Monopoles From an Atmospheric Collider

Syuhei Iguro,^{1,2,*} Ryan Plestid,^{3,4,†} and Volodymyr Takhistov^{5,‡}

¹Institute for Theoretical Particle Physics (TTP),

Karlsruhe Institute of Technology (KIT), Engesserstraße 7, 76131 Karlsruhe, Germany

²Institute for Astroparticle Physics (IAP), Karlsruhe Institute of Technology (KIT),

Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

³Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506, USA

⁴ Theoretical Physics Department, Fermilab, Batavia, IL 60510, USA

⁵Kavli Institute for the Physics and Mathematics of the Universe (WPI),

The University of Tokyo Institutes for Advanced Study,

The University of Tokyo, Kashiwa 277–8583, Japan

(Dated: November 25, 2021)

Magnetic monopoles have a long history of theoretical predictions and experimental searches, carrying direct implications for fundamental concepts such as electric charge quantization. We analyze in detail for the first time magnetic monopole production from collisions of cosmic rays bombarding the atmosphere. This source of monopoles is independent of cosmology, has been active throughout Earth's history, and supplies an irreducible monopole flux for all terrestrial experiments. Using results for robust atmospheric collider flux of monopoles, we systematically establish direct comparisons of previous ambient monopole searches with monopole searches at particle colliders and set leading limits on magnetic monopole production in the $\sim 5 - 100$ TeV mass-range.

Introduction – The existence of magnetically charged monopoles would symmetrize Maxwell's equations of electromagnetism and explain the observed quantization of the fundamental electric charge e, as demonstrated in seminal work by Dirac in 1931 [1]. The charge quantization condition of eg = n/2, considering natural units $c = \hbar = 1$ and where n is an integer, establishes an elementary Dirac magnetic charge of $g_D \simeq 68.5e$. More so, monopoles naturally appear in the context of Grand Unified Theories (GUTs) of unification of forces [2, 3]. Despite decades of searches, monopoles remain elusive and constitute a fundamental target of interest for exploration beyond the Standard Model.

Magnetic monopoles have been historically probed through a variety of effects (see e.g. Ref. [4] for a review). The searches include catalysis of proton decay ("Callan-Rubakov effect") [5–8], modification of galactic magnetic fields ("Parker bound") [9], Cherenkov radiation [10, 11] and ionization deposits due to monopoles accelerated in cosmic magnetic fields and contributing to cosmic radiation [12].

The majority of monopole searches have relied on an abundance of cosmological monopoles, as produced during spontaneous symmetry breaking in the early Universe via the Kibble-Zurek mechanism [13, 14]. However, the cosmological abundance of monopoles is highly sensitive to model details, such as mass of the monopoles and the scale of cosmic inflation expansion that could significantly dilute any previously produced monopoles. This results in a significant uncertainty in the interpretation of searches relying on cosmological monopole abundance and an ambient monopole flux.

While many of the previous studies have focused on ultra-heavy GUT-scale monopoles (i.e. ~ 10^{16} GeV masses), scenarios such as those based on supersymmetry exist with monopole masses $M \ll 10^{16}$ GeV, which are often called intermediate mass monopoles [15]. Recently, reinvigorated interest in monopole searches has been fueled by the identification of scenarios with viable electroweak-scale monopoles [16–21]. Sensitive searches of TeV-scale monopoles have been carried out at the Large Hadron Collider's (LHC) ATLAS [22] and MoEDAL experiments [23].

In this work we explore for the first time monopole production from collisions of cosmic rays bombarding the atmosphere. Historically, atmospheric cosmic ray collisions have been employed as a flagship production site for neutrino studies, leading to the discovery of neutrino oscillations [24]. The resulting monopole flux from the "atmospheric collider" (AtmC) is independent of cosmological uncertainties, and this source has been active for billions of years throughout Earth's history. More importantly, this robust source of monopoles is universal and potentially accessible to all terrestrial experiments. This opens a new window in which to search for magnetic monopoles and allows us to establish the first direct comparison between constraints on monopoles from colliders and historic monopole searches based on an ambient cosmic monopole abundance.

