LHC observables with NNLOJET

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Benchmark processes at LHC

- Low multiplicity processes with large production rates and small experimental uncertainties
- Allow precise determinations of:
  - Masses, couplings
  - Parton distributions
- Enable indirect new physics searches
- Require precise theory
  - Higher orders (with full event properties)
NNLOJET framework

- Common infrastructure for computing NNLO observables for $2 \rightarrow 1$ and $2 \rightarrow 2$ hadron collider processes
  - $pp \rightarrow \text{di-jets}$
  - $pp \rightarrow H+(0,1)\text{jets}$
  - $pp \rightarrow H+2 \text{ jets (VBF)}$
  - $pp \rightarrow V/\gamma(0,1)\text{jets}$
  - $ep \rightarrow e+(1,2)\text{jets}$

- New: $N^3\text{LO}$ differential observables for $2 \rightarrow 1$ processes
  - $ep \rightarrow e+1 \text{ jet}$
  - $pp \rightarrow H$ (See talk by Xuan Chen)

- New: flavour-sensitive observables (this talk)
  - $pp \rightarrow H+V \text{ with } (H \rightarrow \text{bb}) \text{ and } (V \rightarrow \text{leptons})$
  - $pp \rightarrow Z+b\text{-jet with } (Z \rightarrow \text{leptons})$
Triple differential di-jet cross section

- Di-jet cross section: $pp \rightarrow 2 \text{ jets } +X$
  - Measured triple differentially by CMS 8 TeV [arXiv:1705.02628] as function of
    - Average $p_T$ $p_{T,\text{avg}} \equiv (p_{T,1} + p_{T,2})/2$
    - Rapidity separation $y^* = |y_1 - y_2|/2$
    - Boost of the di-jet system $y_b = |y_1 + y_2|/2$
  - Probe of parton distributions: vary $y_b$ at fixed $y^*$
    - Small $y_b [0;1]$: cross section largest for $x_1 \sim x_2$ (PDFs well-known)
    - Large $y_b [1;2]$: probe asymmetric $x_1, x_2$ values (PDFs have large uncertainties)

Rapidity slice: $0 < y^* < 1$
CMS set-up
Triple differential di-jet cross section

- **NNLOJET:** hadron collider jet production at NNLO
  - Single jet inclusive and di-jet observables
  - Recently: independent validation
- **Compare to triple differential CMS results** [arXiv:1705.02628]
  - NNLO + electroweak + hadronization
  - Small $y_b$ ($0 < y_b < 1$): Improved description at NNLO for entire range in $p_{T,\text{avg}}$
  - Large $y_b$ ($1 < y_b < 2$): Data below NNLO predictions (PDF effect)
\( W^{\pm} + \text{jet} \) at forward rapidity

- Production of a vector boson with a forward jet
  \[ p + p \rightarrow W^{\pm} (\rightarrow l^{\pm} + \nu_l) + \text{jet} + X \text{ with } (2 < \eta^j < 4.5) \]
  - Measured by ATLAS @ 7TeV [arXiv:1408.6510] and LHCb @ 8TeV [arXiv: 1605:00951]

Regions probed at LO by LHCb and ATLAS differ:
- LHCb coverage assymmetric: large \( x_1 \), small \( x_2 \)
- \( W^{\pm}J \) fiducial cross sections @NNLO
  - Substantial reduction of scale uncertainty using central scale \( \mu_0 = \sqrt{M_V^2 + \sum_i (p_{T,i})^2} \)
  - agreement with LHCb result within errors

\[
\begin{array}{|c|c|c|}
\hline
\text{Process} & \text{Fiducial } \sigma \text{ [pb]} \\
\hline
W^{+}J & \text{LO} & 46.9_{-2.2}^{+5.6} \\
& \text{NLO} & 62.8_{-3.5}^{+3.6} \\
& \text{NNLO} & 63.1_{-0.5}^{+0.4} \\
& \text{LHCb} & 56.9 \pm 0.2 \pm 5.1 \pm 0.7 \\
W^{-}J & \text{LO} & 27.2_{-2.6}^{+3.2} \\
& \text{NLO} & 36.7_{-2.1}^{+2.2} \\
& \text{NNLO} & 36.8_{-0.2}^{+0.3} \\
& \text{LHCb} & 33.1 \pm 0.2 \pm 3.5 \pm 0.4 \\
\hline
\end{array}
\]
**W^± + jet at forward rapidity**

- **Charged lepton asymmetry in W^± + jet**

\[
A^\pm(\eta_l) = \frac{d\sigma^{W^+j}/d\eta_l - d\sigma^{W^-j}/d\eta_l}{d\sigma^{W^+j}/d\eta_l + d\sigma^{W^-j}/d\eta_l}
\]

