Understanding the First Results from the LHC Run II • MITP, JGU Mainz • 27 June 2016

QCD bound states of 375 GeV particles

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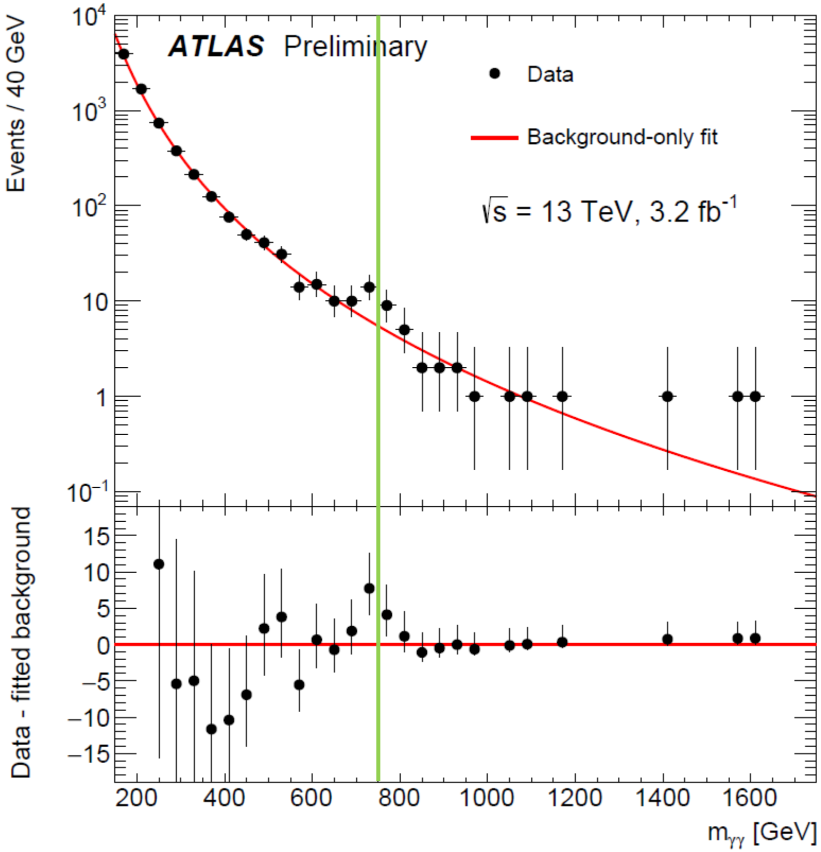
Based on work in collaboration with Matt Strassler

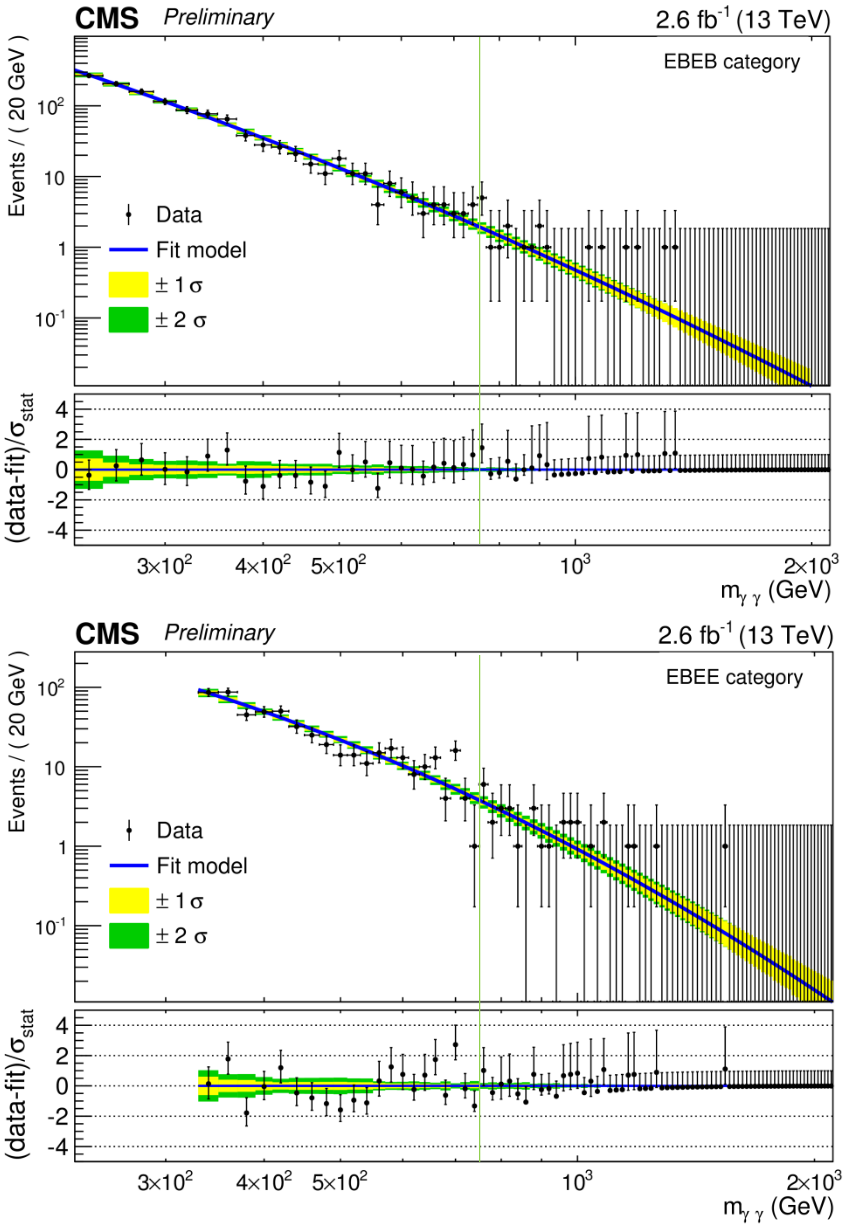
arXiv:1204.1119 [JHEP 1211 (2012) 097]

arXiv:1602.08819 [JHEP 1605 (2016) 092]

Motivation

Resonant diphoton excesses
in ATLAS and CMS





$M \approx 750\,\mathrm{GeV}, \;\; \Gamma \sim 0\text{-}100\,\mathrm{GeV}$

$\sigma \times \mathrm{BR}(\gamma\gamma) \sim 3\text{-}10\,\mathrm{fb}$

Preview of an explanation

BSM particle content

scalar $\Gamma(3,1)_{-4/3}$ $\quad m_\Gamma \approx 375$ GeV

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BSM interactions

$$\mathcal{L}_{\text{int}} = -\frac{c_{ij}}{2}\epsilon_{\alpha\beta\gamma}\mathit{\Gamma}^{*\alpha}\bar{u}_i^{\beta}\bar{u}_j^{\gamma} + \text{h.c.}$$

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Main LHC phenomenology

$$gg,\, q\bar{q} \to \mathit{\Gamma}\mathit{\Gamma}^*, \qquad \mathit{\Gamma} \to \bar{u}\bar{c},\, \bar{t}\bar{u},\, \bar{t}\bar{c}$$

unconstrained

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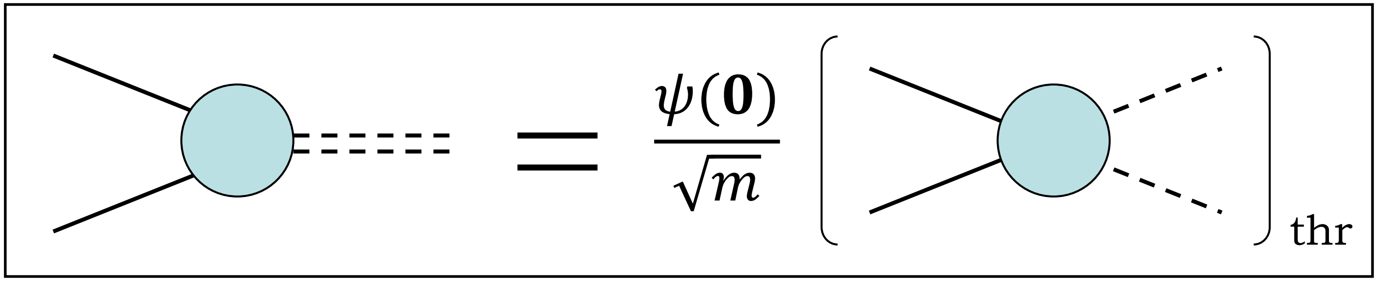
Bound state matrix elements



Explanation:

$$\int \frac{d^3\boldsymbol{p}_{12}}{(2\pi)^3}\,\tilde{\psi}(\boldsymbol{p}_{12})\,\mathcal{M}(\boldsymbol{P},\boldsymbol{p}_{12}) \simeq \mathcal{M}(2m,\mathbf{0})\,\psi(\mathbf{0})$$

up to (non)relativistic normalization

$$\uparrow$$

$$\int d^3\boldsymbol{x}_{12}\,e^{-i\boldsymbol{p}_{12}\cdot\boldsymbol{x}_{12}}\,\psi(\boldsymbol{x}_{12})$$

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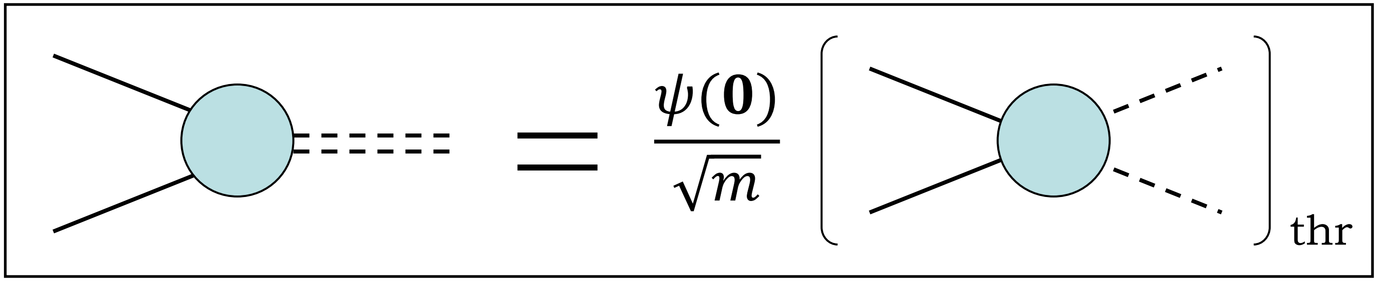

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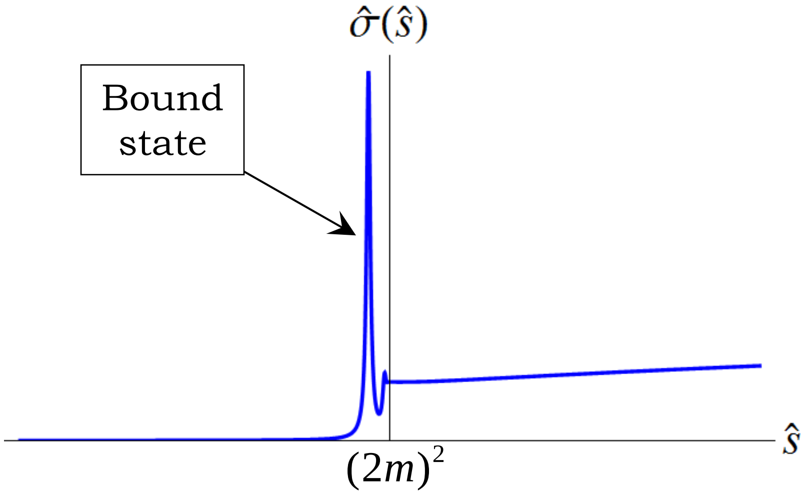
up to (non)relativistic normalization

e.g., if production and dominant annihilation is gg:

$$\hat{\sigma}(\hat{s}) \sim \frac{\alpha_s^2}{m^3}\,|\psi(\mathbf{0})|^2\,\delta(\hat{s}-M^2)$$

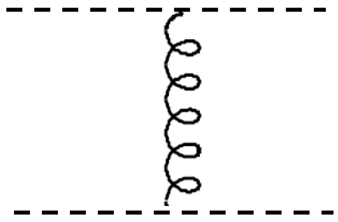
$$\Gamma_{\text{ann}} \sim \frac{\alpha_s^2}{m^2}\,|\psi(\mathbf{0})|^2$$

(See backup slides for detailed expressions.)



