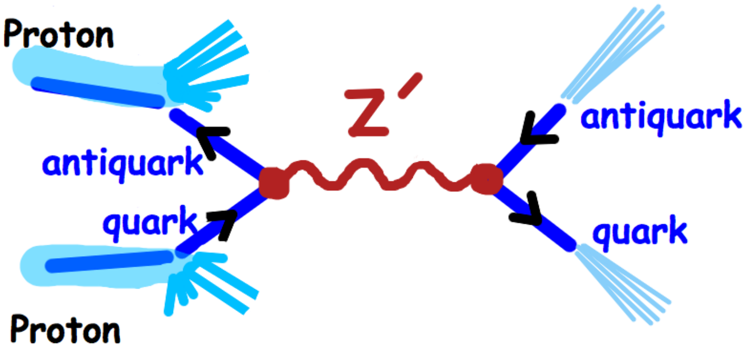
Exploring the laws of nature at the LHC

Bogdan Dobrescu

Fermilab, Particle Theory Department



December 13, 2023 – Meeting of the US LHC Users Association

Tough questions which could eventually be answered by experiments at hadron colliders:

- *Do the SM particles have substructure?*
- *Are there extra dimensions?*
- *Why is the electroweak scale much smaller than the Planck scale?*
- *Can deviations from quantum field theory be eventually measured?*
- *...*

More tractable questions that the LHC experiments have started addressing:

- *Are there any gauge bosons beyond the SM?*
- *What kind of new fermions may exist?*
- *Do 'elementary' spin-0 particles other than h^0 exist?*
- *Are there any new long-lived particles?*
- *...*

Run 3 and the HL-LHC will increase the reach of searches for:

- vectorlike quarks and leptons
- Z' and W' bosons
- color-octet scalars, colorons
- diquark scalars, leptoquarks
- supersymmetric particles
- heavy Higgs bosons
- right-handed neutrinos
- ... other new particles

There are also many searches that have never been performed

$\longrightarrow$ potential for discoveries even with early Run 3 data!

Fermions beyond the Standard Model

Observed elementary particles of spin 1/2:

Chiral quarks and leptons (left-handed doublets, right-handed singlets)

Legacy of LHC Runs 1 & 2: **a 4th generation of chiral quarks and leptons is (effectively) ruled out.**

Direct searches set limits $\gtrsim 1$ **TeV on** b_4, t_4 **masses,**

from $t_4 \to W^+ b$ **or** $b_4 \to W^- t$ **(CMS 1906.11903, ATLAS 1505.04306)**

$\to h^0\,\bar{t}_4 t_4$ **Yukawa coupling no longer perturbative.**

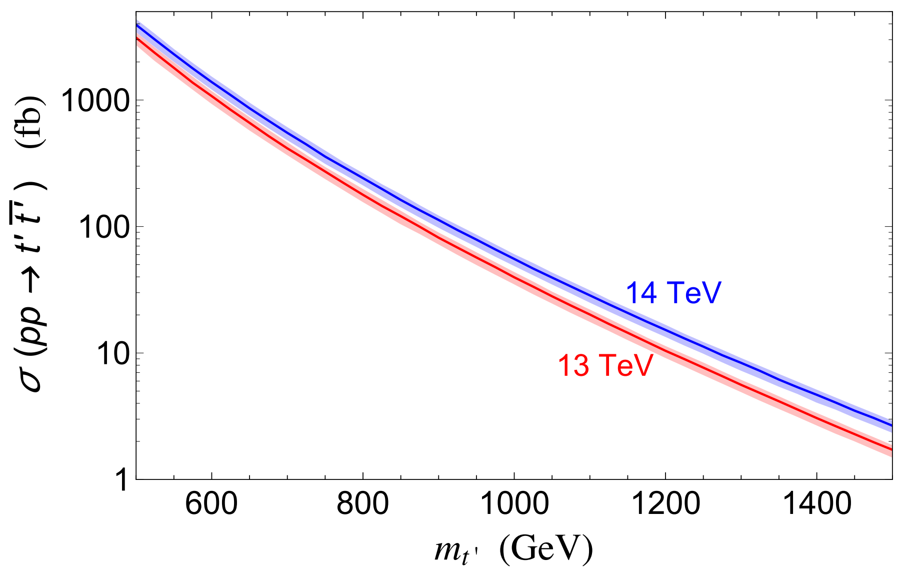
Vectorlike fermions

Fermions beyond the SM may exist if they are vectorlike (non-chiral)
$\longrightarrow$ a different form of matter.

Masses allowed by $SU(3)_c \times SU(2)_W \times U(1)_Y$ gauge symmetry
$\Rightarrow$ naturally heavier than the t quark.

Vectorlike quarks can be pair produced at the LHC due to their coupling to gluons.

Cross section depends only on their mass.



A vectorlike quark χ that transforms as (3,1,+2/3) under $SU(3)_c \times SU(2)_W \times U(1)_Y$ would mix with the SM top quark.

