Recent Progress in Matching and Merging

Marek Schönherr

IKTP TU Dresden

23/08/2011
Outline

1. ME+PS: CKKW & MLM
2. NLO+PS: POWHEG & MC@NLO
3. ME@NLOPS
4. Conclusions
(NLO)ME vs. PS

Approaches to real emission corrections

(NLO) Matrix Element

- **Exact** to fixed order
- Perturbative series breaks down due to **large logarithms**

Parton Shower

- Resums logarithms to **all orders**
- Only **approximation** to real emission ME

Combine Advantages ⇒ ME⊗PS, NLO⊗PS, MENLOPS

- avoid double-counting by dividing phase space ⇒ $Q_{cut}$
- ME to describe **hard radiation**, PS for **intraget evolution**
ME+PS: CKKW & MLM

1. ME+PS: CKKW & MLM

2. NLO+PS: POWHEG & MC@NLO

3. MENLOPS

4. Conclusions
\[ \langle O \rangle = \int d\Phi_B B(\Phi_B) \left[ \Delta(t_0) \ O(\Phi_B) + \int d\Phi_{R|B} K(t, z, \phi) \Delta(t) \ O(\Phi_R) \right] \]

- **ordinary LO+PS** restricted to soft emissions with \( Q < Q_{\text{cut}} \)
- phase space \( Q > Q_{\text{cut}} \) filled by ME
- supplement Sudakov suppression \( \Delta(t) \) to recover unitarity at (N)LL level
- preserves LO accuracy of every ME emission and LL accuracy of PS
- **PS Sudakov form factor** \( \Delta(t) = \exp \left[ - \sum \int d\Phi_{R|B} K(t, z, \phi) \right] \)
- unitarity of PS violated at \( \mathcal{O}(\alpha_s) \) beyond (N)LL

Marek Schönherr
IKTP TU Dresden
Recent Progress in Matching and Merging
\[ \langle O \rangle = \int d\Phi_B B(\Phi_B) \left[ \Delta(t_0) O(\Phi_B) + \int d\Phi_{R|B} \mathcal{K}(t, z, \phi) \Delta(t) \Theta(Q_{\text{cut}} - Q) O(\Phi_R) \right] \]

- ordinary LO+PS restricted to soft emissions with \( Q < Q_{\text{cut}} \)
- phase space \( Q > Q_{\text{cut}} \) filled by ME
- supplement Sudakov suppression \( \Delta(t) \) to recover unitarity at (N)LL level
- preserves LO accuracy of every ME emission and LL accuracy of PS
- PS Sudakov form factor \( \Delta(t) = \exp \left[ - \sum \int d\Phi_{R|B} \mathcal{K}(t, z, \phi) \right] \)
- unitarity of PS violated at \( O(\alpha_s) \) beyond (N)LL
ME+PS: CKKW & MLM

\[
\langle O \rangle = \int d\Phi_B \, B(\Phi_B) \left[ \Delta(t_0) \, O(\Phi_B) \right. \\
+ \int d\Phi_R|_B \, K(t, z, \phi) \, \Delta(t) \, \Theta(Q_{\text{cut}} - Q) \, O(\Phi_R) \\
+ \int d\Phi_R|_B \, \frac{R(\Phi_R)}{B(\Phi_B)} \, \Delta(t) \, \Theta(Q - Q_{\text{cut}}) \, O(\Phi_R) \right]
\]

- ordinary LO+PS restricted to soft emissions with \( Q < Q_{\text{cut}} \)
- phase space \( Q > Q_{\text{cut}} \) filled by ME
- supplement Sudakov suppression \( \Delta(t) \) to recover unitarity at (N)LL level
- preserves LO accuracy of every ME emission and LL accuracy of PS
- PS Sudakov form factor \( \Delta(t) = \exp \left[ - \sum \int d\Phi_R|_B \, K(t, z, \phi) \right] \)
- unitarity of PS violated at \( \mathcal{O}(\alpha_s) \) beyond (N)LL
ME+PS: CKKW & MLM

\[ \langle O \rangle = \int d\Phi_B B(\Phi_B) \left[ \Delta(t_0) O(\Phi_B) \right. \]
\[ \left. + \int d\Phi_{R|B} K(t, z, \phi) \Delta(t) \Theta(Q_{\text{cut}} - Q) O(\Phi_R) \right. \]
\[ \left. + \int d\Phi_{R|B} \frac{R(\Phi_R)}{B(\Phi_B)} \Delta(t) \Theta(Q - Q_{\text{cut}}) O(\Phi_R) \right] \]

