Multi-jet merging at tree-level and 1-loop level

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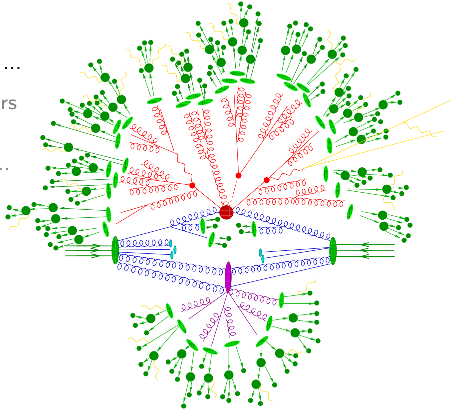
Multi-jet merging: Where do we stand?

ME⊗PS merging at tree level

- Well established around for $\gtrsim 10$ years
  PRD57(1998)5767, NPB632(2002)343, JHEP11(2001)063, ...
- Strong recent activity Truncated showers
  JHEP05(2009)053, JHEP11(2009)038
- Various approaches CKKW(L), MLM, ...
  JHEP05(2002)046, JHEP02(2009)017, ...
- Several automated codes
  e.g. in hep-ph/0602031, EPJC53(2008)473

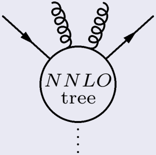


ME⊗PS merging at 1-loop level

- Pioneered by MC@NLO & POWHEG
  JHEP06(2002)029, JHEP11(2004)040, ...
- Multijets recently discussed NL^3, MENLOPS
  JHEP12(2008)070, arXiv:1004.1764 [hep-ph]
- Automation within reach ?

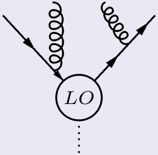
ME⊗PS at tree-level

Problem: Higher-order ME and PS describe the same final state !



- σ from coherent sum of all Feynman graphs
- No resummation

$\leftrightarrow$



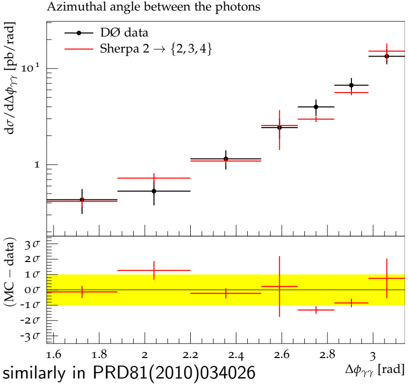
- σ from LO ME & PS splittings
- Proper resummation in parts of phase space

How do we run a parton shower on a N^{x}LO tree-level matrix element ?

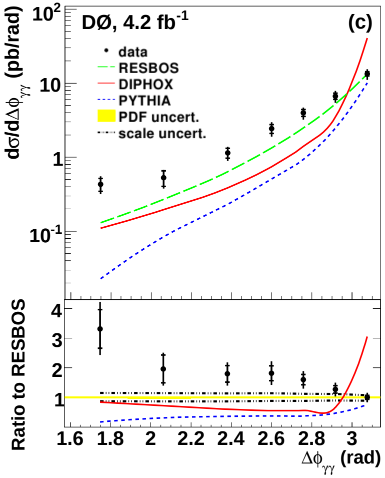
1. Find suitable starting conditions for the parton shower
   i.e. find a tree-structure corresponding to the full ME
   which can be used by the parton shower as a branching history
2. Make sure not to double-count or miss out emissions
   i.e. eventually populate the whole available real emission
   phase space with *either* matrix elements *or* the parton shower

Example results: Diphoton production arXiv:1002.4917 [hep-ex]

$E_T^{\gamma 1} > 21$ GeV, $E_T^{\gamma 1} > 20$ GeV,
$|\eta^\gamma| < 0.9$, $E_T^{R=0.4} - E_T^\gamma < 2.5$ GeV



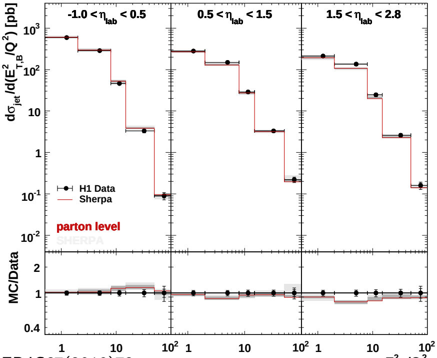
similarly in PRD81(2010)034026



SHERPA prediction: Merged 2→{2,3,4}-jet/γ plus $gg \to \gamma\gamma$ box

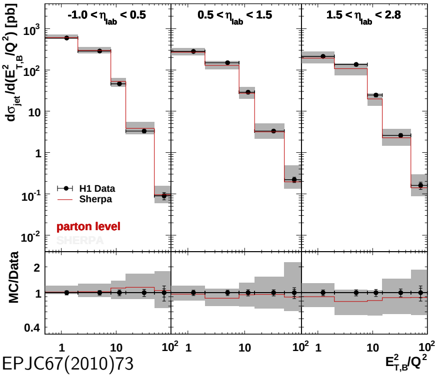
Example results: Inclusive jets in DIS PLB542(2002)193