Monopole production – Collisions between incoming isotropic cosmic ray flux and the atmosphere results in copious production of particles from the model spectrum (see Ref. [25] for a review), as depicted on Fig. 1. Focusing on the dominant proton p constituents, AtmC is directly analogous to the traditional proton-proton (pp)colliders such as the LHC albeit with a boosted center-ofmass (COM) frame. Unlike, conventional collider experi-

^{*} igurosyuhei@gmail.com

[†] rpl225@uky.edu

[‡] volodymyr.takhistov@ipmu.jp



FIG. 1. A schematic of the magnetic monopole (M) production from atmospheric cosmic ray collisions.

ments that operate at a fixed energy, the LHC being ~ 10 TeV-scale, the cosmic ray flux allows for the exploration of new physics with AtmC over a broad energy spectrum reaching monopole masses as large as $\sim 10^6$ GeV.

For detailed analysis of AtmC monopole M flux production we perform Monte Carlo simulations of $pp \rightarrow M\overline{M}$ processes, drawing on the methodology of the LHC MoEDAL experiment [23, 26]. In particular, we employ MADGRAPH5 (MG5) version 3.1.0 [27] simulation tools with NNPDF31luxQED parton distribution functions [28] and input UFO files of Ref. [29] for each incident proton energy in the COM frame. This procedure allows for an "apples-to-apples" comparison between cosmic ray observations and collider searches.

We model monopole production in hadronic collisions by tree-level Feynman diagrams appropriate for an elementary charged particle [29], as employed in LHC searches [23, 26]. In particular, as depicted on Fig. 2, we consider the traditional Drell-Yan (DY) production¹ for magnetic monopoles via quark-pair annihilation through a virtual photon $q\bar{q} \rightarrow \gamma^* \rightarrow M\bar{M}$, as well as photonfusion (PF) $\gamma^*\gamma^* \rightarrow M\bar{M}$. We find numerically that photon fusion always dominates over Drell-Yan production, hence all of our results are dominated by monopole production associated with photon fusion. We note that this methodology is in contrast to other new physics searches with AtmC, which, in analogy with atmospheric neutrino studies [24], have been primarily targeting meson decays [31–34]. Monopoles are also distinct in that



FIG. 2. Diagrams for Drell-Yan and photon-fusion monopole production processes in pp collisions.

they are strongly coupled. Hence, monopoles may have large production cross sections that could allow a nonnegligible flux even when they are sourced by PeV-scale cosmic rays.

A monopole pair production requires that the square of the COM energy is $s \ge 4M^2$. This necessarily leads to highly boosted kinematics in the lab frame. The boost factor relating the lab-frame and COM frame is $\gamma_{\rm cm} = \sqrt{s}/(2m_p)$, where m_p is the proton mass, which leads to $\gamma_{\rm cm} \ge M/m_p$. Since the cosmic ray flux falls rapidly with increasing proton kinetic energy, it is expected that the majority of monopoles are produced near threshold. The typical lab-frame energy for a cosmic ray collision is therefore $\langle E_M \rangle \sim M^2/m_p$.

For simplicity, we focus on a spin-half, $g_D = 1$ and velocity (β -)independent monopole model². We have confirmed that qualitatively our final resulting limit comparison between different AtmC and traditional collider monopole searches will not be significantly impacted by this choice. Our analysis can be readily generalized and extended to other possibilities. The resultant monopoles are then boosted to the lab frame, with $E_{\rm lab} = \gamma_{\rm com} E_{\rm com} + \gamma_{\rm com} \beta_{\rm com} P_{\rm com} \cos \theta$ where $\cos \theta$ is the angle of the monopole momentum relative to the proton momentum.

From each simulation we obtain an overall pp interaction cross section $\sigma(pp \rightarrow M\overline{M})(s)$, which is then used for comparison with data and setting limits. Since lab frame distributions are primarily dictated by kinematics, the dominant uncertainty in this procedure (using tree-level Feynman diagrams to model strongly coupled theory with monopoles) is an overall normalization. Hence, we employ our simulation results as a model of the monopoles' kinematic distribution, but allow the overall normalization of the cross-section to act as a phenomenological free parameter $\sigma(pp \rightarrow M\overline{M}) = \kappa \times \sigma_{sim}$, where

¹ Recently, symmetry arguments within certain classes of theories have been put forth that question Drell-Yan monopole production [30]. In this work we remain agnostic about this traditional monopole channel and include it for direct comparison with existing searches.

