Searches for fractionally charged particles in cosmic rays

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290E

Nov. 28, 2018

Millikan's Oil Drop

- The story begins with the discovery of quantized electric charge
- Early work motivated by disproving Millikan (Felix Ehrenhaft, Univ. of Vienna)
- Later: quarks are fractionally charged particles!

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Searches for *free* fractionally charged particles in cosmic rays

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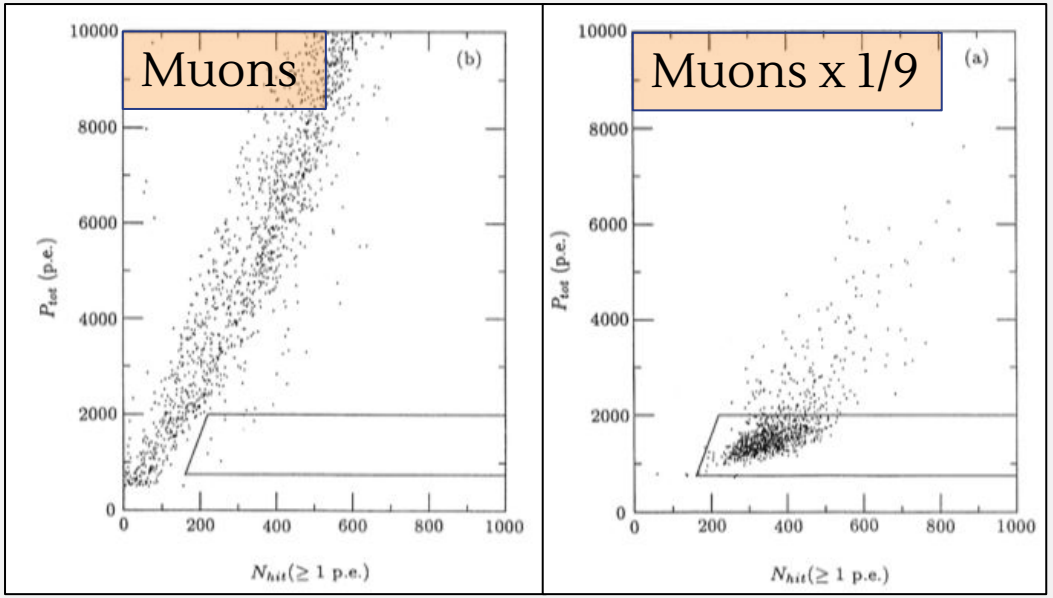
Kamiokande II

- A pretty famous experiment
- Large water-based Cherenkov scintillation detector
- Large background due to minimum ionizing muons
- The number of Cherenkov photons produced by a minimum ionizing charged particle is proportional to its charge squared

Wikimedia commons

KII "Simulations"

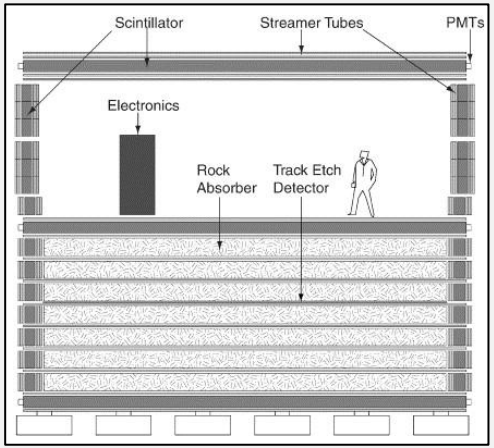
- A free quark has charge magnitude of 1/3 or 2/3 compared to a muon
- K-II scaled their background muon dataset by 1/9 and 4/9 to simulate free quarks in their detector and develop selection cuts
- No observed fractional charges

