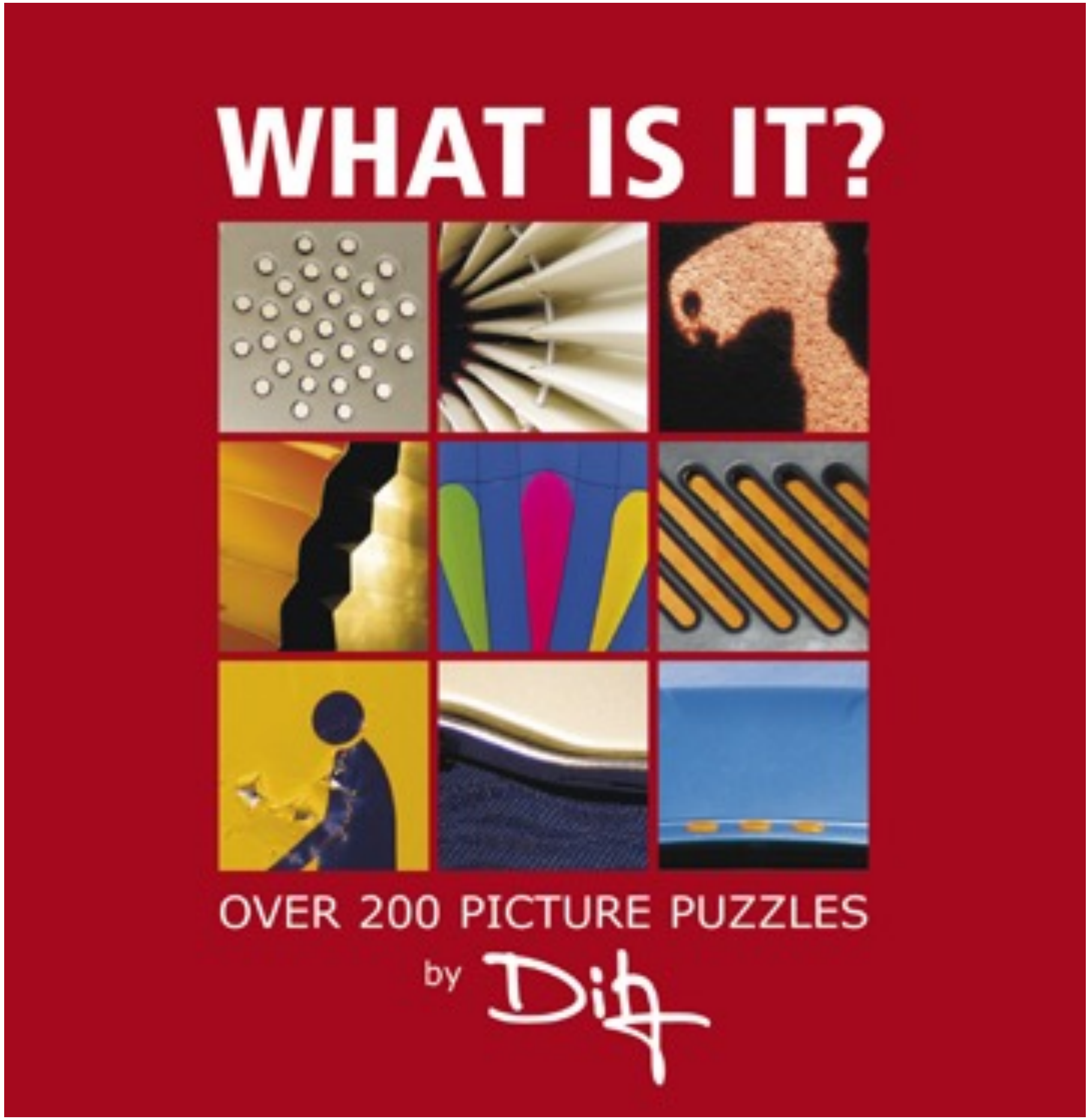
Separating Di-jet Resonances using the Color Discriminant Variable

Elizabeth H. Simmons
Michigan State University

- Introduction
- Coloron Discovery and Properties
- Color Discriminant Variable
- Including Flavor
- Beyond Vector Resonances
- Conclusions

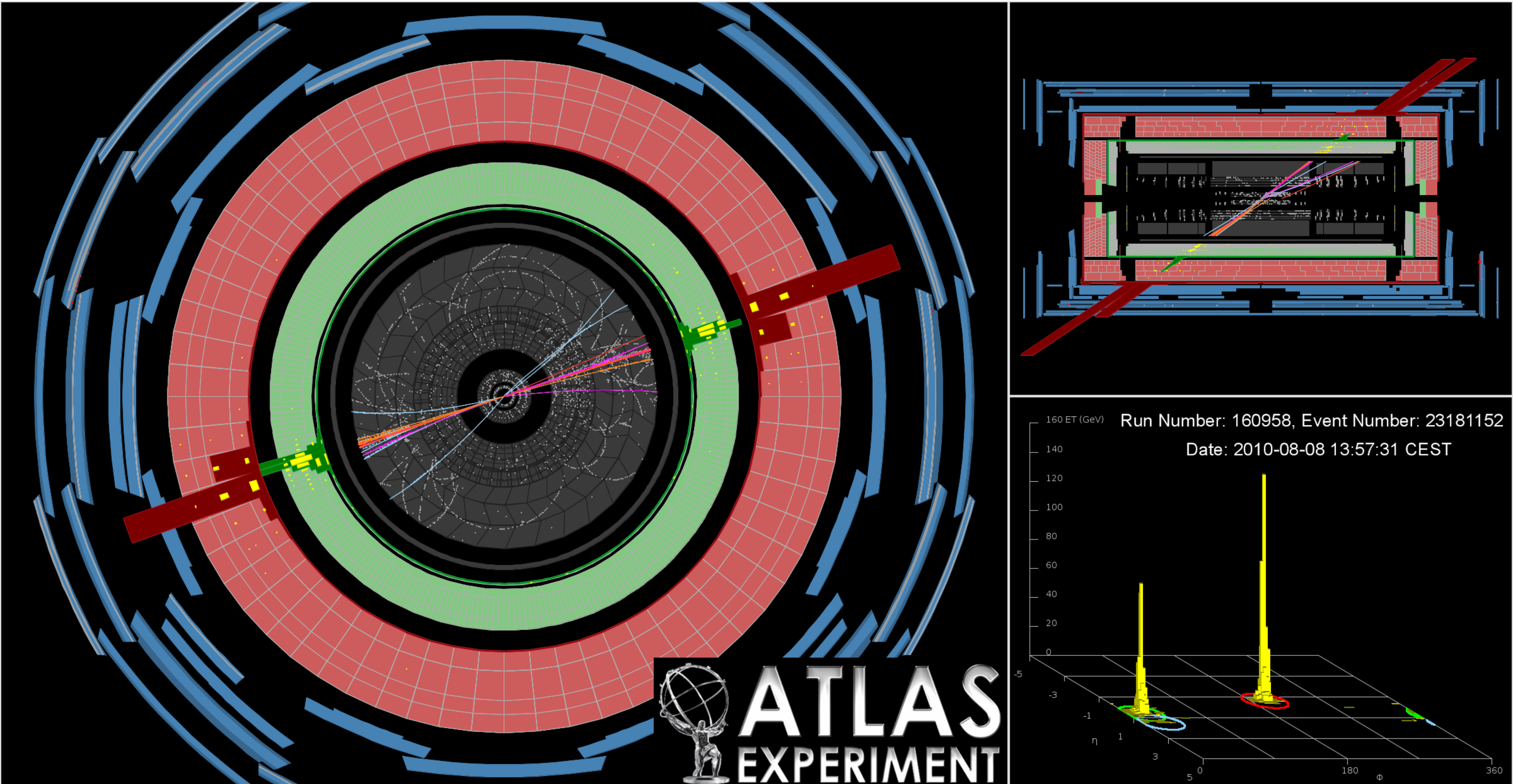
Nagoya University March 6, 2015

If Any New State Is Seen at LHC:

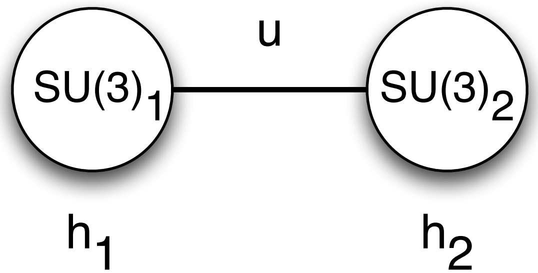


New State Decaying to Dijets:

How can we quickly tell different dijet resonances apart using straightforward measurements of the dijet state?



Coloron Models: Gauge Sector



SU(3)₁ x SU(3)₂ color sector with $M^2 = \frac{u^2}{4}\begin{pmatrix} h_1^2 & -h_1 h_2 \\ -h_1 h_2 & h_2^2 \end{pmatrix}$

unbroken subgroup: $SU(3)_{1+2} = SU(3)_{QCD}$

$$h_1 = \frac{g_s}{\cos\theta} \qquad h_2 = \frac{g_s}{\sin\theta}$$

gluon state: $G_\mu^A = \cos\theta\, A_{1\mu}^A + \sin\theta\, A_{2\mu}^A$

couples to: $g_S J_G^\mu \equiv g_S(J_1^\mu + J_2^\mu)$ $\qquad M_G = 0$

coloron state: $C_\mu^A = -\sin\theta\, A_{1\mu}^A + \cos\theta\, A_{2\mu}^A$ $\qquad M_C = \frac{u}{\sqrt{2}}\sqrt{h_1^2 + h_2^2}$

