NLO QCD effects on quark compositeness search at the LHC

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based on the works RPL 106:142001(2011) and arXiv:1204.4773 in collaboration with Chong Sheng Li, C.-P. Yuan, et. al.

Jet production and new physics

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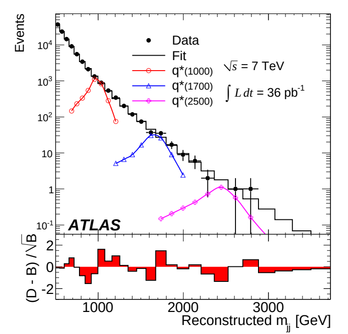
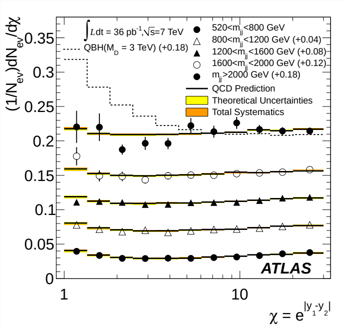
Conclusions

Jet prouction at hadron colliders

- SM QCD jet production has very high statistics but also suffers from large experimental and theoretical uncertaities.
- Jet production measurements are important for: test of QCD theory, measurement of QCD coupling constant and parton distribution functions; search of new physics (NP) beyond SM.

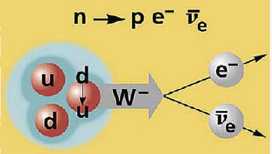




ATLAS Col., New J.Phys.13:053044(2011)

Search for new physics at the LHC

- Unsolved problems of SM: neutrino mass and mixing, dark matter candidate, gauge unification, Higgs mass stability, flavor hierachy.
- Tons of NP model candidates: e.g., SUSY, technicolor, extra dimensions, little Higgs... Direct discovery of new particles from NP at the LHC would be wonderful. But it may happen that the NP scale lies above LHC energy threshold. Thus at the LHC we may only be able to find their hints through some virtual effects.



- Of particular interest, if the quarks are composite state at a high energy scale Λ (quark compositeness), then at energy well below there will be four quark contact interactions due to residual effects of the underlying strong dynamics. E. Eichten, et. al., PRL 77:5336(1996)

Model independent way to study virtual effects of NP

- NP at a high scale Λ will manifest themselves at energies well below Λ through small deviations from the SM, described by higher dimension operators. Assuming NP preserves SM gauge symmetry and lepton, baryon number conservation, then the leading contributions consist of 59 dimension-six operators.

W. Buchmuller, et. al., NPB 268:621(1986)

- The operators relevant to the quark compositeness are the four quark contact interactions. Here we consider $\mathcal{L}_{NP} = \frac{1}{2\Lambda^2}\sum_{i=1}^{6} c_i O_i$, with

$$O_1 = \delta_{ij}\delta_{kl}\left(\bar{q}_{Lci}\gamma_\mu q_{Lcj}\bar{q}_{Ldk}\gamma^\mu q_{Ldl}\right), \quad O_2 = \mathrm{T}^a_{ij}\mathrm{T}^a_{kl}\left(\bar{q}_{Lci}\gamma_\mu q_{Lcj}\bar{q}_{Ldk}\gamma^\mu q_{Ldl}\right)$$

$$O_3 = \delta_{ij}\delta_{kl}\left(\bar{q}_{Lci}\gamma_\mu q_{Lcj}\bar{q}_{Rdk}\gamma^\mu q_{Rdl}\right), \quad O_4 = \mathrm{T}^a_{ij}\mathrm{T}^a_{kl}\left(\bar{q}_{Lci}\gamma_\mu q_{Lcj}\bar{q}_{Rdk}\gamma^\mu q_{Rdl}\right)$$

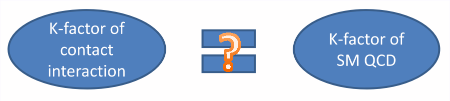
$$O_5 = \delta_{ij}\delta_{kl}\left(\bar{q}_{Rci}\gamma_\mu q_{Rcj}\bar{q}_{Rdk}\gamma^\mu q_{Rdl}\right), \quad O_6 = \mathrm{T}^a_{ij}\mathrm{T}^a_{kl}\left(\bar{q}_{Rci}\gamma_\mu q_{Rcj}\bar{q}_{Rdk}\gamma^\mu q_{Rdl}\right)$$

Contact interactions in dijet production

- Jet angular observable $\chi = exp(|y_1 - y_2|)$: SM QCD dijet production is t-channel dominant with $d\sigma/d\chi \sim constant$. The contact interaction contributions prefer small χ region, e.g., $d\sigma/d\chi \sim 1/(1+\chi^2)$.

