Colored Resonant Signals at the LHC: Largest Rate and Simplest Topology

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TeV Scale New Physics at the LHC

- Much attention has been focused on electroweak physics: EWSB? Higgs? but LHC is a QCD machine: Most initial states consist of colored particles
- New physics discoveries: Focus on largest rate and simplest event topology.
- Simplest Topology:
  - 2 to 2 processes through resonant production: $pp \to X \to \ell\ell, qq, \ldots$
- Largest rate:
  - Strong interactions: $g_s^2 = 4\pi\alpha_s \sim 1$, $\lambda \sim 1$
  - Large parton luminosity: u, d, g
- Colored resonances are expected to couple strongly to SM partons and contribute to dijet events.

Classification of Colored Resonances

Quantum numbers of initial states $(SU_3, SU_2)^J_{Q_e}$
Most prominent initial states are valence quarks and gluons

$$
\begin{array}{lll}
Q & (\mathbf{3},\mathbf{2})^{1/2}_{2/3,-1/3} & \mathrm{Left-handed\ doublet} \\
U & (\mathbf{3},\mathbf{1})^{1/2}_{2/3} & \mathrm{Right-handed\ singlet} \\
D & (\mathbf{3},\mathbf{1})^{1/2}_{-1/3} & \mathrm{Right-handed\ singlet} \\
A & (\mathbf{8},\mathbf{1})^{1}_{0} & \mathrm{vector}.
\end{array}
$$

Classify interactions according to SU_3:

- Quark-quark interactions: $\mathbf{3}\otimes\mathbf{3}$
- Quark-gluon interactions: $\mathbf{3}\otimes\mathbf{8}$
- Gluon-Gluon interactions: $\mathbf{8}\otimes\mathbf{8}$
- Quark-antiquark interactions: $\mathbf{3}\otimes\bar{\mathbf{3}}$

Quark-Quark

initial state	J	$SU_C(3)$
QQ	0	$\overline{\mathbf{3}} \oplus \mathbf{6}$
QU	1	$\overline{\mathbf{3}} \oplus \mathbf{6}$
QD	1	$\overline{\mathbf{3}} \oplus \mathbf{6}$
UU	0	$\overline{\mathbf{3}} \oplus \mathbf{6}$
DD	0	$\overline{\mathbf{3}} \oplus \mathbf{6}$
UD	0	$\overline{\mathbf{3}} \oplus \mathbf{6}$

Two quarks can couple to color sextet and triplet scalars or vectors
Interested in physical states, i.e., color representation, electric charge, and spin
After electroweak symmetry breaking:

- 3 scalar and 3 vector physical states
- $E_{N_D}, U_{N_D}, D_{N_D}$ with charges $-4/3,\ 2/3,\ -1/3$

$$\begin{aligned}\mathcal{L}_{qqD} = \; & K^j_{ab}\Big[\lambda^E_{\alpha\beta}E^j_{N_D}\,\overline{u^C_{\alpha a}}P_\tau u_{\beta b} + \lambda^U_{\alpha\beta}U^j_{N_D}\,\overline{d^C_{\alpha a}}P_\tau d_{\beta b} + \lambda^D_{\alpha\beta}D^j_{N_D}\,\overline{d^C_{\alpha b}}P_\tau u_{\alpha a} \\ & + \lambda^{E'}_{\alpha\beta}E^{j\mu}_{N_D}\,\overline{u^C_{\alpha a}}\gamma_\mu P_R u_{\beta b} + \lambda^{U'}_{\alpha\beta}U^{j\mu}_{N_D}\,\overline{d^C_{\alpha a}}\gamma_\mu P_R d_{\beta b} \\ & + \lambda^{D'}_{\alpha\beta}D^{j\mu}_{N_D}\,\overline{u^C_{\alpha a}}\gamma_\mu P_\tau d_{\beta b}\Big] + \text{h.c.}\end{aligned}$$

Quark-Gluon

initial state	J	$SU_C(3)$
QA	$\frac{1}{2},\ \frac{3}{2}$	$\mathbf{3}\oplus\bar{\mathbf{6}}\oplus\mathbf{15}$
UA	$\frac{1}{2},\ \frac{3}{2}$	$\mathbf{3}\oplus\bar{\mathbf{6}}\oplus\mathbf{15}$
DA	$\frac{1}{2},\ \frac{3}{2}$	$\mathbf{3}\oplus\bar{\mathbf{6}}\oplus\mathbf{15}$