χ is predicted in composite Higgs models (Dobrescu, Hill, hep-ph/9712319),

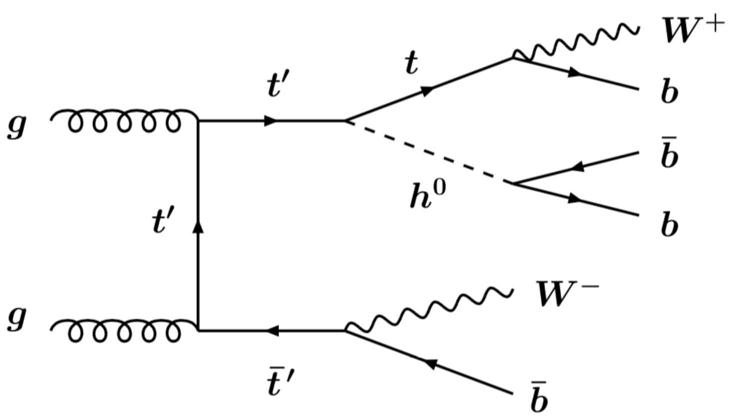
little Higgs models (Arkani-Hamed, Cohen, Georgi, hep-ph/0105239, ...),

...

Mass eigenstates: t and t'. Mixing $\sin\theta_L \equiv s_L$.

'Standard' decay widths of t' are proportional to s_L^2.

$$\Gamma(t' \to W^+ b\,,\, Zt\,,\, h^0 t) = \frac{s_L^2\, m_{t'}^3}{16\pi v_H^2}$$



...

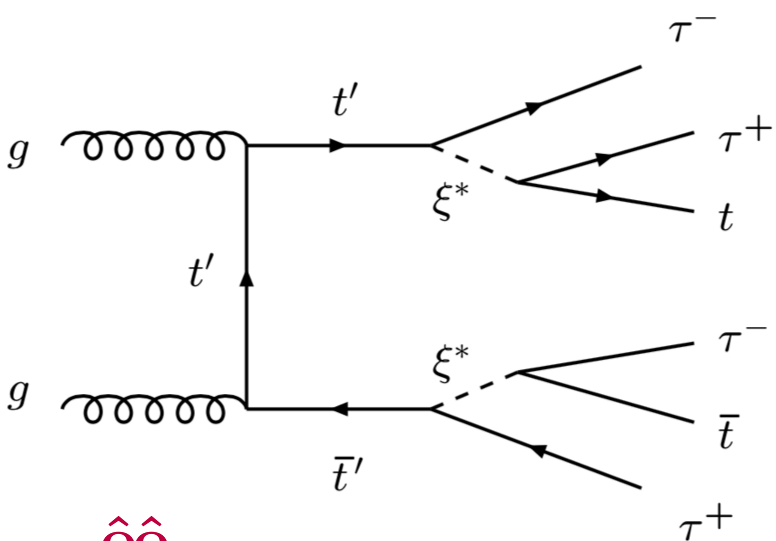
Current limit: $m_{t'} \gtrsim 1.3$ TeV

(CMS 1906.11903)

For $s_L \ll 1$, exotic decays of vectorlike quarks induced by some very heavy particles could dominate!

with Felix Yu, 1612.01909

E.g., **4-fermion operator** $(\overline{\chi}_R\, l_L^3)\, i\sigma_2\, (\overline{\tau}_R\, q_L^3) \quad \Rightarrow \quad t' \to \tau^+\tau^- t$



Other LHC signatures:

$$tb\nu + 3\tau \quad , \quad t\bar{t}\tau^+\tau^-\nu\nu \ ,$$

$$tb\tau + 3\nu \quad , \quad t\bar{t} + 4\nu$$

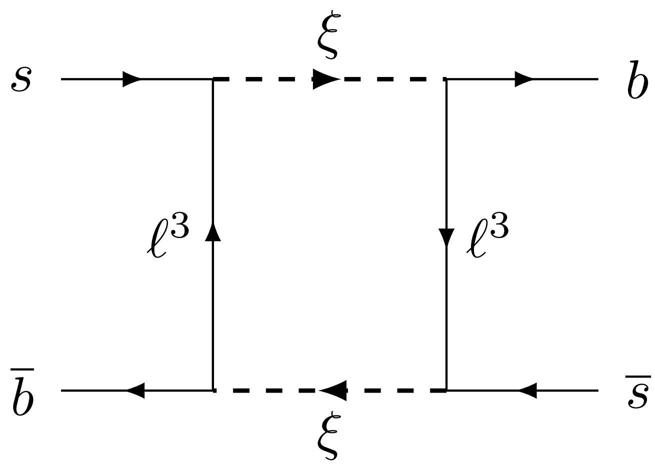
Similar final states with τ replaced by μ or e ($t\bar{t} + 4\mu$, ...)

