Theories Beyond the Standard Model

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<u>*Outline:*</u>

- **Fundamental laws of nature**
- **Vectorlike quarks and leptons**
- **New gauge bosons (Z', G', ...)**

July 26, 2023 - US CMS Interns Program

Classical mechanics

- objects much bigger than atoms
- objects much slower than light

Quantum mechanics

- any size objects (?)
- objects much slower than light

Special relativity

- objects much bigger than atoms
- any speed $\leq c$

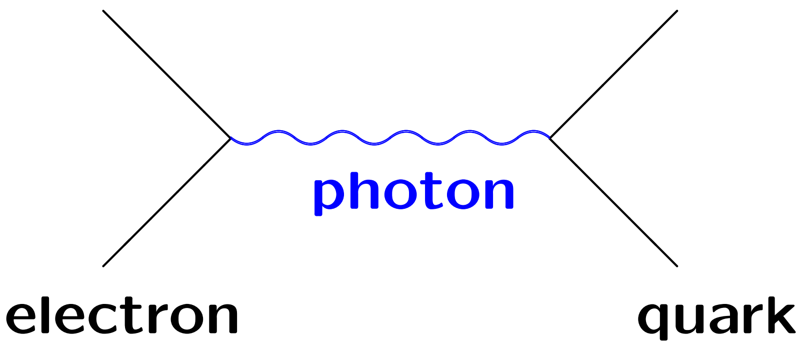
Quantum field theory

- any size objects (?)
- any speed $\leq c$

Elementary particles are manifestations of quantum fields.

Interactions at a distance are mediated by particle exchange.

The force between electric charges is due to photon exchange:



Particle Physics has established that all known natural phenomena can be described by a local quantum field theory invariant under:

- **3+1 dimensional Lorentz transformations & translations**
- $SU(3)_C \times SU(2)_W \times U(1)_Y$ **gauge transformations**

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- $SU(3)_C \times SU(2)_W \times U(1)_Y$ gauge transformations

$\Longrightarrow$ *all elementary particles have certain spin and gauge charges:*

spin 1 - gauge bosons

$$\begin{cases} G^\mu : & (8, 1, \ 0) \\ W^\mu : & (1, 3, \ 0) \\ B^\mu : & (1, 1, \ 0) \end{cases}$$

spin 1/2 - quarks and leptons

$$3 \times \begin{cases} q_L : & (3, 2, \ +1/6) \\ u_R : & (3, 1, \ +2/3) \\ d_R : & (3, 1, \ -1/3) \\ l_L : & (1, 2, \ -1/2) \\ e_R : & (1, 1, \ -1) \end{cases}$$

spin 0 - Higgs doublet: (1,2, 1/2)

spin 2 - graviton : (1,1, 0)

Dark matter particle(s) - spin ?: (1,1, 0)

Chiral fermions

All Standard Model fermions are chiral: left- and right-handed components have different $SU(2)_W \times U(1)_Y$ charges.

E.g., **top quark:**

t_L *(feels the weak interaction)*, t_R *(no interaction with $W^{\pm}$)*

$$\begin{matrix} t_L \\ b_L \end{matrix} \qquad\qquad t_R$$

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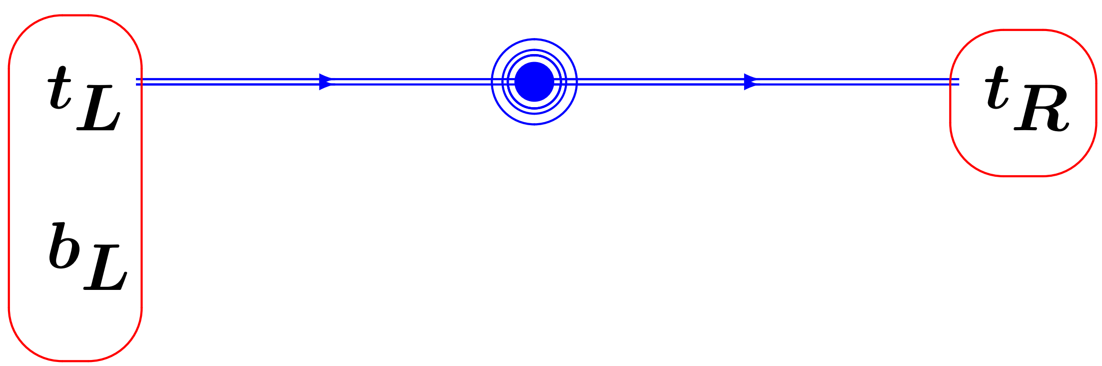
Top mass: t_L turns into t_R and vice-versa

