Event Generator Physics

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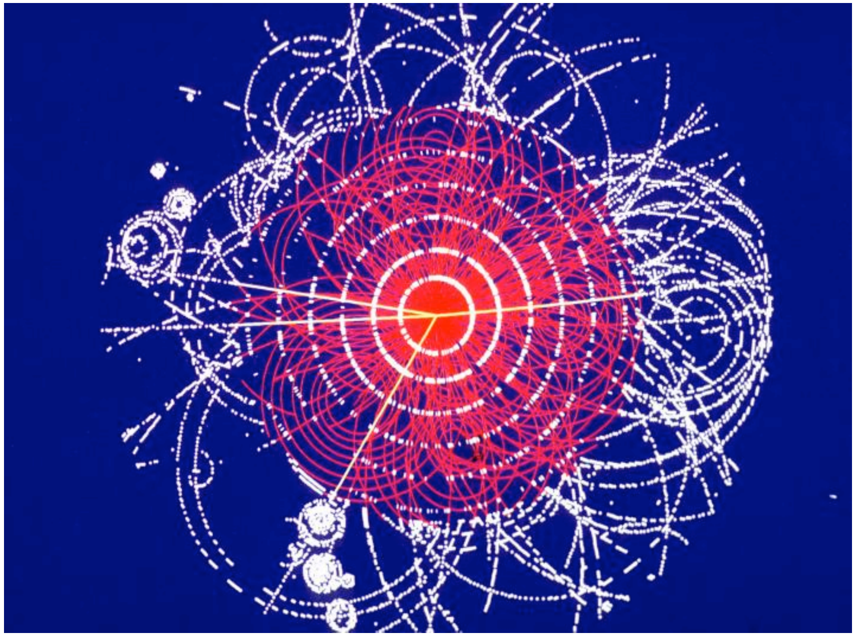
Event Generator Physics

- Basic Principles
- Event Generation
- Parton Showers
- Hadronization
- Underlying Events
- Survey of EGs
- Matching



Lecture 5: Matching

- Two rather different objectives:
- Matching parton showers to NLO matrix elements, without double counting
  – MC@NLO
- Matching parton showers to LO n-jet matrix elements, minimizing jet resolution dependence
  – CKKW
  – Dipole
  – MLM Matching
  – Comparisons

MC@NLO

Recall simple one-dim. example from lecture 1:

$$|\mathcal{M}_{m+1}|^2 \equiv \frac{1}{x}\mathcal{M}(x)$$

x = gluon energy or two-parton invariant mass.

Divergences regularized by $d = 4 - 2\epsilon$ dimensions.

$$|\mathcal{M}_m^{\text{one-loop}}|^2 \equiv \frac{1}{\epsilon}\mathcal{V}$$

Cross section in d dimensions is:

$$\sigma = \int_0^1 \frac{dx}{x^{1+\epsilon}}\,\mathcal{M}(x)\;F_1^J(x) + \frac{1}{\epsilon}\mathcal{V}\;F_0^J$$

Infrared safety: $F_1^J(0) = F_0^J$

KLN cancellation theorem: $\mathcal{M}(0) = \mathcal{V}$

Subtraction Method

Exact identity:

$$\sigma^J = \int_0^1 \frac{dx}{x^{1+\epsilon}} \mathcal{M}(x)\, F_1^J(x) - \int_0^1 \frac{dx}{x^{1+\epsilon}} \mathcal{V}\, F_0^J$$
$$+ \int_0^1 \frac{dx}{x^{1+\epsilon}} \mathcal{V}\, F_0^J + \frac{1}{\epsilon}\mathcal{V}\, F_0^J$$
$$= \int_0^1 \frac{dx}{x} \left(\mathcal{M}(x)\, F_1^J(x) - \mathcal{V}\, F_0^J\right) + \mathcal{O}(1)\, \mathcal{V}\, F_0^J .$$

➡ Two separate finite integrals.

