Onto higher precision in Sherpa

Frank Krauss
(IPPP)

IPMU workshop, Kyoto, September 2011

www.ippp.dur.ac.uk

Outline

- Motivation: Why higher orders?
- Warm-up: Multijet merging
  - Algorithm
  - Results with Sherpa
- Powheg and beyond
  - Summary of the method
  - Automation in Sherpa
  - MENLOPS
- Summary

Motivation: Why higher orders?

- In standard collinear factorisation, the total cross section is calculated as

$$\sigma_{pp\to N}(Q^2) = \sum_{a,b} \int \mathrm{d}x_a \mathrm{d}x_b \; g_a(x_a, Q^2) g_b(x_b, Q^2) \, |\mathcal{M}_{ab\to N}|^2 \; \mathrm{d}\Phi_N$$

- Matrix element $|M_{ab\to N}|^2$ encodes fundamental physics (quantum interferences, off-shell effects etc.)

- It accounts correctly for high-p_T phenomena

- Possible: systematic improvements through higher orders in pert. expansion

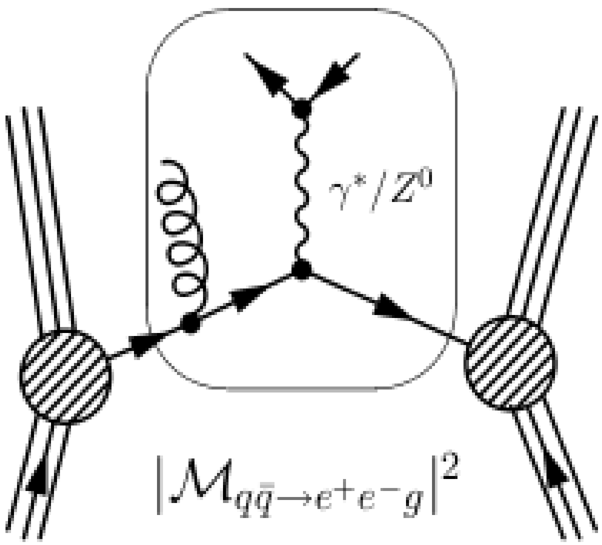
- But: Poor accuracy in soft and collinear regions of phase space (Resummation of large logarithms important)

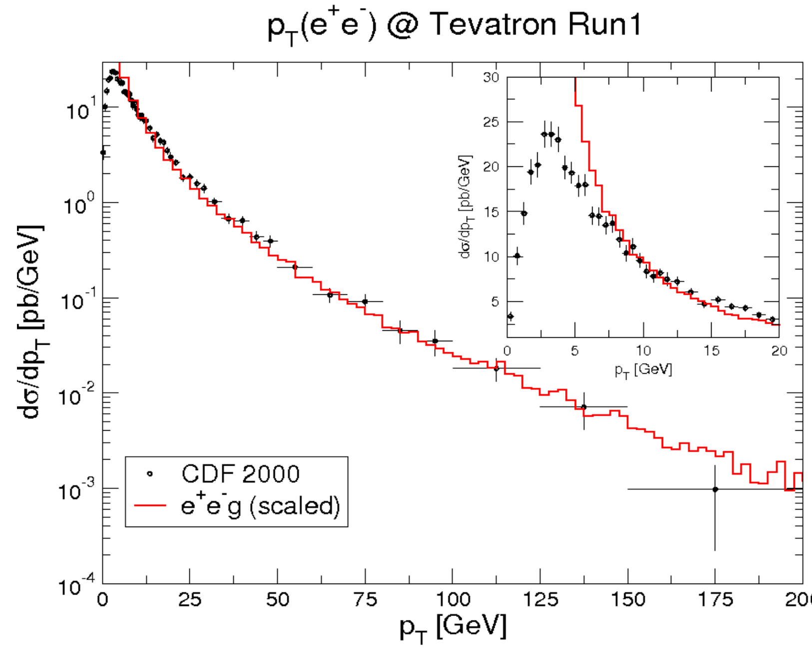
- Only few (<10) partons in final state

- Non-trivial link to hadronisation

Motivation (cont'd)

- Example: Transverse momentrum of Z boson in hadron-hadron collisions

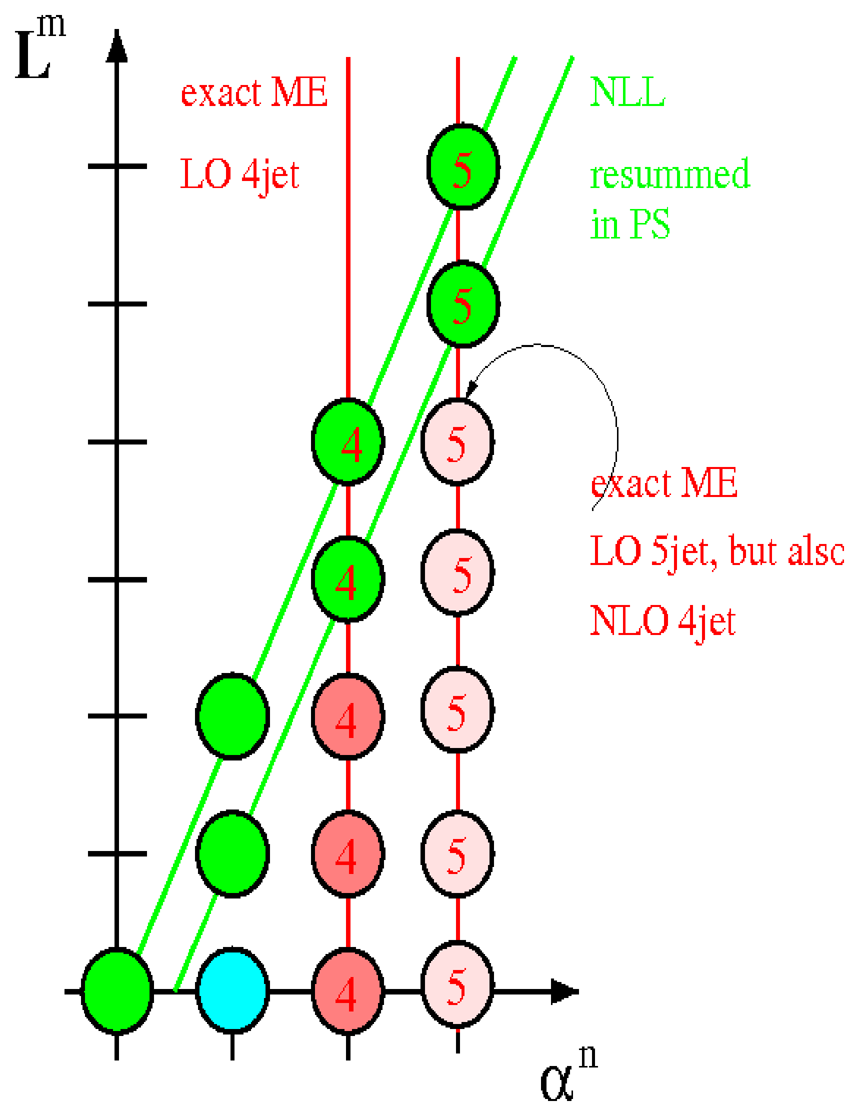




- $|\mathcal{M}_{q\bar{q}\to e^+e^-g}|^2 \sim |\mathcal{M}_{q\bar{q}\to e^+e^-}|^2 \frac{\alpha_S(\mu_R^2)}{p_T^2} \quad \rightsquigarrow \quad \sigma_{pp\to e^+e^-g} \sim \sigma_{pp\to e^+e^-}\, \alpha_S(\mu_R^2) \log \frac{p_T^{max}}{p_T^{min}}$
- Integration over p_T yields large logs, related to divergence in ME
- Divergence needs to be regularised and logs resummed
- Note: Universal IR structure → universal log structure → parton shower
  (parton shower as simple trick to achive the log-resummation)

Motivation (cont'd)

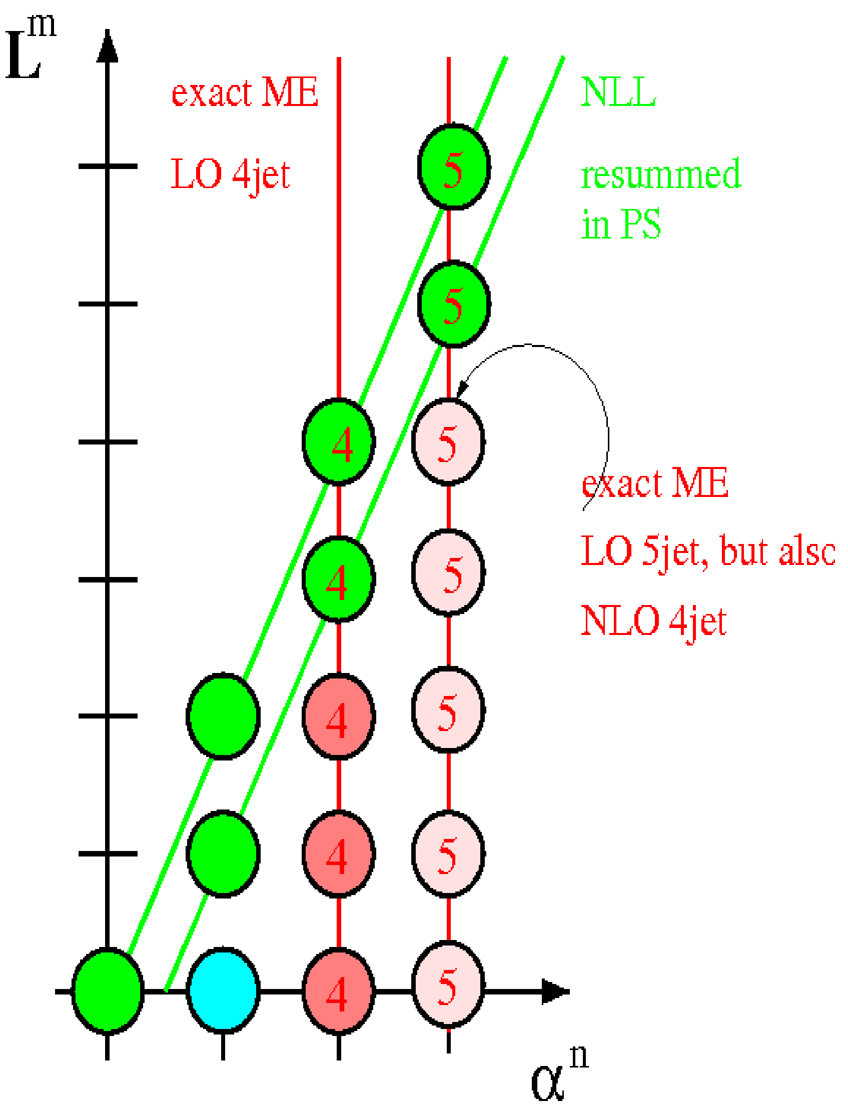
- Parton shower a probabilistic method of resumming the large logs
- It will not account for higher-order corrections to rates
- It will not provide a reliable estimate for hard scattering.
  (and power showers as in Pythia are not very systematic)
- Must combine parton shower with exact higher-order calculations.
- Two methods:
  - Multijet merging and
  - NLO matching



