QCD & Monte Carlo Tools

Frank Krauss

Institute for Particle Physics Phenomenology
Durham University

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Topics of the lectures

1. Lecture 1: *The Monte Carlo Principle*
    - Monte Carlo as integration method
    - Hard physics simulation: Parton Level event generation
2. Lecture 2: *Dressing the Partons*
    - Hard physics simulation, cont'd: Parton Showers
3. Lecture 3: *Modelling beyond Perturbation Theory*
    - Hadronic initial states: PDFs
    - Soft physics simulation: Hadronization
    - Beyond factorization: Underlying Event
4. Lecture 4: *Higher Orders in Monte Carlos*
    - Some nomenclature: Anatomy of HO calculations
    - Merging vs. Matching

Thanks to

- the other Sherpas: T.Gleisberg, S.Höche, S.Schumann, F.Siegert, M.Schönherr, J.Winter;
- other MC authors: S.Gieseke, K.Hamilton, L.Lonnblad, F.Maltoni, M.Mangano, P.Richardson, M.Seymour, T.Sjostrand, B.Webber, ...

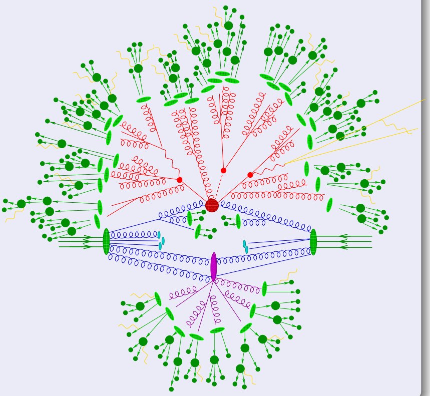
Simulation's paradigm

Basic strategy

Divide event into stages, separated by different scales.

- Signal/background:
  Exact matrix elements.
- QCD-Bremsstrahlung:
  Parton showers (also in initial state).
- Multiple interactions:
  Beyond factorization: Modeling.
- Hadronization:
  Non-perturbative QCD: Modeling.

Sketch of an event

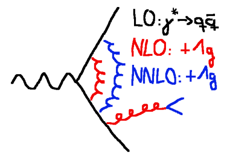


Outline of today's lecture

- Nomenclature: Definition of higher orders.
- ME corrections
- MC@NLO
- ME/PS merging

Nomenclature

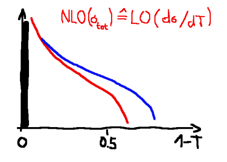
Specfiying higher-order corrections: $\gamma^* \longrightarrow$ hadrons



- In general: N^{n}LO $\leftrightarrow$ $\mathcal{O}(\alpha_s^n)$
- But: only for inclusive quantities

(e.g.: total xsecs like $\gamma^* \longrightarrow$hadrons).

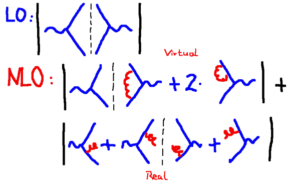
Counter-example: thrust distribution



- In general, distributions are HO.
- Distinguish real & virtual emissions: Real emissions $\longrightarrow$ mainly distributions, virtual emissions $\longrightarrow$ mainly normalisation.

Nomenclature

Anatomy of HO calculations: Virtual and real corrections



NLO corrections: $\mathcal{O}(\alpha_s)$

Virtual corrections	=	extra loops
Real corrections	=	extra legs

- UV-divergenices in virtual graphs $\longrightarrow$ renormalisation
- But also: IR-divergencies in real & virtual contributions
  Must cancel each other, non-trivial to see:
  N vs. $N+1$ particle FS, divergency in PS vs. loop

Nomenclature

Cancelling the IR divergencies: Subtraction method

- Total NLO xsec:
  $\sigma_{\rm NLO} = \sigma_{\rm Born} + \int {\rm d}^D k |\mathcal{M}|^2_V + \int {\rm d}^4 k |\mathcal{M}|^2_R$
- IR div. in real piece $\longrightarrow$ regularise:
  $\int {\rm d}^4 k |\mathcal{M}|^2_R \to \int {\rm d}^D k |\mathcal{M}|^2_R$
- Construct subtraction term with same IR structure:
  $\int {\rm d}^D k \left(|\mathcal{M}|^2_R - |\mathcal{M}|^2_S\right) = \int {\rm d}^4 k |\mathcal{M}|^2_{RS} =$ finite.
  Possible: $\int {\rm d}^D k |\mathcal{M}|^2_S = \sigma_{\rm Born} \int {\rm d}^D k |\tilde{\mathcal{S}}|^2$, universal $|\tilde{\mathcal{S}}|^2$.
- $\int {\rm d}^D k |\mathcal{M}|^2_V + \sigma_{\rm Born} \int {\rm d}^D k |\tilde{\mathcal{S}}|^2 =$ finite (analytical)

