Color Discriminant Variable to Separate Dijet Resonances at the LHC

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based on

arXiv:1507.06676
Phys. Rev. D 91 (2015), 055021 [arXiv:1406.2003]

with R. S. Chivukula, K. Mohan, and E. H. Simmons

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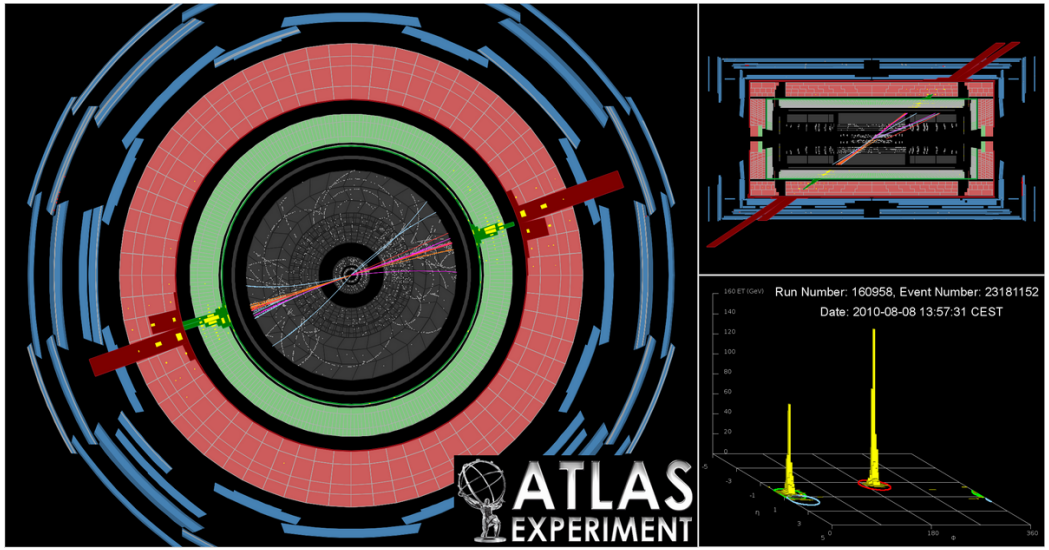
Goal: identifying new dijet resonance

Dijet at the LHC

Large number of events, simple topology, potential discovery channel



Goal

Distinguish new resonances using measurements available <u>with</u> the discovery of the dijet resonance.

Figure: ATLAS

Motivation: leptophobic color-singlet *vs* color-octet vectors

Models predicting dijet resonance

Color-octet vector boson

"Coloron"

Chiral color, Technicolor, Topcolor,

Extradimension, ...

↓

Dijets

Color-singlet vector boson

$\mathbf{Z}'$

Many models have one ...

↓

Dileptons

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Color-singlet vector boson
$\mathbf{Z}'$
Many models have one ...

?

?

Dijets

~~Dileptons~~

Without a discovery in the dilepton channel, is the new dijet resonance a *color-octet* or a *leptophobic color-singlet* vector boson?

Rates for narrow dijet resonances

Parton level, s-channel, $i + k \to R \to x + y$:

$$\hat{\sigma}_R = 16\pi \, \mathcal{N} \, (1 + \delta_{ik}) \, \frac{\Gamma(R \to ik)\Gamma(R \to xy)}{(\hat{s} - m_R^2)^2 + m_R^2 \Gamma_R^2}$$

Spin-color factor $= \frac{N_{S_R}}{N_{S_i} N_{S_k}} \frac{C_R}{C_i C_k}$

For identical initial partons

$\Gamma(R \to ..)$ = Partial width

Γ_R = Total width

$pp \to R \to jj$ in narrow width approximation:

$$\sigma_{jj} \simeq 16\pi^2 \mathcal{N} \frac{\Gamma_R}{m_R^3} \left(\sum_{ik} (1 + \delta_{ik}) \mathrm{BR}(R \to ik) \left[\tau \frac{d\mathcal{L}^{ik}}{d\tau} \right] \right) \left(\sum_{xy=jj} \mathrm{BR}(R \to xy) \right)$$

Observables

$\propto$ parton distribution function

$\tau = m_R^2 / s$

Dijet branching fraction

Color Discriminant Variable $D_{\rm col} \equiv \sigma_{jj} m_R^3/\Gamma_R$

$$D_{\rm col} \equiv \frac{m_R^3 \sigma_{jj}}{\Gamma_R}$$

Observables,

$D_{\rm col}$ is dimensionless

$$= 16\pi^2 \mathcal{N} \left(\sum_{ik} (1+\delta_{ik}) {\rm BR}(R \to ik) \left[\tau \frac{d\mathcal{L}^{ik}}{d\tau} \right] \right) \left(\sum_{xy=jj} {\rm BR}(R \to xy) \right)$$

Spin-color factor $= \frac{N_{S_R}}{N_{S_i} N_{S_k}} \frac{C_R}{C_i C_k}$

$\propto$ parton distribution function

Dijet branching fraction

Color Discriminant Variable is independent of overall couplings: "model-independent".

Atre, Chivukula, P.I., Simmons – arXiv:1306.4715
Chivukula, P.I., Mohan, Simmons – arXiv:1507.06676

Plan

Color Discriminant Variable Separates:

Flavor Universal Vector Bosons

Flavor Non-universal Vector Bosons

Scalar Diquarks vs Vector Bosons

Example: Flavor-universal Coloron vs Leptophobic Z'

Same couplings to all quarks.

