Multijets in the EFT

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LHC Theory ERC meeting

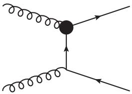
Contents

- No evidence of a light BSM state after the first LHC13 results.
- Study the effect of any heavy state at the LHC energy range.
- EFT approach

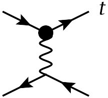
$$\mathcal{L}_{Eff} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + O(\Lambda^{-4})$$

- Uses the SM symmetries to reduce the number of relevant operators. [arXiv:1008.4884]
- It is gauge invariant.
- It is renormalisable order by order in the $(1/\Lambda)$ expansion.
- It assumes that the new possible states are heavier than the energy probed.

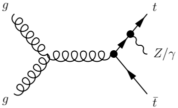
- One cannot be selective on the effect of a new heavy state $\Longrightarrow$ Global EFT analysis is recommended in a process by process basis.
- TopSMEFT



$\longleftarrow O^{(6)}_{tG}, O^{(6)}_{G}, O^{(6)}_{\phi G}$



$\longleftarrow O^{(6)}_{tW}, O^{(6)}_{\phi Q,3}$



$\longleftarrow O^{(6)}_{tG}, O^{(6)}_{G}, O^{(6)}_{\phi Q,3}, O^{(6)}_{\phi Q,1}, O^{(6)}_{\phi t}, O^{(6)}_{tW}, O^{(6)}_{tB}$

$+\ O^{(6)}_{4F}$ operators

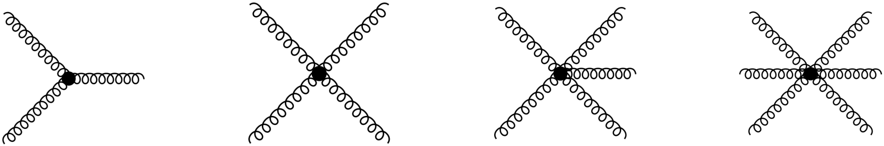
- The more the operators, the more difficult to constrain them.
- What about the operators that enter almost all the LHC processes? Look in specific processes and observables where their effect is enhanced.

Structure of $O_G^{(6)}$

- Operator $O_G^{(6)}$

$$g_s f_{abc} G^{\rho}_{a\nu} G^{\nu}_{b\lambda} G^{\lambda}_{c\rho}\ ,\ \ G^{\rho\nu}_{a} = \partial^{\rho} G^{\nu}_{a} - \partial^{\nu} G^{\rho}_{a} - i g_s f_{abc} G^{b\rho} G^{c\nu}$$

- It provides from 3- to 6- point gluon vertices.



$\frac{g_s c_G}{\Lambda^2} \partial\partial\partial GGG$ $\quad$ $\frac{g_s^2 c_G}{\Lambda^2} \partial\partial GGGG$ $\quad$ $\frac{g_s^3 c_G}{\Lambda^2} \partial GGGGG$ $\quad$ $\frac{g_s^4 c_G}{\Lambda^2} GGGGGG$

Special features of $O_G^{(6)}$

- The helicity structure of the $O_G^{(6)}$ in $gg \to gg$ is orthogonal w.r.t. the QCD one $\Longrightarrow$ The interference term $(O(1/\Lambda^2))$ is zero. [hep-ph/9312363]
- It has been studied in $t\bar{t}$ [hep-ph/9408206] and 3-jet [hep-ph/9312363] production.

