Cosmic Probes of the Next Fundamental Scale of Nature

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Prologue

I do not have specific theoretical predictions for CTA in this talk. My aim is to draw community's attention to a range of new particle physics phenomena which, in the foreseeable future, can only be probed by means of high energy astrophysics.

A little bit of history

- Cosmic rays were instrumental in development of particle physics ~30^{th}-50^{th} discoveries: positron (32'), muon (37')…

- Since ~50^{th} , theoretical developments + collider physics lead to several breakthrough discoveries.

Pattern of these discoveries:
Known theory -> extrapolate to high energies -> define the energy scale where the theory breaks down -> build the collider -> discover new theory ->…

Fermi theory of weak interactions -> $E_* \sim 100\ GeV$ -> SppS (CERN) -> discovery of W,Z-bosons (electroweak unification) -> $E_* \sim 1TeV$ -> LHC (CERN) -> discovery of Higgs boson (Standard Model)

What is the next energy scale to be probed?

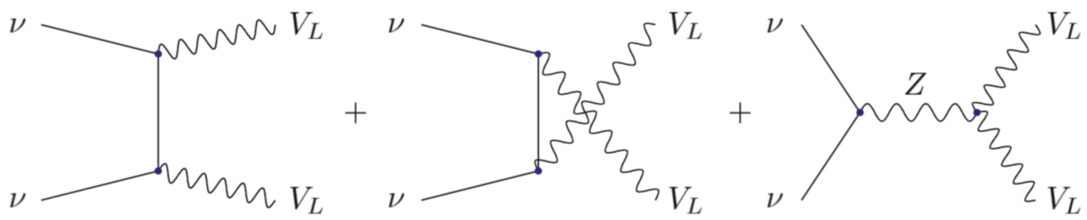
- Neutrino masses - robust evidence from particle physics (neutrino oscillation) experiments

Add neutrino mass to the SM Lagrangian (EW gauge invariance is still OK, but nonlinear):

$$\mathcal{L}_\nu = -\frac{1}{2} m_\nu \nu_L^T C \nu_L + h.c \equiv -\frac{1}{2} m_\nu \left[L^T \epsilon \Sigma\right] C \left[\Sigma^T \epsilon L\right]$$

$$L = (\nu, \ell), \;\; \Sigma = \exp\{i\sigma^a \pi^a(x)\}(0,1)$$

Consider in this theory neutrino scattering off longitudinal EW bosons:



Perturbative unitarity implies:

$$\Lambda \lesssim \frac{4}{\alpha_2} \cdot \frac{M_W^2}{m_\nu} \sim 10^{11} \text{ GeV}$$

Maltoni, Niczyporuk, and Willenbrock, 01’

What is the next energy scale to be probed?

- Dark Matter – robust, but only observed in gravitational interactions

Assuming non-relativistic DM is produced thermally via weak-strength scatterings with SM particles, we arrive at the 'WIMP miracle':

$$\Omega_X h^2 \sim \frac{3 \cdot 10^{-27} \mathrm{cm}^3/\mathrm{sec}}{\langle \sigma v_{\mathrm{rel}} \rangle}$$

Cross section is constrained from perturbative unitarity:

$$\sigma_J \leq \pi(2J+1)/p_i^2 \approx 16\pi(2J+1)/(m_X^2 v_{\mathrm{rel}}) \implies m_X^2 \leq 16\pi/(\sigma_{J=0} v_{\mathrm{rel}}), \;\; [v_{\mathrm{rel}} \approx 1/4]$$

$$\Lambda \sim m_X \lesssim 100 \ \mathrm{TeV}$$

Griest and Kamionkowski, 90'

What is the next energy scale to be probed?

- EW vacuum has topologically non-trivial structure [SU(2) sector].

