Recent Progress in Matching and Merging

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IKTP TU Dresden

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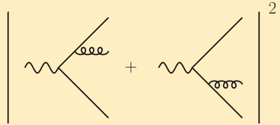
Outline

(NLO)ME vs. PS

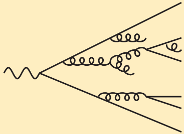
Approaches to real emission corrections

(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 **intrajet evolution**

ME+PS: CKKW & MLM

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

- 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 $\Delta(t) = \exp\left[-\sum \int \mathrm{d}\Phi_{R|B} \, \mathcal{K}(t,z,\phi)\right]$
- unitarity of PS violated at $\mathcal{O}(\alpha_s)$ beyond (N)LL

ME+PS: CKKW & MLM

$$\langle O \rangle = \int \mathrm{d}\Phi_B \, B(\Phi_B) \Big[\Delta(t_0) \, O(\Phi_B) + \int \overbrace{\mathrm{d}\Phi_{R|B} \, \mathcal{K}(t,z,\phi) \, \Delta(t) \, \Theta(Q_{\text{cut}} - Q)}^{\text{PS domain}} \, O(\Phi_R) \Big]$$

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ME+PS: CKKW & MLM

CKKW-like implementations

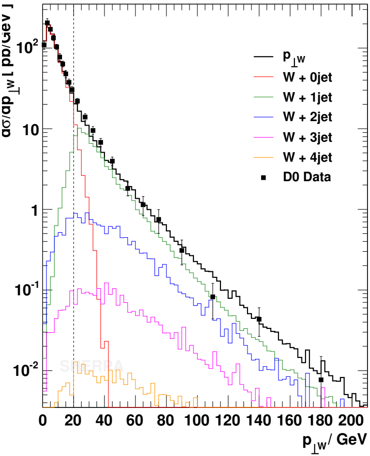
JHEP05(2009)053,JHEP11(2009)038,JHEP11(2001)063,JHEP08(2002)015,JHEP05(2002)046,JHEP07(2005)054

- direct implementation
- phase space separation via arbitrary parton-measure
  $\rightarrow$ PS and ME treated alike
- Sudakov weight via vetoed shower
- truncated showering if Q and t differ

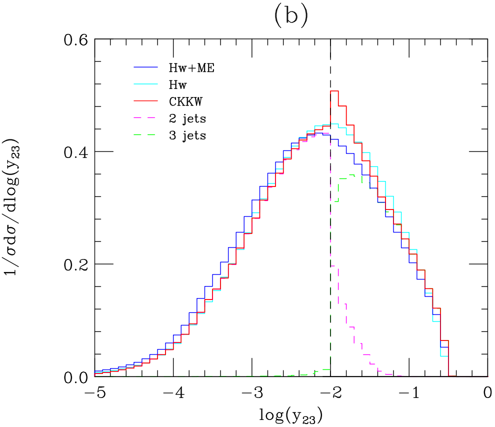
MLM-like implementations

JHEP01(2007)013,NBP632(2002)343,JHEP02(2009)017

- geometric approximation
- phase space separation via
  $\rightarrow$ parton-measure on ME multiplicitywise
  $\rightarrow$ jet-measure on PS after full PS
- Sudakov weight via "jet matching"