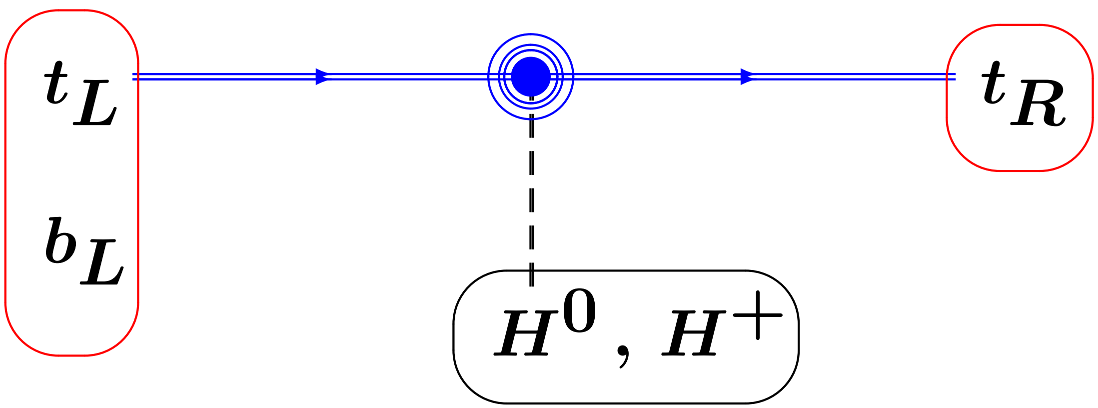


All SM fermion masses require electroweak symmetry breaking, *i.e.*, **interactions with the Higgs doublet.**

E.g., **top quark gets a mass from its interaction with the vacuum:**

$y_t \, \bar{t}_R \, \langle H^0 \rangle \, t_L$, $\langle H^0 \rangle \approx 174$ **GeV is the Higgs VEV.**

Measured top mass $\Rightarrow$ Yukawa coupling is $y_t \approx 1$.



Fermions beyond the Standard Model

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.

Fermions beyond the SM are not chiral, *i.e.,* they are vectorlike.

Vectorlike fermions

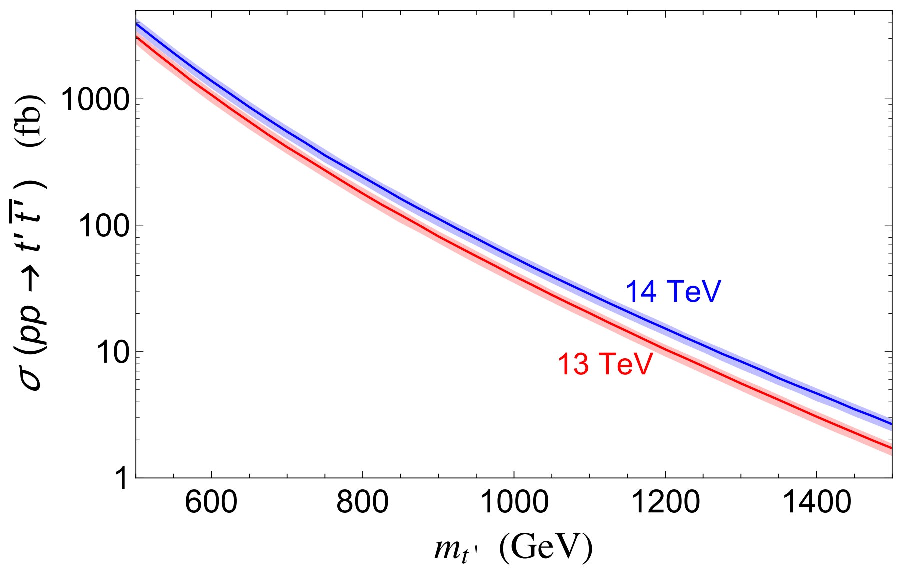
Left- and right-handed components of vectorlike fermions have the same SM gauge charges $\longrightarrow$ a different form of matter.

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.

Homework 1: Draw the main Feynman diagrams responsible for pair production.



Case study: A vectorlike t' quark

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

$$\mathcal{L} = -\left(\overline{u}_L^3 \; , \; \overline{\chi}_L\right) \begin{pmatrix} y_t \langle H^0 \rangle & 0 \\ M_0 & M_\chi \end{pmatrix} \begin{pmatrix} u_R^3 \\ \chi_R \end{pmatrix}$$

M_0 and M_χ are mass parameters

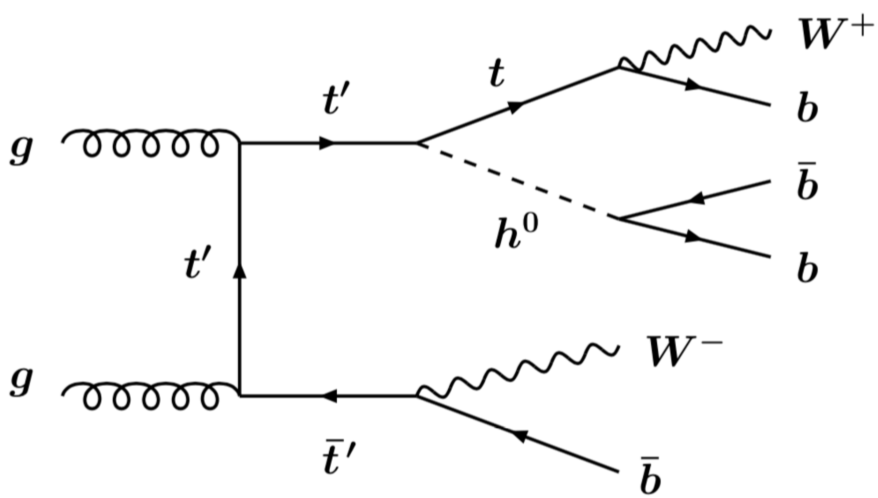
Transform the gauge eigenstates u^3 and χ to the physical states t (discovered in 1995) and t' (remains to be discovered):

