Dim.-6 Gluon Interactions in Multijet Events

at a future 100 TeV pp-collider

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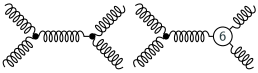
Dimension-6 Gluon Operator

$$\mathcal{O}_G = \frac{c_G}{\Lambda^2} f_{abc} G^{\mu}_{a,\nu} G^{\nu}_{b,\kappa} G^{\kappa}_{c,\mu}$$

- Only one pure gluonic operator at dimension 6
- Operators involving covariant derivatives can be related to quark operators
- Gives rise to effective 3,4,5, and 6 gluon vertices
- $\mathcal{O}_G$ does NOT contribute to massless 2→2 scattering at order Λ^{-2}

2Re $\Bigg\{$



$\Bigg\} = 0$

Collider Constraints

$$\mathcal{O}_G = \frac{c_G}{\Lambda^2} f_{abc} G^{\mu}_{a,\nu} G^{\nu}_{b,\kappa} G^{\kappa}_{c,\mu}$$

- Some effects in specific kinematic regimes of three-jet events:
  experimentally challenging

  [Dixon, Shadmi, Nucl. Phys. B 423 (1994)]

- Four-jet production at LEP:
  small collider energy

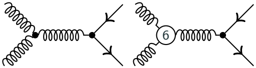
  [Duff, Zeppenfeld, Z. Phys. C 53 (1992)] [Dreiner, Duff, Zeppenfeld, Phys. Lett. B 282 (1992).]

- Higgs+jet production:
  Little sensitivity

  [Ghosh, Wiebusch, Phys. Rev. D 91 (2015)]

Collider Constraints: Top Pair Production

$$\mathcal{O}_G = \frac{c_G}{\Lambda^2} f_{abc} G^{\mu}_{a,\nu} G^{\nu}_{b,\kappa} G^{\kappa}_{c,\mu}$$

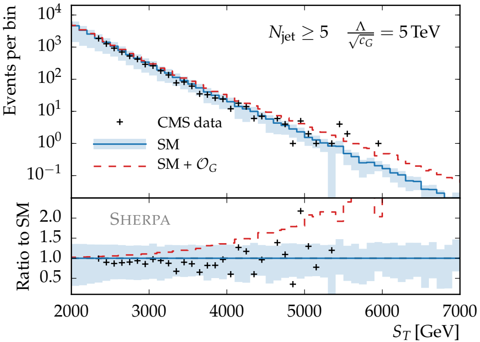
$2\mathrm{Re}\left\{\right.$  $\left.\right\} \neq 0$ for $m_q \neq 0$

- Very sensitive channel already at Tevatron energies $\Lambda/\sqrt{c_G} > 2\,\mathrm{TeV}$

  [Cho, Simmons, Phys. Lett. B 323 (1994)]
- Multitude of other operators affect top sector [Buckley et al., JHEP 04 (2016)]
- Limits in global analyses are weaker: $\Lambda/\sqrt{c_G} > 850\,\mathrm{GeV}$

Collider Constraints: Multijet Production

- Consider higher jet multiplicities $N_{\text{jet}} \geq 4, 5$
- Events produced in abundance at LHC
- 13 TeV-data exists: CMS-PAS-EXO-15-007
- Extended Sherpa to simulate any EFT extension of SM
- Simulation of $p\ p \rightarrow 7$ jets feasible



$$S_T = E_T^{\text{miss}} + \sum_{\text{Objects}} E_T$$

- Use S_T distribution
- Perform CL_s analysis
- $\text{CL}_s < 5\,\% \Rightarrow$ exclusion

$\Rightarrow \Lambda/\sqrt{c_G} > 5.2\,\text{TeV}$

[Krauss, SK, Plehn arXiv:1611.00767]

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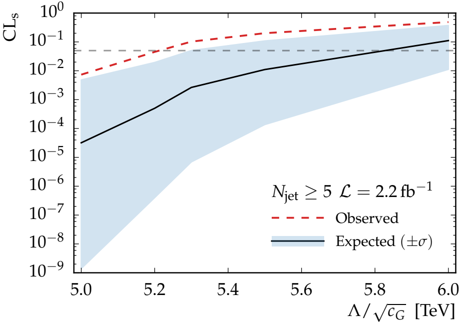