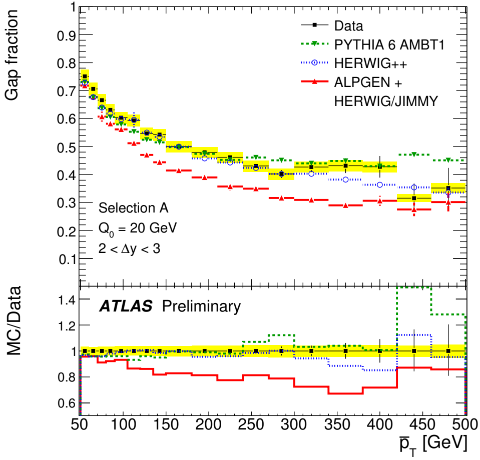
Importance of truncated showering



without 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

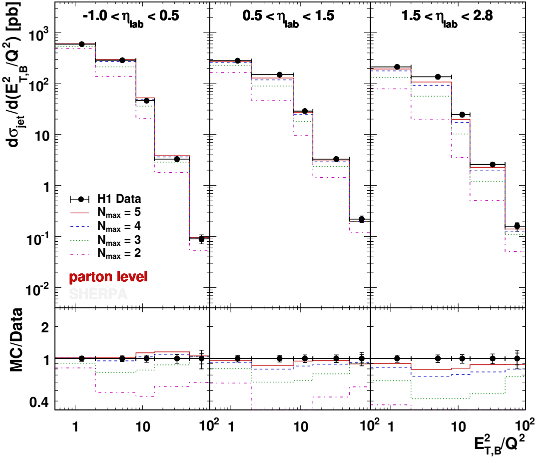
Importance of truncated showering

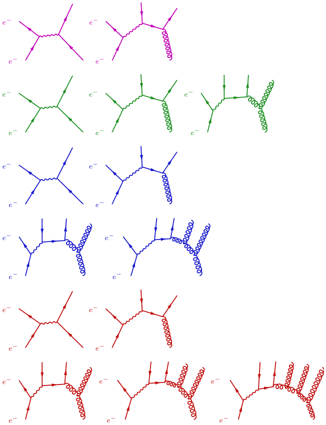


- ATLAS-CONF-2011-038
- gap fraction sensitive to resummation effects
- resummation should be identical for HERWIG and ALPGEN+HERWIG
- proper phase space separation crucial
  $\rightarrow$ neither holes nor doubly filled regions
- truncated showering crucial

EPJC67(2010)73-97

SHERPA – DIS





⇒ higher-order MEs needed to open radiative phase space
data from H1 PLB542(2002)193-206

NLO+PS: POWHEG & MC@NLO

JHEP06(2002)029

MC@NLO Algorithm

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

$$+ \int \mathrm{d}\Phi_R\, \left[R(\Phi_R) - R^{\text{(PS)}}(\Phi_R)\right]\; O(\Phi_R)$$

- [Frixione, Webber] JHEP06(2002)029
- PS approximation $R^{\text{(PS)}} = \sum B \cdot \mathcal{K}$
- modified subtraction with $\bar{B}^{\text{(PS)}} = B + V + \int \mathrm{d}\Phi_{R|B} R^{\text{(PS)}}$
  $\rightarrow$ parton shower needs to be correct in the soft limit
- resums exactly as the parton shower
- implemented for HERWIG/HERWIG++ and PYTHIA showers
  [Frixione etal.] JHEP01(2011)053, [Torelli etal.] JHEP04(2010)110
- correction events to restore NLO accuracy

$\Rightarrow$ **preserves both NLO and (N)LL accuracy**

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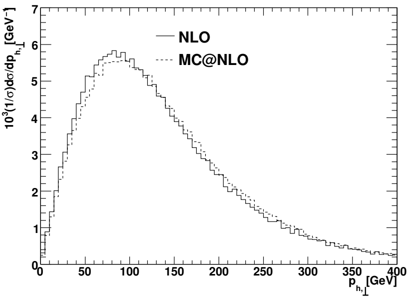
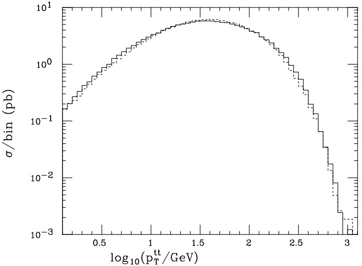
JHEP01(2011)053,EPJC67(2010)617-636