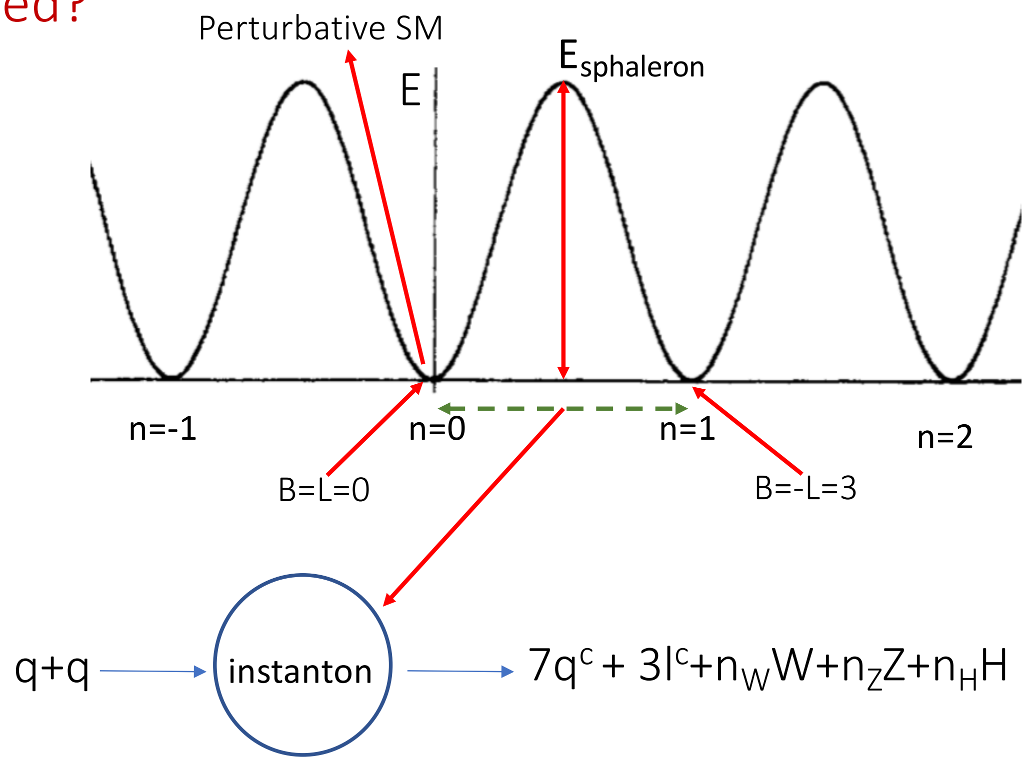
- Neighboring vacua differ by 3 units of B and L:
  ΔB=-ΔL=3Δn (quantum anomaly);
  Δ(B-L)=0.

- EW instantons are classical solution of Euclidean e.o.m., with action, e.g., for Δn =1,

$$S_{\text{inst.}} = \frac{2\pi}{\alpha_2}$$

(multiple of W,Z, H particles in a coherent state)

- describe vacuum-to-vacuum transitions)



$$\mathcal{A}_{\text{inst.}} \sim \exp\{-S_{\text{inst}}\} \approx 10^{-80}$$

$$\Lambda \sim E_{\text{sphaleron}} \sim \frac{4M_W}{\alpha_2} \approx 10\ TeV$$

Shpalerons at high energies

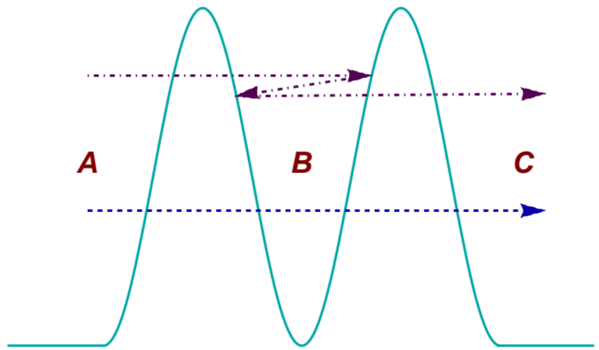
- Jump over barrier is described by production and subsequent decay of a sphaleron.