Nomenclature

State-of-the-art NLO calculations: General strategy

- Construct Born + 1st order terms
- Subtraction term: Born term × (analytical) divergencies

  Evaluate loop term analytically - perform cancellation
- Monte Carlo separately over subtracted real emission and virtual+subtraction term

Limitations

- So far only loops with ≤ 5 propagators under full control

  $\Longrightarrow$ in general, only $2 \to 3$ processes at NLO
- Soft/collinear corners maybe still badly described

Nomenclature

Resummation: Basic idea

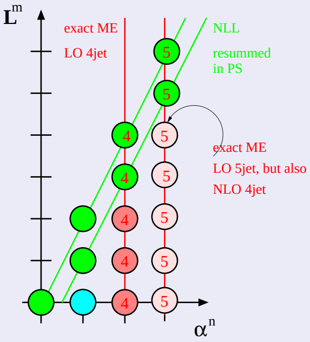
- Observation: Universal soft & collinear divergencies @ all orders
  Cutting them produces universal logarithms.
- Universality $\Longrightarrow$ resummation of leading logs @ all orders possible.
  Improves behaviour in soft/collinear regions of phase space.
  Example: Thrust distribution.
- Nomenclature: LL, NLL, NNLL, ...
  Limitation due to mixing with finite pieces @ some N^{n}LL.
- Leading logs also in parton shower (=resummation!!)

Orders in ME and PS

ME vs. PS

- Matrix elements good for: hard, large-angle emissions; take care of interferences.
- Parton shower good for: soft, collinear emissions; resums large logarithms.
- Want to combine both! Avoid double-counting.

α_s vs. Log

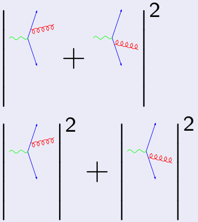


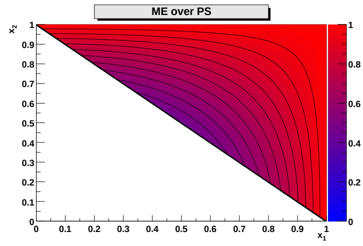
Correcting the parton shower

Example: $e^+e^- \to q\bar{q}g$

ME :

PS :





Correcting the parton shower

Practicalities of ME-corrections

- Obviously, $ME < PS$ is not always fulfilled.
- Could enhance PS expression by a (large) factor.
  Question: Efficiency of the approach?
- Therefore: realised in few processes only:
  Best-known: $ee \longrightarrow q\bar{q}$, $q\bar{q} \longrightarrow V$, $t \longrightarrow bW$

Correcting the parton shower

Power shower

Can use ME corrections for "power shower":

This is the evil empire of MC event generators!

- In $q\bar{q} \to V$, start parton shower @ $s_{\rm pp}$.
- Reweight first emissions on both legs with ME.
- Effect: More hard radiation through showering.

MC@NLO

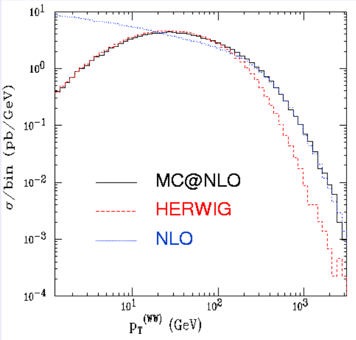
S.Frixione, B.R.Webber, JHEP **0206** (2002) 029
S.Frixione, P.Nason, B.R.Webber, JHEP **0308** (2003) 007

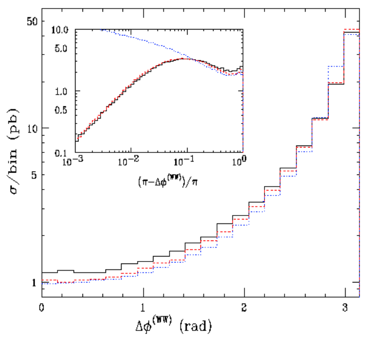
Basic principles

- Want:
  - NLO-Normalization and first (hard) emission correct,
  - Soft emissions correctly resummed in PS.
- Method:
  - Modify subtraction terms for real infrared divergences,
  - use first order parton shower-expression,
  - this is process-dependent!
- In practise much more complicated.
- Implemented for DY, W-pairs, $gg \to H$, Q-pairs.