- ordinary LO+PS restricted to soft emissions with \( Q < Q_{\text{cut}} \)
- phase space \( Q > Q_{\text{cut}} \) filled by ME
- supplement Sudakov suppression \( \Delta(t) \) to recover unitarity at (N)LL level
- preserves LO accuracy of every ME emission and LL accuracy of PS
- PS Sudakov form factor \( \Delta(t) = \exp \left[ - \sum \int d\Phi_{R|B} K(t, z, \phi) \right] \)
- unitarity of PS violated at \( \mathcal{O}(\alpha_s) \) beyond (N)LL
CKKW-like implementations

- direct implementation
- phase space separation via arbitrary parton-measure
  \[ \rightarrow \text{PS and ME treated alike} \]
- Sudakov weight via vetoed shower
- truncated showering if \( Q \) and \( t \) differ

MLM-like implementations

- geometric approximation
- phase space separation via
  \[ \rightarrow \text{parton-measure on ME multiplicitywise} \]
  \[ \rightarrow \text{jet-measure on PS after full PS} \]
- Sudakov weight via “jet matching”
Importance of truncated showering

- truncated showering necessary to maintain logarithmic accuracy if separation measure deviates from evolution measure
- most prominent in HERWIG/HERWIG++: $Q_{\text{cut}} \sim y_{ij}$ vs. $t \sim \theta^2$
- studied by [Hamilton, Richardson, Tully] JHEP11(2009)038
Importance of truncated showering

- ATLAS-CONF-2011-038
- gap fraction sensitive to resummation effects
- resummation should be identical for HERWIG and ALPGEN + HERWIG
- proper phase space separation crucial
  → neither holes nor doubly filled regions
- truncated showering crucial

ATLAS Preliminary

Selection A

\[ Q_0 = 20 \text{ GeV} \]

\[ 2 < \Delta y < 3 \]
**SHERPA – DIS**

![Graph showing differential cross sections for different eta ranges.](image)

⇒ higher-order MEs needed to open radiative phase space
data from H1  *PLB542(2002)193-206*
NLO+PS: Powheg & MC@NLO

1. ME+PS: CKKW & MLM

2. NLO+PS: Powheg & MC@NLO

3. Menlops

4. Conclusions
MC@NLO Algorithm

\[ \langle O \rangle = \int d\Phi_B B(\Phi_B) \left[ \Delta(t_0) O(\Phi_B) + \sum \int_{t_0} d\Phi_{R|B} K(t, z, \phi) \Delta(t) O(\Phi_R) \right] \]

\[ + \int d\Phi_R [R(\Phi_R) - R^{(PS)}(\Phi_R)] O(\Phi_R) \]

- PS approximation \( R^{(PS)} = \sum B \cdot K \)
- modified subtraction with \( \bar{B}^{(PS)} = B + V + \int d\Phi_{R|B} R^{(PS)} \)
  \( \rightarrow \) parton shower needs to be correct in the soft limit
- resums exactly as the parton shower
- implemented for HERWIG/HERWIG++ and PYTHIA showers
- correction events to restore NLO accuracy
  \( \Rightarrow \) preserves both NLO and (N)LL accuracy
MC@NLO Algorithm

\[
\langle O \rangle = \int d\Phi_B \, \tilde{B}^{(PS)}(\Phi_B) \left[ \Delta(t_0) \, O(\Phi_B) + \sum \int_{t_0} d\Phi_{R|B} \, \frac{R^{(PS)}(\Phi_R)}{B(\Phi_B)} \, \Delta(t) \, O(\Phi_R) \right] \\
+ \int d\Phi_R \, [R(\Phi_R) - R^{(PS)}(\Phi_R)] \, O(\Phi_R)
\]