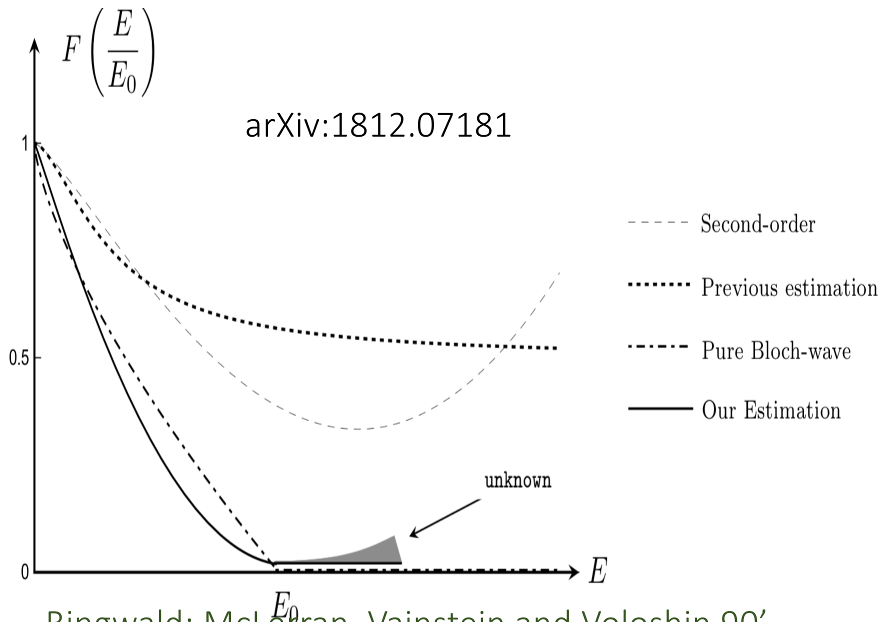
- Sphaleron is an unstable particle-like classical solution with a typical size ~$1/M_W$ and mass ~10 TeV.

- Spectacular B+L – violating processes with multiple of W,Z and H (background-free!)

- Cross section:

$$\sigma \propto \exp\{-2S_{\text{ints.}} F(E/E_0)\}, \quad [E_0 \equiv E_{\text{sphaleron}}]$$





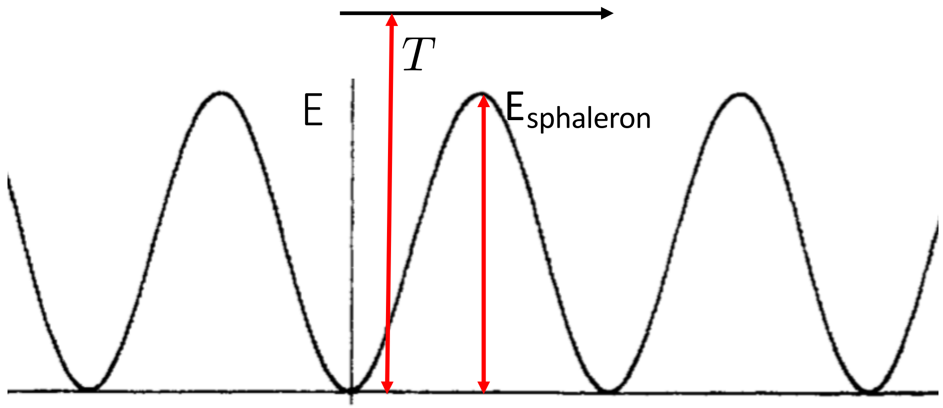
Ringwald; McLerran, Vainstein and Voloshin 90'
Bezrukov and Levkov, 03'
Tye and Wong, 15'

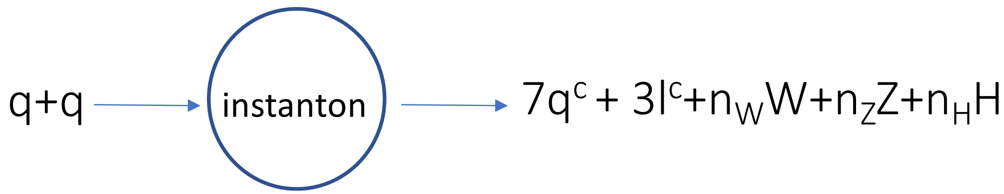
Going back in time

- Let's extrapolate our theory back in time, when the temperature of the universe was $T > E_{sphaleron}$

- Instanton mediated processes are rapid (thermally activated transitions)$\sim \alpha_2 T^4$

- Problem: any pre-existing matter-antimatter asymmetry gets washed-out and we end up in an inhabitable universe without matter.





- Alternatively: In non-equilibrium and with extra CP violation these processes could explain the origin of matter in the visible universe!

