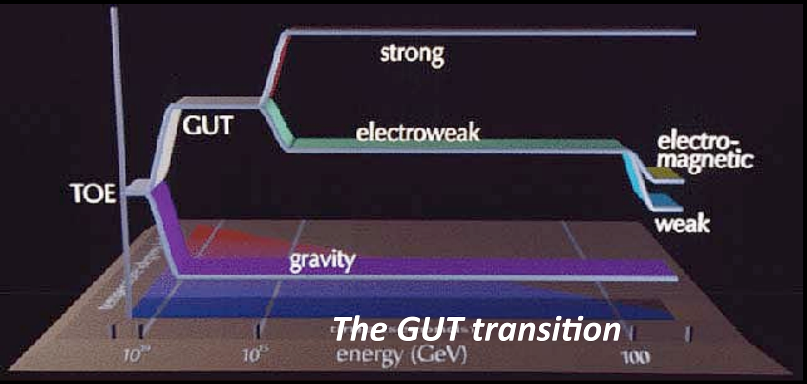
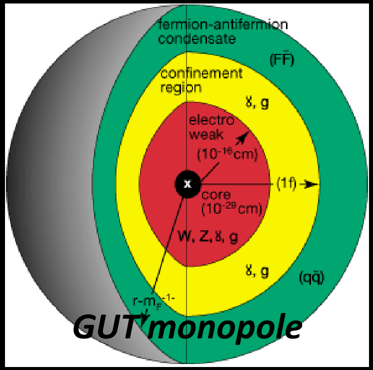
  - *The topology of the soliton's field configuratio*

$10^{15\text{-}16}$ GeV

  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 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*

$$SO(10) \xrightarrow[10^{-35}s]{10^{15}\ GeV} SU(4) \times SU(2) \times SU(2) \xrightarrow[10^{-23}s]{10^{9}\ GeV} SU(3) \times SU(2) \times U(1)$$

GUT Monopole Catalysis of p-Decay

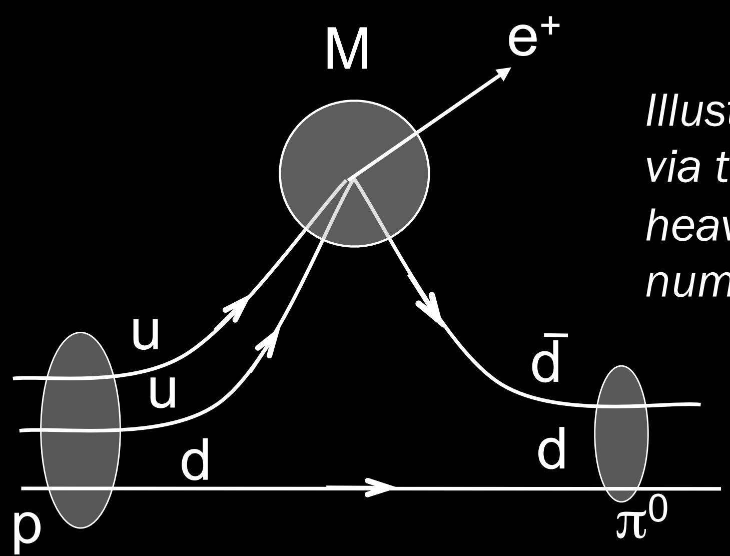


Illustration of monopole catalysis of proton decay via the Rubakov-Callan Mechanism via super heavy gauge bosons that mediate baryon number violation

- *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*

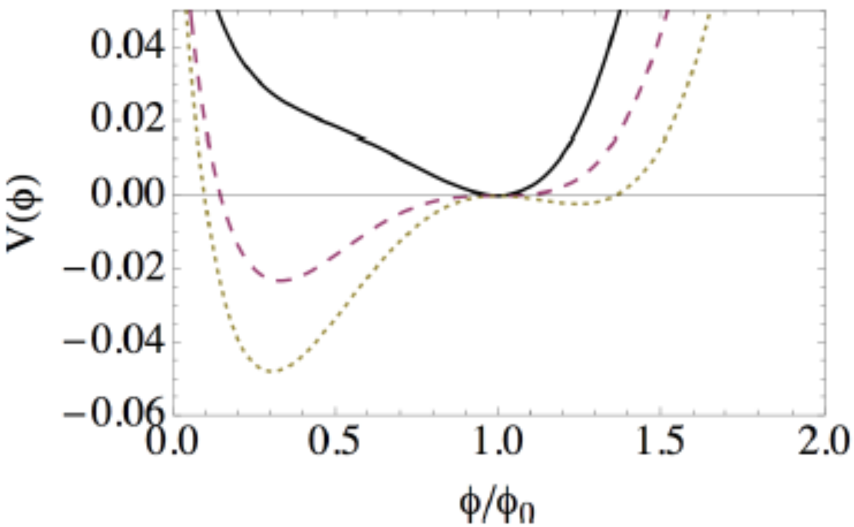
But… GUT monopoles not alone in market

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

Vacuum instabilities & light GUT monopoles?

MOeDAL review : ArXiv:1406.7662

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

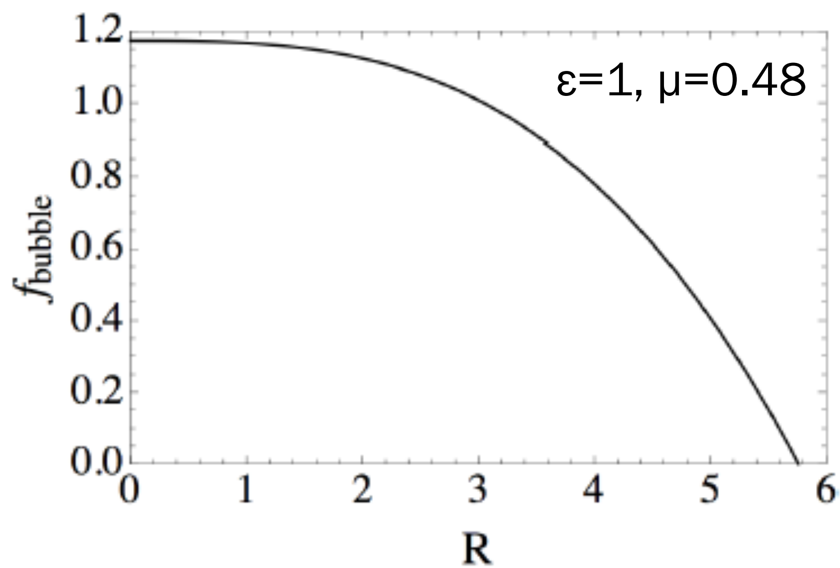


Monopole Energy density

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

@ 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?

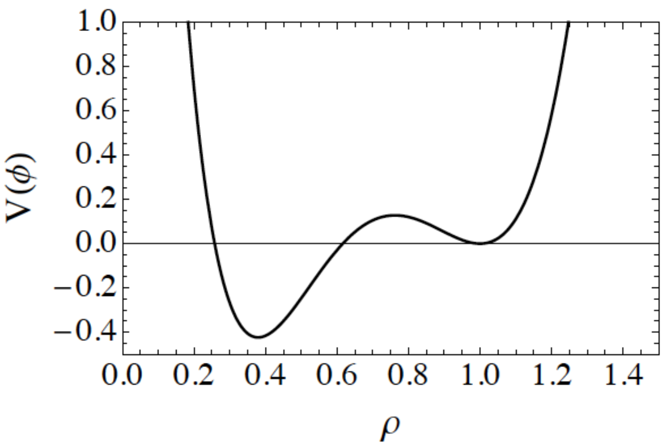
Courtesy: Vicente Vento (Valencia)

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

Modifications of Georgi-Glashow (MGG) model

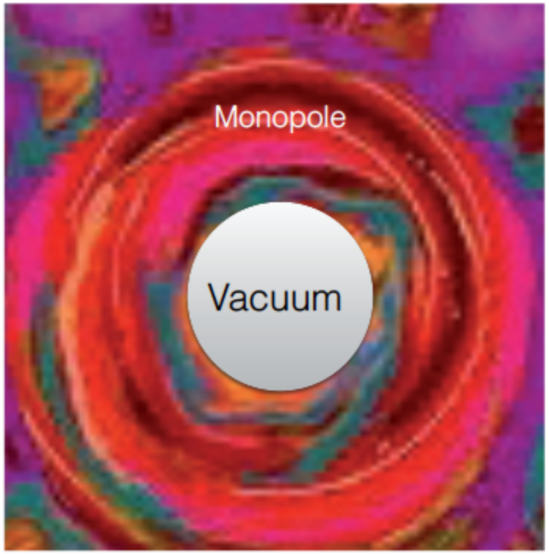
→ towards **smaller** monopole masses **BUT ALSO stable monopoles**

→ **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

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 TeV/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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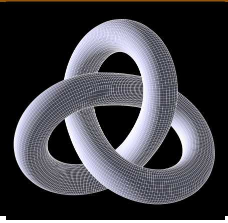

Important role of U_Y (1) for SM admitting monopole solutions

SU(2) x 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…*
  - *Magnetic charge $2g_D$*
  - *Mass in the range 4→7 TeV/c² →*
- *This monopole is a non-trivial hybrid between the abelian Dirac monopole and the non-abelian 't Hooft-Polyakov monopole*
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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

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

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

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

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

...poles

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

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

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

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

...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''

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

Assume Higgs field affects $U_Y(1)$ permittivity of vacuum
e.g. due to quantum (loop) corrections

$U(1)_Y$ gauge coupling → ``running''

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

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For finite energy of Cho-Maison Dyon we need

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

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

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

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

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)

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

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

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

Cho *et al.* 2015

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Cho *et al.* 2015

Dim 6 operators
complete EFT analysis

Ellis, Sanz, You JHEP 1503 (2015)

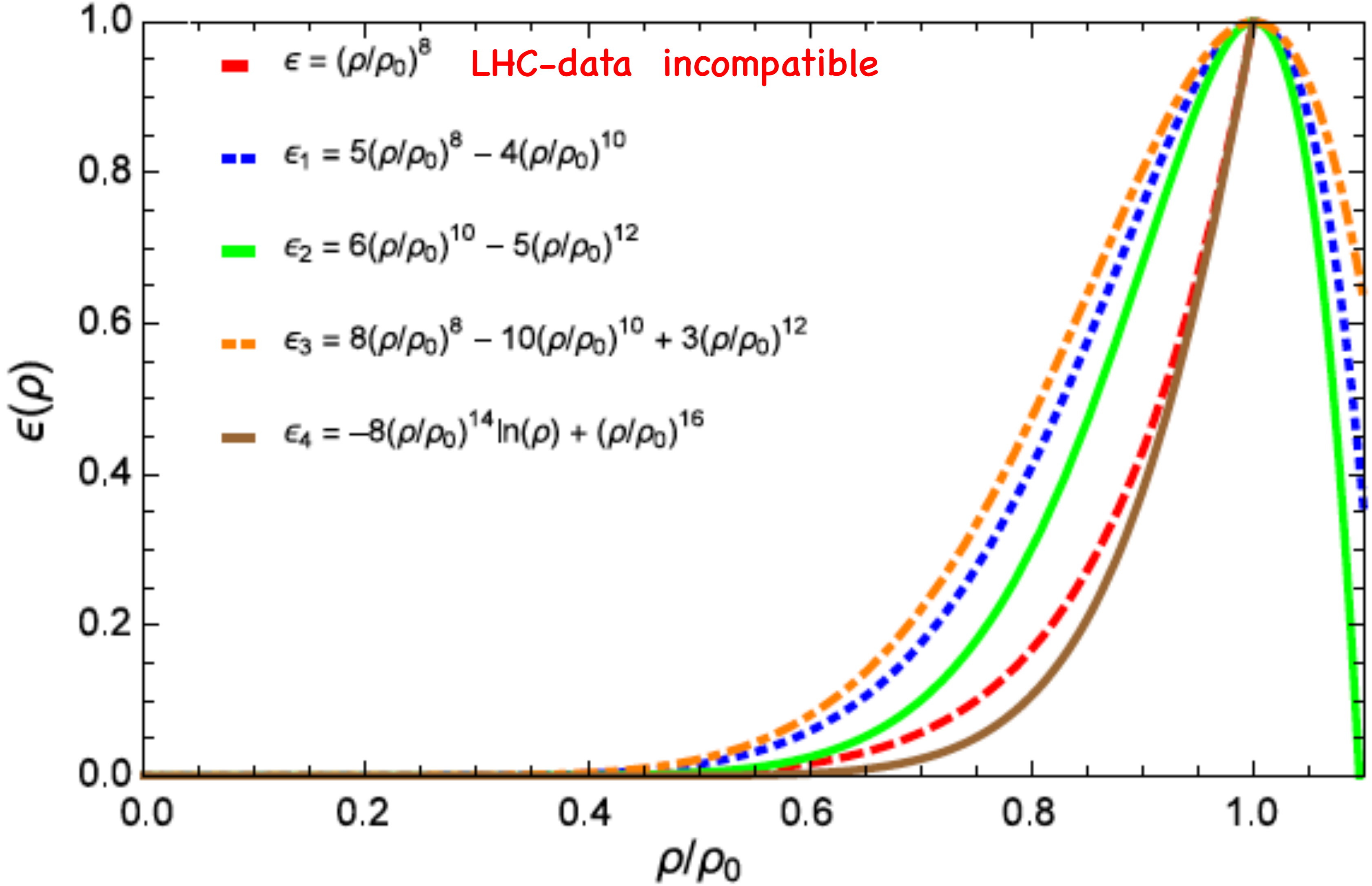
$$\frac{c_\gamma}{\Lambda^2}\mathcal{O}_\gamma \equiv \frac{\bar{c}_\gamma}{M_W^2} g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$

Global fit to LHC data

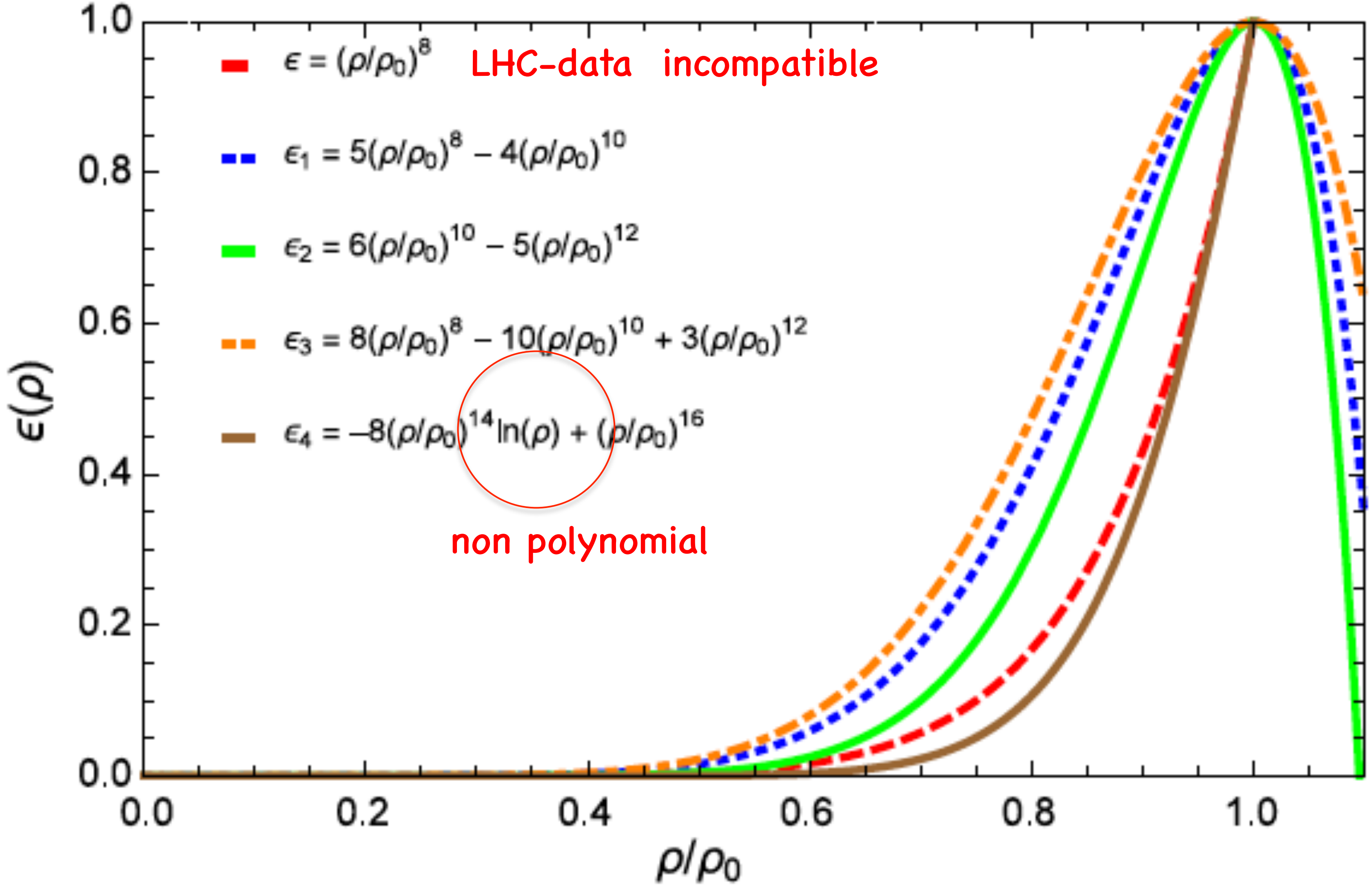
$$\bar{c}_\gamma = O(10^{-3}) < 0$$

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

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



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



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)

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$\left(\frac{\rho}{\rho_0}\right)^8$	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

Cho, Kim, Yoon , arXiv:1605.08129

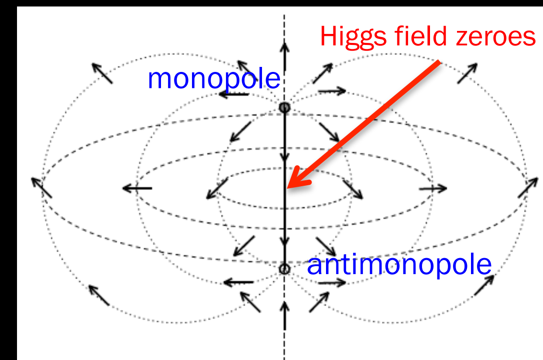
Other Monopole-like EW structures

Review:
Achucarro & Vachaspati
Phys Repts 327 (2000)

- Electroweak Strings (Nambu's Dumb-bell configurations)

$$M_N \simeq \frac{4\pi}{3e} \sin^{5/2}\theta_W \sqrt{\frac{m_H}{m_W}}\mu,$$

$$\mu = m_W/g \qquad M_N \simeq 689 \text{ GeV}$$



- Yang's singular monopole in electroweak SU(2) Yang-Mills

NB: Yang's monopole has IR infinities → regularised if embedded in gravity in even space-time dimensions:

Cebeci, Sarioglu, Tekin
Phys.Rev. D78 (2008) 125016

$$ds^2 = -f^2(r)\,dt^2 + \frac{dr^2}{f^2(r)} + r^2\,d\Omega^2_{n-2}$$

$$f^2(r) = 1 - \frac{2\,m}{r^{n-3}} - \frac{\mu^2}{r^2} - \frac{2\,\Lambda\,r^2}{(n-2)(n-1)}$$

$$\mu^2 = \frac{8\pi(n-3)}{(n-5)\sigma^2}$$

$$E = \frac{1}{4\Omega_{n-2}}\,\Omega_{n-2}\,(2(n-2)\,m) = \frac{m(n-2)}{2}$$

Reissner-Nordstrom Black Hole (BH)

If TeV BH produced @ LHC → could have TeV mass Yang monopoles as well?

Other Monopole-like EW structures

Rosy They,Ban-Loong Ng & Khai-Ming Wong
arXiv: 1406.0978

- ``Half Monopole AXISYMMETRIC Solution in Weinberg-Salam Model:

electromagnetic potential is singular along, say, z axis
with half the magnetic charge of Cho-Maison monopole, g = 2π/e

In U(1) magnetic field: solution is a finite-length line magnetic charge from *r=0*
In SU(2) 't Hooft's magnetic field: is a point magnetic charge located at *r=0*

has magnetic dipole moment that decreases exponentially with increasing Higgs self-coupling $\lambda^{1/2}$ @ $\sin^2\theta_W = 0.23$

IMPORTANT: FINITE TOTAL ENERGY proportional to (1/2) Log λ

λ	0	0.1	0.5	1	2	4	8	10	20	30	40
E	0.563	0.590	0.612	0.625	0.639	0.656	0.674	0.680	0.700	0.711	0.720
μ_m	1.028	0.958	0.916	0.897	0.877	0.858	0.840	0.834	0.816	0.806	0.799

Table 2: Values of total energy E in units of $\frac{1}{4\pi}$ and magnetic dipole moment μ_m of the one-half monopole for various values of λ when $\theta_W = 28.74^o$ and $\zeta = 1$.

