NNLO Phenomenology at the LHC

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Boughezal, XL, Petriello, PRD, 2015
Boughezal, Focke, XL, Petriello, PRL, 2015
Boughezal, Focke, Giele, XL, Petriello, PLB, 2015
Outline

• Motivation

• Theoretical aspects
  • IR subtraction schemes at NNLO

• Phenomenology

• Summary and Outlook
Motivation

• Why QCD
  • LHC is a QCD factory
  • Main background for discovery
  • Major tool for prediction
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• Why QCD

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  • Main background for discovery
  • Major tool for prediction

Factorization:
Separation of long distance and short distance physics
Interference suppressed, classic picture, allows for perturbative calculations..

\[
\sigma_{pp \to X \pi \ldots} = \int \! dx_1 \, dx_2 \, \hat{\sigma}_{ij \to X \ldots}(\mu_R, \mu_F, x_1, x_2; z_1 \ldots) \otimes D_{1\pi}(\mu_F, z_1) \, f_{i/p}(x_1, \mu_F) \, f_{j/p}(x_2, \mu_F) \ldots
\]
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Motivation

• Why QCD

• LHC is a QCD factory

Separation of long distance and short distance physics

Interference suppressed, classic picture, allows:

\[ \sigma_{pp \to X \pi \ldots} = \int dx_1 \, dx_2 \, \hat{\sigma}_{ij \to X \ldots}(\mu_R, \mu_F, x_1, x_2; z_1 \ldots) \otimes D_{\pi}(\mu_F, z_1) \, f_{i/p}(x_1, \mu_F) \, f_{j/p}(x_2, \mu_F) \ldots \]

Jets:

• collections of hadrons
• a natural probe for the QCD matter created at the LHC
• suppress non-perturbative effects
Motivation

- Why QCD
  - LHC is a QCD factory
  - Main background for discovery
  - Major tool for prediction
    - short distance
    - Happens at length scale of order $1/Q$, $Q \sim 100-1000$ GeV
    - pQCD description ($\alpha_s$ expansion)

$$\sigma_{pp\to X\pi\ldots} = \int d\mathbf{x}_1 \, d\mathbf{x}_2 \, \hat{\sigma}_{ij\to X\ldots}(\mu_R, \mu_F, x_1, x_2; z_1 \ldots) \otimes D_N(\mu_F, z_1) \, f_{i/p}(x_1, \mu_F) \, f_{j/p}(x_2, \mu_F) \ldots$$
Motivation

• NNLO at LHC

\[ \sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \ldots \]

Example: H+1j

LO

NLO

NNLO

\[ + \quad \mathcal{O}(10^2) \]
Motivation

- NNLO at LHC
- reduce errors
- possible large corrections

\[ \sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 \]

Gehrmann, et. al. '14

ATLAS Simulation Preliminary
\( \sqrt{s} = 14 \text{ TeV}; \int L dt = 300 \text{ fb}^{-1}; \int L dt = 3000 \text{ fb}^{-1} \)

theoretical uncertainty is going to dominate over experimental errors soon
Motivation

- NNLO at LHC
- reduce errors
- possible large corrections
- 2013 Les Houches Wish-list

\[ \sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 \]

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Higgs production and decay rates at NNLO/QCD
Theory Aspects

• Fully Inclusive
  • sum over all final (QCD) states
  • allows no measurements
  • e.g. DIS form factor ...

• Fully differential
  • maintain full phase space information for resolved physical objects
  • allows arbitrary infra-red safe cuts: jet algorithms, jet veto ...
  • allows attaching parton shower
Theory Aspects

- Fully differential $\sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2$
- Virtual corrections
- dim. reg. $d = 4 - 2\epsilon$
- explicit IR poles
- tremendous progress - analytic or numerical

\[
\int d\Phi_2 \frac{V_4}{\epsilon^4} + \frac{V_3}{\epsilon^3} + \ldots
\]
Theory Aspects

• Fully differential  \[ \sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 \]

• Virtual corrections

• Real corrections

• numerical

• implicit poles - how to extract??

