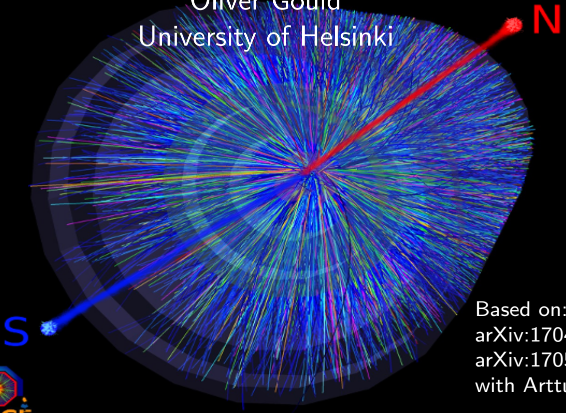
Magnetic monopoles from heavy ion collisions

Oliver Gould
University of Helsinki



ALICE

Based on:
arXiv:1704.04801 (PRD)
arXiv:1705.07052 (PRL)
with Arttu Rajantie

December 4, 2018

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 GUTs '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 magnetic monopoles:

1. Composite,
2. Elementary.

Composite magnetic monopoles

Starting with the Georgi-Glashow theory,

$$\mathcal{L} = -\frac{1}{4}F_a^{\mu\nu}F^a_{\mu\nu} + \frac{1}{2}(D\phi)^\mu_a(D\phi)^a_\mu + \frac{M^2}{2}\phi^a\phi^a - \frac{\lambda}{4}(\phi^a\phi^a)^2,$$

where $a = 1, 2, 3$. There is a localised, static solution to the equations of motion with

't Hooft '74, Polyakov '74

$$\phi^a = \frac{\mathbf{x}^a}{|\mathbf{x}|}\left(\frac{M}{\sqrt{\lambda}} + H(|\mathbf{x}|)\right),$$

$$A_i^a = \epsilon_{iaj}\mathbf{x}^j\left(-\frac{1}{e|\mathbf{x}|^2} + W(|\mathbf{x}|)\right)$$

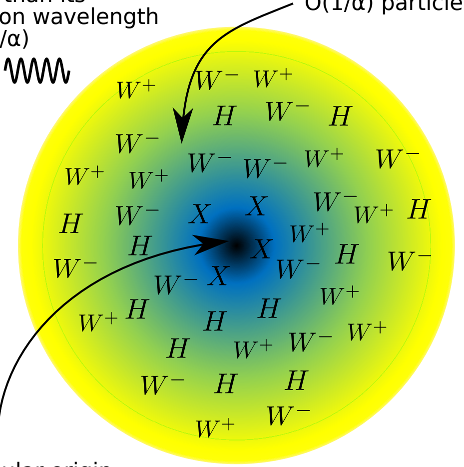
The solution, a 't Hooft-Polyakov monopole, is a composed of elementary bosons and is heavier than them by $O(1/\alpha)$,

$$m \sim \frac{M}{\alpha}.$$

Composite magnetic monopoles

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

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



For GUTs

$M_X \sim 10^{16}\text{GeV}.$

Fig. inspiration from Patrizii & Spurio ’15.