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electrom
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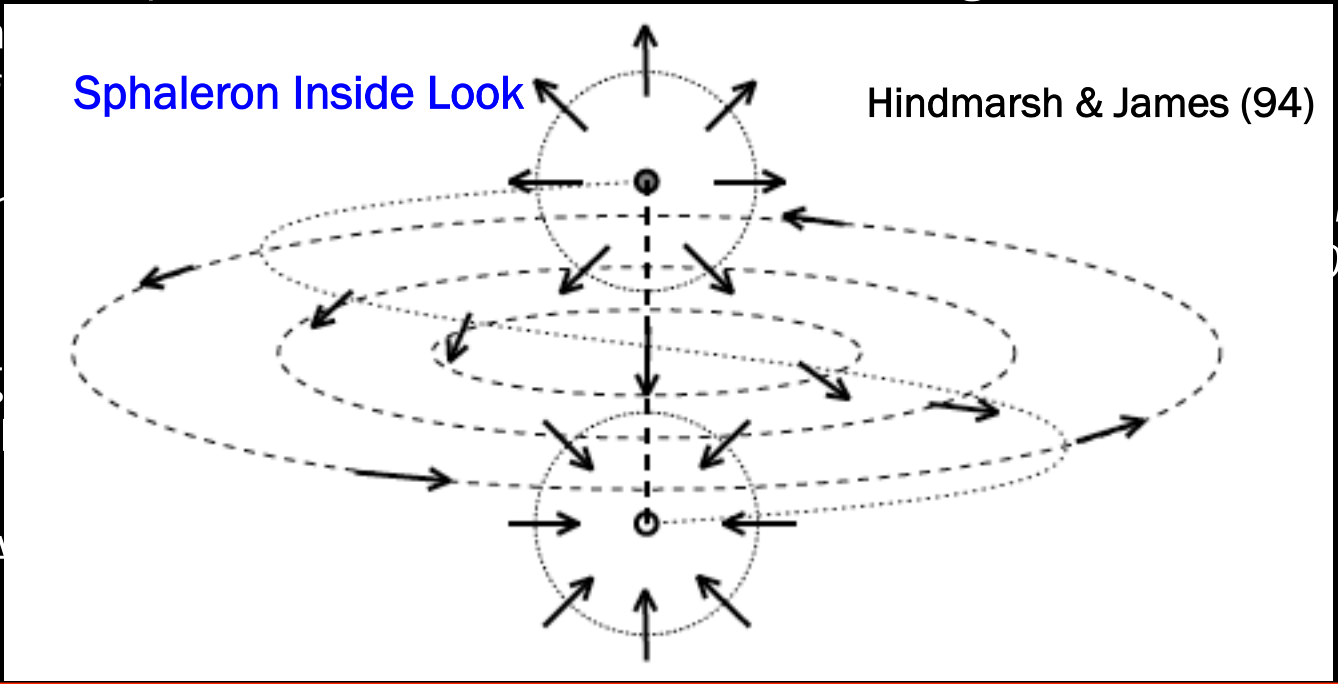
In U(1) m *r=0*
In SU(2))

has mag
Higgs se

IMPORTA



CAN EXIST EITHER AS ISOLATED MAGNETIC LINES OR IN MONOPOLE-ANTIMONOPOLE PAIRS CONNECTED BY A Z^0 FLUX TUBE INSIDE SPHALERONS

Other Monopole-like EW structures

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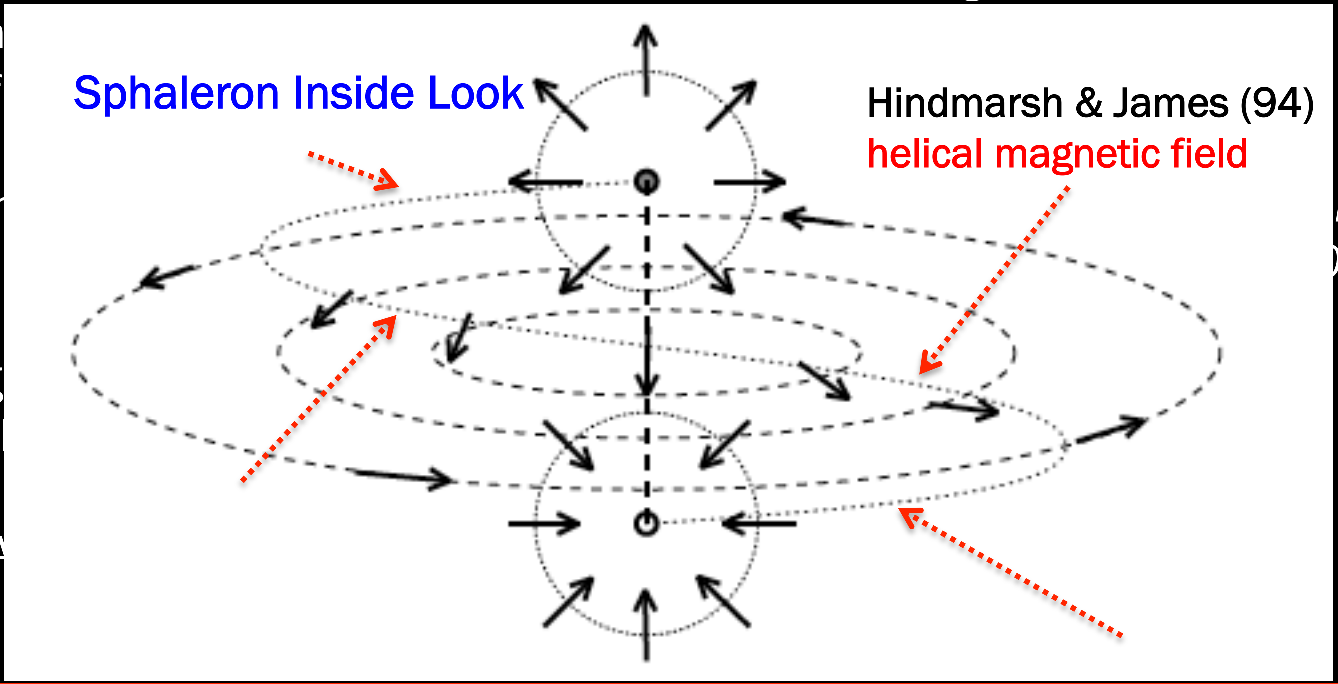
In SU(2) ...)

has mag
Higgs sel

IMPORTA



CAN EXIST EITHER AS ISOLATED MAGNETIC LINES OR IN MONOPOLE-ANTIMONOPOLE PAIRS CONNECTED BY A Z^0 FLUX TUBE INSIDE SPHALERONS

Other Monopole-like EW structures

- Similar sphaleron-related solutions with screened magnetic field have been discussed in

D. G. Pak, P. M. Zhang, and L. P. Zou
arXiv: 1311.7567v3

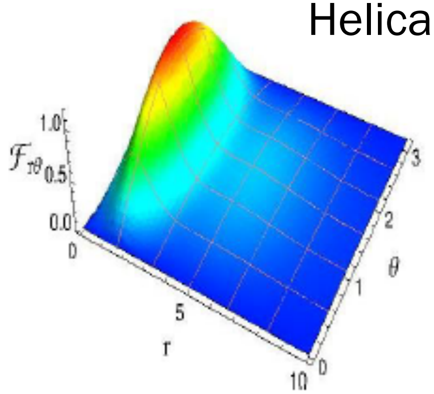


FIG. 4: Helical magnetic field $\mathcal{F}_{r\theta}$.

Helical **screened magnetic field**

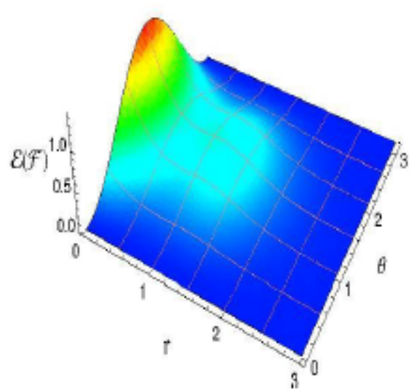


FIG. 5: Energy density $\mathcal{E}(\mathcal{F})$ corresponding to the Abeliam gauge invariant magnetic field $\mathcal{F}_{mn}$.

Energy Density → **FINITE TOTAL ENERGY**

Estimated by a variational method to be **≥ 4.3 TeV**

Other Monopole-like EW structures

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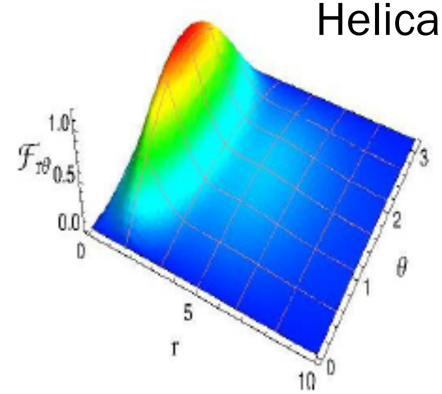
Helical **screened magnetic field**



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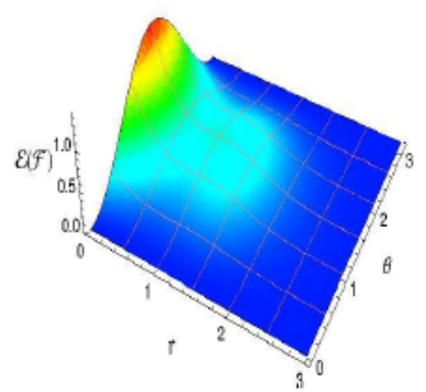


FIG. 5: Energy density $\mathcal{E}(\mathcal{F})$ corresponding to the Abeliam gauge invariant magnetic field $\mathcal{F}_{mn}$.

But such sphaleron related solutions are *unstable*…. could they be stabilised ? → relevant @ LHC & MoeDAL?

Energy Density → **FINITE TOTAL ENERGY**

Estimated by a variational method to be **≥ 4.3 TeV**

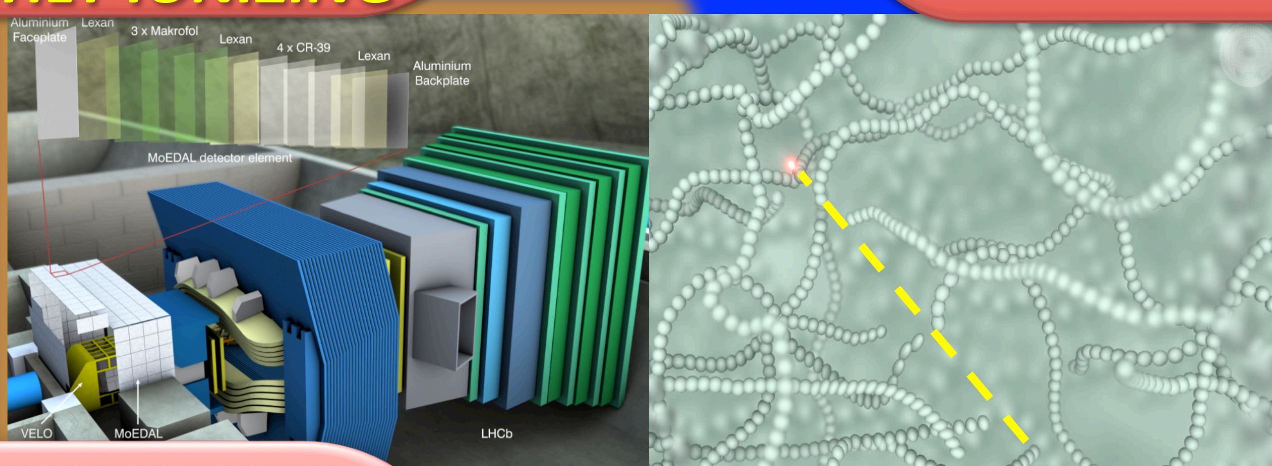
Magnetic Monopole Properties

– behaviour in matter

Magnetic Monopole Properties

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

Coupling constant =
$g/\hbar c$ ~ 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

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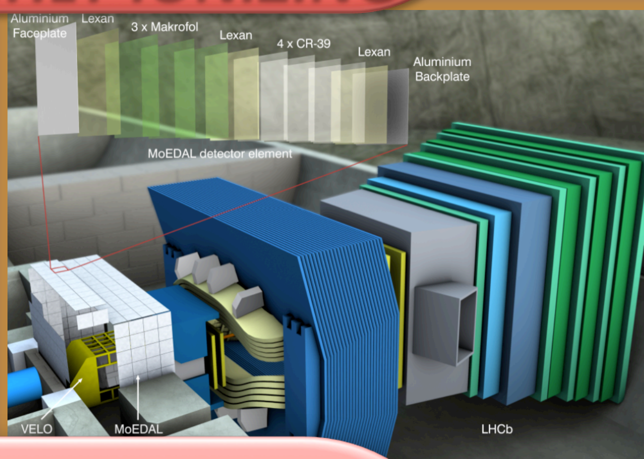
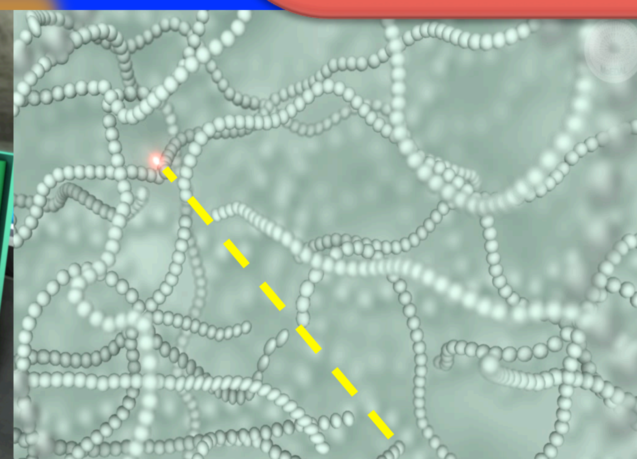




Energy acquired in
a magnetic field
=2.06MeV/gauss.m
= 2TeV in a 10m,
10T LHC magnet

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

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

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

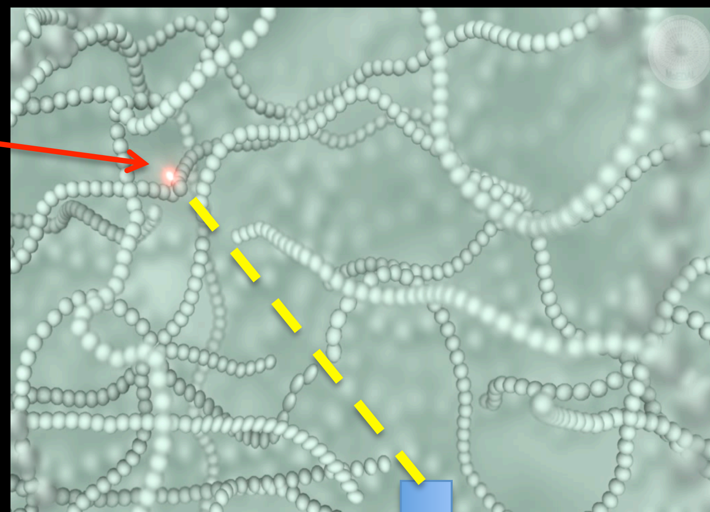
$$-\frac{dE}{dx} = K\frac{Z}{A}g^2\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I_m} + \frac{K|g|}{2} - \frac{1}{2} - B(g)\right]$$

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

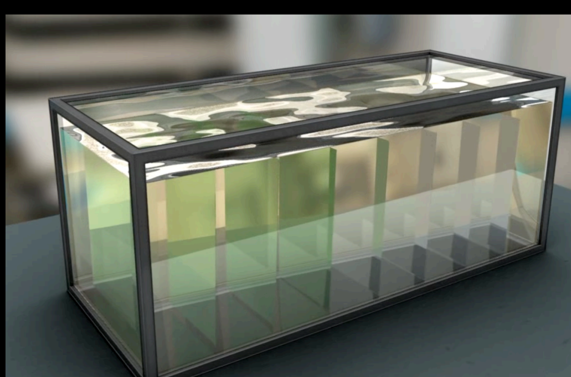
- The ionization of a relativistic monopole is $(ng)^2$ times that of a relativistic proton i.e $4700n^2$!! (n=1,2,3…)

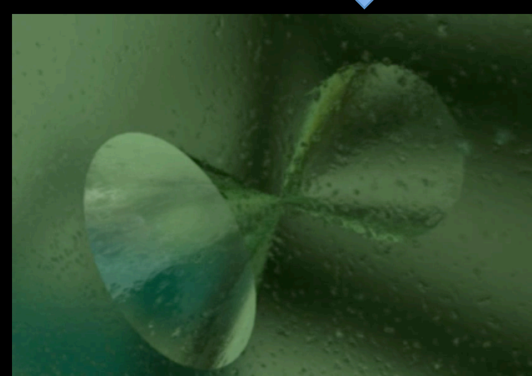
Monopoles in Nuclear Track Detectors (NTDs)

The highly ionizing particle leaves a cylindrical trail of damage in the plastic NTDs



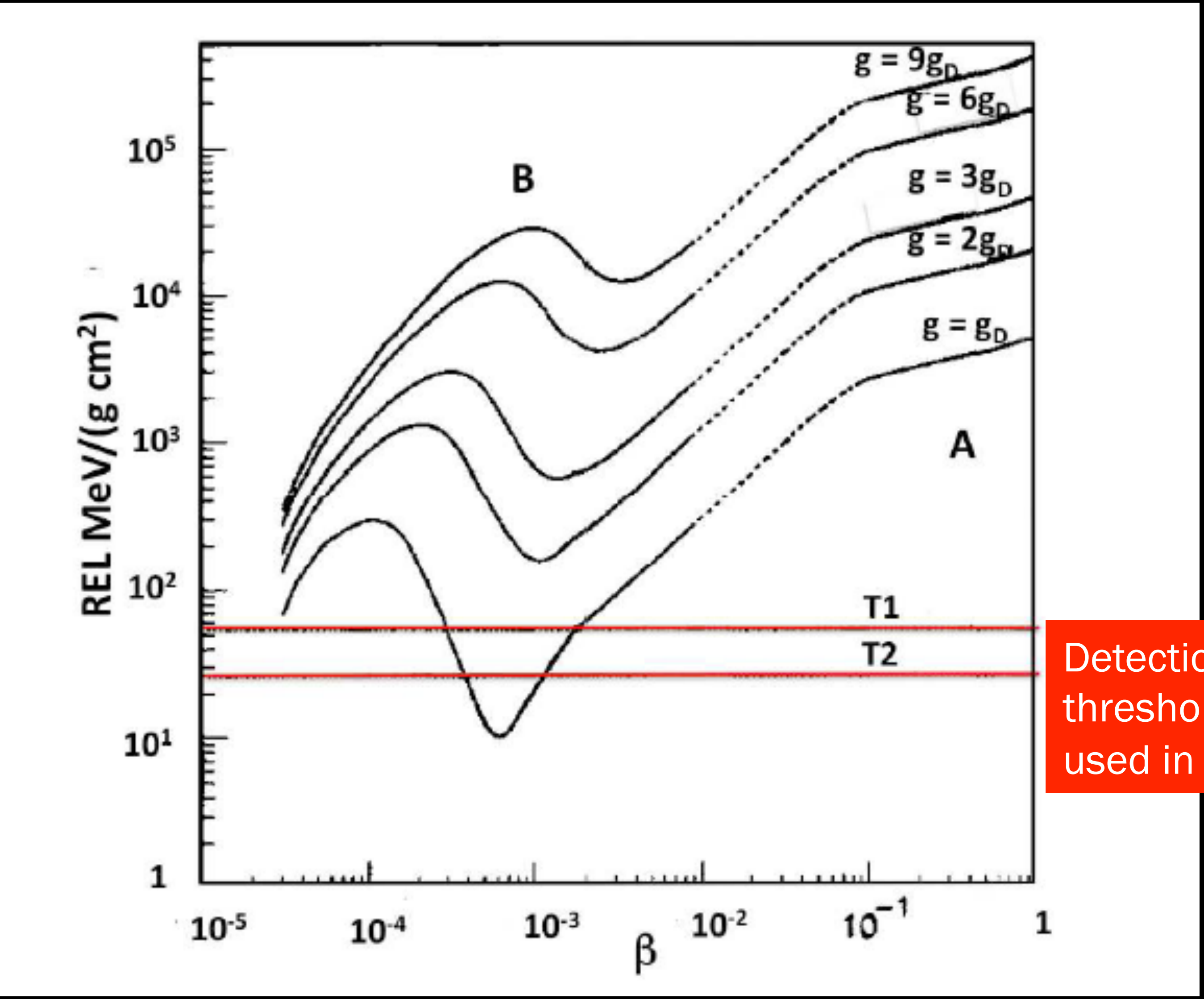
ETCHING PROCESS:





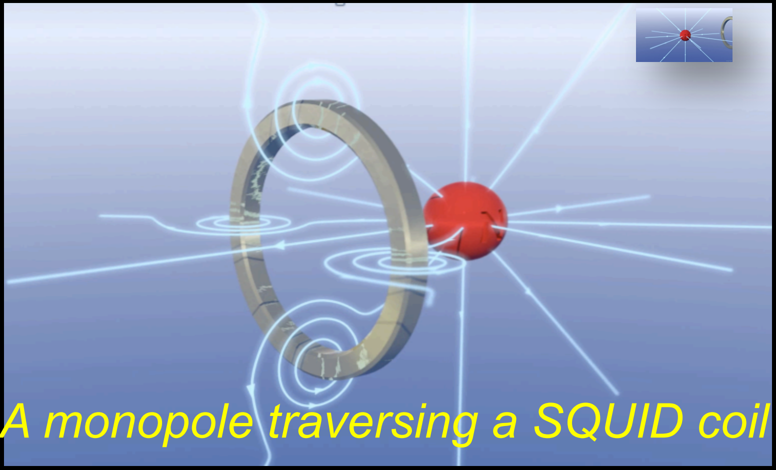
Tracks are revealed as conical etch pits . Charge resolution ~0.05e . Spatial resolution ~ 10 microns/pit – pointing to the IP

Monopole Energy Losses in plastic Nuclear Track Detectors (NTD)



Detection thresholds of CR39 used in MACRO Expt

Induction Experiments



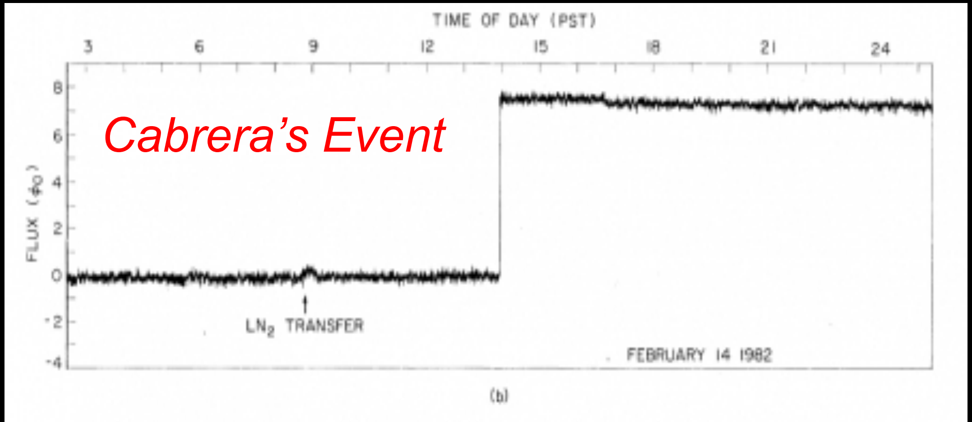
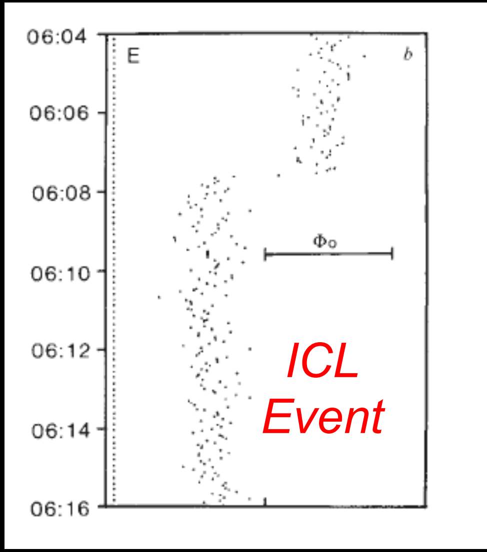


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

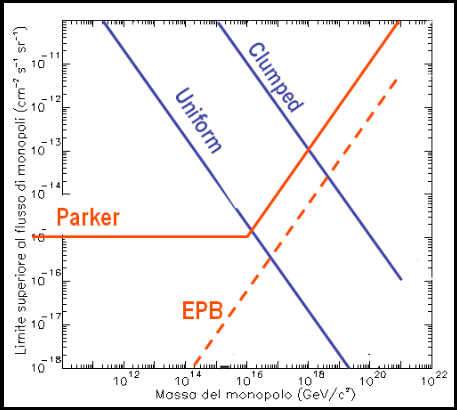
- *Data from Cabrera's apparatus taken on St Valentine's day in 1982 ($A=20\ cm^2$).*
  - *The trace shows a jump – just before 2pm - that one would expect from a monopole traversing the coil.*
- *In August 1985 a groups at ICL reported the:"observation of an unexplained event" compatible with a monopole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



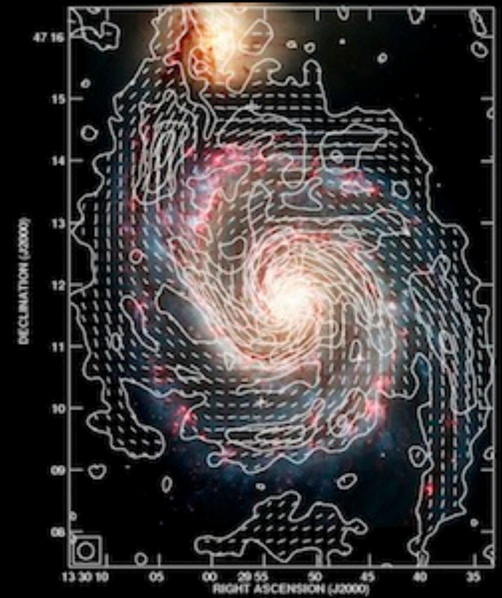
Searching for High Mass (> 10 TeV) (primordial) Magnetic Monopoles

Primordial Monopoles

- *Primordial Monopoles:*
  - *GUT monopoles - m~10^{17} GeV*
  - *IM Monopoles– made in later phase transitions of early universe m ~ 10^{9} GeV*
- *Monopoles accelerate to relativistic speeds in galactic B-fields → ~10^{20} eV*
- *Parker Bound is an upper limit on the density of magnetic monopoles based on the existence of a galactic B- field.*
  - *This bound can be evaded if monopole anti-monopoles pairs are bound*
- *Extended Parker Bound - a more stringent limit.*
  - – *Based on the survival of the small seed field of the protogalaxy*

