Searching for Colorons at the LHC

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Based on work with C. Kao

Colorons?

coloron[kuhl-er-ahn] n. Generically, a massive color-octet spin-1 boson.
May arise in, e.g.,

- Topcolor models.[C.T. Hill, 1991]
- Kaluza-Klein gluons in extra-dimensional models.
- Non-minimal Technicolor.[Farhi and Sussking, 1979]
- String excitations of gluons in TeV Gravity.[Cullen, Perelstein and Peskin, 2000]

Minimally, colorons may arise as a result of new strong dynamics. We treat as an object of generally interest, like a Z'.
We follow the analysis of Kilic, Okui, Sundrum(2008) and Kilic, Schumann and Son(2008).

Basic Analysis

We imagine that there exists a new strong force, hypercolor, which becomes confining at a relatively high scale.
Colorons emerge as bound states of hypercolor-charged hyper-quarks that also carry $SU(3)_C$ charge.
Under $SU(N)_{HC} \times SU(3)_C \times SU(2) \times U(1)$:

$$\Psi(N,3,1,0)\Psi(\overline{N},\overline{3},1,0) \rightarrow \Phi(1,8,1,0)$$

More generally, we might have non-trivial electroweak charges. For now consider the neutral case to avoid electroweak constraints.

Naively, this case is strongly constrained by dijet resonances.

$$q\overline{q}(gg) \rightarrow \Phi \rightarrow q\overline{q}$$

However, this need not be the case.

Analogy to SM Mesons

Our toy model is closely analogous to the SM mesons.

$$e^+e^- \rightarrow \gamma \rightarrow \rho \rightarrow \pi\pi$$

ρ, our coloron analogue, decays primarily to $\pi\pi$, **not** to e^+e^-.
In SM:
$SU(3)_C$ condensate breaks chiral $SU(3)_L \times SU(3)_R \times U(1)_L \times U(1)_R$ to flavor $SU(3)_F \times U(1)$.
We expect 9 Goldstone bosons in flavor $(\mathbf{1}+\mathbf{8})$.
However, $SU(3)_F$ singlet (η') has non-vanishing anomaly with 2 gluons so not an exact broken symmetry.
Moreover, electroweak breaking gives non-zero quark masses/ non-exact flavor symmetries.

- Light but not massless π's.
- Substantially heavier K's and η's due to strange quark mass.

We also see a heavier spin-1 flavor octet: ρ's,etc.

Hypercolor Comparison

SM	Hypercolor
$SU(3)_C$	$SU(N)_{HC}$
$SU(3)_L \times SU(3)_R$	$SU(3)_C \times SU(3)_{L+R}$
q	$\tilde{q}$
π, η, K	$\tilde{\pi}$
ρ, ω, K^*, ϕ	$\tilde{\rho}$
e^-,γ	q,g

Note, $SU(3)_C$ is **gauged** and **exact**, unlike flavor. Therefore $\tilde{\rho}$ and $\tilde{\pi}$ are color octets of equal mass.

Color singlet will have an anomaly giving it a higher mass.
$\tilde{\rho}$s (colorons) and $\tilde{\pi}$s are lightest new states which may be accessible to searches.

Lagrangians

$$\begin{aligned}\mathscr{L}_{QED} = {} & \bar{e} i \not{D} e - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4}\rho_{\mu\nu}\rho^{\mu\nu} + \frac{m_\rho^2}{2}\rho_\mu \rho^\mu + \frac{\varepsilon}{2}\rho_{\mu\nu} F^{\mu\nu} \\ & + \frac{1}{2}\partial_\mu \pi^0 \partial^\mu \pi^0 - m_{\pi^0}^2 \pi^0 \pi^0 + D_\mu \pi^- D^\mu \pi^+ - m_{\pi^\pm}^2 \pi^- \pi^+ \\ & - i * g_{\rho\pi\pi} \rho^\mu (\pi^- D_\mu \pi^+) - \frac{e^2 \epsilon^{\mu\nu\rho\sigma}}{32\pi^2 f_\pi} \pi^0 F_{\mu\nu} F_{\rho\sigma}.\end{aligned}$$

