Baryon number as the fourth color

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The Standard Theory and Beyond in the LHC Era

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In collaboration with Arvind Rajaraman and Tim M.P. Tait

Eve of a particle physics revolution?

➡ **No indisputable direct signal of physics beyond the Standard Model.**

➡ **Some indirect hints of new physics:**

- **dark matter**
- **baryon asymmetry**

Is a discovery just around the corner?

Standard Model

Gauge symmetry

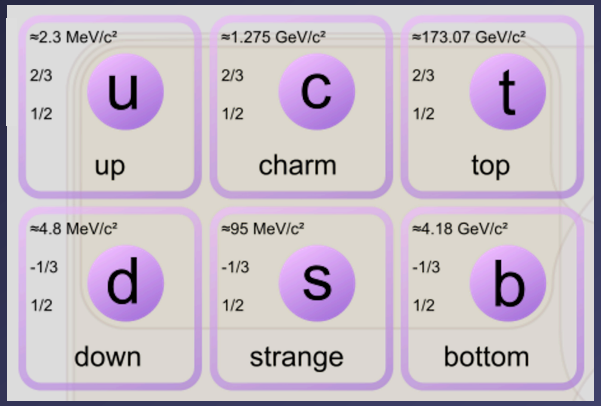
$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Glashow (1961), Weinberg (1967), Salam (1968), Fritzsch and Gell-Mann (1972)

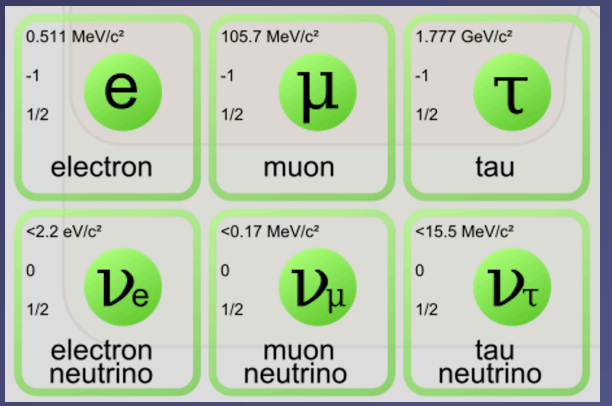
Accidental global symmetry

$$U(1)_B \times U(1)_L$$

quarks



leptons



Simple Standard Model gauge extensions

→ **Gauged baryon and lepton number**

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_B \times U(1)_L$$

Pais (1973); Rajpoot (1988); Foot, Joshi, Lew (1989); Carone, Murayama (1995); Georgi, Glashow (1996); Duerr, Fileviez-Perez, Wise (2013); Arnold, Fileviez-Perez, BF, Spinner (2013)

→ **Unification of color and baryon number**

$$SU(4) \times SU(2)_L \times U(1)_X$$

Baryon number as the fourth color

BF, Arvind Rajaraman, Tim M.P. Tait,
Phys. Rev. D 92, 055022 (2015)

Baryon number as the fourth color

$$SU(4) \times SU(2)_L \times U(1)_X$$

SU(4) **quadruplets:**

$$\hat{Q}_{iL} \equiv \begin{pmatrix} Q_i^r \\ Q_i^b \\ Q_i^g \\ \tilde{Q}_i \end{pmatrix}_L , \quad \hat{u}_R \equiv \begin{pmatrix} u^r \\ u^b \\ u^g \\ \tilde{u} \end{pmatrix}_R , \quad \hat{d}_R \equiv \begin{pmatrix} d^r \\ d^b \\ d^g \\ \tilde{d} \end{pmatrix}_R$$

SU(4) **singlets:**

$$Q'_{iR} , \quad u'_L , \quad d'_L , \quad l_{iL} , \quad e_R$$

Particle content

field	$SU(4)$	$SU(2)_L$	$U(1)_X$
$\hat{Q}_L$	4	2	0
$\hat{u}_R$	4	1	$1/2$
$\hat{d}_R$	4	1	$-1/2$
Q'_R	1	2	$-1/2$
u'_L	1	1	0
d'_L	1	1	-1
l_L	1	2	$-1/2$
e_R	1	1	-1
H	1	2	$1/2$
$\hat{\Phi}$	4	1	$1/2$