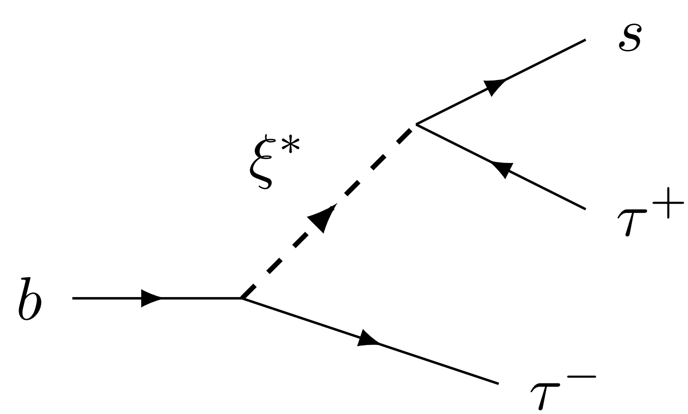
Example of UV completion: scalar leptoquark ξ

transforms as (3, 2, 7/6) under $SU(3)_c \times SU(2)_W \times U(1)_Y$, *and is heavier than* t'.

Yukawa interactions of ξ: $\quad \lambda_\chi\, (\overline{\chi}_R l_L^3)\xi - i\lambda_q\, \xi^\dagger \sigma_2 (\overline{\tau}_R q_L^3) + \lambda_t\, \xi^\dagger (\overline{l}_L^3 t_R)$

Flavor-changing processes beyond the SM that can be probed at LHCb:





LHC probes of the 10 TeV scale

with Robert Harris, Joshua Isaacson, 1810.09429; also 1912.13155

Usual range of masses probed by the LHC extends up to a few TeV.

In the presence of certain ultraheavy new particles called diquarks, the 10 TeV scale can be explored.

Spin-0 particle S_{uu} that interacts with two up quarks:

$$\frac{y_{uu}}{2} \, S_{uu} \, \overline{u}_R \, u^c_R$$

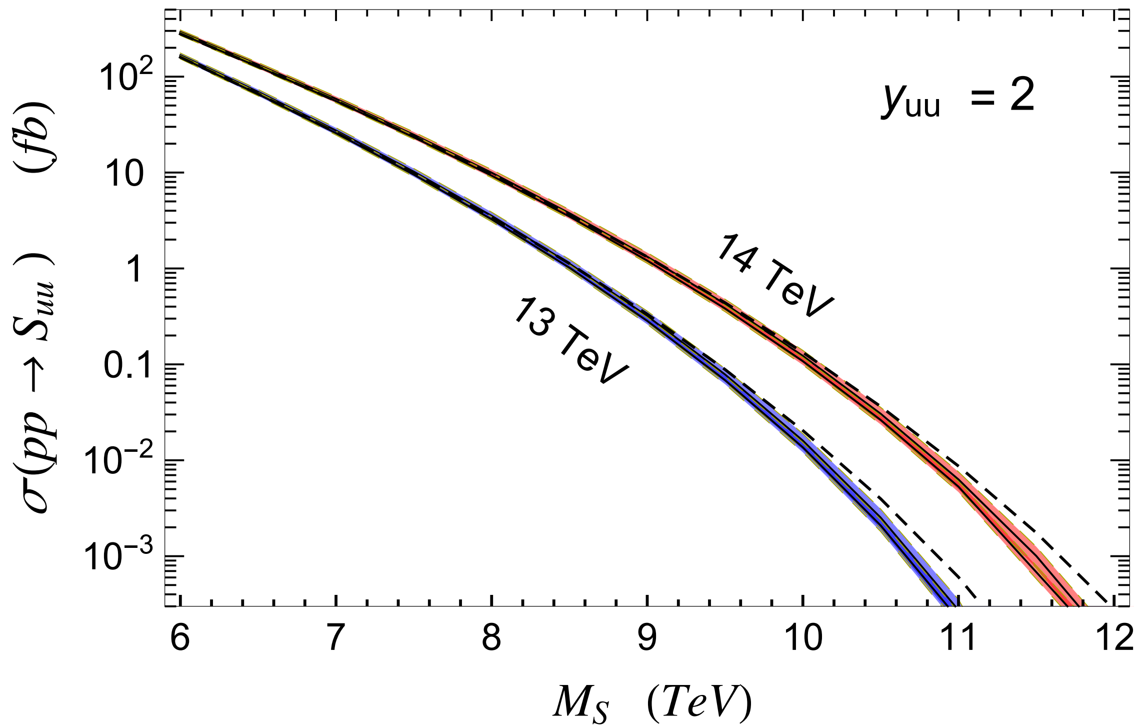
Large production rate because the u PDF is the largest one.

The scalar decays into two jets: $\Gamma_S(S_{uu} \to u\, u) = \frac{y^2_{uu}}{32\pi} M_S$

Narrow resonance: $\Gamma_S / M_S < \begin{cases} 4\% \\ 7\% \end{cases}$ **for** $y_{uu} \leq \begin{cases} 2 \\ 2.7 \end{cases}$

$$\sigma(pp \to S_{uu}) = \frac{\pi}{6\,s}\, y_{uu}^2 \int_{M_S^2/s}^{1} \frac{dx}{x}\, u\Big(x, M_S^2\Big)\; u\Big(M_S^2/(sx), M_S^2\Big)$$

NLO: T. Han, I. Lewis, T. McElmurry, 0909.2666



The QCD jj background is smaller by an order of magnitude.