Quark-gluon annihilation can result in exotic fermions.
Focus on spin $\frac{1}{2}$ and lower dimensional color representations.
Physical states denoted as:

$$u^*_{N_D} \qquad Q_e = 2/3$$

$$d^*_{N_D} \qquad Q_e = -1/3$$

N_D denotes dimension of the color representation 3 or 6

$$\mathcal{L}_{qgF} = \frac{g_s}{\Lambda} F^{A,\mu\nu} \left[\bar{u}\bar{K}_{N_D,A}(\lambda^U_L P_L + \lambda^U_R P_R)\sigma_{\mu\nu} u^*_{N_D} + \bar{d}\bar{K}_{N_D,A}(\lambda^D_L P_L + \lambda^D_R P_R)\sigma_{\mu\nu} d^*_{N_D} \right] + \text{h.c.}$$

Gluon-Gluon

initial state	J	$SU_C(3)$
AA	0, 1, 2	$\mathbf{1}\oplus\mathbf{8}\oplus\mathbf{8}\oplus\mathbf{10}\oplus\overline{\mathbf{10}}\oplus\mathbf{27}$

Gluons annihilate into scalar, vector, and tensor states.
Will focus on color octets.
Couplings to CP-even states utilize symmetric representation:

- Neutral Scalar: S_8
- Neutral Tensor: T_8

$$\mathcal{L}_{gg8} = g_s d^{ABC}\left(\frac{\kappa_S}{\Lambda_S} S_8^A F^B_{\mu\nu} F^{C,\mu\nu} + \frac{\kappa_T}{\Lambda_T}\left(T_8^{A,\mu\sigma} F^B_{\mu\nu} F^{C\ \nu}_{\sigma} + f\, T^{A,\rho}_{8\ \rho} F^{B,\mu\nu} F^C_{\mu\nu}\right)\right)$$

Quark-Antiquark

initial state	J	$SU_C(3)$
$Q\bar{Q}$	1	$\mathbf{1}\oplus\mathbf{8}$
$Q\bar{U}$	0	$\mathbf{1}\oplus\mathbf{8}$
$Q\bar{D}$	0	$\mathbf{1}\oplus\mathbf{8}$
$U\bar{U}$, $D\bar{D}$	1	$\mathbf{1}\oplus\mathbf{8}$
$U\bar{D}$	1	$\mathbf{1}\oplus\mathbf{8}$

Quark-Antiquark can annihilate into color octets and singlets

Physical color-octet vector states.

- Neutral vector: V_8^0
- Charged vector: $V_8^{\pm}$

$$\begin{aligned}\mathcal{L}_{q\bar{q}V} &= g_s\Big[{V_8}^{0,A,\mu}\,\bar{u}T^A\gamma_\mu(g_L^U P_L + g_R^U P_R)u + {V_8}^{0,A,\mu}\,\bar{d}T^A\gamma_\mu(g_L^D P_L + g_R^D P_R)d \\ &\quad + \Big(V_8^{+,A,\mu}\,\bar{u}T^A\gamma_\mu(C_L V_L^{CKM} P_L + C_R V_R^{CKM} P_R)d + \text{h.c.}\Big)\Big]\end{aligned}$$