Coloron
Color $C_C = 8$

$$D^C_{col} = \frac{16\pi^2}{9} \sum_{q=u,c,d,s} \left[\tau \frac{dL^{q\bar{q}}}{d\tau}\right] \mathrm{BR}_{jj}$$

Z'
Color $C_{\mathrm{Z}'} = 1$

$$D^{\mathrm{Z}'}_{col} = \frac{2\pi^2}{9} \sum_{q=u,c,d,s} \left[\tau \frac{dL^{q\bar{q}}}{d\tau}\right] \mathrm{BR}_{jj}$$

$$D^C_{col} = 8 D^{\mathrm{Z}'}_{col}$$

A new resonance with mass M, dijet cross section σ_{jj}, and value of $D_{\rm col}$ could correspond to either a broader Z' or a narrower C.

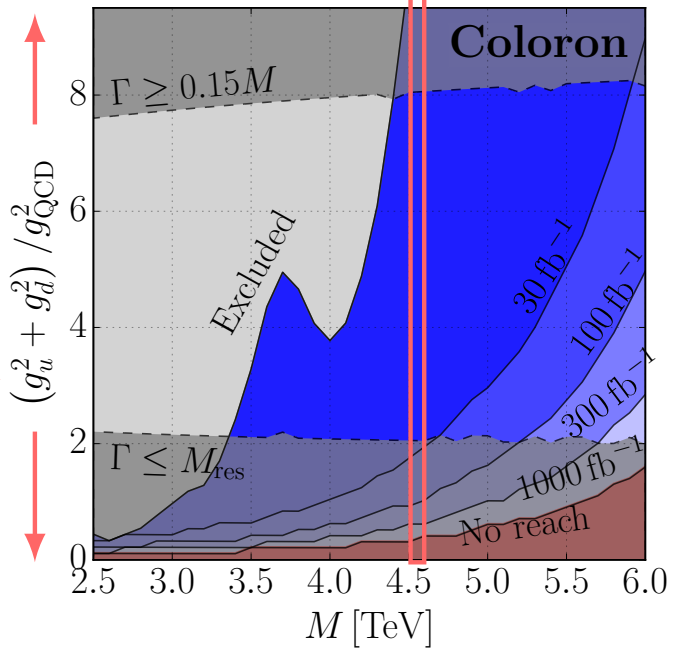
Viable parameter space at LHC14

Same $D_{\rm col}$ for all overall couplings

Too broad[1]

Overall coupling

Too narrow



▲ Here $g_u^2 \equiv (g_{u_L}^2 + g_{u_R}^2) = g_d^2 \equiv (g_{d_L}^2 + g_{d_R}^2)$

The method applies to narrow resonances that are not already excluded, within reach at LHC14, have measurable widths.

[1] Haisch and Westhof *arXiv*:1106.0529

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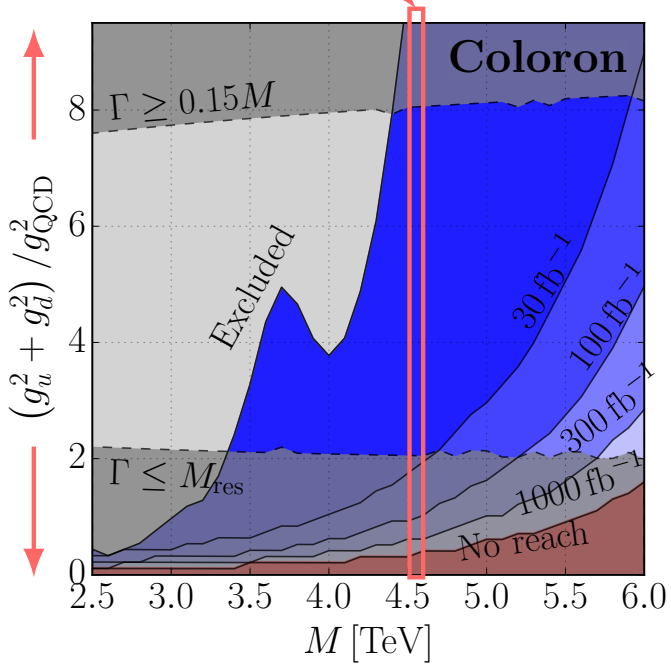