Electroweak monopoles

[Arunasalam, Collison, AK, 18']

- Standard (and incorrect) argument against electroweak monopoles:

$$H^\dagger H \equiv \phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 \overset{r\to\infty}{=} \rho_0^2$$

Map of S^2 (boundary at spatial infinity) onto the vacuum manifold S^3. The map is trivial, hence topological ('t Hooft-Polyakov) monopoles do not exist.

- However, ϕ_i can be singular (gauge d.o.f.). In that case the vacuum manifold may not be S^3.

- Consider an ansatz:

Cho and Maison, 96'

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

$$\mathbf{A}_\mu = -\frac{1}{g_2}A(r)\partial_\mu t\hat{r} + \frac{1}{g_2}(f(r)-1)\hat{r}\times\partial_\mu\hat{r},$$

$$B_\mu = -\frac{1}{g_1}B(r)\partial_\mu t - \frac{1}{g_1}(1-\cos\theta)\partial_\mu\phi.$$

Singular at θ = π/2

Electroweak monopoles

- Denote the components of doublet Higgs as: $z_1 \equiv \phi_1 + i\phi_2,\, z_2 \equiv \phi_3 + i\phi_4$

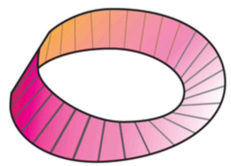
- Are defined up to hypercharge gauge transformations: $(z_1, z_2)^T \equiv (\lambda z_1, \lambda z_2)^T,\ \lambda \in U(1)_Y$;

Hence could be viewed as coordinates on a complex plane C^2 (modulo singularities).

- Remove singularities by using the gauge freedom and defining two monopole solutions on two different patches of space:

$$H_N = i\frac{\rho(r)}{\sqrt{2}}\begin{pmatrix}\sin(\theta/2)e^{-i\phi}\\ -\cos(\theta/2)\end{pmatrix}, \quad B_\phi^N = -\frac{1}{g'}\frac{1-\cos\theta}{r\sin\theta} \quad \text{for } 0 \le \theta \le \pi/2, \text{ and}$$

$$H_S = i\frac{\rho(r)}{\sqrt{2}}\begin{pmatrix}\sin(\theta/2)\\ -\cos(\theta/2)e^{i\phi}\end{pmatrix}, \quad B_\phi^S = \frac{1}{g'}\frac{1+\cos\theta}{r\sin\theta} \quad \text{for } \pi/2 \le \theta \le \pi.$$



- At the equator ($\theta = \pi/2$) the transition function $e^{i\phi}$ is a holomorphic function => (z_1, z_2) actually span a projective complex plane CP^1 .
- Hence, monopole solution is topologically nontrivial: $\pi_2(CP^1) = \pi_2(S^2) = Z$

Electroweak monopoles

- Considering, two monopole solutions on the whole space (with opposite magnetic charges), one gets monopole-antimonopole bound state, which actually is a sphaleron!

- Monopole – particle scattering is known unsuppressed (Rubakov 81'; Callan 82'). By crossing symmetry the process of production of monopole-antimonopole pair in two-particle collision must not be suppressed either. Monopole-antimonopole pair then can form sphaleron:

$$q + q \to M + M^c \to 7q^c + 3l^c + n_W W + n_Z Z + n_H H$$

- EW monopoles inevitably introduce new CP violating phase (Witten effect):

$$\mathcal{L}_\theta = \theta_2 F^a_{\mu\nu}\tilde{F}^{a\mu\nu} + \theta_1 B_{\mu\nu}\tilde{B}^{\mu\nu} \implies \mathcal{L}_\theta = \theta_{ew} F^a_{\mu\nu}\tilde{F}^{a\mu\nu}\ , \quad \theta_{ew} = \theta_2 - \theta_1$$

- Contribute to EDM of known particles
- Successful electroweak baryogenesis scenario [Arunasalam and AK, 17']

The electroweak monopole

- The mass of EW monopoles is divergent. Within the string theory inspired Born-Infeld-type extension of the Standard Model [Arunasalam, AK, 17']:

$$E_{\text{monopole}} \simeq 77.1\sqrt{\beta} + 2.8 \text{ TeV}, \quad \sqrt{\beta} \text{ is the Born-Infeld mass parameter}$$