Modified Subtraction

$$\sigma^J = \int_0^1 \frac{dx}{x} \left(\mathcal{M}(x)\, F_1^J(x) - \mathcal{V}\, F_0^J\right) + \mathcal{O}(1)\, \mathcal{V}\, F_0^J$$

Now add parton shower:

$F_{0,1}^J \Rightarrow$ result from showering after 0,1 emissions.

But shower adds $\mathcal{M}_{\rm MC}/x$ to 1 emission. Must subtract this, and add to 0 emission (so that $F_{0,1}^{\rm tot} = 1 \Rightarrow \sigma^{\rm tot}$ fixed)

$$\begin{aligned} \sigma^J \quad &= \quad \int_0^1 \frac{dx}{x} \left(\{\mathcal{M}(x) - \mathcal{M}_{\rm MC}(x)\}\; F_1^J(x)\right. \\ &\qquad \left. - \{\mathcal{V} - \mathcal{M}_{\rm MC}(x)\}\; F_0^J\right) + \mathcal{O}(1)\, \mathcal{V}\, F_0^J \end{aligned}$$

MC good for soft and/or collinear $\Rightarrow \mathcal{M}_{\rm MC}(0) = \mathcal{M}(0)$

➡ 0 & 1 emission contributions separately finite now!

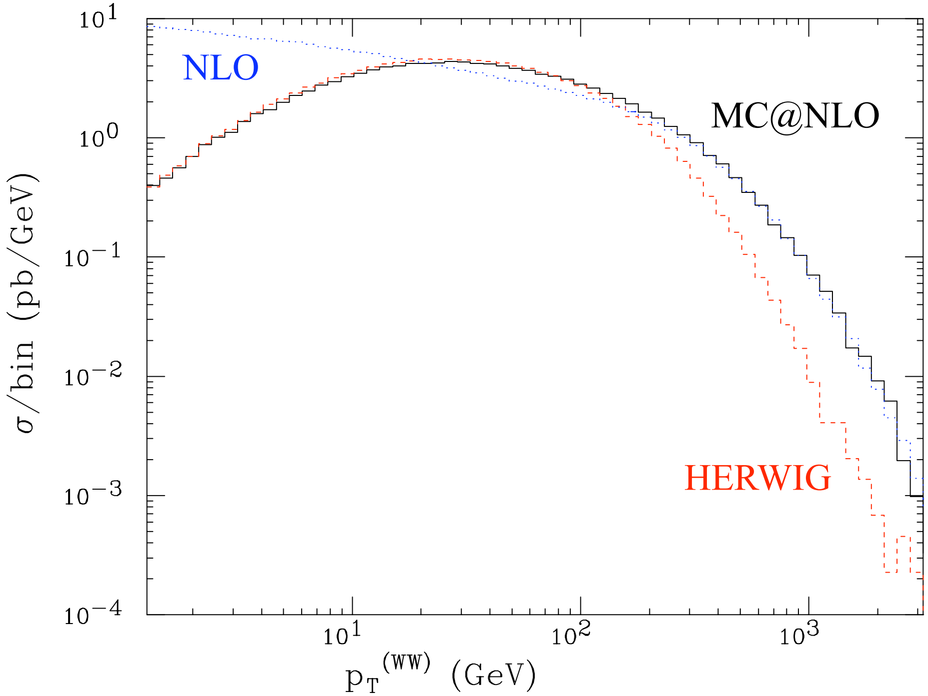
(But some can be negative “counter-events”)