- PS approximation \( R^{(PS)} = \sum B \cdot K \)
- modified subtraction with \( \tilde{B}^{(PS)} = B + V + \int d\Phi_{R|B} R^{(PS)} \) → parton shower needs to be correct in the soft limit
  - resums exactly as the parton shower
  - implemented for HERWIG/HERWIG++ and PYTHIA showers
- correction events to restore NLO accuracy
  ⇒ preserves both NLO and (N)LL accuracy
MC@NLO Algorithm

\[
\langle O \rangle = \int d\Phi_B \, \tilde{B}^{(PS)}(\Phi_B) \left[ \Delta(t_0) \, O(\Phi_B) + \sum \int_{t_0}^{t} d\Phi_R|_B \, \frac{R^{(PS)}(\Phi_R)}{B(\Phi_B)} \, \Delta(t) \, O(\Phi_R) \right] \\
+ \int d\Phi_R \, [R(\Phi_R) - R^{(PS)}(\Phi_R)] \, O(\Phi_R)
\]

- PS approximation \( R^{(PS)} = \sum B \cdot K \)
- modified subtraction with \( \tilde{B}^{(PS)} = B + V + \int d\Phi_R|_B R^{(PS)} \)
  \( \rightarrow \) parton shower needs to be correct in the soft limit
- resums exactly as the parton shower
- implemented for HERWIG/HERWIG++ and PYTHIA showers
- correction events to restore NLO accuracy
  \( \Rightarrow \) preserves both NLO and (N)LL accuracy
MC@NLO Algorithm

\[
\langle O \rangle = \int d\Phi_B \, \tilde{B}^{(PS)}(\Phi_B) \left[ \Delta(t_0) \, O(\Phi_B) + \sum \int_{t_0} d\Phi_R|_B \, \frac{R^{(PS)}(\Phi_R)}{B(\Phi_B)} \Delta(t) \, O(\Phi_R) \right] \\
+ \int d\Phi_R \left[ R(\Phi_R) - R^{(PS)}(\Phi_R) \right] \, O(\Phi_R)
\]

- PS approximation \( R^{(PS)} = \sum B \cdot K \)
- modified subtraction with \( \tilde{B}^{(PS)} = B + V + \int d\Phi_R|_B R^{(PS)} \) → parton shower needs to be correct in the soft limit
- resums exactly as the parton shower
- implemented for HERWIG/HERWIG++ and PYTHIA showers
- correction events to restore NLO accuracy
  ⇒ preserves both NLO and (N)LL accuracy
Recent Progress in Matching and Merging

Marek Schönherr
IKTP TU Dresden

MC@NLO

<table>
<thead>
<tr>
<th>Process</th>
<th>1PRGDC</th>
<th>IV</th>
<th>IL1</th>
<th>IL2</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1350-IL</td>
<td>✓</td>
<td>I</td>
<td>I</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>1360-IL</td>
<td>✓</td>
<td>I</td>
<td>I</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>1370-IL</td>
<td>✓</td>
<td>I</td>
<td>I</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>1460-IL</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>1470-IL</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>1397</td>
<td>X</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>1497</td>
<td>X</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>1500-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>1501-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2000-1C</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2001-1C</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2003-1C</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2004-1C</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2600-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2601-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2602-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2603-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2604-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2605-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2606-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2607-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2608-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2609-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2610-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2611-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2612-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2613-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2614-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2615-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2616-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2617-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2618-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
<tr>
<td>2619-1D</td>
<td>✓</td>
<td>I</td>
<td>i</td>
<td>X</td>
<td>I</td>
</tr>
</tbody>
</table>

**Conclusions**

aMC@NLO

- automated version of MC@NLO
- uses MADGRAPH/MADLOOP framework
  [Frederix et al.] JHEP05(2011)044
- results published for
  $pp \rightarrow ttH$
  [Frederix et al.] PLB 701(2011)427-433
  and $pp \rightarrow V + b\bar{b}$
  [Frederix et al.] arXiv:1106.6019
- code not public yet
**POWHEG Algorithm**

\[
\langle O \rangle = \int d\Phi_B \tilde{B}(\Phi_B) \left[ \Delta^{(\text{ME})}(t_0) O(\Phi_B) + \sum \int_{t_0} d\Phi_{R|B} \frac{R(\Phi_R)}{B(\Phi_B)} \Delta^{(\text{ME})}(t) O(\Phi_R) \right]
\]


