Electroweak baryon number violation in the lab?

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Strong and Electroweak Matter 2026, Helsinki, Finland, 20 January 2026

Baryon Number Violation in the Standard Model

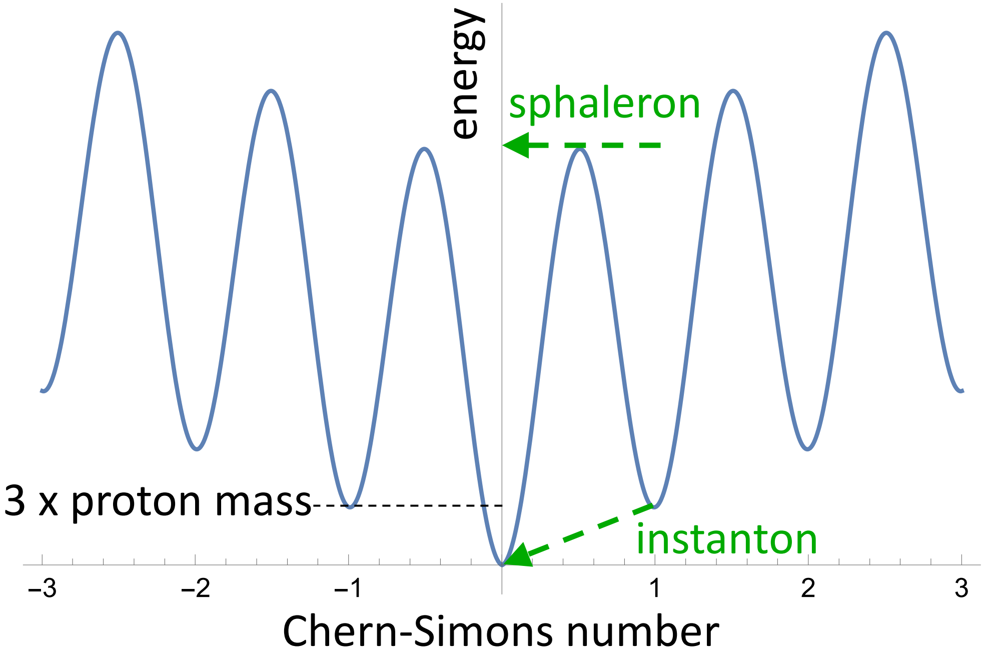
- Chiral anomaly (Adler 1969, Jackiw&Bell 1969)
- $B+L$ violated in the Standard Model ('t Hooft 1976):

$$\Delta B = 3\Delta N_{\rm CS}$$

- Quantum tunnelling rate $\Gamma \propto \exp(-S_{\rm inst})$, where $S_{\rm inst} \approx \frac{8\pi^2}{g^2}$ is the instanton action

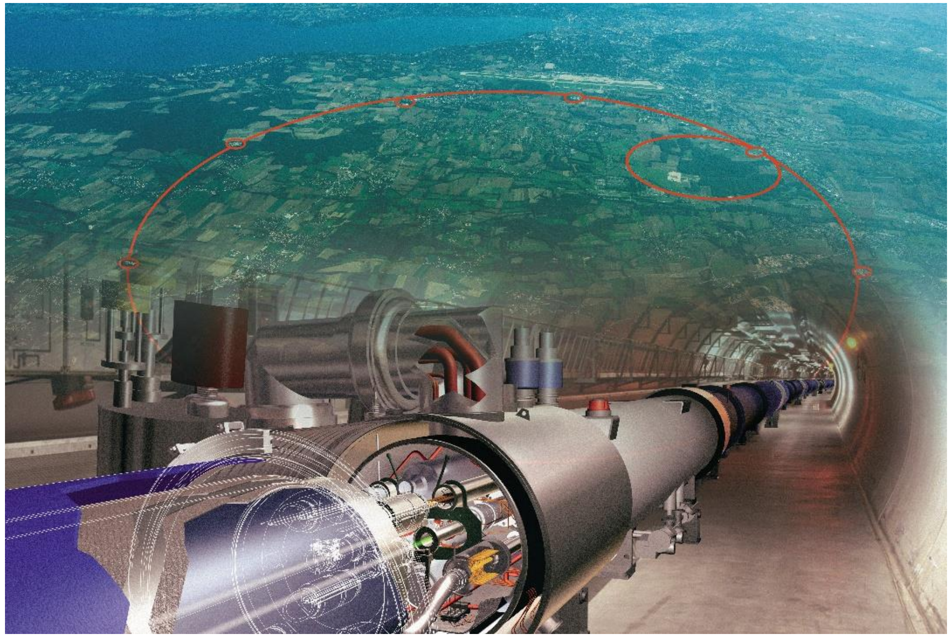
$$\Rightarrow \Gamma \propto 10^{-160}$$

