Magnetic monopoles from heavy-ion collisions

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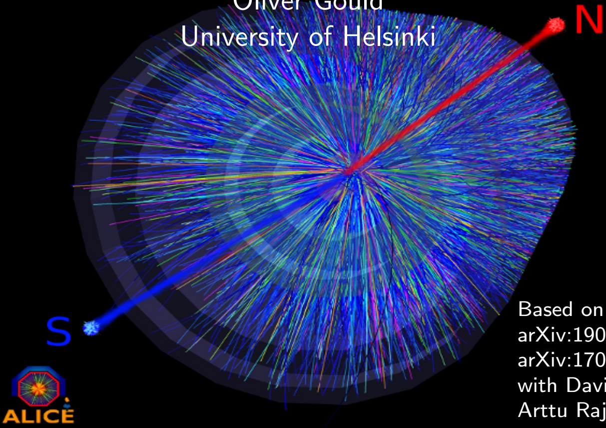
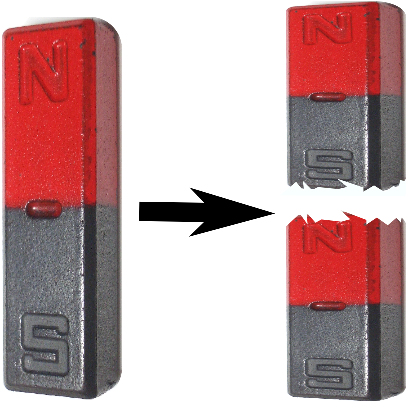


Based on:
arXiv:1902.04388
arXiv:1705.07052 (PRL)
with David Ho and Arttu Rajantie

June 4, 2019

I thought there weren't any magnetic monopoles?



Peregrinus 1269

$$\nabla \cdot \mathbf{B} = 0$$

Maxwell 1865

But magnetic monopoles could exist...

All we need to do is add magnetic sources in Maxwell's equations,

$$\nabla \cdot \mathbf{E} = \rho_e, \qquad \nabla \cdot \mathbf{B} = \rho_m,$$

$$-\nabla \times \mathbf{E} = \mathbf{j}_m + \frac{\partial \mathbf{B}}{\partial t}, \qquad \nabla \times \mathbf{B} = \mathbf{j}_e + \frac{\partial \mathbf{E}}{\partial t},$$

and for magnetic charges, with charge g, we get the dual Lorentz force law,

$$\mathbf{F}_e = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}),$$

$$\mathbf{F}_m = g(\mathbf{B} - \mathbf{v} \times \mathbf{E}).$$

Why magnetic monopoles?

There are good reasons to think monopoles might exist

- They imply electric charge quantisation, Dirac '31

$$\exists \text{ Monopoles} \Rightarrow q/e \in \mathbb{Z}.$$

- Can be added to Standard Model with source term.
- Gravitational instantons for monopole pair production exist in Einstein-Maxwell theory. Garfinkle & Strominger '91
- Predicted by Grand Unified Theories 't Hooft '74, Polyakov '74

$$G \rightarrow SU(3) \times SU(2) \times U(1),$$

and by string theory. Gross & Perry '83

Types of magnetic monopoles

There are two kinds of possible magnetic monopoles:

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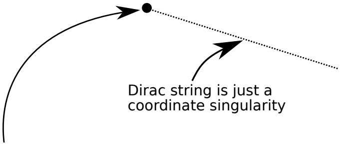
1. Elementary

Consistent QFT of
elementary monopoles
exists

Any mass is possible



Cabibbo & Ferrari '62, Schwinger '66,
Zwanzinger '71

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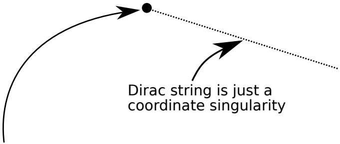


Dirac string is just a coordinate singularity

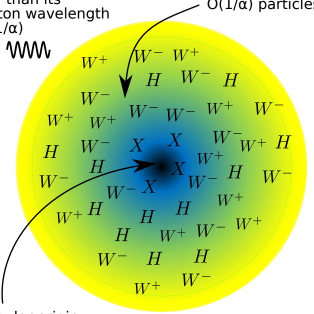
Singular at origin, so need source term in Lagrangian

Cabibbo & Ferrari '62, Schwinger '66, Zwanzinger '71

2. Composite

Larger than its Compton wavelength by O(1/α)