Summary

Particle Names (leading coupling)	J	$SU_C(3)$	$\lvert Q_e \rvert$	B	Related models
$E^{\mu}_{3,6}\ (uu)$	0, 1	$\mathbf{3},\ \bar{\mathbf{6}}$	$\frac{4}{3}$	$-\frac{2}{3}$	scalar/vector diquarks
$D^{\mu}_{3,6}\ (ud)$	0, 1	$\mathbf{3},\ \bar{\mathbf{6}}$	$\frac{1}{3}$	$-\frac{2}{3}$	scalar/vector diquarks; $\tilde{d}$
$U^{\mu}_{3,6}\ (dd)$	0, 1	$\mathbf{3},\ \bar{\mathbf{6}}$	$\frac{2}{3}$	$-\frac{2}{3}$	scalar/vector diquarks; $\tilde{u}$
$u^{*}_{3,6}\ (ug)$	$\frac{1}{2}$, $\frac{3}{2}$	$\mathbf{3},\ \bar{\mathbf{6}}$	$\frac{2}{3}$	$\frac{1}{3}$	excited u; quixes; stringy
$d^{*}_{3,6}\ (dg)$	$\frac{1}{2}$, $\frac{3}{2}$	$\mathbf{3},\ \bar{\mathbf{6}}$	$\frac{1}{3}$	$\frac{1}{3}$	excited d; quixes; stringy
$S_8\ (gg)$	0	$\mathbf{8}_S$	0	0	$\pi_{TC},\ \eta_{TC}$
$T_8\ (gg)$	2	$\mathbf{8}_S$	0	0	stringy
$V^0_8\ (u\bar{u},\ d\bar{d})$	1	$\mathbf{8}$	0	0	axigluon; g_{KK}, ρ_{TC}; coloron
$V^{\pm}_8\ (u\bar{d})$	1	$\mathbf{8}$	1	0	$\rho^{\pm}_{TC}$

LHC Production
and
Dijet Bounds

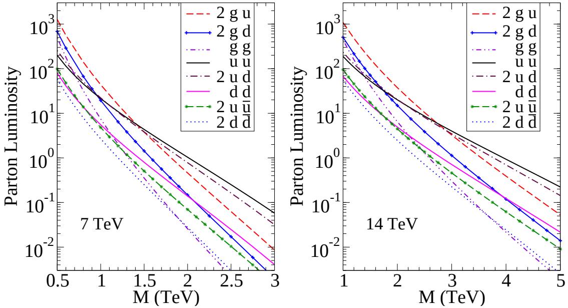
LHC Production

Hadronic production cross section:

$$\sigma(S) = \sum_{ij} \int d\tau \, \frac{dL_{ij}}{d\tau} \, \sigma_{ij}(s)$$

- S (s) hadronic (partonic) c.m. energy squared
- $\tau = s/S$
- $\frac{dL_{ij}}{d\tau} \equiv (f_i \otimes f_j)(\tau) = \int_{\tau}^{1} dx_1 \int_{\tau/x_1}^{1} dx_2 f_i(x_1) f_j(x_2) \delta(x_1 x_2 - \tau)$

For resonant production of mass M: $\sigma_{ij} \sim \delta(s - M^2)$, $\tau = M^2/S = x_1 x_2$



Detector Acceptances

ATLAS excited quark acceptances:

- 31% at $m_{jj} = 300$ GeV
- 48% at $m_{jj} = 1700$ GeV

Model with simple parameterization:

$$\mathcal{A}_{ATLAS} = \begin{cases} \frac{0.17}{1400\ \mathrm{GeV}}(m - 300\ \mathrm{GeV}) + 0.31 & m \leq 1700\ \mathrm{GeV} \\ 0.48 & m > 1700\ \mathrm{GeV} \end{cases}$$

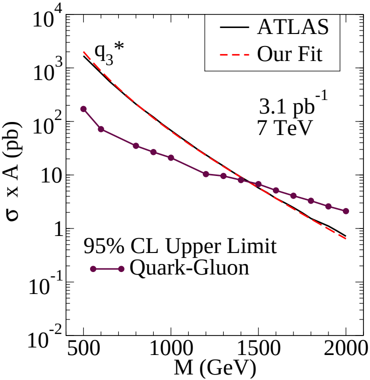
CMS acceptances:

- Compared our results to CMS results with acceptance
- Axigluon production for qq acceptance
- Excited quark production for qg acceptance

Parameterization:

$$\mathcal{A}_{CMS} = \frac{\Delta}{2100\ \mathrm{GeV}}(m - 500\ \mathrm{GeV}) + 0.47$$

