Fractionally Charged Particles at the Energy Frontier

The Standard Model Gauge Group and One-Form Global Symmetry

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(they/them or whatever)

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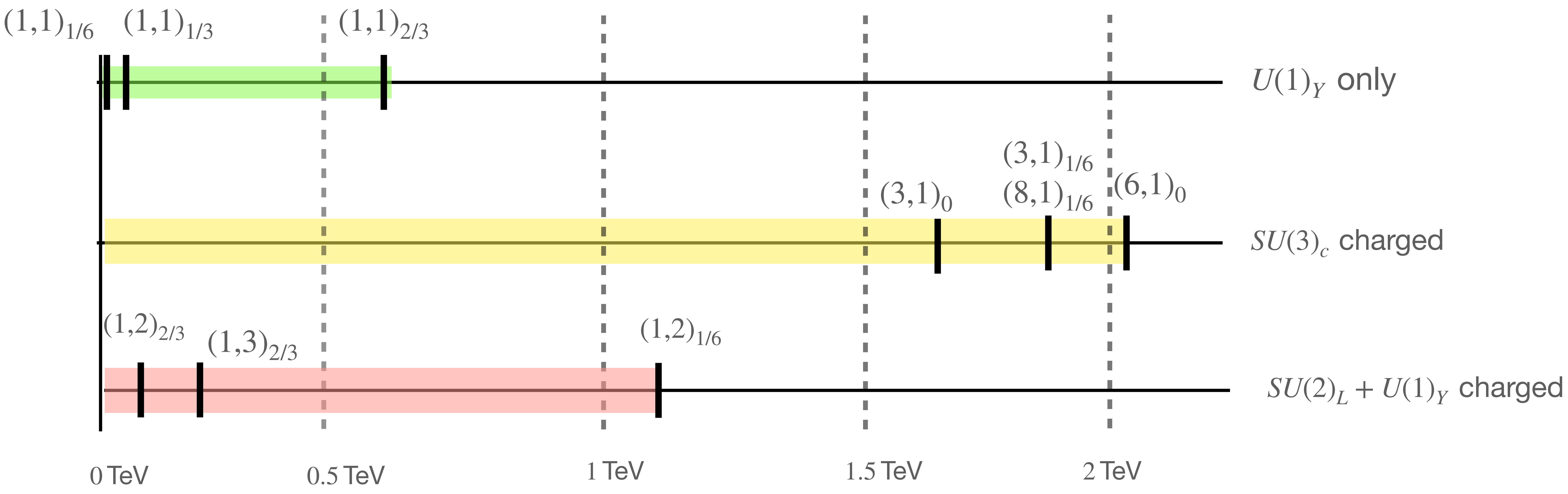

with Adam Martin

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Talk outline

Global Structure of Gauge Groups

Abelian, Non-Abelian, Standard Model

~~Generalized Global Symmetries~~

~~Noether Charges, Gauss' Law, Symmetry-breaking~~

Fractionally Charged Particles at the Energy Frontier

Production, Collider Signatures, Bounds

Why do all the hadrons have $q = ke, k \in \mathbb{Z}$?

With the SM particles, *electric charge in the far infrared* $U(1)_{\text{QED}}$ *below confinement* is quantized in units of e.

Don't be confused by the charges of the quarks! Let's make a colorless interpolating operator.

	u_i	d_i	g
$SU(3)_C$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{8}$
$U(1)_{\text{EM}}$	$\frac{2}{3}$	$-\frac{1}{3}$	0

Fundamentals have $q_i = \dfrac{2}{3}$ (mod 1)

Antifundamentals have $q_i = \dfrac{1}{3}$ (mod 1)

δ^a_b pairs one of each; ϵ_{abc} three of the same

Either way $\sum q_i = 0$ (mod 1)