- Classical transition rate $\Gamma \propto \exp(-E_{\rm sph}/T)$, where $E_{\rm sph} \approx \frac{4\pi v}{g} \approx 9\ {\rm TeV}$



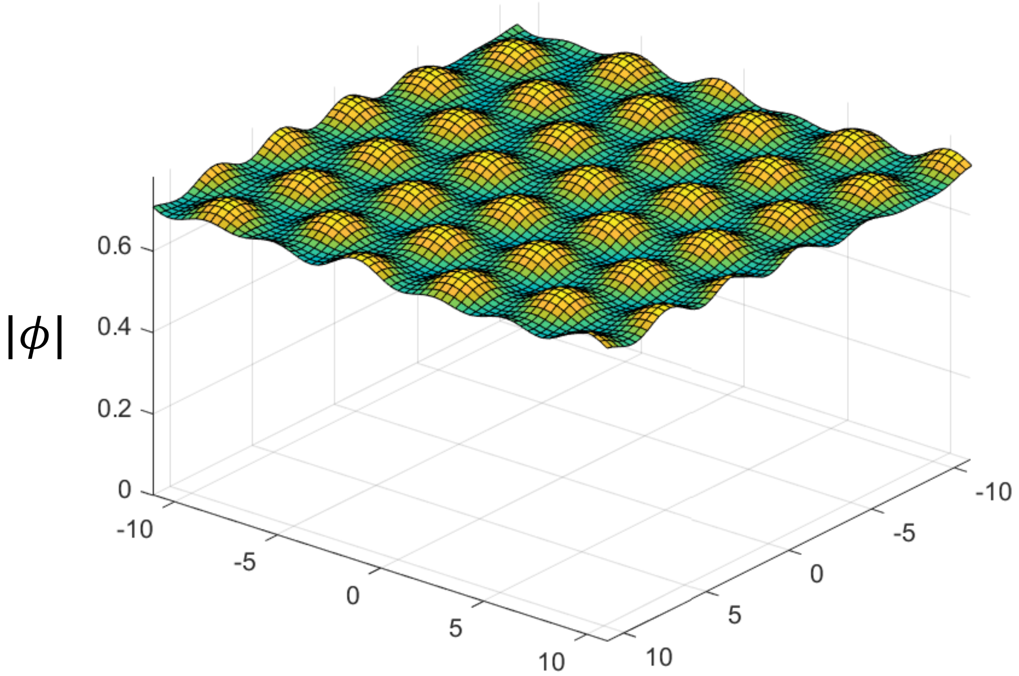
Experimental Test?