 $^{^2}$ We note that the resultant cross-section is ~ 10 times larger than that of spin-zero model but ~ 10 times smaller than that of spin-one model [23]. The β -dependence of the model can suppress the cross section by a factor of 2.



FIG. 3. Flux intensity of monopoles produced in the thicktarget approximation (see text) from the top-of-atmosphere cosmic ray collisions as predicted by simulations and considering cross-section normalization of $\kappa = 1$. The net produced monopole number is two times the event number $(pp \rightarrow M\overline{M})$. Different monopole masses as well as Drell-Yan and photon-fusion production processes are shown.

 $\sigma_{\rm sim}$ is the simulation output cross-section and κ is a constant independent of s.

The outlined procedure allows us to consistently and directly compare different collider monopole searches by constraining κ for different monopole masses, accomplished by taking the ratio of the limited cross section and the simulation predictions at a particular energy. We choose a conventional reference cross section defined at $\sqrt{s} = 4M$ that is twice the threshold production energy. Considering that all incoming cosmic protons are eventually absorbed in the atmosphere, the cross-section calculated with simulations is convoluted with the inelastic cross section σ_{inel} and cosmic proton density [25]. In Fig. 3 we show the resulting weighted AtmC monopole flux event number for $pp \to M\overline{M}$ as a function of relativistic kinematic variables $\beta\gamma$.

Flux attenuation – The above procedure yields AtmC flux of monopoles that would be produced per proton in a finite "thick target" at the top of the atmosphere (TOA). Accounting for the fact that the atmosphere has an altitude-dependent density, the TOA proton flux $\mathcal{I}_p^{\text{TOA}}$ must be replaced with an attenuated proton flux that depends on both the proton energy E_p and height z (thickness of target),

$$\mathcal{I}_p(z, E_p) = \exp\left[-\int_z^\infty \frac{\mathrm{d}s}{\lambda}\right] \mathcal{I}_p^{\mathrm{TOA}}(E_p) , \qquad (1)$$

where $\lambda = 1/[n(s)\sigma_{\text{inel}}(E_p)]$ is the mean free path of a proton, and n(s) is the density profile of air taken from the global reference atmospheric model [35].

Monopoles produced at z must then propagate to a given detector at a height z_0 . In the continuous slowing down approximation (CSDA) the energy of the monopole is deterministic, with an initial monopole energy E_M

mapped to unique final energy $E'_M = E_f$. This can be computed using energy loss per unit length stopping power dE/dx = f(E)n(x) for monopoles passing through a medium of density n(x) from a point z_i to a point z_f by solving

$$\int_{E_f}^{E_i} \frac{1}{f(E)} \mathrm{d}E = \int_{z_f}^{z_i} n(x) \mathrm{d}x \tag{2}$$

for the final energy E_f . The result defines $E_f(z_i, z_f, E_i)$. We note that $f(E) = f(\beta\gamma)$, and hence the attenuation for different monopole masses can be treated by a rescaling of Eq. (2).

Effects responsible for energy deposit of monopoles traversing a medium depend on the monopole velocity, or more precisely on $\beta\gamma$. We focus on monopoles with $\beta\gamma\gtrsim$ 0.03, as relevant for the detectors of interest. Hence, we can reliably estimate the stopping power dE/dx of monopoles passing through matter using the standard Bethe-Bloch formula for ionization losses [25], applicable for quasi-relativistic and relativistic $0.03 \leq \beta \gamma \leq 10^4$ kinematic regimes. At still higher energies monopole energy losses are dominated by photonuclear processes [36] and are expected to grow super-linearly with $\beta\gamma$ for $\beta \gamma \gtrsim 10^4$, with an approximate scaling of $dE/dx \sim \gamma^{1.2}$. This has the important effect of introducing an effective maximum velocity cutoff for propagating monopoles, since any ultra-relativistic monopole is rapidly decelerated until it hits the plateau of the Bethe-Bloch ionization. The breaking effect from photon-nuclear reactions ensures that any monopoles reaching the Earth's surface have $\beta \gamma \lesssim 10^4 - 10^5$, with the precise upper limit being dependent on the monopole mass.

