NNLO phenomenology using jettiness subtraction

Xiaohui Liu

LoopFest XV @ Buffalo, 2016
Why NNLO

- many reasons
  - .......
  - discrepancy between NLO and data
  - .......

CERN-PH-EP-2013-023
Theory Setups

- Real corrections

explosion of calculations in past 18 months

Salam, LHCP '16
## Theory Setups

- **Real corrections**

### Local Subtraction

$$\int dz \frac{f(z) - f(0)}{z} + \int dz z^{-1 - \alpha \varepsilon} f(0)$$

- **sector decomposition, sector improved residue**
  - Binoth, Heinrich; Anastasiou, Melnikov, Petriello
  - Czakon; Boughezal, Melnikov, Petriello
  - Gehrmann-De Ridder, Gehrmann, Glover

- **antenna subtraction**
  - Kosower
  - Gehmann-De Ridder, Gehrmann, Glover

- **projection to Born**
  - Cacciari, Dreyer, Karlberg, Salam, Zanderighi

- **Colorful NNLO**
  - Del Duca, Somogyi and Trócsányi
  - Del Duca, Duhr, Kardos, Somogyi and Trócsányi

### Non-local Subtraction

$$\int \frac{f(z)}{z} \theta(z > z_0) - f(0) \frac{z_0^{-\alpha \varepsilon}}{\alpha \varepsilon} + \ldots$$

- **qT subtraction, N-jettiness subtraction**
  - Catani, Grazzini
  - Gao, Li and Zhu
  - Boughezal, Focke, XL, Petriello; Gaunt, Stahlhofen, Tackmann, Walsh

[4]
Theory Setups

• N-Jettiness subtraction
  Boughezal, Focke, XL, Petriello, ’15  Gaunt, Stahlhofen, Tackmann, Walsh, ’15

• N-jettiness observable
  Stewart, Tackmann, Waalewijn, ’10

\[ T_N = \sum_k \min \{ \omega_a n_a \cdot q_k, \omega_b n_b \cdot q_k, \omega_i n_i \cdot q_k, \ldots, \omega_N n_N \cdot q_k \} \]

- \( N \)  the minimum number of jets required
- \( n_i \)  light-like vectors along beam or jet axes
- \( q_k \)  final state partons’ 4-momenta
- \( \omega_k \)  arbitrary positive weight
Theory Setups

• N-Jettiness subtraction

\[ T_N = \sum_k \min \left\{ w_a n_a \cdot q_k, w_b n_b \cdot q_k, w_i n_i \cdot q_k, \ldots, w_N n_N \cdot q_k \right\} \]

N jets \quad \text{small} \quad T_N \quad \text{large} \quad \text{more than N jets}

• Contribution only from 2-loop, soft+collinear radiations

\[ \text{small } T_N^{\text{cut}} \quad \text{smaller than any experimental cuts} \]
\[ \text{small to suppress power corrections} \]
\[ \text{final result independent of } T_N^{\text{cut}} \]

• At least N+1 hard radiations

\[ \text{small } T_N^{\text{cut}} \]

\[ \text{smaller than any experimental cuts} \]
\[ \text{small to suppress power corrections} \]
\[ \text{final result independent of } T_N^{\text{cut}} \]

\[ \text{NLO N+1 jet calculation} \]
\[ \text{Simply recycle known NLO results/tools} \]

Tr[H \cdot S_N] \otimes B_a \otimes B_b \otimes J_i + \ldots

jet: Becher and Neubert, '06, Becher and Bell, '10

beam: Gaunt, Stahlhofen, Tackmann, '14

soft: Boughezal, XL and Petriello, '15
Theory Setups

• N-Jettiness subtraction
  Boughezal, Focke, XL, Petriello, ’15  Gaunt, Stahlhofen, Tackmann, Walsh, ’15

