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Studying hadronically decaying particles using photons and leptons

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Based on arXiv:1204.1119
(in collaboration with Matt Strassler)

Motivation

From the theoretical perspective, at the moment, no new physics scenario looks very appealing or unique. It is therefore important to find ways in which the LHC searches can cover multiple possibilities in a model-independent fashion.

In this talk we will focus on general scenarios that contain

new pair-produced colored particles

and see how (and when) one can...

- Set limits on such particles regardless of how they decay
- Get resonant singals even if their decays contain invisible particles
- Study the particles using photons and leptons even if they decay only to jets

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Pair-produced colored particles

We will consider particles characterized by

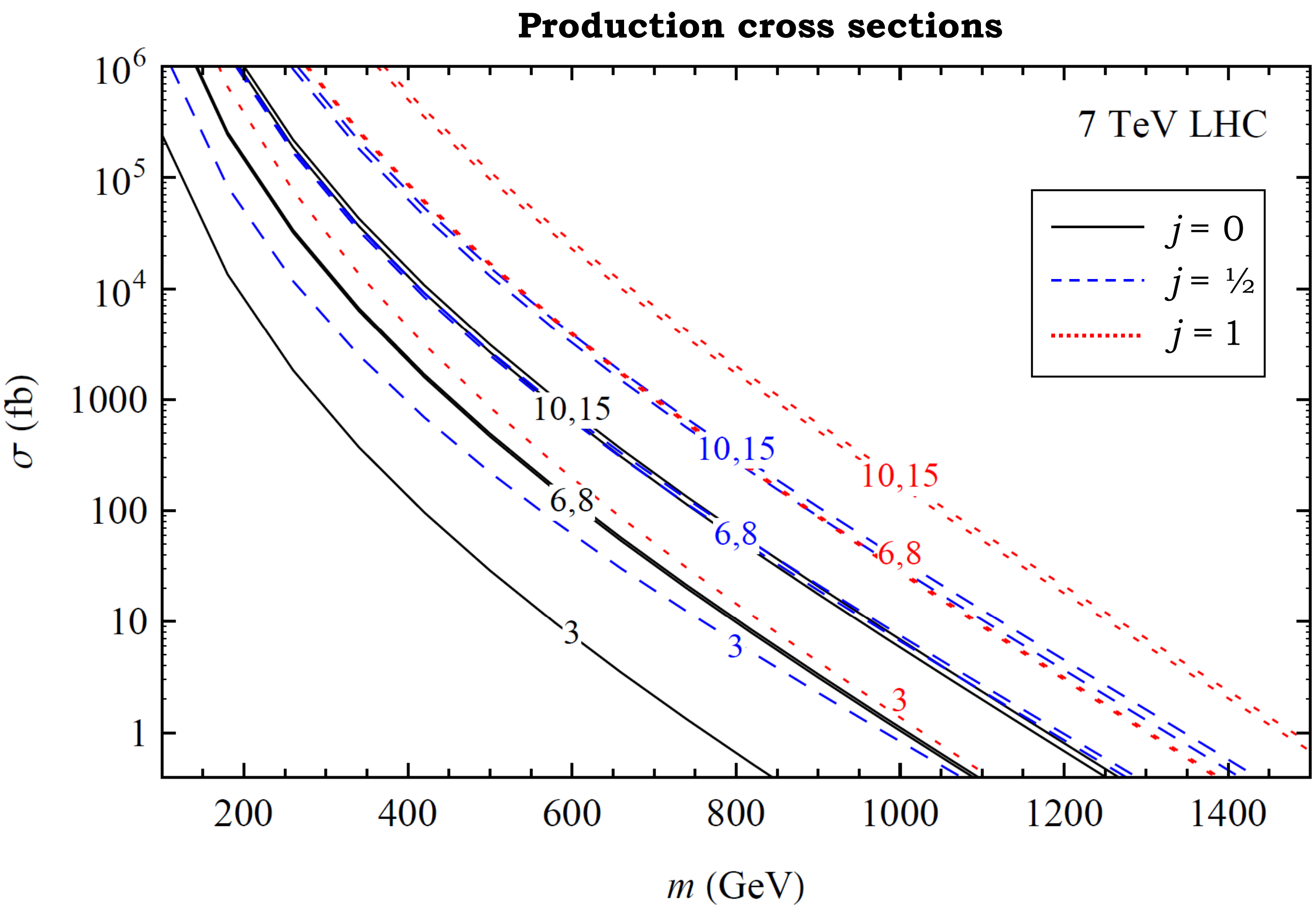
mass $m \sim O(1\ \text{TeV})$

spin $j = 0, \frac{1}{2}$, or 1

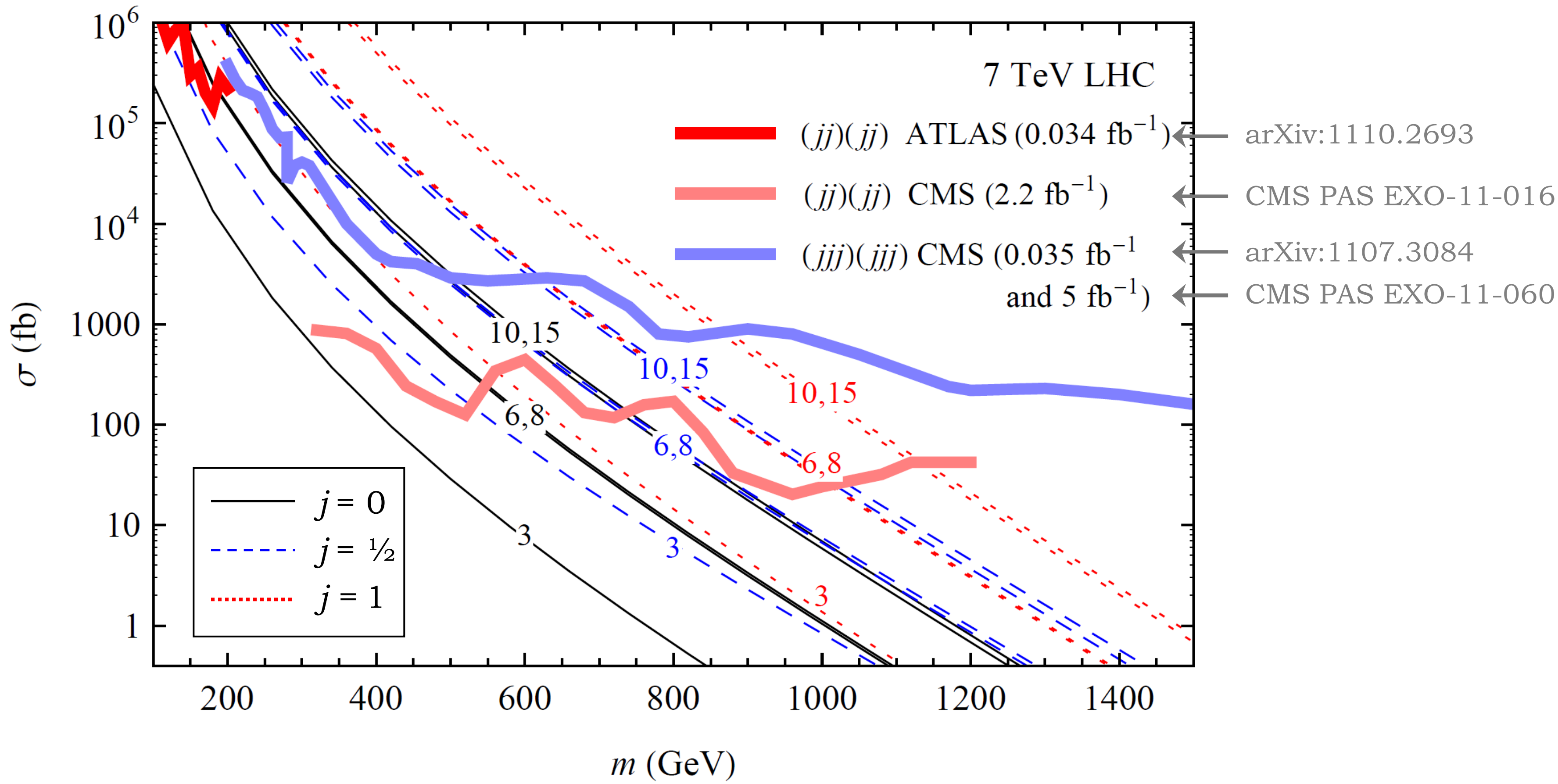
color representation R = **3**, **8**, **6**, **15**, or **10**

electric charge Q

$SU(2)_L$-singlet (only for simplicity of presentation)



Example: limits on particles decaying to jets



For decays to **2 jets**, notice the gap below 320 GeV (due to trigger limitations).