couples to: $g_S J_C^\mu \equiv g_S(-J_1^\mu \tan\theta + J_2^\mu \cot\theta)$

Quarks' $SU(3)_1 \times SU(3)_2$ charges impact phenomenology

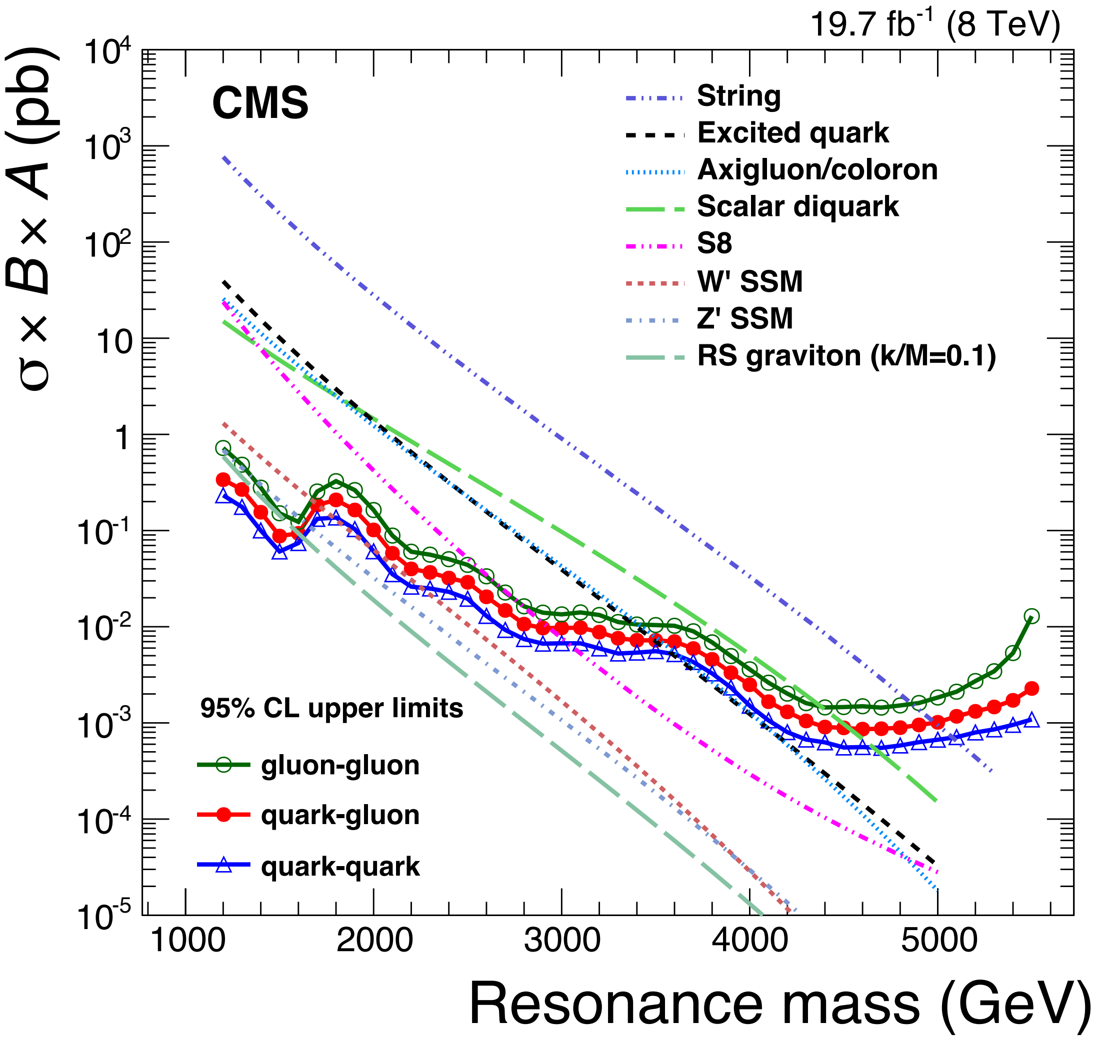
Quark Charges -> Coloron Phenomenology

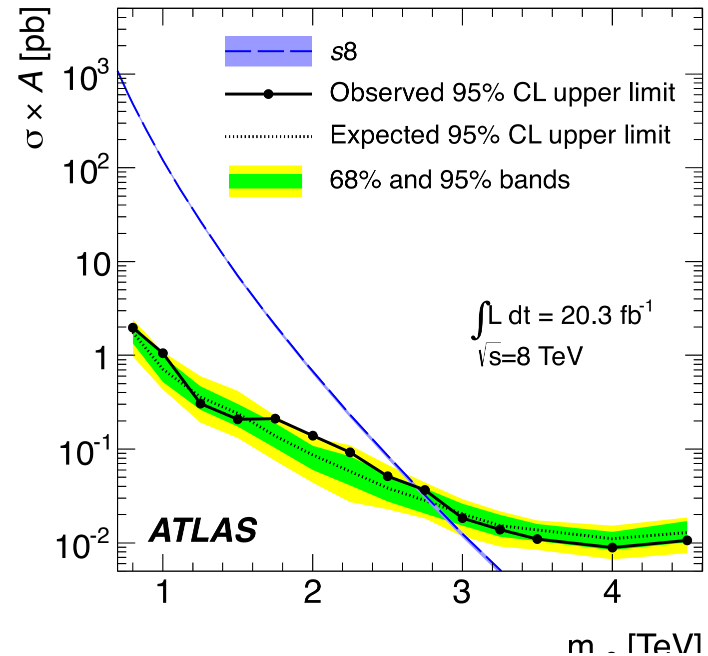
$SU(3)_1$	$SU(3)_2$	model	pheno.
	$(t,b)_L$ q_L t_R,b_R q_R	**coloron**	dijet
q_R	$(t,b)_L$ q_L t_R,b_R		
t_R,b_R	$(t,b)_L$ q_L q_R		
q_L	$(t,b)_L$ t_R,b_R q_R		
q_L t_R,b_R	$(t,b)_L$ q_R	**new axigluon**	dijet, A^t_{FB}, FCNC
q_L q_R	$(t,b)_L$ t_R,b_R	**topgluon**	dijet, tt, bb, FCNC, R_b...
t_R,b_R q_R	$(t,b)_L$ q_L	**classic axigluon**	dijet, A^t_{FB}
q_L t_R,b_R q_R	$(t,b)_L$		

