ZZ+jet and Graviton+jet at NLO QCD: recent applications using GOLEM methods

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Outline

- Motivation and short overview of the tensor reduction with GOLEM
- 2 applications: Results for Z-boson pair +1-jet production and
- Graviton +1-jet production in large extra dimensions at NLO QCD
- Summary

Motivation of NLO calculation and difficulties

- LO predictions usually have large theoretical uncertainties
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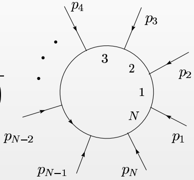
Motivation of NLO calculation and difficulties

- LO predictions usually have large theoretical uncertainties
- Large impact of higher order corrections due to new channels and experimental cuts possible
- huge amount of algebra, long expressions
  $\rightarrow$ Computeralgebra (Maple, Mathematica, FORM,...), automation
- complicated structure of singularities: real and virtual corrections
  $\rightarrow$ e.g. Catani-Seymour Dipole method, ...
- numerically stable evaluation of one-loop tensor-integrals when integrating over the multi-dimensional phasespace

Reduction method:

$$I_N^{n,\mu_1\ldots\mu_r} = \int \frac{d^n k}{i\,\pi^{n/2}} \frac{q_1^{\mu_1}\ldots q_r^{\mu_r}}{(q_1^2 - m_1^2 + i\delta)\ldots(q_N^2 - m_N^2 + i\delta)}$$



- main problem: numerically fast and stable evaluation needed
- classical approach: Passarino-Veltman method: $I_2^{\mu\nu} = A g^{\mu\nu} + B p^\mu p^\nu$
  $A, B \propto 1/\det G * (\sum \text{scalar integrals } I_N^n)$
- our method (GOLEM-coll.): reduce tensor int. to scalar int. in shifted dimensions (Davydychev 91)
  avoids inverse Gram determinants, algebraic separation of IR poles
  (T. Binoth, et al. hep-ph/0504267)

$$I_N^{n,\mu_1\ldots\mu_r} = \sum \tau^{\mu_1\ldots\mu_r}(r_{j_1},\ldots,r_{j_r},g^{\times m})\, I_N^{n+2m}(j_1,\ldots,j_R)$$

$$I_N^D(j_1,\ldots,j_R) = (-1)^N\,\Gamma(N-D/2)\int_0^\infty d^N z\,\delta(1-\sum_{l=1}^N z_l)\frac{z_{j_1}\ldots z_{j_r}}{(z\cdot S\cdot z/2)^{N-D/2}}$$

$$S_{ij} = (r_i - r_j)^2 - m_i^2 - m_j^2,\; r_j = p_1 + \ldots + p_j$$

- two alternatives for evaluation:
  - further algebraic reduction: occuring basis integrals: I_4^{n+2}, I_3^n, I_2^n
    But $1/\det G$ unavoidable ($G_{ij} = 2\, r_i \cdot r_j$)
  - direct numerical evaluation in critical regions of phasespace feasible
    for ZZjet and Gjet: fully algebraic reduction
  - see tomorrows talk by T. Reiter about more information about the GOLEM method, golem95 and GOLEM2.0!

The $PP \to VV jet$ amplitude

(T. Binoth, T. Gleisberg, SK, N. Kauer, G. Sanguinetti)

- Importance for LHC physics: background process to $H \to VV + \text{jet}$, anomalous gauge boson couplings, part of $PP \to VV$ at NNLO
- Virtual corrections: ~ 100 Feynman diagrams: (tensor reduction with GOLEM methods)