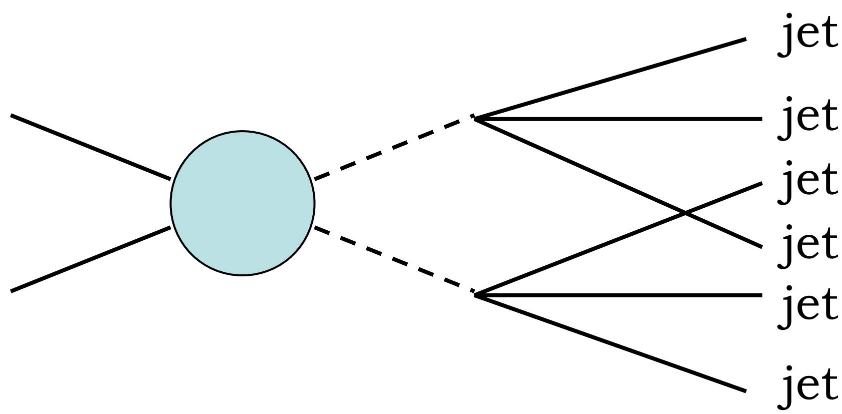
For decays to **3 jets**, notice that the limits are pretty weak (due to low efficiency).

Is there a way to improve the limits on these scenarios?

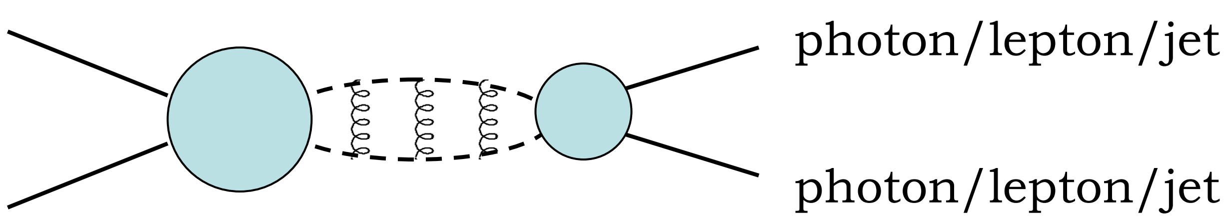
Can we set limits on colored particles for which there are no dedicated searches?

Bound state annihilation signals

Our suggestion: instead of using just the ordinary decays of these particles…



one may also consider the signals from the formation and annihilation of their near-threshold QCD bound states…



which will appear as resonances at $M \approx 2m$.

An important caveat:

The particles may decay before the bound state annihilates. This will typically happen if they have unsuppressed two-body decays (e.g., toponium). We will assume this not to be the case – our only essential assumption.

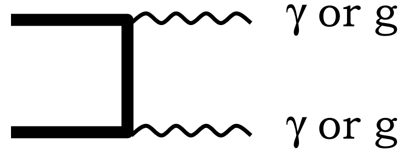
The interesting annihilation channels

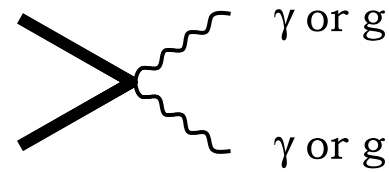
Annihilation channels of spin-0 and spin-2 bound states include:

Diphoton

Photon + jet (gluon)

Dijet (gg)

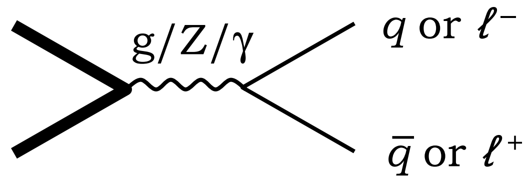




Annihilation channels of spin-1 bound states include:

Dilepton

Dijet ($q\bar{q}$)

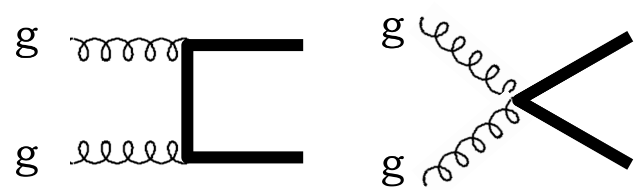


We assume that all the relevant processes are dominated by the SM gauge interactions.

