$W^{\pm}/Z/h$+jets with POWHEG in SHERPA

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LoopFest X

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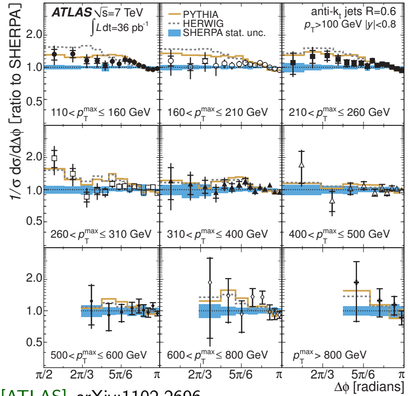
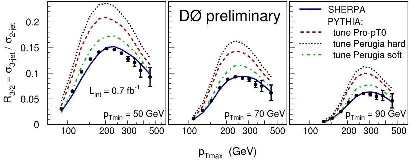
[1] In collaboration with: F. Krauss, M. Schönherr, F. Siegert JHEP04(2011)024

Multi-jet event simulation: Where do we stand?



[ATLAS] arXiv:1102.2696

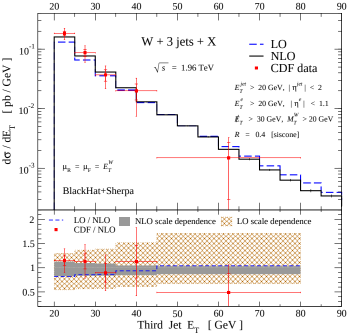


[DØ] DØ Note 6032-CONF

ME⊗PS as today's standard approach

- automatically include arbitrary higher-order tree-level ME
- naturally extend PS phase space
- miss out on virtual corrections

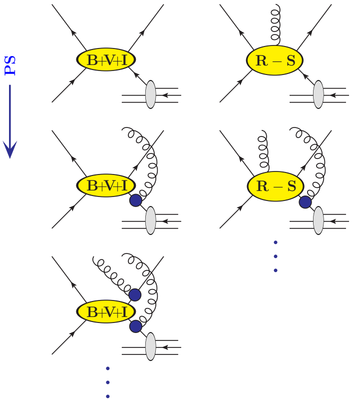
Want full NLO as *new* standard!



[Berger et al.] PRD80(2009)074036

Combining NLO calculations and parton showers

$$\sigma^{NLO} = \int \mathrm{d}\Phi_B \left(\mathrm{B} + \tilde{\mathrm{V}}\right) + \int \mathrm{d}\Phi_R \,\mathrm{R} = \int \mathrm{d}\Phi_B \left[\left(\mathrm{B} + \tilde{\mathrm{V}} + \mathrm{I}\right) + \int \mathrm{d}\Phi_{R|B} \left(\mathrm{R} - \mathrm{S}\right)\right]$$



Requirements for NLO⊗PS:

- Preserve resummation as in PS
- Implement $\mathcal{O}(\alpha_s)$ accuracy from ME

Problems:

- Two kinematically different configurations B-/R-like
- Real-emission term and PS populate same phase-space region
- Naively adding PS on top of ME leads to double-counting

General solutions by MC@NLO [Frixione,Webber] JHEP06(2002)029
and POWHEG (positive weights only) [Frixione,Nason,Oleari] JHEP11(2004)040

NLO calculations and parton-shower Monte Carlo

→ **Real-emission contribution to NLO cross section** $\{\vec{a}\} \to$ set of partons

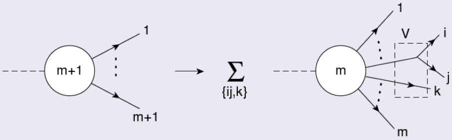
$$\mathrm{d}\sigma_R(\{\vec{p}\}) = \sum_{\{\vec{f}\}} \mathrm{d}\sigma_R(\{\vec{a}\}) \qquad \mathrm{d}\sigma_R(\{\vec{a}\}) = \mathrm{d}\Phi_R(\{\vec{p}\})\,\mathrm{R}(\{\vec{a}\})$$