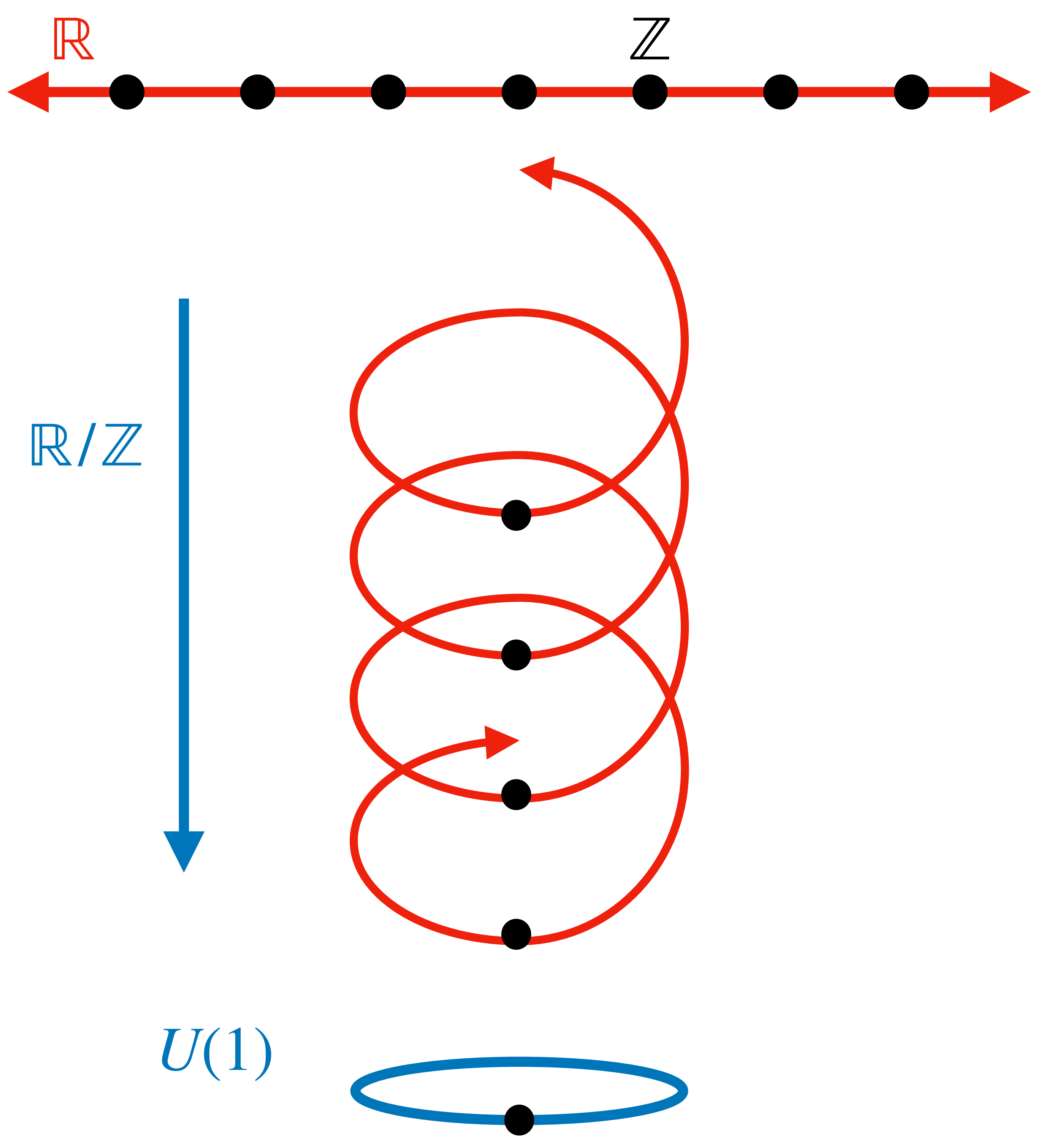
Did it have to be this way?

Abelian Warmup: $\mathbb{R}$ vs. $U(1) \simeq \mathbb{R}/\mathbb{Z}$

Global Structure of Gauge Groups

- Perturbative physics depends only on the structure of the gauge group near the identity (think of D_μ)

- Nonperturbative aspects of physics are sensitive to the 'global structure', including simply the representation theory.



