Automisation of ME+PS Merging with NLO Accuracy in SHERPA

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arXiv:1008.5399

Automisation of the POWHEG Method

- POWHEG master equation, P. Nason et.al JHEP11(2004)040, JHEP11(2007)070
  $\rightarrow$ ME corrected parton shower supplemented by local NLO weight

$$\langle O\rangle = \int \mathrm{d}\Phi_B\, \bar{\mathrm{B}}(\Phi_B)\left[\underbrace{\Delta^{(\mathrm{ME})}(t_0,\mu^2)}_{\text{unresolved}}\, O(\Phi_B) + \sum_{\{\widetilde{\imath\jmath},\tilde{k}\}\to\{ij,k\}} \int_{t_0}^{\mu^2} \mathrm{d}\Phi_{R|B}\, \tilde{J}_{ij,k}\;\, O(\Phi_R) \times \underbrace{\frac{\mathrm{R}_{ij,k}(\Phi_R)}{\mathrm{B}(\Phi_B)}\,\Delta^{(\mathrm{ME})}(t,\mu^2)}_{\text{resolved}}\right]$$

- no-branching probability

$$\Delta^{(\mathrm{ME})}(t,t') = \exp\left\{-\sum_{\{\widetilde{\imath\jmath},\tilde{k}\}\to\{ij,k\}} \int_t^{t'} \mathrm{d}\Phi_{R|B}\, \tilde{J}_{ij,k}\, \frac{\mathrm{R}_{ij,k}(\Phi_R)}{\mathrm{B}(\Phi_B)}\right\}$$

- Jacobian, symmetry factors, etc. absorbed in $\tilde{J}_{ij,k}$
- $\mathrm{R}_{ij,k} = \frac{\mathrm{S}_{ij,k}}{\sum \mathrm{S}_{mn,o}}\,\mathrm{R}$ projection on one singular region

Step I – Phase Space Generation

$$\bar{\mathrm{B}}(\Phi_B) = \mathrm{B}(\Phi_B) + \mathrm{V}(\Phi_B) + \mathrm{I}(\Phi_B) + \int \mathrm{d}\Phi_{R|B} \Big[\mathrm{R}(\Phi_R) - \mathrm{S}(\Phi_R)\Big]$$

- tree-level ME generator AMEGIC++ for B, R JHEP02(2002)044
- automated CS-subtraction in AMEGIC++ for I, S EPJC53(2008)501
- V from BLACKHAT and MCFM PRD78(2008)036003, PRD60(1999)113006

$\Rightarrow$ **use usual Born phase space $\otimes$ tangent plane spanned by dipole variables**

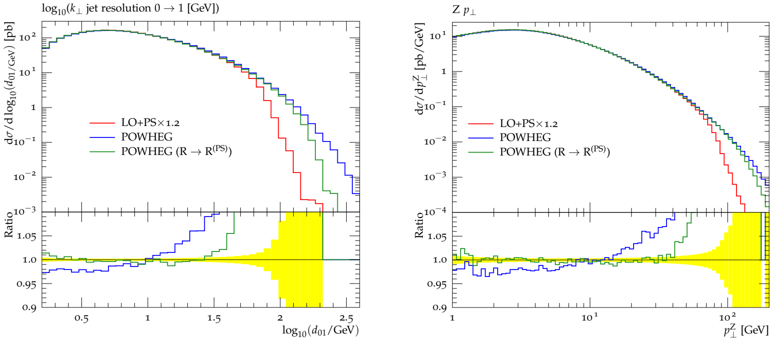
	$e^+e^- \to$ hadrons		$e^+p \to e^+ + j + X$		$p\bar{p} \to e^+e^- + X$	
	$E_{\rm cms} =$ 91.2 GeV		$E_{\rm cms} =$ 300 GeV $Q^2 >$ 150 GeV^2		$E_{\rm cms} =$ 1.96 TeV $66 < m_{\ell\ell} < 116$ GeV	
μ_R, μ_F	$\sqrt{s}$		$\sqrt{Q^2}$		$m_\perp$	
Factor	POWHEG	NLO	POWHEG	NLO	POWHEG	NLO
1/2	30179(18)	30195(20)	3906(9)	3908(10)	243.00(14)	243.06(16)
1	29411(17)	29416(18)	4047(10)	4050(11)	239.01(13)	238.96(15)
2	28680(16)	28697(18)	4180(10)	4188(11)	236.23(13)	236.13(14)