MC@NLO

Example results: W-pairs @ Tevatron





Combining MEs & PS

S.Catani, F.K., R.Kuhn and B.R.Webber, JHEP **0111** (2001) 063
F.K., JHEP **0208** (2002) 015

Basic principles

- Want:
  - All jet emissions correct at tree level + LL,
  - Soft emissions correctly resummed in PS
- Method:
  - Separate Jet-production/evolution by $Q_{\rm jet}$ ($k_\perp$ algorithm).
  - Produce jets according to LO matrix elements
  - re-weight with Sudakov form factor + running α_s weights,
  - veto jet production in parton shower.
- Process-independent implementation.

Combining MEs & PS

n-jet rates @ NLL

S.Catani *et al.* Phys. Lett. **B269** (1991) 432

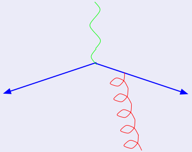
At NLL-Accuracy

$$\mathcal{R}_2(Q_{\rm jet}) = \left[\Delta_q(E_{\rm c.m.}, Q_{\rm jet})\right]^2$$

$$\mathcal{R}_3(Q_{\rm jet}) = 2\Delta_q(E_{\rm c.m.}, Q_{\rm jet}) \cdot \int {\rm d}q \left[\alpha_s(q)\Gamma_q(E_{\rm c.m.}, q)\frac{\Delta_q(E_{\rm c.m.}, Q_{\rm jet})}{\Delta_q(q, Q_{\rm jet})} \Delta_q(q, Q_{\rm jet})\Delta_g(q, Q_{\rm jet})\right]$$

Sudakov weights

Example: $\gamma^* \to q\bar{q}g$



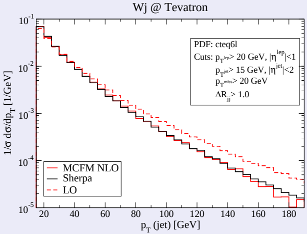
$$\mathcal{W}_{\rm Sud} = \frac{\alpha_s(q)}{\alpha_s(Q_{\rm jet})} \cdot \Delta_q(E_{\rm c.m.}, Q_{\rm jet}) \frac{\Delta_q(E_{\rm c.m.}, Q_{\rm jet})}{\Delta_q(q, Q_{\rm jet})} \Delta_q(q, Q_{\rm jet})\Delta_g(q, Q_{\rm jet})$$

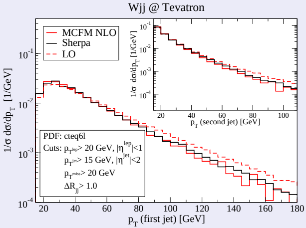
Combining MEs & PS

Algorithm as scale-setting prescription

- Example: $p_\perp$ distribution of jets @ Tevatron
- Consider exclusive $W+1$- and $W+2$-jet production

Comparison with MCFM; J.Campbell and R.K.Ellis, Phys. Rev. D **65** (2002) 113007
in : F.K., A.Schälicke, S.Schumann and G.Soff, Phys. Rev. D **70** (2004) 114009

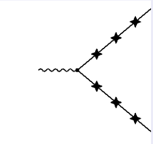




Sherpa = tree-level matrix elements with α_s scales and Sudakov form factors.

Combining MEs & PS

Vetoing the shower



$$\mathcal{W}_{\rm Veto} = \left\{1+\int_{Q_{\rm jet}}^{E_{\rm c.m.}} dq\,\Gamma_q(E_{\rm c.m.},q)+\int_{Q_{\rm jet}}^{E_{\rm c.m.}} dq\,\Gamma_q(E_{\rm c.m.},q)\int_{Q_{\rm jet}}^{q} dq'\,\Gamma_q(E_{\rm c.m.}q')+\dots\right\}^2$$
$$= \left\{\exp\left(\int_{Q_{\rm jet}}^{E_{\rm c.m.}} dq\,\Gamma_q(E_{\rm c.m.},q)\right)\right\}^2 = \Delta_q^{-2}(E_{\rm c.m.},Q_{\rm jet})$$

$\Longrightarrow$ Cancels dependence on $Q_{\rm jet}$.