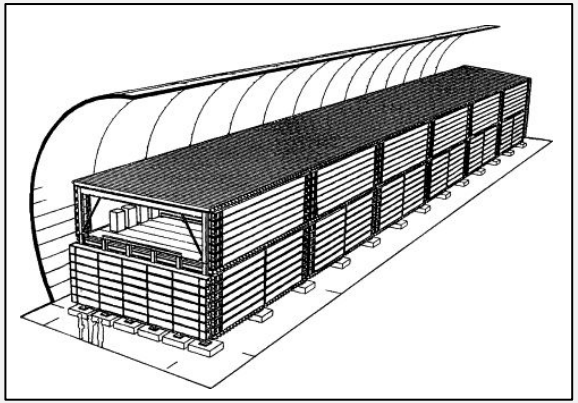


Mori M. et al. Phys. Rev. D 43:2843 (1991)

MACRO (2004)

- Main physics goal was magnetic monopole search
- Streamer tubes used to reconstruct particle trajectory
- Scintillator used for low energy trigger and redundant energy loss measurement in fractionally charged particle search

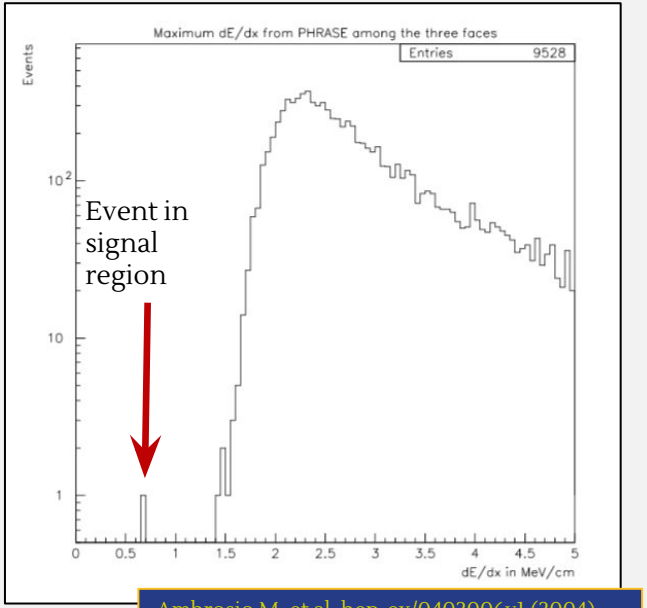




M. Ambrosio, et al. NIM A 486:663 (2004)

MACRO Results (2004)

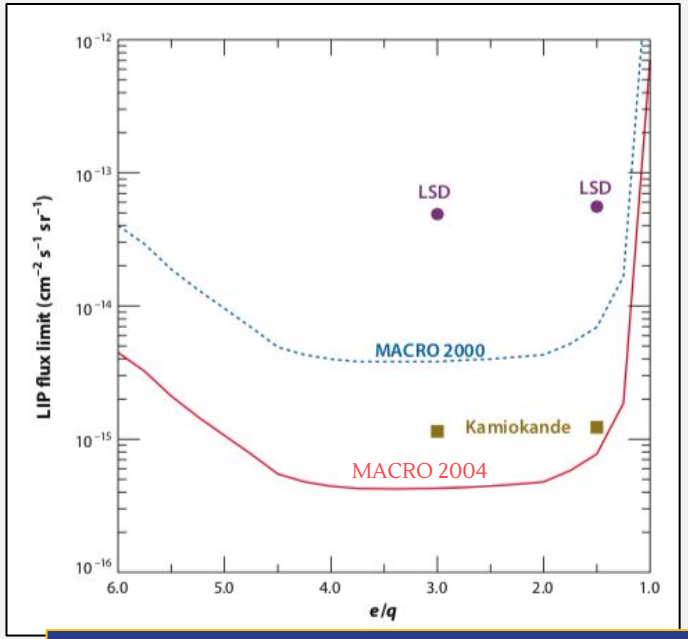
- Fractionally charged particle looks like a lightly ionizing particle (LIP) in the detector
- Looking for muon-like events with reduced dE/dx
- Low energy trigger designed specifically for LIPs
- Signal region [0, 1.35] MeV
- Single event discarded after hand-scanning waveforms