where $\mathrm{R}(\{\vec{a}\}) = \mathcal{L}(\{\vec{a}\})\,\mathcal{R}(\{\vec{a}\})$ and $\mathcal{L}(\{\vec{a}\};\mu^2) = x_1 f_{f_1}(x_1,\mu^2)\; x_2 f_{f_2}(x_2,\mu^2)$
$\mathrm{d}\Phi_R$ contains initial-state phase space $\mathrm{d}\log x_1\,\mathrm{d}\log x_2$
$\mathcal{R}(\{\vec{a}\}) = |\mathcal{M}_R|^2(\{\vec{a}\})/[F(\{\vec{a}\})S(\{\vec{f}\})]$ with symmetry factor S, flux F

Similar formulas for Born-level term $\mathrm{B}(\{\vec{a}\})$ one parton less, of course

Assume generalized "dipole terms", such that think of Catani-Seymour dipoles

$$\mathcal{R}(\{\vec{a}\}) \xrightarrow{\text{soft/collinear}} \sum_{\{i,j\}} \sum_{k\neq i,j} \mathcal{D}_{ij,k}(\{\vec{a}\})$$



Define partition of real-emission term $\mathcal{R}(\{\vec{a}\}) = \sum_{\{i,j\}} \sum_{k\neq i,j} \mathcal{R}_{ij,k}(\{\vec{a}\})$

$$\mathcal{R}_{ij,k}(\{\vec{a}\}) := \rho_{ij,k}(\{\vec{a}\})\,\mathcal{R}(\{\vec{a}\})\,, \quad \text{where} \quad \rho_{ij,k}(\{\vec{a}\}) = \frac{\mathcal{D}_{ij,k}(\{\vec{a}\})}{\sum_{\{m,n\}} \sum_{l\neq m,n} \mathcal{D}_{mn,l}(\{\vec{a}\})}$$

Note: Holds throughout the phase space !

NLO calculations and parton-shower Monte Carlo

$\mathcal{D}_{ij,k}(\{\vec{a}\})$ defines parton maps think of Catani-Seymour dipoles

$$b_{ij,k}(\{\vec{a}\}) = \begin{cases} \{\vec{f}\} \setminus \{f_i, f_j\} \cup \{f_{\widetilde{ij}}\} \\ \{\vec{p}\} \to \{\tilde{\vec{p}}\} \end{cases} \quad \leftrightarrow \quad r_{\widetilde{ij},\tilde{k}}(f_i, \Phi_{R|B}\,; \{\vec{a}\}) = \begin{cases} \{\vec{f}\} \setminus \{f_{\widetilde{ij}}\} \cup \{f_i, f_j\} \\ \{\tilde{\vec{p}}\} \to \{\vec{p}\} \end{cases}$$

- $b_{ij,k}$ converts real-emission configuration to Born-level
- $r_{\widetilde{ij},\tilde{k}}$ converts Born-level to real-emission needs extra flavor & phase space

Trivially factorize real-emission term into Born and radiative contribution

$$\mathrm{d}\sigma_R(\{\vec{a}\}) = \sum_{\{i,j\}} \sum_{k \neq i,j} \mathrm{d}\sigma_B(b_{ij,k}(\{\vec{a}\}))\, \mathrm{dP}_{ij,k}(\{\vec{a}\})$$

differential emission probability is $\mathrm{dP}_{ij,k}(\{\vec{a}\}) = \mathrm{d}\Phi^{ij,k}_{R|B}(\{\vec{p}\})\, \dfrac{\mathrm{R}_{ij,k}(\{\vec{a}\})}{\mathrm{B}(b_{ij,k}(\{\vec{a}\}))}$

Subtraction algorithms predict $\mathrm{dP}_{ij,k}$ in the soft/collinear limits via

$$\mathcal{D}_{ij,k}(\{\vec{a}\}) \xrightarrow{\text{soft/collinear}} \frac{S(b_{ij,k}(\{\vec{f}\}))}{S(\{\vec{f}\})}\, \frac{1}{2\, p_i p_j}\, 8\pi\, \alpha_s\, \mathcal{B}(b_{ij,k}(\{\vec{a}\})) \otimes V_{ij,k}(p_i, p_j, p_k)\,,$$