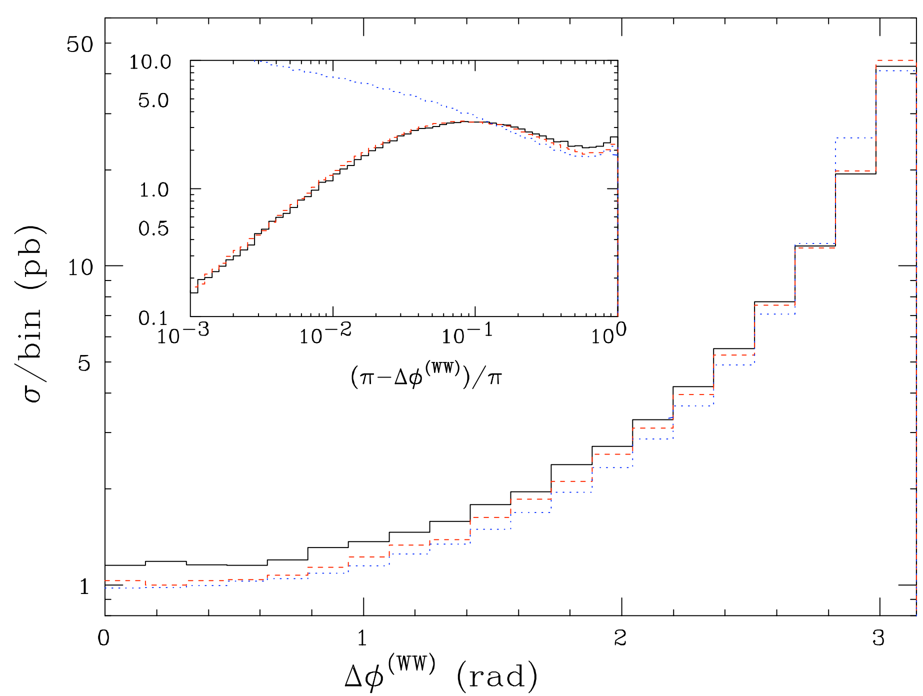
MC@NLO Processes

IPROC	IV	IL_1	IL_2	Spin	Process
–1350–IL				✓	$H_1H_2 \to (Z/\gamma^* \to) l_{IL}\bar{l}_{IL} + X$
–1360–IL				✓	$H_1H_2 \to (Z \to) l_{IL}\bar{l}_{IL} + X$
–1370–IL				✓	$H_1H_2 \to (\gamma^* \to) l_{IL}\bar{l}_{IL} + X$
–1460–IL				✓	$H_1H_2 \to (W^+ \to) l^+_{IL}\nu_{IL} + X$
–1470–IL				✓	$H_1H_2 \to (W^- \to) l^-_{IL}\bar{\nu}_{IL} + X$
–1396				×	$H_1H_2 \to \gamma^*(\to \sum_i f_i\bar{f}_i) + X$
–1397				×	$H_1H_2 \to Z^0 + X$
–1497				×	$H_1H_2 \to W^+ + X$
–1498				×	$H_1H_2 \to W^- + X$
–1600–ID					$H_1H_2 \to H^0 + X$
–1705					$H_1H_2 \to b\bar{b} + X$
–1706				×	$H_1H_2 \to t\bar{t} + X$
–2000–IC				×	$H_1H_2 \to t/\bar{t} + X$
–2001–IC				×	$H_1H_2 \to \bar{t} + X$
–2004–IC				×	$H_1H_2 \to t + X$
–2600–ID	1	7		×	$H_1H_2 \to H^0W^+ + X$
–2600–ID	1	i		✓	$H_1H_2 \to H^0(W^+ \to) l^+_i\nu_i + X$
–2600–ID	-1	7		×	$H_1H_2 \to H^0W^- + X$
–2600–ID	-1	i		✓	$H_1H_2 \to H^0(W^- \to) l^-_i\bar{\nu}_i + X$
–2700–ID	0	7		×	$H_1H_2 \to H^0Z + X$
–2700–ID	0	i		✓	$H_1H_2 \to H^0(Z \to) l_i\bar{l}_i + X$
–2850		7	7	×	$H_1H_2 \to W^+W^- + X$
–2850		i	j	✓	$H_1H_2 \to (W^+ \to) l^+_i\nu_i(W^- \to) l^-_j\bar{\nu}_j + X$
–2860		7	7	×	$H_1H_2 \to Z^0Z^0 + X$
–2870		7	7	×	$H_1H_2 \to W^+Z^0 + X$
–2880		7	7	×	$H_1H_2 \to W^-Z^0 + X$