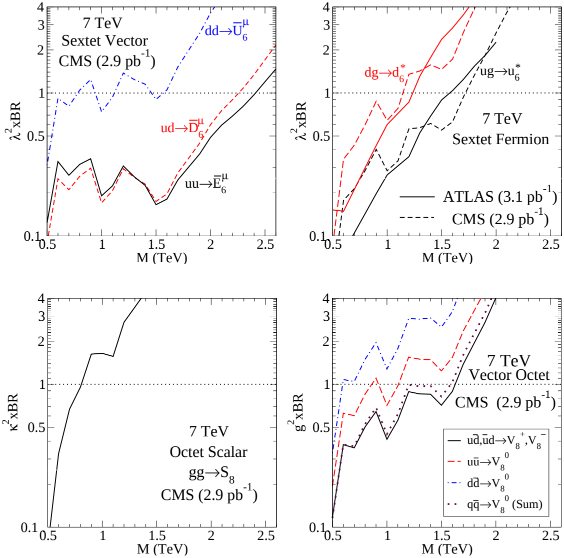
- $\Delta = 0.08$ for qq
- $\Delta = 0.17$ for qg



Use 95% CL upper limits to place bounds on new physics couplings.

- Apply ATLAS bounds on excited quarks.
- Apply relevant CMS bounds on all resonances.

Bounds



7 TeV
Sextet Vector
CMS (2.9 pb^{-1})
$dd\to\bar{U}_6^\mu$
$ud\to\bar{D}_6^\mu$
$uu\to\bar{E}_6^\mu$
λ^2xBR
M (TeV)
$dg\to d_6^*$
$ug\to u_6^*$
7 TeV
Sextet Fermion
ATLAS (3.1 pb^{-1})
CMS (2.9 pb^{-1})
κ^2xBR
7 TeV
Octet Scalar
$gg\to S_8$
CMS (2.9 pb^{-1})
g^2xBR
7 TeV
Vector Octet
CMS (2.9 pb^{-1})
$u\bar{d},\bar{u}d\to V_8^+,V_8^-$
$u\bar{u}\to V_8^0$
$d\bar{d}\to V_8^0$
$q\bar{q}\to V_8^0$ (Sum)

Mass Bounds

Mass bounds for coupling constant and BR of unity.

E_6^μ	2.5 TeV (CMS)	E_6	2.1 TeV
D_6^μ	2.3 TeV (CMS)	D_6	1.9 TeV
U_6^μ	$0.8, 0.9-1.1, 1.4-1.6$ TeV (CMS)	U_6	0.5 TeV
D_3^μ	1.9 TeV (CMS)	D_3	$0.8, 0.9-1.2, 1.3-1.7$ TeV
u_6^*	1.7 TeV (CMS), 1.6 TeV (ATLAS)	d_6^*	1.1 TeV, 1.2 TeV
$V_8^\pm$	1.7 TeV (CMS)	V_8^0	1.6 TeV
S_8	0.8 TeV (CMS)	T_8	0.7 TeV ,

Conclusions

We classified possible color resonances at the LHC

We analyzed the simplest topologies (dijet events) for the production of these color resonances.

Bounds were place on the couplings of these new states to Standard Model partons using ATLAS and CMS dijet data

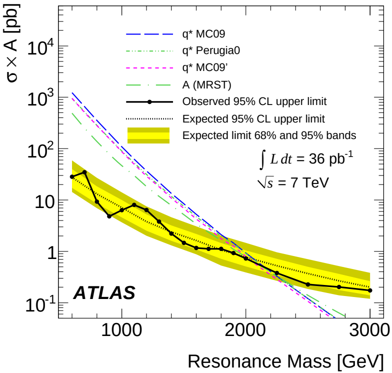
Our approach is quite general and can be applied to other possible signals

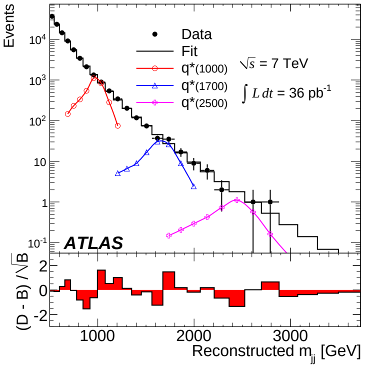
LHC turned on and already probing the high energy frontier.

If a new particle is observed, then it is an exciting time to unravel the underlying dynamics.

With the expected increase in luminosity and c.m. energy, the LHC will undoubtedly shed light on new fundamental physics.