Symmetry breaking

$$SU(4)\times SU(2)_L\times U(1)_X \xrightarrow{\langle\hat{\Phi}\rangle} SU(3)_C\times SU(2)_L\times U(1)_Y$$

SU(4) **Higgs VEV:**

$$\langle\hat{\Phi}\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\0\\0\\V\end{pmatrix}$$

Relation between *X* and hypercharge:

$$Y = X + \frac{1}{6}\begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&-3\end{pmatrix}$$

Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\text{gauge}} &= -\tfrac{1}{4} G^A_{\mu\nu} G^{A\,\mu\nu} - \tfrac{1}{4} W^a_{\mu\nu} W^{a\,\mu\nu} - \tfrac{1}{4} X_{\mu\nu} X^{\mu\nu} \\
\mathcal{L}_{\text{kin}} &= \bar{\hat{Q}}_L \, i\not{D} \, \hat{Q}_L + \bar{\hat{u}}_R \, i\not{D} \, \hat{u}_R + \bar{\hat{d}}_R \, i\not{D} \, \hat{d}_R + \bar{l}_L \, i\not{D} \, l_L + \bar{e}_R \, i\not{D} \, e_R \\
&\quad + \bar{Q}'_R \, i\not{D} \, Q'_R + \bar{u}'_L \, i\not{D} \, u'_L + \bar{d}'_L \, i\not{D} \, d'_L \\
\mathcal{L}_{\text{Higgs}} &= |D_\mu H|^2 + |D_\mu \hat{\Phi}|^2 + \mu^2 |H|^2 - \tfrac{1}{2}\lambda |H|^4 \\
&\quad + \mu_4^2 |\hat{\Phi}|^2 - \tfrac{1}{2}\lambda_4 |\hat{\Phi}|^4 - \lambda_2 |H|^2 |\hat{\Phi}|^2 \\
\mathcal{L}_{\text{Y1}} &= y_u^{ab} \, \bar{\hat{Q}}^a_L \, \tilde{H} \, \hat{u}^b_R + y_d^{ab} \, \bar{\hat{Q}}^a_L \, H \, \hat{d}^b_R + y_e^{ab} \, \bar{l}^a_L \, H \, e^b_R + \text{h.c.} \\
\mathcal{L}_{\text{Y2}} &= y'^{ab}_u \, \bar{Q}'^a_R \, \tilde{H} \, u'^b_L + y'^{ab}_d \, \bar{Q}'^a_R \, H \, d'^b_L + \text{h.c.} \\
\mathcal{L}_{\text{Y3}} &= Y_Q^{ab} \, \bar{\hat{Q}}^a_L \, \hat{\Phi} \, Q'^b_R + Y_u^{ab} \, \bar{\hat{u}}^a_R \, \hat{\Phi} \, u'^b_L + Y_d^{ab} \, \bar{\hat{d}}^a_R \, \hat{\Phi} \, d'^b_L + \text{h.c.}
\end{aligned}
$$

$$Y\langle\hat{\Phi}\rangle \gg y\,\langle H\rangle$$

$$Y\langle\hat{\Phi}\rangle \gg y'\langle H\rangle$$

Covariant derivative:

$$D_\mu = \partial_\mu + i g_4 \, G^A_\mu T^A + i g_2 W^a_\mu t^a + i g_X X_\mu X$$

Gauge bosons

$$SU(4)\times SU(2)_L\times U(1)_X \xrightarrow{\langle\hat{\Phi}\rangle} SU(3)_C\times SU(2)_L\times U(1)_Y$$

15 vector gauge bosons:

- $G_\mu^{1\ldots8}$ → gluons
- $G_\mu^{9\ldots14}$ → $G'^{\,\alpha}_\mu$ with mass $m_{G'} = \frac{1}{2}\, g_4\, V$
- G_μ^{15} and X_μ → B_μ and Z'_μ

$$m_{Z'} = \frac{1}{2}\sqrt{g_X^2 + \tfrac{3}{2}g_4^2}\; V$$

Gauge bosons

Relation between couplings:

$$g_Y = \frac{g_X g_4}{\sqrt{\frac{2}{3} g_X^2 + g_4^2}}$$

$$\approx 1/3$$

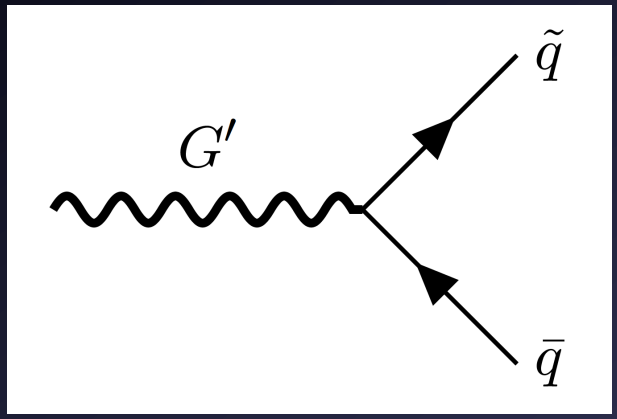
$$\sin\theta_4 \equiv \frac{g_X}{\sqrt{g_X^2 + \frac{3}{2} g_4^2}}$$

$$\approx 0.28$$

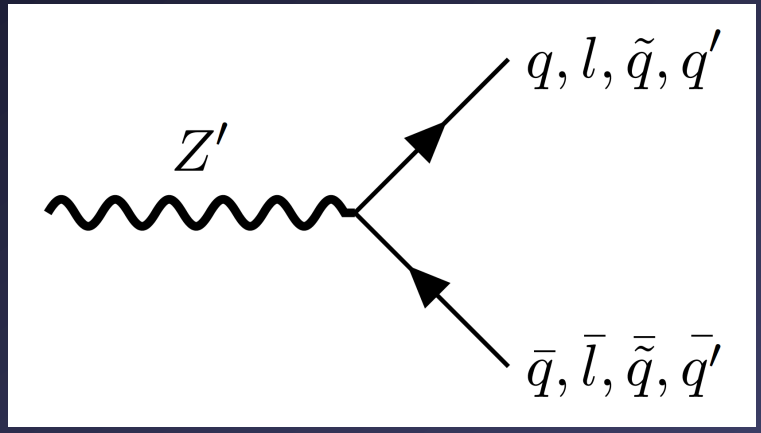
Gauge boson mixing:

$$\begin{pmatrix} Z'_\mu \\ B_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_4 & -\sin\theta_4 \\ \sin\theta_4 & \cos\theta_4 \end{pmatrix} \begin{pmatrix} G^{15}_\mu \\ X_\mu \end{pmatrix}$$

Gauge boson couplings



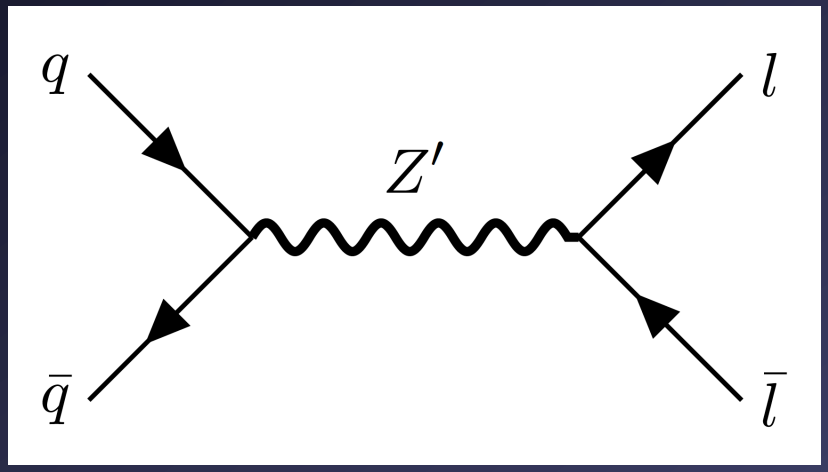
$$g_4$$



$$\frac{g_Y}{\sin\theta_4 \cos\theta_4}\left(-\sqrt{\frac{2}{3}}T^{15} + Y\sin^2\theta_4\right)$$