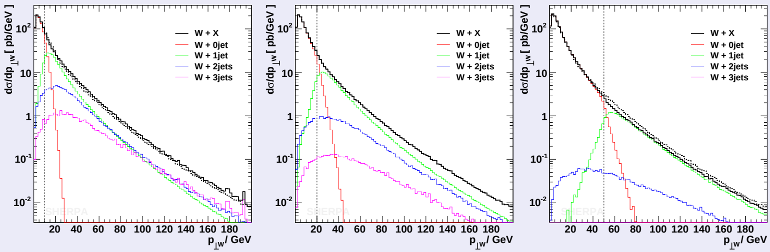
Combining MEs & PS

Independence on $Q_{\rm jet}$

Example: $p_\perp$ of W in $p\bar{p} \to W + X$ @ Tevatron

in F.K., A.Schälicke, S.Schumann and G.Soff, Phys. Rev. D **70** (2004) 114009

$Q_{\rm jet} = 10\,{\rm GeV}$ $Q_{\rm jet} = 30\,{\rm GeV}$ $Q_{\rm jet} = 50\,{\rm GeV}$



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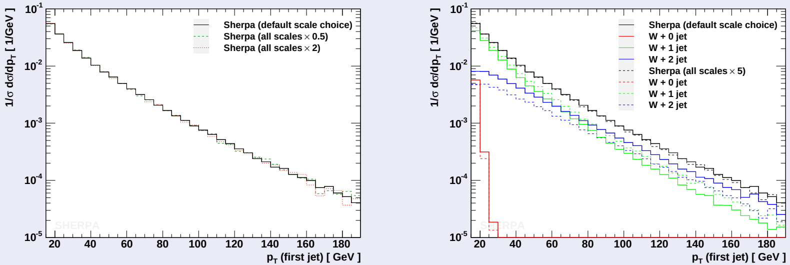
Merging issues: Dependence on scales

$p_\perp$ distribution of 1st jet @ Tevatron

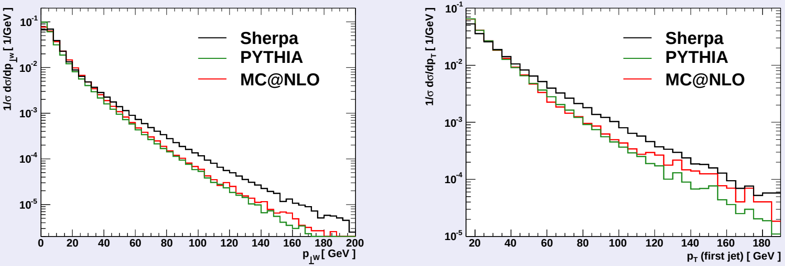


Combining MEs & PS

Comparison with other codes

$p_\perp$ of W-bosons & jets in $p\bar{p} \to W + X$ @ Tevatron

$p_\perp^W$ $p_\perp^{\rm 1st\,jet}$

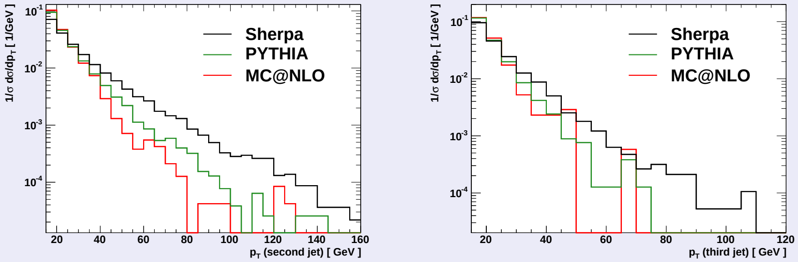


Combining MEs & PS

Comparison with other codes

$p_\perp$ of W-bosons & jets in $p\bar{p} \to W + X$ @ Tevatron

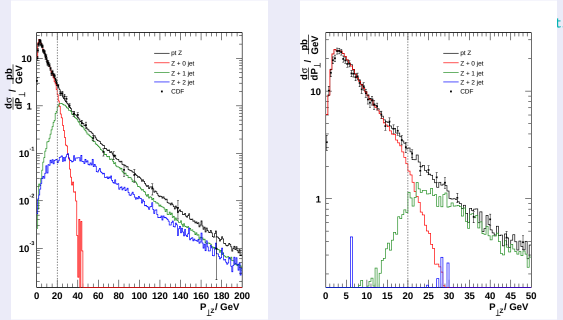
$p_\perp^{\text{2nd jet}}$ $p_\perp^{\text{3rd jet}}$