$5\,\mathrm{GeV}^2 < Q^2 < 100\,\mathrm{GeV}^2, \quad E_{T,B} > 5$ GeV, $\quad -1 < \eta_{\mathrm{lab}} < 2.8$



EPJC67(2010)73

Variation of ME⊗PS parameters



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Scale variations $\mu_F = \mu_R$

SHERPA prediction: Merged 2→{0,2,3,4,5}-jet

Combining ME⊗PS with full NLO

At present ...

- We can merge "arbitrary" tree-level ME's with PS's
  Several automated codes on the market
- Automation of 1-loop QCD corrections seems feasible
  (Semi-)automated codes now emerging

We should make use of both and **automate ME⊗PS at 1-loop**

Strategy: Use whatever is available

- Process NLO parton-level events with PS's
  using MC@NLO or POWHEG method low multiplicity
- Combine NLO simulation with higher-order tree-level
  using standard ME⊗PS technique high multiplicity

The POWHEG algorithm sketchy

The POWHEG master formula schematically

JHEP11(2004)040, JHEP11(2007)070, arXiv:1002.2581 [hep-ph], ...

$$\mathrm{d}\sigma_{\mathrm{NLO}} = \mathrm{d}\Phi_B\, \bar{B}(\Phi_B) \left[\bar{\Delta}(k_{T,0}) + \sum \int_{k_{T,0}} \mathrm{d}\Phi_{R|B}\, \frac{R(\Phi_R)}{B(\Phi_B)}\, \bar{\Delta}(k_T) \right]$$

with the NLO differential cross section $\bar{B} = B + V + I + \mathrm{d}\Phi_{R|B}\,[\,R - S\,]$

and the POWHEG-Sudakov $\bar{\Delta}(k_T) = \exp\left\{ -\sum \int_{k_T} \mathrm{d}\Phi_{R|B}\, \frac{R(\Phi_R)}{B(\Phi_B)} \right\}$

Two problems to be solved

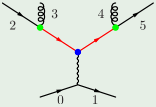
- Generate differential NLO cross section $\mathrm{d}\Phi_B\, \bar{B}(\Phi_B)$
  $\Rightarrow$ Requires integrator for N- and $N+1$-particle phase space
- Generate real emission according to POWHEG-Sudakov $\bar{\Delta}(k_T)$
  $\Rightarrow$ Requires parton shower-like algorithm to exponentiate $\sum \int \mathrm{d}\Phi_{R|B}\, R/B$

Implementing the POWHEG algorithm, Part I

Integration proceeds in two steps ...

Step I: The Born phase space via recycling

Standard phase-space generator, e.g. single channels from NPB9(1969)568
VEGAS-refined CLNS-80/447(1980) and combined in multi-channel CPC83(1994)141

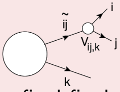


$\leftrightarrow$

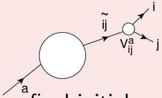
$$D_{iso}(23,45) \otimes P_0(23) \otimes P_0(45) \otimes D_{iso}(2,3) \otimes D_{iso}(4,5)$$

Step II: The real-emission phase space new

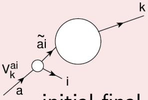
Extra emission generator (EEG) produces additional parton starting from Φ_B
Kinematics according to CS dipole terms NPB485(1997)291, NPB627(2002)189



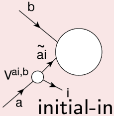
final-final



final-initial



initial-final



initial-initial

Implementing the POWHEG algorithm, Part I

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

$\longleftrightarrow$

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 WhiteHat PRD78(2008)036003

Implementing the POWHEG algorithm, Part II

Need MC generator to exponentiate $\Gamma(k_T) = \sum \int_{k_T}^{Q} \mathrm{d}\Phi_{R|B}\, R/B$

We know how to deal with this CPC82(1994)74

- Dice k_T of emission as $k_T = \Gamma^{-1}\left[\,-\log\#\,\right]$
- If Γ unknown, use overestimate $\tilde{\Gamma}$ and accept as $w = \Gamma(k_T)/\tilde{\Gamma}(k_T) \;\; > \#'$