Ambrosio M, et al. hep-ex/0402006v1 (2004)

Limits (as of 2004)

- None of these experiments observed any LIP candidate events
- Can set limits on the isotropic flux of LIPs
- MACRO moved beyond looking only looking for free quarks because new physics can introduce particles with other fractional charges
- Fractionally charged particles are distinct from LIPs (an event topology)



This figure: M. Perl, et al. Annu. Rev. Nucl. Part. Sci. 59:47 (2009)
Original: Ambrosio M, et al. hep-ex/0402006v1 (2004)

free

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and lightly ionizing particles

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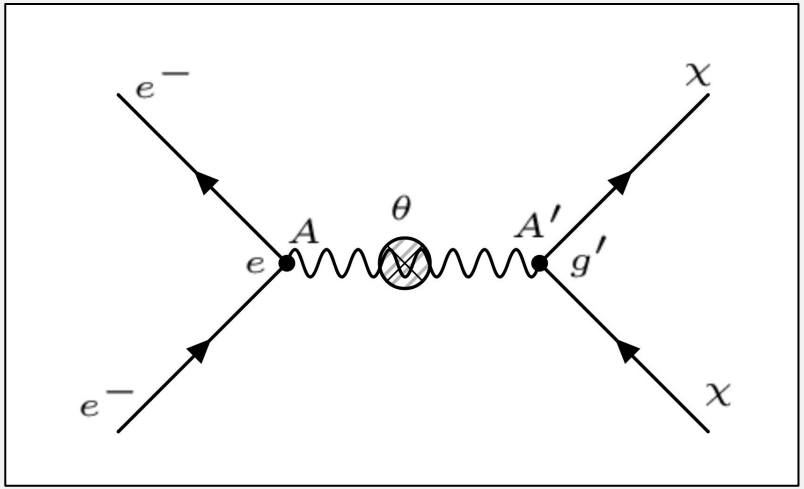
LIPs From the Dark Sector

- Dark photons refer to a U(1) field with massless gauge bosons A'.
- Expect kinetic mixing with standard model photons defined by mixing angle θ
- A' couples to massive dark sector particles, which can make up some or all of dark matter

$$\mathcal{L} = \frac{\theta}{2} F_{\mu\nu} F'^{\mu\nu}$$

LIP Interactions

- Thanks to kinetic mixing, dark sector particles interact with charged SM particles
- 'Millicharge' magnitude $\varepsilon e = \theta g'_e$
- $\varepsilon = 1/q$ (previous plot) $= \delta/e$ (later plot)



~~Searches for fractionally charged particles in cosmic rays~~

A surprise dark matter talk

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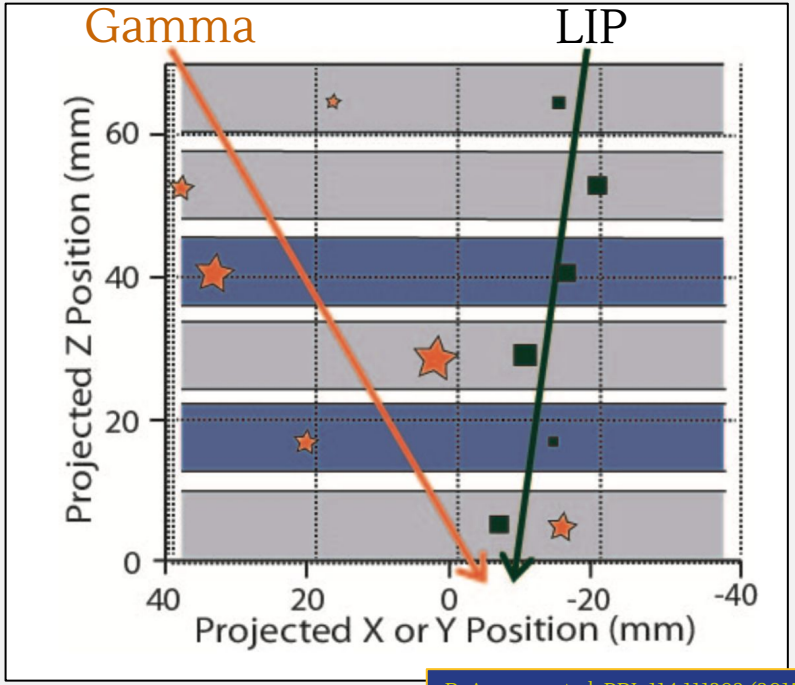
Modern LIP Searches