Combining MEs & PS

Comparison with data from Tevatron

$p_\perp$ of Z-bosons in $p\bar{p} \to Z + X$

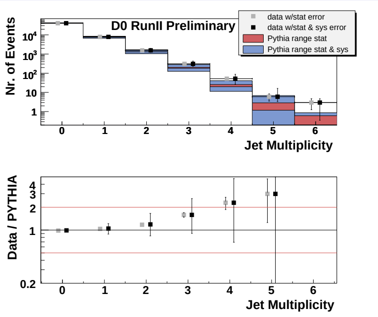


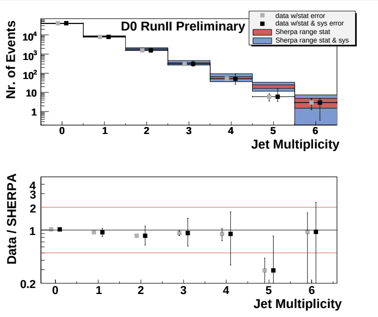
t. 84 (2000) 845

Combining MEs & PS

Comparison with data from Tevatron

Jet rates in $p\bar{p} \to Z + X$ (D0-Note 5066)

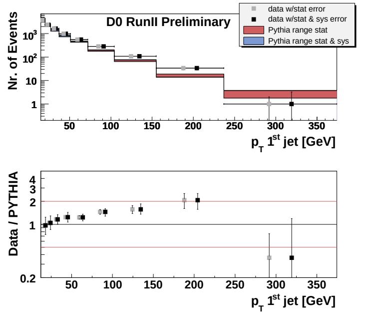


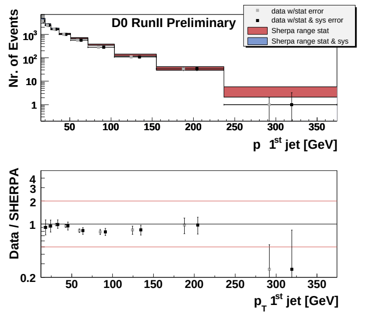


Combining MEs & PS

Comparison with data from Tevatron

Jet spectra (1st jet) in $p\bar{p} \to Z + X$ (D0-Note 5066)

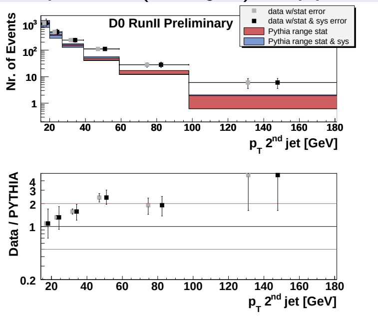


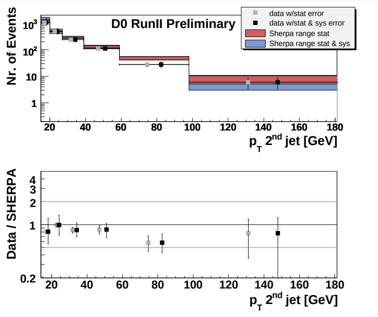


Combining MEs & PS

Comparison with data from Tevatron

Jet spectra (2nd jet) in $p\bar{p} \to Z + X$ (D0-Note 5066)

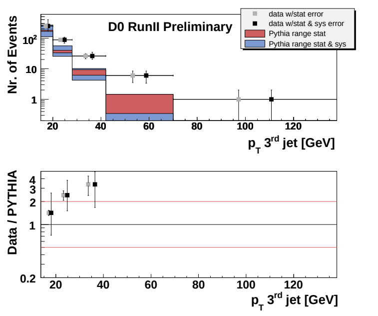


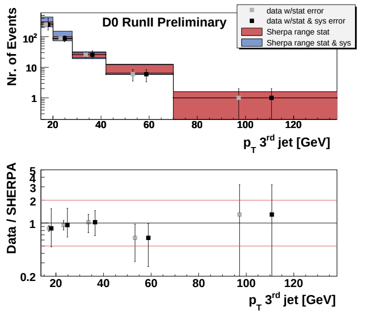


Combining MEs & PS

Comparison with data from Tevatron

Jet spectra (3rd jet) in $p\bar{p} \to Z + X$ (D0-Note 5066)