LHC constraints

Z' production:



LHC bound:

$$m_{Z'} \gtrsim 2.0\ \mathrm{TeV} \quad \Rightarrow \quad V \gtrsim 3.1\ \mathrm{TeV}$$

Quark partners

Yukawa interactions:

$$\mathcal{L}_{\rm Y1} = y_u^{ab}\,\bar{\hat{Q}}_L^a\,\tilde{H}\,\hat{u}_R^b + y_d^{ab}\,\bar{\hat{Q}}_L^a\,H\,\hat{d}_R^b + y_e^{ab}\,\bar{l}_L^a\,H\,e_R^b + \text{h.c.}$$

$$\mathcal{L}_{\rm Y2} = y_u'^{ab}\,\bar{Q}'^a_R\,\tilde{H}\,u'^b_L + y_d'^{ab}\,\bar{Q}'^a_R\,H\,d'^b_L + \text{h.c.}$$

$$\mathcal{L}_{\rm Y3} = Y_Q^{ab}\,\bar{\hat{Q}}_L^a\,\hat{\Phi}\,Q'^b_R + Y_u^{ab}\,\bar{\hat{u}}_R^a\,\hat{\Phi}\,u'^b_L + Y_d^{ab}\,\bar{\hat{d}}_R^a\,\hat{\Phi}\,d'^b_L + \text{h.c.}$$

Notation:

$$\tilde{Q} = \begin{pmatrix} \tilde{U} \\ \tilde{D} \end{pmatrix}$$

Quark partners

After *SU(4)* breaking:

$$\frac{1}{\sqrt{2}}\begin{pmatrix}\overline{\tilde{U}}_L & \overline{u}'_L\end{pmatrix}\begin{pmatrix}Y_Q V & y_u v\\ (y'_u v)^\dagger & (Y_u V)^\dagger\end{pmatrix}\begin{pmatrix}U'_R\\ \tilde{u}_R\end{pmatrix}$$
$$+\frac{1}{\sqrt{2}}\begin{pmatrix}\overline{\tilde{D}}_L & \overline{d}'_L\end{pmatrix}\begin{pmatrix}Y_Q V & y_d v\\ (y'_d v)^\dagger & (Y_d V)^\dagger\end{pmatrix}\begin{pmatrix}D'_R\\ \tilde{d}_R\end{pmatrix} + \text{h.c.}$$

- **6 electrically neutral combinations of $\tilde{u}$ and $\tilde{U}$**
- **6 electrically charged combinations of $\tilde{d}$ and $\tilde{D}$**

Dark matter

Lightest combination of $\tilde{u}$ and $\tilde{U}$:

$$\tilde{u}'$$

$$\tilde{u}'_L = u'_L + \epsilon \tilde{U}_L$$
$$\tilde{u}'_R = \tilde{u}_R + \epsilon U'_R$$

Stabilized by a residual *U(1)* symmetry:

$$\tilde{Q}_L \to e^{i\theta} \tilde{Q}_L \,, \quad \tilde{u}_R \to e^{i\theta} \tilde{u}_R \,, \quad \tilde{d}_R \to e^{i\theta} \tilde{d}_R$$
$$Q'_R \to e^{i\theta} Q'_R \,, \quad u'_L \to e^{i\theta} u'_L \,, \quad d'_L \to e^{i\theta} d'_L$$

Dark matter mass: $m_{\tilde{u}'} \approx \frac{1}{\sqrt{2}} (Y_u)_{ii} V$

Baryogenesis

No asymmetry between baryons and antibaryons from *SU(4)* dynamics.

Dimension six operators:

$$\frac{1}{\Lambda_6^2}\,\epsilon_{abcd}\left[c_4\,\hat{u}_R^a\hat{u}_R^b\hat{d}_R^c\hat{d}_R^d + c_5(\hat{Q}_L^a\epsilon\,\hat{Q}_L^b)(\hat{Q}_L^c\epsilon\,\hat{Q}_L^d)\right]$$

$$\Lambda_6 \gtrsim 5\times 10^{10}\ \mathrm{GeV}$$

Asymmetric dark matter!