With 3000 fb^{-1}, an S_{uu} as heavy as 11.5 TeV may be discovered!

S_{uu} may also interact with two t quarks, or with a u and a t:

$$S_{uu} \left(\frac{y_{tt}}{2} \, \bar{t}_R \, t^c_R + y_{ut} \, \overline{u}_R \, t^c_R \right)$$

$S_{uu} \to u\, t$ and $S_{uu} \to t\, t$ with highly boosted top quarks.

$\overline{u}$ PDF is highly suppressed compared to u at large x.

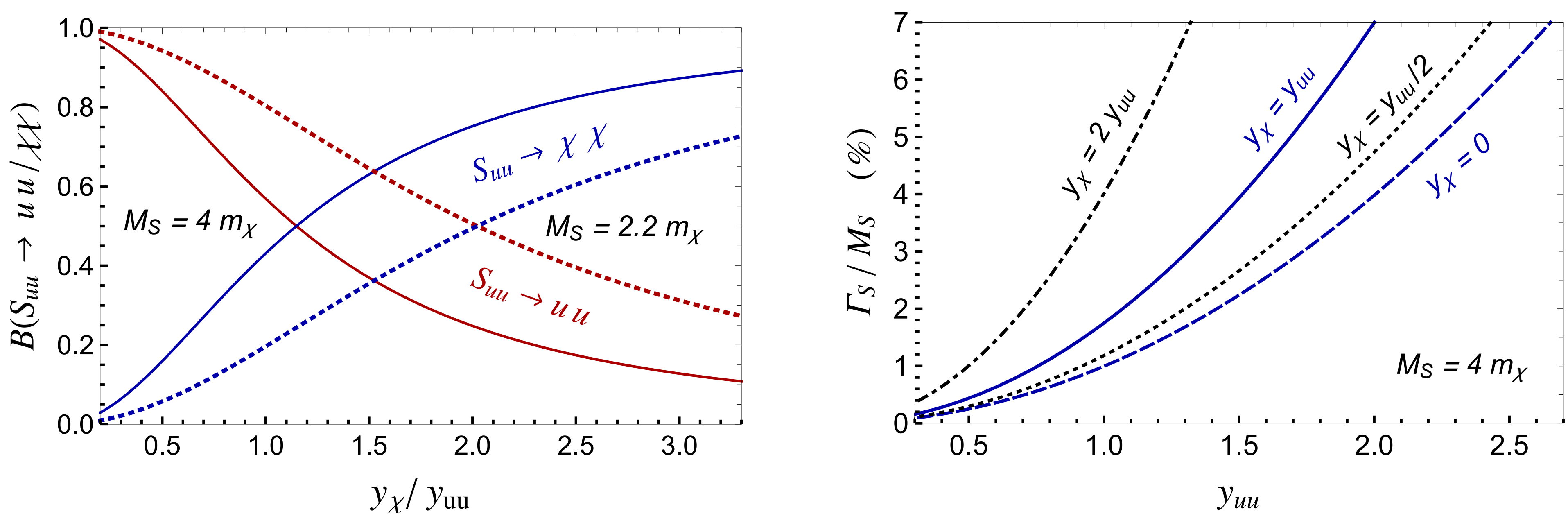
Production cross section for S_{uu} is larger by $\sim 10^2$ than that for its antiparticle, so no similar processes with top antiquarks!

For leptonic decays $t \to \ell^+ b + \not{E}_T$, signal consists entirely of positively charged leptons.

Scalar diquark plus vectorlike quark

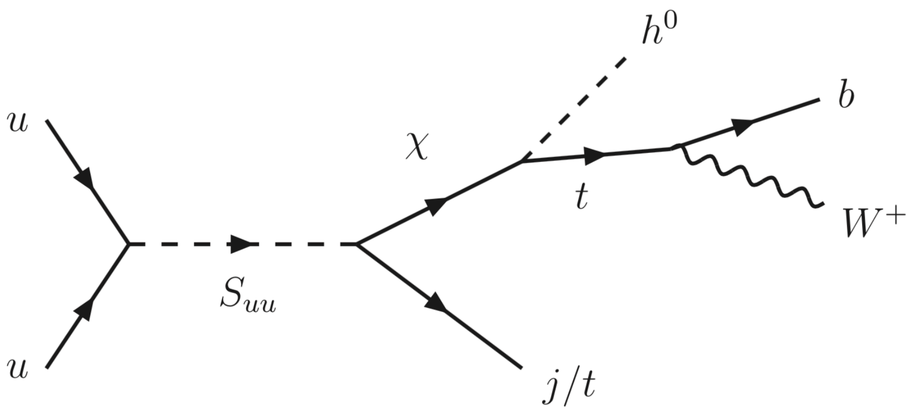
S_{uu} **coupling to a vectorlike quark** χ**:**