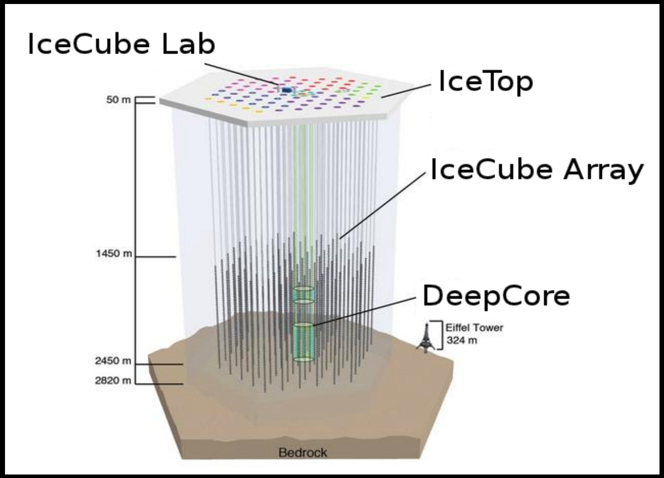


F< 10^{-15} cm^{-2} s^{-1} sr^{-1} for β<3 x 10



B-field in spiral galaxies is ofo 10 μG (microGauss) (Earth's field ofo 0.1G)

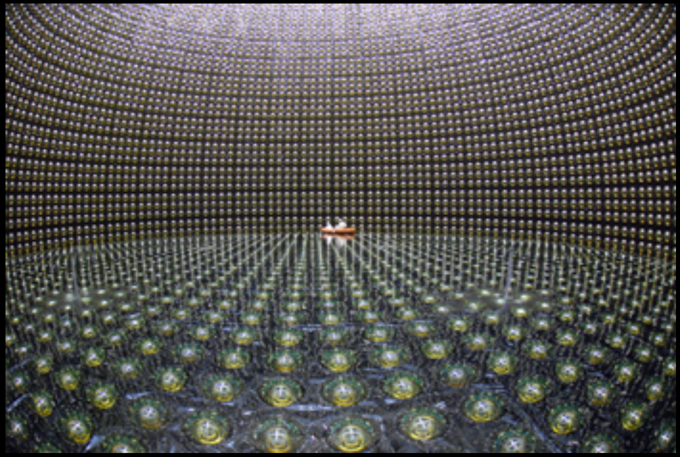
Major Cosmic Monopole Searches



IceCube (Antarctica: -2.4km) - Cerenkov emission& catalyzed p-decay

MACRO (Gran Sasso: -1400m) – high ionization

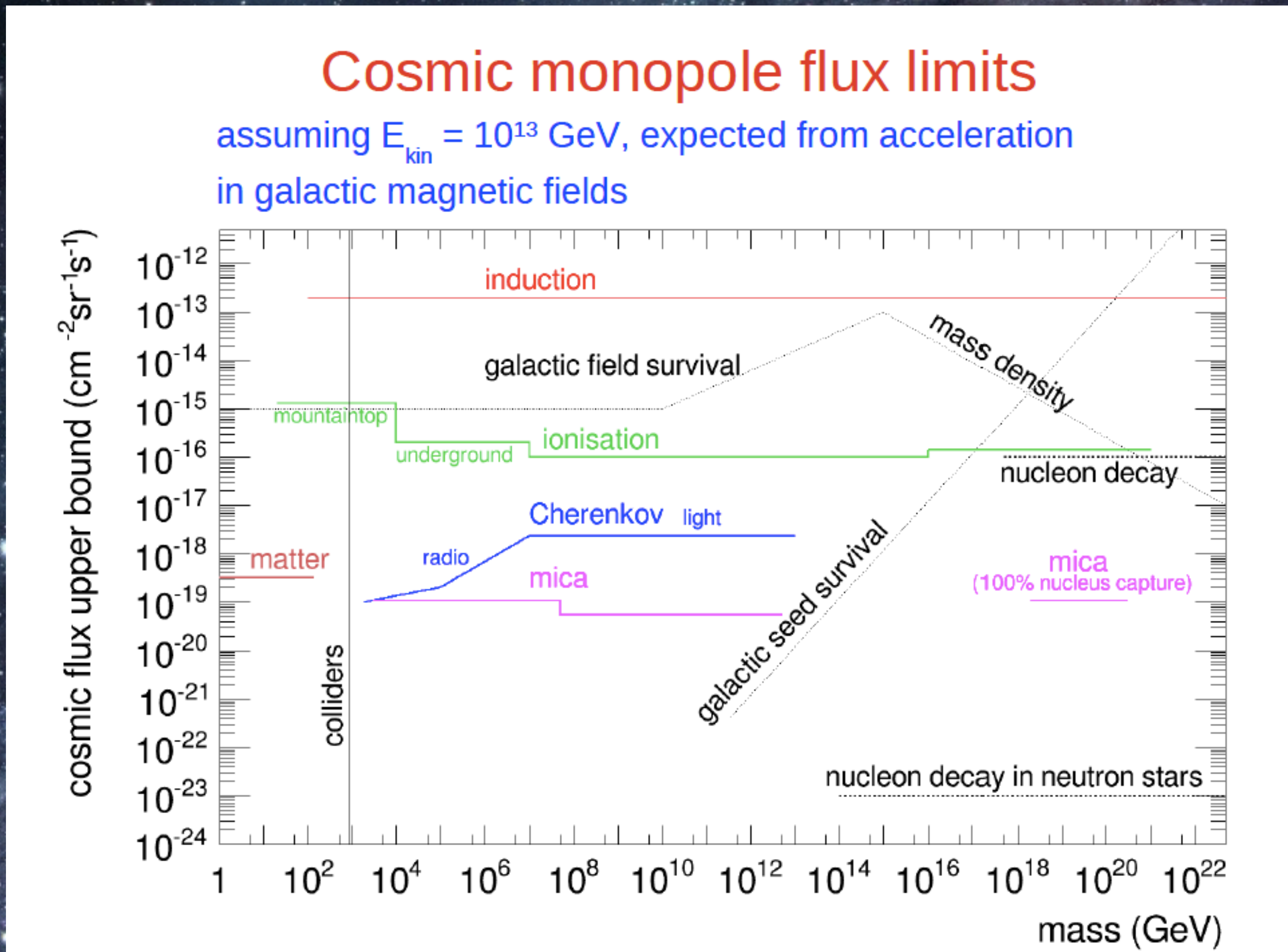
SLIM (Chacaltaya: +5200m) – high ionization



Super-K (Kamioka: -1000m) – catalyzed p-decay

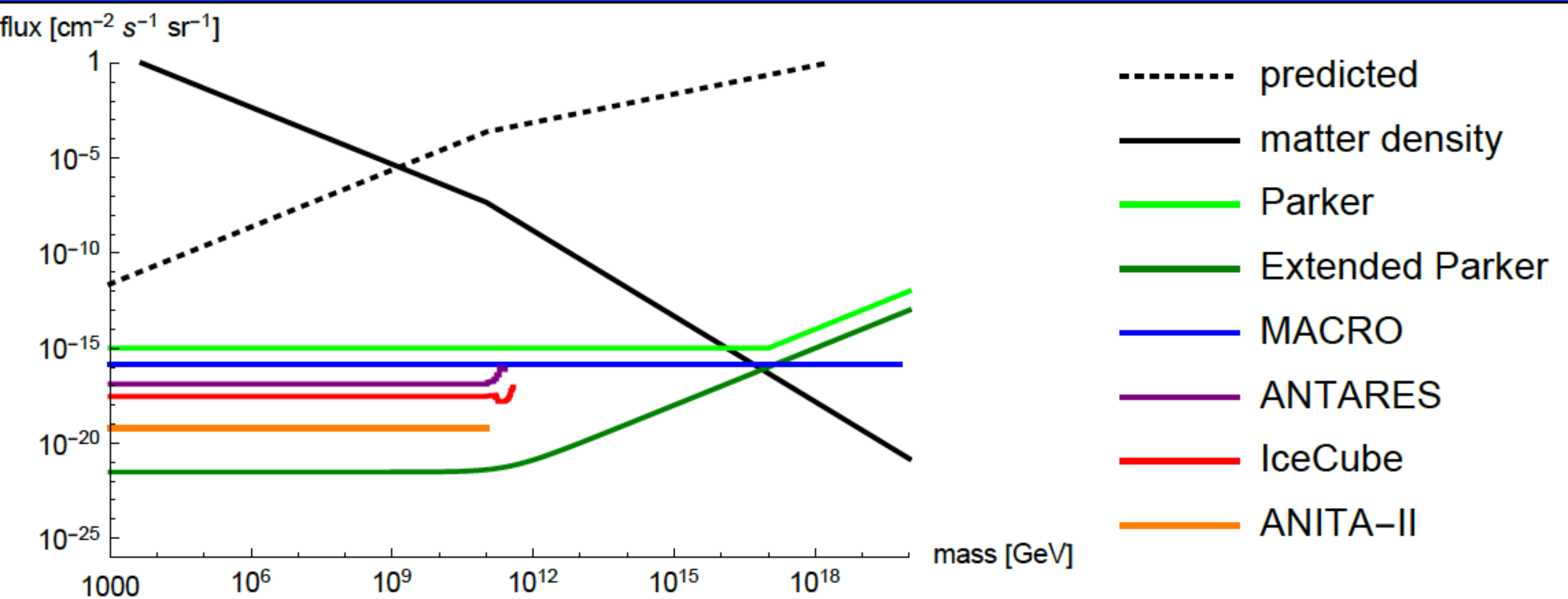
Cosmic Monopole Flux Limits

A. Rajantie,
L. Patrizii



Cosmic Bounds

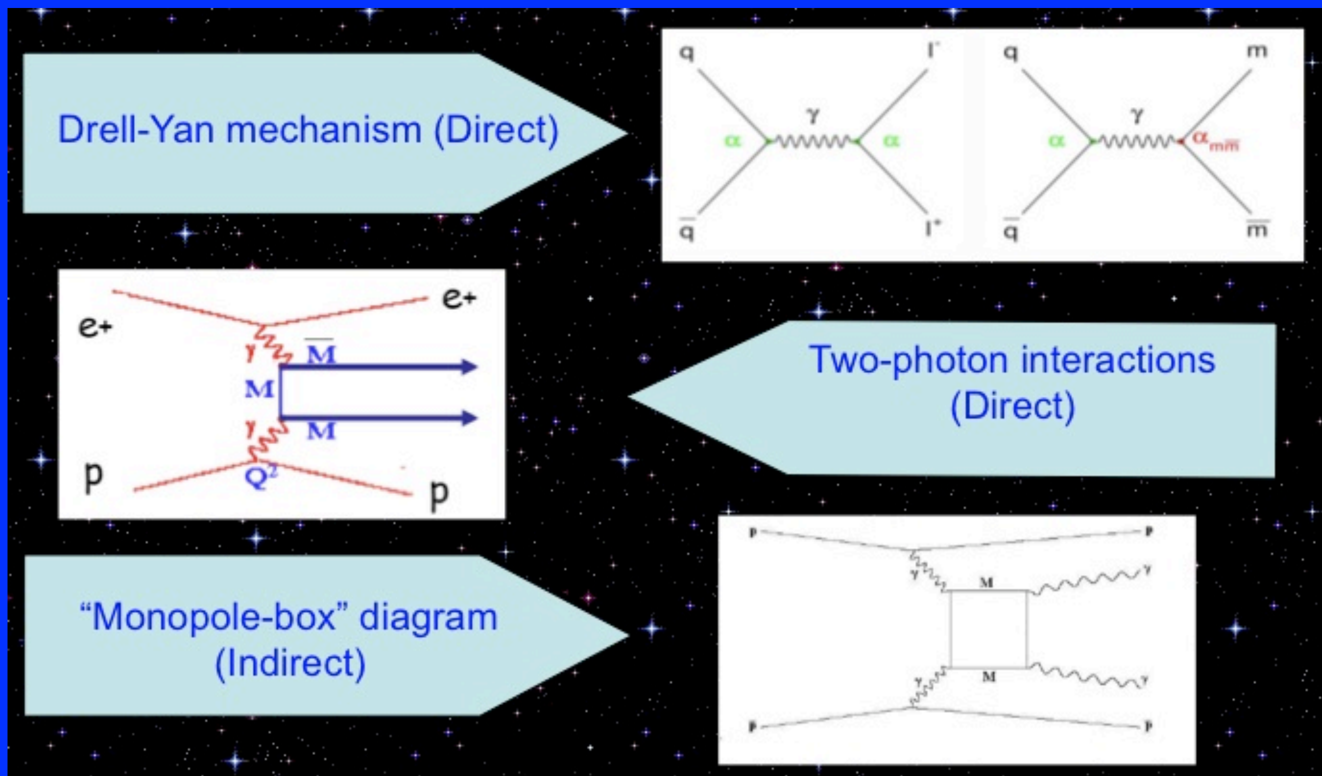
A. Rajantie,
L. Patrizii



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

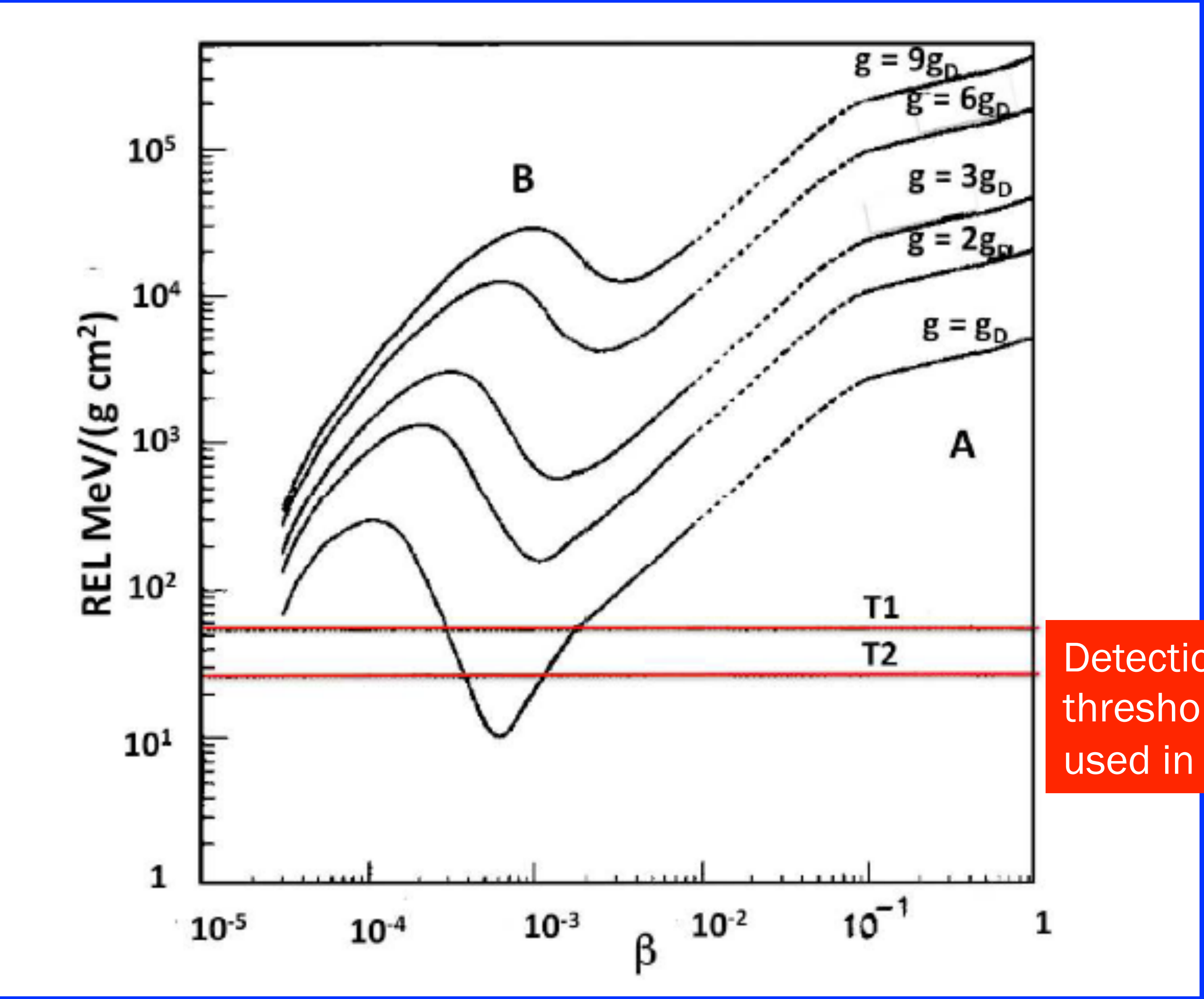
Monopole Production at Colliders

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



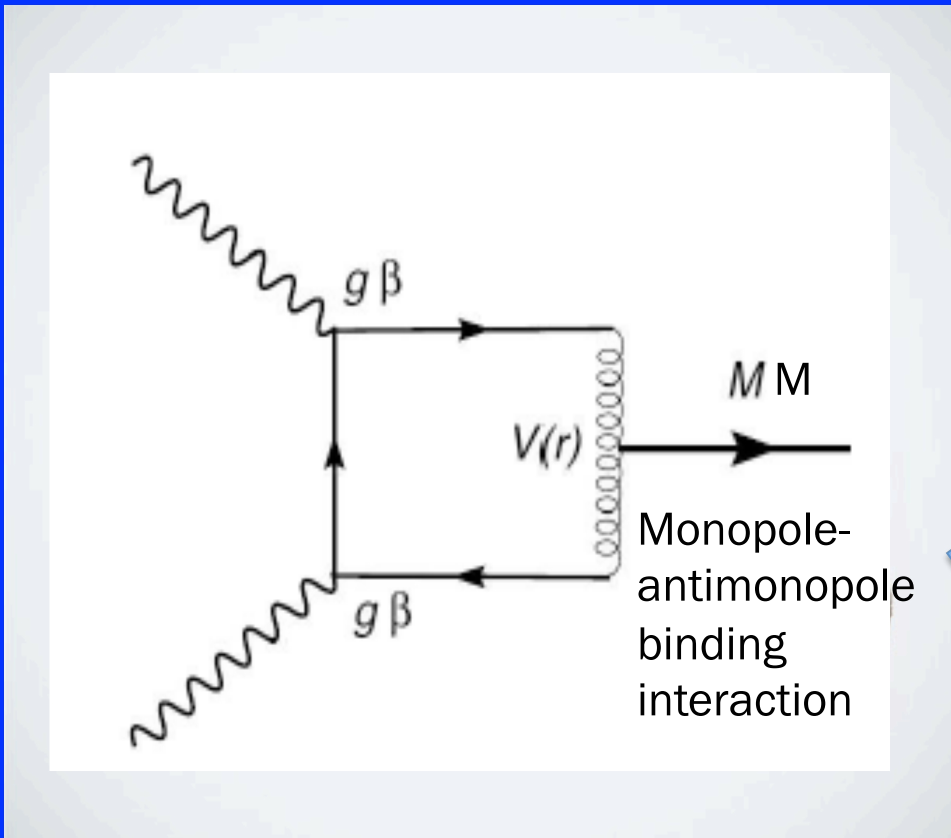
- CDF excluded MM pair production at the 95% CL for cross-section < 0.2 pb and monopole masses 200 < m_M< 700 GeV/c^2

Monopole Energy Losses in plastic Nuclear Track Detectors (NTD)

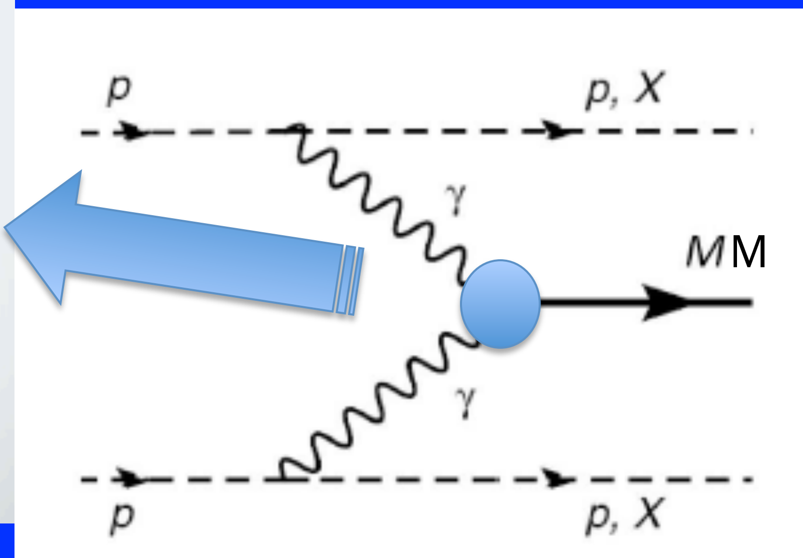


Detection thresholds of CR39 used in MACRO Expt

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?

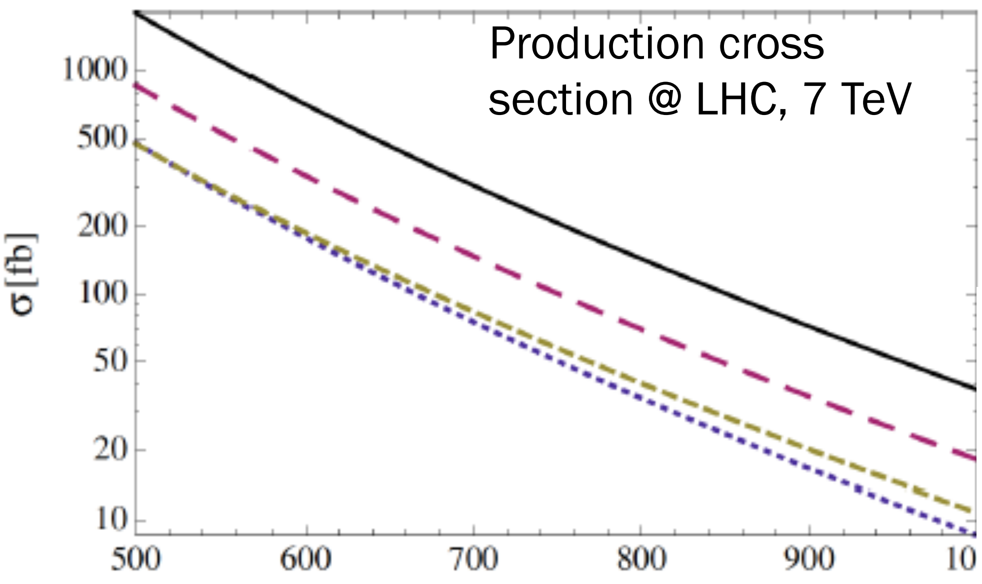


Epele, Fanchiotti, Garcia-Canal, Mitsou, Vento, EPJPlus 127 (2012), 60

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

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

THE SEARCH FOR MONOPOLIA



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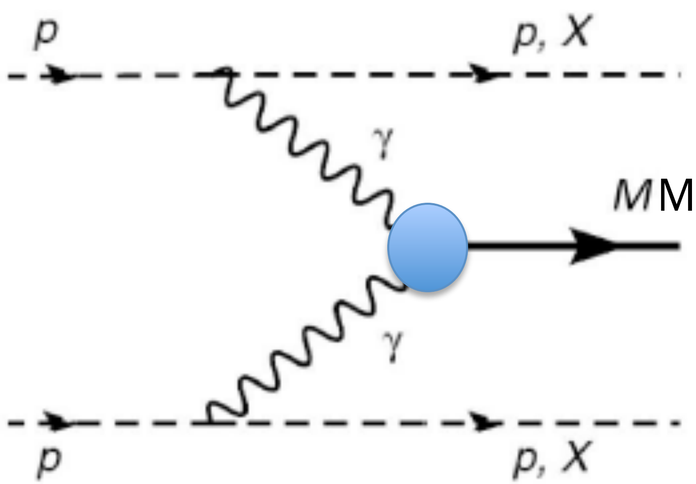


Binding energy fixed BE = 2m/15 , e.g.
for m=750 GeV, binding energy = 100 GeV
→ monopolium mass M= 1400 geV

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

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

V. Vento

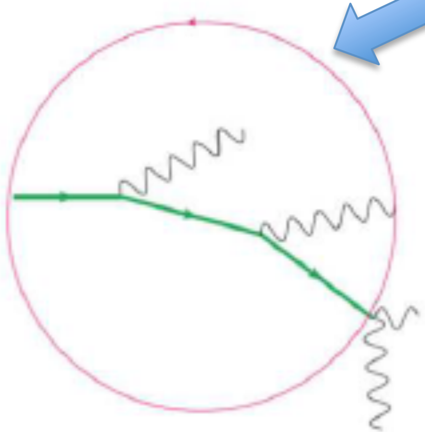
in MOeDAL Physics Review

arXiv:1405.7662

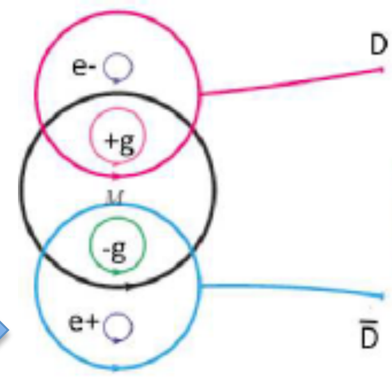
Relevance to LHC & MoEDAL Expts

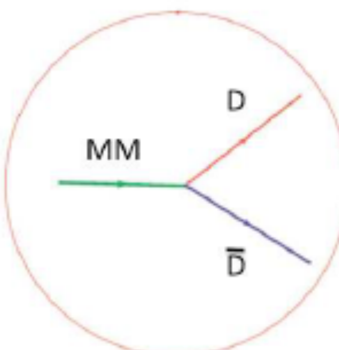
Monopolium is neutral in its ground state & thus if produced in such a state is difficult, probably impossible, to detect in LHC (ATLAS, CMS) or MoeDAL (since damage to plastics from SM background could be higher)

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

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

Monopoles & Diphoton events

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

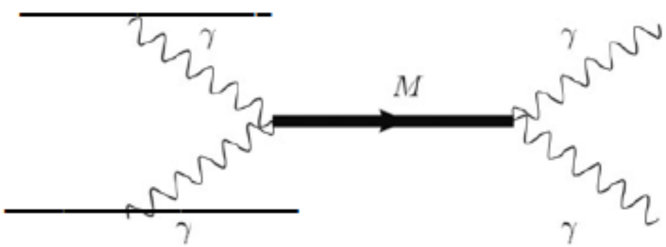


Fig. 10. Diagrammatic description of the monopolium production and decay.