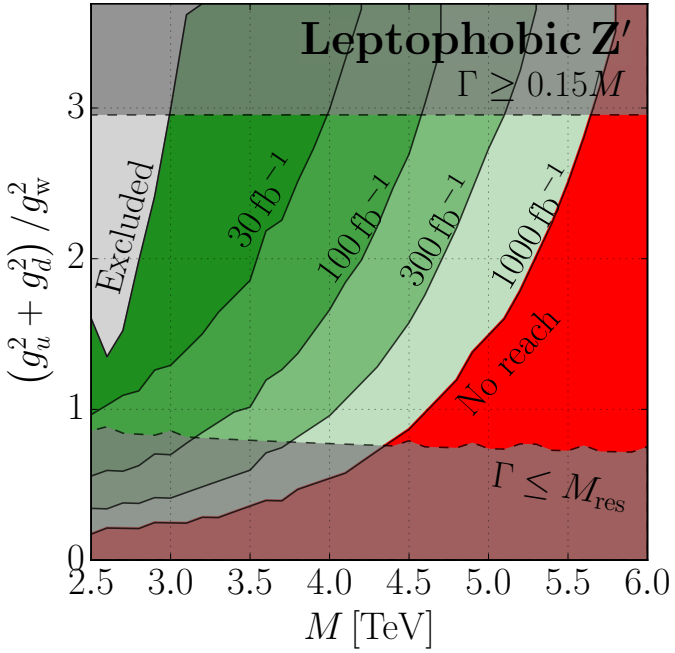

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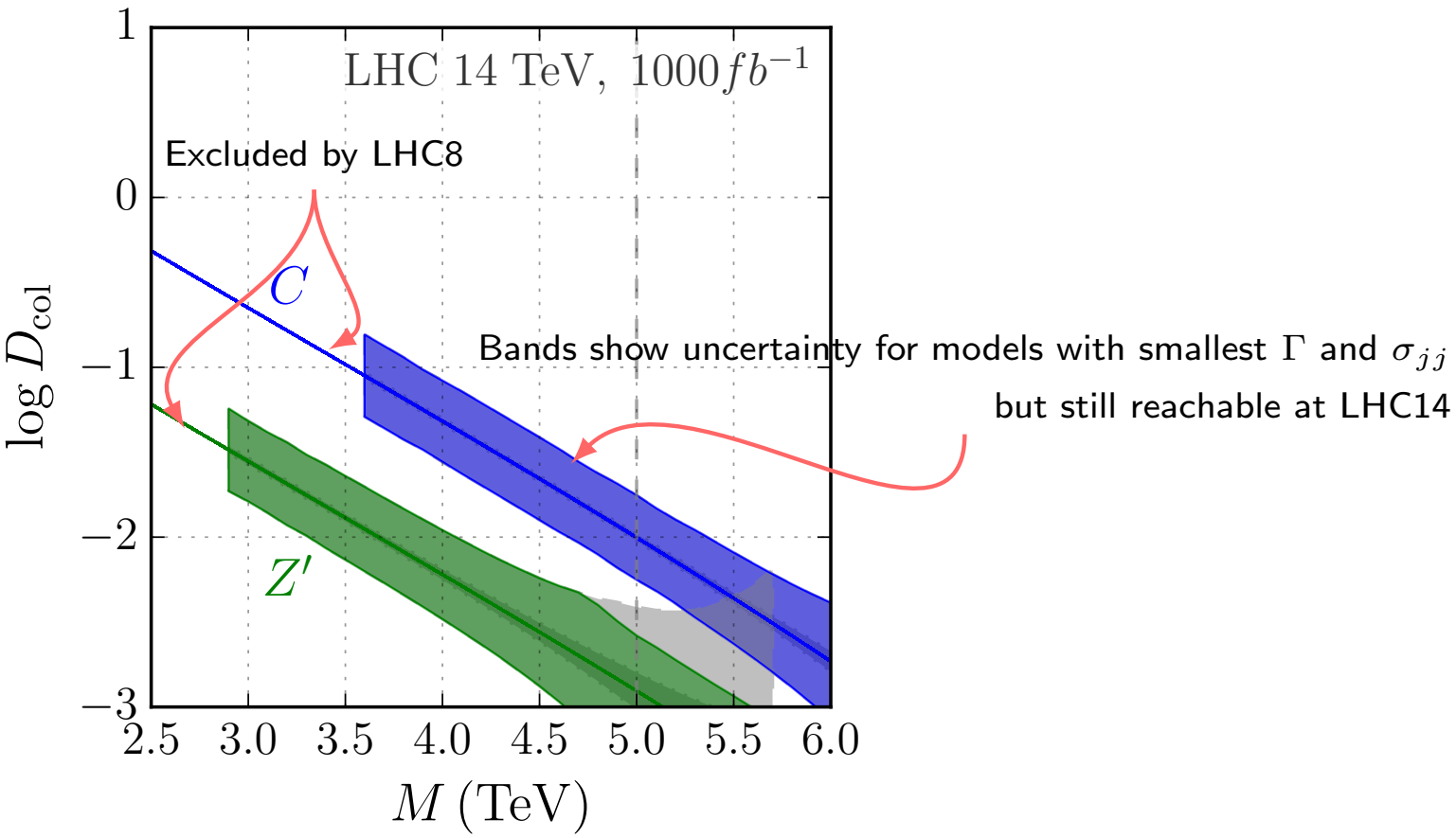
$D_{\rm col}$ separates flavor-universal C from Z'



Models for Z' and C span different $D_{\rm col}$ regions.

Plan

Color Discriminant Variable Separates:

Flavor Universal Vector Bosons

Flavor Non-universal Vector Bosons

Scalar Diquarks vs Vector Bosons

Flavor Non-universal scenario

$$D_{\rm col} \equiv \frac{m_R^3 \sigma_{jj}}{\Gamma_R}$$

$$= 16\pi^2\, \mathcal{N} \left(\sum_{ik} (1+\delta_{ik})\, \mathrm{BR}(R \to ik) \left[\tau \frac{d\mathcal{L}^{ik}}{d\tau} \right] \right) \left(\sum_{xy=jj} \mathrm{BR}(R \to xy) \right)$$

Now both branching fractions depend on relative coupling strengths g_L, g_R to different quarks

Flavor non-universal assumptions motivated by experiments

Flavor-Changing Neutral Current constraints
$\rightarrow$ Assumption: Couplings to 2nd generation same as 1st generation

Coloron		Leptophobic Z'	
$g_L^{u,c} = g_L^{d,s}$	$g_R^{u,c}$, $g_R^{d,s}$	$g_L^{u,c}, g_L^{d,s}$	$g_R^{u,c}$, $g_R^{d,s}$
$g_L^{t} = g_L^{b}$	g_R^{t}, g_R^{b}	g_L^{t}, g_L^{b}	g_R^{t}, g_R^{b}

Observables defining D_{col} are not sensitive to chirality
$\rightarrow$ Only 4 parameters are relevant

$$\begin{matrix} g_u^2 = g_c^2 \\ g_d^2 = g_s^2 \end{matrix} \qquad \text{and} \qquad \begin{matrix} g_t^2 \\ g_b^2 \end{matrix}$$