Estimating $\psi(\mathbf{0})$

Leading-order estimate – Coulomb approximation:



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

$$\bar{\alpha}_s \equiv \alpha_s(r_{\text{rms}})$$

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

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

Assumptions: $r_{\text{rms}} \ll \Lambda_{\text{QCD}}^{-1}$, $\bar{\alpha}_s \ll 1$, $v^2 = C^2\bar{\alpha}_s^2 \ll 1$

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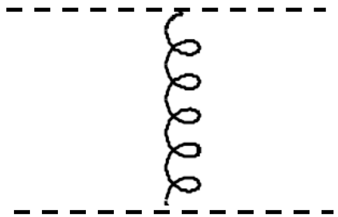

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Similar to the hydrogen atom, for S-wave ground states:

$$r_{\text{rms}} = \frac{2\sqrt{3}}{C\bar{\alpha}_s m} \qquad E_b = -\frac{C^2\bar{\alpha}_s^2}{4}\,m \qquad |\psi(\mathbf{0})|^2 = \frac{C^3\bar{\alpha}_s^3 m^3}{8\pi}$$

- Radial excitations are suppressed: $|\psi_n(\mathbf{0})|^2 \propto 1/n^3$.
- Orbital excitations are suppressed because $\psi(\mathbf{0}) = 0$.

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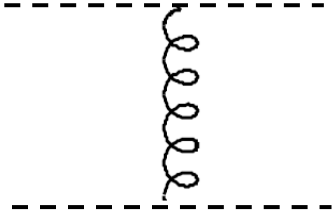

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More detailed potential model: $|\psi(\mathbf{0})|^2$ smaller by a factor of ~2.

Hagiwara, Kato, Martin, Ng, NPB 344 (1990) 1

Lattice QCD: $|\psi(\mathbf{0})|^2$ bigger by a factor of ~2.

Kim, PRD 92 (2015) 094505 [arXiv:1508.07080]

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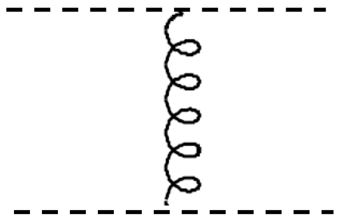

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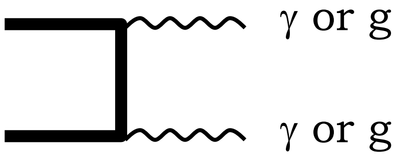
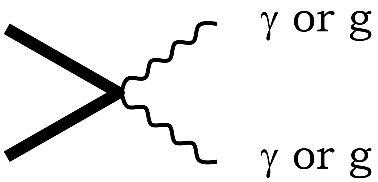
Will use the Coulomb approximation; keep factor-of-2 uncertainty in mind.

Annihilation channels of interest

For states with spin $J = 0$:

(also $J = 2$ for spin-1 constituents)





diphoton

photon + jet (gluon)

dijet (gg)

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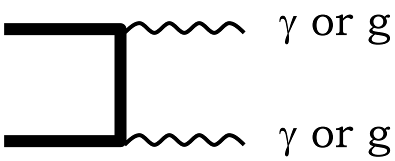
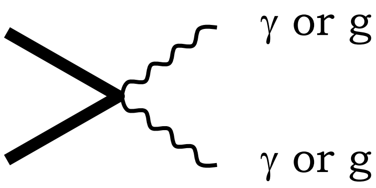


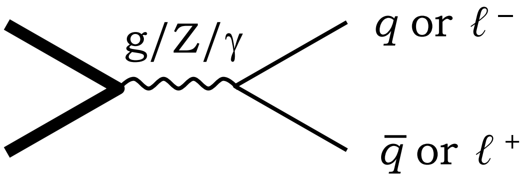


diphoton

photon + jet (gluon)

dijet (gg)

For states with $J = 1$ (for fermion constituents):

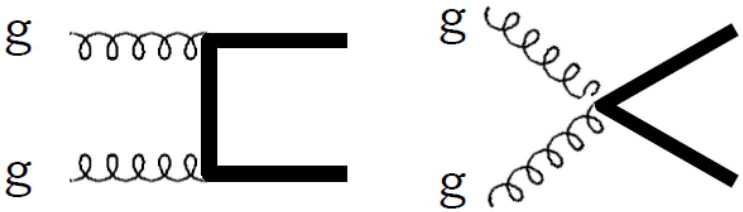


dilepton

dijet ($q\bar{q}$)

Production mechanisms

Diphoton, photon+jet and **dijet** signals arise from $J = 0$ (and $J = 2$) states produced from gg:



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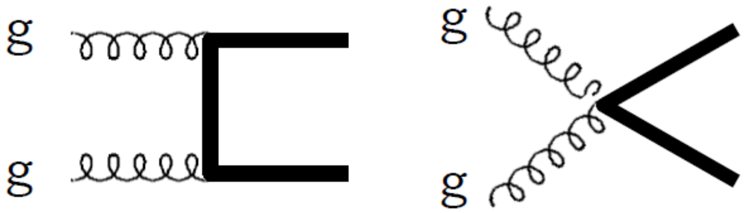
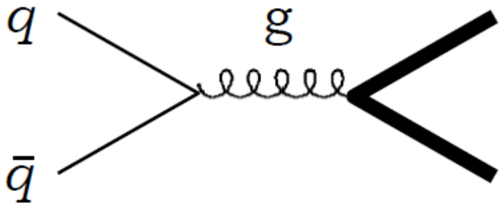


Dijet signals arise also from color-octet $J = 1$ states produced from $q\bar{q}$ (for $R \neq \mathbf{3}$):



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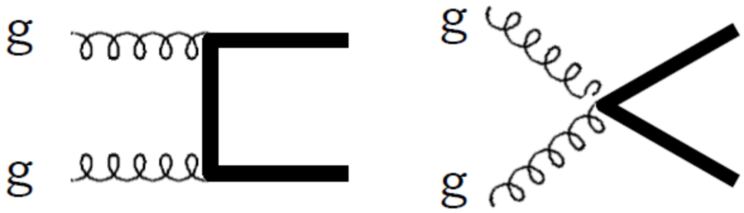

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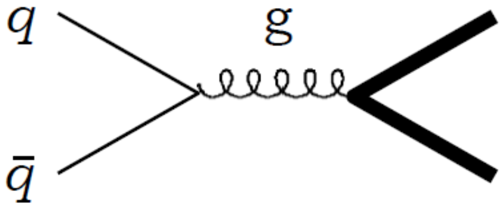
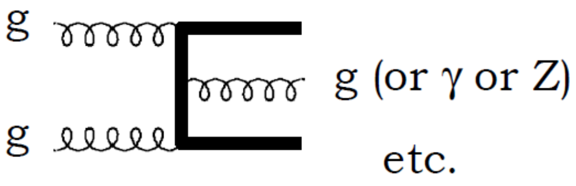


No leading-order QCD production of the color-singlet $J = 1$ states (similar to J/ψ) that would give a **dilepton** signal.

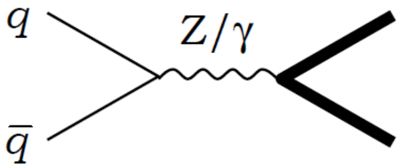
Production mechanisms

Subleading processes for the **dilepton** channel:

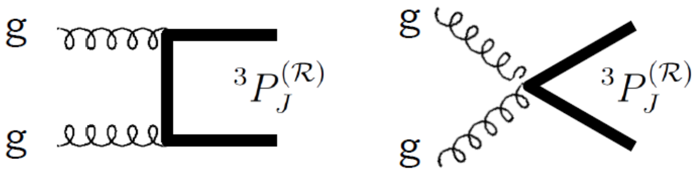
(1) Production from gg in association with g/γ/Z



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

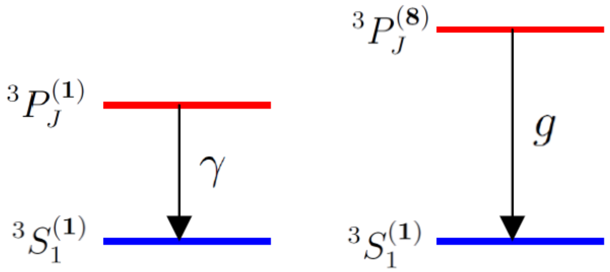


(3) Electric or chromoelectric dipole transition from a P-wave (a.k.a. χ)



$J = 0$ or 2

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



Can such bound states produce enough diphoton signal at 750 GeV?

Diphoton signal

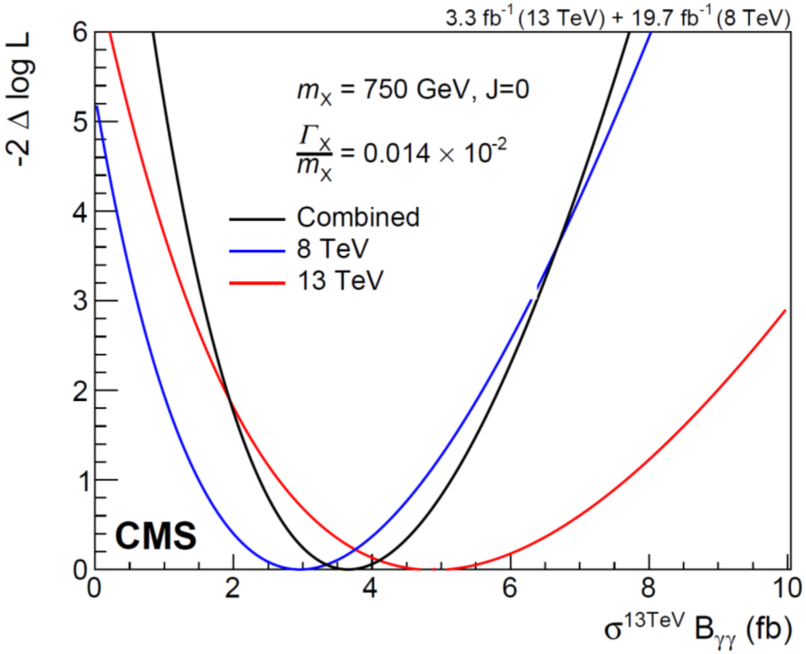
Fit for a narrow gg-produced spin-0 resonance

CMS $\sigma_{13} \times \mathrm{BR}(\gamma\gamma)$: 2.4 – 5.1 fb (at 1σ)