Nonsingular origin, so no source term in Lagrangian

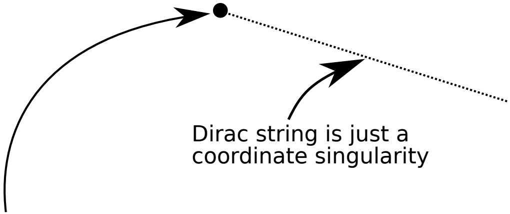
Mostly too heavy for LHC searches

Elementary magnetic monopoles

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

Consistent QFT of elementary monopoles exists

Any mass is possible

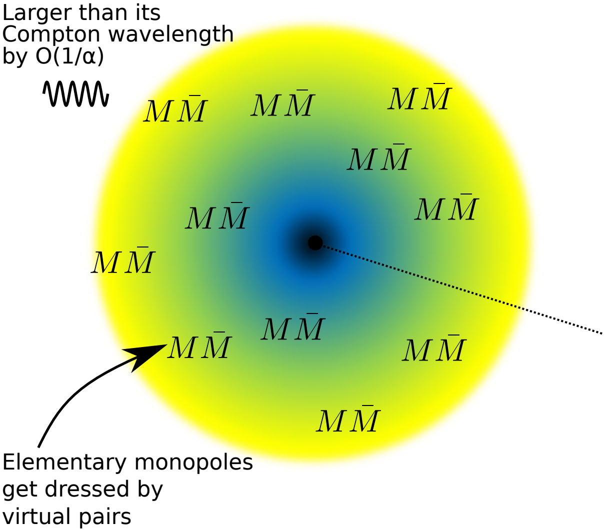


Dirac string is just a coordinate singularity

Dirac ’31, Wu & Yang ’75, Greub & Petry ’75

Singular at origin, so need source term in Lagrangian

Elementary magnetic monopoles



Göbel '70,
Goldhaber '81

Current best mass bound

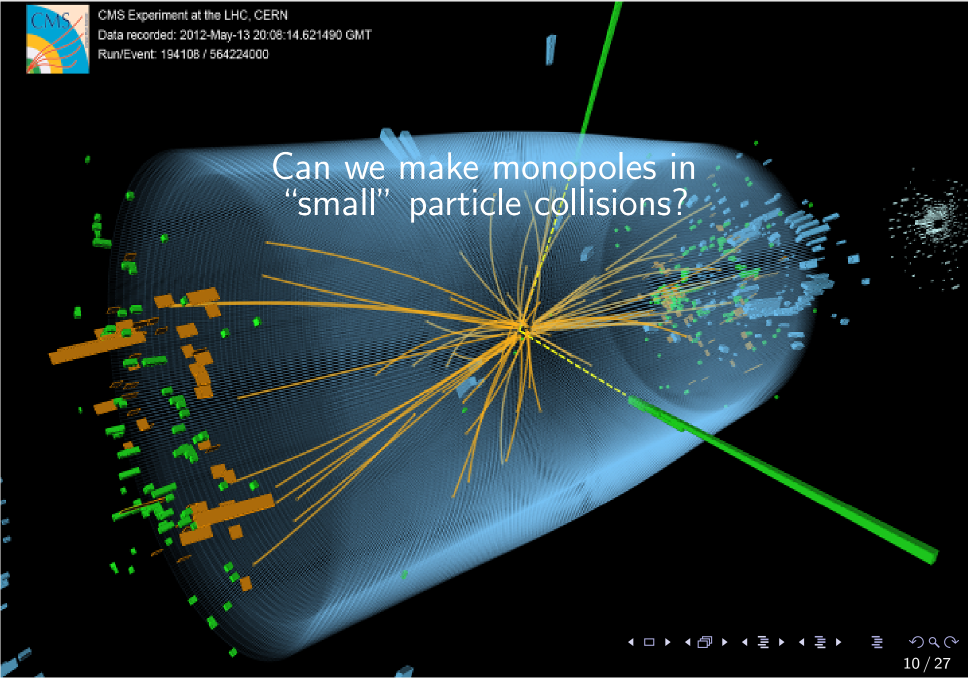
- Sufficiently light magnetic monopoles would have been produced thermally during reheating (RH).
- From constraints on the flux in the universe today, it must be that $m/T_{RH} \gtrsim 45$. Turner et al. '82
- As reheating must have happened before Big Bang Nucleosynthesis (BBN), it must be that $T_{RH}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

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

Key questions of this talk

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

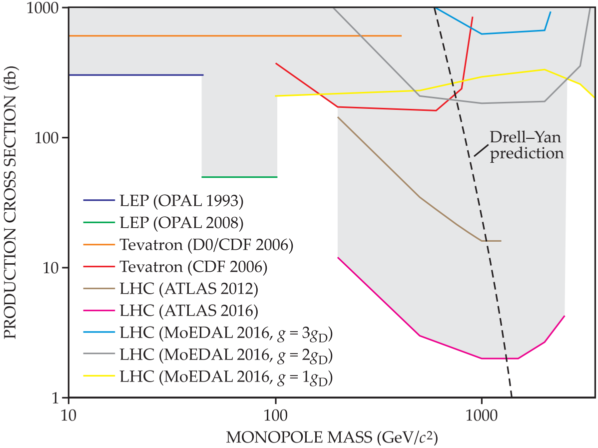


Figure: from Rajantie (2016).