Abelian Lie group representations

In $\mathbb{R}$ we can consider representations with arbitrary charges $q_i/q_j \notin \mathbb{Q}$

$$U(\theta)\psi_i = \left(\frac{1+i\theta}{\sqrt{1+\theta^2}}\right)^{q_i}\psi_i$$

But in $U(1)$ we must demand some finite period e.g. $U(2\pi) \equiv 1$

For $U(\theta)\psi_i = (e^{i\theta})^{q_i}\psi_i$

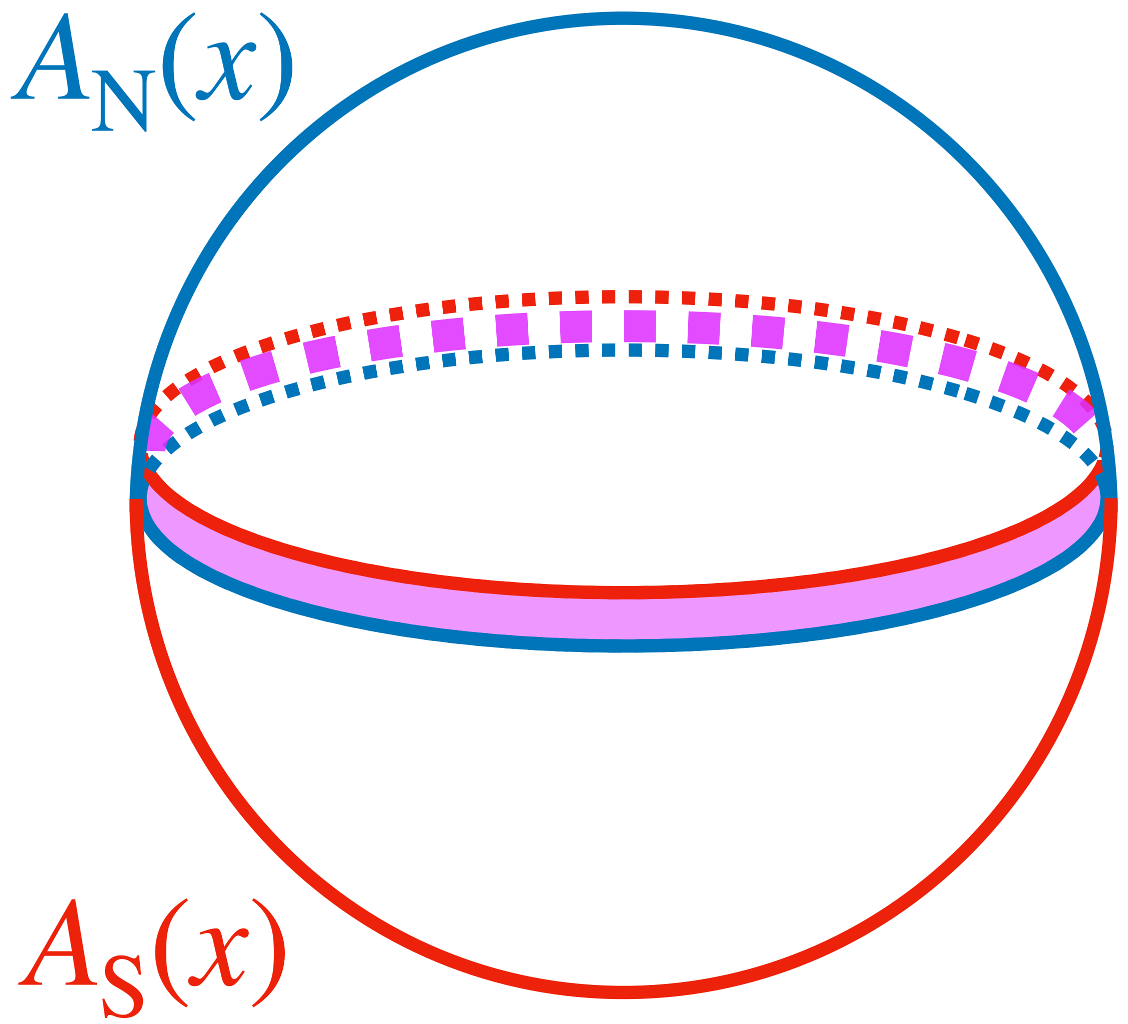
$$U(2\pi)\psi_i = e^{2\pi i q_i}\psi_i \equiv \psi_i \ \forall i \ \Rightarrow q_i \in \mathbb{Z}$$