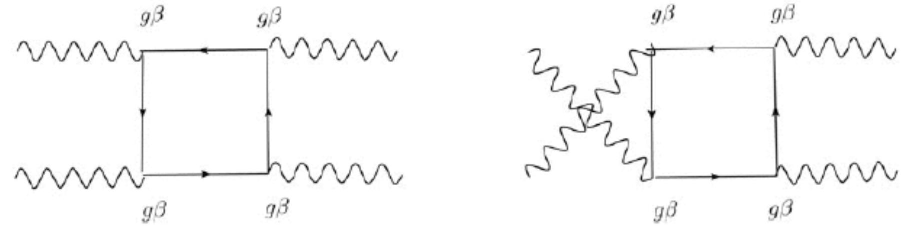
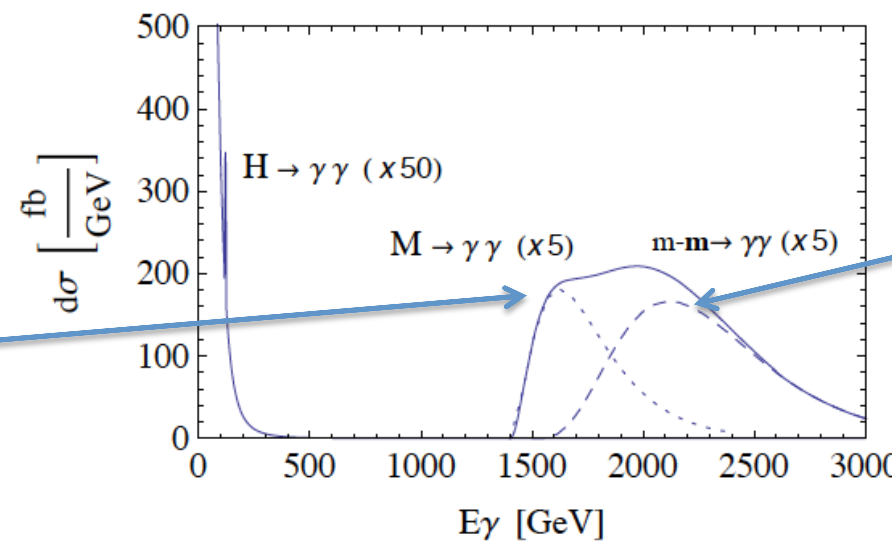


Fig. 4. Elementary processes for monopole-antimonopole production and annihilation into photons.

characteristic signal of monopolium production

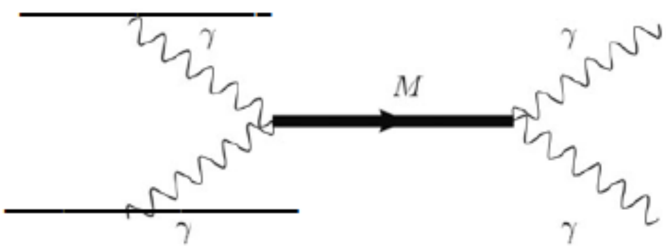


monopole-antimonopole annihilation

NB: ordinary monopoles: Dirac coupling **too large** to reproduce the 750 γγ res, with Γ_{tot} = 45 GeV,

Monopoles & Diphoton events

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



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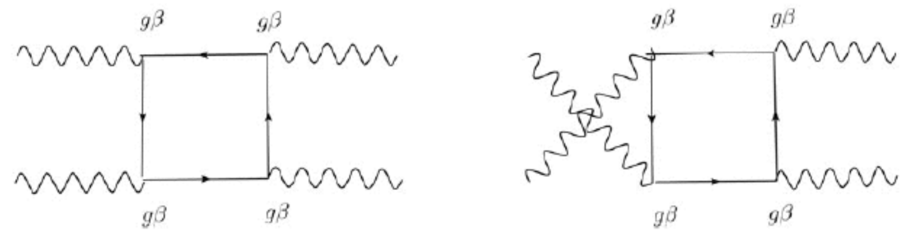

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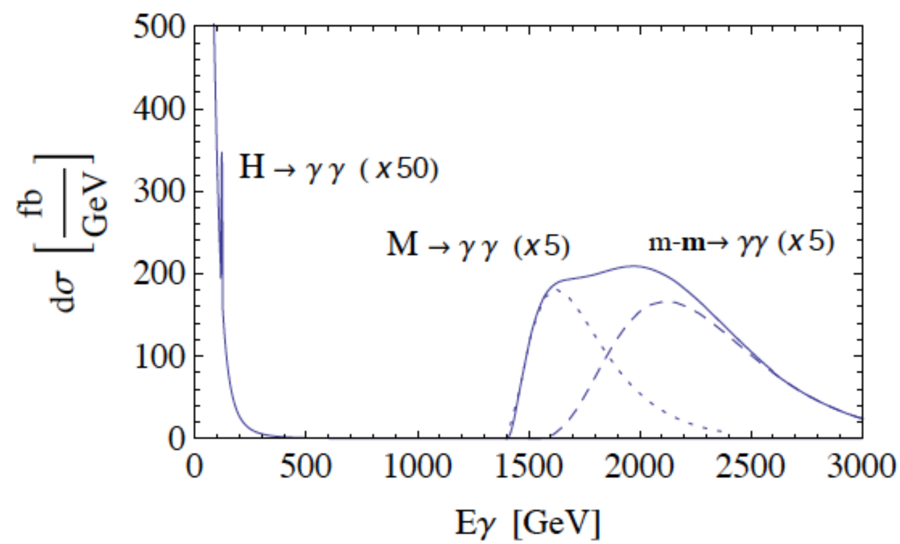


NB: ordinary monopoles: Dirac coupling **too large** to reproduce the 7**X**0 γγ res, with Γ_{tot} = 45 GeV,

ATLAS-LHC Search @ 8 TeV *pp* collisions

$\int L = 7.0\ fb^{-1}$

Atlas Coll.Phys.Rev. D93 (2016) no.5, 052009

Search for magnetic monopoles as highly ionizing particles (HIP):
particle produces high ionization region in Transition Radiation Tracker (TRT), slows down and stops in e/m calorimeter

Negligible bremsstrahlung for HIP → narrower energy deposit in e/m calorimeter than electrons, protons which induce e/m shower

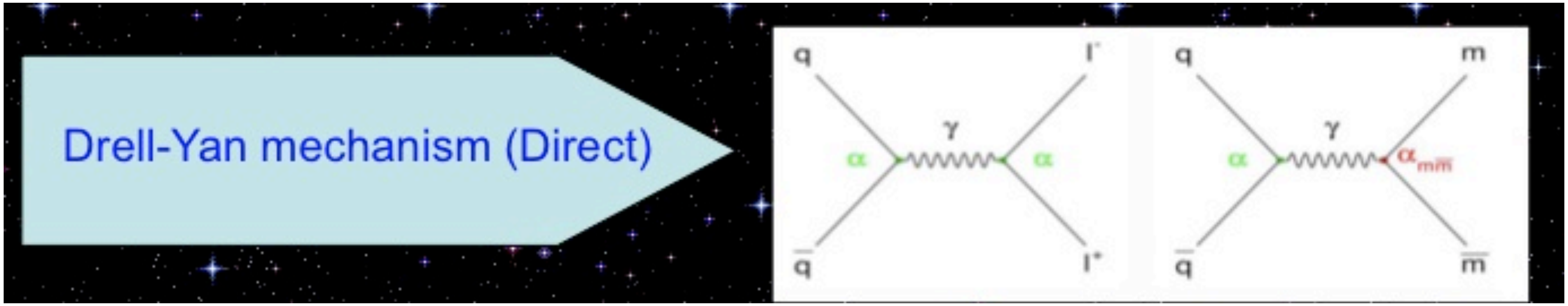
No events found in the signal region → **exclude**
masses **200 GeV ≤ m ≤ 2 500 GeV** for magnetic charge **$0.5g_D < |g| < 2.0g_D$**

$$\frac{g_D}{e} = \frac{1}{2\alpha_e} \approx 68.5$$

Interpretation of Results-Monopole Simulations

Atlas Coll.Phys.Rev. D93 (2016) no.5, 052009

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 GENERATOR for spin ½, and spin 0 monopoles



Interpretation of Results-Monopole Simulations

Atlas Coll.Phys.Rev. D93 (2016) no.5, 052009

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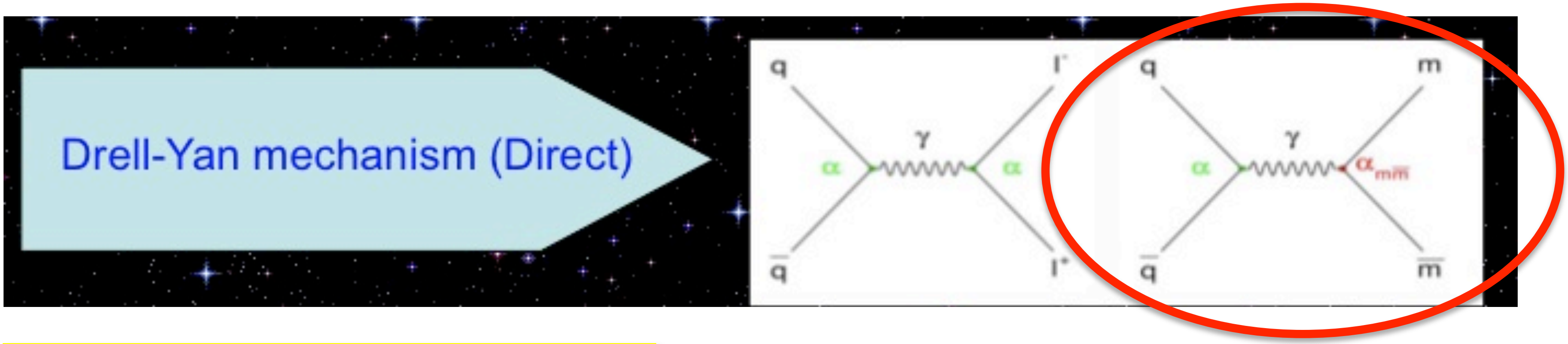
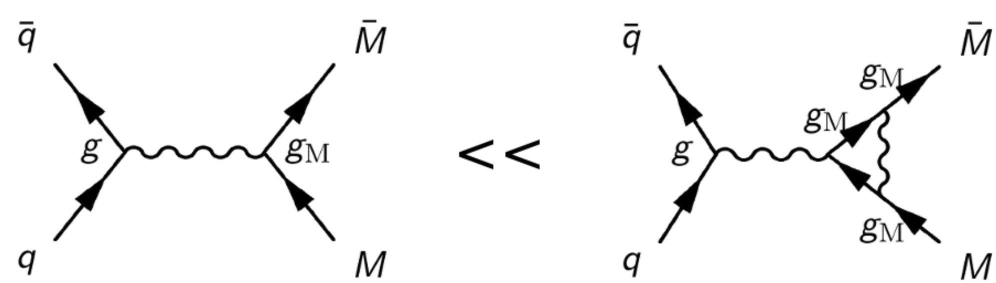
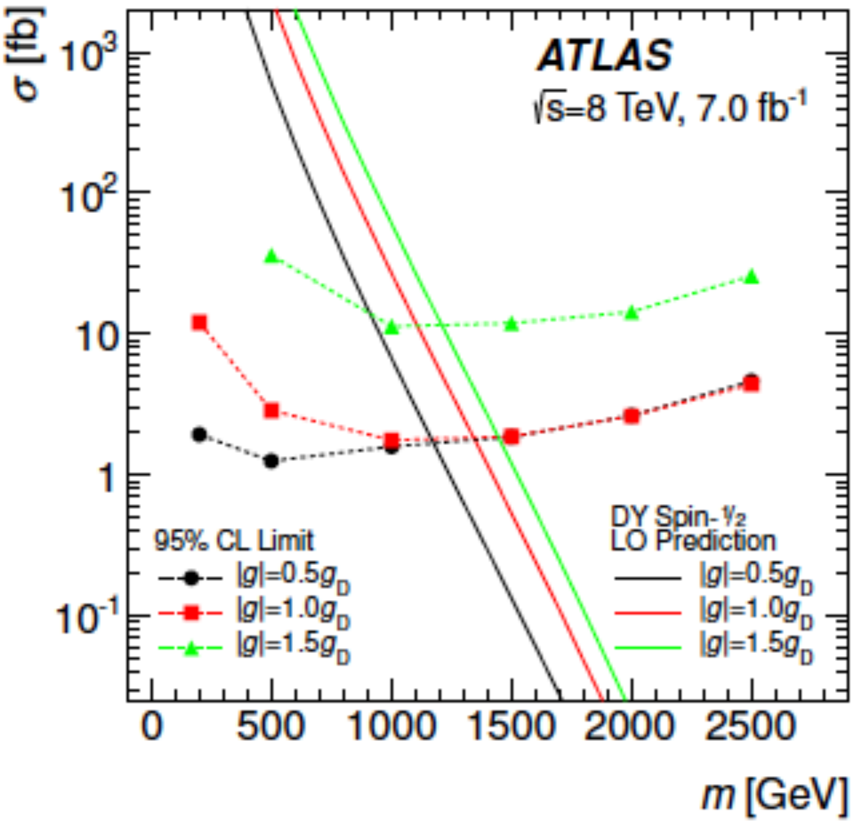
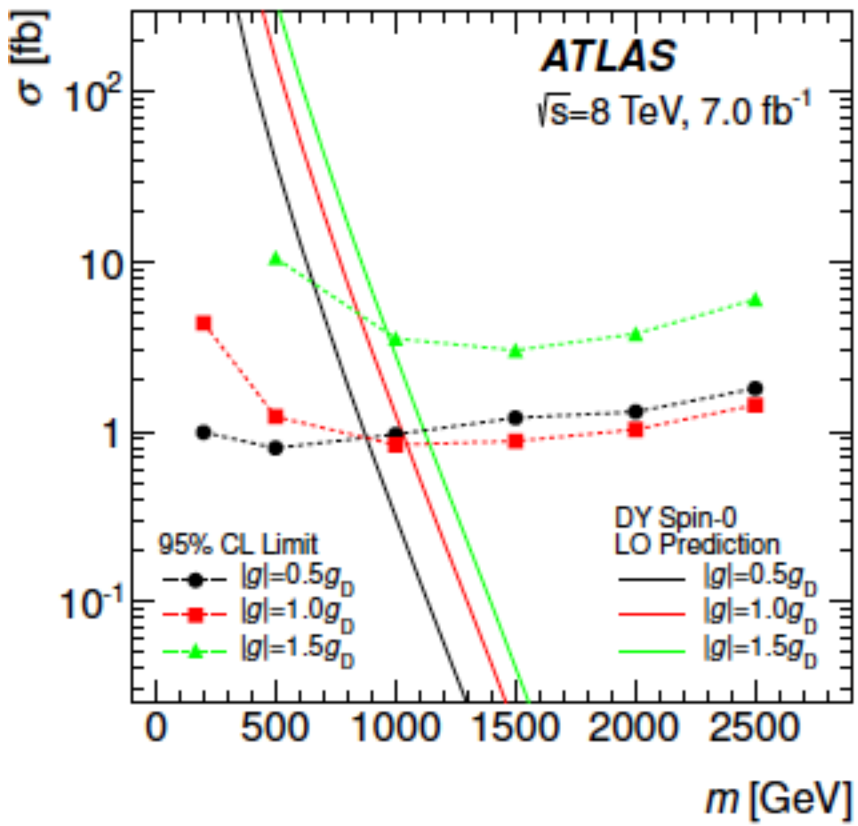


NB: DY processes not reliable perturbatively





spin 1/2



spin 0

	Drell-Yan Lower Mass Limits [GeV]						
	$\lvert g\rvert = 0.5g_D$	$\lvert g\rvert = 1.0g_D$	$\lvert g\rvert = 1.5g_D$	$\lvert z\rvert = 10$	$\lvert z\rvert = 20$	$\lvert z\rvert = 40$	$\lvert z\rvert = 60$
spin-1/2	1180	1340	1210	780	1050	1160	1070
spin-0	890	1050	970	490	780	920	880