Effective constants f_π,ϵ, and $g_{\rho\pi\pi}$ determined from experiment.
Compare:

$$\begin{aligned}\mathscr{L}_{QCD} = {} & \bar{q} i \not{D} q - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} - \frac{1}{4}\tilde{\rho}^a_{\mu\nu}\tilde{\rho}^{a\mu\nu} + \frac{m_{\tilde{\rho}^2}}{2}\tilde{\rho}^a_\mu \tilde{\rho}^{a\mu} + \frac{\varepsilon}{2}\tilde{\rho}^a_{\mu\nu} G^{a\mu\nu} \\ & + \frac{1}{2}(D_\mu \tilde{\pi})^a (D^\mu \tilde{\pi})^a - m_{\tilde{\pi}}^2 \tilde{\pi}^a \tilde{\pi}^a \\ & - i * \tilde{g}_{\rho\pi\pi} f^{abc} \tilde{\rho}^{a\mu} (\tilde{\pi}^b D_\mu \tilde{\pi}^c) - \frac{3 g_3^2 \epsilon^{\mu\nu\rho\sigma}}{16\pi^2 f_{\tilde{\pi}}} tr[\tilde{\pi} G_{\mu\nu} G_{\rho\sigma}].\end{aligned}$$

Working Model

We rotate fields to eliminate $\tilde{\rho} - g$ mixing and add two terms without direct analogues.

$$\mathscr{L}'_{QCD} = \overline{q} i \not{D} q - \frac{1}{4} G^{a}_{\mu\nu} G^{a\mu\nu} - \frac{1}{4} \tilde{\rho}^{a}_{\mu\nu} \tilde{\rho}^{a\mu\nu} + \frac{m_{\tilde{\rho}^2}}{2} \tilde{\rho}^{a}_{\mu} \tilde{\rho}^{a\mu} - g_3 * \varepsilon \tilde{\rho}^{a}_{\mu} \overline{q} \gamma^{\mu} T^{a} q$$

$$+ \frac{1}{2} (D_{\mu} \tilde{\pi})^{a} (D^{\mu} \tilde{\pi})^{a} - m^{2}_{\tilde{\pi}} \tilde{\pi}^{a} \tilde{\pi}^{a} - i * \tilde{g}_{\rho\pi\pi} f^{abc} \tilde{\rho}^{a\mu} (\tilde{\pi}^{b} D_{\mu} \tilde{\pi}^{c})$$

$$- \frac{3 g_3^2 \epsilon^{\mu\nu\rho\sigma}}{16 \pi^2 f_{\tilde{\pi}}} tr[\tilde{\pi} G_{\mu\nu} G_{\rho\sigma}] + i \chi g_3 tr[G_{\mu\nu} [\tilde{\rho}^{\mu}, \tilde{\rho}^{\nu}]] + \xi \frac{2 i \alpha_3 \sqrt{N}}{m^2_{\tilde{\rho}}} tr[\rho^{\mu}_{\nu} [G^{\nu}_{\sigma}, G^{\sigma}{}_{\mu}]].$$

For simplicity we choose $N = 3$. Then effective model parameters can be determined by comparison with QED model.