Note the symmetry factors $\leftrightarrow$ factorization of invariant ME, not of specific process

$\otimes \to$ spin & color-correlations between $\mathcal{B}$ and V

Now make an approximation replace correlated with uncorrelated dipole kernel

$$\mathcal{B}(b_{ij,k}(\{\vec{a}\})) \otimes V_{ij,k}(p_i, p_j, p_k) \to \mathcal{B}(b_{ij,k}(\{\vec{a}\}))\, \mathcal{K}_{ij,k}(p_i, p_j, p_k)$$

Parametrize radiative phase space: $\mathrm{d}\Phi^{ij,k}_{R|B}(\{\vec{p}\}) = \frac{1}{16\pi^2}\,\mathrm{d}t\,\mathrm{d}z\,\frac{\mathrm{d}\phi}{2\pi}\,J_{ij,k}(t,z,\phi)$

Assume phase space gets filled successively in t $\leftrightarrow$ partons can be distinguished

Must adapt symmetry factors: $\frac{S(b_{ij,k}(\{\vec{f}\}))}{S(\{\vec{f}\})} \to \frac{1}{S_{ij}} = \begin{cases} 1/2 & \text{if } i,j>2,\ b_i=b_j \\ 1 & \text{else} \end{cases}$

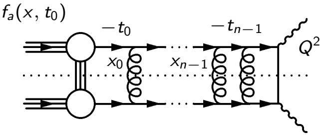
Combining everything gives PS expression for radiation probability

$$\mathrm{dP}^{(\mathrm{PS})}_{ij,k}(\{\vec{a}\}) = \frac{\mathrm{d}t}{t}\,\mathrm{d}z\,\frac{\mathrm{d}\phi}{2\pi}\,\frac{\alpha_s}{2\pi}\,\frac{1}{S_{ij}}\,J_{ij,k}(t,z,\phi)\,\mathcal{K}_{ij,k}(t,z,\phi)\,\frac{\mathcal{L}(\{\vec{a}\};t)}{\mathcal{L}(b_{ij,k}(\{\vec{a}\});t)}$$

Iterate this equation for higher-multi ME

$\to$ ladder-like structure of amplitude squared

with strong ordering in scales $t_0 < \ldots < t_n$ $\leftrightarrow$



Factorization at any stage above Λ_{QCD}

can split emissions off ME one by one

Corrections induced by $\mathrm{dP}^{(\mathrm{PS})}_{ij,k}$ can be large and must be resummed

In inclusive case $t \in [0,\infty)$ divergences in $\mathcal{K}_{ij,k}$ cancel ε-poles in V $\to$ unitarity !

NLO calculations and parton-shower Monte Carlo

$\rightarrow$ **No-emission probability** from Poisson statistics implementing unitarity constraint

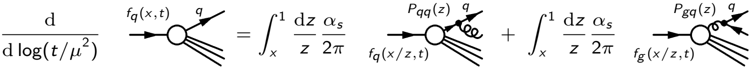
$$\mathcal{P}^{(\mathrm{PS})}_{\widetilde{ij},\tilde{k}}(t',t'';\{\vec{a}\}) = \exp\left\{-\sum_{f_i=q,g}\int_{t'}^{t''}\int_{z_{\min}}^{z_{\max}}\int_0^{2\pi}\mathrm{dP}^{(\mathrm{PS})}_{ij,k}(r_{\widetilde{ij},\tilde{k}}(\{\vec{a}\}))\right\}\,.$$

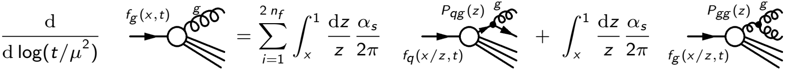
Note: $r_{\widetilde{ij}\tilde{k}}$ implicitly and uniquely defined by subtraction scheme, i.e. $\mathcal{K}_{ij,k}$