(Here integer by convention; generally for $q_i/q_j \in \mathbb{Q}$ you can find *some* period)

In *principle* we could observe a particle of charge $\sqrt{2}e$ and learn it's actually $\mathbb{R}_{\text{QED}}$. This would falsify string theory.

Aside: *Magnetic* Representations

Smooth magnetic monopoles from Wu-Yang



On overlap

$$A_N^{\mu}(x) = A_S^{\mu}(x) - ie^{-i\alpha(x)}\partial^{\mu}e^{i\alpha(x)}$$

Nontrivial if there is a relative twist between the upper and lower hemispheres, and such twists given by by $\pi_1(G)$, so $\mathbb{Z}$-valued monopoles in $U(1)$ and none in $\mathbb{R}$

Nonabelian Case Study 1: $SU(N)$ vs. $SU(N)/\mathbb{Z}_N$

Recall: $SU(N)$ consists of $N \times N$ complex matrices which are unitary ($V^\dagger V = 1$) and special ($\det V = 1$).

$SU(N)$ is non-Abelian but there is a non-trivial subgroup which commutes with everything (the 'center' of the group)

$$\mathbb{Z}_N \subset SU(N) : \left\{ \exp\left(\frac{2\pi k}{N} i\right) \mathbb{I}_N \right\}_{k=0..N-1}$$

The quotient group $SU(N)/\mathbb{Z}_N$ sets element of the center equal to the identity

$SU(N)$ vs. $SU(N)/\mathbb{Z}_N$ Representations

Recall the fundamental representation $\psi^a \to V^a_b \psi^b$, so under a center transformation $\psi^a \to e^{\frac{2\pi k}{N} i} \psi^a$

This is fine in $SU(N)$, but in $SU(N)/\mathbb{Z}_N$ this transformation is literally the identity!

The fundamental representation of $SU(N)$ is not a representation of $SU(N)/\mathbb{Z}_N$!

An $SU(N)/\mathbb{Z}_N$ theory is a theory of *adjoint* fields, as $\psi^a{}_b \to V^{\dagger d}_b \psi^c{}_d V^a{}_c$ is invariant under a center transformation

Nonabelian Case Study 2:

$SU(N) \times U(1)$ vs. $U(N) \cong \big(SU(N) \times U(1)\big)/\mathbb{Z}_N$

This time we quotient by identifying $\mathbb{Z}_N$ subgroups of each factor $e^{\frac{2\pi i}{N}}\mathbb{I} \sim e^{\frac{2\pi i}{N}Q}$

Then in $U(N)$ the diagonal $\mathbb{Z}_N$ must act trivially

$$\exp \frac{2\pi i}{N}\mathbb{I}_N \times \exp \frac{-2\pi i}{N}Q \equiv 1 \text{ on all fields}$$

So now the representations of the two factors are linked

E.g. a fundamental must have $q = 1 \pmod N$, an adjoint $q = 0 \pmod N$

The Standard Models

$$G_{\mathrm{SM_n}} \equiv \left(SU(3)_C \times SU(2)_L \times U(1)_Y\right)/\mathbb{Z}_n \qquad n = 1,2,3,6$$

In $G_{\mathrm{SM_2}}$ we impose $(-1)\mathbb{1}_L \sim e^{\pi i Y}$ - Note the SM fields all obey this!