- NLO event weight \( \tilde{B} = B + V + \int d\Phi_{R|B} R \) defined on \( \Phi_B \)
  \( \rightarrow \) wrong observable dependence on \( R(\Phi_R) \)

- POWHEG Sudakov \( \Delta^{(\text{ME})}(t) = \exp \left[ - \sum \int_t d\Phi_{R|B} \frac{R(\Phi_R)}{B(\Phi_B)} \right] \)
  \( \rightarrow \) intricate cancellation to correct observable dependence on \( R(\Phi_R) \)

- \( \Delta^{(\text{ME})} = \Delta^{(\text{PS})} \) at LL level
  \( \rightarrow \) resums as PS if interface ensures continuous evolution in phase space and colour space
  \( \rightarrow \) importance of truncated showering [Nason] JHEP11(2004)040

\( \Rightarrow \) preserves both NLO and (N)LL accuracy
POWHEG Algorithm

\[ \langle O \rangle = \int d\Phi_B \tilde{B}(\Phi_B) \left[ \Delta^{(ME)}(t_0) O(\Phi_B) + \sum \int_{t_0} d\Phi |_B \frac{R(\Phi_R)}{B(\Phi_B)} \Delta^{(ME)}(t) O(\Phi_R) \right] \]


- NLO event weight \( \tilde{B} = B + V + \int d\Phi |_B R \) defined on \( \Phi_B \)
  \( \rightarrow \) wrong observable dependence on \( R(\Phi_R) \)

- POWHEG Sudakov \( \Delta^{(ME)}(t) = \exp \left[ - \sum \int_t d\Phi_B \frac{R(\Phi_R)}{B(\Phi_B)} \right] \)
  \( \rightarrow \) intricate cancellation to correct observable dependence on \( R(\Phi_R) \)

- \( \Delta^{(ME)} = \Delta^{(PS)} \) at LL level
  \( \rightarrow \) resums as PS if interface ensures continuous evolution in phase space and colour space
  \( \rightarrow \) importance of truncated showering [Nason] JHEP11(2004)040
  \( \Rightarrow \) preserves both NLO and (N)LL accuracy
POWHEG Algorithm

\[
\langle O \rangle = \int d\Phi_B \tilde{B}(\Phi_B) \left[ \Delta^{(\text{ME})}(t_0) O(\Phi_B) + \sum \int_{t_0} \frac{R(\Phi_R)}{B(\Phi_B)} \Delta^{(\text{ME})}(t) O(\Phi_R) \right]
\]

- NLO event weight \( \tilde{B} = B + V + \int d\Phi_{R|B} R \) defined on \( \Phi_B \)
  \( \rightarrow \) wrong observable dependence on \( R(\Phi_R) \)
- POWHEG Sudakov \( \Delta^{(\text{ME})}(t) = \exp \left[ - \sum \int_t d\Phi_{R|B} \frac{R(\Phi_R)}{B(\Phi_B)} \right] \)
  \( \rightarrow \) intricate cancellation to correct observable dependence on \( R(\Phi_R) \)
- \( \Delta^{(\text{ME})} = \Delta^{(\text{PS})} \) at LL level
  \( \rightarrow \) resums as PS if interface ensures continuous evolution in phase space and colour space
  \( \rightarrow \) importance of truncated showering [Nason] JHEP11(2004)040

\( \Rightarrow \) preserves both NLO and (N)LL accuracy
Ambiguities/freedom/choices in the exponentiation