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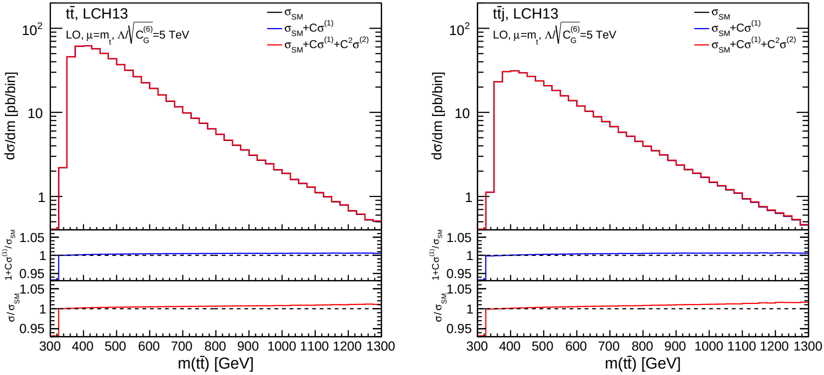
- It has been studied in $t\bar{t}$ [hep-ph/9408206] and 3-jet [hep-ph/9312363] production.
- Start with $t\bar{t}$ and $t\bar{t}j$ processes.
- Small effect in all observables.



Special features of $O_G^{(6)}$

- Search in a rich environment on these vertices: multijet production. [arXiv:1611.00767]
- Choose a sensitive variable

$$S_T = \sum_{j=1}^{Njets} E_{T,j}$$

- Recent experimental results became public on this observable. [CMS-PAS-EXO-15-007]
- Other relevant operators are the $O_{4q}^{(6)}$: strong bounds from di-jet ATLAS analysis. [arXiv:1512.01530]

$O_G^{(6)}$ in multijet production

- The effect changes with the jet multiplicity.

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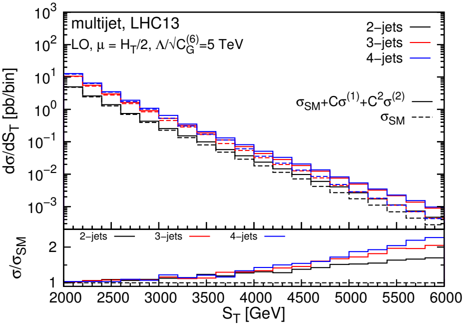
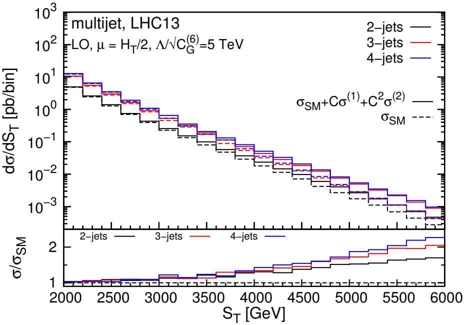


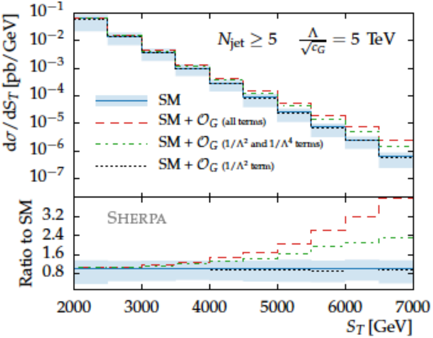
Increasing the jet multiplicity

$O_G^{(6)}$ in multijet production

- The effect changes with the jet multiplicity.

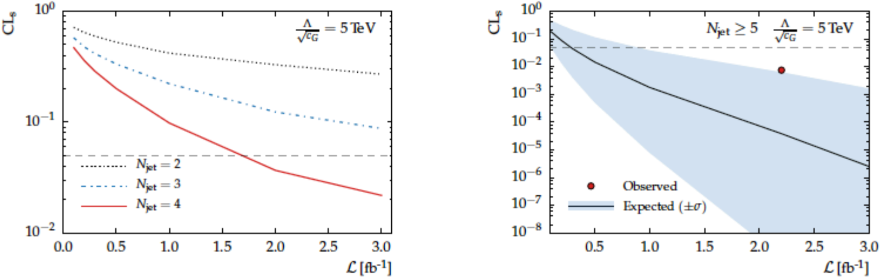


[arXiv:1611.00767]



- The ratio R increases with the jet multiplicity.
- Even in higher multiplicities the interference term is small.
- Multiple insertions become important for $S_T > \Lambda$.

Recent constraints on $O_G^{(6)}$ [arXiv:1611.00767]



- Expected signal CL's vs integrated luminosity.
- Show the EFT validity.
- Understand the increase of the $O_G^{(6)}$ effect with the jet multiplicity.

