Graviton monojet production at QCD NLO

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- Calculation framework
- Virtual corrections
- Real corrections
- Numerical results
- Summary

Introduction

Large Extra Dimensions (ADD, Arkani-Hamed, Dvali & Dimopoulos)

- Assuming the δ-extra dimensions are compacted into δ torus with the same radius r,the metrics in ADD Model are given by:

$$ds^2 = (\eta_{\mu\nu} + h_{\mu\nu})dx^\mu dx^\nu - r^2 d\Omega_\delta^2 + ...,$$

- From dimensional analysis, we have

$$\overline{M}_{Pl}^2 = \overline{M}_s^{\delta+2}(2\pi r)^\delta = r^\delta M_s^{\delta+2}$$

- If r is quite small($\sim$ the Planck length), then $M_s \sim \overline{M}_{Pl}$. The effects of extra dimensions will be negligible. But Newton's law only test at Submillimeter level (0.2mm).
- Possibility of TeV scale extra dimensions:
  - If $\delta = 1$ and $M_s \sim 1$TeV, $\rightarrow r \sim 10^{15}$cm, excluded,
  - If $\delta = 2$ and $r < 0.2$mm, $\rightarrow M_s > 1.5$TeV,
  - If $\delta > 2$ and $M_s \sim$TeV, $\rightarrow r < 10^{-6}$cm $\rightarrow$ High Energy Colliders.

Kaluza-Klein (KK) tower

- In ADD model, there is an infinite tower of 4D KK modes.

$$\mathcal{L}_{int} = -\frac{1}{\overline{M}_{Pl}} \sum_{\vec{n}} (h^{(\vec{n})})^{\mu\nu} T_{\mu\nu},$$

- The mass of the $\vec{n}$-th KK mode $h^{(\vec{n})}_{\mu\nu}$ is $|\vec{n}|/r$.

$$\Delta m \sim \frac{1}{r} = M_s \left(\frac{M_s}{\overline{M}_{Pl}}\right)^{2/\delta} \sim \left(\frac{M_s}{\mathrm{TeV}}\right)^{\frac{\delta+2}{2}} 10^{\frac{12\delta-31}{\delta}} \mathrm{eV}.$$

  - For $M_s = 1$TeV and $\delta =$4, 6 and 8, Δm=20KeV, 7MeV and 0.1GeV, respectively. Thus for $\delta \leq 6$, the KK tower can be looked as continuous.
  - Mass density function:

$$d\vec{n} = S_{\delta-1}|\vec{n}|^{\delta-1} d|\vec{n}| = S_{\delta-1} \frac{\overline{M}_{Pl}^2}{M_s^{2+\delta}} m^{\delta-1} dm, \mathrm{with}\ \mathrm{S}_{\delta-1} = \frac{2\pi^{\delta/2}}{\Gamma(\delta/2)}.$$

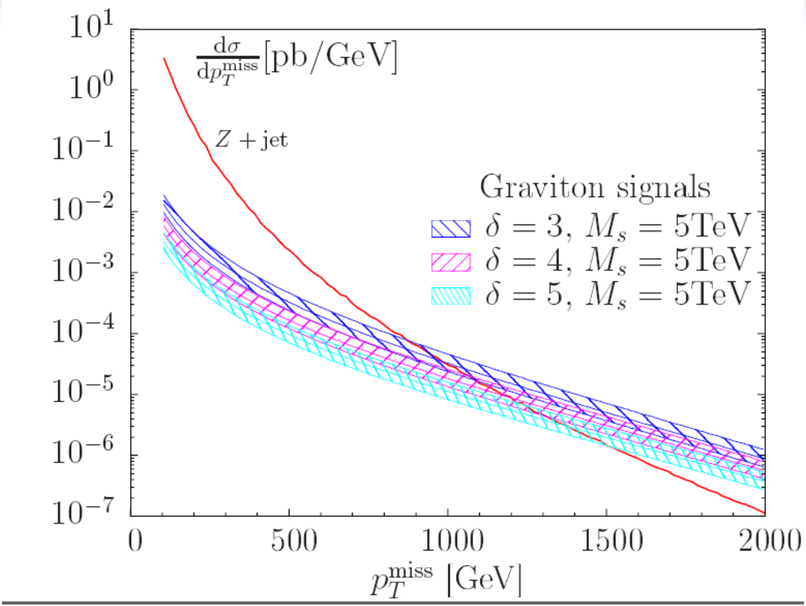
Constraints and Collider Phenomenology

- Supernova (SN1987A) cooling constraints:
  $M_s > 30\text{TeV}$ (δ=2) and 4TeV (δ=3).
  However, the constraints can be relaxed easily (by modifying the background geometry) without large change on collider phenomenology.

