Exploring Colorons at the LHC

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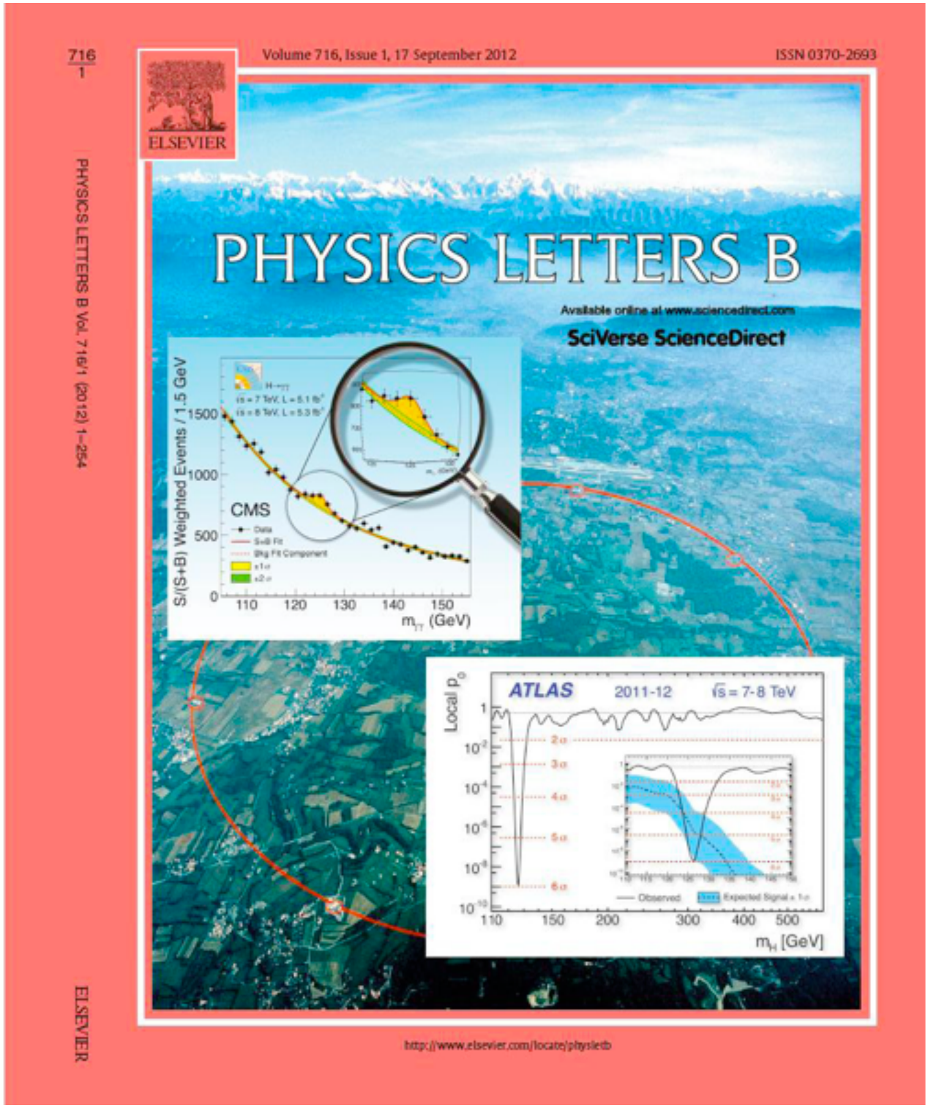
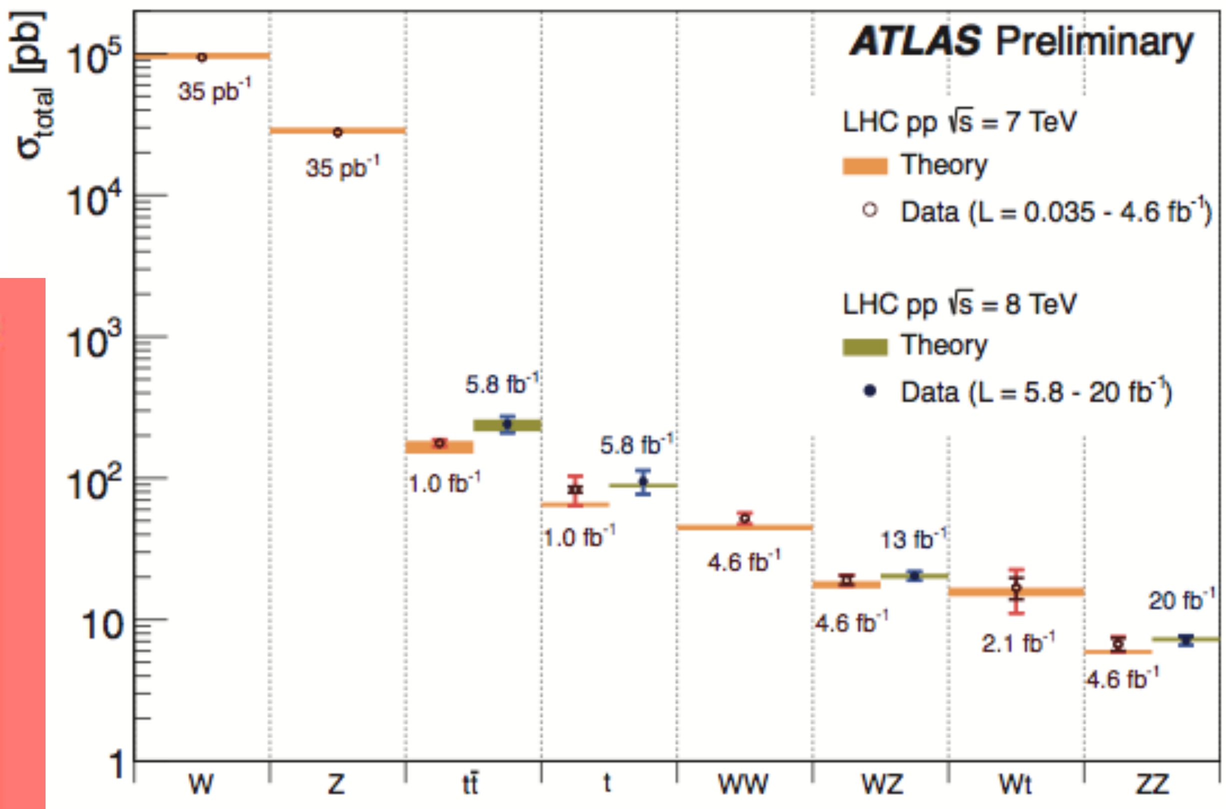
SCGT14Mini

- Introduction
- Modern Coloron Models
- Dijet Coloron Discovery @ NLO
- Coloron Couplings
- But is it Really a Coloron?
- Conclusions

Nagoya University March 5-7, 2014

After Years of Work Pay Off...





What Comes Next?

2015?

What May Leap Out?

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:

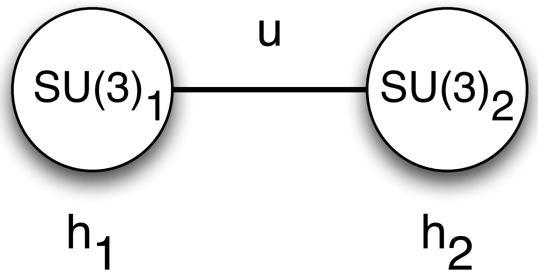
Color sextets, colored scalars, low-scale scale string resonances...

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

Modern Coloron Models

R.S. Chivukula, EHS, N. Vignaroli   arXiv:1302.1069

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' $SU(3)_1$ x $SU(3)_2$ 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

A Flavorful Top-Coloron Model

particles		$SU(3)_1$	$SU(3)_2$	$SU(2)_W$
3rd generation quarks	$(t,b)_L$	3	1	**2**
	t_R, b_R	3	1	1
light quarks	$(u,d)_L \quad (c,s)_L$	1	3	2
	$u_R, d_R \quad c_R, s_R$	1	3	1
vector quarks	Q_L, Q_R	3	1	**2**
light scalar	□□ $\boldsymbol{\varphi}$	1	1	**2**
heavy scalar	$\boldsymbol{\Phi}$	3	3*	1

Next to minimal flavor symmetry:

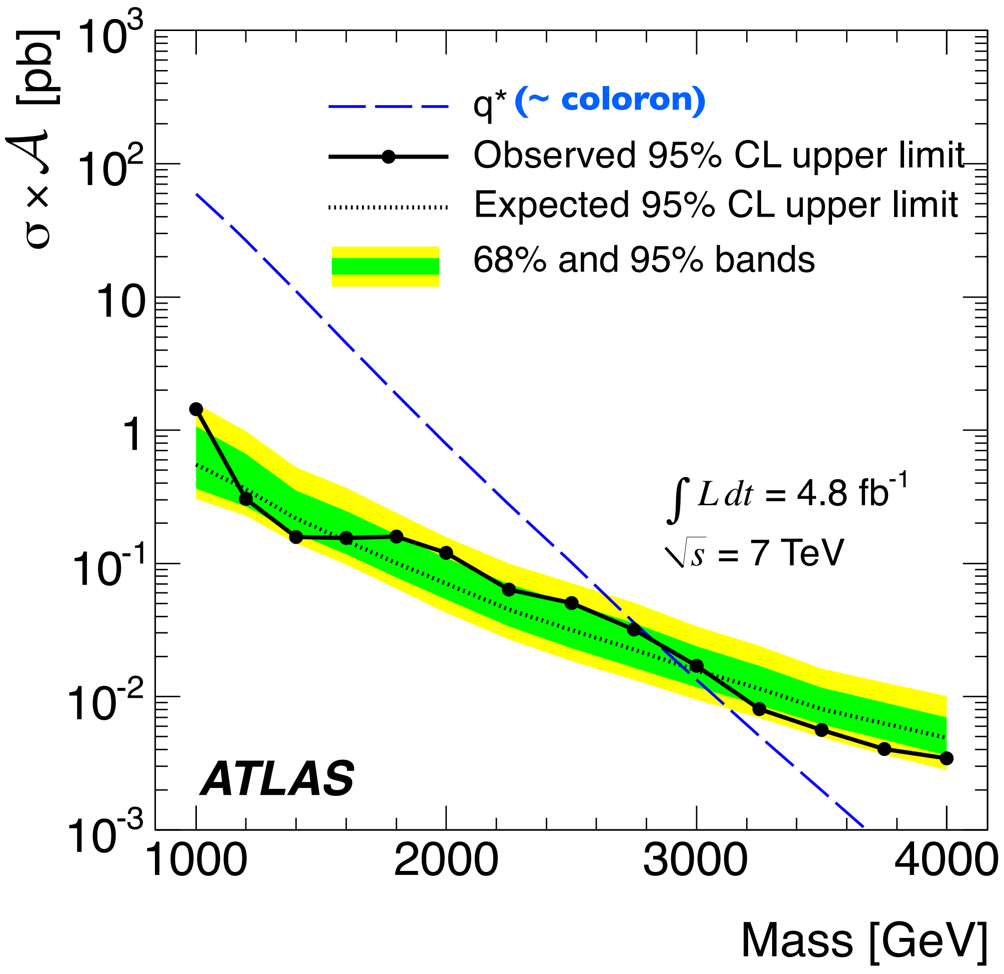
$$U(2)_{\vec{\psi}_L} \times U(2)_{\vec{u}_R} \times U(2)_{\vec{d}_R} \times U(2)_{\vec{\mathcal{Q}}_L} \times U(1)_{t_R} \times U(1)_{b_R} \times U(1)_{Q_R}$$