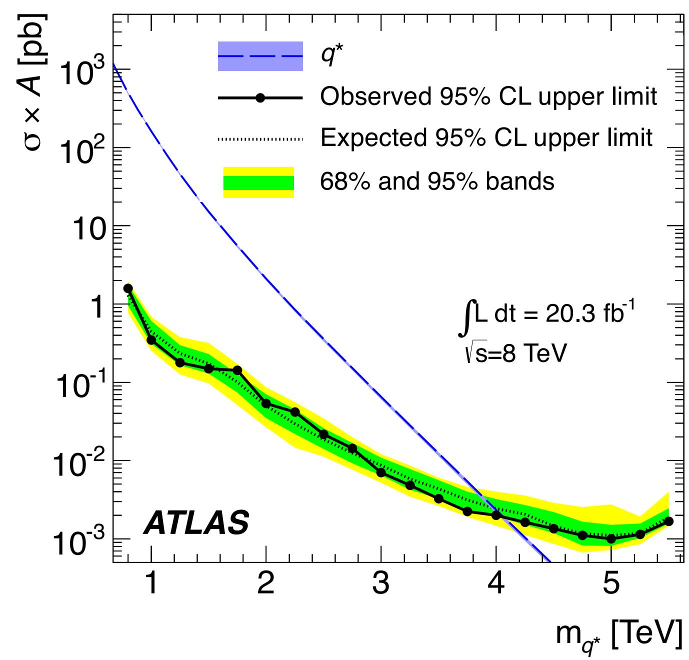
q = u,d,c,s

Coloron Discovery and Properties

LHC Limits on New Dijet Resonances



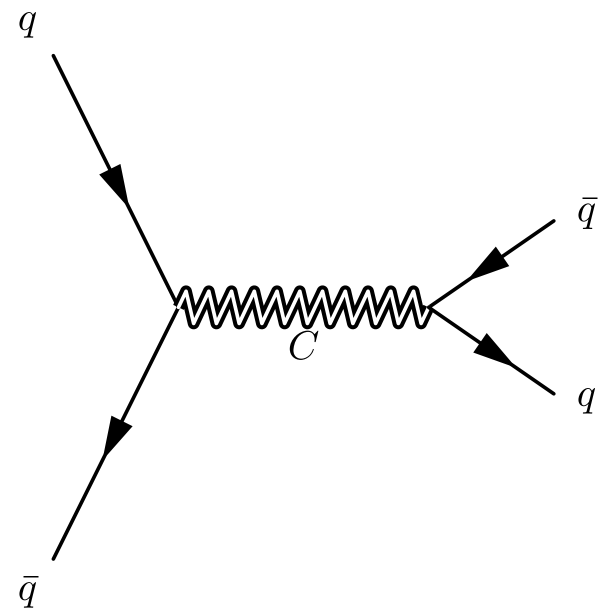




CMS arXiv:1501.04198

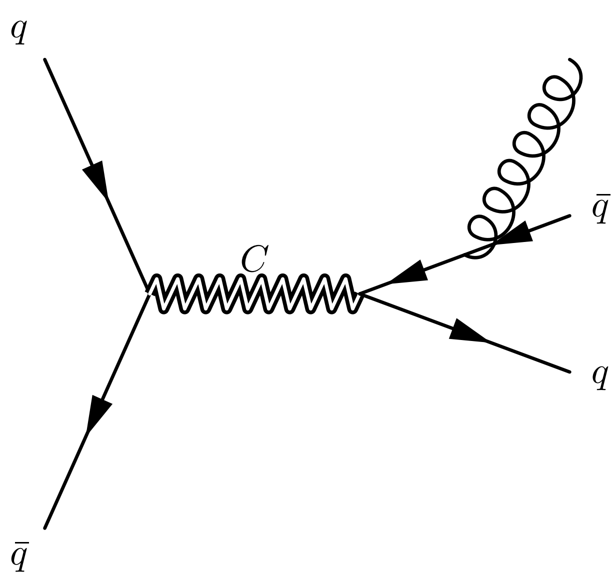
ATLAS arXiv:1407.1376

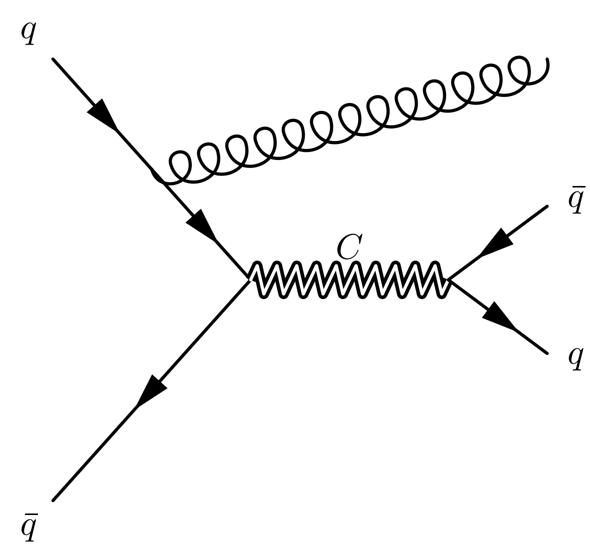
Coloron Production



LO vs NLO production impacts

- cross-section value
- scale-dependence
- p_T of produced coloron



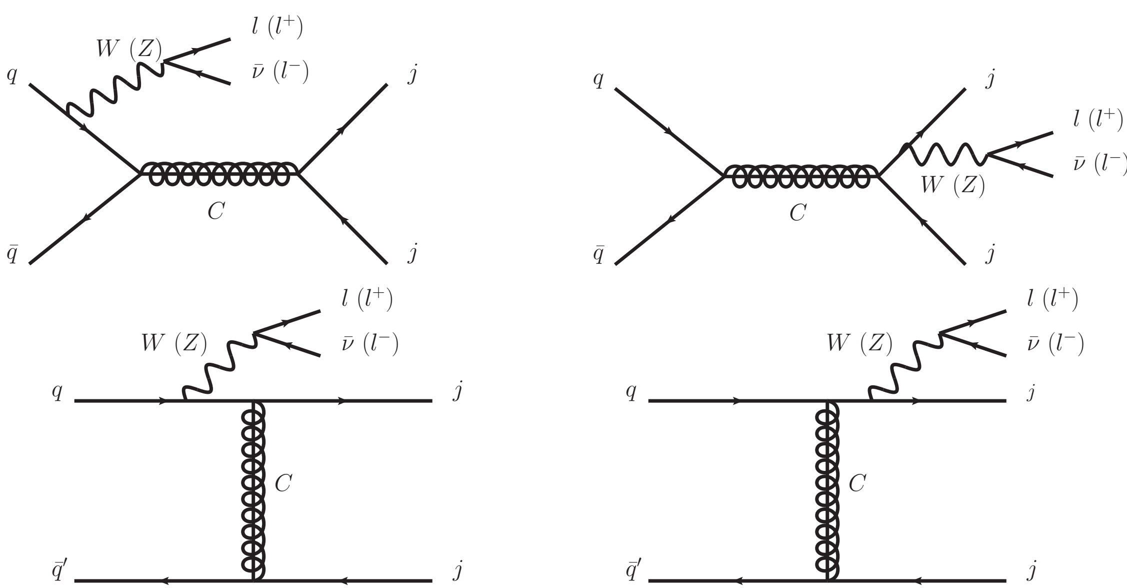


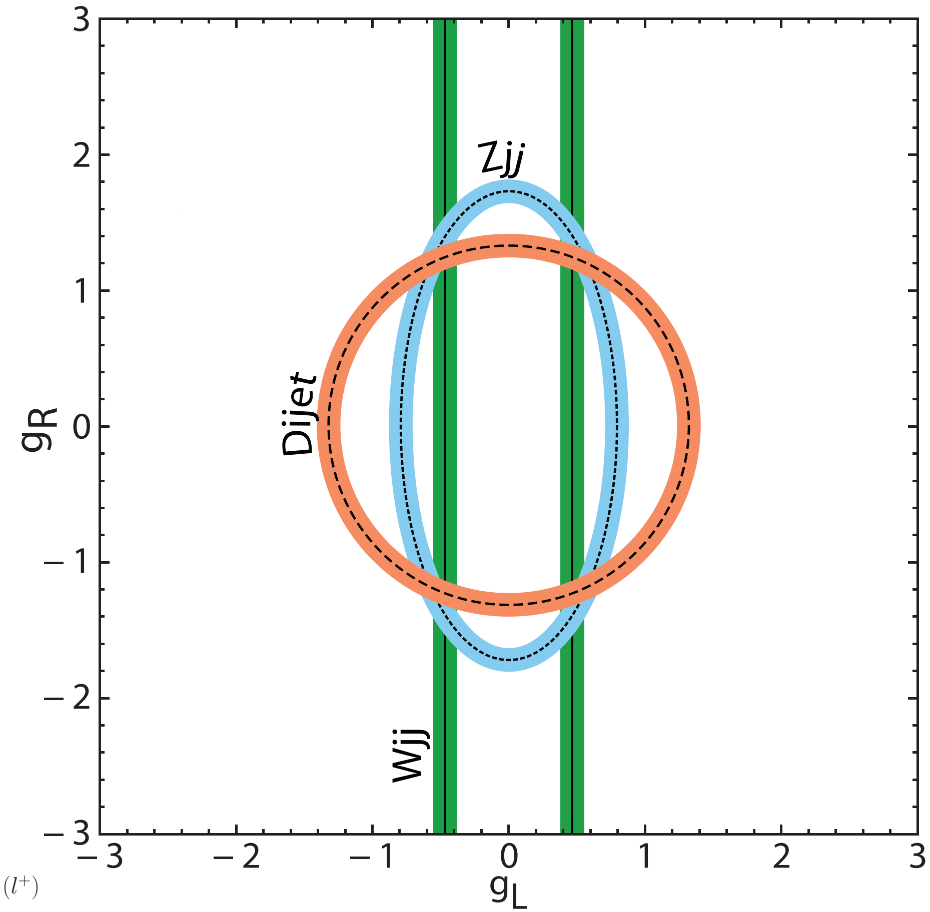
R.S. Chivukula, A. Farzinnia, R. Foadi, EHS arXiv:1111.7261
R.S. Chivukula, A. Farzinnia, J. Ren, EHS arXiv:1303.1120

W+Cᴬ probes Coloron's Chiral Couplings

Associated production probes
a coloron's couplings to
RH and LH fermions:

$$pp \to C^a + W[Z] \to jj\ell\nu[\ell\ell]$$

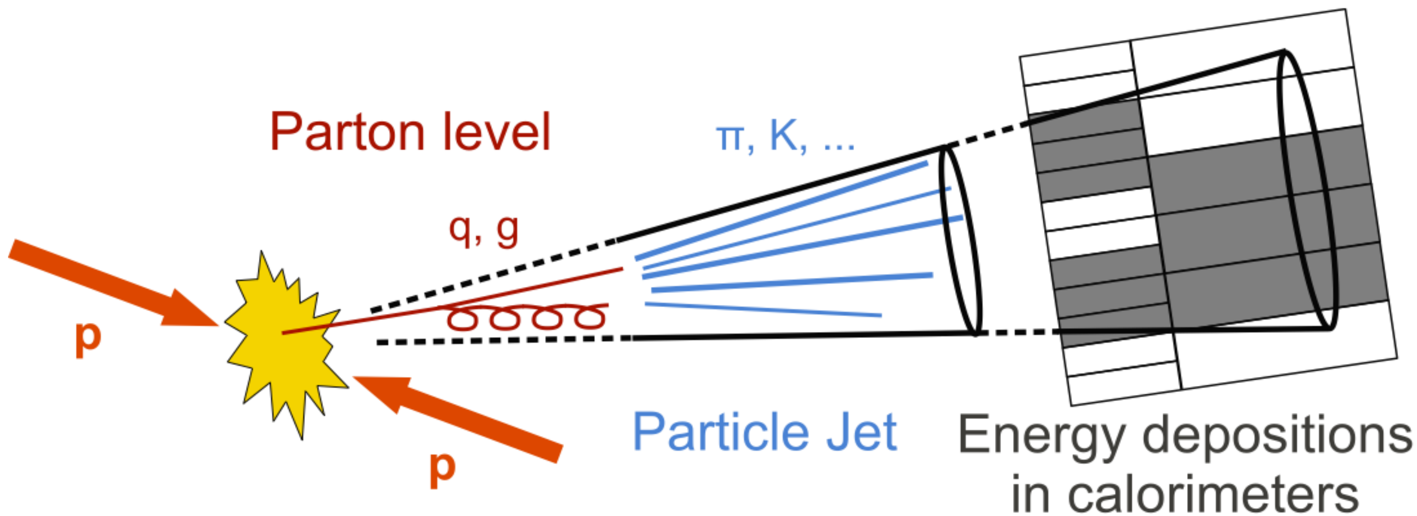




A. Atre, R.S. Chivukula,
P. Ittisamai, EHS
arXiv:1206.1661

Jet Energy Profile

Gluons radiate more than Quarks



Expect quarks to form "tighter" jets than gluons, for fixed p_T

Relative fraction of qq, qg, gg jet pairs in event sample can suggest the nature of any new resonance

R.S. Chivukula, EHS, N. Vignaroli arXiv:1412.3094

Color Discriminant Variable: Basics

A. Atre, R.S. Chivukula, P. Ittisamai, EHS

arXiv:1306.4715

Identifying Dijet Resonances

Suppose a new dijet resonance of mass M and cross-section σ_{jj} is found. **Is it a coloron or a leptophobic Z'?** Assume its quark couplings are **flavor universal** to start.

$$\sigma_{jj}^{C} = \frac{8}{9}\frac{\Gamma_C}{M_C^3}\sum_q W_q(M_C)Br(C \to jj)$$

must be equal

$$\sigma_{jj}^{Z'} = \frac{1}{9}\frac{\Gamma_{Z'}}{M_{Z'}^3}\sum_q W_q(M_{Z'})Br(Z' \to jj)$$

$$W_q(M_V) = 2\pi^2\frac{M_V^2}{s}\int_{M_V^2/s}^{1}\frac{dx}{x}\left[f_q\left(x,Q^2\right)f_{\bar{q}}\left(\frac{M_V^2}{sx},Q^2\right) + f_{\bar{q}}\left(x,Q^2\right)f_q\left(\frac{M_V^2}{sx},Q^2\right)\right]$$

Color Discriminant Variable

$$\sigma_{jj}^{C} = \frac{8}{9}\frac{\Gamma_C}{M_C^3}\sum_q W_q(M_C)Br(C \to jj)$$

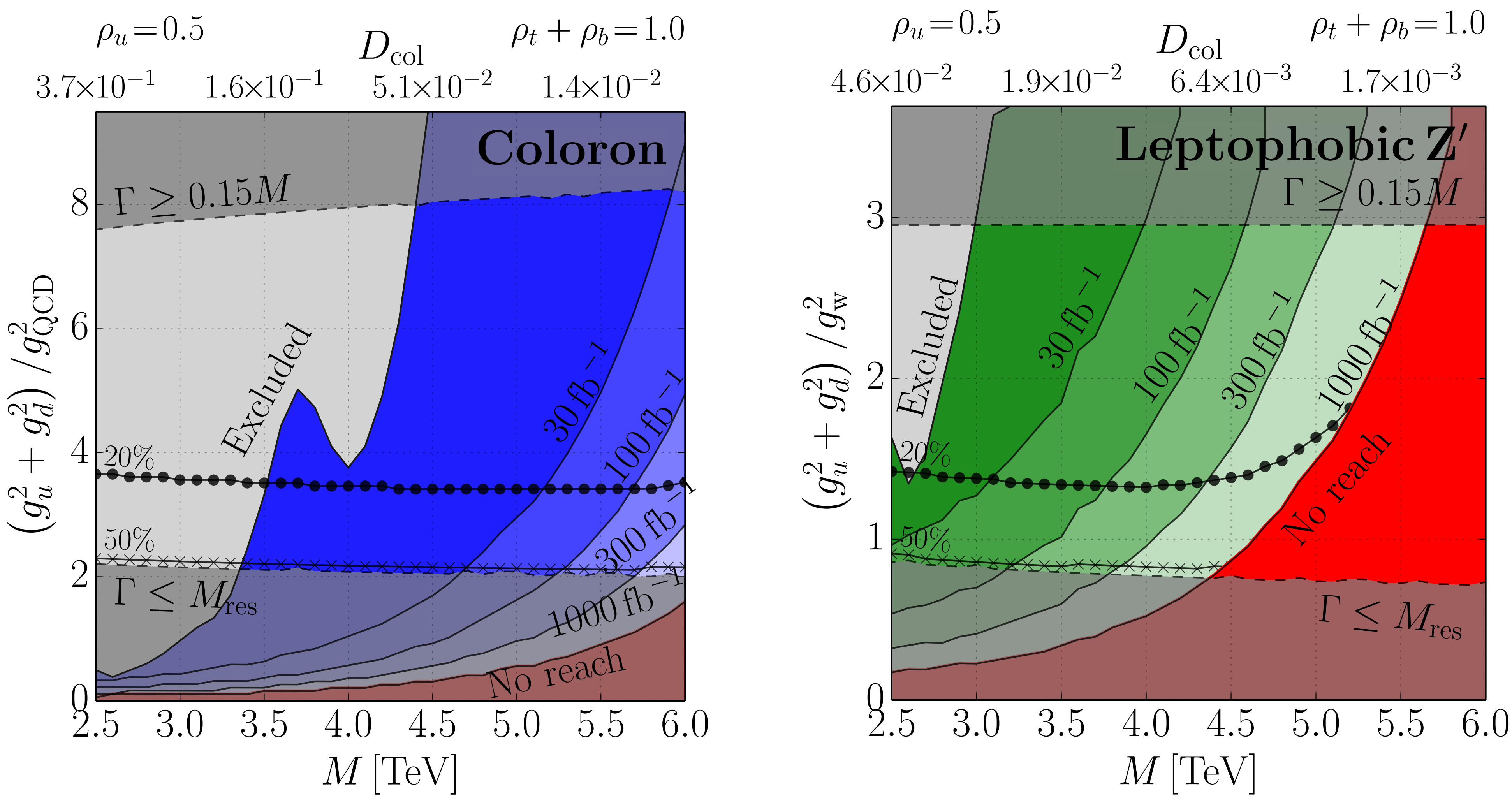
must be equal

$$\sigma_{jj}^{Z'} = \frac{1}{9}\frac{\Gamma_{Z'}}{M_{Z'}^3}\sum_q W_q(M_{Z'})Br(Z' \to jj)$$

Define a color discriminant variable: $D_{\rm col} \equiv \frac{M^3}{\Gamma}\sigma_{jj}$

- based on standard observables
- useful whenever width is measurable
- distinguishes color structure of resonance