$$\begin{pmatrix} t_L \\ t'_L \end{pmatrix} = \begin{pmatrix} \cos\theta_L & -\sin\theta_L \\ \sin\theta_L & \cos\theta_L \end{pmatrix} \begin{pmatrix} u_L^3 \\ \chi_L \end{pmatrix}$$

Homework 2: derive the $W - t' - b$ and $Z - t' - t$ interactions.

‘Standard’ decay widths of t' are proportional to $\sin^2\theta_L$:

$$\Gamma(t'\to Zt) = \Gamma(t'\to h^0 t) = \frac{1}{2}\Gamma(t'\to Wb) = \sin^2\theta_L \,\frac{m_{t'}^3}{64\pi v_H^2}$$



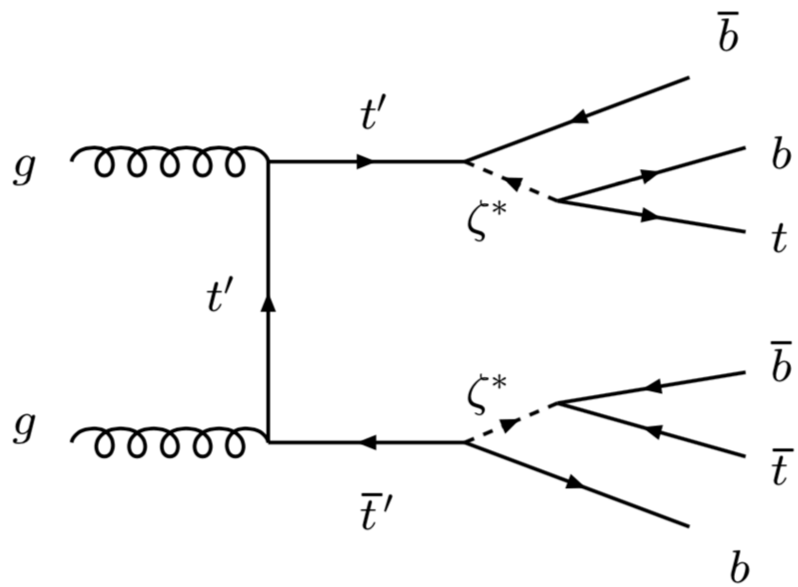
...

Current limit: $m_{t'} \gtrsim 1.5$ **TeV**

(CMS-PAS-B2G-20-011)

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

E.g., 4-fermion operator $(\overline{\chi}^c_R b_R)(\overline{b}_R t^c_R)$ leads to a $t\bar{t} + 4b$ signal:



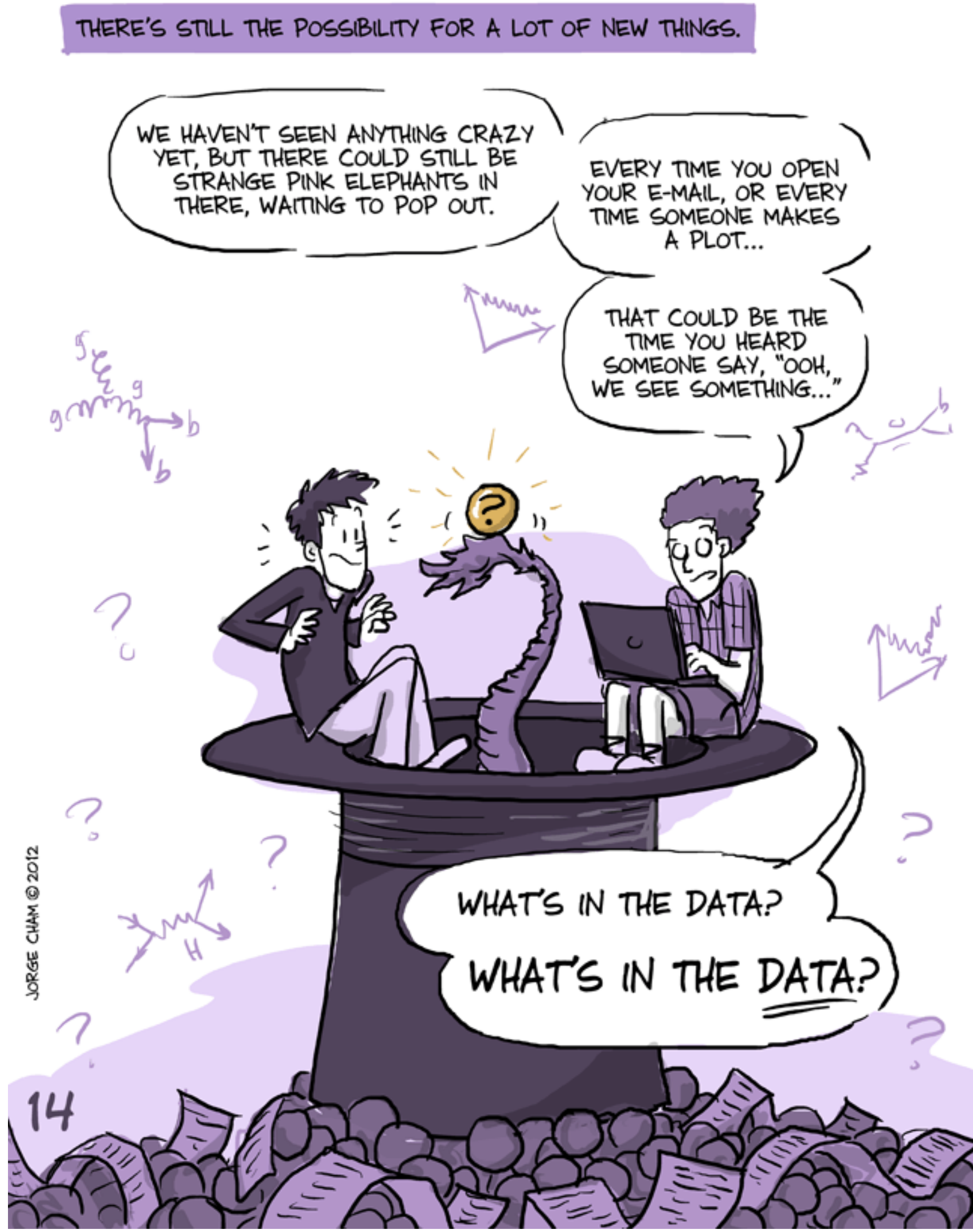
BD, Felix Yu, 1612.01909

Depending on the final state, the mass limit on χ may be lower than 1.5 TeV.

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

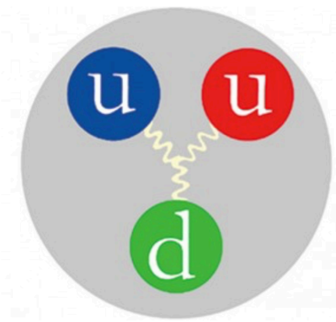
Many hiding places for new physics (including the *tails* of distributions).

We don't know what Run 3 or even new searches based on Run 2 will find...