The monopole intensity at a detector is then given by

$$\mathcal{I}_{M}(z_{0}, E'_{M}) = \int dE_{p} dz \ T(E'_{M}|E_{M}) \times \mathcal{I}_{p}(z, E_{p}) \ n(z) \frac{d\sigma(E_{p})}{dE_{M}} , \qquad (3)$$

where \mathcal{I} is defined in Eq. (1), $T(E'_M|E_M)$ is the CSDA transfer matrix $T(E'_M|E_M) = \delta(E'_M - E_f(z_i, z_f, E_M))$. The *pp* inelastic cross section is a very slowly varying function of E_p at high energies and can be approximated by a constant value [25]. We may then factorize Eq. (3) into two integrals

$$\mathcal{I}_{M}(z_{0}, E'_{M}) = \int dE_{p} \ \mathcal{I}_{p}^{\text{TOA}}(E_{p}) \ \frac{1}{\sigma_{\text{inel}}} \frac{d\sigma}{dE_{M}}$$
(4)
$$\times \left[\int_{z_{0}}^{\infty} dz \ \frac{1}{\lambda(z)} \ T(E'_{M}|E_{M}) \mathrm{e}^{-\int_{z}^{\infty} ds/\lambda} \right].$$

The top line of this formula may be interpreted as the primary flux of monopoles passing through a thick target, $\mathcal{I}_{TT}(E_M)$. We note that the number of monopoles in this treatment is conserved, however their energy is attenuated as they propagate through a medium.

Experimental searches – AtmC establishes a universal sustained monopole flux source that is available for

all terrestrial experiments. As we demonstrate, AtmC monopole flux can be exploited together with existing data from historic experimental searches for ambient uncertain monopole flux to establish novel robust leading limits on magnetic monopoles and their production.

For an experiment located at high-altitude compared to Earth's sea level, such as SLIM [37], the attenuation of the monopole flux by the atmosphere will set a lower bound on the mass of monopoles that can reach the detector site. Given experimental sensitivity threshold to monopoles at β_{\min} , the detector's signal intensity is then found by integrating Eq. (4) from $\beta' = \beta_{\min}$ to ∞ . Within the CSDA, for each fixed z at which a monopole is produced, there is a well defined $E_M^{[\min]}(z)$ above which monopoles will be travelling faster than the cutoff $\beta' \geq \beta_{\min}$ at the detector location.

Hence, the signal flux of down-going monopoles reaching the high altitude experiment $\mathcal{I}_{M}^{\text{high}}$ is given by

$$\mathcal{I}_{M}^{\text{high}} = \int_{z_{\text{exp}}}^{\infty} \frac{\mathrm{e}^{-\int_{z}^{\infty}} \frac{\mathrm{d}s}{\lambda(s)}}{\lambda(z)} \int_{E_{M}^{[\text{min}]}(z)}^{\infty} \mathrm{d}E_{M} \mathcal{I}_{TT}(E_{M}) , \quad (5)$$

where $z_{\rm exp}$ is the height of experimental site above sea level. This treatment can be readily generalized to incorporate different zenith angles. Here, we treat $\sigma_{\rm inel}$ as a function of E_p in calculating \mathcal{I}_{TT} . For the propagation of the flux through the atmosphere, it is the lowest energy monopoles that are most important. Thus, we approximate $\sigma_{\rm inel} = 40$ mb, which is valid for 5 GeV $\leq E_p \leq 10^4$ GeV [25], in calculating the mean free path $\lambda = 1/(n\sigma_{\rm inel})$ in Eq. (5).

Deep underground experiments with significant overburdens, such as IceCube [10] or AMANDA [42], are largely insensitive to atmospheric effects. Any monopole that can penetrate the overburden will loose negligible energy while traversing the atmosphere. Hence, the intensity of monopoles arriving at the surface can be reliably approximated by $\mathcal{I}_{TT}(E_M)$. For deep underground detectors, whose column density of overburden satisfies ρ_{\perp} (overburden) $\gg \rho_{\perp}(air)$, we instead focus on the zenith-angle dependence of the intensity.