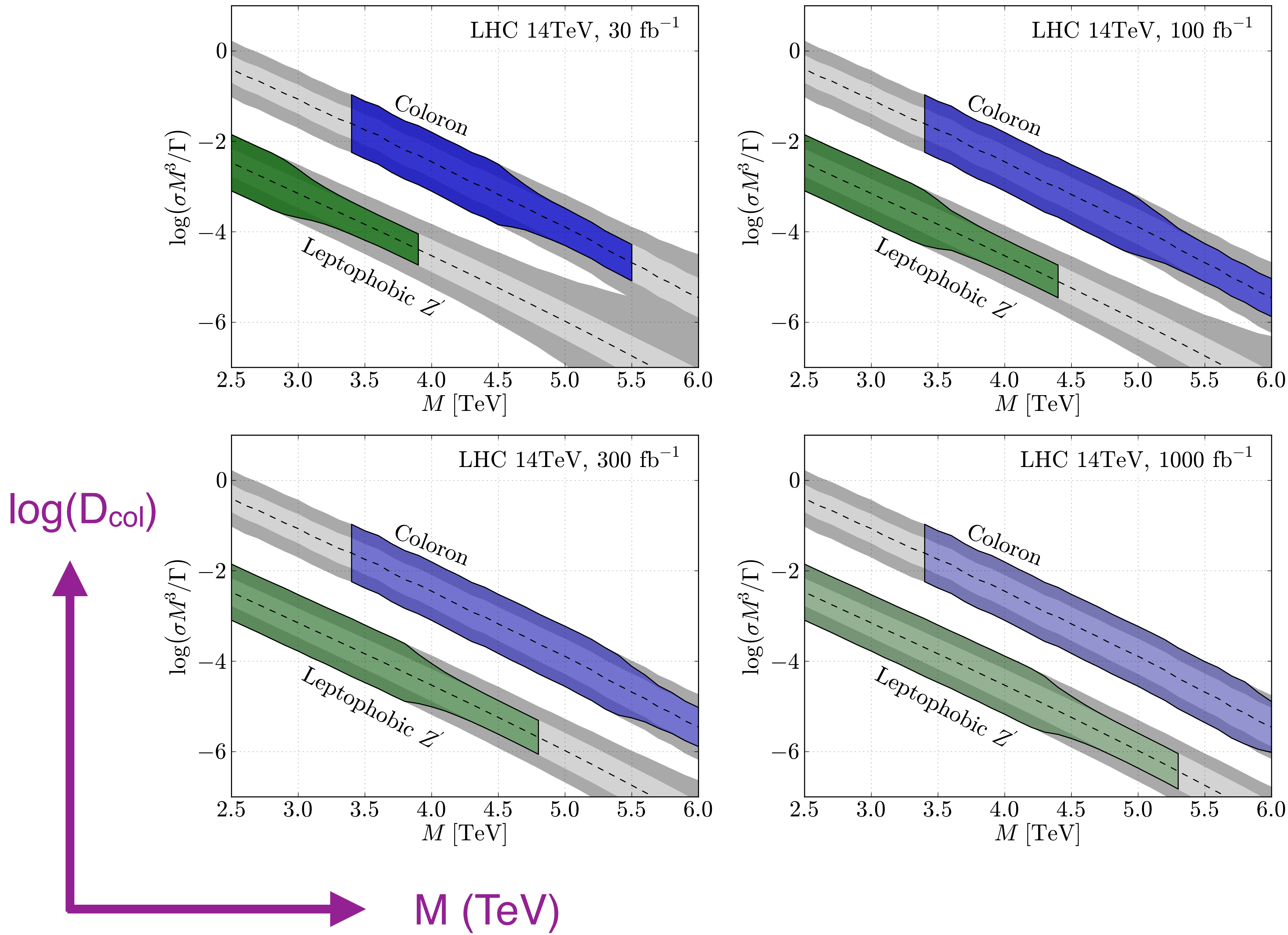
Establish Detection Range



Un-shadowed colored area shows the observable region at LHC

- width is above detector resolution, yet still narrow
- cross-section allows detection, yet is not already excluded

log(D$_{col}$) Separates Coloron from Z'



Color Discriminant Variable: Including Flavor

R.S. Chivukula, P. Ittisamai, EHS

arXiv:1406.2003

Generalize Flavor Structure

Most models of new vector resonances allow different couplings to different fermion flavors (though 1st and 2nd generations experimentally constrained to behave alike).

Can D_{col} still yield information about such models?

Flavor Non-universal Couplings

Flavor non-universal coloron has 6 distinct quark couplings:

$$g_{C_L}^{u,c} = g_{C_L}^{d,s} \qquad \text{and} \qquad g_{C_R}^{u,c},\, g_{C_R}^{d,s}$$
$$g_{C_L}^{t} = g_{C_L}^{b} \qquad \text{and} \qquad g_{C_R}^{t},\, g_{C_R}^{b}$$

Flavor non-universal Z' has 8 distinct quark couplings:

$$g_{Z'_L}^{u,c},\, g_{Z'_L}^{d,s} \qquad \text{and} \qquad g_{Z'_R}^{u,c},\, g_{Z'_R}^{d,s}$$
$$g_{Z'_L}^{t},\, g_{Z'_L}^{b} \qquad \text{and} \qquad g_{Z'_R}^{t},\, g_{Z'_R}^{b}$$

Our observables σ_{jj}, M, D_{col} don't distinguish chirality, reducing the number to 4 for either vector resonance:

$$g_V^{u\,2} = g_V^{c\,2}, \quad g_V^{d\,2} = g_V^{s\,2}, \quad g_V^{t\,2}, \quad g_V^{b\,2}$$

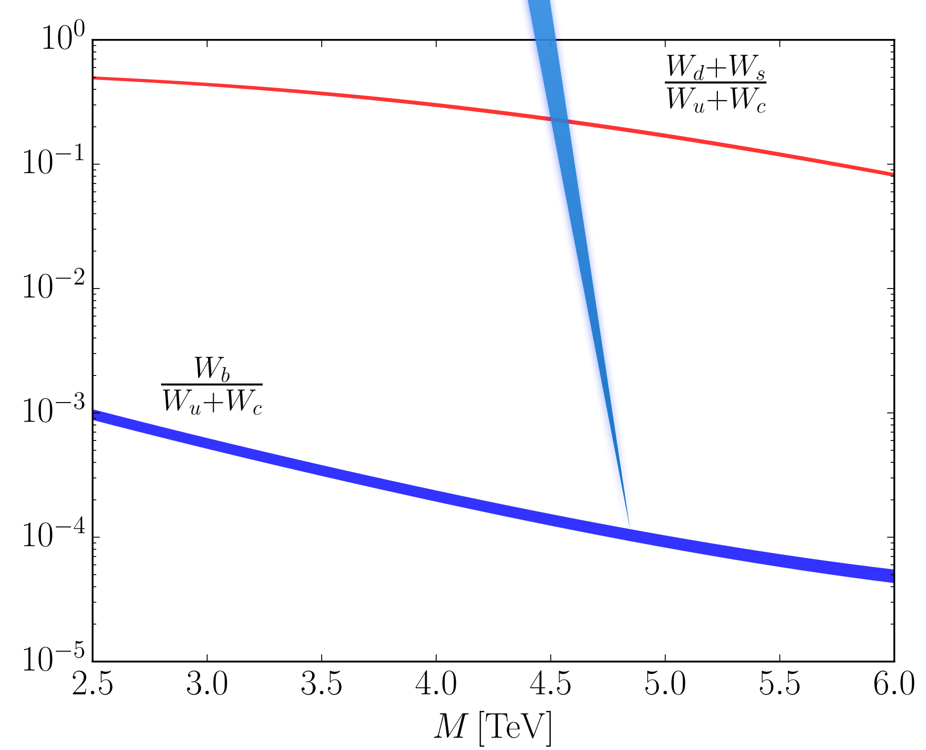
Flavor Implications

$$\sigma(pp \to Z') = \frac{1}{3}\frac{\alpha_w}{M_{Z'}^2}\left(g_{Z'}^{u\,2} + g_{Z'}^{d\,2}\right)\left[\frac{g_{Z'}^{u\,2}}{g_{Z'}^{u\,2}+g_{Z'}^{d\,2}}\left(W_u + W_c\right) + \left(1 - \frac{g_{Z'}^{u\,2}}{g_{Z'}^{u\,2}+g_{Z'}^{d\,2}}\right)\left(W_d + W_s\right) + \frac{g_{Z'}^{b\,2}}{g_{Z'}^{u\,2}+g_{Z'}^{d\,2}} W_b\right]$$

$$\Gamma_{Z'} = \frac{\alpha_w}{2} M_{Z'}\left(g_{Z'}^{u\,2} + g_{Z'}^{d\,2}\right)\left[2 + \frac{g_{Z'}^{t\,2}}{g_{Z'}^{u\,2}+g_{Z'}^{d\,2}} + \frac{g_{Z'}^{b\,2}}{g_{Z'}^{u\,2}+g_{Z'}^{d\,2}}\right].$$

Measurements sensitive to?

- chirality of quark couplings - **NO**
- 1st vs 2nd family quarks - **NO**
- b contribution to production - **NO**
- b, t contribution to width - **YES**



Generalize Flavor Structure

Consider color discriminant variable: $D_{\rm col} \equiv \frac{M^3}{\Gamma}\sigma_{jj}$

$$D^C_{col} = \frac{16}{3}(W_u + W_c)\left[\frac{g_C^{u\,2}}{g_C^{u\,2}+g_C^{d\,2}} + \left(1 - \frac{g_C^{u\,2}}{g_C^{u\,2}+g_C^{d\,2}}\right)\left(\frac{W_d+W_s}{W_u+W_c}\right) + \frac{g_C^{b\,2}}{g_C^{u\,2}+g_C^{d\,2}}\left(\frac{W_b}{W_u+W_c}\right)\right] \times \left\{\frac{2}{\left(2 + \frac{g_C^{t\,2}}{g_C^{u\,2}+g_C^{d\,2}} + \frac{g_C^{b\,2}}{g_C^{u\,2}+g_C^{d\,2}}\right)^2}\right\}$$

Depends on "up", "bottom", "top" coupling ratios:

Measurable: $$\frac{g_b^2}{g_u^2+g_d^2} = 2\frac{\sigma^V_{b\bar{b}}}{\sigma^V_{jj}} \qquad \frac{g_t^2}{g_u^2+g_d^2} = 2\frac{\sigma^V_{t\bar{t}}}{\sigma^V_{jj}}$$

Invisible: $$\frac{g_u^2}{g_u^2+g_d^2}$$

Is the Invisible "up ratio" a problem?

Could the unknown "up ratio" blur the distinction between coloron and Z' in D_{col}?

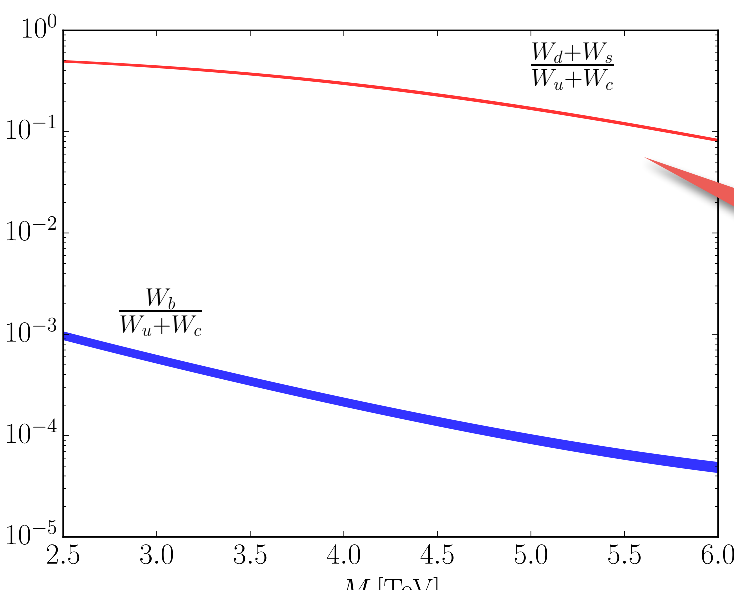
$$\frac{g_u^2}{g_u^2 + g_d^2}$$

$$D_{col}^{Z'} \propto \frac{2}{3}\left[\frac{g_{Z'}^{u\,2}}{g_{Z'}^{u\,2}+g_{Z'}^{d\,2}} + \left(1 - \frac{g_{Z'}^{u\,2}}{g_{Z'}^{u\,2}+g_{Z'}^{d\,2}}\right)\left(\frac{W_d+W_s}{W_u+W_c}\right)\right] \quad \rightarrow \quad \frac{2}{3}$$