MC@NLO

IPROC	IV	IL_1	IL_2	Spin	Process
−1350−IL				✓	$H_1H_2 \to (Z/\gamma^* \to)l_{\rm IL}\bar{l}_{\rm IL} + X$
−1360−IL				✓	$H_1H_2 \to (Z \to)l_{\rm IL}\bar{l}_{\rm IL} + X$
−1370−IL				✓	$H_1H_2 \to (\gamma^* \to)l_{\rm IL}\bar{l}_{\rm IL} + X$
−1460−IL				✓	$H_1H_2 \to (W^+ \to)l^+_{\rm IL}\nu_{\rm IL} + X$
−1470−IL				✓	$H_1H_2 \to (W^- \to)l^-_{\rm IL}\bar{\nu}_{\rm IL} + X$
−1396				✗	$H_1H_2 \to \gamma^*(\to \sum_i f_i f_i) + X$
−1397				✗	$H_1H_2 \to Z^0 + X$
−1497				✗	$H_1H_2 \to W^+ + X$
−1498				✗	$H_1H_2 \to W^- + X$
−1600−ID					$H_1H_2 \to H^0 + X$
−1705					$H_1H_2 \to b\bar{b} + X$
−1706		7	7	✗	$H_1H_2 \to t\bar{t} + X$
−2000−IC		7		✗	$H_1H_2 \to t/\bar{t} + X$
−2001−IC		7		✗	$H_1H_2 \to \bar{t} + X$
−2004−IC		7		✗	$H_1H_2 \to t + X$
−2030		7	7	✗	$H_1H_2 \to tW^-/\bar{t}W^+ + X$
−2031		7	7	✗	$H_1H_2 \to \bar{t}W^+ + X$
−2034		7	7	✗	$H_1H_2 \to tW^- + X$
−2040		7	7	✗	$H_1H_2 \to tH^-/\bar{t}H^+ + X$
−2041		7	7	✗	$H_1H_2 \to \bar{t}H^+ + X$
−2044		7	7	✗	$H_1H_2 \to tH^- + X$
−2600−ID	1	7		✗	$H_1H_2 \to H^0W^+ + X$
−2600−ID	1	i		✓	$H_1H_2 \to H^0(W^+ \to)l_i^+\nu_i + X$
−2600−ID	-1	7		✗	$H_1H_2 \to H^0W^- + X$
−2600−ID	-1	i		✓	$H_1H_2 \to H^0(W^- \to)l_i^-\bar{\nu}_i + X$
−2700−ID	0	7		✗	$H_1H_2 \to H^0Z + X$
−2700−ID	0	i		✓	$H_1H_2 \to H^0(Z \to)l_i\bar{l}_i + X$
−2850		7	7	✗	$H_1H_2 \to W^+W^- + X$
−2860		7	7	✗	$H_1H_2 \to Z^0Z^0 + X$
−2870		7	7	✗	$H_1H_2 \to W^+Z^0 + X$
−2880		7	7	✗	$H_1H_2 \to W^-Z^0 + X$
−1706		i	j	✓	$H_1H_2 \to (t \to)b_k f_i f_i'(\bar{t} \to)\bar{b}_l f_j f_j' + X$
−2000−IC		i		✓	$H_1H_2 \to (t \to)b_k f_i f_i'/(\bar{t} \to)\bar{b}_k f_i f_i' + X$
−2001−IC		i		✓	$H_1H_2 \to (\bar{t} \to)\bar{b}_k f_i f_i' + X$
−2004−IC		i		✓	$H_1H_2 \to (t \to)b_k f_i f_i' + X$
−2030		i	j	✓	$H_1H_2 \to (t \to)b_k f_i f_i'(W^- \to)f_j f_j'/$ $(\bar{t} \to)\bar{b}_k f_i f_i'(W^+ \to)f_j f_j' + X$
−2031		i	j	✓	$H_1H_2 \to (\bar{t} \to)\bar{b}_k f_i f_i'(W^+ \to)f_j f_j' + X$
−2034		i	j	✓	$H_1H_2 \to (t \to)b_k f_i f_i'(W^- \to)f_j f_j' + X$
−2040		i		✓	$H_1H_2 \to (t \to)b_k f_i f_i' H^-/$ $(\bar{t} \to)\bar{b}_k f_i f_i' H^+ + X$
−2041		i		✓	$H_1H_2 \to (\bar{t} \to)\bar{b}_k f_i f_i' H^+ + X$
−2044		i		✓	$H_1H_2 \to (t \to)b_k f_i f_i' H^- + X$
−2850		i	j	✓	$H_1H_2 \to (W^+ \to)l_i^+\nu_i(W^- \to)l_j^-\bar{\nu}_j + X$
−2870		i	j	✓	$H_1H_2 \to (W^+ \to)l_i^+\nu_i(Z^0 \to)l_j'\bar{l}_j' + X$
−2880		i	j	✓	$H_1H_2 \to (W^+ \to)l_i^-\bar{\nu}_i(Z^0 \to)l_j'\bar{l}_j' + X$

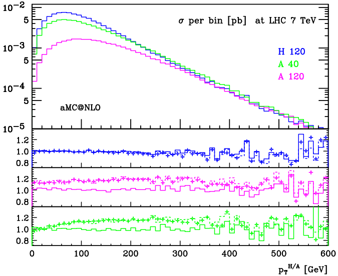


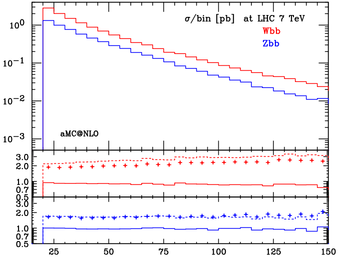


arXiv:1106.6019,PLB 701(2011)427-433

aMC@NLO

- automated version of MC@NLO
- uses MADGRAPH/MADLOOP framework
  [Alwall etal.] JHEP09(2007)028
  [Frederix etal.] JHEP05(2011)044
- results published for $pp \to ttH$
  [Frederix etal.] PLB 701(2011)427-433
  and $pp \to V + b\bar{b}$
  [Frederix etal.] arXiv:1106.6019
- code not public yet