  S. D. Ellis, et. al., PRL69:1496(1992)

- In dijet angular distribution measurement at both the Tevatron and LHC, experimentalists use bin-wise parton level NLO K-factors (σ_{NLO}/σ_{LO}) to correct the Monte simulation results for theory predictions. They have the K-factors for SM QCD dijet production, but not for the contact interaction contributions. The K-factors for contact interaction contributions are needed for a consistent treatment of theory predictions in experiments and also for a more precise measurement.



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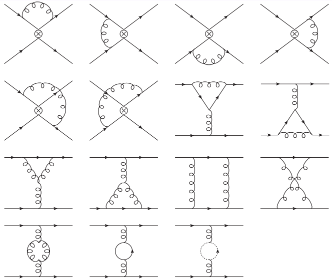
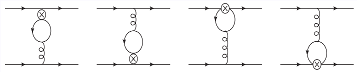
- At LO contact interactions can contribute to dijet production through several subprocesses of quark-quark scattering, including

$$qq'(q) \to qq'(q),\ q\bar{q}' \to q\bar{q}',\ q\bar{q} \to q\bar{q}(q'\bar{q}')$$

- QCD one-loop diagrams for both SM QCD and NP production:

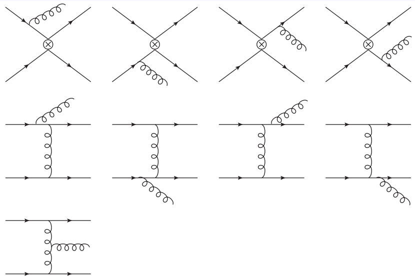




$$\delta Z = D_\epsilon \frac{\alpha_s}{4\pi}\frac{1}{\epsilon}\begin{pmatrix} 0 & -\frac{22}{3} & 0 & -\frac{4}{3} & 0 & 0 \\ -\frac{3C_F}{N} & \frac{20}{3N}-n_f & 0 & \frac{2}{3N}-n_f & 0 & 0 \\ 0 & 0 & 0 & 6 & 0 & 0 \\ 0 & -\frac{n_f}{2} & \frac{3C_F}{N} & 6C_F-\frac{3}{N}-n_f & 0 & -\frac{n_f}{2} \\ 0 & 0 & 0 & -\frac{4}{3} & 0 & -\frac{22}{3} \\ 0 & 0 & 0 & \frac{2}{3N}-n_f & -\frac{3C_F}{N} & \frac{20}{3N}-n_f \end{pmatrix}$$

Beside of renormalization of QCD coupling constants and quark wave functions, we also need to introduce renormalization of the operators, $O_i^{(0)} = (1+\delta Z)_{ij} O_j$, to absorb remaining UV divergences.

- The Wilson coefficients run with the renormalization scale in the $\overline{MS}$ scheme. When Λ is much higher than the physics scale considered, large logarithm of Λ occurs in fixed order calculation. And RG equation can be used to sum them and improve the convergency.
- Real radiation processes (crossing diagrams not shown)



We use both two cutoff and dipole subtraction method to extract the infrared divergences and perform numerical calculations for a cross-check. RMP68, 1125(1996), PRD65:094032(2002), NPB485, 291(1997)

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Inputs for numerical calculations:

- For the numerical results shown here, we assume only $c_1(\Lambda)$ and $c_2(\Lambda)$ are non-zero and rewrite them as $c_{1(2)}(\Lambda) = 4\pi\lambda_{1(2)}$. For the color-singlet case studied in the experiments, it corresponds to $\lambda_{1(2)} = \pm 1(0)$.
- Following the CMS measurement we use anti-kT jet algorithm with $D = 0.5$ and require the two leading jet satisfying $|y_b| = |y_1 + y_2|/2 < 1.11$, $\chi < 16$. CMS Col., PRL106, 201804(2011)
- We only consider the kinematic region with dijet invariant mass between 2 and 3 TeV since the NP contributions are only significant there and above. Instead of calculating the diferential xsecs w.r.t. χ, we choose two representive bins in χ, i.e., bin 1, $[1, 6]$ and bin 2, $[6, 11]$, to simplify the analysis.
- Both factorization and renormalization scales are set to the average p_T of the two leading jets.