CMS-PAS-EXO-16-018 (Moriond)

arXiv:1606.04093

ATLAS no analogous information



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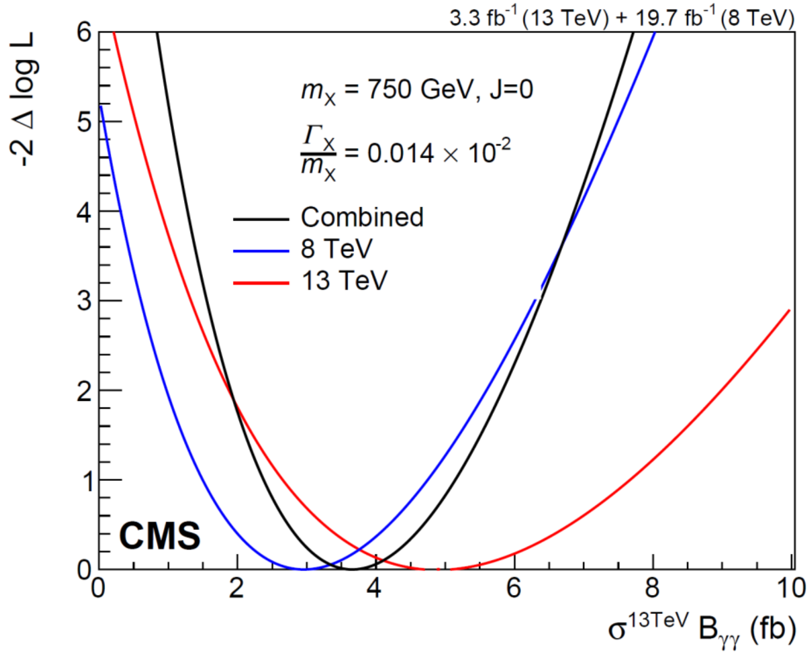

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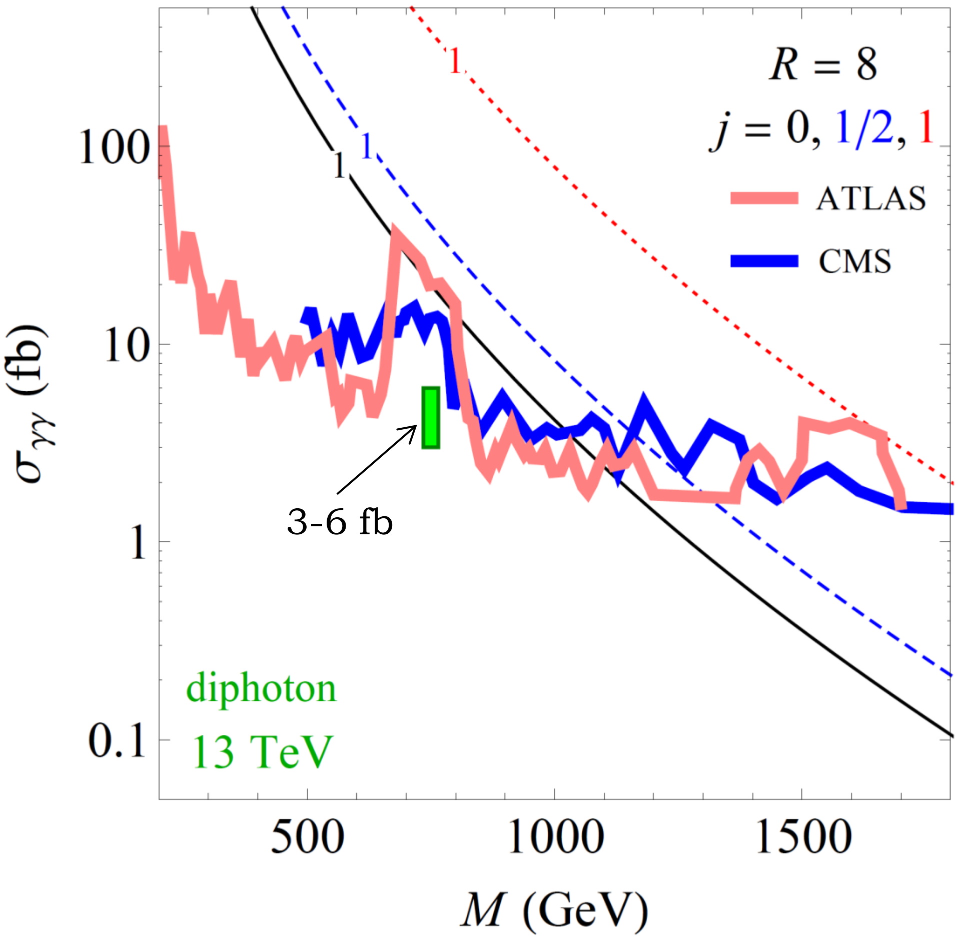
Theorists' combinations of ATLAS + CMS

≈ 2.4 fb	(pre-Moriond)	Falkowski, Slone, Volansky, arXiv:1512.05777
≈ 4 fb	(both pre- and post-Moriond)	Buckley, arXiv:1601.04751
2.5 – 3.9 fb	(post-Moriond)	Kamenik, Safdi, Soreq, Zupan, arXiv:1603.06566
2.1 – 3.5 fb	(post-Moriond)	Strumia, arXiv:1605.09401

Diphoton signal



ATLAS (13 TeV, 3.2/fb)

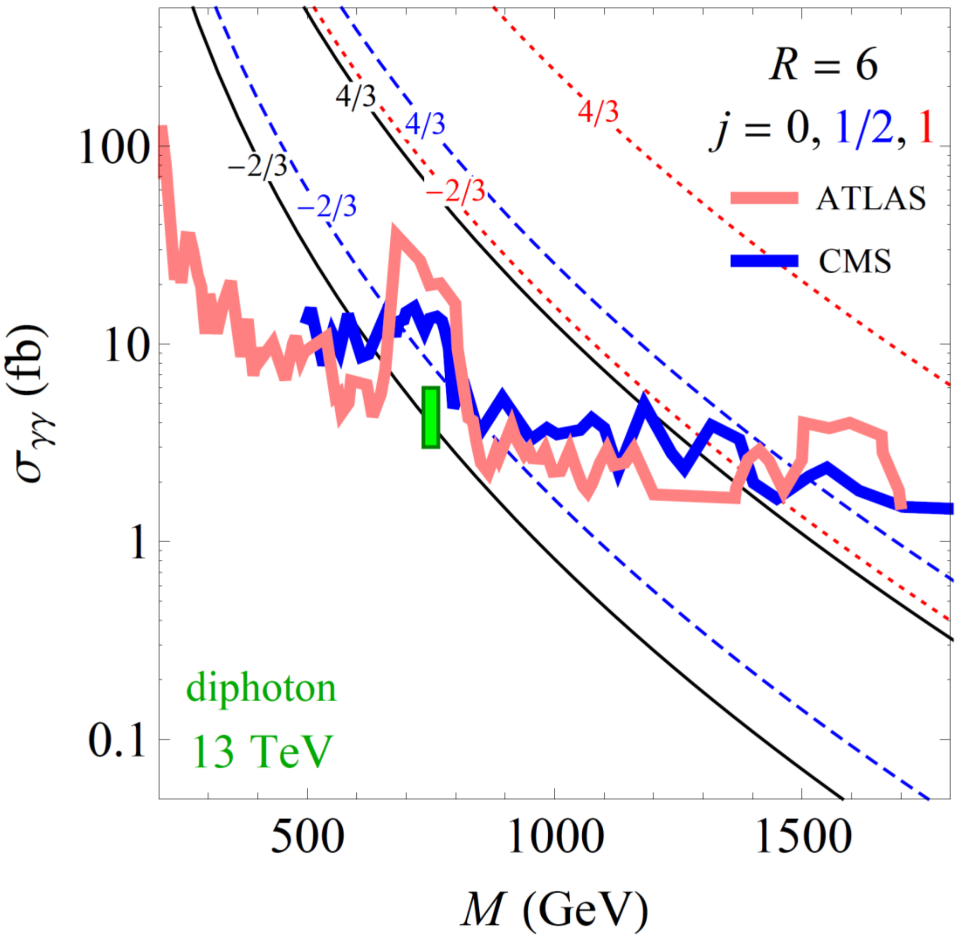
ATLAS-CONF-2015-081

CMS (13 TeV, 2.6/fb)

CMS PAS EXO-15-004

Color-octet constituents produce too much signal!

Diphoton signal



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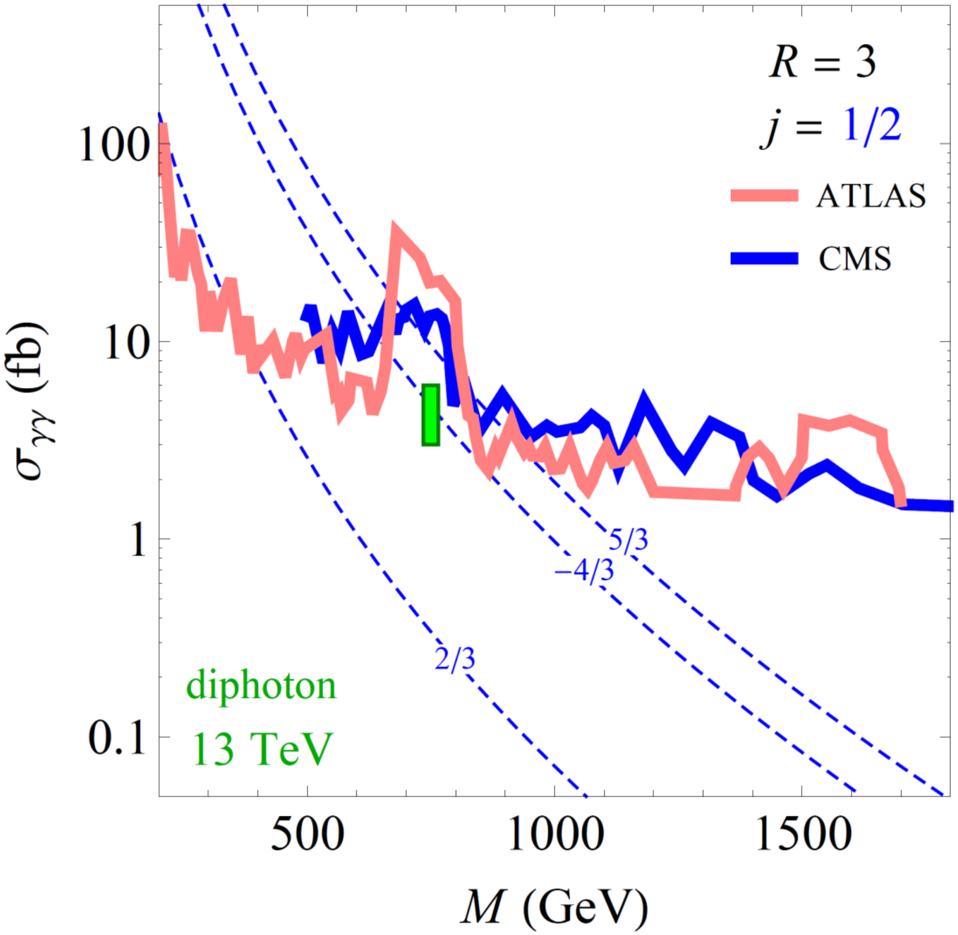
Color-sextet scalar with Q = – 2/3 is a candidate.