Show up after integrating over the phase space

\[ \int d\Phi_3 \frac{RV_2}{\epsilon^2} + \ldots \]

\[ \int d\Phi_4 RR \]

Unresolved, soft and collinear

\[ \int_0 dE_p \, dE_k d\theta \ldots \frac{1}{E_p \, E_k \, (1 - \cos \theta)} \ldots \]
Theory Aspects

• Local subtraction schemes at NNLO

• Sector-improved-decomposition, Antenna subtraction and Colorful NNLO
  - M. Czakon ’10; Boughezal, Melnikov, Petriello’11; Gehrmann-De Ridder, Gehrmann, Glover’05
  - Aglietti, Bolzoni, Del Duca, Duhr, Moch, Somogyi, Tramontano, Trosanyi’ 05-13

• Successfully applied to LHC physics

• Higgs+1jet
  - Boughezal, Caola, Melnikov, Petriello, Schulze ’13, ’15; Chen, Gehrmann, Glover, Jaquier ’14

• Top pair production
  - Czakon, Fiedler, Mitov ’13, Abelof, Gehrmann-De Ridder, Majer’ 15

• Partial results for di-jet production
  - Gehrmann-De Ridder, Gehrmann, Glover, Pires ’13
Theory Aspects

- Local subtraction schemes at NNLO

- Construct IR subtraction point by point in phase space. Relatively smooth integrand

\[
\begin{align*}
\frac{d\sigma_{\text{NNLO}}}{d\Phi_{m+2}} & = \int \left( \frac{d\sigma_{\text{NNLO}}^{R}}{d\Phi_{m+2}} - \frac{d\sigma_{\text{NNLO}}^{S}}{d\Phi_{m+2}} \right) + \int \frac{d\sigma_{\text{NNLO}}^{S}}{d\Phi_{m+2}} \\
& + \int \left( \frac{d\sigma_{\text{NNLO}}^{V,1}}{d\Phi_{m+1}} - \frac{d\sigma_{\text{NNLO}}^{VS,1}}{d\Phi_{m+1}} \right) + \int \frac{d\sigma_{\text{NNLO}}^{VS,1}}{d\Phi_{m+1}} \\
& + \int \frac{d\sigma_{\text{NNLO}}^{V,2}}{d\Phi_{m}}
\end{align*}
\]

- Universal IR counter-term out of IR limit of QCD
- Free of IR divergence, suitable for numerical calculation
- Compensate the subtraction, easier to evaluate. IR singularities cancel against the ones in 2-loop virtual

- Build up calculations from the scratch and it is difficult to directly recycle known NLO results (MCFM …)
Theory Aspects

• Local subtraction schemes at NNLO

• Quite complicated, usually take years to finish one calculation
Theory Aspects

- Non-local subtraction schemes at NNLO

- Pick some physical observable \( v \), with nice properties: \( v \rightarrow 0 \) limit catches all IR behavior which can be predicted using simplified formalisms (CSS or SCET). Non-local due to integrating over part of the phase space to get the observable \( v \)

\[
v \rightarrow 0, \quad d\sigma \rightarrow d\sigma_{\text{sing}}.
\]

\[
d\sigma_{\text{sing.}} \sim d\sigma_0 \sum \alpha_s^n \left( C_{n,m} \left[ \frac{\log^{2n-m}(v)}{v} \right]_+ + C_{n,0} \delta(v) \right) + \nu \left[ \ldots \right]
\]
Theory Aspects

• Non-local subtraction schemes at NNLO

• Small parameter $v_{\text{res}}$

• $v > v_{\text{res}}$, at least 1 additional radiation can be resolved, NO singularities related to NNLO in the problem: NLO problem for Born+1j
Theory Aspects

- Non-local subtraction schemes at NNLO

- Small parameter $v_{res}$
  
  - $v > v_{res}$, at least 1 additional radiation can be resolved, NO singularities related to NNLO in the problem: NLO problem for Born+1j

  - $v < v_{res}$, NO additional radiations are resolved, true NNLO, including “virtual”: loop and soft+collinear: use $d\sigma_{\text{sing}}$. 
Theory Aspects

• Non-local subtraction schemes at NNLO

• Small parameter $\nu_{\text{res}}$

  • $\nu > \nu_{\text{res}}$, at least 1 additional radiation can be resolved, NO singularities related to NNLO in the problem: NLO problem for Born+1j

  • $\nu < \nu_{\text{res}}$, NO additional radiations are resolved, true NNLO, including “virtual”: loop and soft+collinear: use $d\sigma_{\text{sing}}$

• Combine to achieve NNLO, $\nu_{\text{res}}$ independent
Theory Aspects

• Non-local subtraction schemes at NNLO

• Maximally recycle the NLO tools, easy to implement but numerically challenging

• $q_T$-subtraction

  • limited to color neutral final state ($ggH, Drell-Yan, Di-boson \ldots$)