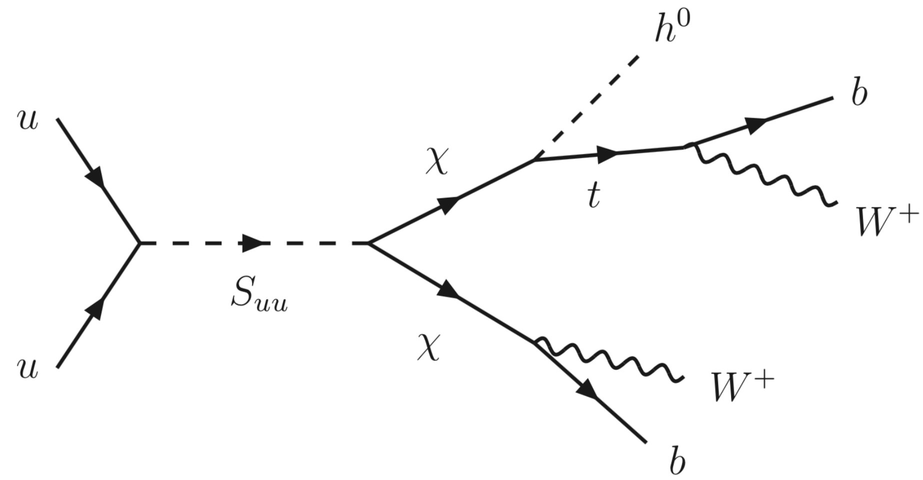
$$S_{uu}\left(y_{u\chi}\,\overline{u}_R\,\chi_R^c + y_{t\chi}\,\overline{t}_R\,\chi_R^c + \frac{1}{2}\,y_{\chi R}\,\overline{\chi}_R\,\chi_R^c + \frac{1}{2}\,y_{\chi L}\overline{\chi}_L\,\chi_L^c\right)$$



$\Rightarrow$ S_{uu} **may be a narrow ultraheavy resonance.**

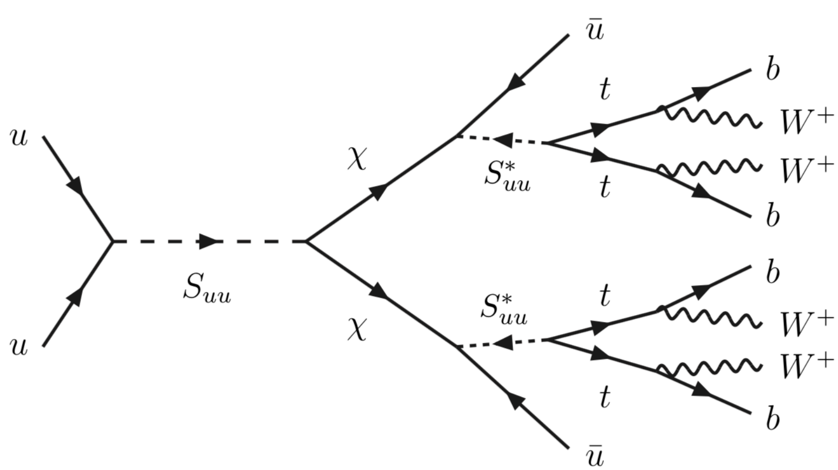
If χ has "standard" decays: **events with boosted h^0, t, W^+ (only charge + leptons)**