The resulting path length that a monopole must travel through the overburden, ℓ , for a detector with an overburden of depth d, is given by

$$\ell = \sqrt{\cos^2 \theta_z (R-d)^2 + d \left(2R - d\right)} - \cos \theta_z (R-d) \,, \ (6)$$

where R is the Earth's radius. Using Eq. (2) we can take $z_i = \ell$, and fix $E_f \ge E_{\text{thr}}$ for the threshold energy (or equivalently velocity β_{\min}) of the given experimental search. This defines $E_M^{[\min]}(\cos \theta_z)$. Including a zenith



FIG. 4. Comparison of novel monopole limits from cosmic ray atmospheric collisions derived in this work using historic data from SLIM, AMANDA-II (AM-II) and RICE experiments. Also displayed is a crude projection for a downgoing monopole search in IceCube experiment (IC Est.) defined by multiplying the sensitivity from AMANDA-II by a factor of 200. Comparison is systematically achieved using the common reference cross section for $pp \to M\overline{M}$ defined by $\kappa \times \sigma_{\rm sim}(s=16M^2)$, where the normalization κ is found by comparing the simulation predictions to the derived constraints for each target experiment. Existing limits for collider monopole searches by OPAL [38], CDF [39], MoEDAL [23], and ATLAS [22] experiments are shown. We have further excluded monopole masses less than 75 GeV due to constraints from Pb-Pb collisions that rely on the calculable Schwinger pair production cross section [40]. Also displayed is the total $pp \to X$ cross section, as parameterized by the COMPETE collaboration [41], which sets an upper limit on the allowed $pp \to M\overline{M}$ cross section.

angle-dependent efficiency³, $\epsilon(\cos \theta_z)$, the observed intensity at an underground experiment, $\mathcal{I}_M^{\text{und}}$, corresponding to an integrated observed intensity $\mathcal{I}_M^{\text{obs}}$ over a solid angle

³ The background of cosmic ray muons depends on zenith angle and so experimental cuts are necessarily more severe for downgoing monopoles. Because the monopole flux is attenuated at large zenith angles there is a competition between these two effects such that an optimum zenith angle will be achieved at intermediate values $\theta_z \sim \pi/6 - \pi/3$.

is given by

$$\mathcal{I}_{M}^{\text{und}} = \int d\Omega \ \mathcal{I}_{M}^{\text{obs}}$$
$$= 2\pi \int d\cos\theta_{z} \ \epsilon(\cos\theta_{z}) \qquad (7)$$
$$\times \int_{E_{M}^{[\min]}(\cos\theta_{z})}^{\infty} dE_{M} \ \mathcal{I}_{TT}(E_{M}) \ .$$

Using Eqs. (5) and (7) and the output of the simulations shown in Fig. 3 we can test and set limits on monopole production cross section in *pp* collisions. Existing experimental limits on an ambient astrophysical monopole flux⁴ include those from AMANDA-II [42], Ice-Cube [10], MACRO [43], SLIM [37], NOvA [44], ANITA-II [36], and the Baikal observatory [11]. We note, however, that some of these limits are not applicable to AtmC monopoles produced in cosmic ray showers.

Experiments without very significant overburden can achieve increased sensitivity by limiting the analysis to up-going monopoles, which suppresses atmospheric muon backgrounds. However, this implicitly assumes massive monopoles traversing the bulk of the Earth's interior with path lengths on the order of thousands of kilometers and is thus not applicable to AtmC monopoles. Therefore, we do not consider such limits from IceCube [10] or Baikal [11] Cherenkov detectors that imposed a cut on the zenith angle of the incoming monopole direction to be up-going.

Searches sensitive to slow-moving monopoles with $\beta\gamma \lesssim 10$ are also ineffective for probing AtmC monopoles. This includes deep underground MACRO experiment analysis focusing on $\beta \leq 0.99$ monopoles [12] and that of surface-based NOvA experiment focusing on $\beta < 5 \times 10^{-3}$ monopoles [44]. Analogously, AtmC flux is also highly suppressed for ultra-relativistic monopoles, as can be seen from Fig. 3. Hence, we do not consider limits from ANITA-II focusing on $\beta\gamma \gtrsim 10^9$ [36].