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

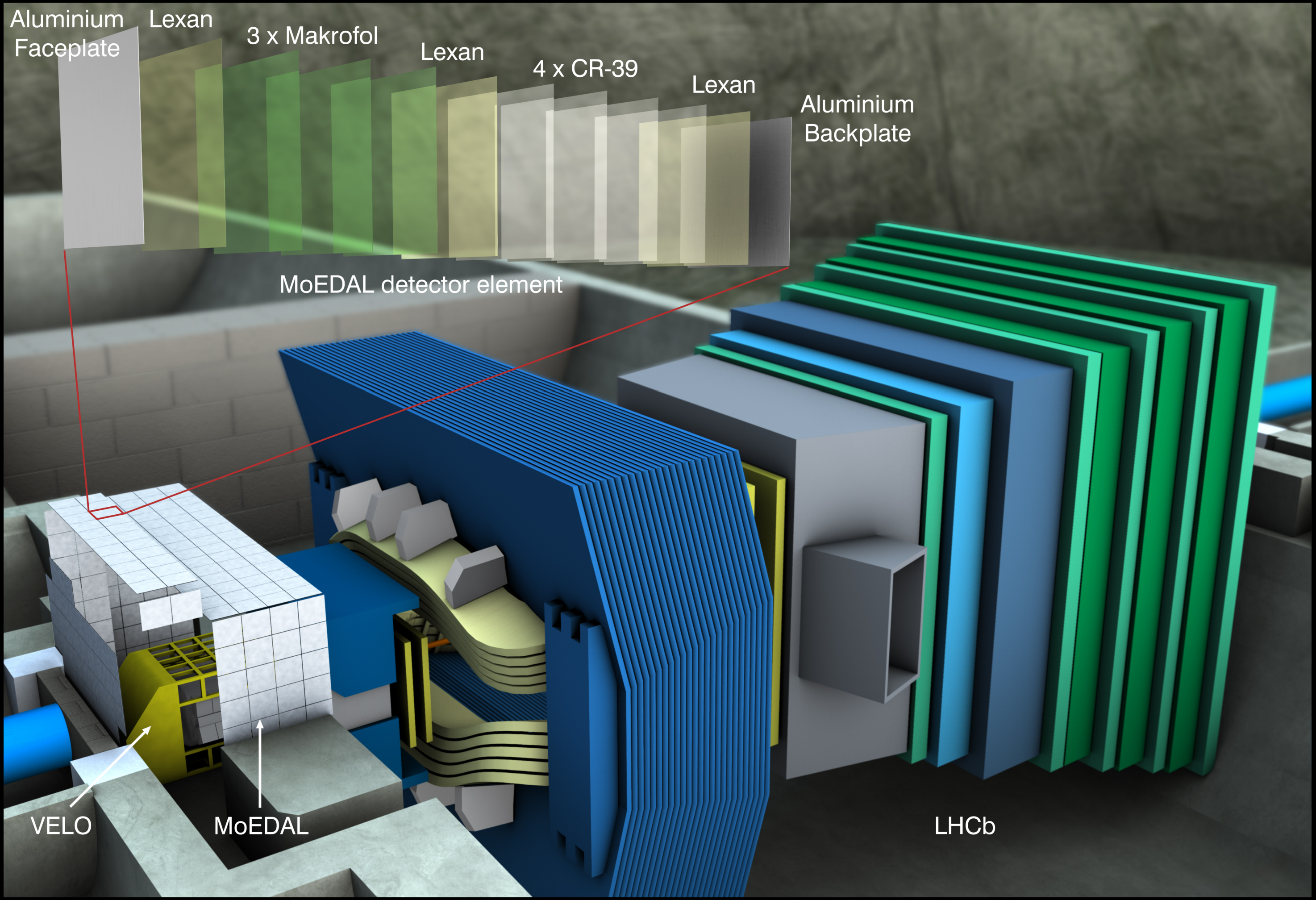
MoEDAL

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

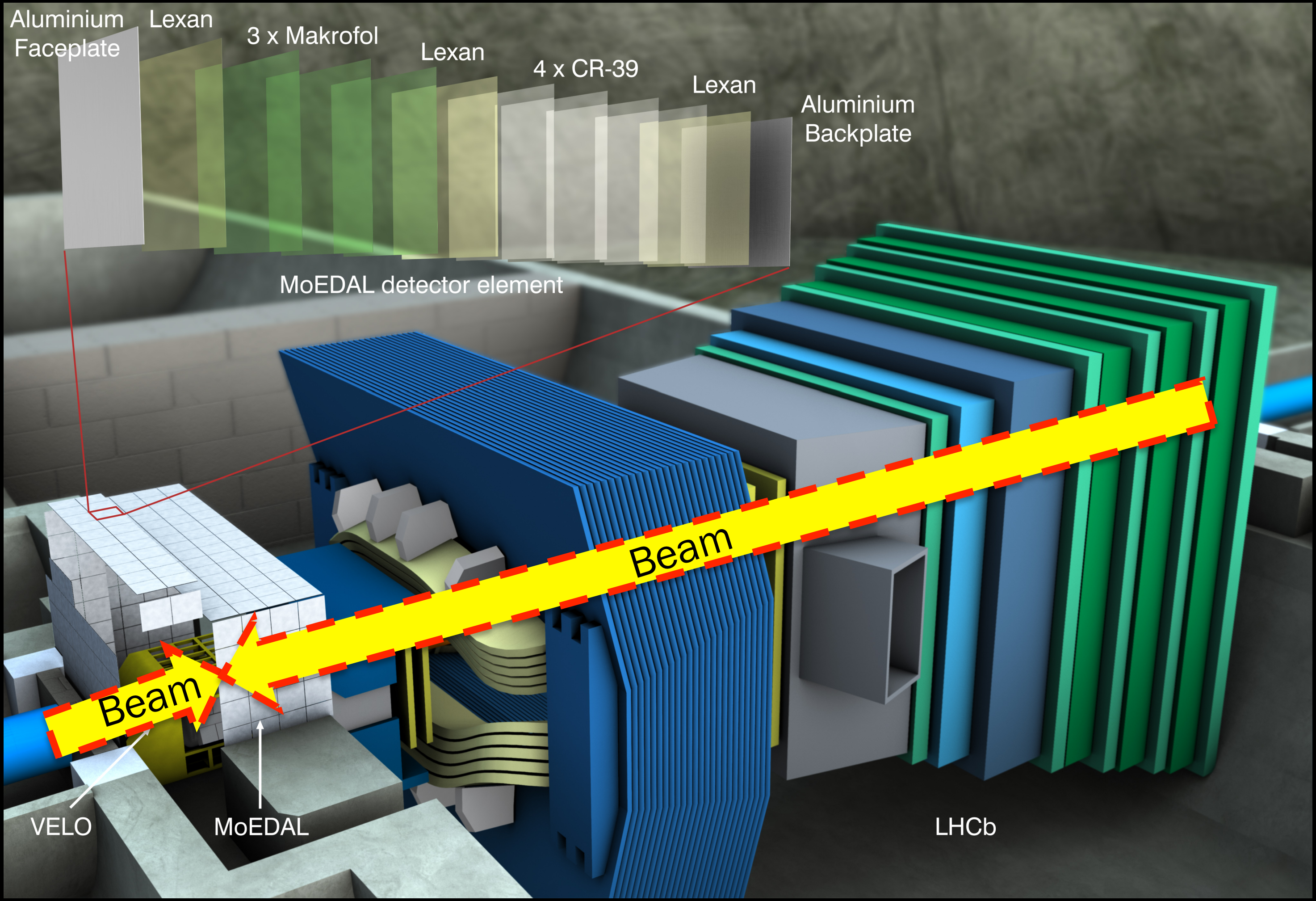
CERN

The MoEDAL Experiment Revealed

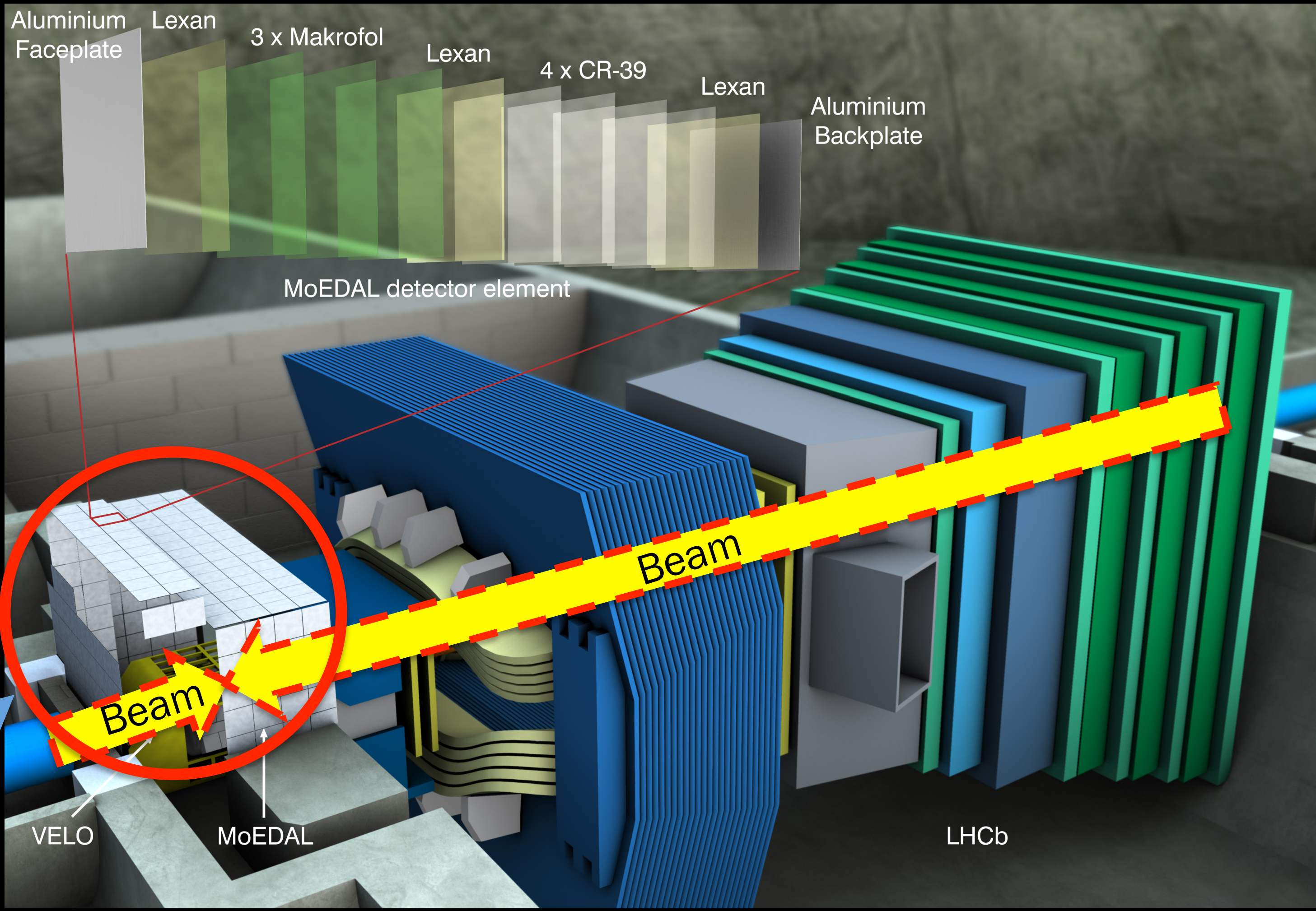


J PINFOLD

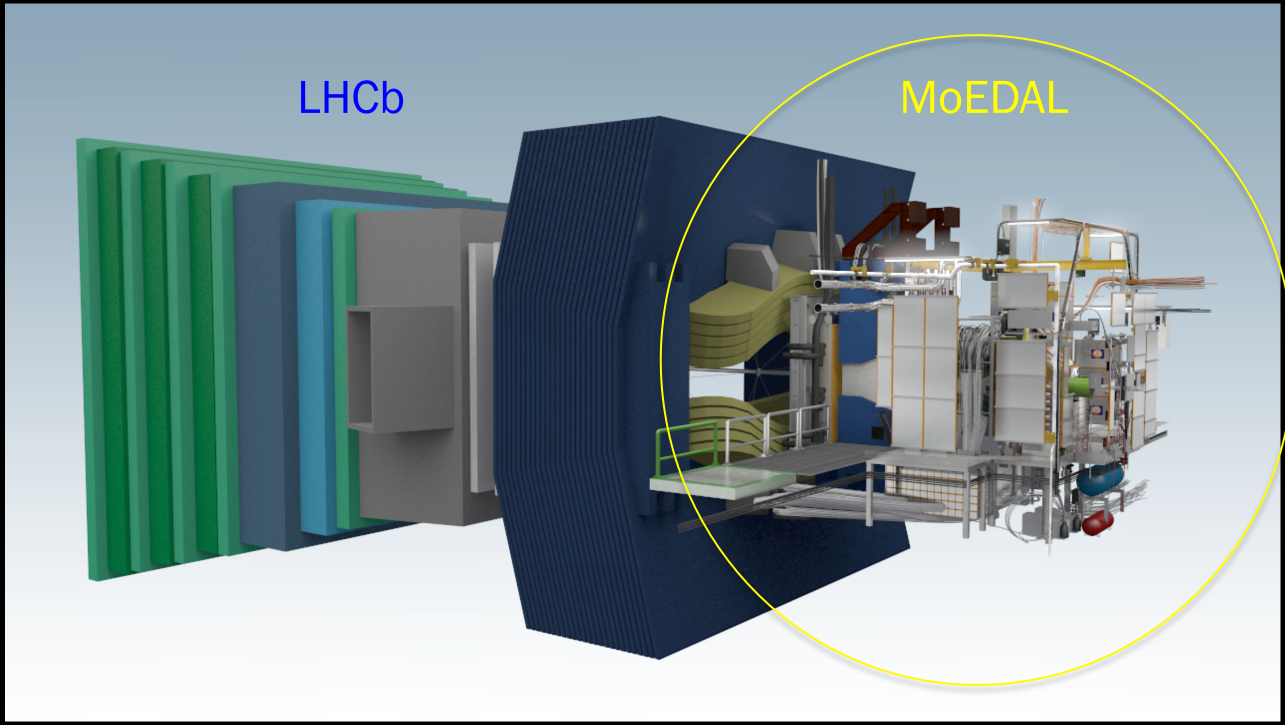
The MoEDAL Experiment Revealed



The MoEDAL Experiment Revealed



The MoEDAL Detector – a Tour



DETECTOR SYSTEMS

1)The TDR NTD array (Z/β > ~5)

2)The Very High Charge Catcher NTD array (Z/β > ~50)

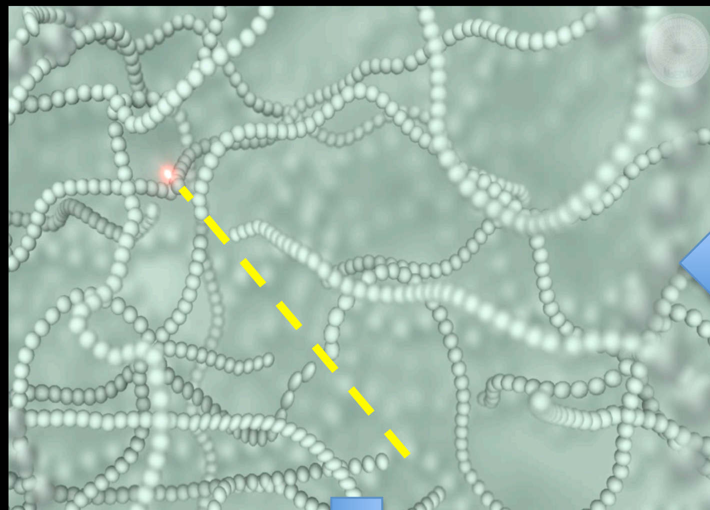
3)The Monopole Trapping detector

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*

The MoEDAL Detector – a Tour

The highly ionizing particle leaves a cylindrical trail of damage in the plastic NTDs



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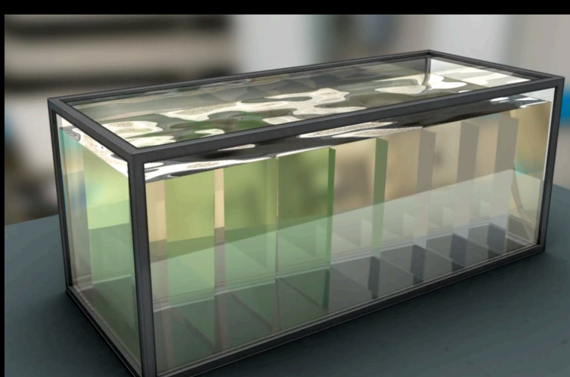
ETCHING PROCESS:



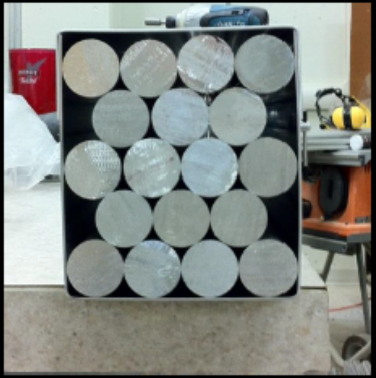
Tracks are revealed as conical etch pits . Charge resolution ~0.05e . Spatial resolution ~ 10 microns/pit – pointing to the IP

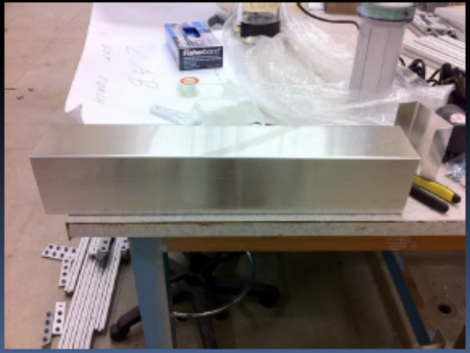
J PINFOLD

The MoEDAL Detector – a Tour

Prototype - MMT

- The Magnetic Monopole Trapper consists of a mass of aluminum
- Prototype consisted of 1" diameter aluminum rods located in front of the VELO below the beampipe





Aluminium good trapping material with its large magnetic moment

R. Soluk --- University of Alberta --- MoEDAL Collaboration Meeting --- CERN June 18-19

DETECTOR SYSTEMS

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4)The TimePix radiation background monitor

The Physics Principle of MMTs

- *We deployed (~ 1 ton) 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*
  - *SNOLAB (2km underground) to detect decays of MSPs*

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*

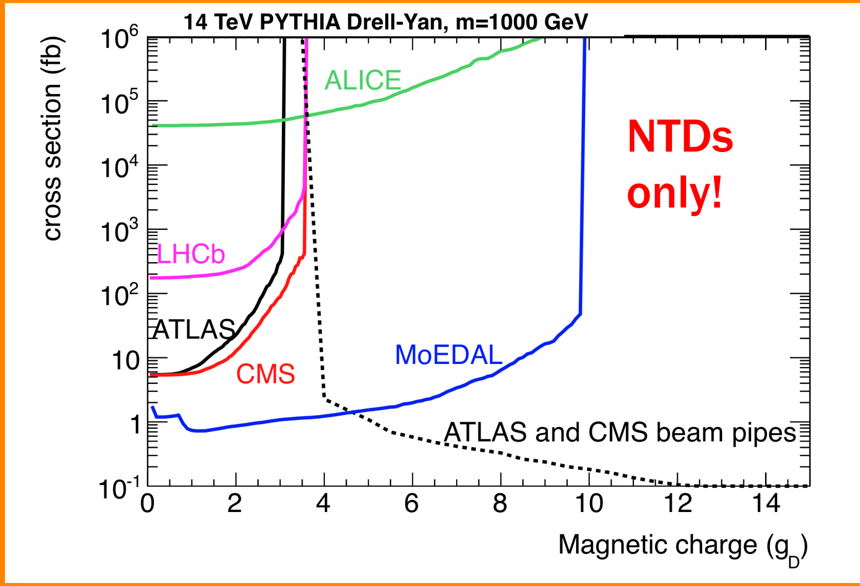
MoEDAL

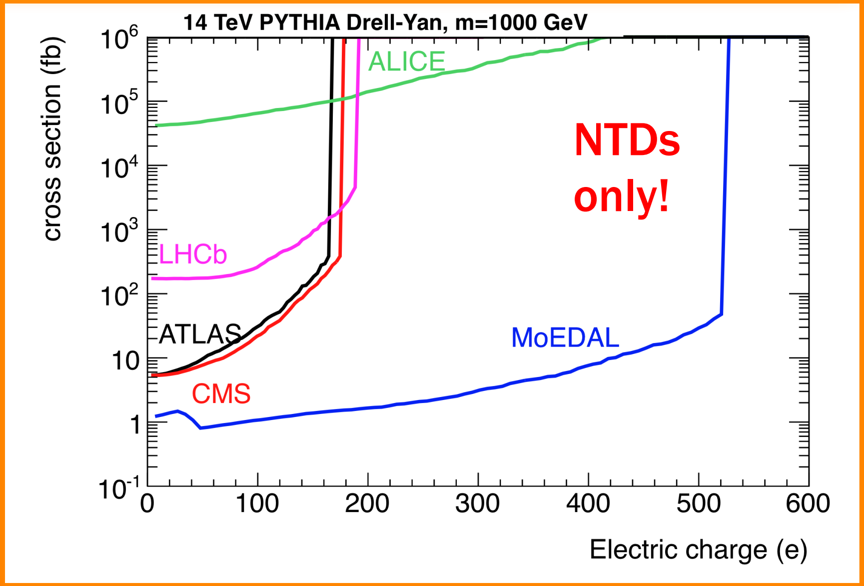
- *MoEDAL is designed to detect charged particles, with effective or actual $Z/\beta > 5$.*
- *As it has no trigger/ electronics slowly moving ($\beta <$ ~5) particles are no problem*
- *One candidate event is enough to establish the signal (no Standard Model backgrounds)*

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 ✔



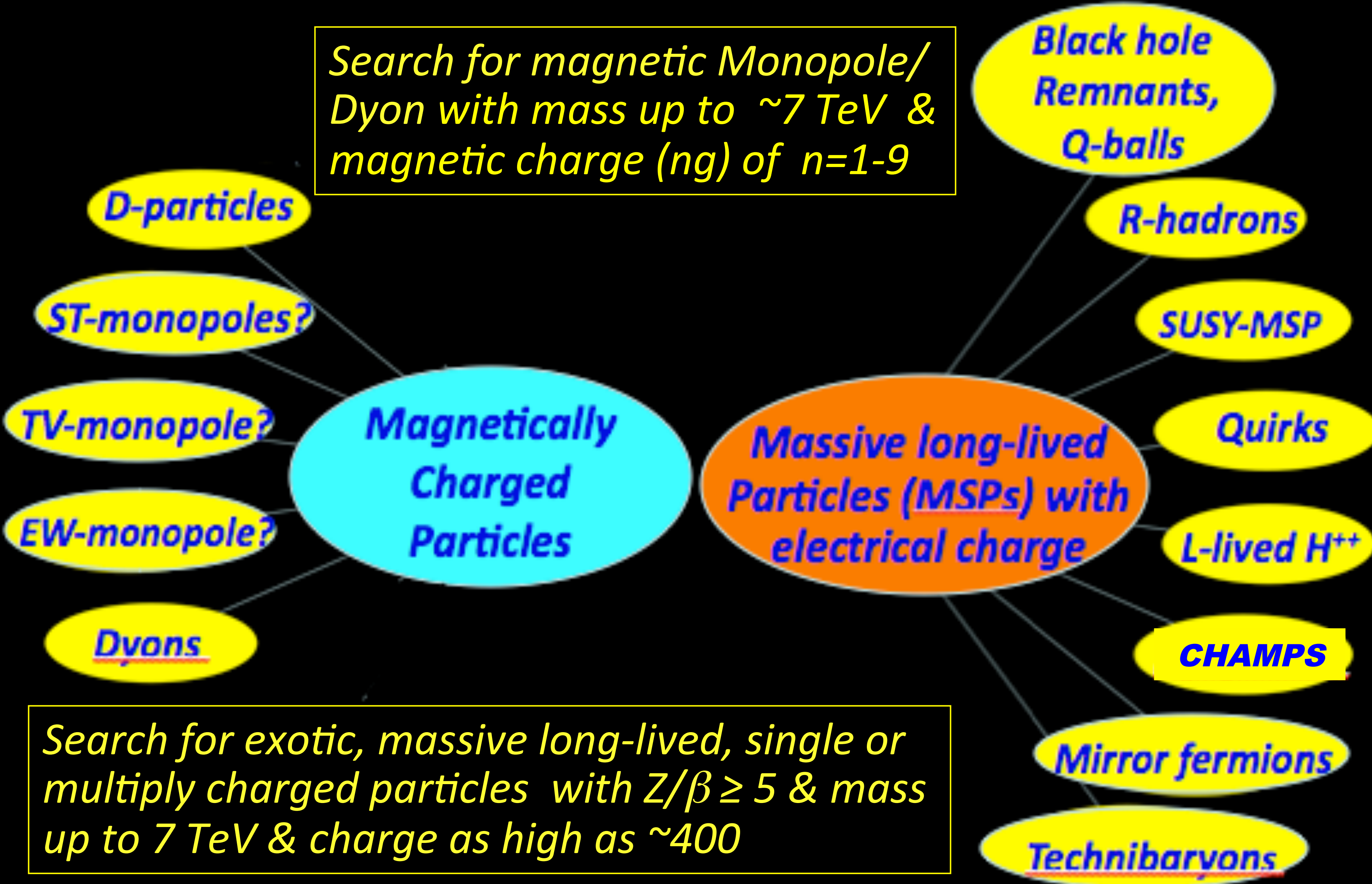


- *Cross-section limits for magnetic (L) and electric charge (R) (from* ***arXiv:1112.2999V2 [hep-ph]****) assuming:*
  - *Only one MoEDAL event is required for discovery and ~100 events in the other (active) LHC detectors*

@ 20 fb^{-1} (assumed)