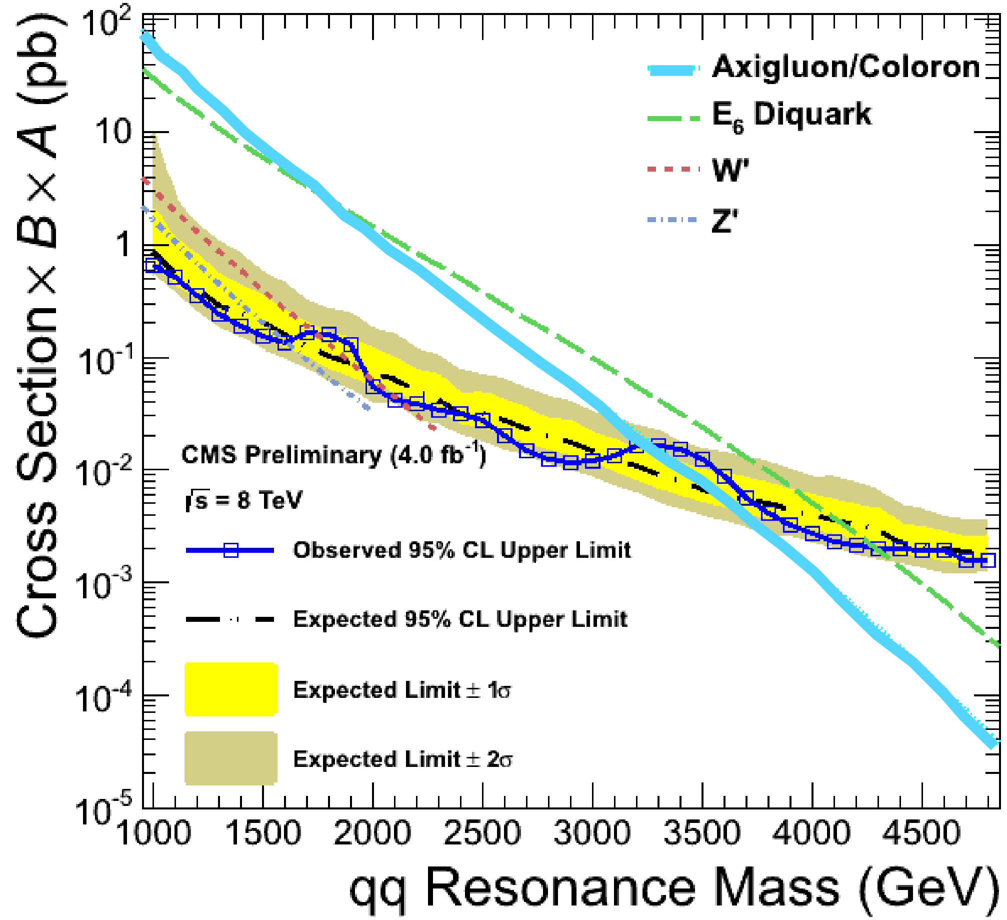
Coloron Discovery in Dijets at NLO

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

LHC Limits on Colorons

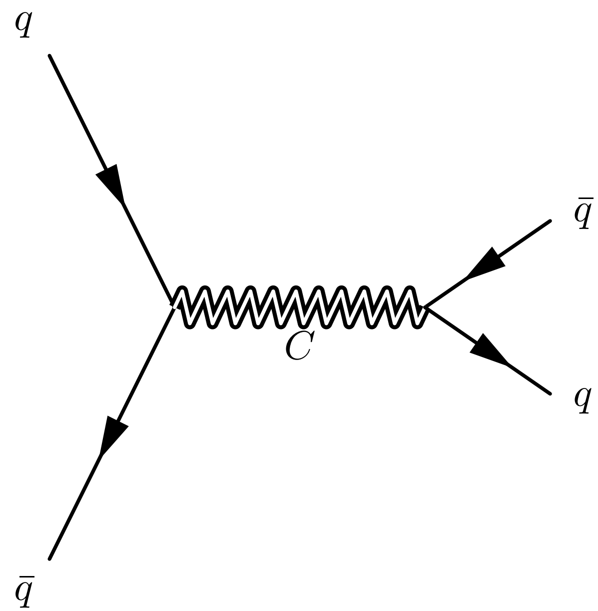
LHC searches for colorons in dijets constrain M_C





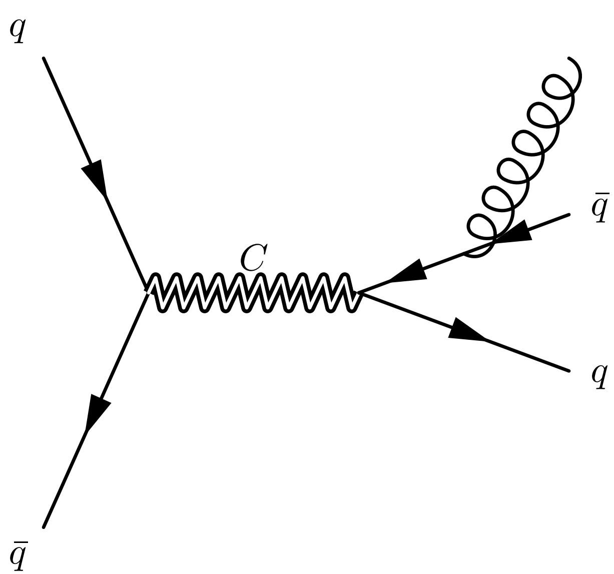
But these calculations have treated the colorons only at LO and QCD to NLO (or beyond) ... we can do better!