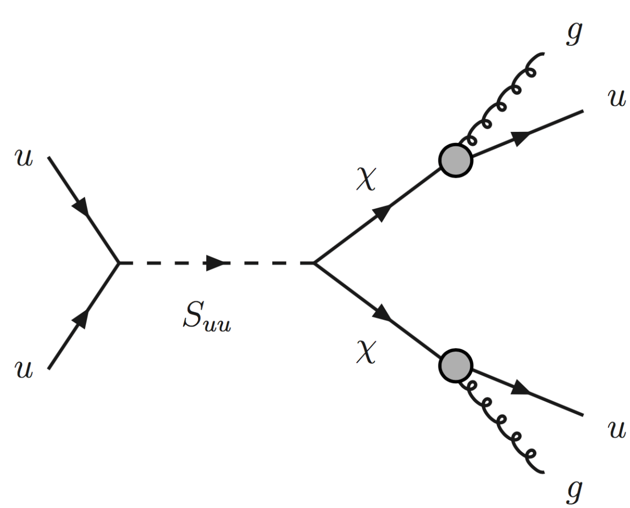




If χ has exotic decays $\rightarrow$ various final states

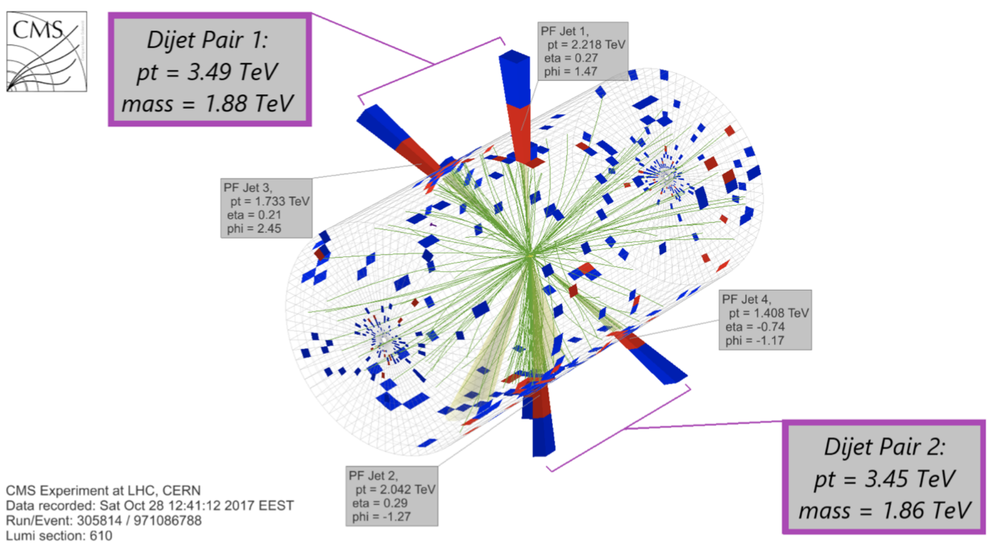
E.g., χ **decay into $tt\bar{u}$ via an off-shell S_{uu}, or into a quark and a gluon via a dimension-5 operator**

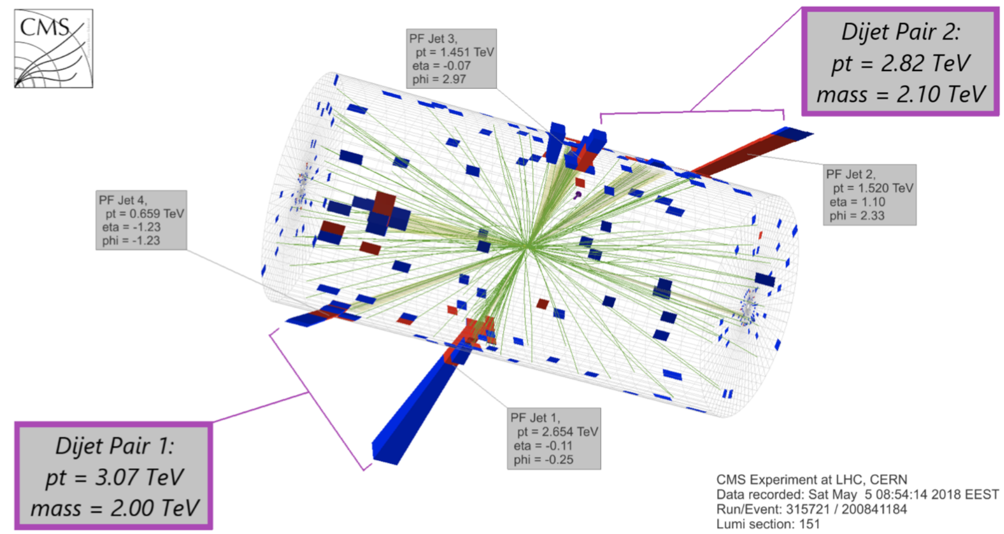


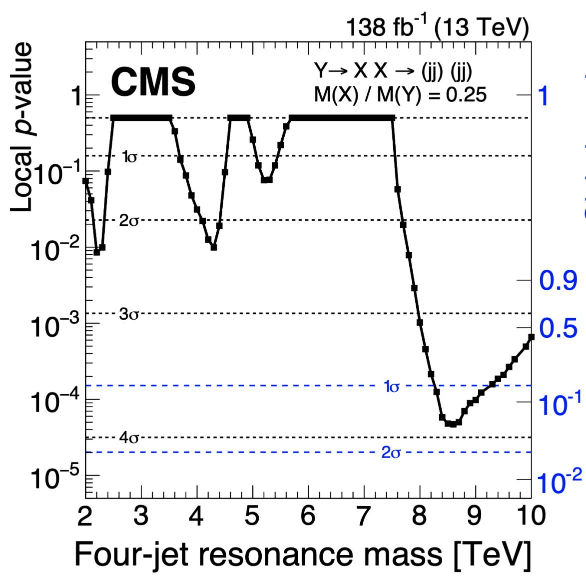


Search for a high-mass particle decaying into a pair of dijet resonances

2 events with 4-jets at a mass of 8.4 TeV (CMS 2206.09997):