Bound state of at least O(1/α) particles



Nonsingular origin, so no source term in Lagrangian

Mostly too heavy for LHC searches

't Hooft '74, Polyakov '74

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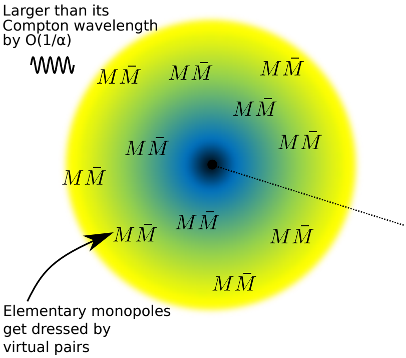
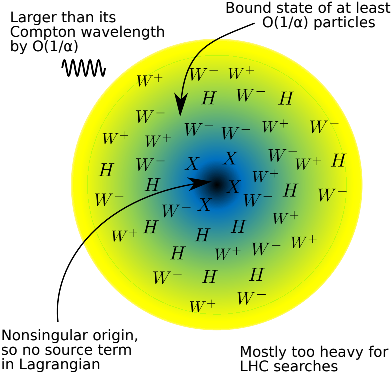


Göbel ’70, Goldhaber ’81

2. Composite

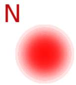


’t Hooft ’74, Polyakov ’74

Magnetic monopoles in the infrared

At large distances all monopoles look the same. One only sees the magnetic charge, g, the spin, s, and the mass, m, of the monopole,

$$\begin{aligned} g &= \frac{2\pi}{e} n, \qquad n \in \mathbb{Z}, \\ s &= \frac{1}{2} k, \qquad k \in \mathbb{Z}, \\ m &\in \mathbb{R}_+. \end{aligned}$$



Monopoles' properties are very weakly constrained

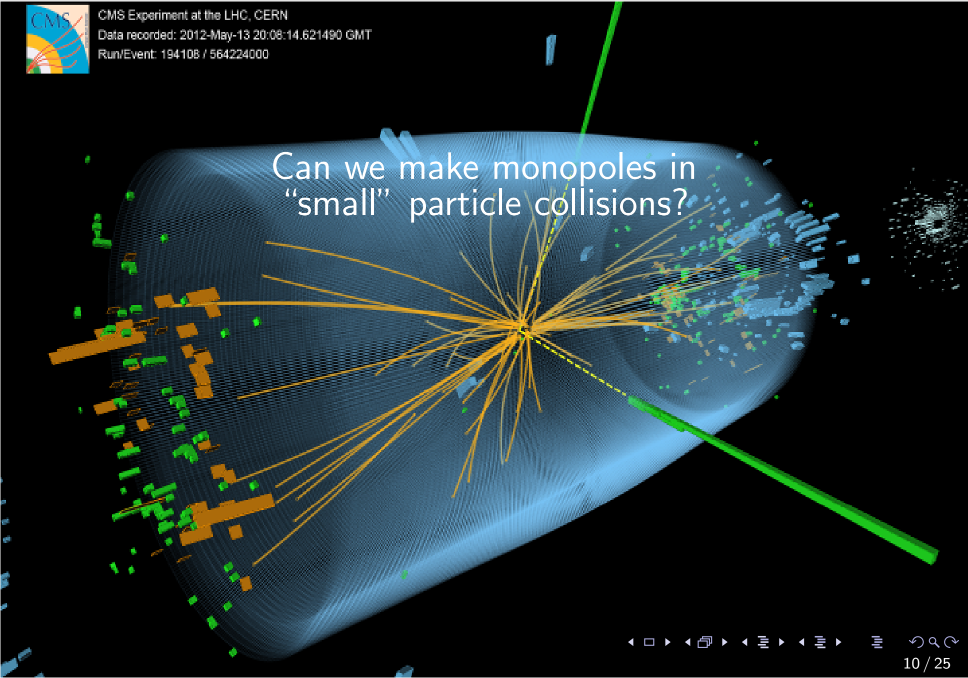
- Sufficiently light magnetic monopoles would have been produced thermally during reheating (RH).
- From constraints on the flux in the universe today, it must be that $m/T_{RH} \gtrsim 45$. Turner et al. '82
- As reheating must have happened before Big Bang Nucleosynthesis (BBN), it must be that $T_{RH} \gtrsim T_{BBN} \approx 10\text{MeV}$.