• New results for processes with a jet
  Boughezal, Focke, XL, Petriello,’15, Boughezal, Focke, Giele, XL, Petriello, ’15
  Boughezal, Campbell, Ellis, Focke, Giele, XL, Petriello,’15, Ablof, Boughezal, XL, Petriello,’16,

• H/W/Z/DIS+1j

• Confirm existing results

• H/W/Z production
  Gaunt, Stahlhofen, Tackmann, Walsh, ‘15

• VH/Di-photon production
  Campbell, Ellis, Williams, ‘16  Campbell, Ellis, Li, Williams, ’16
Validation and Improvements

• N-Jettiness subtraction

Validations

• taucut-independence check in all calculations

Boughezal, Focke, XL, Petriello, '15  Gaunt, Stahlhofen, Tackmann, Walsh, '15
Validation and Improvements

• N-Jettiness subtraction

Validations

• more comparisons

Boughezal, Focke, XL, Petriello, '15 Gaunt, Stahlhofen, Tackmann, Walsh, '15
Validation and Improvements

• N-Jettiness subtraction
  
  Validations
  
  • DIS form factor

  Boughezal, Focke, XL, Petriello, ’15  Gaunt, Stahlhofen, Tackmann, Walsh, ’15

• NNLO Single jet production
  • new channels with large correction
  • integrate over the phase space to reproduce the NNLO form factor
  • interesting for EIC phenomenology

Abelof, Boughezal, XL, Petriello, ’16
Validation and Improvements

- N-Jettiness subtraction

power corrections

- logarithmic nature of dominant power corrections $\alpha_s^n C_n T_N^{\text{cut}} L^{2n-1}$
- can be calculated in an easy way and higher order power corrections can be predicted from lower order calculations
- including power corrections can improve the convergence

\[ W^+: \text{w/o Power Correction v.s. fit v.s. w Power Correction} \]
Validation and Improvements

- N-Jettiness subtraction

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$W^+:$ with LEP and MET cuts, w/o Power Correction v.s. fit v.s. w Power Correction

|y(lep)| < 2.5 + MET > 30GeV

Boughezal, Focke, XL, Petriello, '15
Gaunt, Stahlhofen, Tackmann, Walsh, '15

Boughezal, XL, Petriello, in preparation
Phenomenology

- **Comparison with 7TeV data**  Boughezal, XL, Petriello, ‘16

- **W+1j**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>lepton $p_T$</td>
<td>$p_T &gt; 25$ GeV</td>
<td>$p_T &gt; 25$ GeV</td>
</tr>
<tr>
<td>lepton $\eta$</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>missing $E_T$</td>
<td>$E_T^{miss} &gt; 25$</td>
<td>–</td>
</tr>
<tr>
<td>transverse mass</td>
<td>$m_T &gt; 40$ GeV</td>
<td>$m_T &gt; 50$ GeV</td>
</tr>
<tr>
<td>jet $p_T$</td>
<td>$p_T &gt; 30$ GeV</td>
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<td>jet $\eta$</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>anti-$k_T$ radius</td>
<td>$R = 0.4$</td>
<td>$R = 0.5$</td>
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$$\mu_0 = \sqrt{M_W^2 + \sum_i (p_T^i)^2}$$

- CT14NNLO PDFs for NNLO results, CT14NLO for NLO results
- Vary $\mu_F$ and $\mu_R$ independently
- Non-perturbative corrections included for ATLAS $p_TJ$ and $yJ$
- QED FSR factors included for ATLAS $p_TJ$ and $yJ$

CERN-PH-EP-2014-134
Phenomenology

- Comparison with 7TeV data
  
  Merged tree-level amplitudes combined with a parton shower describe the measurements: higher than but within experimental errors.

  NLO QCD, LoopSim and MEPS@NLO predictions are all lower than the data.

  NNLO QCD corrections increase the NLO prediction, leading to a better agreement with ATLAS data. Scale uncertainty is reduced.