POWHEG Algorithm

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

- [Nason] JHEP11(2004)040, [Frixione etal.] JHEP11(2007)070
- NLO event weight $\bar{B} = B + V + \int \mathrm{d}\Phi_{R|B}\,R$ defined on Φ_B
  $\rightarrow$ wrong observable dependence on $R(\Phi_R)$
- POWHEG Sudakov $\Delta^{(\mathrm{ME})}(t) = \exp\left[-\sum\int_t \mathrm{d}\Phi_{R|B}\,\frac{R(\Phi_R)}{B(\Phi_B)}\right]$
  $\rightarrow$ intricate cancellation to correct observable dependence on $R(\Phi_R)$
- $\Delta^{(\mathrm{ME})} = \Delta^{(\mathrm{PS})}$ 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**

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JHEP06(2002)029, JHEP07(2008)060, JHEP04(2011)024

Ambiguities/freedom/choices in the exponentiation

- divide $R(\Phi_R)$ into singular and regular [Alioli etal.] JHEP07(2008)060

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

then

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

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

with $\bar{B}^{(\mathsf{s})} = B + V + \int \mathrm{d}\Phi_{R|B}\, R^{(\mathsf{s})}$

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

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

$$R^{(\mathsf{s})}(\Phi_R) = R^{(\mathsf{PS})}(\Phi_R) \quad \Rightarrow \quad \text{MC@NLO}$$ [Frixione, Webber]JHEP06(2002)029

JHEP06(2010)043

POWHEG-BOX – toolkit for POWHEG implementations

Toolkit to implement new process given

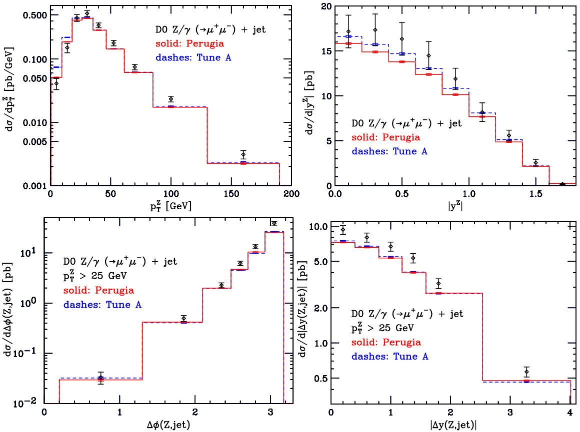
- Born matrix elements, flavour structures & phase space
- colour and spin correlated Born matrix elements B_{ij} and $B_{\mu\nu}$
- virtual matrix elements
- real matrix elements and flavour structures
- Born colour structures in $N_c \to \infty$

$\Rightarrow$ 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
- $t\bar{t}H$, $t\bar{t}j$
- interface to HERWIG/PYTHIA
  $\to$ truncated showering needed but not available