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

- A simple picture of a monopole state, made up of Higgses,

$$|\text{Monopole}\rangle \sim |H_1\rangle \otimes |H_2\rangle \otimes \cdots \otimes |H_{137}\rangle.$$

- Pair creation of monopoles from "small" particle collisions is determined by,

$$\begin{aligned}\langle \text{Monopole}(\mathbf{v})|\hat{\mathcal{O}}|\text{Monopole}(\mathbf{v}')\rangle &\sim \\ &(137)^2 \left(\langle H(\mathbf{v})|H(\mathbf{v}')\rangle\right)^{136} \langle H(\mathbf{v})|\hat{\mathcal{O}}|H(\mathbf{v}')\rangle, \\ &\sim \mathrm{e}^{-136c} \approx \mathrm{e}^{-c/\alpha}.\end{aligned}$$ Witten '79

- It has been argued that $c \approx 2$. Drukier & Nussinov '82

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

- From arguments overleaf, and squaring the amplitude,

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

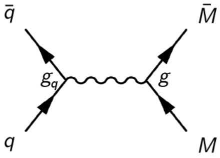
> Composite monopoles will never be produced in pp collisions.

- Analogous suppression explicitly demonstrated for:
  - Kink production, Levkov et al. '05, '11
  - Vacuum decays. Kuznetsov & Tinyakov '97, Bezrukov et al. '03

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

Strong coupling

Large charge of magnetic monopoles, $g = ng_D$, where $g_D := 2\pi/e$ and $n \in \mathbb{Z}$, invalidates perturbation theory.



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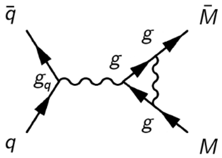


$$\sigma_{tree} = \frac{g_q^2 g^2}{12\pi s} \ll \Delta\sigma_{1-loop} \sim \# g^2 \sigma_{tree}$$

Cross section for elementary monopoles is nonperturbative,

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

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

What about beyond perturbation theory?

- Dressed elementary monopoles are HUGE, having a size $R \sim 1/\alpha m \sim 137\lambda_{\text{Compton}}$.
- The overlap of a hard state with energy $E \geq 2m$ and a monopole pair state is thus exponentially small,

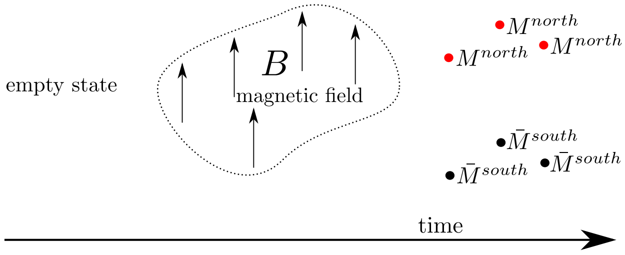
$$\langle E|M\bar{M}\rangle \sim \int dx \mathrm{e}^{-iEx} f_{M\bar{M}}(x), \\ \sim \mathrm{e}^{-ER} \lesssim \mathrm{e}^{-2\times 137}.$$

This suggests the same exponential suppression for elementary monopoles in pp collisions.

How else can we make magnetic monopoles?

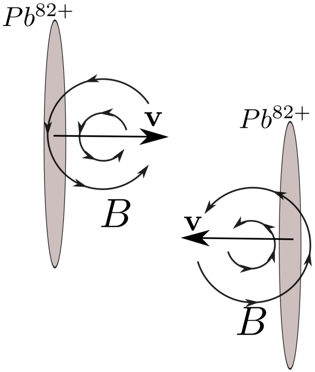
Dual Schwinger process

- Spontaneous production of magnetic monopoles in strong magnetic fields. Affleck & Manton '82
- Rate of production enhanced by:
  - energy from thermal bath,
  - time dependence of magnetic field.



Conditions in heavy-ion collisions

Magnetic fields in heavy-ion collisions are the strongest known in the universe, $O(10\mathrm{GeV}^2) = O(10^{16}\mathrm{T})$ at LHC energies.



The cross section for heavy-ion collisions

Schwinger effect → cross section

Magnetic monopole pair production cross section,

$$\frac{d\sigma_{M\bar{M}}}{db} = 2\pi b P(F_{\mu\nu})$$

where b is the impact parameter and $P(F_{\mu\nu})$ is the probability to produce a magnetic monopole in the electromagnetic field $F_{\mu\nu}$.

The calculation set-up

How do we calculate the production probability, $P(F_{\mu\nu})$?

- We work with an electromagnetic dual theory, at strong coupling.
- Worldline representation of QED (or scalar QED),

"sum over fields" $\equiv$ "sum over worldlines",

$$\int \mathcal{D}A_\mu \mathcal{D}\psi \mathcal{D}\bar{\psi}\ \mathrm{e}^{-S_{\mathrm{QED}}[A_\mu,\psi,\bar{\psi}]}$$

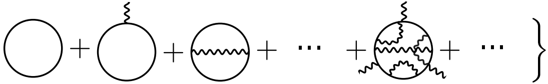
$$\equiv \sum_{n=0}^{\infty} \frac{(-1)^n}{n!} \left(\prod_{m=0}^{n} \int \mathcal{D}x_m^\mu \right) \mathrm{e}^{-S_{WL}[\{x_j\},\{x_k\}]}.$$

The calculation set-up

How do we calculate the production probability, $P(F_{\mu\nu})$?

