Monte Carlo Tools for the LHC

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Outline

A brief introduction

- Higher-order corrections play an important role for physics at the Tevatron and the LHC:
  - Many cross sections experience large K-factors (prime example: $K_{gg\to H} \gtrsim 2$)
  - Distortions of distributions, mainly due to emission of additional partons.
- In past decade: Huge progress in embedding these corrections systematically into multi-purpose MCs like HERWIG, PYTHIA, or SHERPA.
- Two effects:
  - Qualitatively better description of QCD data at all colliders (LEP, Hera, Tevatron), especially for hard radiation/multijet events.
  - Improved handling of systematic uncertainties - often largely reduced scale uncertainties, in POWHEG case: better description of $\sigma_{\rm tot}$.
- In this talk: Will review latest developments, in particular multijet merging at LO, the POWHEG method, and the combination of both ("MENLOPS").

Multijet merging

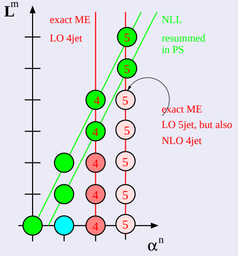
Why multijet merging?

- Parton shower yields approximation to ME
- But: lack of phase space in hadronic collisions typically results in too little QCD activity.

ME vs. PS

- MEs: hard, large-angle emissions; interferences.
- PS: soft, collinear emissions; resummation of large logarithms.
- Combine both, avoid double-counting.
- Right panel: logs in $ee \to$ jets.

α_s vs. Log



Constructing the algorithm

- Want the best of both - what else?
  - Proper description of soft/collinear and hard emissions
  - Combine QCD matrix elements of different parton multiplicity with showers
- General outline of algorithm:
  - Use LO (tree-level) matrix elements for jet production
    - Could use parton shower kernel $K_{ba}^{ME} \propto |\mathcal{M}_{n+1}|^2/|\mathcal{M}_n|^2$ hampered by low efficiency for $n \longrightarrow \infty$.
    - Idea effectively used in traditional reweighting for small n.
    - Also in generation of hardest emission in POWHEG./
  - Preserve original parton shower evolution equation

    (N.B.: this guarantees preservation of log accuracy provided by shower)
  - Avoid double-counting (positive or negative)

    Must slice the phase space: Jet production vs. jet evolution

    $\Longrightarrow$ adds a parameter - the jet resolution criterion $Q_{\rm cut}$

    (but inclusive results should better not depend too strongly on this parameter)

Slicing the phase space

- Decompose splitting kernels of parton showers as $K_{ba}(z,\,t) = K_{ba}(z,\,t)\Theta[Q_{\rm cut} - Q_{ba}(z,\,t)] + K_{ba}(z,\,t)\Theta[Q_{ba}(z,\,t) - Q_{\rm cut}]$.
- In hard region, call $K_{ba}\Theta[Q_{ba}(z,\,t) - Q_{\rm cut}] \to K_{ba}^{ME}$,
- Call $K_{ba}\Theta[Q_{\rm cut} - Q_{ba}(z,\,t)] \to K_{ba}^{PS}$ in soft region.
- Sudakov form factor factorises (exponential):

  $$\Delta_a(\mu^2,\,t) = \Delta_a^{PS}(\mu^2,\,t)\Delta_a^{ME}(\mu^2,\,t)$$

  Also, no emission probability can be rewritten:

  $$\mathcal{P}_a^{\rm no}(z,\,t,\,\bar{t}) = \frac{\Delta_a^{PS}(\mu^2,\,\bar{t})}{\Delta_a^{PS}(\mu^2,\,t)}\,\frac{\Delta_a^{ME}(\mu^2,\,\bar{t})}{\Delta_a^{ME}(\mu^2,\,t)}\,\frac{g_a(z,\,t)}{g_a(z,\,\bar{t})}$$
- In shower, need to veto emissions with $Q_{ba} > Q_{\rm cut}$.
  But may have emissions at $Q < Q_{\rm cut}$ but t larger than those in ME: must cure "mismatch" of shower and jet measure $\longrightarrow$ truncated showers