S_T vs M

- Correlation plot of S_T vs M.
- The variable M is closer to $\sqrt{\hat{s}}$, which should be compared to Λ.

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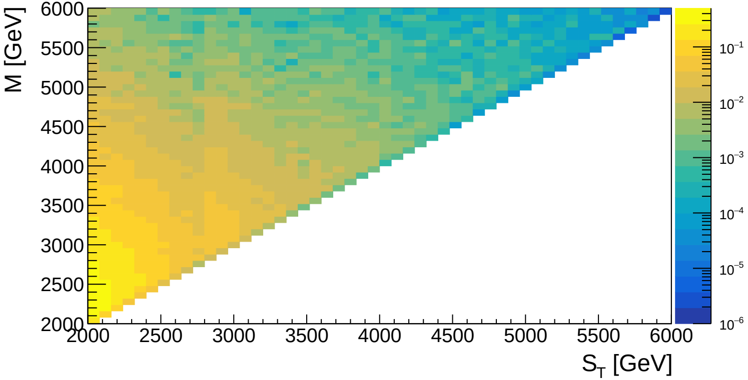

- M is always larger or equal to S_T. Even for $S_T < 5$ TeV we can have $M > 5$ TeV.
- Can we keep these events? What is the effect if we drop them?

S_T vs M

- Compare the results for 4-jet production with an extra cut of $M < 5$ TeV.

S_T vs M

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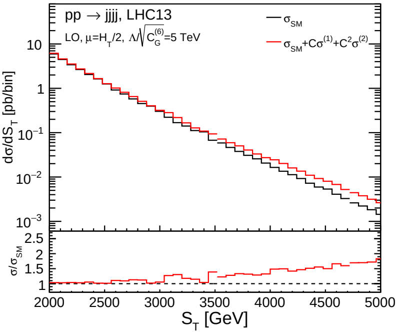

- The ratio R is not affected.
- This behaviour is verified also in 3-jet production.

- Need for dim-8 check because the effect comes from the $O(1/\Lambda^4)$ term.
- List of relevant dim-8 operators. [hep-ph/9408206]
- Choose two

$$O_4^{(8)} = \frac{g_s^2}{2} G^a_{\mu\nu} G_a^{\mu\nu} G^b_{\lambda\sigma} G_b^{\lambda\sigma}$$

$$O_6^{(8)} = \frac{g_s^2}{2} G^a_{\mu\nu} G_b^{\mu\nu} G^a_{\lambda\sigma} G_b^{\lambda\sigma}$$

Include dim-8 operators

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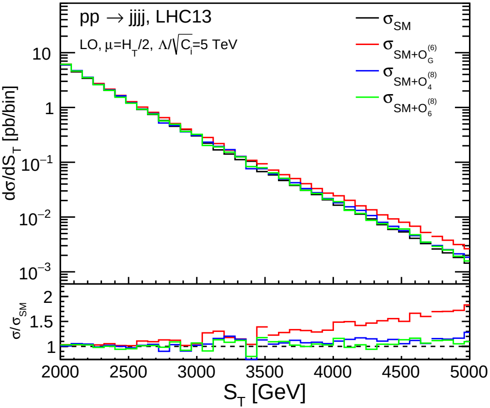
- Very small effect w.r.t. $O_G^{(6)}$.



- We are within the EFT validity regime.

- The higher the multiplicity the higher-point $O_G^{(6)}$ insertions are allowed.
- Check if the high *n*-point vertices are the most important.
- Compare the 4-jet with the 4-q production.