- Virtual KK-graviton exchange and direct KK-graviton production (Missing Energy):
  LEP and Tevatron datas lead to $M_s > 1.31\text{TeV}(\delta=2)$ and $0.88\text{TeV}(\delta=6)$.

Graviton production with jet

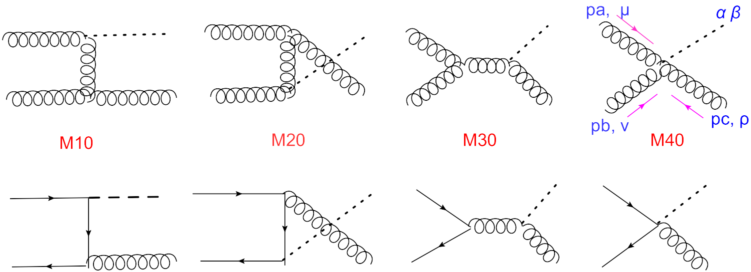
- At the LHC, Graviton production with monojet has been studied and found to have strong ability to probe higher extra dimension scale: jet+missing Energy
- To improve the theoretical accuracy, NLO QCD corrections needed.
- See on next page the scale dependence of $P_T^{\rm miss}$ distributions for $\mu_r = \mu_f = 3\sqrt{\hat{s}}, \sqrt{\hat{s}}/3$
  $\Delta R_{jj} > 0.7$, $|\eta_j| < 4.5$, $P_T^{\rm miss} > 500$ GeV, CTEQ6L1



dσ/dp_T^miss [pb/GeV]
Z + jet
Graviton signals
δ = 3, M_s = 5TeV
δ = 4, M_s = 5TeV
δ = 5, M_s = 5TeV
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
0
500
1000
1500
2000
p_T^miss [GeV]

LO and NLO cross sections

LO Feynman Diagrams



- For hadronic state initial processes with m partons in the final state

$$\sigma^{LO} = \int d\Phi^{(m)} |M^{B}(p_1, \ldots, p_m)|^2 \times F^{(m)}(p_1, \ldots, p_m)$$

$$\sigma^{NLO} = \int d\Phi^{(m+1)} |M^{R}(p_1, \ldots, p_{m+1})|^2 \times F^{(m+1)}(p_1, \ldots, p_m)$$

$$\int d\Phi^{(m)} |M^{V}(p_1, \ldots, p_m)|^2 \times F^{(m)}(p_1, \ldots, p_m)$$

where F includes the jet function: the clustering criterion and combination scheme.

C-S Substraction

- Introducing dipole substraction term $d\sigma^A$ with the same (soft/collinear) singularity structure as $d\sigma^R$:

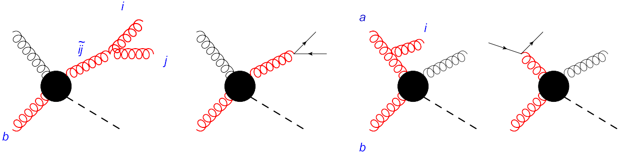
$$d\sigma^{NLO} = \int_{m+1}\left[d\sigma^R - d\sigma^A\right]F^{(m+1)} + \int_{m+1} d\sigma^A F^{(m)} + \int_m d\sigma^V F^{(m)} + \int_m d\sigma^C F^{(m)},$$

$$\Longrightarrow$$

$$d\sigma^{NLO} = \int_{m+1}\left[d\sigma^R_{\epsilon=0} - d\sigma^A_{\epsilon=0}\right]F^{(m+1)} + \int_m \left[d\sigma^V + \int_1 d\sigma^A + d\sigma^C\right]_{\epsilon=0} F^{(m)},$$

- $d\sigma^A$ is given by the sum of all possible dipole functions which can be generated automatically by MadDipole (by Rikkert Frederix, Thomas Gehrmann and Nicolas Greiner) with the ED model directory:

$$d\sigma^A = \Big[\sum_{k\neq i\neq j} \mathcal{D}_{ij,k} + \Big\{ \sum_{i\neq j} \mathcal{D}^a_{ij} + \sum_{k\neq i} \mathcal{D}^{ai}_k + + \sum_i \mathcal{D}^{ai,b} + (a \leftarrow b) \Big\} \Big] d\Phi_{m+1}$$