Defining PS histories

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

$\rightsquigarrow$ shower specific cluster algorithm

$\rightsquigarrow$ predetermined shower emissions

PS starts at core process

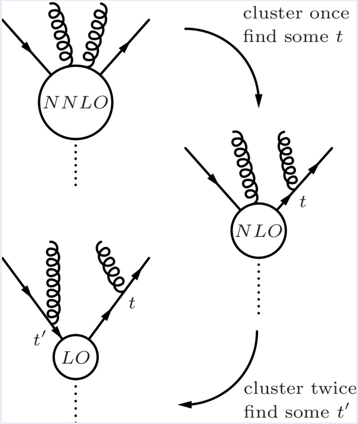
can radiate "between" ME emissions

ME branchings must be respected

evolution-, splitting- & angular variable preserved

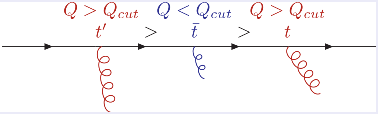
$\rightsquigarrow$ truncated shower

Example branching history



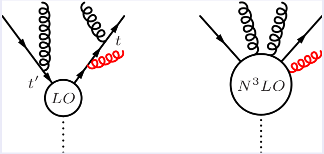
Truncated shower

Shower emission below $Q_{\rm cut}$:



- $\rightsquigarrow$ emission accepted
- $\rightsquigarrow$ large-angle soft emissions
- $\rightsquigarrow$ soft color coherence
- $\rightsquigarrow$ approx. in CKKW only

Shower emission above $Q_{\rm cut}$:



- $\rightsquigarrow$ entire event is rejected
- $\rightsquigarrow$ Sudakov suppression $\mathcal{P}^{\rm ME}_{{\rm no},\,a}(t,t')$
- $\rightsquigarrow$ to be described by ME instead
- $\rightsquigarrow$ $\sigma_{\rm tot}$ preserved at LO

Implementations

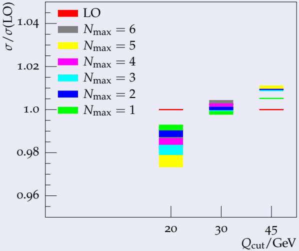
- Available implementations of this method in SHERPA & HERWIG++.
- MLM method for ALPGEN, MADGRAPH etc. (misses some terms)

Z^0+jets at Tevatron: Total cross sections

Q_{cut} and/or N_{max} variation should affect σ_{tot} only beyond (N)LL

- Example: DY-pair production $\sigma_{\rm tot}$ @ Tevatron

		$N_{\rm max}$						
		0	1	2	3	4	5	6
$Q_{\rm cut}$	20 GeV	192.6(1)	191.0(3)	190.5(4)	189.0(5)	189.4(7)	188.2(8)	189.9(10)
	30 GeV		192.3(2)	192.7(2)	192.6(3)	192.9(3)	192.7(3)	193.2(3)
	45 GeV		193.6(1)	194.4(1)	194.3(1)	194.4(1)	194.6(2)	194.4(1)



- improved "merging systematics" of $\boldsymbol{\sigma_{\rm tot}} < \pm 3\%$

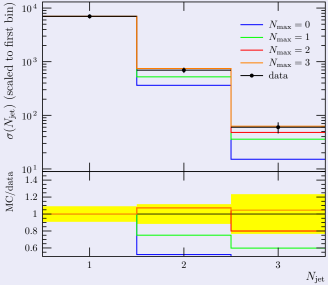
Z^0+jets at Tevatron: jet multiplicities