Analogously to the balloon-based ANITA-II [36], the RICE underground experiment focused on detecting radio emission from in-ice monopole interactions albeit in regimes relevant for AtmC monopoles with $\beta \gamma \gtrsim 10^7$ [45]. At such large boosts the attenuation from the air is negligible, whereas from the Earth it is substantial. We reinterpret RICE limits for AtmC monopoles, multiplying them by an additional factor of 2 to approximately account for the absence of up-going monopoles. In particular, we employ the monopole flux limits of Ref. [45] for $\gamma = 10^7$ and $\gamma = 10^8$ and compare them to our simulation flux predictions integrated over the intervals of $\gamma \in [10^{6.5}, 10^{7.5}]$ and $\gamma \in [10^{7.5}, 10^{8.5}]$, respectively. The resulting novel limits are displayed in Fig. 4.

Particularly favorable for AtmC monopoles is the SLIM nuclear track experiment [37], sensitive to lighter

mass monopoles due to its high elevation of 5230 m above sea level. In setting limits we use SLIM's constraint for $\beta \geq 0.03$ and therefore require that monopoles reaching the detector have $\beta\gamma \geq 0.03$. As the search is for purely down-going ($\cos \theta_z = 1$) monopoles, we employ Eq. (5) directly together with the bound of $\mathcal{I}(\cos \theta_z =$ $1) \leq 1.3 \times 10^{-15}$ cm⁻² s⁻¹ str⁻¹. We find that the newly established bounds on monopoles from AtmC by SLIM are superseded by collider searches at lower masses, as well as RICE and AMANDA-II at higher masses, as shown on Fig. 4.

Dedicated search for down-going monopoles has been performed by the deep-ice South Pole AMANDA-II experiment [42]. For AMANDA-II analysis we take into account the zenith angle dependence of the monopole detection efficiency which we extract from their data (see below). We employ the resulting constraints for Cherenkov emission from a $\beta = 1$ monopole, and require $\beta \gamma \geq 3$ that corresponds to $\beta \geq 0.95$. the down-going monopole search of AMANDA-II imposes a cut on the zenith angle and a cut in the space of $\cos \theta_z$ and ΣADC , a quantity related to the sum of the photomultiplier tube pulse amplitudes. We infer the efficiency as a function of ΣADC from Fig. 11 and the cut on ΣADC as a function of $\cos \theta_z$ from Fig. 12 of Ref. [42]. The AMANDA-II bounds assume an isotropic flux of monopoles such that $\Phi \leq C / \int \epsilon(\cos \theta_z) \mathrm{d} \cos \theta_z$. Extracting C and including an appropriate zenith angle flux we then compute the cross-section normalization factor κ . The results are depicted on Fig. 4. We find that AMANDA-II and RICE establish comparable monopole limits when converted to the reference cross section.

Conclusions – Magnetic monopoles are directly connected with different aspects of fundamental physics and have been a prominent topic of both theoretical and experimental investigations for decades. We have analyzed for the first time monopole production from atmospheric cosmic ray collisions. This source of monopoles is not subject to cosmological uncertainties and is persistent for all terrestrial experiments. Using historic data from RICE, AMANDA-II and SLIM experiments together with monopole flux from atmospheric cosmic ray collisions, we have established leading robust bounds on the production cross section of magnetic monopoles in the $\sim 5 - 100$ TeV mass-range. We project that a dedicated search from IceCube could potentially set the best limits on monopole masses larger than 5 TeV that lie beyond the reach of current colliders.

Acknowledgements – We thank Mihoko Nojiri for discussion of the parton distribution functions. The work of S.I. is supported by the JSPS Core-to-Core Program (Grant No. JPJSCCA20200002). V.T. is supported by the World Premier International Research Center Initiative (WPI), MEXT, Japan. This work was performed in part at Aspen Center for Physics, which is supported by National Science Foundation grant PHY-1607611. R.P. is supported by the U.S. Department of Energy, Office

⁴ We do not consider here searches focusing on GUT monopoles, e.g. Super-Kamiokande [8].