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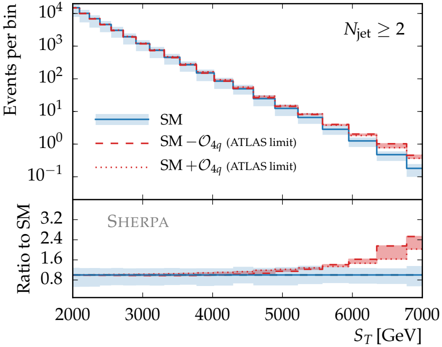
Contamination Due to Four-Quark Operators

Example Operator

$$\mathcal{O}_{q4} = \frac{c_{q4}}{\Lambda^2} \sum_{q,q'} \left(\bar{q}_L \gamma^\mu q_L\right) \left(\bar{q}'_L \gamma^\mu q'_L\right)$$



ATLAS limits

- $\Lambda/\sqrt{c_{q4}} > +4.8\,\text{TeV}$
- $\Lambda/\sqrt{c_{q4}} < -6.8\,\text{TeV}$

[ATLAS, Phys. Lett. B 754 (2016)]

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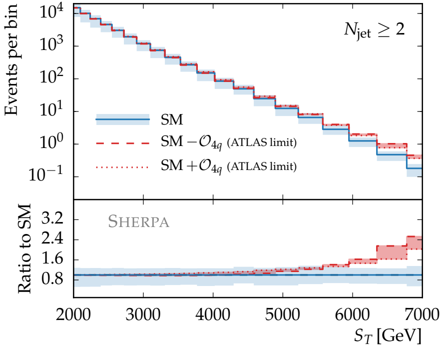
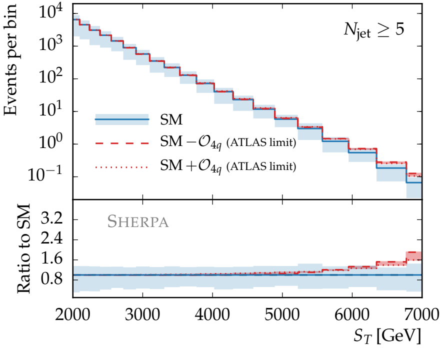
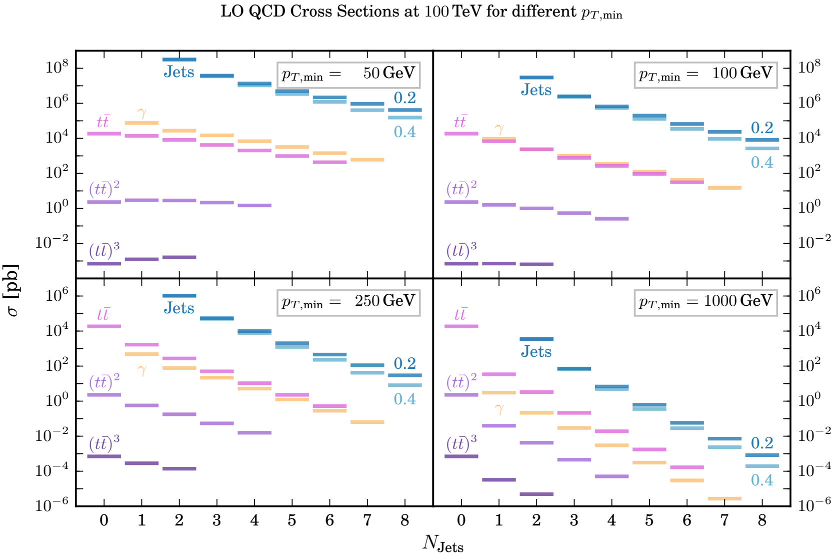




Four-Quark contamination under control in high multiplicity bins

[ATLAS, Phys. Lett. B 754 (2016)]

Fixed-Order Cross Sections at 100 TeV



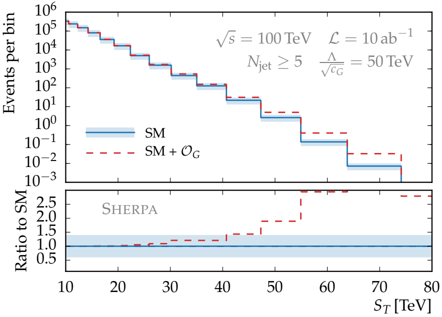
[Bothmann et al., Phys. Rev. D 94 (2016)]

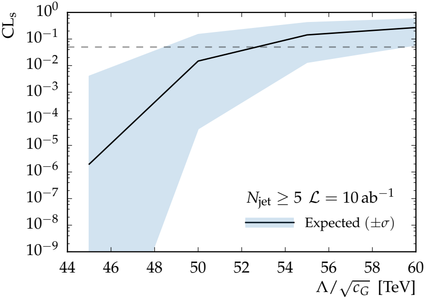
Projected Sensitivity

- Use same observable: S_T
- Anti-k_T jets, $R = 0.4$, $p_T^{\mathrm{min}} = 1\,\mathrm{TeV}$
- Parton-level analysis
- Assume 40 % / 20 % syst. unc.