Z' : if up ratio = 1

C : if up ratio = 0

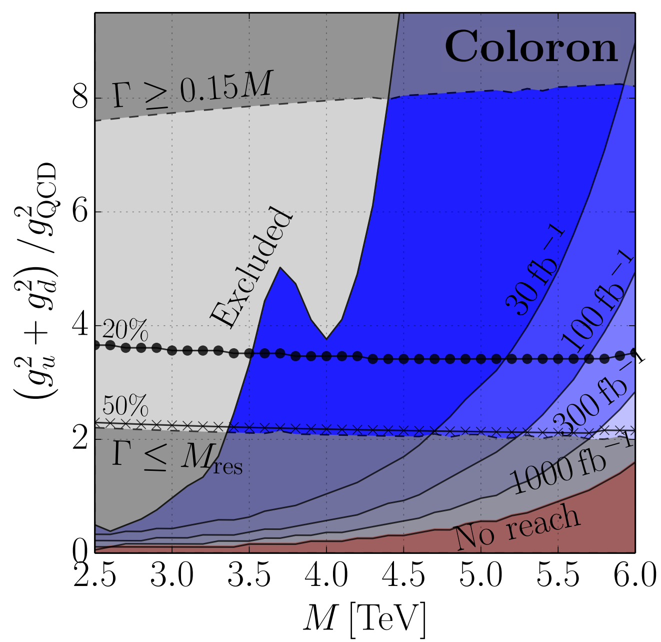
$$D_{col}^{C} \propto \frac{16}{3}\left[\frac{g_{C}^{u\,2}}{g_{C}^{u\,2}+g_{C}^{d\,2}} + \left(1 - \frac{g_{C}^{u\,2}}{g_{C}^{u\,2}+g_{C}^{d\,2}}\right)\left(\frac{W_d+W_s}{W_u+W_c}\right)\right] \quad \rightarrow \quad \frac{16}{3}\left[\frac{W_d+W_s}{W_u+W_c}\right]$$



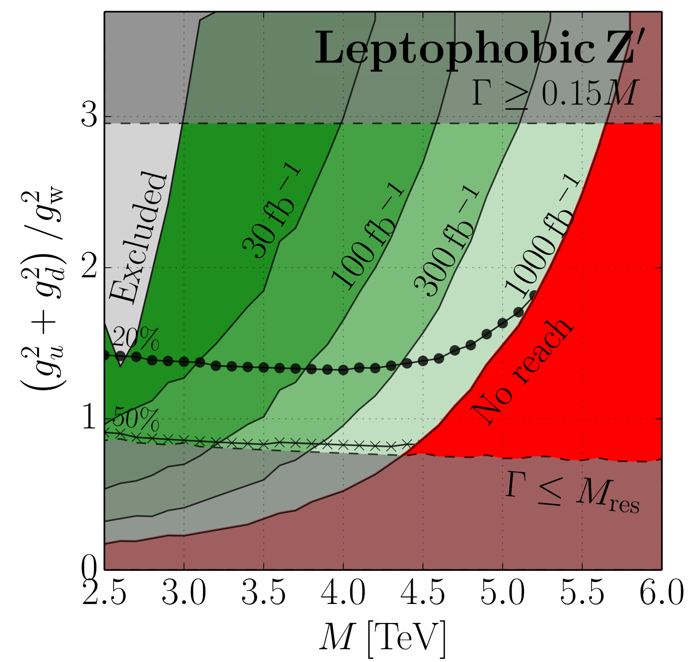
Can this = [1/8] ?

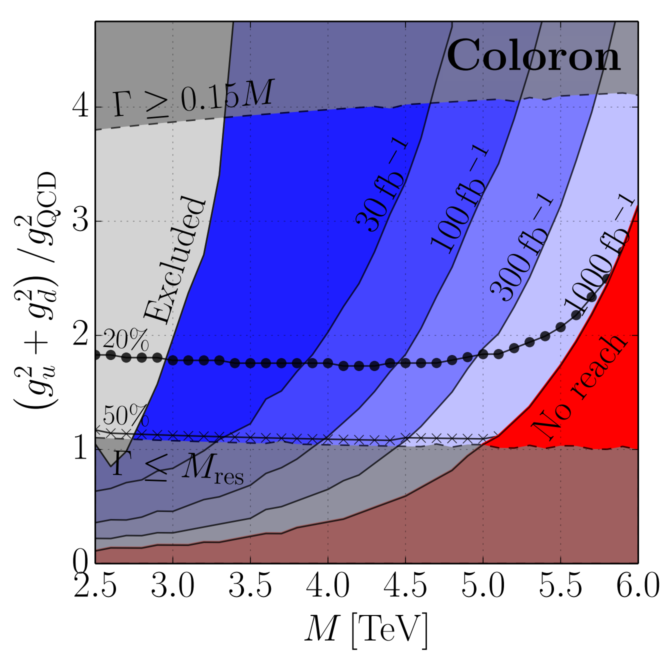
Only at large M is confusion possible

14 TeV LHC Reach for C^A and Z'

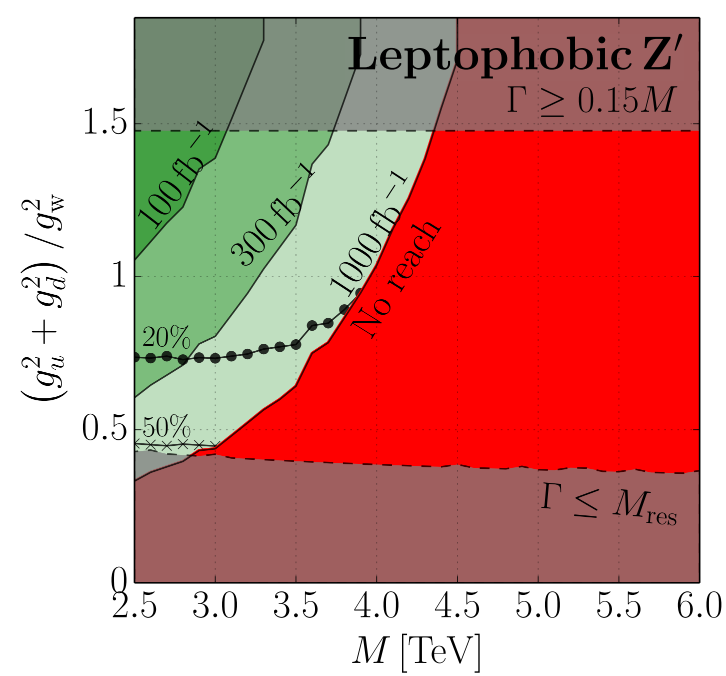


Flavor Universal



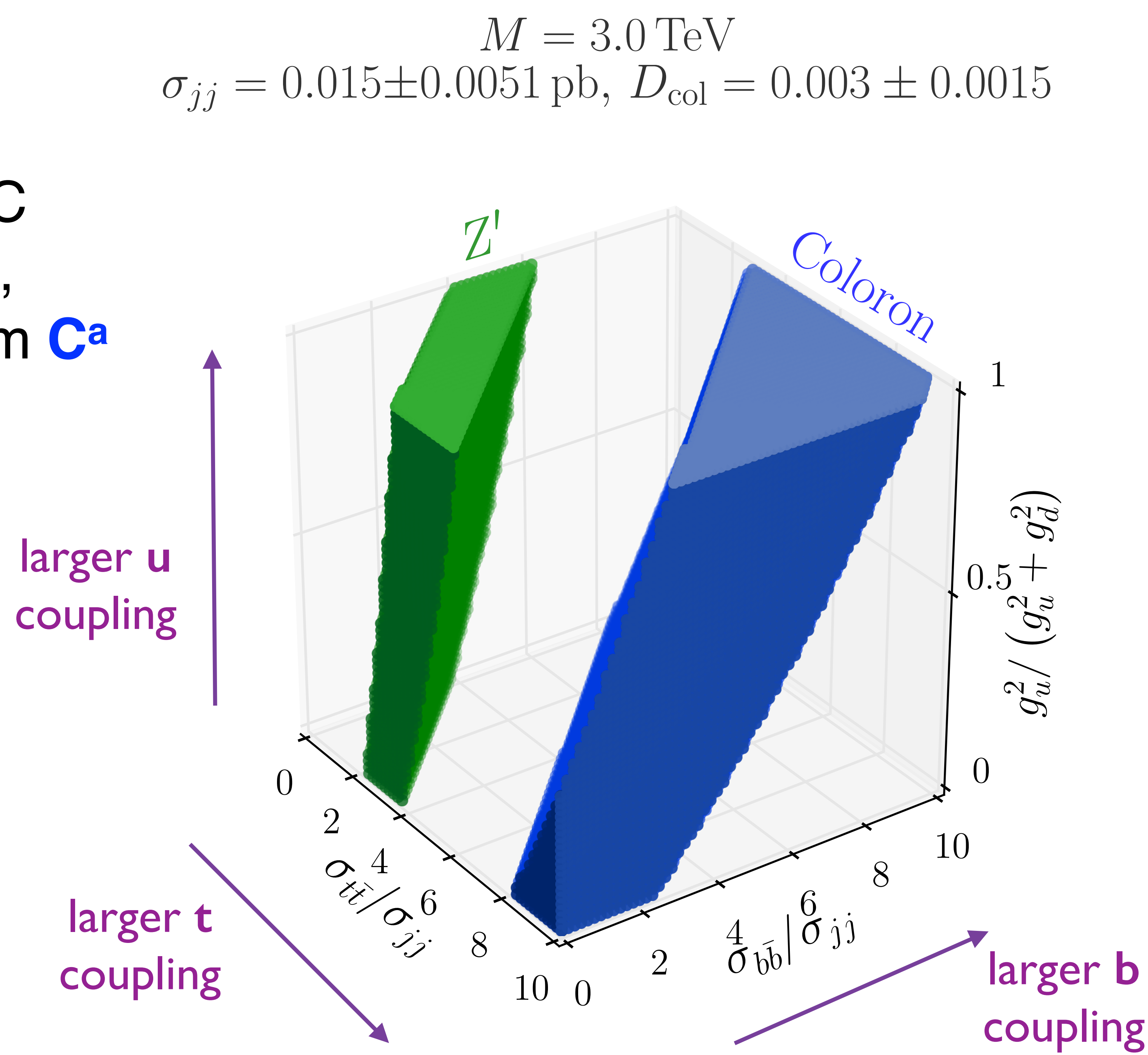


Preferring 3rd generation



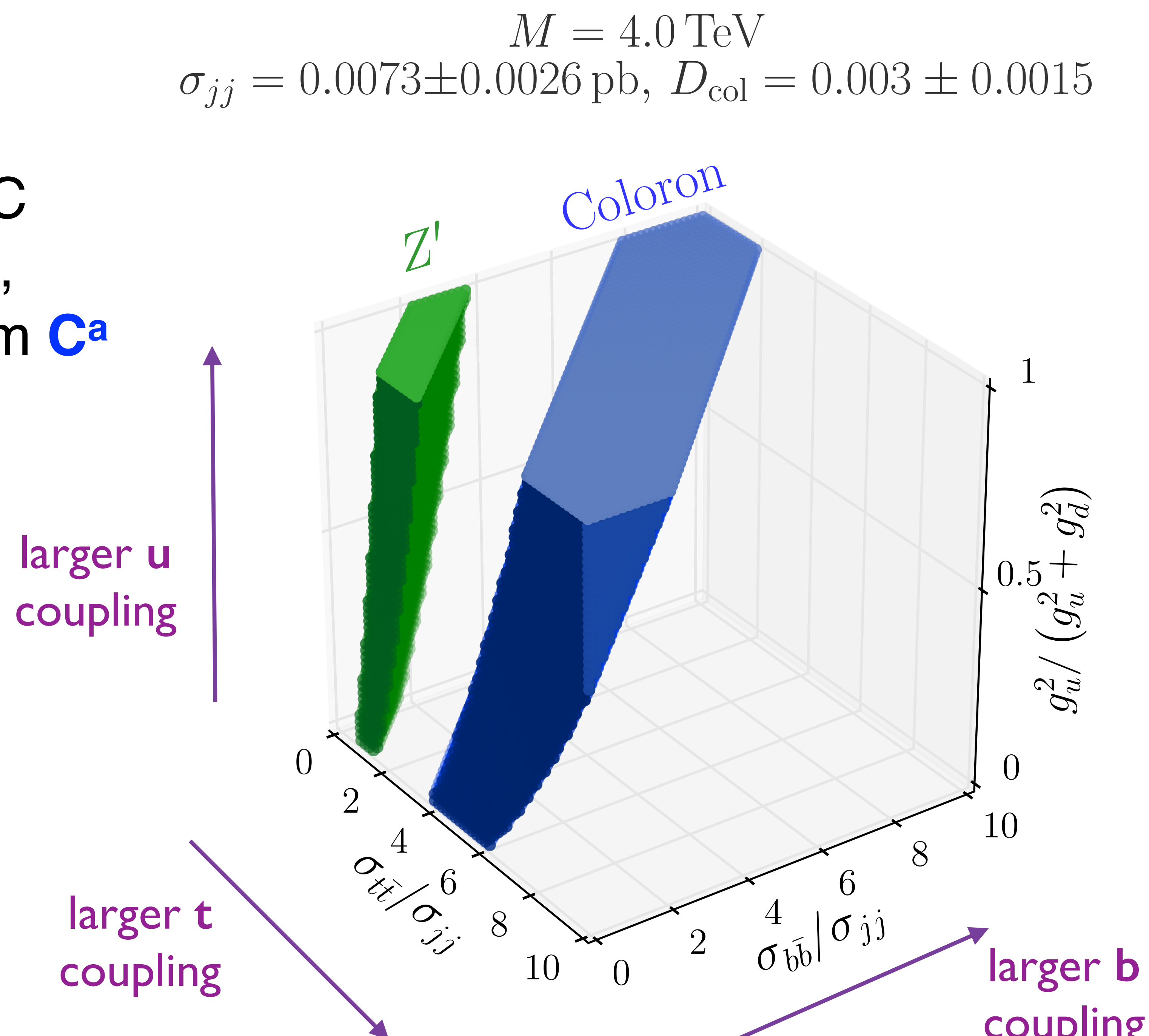
Telling C^A and Z' Apart: M = 3 TeV

For fixed σ_{jj}, M, D_{col}, at 14 TeV LHC with 1000 fb^{-1}, Z' distinct from C^a