- $\varepsilon \simeq 0.2$
- $\tilde{g}_{\rho\pi\pi} \simeq 6$
- $m_{\tilde{\pi}} \simeq 0.3 m_{\tilde{\rho}}$
- $f_{\tilde{\pi}} \simeq f_{\pi} * \frac{m_{\tilde{\rho}}}{m_{\rho}}$

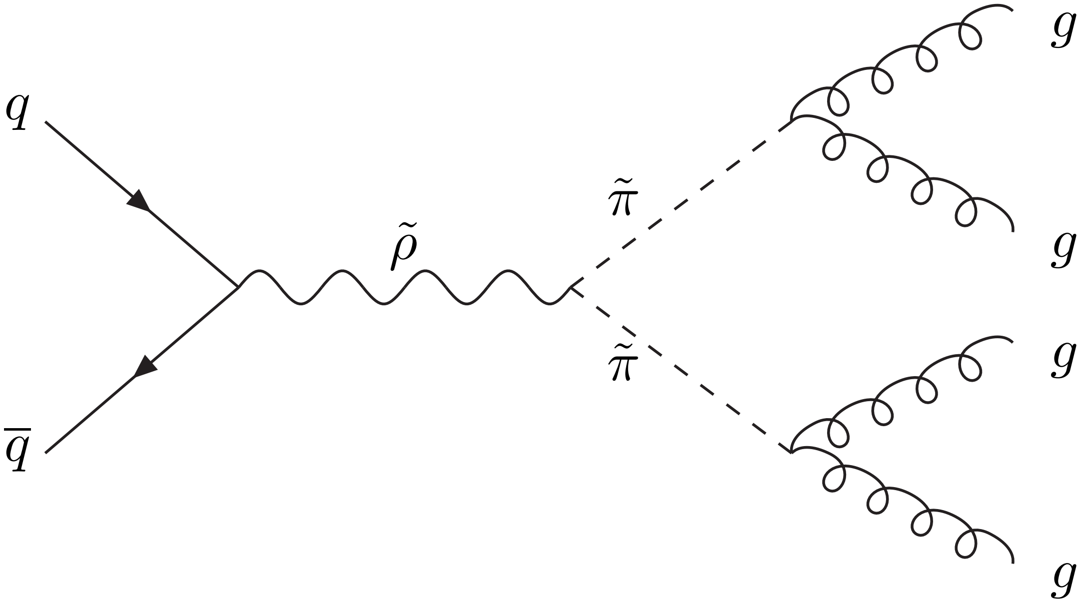
$m_{\tilde{\rho}}$ is the only free parameter.

Search Strategy

Model is bounded by dijet constraints from Tevatron data:

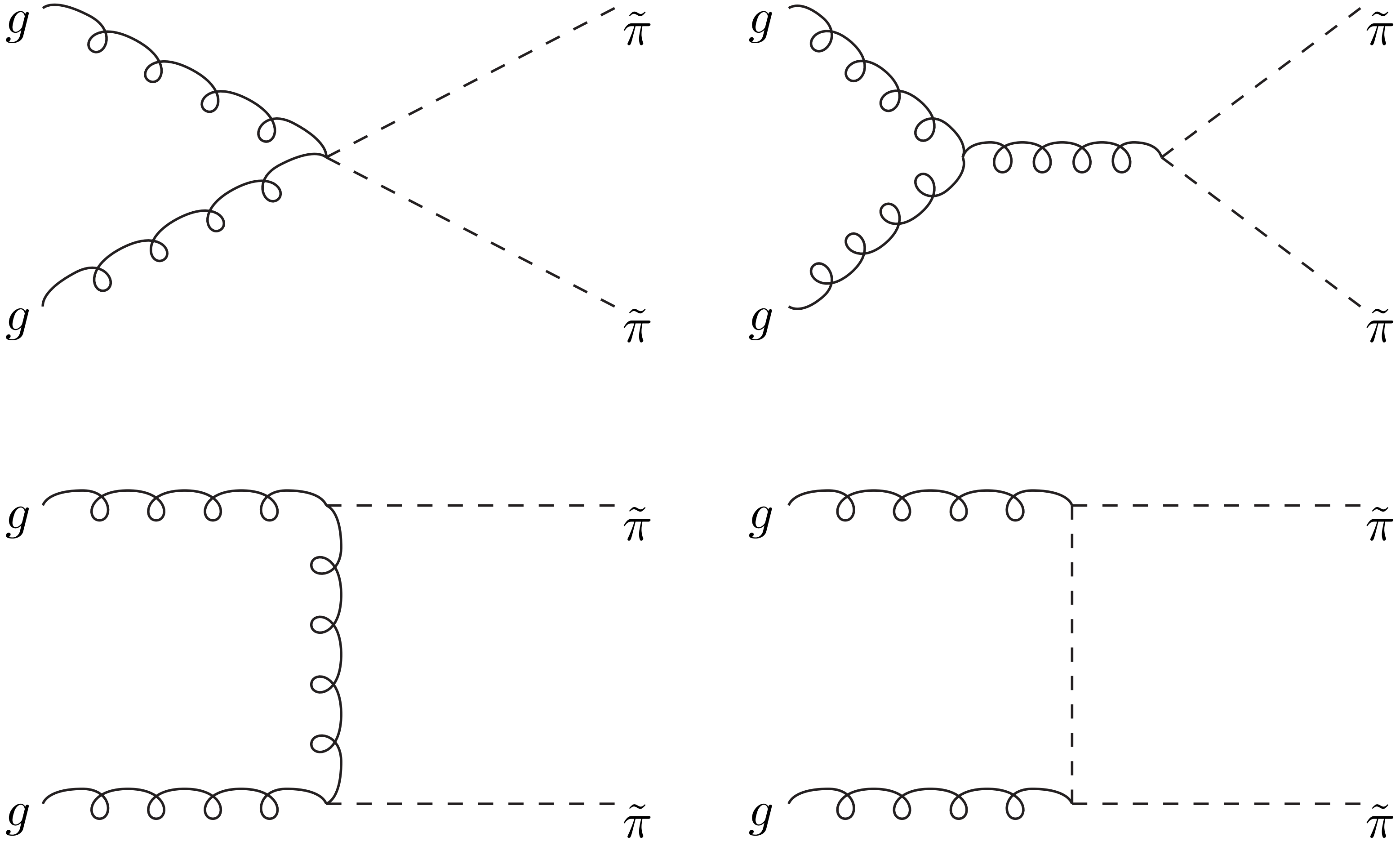
$$q\overline{q} \rightarrow \tilde{\rho} \rightarrow q\overline{q} \quad gg \rightarrow \tilde{\pi} \rightarrow gg$$

However, low branching fraction for $\tilde{\rho} \rightarrow q\overline{q}$ and small coupling for $\tilde{\pi} \rightarrow gg$ avoid bounds.
Leading signal is instead $pp \rightarrow \tilde{\rho} \rightarrow \tilde{\pi}\tilde{\pi} \rightarrow 4g$.