$\Rightarrow$ Sensitive up to $\Lambda \approx 55$TeV

$\Rightarrow$ Insensitive to region $S_T > \Lambda$





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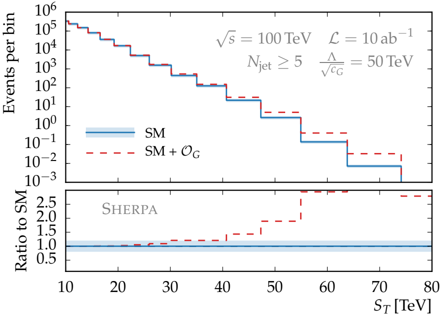
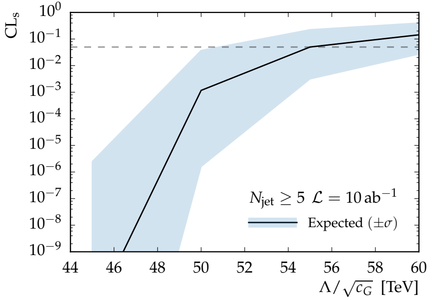
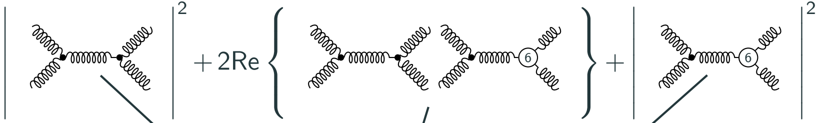




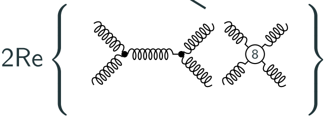
Power Counting

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{c_6}{\Lambda^2}\mathcal{O}_6$$



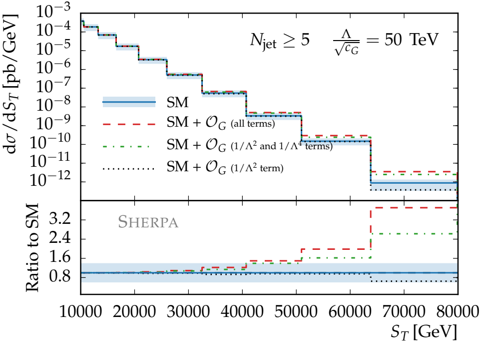
$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\text{SM}} + \frac{1}{\Lambda^2}\,\mathrm{d}\sigma^{(2)} + \frac{1}{\Lambda^4}\,\mathrm{d}\sigma^{(4)} + \dots$$

- For high final state multiplicities: high powers of Λ^{-1} occur
- Terms of Λ^{-4} and higher technically beyond parametric accuracy



Higher Powers in Λ^{-1}

$$d\sigma = d\sigma_{SM} + \frac{1}{\Lambda^2}\, d\sigma^{(2)} + \frac{1}{\Lambda^4}\, d\sigma^{(4)} + \ldots$$



Assess term by term:

Λ^{-2} negligible (but non-zero)

Λ^{-4} numerically leading term (generic problem for G^3)

Λ^{-6} sizable only for $S_T \geq \Lambda$

Conclusions

Summary

- Anomalous dim.-6 interactions in QCD can be probed efficiently in multijet events
- Applies to 4-quark interactions and gluon interactions
- LHC bounds on Λ in $\mathcal{O}(5\,\text{TeV})$ ballpark
- An FCC-pp collider at 100 TeV provides sensitivity up to $\mathcal{O}(50\,\text{TeV})$
- Bounds on $\mathcal{O}_G$ rely on inclusion of terms beyond Λ^{-2}

Backup slides

Background Simulation

Signal and Background Simulation: Multijet-Merging

$$d\sigma = d\sigma_{SM} + \frac{1}{\Lambda^2} d\sigma^{(2)} + \frac{1}{\Lambda^4} d\sigma^{(4)} + \ldots$$