$$m \gtrsim 0.45\text{GeV}$$

Key questions of this talk

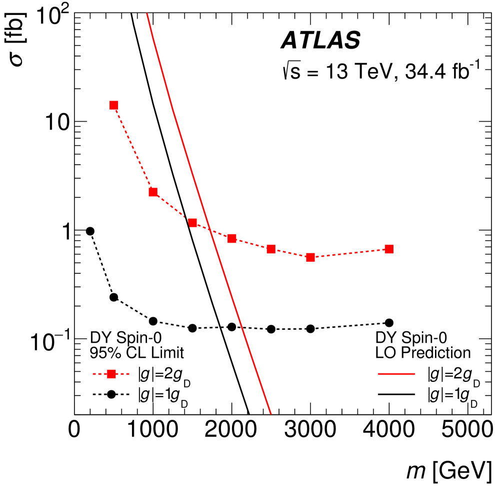
How can we test whether or not magnetic monopoles exist?

1. If **composite** magnetic monopoles exist, how can they be created?
2. If **elementary** magnetic monopoles exist, how can they be created?



Can we make monopoles in “small” particle collisions?

Experimental cross section bounds



ATLAS '19

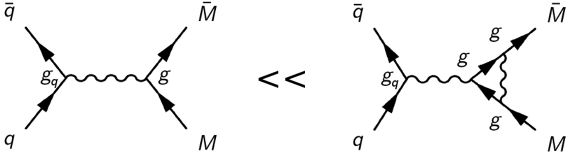
Can we make elementary monopoles in "small" particle collisions?

Strong coupling

Dirac quantisation condition implies magnetic monopoles are strongly coupled,

$$\frac{g^2}{4\pi} = \frac{1}{\pi\alpha} \approx 34,$$

invalidating perturbation theory.



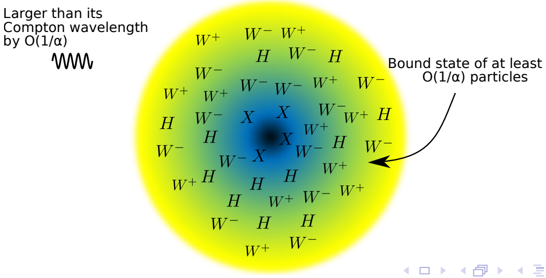
$$\sigma_{M\bar{M}}?$$

Can we make composite monopoles in “small” particle collisions?

Because composite monopoles are coherent on large scales, their pair production in “small” particle collisions is expected to be exponentially suppressed,

$$\sigma_{M\bar{M}} \propto \mathrm{e}^{-4/\alpha} \approx 10^{-238}.$$

Witten ’79, Drukier & Nussinov ’82



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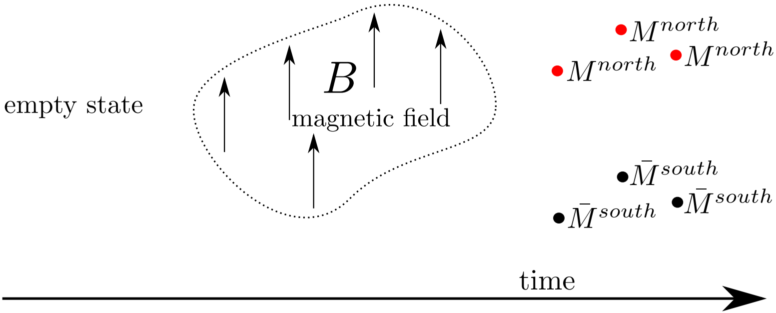
Composite monopoles will never be produced in pp collisions.

How else can we make magnetic monopoles?

Dual Schwinger effect

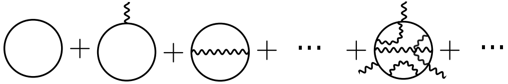


The calculation set-up

How do we calculate the production cross section?

- For slowly varying and not too strong magnetic fields, the cross section is dominated by the "quenched" Feynman diagrams,

$$\sigma_{M\bar{M}} \sim \frac{1}{V} Im \Big\{$$



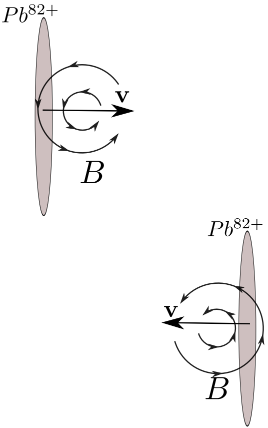
$$\Big\}$$

- This is true even for $g \gg 1$, and allows for a controlled semiclassical expansion for $\sigma_{M\bar{M}}$.