Diphoton signal



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ATLAS-CONF-2015-081

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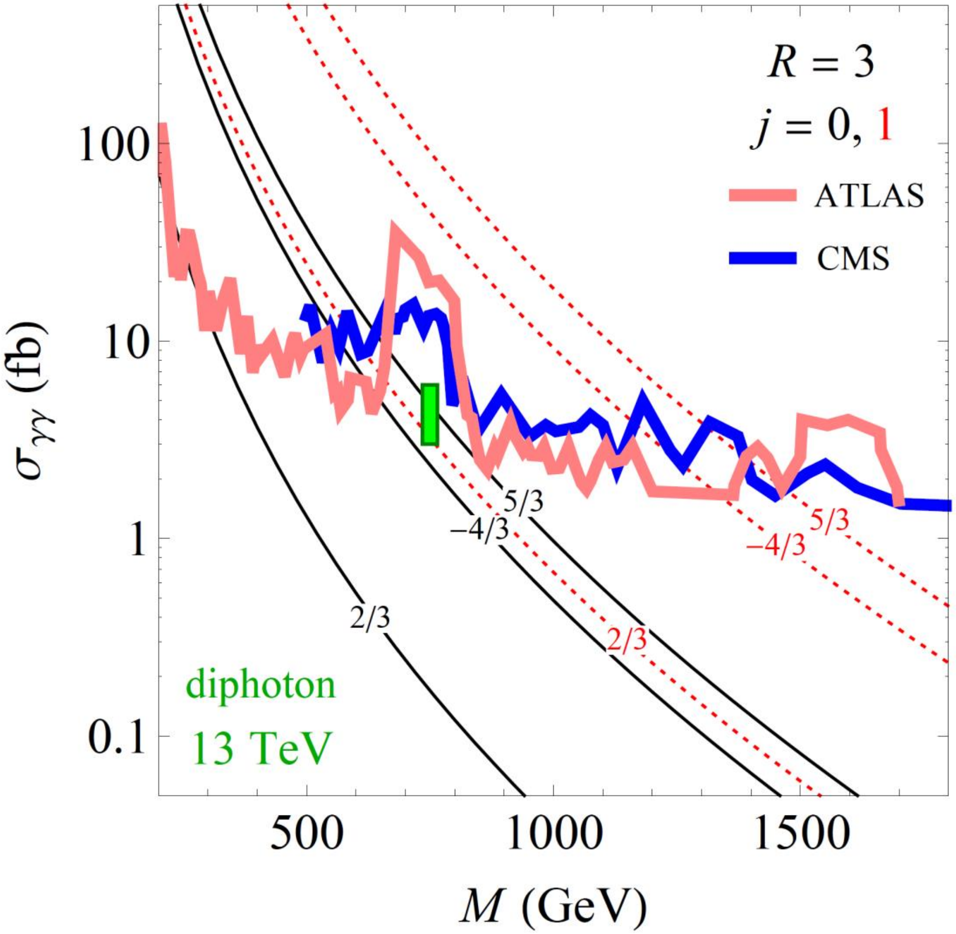
Color-triplet fermion with Q = – 4/3 is a candidate.

Proposed also by Han, Ichikawa, Matsumoto, Nojiri, Takeuchi (arXiv:1602.08100)

Diphoton signal



ATLAS (13 TeV, 3.2/fb)

ATLAS-CONF-2015-081

CMS (13 TeV, 2.6/fb)

CMS PAS EXO-15-004

Color-triplet scalars with Q = – 4/3 or 5/3 are candidates.

(In principle, also a vector with Q = 2/3.)

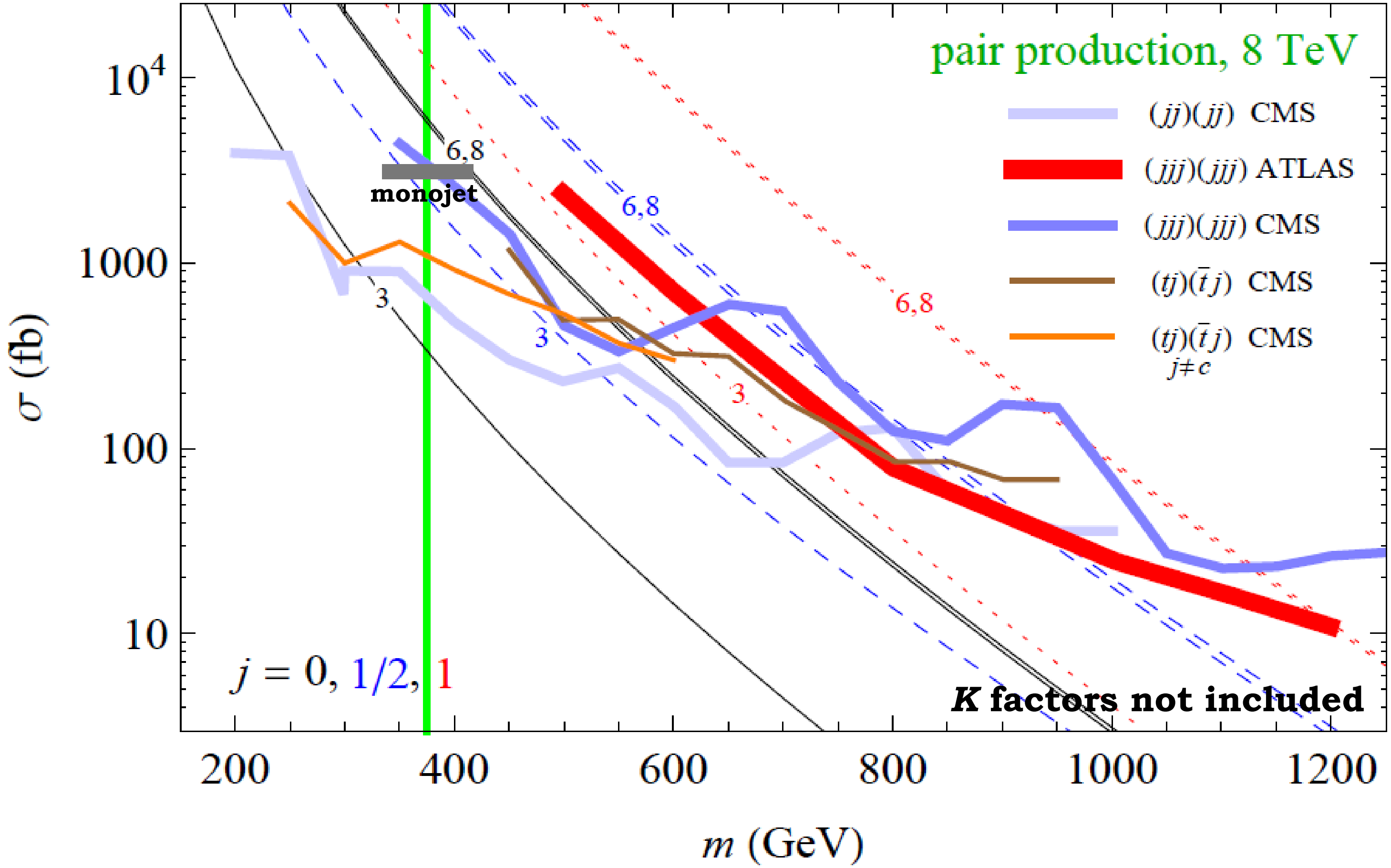
Are these scenarios realistic?

Can pair production of colored 375 GeV particles evade all Run 1 searches?

Limits on $\Gamma\bar{\Gamma}$ pair production

Examples of difficult final states

$\Gamma \rightarrow$ 2 jets, 3 jets, 4 jets, top + jet, compressed spectra (like stealthy stops)



arXiv:1412.7706

arXiv:1502.05686

arXiv:1311.1799

arXiv:1311.5357

CMS-PAS-B2G-12-008

Monojet limit estimated from:

arXiv:1407.0608

CMS-PAS-SUS-13-009

arXiv:1507.05525

Color-triplet scalars have a good chance.

Color-triplet fermions or **color-sextet scalars** need to be lucky.

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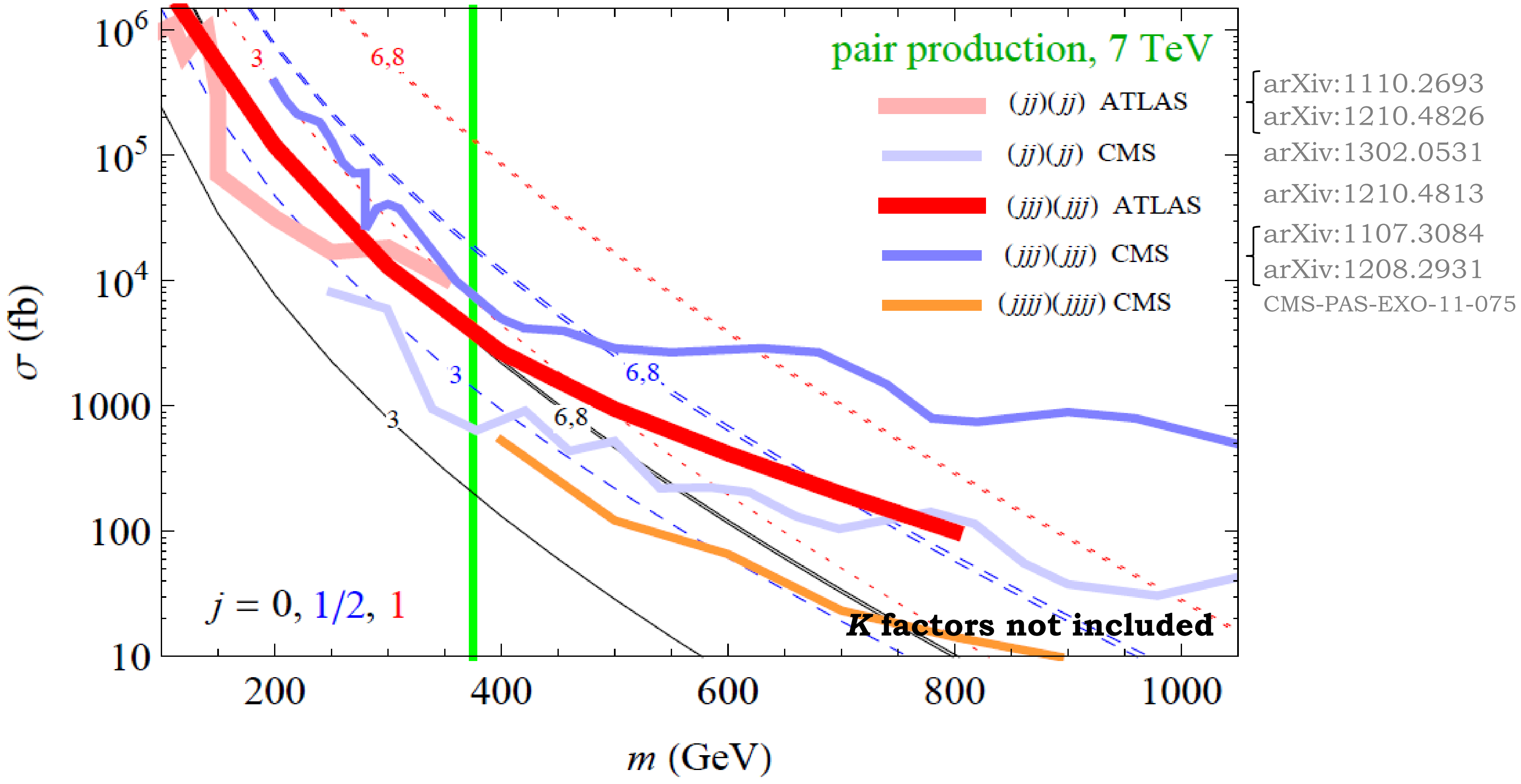

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Example: decay of scalar $\Gamma(3,1)_{-4/3}$

The dimension-4 operator

$$\mathcal{L}_{\text{int}} = -\frac{c_{ij}}{2}\epsilon_{\alpha\beta\gamma}\Gamma^{*\alpha}\bar{u}_i^{\beta}\bar{u}_j^{\gamma} + \text{h.c.}$$

allows decays to 2 jets $\Gamma \;\rightarrow\; \bar{u}\bar{c}$

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c_{ij} necessarily violates flavor, but in a very safe way.