Useful to define "jets" $= \{u,\, d,\, c,\, s\}$

Color discriminant variable for flavor non-universal scenario

$$D_{\rm col} \propto \left\{ \begin{array}{c} \overset{\text{Coloron}}{\downarrow} \\ 8 \\ 1 \\ \underset{\mathrm{Z}'}{\uparrow} \end{array} \right\} \times \sum_q W_{q\bar{q}} \times \mathsf{BR}_{jj}$$

$$\mathsf{BR}_{jj} = \frac{4}{6}$$

$$W_{q\bar{q}} \equiv \left[\tau \frac{\partial \mathcal{L}^{q\bar{q}}}{\partial \tau} \right]_{\tau = M_V^2/s}$$

▲ **Flavor universal**

▼ **Flavor non-universal**

$$D_{\rm col} \propto \left\{ \begin{array}{c} \overset{\text{Coloron}}{\downarrow} \\ 8 \\ 1 \\ \underset{\mathrm{Z}'}{\uparrow} \end{array} \right\} \times \left[\frac{g_u^2}{g_u^2+g_d^2} \left(W_{u\bar{u}} + W_{c\bar{c}}\right) + \left(1 - \frac{g_u^2}{g_u^2+g_d^2}\right) \left(W_{d\bar{d}} + W_{s\bar{s}}\right) + \frac{g_b^2}{g_u^2+g_d^2} W_{s\bar{s}} \right] \times \frac{2}{\left(2 + \frac{g_t^2}{g_u^2+g_d^2} + \frac{g_b^2}{g_u^2+g_d^2}\right)^2}$$

$\downarrow$

Can this cause significant deviation from the factor 8?

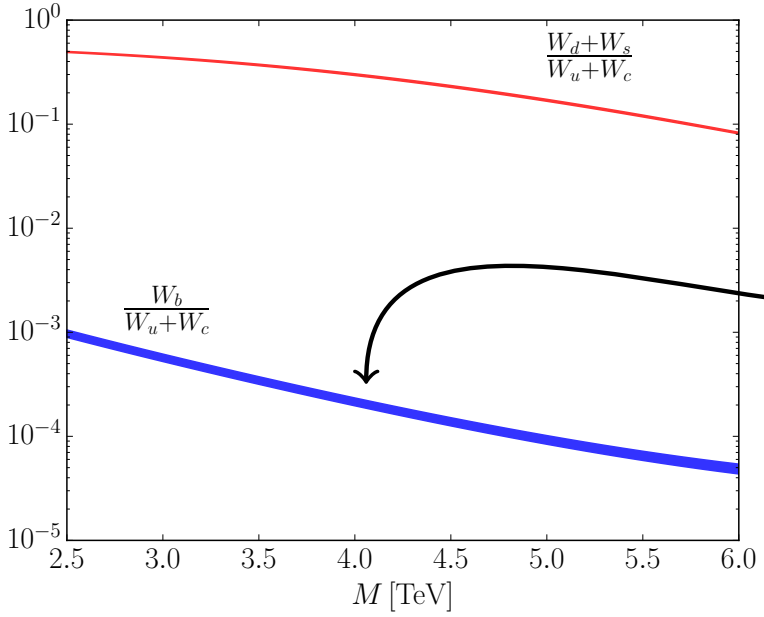
$D_{\rm col}$ not sensitive to bottom quark production

Coloron

$$D_{\rm col} \propto \left\{ \begin{array}{c} 8 \\ 1 \end{array} \right\} \times \left[\frac{g_u^2}{g_u^2+g_d^2} \left(W_{u\bar{u}} + W_{c\bar{c}}\right) + \left(1 - \frac{g_u^2}{g_u^2+g_d^2}\right)\left(W_{d\bar{d}} + W_{s\bar{s}}\right) + \boxed{\frac{g_b^2}{g_u^2+g_d^2} W_{s\bar{d}}} \right] \times \frac{2}{\left(2 + \frac{g_t^2}{g_u^2+g_d^2} + \frac{g_b^2}{g_u^2+g_d^2}\right)^2}$$

Z′

suppressed



Contributions from bottom quark production are generally highly suppressed.

Non-measurable light quark couplings not deter separation

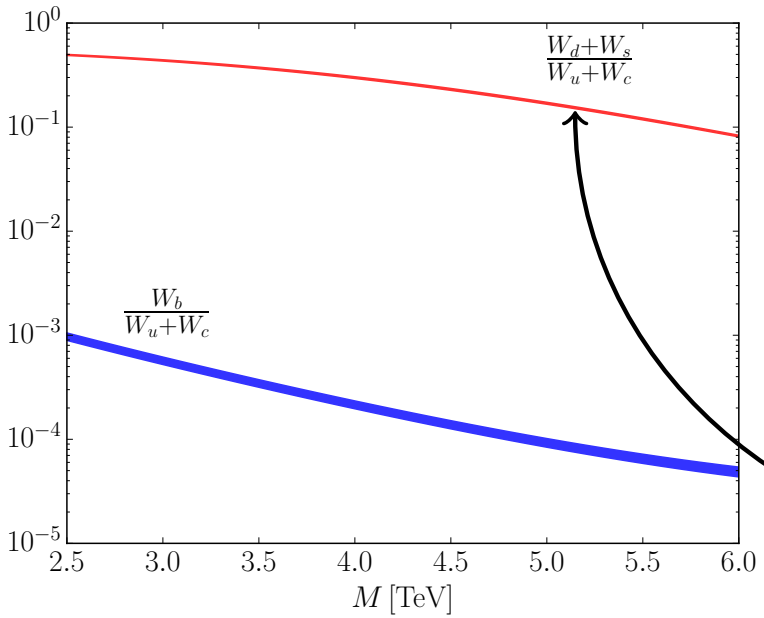
Coloron

unmeasurable, but causes overlap only at high masses

$$D_{\rm col} \propto \left\{ \begin{array}{c} 8 \\ 1 \end{array} \right\} \times \left[\frac{g_u^2}{g_u^2+g_d^2}(W_{u\bar{u}} + W_{c\bar{c}}) + \left(1 - \frac{g_u^2}{g_u^2+g_d^2}\right)(W_{d\bar{d}} + W_{s\bar{s}}) + \frac{g_b^2}{g_u^2+g_d^2} W_{b\bar{b}} \right] \times \frac{2}{\left(2 + \frac{g_t^2}{g_u^2+g_d^2} + \frac{g_b^2}{g_u^2+g_d^2}\right)^2}$$