Multijet merging

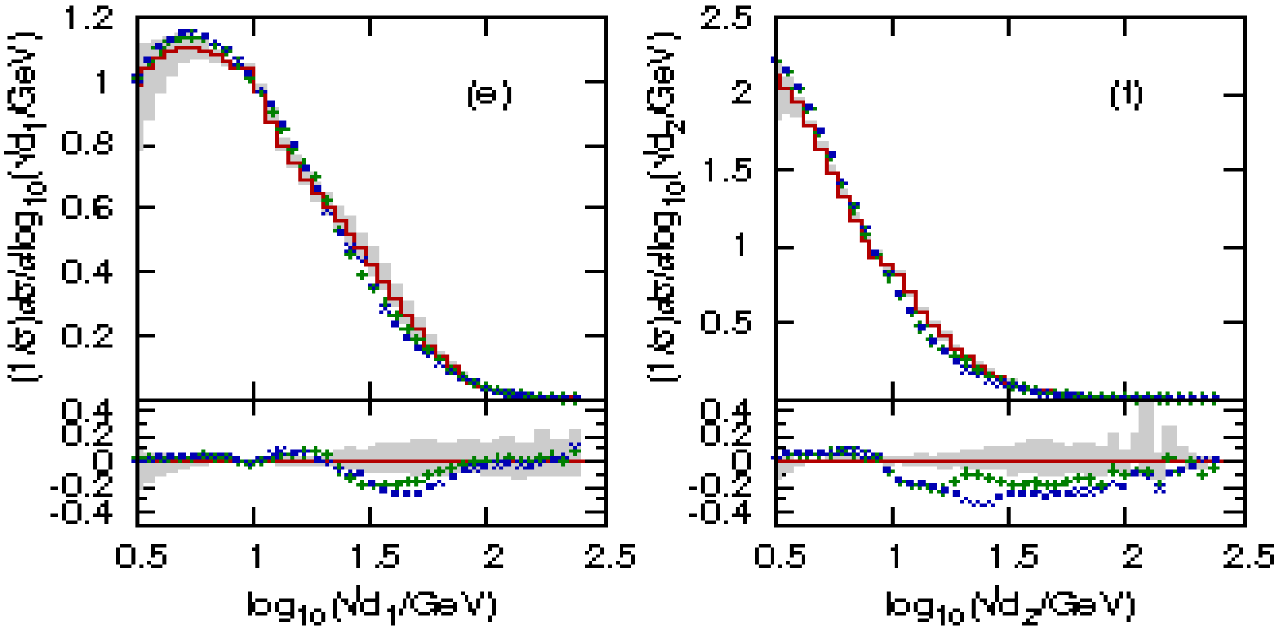
Multijet merging: General thoughts

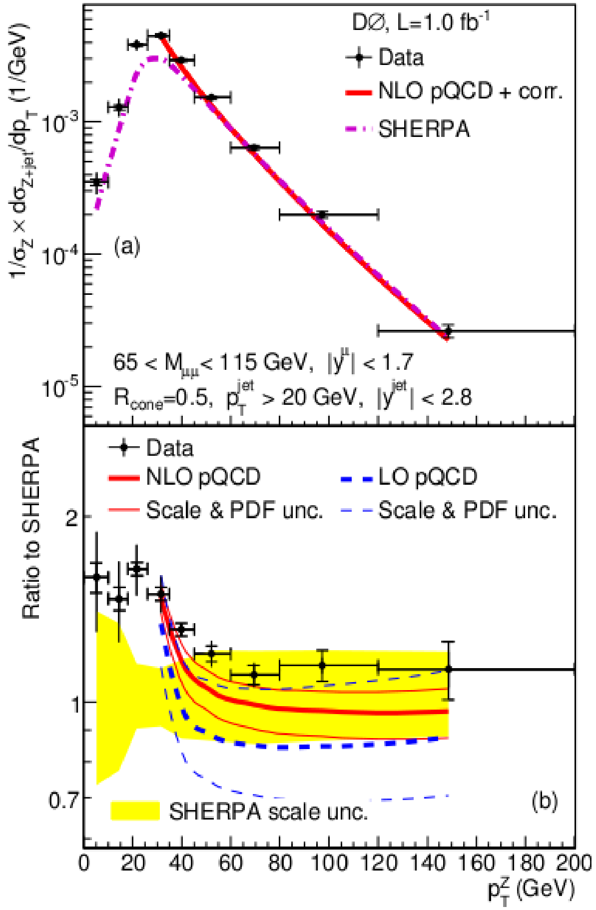
- Want to combine without double-counting
  - large logs of parton shower with
  - exact LO matrix elements
  - for towers of jet multiplicities
- Algorithm
  - To avoid the double-counting divide the phase space in two regimes: Jet-evolution and jet-production (this adds a parameter, Q_{cut})
  - Preserve accuracy of parton shower
    - Reweight the matrix elements
    - Veto/truncate the parton shower



Multijet merging in Sherpa:

- Method has been pioneered for about 10 years in Sherpa
- New algorithm as described before from version 1.2
- Some example results for Sherpa 1.1.3 with old merging algorithm (analytical Sudakov form factors in ME regime)

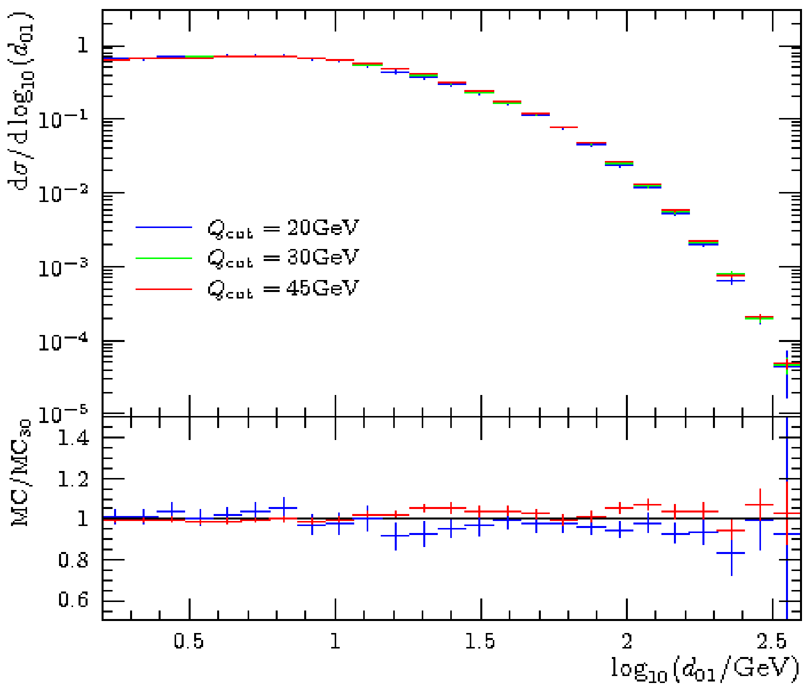


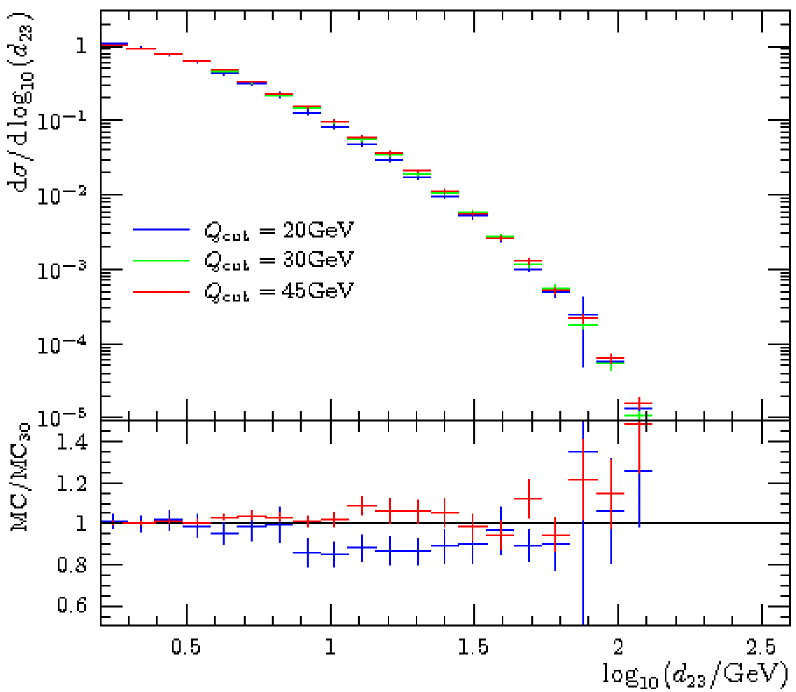


Multijet merging in Sherpa:

(Hoeche, Krauss, Schumann & Siegert, JHEP 0905:053 (2009))

- New improved formalism, greatly reduced merging systematics
  - Sherpa 1.2: <15% for Q_{cut} [20, 50] GeV,
  - Old algorithm in Sherpa 1.1 was better than 20% (up to 40% in extreme bins – see previous slide)
- Shown to preserve formal accuracy of parton shower, i.e. shower logarithms are correctly accounted for; (MLM algorithm does not do that)

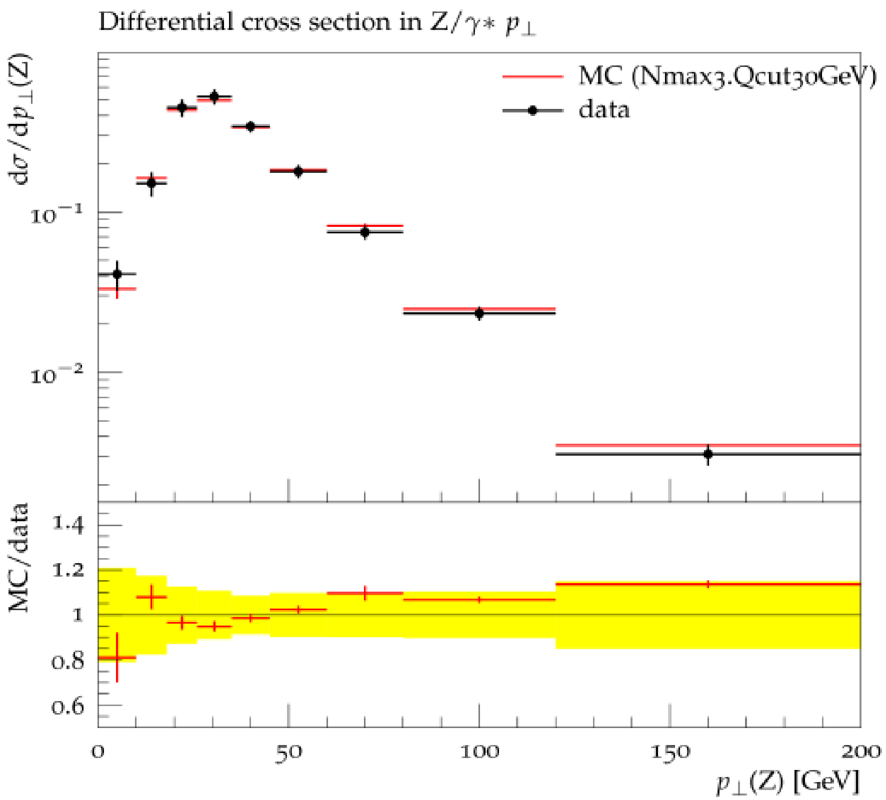


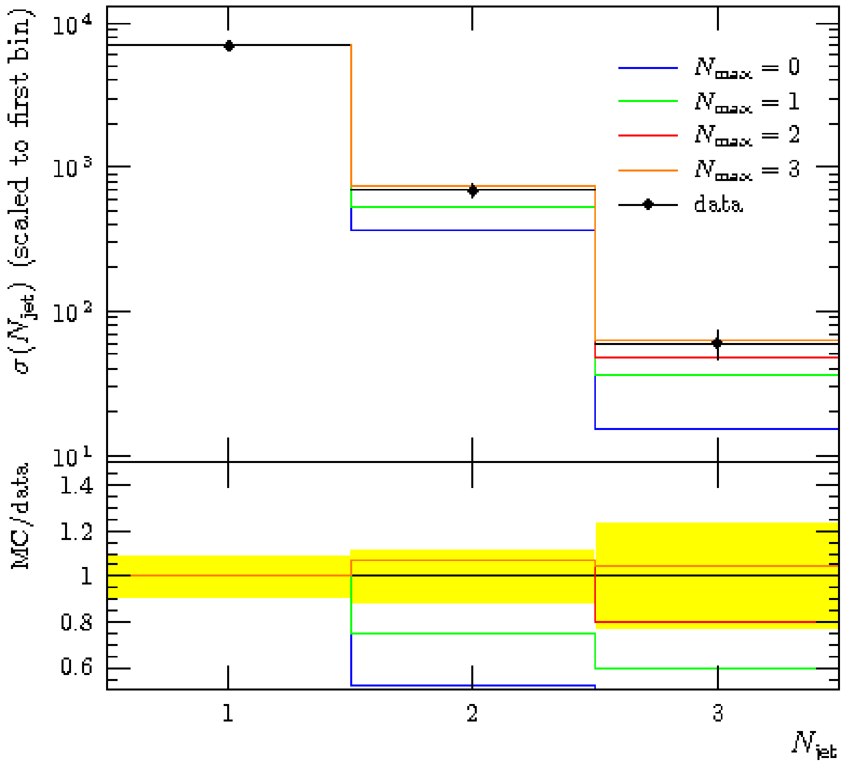


Multijet merging in Sherpa:

(Hoeche, Krauss, Schumann & Siegert, JHEP 0905:053 (2009))

- Typically, Sherpa 1.2 and upwards describes Tevatron data very well:



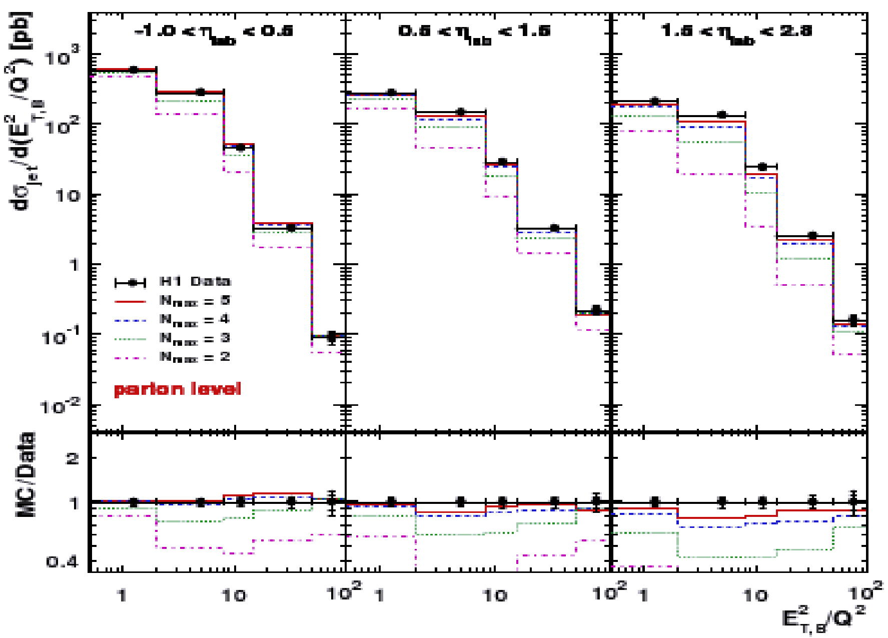


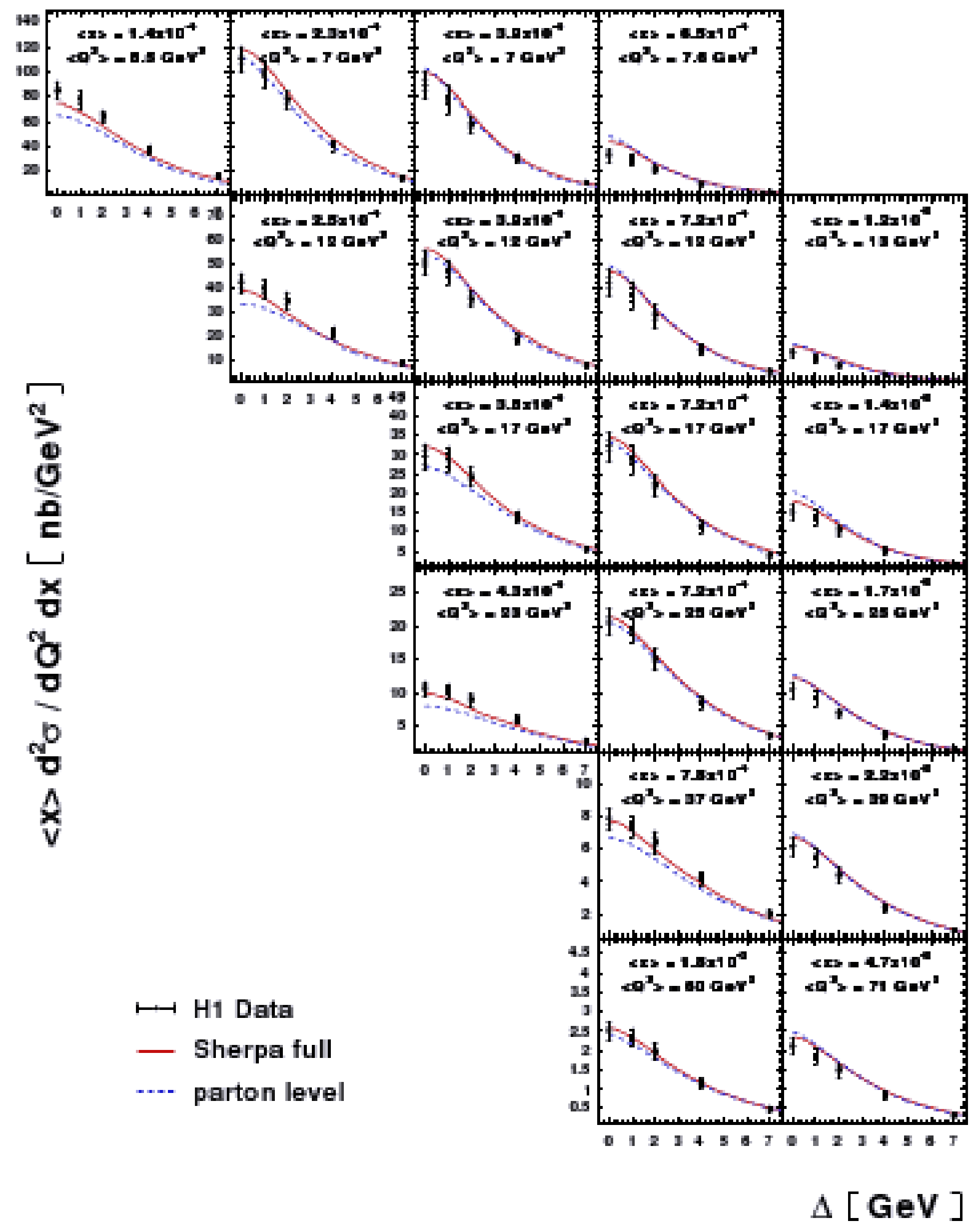
- Similar quality also for other observables and processes like W+jets.

Some results in DIS

(Carli, Gehrmann & Hoeche EPJC 67 (2010) 73)

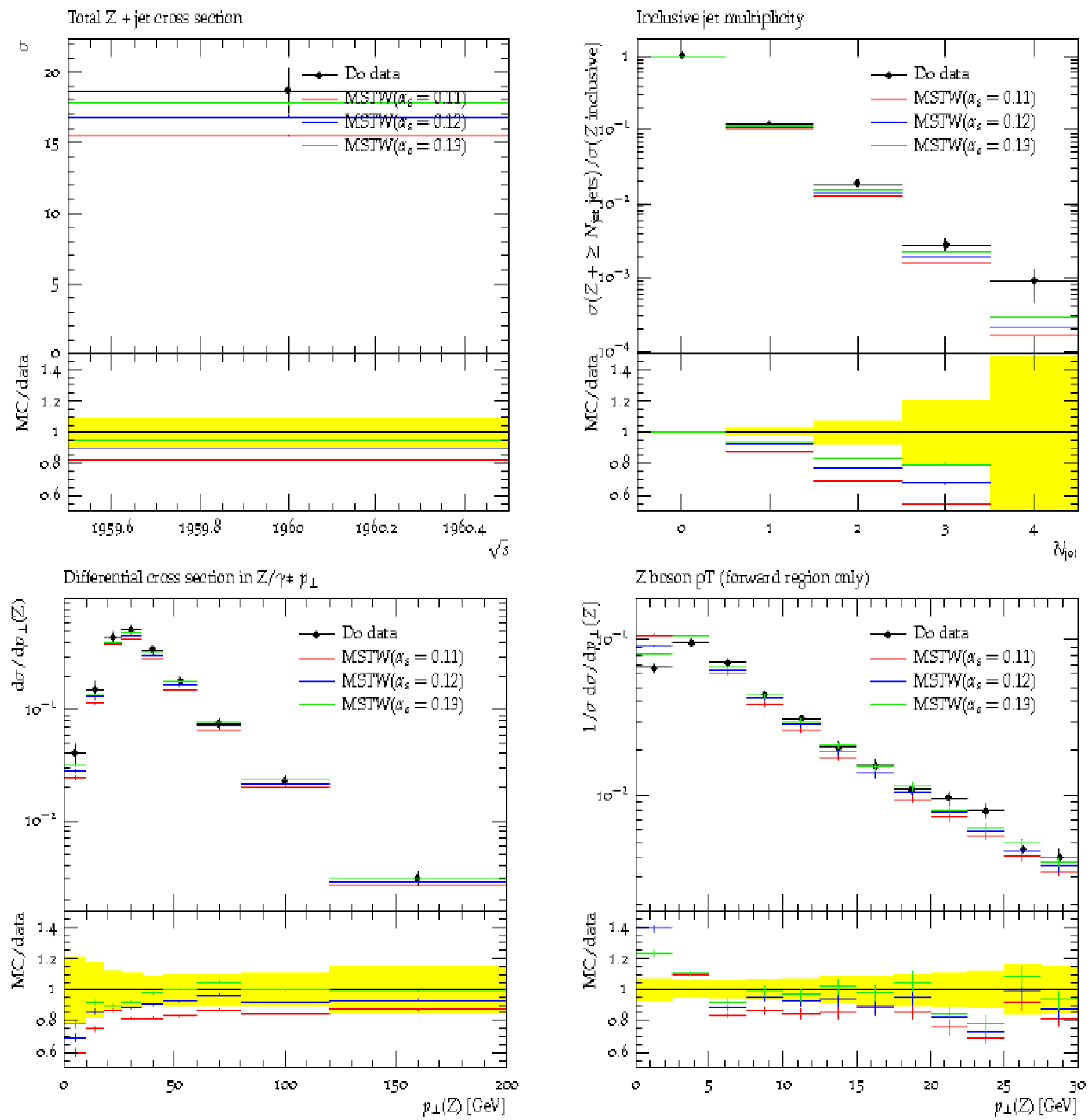
- Inclusive jet and dijet at low-x production, pt-distributions.
- Typically not well described by perturbative Monte Carlo





Merging in Sherpa – Impact of α_s

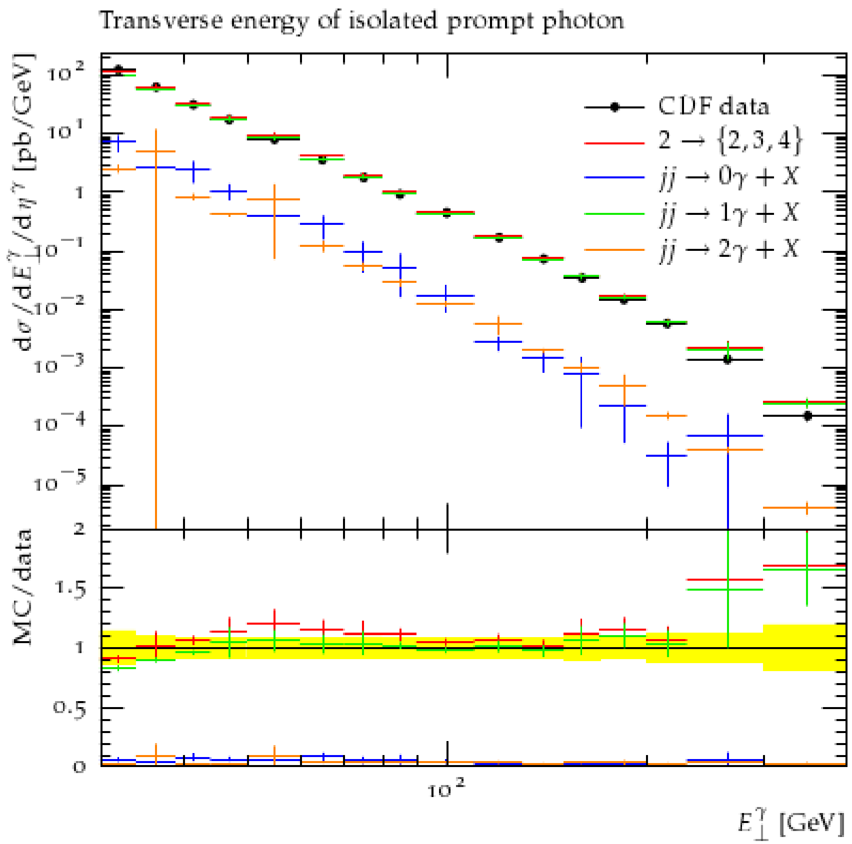
- In contrast to, e.g., Pythia, there is only one strong coupling constant in Sherpa, fixed by the PDF.
- I believe this is the only truly consistent choice, especially in view of treating higher order corrections in multijet merging and NLO matching.
- Therefore: Clear and immediate impact on observables.
- Therefore: Will provide tunes for different PDFs, including those with different values of strong coupling; this will allow for meaningful systematic error estimates