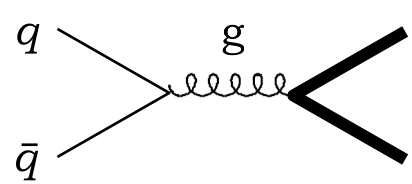
Production mechanisms

In most cases S-wave bound states are available and their signal dominates (see backup slides / paper for details).

For the **diphoton**, **photon+jet** and **dijet** channels, the spin-0 and spin-2 bound states are produced from gg:



For the **dijet** channel, there is also a contribution from (color-octet) spin-1 bound states produced from $q\bar{q}$:

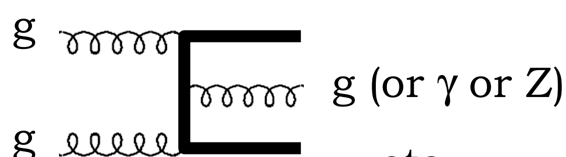


Such leading-order QCD processes do <u>not</u> produce the color-singlet spin-1 bound states (similar to the J/ψ) that are needed for the **dilepton** channel.

Production mechanisms

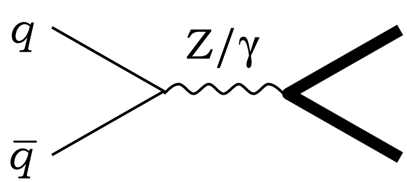
For the **dilepton** channel, the following sub-leading processes contribute (significant only for spin-½ particles – see backup slides):

(1) Production from gg in association with a gluon:

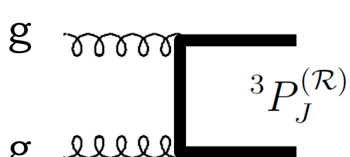


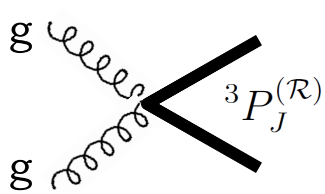
etc.

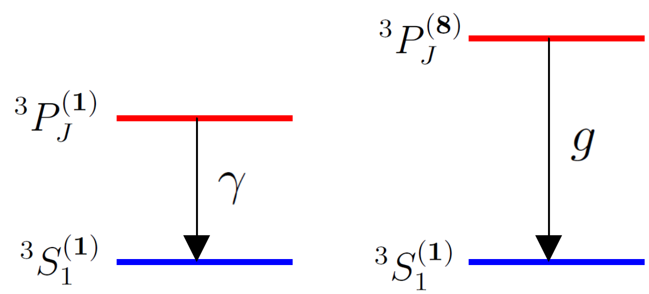
(2) Electroweak production from $q\bar{q}$:



(3) Electric or chromoelectric dipole transition from a P-wave (a.k.a. χ):



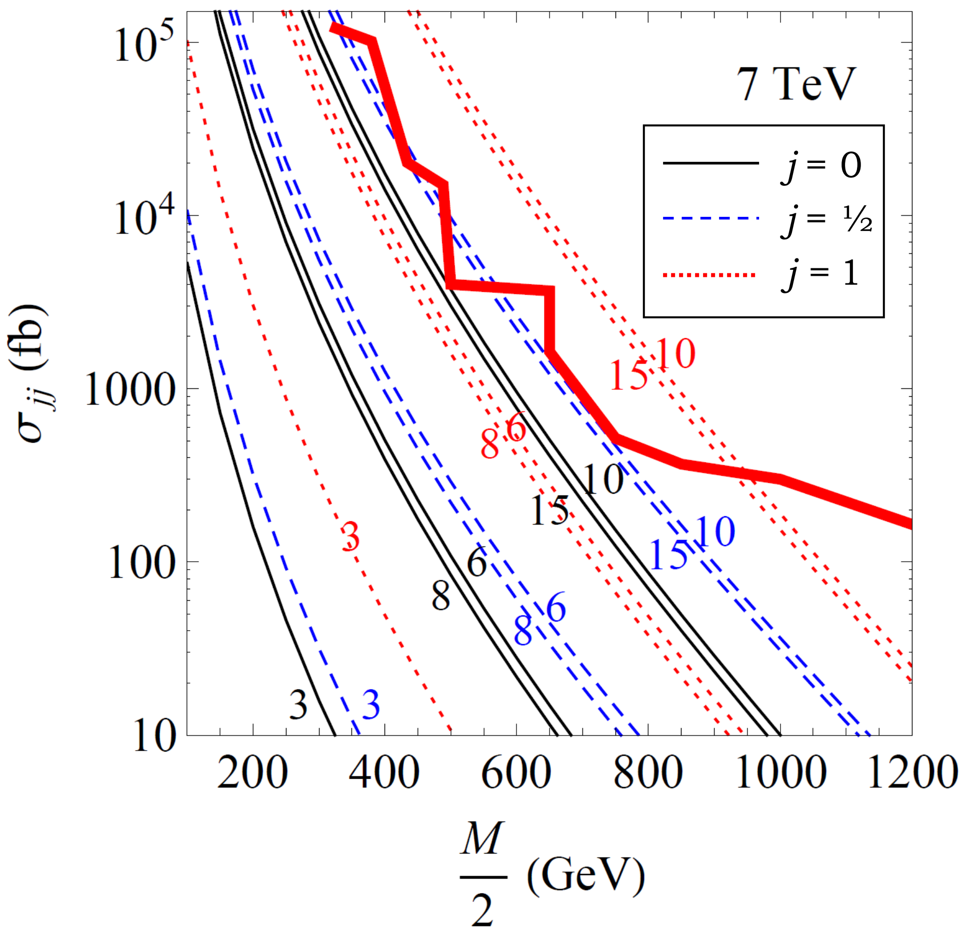




$J = 0$ or 2

$\mathcal{R} = \mathbf{1}$ or $\mathbf{8}$

Dijet channel



ATLAS (5/fb)

ATLAS-CONF-2012-038

For lower masses:

ATLAS (1/fb)

arXiv:1108.6311

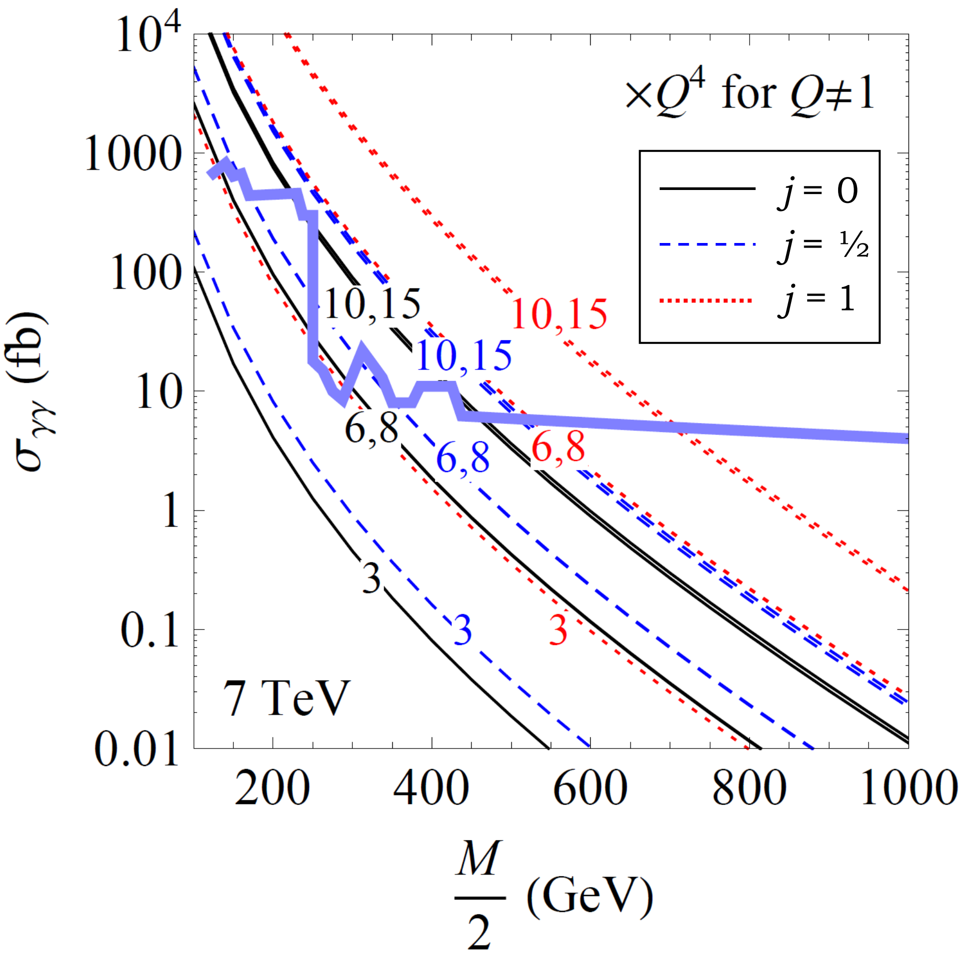
For yet lower masses:

ATLAS (36/pb)

arXiv:1103.3864

- Unfortunately, the low-mass region is limited by triggers. Still, can keep increasing the reach there using pre-scaled triggers.
- It's the only available channel if the particles are neutral.

Diphoton channel



CMS (1/fb)

CMS PAS EXO-11-038

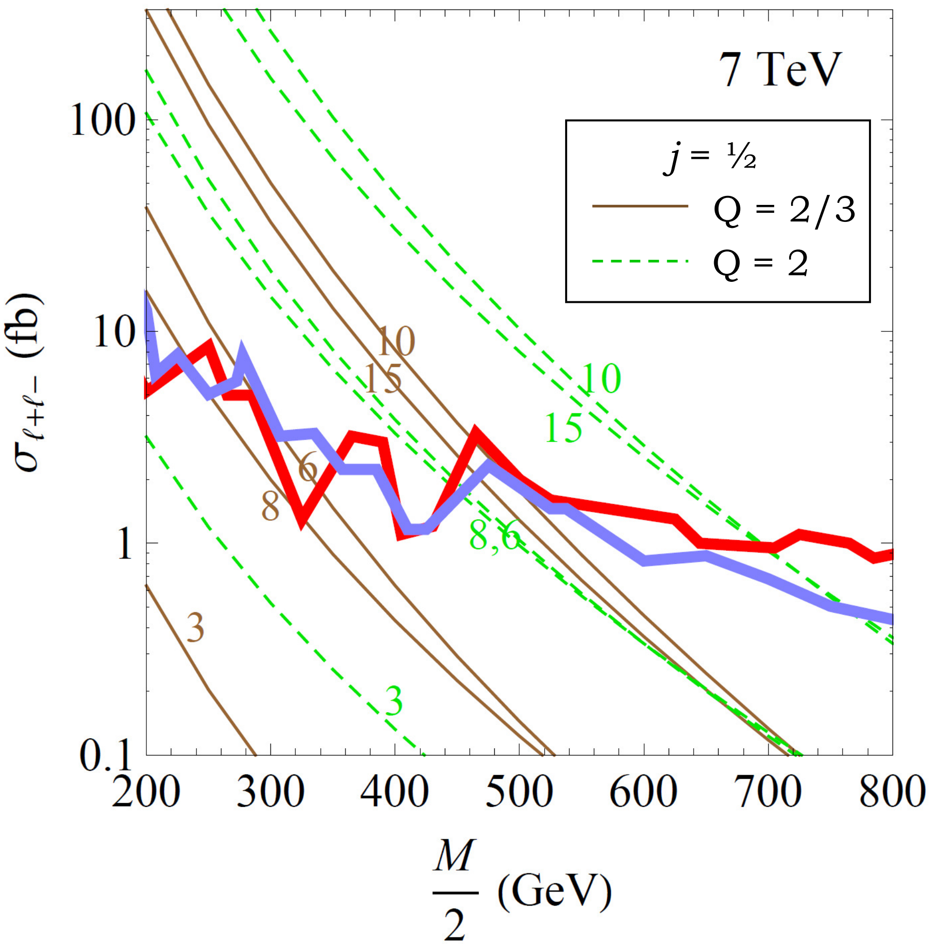
For low masses:

CMS (36/pb)

CMS PAS EXO-10-019

- No trigger issues: limits will keep improving even at very low masses.
- Limits below 320 GeV (the dijet pairs searches gap) are available.
- Low-mass region is accessible also to the 1/fb study, but unfortunately has not been analyzed.