Affleck & Manton '82

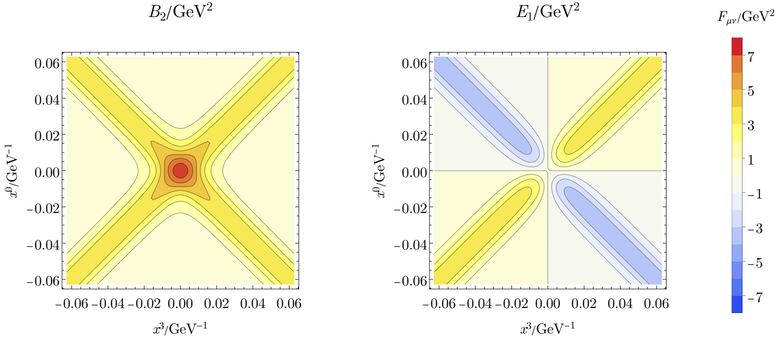
Conditions in heavy-ion collisions

Strong magnetic fields are produced in peripheral heavy-ion collisions by Ampère's Law.



Electromagnetic fields

Magnetic fields produced in peripheral heavy-ion collisions are the strongest known in the universe, $\sim 7.5\mathrm{GeV}^2$ at LHC energies.



Spacetime dependence

The importance of the spacetime dependence for monopole pair production is determined by,

$$\frac{L_{\text{pair production}}}{L_{\text{field variation}}} = \frac{m\omega}{gB} \approx \frac{m}{3n\text{GeV}},$$

where B is the magnetic field strength, ω is the inverse decay time of the field and $n = g/g_D \in \mathbb{Z}$ gives the magnetic charge.

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- For monopoles with $m \ll 3n\text{GeV}$, the electromagnetic fields are effectively constant.
- For monopoles with $m \gg 3n\text{GeV}$, the electromagnetic fields are strongly varying.

Cross section

- For light monopoles, $m \lesssim 3n\mathrm{GeV}$, the cross section can be calculated in a locally constant field approximation,

$$\sigma_{\text{constant}} \sim \frac{(2s+1)(nZ\gamma)^{9/2}}{10^3 m^5 R^3 \gamma^2} \mathrm{e}^{-\frac{4m^2R^2}{\gamma v n Z} + \frac{\pi^2 n^2}{e^2}}.$$

Affleck & Manton '82, Gould & Rajantie '17

- For heavy monopoles, $m \gtrsim 3n\mathrm{GeV}$, the time dependence enhances the rate, but approximations break down.

$$\sigma_{\text{varying}} > \sigma_{\text{constant}}?$$

Gould, Ho & Rajantie '19

Collider searches - heavy ions

M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update.