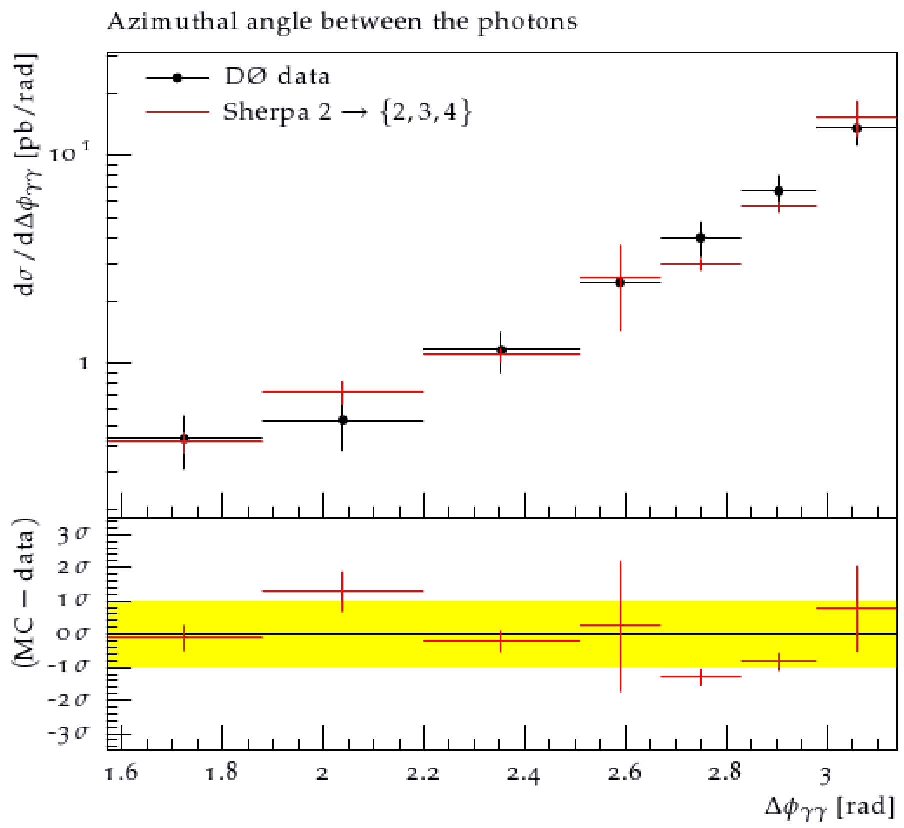


Multijet merging with photons:

(Hoeche, Schumann & Siegert, PRD 81 (2009), 034026)

- Recently extended method also to photons.
- Example results:

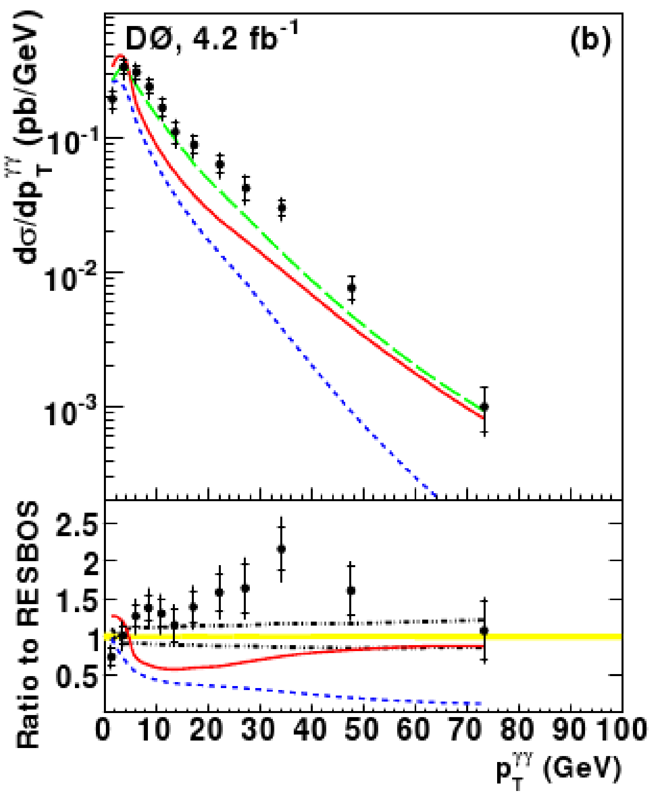


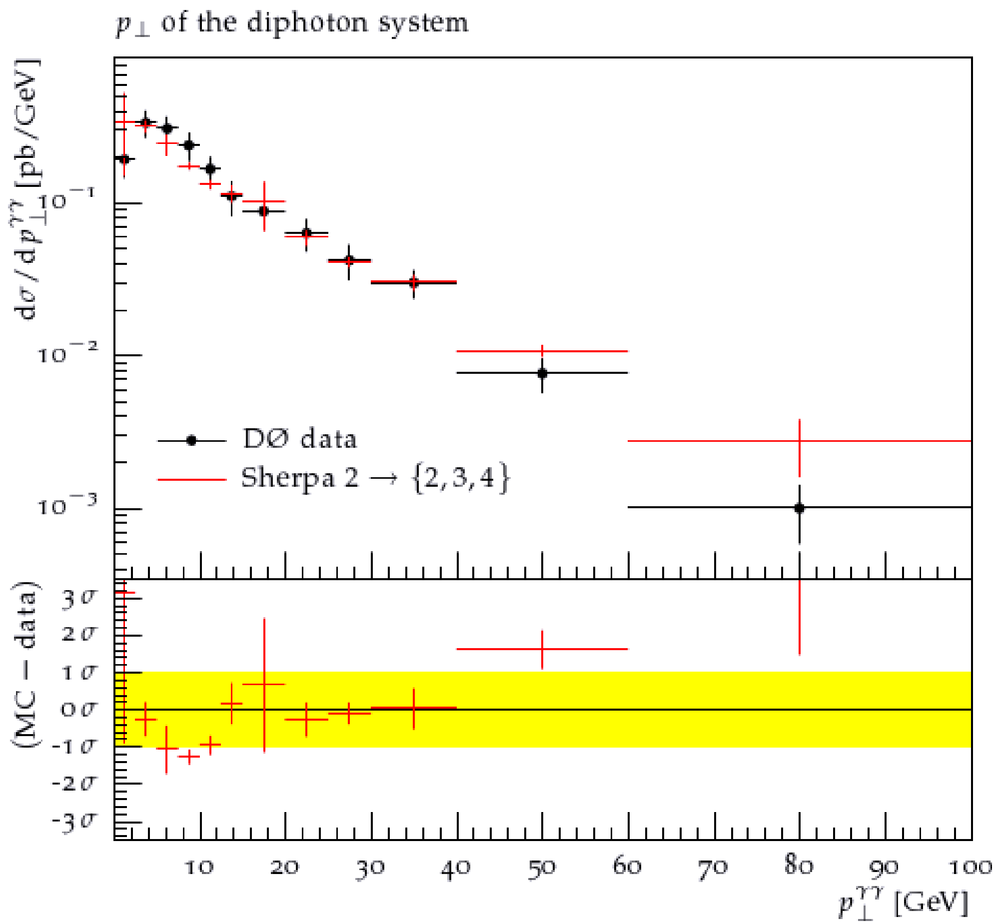


Multijet merging with photons:

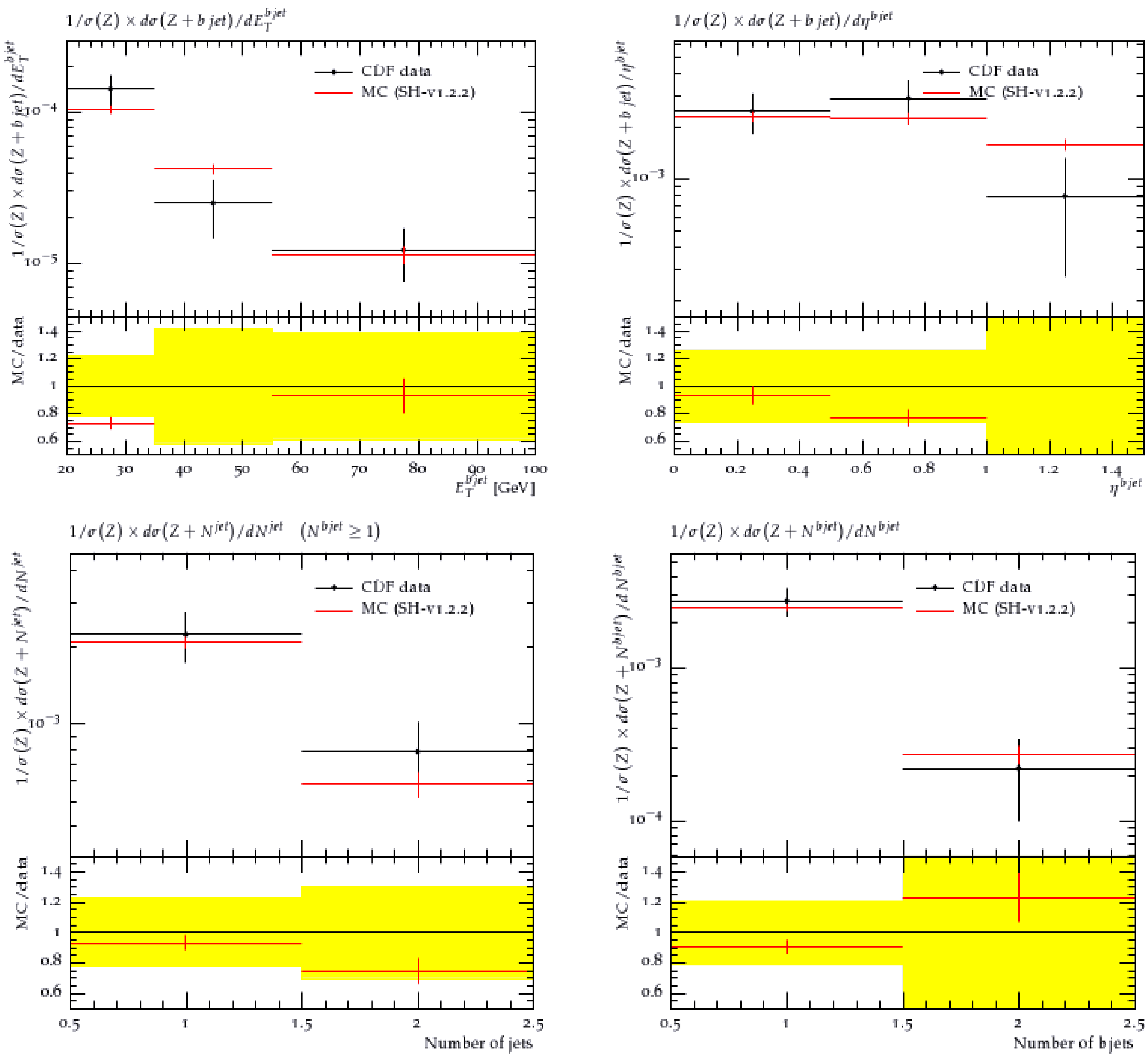
(Hoeche, Schumann & Siegert, PRD 81 (2009), 034026)

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





Multijet merging with heavy flavours:



NLO matching

Aside: Matrix elements in Sherpa

Three kinds of matrix elements:

- Since 1.2.0: Comix - mainly SM, can handle up to 8-10 final state particles

  (implementations for BSM-relevant methods have low priority in Comix.)
- Amegic++ - SM & BSM generator, up to 6 final state particles

  (development stalled, will eventually move to Comix.)
- Specific, hard-coded ME's at LO and NLO.
- Using Comix makes Sherpa even easier to handle:
  - no more libraries written out to be compiled in intermediate step.
- Sherpa/Amegic++ support FeynRules
  - a tool to generate Feynman rules directly from Lagrangians

    (a new standard to propagate BSM models?)