Dilepton channel



CMS (5/fb)

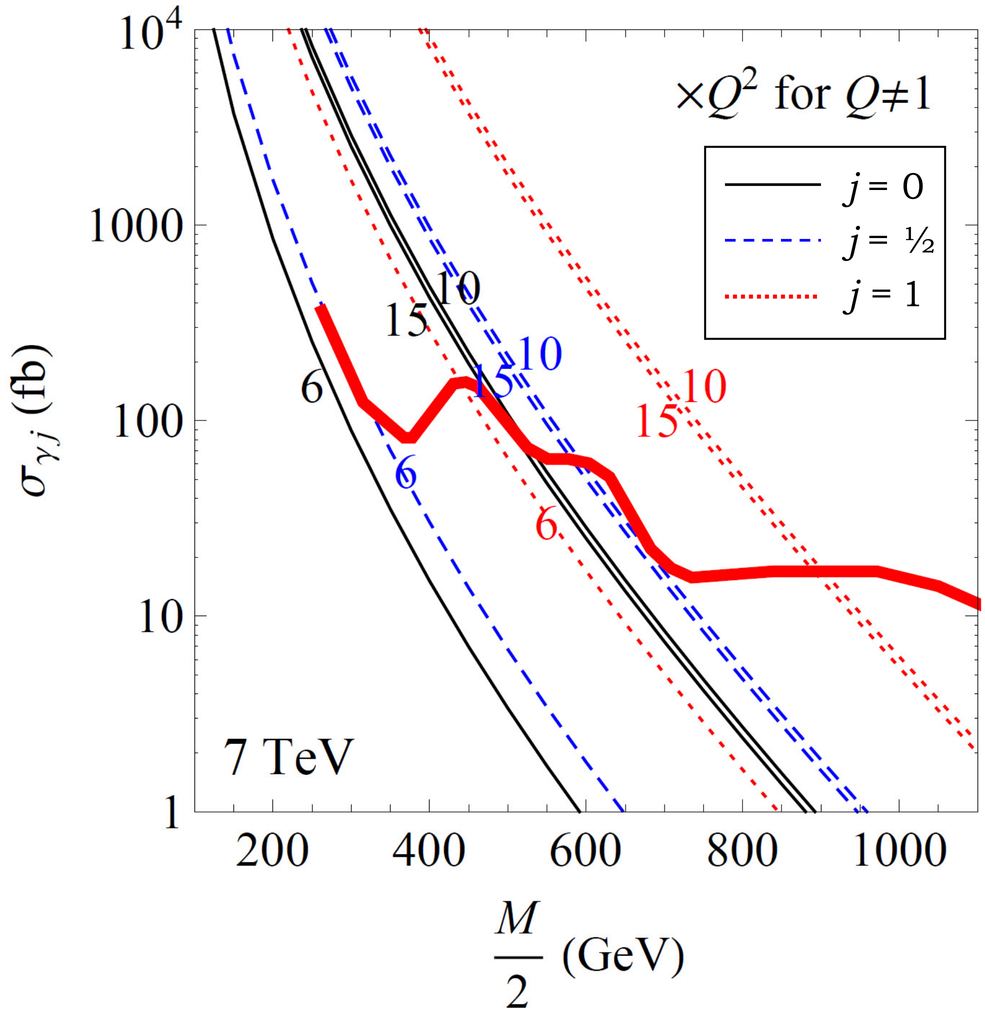
update of CMS PAS EXO-11-019

ATLAS (5/fb)

ATLAS-CONF-2012-007

- No trigger issues: limits will keep improving even at very low masses.
- Limits below 320 GeV (the dijet pairs searches gap) are available.

Photon+jet channel



ATLAS (2/fb)

arXiv:1112.3580

- Underappreciated search channel (first study since Tevatron Run I).
- Limits below 320 GeV (the dijet pairs searches gap) are available.

Competitiveness with direct searches

- For particles decaying to 2 jets, the limits from bound states are typically weaker than the dedicated search.

- For particles decaying to 3 jets, the limits from bound states are often stronger! Examples:

R = **8**, $j = \frac{1}{2}$, $Q = 2$ (decays to qqq)	
$(jjj)(jjj)$ with 5/fb	$\gamma\gamma$ with 1/fb
500 GeV	570 GeV

R = **6**, $j = \frac{1}{2}$, $Q = 5/3$ (decays to $qq\bar{q}$)	
$(jjj)(jjj)$ with 5/fb	$\gamma\gamma$ with 1/fb
500 GeV	500 GeV

R = **10**, $j = \frac{1}{2}$, $Q = 2$ (decays to qqq)			
$(jjj)(jjj)$ with 5/fb	$\gamma\gamma$ with 1/fb	$\ell^+\ell^-$ with 5/fb	γj with 2/fb
600 GeV	750 GeV	760 GeV	800 GeV

R = **10**, $j = 0$, $Q = 1$ (decays to $q\bar{q}g$)	
$(jjj)(jjj)$ with 5/fb	γj with 2/fb
500 GeV	540 GeV

- For many scenarios with more exotic decays (e.g., decays to 4 jets), these are the only limits that can be inferred easily from existing searches.

Determining the quantum numbers of the new particles

Step 1 – Spin:

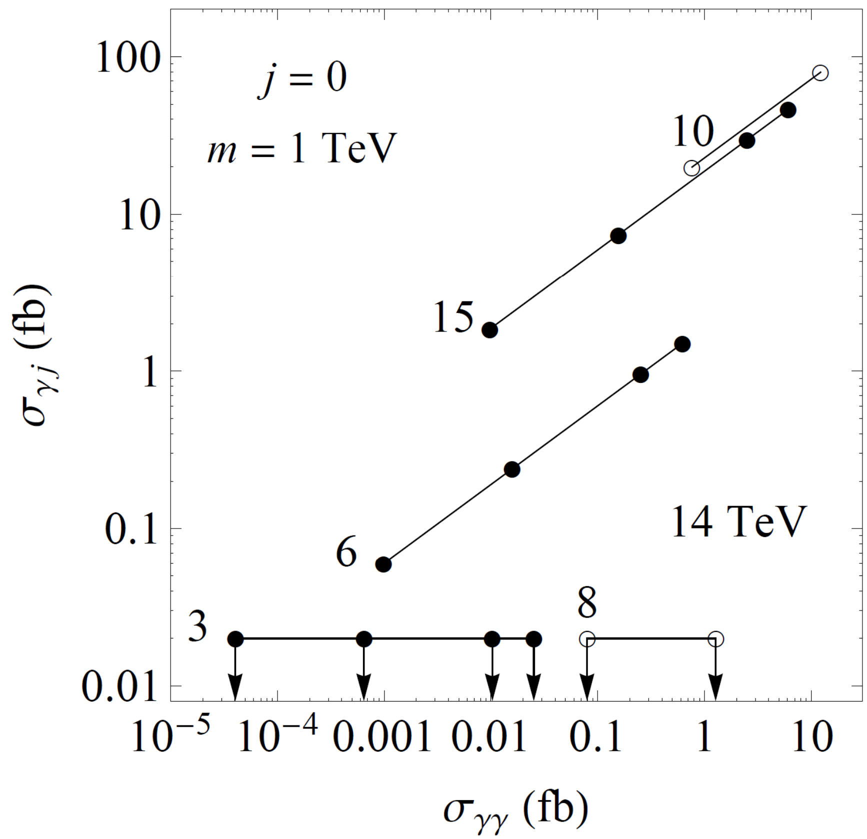
If the *dilepton* signal is present, the particles must be spin-½.