- tuned comparison of WWjet with [Dittmaier, Kallweit, Uwer 07], [Campbell, Ellis, Zanderighi 07] → [NLM Les Houches report 08]
- 6 scales: $s_{12}, s_{23}, s_{34}, s_{45}, s_{15}, M_Z^2$
- regularisation scheme: 'tHooft/Veltman (anti-commuting γ_5), $\overline{\text{MS}}$
- 36 helicity amplitudes, related by bose symmetry, charge conjugation and parity transformation
  $\mathcal{M}^{\lambda_1\lambda_2\lambda_3\lambda_4\lambda_5} = \epsilon^{\lambda_3}_{3,\mu_3}\epsilon^{\lambda_4}_{4,\mu_4}\epsilon^{\lambda_5}_{5,\mu_5}\ \langle 2^{\lambda_2}|\Gamma^{\mu_3\mu_4\mu_5}|1^{\lambda_1}\rangle$
- real emissions: Sherpa dipoles (Gleisberg, Krauss), cross checked with MadDipole (Frederix,Gehrmann, Greiner), Helac dipoles (Czakon, Papadopoulos, Worek) and partial in house implementation

Helicity projection for $q\bar{q}VVg \to 0$

- replace momenta of the massive vectorbosons ($p_{3,4}$) with light-like momenta ($k_{3,4}$) to apply spinor formalism

$$k_{3,4} = \frac{1}{2\beta}\left[(1+\beta)p_{3,4} - (1-\beta)p_{4,3}\right] \quad \text{with } k_{3,4}^2 = 0$$

$$\epsilon^{+}_{3,\mu} = \frac{1}{\sqrt{2}}\frac{\langle 4^-|\mu|3^-\rangle}{\langle 43\rangle}, \quad \epsilon^{0}_{3,\mu} = \frac{1}{\sqrt{2}}\frac{(1+\beta)k_{3,\mu} - (1-\beta)k_{4,\mu}}{2M_V}$$

Use to define projectors on helicity amplitudes, schematically:

$$\begin{aligned}\mathcal{M}^{\lambda_1\lambda_2\lambda_3\lambda_4\lambda_5} &= \mathcal{P}^{\lambda_3\lambda_4\lambda_5}_{\mu_3\mu_4\mu_5}\langle 2^{\lambda_2}|\Gamma^{\mu_3\mu_4\mu_5}|1^{\lambda_1}\rangle \\ &= (\text{global spinorial factor}) \times (\text{contracted tensor integrals})\end{aligned}$$

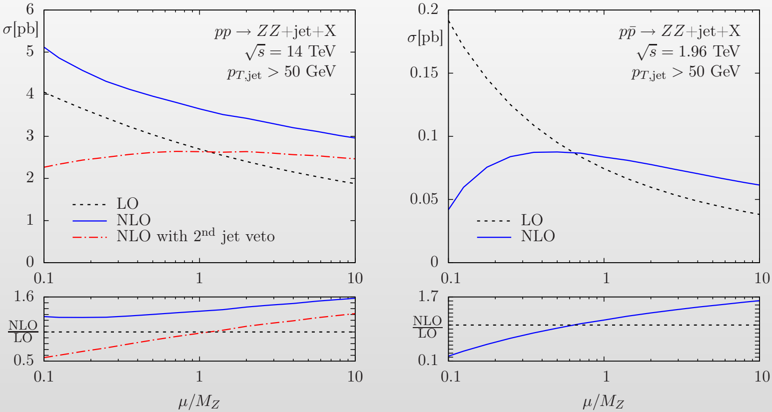
- Lorentz indices saturated, at most rank 1 pentagons (+ rank 3 boxes)
- spinor products can be treated as global factors
- further simplifications in analytical expressions possible and performed

Results for $ZZ + \text{jet}$

- differences to $WW + \text{jet}$: additional Bose symmetry, also right-handed couplings to fermions, no box-type diagrams from WWZ, WWA vertex
- Input parameters/settings:
  $N_F = 5$, $m_q = 0$, $M_Z = 91.188$ GeV, $\alpha(M_Z) = 0.00755391226$,
  $\sin^2\theta_W = 0.222247$
  PDFs: CTEQ6L1(LO), CTEQ6M(NLO)
  Cuts: $p_{T\mathrm{jet}} > 50$ GeV
  central scale choice: $\mu_F = \mu_R = M_Z$