- PVLAS measurements of nonlinearity in light propagation:

$$\sqrt{\beta} \gtrsim 5.0 \cdot 10^{-4} \text{ GeV} \implies E_{\text{monopole}} \gtrsim 2.8 \text{ TeV}$$

- Constraints from the light-by-light scattering data extracted from heavy ion collisions at LHC:

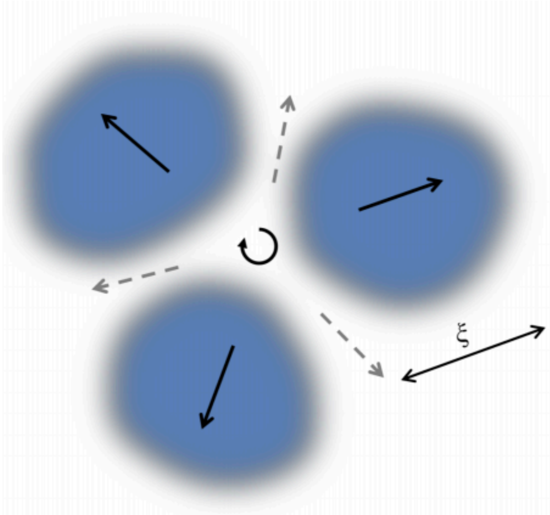
$$\sqrt{\beta} \gtrsim 88 \text{ GeV} \implies E_{\text{monopole}} \gtrsim 9.6 \text{ TeV}$$ Ellis, Mavromatos, You, 17'

- LHC is not capable to produce EW monopoles. Higher energy collider or search in cosmic rays!

- 'Sweet spot' value for EW monopole mass ~ 10^7 GeV (baryogenesis)

Cosmological production of EW monopoles

- The EW monopoles are produced during the electroweak phase transition when the temperature of the universe was T_{EW}~ 100 GeV (~10^{-32} s after Big Bang) via the Kibble mechanism.



- The estimated monopole number density today:

$$n_M \sim \frac{1}{\alpha_g^3}\left(\frac{M}{M_{\rm Pl}}\right) T_{\rm CMB}^3 \sim 10^{-26}\left(\frac{M}{10^7\ {\rm GeV}}\right)\ {\rm cm}^{-3}.$$

$\alpha_g = 1/2\alpha \simeq 68.5$ - the magnetic ‘fine structure’ constant

Astrophysics of EW monopoles

- While produced non-relativistic, (not very heavy) EW monopoles are easily accelerated in a galactic magnetic field B ~ 3μG:

$$v_{\rm mag} \sim \begin{cases} c, & M \lesssim 10^{11}{\rm GeV} \ , \\ 10^{-3} c \left(\frac{10^{17}\,{\rm GeV}}{M} \right)^{1/2}, & M \gtrsim 10^{11}{\rm GeV} \ . \end{cases}$$

- The flux of relativistic monopoles:

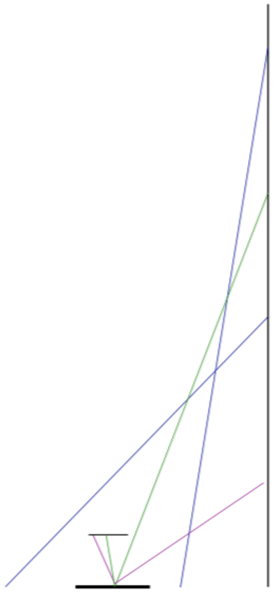
$$F = \frac{c n_M}{4\pi} \approx 2.3 \cdot 10^{-19} \left(\frac{M}{10^7 \ GeV} \right) \ {\rm cm}^{-2} \ {\rm sr}^{-1} \ {\rm s}^{-1}$$

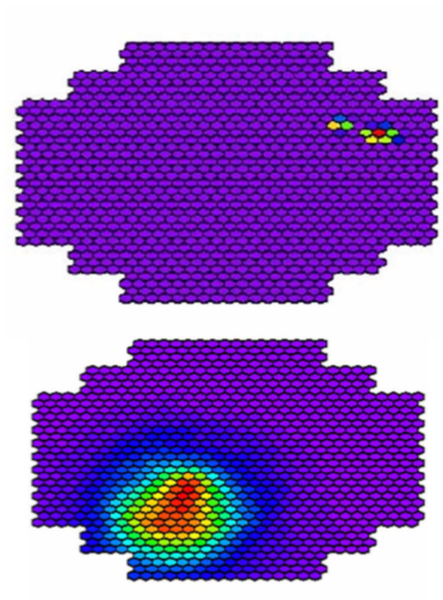
Cherenkov light from relativistic monopoles