If not, use *angular distributions* for distinguishing between spin 0 and 1: in the spin-1 case, 16/19 of the *diphoton* signal is coming from $J = 2$ states.

Step 2 – Charge and color representation:

By triality considerations (see backup slides):
For **8** and **10**: $|Q|$ = (0), 1, 2, …
For **3**, **6**, **15**: $|Q|$ = 1/3, 2/3, 4/3, 5/3, …

Then can use, for example, the combination of the *diphoton* and *photon+jet* signals.



Step 3 – Mass:

Immediately known to within few % from the location of the resonances.
Can be determined even more accurately by correcting for the binding energy.

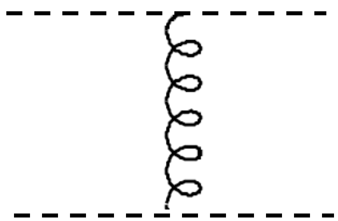
Summary

- Pair-produced colored particles form near-threshold QCD bound states.
- If the particles do not decay too fast, the bound states annihilate, leading to resonances in the $\gamma\gamma$, $\ell^+\ell^-$, γ+jet, dijet and other channels.
- Motivation for the experiments to keep searching for low cross section resonances at low masses.
- In the case of discovery (by this or a more conventional method), the multiple available bound state signals will allow determining the properties of the new particles.
- The method is largely model-independent, and is especially relevant to cases with difficult decays, where the more standard search and characterization techniques are limited.

Backup slides

Bound state formalism

Since we are dealing with TeV-scale particles, we work at leading order in α_s and the Coulomb approximation for the potential:



$$V(r) = -C\frac{\overline{\alpha}_s}{r}$$

$$\overline{\alpha}_s \equiv \alpha_s(1/a_0)$$

For particles in representation R forming a bound state in representation $\mathcal{R} \subset R \otimes \overline{R}$:

$$C = C_R - \frac{1}{2}C_{\mathcal{R}}$$

R	D_R	$R \otimes \overline{R}$
$(1,0)$	$\mathbf{3}$	$\mathbf{1}\ (\oplus\mathbf{8})$
$(1,1)$	$\mathbf{8}$	$\mathbf{1} \oplus \mathbf{8}^2\ (\oplus\mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{27})$
$(2,0)$	$\mathbf{6}$	$\mathbf{1} \oplus \mathbf{8}\ (\oplus\mathbf{27})$
$(2,1)$	$\mathbf{15}$	$\mathbf{1} \oplus \mathbf{8}^2 \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{27}^2\ (\oplus\mathbf{35} \oplus \overline{\mathbf{35}} \oplus \mathbf{64})$
$(3,0)$	$\mathbf{10}$	$\mathbf{1} \oplus \mathbf{8} \oplus \mathbf{27}\ \ (\oplus\mathbf{64})$

(in parentheses – potential not attractive)

Possible color representations of the bound states

Within these approximations, everything is like in the hydrogen atom.

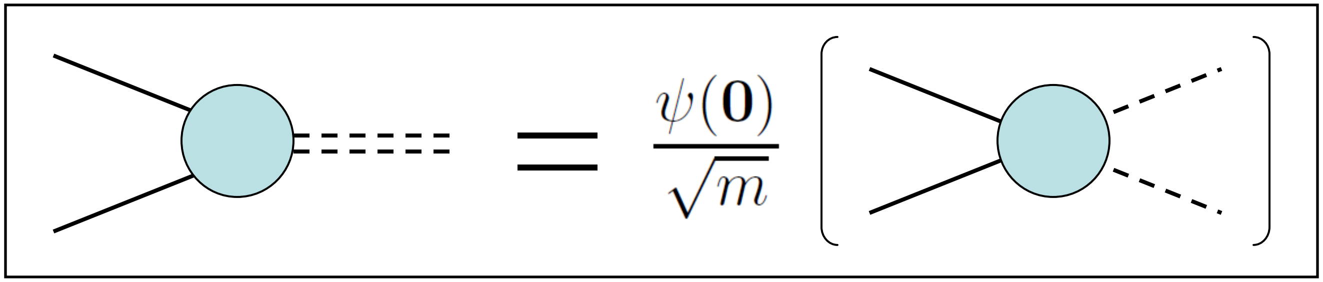
For example, for S-wave ground states:

$$E_b = -\frac{1}{4}C^2\overline{\alpha}_s^2 m \qquad |\psi(\mathbf{0})|^2 = \frac{C^3\overline{\alpha}_s^3 m^3}{8\pi}$$

Higher order corrections are likely to be large, but they are computable.

Bound state formalism

Matrix element for S-wave bound state production or annihilation:



which comes from $\displaystyle\int \frac{d^3\mathbf{p}_{12}}{(2\pi)^3}\,\tilde{\psi}(\mathbf{p}_{12})\,\mathcal{M}(\overline{\mathbf{p}},\mathbf{p}_{12}) \simeq \mathcal{M}(\overline{\mathbf{p}},0)\,\psi(\mathbf{0})$

Typical production cross-section:

$$\hat{\sigma}^{\mathrm{bound}}(\hat{s}) \sim \frac{\alpha_s^2}{m^4}\,|\psi(\mathbf{0})|^2\,\delta\left(\sqrt{\hat{s}}-2m\right)$$

where

$$|\psi(\mathbf{0})|^2 = \frac{C^3\overline{\alpha}_s^3 m^3}{8\pi}$$

Typical annihilation rate:

$$\Gamma_{\mathrm{ann}} \sim \frac{\alpha_s^2}{m^2}\,|\psi(\mathbf{0})|^2$$

Annihilation rate *vs.* decay rate *vs.* binding energy

- **Annihilation rate** $\Gamma_{\rm ann} \sim \frac{\alpha_s^2}{m^2} |\psi(\mathbf{0})|^2 \sim \alpha_s^2 \overline{\alpha}_s^3 m$
- **Binding energy** $E_b \sim \overline{\alpha}_s^2 \, m$
- **Decay rate** of the consistuent particles $\Gamma_{\rm decay}$ (model-dependent)