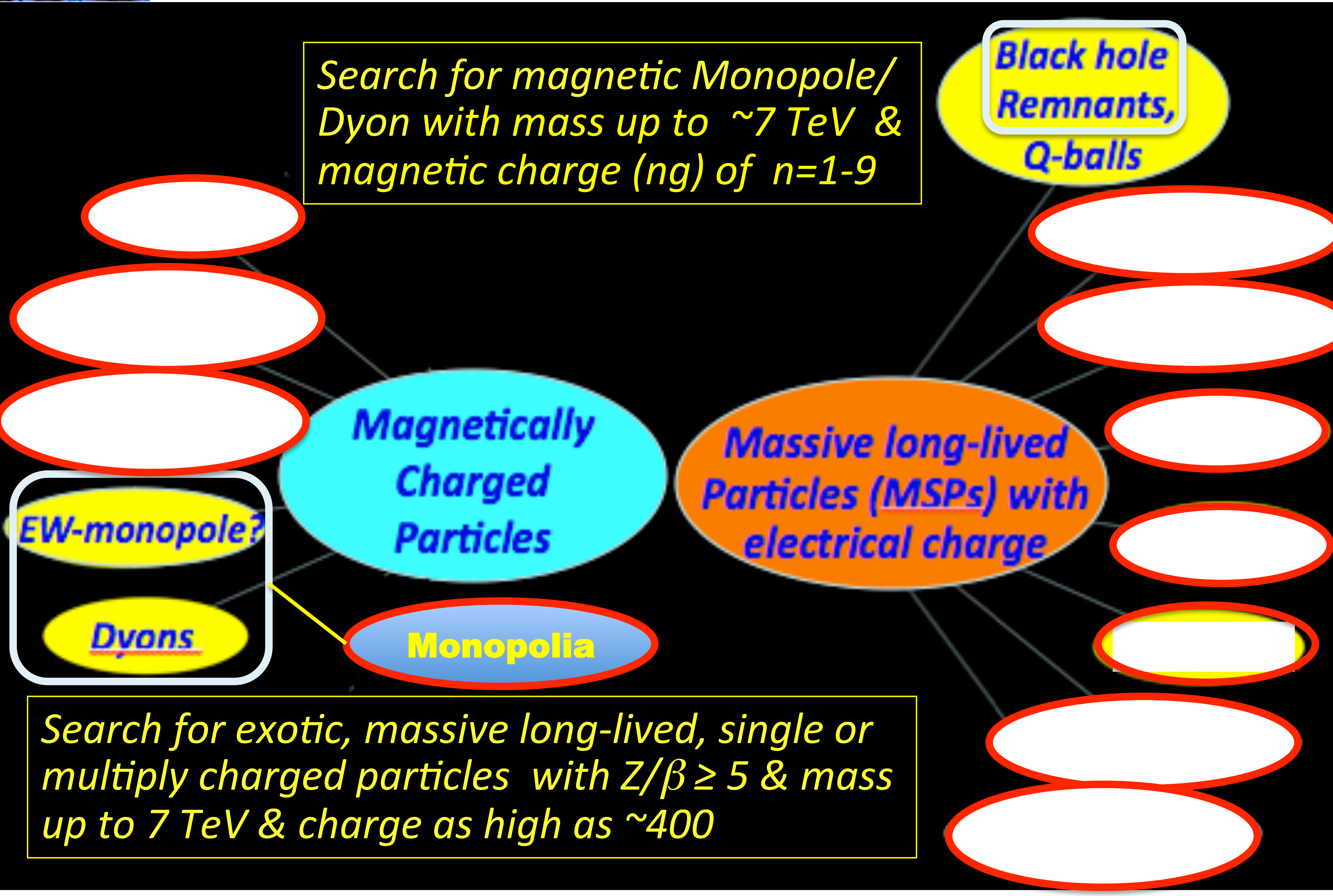
The MoEDAL Physics Program

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

MoEDAL Physics: this talk



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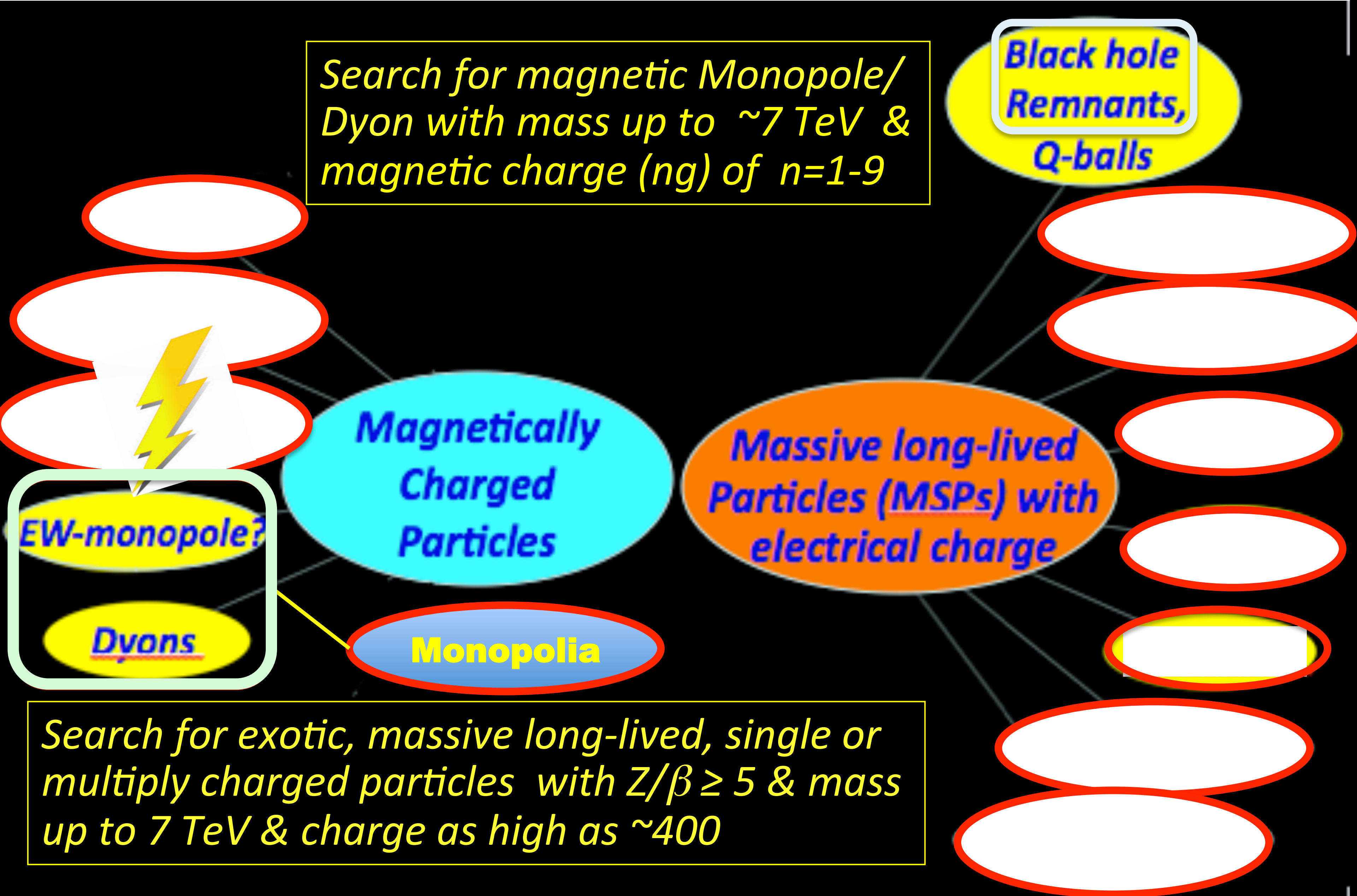


THE PHYSICS of MoEDAL on paper

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

FIRST PAPER ON BOUNDS OF MONOPOLE MASSES FOR THE 2012 LHC RUN @ 8 TeV, in integrated luminosity 0.75 fb^{-1}, arXive:1604.06645 **JHEP 1608 (2016) 067**

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

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

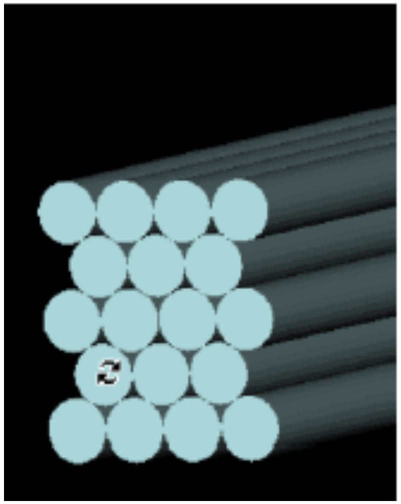
Stay tuned for 13 TeV run data bounds

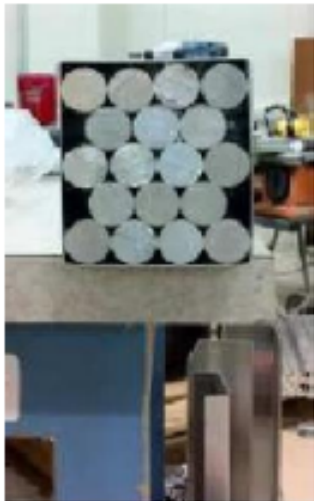
First MoEDAL Monopole Searches in 2012 @ 8 TeV LHC Energies, and $\int L = 0.75\ fb^{-1}$

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

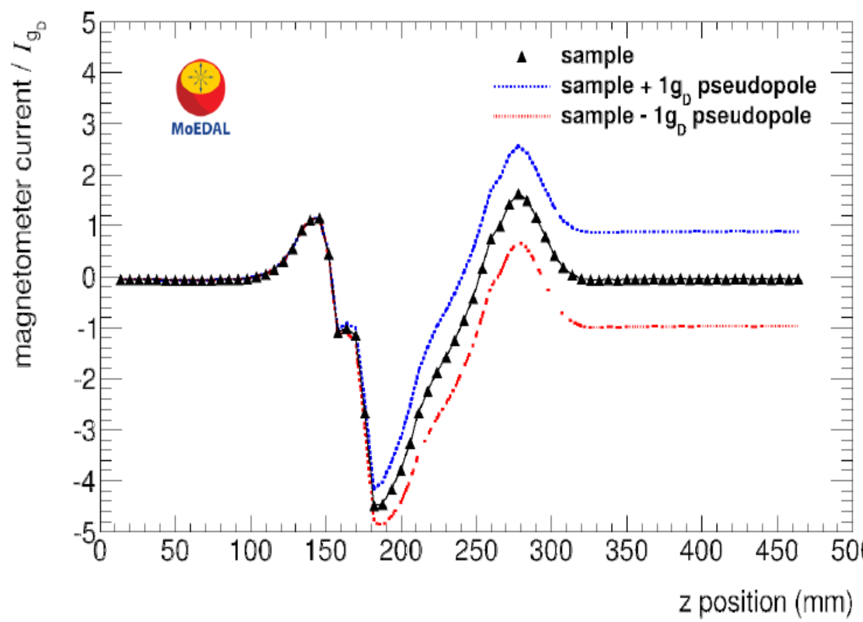
Test Monopole Trapping Detector (MTD)

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.



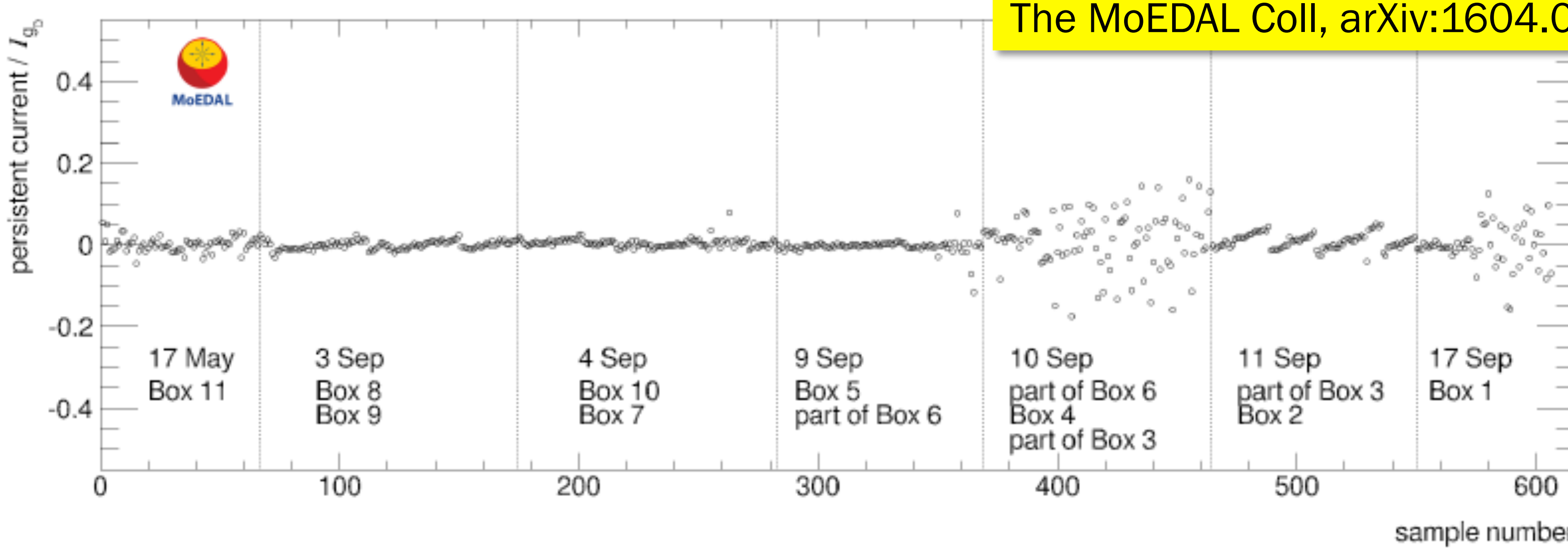
Magnetometer response profile for a typical aluminium sample of the MTD

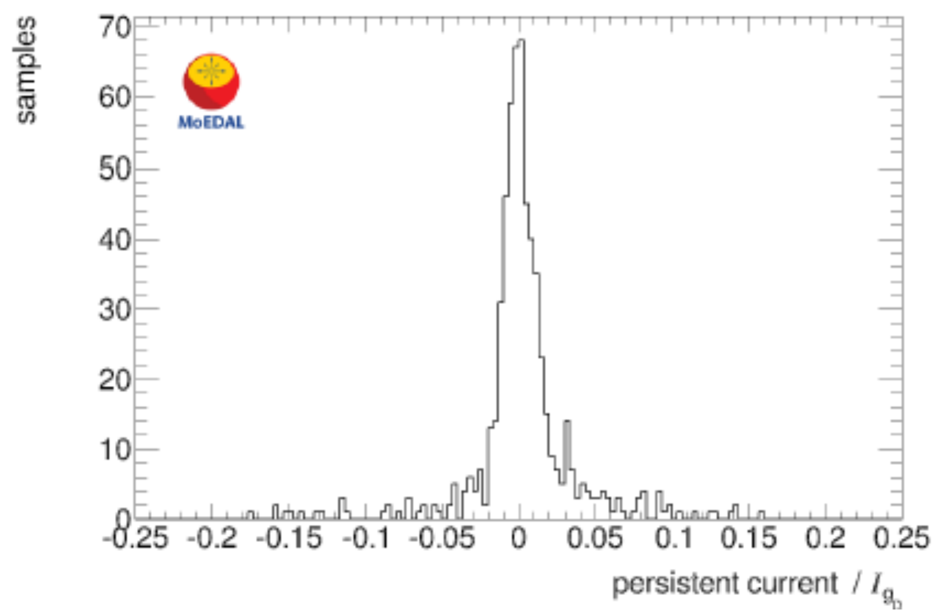
The physics principle of Monopole Detection: if monopole is present in MTD then **persistent current** exist: difference (jump) in current before and after passage of the sample through sensing coil

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

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

The MoEDAL Coll, arXiv:1604.06645





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

The MoEDAL Coll, arXiv:1604.06645

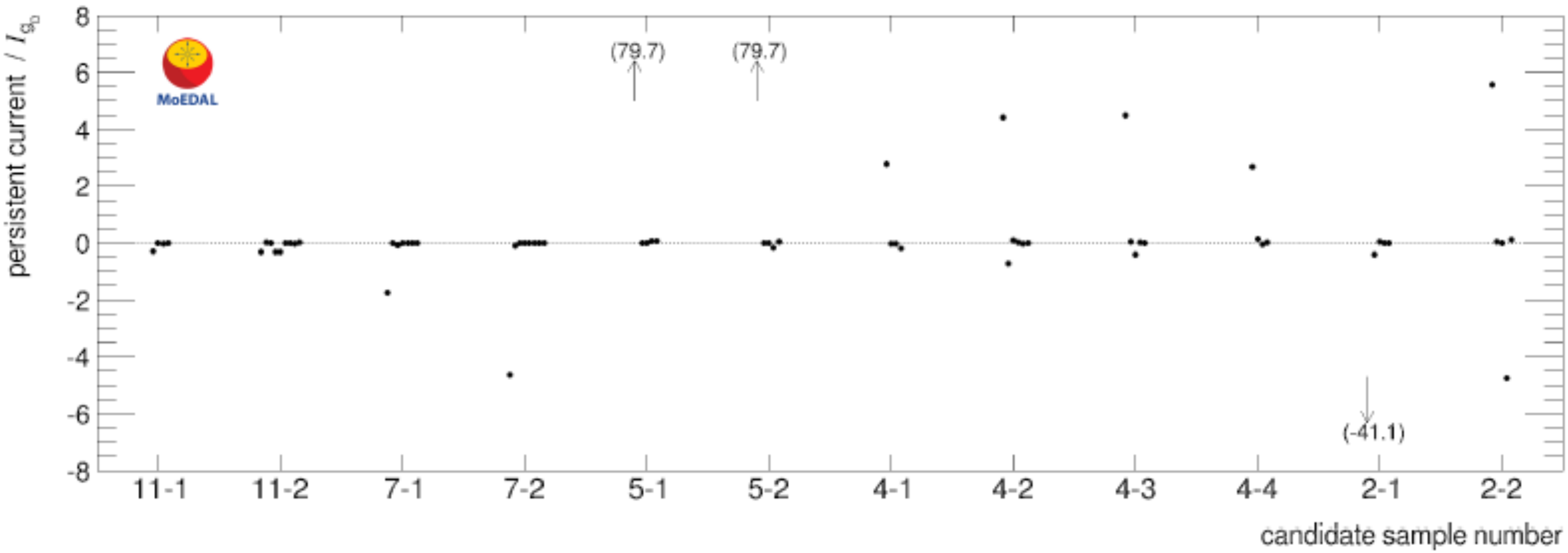


Figure 3. Results of multiple persistent current measurements (in units of the Dirac charge) for the 12 samples which yielded large ($|g| > 0.25\ g_D$) values for the first measurement. Repeated measured values consistent with zero magnetic charge show that the first measurement was affected by a spurious jump. The arrows indicate values which lie off the scale of the plot.

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

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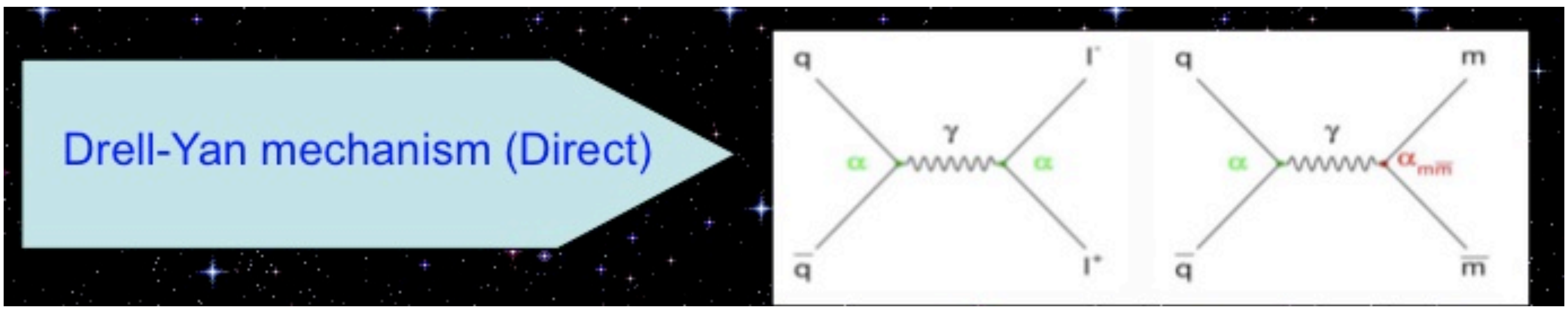

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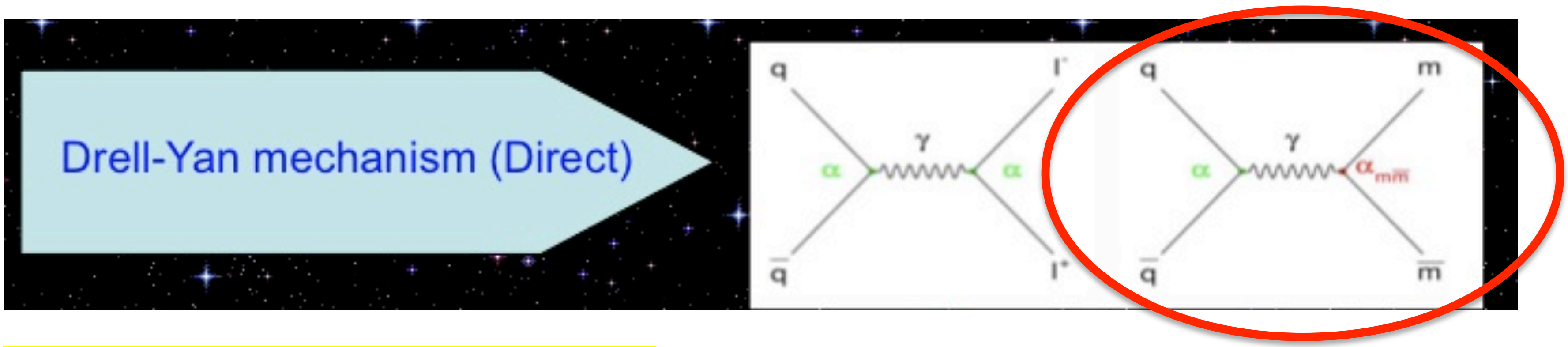
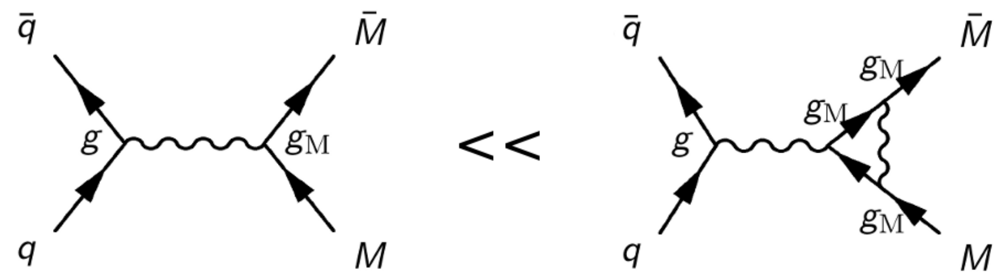
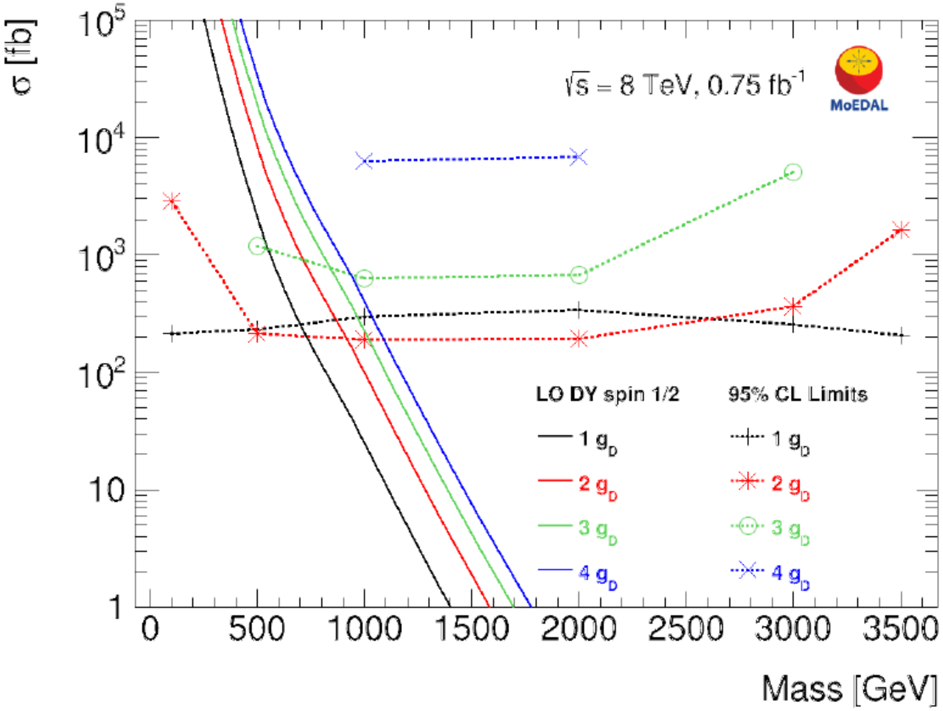