Step II – Shower Reweighting

- need maximum reweighting factor $w_{ij,k}$ for every splitting function
  $\rightarrow$ bookkeeping during integration

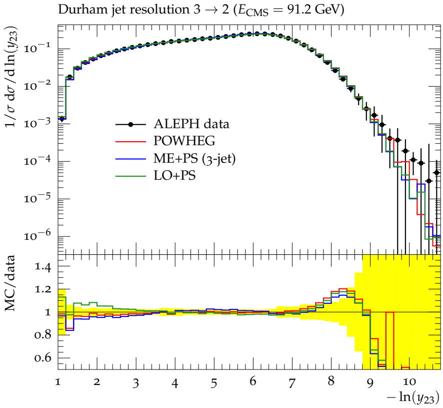
$$\frac{\mathrm{R}_{ij,k}}{\mathrm{B}} = \frac{\mathrm{R}_{ij,k}}{\mathrm{R}_{ij,k}^{(\mathsf{PS})}} \frac{\mathrm{R}_{ij,k}^{(\mathsf{PS})}}{\mathrm{B}} = w_{ij,k} \cdot \mathcal{K}_{ij,k}$$

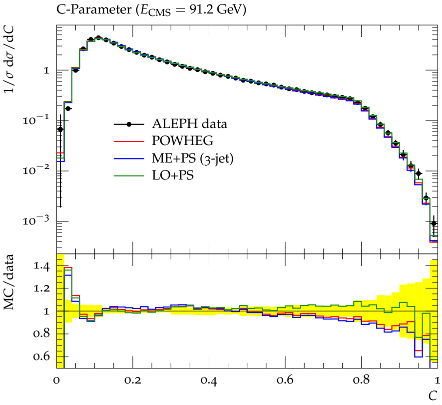
- check implementation by replacing $\mathrm{R}_{ij,k} \rightarrow \mathrm{R}_{ij,k}^{(\mathsf{PS})}$