LO results and analysis:

- Dependence of the NP contributed cross sections on the compositeness scale and cuoplings can be written as

$$\sigma_{\rm LO} = (\lambda_1 b_{\rm L,1} + \lambda_2 b_{\rm L,2})/\Lambda^2 + (\lambda_1^2 b_{\rm L,11} + \lambda_2^2 b_{\rm L,22} + \lambda_1\lambda_2 b_{\rm L,12})/\Lambda^4$$

with the coefficients given by

$[\mathrm{fb}\cdot(5\,\mathrm{TeV})^{2(4)}]$	$b_{\rm L,1}$	$b_{\rm L,2}$	$b_{\rm L,11}$	$b_{\rm L,22}$	$b_{\rm L,12}$
bin 1	-258	-179	614	93.4	259
bin 2	-99.1	-70.4	113	17.2	46.8

- We can see that the absolute values of b are much larger in bin 1 than in bin 2 especially for the NP squared terms, since the NP contributions prefer small χ values.

NLO results and analysis:

- At NLO the dependence on Λ includes additional logarithm term, $r = \ln(\Lambda/p_0)$, from running of Wilson coefficients

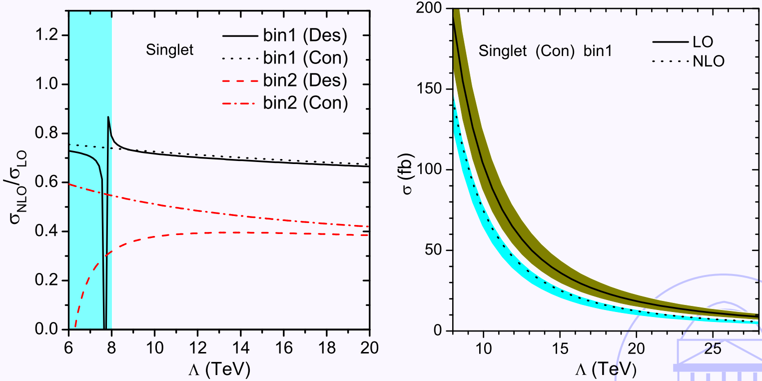
$$\sigma_{\rm NLO} = \big(\lambda_1(b_{\rm N,1} + a_1 r) + \lambda_2(b_{\rm N,2} + a_2 r)\big)/\Lambda^2 + \big(\lambda_1^2(b_{\rm N,11} + a_{11} r) + \lambda_2^2(b_{\rm N,22} + a_{22} r) + \lambda_1\lambda_2(b_{\rm N,12} + a_{12} r)\big)/\Lambda^4$$

with a and b given by

$[\rm fb \cdot (5\,TeV)^{2(4)}]$	$b_{\rm N,1}(a_1)$	$b_{\rm N,2}\ (a_2)$	$b_{\rm N,11}(a_{11})$	$b_{\rm N,22}(a_{22})$	$b_{\rm N,12}(a_{12})$
bin 1	-232(20)	-159(19)	506(-26)	74.3(-12)	172(-51)
bin 2	-68.3(8.7)	-44.1(9.2)	89.2(-4.9)	13.0(-2.3)	33.1(-9.8)

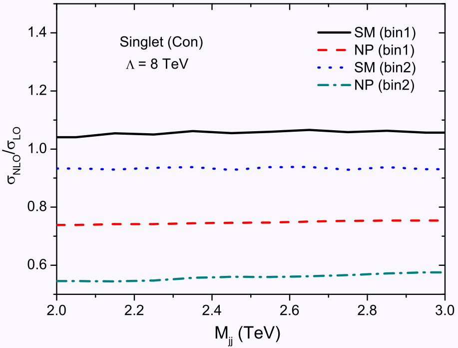
- The NLO QCD corrections reduce the NP contributions significantly mainly due to the large negative constant terms in the virtual corrections and also the logarithms of Λ from running of the Wilson coefficients.

NLO K-factors and scale variations of the cross sections:



Note that the K-factors depend on scale choice and definition of LO cross sections in perturbation series.

- Comparison of K-factors for pure SM dijet production cross sections and NP induced contributions:



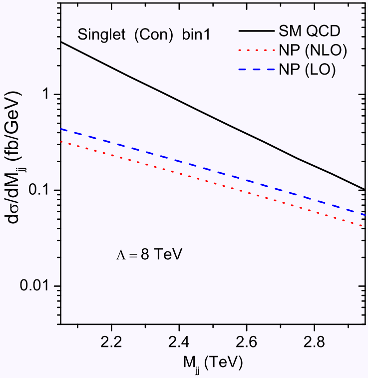
- In this work we develop two numerical programs, MEKS for the NLO computation of SM double differential jet cross sections, and CIDIJET for contact interactions including all chiral and color structrues.