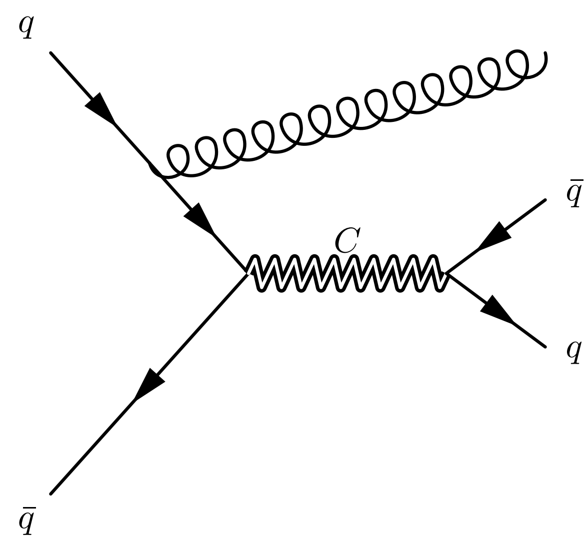
Coloron Production



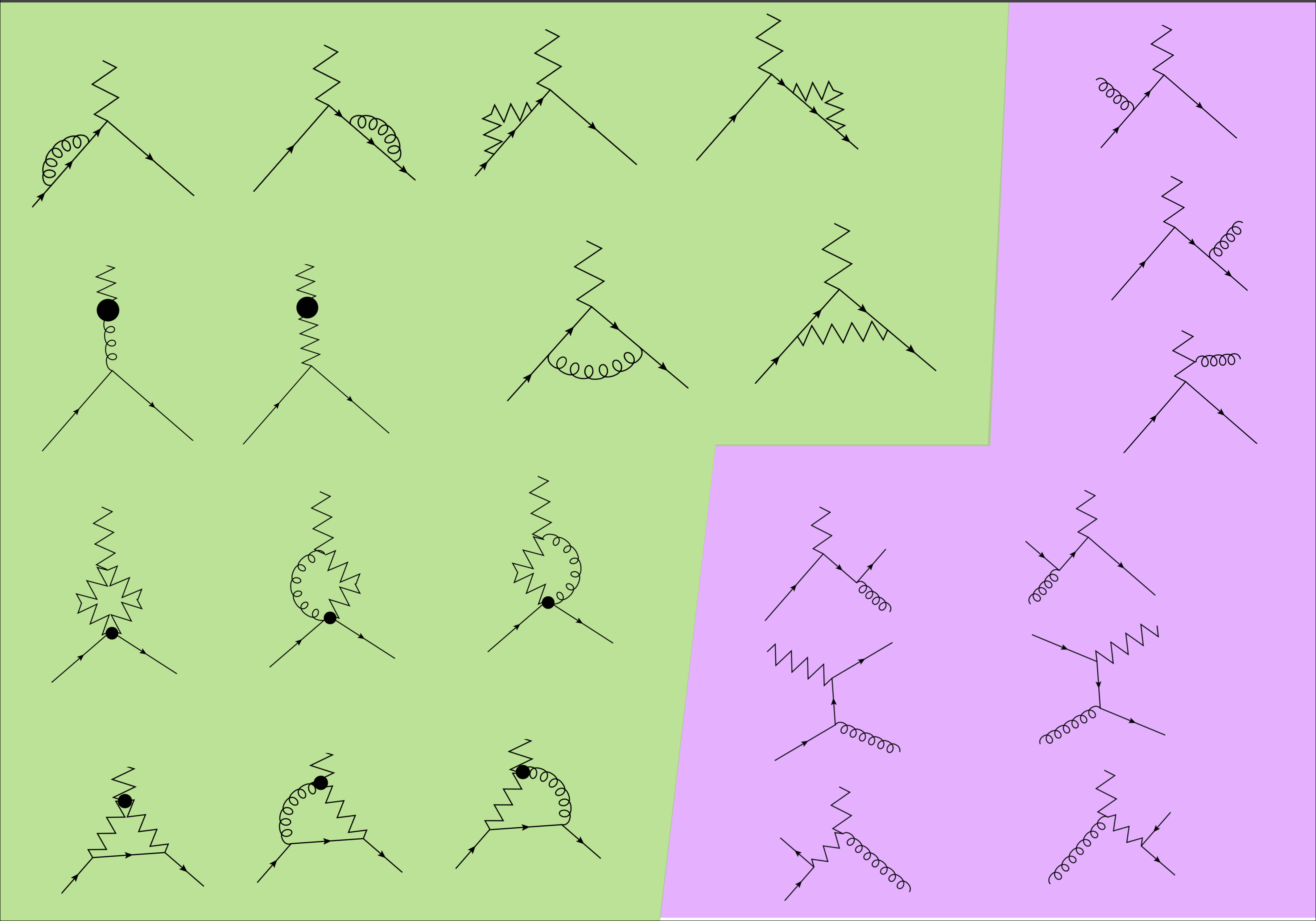
LO vs NLO production

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



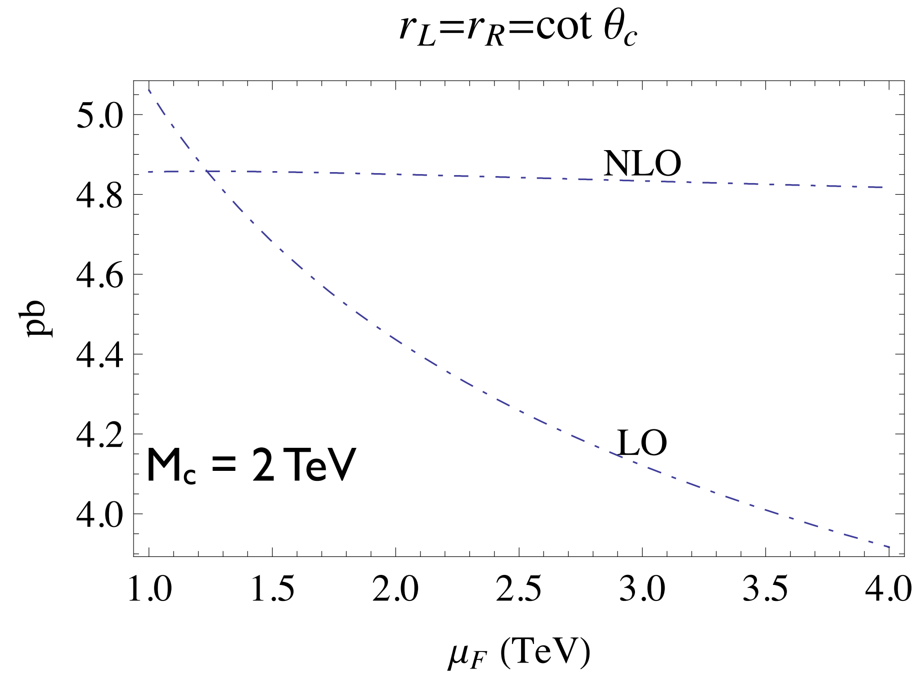


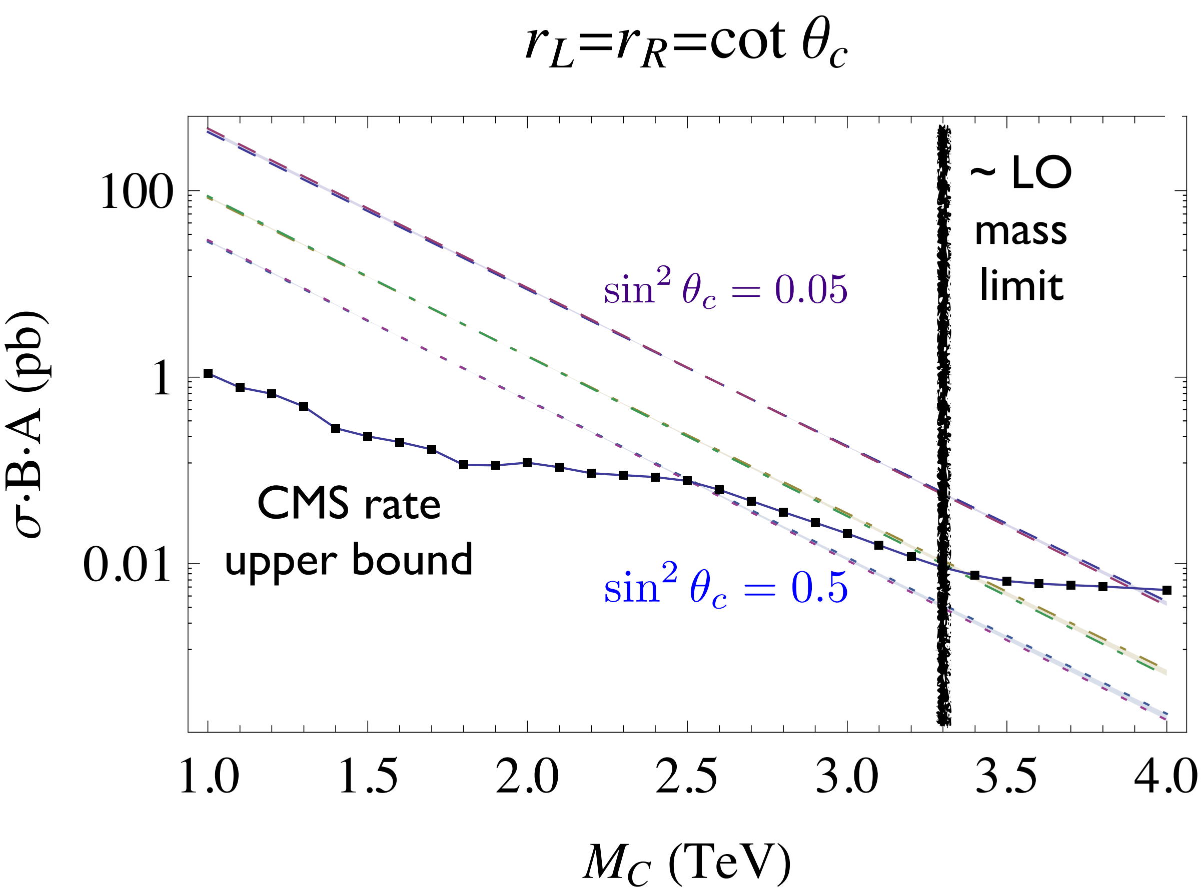
NLO Colorons: Virtual & Real Corrections



NLO Cross-Section

NLO coloron shows altered rate (below) and less scale-dependence (right) compared to LO



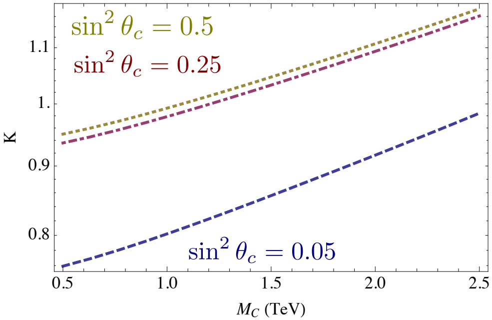


} NLO rate predictions

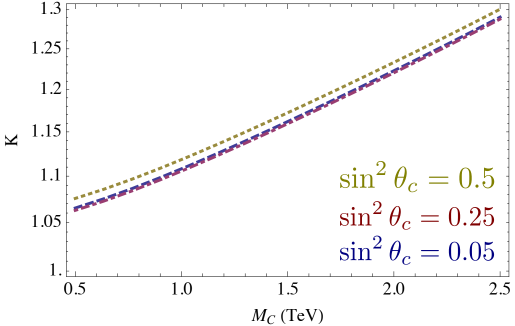
K-factor for Coloron & Axi-gluon

$$K \equiv \frac{\sigma^{\rm NLO}_{q\bar{q}\to C}}{\sigma^{\rm LO}_{q\bar{q}\to C}}$$