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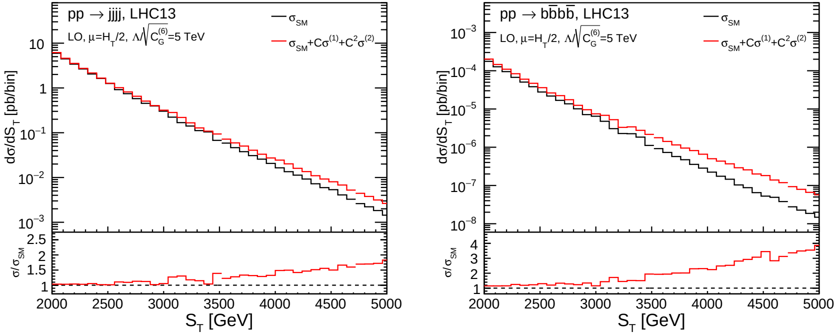

- In 4-*q* production the 5- and 6- point vertices are absent, but the ratio R increases.

- Isolate the gluonic channels.

Gluonic channels

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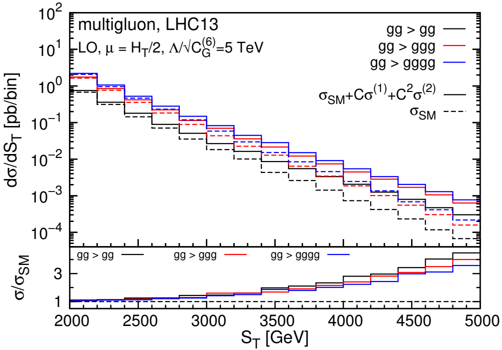
- Gluons $\uparrow \Longrightarrow R \downarrow$
- What we see at multijet production is not seen in the gluonic channels.
- $G \uparrow \Longrightarrow \partial \downarrow$
- Look at the different channel luminosities in all cases.



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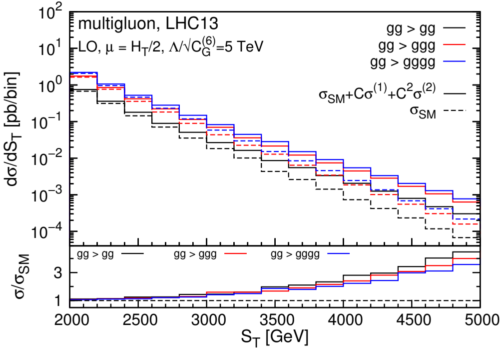

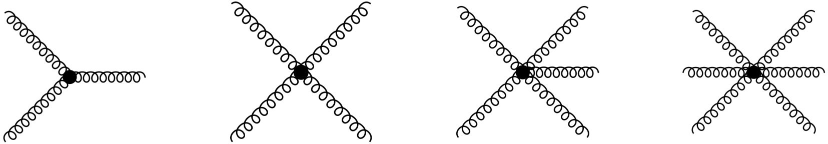

$\frac{g_s c_G}{\Lambda^2} \partial\partial\partial GGG$ $\frac{g_s^2 c_G}{\Lambda^2} \partial\partial GGGG$ $\frac{g_s^3 c_G}{\Lambda^2} \partial GGGGG$ $\frac{g_s^4 c_G}{\Lambda^2} GGGGGG$

2-jet production

ST>4.7 TeV

SM			SM+OG		
channel	xsec	(%)	channel	xsec	(%)
GG -> GG	1.98E-04	2.115	GG -> GG	1.00E-03	6.950
GG -> qq	9.64E-06	0.103	GG -> qq	1.10E-04	0.764
Gq -> Gq	2.62E-03	27.888	Gq -> Gq	6.44E-03	44.636
qq -> GG	2.92E-05	0.312	qq -> GG	3.48E-04	2.414
qq -> qq	6.52E-03	69.577	qq -> qq	6.52E-03	45.233
total	9.38E-03	99.995	total	1.44E-02	99.997

(SM+OG)/SM	
GG -> GG	5.05
GG -> qq	11.42
Gq -> Gq	2.46
qq -> GG	11.91
qq -> qq	1.00
total	1.54

- $R(q\bar{q} \to q\bar{q}) = 1$ regardless S_T, no $O_G^{(6)}$ insertions.
- At large S_T values the high R subprocesses are not the ones that dominate.

