Jets and Photons (theory)

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Introduction

Single inclusive and dijet inclusive production:

- $pp \rightarrow \text{jet} + X ; pp \rightarrow 2\text{jet} + X$
- inclusive jet $p_T$: all reconstructed jets in the event contribute to the observable
- inclusive over all additional radiation

Single inclusive and diphoton inclusive production:

- $pp \rightarrow \gamma + X ; pp \rightarrow \gamma\gamma + X$
- isolated photon pairs $\rightarrow$ clean final state. Photon energies/momenta measured with high precision.

Consider inclusive jet and photon production at 14 TeV and 27 TeV

- higher order corrections effects
- ratios of cross section and kinematical range at 14 TeV and 27 TeV
Inclusive jet production at HE/HL-LHC

Single jet inclusive production:

• $pp \to jet + X$ run with NNLOJET* for the fixed order perturbative QCD predictions
• PDF=CT14nnlo, $\alpha_s=0.118$
• $\mu_R=\mu_F=\hat{H}_T$ (scalar sum of parton transverse momenta)
• Jets: anti-$k_T$ with $R=0.4$
• Fiducial volume defined through the cuts

\[ |y^j| < 4.0, \quad p_T^j > 100 \text{ GeV} \]

Subprocess fractions

- enhanced *gluon*-luminosity at 27 TeV over 14 TeV → large-x PDF turn into medium-x PDFs
- increased sensitivity to *qg*/*gg* initiated channels → dominate between 100 GeV-4000 GeV
- *qq* contribution dominant at high-*p_T* > 4 TeV
- *q\bar{q}* contribution small across the entire *p_T* range
Jet $p_T$ and rapidity at 14 and 27 TeV

- NLO prediction shown
- Increased range of the observable into the TeV region at 27 TeV
- Large rates allow multi-differential measurements

$$x_1 = \frac{p_T}{\sqrt{s}} (e^{y_{j_1}} + e^{y_{j_2}})$$

$$x_2 = \frac{p_T}{\sqrt{s}} (e^{-y_{j_1}} + e^{-y_{j_2}})$$

- Higher $Q^2$ coverage $\rightarrow$ sensitivity to higher order effects QCD-EW/BSM signals
- Increased coverage in lower-$x$ $\rightarrow$ sensitivity to role of resummation effects
Double differential k-factors at 14 TeV and 27 TeV

- large NLO QCD effects at high-pT and central rapidity ~ 90% (14 TeV) ~ 50% (27 TeV) with large NLO scale uncertainties $\delta(50\%) \Rightarrow$ **NNLO numbers needed for the final report**

- NLO k-factor rapidity dependent probing different PDF x-ranges
Jet $p_T$ and rapidity at 14 and 27 TeV

- Fiducial single jet inclusive cross section ratio 27 TeV/14 TeV

- Enhancement of the cross section by a factor between 2-100 growing with the jet $p_T$ in the LHC-range and larger at the HE-LHC

- with HL-LHC more events in tails with higher statistics → increased resolution at high-$x$ where BSM effects and PDFs are less constrained

- with HE-LHC factor of $10^3 \sim 10^4$ increase in the cross section extend the $p_T$ range of the measurement by a factor of 2 up to 10 TeV
Inclusive direct photon production at HE/HL-LHC

Numerical setup:

- $pp \rightarrow \gamma + X$ at $\sqrt{s} = 14$ and 27 TeV
- $E_T^{\gamma} > 40$ GeV.
- $|\eta_\gamma| < 2.5$.
- $R < 0.4$, $E_{T_{\text{max}}} < 4.8$ GeV + $4.2 \times 10^{-3} E_T^{\gamma}$.