- Can we test electroweak baryon number violation experimentally?
  - Crucial for explaining the baryon asymmetry
  - New and qualitatively different test of the Standard Model
- Elementary particle collisions:
  - Exponential suppression even at high energy (Bezrukov et al. 2003)
- High temperature: Sphaleron transition
  - Needs $T \gtrsim 100\ \mathrm{GeV}$
- Heavy ion collisions?
  - Scaling with collision energy $T \sim \left(\sqrt{s_{NN}}\right)^{0.1}$
  - Would require $\sqrt{s_{NN}} \gg M_{\mathrm{Pl}}$



Electroweak Theory in a Magnetic Field

- Sphaleron has a non-zero magnetic dipole moment (Klinkhamer 1990)
  ⇒ Magnetic field enhances the rate of baryon number violation
- Electroweak vacuum changes in strong magnetic fields
  (Ambjørn&Olesen 1988, 1989, 1990)
  - $B > B_{\rm crit}^{(1)} = \frac{m_W^2}{e} \approx 2.1 \times 10^4\ \mathrm{GeV}^2$:
    vortex lattice
  - $B > B_{\rm crit}^{(2)} = \frac{m_H^2}{e} \approx 5.2 \times 10^4\ \mathrm{GeV}^2$:
    $\mathrm{SU}(2) \times \mathrm{U}(1)$ symmetry restored



(Ho&AR 2020)

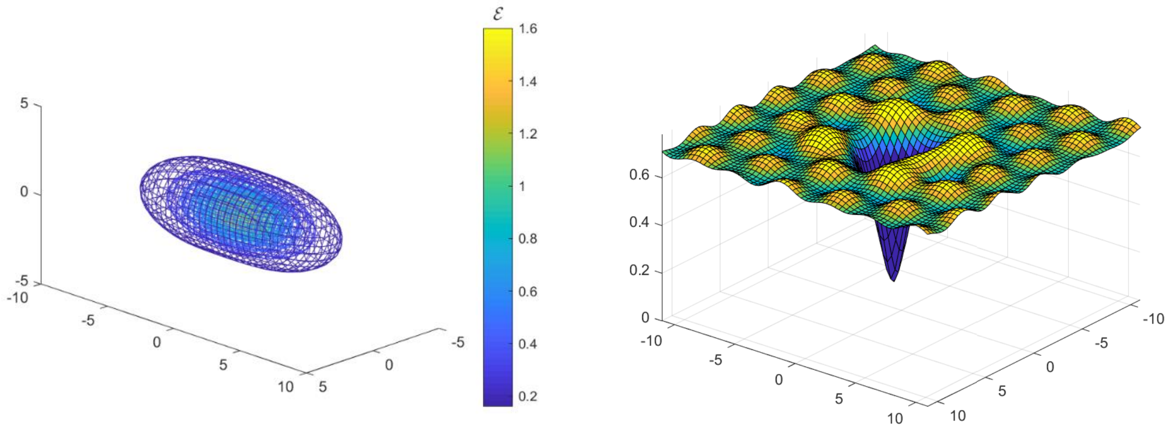
Sphaleron in a Magnetic Field

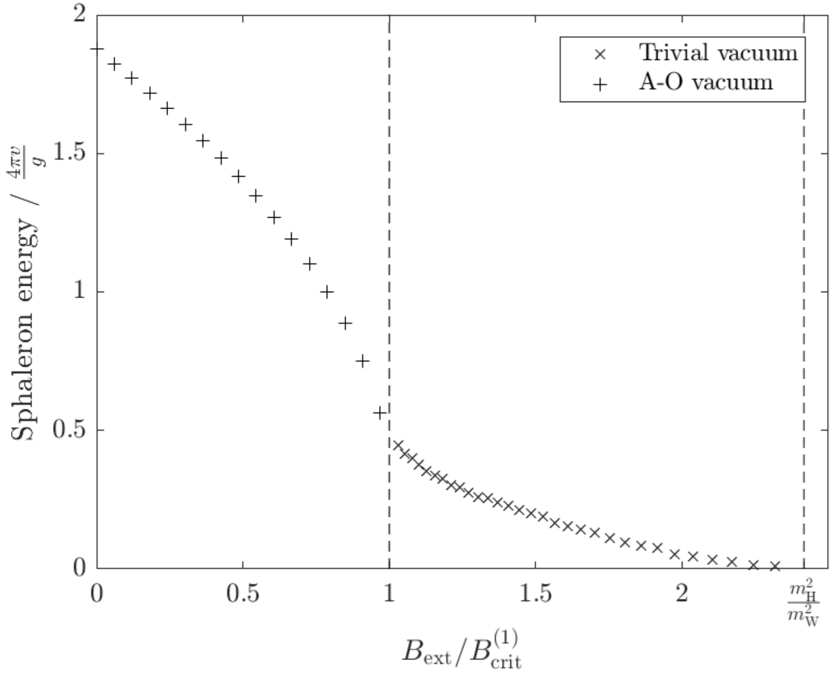
- Numerical solutions (Ho&AR 2020)