3-jet production

ST>4.7 TeV

SM		
channel	xsec	(%)
GG -> GGG	4.25E-04	2.792
GG -> Gqq	4.20E-05	0.276
Gq -> GGq	4.99E-03	32.817
Gq -> qqq	2.31E-04	1.521
qq -> GGG	3.85E-05	0.253
qq -> Gqq	9.48E-03	62.346
total	1.52E-02	100.004

SM+OG		
channel	xsec	(%)
GG -> GGG	1.99E-03	7.406
GG -> Gqq	3.00E-04	1.120
Gq -> GGq	1.19E-02	44.452
Gq -> qqq	5.97E-04	2.227
qq -> GGG	5.65E-04	2.106
qq -> Gqq	1.15E-02	42.700
total	2.68E-02	100.011

(SM+OG)/SM	
GG -> GGG	4.68
GG -> Gqq	7.16
Gq -> GGq	2.39
Gq -> qqq	2.58
qq -> GGG	14.68
qq -> Gqq	1.21
total	1.76

- $q\bar{q}$ still dominant, but there are no subprocess with $R = 1$.
- From 2- to 3- jets the qg channel is enhanced.

4-jet production

ST>4.7 TeV

SM			SM+OG			(SM+OG)/SM	
channel	xsec	(%)	channel	xsec	(%)		
GG -> GGGG	6.09E-04	3.857	GG -> GGGG	2.21E-03	7.492	GG -> GGGG	3.63
GG -> GGqq	7.52E-05	0.476	GG -> GGqq	4.34E-04	1.471	GG -> GGqq	5.77
GG -> qqqq	1.30E-06	0.008	GG -> qqqq	8.58E-06	0.029	GG -> qqqq	6.62
Gq -> GGGq	5.45E-03	34.530	Gq -> GGGq	1.24E-02	42.057	Gq -> GGGq	2.28
Gq -> Gqqq	4.58E-04	2.900	Gq -> Gqqq	1.38E-03	4.684	Gq -> Gqqq	3.02
qq -> GGGG	3.52E-05	0.223	qq -> GGGG	4.78E-04	1.622	qq -> GGGG	13.60
qq -> GGqq	8.89E-03	56.350	qq -> GGqq	1.21E-02	40.870	qq -> GGqq	1.36
qq -> qqqq	2.62E-04	1.660	qq -> qqqq	5.23E-04	1.775	qq -> qqqq	2.00
total	1.58E-02	100.005	total	2.95E-02	99.999	total	1.87

- Further increase of R for high S_T.

4-b production

ST>4.7 TeV

SM		
channel	xsec	(%)
GG -> qqqq	6.92E-08	45.652
qq -> qqqq	8.24E-08	54.348
total	1.52E-07	100.000

SM+OG		
channel	xsec	(%)
GG -> qqqq	4.28E-07	74.789
qq -> qqqq	1.44E-07	25.221
total	5.73E-07	100.010

(SM+OG)/SM	
GG -> qqqq	6.18
qq -> qqqq	1.75
total	3.77

- No qg channel.
- gg channel is large even at the tail with a large R (from 2-jet $R(gg \to gg) \approx 5$).
- 4-q channel is even more sensitive to $O_G^{(6)}$, but it is cross section suppressed.
- Increase of the $O_G^{(6)}$ effect at the high jet multiplicities $\Longleftarrow$ The large R channels become luminosity favoured.

- Operator $O_{\tilde{G}}^{(6)}$

$$g_s f_{abc} \varepsilon^{\mu\nu\rho\sigma} G^a_{\rho\sigma} G^b_{\mu\lambda} G^{c\lambda}_{\nu}\ ,\ G^{\rho\nu}_a = \partial^\rho G^\nu_a - \partial^\nu G^\rho_a - ig_s f_{abc} G^{b\rho} G^{c\nu}$$

- Contributes to neutron EDM: strong limits. [arXiv:1303.3156]
- Subject to large uncertainties, 1-$O_i^{(6)}$ fit.