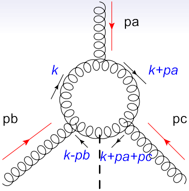


D^b_{ij} $D^{ai,b}$

Virtual corrections

Calculating/Conventions

- Dimension regularization, with $D = 4 - 2\epsilon$.
- Using FeynCalc to preform the momentum integration, and reduction of tensor coefficient with rank up to 3.
- Higher rank 4-point tensor coefficients D_4 and D_5 were reducted carefully in order not to make the expression lengthy: Divergent parts enter the recursion formulae at every step, while finite parts not.
  Thus we get the explicit divergent and compact finite terms of D_{ijk}, D_{ijkl} and D_{ijklm} from the lower rank functions.
- Finite terms of virtual corrections for gg, $qg(gq)$ and $q\bar{q}(\bar{q}q)$ channels have been implemented into out MC codes. Gauge checking has been passed.
- Moreover, comparison has been performed with a second calculation successfully for random chosen phase space points.



$$(i\pi^2)^{-1}(2\pi\mu)^{2\epsilon}\int d^D k \frac{k^\alpha k^\beta k^\mu k^\rho k^\nu}{k^2(k-pb)^2(k+pa)^2(k+pa+pc)^2}$$
$$= D^{\alpha\beta\mu\rho\nu}(P_1=-pb, P_2=pa, P_3=pa+pc)$$

$$D^{\alpha\beta\mu\rho\nu} = \sum_{j=1}^{3} g^{[[\alpha\beta}g^{\mu]\rho}p_j^{\nu]}D_{0000j}$$
$$+ \sum_{j,k,l,=1}^{3}(g^{[\alpha\beta}p_j^\mu p_k^\rho p_l^{\nu]} + g^{[\alpha\mu}p_j^\nu p_k^\beta p_l^{\rho]})D_{00jkl}$$
$$+ \sum_{j,k,l,m,n=1}^{3} p_j^\alpha p_k^\beta p_l^\mu p_m^\rho p_n^\nu D_{jklmn}.$$

A second independent calculation for virtual corrections: rough introduction

- Spinor formalism for massless polarization vectors, to reduce the tensor rank.

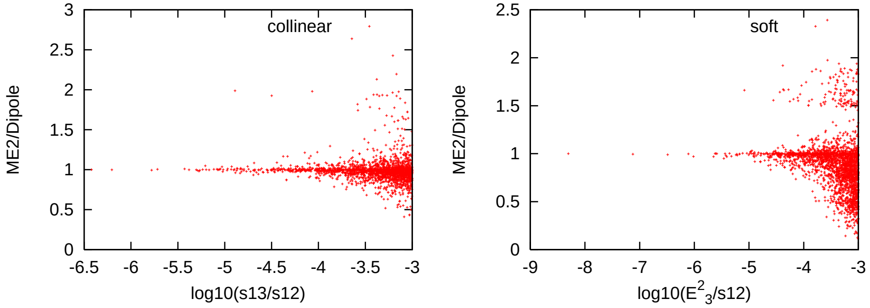
$$\epsilon_\mu^+(k) = \frac{1}{\sqrt{2}} \frac{\langle n^- | \mu | k^- \rangle}{\langle n^- k^+ \rangle}, \; \epsilon_\mu^-(k) = \frac{1}{\sqrt{2}} \frac{\langle n^+ | \mu | k^+ \rangle}{\langle k^+ n^- \rangle},$$

  n is an arbitrary light-like reference momentum.
- Implementing large extra dimension model into QGRAPH, generating automatically the Feynman diagrams and matrix elements. Sorting matrix elements by helicity and color properties.
- Using Form to map the matrix elements into a Lorentz tensor basis.
- Using GOLEM (A General One-Loop Evaluator for Matrix elements) to reduce the integrated results into the GOLEM integral basis.
- Numerical works.

Real corrections

- Graviton QCD production with 2 jets at the LHC in large extra dimensions has already been studied in our previous paper [JHEP 0804:019,2008] (With K.Hagiwara, P.Konar, K.Mawatari and D.Zeppenfeld)]
  $qg \to qgG$: 21 diagrams; $gg \to ggG$: 34 diagrams;
  $qq \to qqG$:14 diagrams; $qQ \to qQG$:7 diagrams.
- Include further $q\bar{q} \to q\bar{q}G$: 14 diagrams; $q\bar{q} \to ggG$: 21 diagrams; $q\bar{q} \to Q\bar{Q}G$: 7 diagrams; $gg \to q\bar{q}G$: 21 diagrams.
- Dipole substraction terms $d\sigma^A$ are got in help with MadDipole.