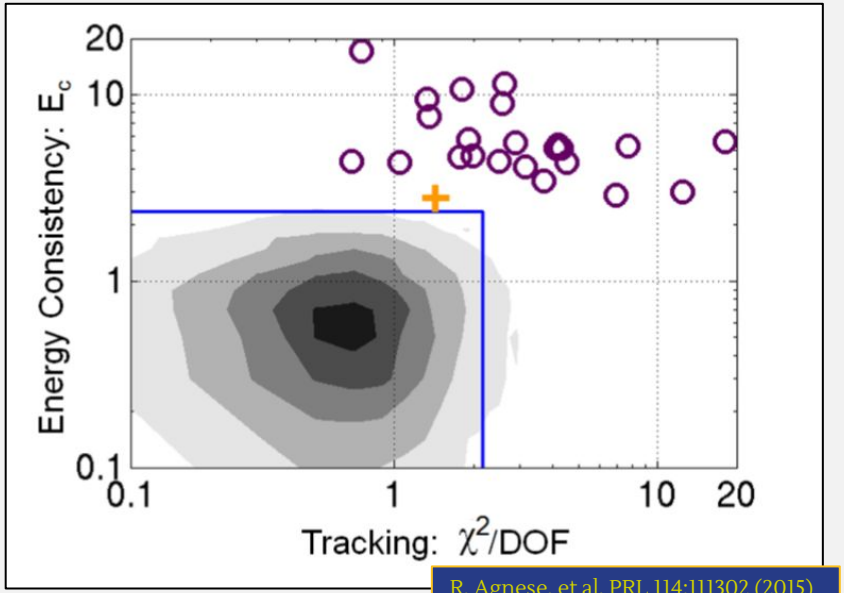
- Leverage existing rare event search experiments with low energy thresholds and low background rates
- So far, only results from cryogenic Si and Ge detector experiments (CDMS II simulation at right)
- Try to find electron recoil events where the deposits lie on a line since LIPs are assumed to be highly relativistic (minimally deflected)



R. Agnese, et al. PRL 114:111302 (2015)

CDMS II Results (2015)

- Chi2 is a measure of linearity of the deposits in an event
- Energy consistency is a measure of how uniform in magnitude deposits are
- Results for $q^{-1} = 15$, where acceptance region is inside blue square and contours are expected LIP distribution from simulation
- Sensitivity limited by position uncertainties and detector thresholds