• divide $R(\Phi_R)$ into singular and regular \cite{Alioli et al. JHEP07(2008)060}

$$R(\Phi_R) = R^{(s)}(\Phi_R) + R^{(r)}(\Phi_R)$$

then

$$\langle O \rangle = \int d\Phi_B \bar{B}^{(s)}(\Phi_B) \left[ \Delta^{(\text{ME})}_{(s)}(t_0) O(\Phi_B) + \sum \int_{t_0} d\Phi_R|R_B \frac{R^{(s)}(\Phi_R)}{B(\Phi_B)} \Delta^{(\text{ME})}_{(s)}(t) O(\Phi_R) \right]$$

$$+ \int d\Phi_R R^{(r)}(\Phi_R) O(\Phi_R)$$

with $\bar{B}^{(s)} = B + V + \int d\Phi_R|R_B R^{(s)}$

and $\Delta^{(\text{ME})}_{(s)}(t) = \exp \left[ - \sum \int_t d\Phi_R|R_B \frac{R^{(s)}(\Phi_R)}{B(\Phi_B)} \right]$.

• different $K$-factors for reweighted PS, different exponentiation behaviour
  $\rightarrow$ beyond NLO and (N)LL accuracy

• specific choice:

$$R^{(s)}(\Phi_R) = R^{(\text{PS})}(\Phi_R) \quad \Rightarrow \quad \text{MC@NLO} \cite{Frixione, Webber JHEP06(2002)029}$$
**POWHEG-BOX — toolkit for POWHEG implementations**

Toolkit to implement new process given

- Born matrix elements, flavour structures & phase space
- colour and spin correlated Born matrix elements $B_{ij}$ and $B_{\mu\nu}$
- virtual matrix elements
- real matrix elements and flavour structures
- Born colour structures in $N_c \to \infty$

$\Rightarrow$ internal FKS subtraction and real emission phase space integration

$\Rightarrow$ generates radiation using POWHEG Sudakov form factor

**Wide range of processes**

- $V, VV, Q\bar{Q}, Wb\bar{b}, W^+W^+jj, H(GF,VBF)$, single-top
- $Vj$, dijets
- $ttH, ttj$
- interface to HERWIG/PYTHIA
  $\rightarrow$ truncated showering needed but not available
**POWHEG-BOX** → $pp \rightarrow \ell^+ \ell^- j$

$p\bar{p} \rightarrow Z + j$

DØ $Z + j$ analyses


good description of data

some dependence on

PYTHIA tune
**POWHEG-BOX** — $pp \rightarrow Wb\bar{b}$

Large ratio $\bar{B}/B$

→ large effect of choice

what to exponentiate and what to generate explicitly

Small deviation of

POWHEG-BOX $\otimes$ HERWIG & POWHEG-BOX $\otimes$ PYTHIA
**POWHEG-BOX – dijets**

**ATLAS-CONF-2011-047**:

- $p_{\perp,j}$ supposedly described at NLO⊗LL
- ~20% difference between using HERWIG or PYTHIA for parton showering

**Issues for logarithmic accuracy:**

- truncated showering implemented neither for HERWIG or PYTHIA interfaces → especially important for HERWIG’s angular ordering
- consistent settings for PDFs, $\mu_R$ and $\mu_F$ scales, etc.
- no conclusive answers so far
**POWHEG in HERWIG++**

- **Processes:**
  - $V, VV, H(GF,VBF), VH$
  - $ee \rightarrow q\bar{q},$ DIS
  - $H \rightarrow q\bar{q}$ decay
- includes truncated showering
POWHEG – Automation in SHERPA

- [Höche, Krauss, MS, Siegert] JHEP04(2011)024
- reinterprete POWHEG as ME reweighted PS with local $K$-factor
- NLO event weight $\bar{B} = B + V + I + \int d\Phi_{R|B} [R - S]$
  - Born, Real from automated tree-level generators
  - automated phase space
  - Virtual e.g. via Binoth Les Houches Accord CPC181(2010)1612
    → for results here BLACKHAT & MCFM libraries interfaced
  - Integrated/Subtraction terms from automated implementation of Catani-Seymour subtraction terms EPJC53(2008)501
    - dedicated automated CS-like phase-space for $R - S$ integral
  - correct PS to ME via weight $w(\Phi_R) = R(\Phi_R)/R^{(PS)}(\Phi_R)$
    → alleviated by good approximation of CSSHOWER++ JHEP03(2008)038
    → truncated showering not needed
- included since SHERPA-1.2.3 (Nov ’10)
**SHERPA – inclusive $W/Z$ production at Tevatron**