- Sphaleron energy vanishes at the upper Ambjørn-Olesen field

$$B_{\mathrm{crit}}^{(2)} = \frac{m_H^2}{e} \approx 5.2 \times 10^4\ \mathrm{GeV}^2$$

- No classical barrier to baryon number violation



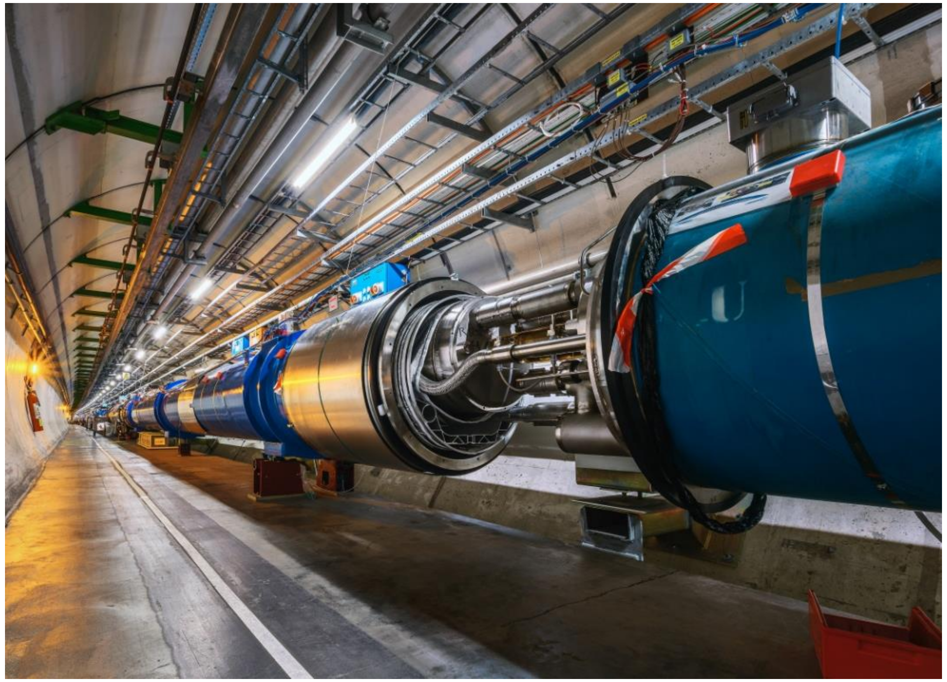


Magnetic Field Strengths

- Baryon number violation needs

$$\left|\vec{B}\right| \gtrsim 5.2 \times 10^{4}\ \mathrm{GeV}^{2} \sim 2.7 \times 10^{20}\ \mathrm{T}$$

- LHC magnets $\left|\vec{B}\right| \sim 8.3\ \mathrm{T} \sim 1.6 \times 10^{-15}\ \mathrm{GeV}^{2}$