  Catani and Grazzini '07; Catani, Cieri, Ferrera, de Florian, Grazzini '09 \ldots

  can not handle final state IR divergence, even for $q_T \neq 0$. 
Theory Aspects

• Non-local subtraction schemes at NNLO

  • Maximally recycle the NLO tools, easy to implement but numerically challenging

• Other pioneer works

  • top quark decay and top pair production in lepton annihilation

Gao, Li and Zhu ’13; Gao and Zhu ’14
Theory Aspects

• Non-local subtraction schemes at NNLO
  • Maximally recycle the NLO tools, easy to implement but numerically challenging
  • A more generic observable
    • Catches all IR behaviors?
  • Universal
Theory Aspects

- **N-Jettiness**  
  Stewart, Tackmann, Waalewijn'10

  - A global inclusive event-shape to distinguish between N-jet events and more-than-N-jet events

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

  - \(n_i\)'s are arbitrary unit light-like vectors, but in practice they are determined most efficiently by a jet algorithm. \(w_i\)'s are arbitrary positive weights. \(k\) runs over all colored partons in the final state. \(q_k\) is the four momentum for \(k\). Does not include color neutral particles like leptons, W/Z/H...
Theory Aspects

• N-Jettiness

• A global inclusive event-shape to distinguish between N-jet events and more-than-N-jet events

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

• \( n_i \)'s are arbitrary unit light-like vectors, but in practice they are determined most efficiently by a jet algorithm. \( w_i \)'s are arbitrary positive weights. \( k \) runs over all colored partons in the final state. \( q_k \) is the four momentum for \( k \). Does not include color neutral particles like leptons, W/Z/H…
Theory Aspects

• N-Jettiness

• A global inclusive event-shape to distinguish between N-jet events and more-than-N-jet events

\[ \mathcal{T}_N = \sum_k \min \{ w_a n_a \cdot q_k, w_b n_b \cdot q_k, w_i n_i \cdot q_k, \ldots, w_N n_N \cdot q_k \} \]

• \( \mathcal{T}_N = 0 \) forces an N-jet final state, i.e. \( q_k \)'s must be soft or collinear to one of \( p_i \), hence \( \mathcal{T}_N \) will control all the IR behaviors for N-jet. In the IR limit, \( n_i \)'s do not depend on any IR safe jet algorithm and are solely determined by the Born topology. \( \mathcal{T}_N = 0 \) behavior is universal for any physical IR safe measurement on N jets.
Theory Aspects

- N-Jettiness
- Universal IR behavior

\[ \sigma(\mathcal{T}_N) = \text{Tr} \left[ H \cdot S_N \right] \otimes B_a \otimes B_b \prod_{i} \otimes J \]
Theory Aspects

• N-Jettiness

\[ \sigma(\mathcal{T}_N) = \text{Tr} [H \cdot S_N] \otimes B_a \otimes B_b \prod_{i}^{N} \otimes J \]

• process dependent, virtual corrections (1-loop, 2-loop)
• known to 2-loop for many processes
Theory Aspects

• N-Jettiness

\[ \sigma(T_N) = \text{Tr} \left[ H \cdot S_N \right] \otimes B_a \otimes B_b \prod_{i} \otimes J \]

• quark and gluon jets
• known to 2-loop for a long time

Becher and Neubert ’06, Becher and Bell ’10
Theory Aspects

• N-Jettiness

$N$-Jettiness

\[ N_{\text{Jettiness}} \]

\[
(N) = \text{Tr} \left[ H \cdot S_N \right] \otimes B_a \otimes B_b \prod_{i=1}^{N} \otimes J
\]

• quark and gluon beam function
• known to 2-loop now

\[
B_i(x) = \int_x^1 \frac{dz}{z} I_{ij} \left( \frac{x}{z} \right) f_j(z)
\]

Gaunt, Stahlhofen, Tackmann '14
Theory Aspects

• N-Jettiness

\[ \sigma(\mathcal{T}_N) = \text{Tr} \left[ H \cdot S_N \right] \prod_{i} B_i \otimes J \]

- color source
- depends on the number of the jets
- now known to 2-loop numerically using a general framework

Boughezal, XL and Petriello ’15
Jettiness

• N-Jettiness

• Calculate the 2-loop soft function \( \text{Boughezal, XL and Petriello '15} \)