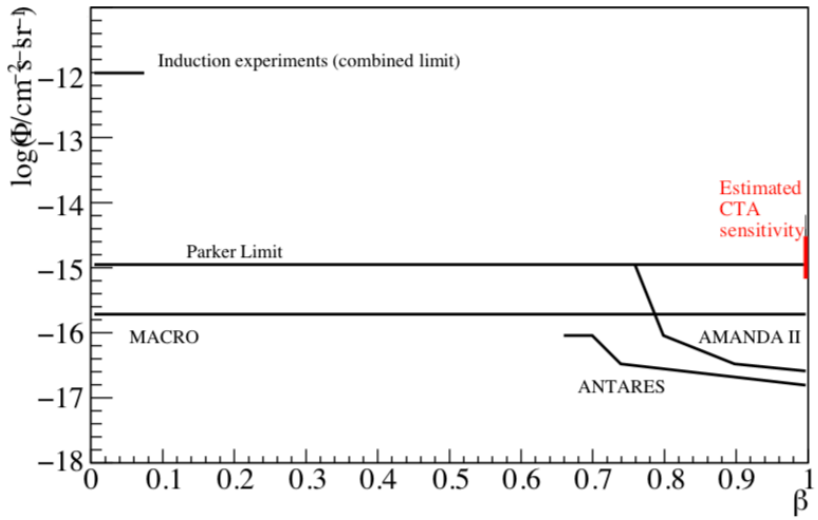
- Because much stronger electromagnetic interactions a relativistic monopole produces

$\sim n^2 \left(\frac{g}{e}\right)^2 = 2n^2\alpha_g^2 \approx 9400$ more photons than e.g., a relativistic muon.

- If no other interactions, very distinct image [Spengler, Schwanke, 11']:







M. Doro et al, 2012

More exotic signatures from EW monopoles and sphalerons

- B+L-violating electroweak scatterings:

$$M + N \to M + 6q^c + 3l^c + \text{ [Higgses, W's, Z's]}$$

Much more brighter showers than usual hadronic ones.

- More theoretical work required
- Are we throwing them out as a ‘background’?
- A dedicated image cleaning? A dedicated analysis?

Cosmic ray air showers from sphalerons

- Available energy transfer $E = \sqrt{E_{CR} m_N} \approx 500\ TeV!$

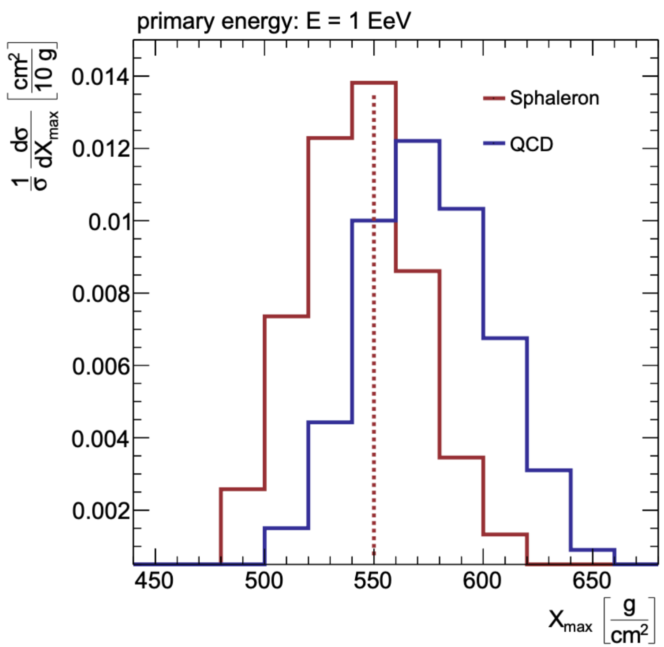
$$q + q \rightarrow 7q^c + 3l^c + n_W W + n_Z Z + n_H H$$

- At least one hard muon
- Different radial size of the air shower

Can be probed/constrained at Pierre Auger.

