QCD predictions and hadronic final states

Frank Siegert

DIS 2015
XXIII International Workshop on Deep-Inelastic Scattering and Related Subjects
April 27, Dallas
QCD precision predictions and hadronic final states

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Precision vs. Hadronic Final States
Precision vs. Hadronic Final States
**Vision:** bring progress in higher order calculations and resummation to the hadron level.
Basic problem

- no exact solution to QCD, only perturbative series in $\alpha_s$

- predictions at hadron level: confinement at "resolution" scale $\Lambda \sim 1$ GeV
  - finite remainders of infrared divergences:
    - logarithms of $\frac{\mu^2_{\text{hard}}}{\Lambda^2}$ with each $\mathcal{O}(\alpha_s)$ can become large and spoil convergence of perturbative series
  - Need to resum the series to all orders
    - Problem: We are not smart enough for that.
    - Workaround: Resum only the logarithmically enhanced terms in the series
  - Parton Showers!
Event generation programs

**Parton level generators**

**Parton shower and hadronisation programs**

**In production:**
- Herwig++
- Pythia
- Sherpa

Interesting new approaches for showers:
- dipole-antenna showers (Vincia, Adicic/Ants)
- “analytic” showers (Geneva, Whizard)
- Deductor
- ...

**HERE:** focus on fixed-order improvements in QCD parton shower event generators

**SEE ALSO:**
- parton-level review
  - Frank Petriello, Mon 17:10
- EW corrections
  - Jia Zhou, Tue 17:00
Multi-jet production

- high multi-jet production rates at LHC
  - talks by Kwan (Tue 8:55), Perry (Wed 18:00), Schwanenberger (Wed 9:45)
- important backgrounds for BSM searches
- even data-driven background estimation relies on good simulation of shapes between control and signal region
- in some cases precision measurements very sensitive to simulation of multi-jet production ($Z$ polarization, $\phi^*$)
- “naive” inclusive NLO accuracy at best status quo, often not sufficient
  - precision predictions for multi-jet processes are one of the current frontiers for event generators

Problem:
Combination of higher-order matrix elements and parton shower evolution
Todo list

- avoid double counting of higher order corrections
  → preserve fixed-order accuracy of MEs in combined sample
- preserve logarithmic accuracy in the parton shower resummation
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Two long established approaches

- NLO matrix elements matched with parton shower emissions
  (NLO+PS matching)
  e.g. MC@NLO, Powheg

- Merging tree-level multi-jet matrix elements with parton showering into one inclusive sample
  (Multi-jet merging)
  e.g. CKKW(-L), MLM, UMEPS
Shower generators over the years

**Parton showers:**
- first Markov chains
- color coherence
- angular ordering
- initial state evolution

**Early hadronisation models**

- 1975
- 1980
- 1985
- 1990
- 1995
- 2000
- 2005
- 2010
- 2015

Pythia 1.0

Herwig 2.2

...
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Pythia 1.0
Herwig 2.2
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MENLO+PS merging
Multi-jet merging
NLO+PS matching

(Lavesson, Lönblad (2008)
Höche, Krauss, Schönherr, FS (2012)
Frederix, Frixione (2012)
Plätzer (2012)
Alioli, Bauer, Berggren, Hornig, Tackmann, Vermilion, Walsh, Zuberi (2012)
Lönblad, Prestel (2012)
Hamilton, Nason, Oleari, Zanderighi (2012)
Höche et al. (2013)
Cascioli et al. (2013)
Höche et al. (2014)
Höche et al. (2014)
Buschmann et al. (2014)
...
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2012 – Year of the Higgs

Pythia 1.0

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Lavesson, Lonnblad (2008)

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Alioli, Bauer, Berggren, Hornig, Tackmann, Vermilion, Walsh, Zuberi (2012)

Lonnblad, Prestel (2012)

Hamilton, Nason, Oleari, Zanderighi (2012)

... and applications

- p\bar{p} \rightarrow t\bar{t} + 0, 1 jets
  Higgs et al. (2013)

- pp \rightarrow 4\ell + 0, 1 jets
  Cascioli et al. (2013)

- pp \rightarrow H + 0, 1, 2 jets
  Higgs et al. (2014)

- pp \rightarrow t\bar{t} + 0, 1, 2 jets
  Higgs et al. (2014)

- pp \rightarrow VV + 0, 1 jets
  Higgs et al. (2014)

- pp \rightarrow t\bar{t} + 0, 1, 2 jets
  Higgs et al. (2014)

- pp \rightarrow H + 0, 1 jets
  Buschmann et al. (2014)

Alwall et al. (2014)

- pp \rightarrow H/W + 0, 1, 2 jets
  pp \rightarrow t\bar{t}/ZZ + 0, 1 jets
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2012 – Year of the Higgs multi-jet merging at NLO

Many algorithmic developments . . .