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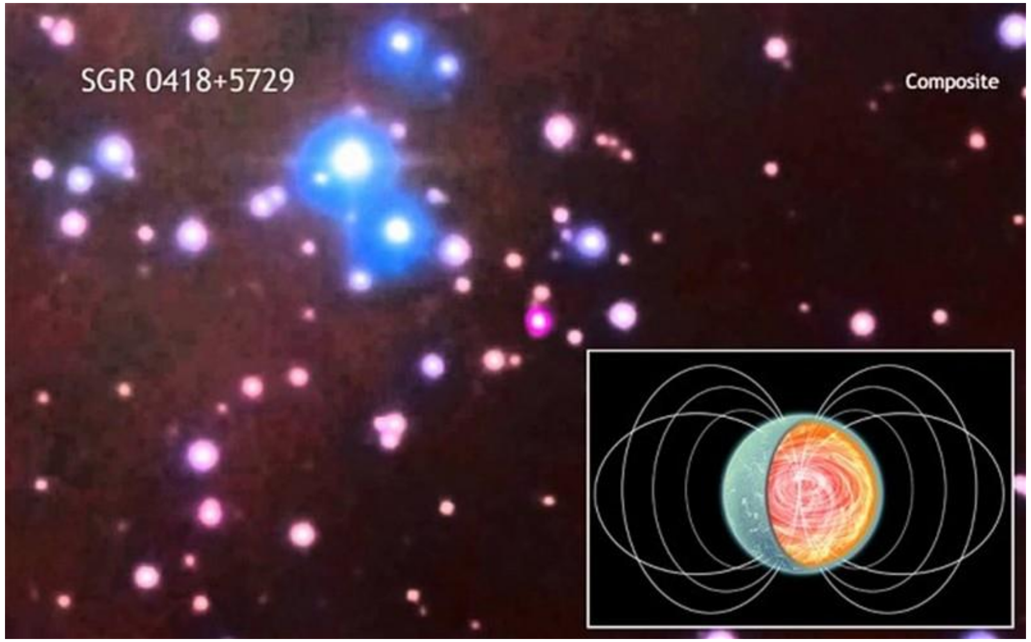