- Enhanced neutrino-nucleon scattering (IceCube)

$$\nu + q \rightarrow 8q^c + 2l^c + n_W W + n_Z Z + n_H H$$



arXiv:1602.00647

Conclusion

- The robust prediction for a new physics scale within SM is ~10 TeV.

- This scale is associated with a non-perturbative aspects of electroweak theory and potentially provides (less explored) portal to the BSM physics.

- Ultimate relation to one of the most fundamental puzzles of modern cosmology – the origin of matter in the universe

- High energy astrophysics is the only feasible option to probe these phenomena in the visible future

- Several theoretical/computational issues must be solved. Dedicated analyses and modelling.

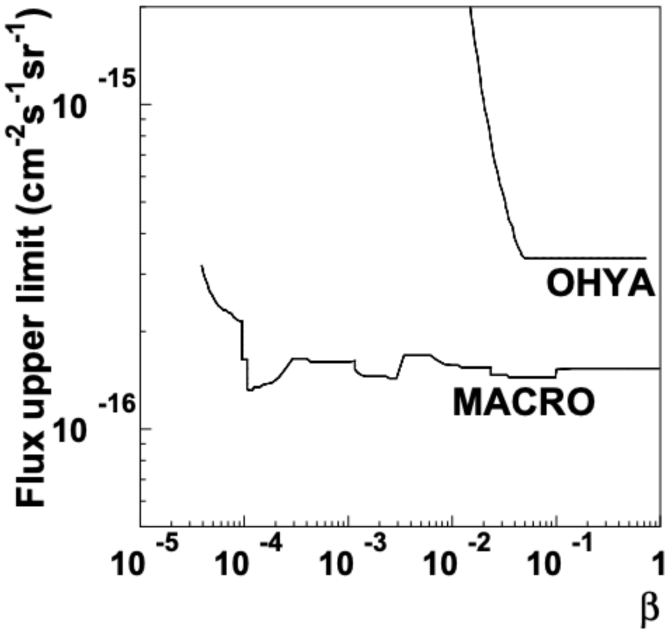
Astrophysics of EW monopoles

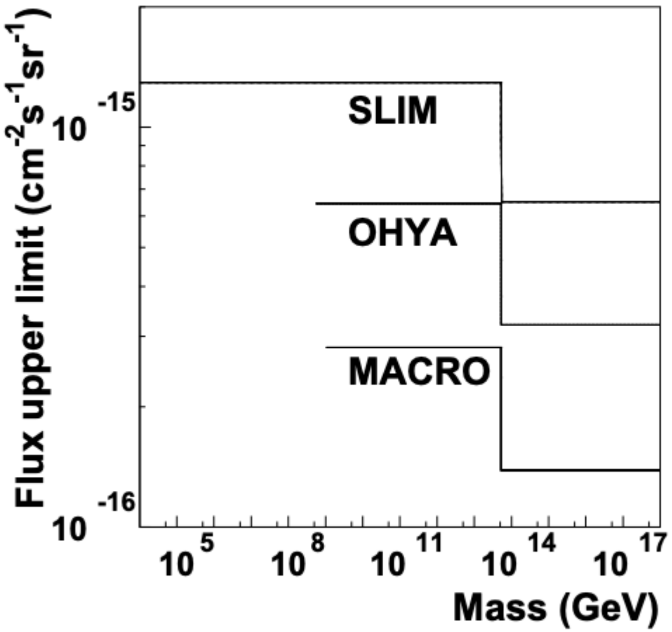
- Constraints from the survival of galactic magnetic field (the Parker bound):

$$F < \begin{cases} 10^{-15}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{sec}^{-1}\,, & M \lesssim 10^{17}\,\mathrm{GeV}\ , \\ 10^{-15}\left(\frac{M}{10^{17}\,\mathrm{GeV}}\right)\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{sec}^{-1}\,, & M \gtrsim 10^{17}\,\mathrm{GeV}\ . \end{cases}$$

- EW monopoles do not catalyze proton decay (like GUT monopoles). Therefore, bounds from the heating of compact objects do not directly apply. However, they mediate different B+L violating processes, requires careful study.

Summary of constraints





D. Mealsted & E.J. Weinberg, PDG 2017