Colored Resonances at the Tevatron: Phenomenology and Discovery

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work done with Takemichi Okui and Raman Sundrum
Outline

• Introduction: Why colorons are interesting
• A minimal model:
  – Description: qualitative
  – Phenomenology: quantitative
• Constraints
• Looking for a colorful needle in a haystack
• Outlook and Conclusions
INTRODUCTION
THE AGE OF COLOR

• The 90’s and 00’s:
The Tevatron Age
  – Run I: $E_{CM}=1.8$ TeV
  – Run II: $E_{CM}=1.96$ TeV
• The 10’s (and 20’s?):
The LHC Age: $E_{CM}=14$ TeV
• Our greatest strength is the production of new colored states.
• Our greatest weakness is the production of old colored states.
• Discovery strategy for most BSM models lie in distinctive signatures:
  – leptons
  – heavy flavors
  – missing energy
INTRODUCTION
WHAT DREAMS MAY COME (TRUE)

Solutions to the hierarchy problem:

- New states carry EW quantum numbers
- Highly constrained by precision data
- Must be heavy, small cross section (usually $2 \rightarrow 2$). Background reasonable
- Many search strategies devised

Incidentals: (“Who ordered this?”)

- New states can be EW singlets
- Then color is our best (only) bet
- Need large signal to beat large background ($2 \rightarrow 1$ ideal)
- Search strategies based on kinematic signatures
INTRODUCTION
A BRIEF HISTORY OF COLORONS

<table>
<thead>
<tr>
<th>KK Gluons</th>
<th>TeV Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_c$</td>
<td>$V_8$ non-minimal TC</td>
</tr>
</tbody>
</table>

Topcolor
INTRODUCTION
A MORE GENERAL MOTIVATION

- This should be familiar from $e^+e^- \rightarrow \rho$
- Also known as $\gamma/\rho$ mixing
- *Resonant* production, large cross section
INTRODUCTION
DIFFICULTIES

• Colorons proposed before in order to explain high-$p_T$ excess.
• Coming from $q\bar{q}$ the coloron can decay back to dijets.
• O(1) BF into dijets has been excluded in the sub-TeV regime.
• O(1) coupling to $t\bar{t}$ excluded by top production measurements.
• $\tilde{\rho} \to \tilde{\pi}\tilde{\pi}$ is allowed.
• The coloron is a generic object that can arise in many BSM scenarios, motivated or incidental.
• One should keep an open mind in devising search strategies.
• A light coloron can be consistent with existing bounds if it carries no EW charge and is flavor blind.
• It can be detected at the Tevatron in multijets.
• The LHC will have lessened sensitivity to such a state.
A MINIMAL MODEL
QUALITATIVE DESCRIPTION

\[ \mathcal{L} = \mathcal{L}_{SM} + \bar{\psi} (i \slashed{D} - m) \psi - \frac{1}{4} H_{\mu\nu} H^{\mu\nu} \]

Ingredients:
• New colored fermions (EW singlets)
• Confining gauge interactions (“Hypercolor”)

Consequences:
• QCD gauges unbroken flavor symmetry
• For \( G_{HC} = SU(3) \) with massless hyperquarks, we can use QCD as an analog computer.
• Renormalizable, possible separation of scales from EWB or flavor physics
## A DICTIONARY