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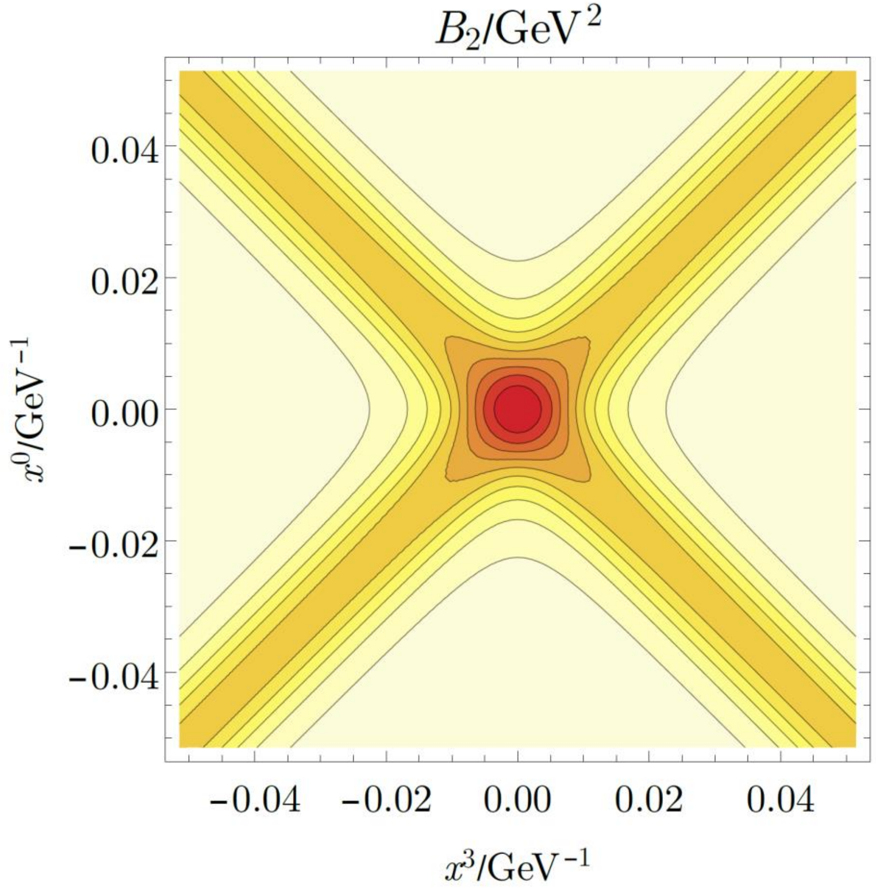
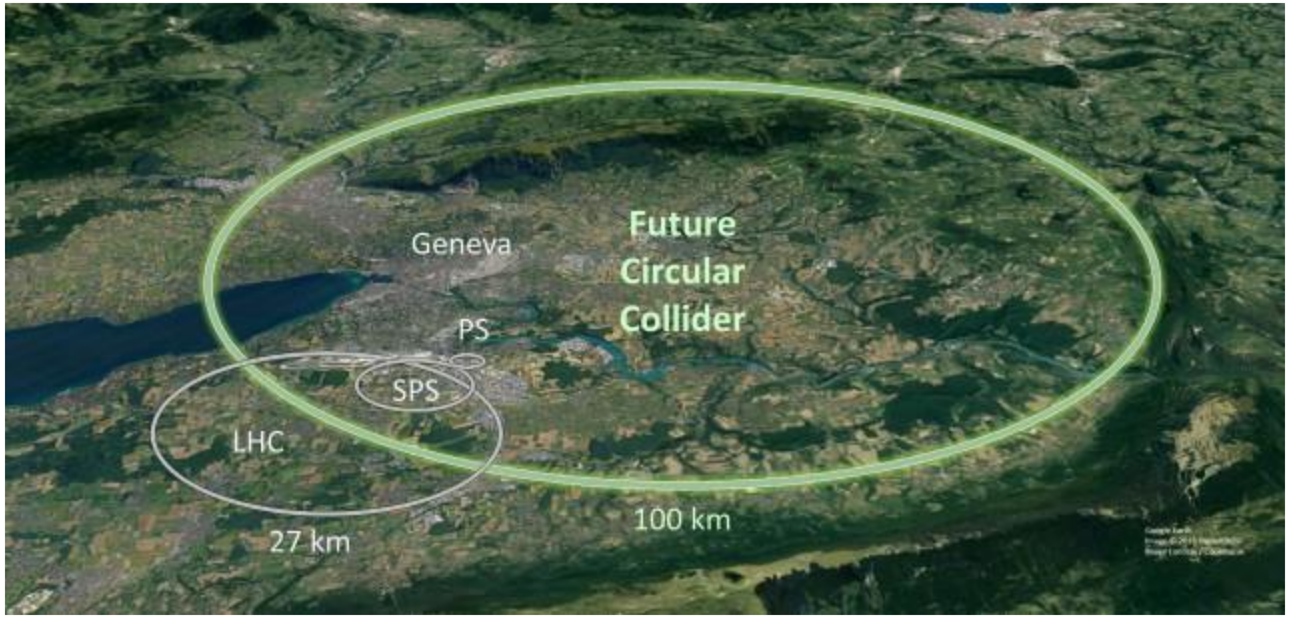
- Magnetars $|\vec{B}| \sim 10^{11}\ \mathrm{T} \sim 10^{-4}\ \mathrm{GeV}^2$
- Ultraperipheral heavy-ion collisions at the LHC
$$|\vec{B}| \sim 10^{16}\ \mathrm{T} \sim 10\ \mathrm{GeV}^2$$
for a short time $\Delta t \sim (100\ \mathrm{GeV})^{-1}$
- Still need four more orders of magnitude



(Gould,Ho&AR 2020)

Future Prospects

- Peak field strength $B \approx \frac{Ze\gamma}{2\pi R^2}$ scales with collision energy
- $B > B_{\mathrm{crit}}^{(2)} \approx 5.2 \times 10^4\ \mathrm{GeV}^2$ needed for baryon number violation requires $\sqrt{s_{NN}} \gtrsim 35\ \mathrm{PeV}$
- cf. FCC-hh : $\sqrt{s_{NN}} \sim 100\ \mathrm{TeV}$