$r_L = r_R = \cot\theta_c, \mu = \mu_F = M_C$



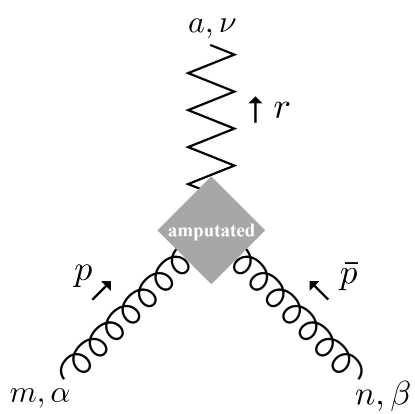
$r_L \neq r_R, \mu = \mu_F = M_C$

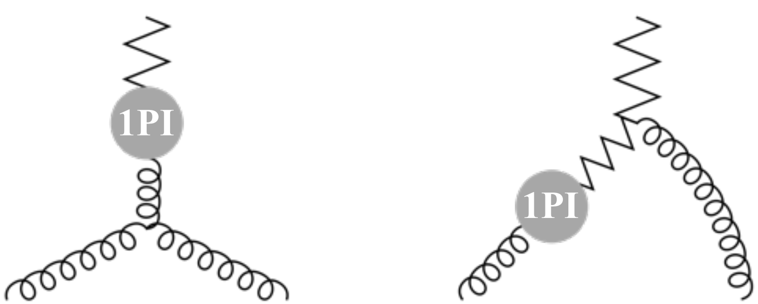


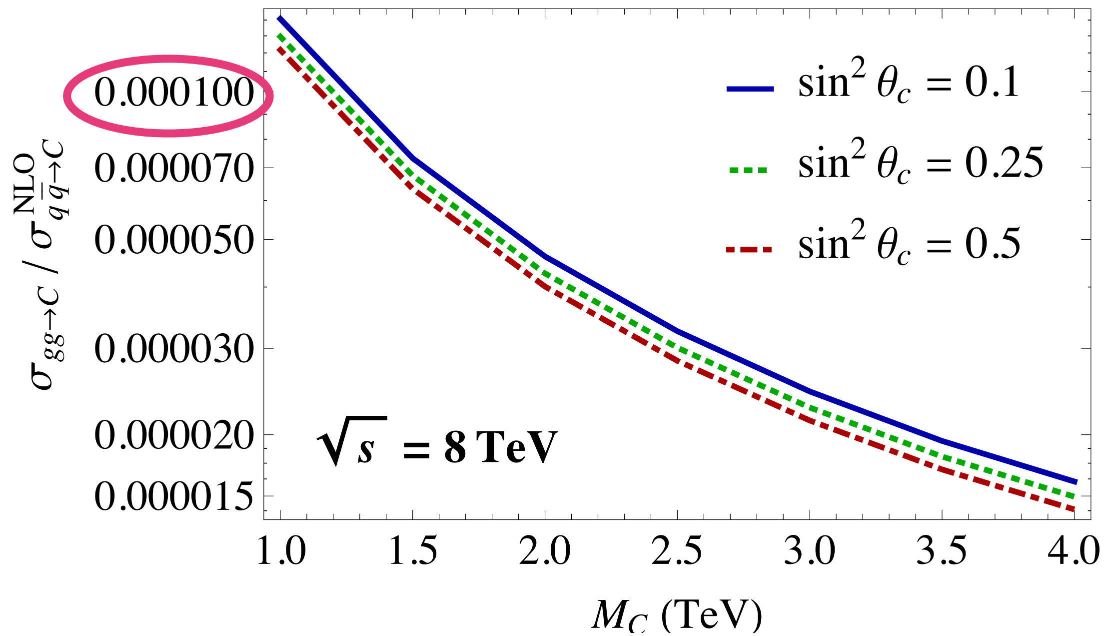
Also: 30% of produced colorons have p_T > 200 GeV!

Cgg Vertex at NLO

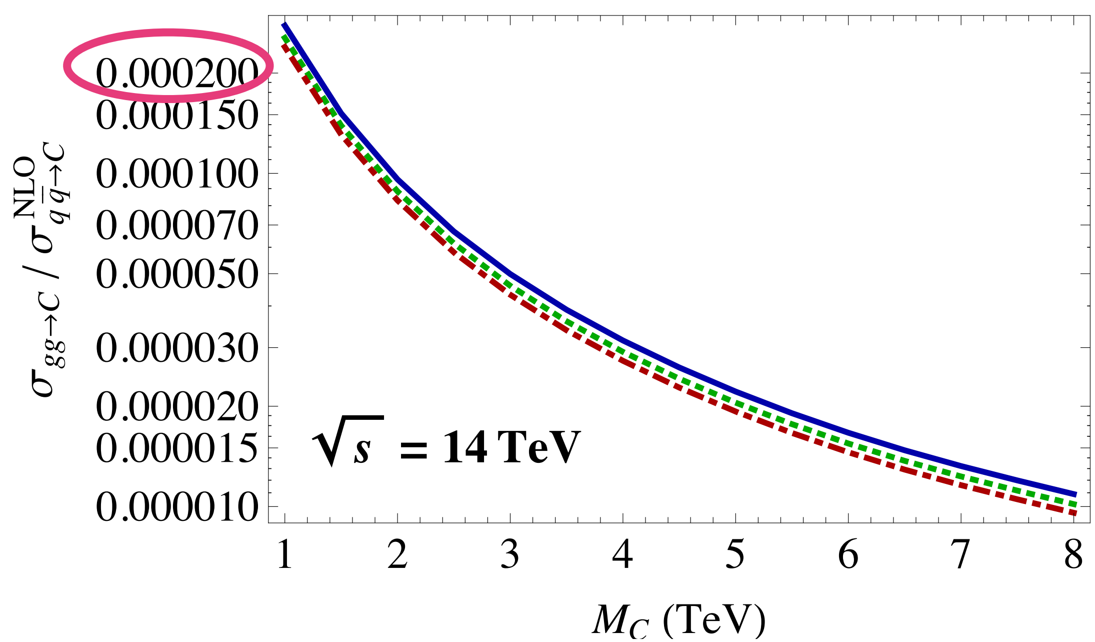
Can we harness the incoming gluons at NLO?







$r_L = r_R = \cot\theta_c$



Coloron Couplings

A. Atre, R.S. Chivukula, P. Ittisamai, EHS, J.-H. Yu arXiv:1206.1661

Suppose A Coloron is found in Dijets

As noted earlier, a variety of chiral and flavor structures for the coloron coupling to quarks is open...

$$\underbrace{g_s \bar{q}\, C^\mu \gamma_\mu \left(g_V^q + g_A^q \gamma_5\right) q}_{q=u,d,c,s}$$

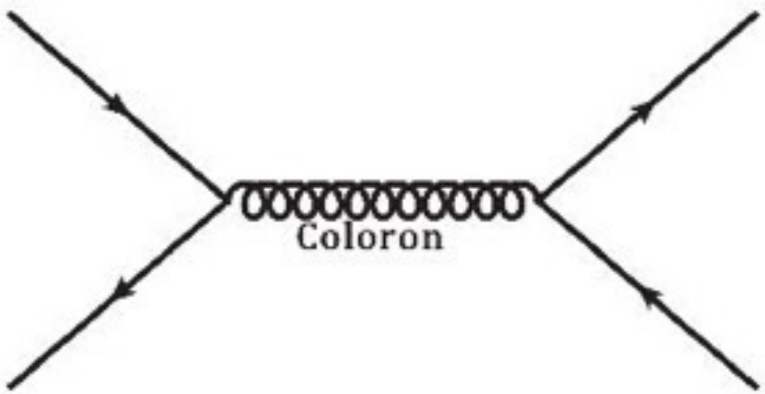
$$\underbrace{g_s \bar{T}\, C^\mu \gamma_\mu \left(g_V^T + g_A^T \gamma_5\right) T}_{T=t,b}$$

$SU(3)_1$	$SU(3)_2$	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	$(t,b)_L$		

How to establish which kind of coloron has been found?

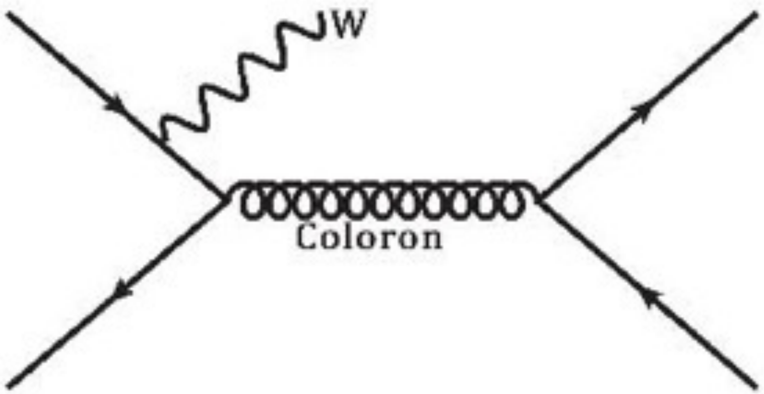
Associated Production:

Dijet



Discovery

Associated production with W



Measurement

Goal

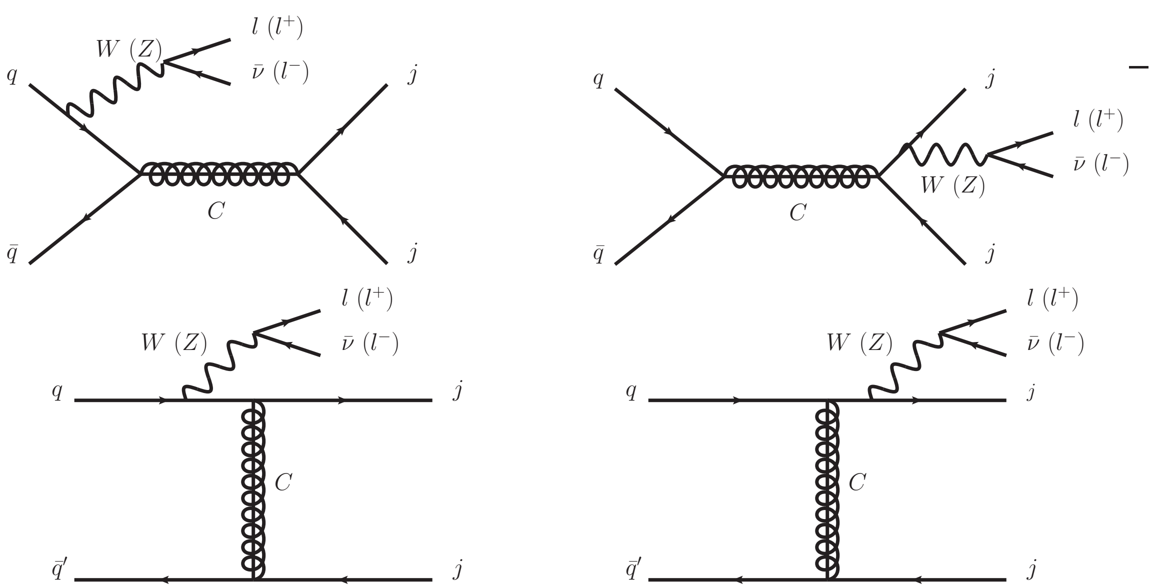
" Using associated production* with W and dijet resonance to determine colorons/axigluons couplings."