  Boughezal, XL, Petriello, '16
Phenomenology

• **Comparison with 7TeV data**

  All predictions compared are systematically higher than the CMS data

  NNLO QCD corrections reduce the NLO scale uncertainty to make it clear

  **pTJ1:** $W+1j$
Phenomenology

- Comparison with 7TeV data  

\[ H_T(S_T) : \]

- ALPGEN agrees with data while SHERPA overshoots the measurements
- The NLO predictions far undershoot the data while MEPS@NLO does a good job
- The NNLO corrections bring theory into good agreement with experiment, with a slight undershoot at very high ST
Phenomenology

- Comparison with 7TeV data
  Boughezal, XL, Petrello, ‘16

Merged tree-level amplitudes combined with a parton shower are higher than the measurements.

- NLO QCD corrections lower than the data.
- NNLO can predict this distribution well.
Phenomenology

- Comparison with 7TeV data

Z+1j

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<td>lepton $\eta$</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>lepton separation</td>
<td>$\Delta R_{ll} &gt; 0.2$</td>
<td>$\Delta R_{ll} &gt; 0.2$</td>
</tr>
<tr>
<td>lepton invariant mass</td>
<td>60 GeV $&lt; m_{ll} &lt; 116$ GeV</td>
<td>71 GeV $&lt; m_{ll} &lt; 111$ GeV</td>
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<td>jet $p_T$</td>
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- Vary $\mu_F$ and $\mu_R$ independently
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Phenomenology

- Comparison with 7TeV data

- The NLO prediction agrees with the data within errors.
- The NNLO QCD prediction is in better agreement with the CMS data over the entire pTJ1 range.
- The NNLO QCD prediction increases NLO but still undershoots the ATLAS data.

\( p_{TJ1} : \)

\[ Z+1j \]
Phenomenology

• Comparison with 7TeV data  Boughezal, XL, Petriello, ‘16

\[ H_T(S_T) : \]

- The NLO prediction below the data.
- The NNLO QCD prediction is in good agreement with both experiments over the entire range.
Phenomenology

• Comparison with 13TeV data  
  Boughezal, XL, Petriello, ‘16

Non-perturbative (hadronisation and underlying event) and FSR corrections included

• SHERPA AND MG5_aMC+PY8 FxFx describes well the data

• ALPGEN+PY6 AND MG5_aMC+PY8 CKKW overshot at large $H_T$

• BlackHat+SHERPA under-estimates the cross section for large values of $H_T > 300$ GeV

• The agreement is recovered by adding NNLO corrections in perturbative QCD

ATLAS-CONF-2016-046
Phenomenology

- Comparison with 13TeV data  
  Boughezal, XL, Petriello, ‘16

Non-perturbative (hadronisation and underlying event) and FSR corrections included

- all predictions show a good agreement with the measured data within the uncertainties

ATLAS-CONF-2016-046
Phenomenology

- Comparison with 13 TeV data

  Boughezel, XL, Petriello, ‘16

Non-perturbative (hadronisation and MPI) and FSR corrections included

  - the merged NLO generator for all inclusive jet multiplicities describes the data well
  - LO MG+PY8 is slightly lower than the data in the small HT region
  - the NNLO calculation for one inclusive jet multiplicity describes the data well

CMS PAS SMP-16-005
Phenomenology

- **Comparison with 13TeV data**  
  Boughezal, XL, Petriello, '16

  Non-perturbative (hadronisation and MPI) and FSR corrections included

  - the merged NLO generator for all inclusive jet multiplicities describes the data well
  - LO MG+PY8 is slightly lower than the data
  - the NNLO calculation for one inclusive jet multiplicity describes the data well

**CMS PAS SMP-16-005**
Conclusions

• N-jettiness subtraction
  
  • a subtraction scheme for jet production
  
  • confirm the known V/H inclusive, VH and di-photon productions
  
  • used for H/V/DIS+1J
Thanks