- Lavesson, Lönnblad (2008)
- Höche, Krauss, Schönherr, FS (2012)
- Frederix, Frixione (2012)
- Plätzer (2012)
- Alioli, Bauer, Berggren, Hornig, Tackmann, Vermilion, Walsh, Zuberi (2012)
- Lönnblad, Prestel (2012)  \[ \rightsquigarrow \] talk Tue 8:30

. . . and applications

- \( p\bar{p} \rightarrow t\bar{t} + 0, 1 \text{ jets} \)  
  Höche et al. (2013)
- \( pp \rightarrow 4\ell + 0, 1 \text{ jets} \)  
  Cascioli et al. (2013)
- \( pp \rightarrow H + 0, 1, 2 \text{ jets} \)  
  Höche et al. (2014)
- \( pp \rightarrow tt + 0, 1, 2 \text{ jets} \)  
  Höche et al. (2014)
- \( pp \rightarrow VVV + 0, 1 \text{ jets} \)  
  Höche et al. (2014)
- \( pp \rightarrow H/W + 0, 1, 2 \text{ jets}, \) 
  \( pp \rightarrow tt/ZZ + 0, 1 \text{ jets} \)  
  Alwall et al. (2014)
- \( pp \rightarrow H + 0, 1 \text{ jets} \)  
  Buschmann et al. (2014)
- . . .
Multi-jet merging at NLO

**Basic idea**

- **NLO accuracy for multiple jet bins in inclusive simulation**

- Continuation from tree-level multi-jet merging:
  - Phase space slicing to separate ME and parton shower contributions
  - Showering on multi-parton final states, leading to Sudakov shape/vetoes

  \[ \Rightarrow \text{jet production with exact matrix elements, intrajet evolution with parton shower} \]

- Replace individual LO+PS with NLO+PS simulations in each multiplicity
- Adjust Sudakov to take existing emission into account
Example: $pp \rightarrow H + 0, 1, 2j@NLO$

- Higgs production in gluon-fusion with up to 2 jets at NLO accuracy
- merging cut variation to assess systematic uncertainties
- debate about reasonable choice of merging cut value:
  - too large: loss of NLO accuracy in hard regions
  - too low: sensitivity to resummation uncertainties
  → reasonable range for systematic uncertainty?
Example: $pp \rightarrow t\bar{t} + 0, 1, 2j@NLO$

Höche, Krauss, Maierhöfer, Pozzorini, Schönherr, FS (2014)

- ME+PS@NLO simulation for $t\bar{t} + 0, 1, 2\text{jets@NLO}$

**Inclusive light jet multiplicity**

- $\sigma(\geq N_{\text{jet}}) \text{[pb]}$
- $p_T^{\text{jet}} > 40 \text{GeV}$

**Total transverse energy**

- $d\sigma/dH_T \text{[pb/GeV]}$
- $H_T > 500 \text{GeV}$

- Comparison with LO multi-jet merging
- Perturbative uncertainties reduced in particular in $+0, 1, 2$-jet bins
- BSM search region $H_T^{\text{tot}} > 500 \text{ GeV}$ significantly improved
Relevance for non-jet processes?

Grazzini, Kallweit, Moretti, Pozzorini, Rathlev (in progress)

- jet vetoes important tool for background suppression, e.g. in $H \rightarrow WW$ vs. $t\bar{t}$
- recently: differential calculation of $pp \rightarrow W^+W^-$ at NNLO
- interesting comparison to shower predictions for jet veto efficiencies:
  - S-MC@NLO is Sherpa with NLO+PS matching
  - ME+PS@NLO is Sherpa with multi-jet merging for $pp \rightarrow W^+W^- + 0, 1 j@NLO$
continuation from tree-level merging
Carli, Gehrmann, Höche (2009)
Höche (private comm.)

special in DIS: kinematics with low factorisation scale but hard jets
⇒ related to boosted $pp \rightarrow Z + \text{jets}$

• notoriously difficult for parton showers!