Extra Slides





- Most stringent bounds on new physics [1103.3864[hep-ex] (ATLAS), 1102.2020 1009.5069[hep-ex] (CMS)]
- LHC entering discovery phase

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- Quark-antiquark interactions: $\mathbf{3}\otimes\bar{\mathbf{3}}$

Group Theory Decomposition

initial state	J	$SU_C(3)$	$SU(2)_L$	$U(1)_Y$	$\lvert Q_e\rvert$	B
QQ	0	$\bar{\mathbf{3}}\oplus\mathbf{6}$	$\mathbf{1}\oplus\mathbf{3}$	$\frac{1}{3}$	$\frac{4}{3},\frac{2}{3},\frac{1}{3}$	$\frac{2}{3}$
QU	1	$\bar{\mathbf{3}}\oplus\mathbf{6}$	$\mathbf{2}$	$\frac{5}{6}$	$\frac{4}{3},\frac{1}{3}$	$\frac{2}{3}$
QD	1	$\bar{\mathbf{3}}\oplus\mathbf{6}$	$\mathbf{2}$	$-\frac{1}{6}$	$\frac{2}{3},\frac{1}{3}$	$\frac{2}{3}$
UU	0	$\bar{\mathbf{3}}\oplus\mathbf{6}$	$\mathbf{1}$	$\frac{4}{3}$	$\frac{4}{3}$	$\frac{2}{3}$
DD	0	$\bar{\mathbf{3}}\oplus\mathbf{6}$	$\mathbf{1}$	$-\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
UD	0	$\bar{\mathbf{3}}\oplus\mathbf{6}$	$\mathbf{1}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{2}{3}$
QA	$\frac{1}{2},\frac{3}{2}$	$\mathbf{3}\oplus\bar{\mathbf{6}}\oplus\mathbf{15}$	$\mathbf{2}$	$\frac{1}{6}$	$\frac{2}{3},\frac{1}{3}$	$\frac{1}{3}$
UA	$\frac{1}{2},\frac{3}{2}$	$\mathbf{3}\oplus\bar{\mathbf{6}}\oplus\mathbf{15}$	$\mathbf{1}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{1}{3}$
DA	$\frac{1}{2},\frac{3}{2}$	$\mathbf{3}\oplus\bar{\mathbf{6}}\oplus\mathbf{15}$	$\mathbf{1}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
AA	0, 1, 2	$\mathbf{1}\oplus\mathbf{8}\oplus\mathbf{8}\oplus\mathbf{10}\oplus\overline{\mathbf{10}}\oplus\mathbf{27}$	$\mathbf{1}$	0	0	0
$Q\bar{Q}$	1	$\mathbf{1}\oplus\mathbf{8}$	$\mathbf{1}\oplus\mathbf{3}$	0	1,0	0
$Q\bar{U}$	0	$\mathbf{1}\oplus\mathbf{8}$	$\mathbf{2}$	$-\frac{1}{2}$	1,0	0
$Q\bar{D}$	0	$\mathbf{1}\oplus\mathbf{8}$	$\mathbf{2}$	$\frac{1}{2}$	1,0	0
$U\bar{U}$, $D\bar{D}$	1	$\mathbf{1}\oplus\mathbf{8}$	$\mathbf{1}$	0	0	0
$U\bar{D}$	1	$\mathbf{1}\oplus\mathbf{8}$	$\mathbf{1}$	1	1	0

Will focus on lower dimensional representations.

Other than being phenomenologically interesting, many of these states are theoretically motivated.

- Quark-Quark: Color-antitriplet scalar: $\widetilde{q}$
  Color-sextet scalars: Diquark Higgs
- Quark-Gluon: Color-triplet fermions: q^*
  Color-sextet fermions: quixes
- Gluon-Gluon: Color-octet scalars: π_{TC}
- Quark-Antiquark: Color octet vectors: ρ_{TC}, g_{KK}, axigluon