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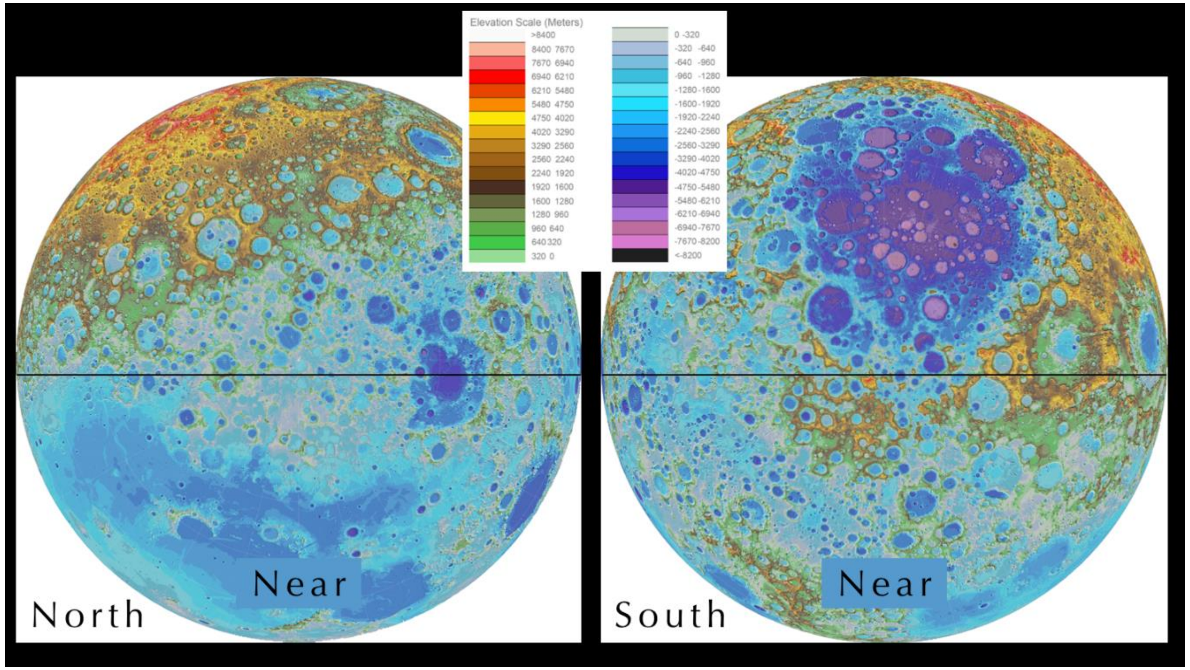
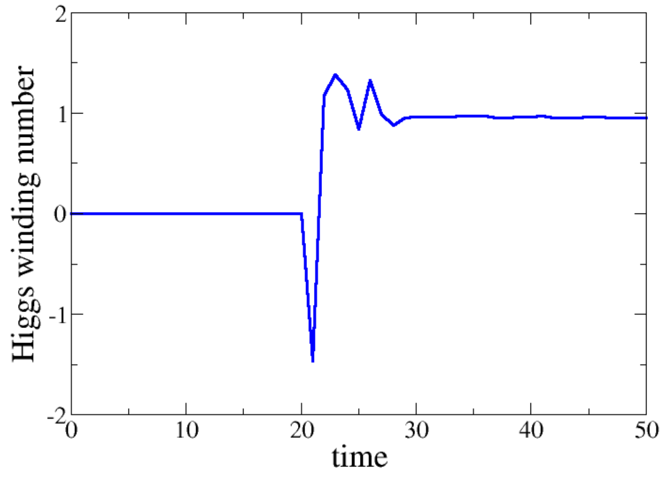
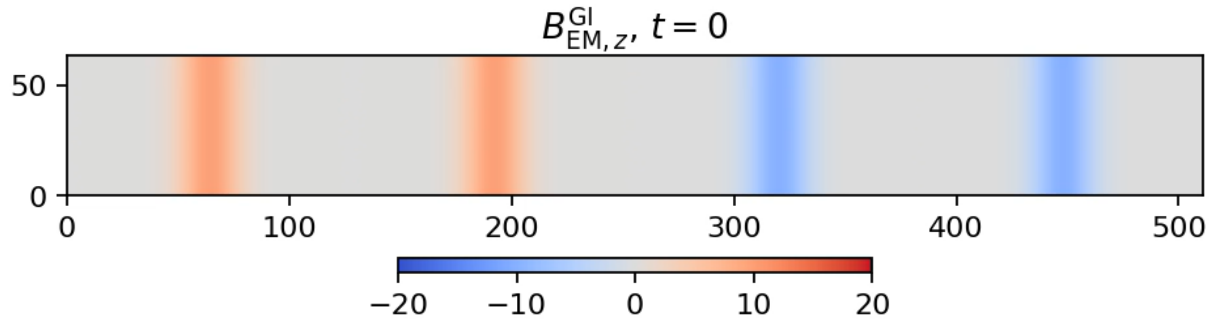
- CCM: “Circular Collider on the Moon” with $20\ \mathrm{T}$ magnets: $14\ \mathrm{PeV}$ pp collisions (Beacham&Zimmermann 2021)
- Baryon number violation with $\sim 100\ \mathrm{T}$ magnets !?