- Sensitive to (u/d) PDF ratio at large x
- Similarities in \(W^\pm\) process: Apply correlations
  - Scale uncertainty quantified by independent variation of numerator and denominator
    taken as the physical quantities
  
  Observe: theory above data in last \(\eta_l\) bin

- Study of PDF parametrisation sensitivity:
  - Observe: Spread of predictions
    - (most pronounced in last \(\eta_l\) bin)
    - reflecting the discriminative power of \(A^\pm\)
Flavour-sensitive jet observables

- Knowledge of V + HQ-jet(s) processes essential for phenomenology
  - Testing ground for probing the heavy quark content of the proton (4FNS vs. 5FNS)
  - Background to VH with H → bb and V → leptons
    - Most promising channel for precise determination of H → bb Yukawa coupling ($y_b$)

- Data available and compared with NLO (+PS)
- Computations at NLO level not sufficient
  - Needed: NNLO massless computations (5FNS)

- HQ-jet identification: Essential in theory and experiment
  - For comparisons: similar prescription required

[ CMS: arXiv 1611.06507v2]
Selection of flavoured jets: Experiment

• Experimentally: flavoured jets constructed from flavour-less jets
  – Step 1: Jets defined by a flavour-blind jet clustering algorithm
    distance measure for final state pseudo-jets \((i,j)\) \[d_{ij} = \frac{\Delta y_{ij}^2 + \Delta \phi_{ij}^2}{R^2} \min(k_{ti}, k_{tj})^{2p}\]
      \(k_t\): \(p=1\), \(\text{anti-}k_t\): \(p=-1\) \[\text{anti-}k_t\]: [M.Cacciari ,G. Salam: arXiv: 0802.1189]
  – Step 2: Partonic flavour assignment of the identified jet
    using vertex + track reconstruction tools

• Flavour of jet: counting the number of flavoured partons in the jet
  – Jet viewed as flavoured if \(|Nb(q_f) - Nb(\bar{q}_f)| \neq 0\)
    and jets with no net flavour are identified as gluon jets
Selection of flavoured jets @ NNLO

- **Flavour jet definition: problematic at parton level**
  - When used with anti-$k_T$: not infrared safe from NNLO onwards
    
    Large-angle gluon-to-soft-$bb$ splitting can alter the flavour of hard jet

- **Need a flavour-sensitive jet algorithm**
  - IR-safe flavour-$k_T$: A. Banfi, G. Salam, G. Zanderighi,
    [arXiv: 0601139, 0704.2999] (pre-dates anti-$k_T$)
    
    Treating flavoured and unflavoured partons differently:
    
    Use a flavour-dependent distance measure for final state pseudo-jets $(i,j)$
    $$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta \phi_{ij}^2}{R^2} \begin{cases} 
    \max(k_{ii}^2, k_{ij}^2) & \text{softer of } i, j \text{ is flavoured.} \\
    \min(k_{ii}^2, k_{ij}^2) & \text{softer of } i, j \text{ is unflavoured}
    \end{cases}$$

  - Not used (so far) on the experimental side
Selection of flavoured jets @ NNLO

- Flavour information of individual partons is required before application of the flavour-sensitive jet algorithm
  - Step 1: Flavour assignment using a flavour dressing procedure
  - Step 2: Flavour-aware jet reconstruction with flavour-\(k_T\) using the identified partonic momenta and flavours
  Note: Steps 1 and 2 inverted compared to the experimental procedure

- Flavour dressing: Applied on top of existing flavour-blind computations in NNLOJET
  - Example: Z+b-jet using the existing Z+jet calculation (not a new process)
  - Requires tracking and storing of the flavour information for each parton present in all squared amplitudes of parton-level sub-processes
  - Applied so far to: VH (with H→bb) and Z+b-jet observables
Associated Higgs production at LHC

• Associated Higgs production: \( pp \rightarrow VH + X \rightarrow l \bar{l} b \bar{b} + X \)
  
  – Experimental status
    • Clear leptonic signature
    • First evidence for \( H \rightarrow bb \) decay through VH channel
  
  – Towards differential distributions:
    Measurement as function of \( p_T^V \)
    • Using a simplified cross section (NRWA)
      \[ \sigma = \sigma_{VH} \times Br_{bb}^H \times Br_{ll}^V \]
    • Factorization of Higgs boson production and decay
    • In agreement with SM within uncertainties

\[ [\text{arXiv: 1903.04618}] \]
VH observables: Theory status

- **Most accurate predictions:** NNLO\_Production ⊗ NNLO\_Decay
    - Total cross section validated against [arXiv:1712.06954]