Giudice, Gripaios, Sundrum, arXiv:1105.3161

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We assume $10^{-7} \underset{\uparrow}{\lesssim} |c_{ij}| \underset{\uparrow}{\lesssim} 10^{-2}$ (like most SM Yukawas!)

so that…
Γ decays are prompt
Γ annihilation is faster than intrinsic Γ decays

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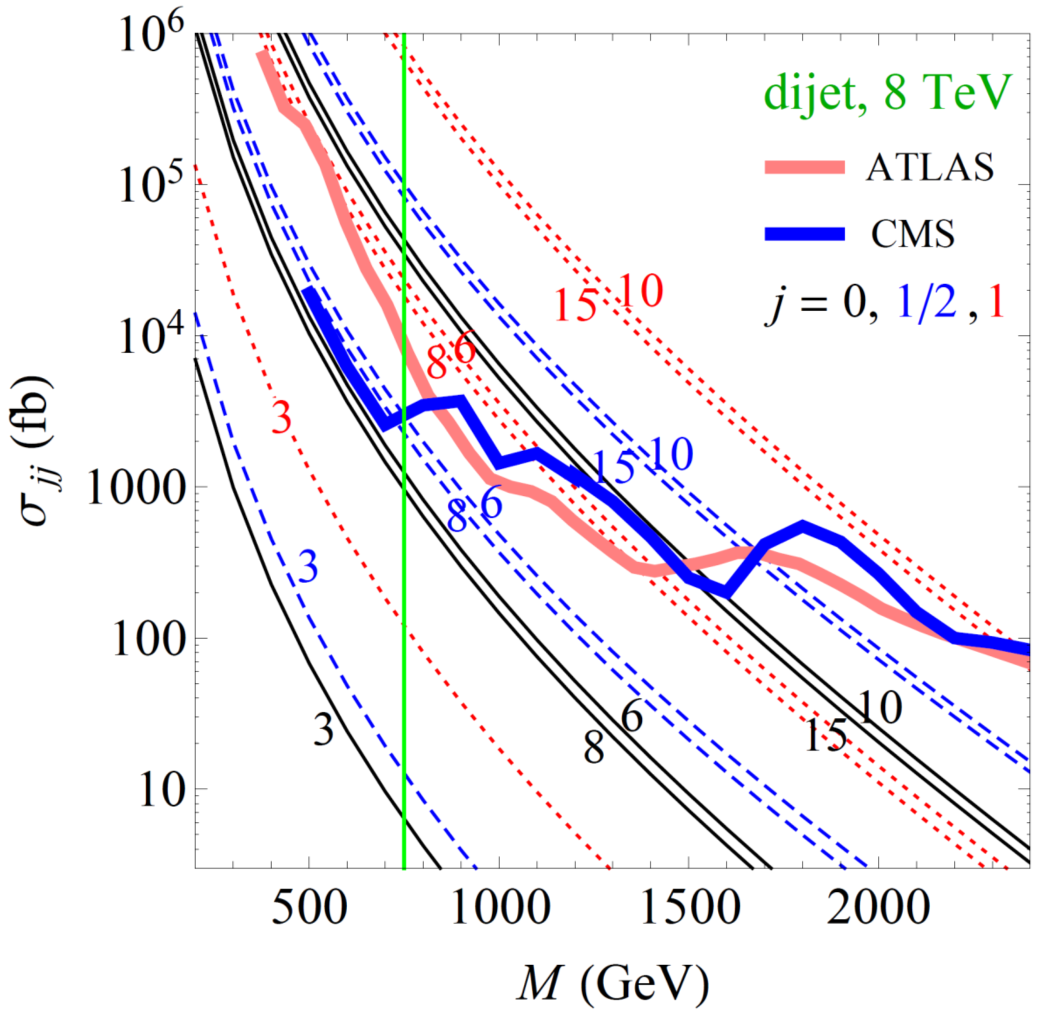
Places to discover this 375 GeV particle

- Pairs of dijet resonances
  e.g. 1302.0531 (CMS), 1412.7706 (CMS), 1601.07453 (ATLAS)
  but without b tagging
- Pairs of top+jet resonances
  e.g. 1311.5357 (CMS), CMS-PAS-B2G-12-008 (CMS)
- Top+jet on one side, dijet on another

Charm
tagging
may help

750 GeV peaks expected in other channels

Dijet signals



ATLAS (8 TeV, 20/fb)

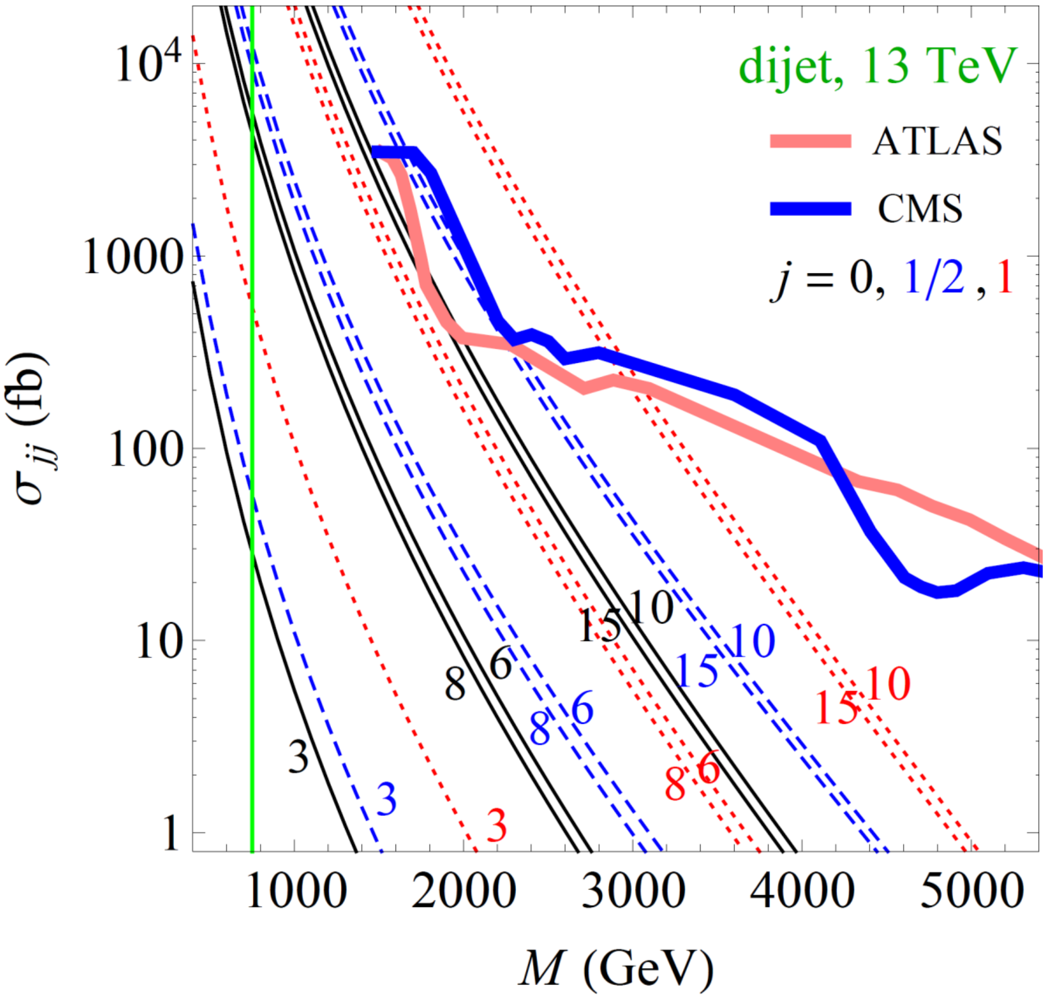
arXiv:1407.1376

CMS (8 TeV, 20/fb)

arXiv:1501.04198
CMS-PAS-EXO-14-005

- Color triplets (R = **3**) are far below sensitivity.
- Fermions in R = **6** or **8** are disfavored; higher representations excluded.

Dijet signals



ATLAS (13 TeV, 3.6/fb)

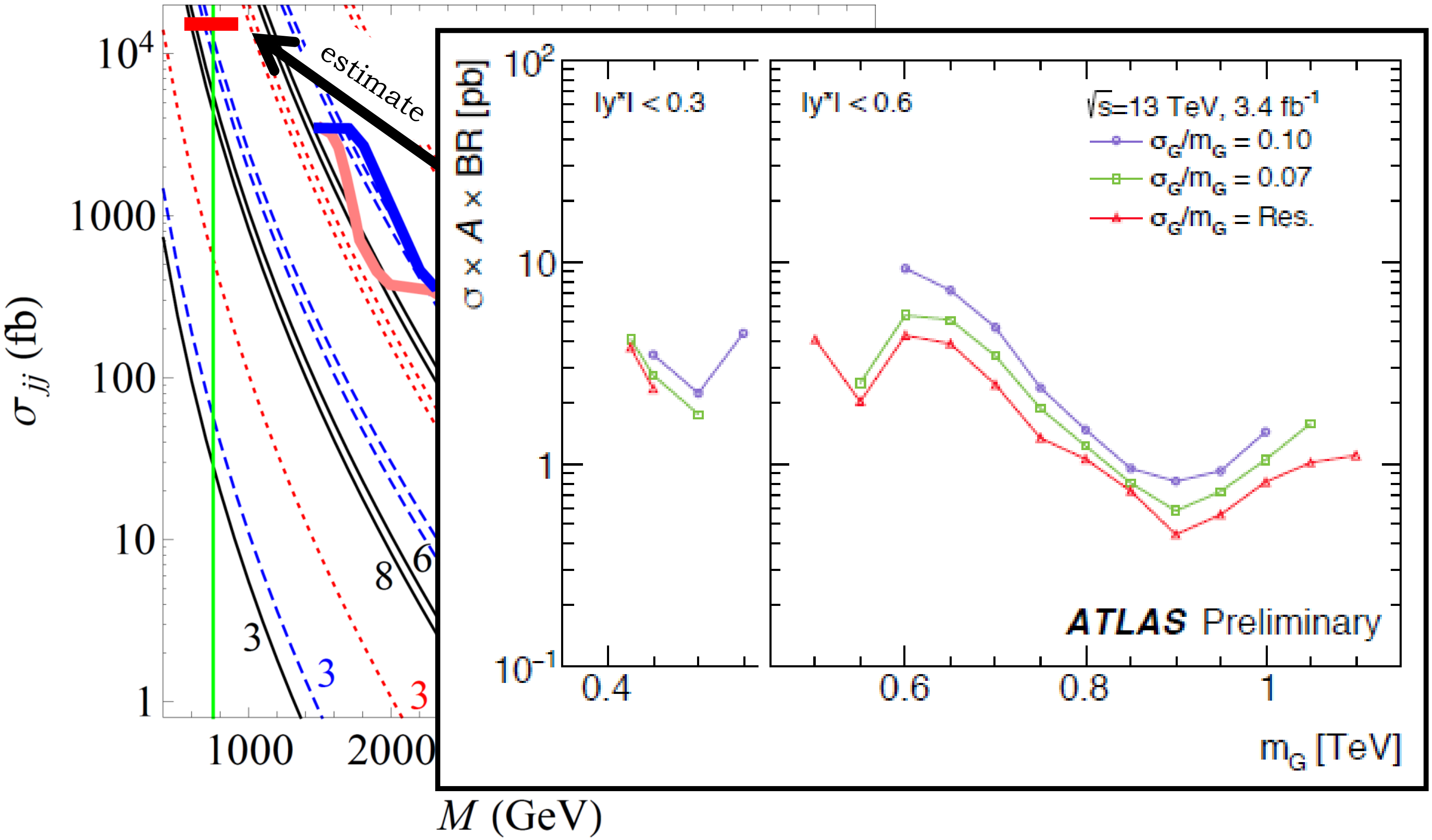
arXiv:1512.01530

CMS (13 TeV, 2.4/fb)

arXiv:1512.01224

At the time of publication, no Run-2 limits below 1 TeV: trigger limitations require special techniques.