Assume IF-splitting $\rightarrow$ Lumi ratio $\frac{x}{z}f_{f_i}(\frac{x}{z},t)/xf_{f_{\widetilde{ij}}}(x,t)$, symmetry factor 1

$$\frac{\partial\log\mathcal{P}^{(\mathrm{PS})}_{\widetilde{ij},\tilde{k}}(t,t';\{\vec{a}\})}{\partial\log(t/\mu^2)} = \int_x^{z_{\max}}\frac{\mathrm{d}z}{z}\int_0^{2\pi}\frac{\mathrm{d}\phi}{2\pi}\sum_{f_i=q,g}\frac{\alpha_s}{2\pi}\,J_{ij,k}(t,z,\phi)\,\mathcal{K}_{ij,k}(t,z,\phi)\,\frac{f_{f_i}(\frac{x}{z},t)}{f_{f_{\widetilde{ij}}}(x,t)}$$

Voilà, the DGLAP equation ! imagine $J_{ij,k}(t,z,\phi)\mathcal{K}_{ij,k}(t,z,\phi)\rightarrow P_{i\,\widetilde{ij}}(z)$





The POWHEG method

Recover NLO-accurate radiation pattern in PS through correction weight

$$w_{ij,k}(\{\vec{a}\}) = \mathrm{dP}_{ij,k}(\{\vec{a}\})\,/\,\mathrm{dP}^{(\mathrm{PS})}_{ij,k}(\{\vec{a}\})$$

Easy to compute in general-purpose Monte-Carlo, all input is tree-level only

Approximate "seed cross section" using local K-factor $\bar{\mathrm{B}}/\mathrm{B}$

$$\frac{\bar{\mathrm{B}}(\{\vec{a}\})}{\mathrm{B}(\{\vec{a}\})} = 1 + \frac{\tilde{\mathrm{V}}(\{\vec{a}\}) + \mathrm{I}(\{\vec{a}\})}{\mathrm{B}(\{\vec{a}\})} + \sum_{\{\widetilde{ij},\tilde{k}\}} \sum_{f_i=q,g} \int \mathrm{d}\Phi^{ij,k}_{R|B} \frac{\mathrm{R}_{ij,k}(r_{\widetilde{ij},\tilde{k}}(\{\vec{a}\})) - \mathrm{S}_{ij,k}(r_{\widetilde{ij},\tilde{k}}(\{\vec{a}\}))}{\mathrm{B}(\{\vec{a}\})}$$

Note: Implies wrong dependence of observables on final-state momenta $\{\vec{p}\}$ $\rightarrow$ resolved by PS

Combine ME-correction and local K-factor $\rightarrow$ observable O to $\mathcal{O}(\alpha_s)$ from

$$\begin{aligned}\langle O\rangle^{(\mathrm{POWHEG})} = \sum_{\{\vec{f}\}} \int \mathrm{d}\Phi_B(\{\vec{p}\})\,\bar{\mathrm{B}}(\{\vec{a}\}) \Bigg[\mathcal{P}^{(\mathrm{ME})}(t_0,\mu^2;\{\vec{a}\})\, O(\{\vec{p}\}) \\ + \sum_{\{\widetilde{ij},\tilde{k}\}} \sum_{f_i=q,g} \frac{1}{16\pi^2} \int_{t_0}^{\mu^2} \mathrm{d}t \int_{z_{\min}}^{z_{\max}} \mathrm{d}z \int_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi}\, J_{ij,k}(t,z,\phi) \\ \times \frac{1}{S_{ij}} \frac{S(r_{\widetilde{ij},\tilde{k}}(\{\vec{f}\}))}{S(\{\vec{f}\})} \frac{\mathrm{R}_{ij,k}(r_{\widetilde{ij},\tilde{k}}(\{\vec{a}\}))}{\mathrm{B}(\{\vec{a}\})}\, \mathcal{P}^{(\mathrm{ME})}(t,\mu^2;\{\vec{a}\})\, O(r_{\widetilde{ij},\tilde{k}}(\{\vec{p}\})) \Bigg]\end{aligned}$$

POWHEG master formula [Nason] JHEP11(2004)040 [Frixione,Nason,Oleari] JHEP11(2007)070