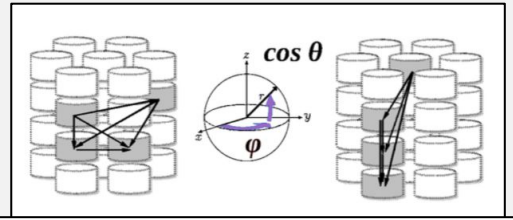


R. Agnese, et al. PRL 114:111302 (2015)

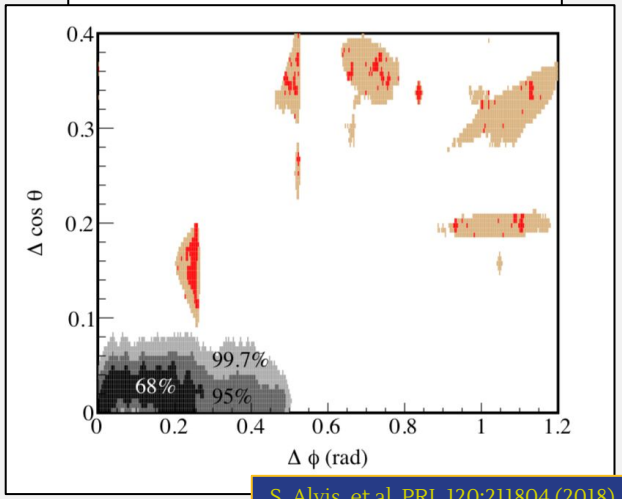
MAJORANA Demonstrator Results (2018)

- MAJORANA Demonstrator detectors are not uniform enough to do CDMS energy consistency cut
- Thicker detectors, lower thresholds, and a similar linearity cut make the experiment more sensitive to LIPs
- Expected LIPs from isotropic distribution are in black/grey contours, while data is brown and muon-vetoed events are red

Not linear enough



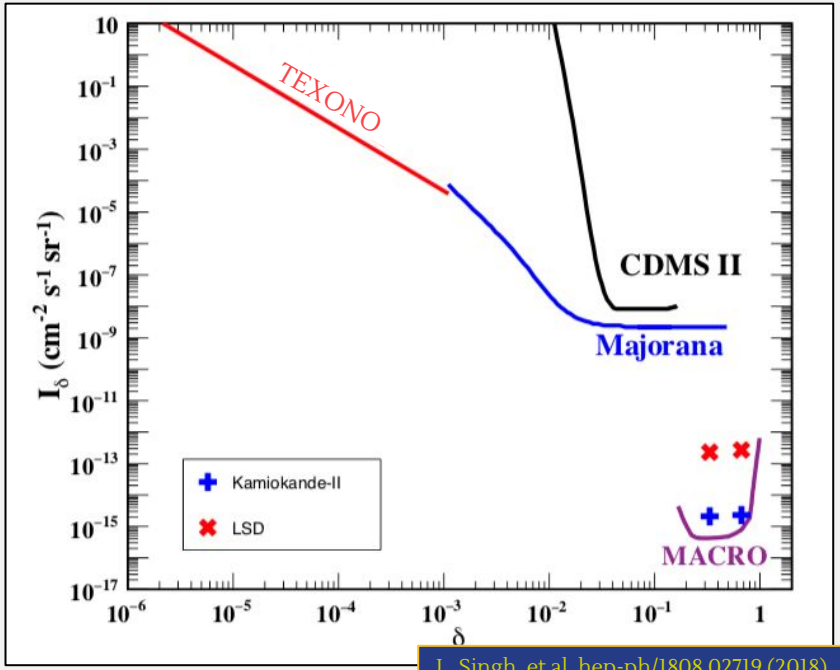
Potential LIP



S. Alvis, et al. PRL 120:211804 (2018)

Limits on LIPs and Fractional Charges

- This is the state-of-the-art LIP and fractional charge exclusion plot
- Isotropic LIP distribution assumed; if LIPs are produced in upper atomsphere, limits generally weaker
- Most conservative limit comes from minimum ionizing assumption, since dE/dx larger for other momenta



L. Singh, et al. hep-ph/1808.02719 (2018)

Not LIPs But Blobs

- This slide isn't really about fractional charges anymore
- What if dark sector has strong self-interactions?
- Dark matter would be "blobby" and lead to different experimental signatures
- Possibly tracks of nuclear recoils (similar to LIPs), or things like inducing spin precession and variation of fundamental constants

D. Grabowska, et al. hep-ph/1807.03788

Summary

- Searches for fractionally charged particles began pretty much as soon as Millikan showed quantized charge
- In any form, discovery of fractional charges would strongly challenge our understanding of physics
- The widening search for dark matter candidates has reinvigorated interest in searches for apparent fractional charge. Expect more of these searches moving forward