The CP-odd triple-gluon operator

- Operator $O^{(6)}_{\tilde{G}}$

$$g_s f_{abc} \varepsilon^{\mu\nu\rho\sigma} G^a_{\rho\sigma} G^b_{\mu\lambda} G^{c\lambda}_{\nu} \ , \ G^{\rho\nu}_a = \partial^\rho G^\nu_a - \partial^\nu G^\rho_a - i g_s f_{abc} G^{b\rho} G^{c\nu}$$

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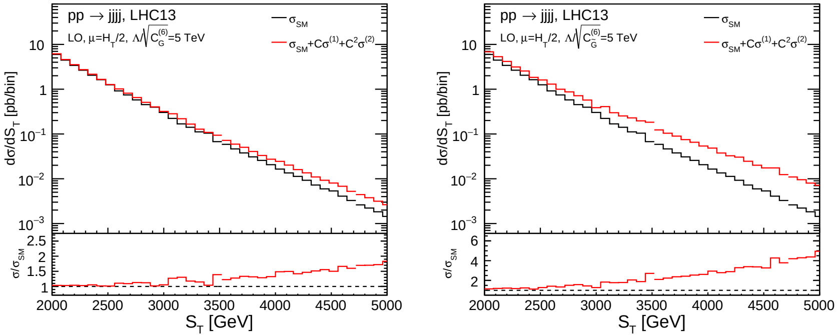

- Independent direct limits from colliders.

Conclusions- Further research

- The S_T variable in multijet processes can be used to constrain the $O_G^{(6)}$ operator. [see also the arXiv:1611.00767]
- Strong limit in high jet multiplicity within the EFT validity region.
- The effect of the $O_G^{(6)}$ is a combination of the different channel luminosities and the energy dependence of different $O_G^{(6)}$ parts.
- Larger enhancement in 4-b but this process is cross-section suppressed.
- Include the CP-odd $O_{\tilde{G}} \sim \tilde{G}GG$ operator.
- Use this result to put indirect bounds to heavy states (stops, vector-like quarks), appearing in loop corrections of the gluonic vertices.

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...Thank you

Operators

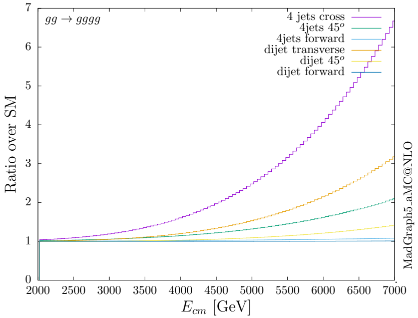
- $$O_{tG}^{(6)} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$
  $$O_{\phi G}^{(6)} = g_s (\phi^\dagger \phi) G^a_{\mu\nu} G^{a\mu\nu}$$

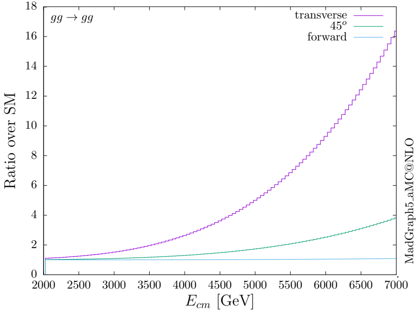
- $$O_{\varphi Q,3}^{(6)} = i\frac{1}{2} y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$
  $$O_{\varphi Q,1}^{(6)} = i\frac{1}{2} y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$
  $$O_{\varphi t}^{(6)} = i\frac{1}{2} y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$
  $$O_{tW}^{(6)} = y_t g_w (\bar{Q}\sigma^{\mu\nu} \tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$
  $$O_{tB}^{(6)} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

- $$O_{4q}^{(6)} = \sum_{q,q'} (\bar{q}_L \gamma^\mu q_L)(\bar{q}'_L \gamma^\mu q'_L)$$