Assembling the local K-factor

Virtual corrections not automated in SHERPA $\Rightarrow$ **share the workload**

$$\bar{\mathrm{B}} = \mathrm{B} + \tilde{\mathrm{V}} + \mathrm{I} + \sum_{\{\widetilde{ij},\tilde{k}\}} \sum_{f_i=q,g} \int \mathrm{d}\Phi_{R|B}^{ij,k} \left[\mathrm{R}_{ij,k} - \mathrm{S}_{ij,k} \right]$$

Standardized interface exists as Binoth Les Houches accord CPC181(2010)1612

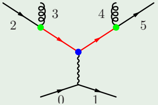
- "One-Loop Engines" like BlackHat PRD78(2008)036003, PRL102(2009)222001 or GOLEM CPC180(2009)2317, PLB683(2010)154 provide virtual piece or more
- ME generator takes care of Born, real emission and subtraction
- Phase-space generator employs modified tree-level integrators
  Specialized two-step procedure for underlying Born plus real emission

Assembling the local K-factor

Integration of $\bar{\mathrm{B}}(\Phi_B)$ proceeds in two steps ...

Step I: Born phase space via recycling

Standard phase-space generator, e.g. single channels from NPB9(1969)568
VEGAS-refined JCP27(1978)192 and combined in multi-channel CPC83(1994)141

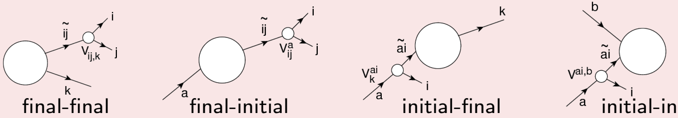


$\leftrightarrow$

$$D_{iso}(23,45) \otimes P_0(23) \otimes P_0(45) \otimes D_{iso}(2,3) \otimes D_{iso}(4,5)$$

Step II: Constrained real-emission phase space new

Extra emission generator (EEG) produces additional parton starting from Φ_B
Kinematics according to CS dipole terms NPB485(1997)291, NPB627(2002)189



Assembling the local K-factor

Extra emission generator (EEG)
with multi-channeling over all
dipole configurations

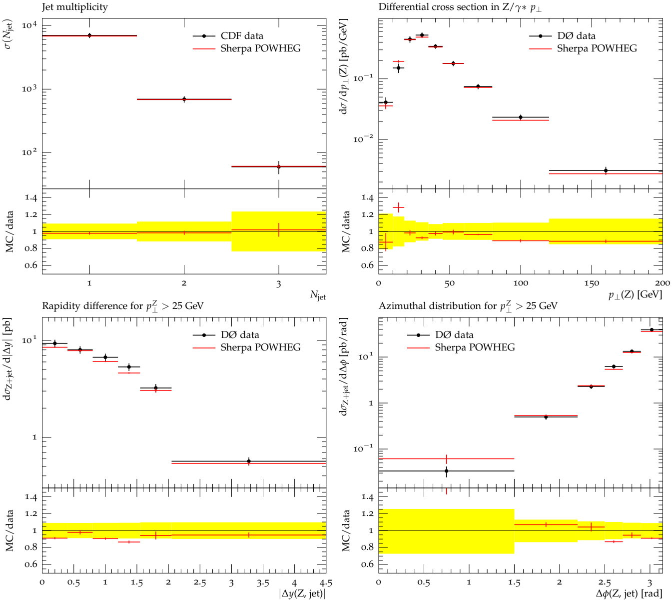
$\leftrightarrow$

Separate integration (sep)
of Born and real-emission kinematics
with (modified) standard integrator

Process	σ [pb] (EEG)	σ [pb] (sep)	σ [pb] (LO)
$e^+e^- \to 2jets$ $E_{\rm cms}$=91.2 GeV	29449(19)	29454(18)	28381(18)
$e^+e^- \to 3jets$ as above, $y_{\rm cut} = 10^{-1.92}$	9399(38)	9418(60)	7724(21)
$e^+e^- \to 4jets$ as above, $y_{\rm cut} = 10^{-1.92}$	1377(14)	1357(21)	907(10)
$p\bar{p} \to e^-\bar{\nu}_e$ $E_{\rm cms} = 1.96$ TeV, CTEQ 6.6	1331.7(5)	1332.2(4)	1098.6(3)
$p\bar{p} \to e^-\bar{\nu}_e + jet$ as above, $k_T = 10$ GeV, $D = 0.7$	389.0(16)	390.6(17)	282.9(5)
$p\bar{p} \to e^-\bar{\nu}_e + 2jets$ as above, $k_T = 10$ GeV, $D = 0.7$	104.2(7)	105.5(9)	73.9(2)