Jet rates and -spectra improved compared to pure PS simulation

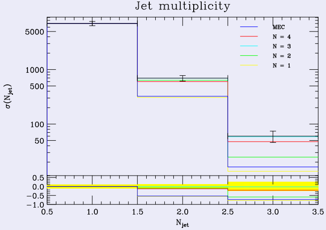
- Example: DY-pair production $\sigma_{\mathrm{e^+e^-+N_{jet}}}$

CDF Data: PRL **100** (2008) 102001

SHERPA, $Q_{\mathrm{cut}} = 30$ GeV

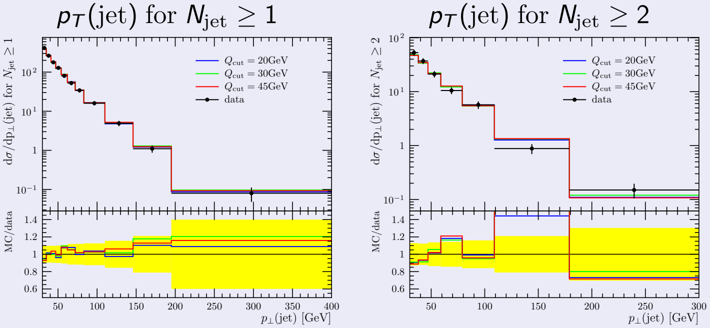


HERWIG++, $Q_{\mathrm{cut}} = 30$ GeV



Z^0+jets at Tevatron: jet spectra

- Example: All-jets p_T's in DY-pair production — CDF Data: PRL **100** (2008) 102001
- Compare with results from SHERPA



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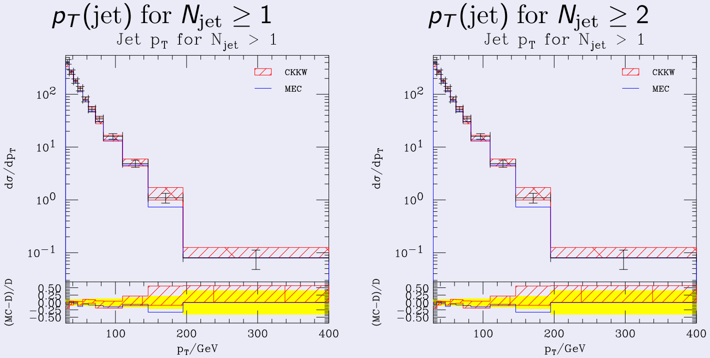
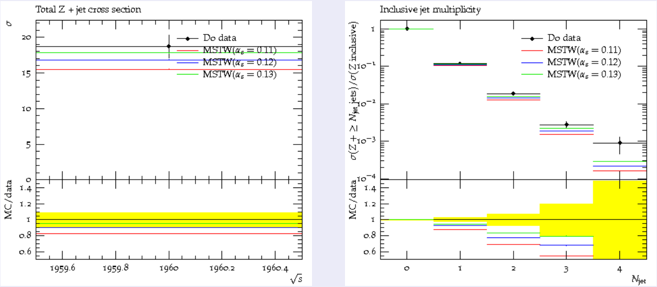


Z^0+jets at Tevatron: cross sections

CDF data from PRL 100 (2008) 102001 and D0/, arXiv:0808:1296

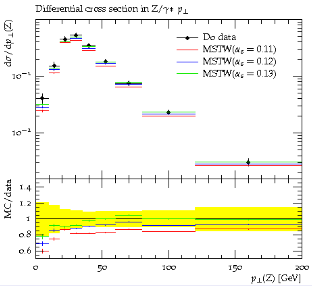
Impact of α_S - global in SHERPA

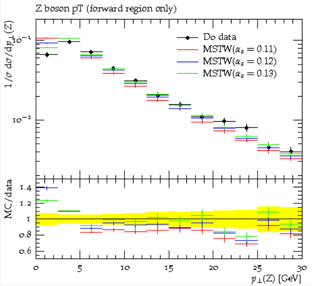


Z^0+jets at Tevatron: Z/γ^* transverse momentum

DØ data: PRL 100 (2008) 102002

Impact of α_S - global in SHERPA





A new Monte Carlo approach for Prompt-Photon Production

(S.Höche, S.Schumann, F.Siegert PRD **81** (2010) 034026)