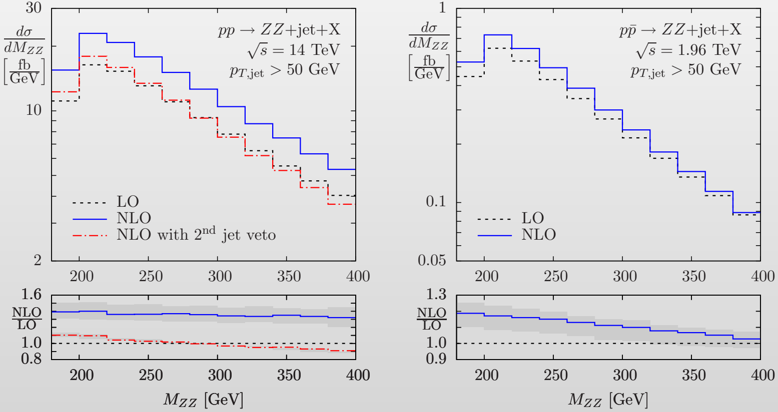
	$\sigma(pp \to ZZ + \text{jet})$ [pb], $\sqrt{s} = 14$ GeV			
$p_{T,\text{jet}}$ cut [GeV]	20	50	100	200
LO	6.500(6)	2.696(2)	1.0057(9)	0.2297(2)
NLO	8.01(3)	3.653(9)	1.511(4)	0.415(2)
NLO with 2^{nd} jet veto		2.637(9)	0.755(4)	0.1005(9)

Scale variations:



	$\Delta\sigma/\sigma(pp \to ZZ + \text{jet})$, $\sqrt{s} = 1.96(14)$ TeV		
	$\mu/M_Z \in [\frac{1}{2}, 2]$	$\mu/M_Z \in [\frac{1}{4}, 4]$	$\mu/M_Z \in [\frac{1}{8}, 8]$
LO	23%	44%	62%
NLO	6%	11%	19%
LO	12%	23%	34%
NLO	7%	15%	23%
NLO with 2nd jet veto	0.5%	3%	6%

Distributions:



The $PP \rightarrow G + jet$ amplitude

(SK, M. Krämer, Q. Li, D. Zeppenfeld)

Large Extra Dimensions

- Gravity is weaker by a factor 10^{40}. Why? (or equivalently, why is $v \ll M_{\mathtt{Planck}}$?) $\rightarrow$ Hierarchy problem
- one possible solution:
  Extra Dimensions allow the fundamental Planck scale to be as low as the EW scale

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- various models, e.g. the ADD model: Arkani-Hamed, Dvali & Dimopoulos (1998)
  - δ extra dimensions, compactified at radius r
  - SM is confined to a brane in a higher dimensional space
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  - only gravity can access extra dimensions
- From dimensional analysis, we have $M_{Pl}^2 \propto r^\delta M_s^{\delta+2}$
  - 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 (direct probes of Newtons law)
  - If $\delta > 2$ and $M_s \sim$TeV, $\rightarrow r < 10^{-6}$cm $\rightarrow$ only testable at high energy colliders

Kaluza-Klein (KK) tower

- periodic boundary conditions for the compactified extra dimensions
- quantized momentum in extra dimensions ($p = n/r$) $\rightarrow$ massive Gravitons: $m_G^2 = m_0^2 + p^2$
- Infinite tower of 4D KK modes: mass splittings $\Delta m \propto 1/r$
  $\delta = 2 : \Delta m_G \propto 10^{-4}$eV, $\delta = 6 : \Delta m_G \propto 10$MeV
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- Interaction described by an effective quantum gravity Lagrangian:
  $\mathcal{L}_{\text{int}} = -\frac{1}{\overline{M}_{Pl}} \sum_{\vec{n}} (h^{(\vec{n})})^{\mu\nu} T_{\mu\nu}$ (h: KK mode, T: energy mom. tensor)

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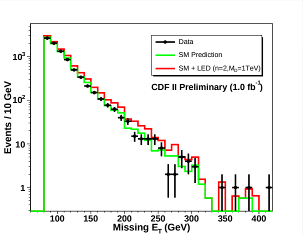
- summation over the KK tower: M_{Planck} suppression replaced by M_s suppression in cross sections! $\rightarrow \frac{d\sigma}{dt} \propto \frac{1}{M_s^{2+\delta}} \int m_G^{\delta-1} \frac{d\sigma_m}{dt} dm_G$