Z′

suppressed



The worst-case scenario

$$D_{\rm col}^{C} \propto 8[\cdots] \xrightarrow{\frac{g_u^2}{g_u^2+g_d^2}=0} 8\,[W_{d\bar{d}} + W_{s\bar{s}}]$$

$$D_{\rm col}^{Z'} \propto [\cdots] \xrightarrow{\frac{g_u^2}{g_u^2+g_d^2}=1} [W_{u\bar{u}} + W_{c\bar{c}}]$$

causes overlap only at large masses,

where $\dfrac{[W_{d\bar{d}} + W_{s\bar{s}}]}{[W_{u\bar{u}} + W_{c\bar{c}}]} \lesssim \dfrac{1}{8}$

Need to measure heavy flavor final states to determine $D_{\rm col}$

Coloron

unmeasurable, but causes overlap only at high masses

$$D_{\rm col} \propto \left\{ \begin{array}{c} 8 \\ \\ 1 \end{array} \right\} \times \left[\frac{g_u^2}{g_u^2+g_d^2} \left(W_{u\bar{u}} + W_{c\bar{c}}\right) + \left(1 - \frac{g_u^2}{g_u^2+g_d^2}\right)\left(W_{d\bar{d}} + W_{s\bar{s}}\right) + \frac{g_b^2}{g_u^2+g_d^2} W_{b\bar{b}} \right] \times \frac{2}{\left(2 + \frac{g_t^2}{g_u^2+g_d^2} + \frac{g_b^2}{g_u^2+g_d^2}\right)^2}$$

Z′

suppressed

$\propto \sigma_{b\bar{b}}/\sigma_{jj}$

$\propto \sigma_{t\bar{t}}/\sigma_{jj}$

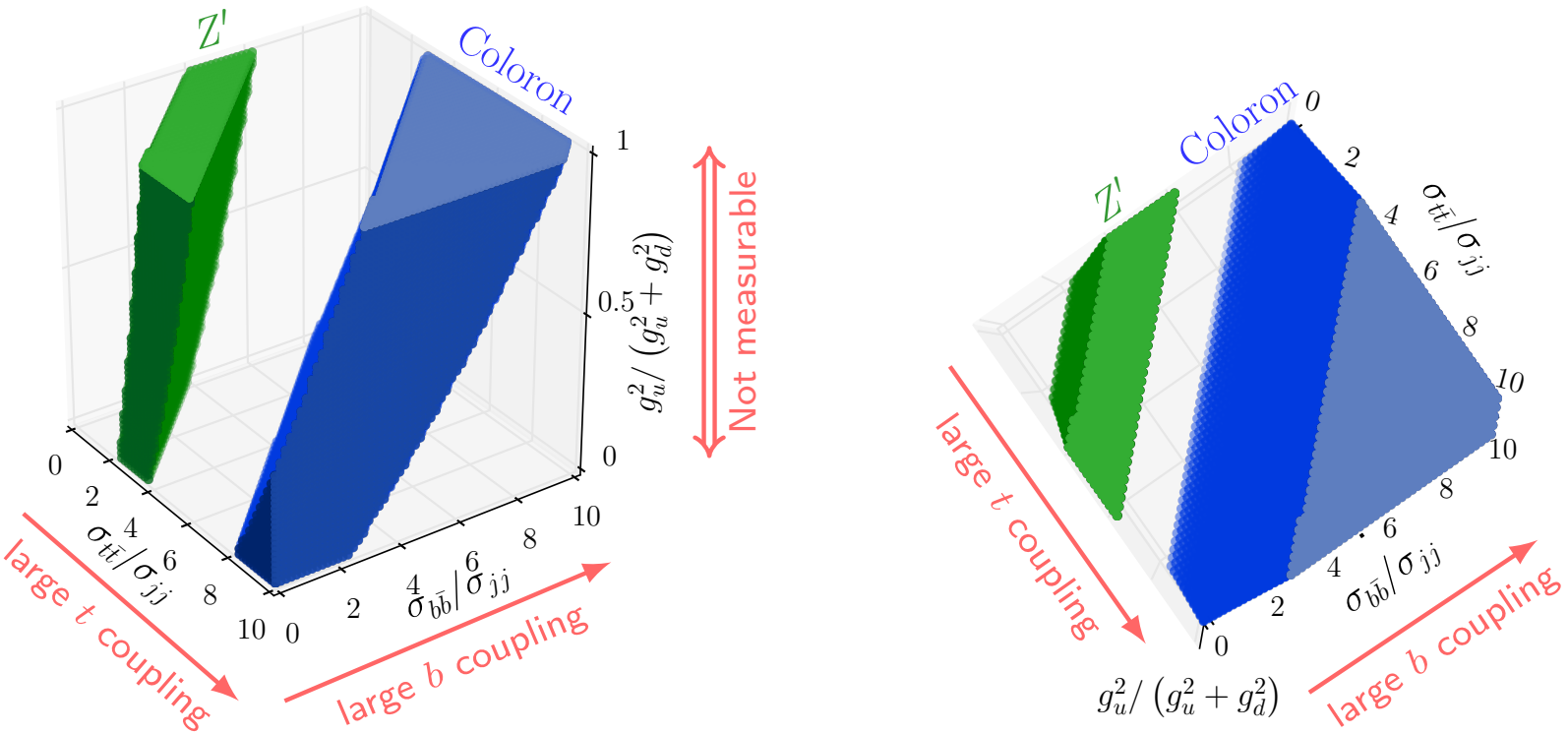
Cross sections for resonance decaying to $t\bar{t}$ and $b\bar{b}$ play key role distinguishing C from Z'.