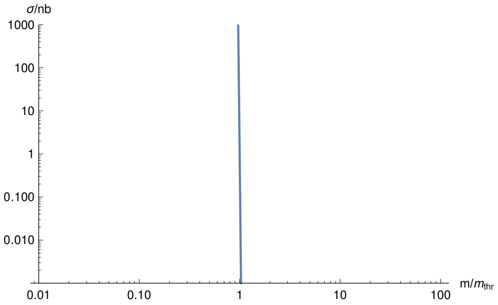
- For sufficiently heavy monopoles, $m^2 \gg gB$, the leading term consists of the "quenched" Feynman diagrams,

$$P(F_{\mu\nu}) \sim \frac{1}{\mathcal{V}} Im \Big\{ \cdots \Big\}$$



- This is true even for $g \gg 1$, and allows for a controlled semiclassical expansion for $P(F_{\mu\nu})$ using worldline instantons.

Understanding the production probability



Viewed as a function of mass, m, for fixed g and $F_{\mu\nu}$,

$$P(F_{\mu\nu})(m) = \begin{cases} \text{slow} & , \ m \gtrsim m_{thr}(g, F_{\mu\nu}), \\ \text{fast} & , \ m \lesssim m_{thr}(g, F_{\mu\nu}). \end{cases}$$

OG & Rajantie '17

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 $g \geq 2g_D$.

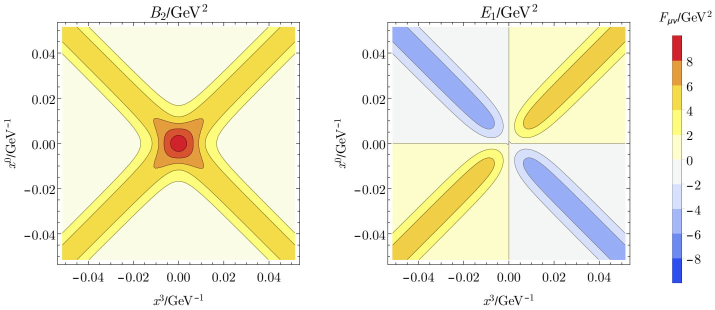
From this, and by comparison with the calculated cross section, we find the following mass bound,

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

Higher energy heavy-ion collisions

What to expect from higher energies?

$$B \propto \sqrt{s_{NN}}, \qquad \omega \propto \sqrt{s_{NN}}.$$



Strong spacetime dependence requires new calculations.

Experimental prospects

- MoEDAL, at LHC, is a dedicated experiment searching for magnetic monopoles. ALICE, ATLAS, CMS etc. also conduct magnetic monopole searches.
- LHC Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$TeV happening November 2018.

Magnetic monopole mass bounds

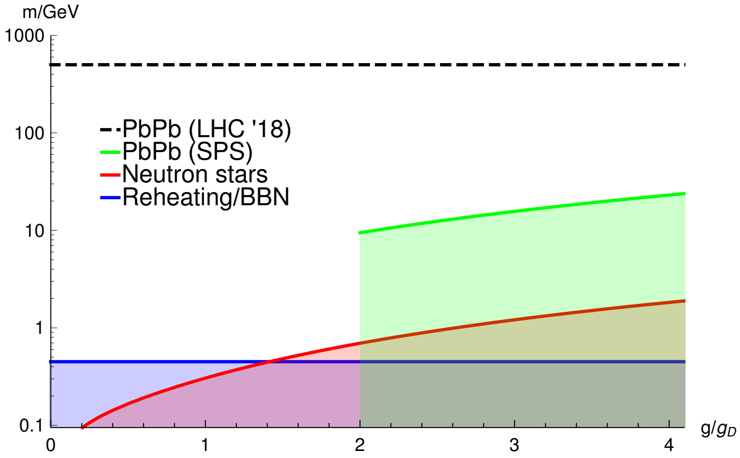


Figure: adapted from OG & Arttu Rajantie ’17.

Theoretical prospects

Theory to-do list:

- Non-constant electromagnetic fields at higher collision energies.

OG, Ho & Rajantie forthcoming

- Kinematic distribution for produced monopoles.
- Finite size corrections.

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!