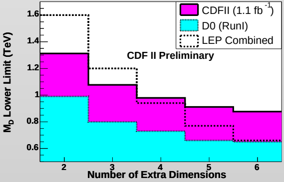
Collider Signatures

- How do we get evidence of LEDs at colliders? $\longrightarrow$ two different signatures (ADD model)
- direct graviton production and virtual graviton exchange (more model dependent)

Graviton plus 1-jet production

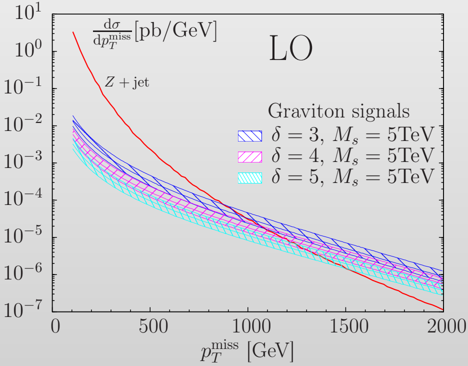
- Monojet + nothing is a striking signal for new physics at the LHC
- major background: $Z(\rightarrow \nu\bar{\nu}) + jet$ both theoretically and experimentally under good control
- Experimental studies (Tevatron) for Graviton production with monojet have found a strong ability to probe higher extra dimension scale: jet+missing Energy, photon+missing Energy,



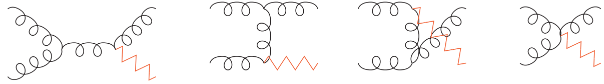


Graviton plus 1-jet at NLO QCD

- Need for QCD corrections: reduction of large scale uncertainties at LO, sizable contribution to the cross section possible (K-factor)



- 2 subprocesses at LO: $gg \to Gg$, $q\bar{q} \to Gg$ + crossed



- Graviton = massive spin-2 vector boson
  (polarization tensor: $\epsilon^{\lambda_4}_{\mu\nu}$, $\lambda_4 = \{++, +, 0, -, --\}$)
- 3 scales: s, t, M_G

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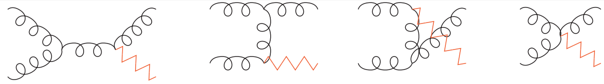

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- virtual corrections: 43 diagrams for $q\bar{q}$, 108 diagrams for gg Most complicated diagrams: box diagrams with tensor rank $r = 5$ due to the complicated tensor structure of the Graviton
- application of the spinor formalism to project onto helicity amplitudes
- fully analytic reduction to scalar integrals: I_4^{n+2}, I_3^n, I_2^n
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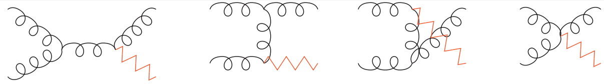

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- real corrections: dipole subtraction method, code based on modified MadDipole