Asymmetric dark matter

Baryon and dark matter asymmetry:

$$\Delta B_i = -\Delta\chi$$

Final baryon asymmetry:

$$\Delta B_f = -\frac{28}{79}\,\Delta\chi$$

Dark matter mass:

$$m_{\tilde{u}_1'} = \left|\frac{\Delta B_f}{\Delta\chi}\right| \frac{\Omega_{\rm DM}}{\Omega_B}\, m_{\rm proton} \simeq 1.75\ {\rm GeV}$$

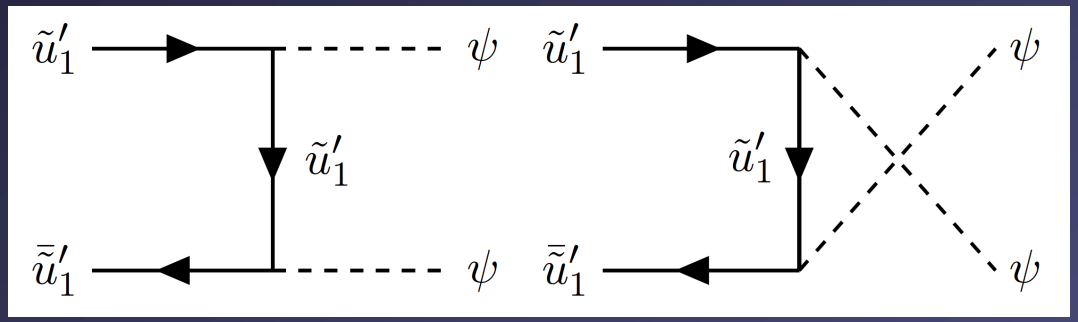
Asymmetric dark matter

DM candidate $\tilde{u}'_1$ with mass $m_{\tilde{u}'_1} \approx 1.75\ \mathrm{GeV}$

➡ direct detection: no current constraints

➡ relic density:

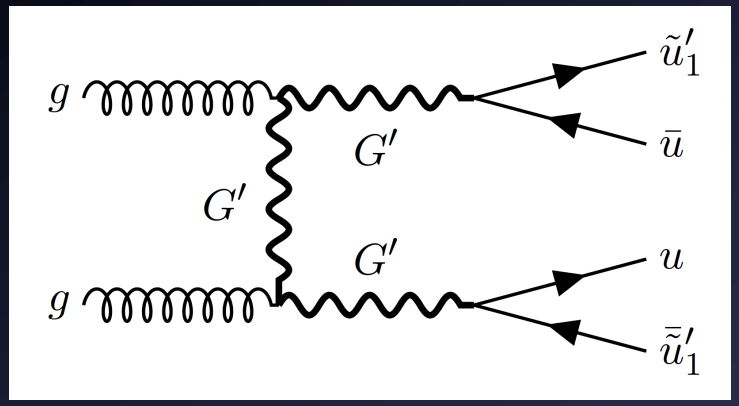
- *SU(4)* Higgs mass < 1.75 GeV
- additional gauge multiplet $\mathcal{L}_\psi = g\,\psi\,\bar{\tilde{u}}'_1\tilde{u}'_1$