For the bound state to be well-defined: $\boxed{2\Gamma_{\rm decay} + \Gamma_{\rm ann} \lesssim E_b}$

For the annihilation signals to be useful: $\boxed{2\Gamma_{\rm decay} \lesssim \Gamma_{\rm ann}}$

For example, "toponium" is unlucky:

$$2\Gamma_{\rm decay} = 2.6 \text{ GeV} \qquad \Gamma_{\rm ann} = 0.004 \text{ GeV} \qquad E_b = 1.5 \text{ GeV}$$

Due to the 1st condition, the resonance is rather broad.
Due to the 2nd condition, the annihilation signals are unobservable.

But if the decay goes via a heavier off-shell particle or a non-renormalizable interaction, $\Gamma_{\rm decay}$ can be significantly smaller.

Also, for the higher representations, the annihilation rate is enhanced by several orders of magnitude: $\Gamma_{\rm ann} = \frac{D_R C_R^5}{16} \alpha_s^2 \, \overline{\alpha}_s^3 \, m$

Beyond the S-wave ground states

- For **radial excitations** of S waves: $|\psi(\mathbf{0})|^2 \propto \frac{1}{n^3}$

  This can be summed to an overall factor of $\zeta(3) = \sum_{n=1}^{\infty} \frac{1}{n^3} \approx 1.2$

- For **angular excitations**, $\psi(\mathbf{0}) = 0$, so they can usually be neglected relative to S waves.
  When S waves are suppressed for some reason, we consider P wave processes as well. Their rates $\propto |\psi'(\mathbf{0})|^2$.

- There may be **radiative transitions** between the different states.
  They are important in the case of the dilepton signal.

Expressions for the cross sections

$$\mathcal{L}_{ab}(\hat{s}) = \frac{\hat{s}}{s}\int_{\hat{s}/s}^{1}\frac{dx}{x}\, f_{a/p}(x)\, f_{b/p}\left(\frac{\hat{s}}{xs}\right)$$

Diphoton signal:

$$\sigma_{\gamma\gamma} = \frac{Q^4 C_R^3 D_R}{64}\,\pi^2\alpha^2\overline{\alpha}_s^3\,\frac{\mathcal{L}_{gg}(M^2)}{M^2}$$

R	D_R	C_R	T_R	A_R
$(1,0)$	**3**	$4/3$	$1/2$	1
$(1,1)$	**8**	3	3	0
$(2,0)$	**6**	$10/3$	$5/2$	7
$(2,1)$	**15**	$16/3$	10	14
$(3,0)$	**10**	6	$15/2$	27

Photon+jet signal:

$$\sigma_{\gamma g} = \frac{Q^2\left(C_R - \frac{3}{2}\right)^3 T_R}{8}\,\pi^2\alpha\,\alpha_s\,\overline{\alpha}_s^3\,\frac{\mathcal{L}_{gg}(M^2)}{M^2}$$

Dijet signal:

$$\sigma_{jj,\mathbf{1}}^{gg} = \frac{D_R C_R^5}{512}\,\pi^2\alpha_s^2\overline{\alpha}_s^3\,\frac{\mathcal{L}_{gg}(M^2)}{M^2}$$

$$\sigma_{jj,\mathbf{8}}^{gg} = \frac{D_R C_R\left(C_R + \frac{3}{4}\right)\left(C_R - \frac{3}{2}\right)^3}{320}\,\pi^2\alpha_s^2\overline{\alpha}_s^3\,\frac{\mathcal{L}_{gg}(M^2)}{M^2}$$

$$\sigma_{jj,\mathbf{27}}^{gg} = \frac{27 D_R C_R\left(C_R - \frac{4}{3}\right)\left(C_R - 4\right)^3}{2560}\,\pi^2\alpha_s^2\overline{\alpha}_s^3\,\frac{\mathcal{L}_{gg}(M^2)}{M^2}$$

All the expressions on this slide are for spin-0 particles.
Multiply them by 2 for spin-½ particles, or 19 for spin-1 particles.
For spin-½ particles, add the following dijet contribution:

$$\sigma_{jj,\mathbf{8}}^{q\overline{q}} = \frac{D_R C_R\left(C_R - \frac{3}{2}\right)^3}{9}\,\pi^2\alpha_s^2\overline{\alpha}_s^3\,\frac{\sum_q \mathcal{L}_{q\overline{q}}(M^2)}{M^2}$$

Expressions for the cross sections

Dilepton signal (only for spin-½ particles):

Dominant annihilation rates of the S-wave spin-1 bound state:

$$\Gamma_{\mathcal{B}\to f\bar{f}} = \frac{n_c}{12} D_R C_R^3 \sum_{\sigma=R,L} \left(\frac{Y_{f_\sigma} Y}{\cos^2\theta_W} + \frac{(Q_{f_\sigma} - Y_{f_\sigma})(Q-Y)}{\sin^2\theta_W} \right)^2 \alpha^2 \overline{\alpha}_s^3 m$$

$$\Gamma_{\mathcal{B}\to ggg} = \frac{5(\pi^2-9)}{27\pi} \frac{A_R^2 C_R^3}{D_R} \alpha_s^3 \overline{\alpha}_s^3 m$$

Dominant production mechanisms:

(1) Electroweak production:

$$\sigma = \frac{\pi^2}{108} D_R C_R^3 Q^2 \frac{\alpha^2 \overline{\alpha}_s^3}{\cos^4\theta_W} \left(17 \sum_{q=u,c} + 5 \sum_{q=d,s,b} \right) \frac{\mathcal{L}_{q\bar{q}}(M^2)}{M^2}$$

(2) Production in association with a gluon:

$$\sigma = \frac{5\pi}{192\, m^2} \frac{A_R^2 C_R^3}{D_R} \alpha_s^3 \overline{\alpha}_s^3 \int_0^1 dx_1 \int_0^1 dx_2\; f_{g/p}(x_1)\, f_{g/p}(x_2)\; I\left(\frac{x_1 x_2 s}{M^2}\right)$$

where $I(x) = \theta(x-1) \left[\frac{2}{x^2} \left(\frac{x+1}{x-1} - \frac{2x\ln x}{(x-1)^2} \right) + \frac{2(x-1)}{x(x+1)^2} + \frac{4\ln x}{(x+1)^3} \right]$