Example: DIS with ME+PS@NLO
- similarly good description of rescaled momentum fractions
- tree-level merging (at LO or NLO) necessary to describe difficult DIS regions
- NLO accuracy comes “for free” with today’s automated merging tools
- same concepts can be applied to charged-current DIS, e.g. at a potential LHeC
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Beyond NLO: Matching NNLO matrix elements and parton showers
Shower generators over the years

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**Beyond NLO:**
- Matching NNLO matrix elements and parton showers

**NLO Multi-jet merging**
- NLO+PS matching

**MENLO+PS merging**
Matching NNLO and parton showers

- more accurate inclusive rates for processes with large $K$-factor or high experimental precision
- two independent approaches on the market:

**NNLOPS**

*Hamilton, Nason, Re, Zanderighi (2013)*

- matching scheme based on MiNLO method
  - use $pp \rightarrow X + j$ NLO+PS simulation
  - apply scale choice and Sudakov form factor (like in multi-jet merging)
    \[ \Rightarrow \text{finite for } p_j^\perp \rightarrow 0 \]
- reweight with fully-differential $pp \rightarrow X \ @ \ NNLO$

**UN$^2$LOPS**

*Höche, Li, Prestel (2014)*

- matching scheme based on unitarised merging method *Lönnblad, Prestel (2012)*
- dedicated NNLO calculation using $q_T$-cutoff subtraction

\[ \sim \text{talk by Stefan Prestel, Tue 8:30} \]
Higgs production in gluon fusion with NNLOPS

- **NNLOPS** predictions in the large $m_t$ limit
  Hamilton, Nason, Re, Zanderighi (2013)

- comparison against analytical resummation from HqT (NNLL+NLO)

\[ \frac{d\sigma}{dp_T^{H}} \quad \text{[pb/GeV]} \]

\[
\begin{array}{cccc}
\text{p}_T^{H} [\text{GeV}] & \text{Ratio} & \text{NNLOPS} & \text{HqT} \\
0 & 0.001 & 0.75 & 1.0 \\
50 & 0.01 & 1.25 & 1.4 \\
100 & 0.1 & & \\
200 & 1 & & \\
300 & 1 & & \\
\end{array}
\]

- supplemented with finite quark mass effects at NLO

- sizable effects of $m_t$ at high and $m_b$ at low $p_T^{H}$
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- comparison against analytical resummation from HqT (NNLL+NLO)

- supplemented with *finite quark mass* effects at NLO

- sizable effects of $m_t$ at high and $m_b$ at low $p_T^{H}$
NNLO + PS matching for W/Z production

W/Z production with UN^2LOPS

- UN^2LOPS predictions for vector boson production
  Höche, Li, Prestel (2014)

→ comparison with experimental data

\[ Z p_T \text{ reconstructed from dressed electrons} \]
NNLO + PS matching for W/Z production

W/Z production with UN$^2$LOPS

- UN$^2$LOPS predictions for vector boson production
  Höche, Li, Prestel (2014)

  → comparison with experimental data

- interesting study of PDF impact in NLO+PS simulations
  Höche (Loopfest 2014)

S-MC@NLO with
← NLO PDFs
NNLO + PS matching for W/Z production

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→ Stefan Prestel, Tue 8:30

S-MC@NLO with NNLO PDFs

S-MC@NLO' with NNLO PDFs
Conclusions

Summary

• parton shower event generators have evolved into precision tools
• realistic simulation of hadronic final state makes them crucial for the LHC physics program
• current state of the art: NLO accuracy for multi-jet final states, NNLO accuracy for simple inclusive processes

Outlook

• perturbative improvements to be applied to more complicated processes
• possibly combination of NNLO+PS and NLO multi-jet merging?
• skipped today:
  – non-perturbative effects
    → no ground breaking developments fruitful yet, mainly tuning of phenomenological models
  – developments on resummation accuracy of parton showers
    → will become important field over the next years