Ratio of matrix element for $PP \to jjG$ over the dipole terms as a function of s_{13}/s_{12} or E_g^2/s_{12}, with $\delta = 4$, $\Lambda = 4\,\text{TeV}$ and $\mu_r = \mu_f = PT_j^{(max)}$.



Numerical results

$PP \to jG$ at LO/NLO

- MSTW2008lo(nlo) PDF at LO(NLO). $\mu_r = \mu_f = P_T^{\rm G}$ unless in the scale plot.
- at the LHC, we require

$$P_T^{\rm miss} > 500 \ {\rm GeV} \ .$$

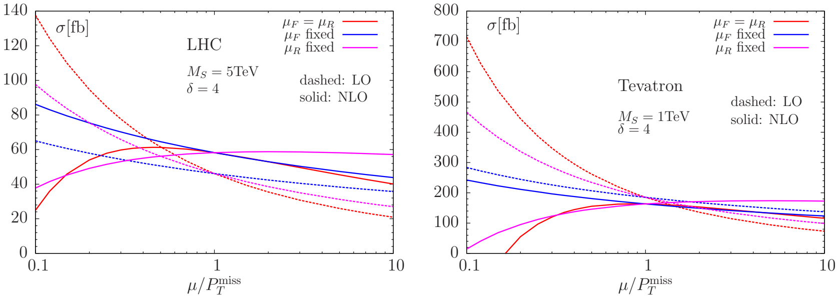
Jets are recombined via the k_T algorithm from massless partons, with the resolution parameter $D = 0.6$, and are required to satisfy $|\eta_j| < 4.5$ and $P_T^j > 50\,\text{GeV}$.

- At the Tevatron, we use the same setting as in the CDF II study, i.e.

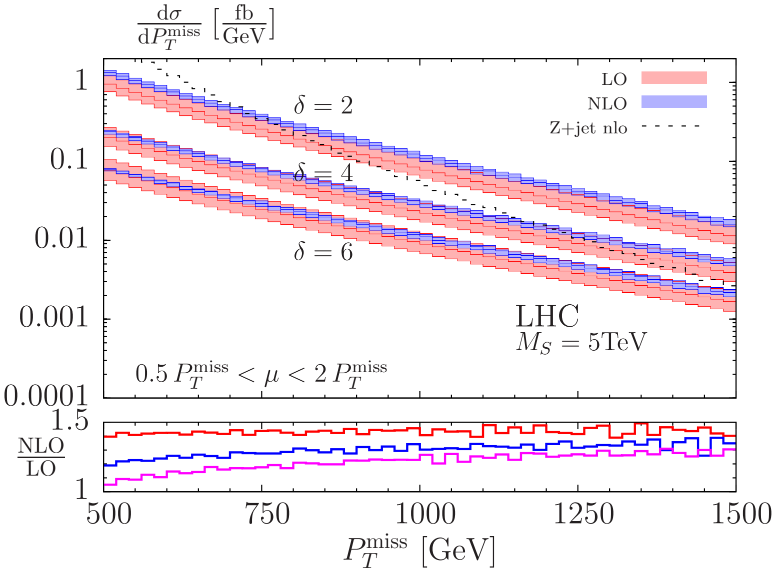
$$P_T^{\rm miss} > 120 \ {\rm GeV} \ .$$
$$P_T^{j1} > 150 \ {\rm GeV}, \quad |\eta_{j1}| < 1$$

k_T algorithm with $D = 0.7$, $|\eta_j| < 3.6$ and $P_T^j > 20\,\text{GeV}$. A second jet with $P_T > 60$ GeV is vetoed.