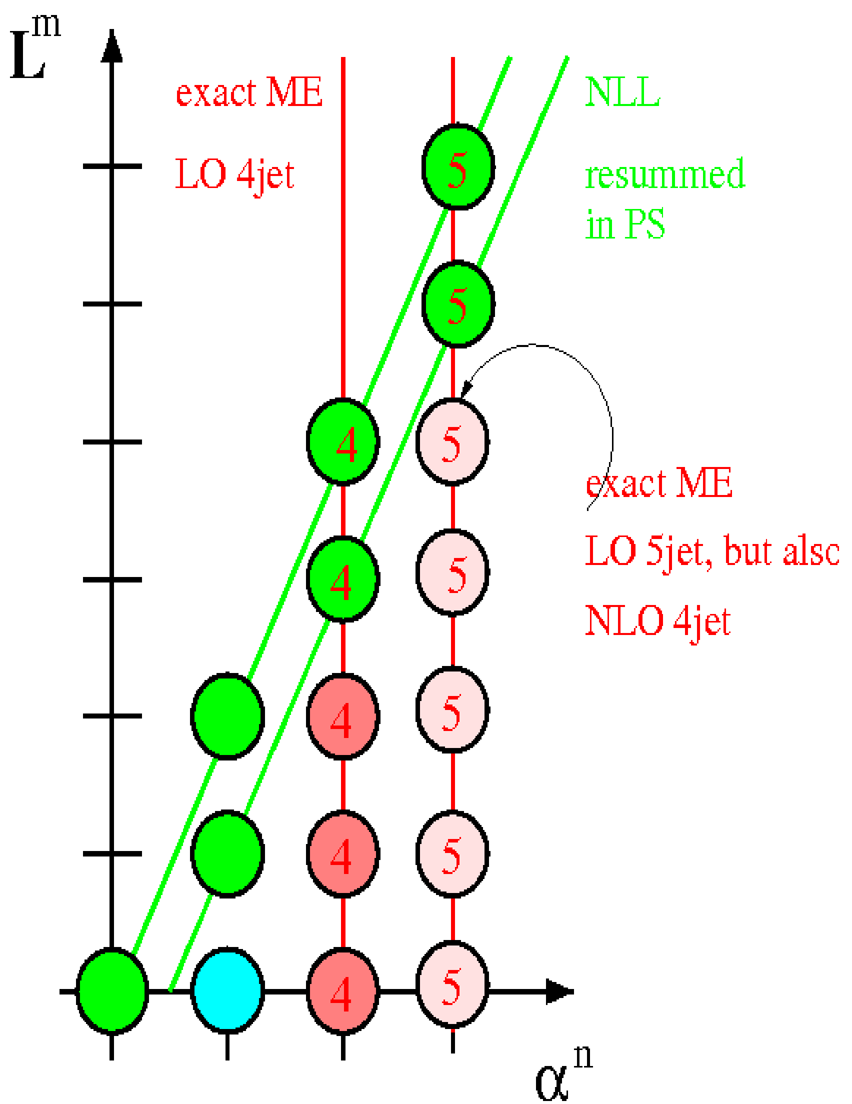
Aside: Some NLO stuff in Sherpa

- Sherpa was the first code to automate Catani-Seymour subtraction kernels
- Method to isolate IR divergences in real-emission part of NLO correction (consists of two parts: the actual subtraction term *S*, acting on the real emission bit *R*, and the term to be added to the virtual bit *V*)
- By now extensively used by the Blackhat collaboration, some state-of-the-art results (W+3,4 jets and Z+3,4 jets) done as Blackhat+Sherpa
- Nice connection to parton shower: Sherpa's new default shower bases on the same phase-space mappings
- This made the automation of the Powheg method in Sherpa quite straightforward – first processes in release 1.3.0

(Expect a full release Sherpa 2.0.α in the next few months)

NLO matching: General thoughts

- Want to combine without double-counting
  - large logs of parton shower with
  - exact NLO matrix element
  - for one core process
- Algorithm (Powheg)
  - To avoid double-counting of NLO emission **correct first (hardest) emission to ME** accuracy with R/B
  - This is **identical to the good old ME reweighting procedure**
  - To retain NLO normalisation start with suitably weighted core configurations (**NLO-weighted Born configs**)



Comparison of ME+PS, Powheg and MENLOPS

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

$$d\sigma^{\mathrm{MEPS}} = d\phi_B \mathcal{B}(\phi_B) \left[\Delta(p_{\perp,\min}) + \int\limits_{p_{\perp,\min}}^{Q_{\mathrm{cut}}} d\Phi_{R|B} \mathcal{K}(\phi_{R|B}) \Delta(p_\perp) + \int\limits_{Q_{\mathrm{cut}}} d\Phi_{R|B} \frac{\mathcal{R}(\phi_{\mathcal{R}})}{\mathcal{B}(\phi_{\mathcal{B}})} \Delta(p_\perp) \right]$$

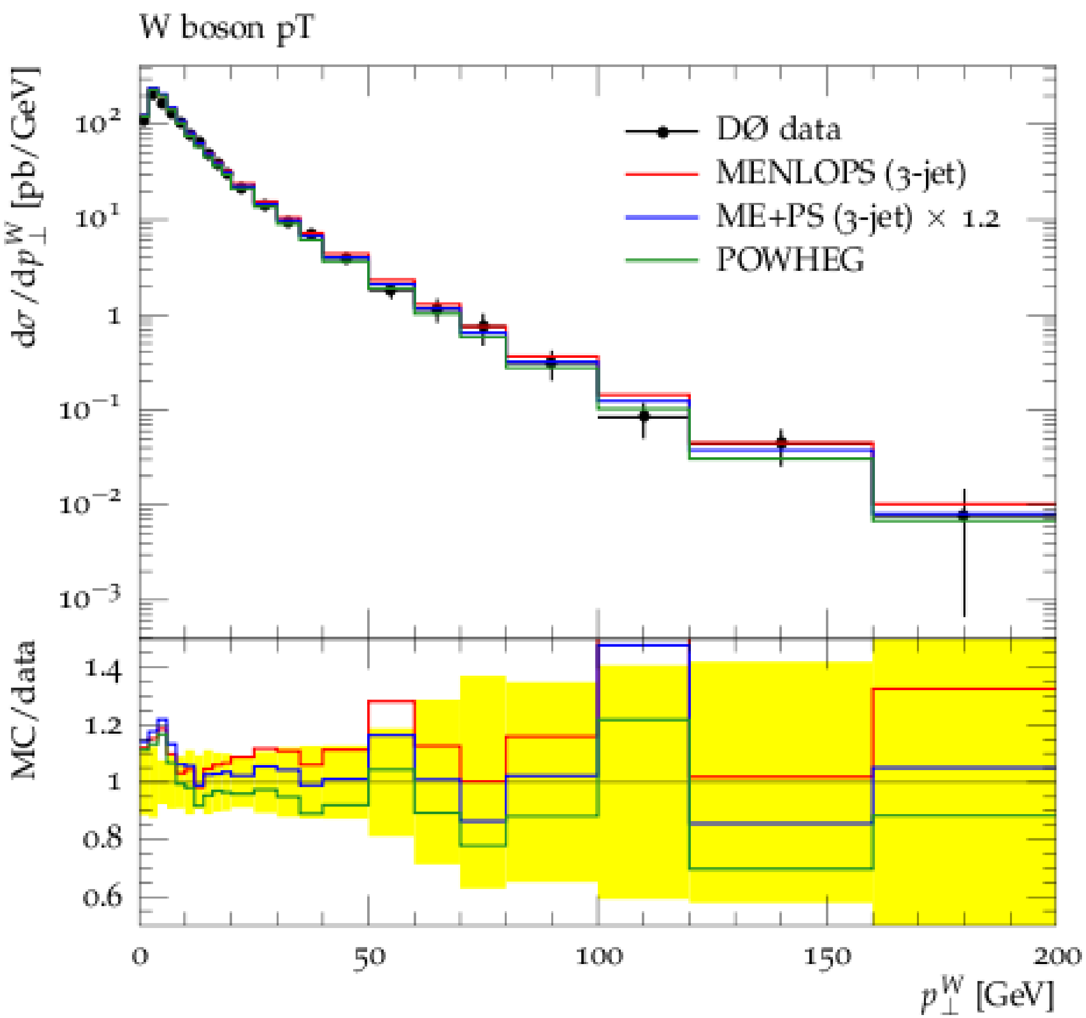
- Form of NLO cross sections for both methods nearly identical.
- Most notably NLO vs. LO normalisation ($\bar{B}$ vs. B), but also argument of Sudakov form factors ($\mathcal{R}/\mathcal{B}$ vs. splitting kernels $\mathcal{K}$) in different regions of phase space (jet production vs. jet evolution)

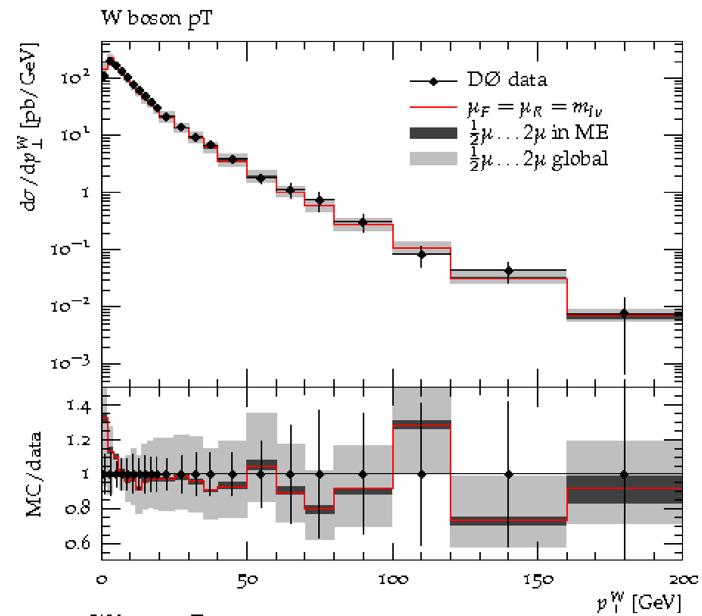
MENLOPS for first emission

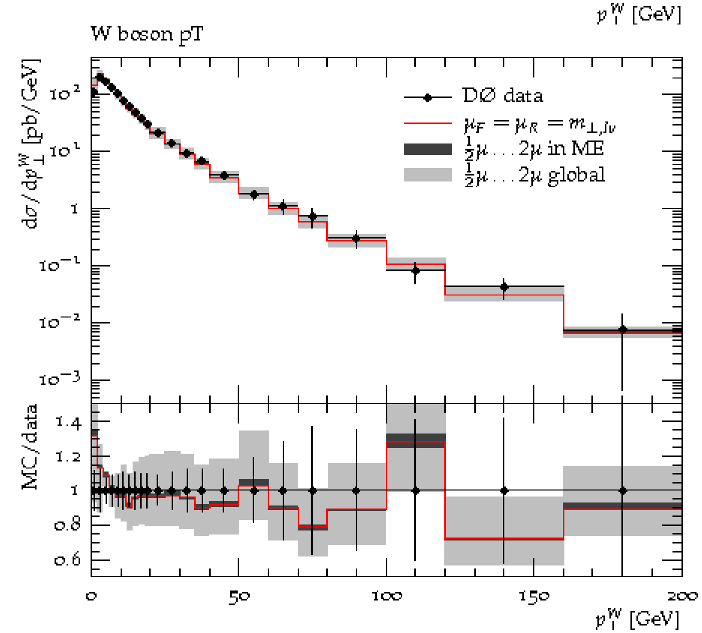
- To combine (MENLOPS): Cluster multijet configuration back to a Born-level configuration, where NLO accuracy is implemented, reweight the emerging Born-level expression with the NLO-reweighted term.