	Q_i	$\overline{u}_i$	$\overline{d}_i$	L_i	$\overline{e}_i$	H
$SU(2)_L$	$\mathbf{2}$	–	–	$\mathbf{2}$	–	$\mathbf{2}$
$U(1)_Y$	$+1$	-4	$+2$	-3	$+6$	-3

In $G_{\mathrm{SM_3}}$ we impose $e^{\frac{2\pi i}{3}}\mathbb{1}_C \sim e^{\frac{2\pi i}{3}Y}$, in $G_{\mathrm{SM_6}}$ we impose both

Fractionally charged particles distinguish

The quantization of IR electric charges with the SM particles is *not* necessarily a feature of the full theory of the universe

In G_{SM_n} electric charges are quantized in terms of $ne/6$!

So discovering a particle with charge a multiple of $e/6,\ e/3,\ e/2$ would falsify some versions of the SM.

For these non-Abelian reps, fractional charge is avoided only with this hypercharge

$SU(3)_C$	$SU(2)_L$	$6Y \mod 6$
–	–	0
–	**2**	3
–	**3**	0
3	–	4
6	–	2
8	–	0
3	**2**	1
6	**2**	5
8	**3**	0

And different GUTs demand different versions of the SM!

$SU(5) \rightarrow G_{\mathrm{SM}_6}$, Pati-Salam $\rightarrow G_{\mathrm{SM}_3}$, Trinification $\rightarrow G_{\mathrm{SM}_2}$

Phenomenology

- Fractionally charged particles transform under (some of) the $\mathbb{Z}_6 \subset G_{\mathrm{SM}_1}$ which the SM fields are neutral under, which means such fields ψ must couple in pairs
- Minimally is coupled to gauge fields through gauge covariant derivative. For simplicity we only consider this interaction.
- At LHC there's always Drell-Yan $\bar{q}q \to \bar{\psi}\psi$ through photon/Z, for non-trivial $SU(2)_L$ also production through $W^{\pm}$ and for non-trivial $SU(3)_C$ of course production through the gluon is most important

Searches

- Only dedicated search at CMS, uses low dE/dx in tracker (but triggers with muon system)

Search for fractionally charged particles in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

A search is presented for fractionally charged particles with charge below $1e$, using their small energy loss in the tracking detector as a key variable to observe a signal. The analyzed data set corresponds to an integrated luminosity of $138\,\text{fb}^{-1}$ of proton-proton collisions collected at $\sqrt{s} = 13\,\text{TeV}$ in 2016–2018 at the CERN LHC. This is the first search at the LHC for new particles with charges between $e/3$ and e. Masses up to 640 GeV and charges as low as $e/3$ are excluded at 95% confidence level. These are the most stringent limits to date for the considered Drell-Yan-like production mode.

Hypercharge only

- Simplest case, $Q = Y$, the CMS search works best for $e/2,\ 2e/3$
- Larger doesn't look anomalous and smaller doesn't get picked up by tracking algorithm

CERN-EP-2024-002
2024/02/16

CMS-EXO-19-006

Search for fractionally charged particles in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