**Data from DØ :**

**Data from DØ :**
SHERPA – Non-trivial colour structures – \( pp \rightarrow Wj \)

- **POWHEG** method sufficiently general
- Subtraction and PS need to have identical phase space maps
- \( N_c \rightarrow \infty \) in parton shower vs. \( N_c = 3 \) in matrix elements
  - \( \rightarrow \) no issue for \( O(\Phi_R) \) if parton shower can fill full phase space
  - \( \rightarrow O(\Phi_B) \) formally at LC-NLO\( \times (N)\)LL accuracy

Inclusive jet multiplicity (electron channel)

\[
\sigma(W^+ + \geq N_{\text{jet}}) \ [\text{pb}]
\]

\[
\frac{d^2\sigma}{dp_T^2} \ [\text{pb/GeV}]
\]

\[
p_T \text{ of 1st jet (electron channel)}
\]

\[
p_T \text{ of 2nd jet (electron channel)}
\]

inclusively jet multiplicity and \( p_T \) of 1st & 2nd jet in \( W+jets \) events,

data from ATLAS  *Phys.Lett.B698(2011)325-345*
**SHERPA** – $p\bar{p} \rightarrow Z j$ at Tevatron

Differential cross section in $Z/\gamma^* p_{\perp}$

$\frac{d\sigma}{dp_{\perp}(Z)}$ [pb/GeV]

$0 \rightarrow 0.6 \rightarrow 1 \rightarrow 1.2 \rightarrow 1.4 \rightarrow 1.6 \rightarrow 200$

$0.6 \rightarrow 0.8 \rightarrow 1 \rightarrow 1.2 \rightarrow 1.4 \rightarrow 1.6 \rightarrow 200$

Azimuthal distribution for $p_{\perp}^Z > 25$ GeV

$\frac{d\sigma}{d\Delta\phi(Z, \text{jet})}$ [pb/rad]

$0 \rightarrow 0.5 \rightarrow 1 \rightarrow 1.5 \rightarrow 2 \rightarrow 2.5 \rightarrow \Delta\phi(Z, \text{jet}) [\text{rad}]$

Rapidity difference for $p_{\perp}^Z > 25$ GeV

$\frac{d\sigma}{d|\Delta y(Z, \text{jet})|}$ [pb]

$0 \rightarrow 0.5 \rightarrow 1 \rightarrow 1.5 \rightarrow 2 \rightarrow 2.5 \rightarrow |\Delta y(Z, \text{jet})|$

$p\bar{p} \rightarrow Z + j$

DØ $Z + j$ analyses


LC-NLO⊗(N)LL

accuracy
1. ME+PS: CKKW & MLM

2. NLO+PS: POWHEG & MC@NLO

3. MENLOPS

4. Conclusions
Multijet Merging with NLO MEs – MENLOPS

\[ \langle O \rangle = \int d\Phi_B \bar{B}(\Phi_B) \left[ \Delta^{(\text{ME})}(t_0) O(\Phi_B) \right. \]
\[ + \int d\Phi_R|B \frac{R(\Phi_R)}{B(\Phi_B)} \Delta^{(\text{ME})}(t) \Theta(Q_{\text{cut}} - Q) O(\Phi_R) \]
\[ + \int d\Phi_R|B \frac{R(\Phi_R)}{B(\Phi_B)} \Delta^{(\text{PS})}(t) \Theta(Q - Q_{\text{cut}}) O(\Phi_R) \]