Calculation

```
#
# File created by Simplify_Graphsum.map
#
#
amp[PMMPP] :=
   +ONE*(8/3*I*(72*es12^7*es23^3+24*es12^7*MG2^3-284*es23^4*MG2^6+426*es23^5*MG2^5-
219*es12^4*MG2^6+237*es12^5*MG2^5-24*es23*es12^7*MG2^2-72*es23^2*es12^7*MG2-
1635*es23^2*es12^2*MG2^6+213*es23*es12^2*MG2^7+213*es12*MG2^7*es23^2-2*es23^7*es12^3-
284*es23^6*MG2^4+71*es23^7*MG2^3+106*es23^4*es12^6-107*es12^6*MG2^4+12*es23^6*es12^4-
6*es12^8*MG2^2+71*es23^3*MG2^7+71*es12^3*MG2^7+18*es23^2*es12^8+66*es23^5*es12^5+4554*es23^3*es12^2
*MG2^5-5760*es23^4*es12^2*MG2^4+3417*es23^5*es12^2*MG2^3-855*es23^6*es12^2*MG2^2-
1013*es12^3*MG2^6*es23+4206*es12^3*MG2^5*es23^2-7540*es12^3*MG2^4*es23^3+5685*es23^3*es12^4*MG2^3-
2799*es23^4*es12^4*MG2^2+1785*es23*es12^4*MG2^5-4830*es23^2*es12^4*MG2^4+6223*es23^4*es12^3*MG2^3-
2253*es23^5*es12^3*MG2^2+308*es23^6*es12^3*MG2-1143*es23^3*es12*MG2^6+2268*es23^4*es12*MG2^5-
2088*es23^5*es12*MG2^4+72*es23^7*es12^2*MG2+873*es23^6*es12*MG2^3-123*es23^7*es12*MG2^2-
1641*es23^3*es12^5*MG2^2+264*es23^4*es12^5*MG2+486*es23^5*es12^4*MG2-
1407*es23*es12^5*MG2^4+2481*es23^2*es12^5*MG2^3+446*es23*es12^6*MG2^3-381*es23^2*es12^6*MG2^2-
58*es23^3*es12^6*MG2)*(es12+es23-MG2)*es12*sf5*sf4*es23^2/(es12+es23)^3/(-MG2+es23)^2/(es12-MG2)^3)
   +BUBd4(MG2,0,0)*(16*I*(es12+es23-MG2)*(-12*es23^8*es12^2*MG2-
11*es23^8*MG2^3+72*es12^8*es23^3+108*es12^7*es23^4+44*es23^5*MG2^6-
66*es23^6*MG2^5+44*es12^5*MG2^6-
66*es12^6*MG2^5+44*es23^7*MG2^4+102*es23^5*es12^6+44*es12^7*MG2^4+54*es23^6*es12^5+12*es23^7*es12^4
-11*es12^8*MG2^3+6*es23*es12^10-11*es23^4*MG2^7-
11*es12^4*MG2^7+30*es23^2*es12^9+536*es23^2*es12^7*MG2^2-177*es23^2*es12^8*MG2-
456*es23^3*es12^7*MG2+338*es23^2*es12^3*MG2^6+352*es23^3*es12^2*MG2^6-32*es23*es12^3*MG2^7-
45*es23^2*es12^2*MG2^7-32*es12*MG2^7*es23^3-30*es23*es12^9*MG2-1304*es23^3*es12^3*MG2^5-
1030*es23^4*es12^2*MG2^5+2356*es23^4*es12^3*MG2^4+1362*es23^5*es12^2*MG2^4-
2044*es23^5*es12^3*MG2^3-829*es23^6*es12^2*MG2^3+794*es23^6*es12^3*MG2^2+202*es23^7*es12^2*MG2^2-
944*es12^4*MG2^5*es23^2+2320*es12^4*MG2^4*es23^3-2282*es23^3*es12^5*MG2^3-
2808*es23^4*es12^4*MG2^3+1874*es23^4*es12^5*MG2^2+1600*es23^5*es12^4*MG2^2+1326*es23^2*es12^5*MG2
^4+92*es23*es12^8*MG2^2-369*es23^6*es12^4*MG2-108*es23^7*es12^3*MG2+1330*es23^3*es12^6*MG2^2-
690*es23^4*es12^6*MG2-654*es23^5*es12^5*MG2-1064*es23^2*es12^6*MG2^3-
232*es23*es12^7*MG2^3+198*es23^4*MG2^6*es12-422*es23^5*MG2^5*es12+172*es12^4*MG2^6*es23-
362*es12^5*MG2^5*es23+398*es23^6*MG2^4*es12+386*es12^6*MG2^4*es23-
162*es23^7*es12*MG2^3+20*es23^8*es12*MG2^2)*es12*MG2*sf5*sf4*es23^2/(es12+es23)^4/(-MG2+es23)^2/(es12-
MG2)^4)
   +BUBd4(es12,0,0)*(-16*I*es12^2*sf5*sf4*(es12+es23-MG2)^2*es23^3*(3*es12^4*es23-
120*es23*es12*MG2^3+54*es23^2*es12*MG2^2+66*es12*MG2^4-72*es12^2*MG2^3+102*es23*es12^2*MG2^2-
24*es12^4*MG2-33*es12^3*es23*MG2-44*es12^2*es23^2*MG2-24*MG2^5+48*es23*MG2^4-
24*es23^2*MG2^3+48*es12^3*MG2^2+6*es12^5+11*es23^2*es12^3)/(-MG2+es23)^2/(es12-MG2)^4)
   +BUBd4(es13,0,0)*(16*I*(14*es23^5+51*es23^4*es12-16*es23^4*MG2-65*es12*MG2*es23^3+75*es23^3*es12^2-
10*es23^3*MG2^2+59*es23^2*es12^3-7*es23^2*es12*MG2^2-88*es12^2*es23^2*MG2+12*es23^2*MG2^3-
45*es12^3*es23*MG2+21*es23*es12*MG2^3+15*es23*es12^2*MG2^2+27*es12^4*es23+6*es12^5+12*es12^3*MG2^2
+12*es12^2*MG2^3-6*es12^4*MG2)*sf5*sf4*(es12+es23-MG2)^2*es12^2*es23^3/(-MG2+es23)^2/(es12+es23)^4)
   +TRId4(es12,0,0,0,0,0)*(-48*I*(es12+es23-MG2)*sf5*sf4*es12^2*(-MG2+es23)^2*es23^2)
   +TRId4(es13,0,0,0,0,0)*(48*I*es12*sf5*sf4*(es12+es23-MG2)^2*(-MG2+es23)^2*es23^2)
   +TRId4(es23,0,0,0,0,0)*(-48*I*(es12+es23-MG2)*es12*sf5*sf4*(-MG2+es23)^2*es23^3)
   +BOXd6(es12,es13,MG2,0,0,0,0,0,0,0)*(24*I*(2*es12^2+2*es23*es12-2*es12*MG2+2*I*es23*es12-
2*I*es12*MG2+es23^2-2*es23*MG2+MG2^2+I*es23^2-2*I*es23*MG2+I*MG2^2)*(es12+es23-MG2)*(es23^2-
I*es23^2+2*es23*es12-2*I*es23*es12+2*es12^2-2*es23*MG2+2*I*es23*MG2-2*es12*MG2+2*I*es12*MG2+MG2^2-
I*MG2^2)*es12*sf5*sf4*es23^3/(-MG2+es23)^2)
   +BOXd6(es12,es23,MG2,0,0,0,0,0,0,0)*(-48*I*es12*sf5*sf4*(es12+es23-MG2)^2*(-MG2+es23)^2*es23^2)
   +BOXd6(es13,es23,MG2,0,0,0,0,0,0,0)*(48*I*(es12+es23-MG2)*sf5*sf4*es12^2*(-MG2+es23)^2*es23^2):
```