$p\,p \to j\,j$	(N)LO+PS		
$p\,p \to j\,j\,j$	LO+PS	$p\,p \to j\,j$	LO+PS
$p\,p \to j\,j\,j\,j$	LO+PS	$p\,p \to j\,j\,j$	LO+PS
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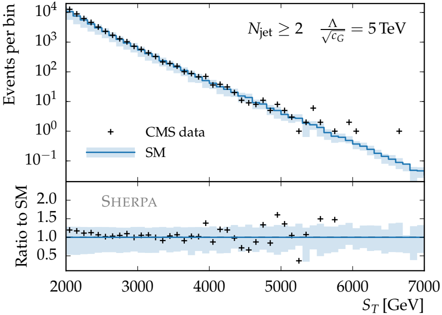
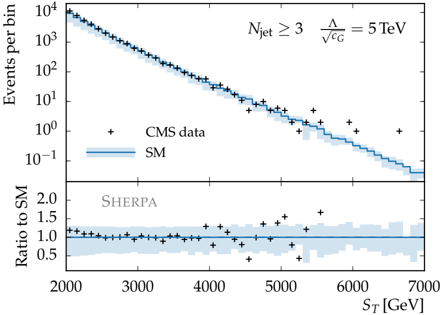
- Combine all parton shower matched samples into one
- Describe jets above hardness threshold Q_{cut} by fixed order ME
- Parton shower fills remaining phase space
- Restore all-order resummation properties of parton shower
- Several schemes on the market, use CKKW (Sherpa) here

[Catani et al., JHEP 0111 (2001)] [Krauss et al., JHEP 0905 (2009)] [Hoeche et al., JHEP 1304 (2013)] [Gehrmann et al., JHEP 1301 (2013)]

Background Simulation: Performance in LHC Environment

Shape and normalization well described, uncertainty $\approx \pm 40\%$





$N_{\text{jet}} \geq 2$

$N_{\text{jet}} \geq 3$

Uncertainty estimate: μ_f and μ_r variations by factors of 2

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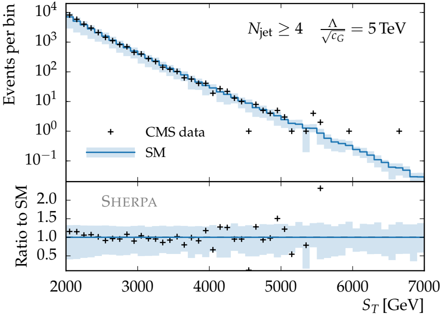
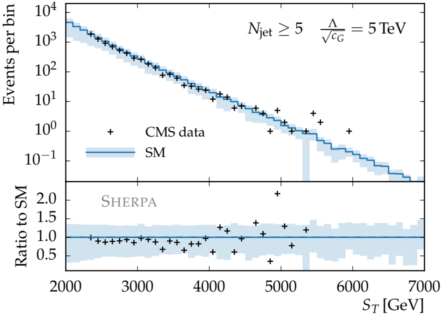




$N_{\text{jet}} \geq 4$ $N_{\text{jet}} \geq 5$

Uncertainty estimate: μ_f and μ_r variations by factors of 2

CMS Analysis

Existing Run-II Data on Multijets

CMS PAS EXO-15-007

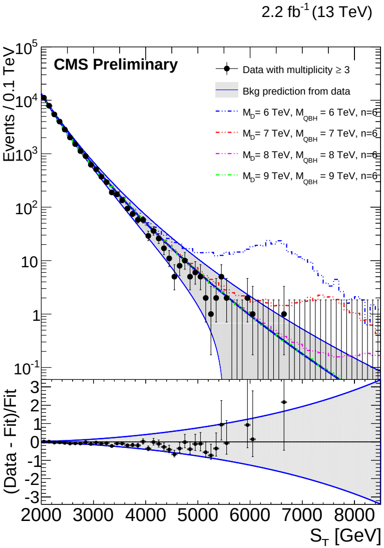
- $2.2\,\text{fb}^{-1}$
- Search for macroscopic black holes
- Main observable: transverse energy