• Radiations from eikonal lines.
Jettiness

- **N-Jettiness**

- Calculate the 2-loop soft function

- **Dipole structure**

  only need to calculate the building blocks subject to the jettiness cut (4 reference vectors)

\[
\begin{align*}
\mathcal{J}_{ij} & = \mathcal{J}_{ij}^{I} + \mathcal{J}_{ij}^{II} \\
\mathcal{J}_{ij}^{I} & = -2 \frac{[p_i \cdot q_j p_j \cdot q_2 + p_j \cdot q_1 p_i \cdot q_2]^2}{(q_1 \cdot q_2)^2 [p_i \cdot (q_1 + q_2)]^2 [p_j \cdot (q_1 + q_2)]^2} \\
\mathcal{J}_{ij}^{II} & = 2 \frac{p_i \cdot p_j}{(q_1 \cdot q_2)[p_i \cdot (q_1 + q_2)][p_j \cdot (q_1 + q_2)]} \\
\mathcal{T}_{ij} & = (1 - \epsilon) \mathcal{J}_{ij}^{I} + 2 \mathcal{J}_{ij}^{II} + \left( \frac{p_i \cdot q_1 p_j \cdot q_2 + p_j \cdot q_1 p_i \cdot q_2}{[p_i \cdot (q_1 + q_2)][p_j \cdot (q_1 + q_2)]} - 2 \right) S_{ij}^{(s.o.)}, \\
S_{ij}^{(s.o.)} & = \frac{p_i \cdot p_j}{q_1 \cdot q_2} \left( \frac{1}{p_i \cdot q_j p_j \cdot q_2} + \frac{1}{p_j \cdot q_1 p_i \cdot q_2} \right) - \frac{(p_i \cdot p_j)^2}{p_i \cdot q_1 p_i \cdot q_2 p_j \cdot q_1 p_j \cdot q_2}.
\end{align*}
\]

Catani, Grazzini '98
Jettiness

- N-Jettiness

- Calculate the 2-loop soft function

- Dipole structure

  - only need to calculate the building blocks subject to the jettiness cut (4 reference vectors)

\[ \frac{n_i^\mu}{n_i \cdot q} \]

\[ V/H + 1j \]

\[
S_{qq} = T_R \left[ C_a \mathcal{J}_{12} + C_{a3} \left( -\frac{1}{2} \mathcal{J}_{12} + \frac{1}{2} \mathcal{J}_{13} + \frac{1}{2} \mathcal{J}_{23} \right) \right]
\]
Jettiness

- N-Jettiness
  - Calculate the 2-loop soft function
  - Has both UV and IR divergence
    - No hard scales $\sim Q >> T_N$ in the soft function, relax cuts
    - Allows the soft radiation energy $E$ can go to infinity, regularized using dim-reg.
      $$\int_{E \sim Q} \text{d}E \rightarrow \int_{\infty} \text{d}E$$
Jettiness

• N-Jettiness

• Calculate the 2-loop soft function

• Finite $\mathcal{T}_N$ forces $n_i \cdot q = 0$, when $E \to \infty$. Map UV divergence to collinear divergence: variable change

$$\mathcal{T}_N = \sum_k \min \{ w_a n_a \cdot q_k , w_b n_b \cdot q_k , w_i n_i \cdot q_k , \ldots , w_N n_N \cdot q_k \}$$

• Use standard techniques to calculate, e.g. sector decomposition. Framework valid for a large class of observables!
Theory Aspects

- N-Jettiness

- 2-loop soft function

\[ \Sigma^{(2)}_{soft} = \int_0^{\mathcal{T}_N^{cut}} d\mathcal{T}_N \frac{d\sigma}{d\mathcal{T}_N} = \left( \frac{\alpha_s}{2\pi} \right)^2 (C_4 L^4 + C_3 L^3 + C_2 L^2 + C_1 L + C_0) \quad L = \log \frac{T_N^{cut}}{\mu} \]
Theory Aspects

• N-Jettiness

• 2-loop soft function

$$\Sigma^{(2)}_{\text{soft}} = \int_0^{T_N^{\text{cut}}} dT_N \frac{d\sigma}{dT_N} = \left(\frac{\alpha_s}{2\pi}\right)^2 (C_4 L^4 + C_3 L^3 + C_2 L^2 + C_1 L + C_0)$$

$$L = \log \frac{T_N^{\text{cut}}}{\mu}$$
Theory Aspects

- N-Jettiness

\[ \sigma(T_N) = \text{Tr} [H \cdot S_N] \otimes B_a \otimes B_b \prod_{i}^{N} \otimes J \]