<table>
<thead>
<tr>
<th></th>
<th>QCD</th>
<th>HYPERCOLOR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gauge</strong></td>
<td>SU(3)$_c$</td>
<td>SU(3)$_{HC}$</td>
</tr>
<tr>
<td><strong>Flavor</strong></td>
<td>SU(3): broken by quark masses, U(1) gauged</td>
<td>SU(3)$_c$ No quark masses All gauged</td>
</tr>
<tr>
<td><strong>Scale</strong></td>
<td>1 GeV</td>
<td>~500 GeV</td>
</tr>
<tr>
<td><strong>Goldstones</strong></td>
<td><img src="image1" alt="Goldstones" /></td>
<td>$\tilde{\pi}$</td>
</tr>
<tr>
<td><strong>Vectors</strong></td>
<td><img src="image2" alt="Vectors" /></td>
<td>$\tilde{\rho}$</td>
</tr>
<tr>
<td></td>
<td>QCD</td>
<td>HYPERCOLOR</td>
</tr>
<tr>
<td>-------------------------</td>
<td>----------------------------------------------------------------------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td><strong>Kinetic</strong></td>
<td>( \bar{e} i \slashed{D} e - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} )</td>
<td>( \bar{q} i \slashed{D} q - \frac{1}{4} G_{\mu\nu}^{a} G^{a\mu\nu} )</td>
</tr>
<tr>
<td><strong>Mixing/Production</strong></td>
<td>( -\frac{1}{4} \rho_{\mu\nu} \rho^\mu + \frac{m_\rho^2}{2} \rho_\mu \rho^\mu + \frac{\varepsilon}{2} \rho_{\mu\nu} F^{\mu\nu} )</td>
<td>( -\frac{1}{4} \tilde{\rho}<em>\mu \tilde{\rho}<em>a^{a\mu} + \frac{m</em>\rho^2}{2} \tilde{\rho}</em>\mu \tilde{\rho}<em>a^{a\mu} + \frac{\tilde{\varepsilon}}{2} \tilde{\rho}</em>\mu G^{a\mu\nu} )</td>
</tr>
<tr>
<td><strong>Strong sector Decay</strong></td>
<td>( -i g_{\rho \pi \pi} \rho^\mu (\pi^- \rightarrow D_\mu \pi^+) )</td>
<td>( -g \tilde{\rho} \tilde{\pi} \tilde{\pi} f^{abc} \tilde{\rho}<em>\mu \tilde{\pi}^b \partial</em>\mu \tilde{\pi}^c )</td>
</tr>
<tr>
<td><strong>Goldstones Decay</strong></td>
<td>( -\frac{e^2 \varepsilon_{\mu\nu\rho\sigma}}{32\pi^2 f_\pi} \pi^0 F_{\mu\nu} F_{\rho\sigma} )</td>
<td>( -\frac{3g_3^2 \varepsilon_{\mu\nu\rho\sigma}}{16\pi^2 f_\tilde{\pi}} \text{tr} [\tilde{\pi} G_{\mu\nu} G_{\rho\sigma}] )</td>
</tr>
</tbody>
</table>
### MOVING ON UP - I

<table>
<thead>
<tr>
<th>QCD</th>
<th>HYPERCOLOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Lambda_{\text{QCD}} \sim m_\rho )</td>
<td>( \Lambda_{\text{HC}} \sim m_{\tilde{\rho}} )</td>
</tr>
<tr>
<td>( f_\pi \simeq 92 \text{ MeV} )</td>
<td>( f_{\tilde{\pi}} \simeq 92 \text{ GeV} \frac{m_{\tilde{\rho}}}{10^3 m_\rho} )</td>
</tr>
<tr>
<td>( g_{\rho \pi \pi} \simeq 6 ) ((\Gamma_{\rho \rightarrow \pi \pi} = 149 \text{ MeV}))</td>
<td>( g_{\tilde{\rho} \tilde{\pi} \tilde{\pi}} = g_{\rho \pi \pi} ) (( f^{abc} \rho^a_\mu \pi^b \partial^\mu \pi^c = i\rho^\mu (\pi^- \overleftarrow{\partial}_\mu \pi^+) + \cdots ))</td>
</tr>
</tbody>
</table>

Determines \( \Gamma_{\tilde{\rho} \rightarrow \tilde{\pi} \tilde{\pi}} \)
<table>
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</thead>
<tbody>
<tr>
<td>$-e\varepsilon \rho_{\mu} \bar{e} \gamma^{\mu} e$</td>
<td>$-g_3 \tilde{\varepsilon} \tilde{\rho}_{\mu}^{\alpha} \bar{q} \gamma^{\mu} T^{a} q$</td>
</tr>
<tr>
<td>$\varepsilon \approx 0.06$</td>
<td>$\tilde{\varepsilon} = \frac{g_3}{e} \varepsilon \approx 0.2$</td>
</tr>
<tr>
<td>$(\Gamma_{\rho \rightarrow e^+e^-} = 7.04\ \text{keV})$</td>
<td>$\sigma_{\text{prod}} \text{ fixed}$</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_{\tilde{\rho} \rightarrow q\bar{q}}/\Gamma_{\tilde{\rho} \rightarrow \pi\bar{\pi}} \text{ fixed by}$</td>
</tr>
<tr>
<td></td>
<td>$\tilde{\varepsilon}/g_{\tilde{\rho}\pi\bar{\pi}}$</td>
</tr>
</tbody>
</table>
### MOVING ON UP - III

<table>
<thead>
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<th>HYPERCOLOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c m_\rho^2 f_\pi^2 \text{Tr} \left[ \Sigma^\dagger Q \Sigma Q \right]$ $\rightarrow$ $m_{\pi^\pm}^2 - m_{\pi^0}^2$</td>
<td>$c m_\rho^2 f_\pi^2 \sum_a \text{Tr} \left[ \tilde{\Sigma}^\dagger T^a \tilde{\Sigma} T^a \right]$ $\rightarrow$</td>
</tr>
<tr>
<td>$m_{\pi^\pm}^2 = \frac{3 g_3^2}{e^2} m_{\pi^0}^2$</td>
<td>$m_{\tilde{\pi}} \approx 0.3 m_{\tilde{\rho}}$</td>
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$$m_{\pi^\pm} - m_{\pi^0}$$

$$m_{\pi^\pm} = \frac{3 g_3^2}{e^2} m_{\pi^0}$$

$$m_{\tilde{\pi}} \approx 0.3 m_{\tilde{\rho}}$$
Coloron Decay

![Graph showing branching fraction vs. m_ρ (GeV) with lines for ππ, qq (per flavor), and tt. The graph plots branching fraction on the y-axis and m_ρ (GeV) on the x-axis.]
Constraints on $\tilde{\rho}$