NB: DY processes not reliable perturbatively

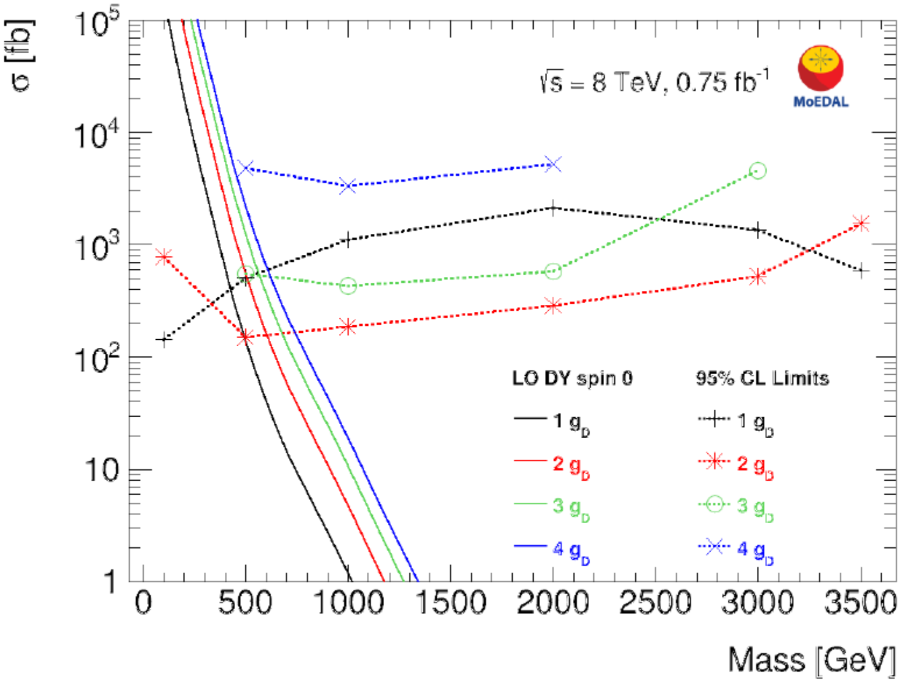


MoEDAL Limits on Monopole Production

The MoEDAL Coll, arXiv:1604.06645



spin ½

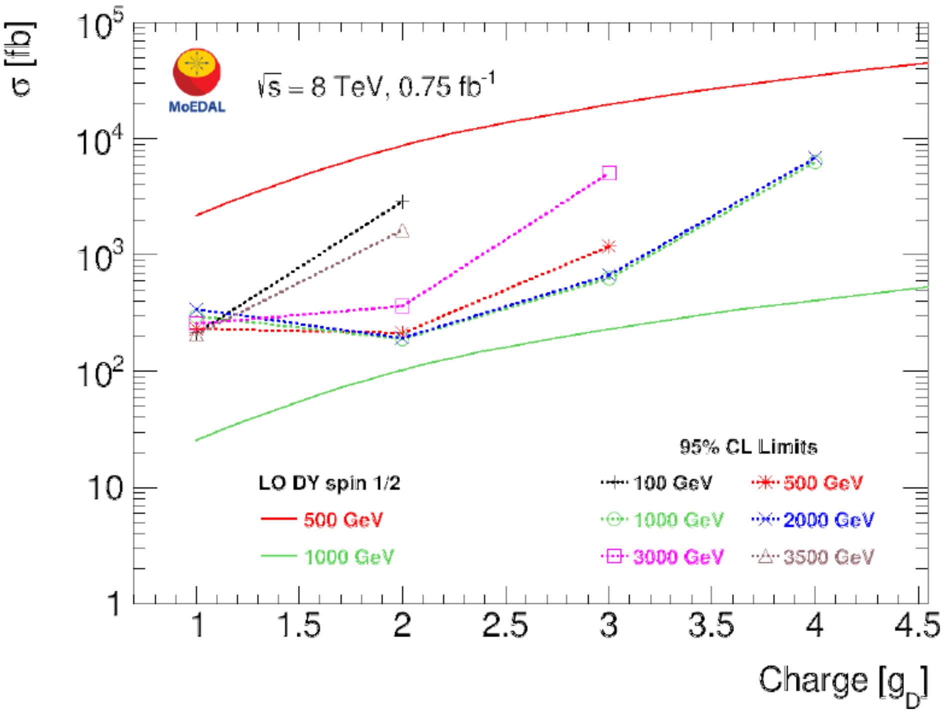


spin 0

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

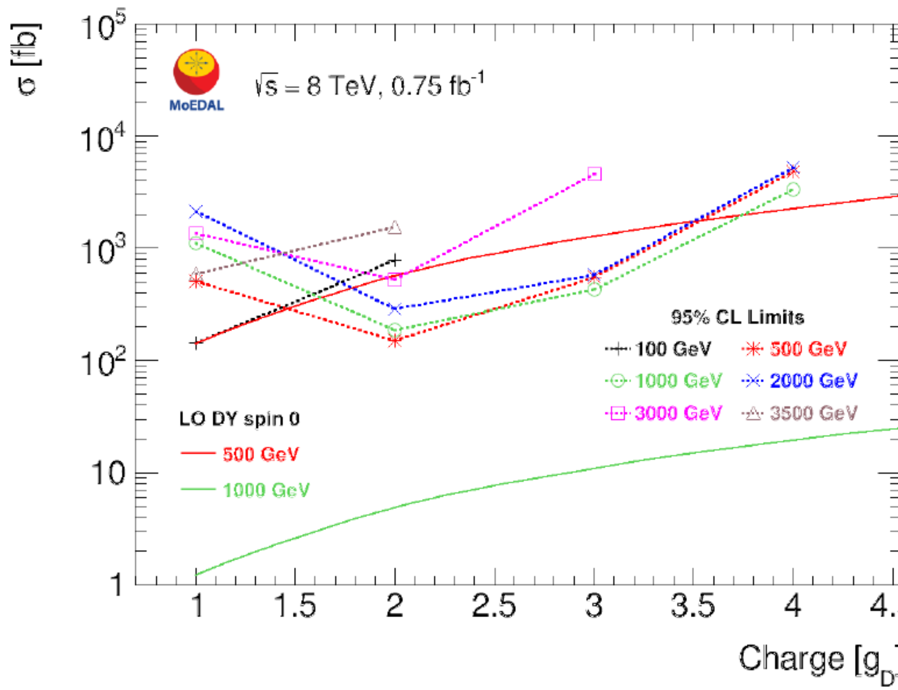
MoEDAL Limits on Monopole Production

The MoEDAL Coll, arXiv:1604.06645



spin ½

spin 0



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 , $\int L = 0.75\ \text{fb}^{-1}$

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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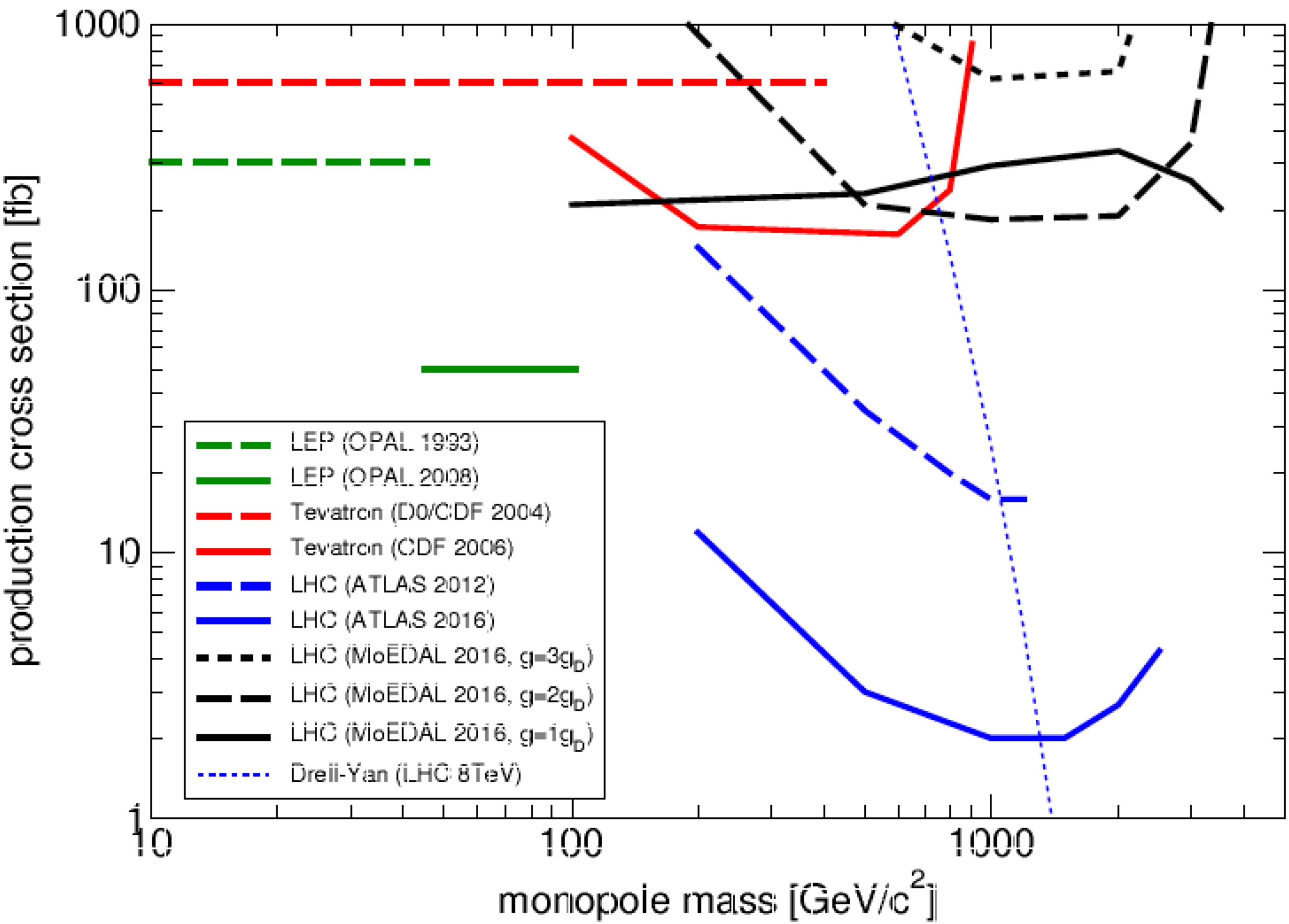
For the first time @ LHC , surpass previous collider results

MoEDAL

Summary for Production Cross sections @ Colliders

A. Rajantie
Phys. Today



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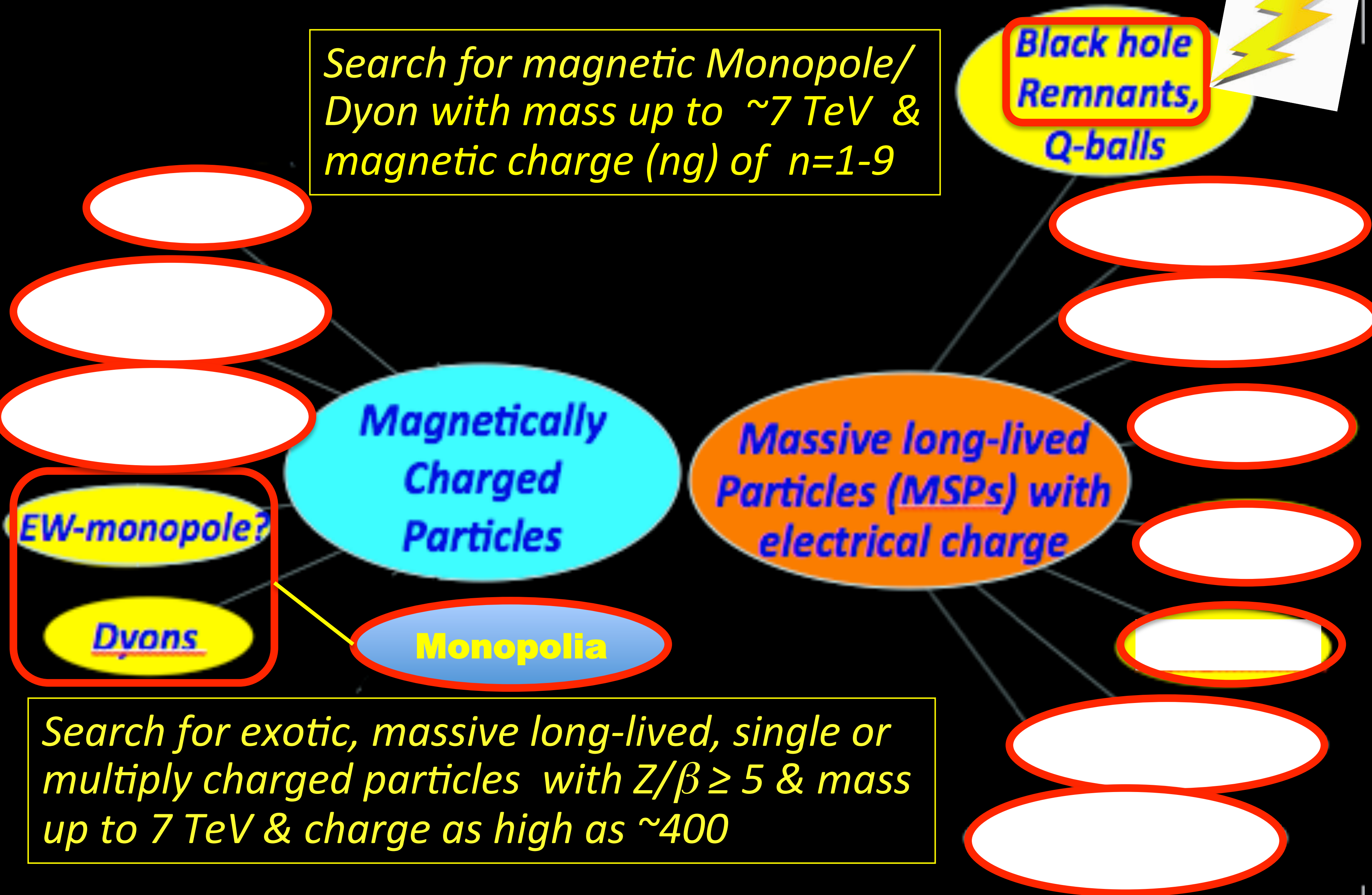
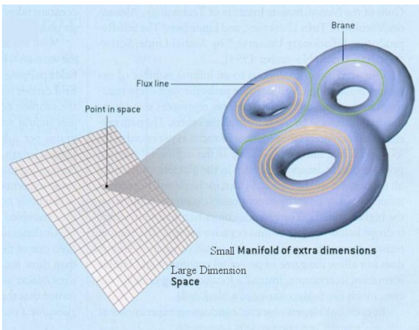


Search for exotic, massive long-lived, single or multiply charged particles with $Z/\beta \geq 5$ & mass up to 7 TeV & charge as high as ~400

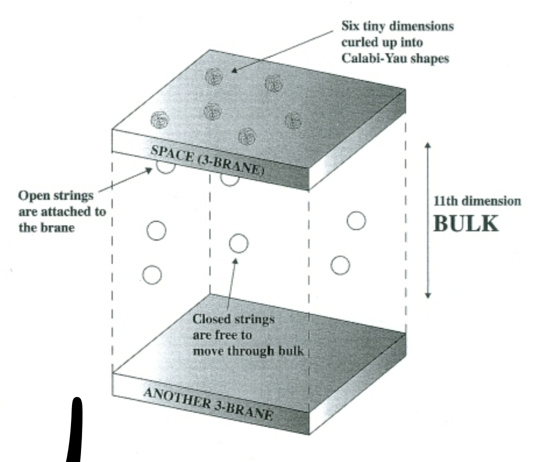
Black-Hole Remnants in Large extra dimensions

Large Extra dimension models motivated by string theory

Arkani-Hamed Dimopoulos, Dvali (string models)



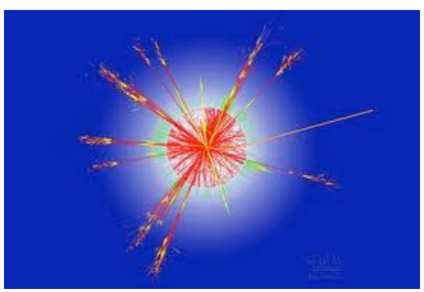
Randall Sundrum (brane models)



gravitons propagate in bulk as well as brane

Both relevant for providing resolution of the hierarchy problem in field theory

Stringy effects @ low scales (TeV) possible



Dimopoulos, Landsberg

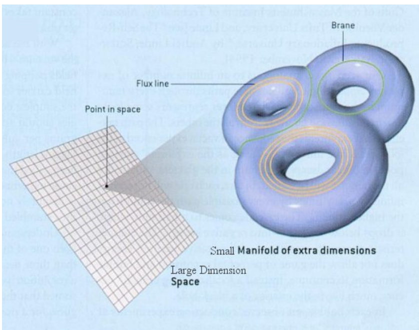
Formation of TeV Black Holes (BH) by high energy SM particle Collisions

BH produced in proton-proton collisions can carry **electric charge**

Charged BH Hawking evaporate but not completely → certain fraction of final BH **remnants** carry charge ($BH^{\pm}$)

Large Extra dimension models motivated by string theory

Arkani-Hamed Dimopoulos, Dvali (string models)



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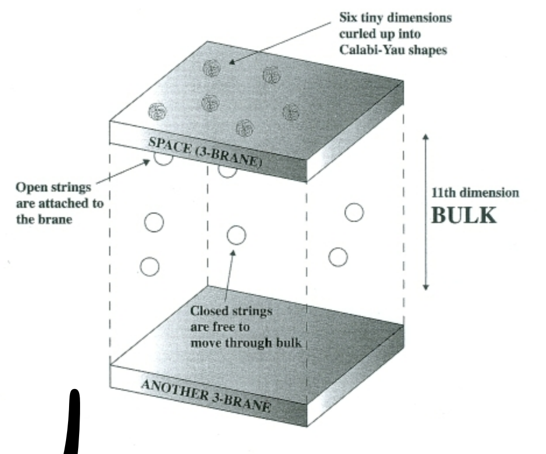

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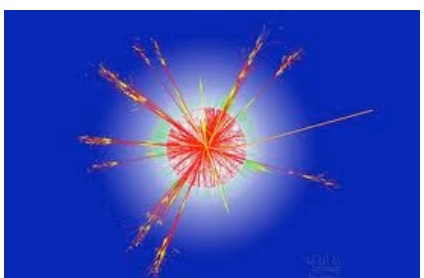

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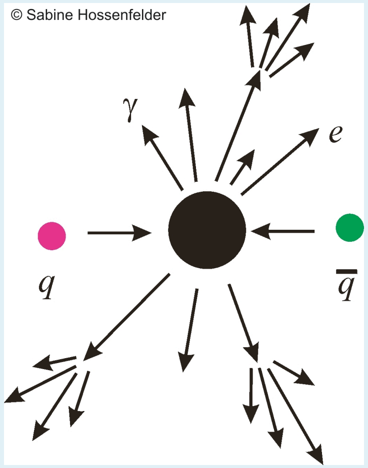
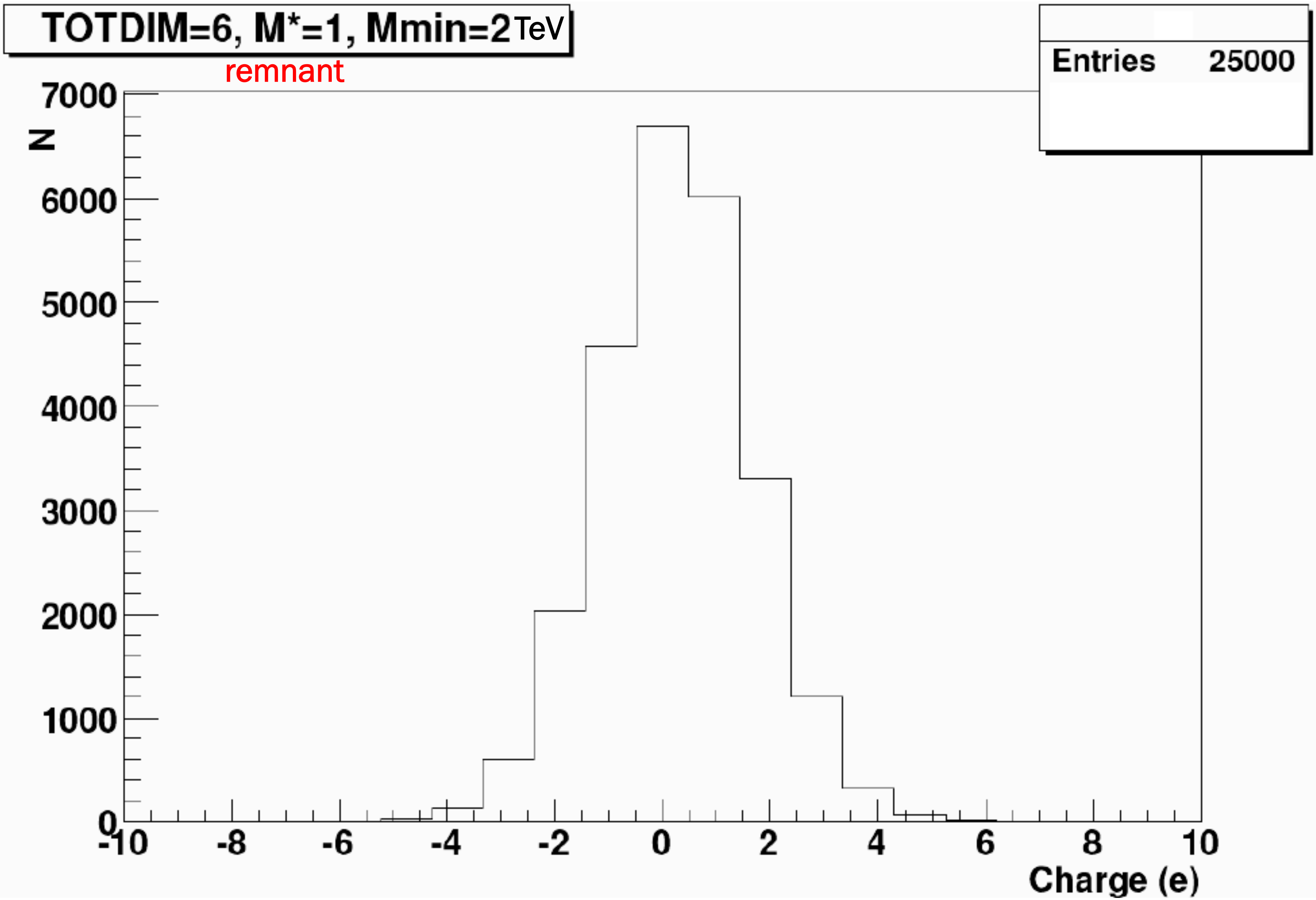
Charged BH Hawking evaporate but not completely → certain fraction of final BH **remnants** carry charge ($BH^{\pm}$)

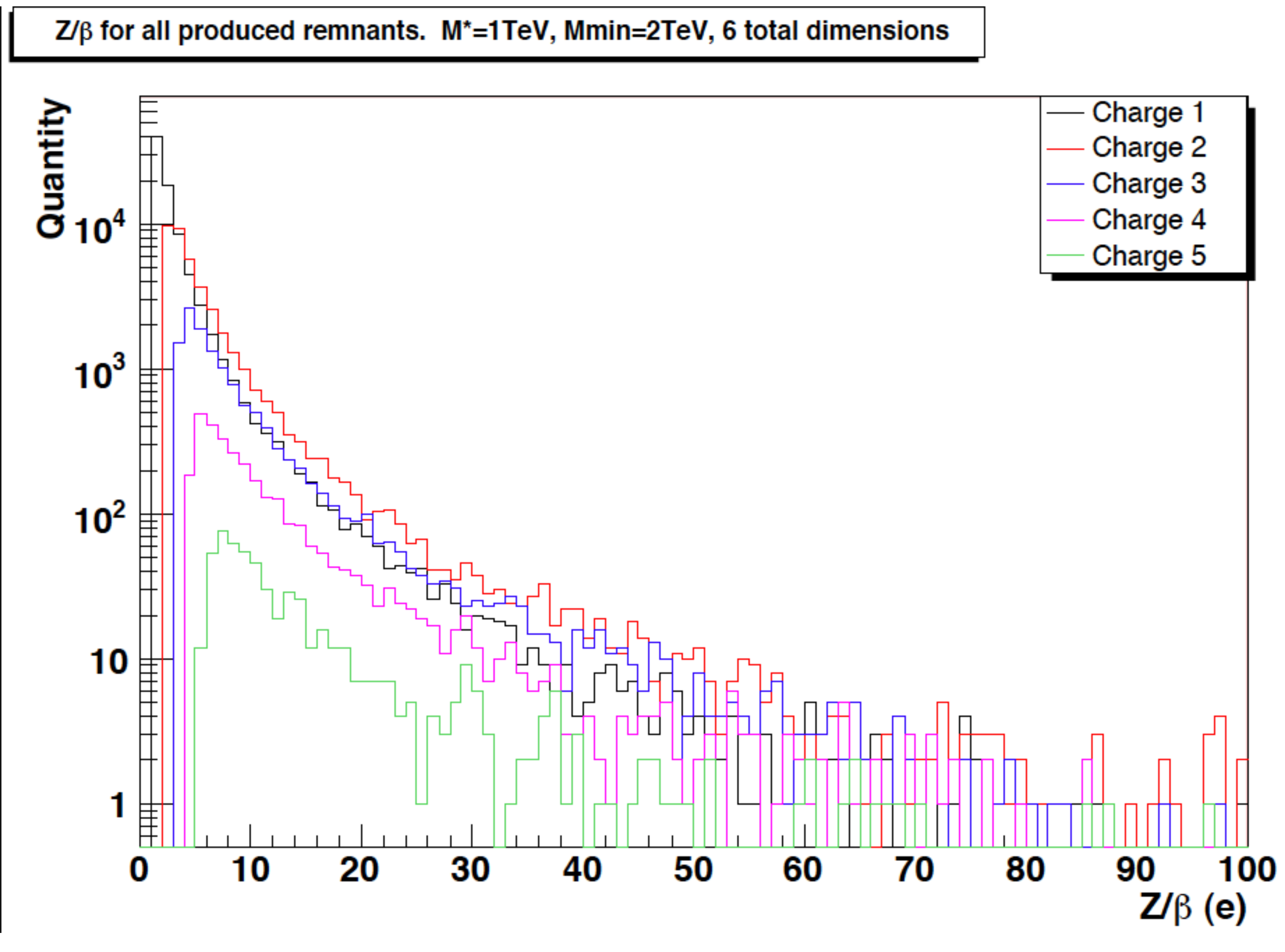
BH formed from proton-proton collisions are formed from interactions of valence quarks (carry largest available momenta of partonic system) → *BH average charge 4/3* → after evaporation to stable remnants, some accumulated net charge



Most of BH remnants carry charge zero or one (in units of electron charge) smaller but non negligible fraction carry multiple charges → **highly ionizing, relevant to MoEDAL**

Estimated number of BH remnants vs charge using PYTHIA event generator & CHARIBDIS program for BH decay


TOTDIM=6, M*=1, Mmin=2TeV
remnant
Entries 25000
N
7000
6000
5000
4000
3000
2000
1000
0
-10
-8
-6
-4
-2
0
2
4
6
8
10
Charge (e)


Z/β for all produced remnants. M*=1TeV, Mmin=2TeV, 6 total dimensions
Quantity
10^4
10^3
10^2
10
1
Charge 1
Charge 2
Charge 3
Charge 4
Charge 5
0
10
20
30
40
50
60
70
80
90
100
Z/β (e)

Conclusions - Outlook

- **PROSPECTS LOOK GREAT FOR LHC Expts**

  HIGGS(like) Discovery in 2012, → more measurements to come during > 2015 RUN II may unveil the nature of the Boson & possibly New Physics – **machine operates fine @ 13 TeV collisions**

- **We discussed Black Holes (BH), both astrophysical and mini (in extra dimensional theories) and their searches in space and at colliders.**

  Large Astrophysical BHs: plethora of evidence (including GW) they exist .