POWHEG-BOX – $pp \to \ell^+\ell^- j$



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

DØ $Z + j$ analyses

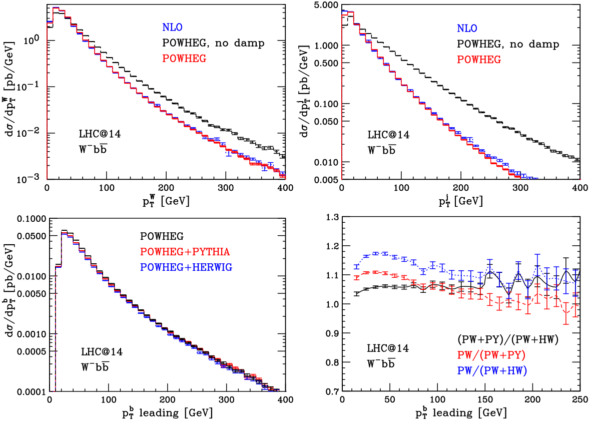
Phys.Lett.B669(2008)278-286

Phys.Lett.B682(2010)370-380

good description of data

some dependence on PYTHIA tune

POWHEG-BOX – $pp \to Wb\bar{b}$

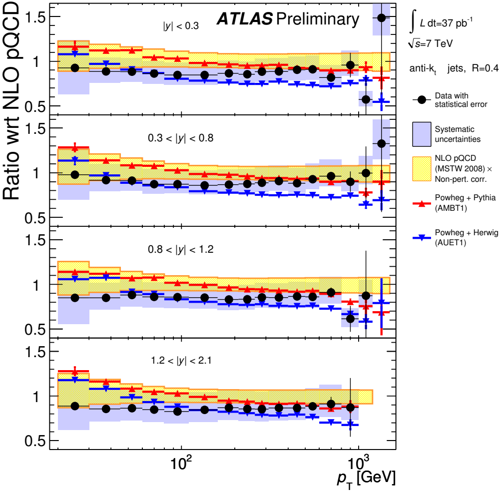


$pp \to Wb\bar{b}$

large ratio $\bar{B}/B$
$\to$ 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:

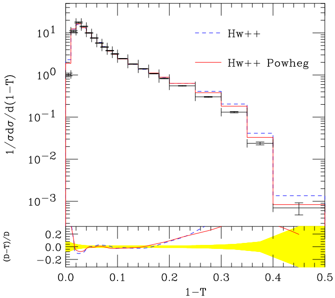
- $p_{\perp,j}$ supposedly described at NLO⊗LL
- ∼20% difference between using HERWIG or PYTHIA for parton showering

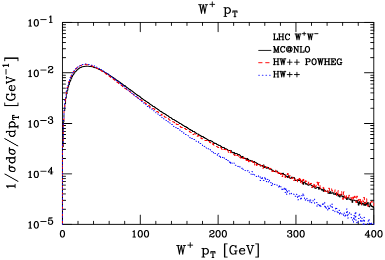
Issues for logarithmic accuracy:

- truncated showering implemented neither for HERWIG or PYTHIA interfaces → especially important for HERWIG's angular ordering
- consistent settings for PDFs, μ_R and μ_F scales, etc.
- no conclusive answers so far

POWHEG in HERWIG++

- Processes:
  - V, VV, H(GF,VBF), VH
  - $ee \to q\bar{q}$, DIS
  - $H \to q\bar{q}$ decay
- includes truncated showering



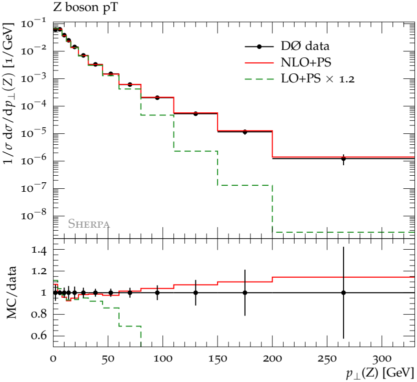


POWHEG – Automation in SHERPA

- [Höche,Krauss,MS,Siegert] JHEP04(2011)024
- reinterprete POWHEG as ME reweighted PS with local K-factor
- NLO event weight $\bar{B} = B + V + I + \int \mathrm{d}\Phi_{R|B}\,[R - S]$
  - **B**orn, **R**eal from automated tree-level generators
  - automated phase space
  - **V**irtual e.g. via Binoth Les Houches Accord CPC181(2010)1612
    $\rightarrow$ for results here BLACKHAT & MCFM libraries interfaced
  - **I**ntegrated/**S**ubtraction 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 $w(\Phi_R) = R(\Phi_R)/R^{(\mathrm{PS})}(\Phi_R)$
  $\rightarrow$ alleviated by good approximation of CSSHOWER++ JHEP03(2008)038
  $\rightarrow$ truncated showering not needed
- included since SHERPA-1.2.3 (Nov '10)

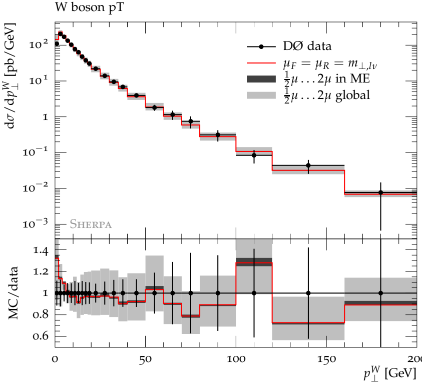
JHEP04(2011)024

SHERPA – inclusive W/Z production at Tevatron



Data from DØ :