of Science, Office of High Energy Physics, under Award Number DE-SC0019095. This manuscript has been au-

thored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

- P. A. M. Dirac, "Quantised singularities in the electromagnetic field,," Proc. Roy. Soc. Lond. A 133 (1931) 60-72.
- [2] A. M. Polyakov, "Particle Spectrum in Quantum Field Theory," JETP Lett. 20 (1974) 194–195.
- [3] G. 't Hooft, "Magnetic Monopoles in Unified Gauge Theories," Nucl. Phys. B 79 (1974) 276–284.
- [4] N. E. Mavromatos and V. A. Mitsou, "Magnetic monopoles revisited: Models and searches at colliders and in the Cosmos," Int. J. Mod. Phys. A 35 (2020) 2030012 [arXiv:2005.05100].
- [5] V. A. Rubakov, "Superheavy Magnetic Monopoles and Proton Decay," JETP Lett. 33 (1981) 644–646.
- [6] V. A. Rubakov and M. S. Serebryakov, "Anomalous Baryon Number Nonconservation in the Presence of SU(5) Monopoles," Nucl. Phys. B 218 (1983) 240–268.
- [7] C. G. Callan, Jr., "Monopole Catalysis of Baryon Decay," Nucl. Phys. B 212 (1983) 391–400.
- [8] Super-Kamiokande Collaboration, "Search for GUT monopoles at Super-Kamiokande," Astropart. Phys. 36 (2012) 131-136 [arXiv:1203.0940].
- [9] E. N. Parker, "The Origin of Magnetic Fields," Astrophys. J. 160 (1970) 383.
- [10] IceCube Collaboration, "Searches for Relativistic Magnetic Monopoles in IceCube," Eur. Phys. J. C 76 (2016) 133 [arXiv:1511.01350].
- [11] C. de los Heros, ed., "Search for relativistic magnetic monopoles with the Baikal Neutrino Telescope," Astropart. Phys. 29 (2008) 366–372.
- [12] MACRO Collaboration, "Final results of magnetic monopole searches with the MACRO experiment," Eur. Phys. J. C 25 (2002) 511–522 [hep-ex/0207020].
- [13] T. W. B. Kibble, "Topology of Cosmic Domains and Strings," J. Phys. A 9 (1976) 1387–1398.
- [14] W. H. Zurek, "Cosmological Experiments in Superfluid Helium?" Nature **317** (1985) 505–508.
- [15] T. W. Kephart, G. K. Leontaris, and Q. Shafi, "Magnetic Monopoles and Free Fractionally Charged States at Accelerators and in Cosmic Rays," JHEP 10 (2017) 176 [arXiv:1707.08067].
- [16] Y. M. Cho and D. Maison, "Monopoles in Weinberg-Salam model," Phys. Lett. B **391** (1997) 360–365 [hep-th/9601028].
- [17] Y. M. Cho, K. Kim, and J. H. Yoon, "Finite Energy Electroweak Dyon," Eur. Phys. J. C 75 (2015) 67 [arXiv:1305.1699].
- [18] J. Ellis, N. E. Mavromatos, and T. You, "The Price of

an Electroweak Monopole," Phys. Lett. B **756** (2016) 29–35 [arXiv:1602.01745].

- [19] S. Arunasalam and A. Kobakhidze, "Electroweak monopoles and the electroweak phase transition," Eur. Phys. J. C 77 (2017) 444 [arXiv:1702.04068].
- [20] M. Arai, F. Blaschke, M. Eto, and N. Sakai, "Localization of the Standard Model via the Higgs mechanism and a finite electroweak monopole from non-compact five dimensions," PTEP **2018** (2018) 083B04 [arXiv:1802.06649].
- [21] J. Ellis, N. E. Mavromatos, and T. You, "Light-by-Light Scattering Constraint on Born-Infeld Theory," Phys. Rev. Lett. 118 (2017) 261802 [arXiv:1703.08450].
- [22] ATLAS Collaboration, "Search for Magnetic Monopoles and Stable High-Electric-Charge Objects in 13 Tev Proton-Proton Collisions with the ATLAS Detector," Phys. Rev. Lett. 124 (2020) 031802 [arXiv:1905.10130].
- [23] MOEDAL Collaboration, "Magnetic Monopole Search with the Full MoEDAL Trapping Detector in 13 TeV pp Collisions Interpreted in Photon-Fusion and Drell-Yan Production," Phys. Rev. Lett. **123** (2019) 021802 [arXiv:1903.08491].
- [24] Super-Kamiokande Collaboration, "Evidence for oscillation of atmospheric neutrinos," Phys. Rev. Lett. 81 (1998) 1562–1567 [hep-ex/9807003].
- [25] Particle Data Group Collaboration, "Review of Particle Physics," PTEP 2020 (2020) 083C01.
- [26] MoEDAL Collaboration, "Search for magnetic monopoles with the MoEDAL forward trapping detector in 2.11 fb⁻¹ of 13 TeV proton-proton collisions at the LHC," Phys. Lett. B 782 (2018) 510–516 [arXiv:1712.09849].
- [27] J. Alwall, et al., "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations," JHEP 07 (2014) 079 [arXiv:1405.0301].
- [28] NNPDF Collaboration, "Illuminating the photon content of the proton within a global PDF analysis," SciPost Phys. 5 (2018) 008 [arXiv:1712.07053].
- [29] S. Baines, N. E. Mavromatos, V. A. Mitsou, J. L. Pinfold, and A. Santra, "Monopole production via photon fusion and Drell-Yan processes: MadGraph implementation and perturbativity via velocity-dependent coupling and magnetic moment as novel features," Eur. Phys. J. C 78 (2018) 966 [arXiv:1808.08942]. [Erratum: Eur.Phys.J.C 79, 166 (2019)].
- [30] J. Terning and C. B. Verhaaren, "Spurious Poles in the