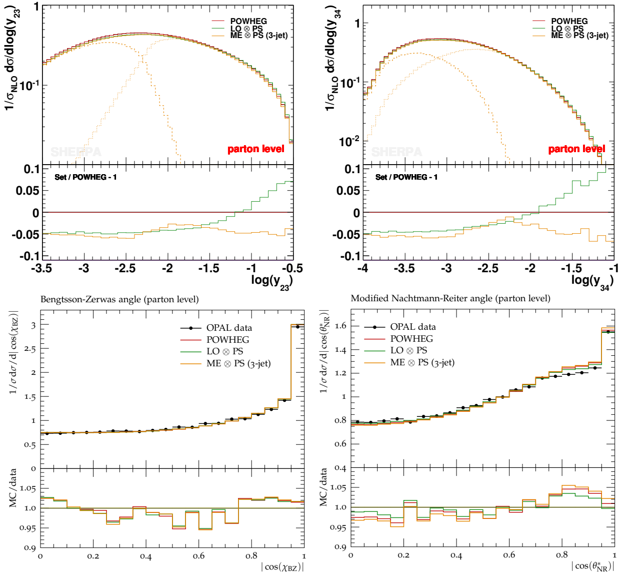
Now the whole trick is to find a suitable $\tilde{\Gamma}$

In fact, we have a pretty good estimate ...

Γ's of existing parton showers are an ideal candidate

- We employ SHERPA's dipole-like parton shower (CSS) based on CS subtraction JHEP03(2008)038, PRD81(2010)034026
- Splitting functions are potentially enhanced, adapting to R/B larger than CSS approximation

Implementing the POWHEG algorithm, Part II



Jet rates and event shapes in $e^+e^- \to$jets

Compare:

- POWHEG
  NLO rate & shape
  → reference
- ME⊗PS 3-jet
  "NLO shape"
  Shape agrees well with POWHEG result
  Rate down by α_s/π
  → useful check !
- Parton shower
  Shape & rate differ

⇒POWHEG simulation ok for $e^+e^- \to 2$ jets

Combining ME⊗PS with full NLO

POWHEG:

$$\mathrm{d}\sigma_{\mathrm{NLO}} = \mathrm{d}\Phi_B\, \bar{B}(\Phi_B)\Big[\bar{\Delta}(k_{T,0}) + \sum \int_{k_{T,0}} \mathrm{d}\Phi_{R|B}\, \frac{R(\Phi_R)}{B(\Phi_B)}\,\bar{\Delta}(k_T)\Big]$$

- $\bar{B}(\Phi_B)$ has NLO accuracy
- Bracket integrates to one

ME⊗PS:

$$\mathrm{d}\sigma_{\mathrm{NLO}} = \mathrm{d}\Phi_B\, B(\Phi_B)\Big[\Delta(k_{T,0}) + \sum \int_{k_{T,0}} \mathrm{d}\tilde{\Phi}_{R|B}\, \frac{R(\tilde{\Phi}_R)}{B(\Phi_B)}\,\Delta(k_T)\Big]$$

- $B(\Phi_B)$ has LO accuracy
- Bracket integrates to $N(\Phi_B) \approx 1$

Striking similarity and similar accuracy up to local K-factor $\bar{B}(\Phi_B)/B(\Phi_B)$

$\Rightarrow$ **Recent proposal by K. Hamilton & P. Nason** arXiv:1004.1764 [hep-ph]

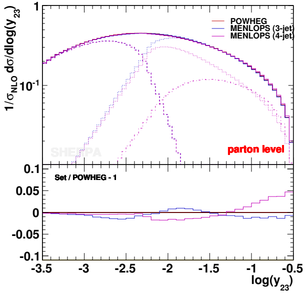
Combine POWHEG and ME⊗PS via phase-space slicing → MENLOPS

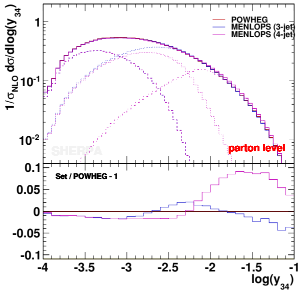
ME⊗PS rescaled to correct norm by global K-factor cut dependent

Sole drawback: Norm of event sample unknown due to non-unitarity of ME⊗PS
Not an issue as long as correction is smaller than NLO effects!

