Color Discriminant Variable to Separate Dijet Resonances at the LHC

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based on
arXiv:1507.06676
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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 with 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

$Z'$

Many models have one ...

→ Dileptons
Motivation: leptophobic color-singlet vs color-octet vectors

Models predicting dijet resonance

Color-octet vector boson

“Coloron”

Chiral color, Technicolor, Topcolor,
Extradimension, ...

? \uparrow

Dijets

Color-singlet vector boson

\( Z' \)

Many models have one ...

Without a discovery in the dilepton channel, is the new dijet resonance a \textit{color-octet} or a \textit{leptophobic color-singlet} vector boson?
Rates for narrow dijet resonances

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

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

Spin-color factor

$$= \frac{N_{SR}}{N_{Si}N_{Sk}} \frac{C_R}{C_iC_k}$$

For identical initial partons

$\Gamma(R \rightarrow ..) = \text{Partial width}$

$\Gamma_R = \text{Total width}$

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

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

Observables

$\propto \text{parton distribution function}$

$\tau = m_R^2/s$

Dijet branching fraction
**Color Discriminant Variable**  
\[ D_{\text{col}} \equiv \sigma_{jj} m_R^3 / \Gamma_R \]

\[ D_{\text{col}} \equiv \frac{m_R^3 \sigma_{jj}}{\Gamma_R} \]

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

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

*Observables,\ D_{\text{col}} \text{ is dimensionless}\]

*Color Discriminant Variable is independent of overall couplings: \ “model-independent”.*

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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 $C_C = 8$

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

Z' (Leptophobic)

- Color $C_{Z'} = 1$

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

$$D_{col}^C = 8D_{col}^{Z'}$$

A new resonance with mass $M$, dijet cross section $\sigma_{jj}$, and value of $D_{col}$ could correspond to either a broader $Z'$ or a narrower $C$. 
Viable parameter space at LHC14

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

Overall coupling

Too broad

Too narrow

$\Gamma \geq 0.15M$

$\Gamma \leq M_{\text{res}}$

No reach

Excluded

$\rho_u = 0.5 \rho_t + \rho_b = 1.0$

$g_u \equiv (g_{uL} + g_{uR}) = g_d \equiv (g_{dL} + g_{dR})$

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
Viable parameter space at LHC14

Same $D_{col}$ for all overall couplings

Too broad

Overall coupling

Too narrow

▲ Here $g_u^2 \equiv (g_{uL}^2 + g_{uR}^2) = g_d^2 \equiv (g_{dL}^2 + g_{dR}^2)$

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

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

Color Discriminant Variable Separates:

Flavor Universal Vector Bosons

**Flavor Non-universal Vector Bosons**

Scalar Diquarks vs Vector Bosons
Flavor Non-universal scenario

\[ D_{\text{col}} \equiv \frac{m_R^3 \sigma_{jj}}{\Gamma_R} \]

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

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
→ Assumption: Couplings to 2\textsuperscript{nd} generation same as 1\textsuperscript{st} generation

**Coloron**
\[
\begin{align*}
 g_{L}^{u,c} &= g_{L}^{d,s} & g_{R}^{u,c}, g_{R}^{d,s} \\
 g_{L}^{t} &= g_{L}^{b} & g_{R}^{t}, g_{R}^{b}
\end{align*}
\]

**Leptophobic Z’**
\[
\begin{align*}
 g_{L}^{u,c}, g_{L}^{d,s} & & g_{R}^{u,c}, g_{R}^{d,s} \\
 g_{L}^{t}, g_{L}^{b} & & g_{R}^{t}, g_{R}^{b}
\end{align*}
\]

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

\[
\begin{align*}
 g_{u}^{2} &= g_{c}^{2} \\
 g_{d}^{2} &= g_{s}^{2} \\
 g_{t}^{2} &= g_{b}^{2}
\end{align*}
\]

Useful to define “jets” = \{u, d, c, s\}
Color discriminant variable for flavor non-universal scenario

\[ D_{\text{col}} \propto \left\{ \begin{array}{c} 8 \\ 1 \\ \uparrow \text{Z'} \end{array} \right\} \times \sum_q W_{q\bar{q}} \times \text{BR}_{jj} \]

\[ \equiv \left[ \tau \frac{\partial L^{q\bar{q}}}{\partial \tau} \right]_{\tau=M^2_{Z'}/s} = \frac{4}{6} \]

\(\Box\) Flavor universal

\(\nabla\) Flavor non-universal

\[ D_{\text{col}} \propto \left\{ \begin{array}{c} 8 \\ 1 \\ \uparrow \text{Z'} \end{array} \right\} \times \left[ \begin{array}{c} \frac{g^2_u}{g^2_u+g^2_d} (W_{u\bar{u}} + W_{c\bar{c}}) + \left(1 - \frac{g^2_u}{g^2_u+g^2_d} \right) (W_{d\bar{d}} + W_{s\bar{s}}) \\ \left. + \frac{g^2_b}{g^2_u+g^2_d} W_{s\bar{s}} \right] \times \frac{2}{\left(2 + \frac{g^2_t}{g^2_u+g^2_d} + \frac{g^2_b}{g^2_u+g^2_d} \right)^2} \right] \]