- **Common features:**
  - Selection of b-jets with flavour–\( k_T \) clustering algorithm
  - Common ingredients in production process at \( O(\alpha_s^2) \):
    - Drell-Yan like: Higgs couples to off-shell V
    - \( O(y_t) \) qq-induced: present for ZH and WH
    - \( O(y_t) \) gluon-gluon induced ZH: sizeable effects on observables
VH: comparison of predictions

• Treatment of Higgs decay part: Noticeable differences
  
  – Previously: cross section scaled to a fixed branching ratio $Br(H \rightarrow b\bar{b})$

  $$
  K^{(i)} = \frac{Br(H \rightarrow b\bar{b}) \Gamma_H}{\sum_j^{i} \Gamma_{H \rightarrow b\bar{b}}^j}
  $$

  $$
  \begin{align*}
  d\sigma^{scaled}_{NNLO} &= d\sigma_{VH}^{(0)} \times \left( d\sigma_{H \rightarrow b\bar{b}}^{(0)} + d\sigma_{H \rightarrow b\bar{b}}^{(1)} + d\sigma_{H \rightarrow b\bar{b}}^{(2)} \right) \times K^{(2)} \\
  &+ d\sigma_{VH}^{(1)} \times \left( d\sigma_{H \rightarrow b\bar{b}}^{(0)} + d\sigma_{H \rightarrow b\bar{b}}^{(1)} \right) \times K^{(1)} \\
  &+ d\sigma_{VH}^{(2)} \times \left( d\sigma_{H \rightarrow b\bar{b}}^{(0)} \right) \times K^{(0)}.
  \end{align*}
  $$

  – Unscaled cross section used in NNLOJET
    • Independent variation of QCD scales in production and decay using the central values:
      $$
      \mu^{prod.} = m_{VH} ; \mu^{dec.} = m_H
      $$

  – Compare fiducial results for $W^+H$ up to $O(\alpha_s^2)$:
    • Essentially no difference on central value at NNLO
    • Theory uncertainty reduction

      Spoiled in scaled case: Different factors accompanying different production parts

      Achieved in unscaled case: (<2% at NNLO), use for computing distributions
Flavour-sensitive VH observables @13 TeV

• Kinematical set-up for 13 TeV from LHC HXSWG [arXiv: 1610.07922]
  – at least two b-jets ($p_{T,b} > 25$ GeV, $|y_b| < 2.5$) selected according to the new flavour tagging procedure
  • Parton-level flavour dressing + flavour-$k_T$ jet algorithm

• $b$-jet pair $p_T$ spectrum for $W^+ H$ and $ZH$: sizeable differences

$W^+ H$:
• stabilisation at NNLO
• clear reduction of scale uncertainty over the whole range in $p_{t,bb}$

$ZH$:
• Sizeable impact of gg-loop induced contributions at NNLO
• distortion of shape in central region (top quark threshold effects)
• Large remaining uncertainty band
Z+b-jet observables @ NNLO

- **Z+b-jet production with Z→leptons:**
  \[ pp \rightarrow Z + b + X \rightarrow l^+l^- + b - \text{jet} + X \]
  - Computed with flavour tagging procedure to select b-jets
  - Use flavour dressing procedure applied to Z+jet@NNLO and flavour-\(k_t\) jet algorithm
  - Determine NNLO effects on distributions (central scale: \(\mu_0 = \sqrt{m_Z^2 + p_{T,Z}^2}\))

\[ p_{T,b} \]
- small NNLO corrections
- sizeable reduction of scale uncertainty (per-cent level)

\(\Delta\phi(Z, b)\)
- NNLO is NLO-like, since at LO \(\Delta\phi=\pi\) (only in last bin)
- New phase space regions open @NLO
- Sizeable change in shape and normalisation at NNLO
Conclusions

• NNLO predictions are required for precision phenomenology of LHC benchmark processes

1) PDF-sensitive jet observables
   – Triple differential di-jet cross section
   – Charged lepton asymmetry in W± +jet
   – Observe: Understanding of parton content of the proton (at large x) can be improved by inclusion of corresponding data in global PDF fits

2) Flavour-sensitive observables: New feature in NNLOJET
   – Presented: Procedure for selecting b-jets in theory and experiment
     • Experiment: use flavour-blind anti-k_t, safe only up to NLO
     • Theory @NNLO: use flavour-k_t, IR-safe and flavour-dependent
   – Study: Impact of NNLO corrections in b-jet dependent distributions for VH (with H→bb) and Z+b-jet production