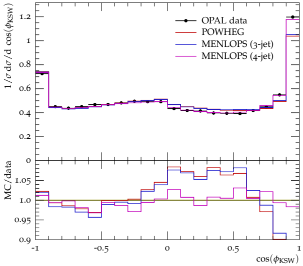
We use a variant of this scheme: K-factor is local rather than global

MENLOPS Results

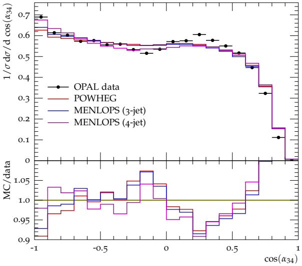




Körner-Schierholz-Willrodt angle (parton level)



Angle between the two softest jets (parton level)



Jet rates and event shapes in $e^+e^- \to$jets

Compare:

- POWHEG
  $\to$ reference
- MENLOPS 3-jet
  2 jets @ NLO
  Shape & norm agree with POWHEG
- MENLOPS 4-jet
  2 jets @ NLO
  Shape & norm agree with POWHEG
  Improved 4-jet predictions

$\Rightarrow$MENLOPS ok for 2 jets @ NLO

Note that this is not a merging of NLO 2-jet with NLO 3-jet ! yet ...

Summary

ME$\otimes$PS at tree-level ...

- Becomes new standard in MC simulations
- Works well even for nontrivial processes
- No open questions except technical issues

ME$\otimes$PS at 1-loop level

- NLO events at ME level largely automated
- POWHEG allows to shower these NLO events in principle
- Merging with higher-order tree-level straightforward
- The big challenge is to merge multiple NLO processes

We are on the way to automating ME$\otimes$PS at 1-loop level !

ME⊗PS part I: Defining PS histories

Basic idea: **Interpret ME as if PS had produced it**

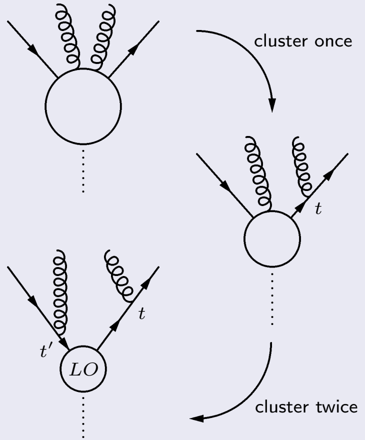
- Identify parton splittings acc. to PS branching probability
- Combine partons into mother parton acc. to inverse PS kinematics
- Continue until $2 \to 2$ core process

→ Cluster algorithm similar to k_T algo

PS starts at core process and possibly radiates additional partons on intermediate lines i.e. "between" ME partons

ME branchings must be respected
evolution-, splitting- & angular variable preserved

→ Truncated shower
universal concept for ME-PS merging



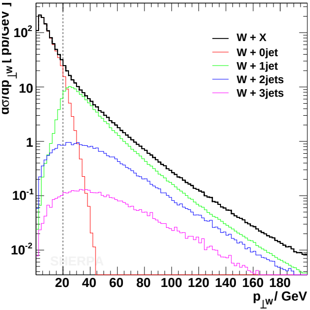
ME⊗PS part II: Slicing the phase space

Basic idea: **Separate phase space into "hard" and "soft" region**

- Matrix elements populate hard domain
- Parton shower populates soft domain

need criterion to define "hard" & "soft" as above and below a certain cut value
$\rightarrow$ **Jet criterion** Q e.g. k_T-jet measure

$\longleftrightarrow$



First replace kernels $\mathcal{K}_{ab}$ in QCD evolution equations with

$$\mathcal{K}^{\rm ME}_{ab}(\xi,\bar{t}) = \mathcal{K}_{ab}(\xi,\bar{t})\;\Theta\left[Q_{ab}(\xi,\bar{t})-Q_{\rm cut}\right] \qquad \mathcal{K}^{\rm PS}_{ab}(\xi,\bar{t}) = \mathcal{K}_{ab}(\xi,\bar{t})\;\Theta\left[Q_{\rm cut}-Q_{ab}(\xi,\bar{t})\right]$$

Then replace evolution kernel in ME domain with ratio of full MEs

$$\mathcal{K}^{\rm ME}_{ab}(z,t) \;\rightarrow\; \frac{2\pi/\alpha_s(z,t)}{{\rm d}\hat{\sigma}^{(N)}_a(\Phi_N)}\,\frac{{\rm d}\hat{\sigma}^{(N+1)}_b(z,t;\Phi_N)}{{\rm d}\log(t/\mu^2)\,{\rm d}z}\;\Theta\left[Q_{ab}(\xi,\bar{t})-Q_{\rm cut}\right]$$