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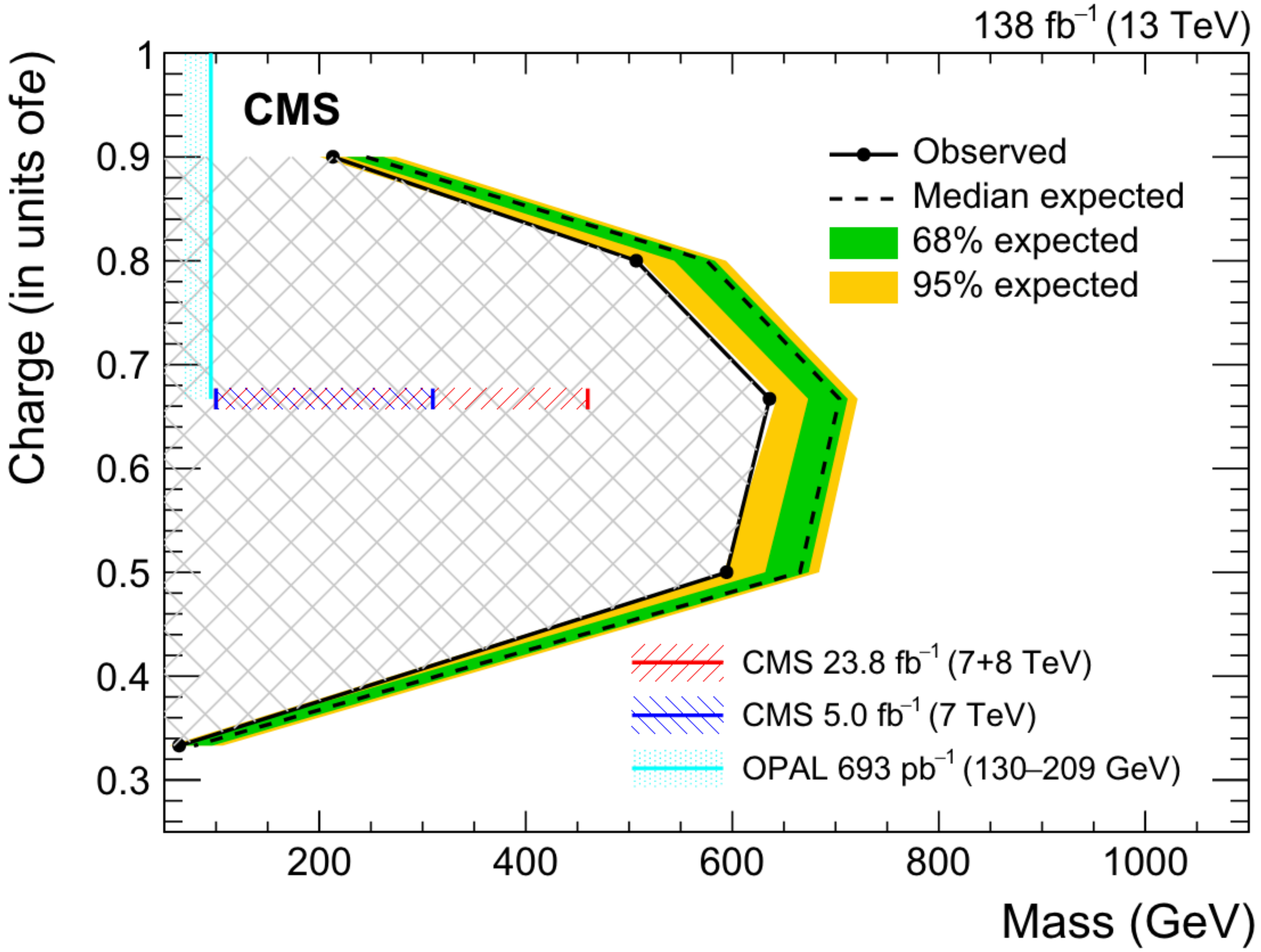


Colored particles

- Must hadronize; all hadrons containing will have fractional electric charge differing by units of e depending on the quarks.
- E.g. color triplet $Y = 0$ forms mesons with $|Q| = 1/3,\ 2/3$ use CMS search
- E.g. color octet $Y = 1/6$ forms hadrons with $|Q| = 1/6,\ 5/6,\ 7/6,$ use R-hadron searches

Search for heavy charged long-lived particles in the ATLAS detector in 36.1 fb^{-1} of proton–proton collision data at $\sqrt{s}$ = 13 TeV