Scattering of Electric and Magnetic Charges," JHEP 12 (2020) 153 [arXiv:2010.02232].

- [31] P. Coloma, P. Hernández, V. Muñoz, and I. M. Shoemaker, "New constraints on Heavy Neutral Leptons from Super-Kamiokande data," Eur. Phys. J. C 80 (2020) 235 [arXiv:1911.09129].
- [32] R. Plestid, et al., "New Constraints on Millicharged Particles from Cosmic-ray Production," Phys. Rev. D 102 (2020) 115032 [arXiv:2002.11732].
- [33] C. A. Argüelles Delgado, K. J. Kelly, and V. Muñoz Albornoz, "Millicharged Particles from the Heavens: Single- and Multiple-Scattering Signatures." arXiv:2104.13924.
- [34] P. Candia, G. Cottin, A. Méndez, and V. Muñoz, "Searching for light long-lived neutralinos at Super-Kamiokande," Phys. Rev. D 104 (2021) 055024 [arXiv:2107.02804].
- [35] J. M. Picone, A. E. Hedin, D. P. Drob, and A. C. Aikin, "NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues," Journal of Geophysical Research: Space Physics **107** (2002) SIA 15–1–SIA 15–16.
- [36] ANITA-II Collaboration, "Ultra-Relativistic Magnetic Monopole Search with the ANITA-II Balloon-borne Radio Interferometer," Phys. Rev. D 83 (2011) 023513 [arXiv:1008.1282].
- [37] S. Balestra *et al.*, "Magnetic Monopole Search at high altitude with the SLIM experiment," Eur. Phys. J. C 55

(2008) 57-63 [arXiv:0801.4913].

- [38] OPAL Collaboration, "Search for Dirac magnetic monopoles in e+e- collisions with the OPAL detector at LEP2," Phys. Lett. B 663 (2008) 37-42 [arXiv:0707.0404].
- [39] **CDF** Collaboration, "Direct search for Dirac magnetic monopoles in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV," Phys. Rev. Lett. **96** (2006) 201801 [hep-ex/0509015].
- [40] B. Acharya et al., "First experimental search for production of magnetic monopoles via the Schwinger mechanism." arXiv:2106.11933.
- [41] COMPETE Collaboration, "Benchmarks for the forward observables at RHIC, the Tevatron Run II and the LHC," Phys. Rev. Lett. 89 (2002) 201801 [hep-ph/0206172].
- [42] R. Abbasi *et al.*, "Search for relativistic magnetic monopoles with the AMANDA-II neutrino telescope," Eur. Phys. J. C 69 (2010) 361–378.
- [43] MACRO Collaboration, "Search for nucleon decays induced by GUT magnetic monopoles with the MACRO experiment," Eur. Phys. J. C 26 (2002) 163–172 [hep-ex/0207024].
- [44] NOvA Collaboration, "Search for slow magnetic monopoles with the NOvA detector on the surface," Phys. Rev. D 103 (2021) 012007 [arXiv:2009.04867].
- [45] D. P. Hogan, D. Z. Besson, J. P. Ralston, I. Kravchenko, and D. Seckel, "Relativistic Magnetic Monopole Flux Constraints from RICE," Phys. Rev. D 78 (2008) 075031 [arXiv:0806.2129].