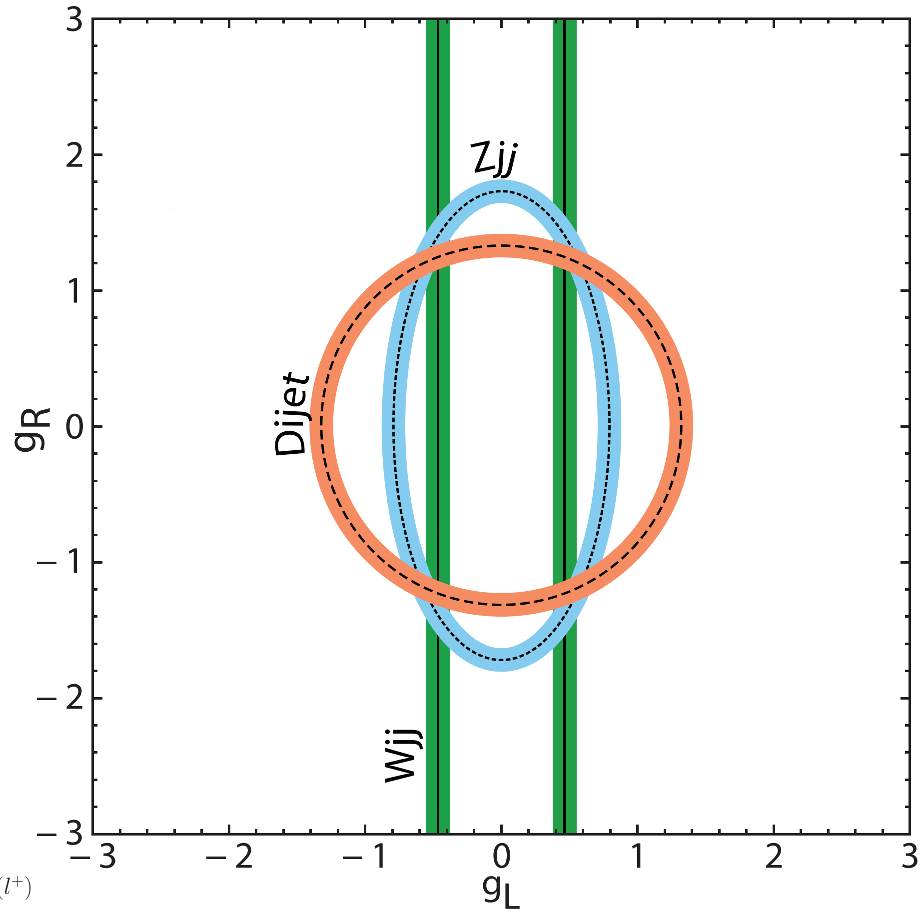
*Idea introduced by Cvetic and Langacker (1992) for measuring Z' couplings

W+Cᴬ probes Coloron's Chiral Couplings

Different production modes probe several combinations of the coloron's couplings to RH and LH fermions:

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



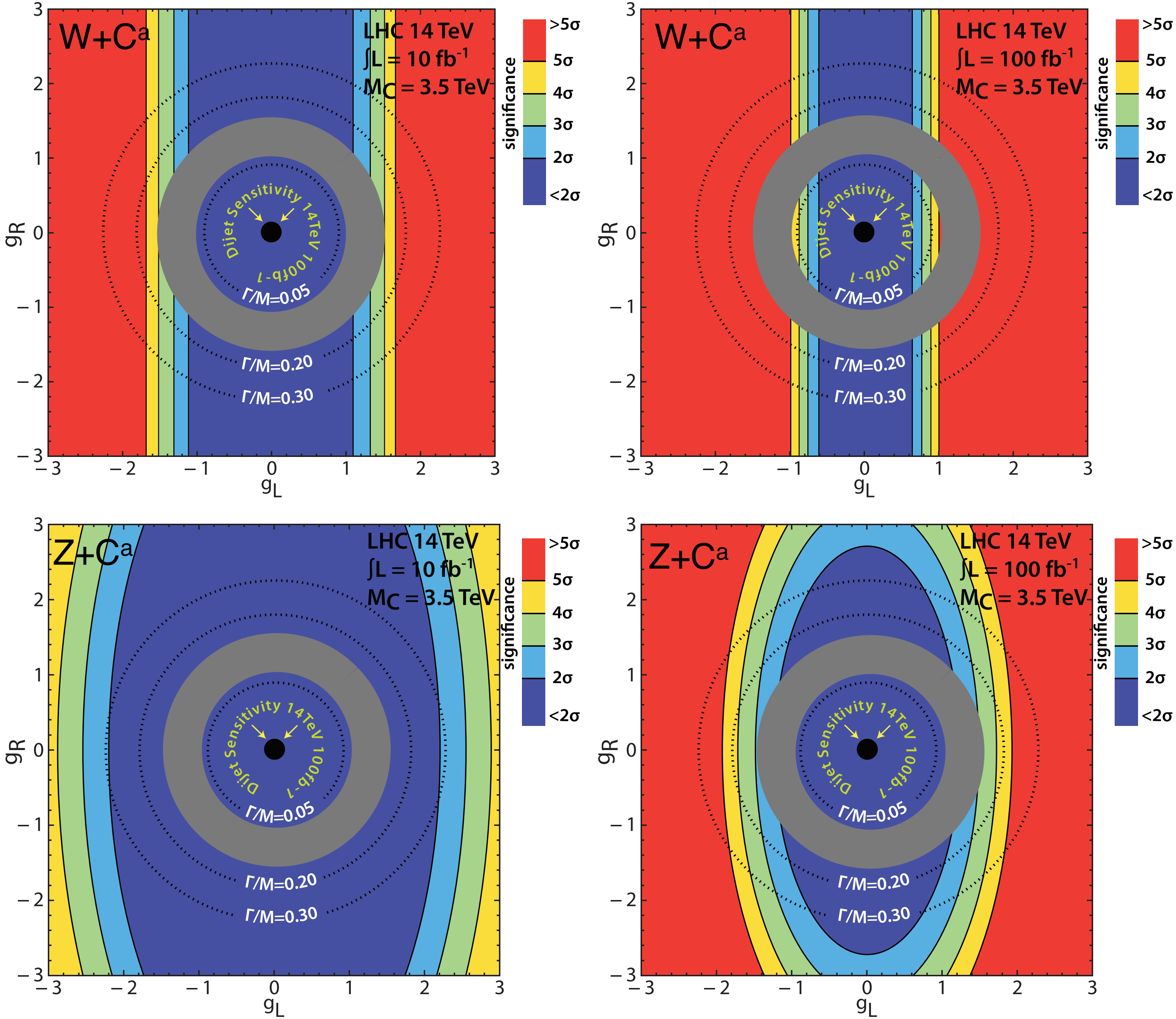


A. Atre, R.S.Chivukula, P. Ittisamai, EHS arXiv:1206.1661

W+C^a: Heat Map of Significance

all of these heat maps are for M_c = 3.5 TeV at **14 TeV LHC**

grey ring is excluded by 7 TeV LHC dijet searches with 5 fb^{-1} of data



But is it Really a Coloron?

A. Atre, R.S. Chivukula, P. Ittisamai, EHS arXiv:1306.4715
A. Atre, R.S. Chivukula, P. Ittisamai, EHS 2014 in preparation

Distinguishing Among 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.