arXiv:1008.5399

Results – $e^+e^- \to$ hadrons – 91.2 GeV

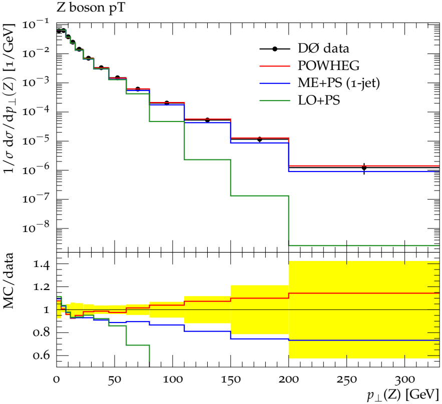


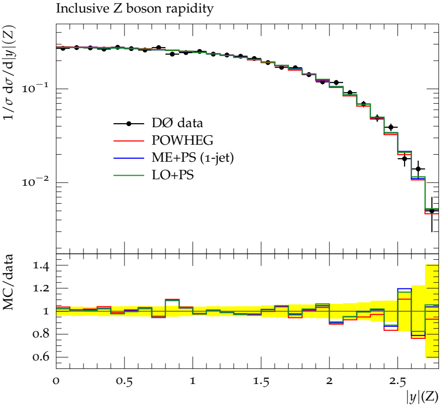


Data from ALEPH EPJC35(2004)457

arXiv:1008.5399

Results – $p\bar{p} \to \ell^+\ell^- + X$ – 1.96 TeV

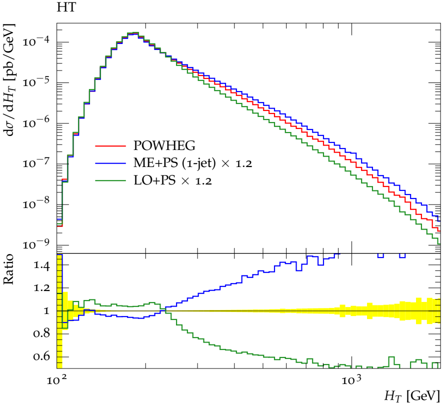


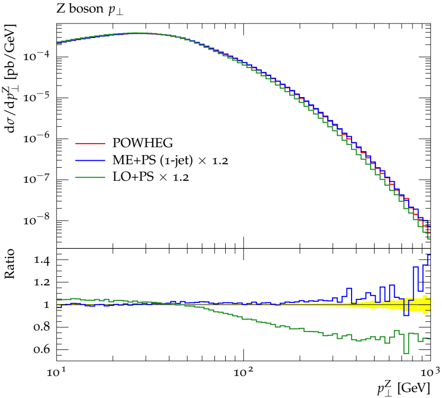


Data from DØ arXiv:1006.0618, PRD76(2007)012003

arXiv:1008.5399

Results – $pp \to Z[\to e^+e^-]\ Z[\to \mu^+\mu^-]$ – 14 TeV





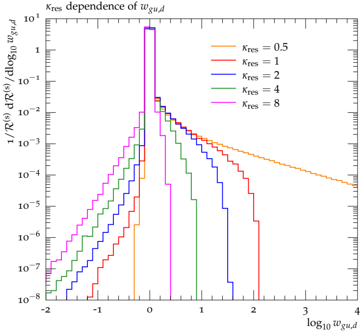
Vanishing Borns

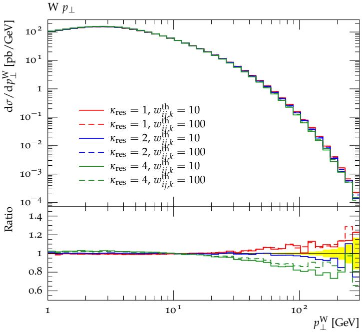
- spurious singularities when $\mathrm{B} \to 0$ but R finite, as noted in JHEP07(2008)060
  $\to \mathrm{R}/\mathrm{B}$ does not exponentiate
- split $\mathrm{R} = \mathrm{R}^{(\mathsf{s})} + \mathrm{R}^{(\mathsf{r})} = \mathrm{R}\frac{Z}{Z+H} + \mathrm{R}\frac{H}{Z+H}$

$$Z = \frac{\mathrm{B}}{\mathrm{B}_{\mathsf{max}}} \qquad\qquad H = \kappa_{\mathsf{res}}^2\,\frac{t}{t_{\mathsf{max}}}\,\Theta\left(w_{ij,k} - w_{ij,k}^{\mathsf{th}}\right)$$

$\to$ only exponentiate $\mathrm{R}^{(\mathsf{s})}$, $\mathrm{R}^{(\mathsf{r})}$ forms separate sample ($\notin \bar{\mathrm{B}}$)

- **two parameters κ_{res} and $w_{ij,k}^{\mathsf{th}}$**





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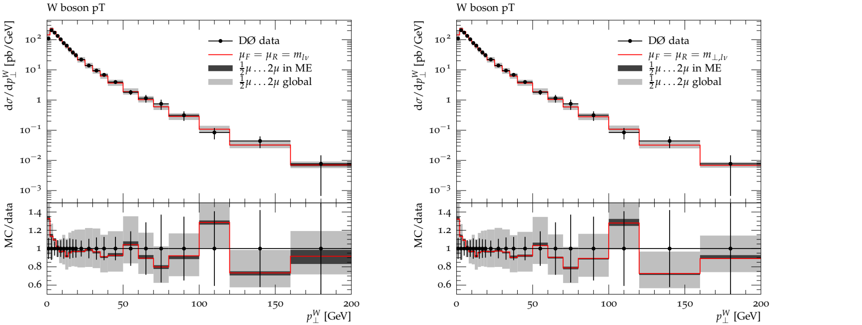
Scale Variations

- reduced scale dependence in $\bar{\mathrm{B}}$
- compare two scale choices $\mu = m_{\ell\nu}$ and $\mu = m_\perp$
- vary scales locally in $\bar{\mathrm{B}}$ (dark), or globally (light) also in PS