500k MC-points before cuts, no time limit, no error target
virtual part delivered by BlackHat PRD78(2008)036003

Results for Z+jet



Preliminary

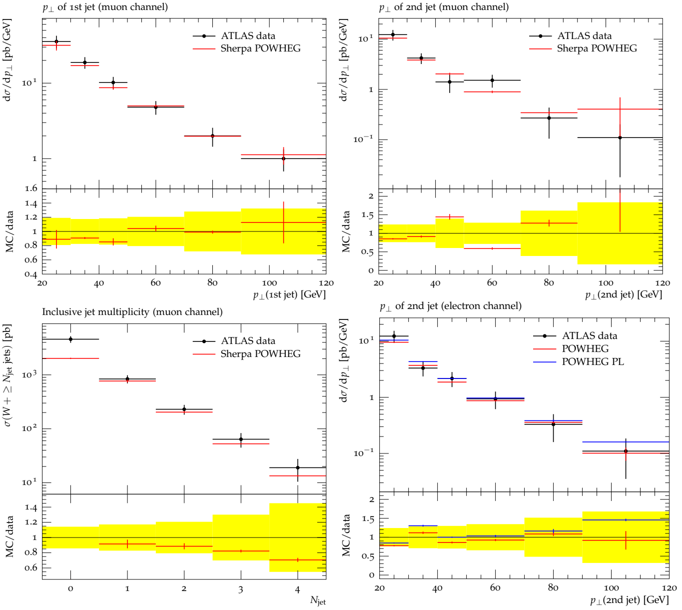
SHERPA POWHEG vs. Tevatron data

[CDF] PRL100(2008)102001

[DØ] PLB669(2008)278

[DØ] PLB682(2010)370

Results for W+jet

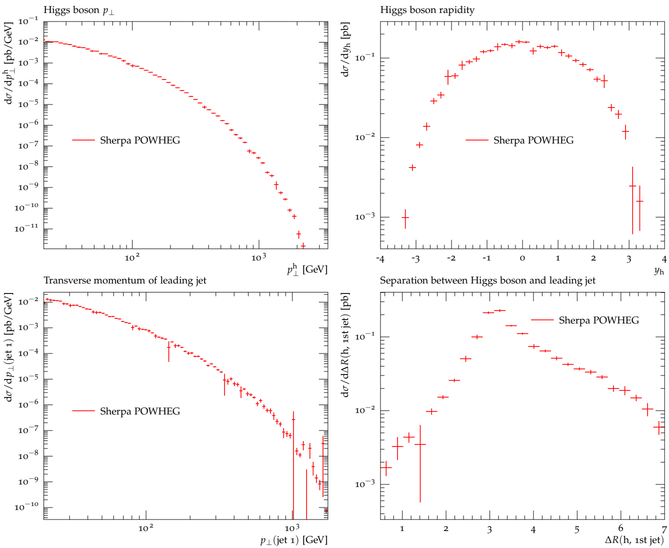


Preliminary

SHERPA POWHEG vs. LHC data

[Atlas] PLB698(2011)325

Predictions for h+jet



Preliminary

SHERPA POWHEG

Loop-ME: MCFM

[Campbell, Ellis, Williams]

Summary & Outlook

Status quo

- First "non-trivial" POWHEG processes available in SHERPA
- General, automated algorithm, only virtual ME to be provided
- Precise predictions for Tevatron and LHC

What's next?

- Apply to more processes
- Merge with higher multiplicity through MENLOPS
- Merge with lower multiplicity POWHEG

More and more higher-order pQCD built into MC

Computing jet-p_T spectra at NLO through MC feasible