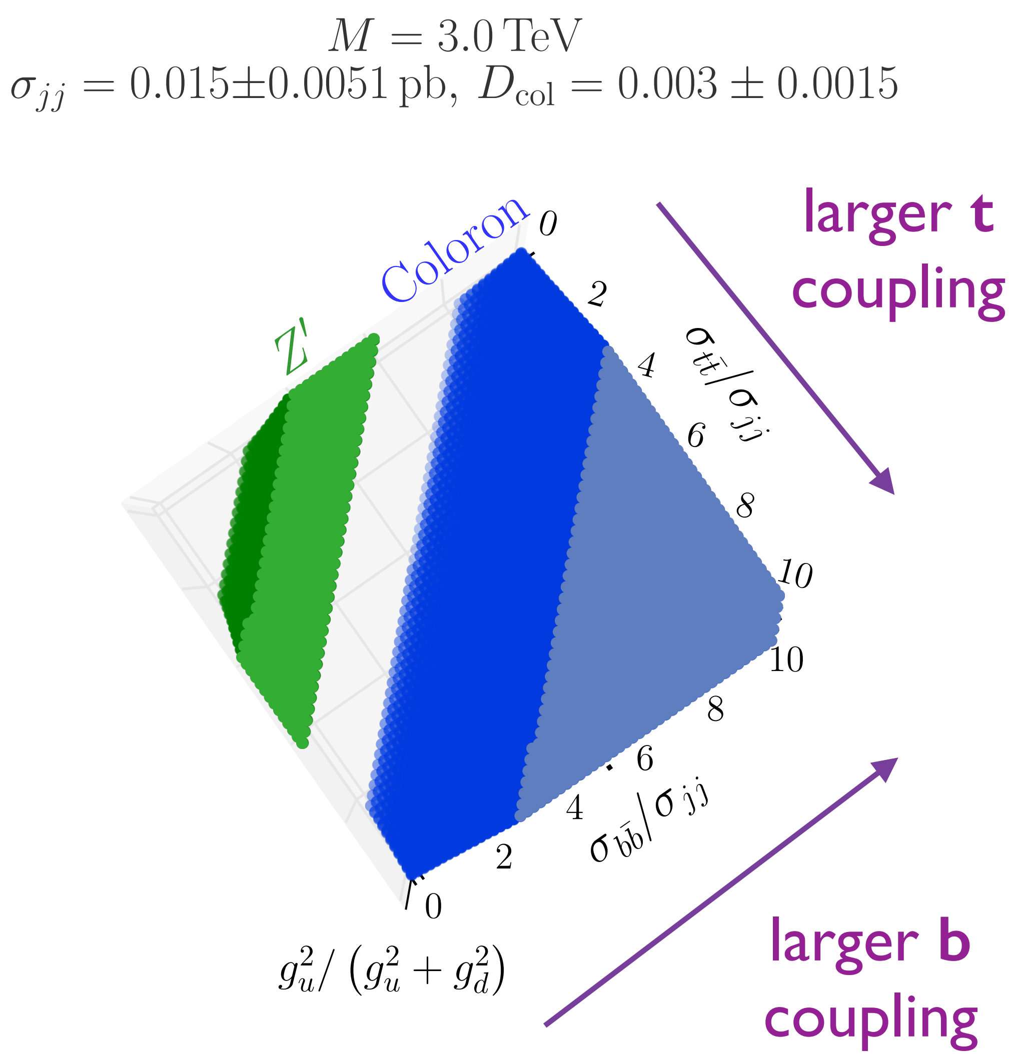


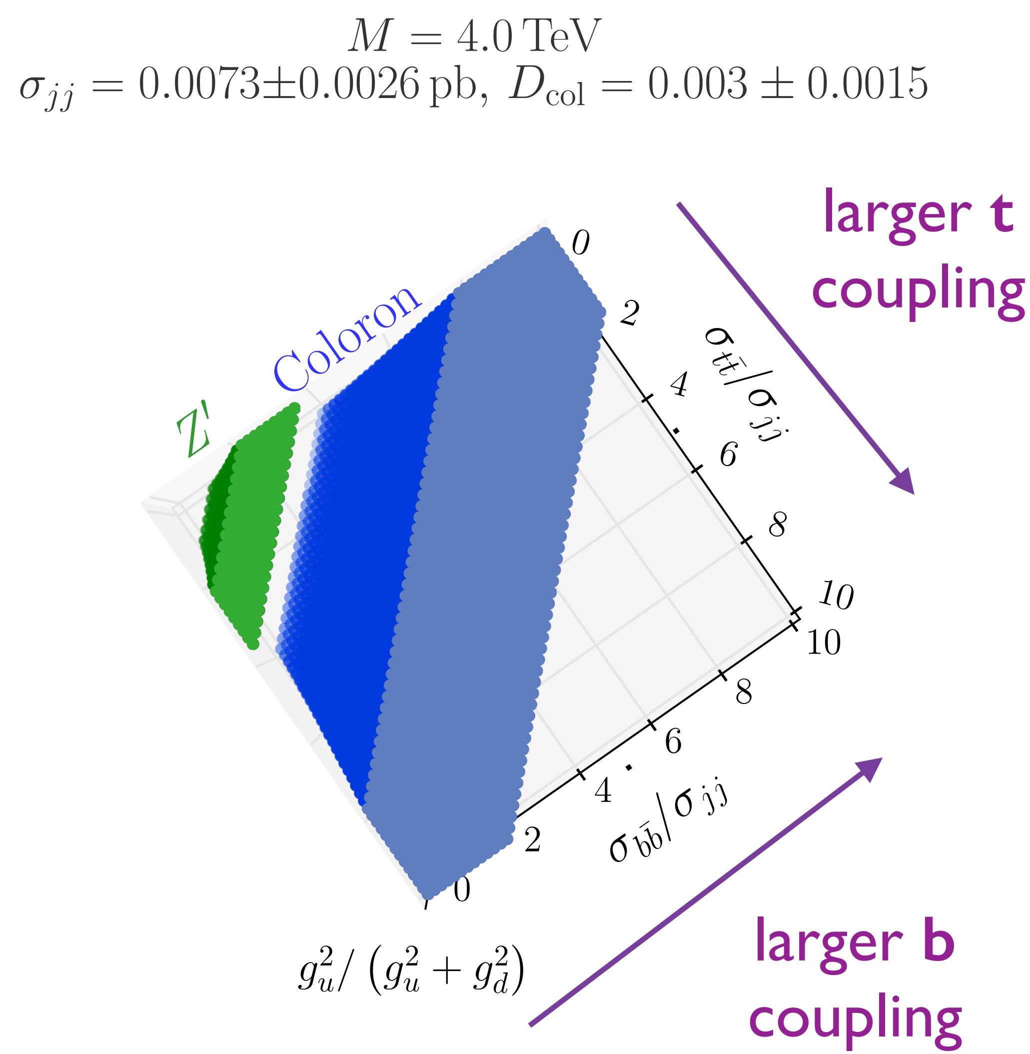
Telling C^A and Z' Apart: M = 4 TeV

For fixed
σ_{jj}, M, D_{col},
at 14 TeV LHC
with 1000 fb^{-1},
Z' distinct from **C^a**



3 TeV   TOP VIEW   4 TeV

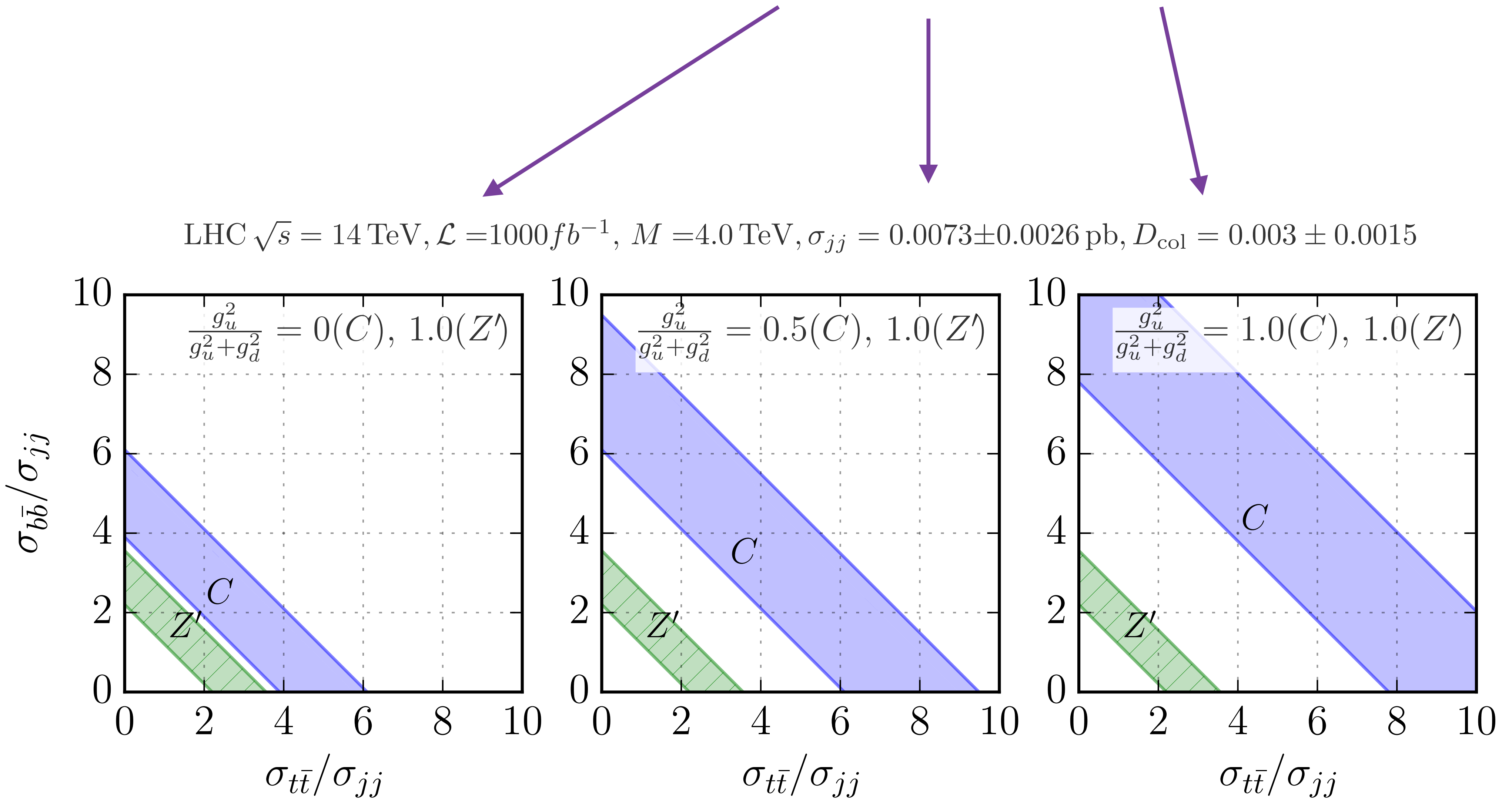




Looking down the "**u**" axis from above, we see no overlap between **Z'** and **C^a** for either value of resonance mass