Data from DØ Phys.Lett.B513(2001)292

Automisation of the MENLOPS Method

- ME+PS method JHEP11(2001)063, JHEP05(2009)053

$$\langle O\rangle = \int d\Phi_B\, \mathrm{B}(\Phi_B) \Bigg[\underbrace{\Delta^{(\mathrm{PS})}(t_0,\mu^2)}_{\text{unresolved}}\, O(\Phi_B) + \sum_{\{\tilde{ij},\tilde{k}\}\to\{ij,k\}} \int_{t_0}^{\mu^2} d\Phi_{R|B}\, \tilde{J}_{ij,k}\;\; O(\Phi_R)$$

$$\times \Bigg(\underbrace{\mathcal{K}_{ij,k}(\Phi_{R|B})\, \Delta^{(\mathrm{PS})}(t,\mu^2)\, \Theta\left(Q_{\mathrm{cut}} - Q_{ij,k}\right)}_{\text{resolved, PS domain}}$$

$$+ \underbrace{\frac{\mathrm{R}_{ij,k}(\Phi_R)}{\mathrm{B}(\Phi_B)}\, \Delta^{(\mathrm{PS})}(t,\mu^2)\, \Theta\left(Q_{ij,k} - Q_{\mathrm{cut}}\right)}_{\text{resolved, ME domain}} \Bigg) \Bigg]$$

- σ_{incl} at LO accuracy
- real emission phase space sliced into ME regime and PS regime using Q_{cut}
- explicit unitarity violation
- importance of truncated showering to retain PS accuracy

arXiv:1009.1127

Automisation of the MENLOPS Method

- idea first published by K. Hamilton, P. Nason JHEP06(2010)039

$$\langle O\rangle = \int \mathrm{d}\Phi_B\,\bar{\mathrm{B}}(\Phi_B)\Bigg[\underbrace{\Delta^{(\mathrm{ME})}(t_0,\mu^2)}_{\text{unresolved}}\;O(\Phi_B) + \sum_{\{\widetilde{ij},\tilde{k}\}\to\{ij,k\}}\int_{t_0}^{\mu^2}\mathrm{d}\Phi_{R|B}\,\tilde{J}_{ij,k}\;O(\Phi_R)$$

$$\times\frac{\mathrm{R}_{ij,k}(\Phi_R)}{\mathrm{B}(\Phi_B)}\left(\underbrace{\Delta^{(\mathrm{ME})}(t,\mu^2)\,\Theta\left(Q_{\mathrm{cut}}-Q_{ij,k}\right)}_{\text{resolved, POWHEG domain}}+\underbrace{\Delta^{(\mathrm{PS})}(t,\mu^2)\,\Theta\left(Q_{ij,k}-Q_{\mathrm{cut}}\right)}_{\text{resolved, ME domain}}\right)\Bigg]$$

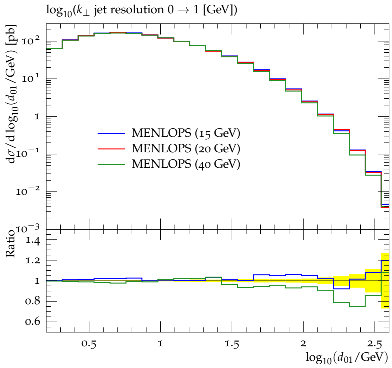
- $\mathrm{B}\to\bar{\mathrm{B}}\Rightarrow\sigma_{\mathrm{incl}}$ at NLO accuracy
- PS domain filled by POWHEG
- explicit local K-factor $\frac{\bar{\mathrm{B}}}{\mathrm{B}}$ for higher order ME samples
  $\to$ determined by backwards clustering on to Born configuration
- explicit unitarity violation, less severe than in ME+PS
  $\to$ does not spoil NLO accuracy