$$\frac{g_b^2}{g_u^2+g_d^2} = 2\frac{\sigma^V_{b\bar{b}}}{\sigma^V_{jj}}$$

$$\frac{g_t^2}{g_u^2+g_d^2} = 2\frac{\sigma^V_{t\bar{t}}}{\sigma^V_{jj}}$$

After discovering a dijet resonance at $14\,\mathrm{TeV}$ LHC...

Models for a $3\,\mathrm{TeV}$ resonance with fixed σ_{jj} ($\pm 30\,\%$) and $D_{\rm col}$ ($\pm 50\,\%$):



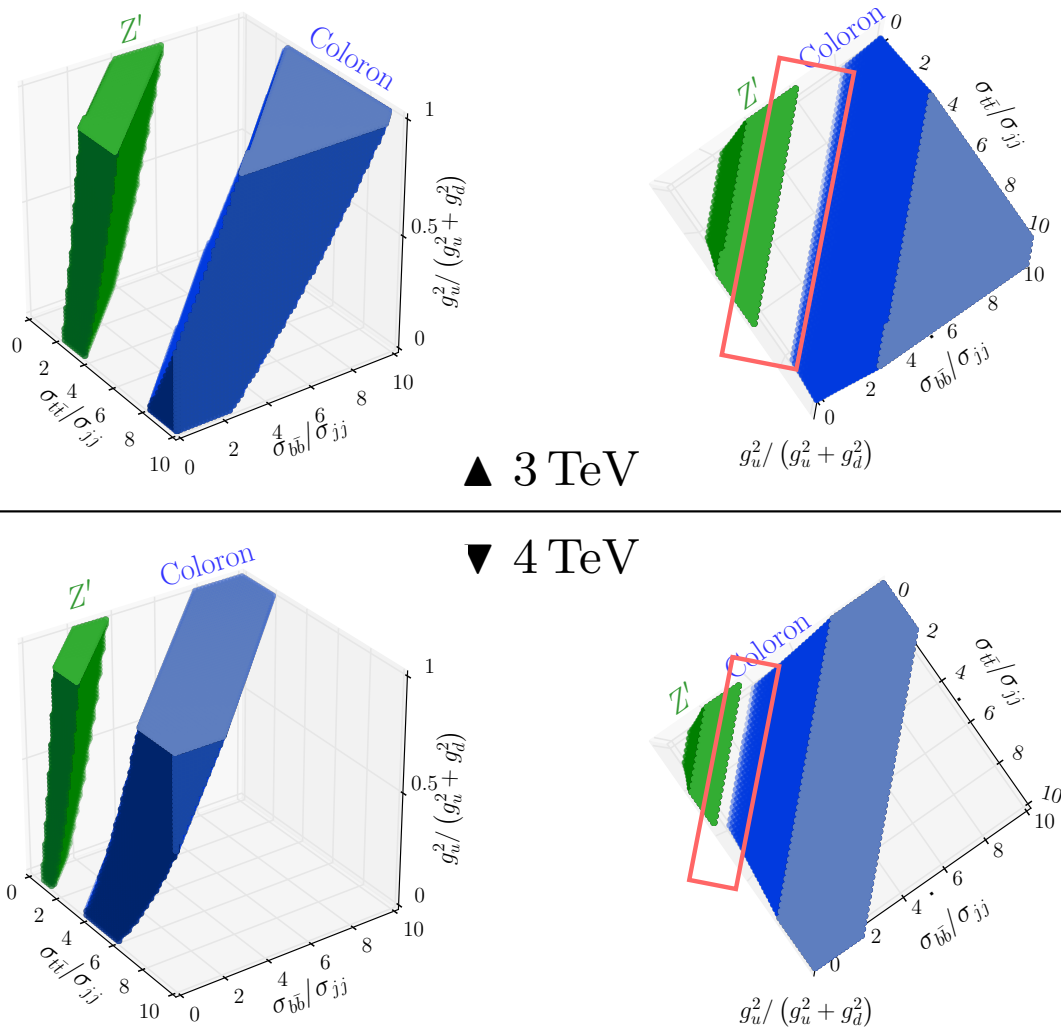
$\sigma_{jj} = 0.015 \pm 0.0051\,\mathrm{pb},\ D_{\rm col} = 0.003 \pm 0.0015,\ \mathcal{L} = 1000\,\mathrm{fb}^{-1}$

Coloron and Z' models live in different region of parameter space.

Chivukula, P.I., Simmons – arXiv:1406.2003

Different u & d couplings?