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

must be equal

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

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

Color Discriminant Variable

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

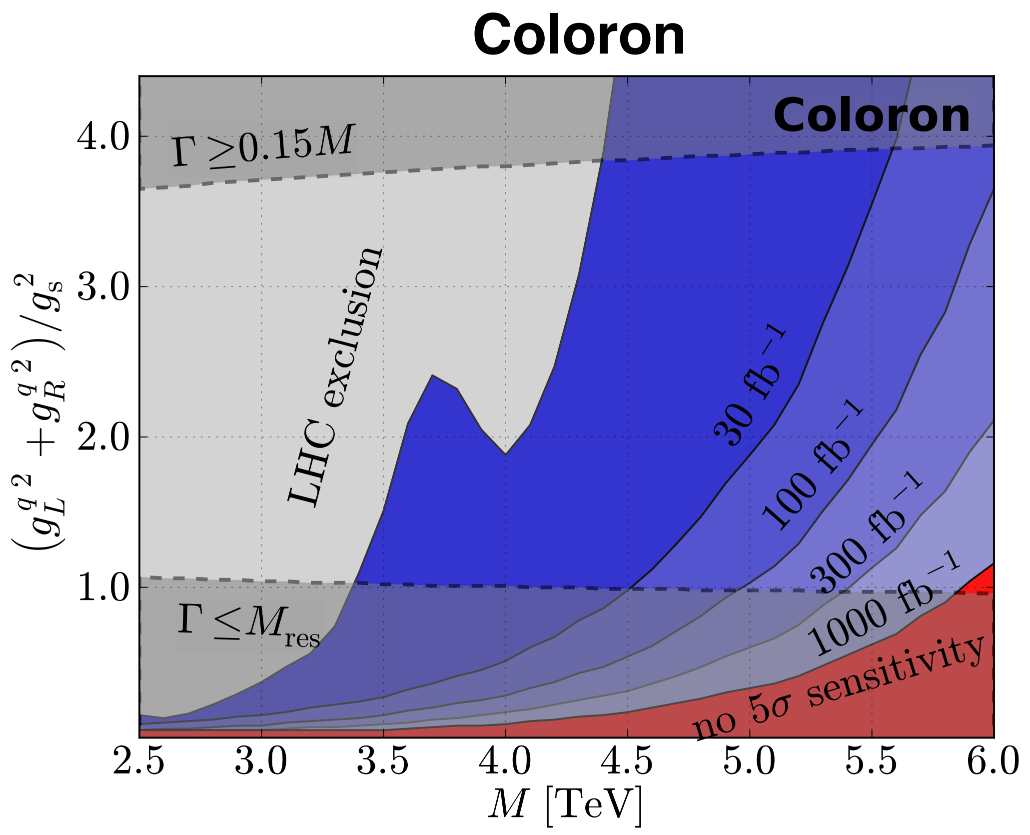
must

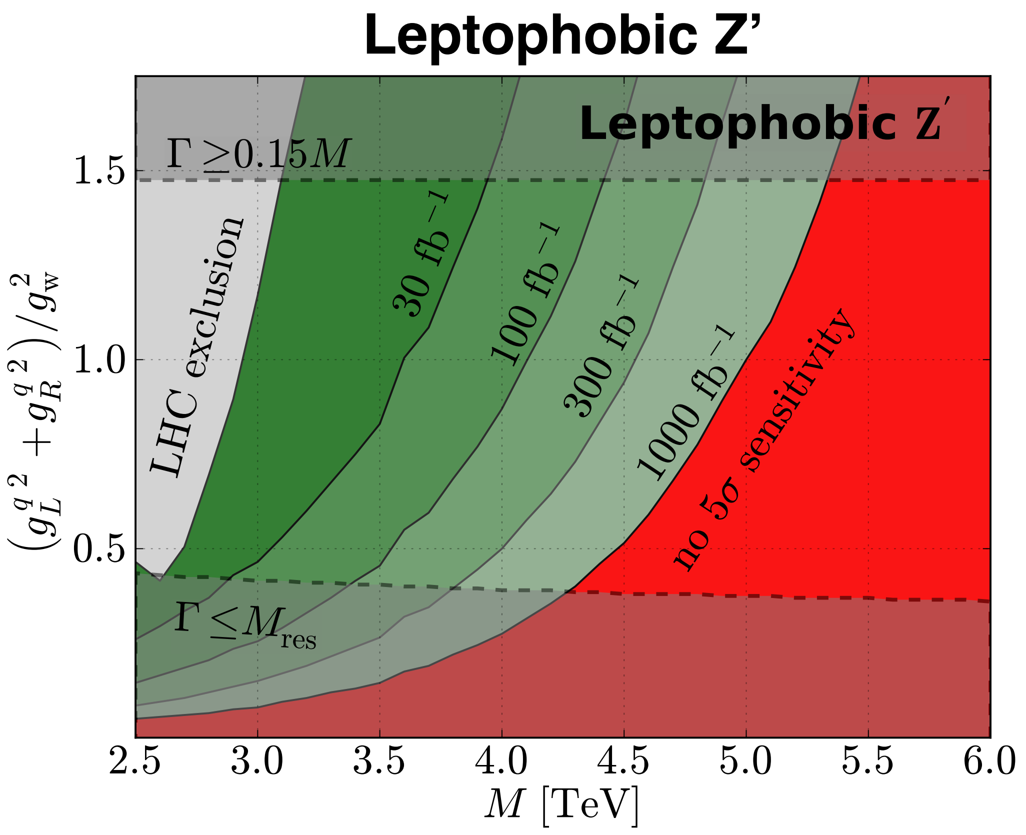
$$\sigma_{jj}^{Z'} = \frac{1}{9}\frac{\Gamma_{Z'}}{M_{Z'}^3}\sum_q W_q(M_{Z'})Br(Z' \to jj)$$

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

- based on standard observables
- requires width to be measurable
- distinguishes color structure of resonance

Establish Detection Range

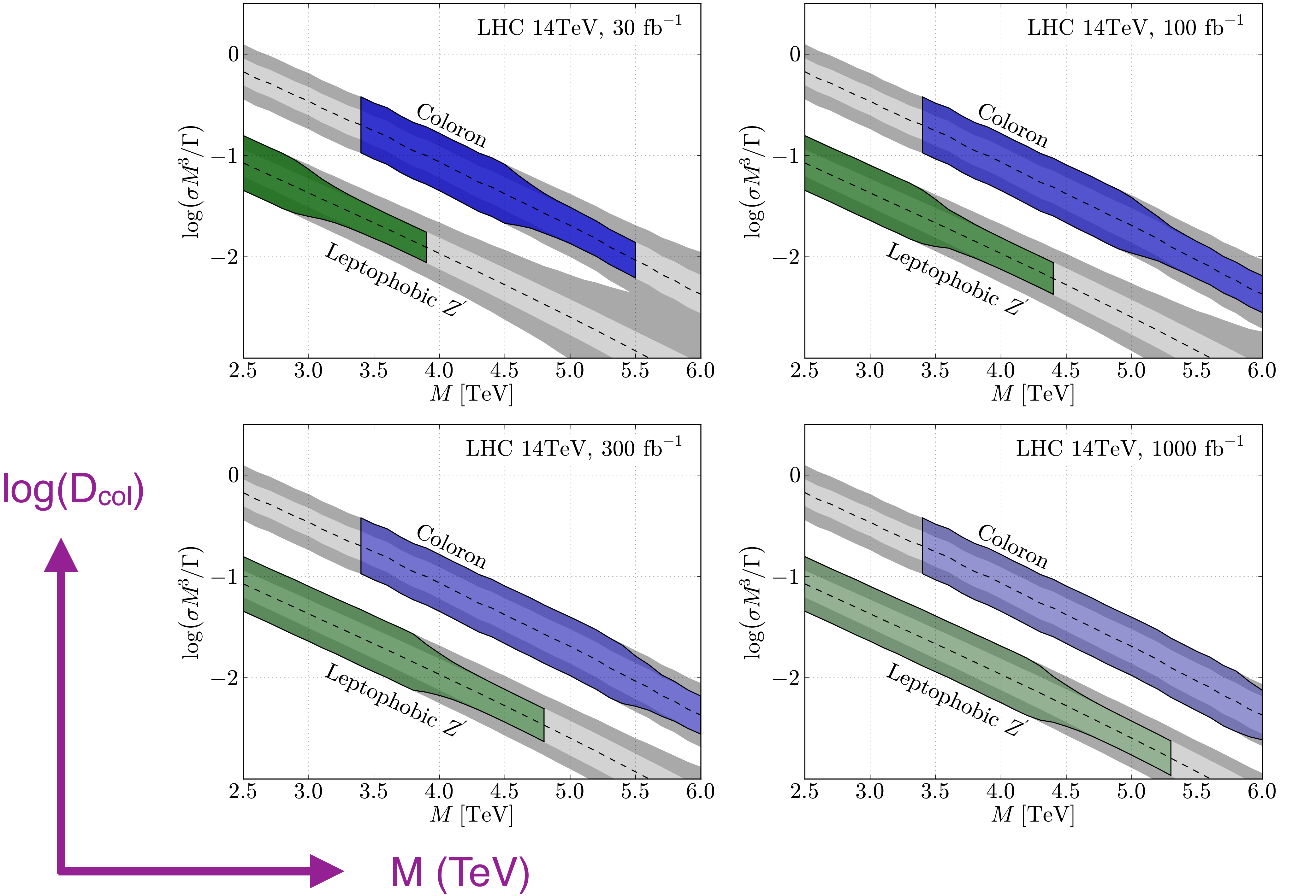




Un-greyed color shows the observable region at LHC

- width above detector resolution, yet narrow
- cross-section sufficient to allow detection, yet not already excluded

Color Discriminant Variable in Action



Generalize Flavor Structure?

For more generality, allow $g^t \equiv \xi\, g^q$

As a result: $\Gamma \to \Gamma * \left(\frac{4+2\xi^2}{6}\right)$ $\quad Br(V \to jj) : \frac{5}{6} \to \left(\frac{4+\xi^2}{4+2\xi^2}\right)$

which changes the detail but not the substance of

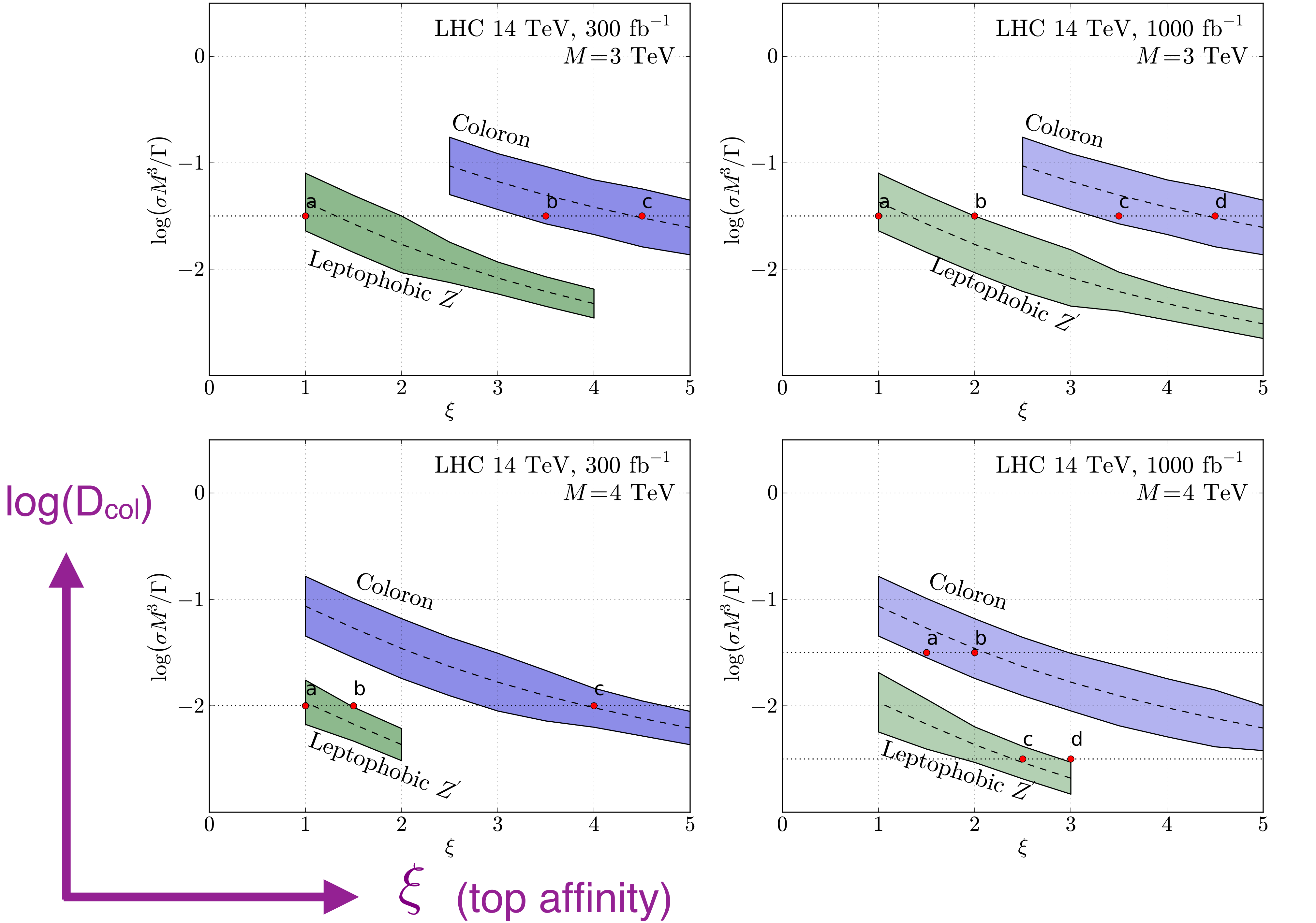
$$\sigma^C_{jj} = \frac{8}{9}\frac{\Gamma_C}{M_C^3}\sum_q W_q(M_C) Br(C \to jj)$$