$$
\begin{aligned}
d\sigma^{\mathrm{MENLOPS}} = \; & d\phi_B \bar{\mathcal{B}}(\phi_B) \left[\bar{\Delta}(p_{\perp,\mathrm{min}}) + \int_{p_{\perp,\mathrm{min}}}^{Q_{\mathrm{cut}}} d\Phi_{R|B} \frac{\mathcal{R}(\phi_{\mathcal{R}})}{\mathcal{B}(\phi_{\mathcal{B}})} \bar{\Delta}(p_\perp) \right. \\
& \left. + \int_{Q_{\mathrm{cut}}} d\Phi_{R|B} \frac{\mathcal{R}(\phi_{\mathcal{R}})}{\mathcal{B}(\phi_{\mathcal{B}})} \Delta(p_\perp) \right]
\end{aligned}
$$

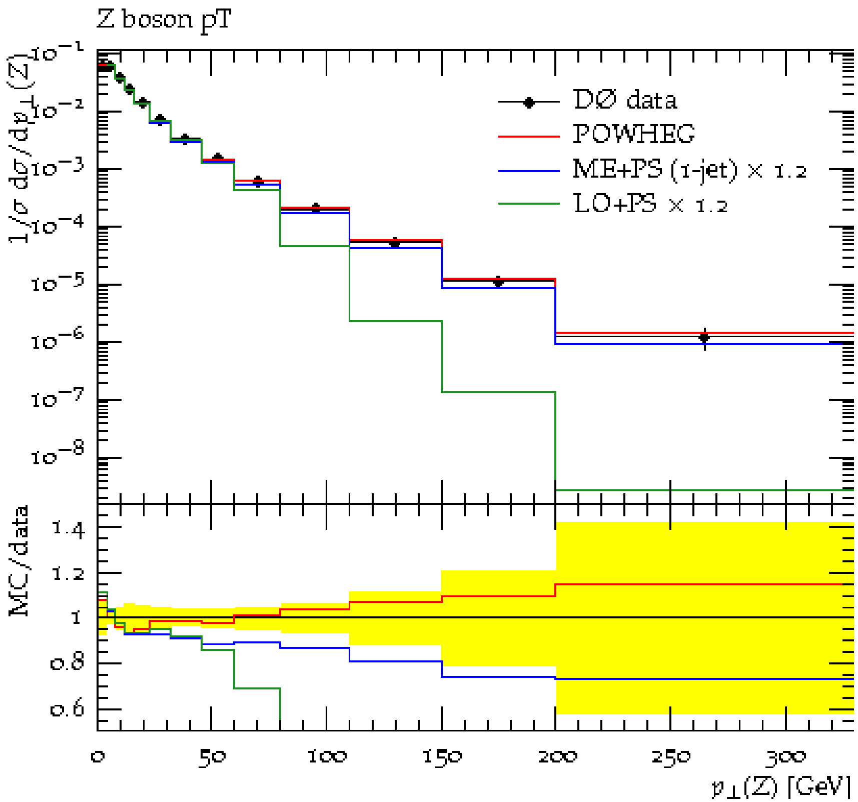
p_T^W at Tevatron: playing with scales

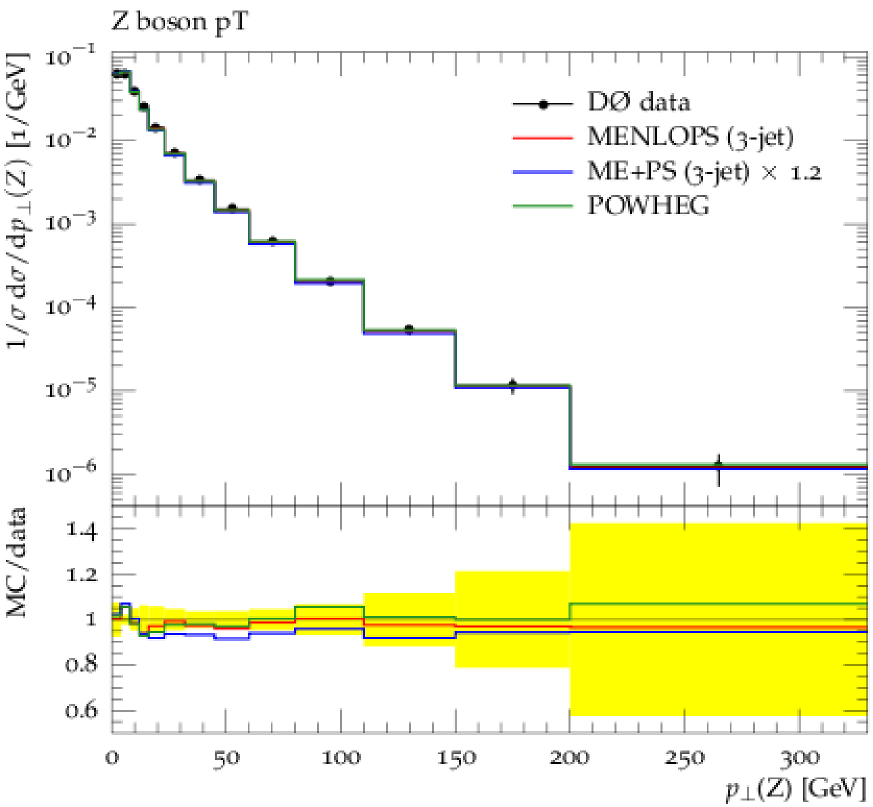




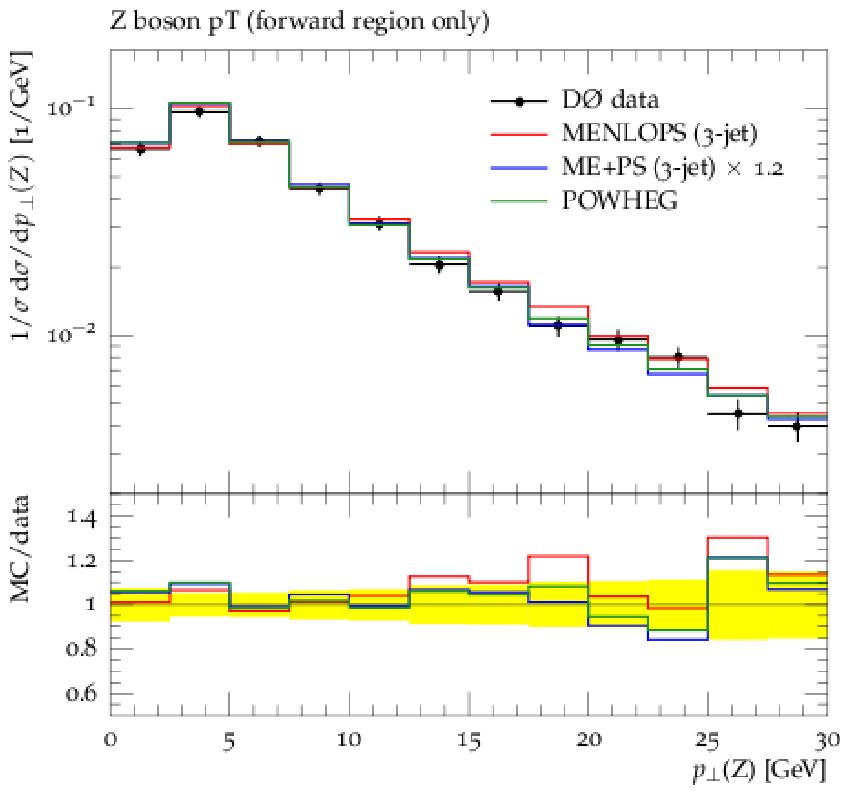


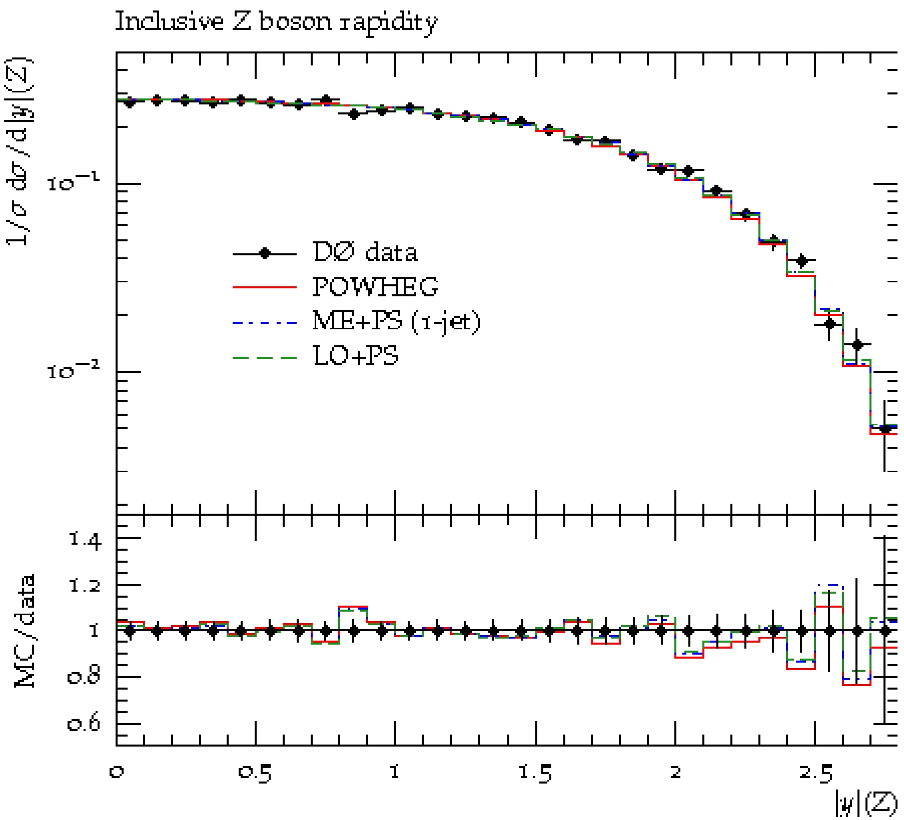
p_T^Z at Tevatron



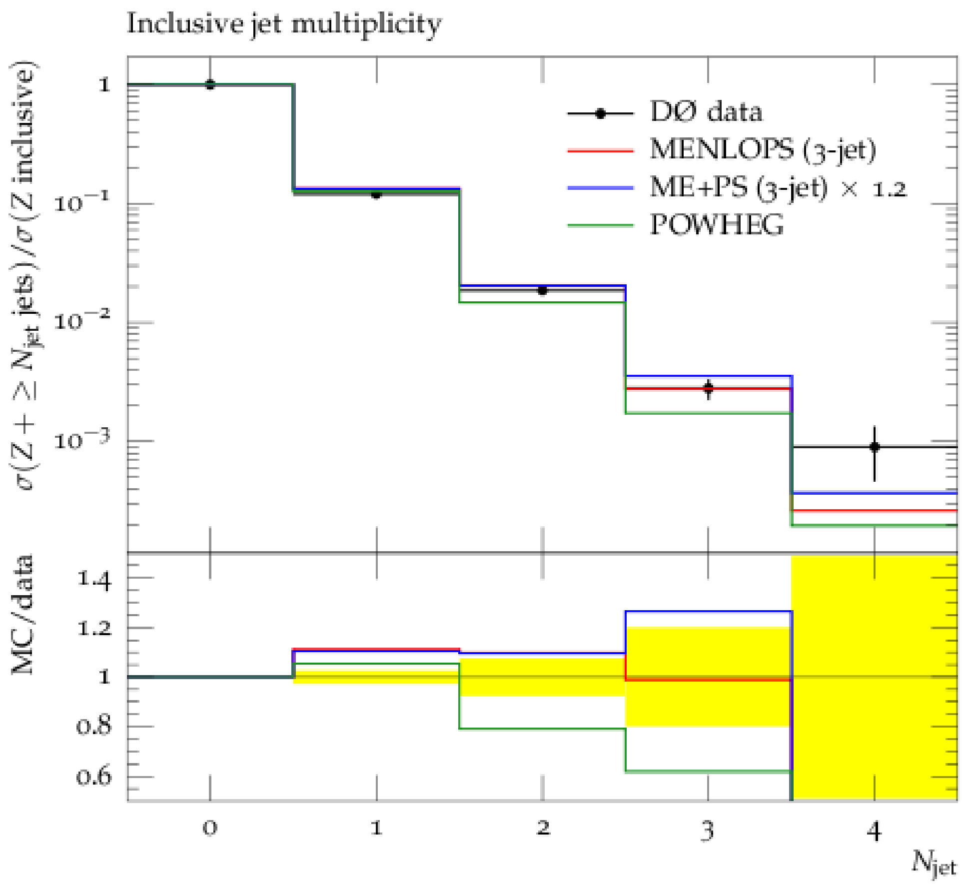


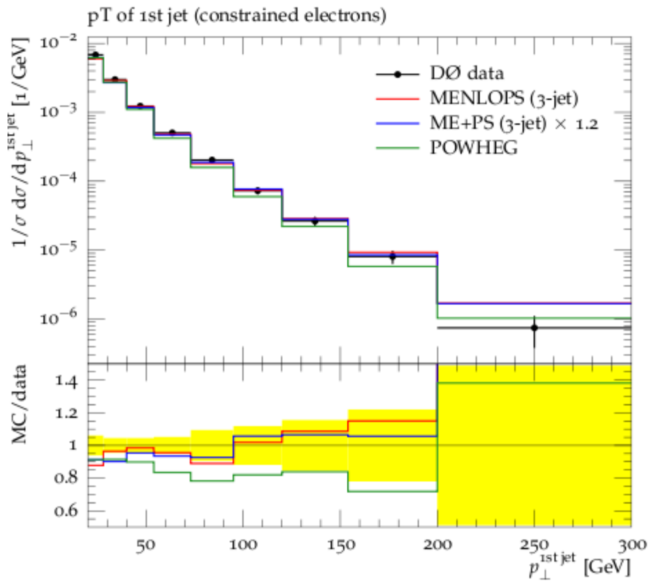
p_T^Z(forward) and y^Z at Tevatron

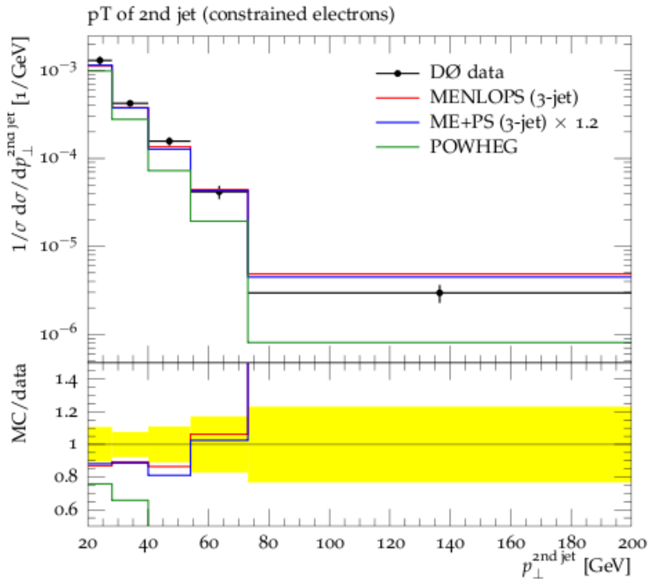




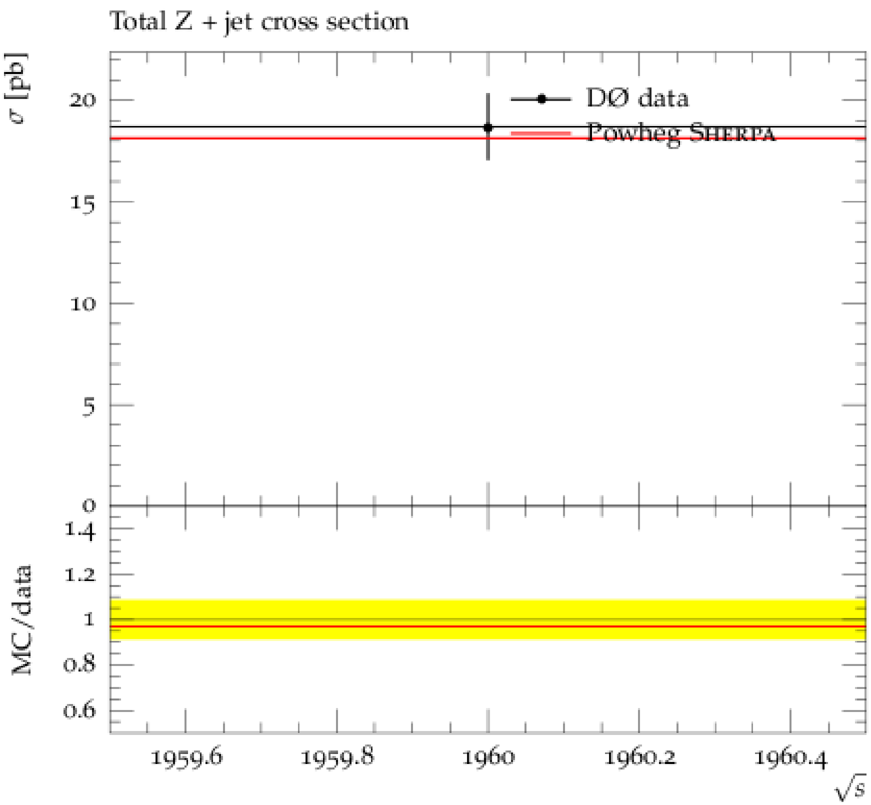
Z production at Tevatron: jets

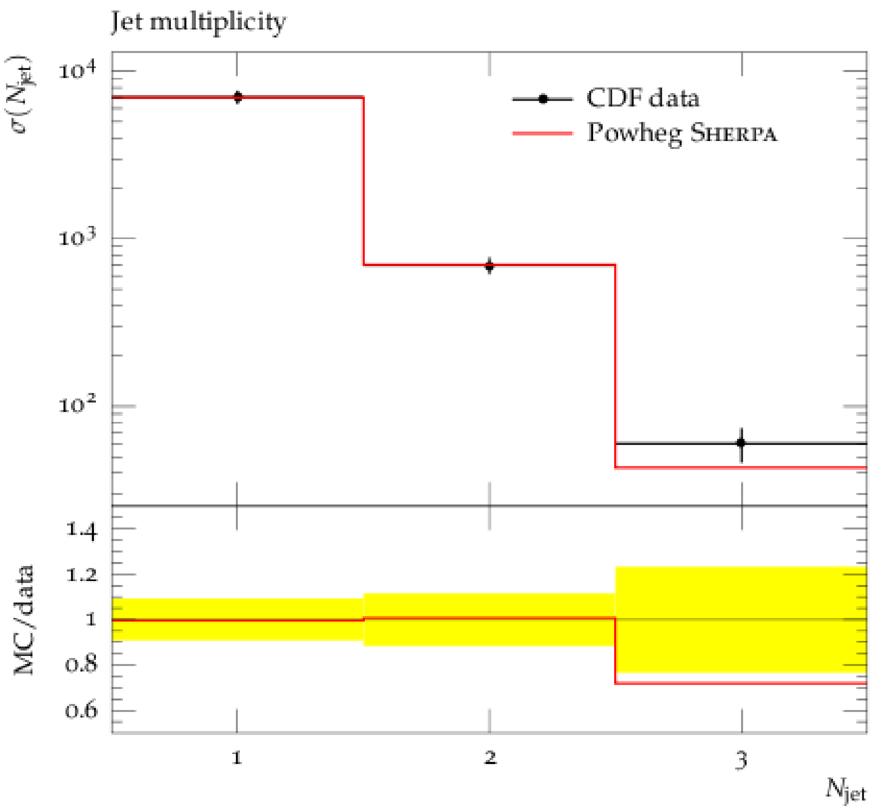




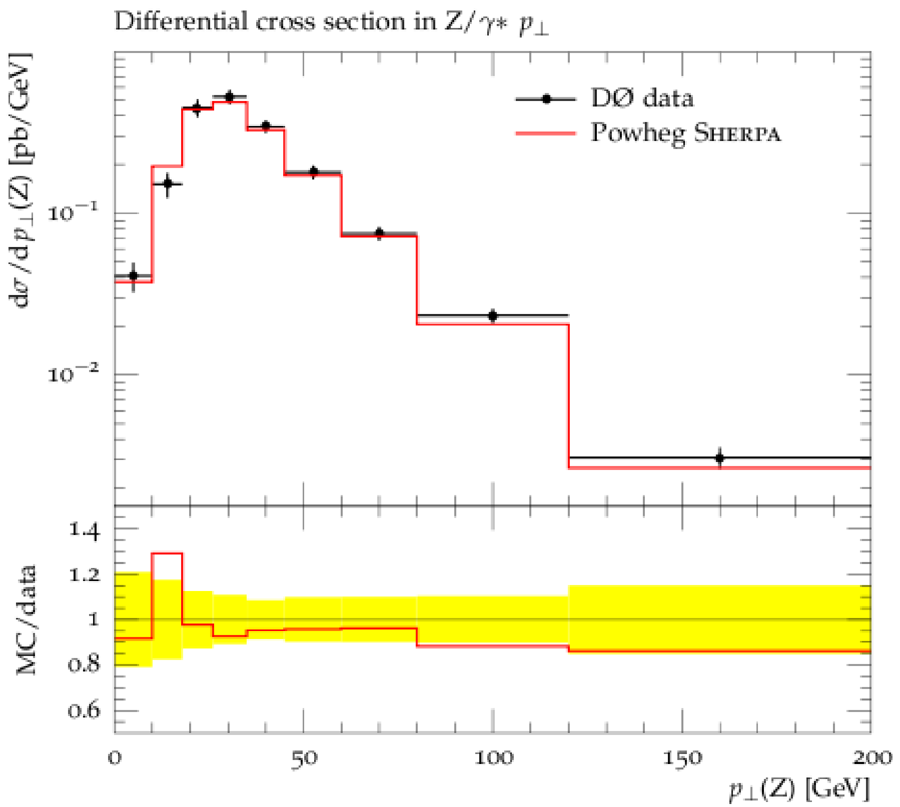