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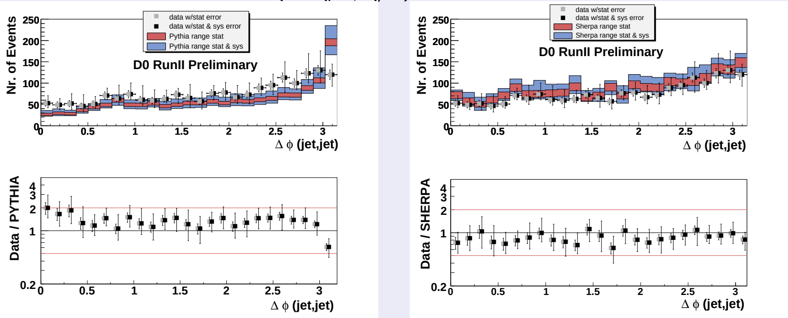
Comparison with data from Tevatron

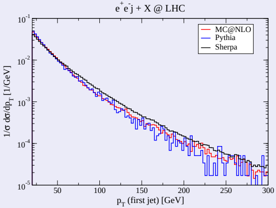
Azimuthal correlation ($\angle_{1.\mathrm{jet},2.\mathrm{jet}}$) in $p\bar{p} \to Z + X$ (D0-Note 5066)

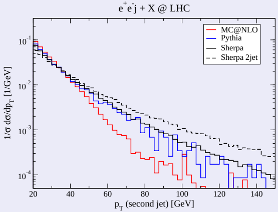


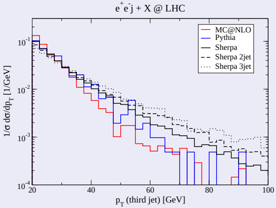
Extrapolation to LHC: Jets

$p_\perp$ of jets in inclusive Z+jets

- Influence of more jets.
- Displayed here: x-sections.
- Difference in shape & x-sec.



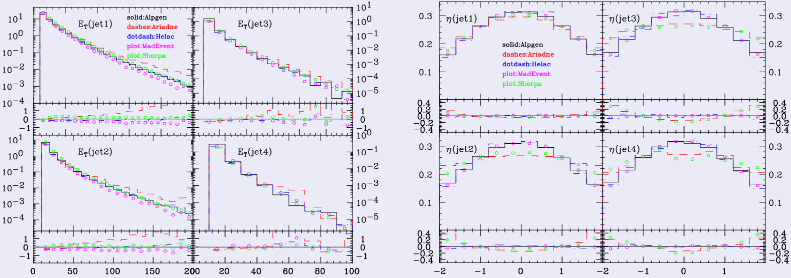




Combining MEs & PS

Comparison with other merging algorithms: MLM

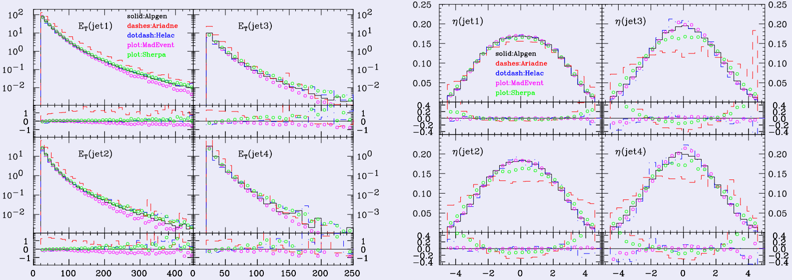
$p_\perp$ of jets in inclusive W+jets at Tevatron



Combining MEs & PS

Comparison with other merging algorithms: MLM

$p_\perp$ of jets in inclusive W+jets at LHC



Summary & outlook

Summary: QCD & simulation tools

- Many interesting signals at LHC "spoiled" by QCD.
- Need to understand & describe QCD to high precision.
- Simulation tools mandatory for success of LHC (example: jets in backgrounds)
- Time to improve & validate essential tools is now!
- New methods of merging of ME& PS extremely powerful.
- Different, complementary aspects w.r.t. MC@NLO.
- Important: educated choice which tool to use!
- Important: know your Monte Carlo!
- Important: know the assumptions!