must

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

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

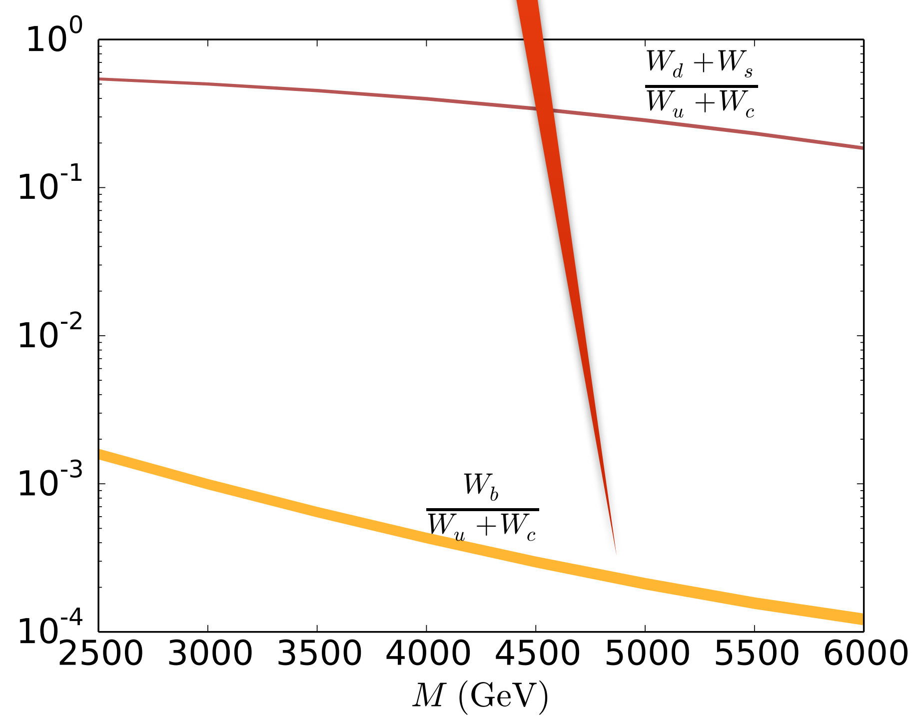
Incorporating Flavor Non-Universality



MORE GENERAL FLAVOR STRUCTURE

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

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



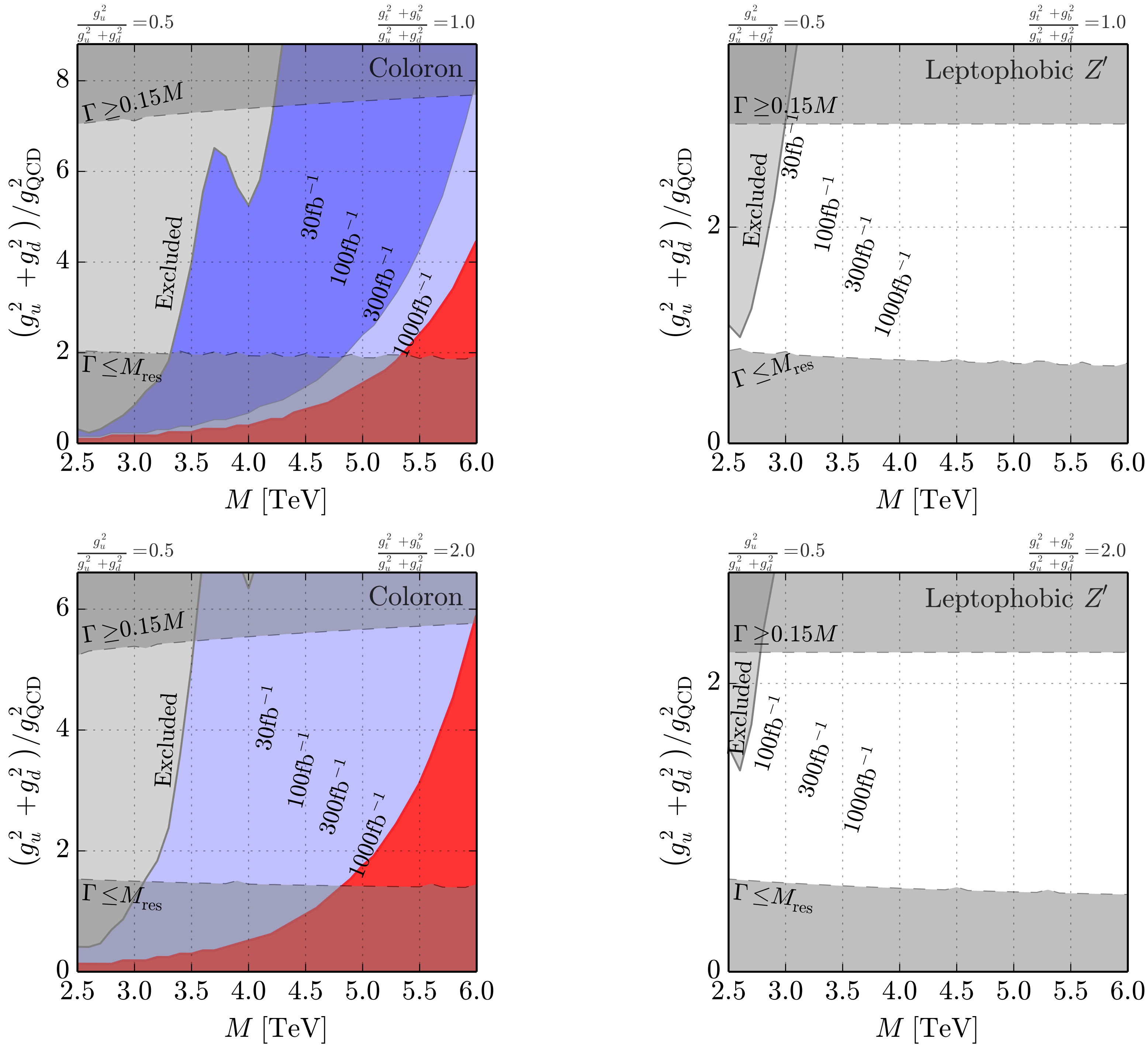
Measurements sensitive to?

- chirality of quark couplings - **NO**
- distinct light quark flavors - **NO**
- b contribution to production - **NO**
- b, t contribution to width - **YES**

14 TeV LHC Reach for C^A and Z'

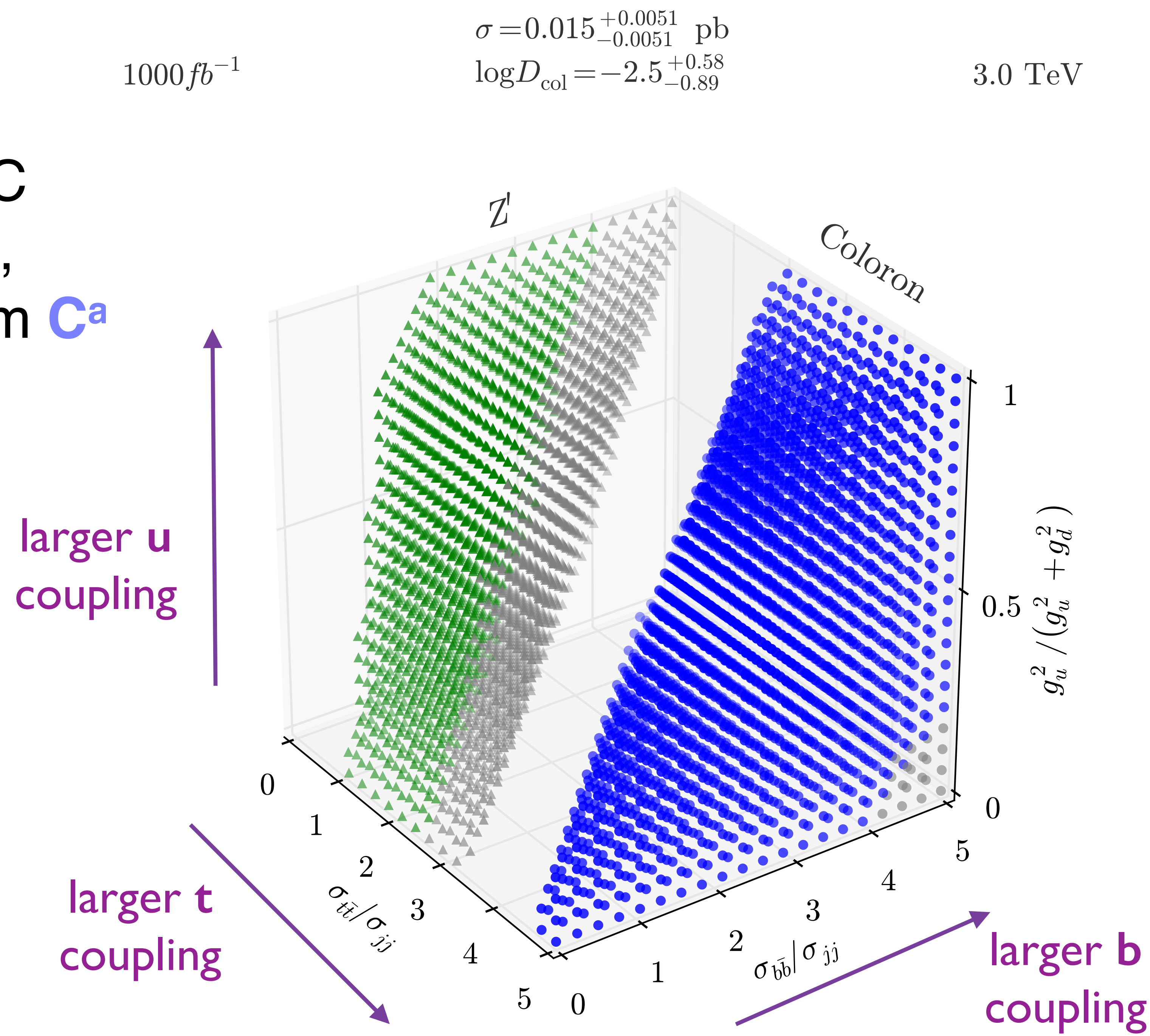
Flavor Universal

Prefers 3rd gen.