MC@NLO Results

- WW production at LHC



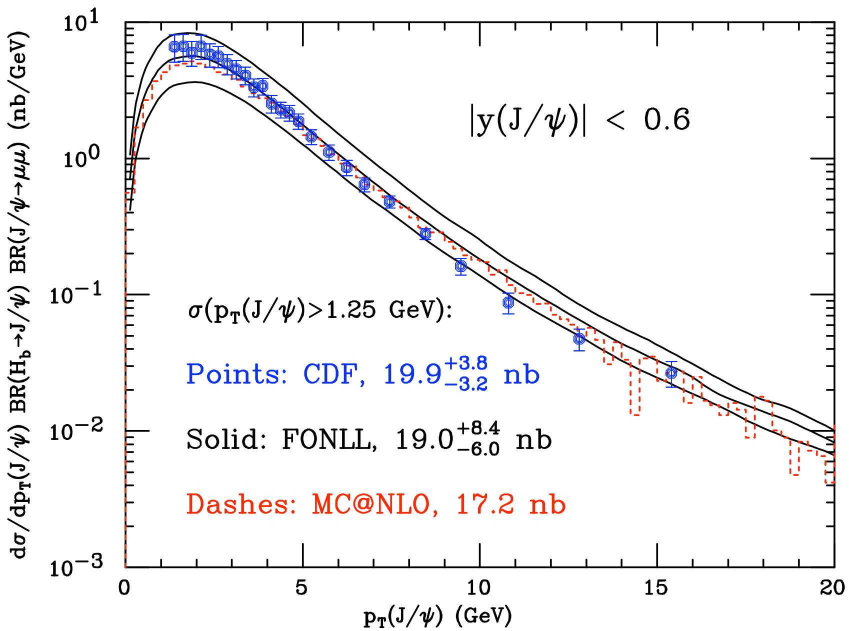


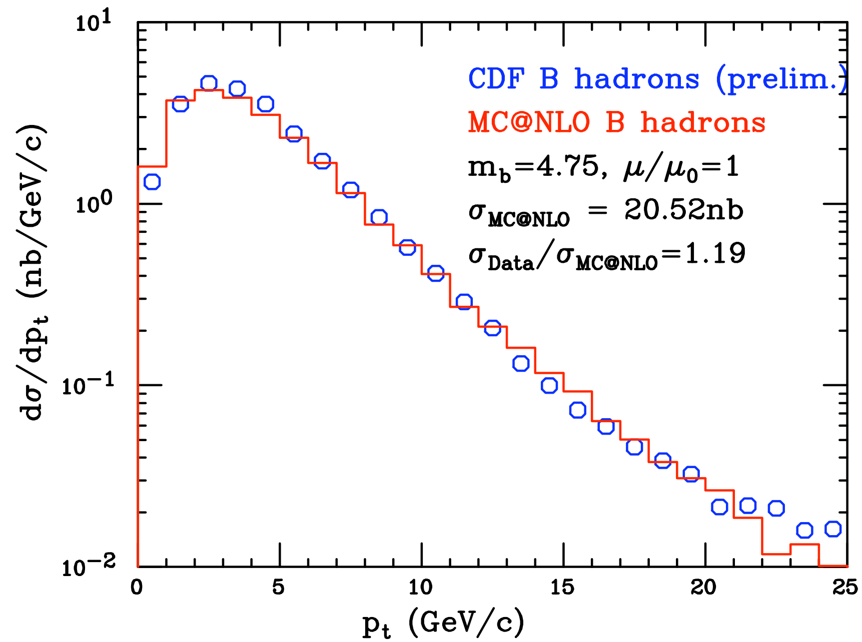
- Interpolates between MC & NLO in $p_T^{(WW)}$
- Above both at $\Delta\phi^{(WW)} \simeq 0$