- treat photons and QCD partons fully democratically

(Glover, Morgan Z. Phys. C **62** (1994) 311)

- combine matrix elements of different parton/photon multiplicity with
- QCD$\oplus$QED evolution and hadronisation $\rightsquigarrow$ models $D^{\gamma}_{q,g}(z, Q^2)$

Generalised merging formalism

- Emission probabilities factorise trivially as before

$$\Delta_a(Q_0^2, Q^2) = \Delta_a^{(\mathrm{QCD})}(Q_0^2, Q^2)\Delta_a^{(\mathrm{QED})}(Q_0^2, Q^2)$$

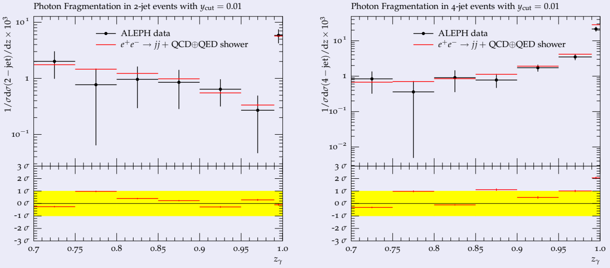
- Implemented by adding splitting functions $q \to q\gamma$
- Different then large-N_C QCD: spectators *all* particles with opposite charge
- Neglect (negative) interference with same-sign charges

(S.Dittmaier, Nucl. Phys. B **565** (2000) 69)

Results: photon fragmentation function in $e^+e^- \to$ Hadrons

(Aleph data from Z. Phys. C **69** (1996) 365)

- Validation of the shower/hadronisation component
- Perform jet finding including final-state photons
- Study photon-energy fraction wrt its containing jet: $z_\gamma \equiv E_\gamma / E_{\rm jet}$



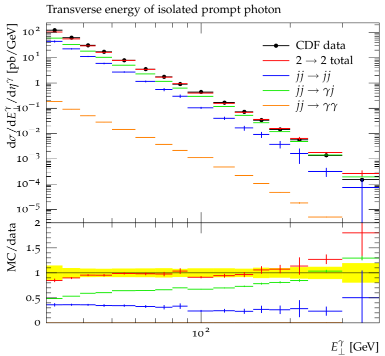
Isolated prompt-photon production at Tevatron

(Data from CDF, Phys. Rev. D **80** (2009) 111106)

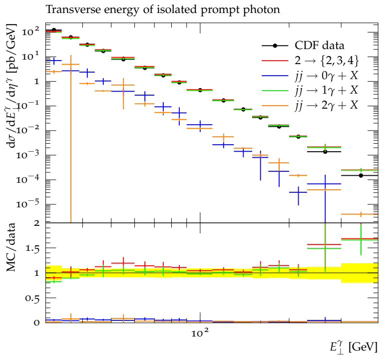
cuts: $30 < E_T^\gamma < 400$ GeV, $|\eta^\gamma| < 1$, isolation: $E_T^{R=0.4} - E_T^\gamma < 2$ GeV

- Sherpa: pure shower vs. ME⊕TS

E_T^γ – pure shower



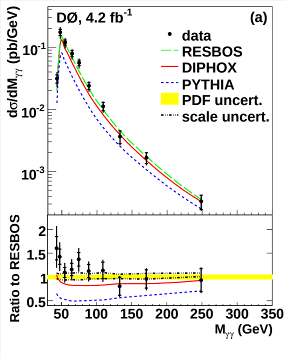
E_T^γ – ME⊕TS

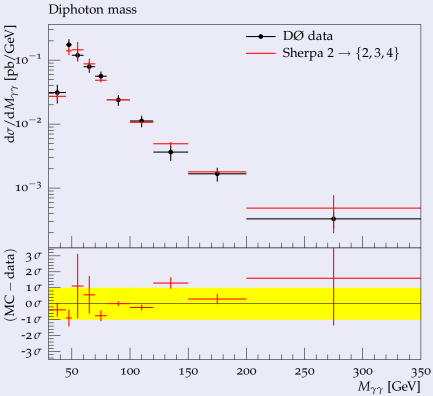


Di-Photon production at Tevatron: Invariant mass

(D0/ data, arXiv:1002.4917)