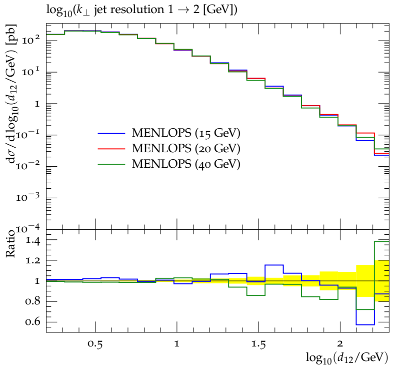
arXiv:1009.1127

Merging Systematics – $p\bar{p} \to \ell^+\ell^- + X$ – 1.96 TeV

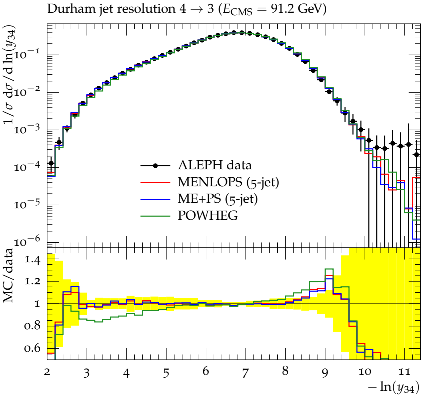
N_{max}	0	3		
Q_{cut}		15 GeV	20 GeV	40 GeV
σ_{incl}	478.3(4)	497(4)	489(3)	482(2)

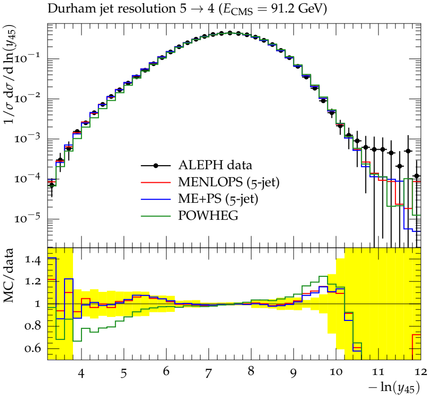
$\Rightarrow\ < 5\%$





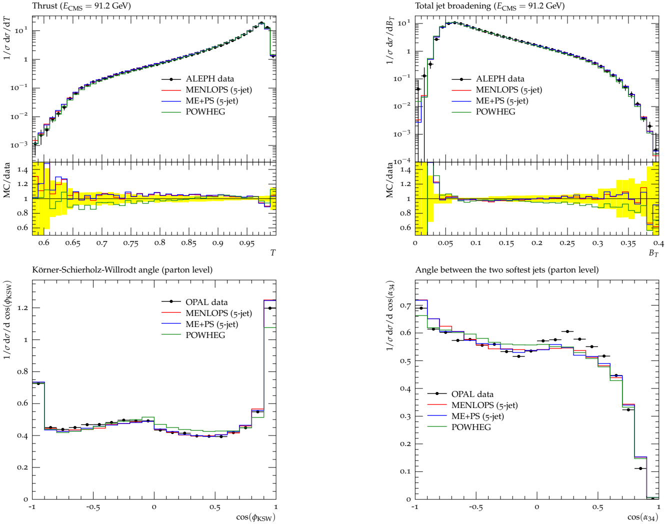
Results – $e^+e^- \to$ hadrons – 91.2 GeV