Quark-Quark

Interaction Lagrangian:

$$\begin{aligned}\mathcal{L}_{qqD} &= K^j_{ab}\Big[\lambda^E_{\alpha\beta}E^j_{N_D}\,\overline{u^C_{\alpha a}}P_\tau u_{\beta b}+\lambda^U_{\alpha\beta}U^j_{N_D}\,\overline{d^C_{\alpha a}}P_\tau d_{\beta b}+\lambda^D_{\alpha\beta}D^j_{N_D}\,\overline{d^C_{\alpha b}}P_\tau u_{\alpha a}\\ &+\lambda^{E'}_{\alpha\beta}E^{j\mu}_{N_D}\,\overline{u^C_{\alpha a}}\gamma_\mu P_R u_{\beta b}+\lambda^{U'}_{\alpha\beta}U^{j\mu}_{N_D}\,\overline{d^C_{\alpha a}}\gamma_\mu P_R d_{\beta b}\\ &+\lambda^{D'}_{\alpha\beta}\,D^{j\mu}_{N_D}\overline{u^C_{\alpha a}}\gamma_\mu P_\tau d_{\beta b}\Big]+\text{h.c.}\end{aligned}$$

- K^j_{ab} are $SU(3)_C$ Clebsch-Gordan coefficients.

Quark-Gluon

actions Lagrangian:

$$\mathcal{L}_{qgF} = \frac{g_s}{\Lambda} F^{A,\mu\nu} \left[\bar{u}\bar{K}_{N_D,A}(\lambda_L^U P_L + \lambda_R^U P_R)\sigma_{\mu\nu} u^*_{N_D} + \bar{d}\bar{K}_{N_D,A}(\lambda_L^D P_L + \lambda_R^D P_R)\sigma_{\mu\nu} d^*_{N_D} \right] + \text{h.c.}$$

- For **3**: $K^A = \sqrt{2}T^A$

Gluon-Gluon

Leading order interaction Lagrangian:

$$\mathcal{L}_{gg8} = g_s d^{ABC} \left(\frac{\kappa_S}{\Lambda_S} S_8^A F_{\mu\nu}^B F^{C,\mu\nu} + \frac{\kappa_T}{\Lambda_T} \left(T_8^{A,\mu\sigma} F_{\mu\nu}^B F_\sigma^{C\ \nu} + f\, T_{8\ \rho}^{A,\rho} F^{B,\mu\nu} F_{\mu\nu}^C \right) \right)$$

Possible to have CP-Odd tensors and scalars.

- Replace one $F^{\mu\nu}$ with $\widetilde{F}^{\mu\nu} = \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$
- Also have f^{ABC} term: $\widetilde{T}_8^{\mu\sigma} \widetilde{F}_{\mu\nu} F_\sigma^{\ \nu}$

Quark-Antiquark

Physical color-octet vector states: $V_8^0, V_8^\pm$

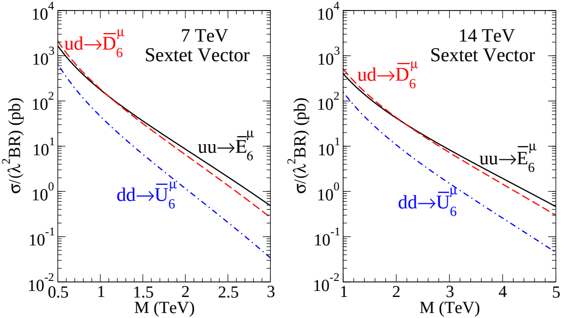
$$\mathcal{L}_{q\bar{q}V} = g_s \Big[{V_8}^{0,A,\mu}\, \bar{u} T^A \gamma_\mu (g_L^U P_L + g_R^U P_R) u + {V_8}^{0,A,\mu}\, \bar{d} T^A \gamma_\mu (g_L^D P_L + g_R^D P_R) d$$
$$+ \Big(V_8^{+,A,\mu}\, \bar{u} T^A \gamma_\mu (C_L V_L^{CKM} P_L + C_R V_R^{CKM} P_R) d + \text{h.c.} \Big) \Big]$$

- $C_{L,R}, g_{L,R}$ diagonal in mass basis and of order unity
- $V_{L,R}^{CKM}$ left- and right-handed CKM matrices

Singlets: Replace T^A with Kronecker delta.

Did not consider scalar octet production because of Minimal Flavor Violation.