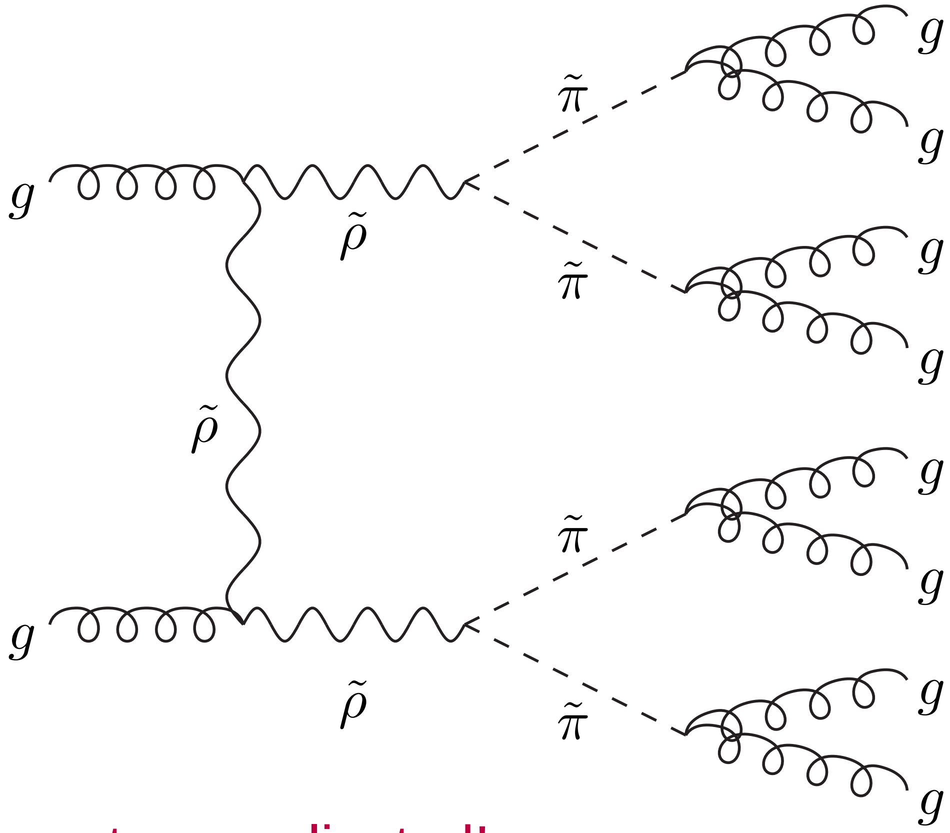
At the LHC

$\tilde{\pi}$ resonances can be easily constructed. However, as gluons become important the s-channel $\tilde{\rho}$ is obscured.



Eight-Gluon Channel

To discover primary coloron resonances, we may need to go to pair production:



Obviously this gets complicated!

Implementation

To calculate signal matrix elements, we implement the model in MadGraph/MadEvent.[Alwall, Demin, Visscher, Frederix, Herquet, Maltoni, Plehn, Rainwater and Stelzer; 2007]
This is non-trivial!(It turns out.) Must modify MG/ME to include:

- Non-SM like vertices and color structures, e.g.: $\tilde{\pi} gg \propto tr[T^a\{T^b, T^c\}]\epsilon^{\mu\nu\rho\sigma} p_{2\rho} p_{1\sigma}$.
- 8-gluon signal requires several tricks to handle large color and symmetry factors.

Parton-level results are fed to Pythia 6.4 and PGS 4 before final analysis.

8-jet background cannot be done with MadGraph. Use COMIX ME generator in Sherpa platform. [Gleisberg, Höche, Krauss, Schälicke, Schumann and Winter; 2004]
-Color-flow dressed Berends-Giele recursive relations are efficient for large multiplicities.

Analysis

We take
Four-jet case:

- For 4 leading jets, $p_T > 150$ GeV.
- $\Delta R > 0.5$.
- $\eta < 2.0$.
- At least one pair of dijet invariant masses within 50 GeV of each other.

Eight-jet case:

- Background not passed through Pythia-PGS.
- Large uncertainties → require no detailed kinetic information.
- p_T's for ordered jets: $> 320; 250; 200; 160; 125; 90; 60; 40$ GeV.

Results

Preliminary

Channel	Signal(pb)	Background(pb)	Significance(1 fb^{-1})
4-jet	2.0	41	9.8
8-jet	~ 0.4	~ 1	~ 10

- Comparable to Hopkins results.
- We currently find slightly lower signal and higher backgrounds in 4-jet case.
- Our calculation for the 8-jet signal is significantly lower.

Future Work and Conclusions

- Colorons can be viewed as a general object of interest in BSM physics.
- A simple model based on analogy with low-energy mesons shows interesting phenomenology.
- Present bounds allow for relatively light exotic particles which may be discoverable at Tevatron or LHC.

To Do:

- Analysis of 8-jet signal can extract $\tilde{\rho}$ resonance.
- Study effects of different cuts/scales.
- Compare results for generalized models.
- Consider other discovery channels.