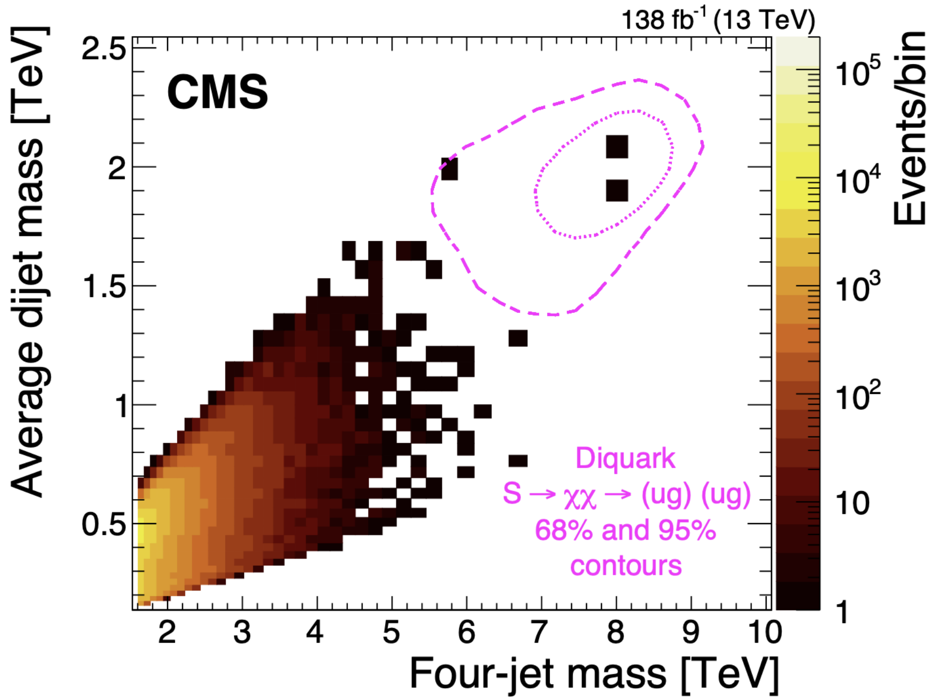


This is a case where sensitivity grows much faster than $\sqrt{\mathcal{L}}$.

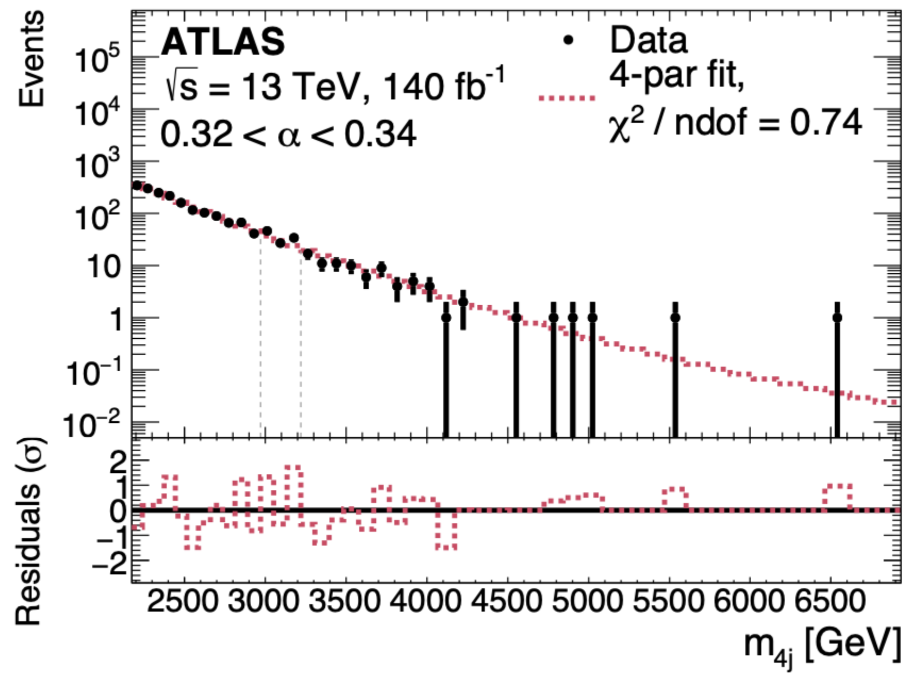
In principle, a discovery could be made with slightly more data.

Searches for a high-mass particle decaying into a pair of dijet resonances

CMS 2206.09997



ATLAS 2307.14944



Many other interesting searches remain to be performed

- **Type-I two Higgs doublet model:**

parameter range where non-SM Higgs bosons are fermiophobic and lighter than ~ 150 GeV.

P. Fox, N. Weiner, 1710.07649

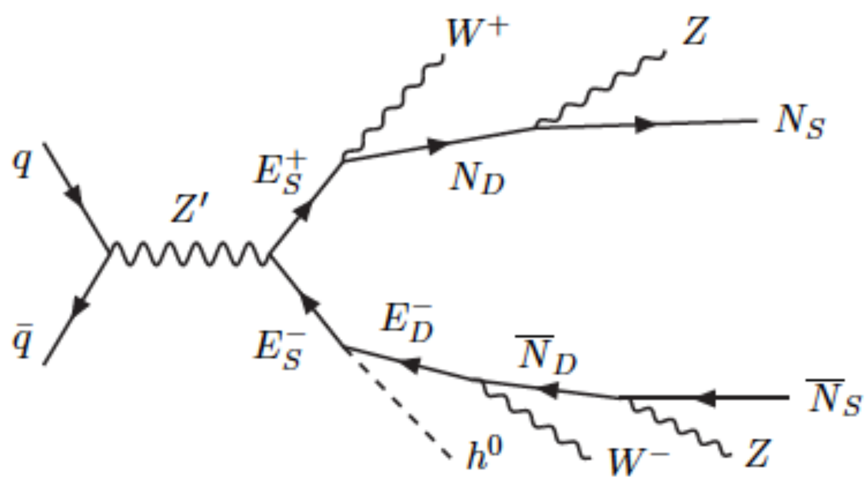
$pp \to t\bar{t}$ **followed by** $t \to H^+ b$ **and** $H^+ \to H^0 W^* \to (\gamma\gamma) jj$