- Compare with other codes: DiPhox, ResBos, Pythia
- Sherpa: merged $2 \to \{2,3,4\}$ plus $gg \to \gamma\gamma$ box

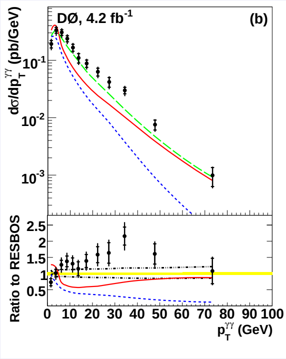


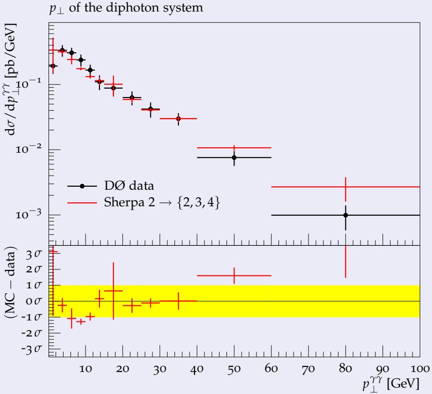


Di-Photon production at Tevatron: Transverse momentum of pair

(D0/ data, arXiv:1002.4917)

- Compare with other codes: DiPhox, ResBos, Pythia
- Sherpa: merged $2 \to \{2,3,4\}$ plus $gg \to \gamma\gamma$ box

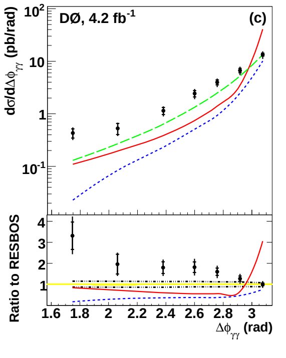


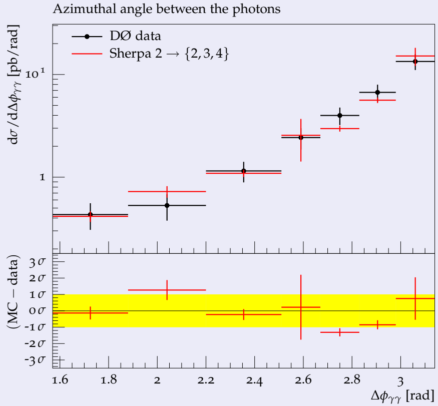


Di-Photon production at Tevatron: Azimuthal decorrelation

(D0/ data, arXiv:1002.4917)

- Compare with other codes: DiPhox, ResBos, Pythia
- Sherpa: merged $2 \to \{2, 3, 4\}$ plus $gg \to \gamma\gamma$ box





The POWHEG method

Basic idea

- Want total cross section and first emission correct at $\mathcal{O}(\alpha_S)$
- Master formula:

$$\mathrm{d}\sigma_{\mathrm{NLO}} = \mathrm{d}\Phi_{\mathcal{B}}\bar{\mathcal{B}}(\Phi_{\mathcal{B}})) \left[\bar{\Delta}(p_{\perp,\,\mathrm{min}}) + \int\limits_{p_{\perp,\,\mathrm{min}}} \mathrm{d}\Phi_{\mathcal{R}|\mathcal{B}} \frac{\mathcal{R}(\Phi_{\mathcal{R}})}{\mathcal{B}(\Phi_{\mathcal{R}})} \bar{\Delta}(p_\perp)\right] .$$