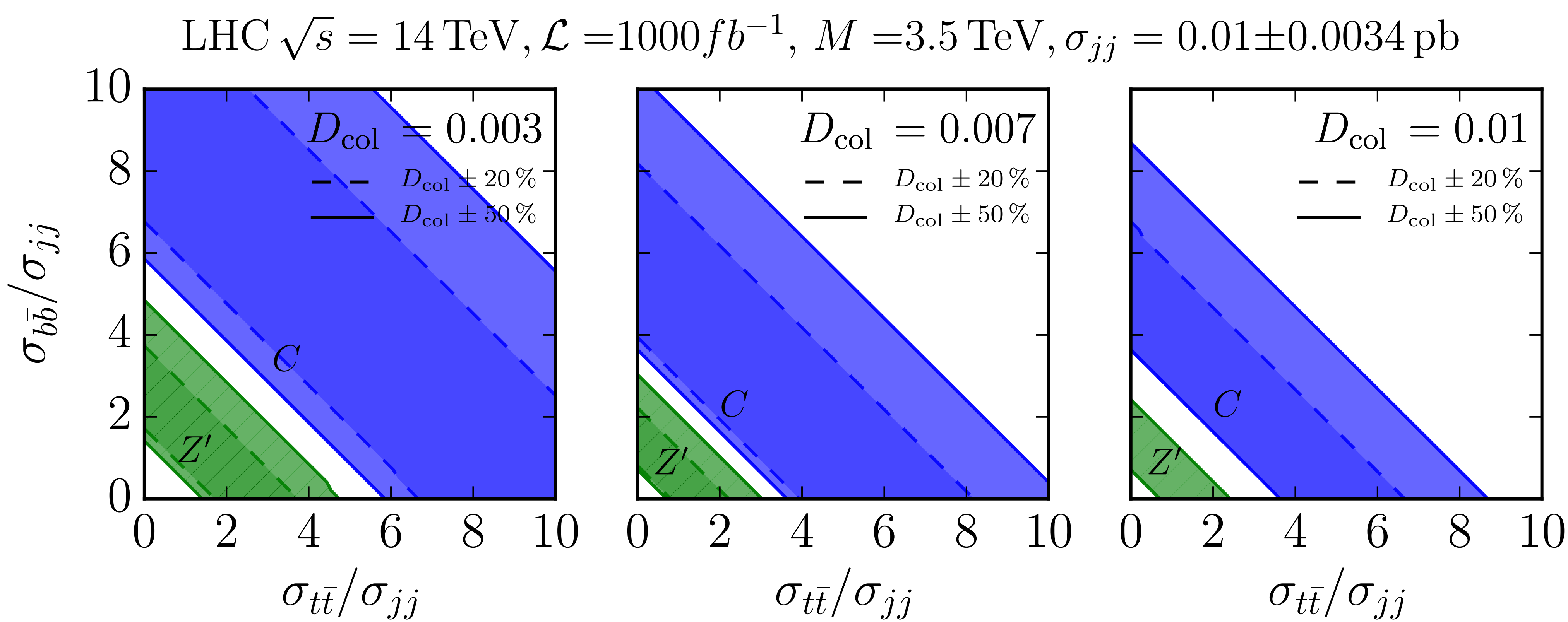
Telling C^A and Z' Apart

For fixed values of σ_{jj} , M, D_{col}
flavor measurements distinguish **Z'** from **C^a**
even if **C^a** couples to u less, same, or more than **Z'**



Required Measurement Precision

For viable, fixed σ_{jj}, M, how well must we measure D_{col} and heavy flavor decays?



Beyond Vector Resonances

R.S. Chivukula, EHS, N. Vignaroli

arXiv:1412.3094

Various New Colored States

Gauge bosons from extended color groups:

Classic Axigluon: P.H. Frampton and S.L. Glashow, Phys. Lett. B 190, 157 (1987).

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

Flavor-universal Coloron: R.S. Chivukula, A.G. Cohen, & E.H. Simmons, Phys. Lett. B 380, 92 (1996).

Chiral Color with $g_L \neq g_R$: M.V. Martynov and A.D. Smirnov, Mod. Phys. Lett. A 24, 1897 (2009).

New Axigluon: P.H. Frampton, J. Shu, and K. Wang, Phys. Lett. B 683, 294 (2010).

Similar color-octet states:

KK gluon: H. Davoudiasl, J.L. Hewett, and T.G. Rizzo, Phys. Rev. D63, 075004 (2001)
B. Lillie, L. Randall, and L.-T. Wang, JHEP 0709, 074 (2007).

Techni-rho: E. Farhi and L. Susskind, Physics Reports 74, 277 (1981).

More exotic colored states:

Color sextets, colored scalars, low-scale scale string resonances...

T. Han, I. Lewis, Z. Liu, JHEP 1012, 085 (2010).

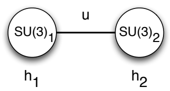
Vector, Fermion, Scalar

Flavor-universal coloron:

Chivukula, Cohen, EHS

Phys. Lett. B 380 (1996) 92

Coloron Models: Gauge Sector



$SU(3)_1$ x $SU(3)_2$ color sector with $M^2 = \frac{u^2}{4}\begin{pmatrix} h_1^2 & -h_1 h_2 \\ -h_1 h_2 & h_2^2 \end{pmatrix}$

unbroken subgroup: $SU(3)_{1+2} = SU(3)_{QCD}$

$h_1 = \frac{g_s}{\cos\theta} \qquad h_2 = \frac{g_s}{\sin\theta}$

gluon state: $G^A_\mu = \cos\theta\, A^A_{1\mu} + \sin\theta\, A^A_{2\mu}$

couples to: $g_S J^\mu_G \equiv g_S (J^\mu_1 + J^\mu_2)$ $\qquad M_G = 0$

coloron state: $C^A_\mu = -\sin\theta\, A^A_{1\mu} + \cos\theta\, A^A_{2\mu}$ $\qquad M_C = \frac{u}{\sqrt{2}}\sqrt{h_1^2 + h_2^2}$

couples to: $g_S J^\mu_C \equiv g_S(-J^\mu_1 \tan\theta + J^\mu_2 \cot\theta)$

Quarks' $SU(3)_1$ x $SU(3)_2$ charges impact phenomenology

Excited quark:

Baur, Spira, Zerwas: PRD 42 (1990) 815

$$\mathcal{L}_{int} = \frac{1}{2\Lambda}\bar{q}^*_R \sigma^{\mu\nu}\left[g_S f_S \frac{\lambda^a}{2} G^a_{\mu\nu} + g f \frac{\tau}{2}\cdot \mathbf{W}_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu}\right] q_L + \mathrm{H.c.}$$

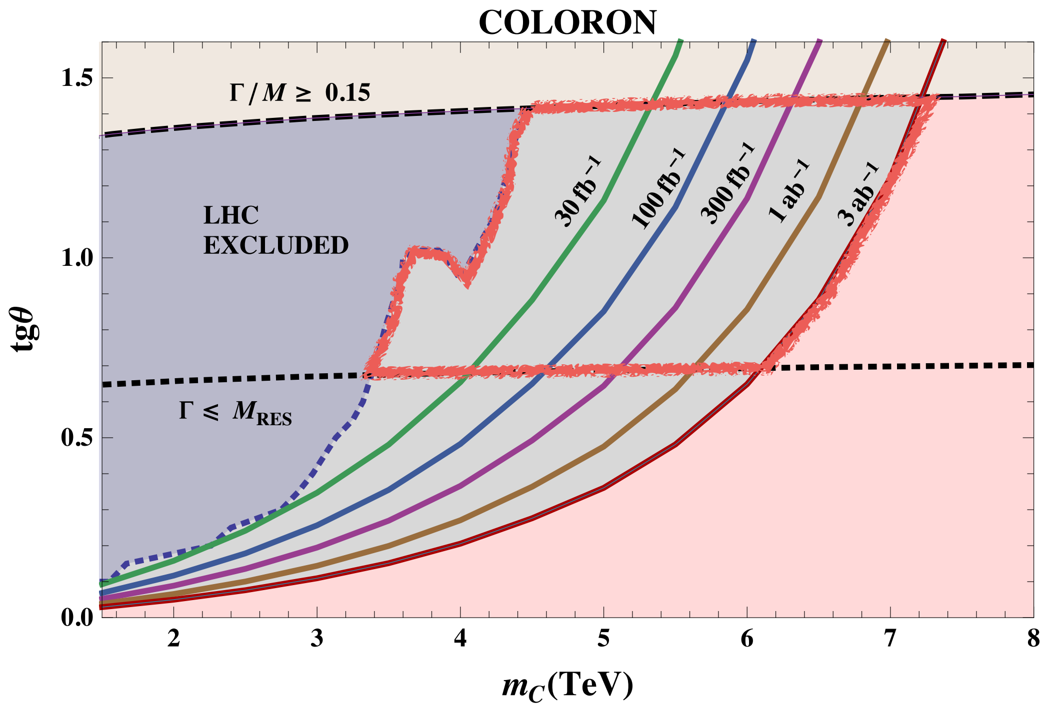
$$\Gamma(q^* \to qg) = \frac{1}{3}\alpha_S f_S^2 \frac{m^3_{q*}}{\Lambda^2}$$

Colored scalar:

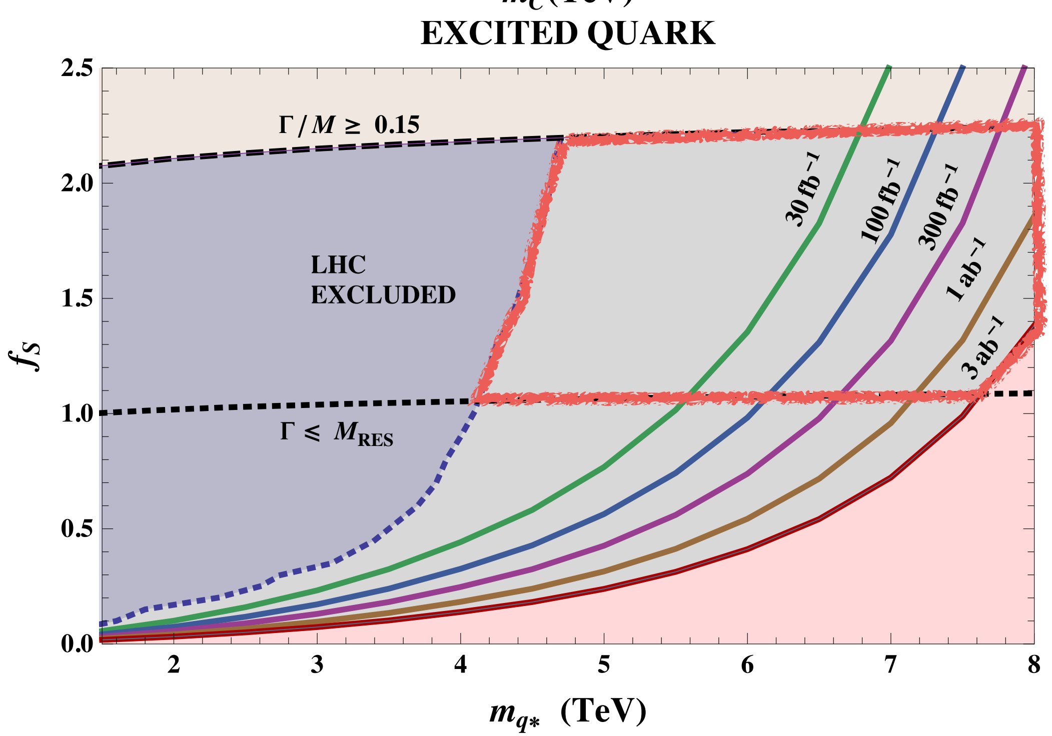
Han, Lewis, Liu arXiv:1010.4309

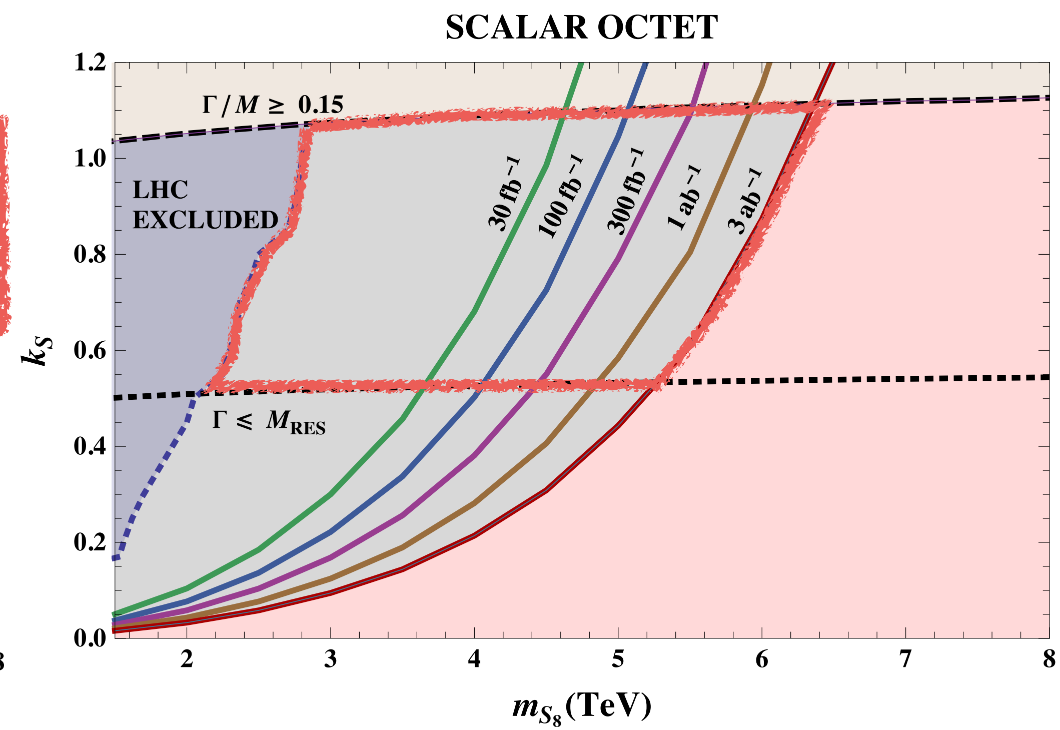
$$\mathcal{L}_{S_8} = g_S d^{ABC} \frac{k_S}{\Lambda_S} S^A_8 G^B_{\mu\nu} G^{C,\mu\nu} \qquad \Gamma(S_8) = \frac{5}{3}\alpha_S \frac{k_S^2}{\Lambda_S^2} m^3_{S_8}$$

VECTOR, FERMION, SCALAR



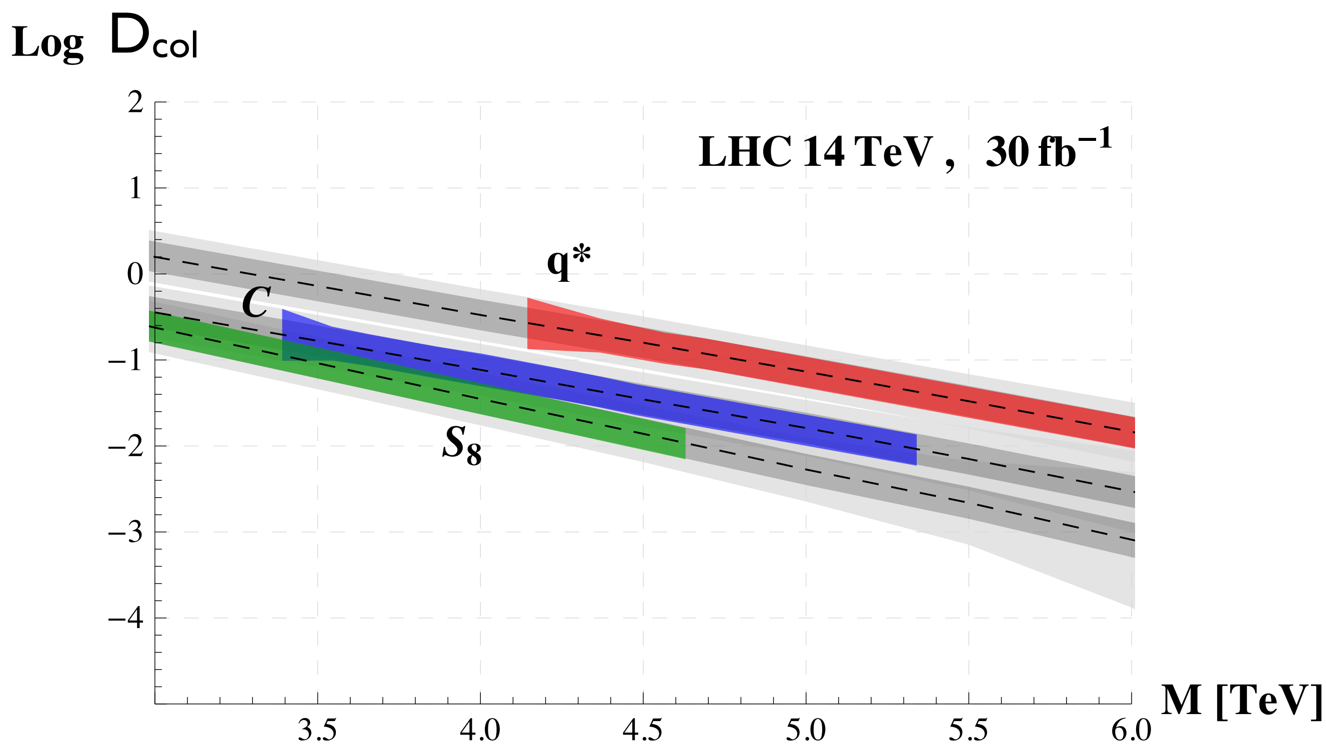
LHC-14 can both *discover* flavor-universal colorons (C), excited quarks (q*), and color-octet scalars (S_8) and also **measure D_{col}**

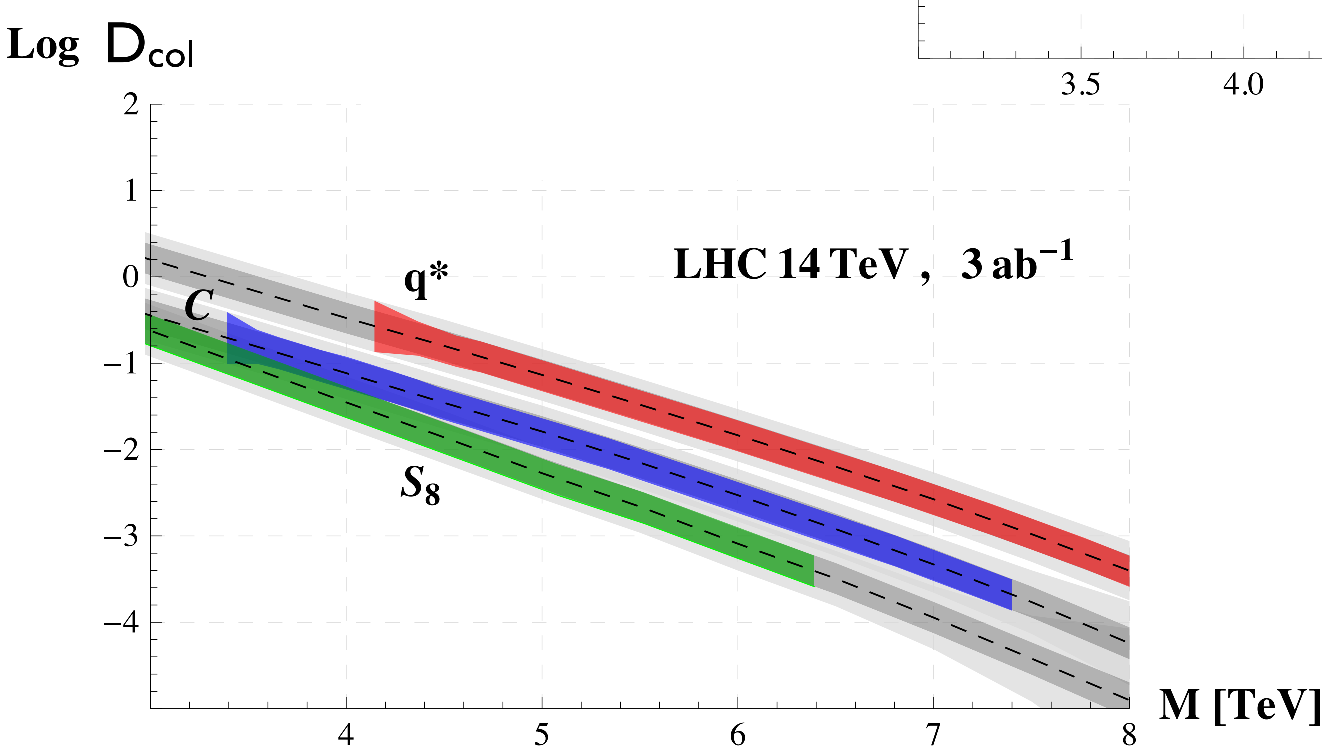




DISTINGUISHING C, q*, S_8

D_{col} can reveal the nature of a colored dijet resonance





Conclusions

Conclusions

When LHC reveals a new BSM resonance decaying to dijets, how will we determine what has been discovered?

$$D_{\rm col} \equiv \frac{M^3}{\Gamma}\sigma_{jj}$$

D_{col} on its own

- distinguishes coloron from Z' in flavor-universal models
- likewise, can separate scalar, fermion, vector resonances discovered in dijet decays

D_{col} plus heavy flavor cross-sections

- reliably separates coloron and Z' in models with flavor non-universal resonance couplings to quarks
- is not impacted by our inability to measure relative couplings of up, down quarks to the vector resonance

Library

Uncertainty in D_{col}

$$\left(\frac{\Delta D}{D}\right)^2 = \left(\frac{\Delta\sigma_{jj}}{\sigma_{jj}}\right)^2 + \left(3\frac{\Delta M}{M}\right)^2 + \left(\frac{\Delta\Gamma}{\Gamma}\right)^2$$

$$\left(\frac{\Delta\sigma_{jj}}{\sigma_{jj}}\right)^2 = \frac{1}{N} + \epsilon^2_{\sigma SYS}$$

$$\left(\frac{\Delta M}{M}\right)^2 = \frac{1}{N}\left[\left(\frac{\sigma_\Gamma}{M}\right)^2 + \left(\frac{M_{res}}{M}\right)^2\right] + \left(\frac{\Delta M_{JES}}{M}\right)^2$$

$$\left(\frac{\Delta\Gamma}{\Gamma}\right)^2 = \frac{1}{2(N-1)}\left[1 + \left(\frac{M_{res}}{\sigma_\Gamma}\right)^2\right]^2 + \left(\frac{M_{res}}{\sigma_\Gamma}\right)^4 \left(\frac{\Delta M_{res}}{M_{res}}\right)^2$$

$\epsilon_{\sigma SYS} = 0.41$ (14 TeV LHC [48]) $\quad$ $M_{res}/M = 0.035$ (8 TeV CMS [2])

$\Delta M_{res}/M_{res} = 0.1$ (8 TeV CMS [3]) $\quad$ $(\Delta M_{JES}/M) = 0.013$ (8 TeV CMS [3])

Reference numbers are from:
R.S. Chivukula, EHS, N. Vignaroli, arXiv:1412.3094