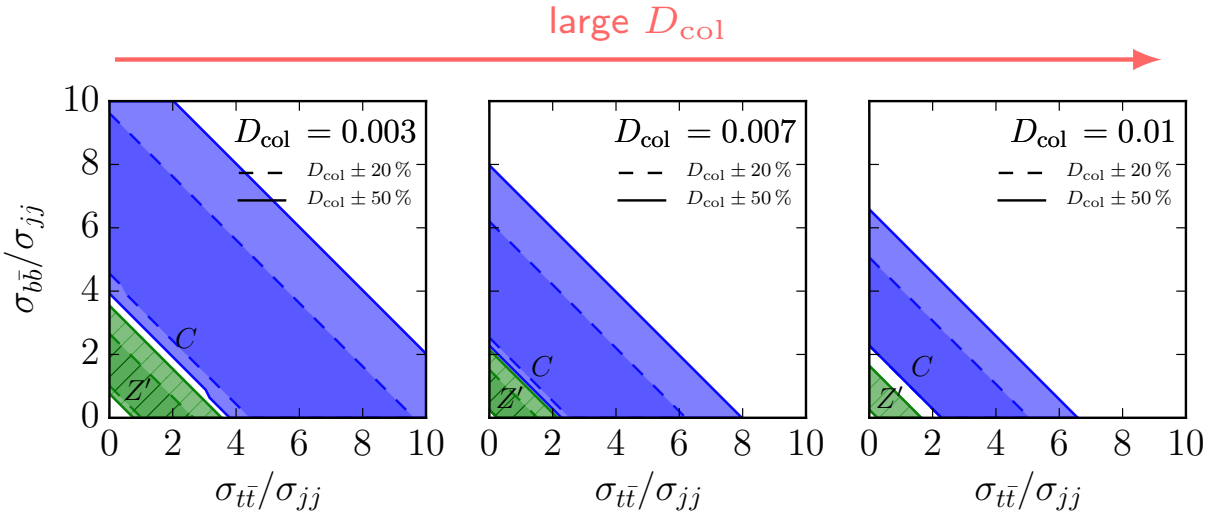
Both with $D_{\rm col} = 0.003 \pm 0.0015$



Unmeasurable u/d couplings generally do not deter separating "light" resonances.

How well must we measure $D_{\rm col}$ and heavy decays?

Partial C-Z' overlap possible for some $D_{\rm col}$, more likely at higher masses



Measuring $\sigma_{t\bar{t}}/\sigma_{jj}$ and $\sigma_{b\bar{b}}/\sigma_{jj}$ to $\mathcal{O}(1)$ is sufficient to separate C and Z'.

$M = 4\,\mathrm{TeV}$

Plan

Color Discriminant Variable Separates:

Flavor Universal Vector Bosons

Flavor Non-universal Vector Bosons

Scalar Diquarks vs Vector Bosons

Separating scalar resonances

$$D_{\rm col} \equiv \frac{m_R^3 \sigma_{jj}}{\Gamma_R}$$

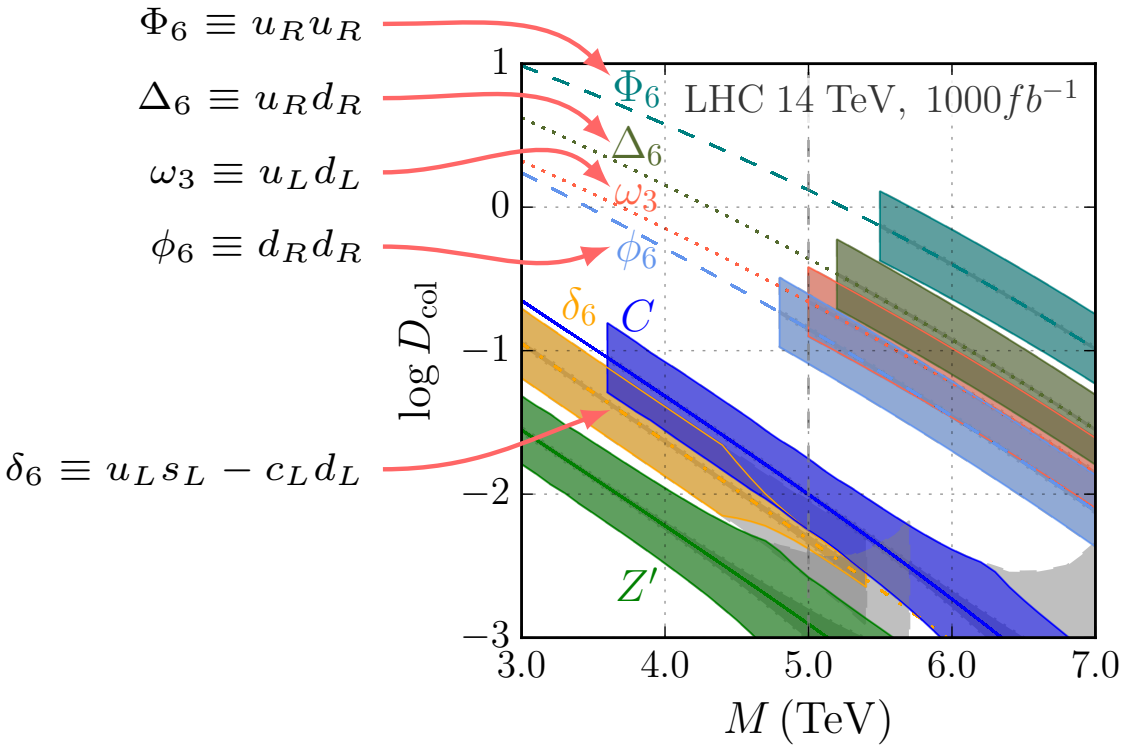
$$= 16\pi^2 \mathcal{N} \left(\sum_{ik} (1+\delta_{ik}) \mathrm{BR}(R \to ik) \left[\tau \frac{d\mathcal{L}^{ik}}{d\tau} \right] \right) \left(\sum_{xy=jj} \mathrm{BR}(R \to xy) \right)$$

Spin-color factor

$$= \frac{N_{S_R}}{N_{S_i} N_{S_k}} \frac{C_R}{C_i C_k}$$

Color Discriminant Variable can separate resonances with different spins.