- $\mathcal{B}$, $\mathcal{R}$ denote Born and real emission ME, respective phase space $\Phi_{\mathcal{B},\mathcal{R}}$.
- $\Phi_{\mathcal{R}|\mathcal{B}}$ is the phase space for one particle splitting connecting both.
- Since Sudakov form factor $\bar{\Delta}$ reads:

$$\bar{\Delta}(p_\perp) = \exp\left[-\int \mathrm{d}\Phi_{\mathcal{R}|\mathcal{B}}\Theta[k_\perp(\Phi_R) - p_\perp]\frac{\mathcal{R}(\Phi_{\mathcal{R}})}{\mathcal{B}(\Phi_{\mathcal{R}})}\right],$$

  the expression in square bracket above $= 1$ (unitarity).
- $\bar{\mathcal{B}}(\Phi_{\mathcal{B}})$ denotes the NLO-weighted differential xsec for Born configuration.

Algorithm

- Generate a starting Born-type parton configuration distributed according to
$$\mathrm{d}\Phi_{\mathcal{B}}\bar{\mathcal{B}}(\Phi_B) = \mathrm{d}\Phi_{\mathcal{B}}\left[\mathcal{B}(\Phi_{\mathcal{B}}) + \mathcal{V}(\Phi_{\mathcal{B}}) + \int \mathrm{d}\Phi_{\mathcal{R}|\mathcal{B}}\mathcal{R}(\Phi_{\mathcal{R}})\right]$$
with $\mathcal{B}$ the Born, $\mathcal{V}$ the virtual, and $\mathcal{R}$ the real emission contribution.
- Generate the hardest emission according to $\bar{\Delta}$, where the usual splitting kernel $\mathcal{K}(t,\,z)$ is replaced by the ratio $\mathcal{R}(\Phi_{\mathcal{R}})/\mathcal{B}((\Phi_{\mathcal{B}})$:
$$\frac{\mathrm{d}t}{t}\mathrm{d}z\,\mathcal{K}(t,\,z) \to \mathrm{d}\Phi_{\mathcal{R}|\mathcal{B}}(t,\,z)\frac{\mathcal{R}(\Phi_{\mathcal{R}})}{\mathcal{B}(\Phi_{\mathcal{B}})}$$
- Perform a regular truncated shower on the resulting parton configuration.

Algorithm

- Two public implementations: In HERWIG++ and in the POWHEGBOX, SHERPA in progress (see next talk).
- The POWHEGBOX implementation "sits" on top of arbitrary parton shower through LHE-Interface, harms truncating the shower.

Available processes/implementations

- $pp \to W/Z$ (POWHEGBOX & HERWIG++)
- $pp \to H$ (POWHEGBOX & HERWIG++)
- $pp \to V + H$ (HERWIG++)
- $pp \to ZZ$ (POWHEGBOX)
- $pp \to QQ$ (POWHEGBOX)
- single-top (POWHEGBOX)
- VBF (POWHEGBOX)

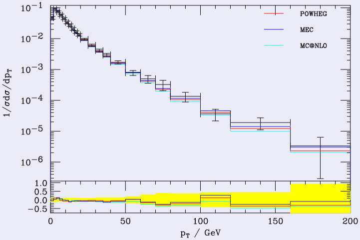
In preparation:

- $pp \to VV$ (POWHEGBOX)
- $pp \to V$+jet (POWHEGBOX)

W+jets at Tevatron: $p_\perp^W$-spectra

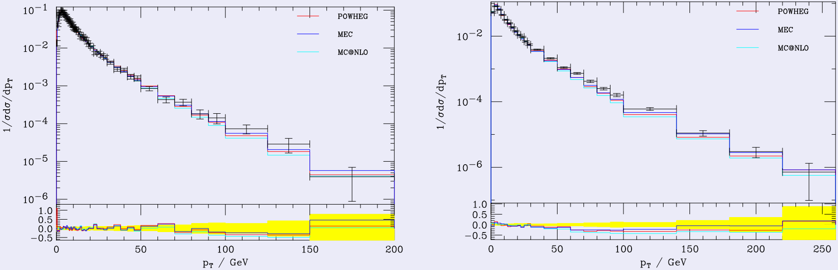
- POWHEG method as implemented in HERWIG++ vs. MC@NLO and HERWIG++.
  (Note: when only shape considered, do not expect difference to native HERWIG++ with ME corrections included

  $\Longrightarrow$ simple check of implementation.)