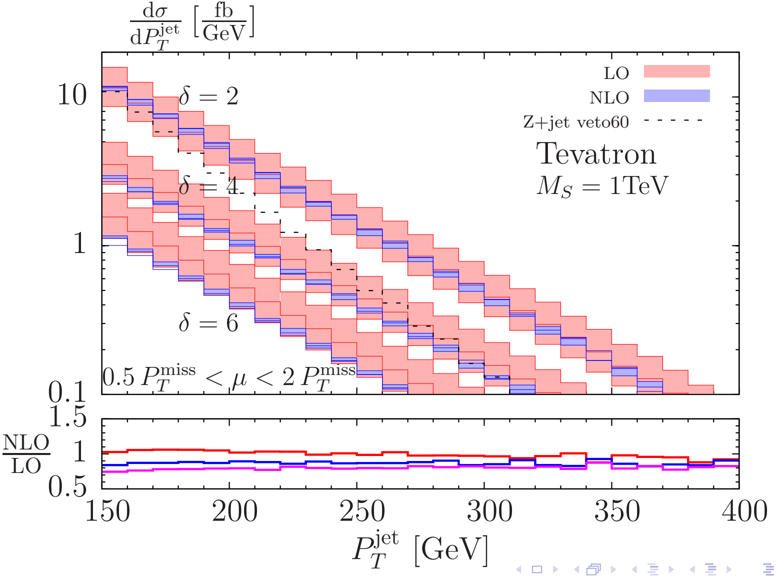
Scale plot


σ[fb]
LHC
$M_S = 5$TeV
$\delta = 4$
$\mu_F = \mu_R$
μ_F fixed
μ_R fixed
dashed: LO
solid: NLO
μ/P_T^{miss}
σ[fb]
Tevatron
$M_S = 1$TeV
$\delta = 4$
$\mu_F = \mu_R$
μ_F fixed
μ_R fixed
dashed: LO
solid: NLO
μ/P_T^{miss}

Scale uncertainty bands on $P_T^{\rm miss}$ distributions at the LHC

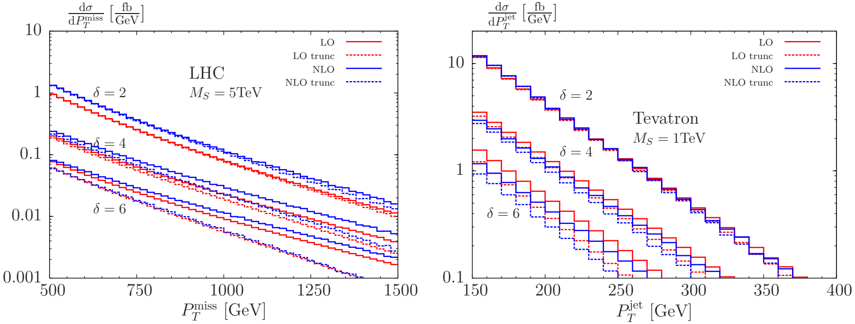


Scale uncertainty bands on P_T^{miss} distributions at the Tevatron



Theory UV completion uncertainty

Setting cut $Q_{\mathrm{truncation}} < M_s$ with $Q_{\mathrm{truncation}} = |P^{\mathrm{G}} + P^{\mathrm{jet(s)}}|^2$,



Summary

- We have presented the first calculation on the the NLO QCD corrections to KK graviton monojet production in the large extra dimensions model, in the form of a fully-flexible parton-level Monte Carlo program. The QCD corrections are found to be modest at the Tevatron, while sizable at the LHC (which can reach $30 - 50\%$ for $\delta = 2, 4, 6$), and the relevant K factors depend on the kinematical region and can not be simplified by an overall K-factor.

- The scale variation are investigated for three cases: (a) $\mu_r = \mu_f$; (b) μ_f fixed; and (c) μ_r fixed. When μ ranges between $P_T^{\mathrm{G}}/2$ and $2P_T^{\mathrm{G}}$, the largest LO scale dependence is $\sim \pm 26.8\%$ ($\sim \pm 31.7\%$), while the NLO one is $\sim \pm 9.8\%$ ($\sim \pm 9.7\%$), for the LHC and Tevatron settings, respectively. Thus the NLO QCD corrections reduce the scale uncertainty significantly.

- We have also studied uncertainties arising from the theory UV completion, the magnitude of which can be larger than 40% for large P_T^{miss} (P_T^{jet}) and extra dimension number δ. However, our work applies also for scenarios as the Randall-Sundrum model, of which the UV part of the theory is clear and thus contains no ambiguity. Moreover, one can set relative lower P_T^{miss} (P_T^{jet}) upper limit in experimental search to avoid the large theory uncertainty, but then one decrease the signal background ratio, and thus need higher integrated luminosities for the Hadron Collider to compensate for that.

- Finally, we mention that we also investigated the PDF uncertainty with the MSTW2008nlo68 41-set PDFs. We estimated the uncertainty for the total cross sections at NLO, and found it quite small as about 12% with the LHC setting.