$$S_T = E_T^{\text{miss}} + \sum_{\text{Objects}} E_T$$

- Measured in multi-TeV region
- Binned according to jet multiplicity

$$N_{\text{jet}} \geq 1, \ldots, 10$$

- In SM: S_T purely QCD driven



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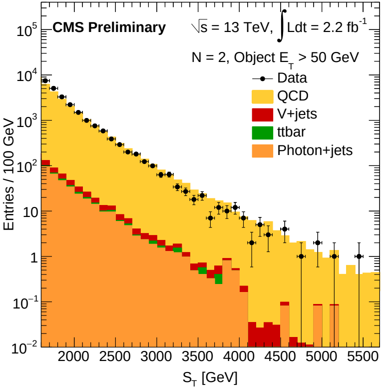
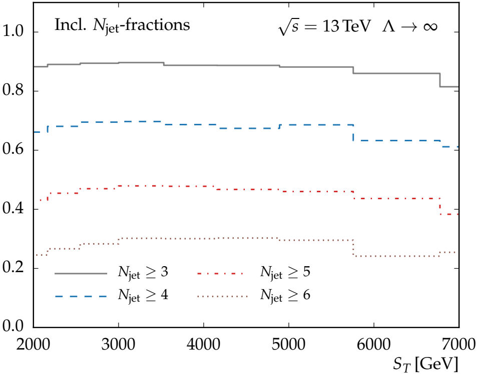


Jet multiplicites



Statistical analysis

Setting exclusion limits

- Input: individual bins in S_T-distribution
- Treat bins uncorrelated, use likelihood ratio as test statistic:

$$\chi(\text{data}) = 2\log\frac{P_{s+b}(\text{data})}{P_b(\text{data})}$$
$$= 2\log\prod_{i=1}^{N_{\text{bins}}}\frac{P^i_{s+b}(n_i)}{P^i_b(n_i)}$$

- Assume Poisson distribution

$$P^i_b(n_i) = b_i^{n_i}\frac{e^{-b_i}}{n_i!} \qquad \text{No syst. unc.}$$

$$P^i_b(n_i) = \frac{1}{b^1_i - b^0_i}\int_{b^0_i}^{b^1_i} b^{n_i}\frac{e^{-b}}{n_i!}\,\mathrm{d}b \qquad \text{Unc. band } b^0_i < b_i < b^1_i$$

Setting exclusion limits

- Given some data, define the standard frequentist confidence levels

$$\mathrm{CL}_b = P_b(\chi < \chi(\mathrm{data}))$$
$$\mathrm{CL}_{s+b} = P_{s+b}(\chi < \chi(\mathrm{data}))$$

- Calculate them by brute force (using Metropolis-Hastings MC)
- Use modified frequentist confidence level to set exclusion limits

$$\mathrm{CL}_s = \mathrm{CL}_{s+b}/\mathrm{CL}_b$$

- Consider "signal+background" hypothesis excluded if

$$\mathrm{CL}_s \leq 5\,\%$$

Signal simulation

Model Implementation via FeynRules and UFO

Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{c_G}{\Lambda^2} G^3 + \dots$$

FeynRules

[Alloul et al., Comput. Phys. Commun. 185 (2014)]

UFO Output

[Degrande et al., Comput. Phys. Commun. 183 (2012)]

Input parameters

Particle spectrum

Vertices

Color structures

Lorentz Structures

Monte Carlo

Sherpa

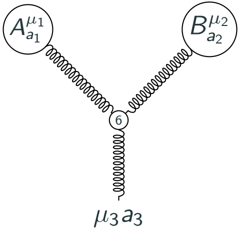
MadGraph

...

Matrix Element Building Blocks

Matrix Elements with Comix/Sherpa

- Non-diagrammatic approach: Berends-Giele type recursions
- Highly efficient for multi-leg amplitudes
- Computes amplitudes in terms of *currents*
- Needs numerical routines for Lorentz and color structures
- Fully automated for arbitrary (higher dimensional) interactions



$$= \underbrace{A^{\mu_1}{}_{a_1} B^{\mu_2}{}_{a_2} \Gamma^{\mu_1 \mu_2}_{\mu_3}} C^{a_1, a_2, a_3}$$

[Höche, SK, Schumann, Siegert, Eur. Phys. J. C 75 (2015)]

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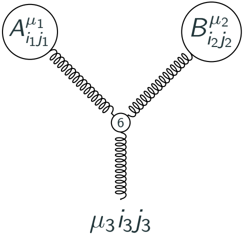


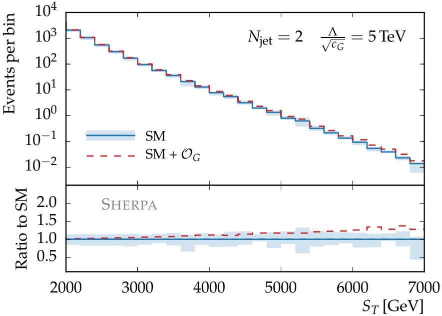
$$= \underbrace{A^{\mu_1}{}_{i_1 j_1} B^{\mu_2}{}_{i_2 j_2} \Gamma^{\mu_1 \mu_2}_{\mu_3}} \overbrace{C^{a_1, a_2, a_3} [\lambda_{a_1}]_{i_1 j_1} [\lambda_{a_2}]_{i_2 j_2} [\lambda_{a_3}]_{i_3 j_3}}$$