Phys.Lett.B693(2010)522-530



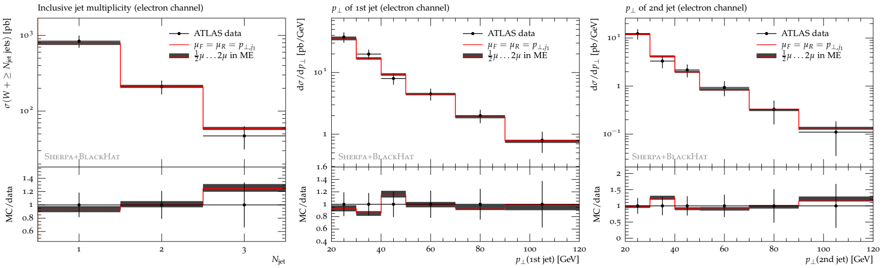
Data from DØ :

Phys.Lett.B513(2001)292-300

preliminary

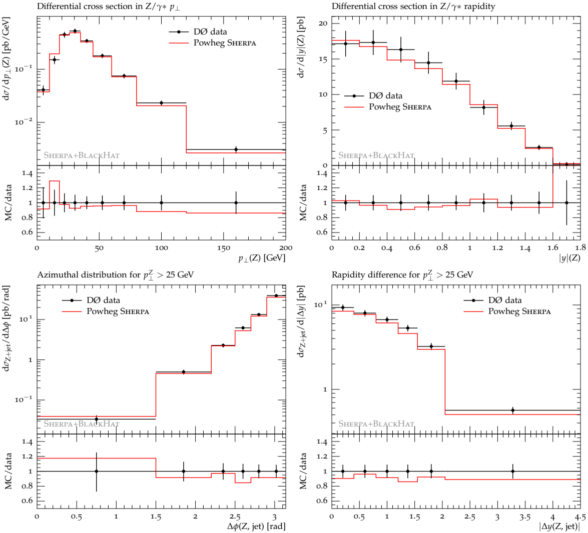
SHERPA – Non-trivial colour structures – $pp \to Wj$

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



inclusive jet multiplicity and $p_\perp$ of 1st & 2nd jet in W+jets events, data from ATLAS Phys.Lett.B698(2011)325-345 preliminary

Sherpa – $p\bar{p} \to Zj$ at Tevatron



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

DØ $Z + j$ analyses

Phys.Lett.B669(2008)278-286

Phys.Lett.B682(2010)370-380

LC-NLO⊗(N)LL accuracy

MENLOPS

Multijet Merging with NLO MEs – MENLOPS

$$\langle O\rangle = \int \mathrm{d}\Phi_B\, \bar{B}(\Phi_B) \Bigg[\Delta^{(\mathrm{ME})}(t_0)\, O(\Phi_B) + \overbrace{\int \mathrm{d}\Phi_{R|B}\, \frac{R(\Phi_R)}{B(\Phi_B)}\, \Delta^{(\mathrm{ME})}(t)\, \Theta(Q_{\mathrm{cut}} - Q)}^{\text{POWHEG domain}}\, O(\Phi_R) + \underbrace{\int \mathrm{d}\Phi_{R|B}\, \frac{R(\Phi_R)}{B(\Phi_B)}\, \Delta^{(\mathrm{PS})}(t)\, \Theta(Q - Q_{\mathrm{cut}})\, O(\Phi_R)}_{\text{ME domain}} \Bigg]$$

- [Hamilton,Nason] JHEP06(2010)039, [Höche,Krauss,MS,Siegert] arXiv:1009.1127
- POWHEG domain restricted to soft emissions $Q < Q_{\mathrm{cut}}$
  $\Rightarrow$ **NLO accuracy preserved for inclusive observables**
- ME⊗PS used for hard emission & higher order emissions
  $\Rightarrow$ **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
  $\rightarrow$ pushed to $\mathcal{O}(\alpha_s^2)$ beyond (N)LL

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$$\overbrace{+\int \mathrm{d}\Phi_{R|B}\,\frac{R(\Phi_R)}{B(\Phi_B)}\,\Delta^{(\mathrm{ME})}(t)\,\Theta(Q_{\mathrm{cut}}-Q)\,O(\Phi_R)}^{\text{POWHEG domain}}$$
$$\left.\underbrace{+\int \mathrm{d}\Phi_{R|B}\,\frac{R(\Phi_R)}{B(\Phi_B)}\,\Delta^{(\mathrm{PS})}(t)\,\Theta(Q-Q_{\mathrm{cut}})\,O(\Phi_R)}_{\text{ME domain}}\right]$$