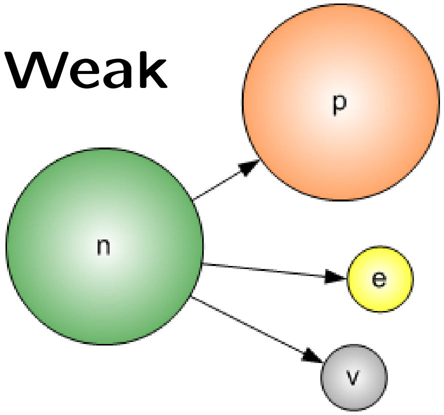


phdcomics.com/higgs

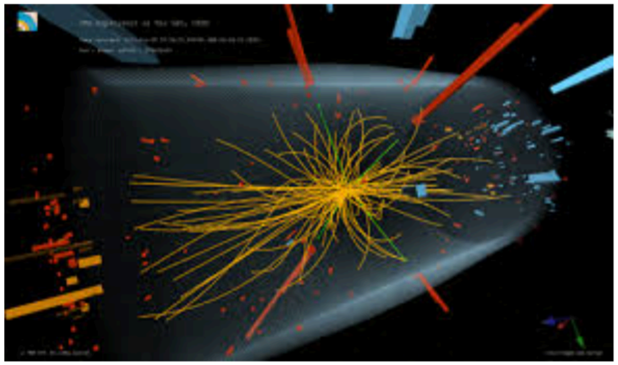
Strong



Weak

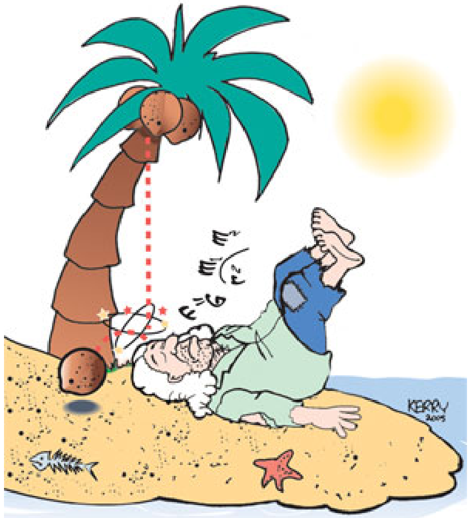


Higgs interactions



Electromagnetic

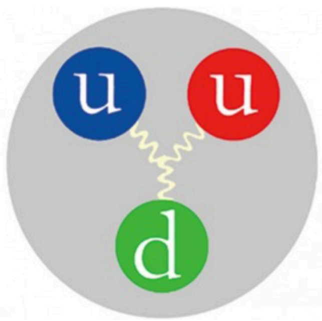
Gravity



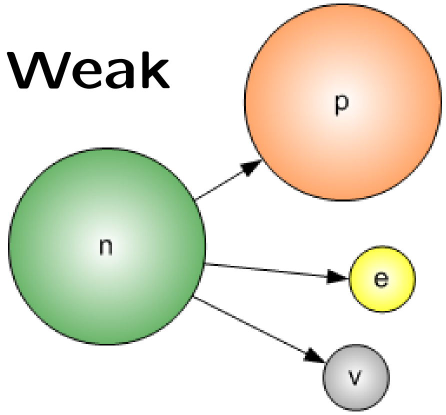
Why gravity was not discovered in Tahiti.

Based on an idea submitted by Zachary H. Levine and Ellen S. Levine

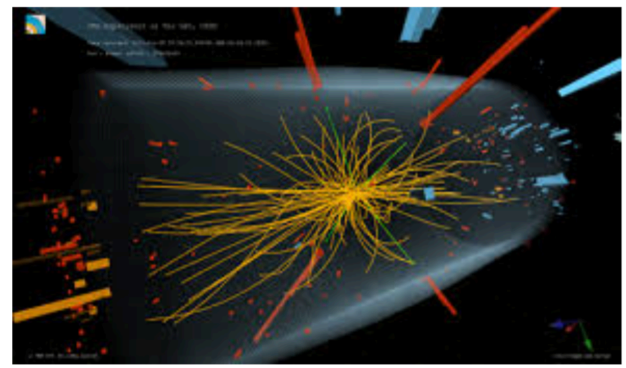
Strong



Weak

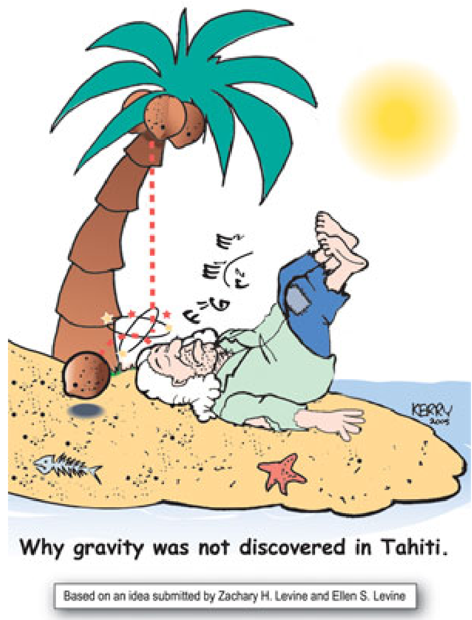


Higgs interactions



Electromagnetic

Gravity

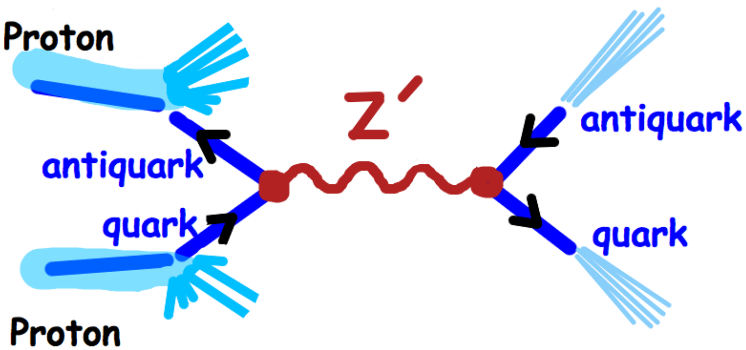


Could there exist additional interactions?

Yes, if new particles are sufficiently heavy, or very weakly coupled.

What new gauge bosons could exist?

Hypothetical heavy particle of spin 1 and charge 0: Z' boson.



Spin-1 fields are well behaved in the UV provided that they are bound states (not discussed here) or gauge bosons.