Z+jets at Tevatron: $p_\perp^Z$-spectra

POWHEG method as implemented in HERWIG++ vs. MC@NLO and HERWIG++.

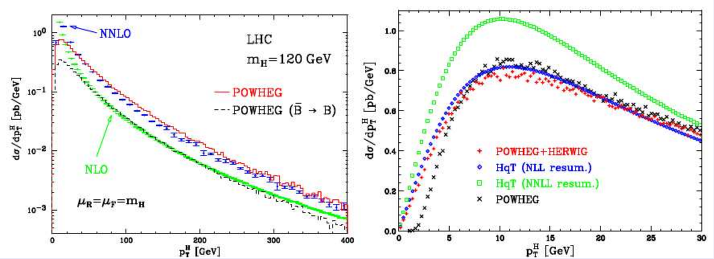


CDF Run I

D0 Run II

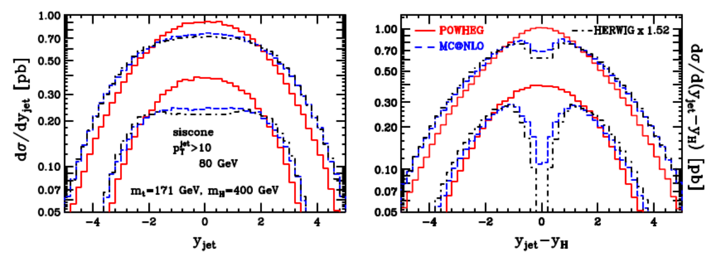
H+jets at LHC: Implicit higher orders in POWHEG

- Can replace $\bar{\mathcal{B}} \to \mathcal{B}$ in $\mathrm{d}\sigma$ to check if huge K-factor of $\mathcal{O}(2)$ is just due to proper NLO correction (left panel): expect only a vertical shift.
- Can also check for shape w.r.t. higher-order code and switch on/off shower & hadronisation effects (right panel)



H+jets at LHC: Implicit higher orders in POWHEG

- Cross check with MC@NLO, which has similar goal, but different algorithm.
- Problem in MC@NLO becomes apparent: resides on HERWIG-shower, which does not have full phase space coverage - interplay of positive and negative weights with this partial phase space filling produces dips.
- That's why I like POWHEG better - and it's easier to implement.



The MENLOPS method

Basic idea

- At present:
  - can merge "arbitrary" tree-level MEs with PS
  - Several automated codes on the market
  - Automation of 1-loop QCD corrections seems feasible (automated codes now emerging)
- We should make use of both and automate ME$\otimes$PS at 1-loop
- Strategy: Use whatever is available
  - Process NLO parton-level events with PS at low multiplicities (through MC@NLO or, preferably, POWHEG method)
  - Combine NLO simulation with higher-order tree-level using standard ME$\otimes$PS technique for high multiplicities
- First step: POWHEG for lowest multiplicity only.