- POWHEG domain restricted to soft emissions \( Q < Q_{\text{cut}} \) 
  \[ \Rightarrow \text{NLO accuracy preserved for inclusive observables} \]
- ME\( \otimes \)PS used for hard emission & higher order emissions 
  \[ \Rightarrow \text{preserves LO accuracy of every ME emission & LL accuracy of PS} \]
- higher order emissions receive local K-factor \( \frac{\bar{B}(\Phi_B)}{B(\Phi_B)} \)
- inherits unitarity violation from ME\( \otimes \)PS 
  \[ \rightarrow \text{pushed to } \mathcal{O}(\alpha_s^2) \text{ beyond (N)LL} \]
Multijet Merging with NLO MEs – MENLOPS

\[ \langle O \rangle = \int d\Phi_B \bar{B}(\Phi_B) \left[ \Delta^{(\text{ME})}(t_0) O(\Phi_B) + \int d\Phi_R |_{B} \frac{R(\Phi_R)}{B(\Phi_B)} \Delta^{(\text{ME})}(t) \Theta(Q_{\text{cut}} - Q) O(\Phi_R) + \int d\Phi_R |_{B} \frac{R(\Phi_R)}{B(\Phi_B)} \Delta^{(\text{PS})}(t) \Theta(Q - Q_{\text{cut}}) O(\Phi_R) \right] \]

- POWHEG domain restricted to soft emissions \( Q < Q_{\text{cut}} \) ⇒ NLO accuracy preserved for inclusive observables
- ME⊗PS used for hard emission & higher order emissions ⇒ preserves LO accuracy of every ME emission & LL accuracy of PS
- higher order emissions receive local K-factor \( \frac{\bar{B}(\Phi_B)}{B(\Phi_B)} \)
- inherits unitarity violation from ME⊗PS → pushed to \( \mathcal{O}(\alpha_s^2) \) beyond (N)LL
Multijet Merging with NLO MEs – MENLOPS

\[
\langle O \rangle = \int d\Phi_B \, B(\Phi_B) \left[ \Delta^{(\text{ME})}(t_0) \, O(\Phi_B) + \int d\Phi_{R|B} \, \frac{R(\Phi_R)}{B(\Phi_B)} \Delta^{(\text{ME})}(t) \, \Theta(Q_{\text{cut}} - Q) \, O(\Phi_R) + \int d\Phi_{R|B} \, \frac{R(\Phi_R)}{B(\Phi_B)} \Delta^{(\text{PS})}(t) \, \Theta(Q - Q_{\text{cut}}) \, O(\Phi_R) \right]
\]

- POWHEG domain restricted to soft emissions \( Q < Q_{\text{cut}} \) ⇒ **NLO accuracy preserved for inclusive observables**
- ME⊗PS used for hard emission & higher order emissions ⇒ **preserves LO accuracy of every ME emission & LL accuracy of PS**
- higher order emissions receive local K-factor \( \frac{B(\Phi_B)}{\bar{B}(\Phi_B)} \)
- inherits unitarity violation from ME⊗PS → pushed to \( \mathcal{O}(\alpha_s^2) \) beyond (N)LL
**MENLOPS – Unitarity violations**

\[ e^+e^- \rightarrow \text{jets at } \sqrt{s} = 91.25 \text{ GeV} \]

- \( \log \frac{y_{\text{cut}}}{\text{GeV}} = -1.25/-1.75/-2.25 \) (ME+PS)
- \( \log \frac{y_{\text{cut}}}{\text{GeV}} = -1.25/-1.75/-2.25 \) (MENLOPS)

\[ pp \rightarrow W^+W^- + \text{jets at } \sqrt{s} = 14 \text{ TeV} \]

- \( Q_{\text{cut}} = 20/40/80 \text{ GeV} \) (ME+PS)
- \( Q_{\text{cut}} = 20/40/80 \text{ GeV} \) (MENLOPS)

\[ \Rightarrow \text{reduced unitarity violation} \]

\[ \mathcal{O}(\alpha_s) \text{ and beyond (N)LL for ME} \otimes \text{PS} \]

\[ \mathcal{O}(\alpha_s^2) \text{ and beyond (N)LL for MENLOPS} \]
SHERPA – DIS

**SHERPA** - $p\bar{p} \rightarrow \ell^+\ell^- + X$

Data from DØ:


**POWHEG** and **MENLOPS** agree well on $p_\perp$ of hardest jet

**MENLOPS** superior for 2nd and 3rd jet
**SHERPA** \(- pp \rightarrow W^+ W^- + X \)

\[ \frac{d\sigma}{dH_T} [\text{pb}/\text{GeV}] \]

\[ \frac{d\sigma}{d\Delta \phi(jet_1, jet_2)} [\text{pb}] \]