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- gauge invariance
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- gauge invariance
- discrete symmetries
- cancellation of the IR poles ($1/\epsilon$, $1/\epsilon^2$) in virtual and real corrections
- two independent calculations (not yet fully completed)

Results for Graviton + jet at NLO

Setup:

- $\delta = 2, 4, 6$, $M_S = 5$ (1) TeV, (LHC,Tevatron) PDFs: MSTW2008(n)lo
- central scale choice : $\mu_F = \mu_R = p_T^{miss}$
- cuts: $p_T^{miss} > 500$ GeV (for Tevatron: cuts from CDF II study)

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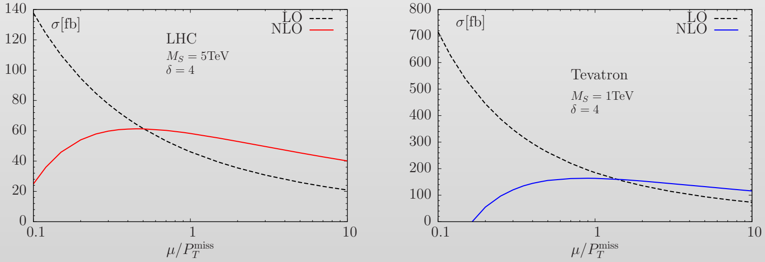