Dijet signals



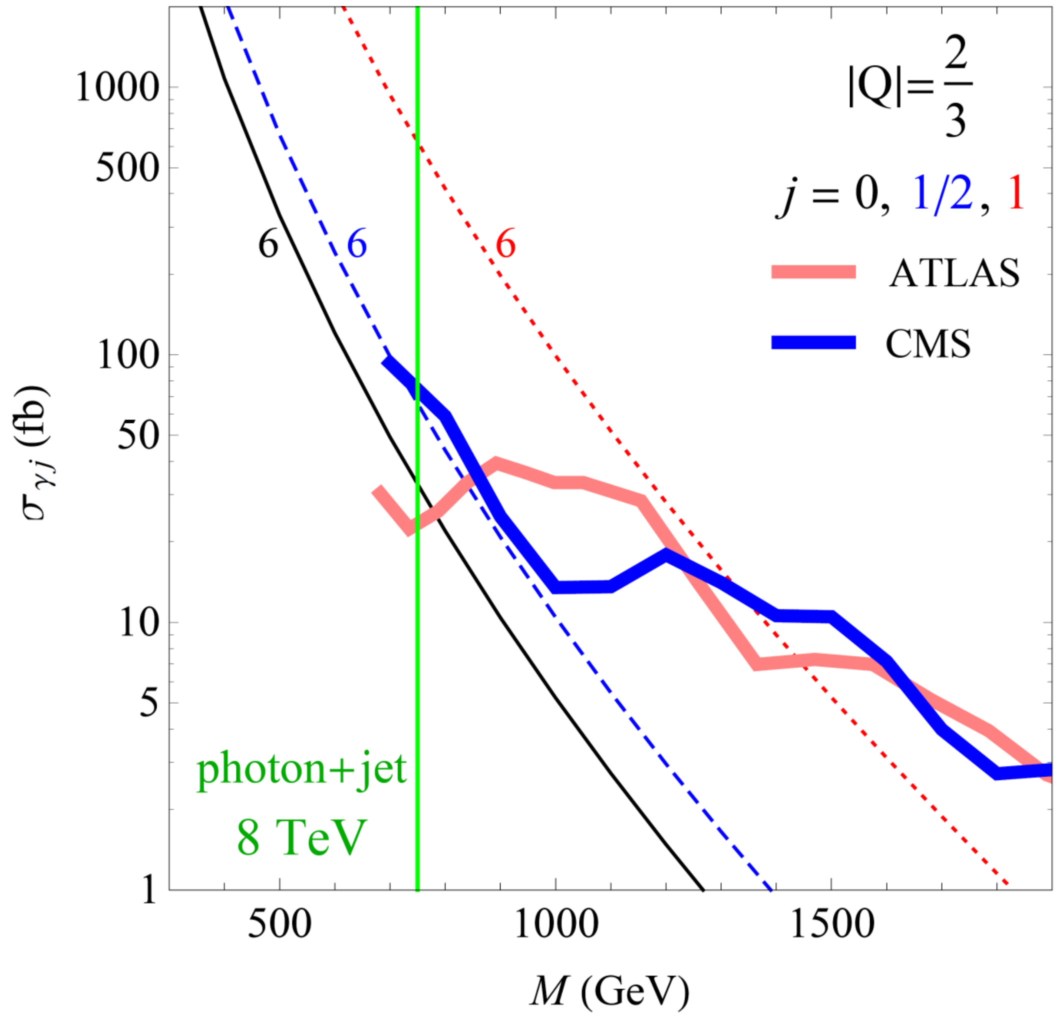
ATLAS (13 TeV, 3.4/fb)

ATLAS-CONF-2016-030

Just appeared: ATLAS's trigger-level analysis!

Signal of $j = 0$, R = **6**, Q = 2/3 may soon become observable.

Photon+jet signals



ATLAS (8 TeV, 20/fb)

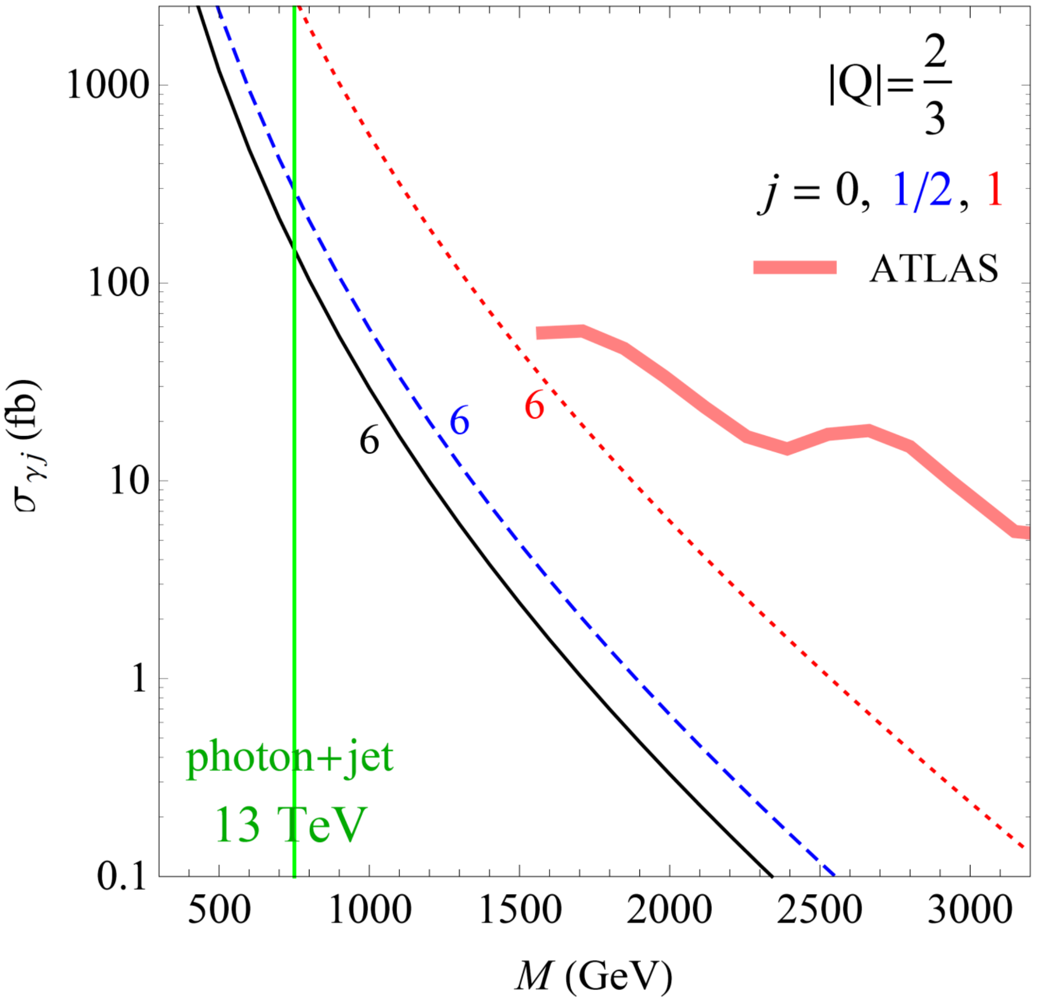
arXiv:1309.3230

CMS (8 TeV, 20/fb)

arXiv:1406.5171

- Irrelevant for R = **3** (no color-octet bound states).
- Marginal exclusion of j = 0, R = **6**, Q = 2/3.

Photon+jet signals

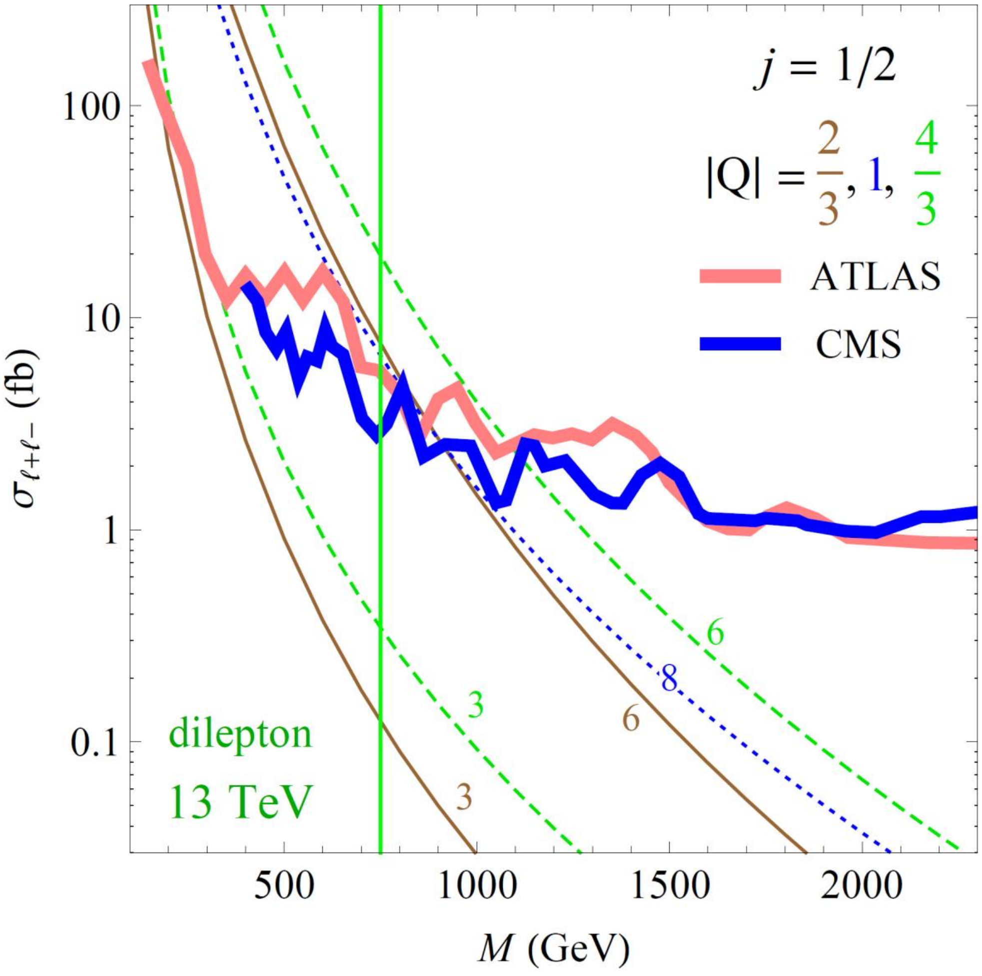


ATLAS (13 TeV, 3.2/fb)

arXiv:1512.05910

Run-2 limit does not extend down to 750 GeV.