- Z' **decay into "anomalons"**

Vectorlike fermions must carry $U(1)$ charge to cancel the gauge anomalies.

Cascade decays via anomalons: signals with W's, Z's, Higgs + $\not{E}_T$

(1506.04435)



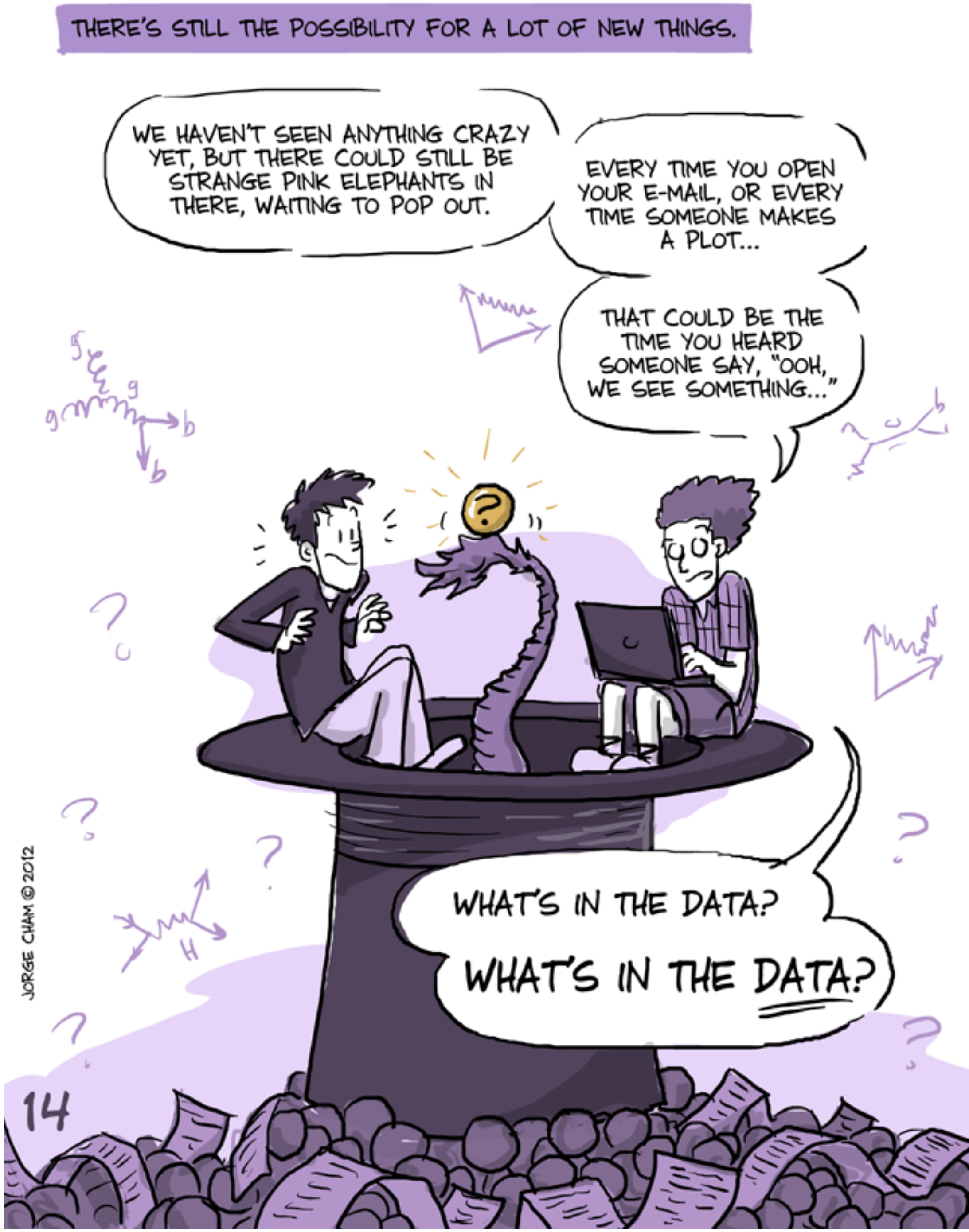
- **... various other examples.**

Conclusions

LHC experiments are probing the laws of nature at the shortest distances accessible by humans so far.

Many hiding places for new physics (including the *tails* of distributions).

We don't know what Run 3 will find...



Bogdan Dobrescu (Fermilab)

phdcomics.com/higgs