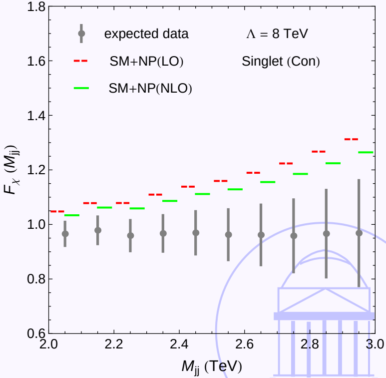
Exclusion limits of compositeness scale at the LHC:

- To derive the expected exclusion limits of the compositeness scale, we further divide the invariant mass region $[2\,\mathrm{TeV}, 3\,\mathrm{TeV}]$ into 10 mass bins with equal width, and define the measure in each mass bin, $F_\chi(M_{jj}) = \sigma_{\mathrm{bin1}}(M_{jj})/\sigma_{\mathrm{bin2}}(M_{jj})$.
- We take the pure SM QCD contributions as the expected experimental data. The experimental errors of F_χ include statistical errors (calculated assuming $\mathcal{L} = 5\mathrm{fb}^{-1}$), and systematic ones mainly from jet energy calibration, jet p_T resolution, and unfolding corrections. Most of the systematic uncertainties cancel in the ratio F_χ. We estimate an overall systematic uncertainty of 3% on F_χ in all mass bins based on the CMS results. We don't consider possible correlations of errors in different mass bins.

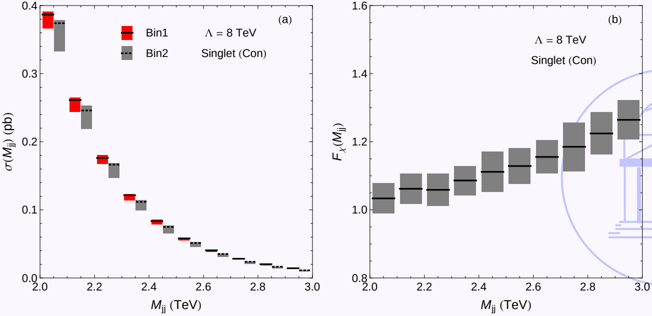
CMS Col., PRL106, 201804(2011)

- Comparison of SM and NP cross sections and NP predictions for F_χ compared to expected data:





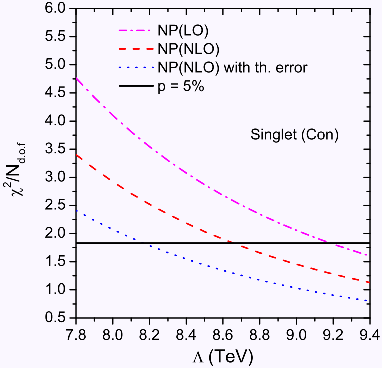
- On another hand we also need to consider theoretical uncertainties while comparing theory predictions to data, which include ones from PDFs, non-perturbative corrections, and most importantly the unknown higher order QCD corrections. The former two can be neglected here for F_χ.
- Conventional way to estimate the last one is to look at QCD scale variations of the observable. Here we take half of the total scale variations of F_χ as the error assuming a Gaussian distribution.



- We perform a log-likelihood χ^2 test on the NP hypothesis with

$$\chi^2 = \sum_{i=1,\,10} \frac{(F_\chi^{SM+NP}(i) - F_\chi^{SM}(i))^2}{\Delta^2_{exp}(i) + \Delta^2_{th}(i)}$$

- Below we show χ^2 as functions of compositeness scale Λ for 3 cases. The 95% C.L. exclusion limits can be read directly as intersections of curves with the horizontal line.



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- We have calculated the NLO QCD corrections to the dijet production at the LHC via quark contact interactions with different color and chiral structures induced by new physics.
- By applying our results to quark compositeness search at the LHC, we show that the NLO QCD corrections can lower the cross sections from NP contributions by several tens percent, depending on the parameters and kinematic regions considered, and reduce the dependence of the cross sections on factorization and renormalization scales.
- Moreover, we further investigate the NLO QCD effects on the corresponding experimental observables and also exclusion limits of the quark compositeness scale.