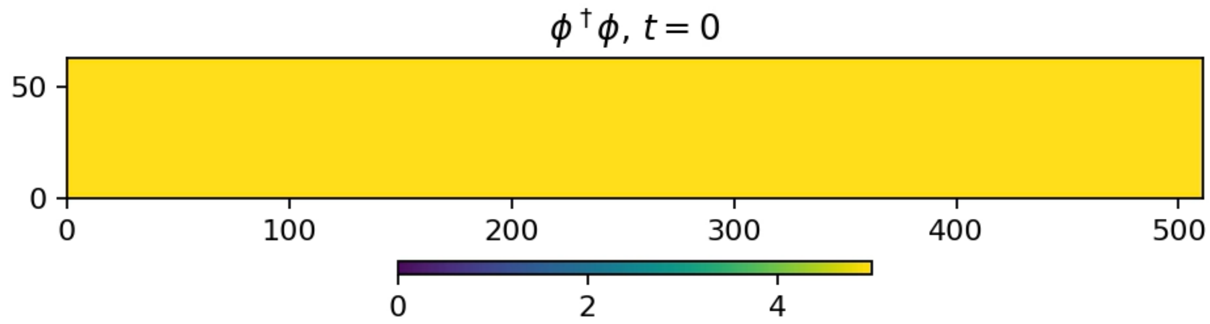


Numerical Simulation

- Two Gaussian EM wave packets:
  - Field $B_0 = 5m_H^2$, width $\Delta z = \sqrt{5}m_H^{-1}$
- Single wave packet: $\vec{B}^2 = \vec{E}^2$
  - No effect on vacuum
- Collision: $\vec{B}^2 \gg \vec{E}^2 \Rightarrow$ Ambjørn&Olesen
  - $\Delta N_H \neq 0 \Rightarrow \Delta N_{CS} \neq 0 \Rightarrow \Delta B \neq 0$







Summary

- Strong magnetic fields $B > B_{\text{crit}}^{(2)} \approx 5.2 \times 10^4\ \text{GeV}^2$ restore the electroweak symmetry and remove the sphaleron barrier
- Strongest known magnetic fields are generated in ultraperipheral heavy ion collisions
- Achieving sufficient field strength requires $\sqrt{s_{NN}} \gtrsim 35\ \text{PeV}$: Circular Collider on the Moon with $\sim 100\ \text{T}$ magnets
- Classical simulations confirm topological transition $\Rightarrow \Delta B \neq 0$ Quantum effects, particle collisions may well enhance it
- Baryon number violation may be achievable with current technology, but is prohibited by cost