S Frixione & BW, JHEP 06(2002)029

MC@NLO: B Production at Tevatron

- $B \to J/\psi$ results from Tevatron Run II $\Rightarrow$ B hadrons

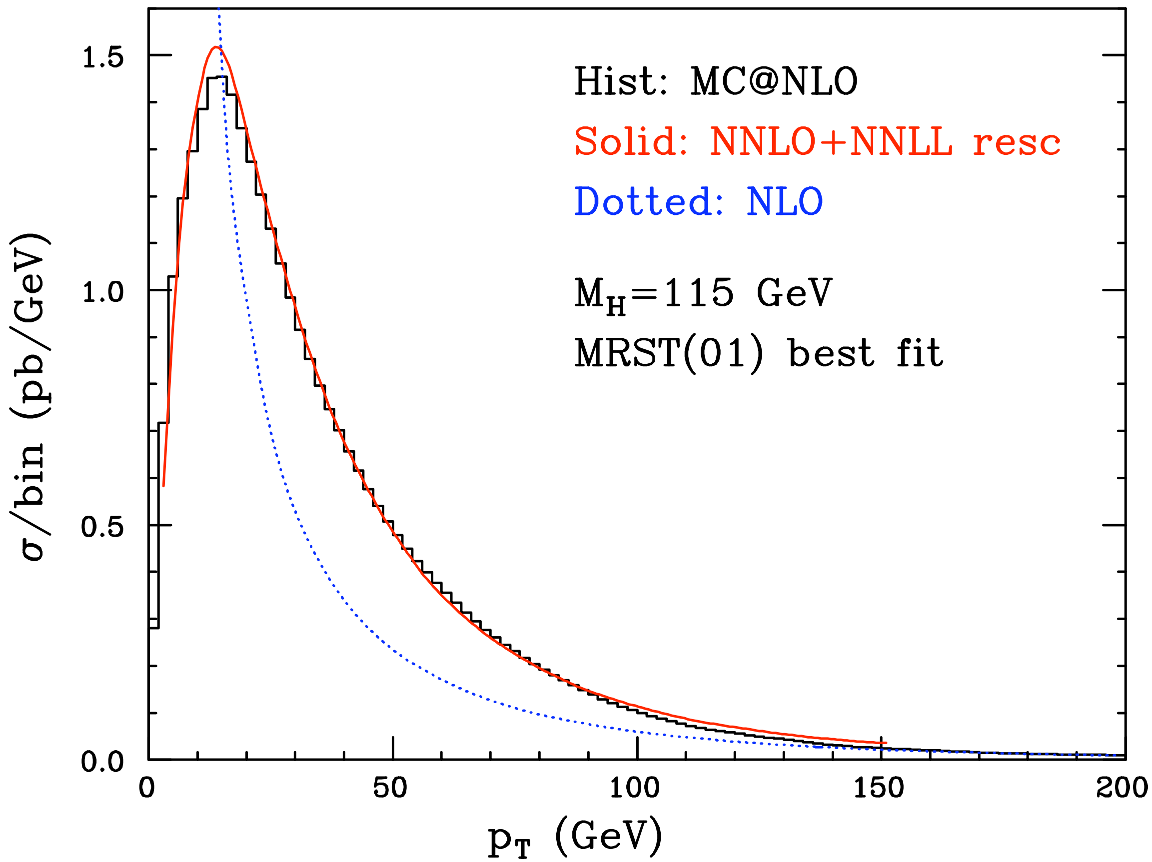




➡ Good agreement (and MC efficiency)

S Frixione, P Nason & BW, JHEP 08(2003)007

MC@NLO: Higgs Production at LHC



V Del Duca, S Frixione, C Oleari & BW, in prep.