+ similar processes in association with a photon or Z

Expressions for the cross sections

Dilepton signal (only for spin-½ particles) – cont'd:

(3) Production via color-singlet P waves ${}^3P_J^{(\mathbf{1})}$:

P-wave production cross section: $$\sigma = \frac{D_R C_R^7}{2^{13}}\,\pi^2\alpha_s^2\overline{\alpha}_s^5\,\frac{\mathcal{L}_{gg}(M^2)}{M^2} \times \left\{\frac{3}{4}\,,\,1\right\} \quad \text{for } J = \{0,\,2\}$$

radiative transition rate: $$\Gamma({}^3P_J^{(\mathbf{1})} \to {}^3S_1^{(\mathbf{1})}\gamma) = \frac{128}{6561} Q^2 C_R^4\,\overline{\alpha}\,\overline{\alpha}_s^4 m$$

annihilation rate: $$\Gamma({}^3P_J^{(\mathbf{1})} \to gg) = \frac{1}{512} D_R C_R^7\,\alpha_s^2\overline{\alpha}_s^5\,m \times \left\{\frac{3}{4}\,,\,\frac{1}{5}\right\}$$

(4) Production via color-octet P waves ${}^3P_J^{(\mathbf{8})}$:

P-wave production cross section: $$\sigma = \frac{5}{768}\,\frac{A_R^2\left(C_R - \frac{3}{2}\right)^5}{D_R C_R}\,\pi^2\alpha_s^2\overline{\alpha}_s^5\,\frac{\mathcal{L}_{gg}(M^2)}{M^2} \times \left\{\frac{3}{4}\,,\,1\right\}$$

radiative transition rate: $$\Gamma({}^3P_J^{(\mathbf{8})} \to {}^3S_1^{(\mathbf{1})}g) = \frac{16}{6561} C_R^4 \frac{\left(C_R + \frac{3}{2}\right)^3\left(C_R - \frac{3}{2}\right)^5}{\left(C_R - \frac{1}{2}\right)^7}\overline{\alpha}_s^5 m$$

annihilation rate: $$\Gamma({}^3P_J^{(\mathbf{8})} \to gg) = \frac{5}{384}\,\frac{A_R^2\left(C_R - \frac{3}{2}\right)^5}{D_R C_R}\,\alpha_s^2\overline{\alpha}_s^5\,m \times \left\{\frac{3}{4}\,,\,\frac{1}{5}\right\}$$

Expressions for the cross sections

Dilepton signal (only for spin-½ particles) – cont'd:

The relative contributions of the above-mentioned processes are shown in the tables below (in %). Each of them is important in a certain regime, depending on the color representation, charge, mass and the LHC energy.

7 TeV LHC	$Q=\frac{2}{3}$					$Q=2$				
$m = 1$ TeV	**3**	**8**	**6**	**15**	**10**	**3**	**8**	**6**	**15**	**10**
$q\bar{q} \to \mathcal{B}$	97	92	71	68	22	99	96	92	88	66
$gg \to \mathcal{B}g$	2	–	14	9	24	0	–	2	1	8
$gg \to \mathcal{B}(\gamma/Z)$	0	1	1	2	1	0	1	1	3	3
$gg \to {}^3P_J^{(1)} \to \mathcal{B}\gamma$	2	7	8	5	3	0	3	4	5	6
$gg \to {}^3P_J^{(8)} \to \mathcal{B}g$	–	–	6	16	50	–	–	1	2	16

14 TeV LHC	$Q=\frac{2}{3}$					$Q=2$				
$m = 1$ TeV	**3**	**8**	**6**	**15**	**10**	**3**	**8**	**6**	**15**	**10**
$q\bar{q} \to \mathcal{B}$	87	77	36	35	7	97	87	73	65	33
$gg \to \mathcal{B}g$	8	–	40	24	40	1	–	9	5	22
$gg \to \mathcal{B}(\gamma/Z)$	1	5	3	7	2	1	5	6	13	8
$gg \to {}^3P_J^{(1)} \to \mathcal{B}\gamma$	5	18	12	8	2	1	8	10	12	10
$gg \to {}^3P_J^{(8)} \to \mathcal{B}g$	–	–	10	26	49	–	–	2	6	27

Dilepton signal from spin-0 or 1 particles

There is no significant **dilepton** signal for $j = 0$ or 1 particles.

The analogous spin-1 *S wave* bound state is unavailable:
$j = 0$: cannot form S-wave spin-1 bound states at all.
$j = 1$: the color-singlet S-wave spin-1 bound state has $J^{PC} = 1^{+-}$
so it cannot couple to leptons.

We can consider spin-1 *P waves* decaying to leptons.
For both $j = 0$ and 1, there exists a P wave with $J^{PC} = 1^{--}$.
But P wave processes are suppressed by two extra powers of $\overline{\alpha}_s$.
As a result:

– P waves have suppressed *annihilation* rates and would rather transition down to S waves.

– P waves have suppressed *production* rates:
Analogously to the S waves for $j = ½$, they cannot be produced directly, but need:
  – Production in association with a gluon, or
  – Electroweak production, or
  – Transitions from D waves: production suppressed even more than P waves, or
  – Transitions from excited S waves, but those would rather annihilate, canceling the advantage of them being S waves.

Constraints from triality

Requiring the particles to be unstable restricts their quantum numbers.

Representations $R = (a, b)$ of SU(3) can be assigned “triality”:

$$t_R = (a + 2b) \bmod 3$$

It has the property that for any representation R in $R_1 \otimes R_2$:

$$t_R = (t_{R_1} + t_{R_2}) \bmod 3$$

R	D_R	t_R
$(1,0)$	$\mathbf{3}$	1
$(1,1)$	$\mathbf{8}$	0
$(2,0)$	$\mathbf{6}$	2
$(2,1)$	$\mathbf{15}$	1
$(3,0)$	$\mathbf{10}$	0

As a result, the triality of a particle must be the sum of the trialities of its decay products.

For all SM particles (+ any new neutral particle), the triality is related to the electric charge as

$$t_R = (-3Q) \bmod 3$$

So this relation must hold also for our new particles:
particles in **8** and **10** can only have |Q| = 0, 1, 2, ...
particles in **3**, **6**, **15** can only have |Q| = 1/3, 2/3, 4/3, 5/3, ...