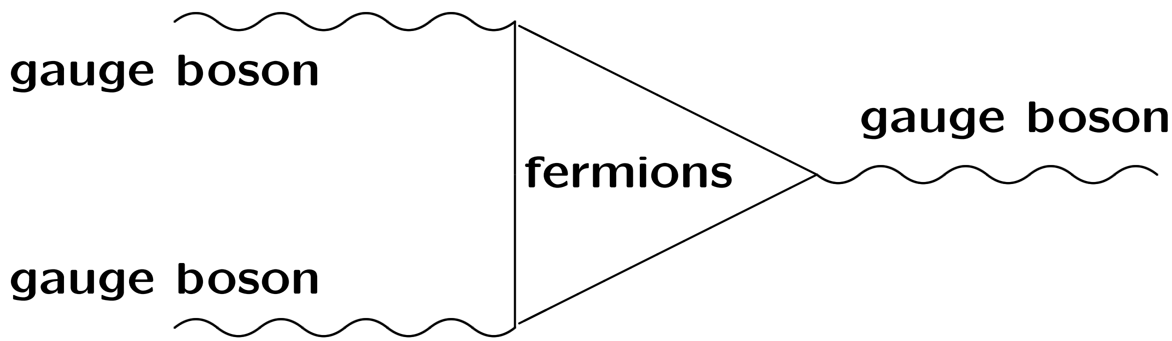
Implication: **if a new spin-1 particle exists, then additional new particles of similar mass or lighter must exist.**

This could change the discovery channels.

Gauge anomaly cancellation

Gauge symmetries may be broken by quantum effects.

Cure: sums over fermion triangle diagrams must vanish.



Standard Model – anomalies cancel within each fermion generation:

$[U(1)_Y]^3$: $\quad 3\left[2(1/6)^3 + (-2/3)^3 + (1/3)^3\right] + 2(-1/2)^3 + (1)^3 = 0$

(u_L, d_L) $\quad u_R \quad d_R \quad (\nu_L, e_L) \quad e_R$

...

Z' is associated with a new gauge symmetry.

Simple choice: $SU(3)_c \times SU(2)_W \times U(1)_Y \times U(1)'$

• $U(1)'$ must be spontaneously broken $\rightarrow$ a new scalar field ϕ acquires a VEV.

• All $U(1)'$ gauge anomalies should cancel $\rightarrow$ there must be new fermions ('anomalons') carrying SM charges.

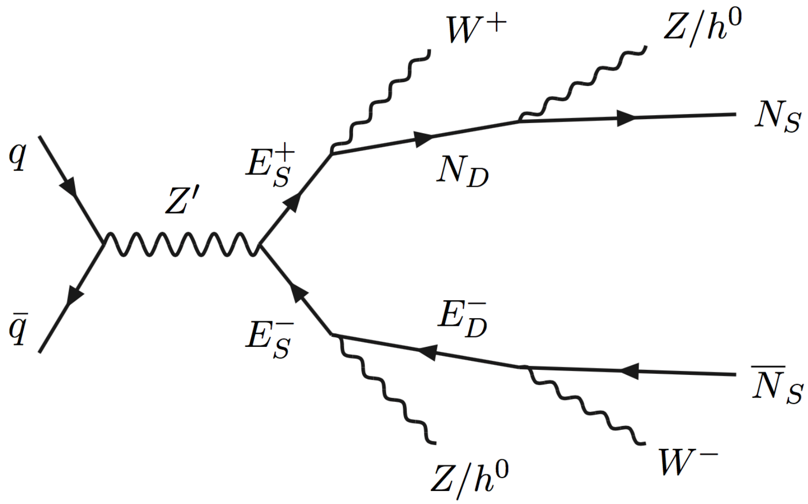
E.g., "Baryonic" Z'_B: same coupling to all quarks, none to leptons

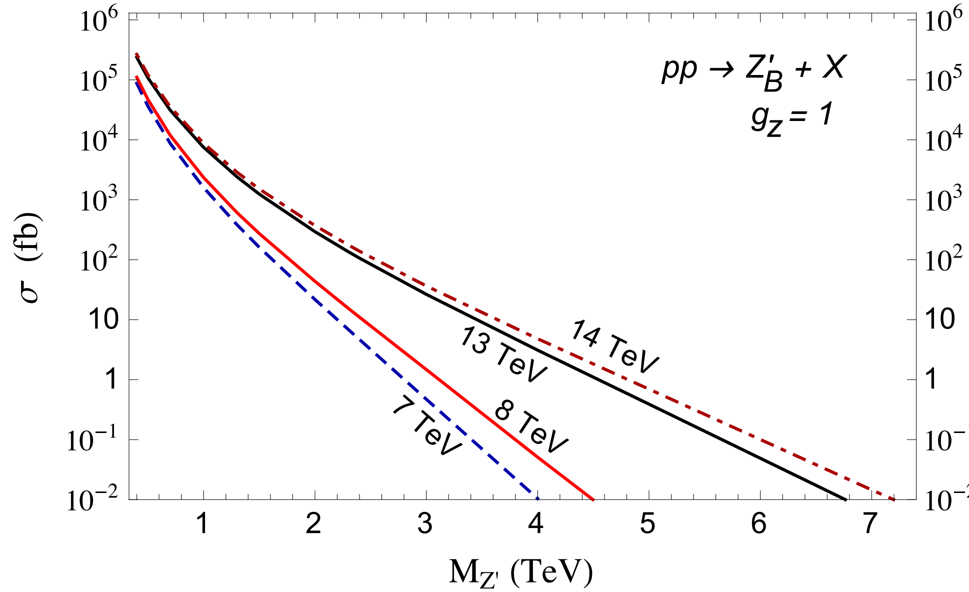
New fields carrying $U(1)_B$ charge in a minimal model:

field	spin	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_B$
L_L L_R	1/2	1	2	$-1/2$	-1 $+2$
E_L E_R	1/2	1	1	-1	$+2$ -1
N_L N_R	1/2	1	1	0	$+2$ -1
ϕ	0	1	1	0	$+3$