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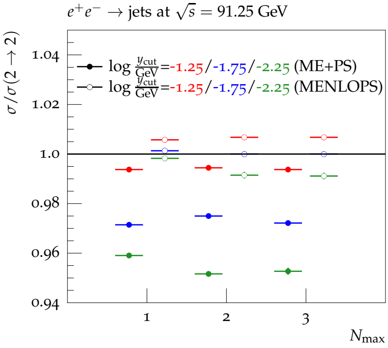
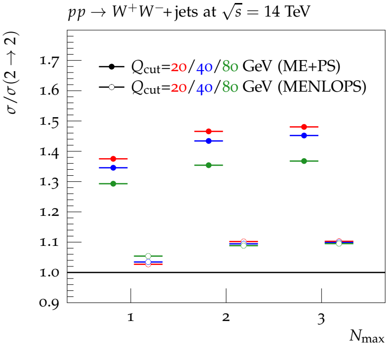
arXiv:1009.1127

MENLOPS – Unitarity violations

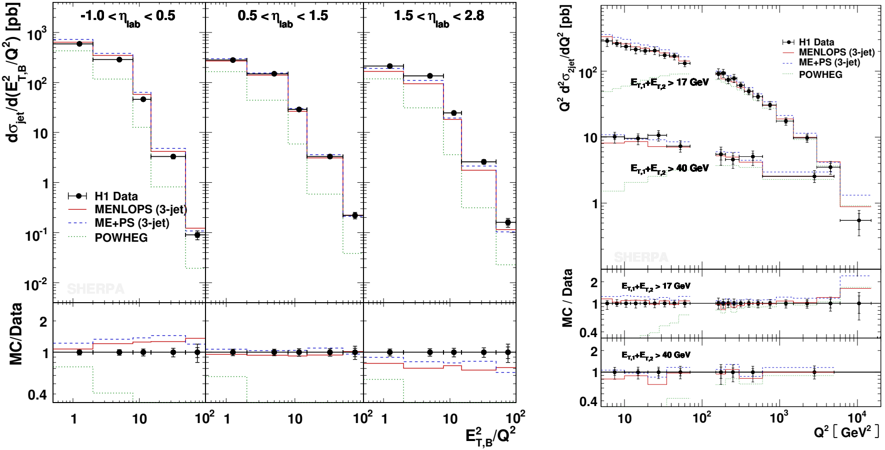




$\Rightarrow$ reduced unitarity violation
$\mathcal{O}(\alpha_s)$ and beyond (N)LL for ME$\otimes$PS
$\mathcal{O}(\alpha_s^2)$ and beyond (N)LL for MENLOPS

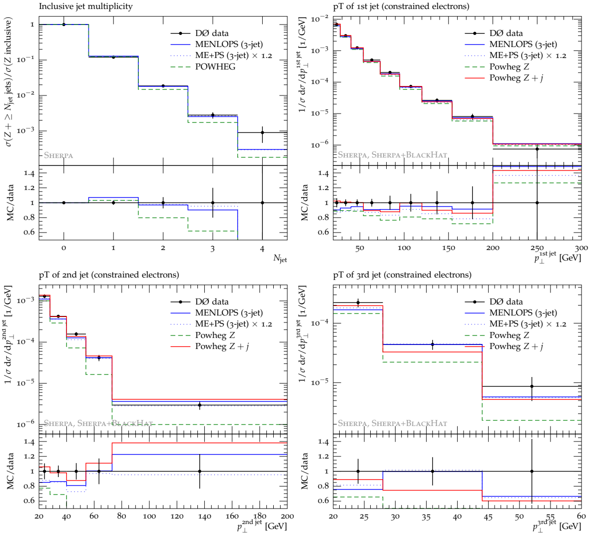
arXiv:1009.1127

SHERPA – DIS



⇒ good description, data from H1 PLB542(2002)193-206,EPJC19(2001)289-311

SHERPA – $p\bar{p} \to \ell^+\ell^- + X$



Data from DØ :