Results for Graviton + jet at NLO

Setup:

- $\delta = 2, 4, 6$, $M_S = 5$ (1) TeV, (LHC,Tevatron) PDFs: MSTW2008(n)lo
- central scale choice : $\mu_F = \mu_R = P_T^{miss}$
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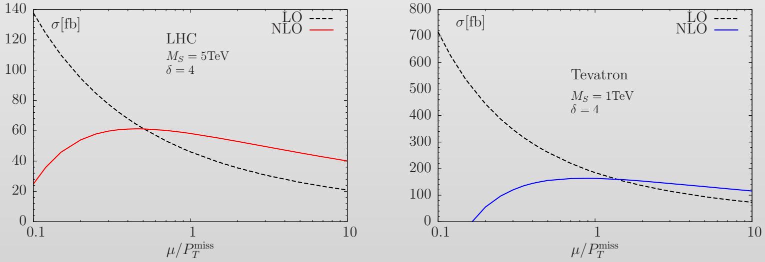
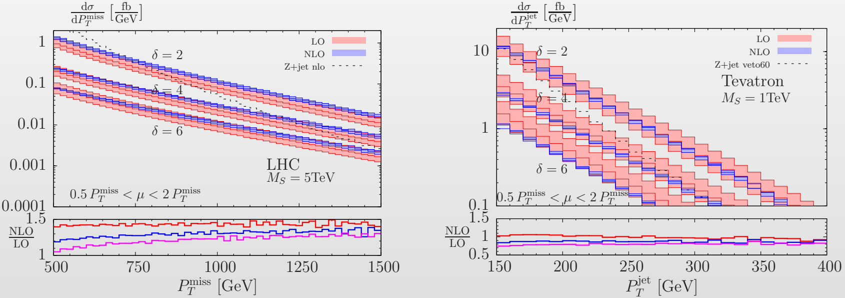


⟶ scale variation by a factor 2: ±27% (±32%) at LO, ±10%(±3%) at NLO

⟶ K-factor: $\sigma_{NLO}/\sigma_{LO} = 1.26(0.9)$ (at $\mu = P_T^{miss}$)



→ sufficiently large signal cross section
→ error bands from scale variation strongly reduced at NLO
→ small K-factor dependence on P_T for the LHC and $\delta = 4, 6$

low energy eff. theory not applicable above fund. scale M_s:
$\rightarrow$ results with hard truncation scheme: $\sqrt{\hat{s}} < M_s$

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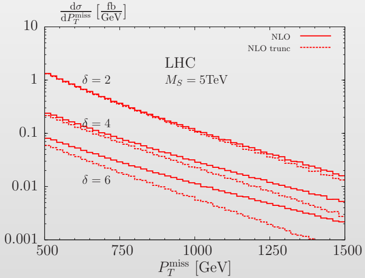

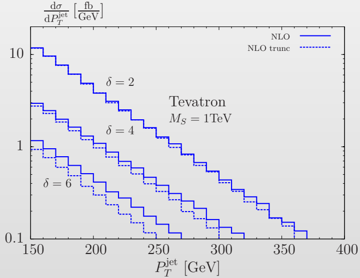

e.g. at $P_T^{miss} = 1500$ GeV: uncertainty: $\pm 10\%$ ($\pm 60\%$) for $\delta = 2(6)$
$\rightarrow$ eff.theory has limited applicability energy range, but large enough to be useful for collider predictions

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- fully analytic approach to ZZ+jet and G+jet at NLO with GOLEM methods
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- Reduced scale uncertainties (at the LHC: only after a jet veto)
- corrections for the M_{ZZ} distribution depend on the kinematical region (Tevatron, LHC NLO(excl))
- Computation of Graviton+jet production at NLO QCD as an important probe for large extra dimensions
- Significant reduction of scale uncertainties for LHC and Tevatron, sizable QCD corrections for LHC, depending on the kinematical region
- studied also other uncertainties (eff. theory approach, pdfs, jet veto)
- Results should be taken into account in experimental studies