- Dijet resonance searches
- $t\bar{t}$ production
- Multi-jet studies
  - Run I (105 pb$^{-1}$)
  - Severe cuts
- Global searches
Constraints on $\tilde{\pi}$

- $gg \rightarrow \tilde{\pi}$ is loop suppressed
  - $S p \bar{p} S$:
    $\sigma(p \bar{p} \rightarrow \tilde{\pi}) \approx 21\, \text{pb}$
    for $m_{\tilde{\pi}} = 100\, \text{GeV}$
  - Tevatron Run I:
    $\sigma(p \bar{p} \rightarrow \tilde{\pi}) \approx 4.8\, \text{pb}$
    for $m_{\tilde{\pi}} = 250\, \text{GeV}$

- Pair production
- How light?
Other Sources of Constraints

- LEP direct searches
- Precision Electroweak $\frac{m_{\tilde{\rho}}}{\tilde{\xi}} \geq 450$ GeV
- FCNC
- Compositeness
- Other states: Lightest Hyper-Baryon
  Stable if $U(1)_{HB}$ is exact
  Same quantum numbers as a gluino
  Straightforward to break $U(1)_{HB}$
Search Strategy

- **Signal** \( \tilde{\rho} \rightarrow \tilde{\pi} \tilde{\pi} \rightarrow gggg \)
- **Background:** QCD 4j
- **Effect of PDF’s**
- **Margin of error**
- **Two benchmarks:**
  
  \[ m_{\tilde{\rho}} = 350 \text{ GeV} \quad \text{and} \quad m_{\tilde{\pi}} = 100 \text{ GeV} \]
  
  \[ m_{\tilde{\rho}} = 600 \text{ GeV} \quad \text{and} \quad m_{\tilde{\pi}} = 180 \text{ GeV} \]

- **Emulate triggers**
  
  leading jet \( p_T \gtrsim 120 \text{GeV} \)
Case I : Lighter Coloron

• Event generation:
  parton level: MadEvent
  shower/hadronization: Pythia
  detector simulation: PGS
  cone jets: $\Delta R=0.7$

• Use different $p_T$ hierarchy in signal vs. background
  Cut: Four jets with $p_T \geq 40\text{GeV}$

• Signal: 1fb$^{-1}$, 3.6 pb after cuts
  Background: 2fb$^{-1}$, 66 pb after cuts

• Pairing:
  signal: 2.7 pb after cuts
  background: 21 pb after cuts

• Significance estimate
  \[ \chi^2 = \sum_{bins} \left( \frac{n_s}{\sqrt{n_b}} \right)^2 \]
The Result:
Significance of Excess is 32.3σ
Model Independent Search

- Without pairing: Sensitive to alternative models but smaller significance
- Signal in the lower bins $\frac{S}{\sqrt{B}}$ is 13.4σ (8.3σ for bins above 400 GeV)
- Caveats: Cannot impose harder cuts without losing signal
Case II: Heavier Coloron

- Light coloron discoverable despite low trigger efficiency, larger background
- Now we can impose harder cuts (4 jets with $p_T \geq 90\text{GeV}$)
- Signal: 1fb$^{-1}$, 0.36 pb  
  Background: 2fb$^{-1}$, 0.99 pb  
  (after cuts)
- Pairing:
  signal: 0.27 pb  
  background: 0.38 pb
- Significance: 17.2$\sigma$
- 10.8$\sigma$ for less model-dependent search, excess shape is more reliable than before.
OUTLOOK AND CONCLUSIONS

• Colorons are generic physics objects appearing in various contexts.
• Model with QCD analog experimentally allowed for masses as light as few hundred GeV.
• Search strategy in multijet channel at the Tevatron looks promising for a range of parameters.
• Prospects for the LHC:
  – pp machine: PDF’s for signal vs. background
  – higher luminosity and trigger thresholds
  – other states in the model
• Variations of the model:
  – direct couplings to quarks
  – less minimal flavor structure
  – LHC regime: better prospects than minimal model
  – additional states: heavy colored fermions
BACKUP SLIDES
SEEKING ADRONIC RESONANCES IN MULTIJET PEAKS
Search Plot Without Coloring
Heavier Coloron

\[ \langle m_{2j} \rangle \text{ (GeV)} \]

\[ m_{4j} \text{ (GeV)} \]