Angles

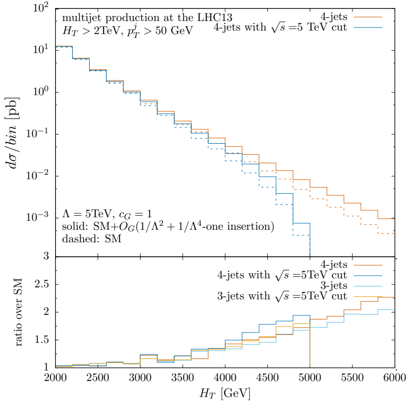
- Cross $\Longrightarrow S_T \approx M$ (largest ratio R)
- 45° $\Longrightarrow S_T < M$
- Forward $\Longrightarrow S_T << M$

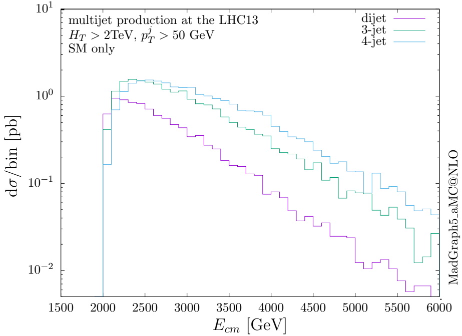




3-jet production, $M < 5$ TeV

- 4-jet and 3-jet S_T distribution with and without the $M < 5$ TeV cut
- E_{cm} for 4-jet, 3-jet and dijet





$t\bar{t}$ **production**

Enhance the $GG \to qq$ channel ($R = 11.42$)

ST>2 TeV

SM			SM+OG			(SM+OG)/SM	
channel	xsec	(%)	channel	xsec	(%)		
GG -> ttx	1.08E-02	50.730	GG -> ttx	1.56E-02	59.775	GG -> ttx	1.44
qq -> ttx	1.05E-02	49.278	qq -> ttx	1.05E-02	40.233	qq -> ttx	1.00
total	2.13E-02	100.008	total	2.61E-02	100.008	total	1.22

ST>4.7 TeV

SM			SM+OG			(SM+OG)/SM	
channel	xsec	(%)	channel	xsec	(%)		
GG -> ttx	1.86E-06	15.891	GG -> ttx	2.15E-05	68.627	GG -> ttx	11.58
qq -> ttx	9.82E-06	84.106	qq -> ttx	9.83E-06	31.385	qq -> ttx	1.00
total	1.17E-05	99.998	total	3.13E-05	100.011	total	2.68

- No qg channel
- Probes the $gg \to qq$ with the largest R, but there is also the $qq \to qq$ with $R = 1$
- Smaller effect w.r.t. $t\bar{t}j$

Enhance the $GG \to qqG$ channel ($R = 7.16$)

ST>2 TeV

SM			SM+OG			(SM+OG)/SM	
channel	xsec	(%)	channel	xsec	(%)		
GG -> ttxG	4.46E-02	37.056	GG -> ttxG	5.83E-02	40.556	GG -> ttxG	1.31
Gq -> ttxq	6.33E-02	52.532	Gq -> ttxq	7.25E-02	50.456	Gq -> ttxq	1.15
qq -> ttxG	1.25E-02	10.412	qq -> ttxG	1.29E-02	8.988	qq -> ttxG	1.03
total	1.20E-01	99.999	total	1.44E-01	100.000	total	1.19

ST>4.7 TeV

SM			SM+OG			(SM+OG)/SM	
channel	xsec	(%)	channel	xsec	(%)		
GG -> ttxG	9.82E-06	14.185	GG -> ttxG	7.70E-05	32.620	GG -> ttxG	7.85
Gq -> ttxq	4.26E-05	61.532	Gq -> ttxq	1.34E-04	56.703	Gq -> ttxq	3.14
qq -> ttxG	1.68E-05	24.272	qq -> ttxG	2.52E-05	10.676	qq -> ttxG	1.50
total	6.92E-05	99.989	total	2.36E-04	99.998	total	3.41

- Large qg and gg contribution with large R's
- No effect from $O_{tG}^{(6)}$ operator ($O_{tG}^{(6)} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}$)