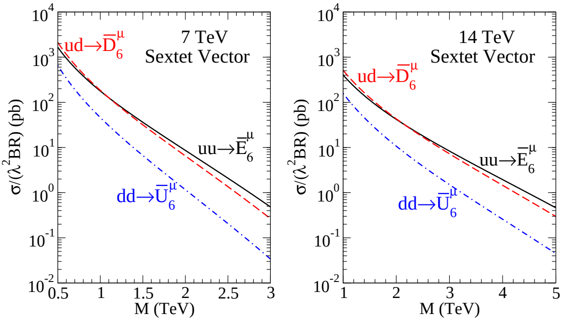
Dijet Production Rates: Quark-Quark Annihilation



$$\sigma_{qq} = \lambda^2 \frac{\pi N_D}{2^2 N_C^2} \frac{1+\delta_{1J}}{S} (q \otimes q')(\tau_0)$$

Conjugate production rate also included.

Dijet Production Rates: Quark-Quark Annihilation



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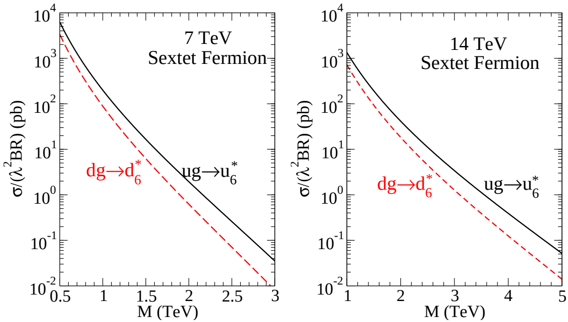
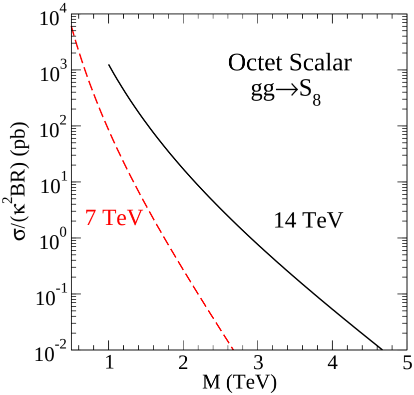
Quark-Gluon Annihilation



$$\sigma_{qg} = 8\pi^2\lambda^2 \frac{\alpha_s}{N_C} \frac{M^2}{\Lambda^2} \frac{1}{S} (g \otimes q)(\tau_0)$$

- $\Lambda = 2\,M$
- Tripelt and antisextet production rates are the same for our normalization of CG coefficients

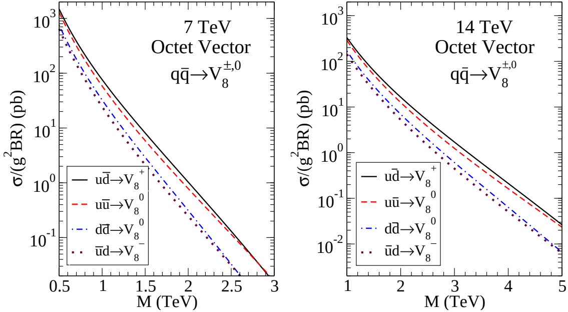
Gluon-Gluon Annihilation



$$\sigma_{gg} = 4\pi^2\alpha_s\kappa^2 \frac{N_C^2-4}{N_C(N_C^2-1)} \frac{M^2}{\Lambda^2} \frac{1+\delta_{0J}}{S} (g\otimes g)(\tau_0)$$

- $\Lambda = M$

Quark-Antiquark Annihilation

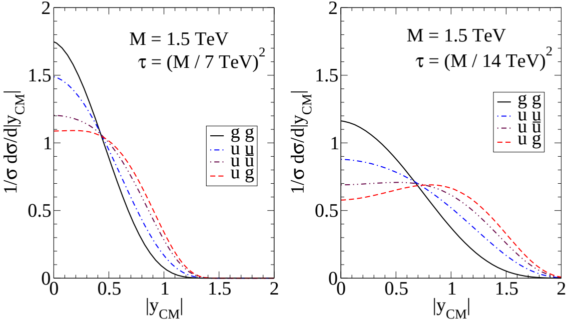


$$\sigma_{q\bar{q}} = 4\pi^2 g^2 \alpha_s \frac{C_F}{N_C}\frac{1}{S}(q\otimes\bar{q}')(\tau_0)$$

where

$$g^2 = \begin{cases} \frac{1}{2}(|C_L V_L^{CKM}|^2 + |C_R V_R^{CKM}|^2) & \text{for charged states,} \\ \frac{1}{2}(|g_L^{U,D}|^2 + |g_R^{U,D}|^2) & \text{for neutral states.} \end{cases}$$