Can this cause significant deviation from the factor 8?
$D_{\text{col}}$ not sensitive to bottom quark production

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

Contributions from bottom quark production are generally highly suppressed.
Non-measurable light quark couplings not deter separation

\[ D_{\text{col}} \propto \left\{ \begin{array}{c} 8 \\ 1 \\ Z' \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}}) \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}

\text{unmeasurable, but causes overlap only at high masses}

\text{suppressed}

The worst-case scenario

\[ D_{\text{col}}^C \propto 8 \left[ \cdots \right] \xrightarrow{g_u^2 = 0} 8 [W_{d\bar{d}} + W_{s\bar{s}}] \]

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

causes overlap only at large masses,

where \[ \frac{[W_{d\bar{d}} + W_{s\bar{s}}]}{[W_{u\bar{u}} + W_{c\bar{c}}]} \lesssim \frac{1}{8} \]
Need to measure heavy flavor final states to determine $D_{\text{col}}$

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

unmeasurable, but causes overlap only at high masses

suppressed

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

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

$$\frac{g_t^2}{g_u^2 + g_d^2} = 2 \frac{\sigma_{t\bar{t}}}{\sigma_{jj}}$$
After discovering a dijet resonance at 14 TeV LHC...

Models for a 3 TeV resonance with fixed $\sigma_{jj}$ (±30%) and $D_{col}$ (±50%):

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

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

Different $u$ & $d$ couplings?

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

Unmeasurable $u/d$ couplings generally do not deter separating “light” resonances.
How well must we measure $D_{\text{col}}$ and heavy decays?

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

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

$LHC \sqrt{s} = 14 \text{ TeV}, L = 1000 \text{ fb}^{-1}, M = 4.0 \text{ TeV}, \sigma_{jj} = 0.0073 \pm 0.0026 \text{ pb}$
Plan

Color Discriminant Variable Separates:

Flavor Universal Vector Bosons

Flavor Non-universal Vector Bosons

Scalar Diquarks vs Vector Bosons
**Separating scalar resonances**

\[ D_{\text{col}} \equiv \frac{m_R^3 \sigma_{jj}}{\Gamma_R} \]

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

**Spin-color factor**

\[ = \frac{N_{SR}}{N_{Si} N_{S_k}} \frac{C_R}{C_i C_k} \]

Color Discriminant Variable can separate resonances with different spins.
Example: scalar diquarks vs vector resonances

\[ \Phi_6 \equiv u_R u_R \]
\[ \Delta_6 \equiv u_R d_R \]
\[ \omega_3 \equiv u_L d_L \]
\[ \phi_6 \equiv d_R d_R \]
\[ \delta_6 \equiv u_L s_L - c_L d_L \]

\( Z' \) 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 $D_{\text{col}} \equiv \sigma_{jj} M^3 / \Gamma$ by itself could determine spin and color structures of flavor universal resonance discoverable at 14 TeV LHC.

$D_{\text{col}}$ 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

\[ \tau \frac{\partial L_{ik}}{\partial \tau} = \tau \int_{\tau=M^2_V/s}^{1} \frac{dx}{x} \left[ f_i(x, \mu^2_F) f_k \left( \frac{\tau}{x}, \mu^2_F \right) + f_k(x, \mu^2_F) f_i \left( \frac{\tau}{x}, \mu^2_F \right) \right] \]

\( f_i(x, \mu^2_F) \) is the parton distribution function of parton \( i = q, \bar{q} \) at the factorization scale \( \mu^2_F \).

We use \( \mu^2_F = M^2_V \).
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 $Z'$.

$M = 4\text{ TeV}, \quad D_{\text{col}} = 0.003 \pm 0.0015$
Non-standard invisible decays?

\[
D_{\text{col}} \propto \left\{ \frac{g_u^2}{g_u^2 + g_d^2} (W_u \bar{u} + W_c \bar{c}) + \left( 1 - \frac{g_u^2}{g_u^2 + g_d^2} \right) (W_d \bar{d} + W_s \bar{s}) \right\} \times \frac{2}{\left( 2 + \frac{g_t^2}{g_u^2 + g_d^2} + \frac{g_b^2}{g_u^2 + g_d^2} \right)^2}
\]

Coloron
\[
\begin{array}{c}
\downarrow \\
8 \\
1 \\
\uparrow
\end{array}
\]

Non-standard invisible decays of \( Z' \)
only make
\[ \Gamma_{Z'} \] larger \( \rightarrow \) smaller \( D_{\text{col}}^{Z'} \)
\[ \rightarrow \] easier to distinguish