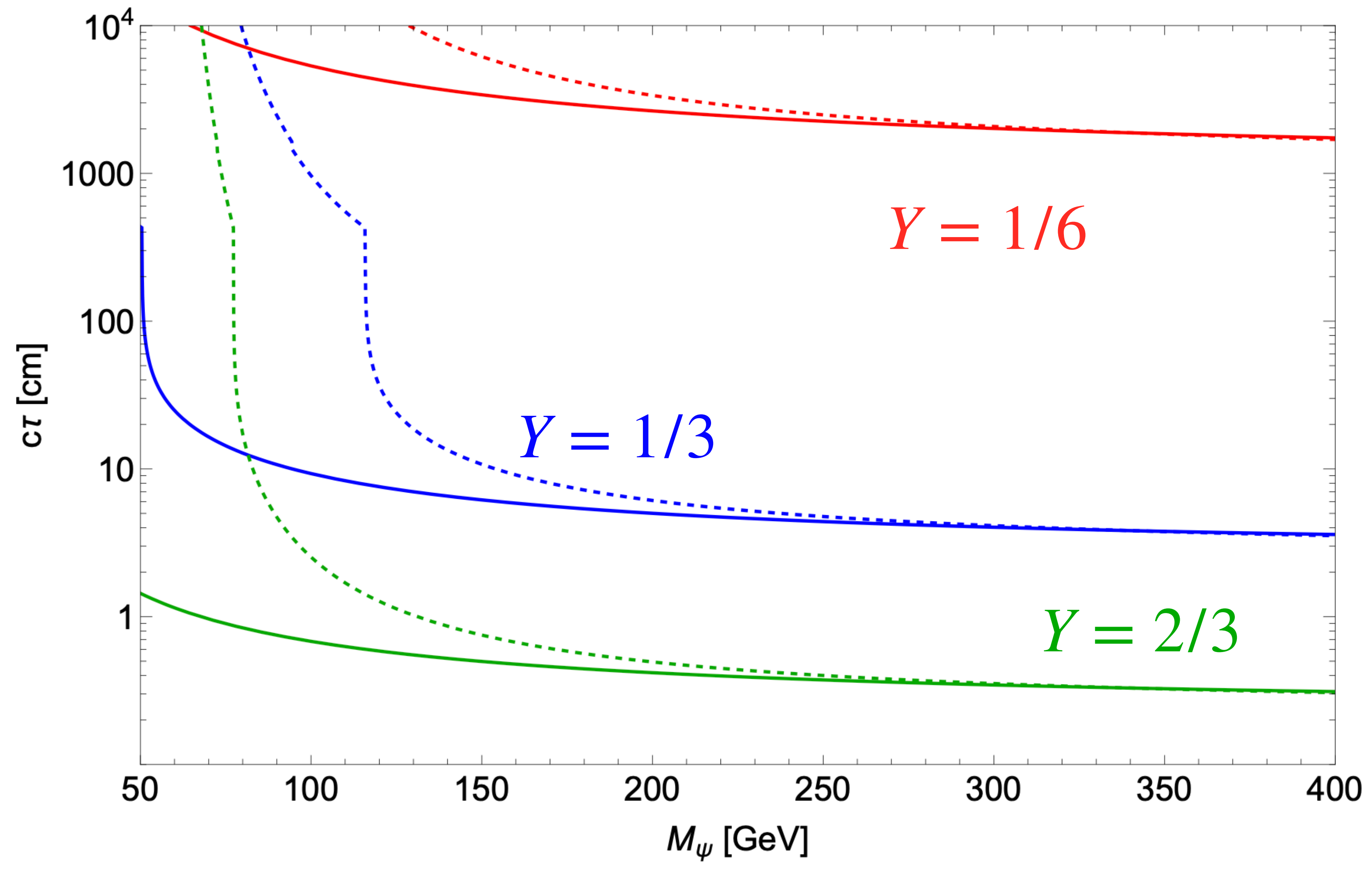
The ATLAS Collaboration

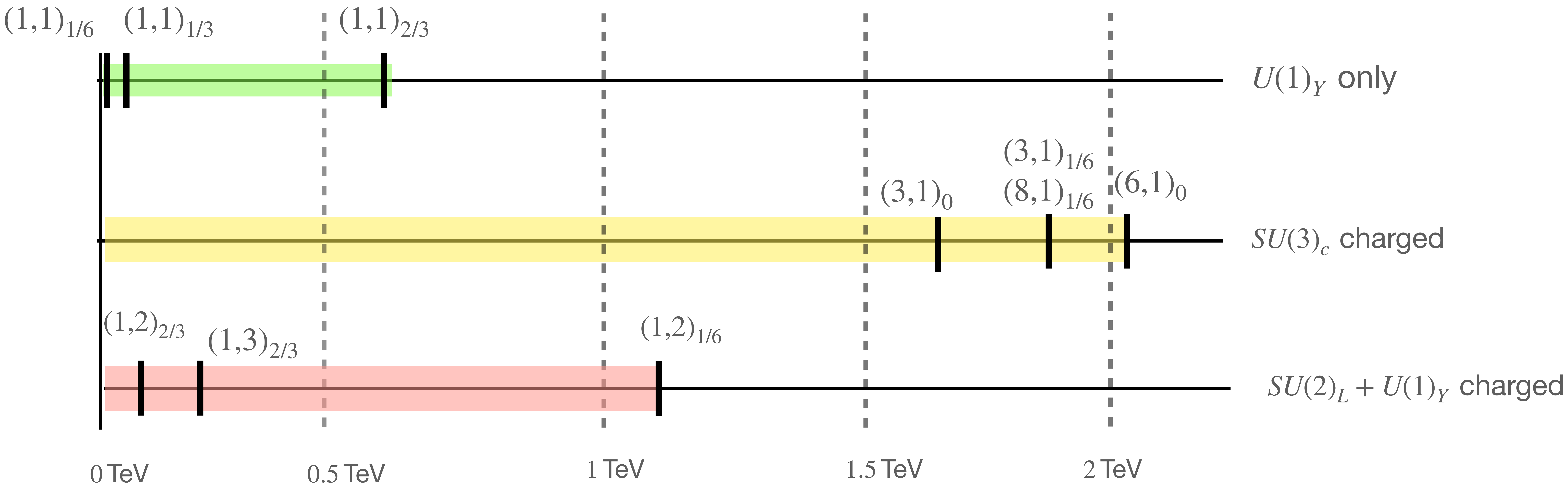
A search for heavy charged long-lived particles is performed using a data sample of 36.1 fb^{-1} of proton–proton collisions at $\sqrt{s}$ = 13 TeV collected by the ATLAS experiment at the Large Hadron Collider. The search is based on observables related to ionization energy loss and time of flight, which are sensitive to the velocity of heavy charged particles traveling significantly slower than the speed of light. Multiple search strategies for a wide range of lifetimes, corresponding to path lengths of a few meters, are defined as model-independently as possible, by referencing several representative physics cases that yield long-lived particles within supersymmetric models, such as gluinos/squarks (R-hadrons), charginos and staus. No significant deviations from the expected Standard Model background are observed. Upper limits at 95% confidence level are provided on the production cross sections of long-lived R-hadrons as well as directly pair-produced staus and charginos. These results