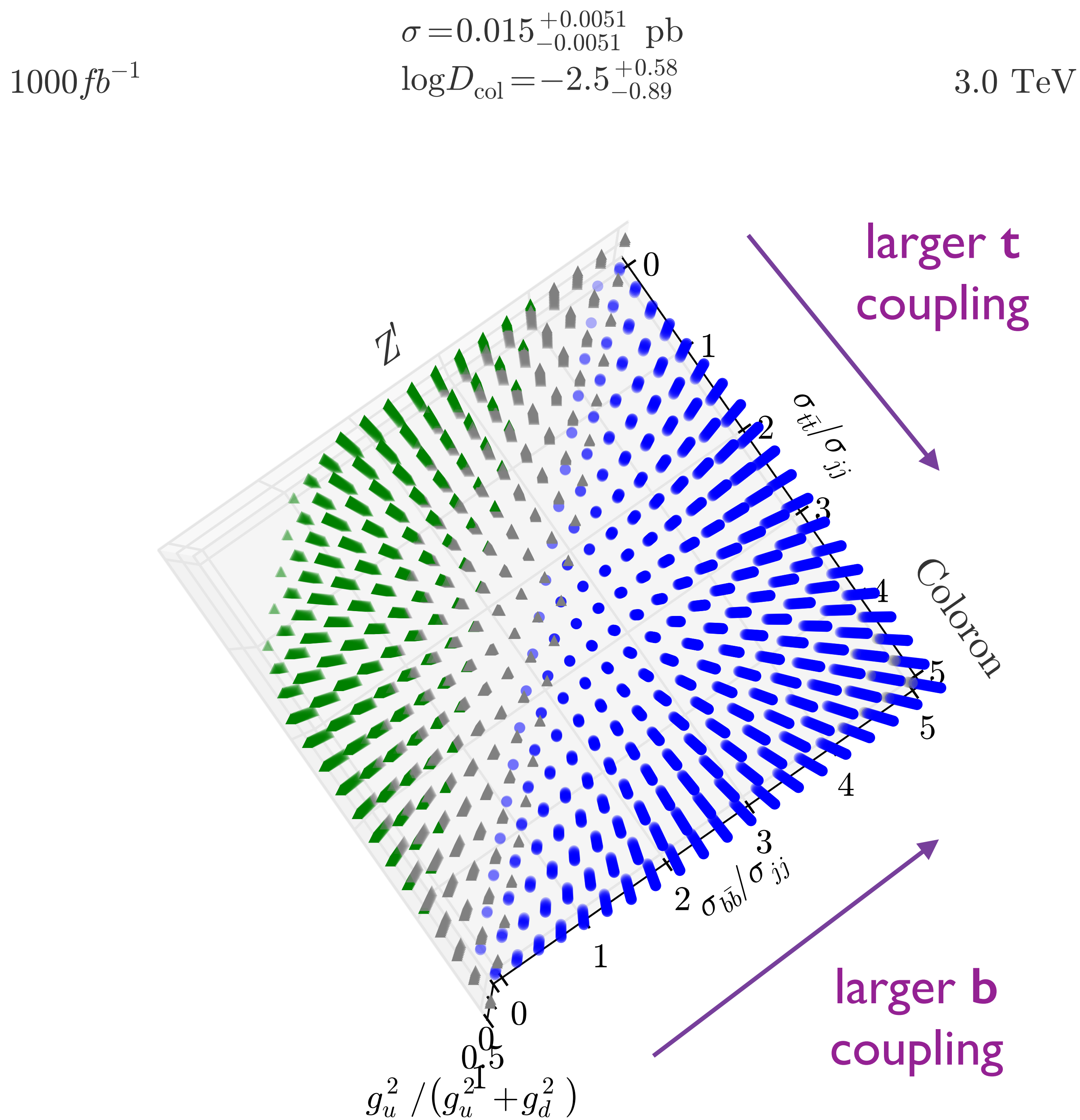
TELLING C^A AND Z' APART

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



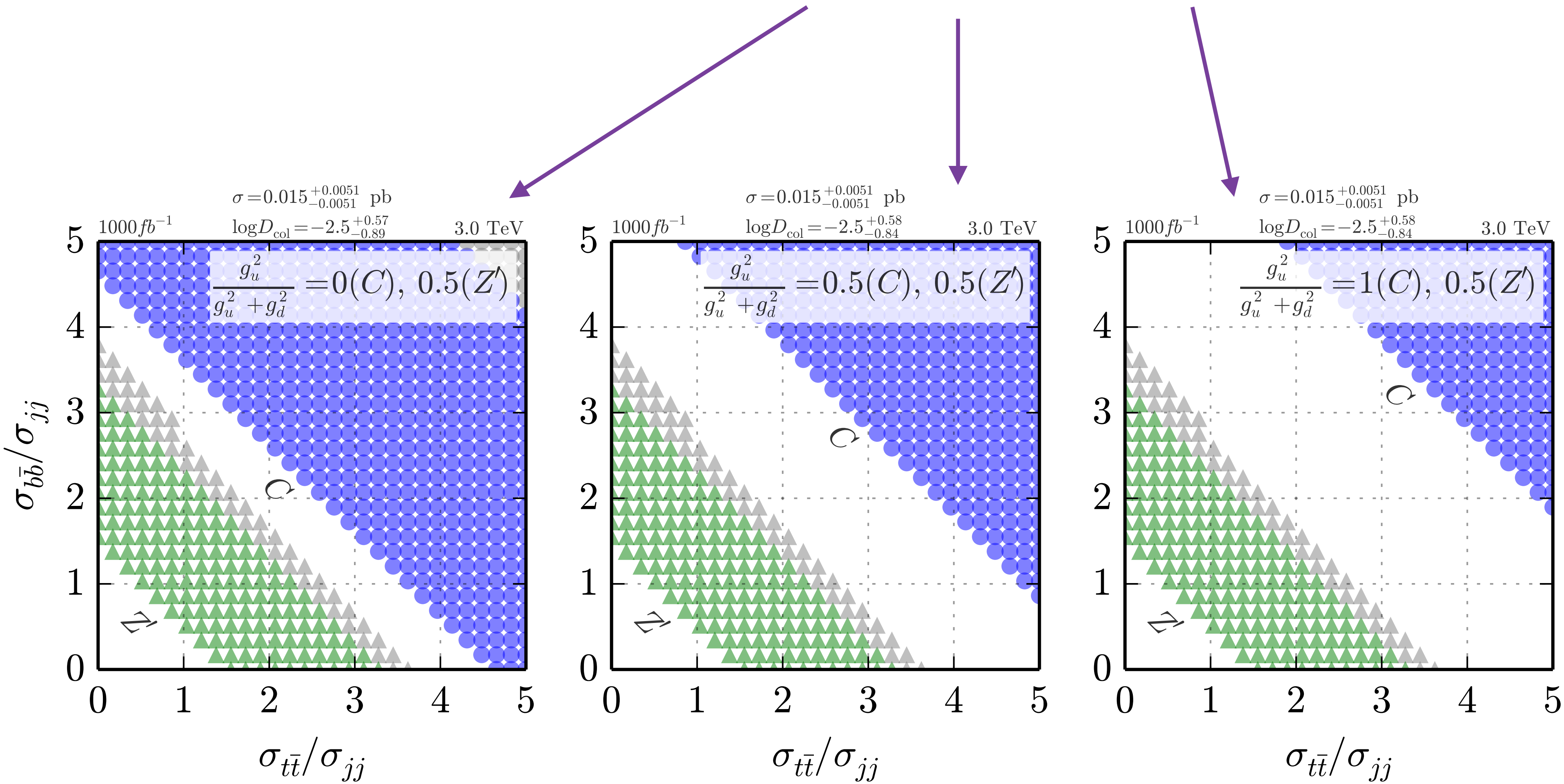
Telling C^A and Z' Apart

Looking down tl
"**u**" axis, we see
no overlap
between
Z' and C^a



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'



Conclusions

Conclusions

BSM Physics may yet lurk in the strong interactions!

*<u>LHC can not just discover, but **identify** colorons</u>*,

- **NLO K-factor and p_T distribution** improve dijet searches
- **associated W+ C^a production** probes coloron's couplings
- **width distinguishes color structure** of a new dijet resonance

Library

Simulation Details

Event Generation: MadGraph 5.1.3 $\rightarrow$ Pythia 6.4 $\rightarrow$ PGS4

Event Selection ("Basic cuts"):

- At least two isolated jets
  - $p_T > 40\,\mathrm{GeV}$
  - $|\eta| < 2.5$
  - $\Delta R_{jj} > 0.4$
- One isolated electron or muon
  - $p_T > 25\,\mathrm{GeV}$
  - $\Delta R_{jl} > 0.4$, $\Delta R_{ll} > 0.2$
- Missing energy $> 25\,\mathrm{GeV}$

Optimization:

- p_T of leading jets
- total transverse jet energy ($H_T \simeq \sum p_T$)
- Invariant masss m_{jj} or m_{jjW}

maximize significance $\simeq \frac{s}{\sqrt{b}}$ at $10\,fb^{-1}$ and $100\,fb^{-1}$ for LHC $14\,\mathrm{TeV}$

W+C^A: Heat Map and A^{T}FB range