Monopole Production Cross Section — Accelerator Searches

INSPIRE search

X-SECT (cm^2)	MASS (GeV)	CHG (g)	ENERGY (GeV)	BEAM	DOCUMENT ID		TECN
					1 ACHARYA	2018A	INDU
<2.5E-37	200 - 6000	1	13000	pp	2 ACHARYA	2017	INDU
<2E-37	200 - 6000	2	13000	pp	2 ACHARYA	2017	INDU
<4E-37	200 - 5000	3	13000	pp	2 ACHARYA	2017	INDU
<1.5E-36	400 - 4000	4	13000	pp	2 ACHARYA	2017	INDU
<7E-36	1000 - 3000	5	13000	pp	2 ACHARYA	2017	INDU
<5E-40	200 - 2500	0.5 - 2.0	8000	pp	3 AAD	2016AB	ATLS
<2E-37	100 - 3500	1	8000	pp	4 ACHARYA	2016	INDU
<2E-37	100 - 3500	2	8000	pp	4 ACHARYA	2016	INDU
<6E-37	500 - 3000	3	8000	pp	4 ACHARYA	2016	INDU
<7E-36	1000 - 2000	4	8000	pp	4 ACHARYA	2016	INDU
<1.6E-38	200 - 1200	1	7000	pp	5 AAD	2012CS	ATLS
<5E-38	45 - 102	1	206	e^+e^-	6 ABBIENDI	2008	OPAL
<0.2E-36	200 - 700	1	1960	$p\bar{p}$	7 ABULENCIA	2006K	CNTR
< 2.E-36		1	300	e^+p	8, 9 AKTAS	2005A	INDU
< 0.2 E-36		2	300	e^+p	8, 9 AKTAS	2005A	INDU
< 0.09E-36		3	300	e^+p	8, 9 AKTAS	2005A	INDU
< 0.05E-36		$\geq$ 6	300	e^+p	8, 9 AKTAS	2005A	INDU
< 2.E-36		1	300	e^+p	8, 10 AKTAS	2005A	INDU
< 0.2E-36		2	300	e^+p	8, 10 AKTAS	2005A	INDU
< 0.07E-36		3	300	e^+p	8, 10 AKTAS	2005A	INDU
< 0.06E-36		$\geq$ 6	300	e^+p	8, 10 AKTAS	2005A	INDU
<0.6E-36	> 265	1	1800	$p\bar{p}$	11 KALBFLEISCH	2004	INDU
<0.2E-36	> 355	2	1800	$p\bar{p}$	11 KALBFLEISCH	2004	INDU
<0.07E-36	> 410	3	1800	$p\bar{p}$	11 KALBFLEISCH	2004	INDU
<0.2E-36	> 375	6	1800	$p\bar{p}$	11 KALBFLEISCH	2004	INDU
<0.7E-36	> 295	1	1800	$p\bar{p}$	12, 13 KALBFLEISCH	2000	INDU
<7.8E-36	> 260	2	1800	$p\bar{p}$	12, 13 KALBFLEISCH	2000	INDU
<2.3E-36	> 325	3	1800	$p\bar{p}$	12, 14 KALBFLEISCH	2000	INDU
<0.11E-36	> 420	6	1800	$p\bar{p}$	12, 14 KALBFLEISCH	2000	INDU
<0.65E-33	< 3.3	$\geq$ 2	11	^{197}Au	15, 16 HE	1997	
<1.90E-33	< 8.1	$\geq$ 2	160	^{208}Pb	15, 16 HE	1997	

Heavy-ion collisions at SPS

Magnetic monopole search in heavy-ion collisions at SPS (He 1997)

- Pb-Pb collisions at $\sqrt{s_{NN}} \approx 17\text{GeV}$.
- Experimental bound derived,

$$\sigma_{M\bar{M}} \lesssim \sigma_{UB} = 1.9\text{nb}.$$

- Only sensitive to $g \geq 2g_D$.

From this, and by comparison with the calculated cross section, we derive the following mass bound,

$$m \gtrsim \left(2.0 + 2.6\left(\frac{g}{g_D}\right)^{3/2}\right)\text{GeV}.$$

Experimental prospects

- ATLAS and MoEDAL have conducted magnetic monopole searches in pp collisions at LHC. No searches yet in heavy ions!
- LHC $PbPb$ collisions at $\sqrt{s_{NN}} = 5.02$TeV happened in November 2018.

Magnetic monopole mass bounds

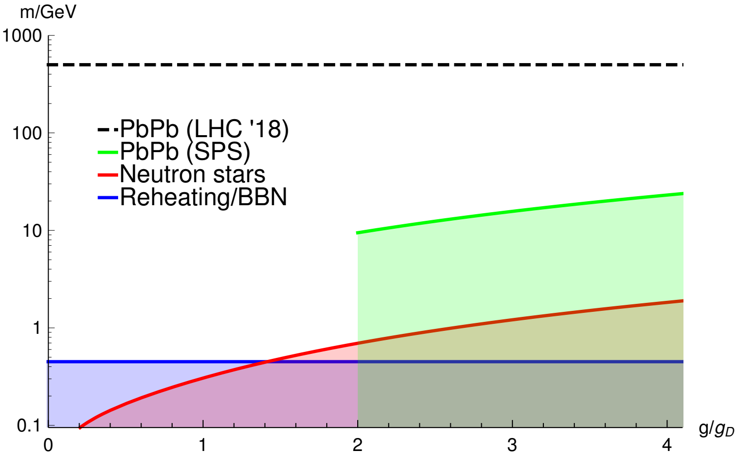

Figure: adapted from OG & Arttu Rajantie '17.

Current best answers to our questions

1. If **composite** magnetic monopoles exist, how can they be created?

   ~~pp collisions~~, ~~e^+e^- collisions~~ ...

   $PbPb$ collisions ✓, $AuAu$ collisions ✓, ...

2. If **elementary** magnetic monopoles exist, how can they be created?

   pp collisions? e^+e^- collisions? ...

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Thank you for listening!