- Good agreement with state-of-the-art resummation

CKKW Matching

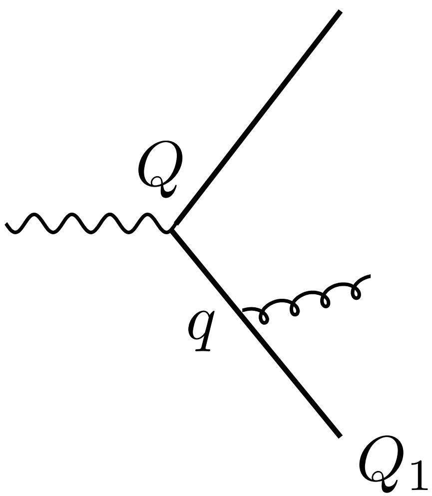
- Use Matrix Elements down to scale Q_1
- Use Parton Showers below Q_1
- Correct ME by reweighting
- Correct PS by vetoing
- Ensure that Q_1 cancels (to NLL)

S Catani, F Krauss, R Kuhn & BW, JHEP11 (2001) 063

Example: $e^+e^- \to$ hadrons

- 2- & 3-jet rates at scale Q_1:

$$
\begin{aligned}
R_2(Q,Q_1) &= \left[\Delta_q(Q,Q_1)\right]^2 \;, \\
R_3(Q,Q_1) &= 2\Delta_q(Q,Q_1)\int_{Q_1}^{Q} dq\, \frac{\Delta_q(Q,Q_1)}{\Delta_q(q,Q_1)}\Gamma_q(Q,q) \\
&\quad \times\Delta_q(q,Q_1)\Delta_g(q,Q_1) \\
&= 2\left[\Delta_q(Q,Q_1)\right]^2 \int_{Q_1}^{Q} dq\,\Gamma_q(Q,q)\Delta_g(q,Q_1)
\end{aligned}
$$



$$\Gamma_q(Q,q) = \frac{2C_F}{\pi}\frac{\alpha_S(q)}{q}\left(\ln\frac{Q}{q} - \frac{3}{4}\right)$$