Phys.Lett.B658(2008)112-119

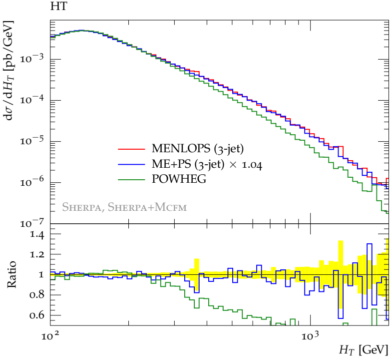
Phys.Lett.B678(2009)45-54

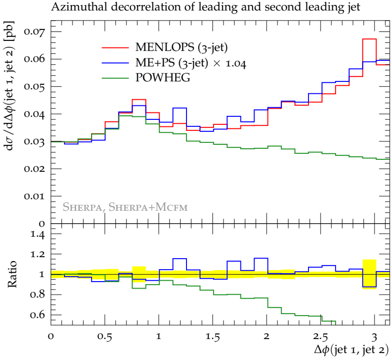
POWHEG and MENLOPS agree well on $p_\perp$ of hardest jet

MENLOPS superior for 2nd and 3rd jet

arXiv:1009.1127

SHERPA – $pp \to W^+W^- + X$





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

Conclusions

- ME$\otimes$PS works well for shapes, but needs K-factor
  $\rightarrow$ 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$\otimes$PS and POWHEG
  $\Rightarrow$ NLO accuracy in core process
  $\Rightarrow$ multijet observables as in ME$\otimes$PS

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

Available processes*

	POWHEG			MC@NLO	
Process	POWHEG-BOX	HERWIG++	SHERPA	MC@NLO	aMC@NLO
$e^+e^- \to jj$	✗	✓	✓	✗	✗
DIS	✗	✓	✓	✓	✗
$pp \to W/Z$	✓	✓	✓	✓	✗
$pp \to H$ (GF)	✓	✓	✓	✓	✗
$pp \to V + H$	✗	✓	✓	✓	✗
$pp \to VV$	✗	✓	✓	✓	✗
VBF	✓	✓	in prep.	✗	✗
$pp \to Q\bar{Q}$	✓	✗	✗	✓	✗
$pp \to Q\bar{Q} + j$	✓	✗	✗	✗	✗
single-top	✓	✗	✗	✓	✗
$pp \to V + j$	✓	✗	in prep.	✗	✗
$pp \to V + jj$	in prep.	✗	in prep.	✗	✗
$pp \to H + j$ (GF)	✗	✗	in prep.	✗	✗
$pp \to H + t\bar{t}$	✓	✗	✗	✗	✓
$pp \to W^+W^+jj$	✓	✗	✗	✗	✗
$pp \to V + b\bar{b}$	✓	✗	in prep.	✗	✓
diphotons	?	✓	in prep.	✗	✗
dijets	✓	✗	in prep.	✗	✗

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

Thank you.

JHEP05(2009)053

Backup: ME⊗PS Merging – Scales

Divide phase space using jet measure Q_{cut}:

→ emissions with $Q > Q_{\text{cut}}$ by ME
→ 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)

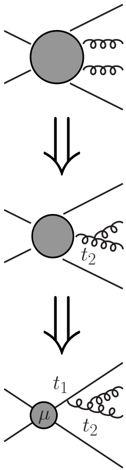
⇒ **ME final state with branching history and PS starting scale μ and branching scales t_i**

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

Veto PS emissions with $Q > Q_{\text{cut}}$
→ Reject event → Sudokov suppression

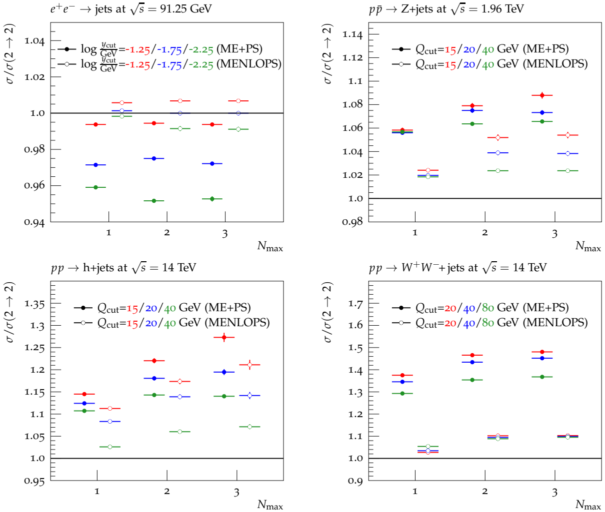
If $t \neq Q^2$ then truncated shower necessary

Scales:



arXiv:1009.1127

Backup: Unitarity Violation in MENLOPS & ME+PS



Formally of $\mathcal{O}(\alpha_s^2)$ in MENLOPS
$\to N_{\text{max}} = 1$ 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