Dilepton signals



ATLAS (13 TeV, 3.2/fb)

ATLAS-CONF-2015-070

CMS (13 TeV, 2.6/fb)

CMS-PAS-EXO-15-005

- Irrelevant for scalars.
- Color-triplet fermion with Q = – 4/3 is safe.
- Color-sextet fermion with Q = 2/3 is excluded.

Diboson signals

Same diagrams with Z or W instead of γ.

For SU(2)-singlet constituents:

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{\gamma\gamma}} = 2\tan^2\theta_W \approx 0.6$$

$$\frac{\Gamma_{ZZ}}{\Gamma_{\gamma\gamma}} = \tan^4\theta_W \approx 0.1$$

$$\frac{\Gamma_{WW}}{\Gamma_{\gamma\gamma}} = 0$$

i.e. well below current and near-future sensitivity.

e.g., Sato, Tobioka, arXiv:1605.05366

For constituents in higher SU(2) reps: see paper.

Narrow or broad?

Annihilation width (dominated by $\Gamma_{gg} \sim \alpha_s^2 \bar{\alpha}_s^3 M$) is tiny.

For example,

$$\Gamma_{\mathrm{ann}} \approx 0.005\ \mathrm{GeV} \ll 45\ \mathrm{GeV}$$

in the $\mathit{\Gamma}(3,1)_{-4/3}$ scalar case.

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(or require unreasonably large charges / color reps).

The **binding energy** (in the Coulomb approximation) is

$$E_b \approx -3.4 \text{ GeV} \quad \text{for } R = \mathbf{3}$$

$$-20 \text{ GeV} \quad \text{for } R = \mathbf{6}$$

Might produce an apparent width in the sextet case.

Overview of signatures

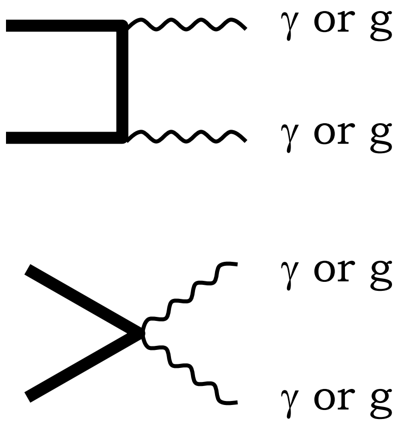
Constituents			**Diphoton signal**	**Most important accompanying signatures**	
j	R	Q	σ BR$_{\gamma\gamma}$ (fb)	**non-resonant (examples)**	**resonant**
0	3	– 4/3	2.3	$(jj)(jj)$ $(tj)(\bar{t}j)$	
0	3	5/3	4.8	$(jjjj)(jjjj)$	
½	3	– 4/3	4.7	~~$(jjj)(jjj)$~~ $(tjj)(\bar{t}jj)$? ~~monojet~~	$\ell^+\ell^-$
0	6	– 2/3	3.9	~~$(jj)(jj)$~~ ~~monojet~~	gg, ~~γg~~ $\gamma\gamma$ of rad. excit. ($\Delta M \sim 15$ GeV) If SU(2) doublet: $Z\gamma$, ZZ, WW If spin ½: ~~$\ell^+\ell^-$~~

CMS: 2.4–5.1 fb (at 1σ) ↔ Theory prediction has a factor-of-2 uncertainty.

Thank You!

Backup slides

Annihilation channels of interest



Relevant to bound states with **J = 0 or 2**

$J = 0$: S-waves possible for $j = 0, \frac{1}{2}, 1$

$J = 2$: S-waves possible for $j = 1$

Diphoton: color-singlet

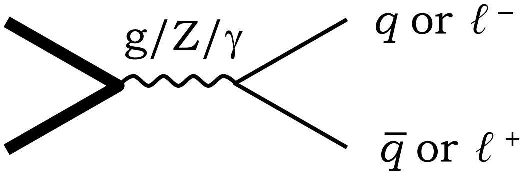
possible for any R using δ_{ij}

Photon + jet (gluon): color-octet

possible for any R using T^a_{ij} (but repulsive for **3**)

Dijet (gg): color **1**, **8**, **10**, or **27**

at least the singlet is possible for any R



Relevant to bound states with **J = 1**

S-waves possible for $j = \frac{1}{2}$

Also possible for $j = 1$, but with $J^{PC} = 1^{+-}$ (not useful)

Dilepton: color-singlet

possible for any R using δ_{ij}

Dijet ($q\bar{q}$): color-octet

possible for any R using T^a_{ij} (but repulsive for **3**)

Cross sections

Diphoton

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

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

Photon+jet

$$\sigma_{\gamma g} = \frac{Q^2\left(C_R - \frac{3}{2}\right)^3 T_R}{4}\,\pi^2 \alpha\, \alpha_s\, \overline{\alpha}_s^3\,\frac{\mathcal{L}_{gg}(M^2)}{M^2}$$

(except for **8**, since production is proportional to A_R)

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

Dijet

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

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

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

All the expressions on this slide are for spin-0 particles.

Multiply by 2 for spin-½ particles, or 19 for spin-1 particles.

For spin-½ particles with $R \neq 3$, also $q\bar{q}$ dijets:

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

Cross sections

Dilepton (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

Cross sections

Dilepton (only for spin-½ particles) – cont’d

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

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

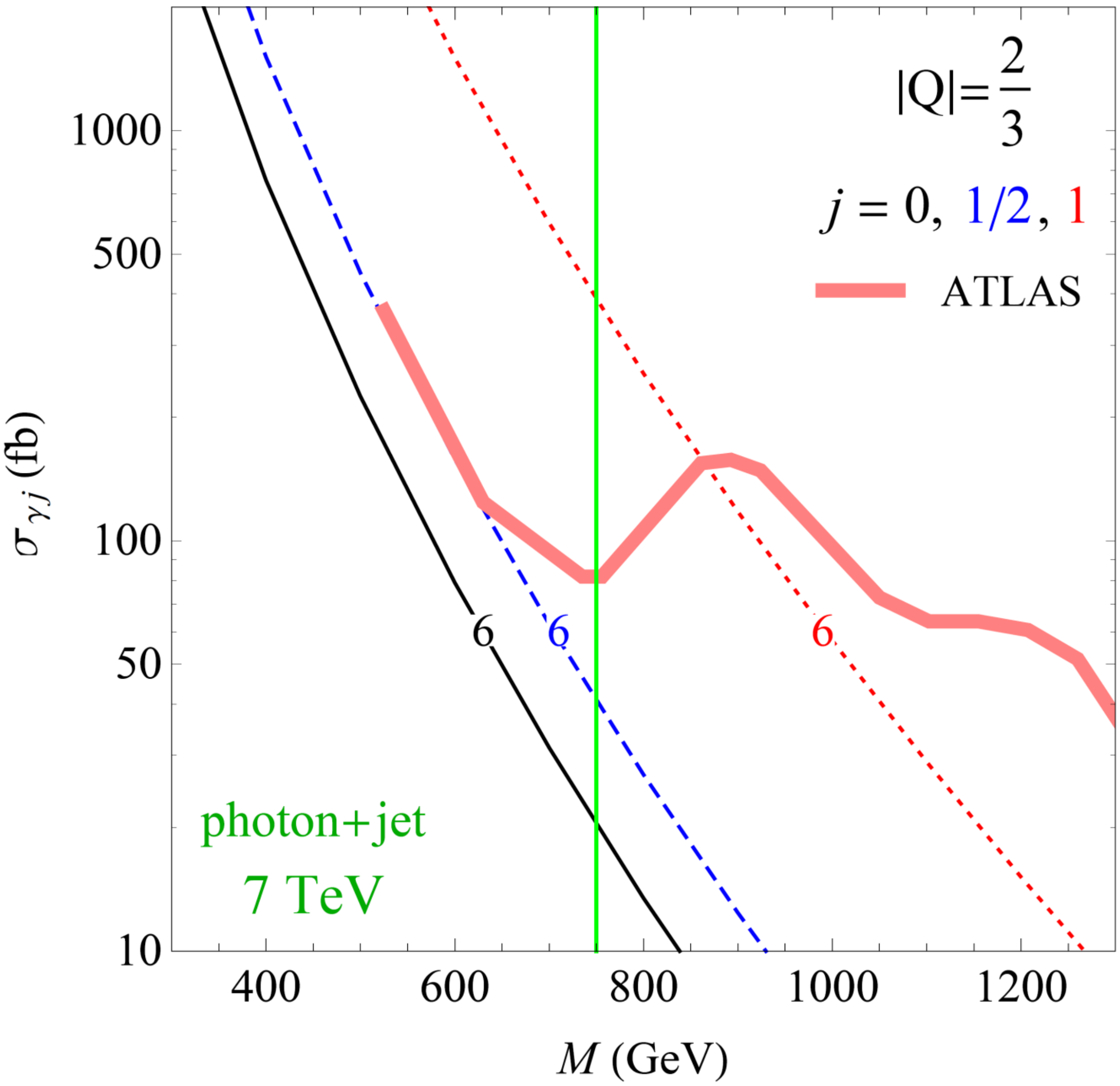
(4) Production via color-octet P waves $^3P_J^{(\mathbf{8})}$:

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

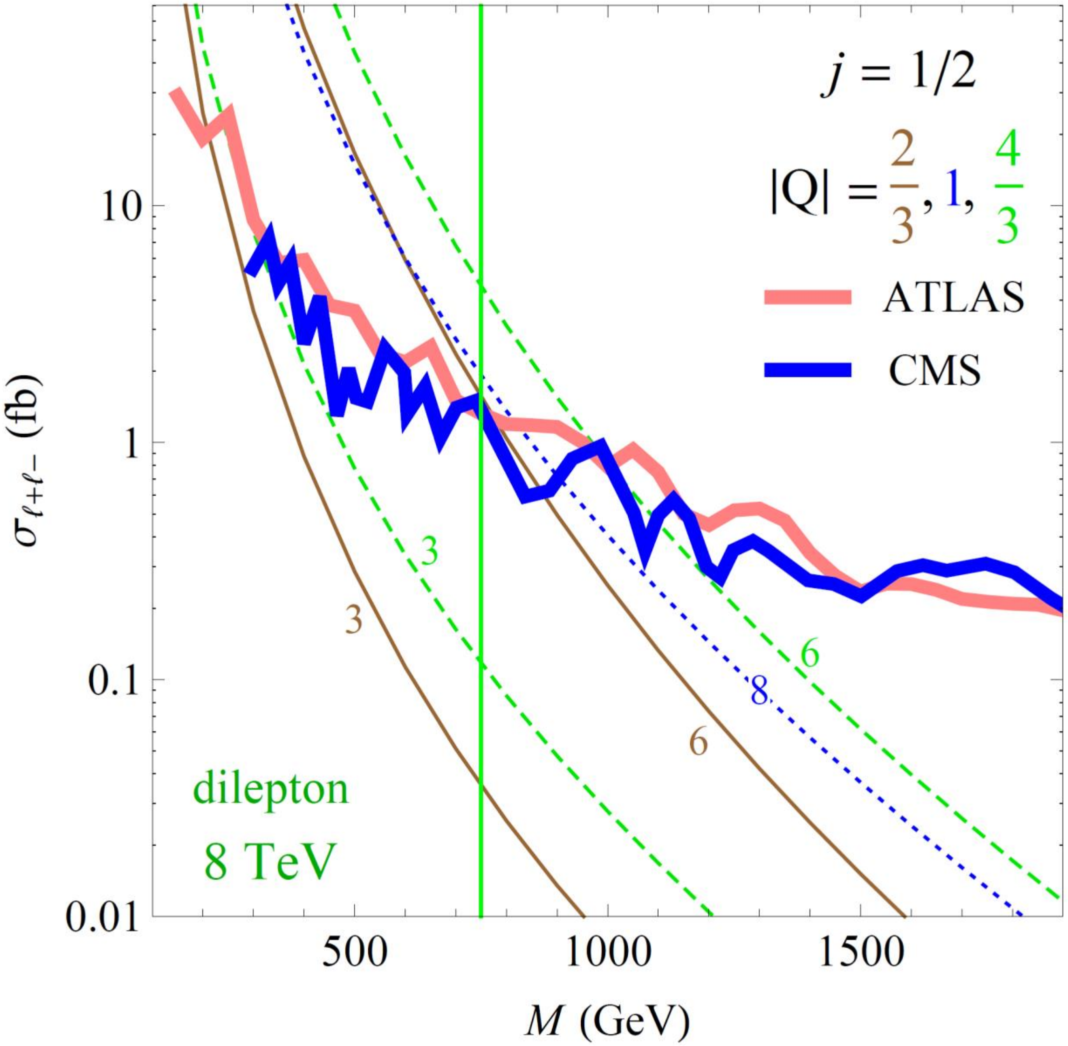
Photon+jet limit from the 7 TeV LHC



ATLAS (7 TeV, 2.1/fb)

arXiv:1112.3580

Dilepton limits from the 8 TeV LHC



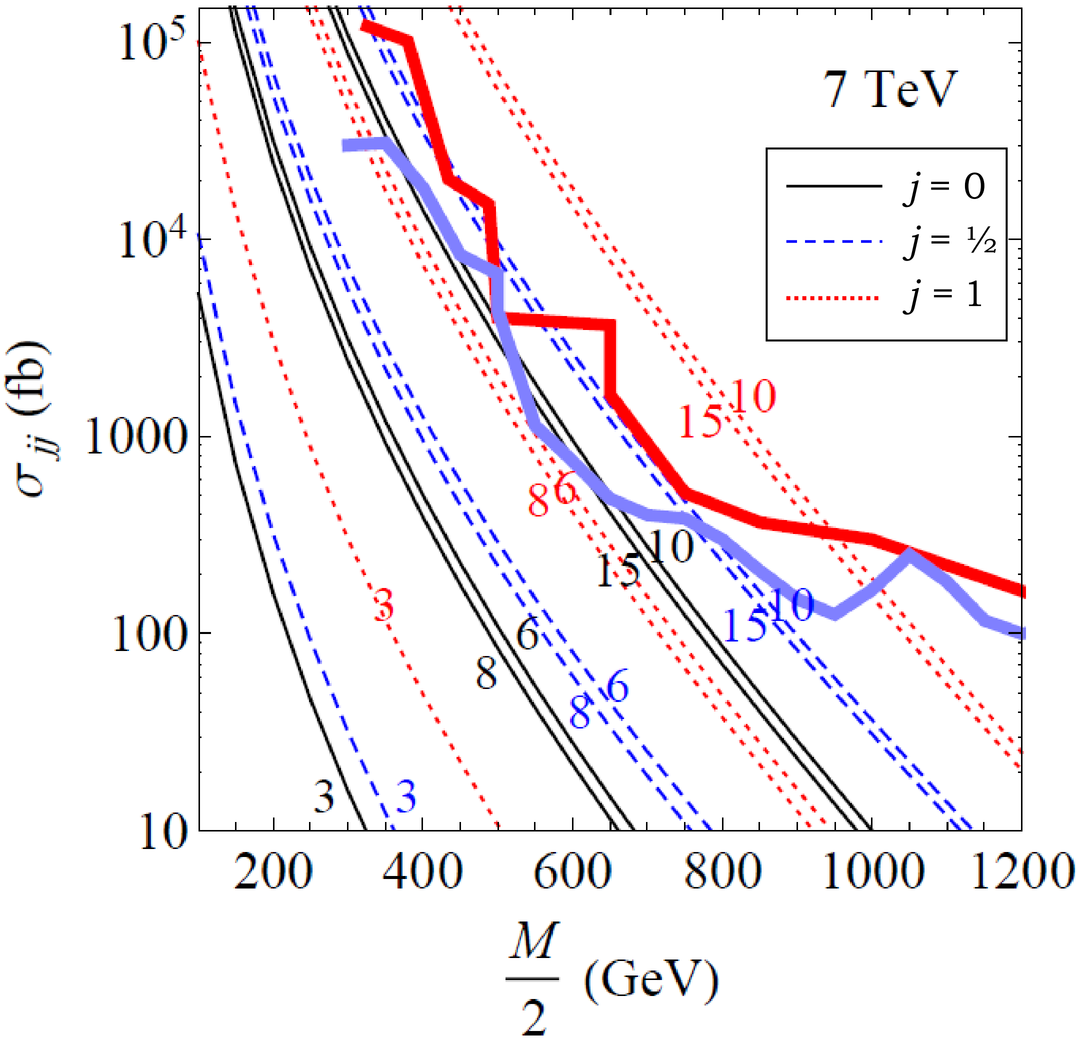
ATLAS (8 TeV, 20/fb)

arXiv:1405.4123

CMS (8 TeV, 20/fb)

arXiv:1412.6302

Dijet limits from the 7 TeV LHC



ATLAS (7 TeV, 5/fb)

ATLAS-CONF-2012-038

For lower masses:

ATLAS (7 TeV, 1/fb)

arXiv:1108.6311

For yet lower masses:

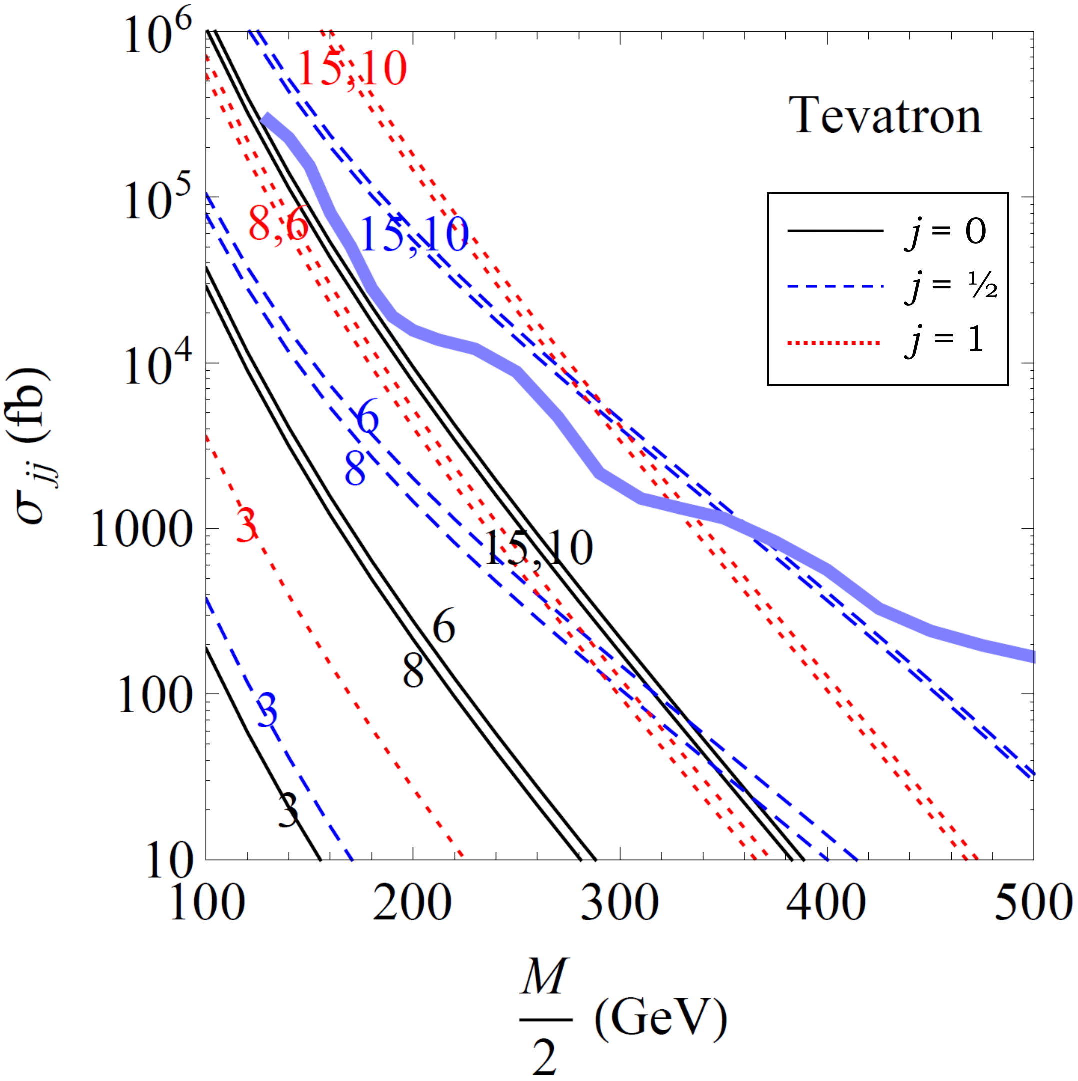
ATLAS (7 TeV, 36/pb)

arXiv:1103.3864

CMS (7 TeV, 5/fb)
(0.13/fb for $M/2$ < 500 GeV)

CMS PAS EXO-11-094

Dijet limit from the Tevatron



CDF (1.96 TeV, 1.1/fb)

arXiv:0812.4036

Broader spectrum of ideas

QCD production, QCD binding

WE ARE HERE

1512.06670	Luo, Wang, Xu, Zhang, Zhu
1512.08221	Chway, Dermisek, Jung, Kim (above threshold)
1602.08100	Han, Ichikawa, Matsumoto, Nojiri, Takeuchi
1604.07828	Hamaguchi, Liew

QCD production, QCD + hidden QCD binding

1512.05753	Curtin, Verhaaren
1512.05775	Agrawal, Fan, Heidenreich, Reece, Strassler
1512.07733	Craig, Draper, Kilic, Thomas
1603.07719	Kamenik, Redi
1603.08802	Ko, Yu, Yuan
1604.06180	Foot, Gargalionis

Photon-fusion production, QED binding

1604.02803	Barrie, Kobakhidze, Liang, Talia, Wu

Photon-fusion production, QED + hidden QCD binding

1604.07776	Iwamoto, Lee, Shadmi, Ziegler
1605.01937	Anchordoqui, Goldberg, Huang

Heavy-Higgs-portal production, dark QED binding, displaced e^+e^- fake γ

1602.08816	Bi, Kang, Ko, Li, Li (asymmetric dark matter context)