Does catch the singular behavior!
Theory Aspects

- N-Jettiness

- N-jettiness scheme

Example: H+1j

- below tau-cut: 2-loop, soft or collinear limit: use effective theory
- above tau-cut: hard enough, well separated: recycle NLO H+2j

1-jettiness to distinguish, measure final state phase space to determine result will be tau-cut independent

Boughezal, Focke, XL and Petriello ’15, see also Gaunt, Stahlhofen, Tackmann, Walsh ’15
Jettiness-subtraction scheme

- Jettiness-subtraction

- Final massive colored state?

- less final collinear singularities, less N.

- For example, need only $T_0$ for $pp \rightarrow ttbar$

  similar ideas using transverse momentum see also: Zhu, Li, Li, Shao and Yang'12; Catani, Grazzini and Torre ‘15

- Same beam/jet functions. Soft function can be obtained using the same framework in 1504.02540

  $\frac{n_i^\mu}{n_i \cdot q} \rightarrow \frac{v_i^\mu}{v_i \cdot q}$
Phenomenology
Phenomenology

- Fully differential NNLO H+1j  
  Boughezal, Focke, Giele, XL and Petriello '15

- Selection of experimental events uses jet binning to reduce the background
  \[ \sigma(0\text{jet}) = \sigma(\text{tot}) - \sigma(1\text{jet incl.}) \]

- Theory uncertainties in the jet bins are currently a limiting factor

- Looking for BSM effects relies on the precision control of the differential distributions, eg. Higgs pT
Phenomenology

- Fully differential NNLO H+1j
- validation

$T_{\text{cut}}$ independent!
Phenomenology

- Fully differential NNLO H+1j
  - NNPDF2.3, $m_H=125\text{GeV}$, anti-$K_T$ with $R = 0.5$
  - all channels
  - convergent series
  - reduced uncertainty

$p_T^{jet} > 30\text{GeV}$
Phenomenology

- Fully differential NNLO H+1j

\[ N_{NPDF2.3}, \, m_H=125\text{GeV}, \, \text{anti-}K_T \text{ with } R = 0.5 \]

\[ p_T^{jet} > 30\text{GeV} \]

Non-trivial K-factor shape as a functions of pTj and pTH
Phenomenology

• Fully differential NNLO W+1j
  Boughezal, Focke, XL and Petriello ‘15

• Benchmark process in the SM

• Z/W+1j can be used to constrain gluon PDF at large x but limited by large theoretical uncertainty at NLO. 1% experimental errors versus 10% theoretical uncertainty at pTZ ~100GeV
  see for instance Rojo et. al. ’15

• It is suggested that W+j with 14TeV LHCb is sensitive to quark PDF for x>0.5
  Farry and Gauld ’15
Phenomenology

- Fully differential NNLO W+1j
- all channels
- convergent series
- reduced uncertainty

\[ p_T^{\text{jet}} > 30 \text{GeV} \]
Phenomenology

- Fully differential NNLO $W+1j$

A qualitative comparison with $Z$ $p_T$ distribution

- full results using jetiness subtraction
- small scale uncertainty $\sim O(1\%)$, suitable for precision measurement

Boughezal, Focke, XL and Petriello '15, full NNLO, use jetiness-subtraction

- Leading Color using antenna subtraction
- small scale uncertainty at NNLO

T. Morgan 2015 LoopFest talk, partial results, use antenna subtraction
Summary and Outlook

- Jettiness-subtraction for generic N-jet production at NNLO
  - applicable to both massless and massive cases
  - All building blocks are known to NNLO
- Applied to W+1j and Higgs+1j at the LHC
  - fully differential
  - all channels included
Summary and Outlook

- Future Plans
  - Short term
    - full Z+1j
    - DIS jet production

$O(\alpha_s^2)$ contribution to the form factor, q-channel only

reproduce inclusive results when integrate over phase space
Summary and Outlook

• Future Plans

• Long term
  • upgrade NLO event generators to NNLO using jettiness-subtraction
  • realize NNLO + parton shower for jet production
Summary and Outlook

• Future Plans

  • By-product

    • resummation up to NNLL
Thanks