  Mini BHs (extra dimensions): producible @ colliders ...no current evidence @ LHC

- **We discussed prospects of Sphaleron-induced processes @ ICE CUBE & LHC: unsuppressed tunneling processes for ≥ 9 TeV (= E_{sph}) total quark collision energies**

- **We discussed TeV-mass scale (``electroweak" and other types) monopoles and their current searches @ LHC, in particular MoEDAL** *

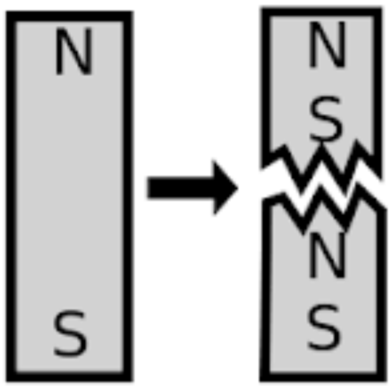
- **FUTURE LOOKS BRIGHT FOR MoEDAL** – ROLE AS A PROBE OF THE TOPOLOGICAL AVATARS BEYOND THE SM ....

  MAY DETECT NOT ONLY MONOPOLES BUT OTHER EXOTICS AS WELL (INCLUDING BRANE/STRING THEORY HIP DEFECTS)

  probably exclusively ...

...Surprises may be around the corner...
EVEN FOR THEORISTS
...Carry on Searching ...

*



Cannot be the property of ordinary matter

If magnetic monopole exists should be a NEW elementary particle !

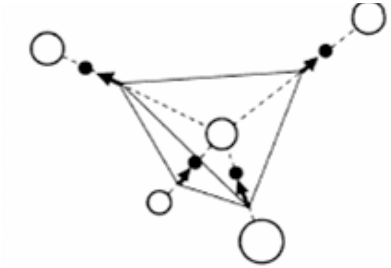
This is what Particle Physics Experiments at LHC such as MoeDAL are currently searching

U. Alberta-IC-KCL-Langdon School Collaboration

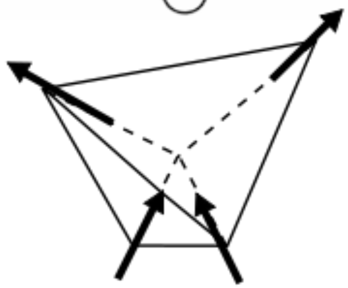
Conclusions - Outlook

SPARES

Spin Ice Monopole-like Quasiparticles



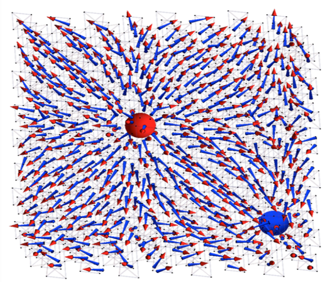
The arrangement of hydrogen atoms (black circles) about oxygen atoms (open circles) in **ice**



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

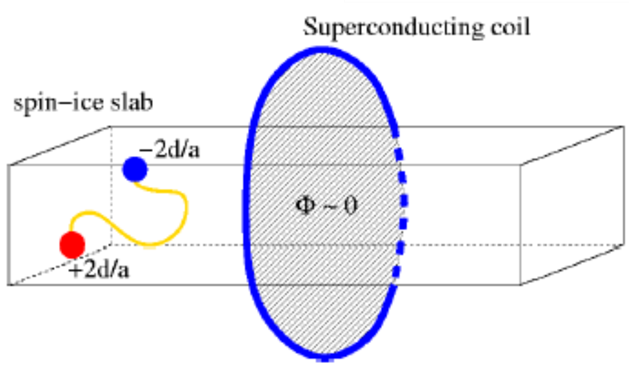
Monopole-like quasiparticles (excitations):

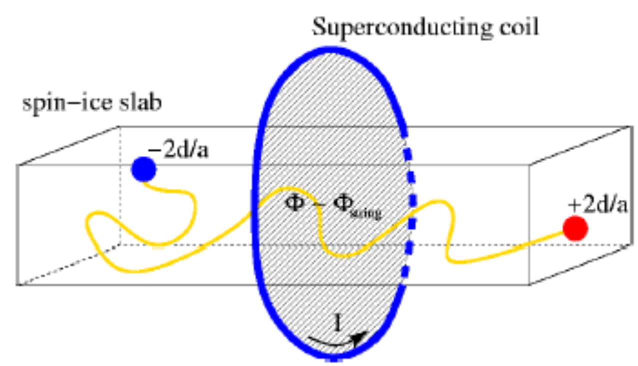
These excitations are **NOT** describing a fundamental particle unlike the real monopole.

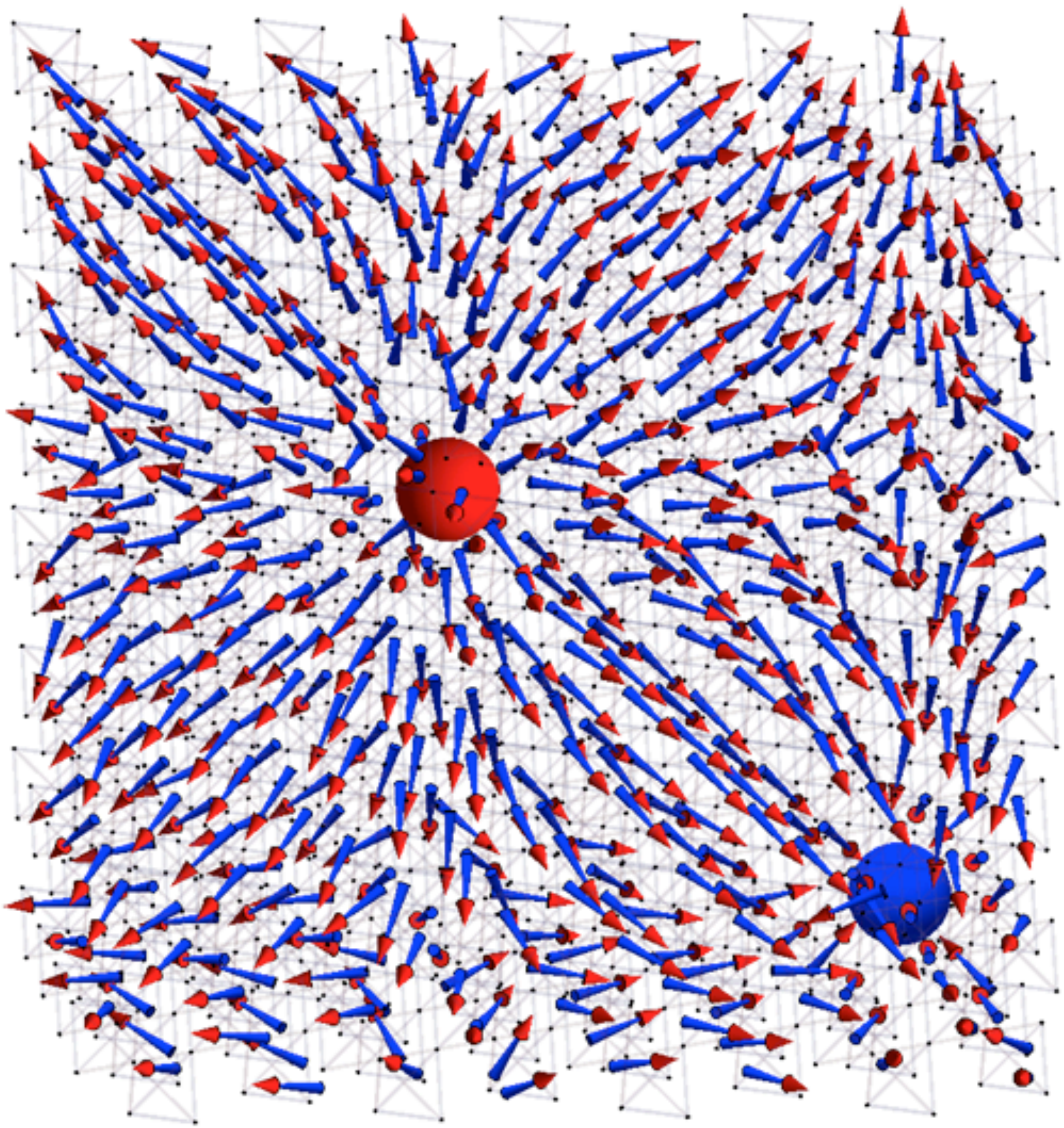


C. Castelnovo, R. Moessner, S. L. Sondhi
Nature 451, 42-45 (2008)

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



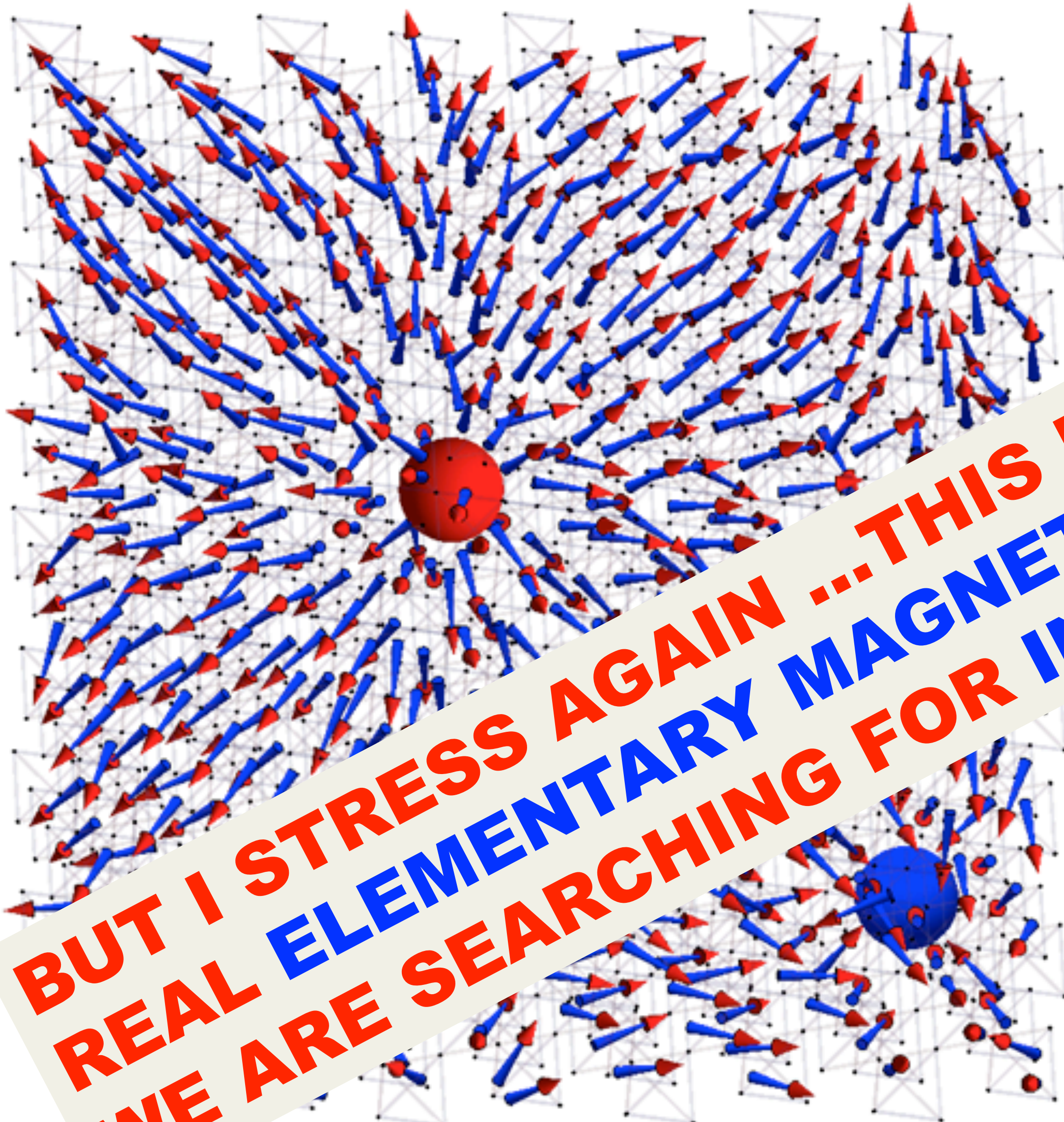




Dr C Castelonovo
https://www.royalholloway.ac.uk/cmt/research/frustratedmagnetism.aspx

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

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Expand around the Higgs v.e.v

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

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

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

$$-\frac{1}{4}\left(\frac{\rho}{\rho_0}\right)^2 B_{\mu\nu}B^{\mu\nu} \supset -\frac{n}{4}\frac{\tilde{\rho}}{\rho_0} B_{\mu\nu}B^{\mu\nu},$$

$$\bar{c}_\gamma = -\frac{1}{32}\left(\frac{g}{g'}\right)^2 n \simeq -0.1n.$$

$$n \geq 8 \Rightarrow \bar{c}_\gamma \lesssim -0.8$$

observed

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

x

Implementing the $H \rightarrow \gamma\gamma$ constraint

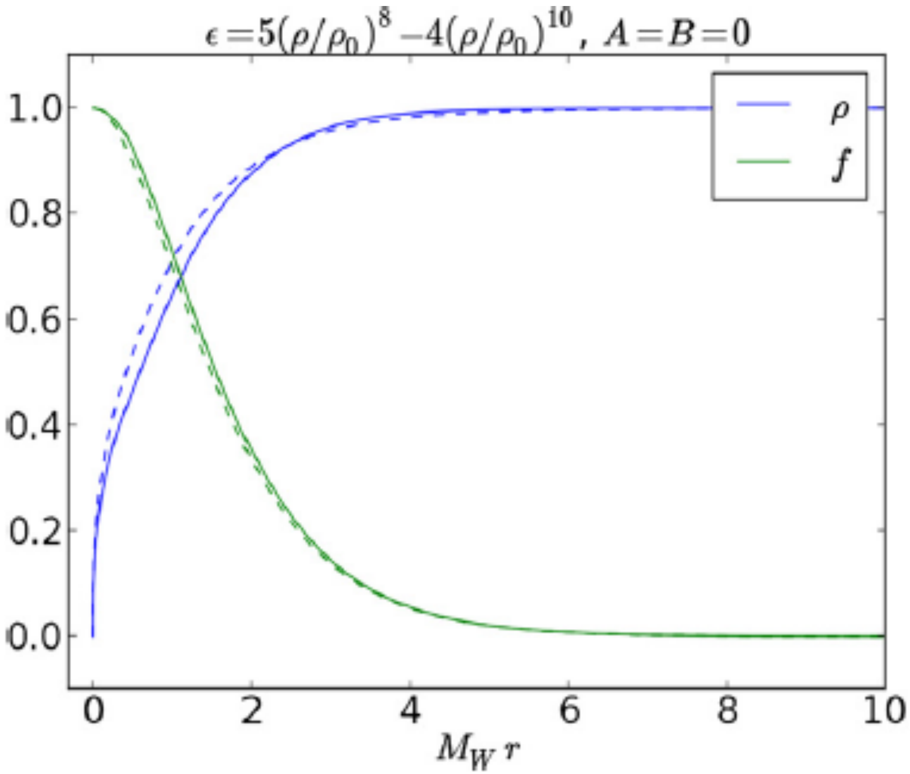
Try more general (phenomenological) function of $\varepsilon(\phi\,\phi^{+})$

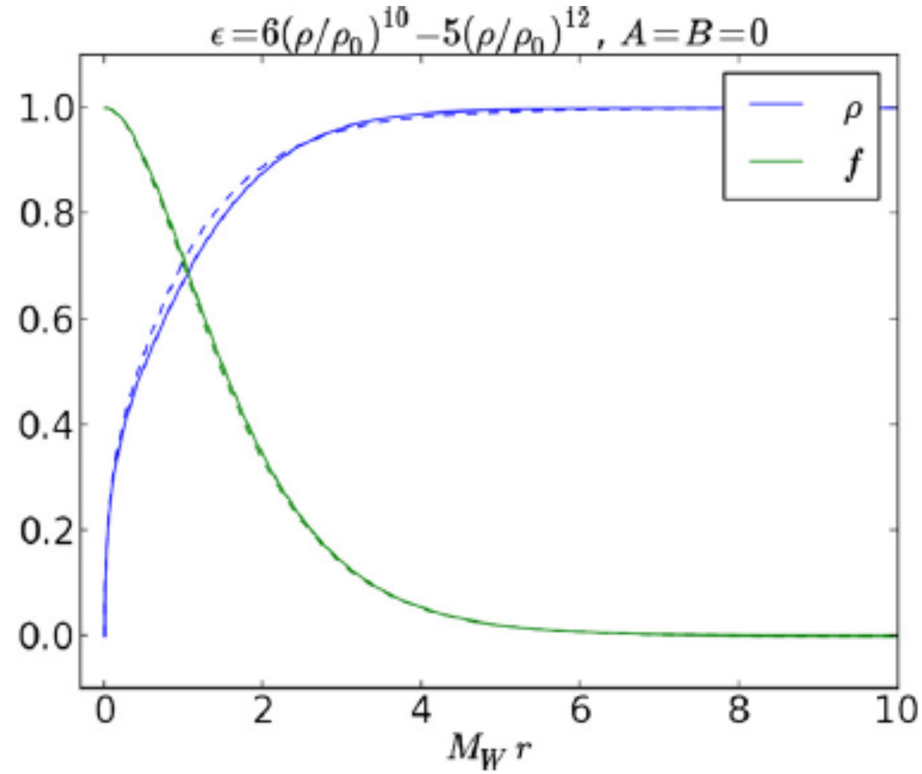
$$\text{e.g.} \quad \epsilon_n(\rho) = \sum_{n \in Z^+} C_n \left(\frac{\rho}{\rho_0}\right)^{8+2n}$$

Require Maximal Entropy

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

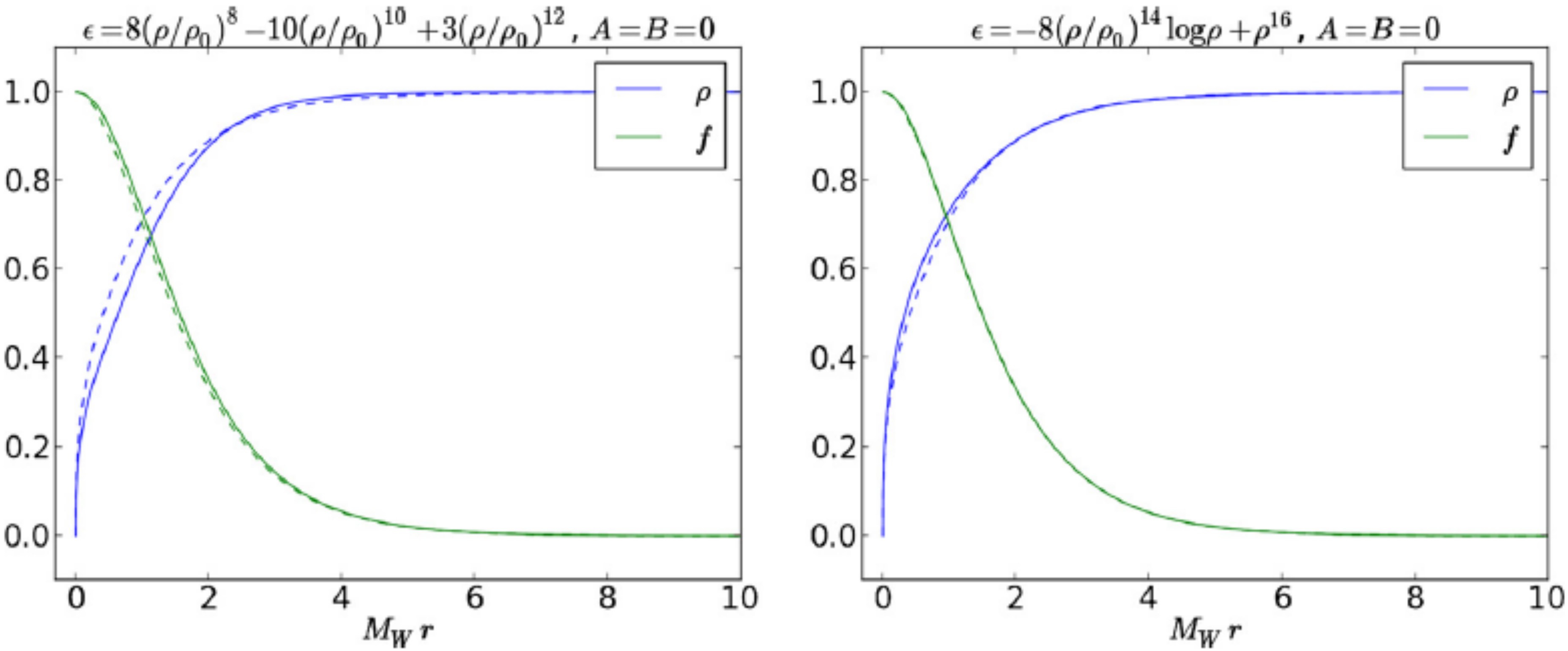
Ellis, NEM, You PLB 756, 25 (2016)





Modified Finite-Energy Electroweak Monopole

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



Modified Finite-Energy Electroweak Monopole