Rapidity Distribution

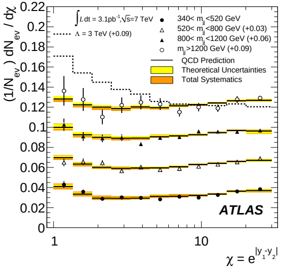


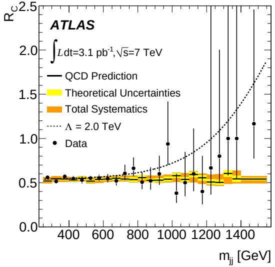
$$y_{cm} = \frac{1}{2} \log \frac{x_1}{x_2}$$

Partonic c.m. rapidity distribution is also of significant interest.

Will have impact on experimental acceptance of events.

4 Fermion Contact Interaction





ATLAS has placed a bound of 3.4 TeV and CMS a bound of 4 TeV on the new physics scale of the four fermion contact interaction.

This bound is relevant to our $\mathbf{3} \otimes \mathbf{3}$ and $\mathbf{3} \otimes \bar{\mathbf{3}}$ interactions

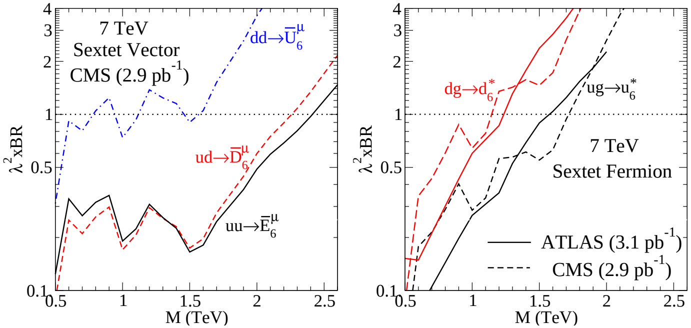
The standard form of the contact interaction is:

$$\mathcal{L}_{4q} = \frac{2\pi}{\Lambda^2} \bar{q}_L \gamma^\mu q_L \bar{q}_L \gamma_\mu q_L$$

$$\frac{2\pi}{\Lambda^2} \sim \frac{\lambda^2}{2M^2}$$

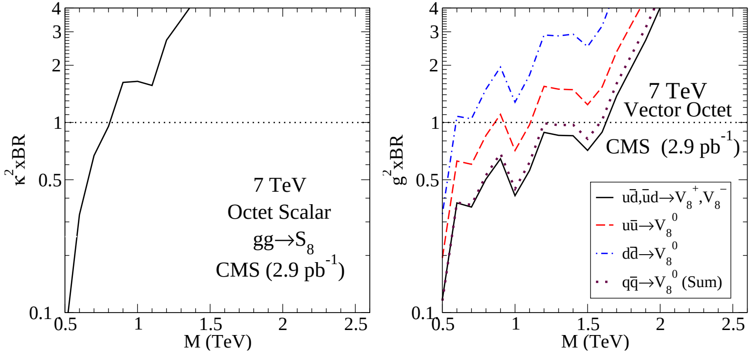
Assuming $\lambda = 1$, obtain mass bound of 960 GeV from ATLAS and 1.1 TeV from CMS.

Bounds



Everything above curves is excluded.

- $K = 1.2$ included for color-sextet vector production
- Bounds on sextet scalars are twice weaker
- Utilizing K-factors: D_6^μ is 1.8 times stronger than D_3^μ
  D_6^μ is 3.7 times stronger than D_3.
- $\Lambda = 2M$ for sextet fermions
- Color-triplet fermion bounds the same as color-sextet



- $\Lambda = M$ for scalar octet.
- Scalar octet bounds twice as strong as tensor octet.