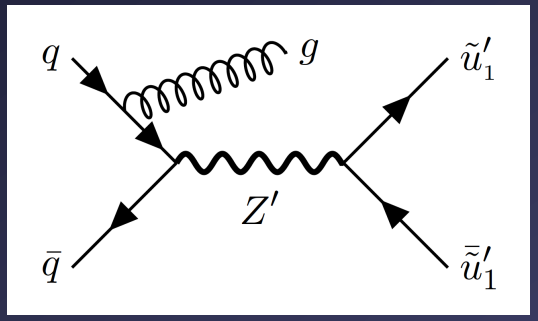
$g \gtrsim 0.05$

LHC signatures – 1st generation DM

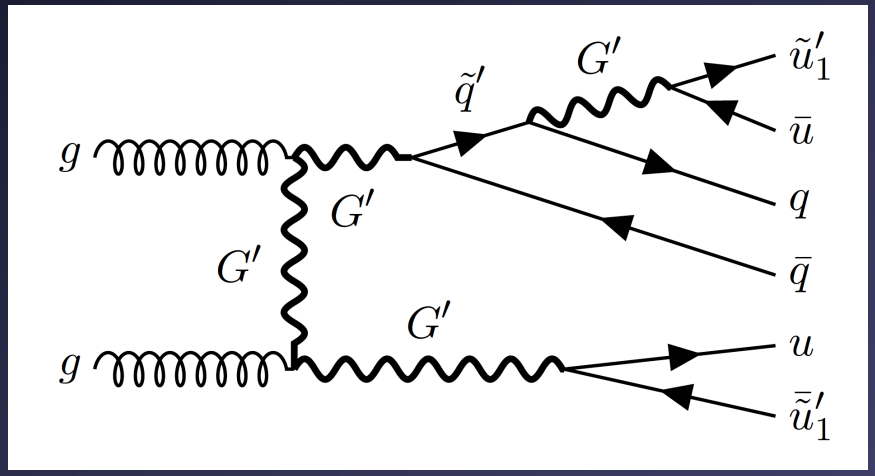
BF, Edison Weik, Daniel Whiteson (in progress)