$b\bar{b}j$ production

ST>2 TeV

SM		
channel	xsec	(%)
GG -> bbxG	1.85E-01	35.479
Gq -> bbxq	3.05E-01	58.430
qq -> bbxG	3.18E-02	6.094
total	5.22E-01	100.003

SM+OG		
channel	xsec	(%)
GG -> bbxG	2.25E-01	38.464
Gq -> bbxq	3.27E-01	55.792
qq -> bbxG	3.37E-02	5.748
total	5.86E-01	100.005

(SM+OG)/SM	
GG -> bbxG	1.22
Gq -> bbxq	1.07
qq -> bbxG	1.06
total	1.12

ST>4.7 TeV

SM		
channel	xsec	(%)
GG -> bbxG	1.35E-05	9.039
Gq -> bbxq	1.04E-04	69.563
qq -> bbxG	3.21E-05	21.423
total	1.50E-04	100.025

SM+OG		
channel	xsec	(%)
GG -> bbxG	1.23E-04	27.723
Gq -> bbxq	2.69E-04	60.709
qq -> bbxG	5.12E-05	11.568
total	4.43E-04	100.000

(SM+OG)/SM	
GG -> bbxG	9.06
Gq -> bbxq	2.58
qq -> bbxG	1.60
total	2.95

- Smaller effect w.r.t. $t\bar{t}j$

4-jet production $O_{\tilde{G}}^{(6)}$

ST>2 TeV

SM channel	SM xsec	SM (%)	SM+OG channel	SM+OG xsec	SM+OG (%)	(SM+OG)/SM channel	(SM+OG)/SM
GG -> GGGG	3.93E+00	15.138	GG -> GGGG	5.88E+00	17.993	GG -> GGGG	1.50
GG -> GGqq	6.71E-01	2.585	GG -> GGqq	1.16E+00	3.534	GG -> GGqq	1.72
GG -> qqqq	1.36E-02	0.052	GG -> qqqq	2.74E-02	0.084	GG -> qqqq	2.02
Gq -> GGGq	1.21E+01	46.490	Gq -> GGGq	1.49E+01	45.533	Gq -> GGGq	1.23
Gq -> Gqqq	1.34E+00	5.154	Gq -> Gqqq	1.82E+00	5.575	Gq -> Gqqq	1.36
qq -> GGGG	4.68E-02	0.180	qq -> GGGG	1.41E-01	0.431	qq -> GGGG	3.01
qq -> GGqq	7.53E+00	29.027	qq -> GGqq	8.36E+00	25.579	qq -> GGqq	1.11
qq -> qqqq	3.56E-01	1.373	qq -> qqqq	4.13E-01	1.263	qq -> qqqq	1.16
total	2.59E+01	100.000	total	3.27E+01	99.993	total	1.26

ST>4.7 TeV

SM channel	SM xsec	SM (%)	SM+OG channel	SM+OG xsec	SM+OG (%)	(SM+OG)/SM channel	(SM+OG)/SM
GG -> GGGG	6.09E-04	3.857	GG -> GGGG	8.63E-03	10.913	GG -> GGGG	14.18
GG -> GGqq	7.52E-05	0.476	GG -> GGqq	1.79E-03	2.263	GG -> GGqq	23.82
GG -> qqqq	1.30E-06	0.008	GG -> qqqq	3.87E-05	0.049	GG -> qqqq	29.85
Gq -> GGGq	5.45E-03	34.530	Gq -> GGGq	3.72E-02	47.074	Gq -> GGGq	6.83
Gq -> Gqqq	4.58E-04	2.900	Gq -> Gqqq	4.64E-03	5.872	Gq -> Gqqq	10.15
qq -> GGGG	3.52E-05	0.223	qq -> GGGG	2.08E-03	2.627	qq -> GGGG	59.12
qq -> GGqq	8.89E-03	56.350	qq -> GGqq	2.35E-02	29.651	qq -> GGqq	2.64
qq -> qqqq	2.62E-04	1.660	qq -> qqqq	1.23E-03	1.549	qq -> qqqq	4.68
total	1.58E-02	100.005	total	7.91E-02	99.999	total	5.01