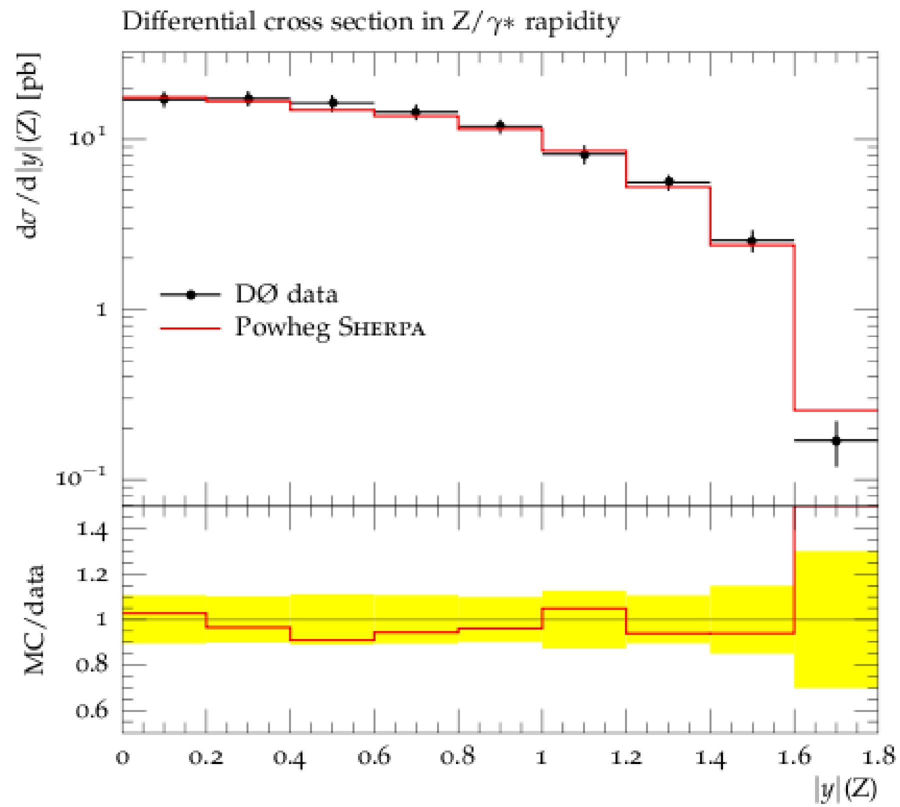
Z+j production at Tevatron



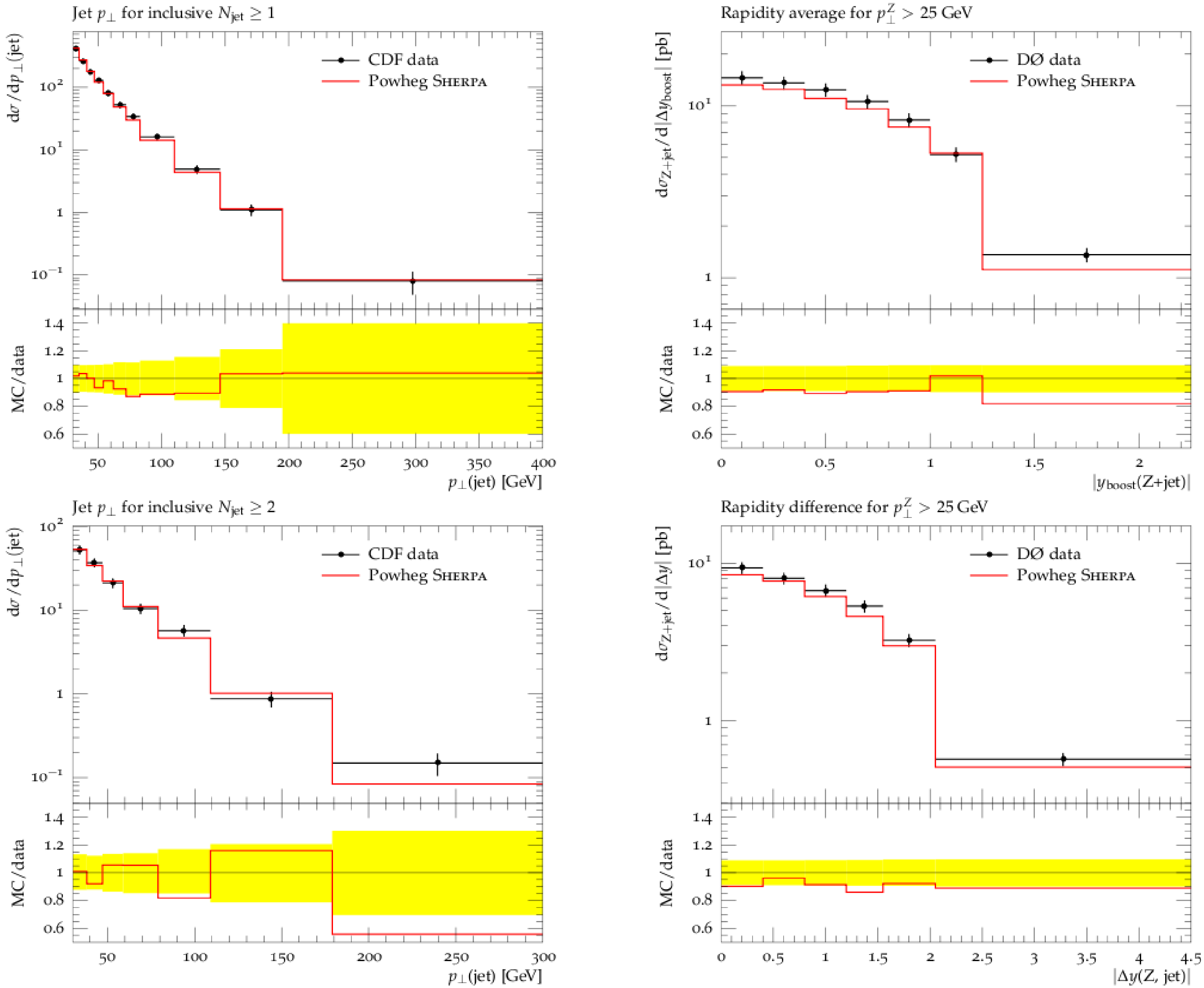


Z+j production at Tevatron

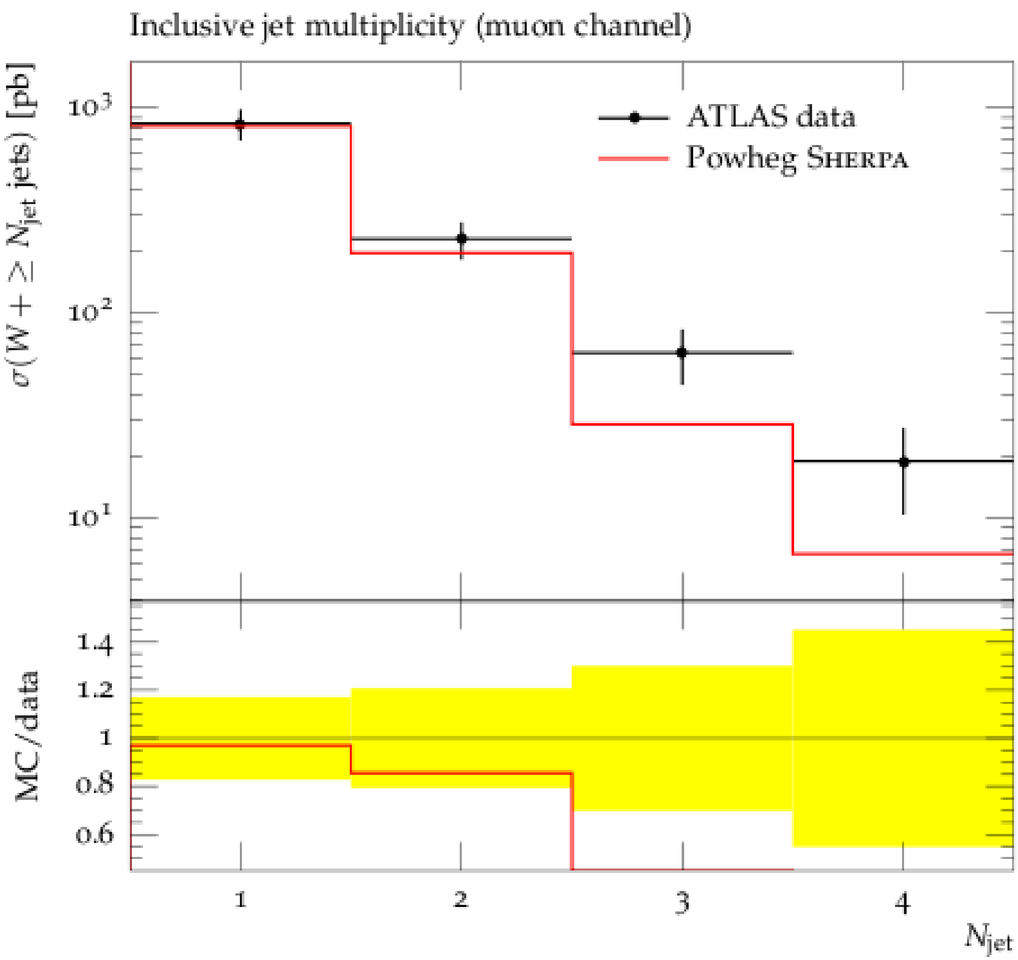


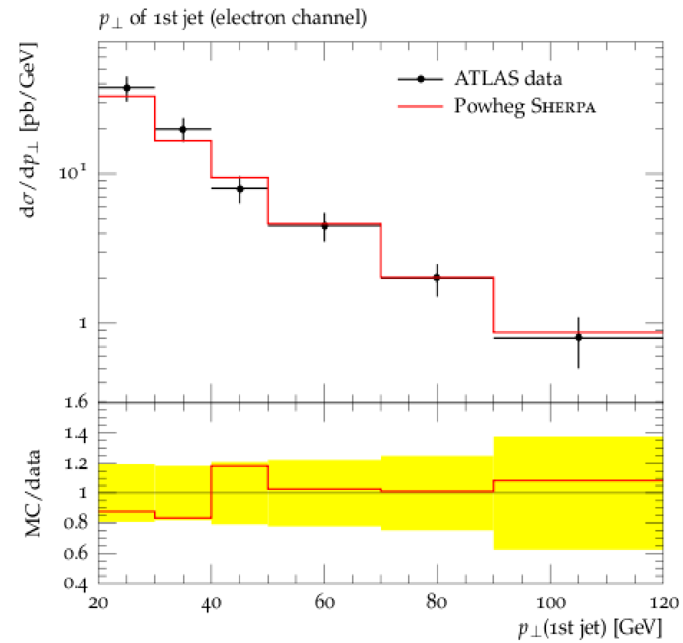


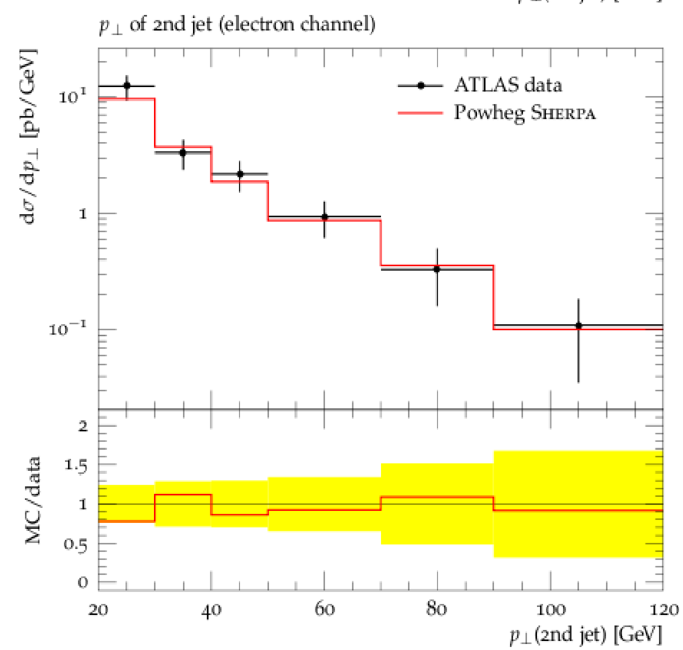
Z+j production at Tevatron: jets



W+j production at LHC







Conclusions and Outlook:

- Merging and matching methods extremely powerful tools, but some care needs to be taken:
  - Note that codes such as Alpgen, Helac, and Madgraph inherit α_s and to some extent scale choices from underlying event generator – may lead to inconsistencies and deserves careful studies (see talks during V+jet workshop at IPPP on this topic)
- Especially event generators Herwig++ and Sherpa made huge progress towards embedding HO accuracy in a systematic way, first steps also in Pythia8 (W+jets, by Lonnblad & Prestel)
- Full automation of Powheg method for trivial processes in Sherpa successful (need only virtual ME), work on non-trivial processes started.
- MENLOPS method will become the standard for simulations, incorporating the best of both worlds (merging and matching).
- Systematic multijet merging at NLO for hadronic collisions in reach ....

Sherpa status:

- Construction started in late 1990's, mainly through diploma and PhD theses.
- Up to date: 7 PhD theses and 12 diploma theses finished, in total around 50 man-years of code development and physics improvement.
- First release in 2002: Proof-of-concept version Sherpa 1.0 by now 1.3.0.
- Structure very modular, essentially bottom-up as design principle.
- Focus on perturbative aspects, especially multi-jet merging.
- By now: Two independent matrix element generators, a new shower, an independent version of cluster hadronization, an independent implementation of Pythia's old UE model, elaborate hadron decays, & QED final state radiation.
- Current main focus: NLO accuracy in multijet merging.
- In addition: New, independent Minimum Bias and Underlying Event model under active development.