⇒ considerable corrections from higher-order tree-level matrix elements
Conclusions

- **ME⊗PS** works well for shapes, but needs K-factor
  → truncated showering essential to recover PS resummation
- **MC@NLO & POWHEG** reproduce NLO cross section and shape of first emission, but additional hard jets at (N)LL only
- various implementations with various degrees of automation
- **MENLOPS** combines **ME⊗PS** and **POWHEG**
  ⇒ NLO accuracy in core process
  ⇒ multijet observables as in **ME⊗PS**

- **ME⊗PS, POWHEG & MENLOPS** automated (except V) in SHERPA framework
  ⇒ for trivial colour structures included in current release v1.3.0
  ⇒ for new process need function $V(\Phi_B, \mu_R) \rightarrow (BLHA)$ interface
- also want NLO accuracy in higher order emission in inclusive sample
  ⇒ multijet emission dependent observables described at NLO
- crucial to recover desired accuracies for arbitrary observables
  ... working on it
# Available processes*

<table>
<thead>
<tr>
<th>Process</th>
<th><strong>POWHEG</strong></th>
<th><strong>HERWIG++</strong></th>
<th><strong>SHERPA</strong></th>
<th><strong>MC@NLO</strong></th>
<th><strong>aMC@NLO</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \rightarrow jj$</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>DIS</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>$pp \rightarrow W/Z$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>$pp \rightarrow H$ (GF)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>$pp \rightarrow V + H$</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>$pp \rightarrow VV$</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>VBF</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>$pp \rightarrow Q\bar{Q}$</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>$pp \rightarrow Q\bar{Q} + j$</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>single-top</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>$pp \rightarrow V + j$</td>
<td>✓</td>
<td>x</td>
<td>in prep.</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$pp \rightarrow V + jj$</td>
<td>in prep.</td>
<td>x</td>
<td>in prep.</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$pp \rightarrow H + j$ (GF)</td>
<td>x</td>
<td>x</td>
<td>in prep.</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$pp \rightarrow H + t\bar{t}$</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>✓</td>
</tr>
<tr>
<td>$pp \rightarrow W^+W^-jj$</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$pp \rightarrow V + bb$</td>
<td>✓</td>
<td>x</td>
<td>in prep.</td>
<td>x</td>
<td>✓</td>
</tr>
<tr>
<td>diphotons</td>
<td>?</td>
<td>✓</td>
<td>in prep.</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>dijets</td>
<td>✓</td>
<td>x</td>
<td>in prep.</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

*Table includes SM processes presented so far. Automated codes and toolkits can, in principle, be used for any process.*

Marek Schönher
IKTP TU Dresden
Recent Progress in Matching and Merging
Thank you.
Backup: ME⊗PS Merging – Scales

Divide phase space using jet measure $Q_{\text{cut}}$:

$\rightarrow$ emissions with $Q > Q_{\text{cut}}$ by ME
$\rightarrow$ emissions with $Q < Q_{\text{cut}}$ by PS

Shower on top of higher order ME:

Problem: ME only gives final state, no history as PS input

Solution: Backward clustering (inverted probabilistic PS splittings)

$\Rightarrow$ ME final state with branching history and PS starting scale $\mu$ and branching scales $t_i$

\[ \alpha_s^{k+n}(\mu_{\text{eff}}) = \alpha_s^k(\mu) \alpha_s(t_1) \cdots \alpha_s(t_n) \]

Veto PS emissions with $Q > Q_{\text{cut}}$

$\rightarrow$ Reject event $\rightarrow$ Sudakov suppression

If $t \neq Q^2$ then truncated shower necessary
Backup: Unitarity Violation in MENLOPS & ME+PS

Formally of $\mathcal{O}(\alpha_s^2)$ in MENLOPS

$\rightarrow N_{\text{max}} = 1$ shows size of unitarity violation in MENLOPS alone

Due to mismatch in non-logarithmic terms in ME and PS in real emission correction and Sudakov

Indicates potential size of higher order corrections