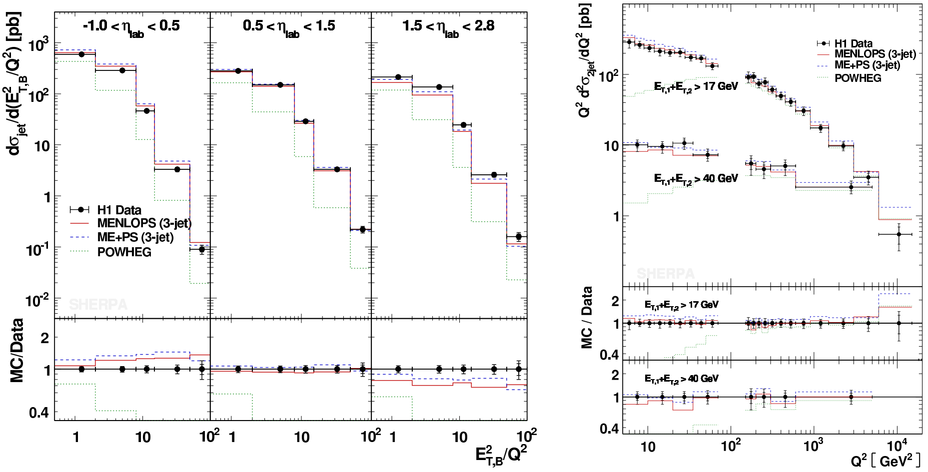
Data from ALEPH EPJC35(2004)457

Results – $e^+e^- \to$ hadrons – 91.2 GeV



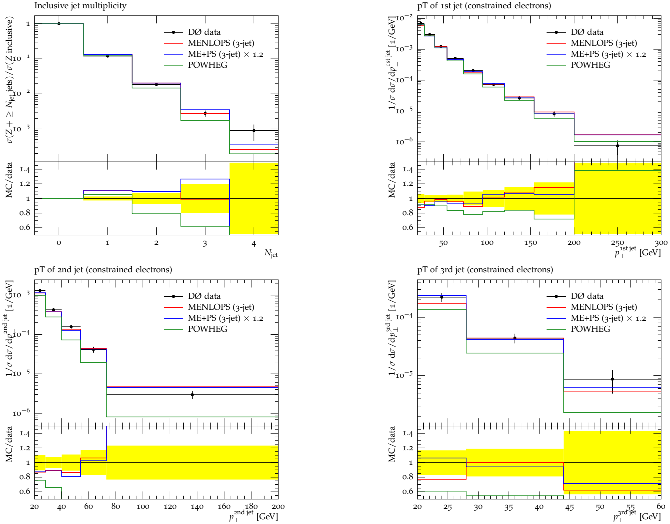
Data from ALEPH and OPAL EPJC35(2004)457, EPJC20(2001)601

Results – $e^+p \to e^+ + j + X$ – 300 GeV



Data from H1 Phys.Lett.B542(2002)193, EPJC19(2001)289

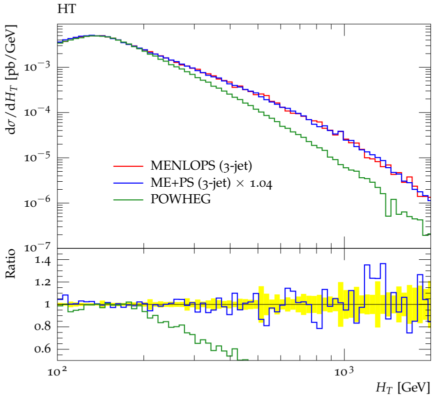
Results – $p\bar{p} \to \ell^+\ell^- + X$ – 1.96 TeV

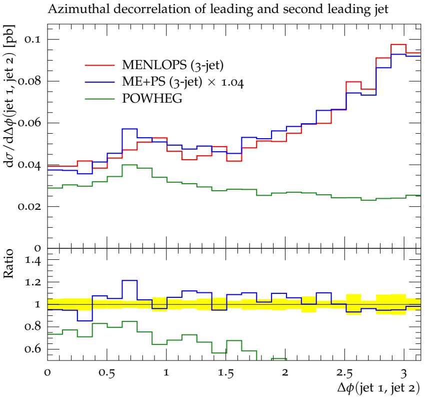


Data from DØ Phys.Lett.B658(2008)112, Phys.Lett.B678(2009)045

arXiv:1009.1127

Results – $pp \to W^+[\to e^+\nu_e]\ W^-[\to \mu^-\bar{\nu}_\mu]$ – 14 TeV





Conclusions

- POWHEG method fully automated (phase space integration and PS reweighting)
- extended automated ME+PS merging to include NLO core process
  $\rightarrow$ MENLOPS
  $\rightarrow$ inclusive observables at NLO accuracy
  $\rightarrow$ $\langle O(\text{extra jets})\rangle$ with LO+(N)LL accuracy
- challenge to merge multiple NLO processes
  $\rightarrow$ $\langle O(\text{extra jets})\rangle$ formally with NLO+(N)LL accuracy
- no automisation of V available
  $\rightarrow$ have to link libraries like BLACKHAT and MCFM
  $\rightarrow$ Binoth-LesHouches Interface available