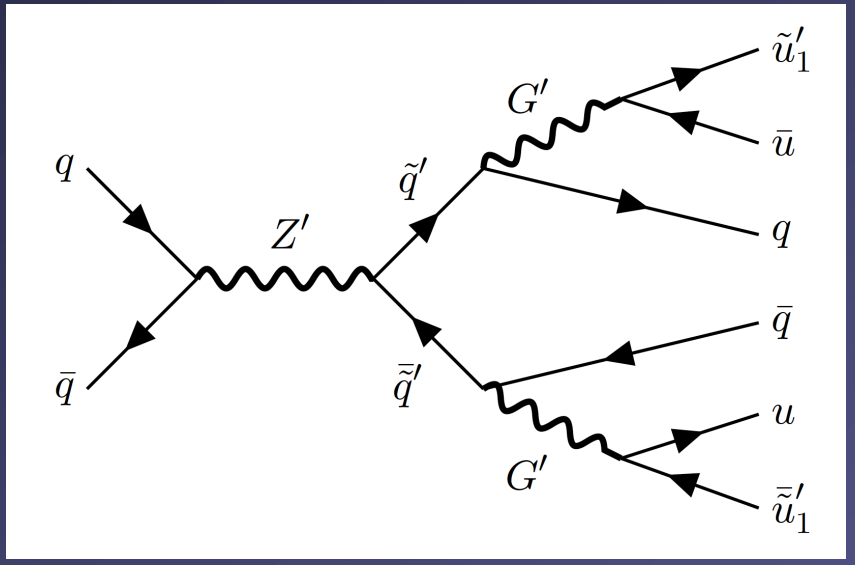
2 jets + MET



1 jet + MET



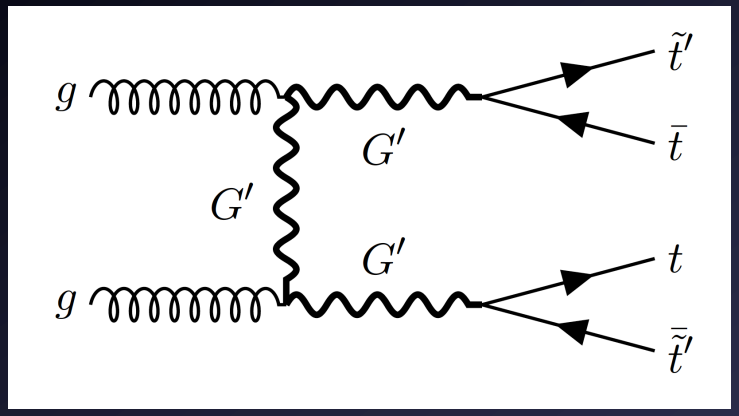
4 jets + MET



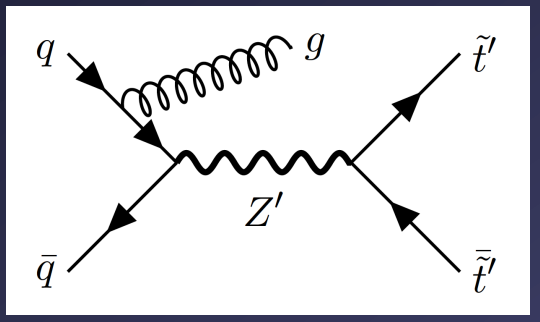
4 jets + MET

LHC signatures – 3rd generation DM

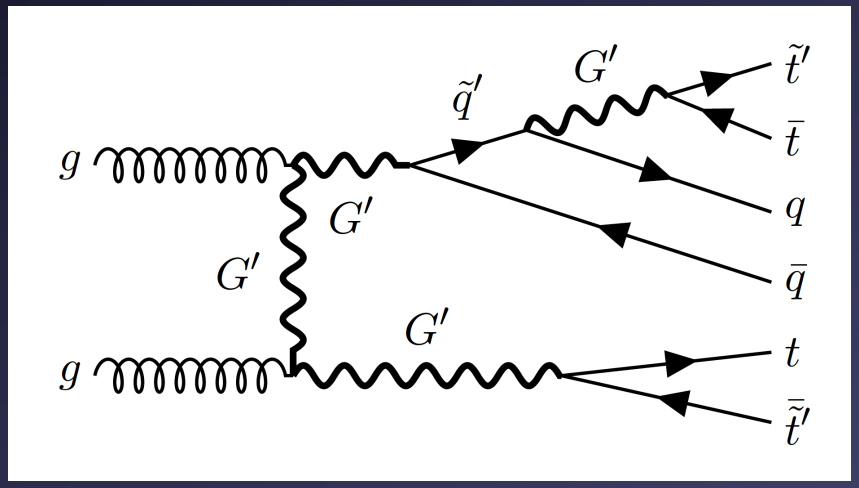
BF, Tim M.P. Tait (in preparation); BF, Edison Weik, Daniel Whiteson (in progress)



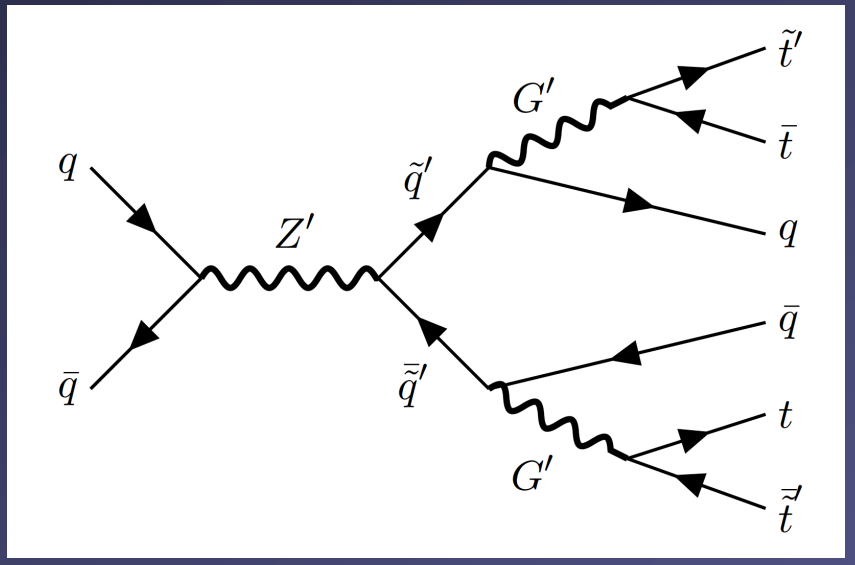
$t\,\bar{t}$ + MET



1 jet + MET



2 jets + $t\,\bar{t}$ + MET



2 jets + $t\,\bar{t}$ + MET

Conclusions

- Standard Model with gauged baryon and lepton number is a relatively unexplored territory with possible hidden treasures.
- Unifying color and baryon number into an *SU(4)* gauge symmetry has a number of nice features.
- Analyzing other simple Standard Model gauge extensions seems like a worthwhile effort.


Thank you!