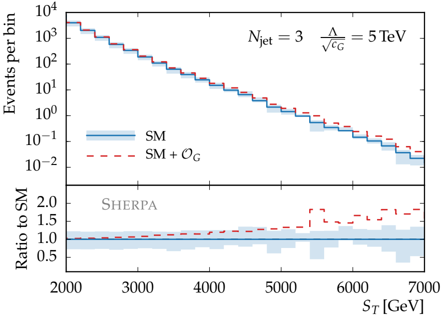
New!

[Höche, SK, Schumann, Siegert, Eur. Phys. J. C 75 (2015)]

Signal Simulation: Results

Signal contributions become sizable for large N_{jet}





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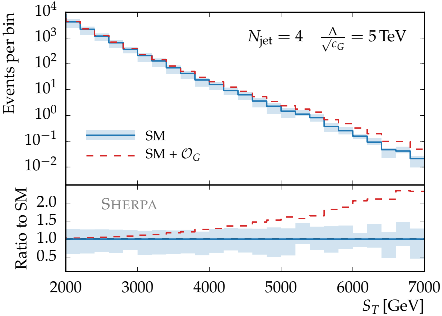
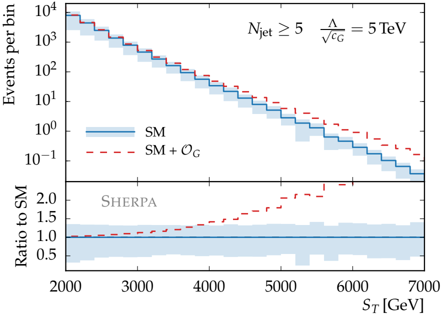


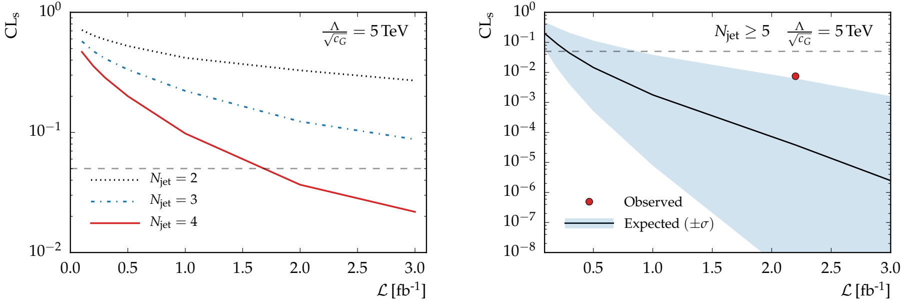


$N_{\text{jet}} = 4$

$N_{\text{jet}} \geq 5$

Confidence levels for $\Lambda/\sqrt{c_G} = 5\text{TeV}$ hypothesis

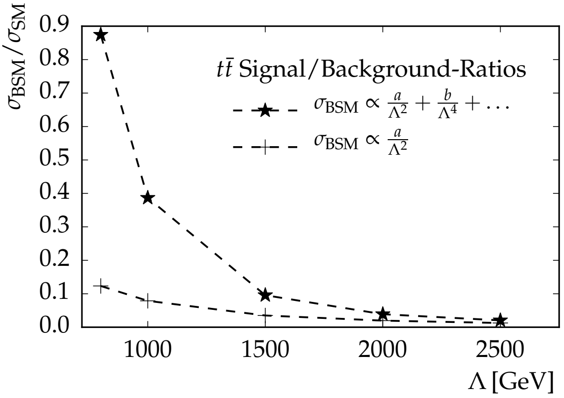
Can exclude benchmark point with existing Run-II data



$\mathbf{N_{jet} = 2, 3, 4}$

$\mathbf{N_{jet} \geq 5}$

Higher Powers of Λ^{-1} in $t\bar{t}$



σ_{BSM}/σ_{SM}
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
$t\bar{t}$ Signal/Background-Ratios
$\sigma_{BSM} \propto \frac{a}{\Lambda^2} + \frac{b}{\Lambda^4} + \ldots$
$\sigma_{BSM} \propto \frac{a}{\Lambda^2}$
1000
1500
2000
2500
Λ [GeV]