Some theoretical considerations

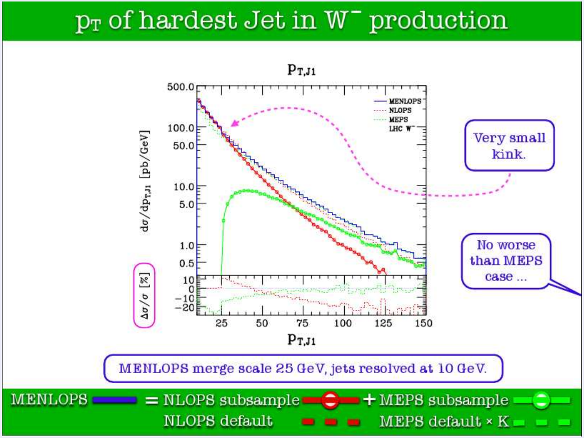
- Compare $\sigma_{(\mathrm{NLO})}$ for POWHEG and ME⊗PS:

$$d\sigma^{(\mathrm{POW})}_{\mathrm{NLO}} = d\Phi_{\mathcal{B}}\bar{\mathcal{B}}(\Phi_{\mathcal{B}})) \left[\bar{\Delta}(p_{\perp,\,\mathrm{min}}) + \int\limits_{p_{\perp,\,\mathrm{min}}} d\Phi_{\mathcal{R}|\mathcal{B}} \frac{\mathcal{R}(\Phi_{\mathcal{R}})}{\mathcal{B}(\Phi_{\mathcal{R}})} \bar{\Delta}(p_{\perp})\right];$$

$$d\sigma^{(\mathrm{MEPS})}_{\mathrm{NLO}} = d\Phi_{\mathcal{B}}\mathcal{B}(\Phi_{\mathcal{B}})) \left[\Delta(p_{\perp,\,\mathrm{min}}) + \int\limits_{p_{\perp,\,\mathrm{min}}} d\tilde{\Phi}_{\mathcal{R}|\mathcal{B}} \frac{\mathcal{R}(\Phi_{\mathcal{R}})}{\mathcal{B}(\Phi_{\mathcal{R}})} \Delta(p_{\perp})\right].$$

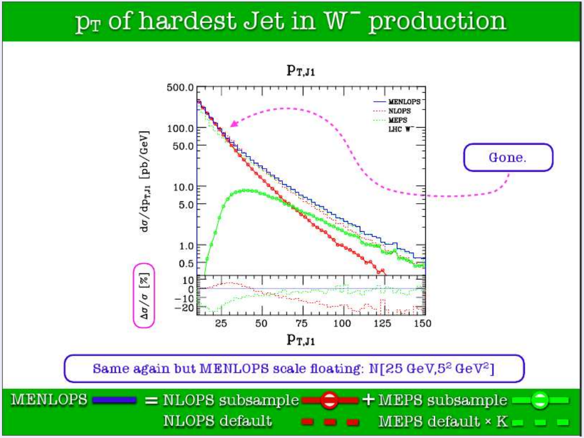
- Nearly the same. Most notably: NLO vs. LO normalisation. Boils down to a local K factor $= \bar{\mathcal{B}}\ /\mathcal{B}$
- Also note: different Sudakovs, in ME⊗PS [...] does not integrate to one. Reason: Kernel in Sudakov Δ differs from $\mathcal{R}/\mathcal{B}$.
- Proposal by Hamilton & Nason: scale up ME⊗PS by global K-factor, use MLM merging scheme.
- See next talk for version on improved CKKW merging.

Some results



(From K.Hamilton's talk at MC4LHC Tools Readineess, March 2010)

Some results



(From K.Hamilton's talk at MC4LHC Tools Readiness, March 2010)

Conclusions

- Predictions by Monte Carlo event generators benefitted dramatically from inclusion of higher-order corrections in various ways: Total cross section under NLO control, emission pattern for each jet according to full ME.
- LO-merging technology now very mature, many implementations, theoretical framework is fully established

(NLO calculations discover scale setting prescription of merging algorithms, may lead to better NLO predictions.)

- For simple processes (about one colour line) two ways of including full NLO calculation into shower: MC@NLO (maybe a bit tedious) and POWHEG.
- The latter opens the door to combining both merging and matching.
- The ultimate goal, of course, of this development is a multijet merging with NLO matrix elements

$\longrightarrow$ work in progress.