Differential distributions:

- $E_{T_{\gamma}}$ at NLO and NNLO QCD + EW
- Ratios of $\sqrt{s} = 27$ over 14 TeV predictions
- Theory uncertainties: standard (7-points) scale variation bands and differences between NNLO and NLO predictions.
Diphoton production at HE/HL-LHC

(thanks to L.Cieri)

Numerical setup:

► $pp \rightarrow \gamma\gamma + X$ at $\sqrt{s} = 14$ and 27 TeV
► $E_{\gamma,1}^\gamma > 40$ GeV, $E_{\gamma,2}^\gamma > 30$ GeV.
► $|\eta_\gamma| < 2.5$.
► $R < 0.4, E_{T,\text{max}} < 5$ GeV.

Differential distributions:

► $p_{T,\gamma\gamma}$ at NLO and NNLO QCD + EW
► $M_{\gamma\gamma}$ at NLO and NNLO QCD + EW
► Ratios of $\sqrt{s} = 27$ over 14 TeV predictions
► Theory uncertainties: standard (7-points) scale variation bands and differences between NNLO and NLO predictions.
Diphoton planned contributions

Photon isolation comparison at HL/HE-LHC

Study of differences between standard cone (used in exp. measurements) and smooth cone (used in NNLO QCD th. predictions) isolation prescriptions. Comparison between standard and smooth cone at $\sqrt{s} = 14$ and 27 TeV (similar to analogous studies performed at $\sqrt{s} = 7$ TeV in S.Catani et al. [arXiv:1802.02095]).

\[
\begin{array}{c|c|c|c|c|}
 & E_{T_{\text{max}}} = 2 \text{ GeV} & & E_{T_{\text{max}}} = 10 \text{ GeV} \\
 & \sigma_{\text{LO}} \ (\text{pb}) & \sigma_{\text{NLO}} \ (\text{pb}) & \sigma_{\text{LO}} \ (\text{pb}) & \sigma_{\text{NLO}} \ (\text{pb}) \\
\hline
\text{Standard} & 12.15 & +14.5 \% & -14.3 \% & 19.51 & +25.0 \% & -20.8 \% \\
\text{[direct]} & 10.56 & +10.7 \% & -12.0 \% & 10.56 & +10.7 \% & -12.0 \% \\
\text{Smooth} & 10.56 & +10.7 \% & -12.0 \% & 10.56 & +10.7 \% & -12.0 \% \\
\end{array}
\]

\[
pp \rightarrow \gamma\gamma + X \text{ at } \sqrt{s} = 7 \text{ TeV}.
\]
Jets and Photons planned contributions

Studies for 14 and 27 TeV:

• NLO QCD numbers available for single jet inclusive production

• Ongoing runs for dijet and photon observables defined with the fiducial cuts
  • Opportunity to test ideas for new measurements and observables that can maximize the:
    • increased reach with increased luminosity → more events in tails
    • extended kinematical range in $p_T$ and rapidity $y$ at $\sqrt{s}=$27 TeV
    • increased sensitivity to BSM making use of the beneficial 27 TeV over 14 TeV cross section ratios

Planned contributions:

• NNLO QCD numbers needed to properly assess accuracy of the theory on:
  • scale uncertainties when confronting precision data at HL-LHC
  • uncertainty due to missing higher order corrections, i.e, perturbative convergence

• NLO EW effects needed:
  • large effects at high-$p_T$ from EW Sudakov logarithms needed for a good description of data
Inclusive dijet production at HE/HL LHC

- \( pp\rightarrow 2jet +X \) run with \textit{NNLOJET} for the fixed order perturbative QCD predictions

- PDF=CT14nnlo, \( \alpha_s=0.118 \)

- \( \mu_R=\mu_F=M_{JJ} \) (dijet mass)

- Jets: anti-\( k_T \) with \( R=0.4 \)

- Fiducial volume defined through the cuts

\[
p_T^1 > 100 \text{ GeV} \quad |y_j| < 4.0
\]
\[
p_T^2 > 75 \text{ GeV}
\]

\textit{Differential distributions:}

- \( M_{JJ} \) at NLO and NNLO QCD+EW

\[
M_{JJ} \in [310, 26250] \text{ GeV}
\]
\[
y^* = \frac{1}{2} |y_{j1} - y_{j2}| = \{0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0\}
\]

- ...