Cascade decays via anomalons:

(1506.04435)





$$W^+W^-ZZ + \not{E}_T\ ,\quad \text{or } W^+W^-Zh^0 + \not{E}_T\ ,\quad \text{or } W^+W^-h^0h^0 + \not{E}_T$$

Gauge extension of QCD

$SU(3)_1 \times SU(3)_2 \to SU(3)_c$ implies the existence of a heavy color-octet spin-1 particle: $G' =$ "coloron"

C. T. Hill, Phys. Lett. B **266**, *419 (1991)*

Coloron interactions with quarks have the same form as those of the gluon, with an extra factor of $\tan\theta$:

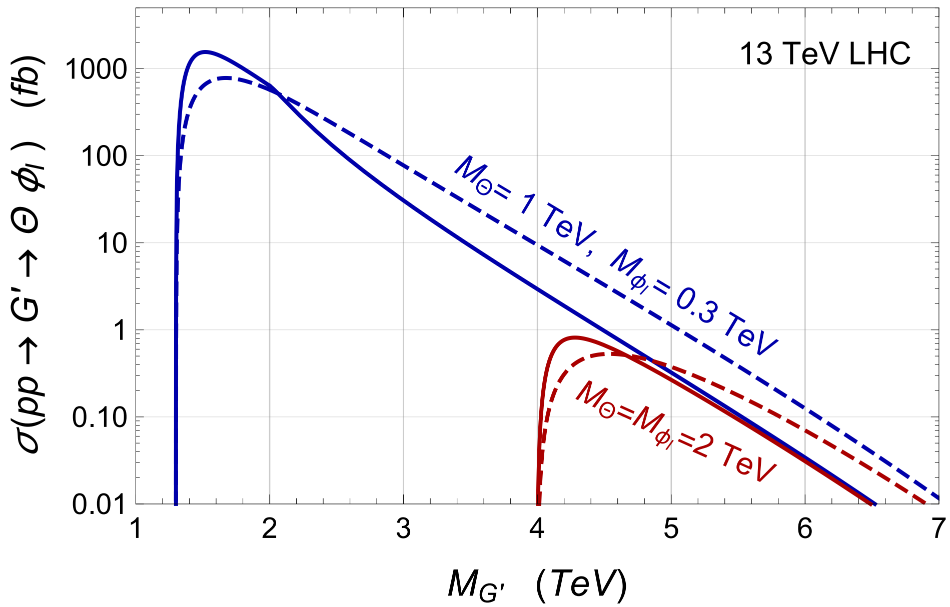
$$g_s \tan\theta \, \bar{q}\gamma^\mu T^a G'^a_\mu \, q$$

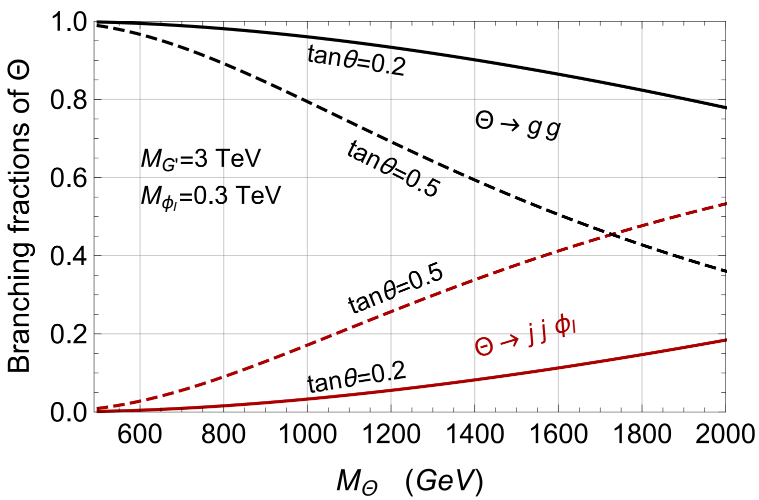
$SU(3)_1 \times SU(3)_2$ **breaking sector:** *color-octet scalar* $- \Theta$

color-singlet scalar $- \phi_I$

Interactions of the coloron with scalars

Coloron production times branching fractions into scalars:



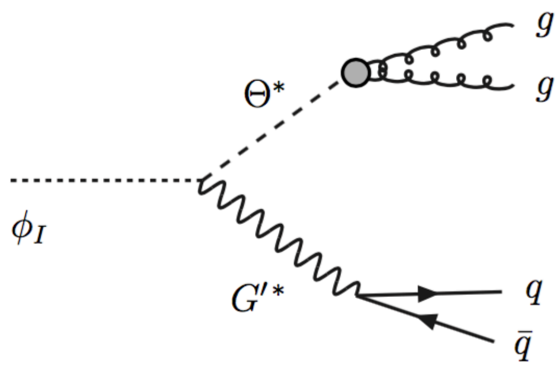


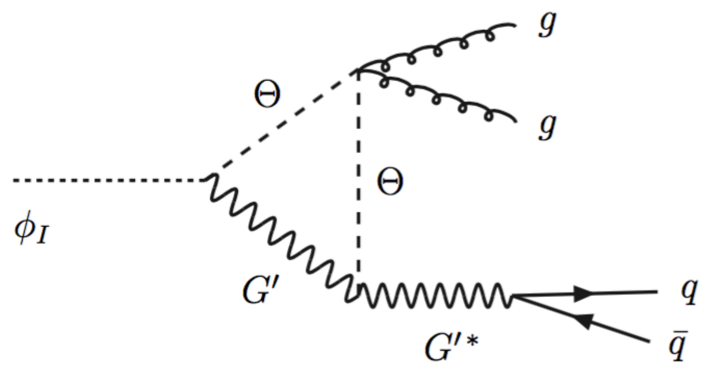
For $M_\Theta > M_{\phi_I}$, Θ has a 3-body decay ($\Theta \to \phi_I q\bar{q}$) or a 1-loop 2-body decay ($\Theta \to gg$).

1802.03005

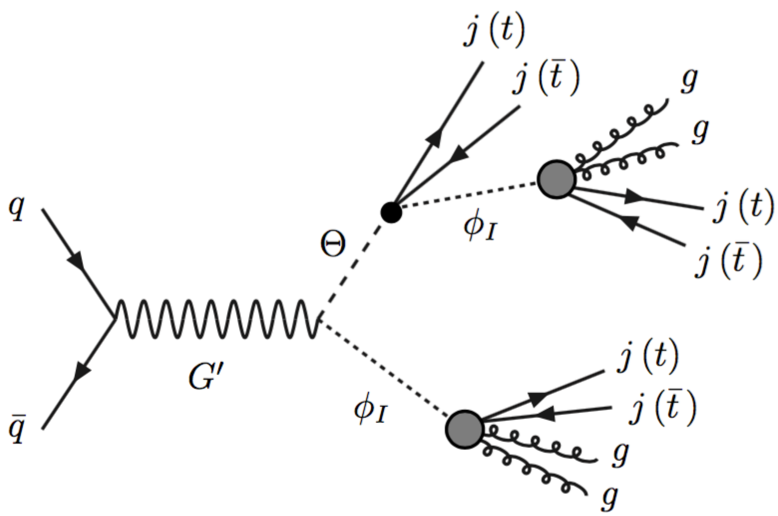
Multi-jet resonances with substructure

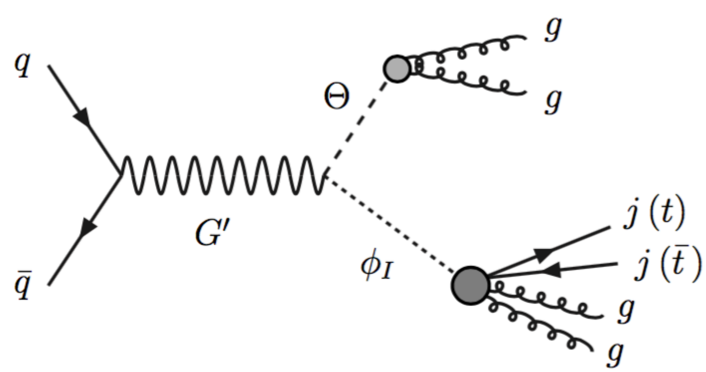
The CP-odd singlet scalar has 4-body decays: $\phi_I \to gg q\bar{q}$





For $M_{\phi_I} \gtrsim 1$ TeV, the 4-body decays dominate → multi-jet signatures:





Conclusions

If new fermions exist, they must be vectorlike under $SU(3)_C \times SU(2)_W \times U(1)_Y$ (can be chiral under a new group).

A vectorlike fermion that mixes with a SM quark or lepton would typically decay into that SM fermion and a SM boson.

$\hat{Q}\hat{Q}$ $\hat{Q}\hat{Q}$ $\hat{Q}\hat{Q}$

New gauge bosons typically require new fermions to cancel the gauge anomalies, and new scalars to break the gauge symmetry.

This leads to interesting signals beyond the usual LHC searches for resonances.

Current understanding of the fundamental laws of nature (Standard Model) is a profound achievement of the humankind. ***You can take it to the next level!***