Example: scalar diquarks *vs* vector resonances



Z' would not be confused with weak-singlet scalar diquarks.
Color-sextets would not be confused with one another.

Chivukula, P.I., Mohan, Simmons – arXiv:1507.06676

Summary

Color discriminant variable $D_{\rm col} \equiv \sigma_{jj} M^3/\Gamma$ by itself could determine spin and color structures of flavor universal resonance discoverable at $14\,\mathrm{TeV}$ LHC.

$D_{\rm col}$ separates flavor non-universal vector resonances:

- Required observables are not sensitive to chiral couplings.
- Method is not impacted by non-measurable light u, d couplings.
- Measurements of $t\bar{t}$ and $b\bar{b}$ cross sections help distinguish flavor non-universal resonances.

Thank you!

Supplementary Materials

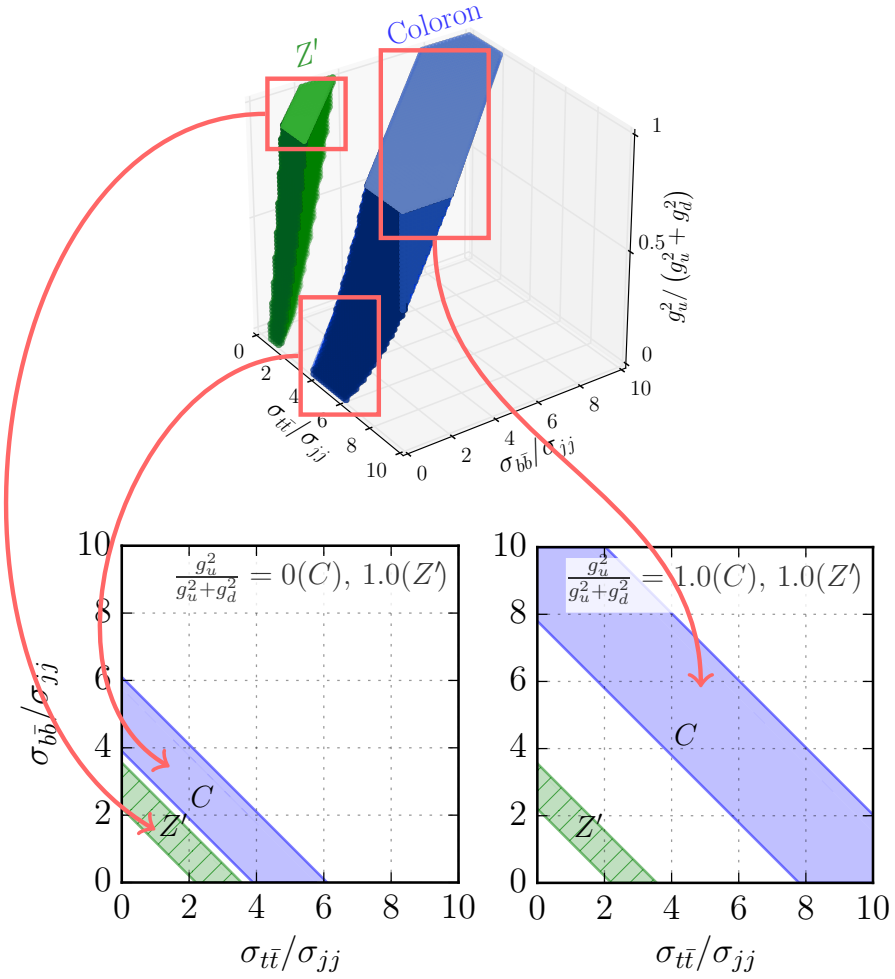
Parton Luminosity Function

$$\tau \frac{\partial \mathcal{L}^{ik}}{\partial \tau} = \tau \int_{\tau = M_V^2/s}^{1} \frac{dx}{x} \left[f_i\left(x, \mu_F^2\right) f_k\left(\frac{\tau}{x}, \mu_F^2\right) + f_k\left(x, \mu_F^2\right) f_i\left(\frac{\tau}{x}, \mu_F^2\right) \right]$$

$f_i\left(x, \mu_F^2\right)$ is the parton distribution function of parton $i = q, \bar{q}$
at the factorization scale μ_F^2.
We use $\mu_F^2 = M_V^2$.

Overlap?

Potentially overlapping scenario between Z' with much stronger "up-coupling" than C



Cross sections for resonance decaying to $t\bar{t}$ and $b\bar{b}$ play key role distinguishing C from Z'.

$M = 4\,\mathrm{TeV},\ D_{\mathrm{col}} = 0.003 \pm 0.0015$

Non-standard invisible decays?

$$D_{\rm col} \propto \left\{ \begin{array}{c} \overset{\text{Coloron}}{\downarrow} \\ 8 \\ 1 \\ \underset{\mathrm{Z}'}{\uparrow} \end{array} \right\} \times \left[\frac{g_u^2}{g_u^2+g_d^2} \left(W_{u\bar{u}} + W_{c\bar{c}}\right) + \left(1 - \frac{g_u^2}{g_u^2+g_d^2}\right)\left(W_{d\bar{d}} + W_{s\bar{s}}\right) + \frac{g_b^2}{g_u^2+g_d^2} W_{b\bar{b}} \right] \times \frac{2}{\left(2 + \frac{g_t^2}{g_u^2+g_d^2} + \frac{g_b^2}{g_u^2+g_d^2}\right)^2}$$

Non-standard invisible decays of Z' only make
$\rightarrow \Gamma_{\mathrm{Z}'}$ larger $\rightarrow$ smaller $D_{\rm col}^{\mathrm{Z}'}$
$\rightarrow$ easier to distinguish