translate into lower limits on the masses of long-lived gluino, sbottom and stop R-hadrons, as well as staus and charginos of 2000 GeV, 1250 GeV, 1340 GeV, 430 GeV and 1090 GeV, respectively.

Weakly Charged

- Components of multiplet are split from EWSB; have wide variety of LLP phenomenology
- Depending on mass ordering get displaced vertices, disappearing tracks, kinked tracks

Doublet excited state lifetime





(1,1)1/6
(1,1)1/3
(1,1)2/3
U(1)Y only
(3,1)1/6
(8,1)1/6
(3,1)0
(6,1)0
SU(3)c charged
(1,2)2/3
(1,3)2/3
(1,2)1/6
SU(2)L + U(1)Y charged
0 TeV
0.5 TeV
1 TeV
1.5 TeV
2 TeV

Conclusions

- Fractionally charged particles are extremely high stakes sorts of particles to search for
- Probably lots of room for experimentalists and phenomenologists to optimize search strategies and analyses
- We considered one species at a time, but with multiple species can get richer interactions with SM particles $H\psi\chi$ or $\phi\{Q, \bar{u}, \bar{d}, L, \bar{e}, \bar{\nu}\}\chi$ but they remain automatically one-loop suppressed in coming into SMEFT operators. What are the bounds from e.g. precision?