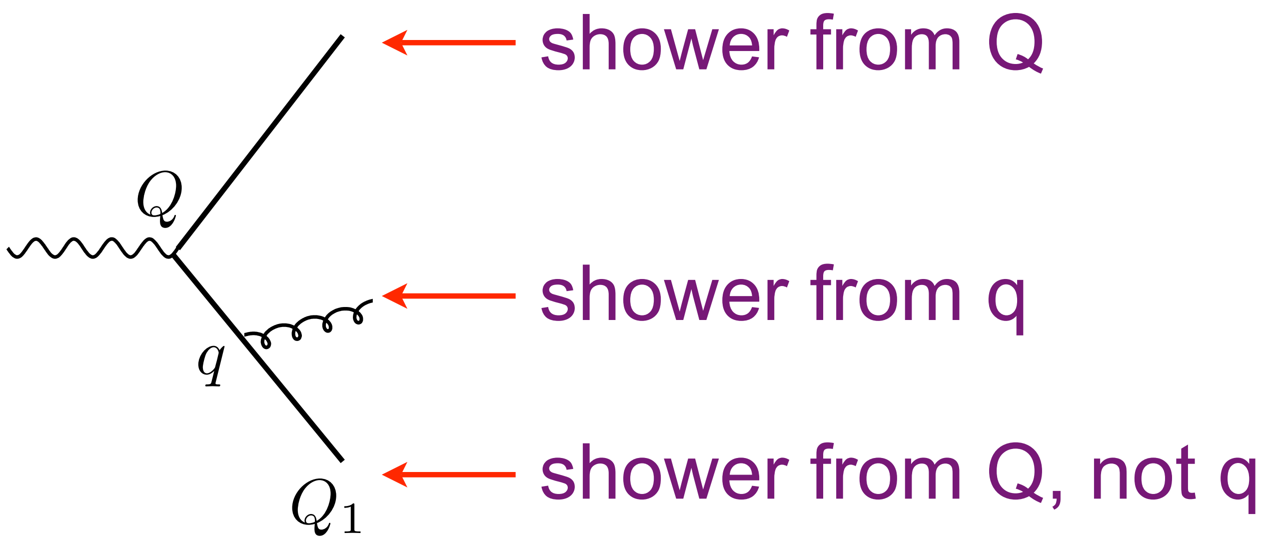
CKKW reweighting

- Choose n according to $R_n(Q, Q_1)$ (LO)
  - use $[\alpha_S(Q_1)]^n$
- Use exact LO ME to generate n partons
- Construct "equivalent shower history"
  - preferably using k_T-type algorithm
- Weight vertex at scale q by $\alpha_S(q)/\alpha_S(Q_1) < 1$
- Weight parton of type i from Q_j to Q_k by

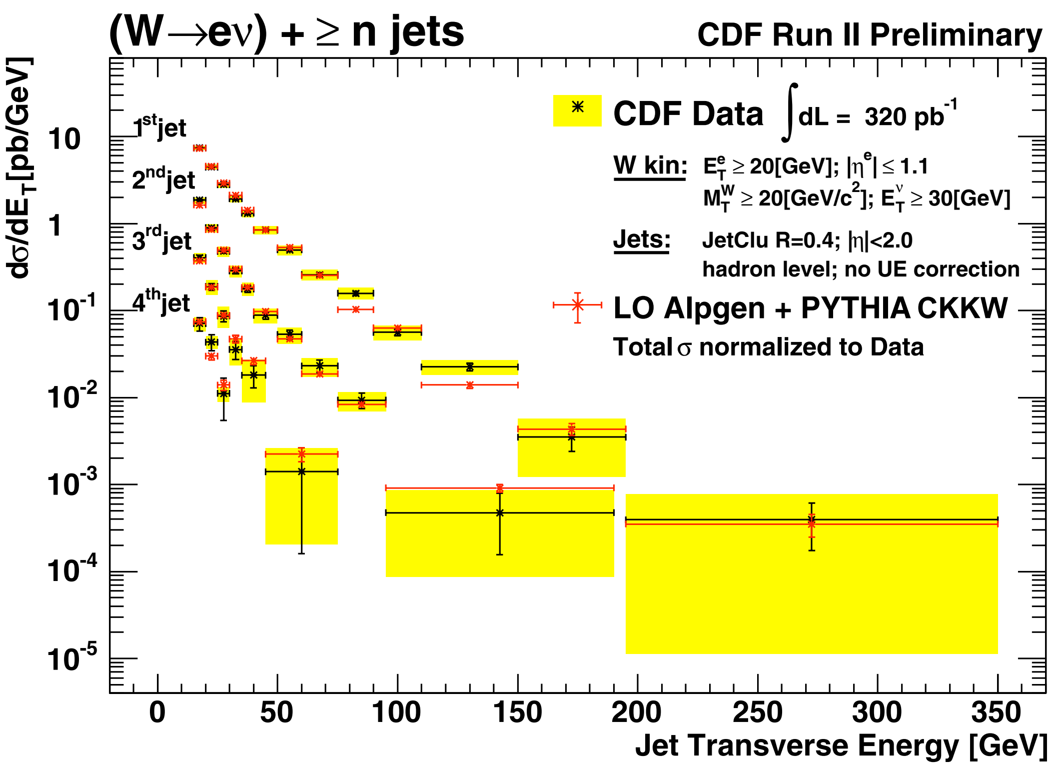
$$\Delta_i(Q_j, Q_1)/\Delta_i(Q_k, Q_1)$$

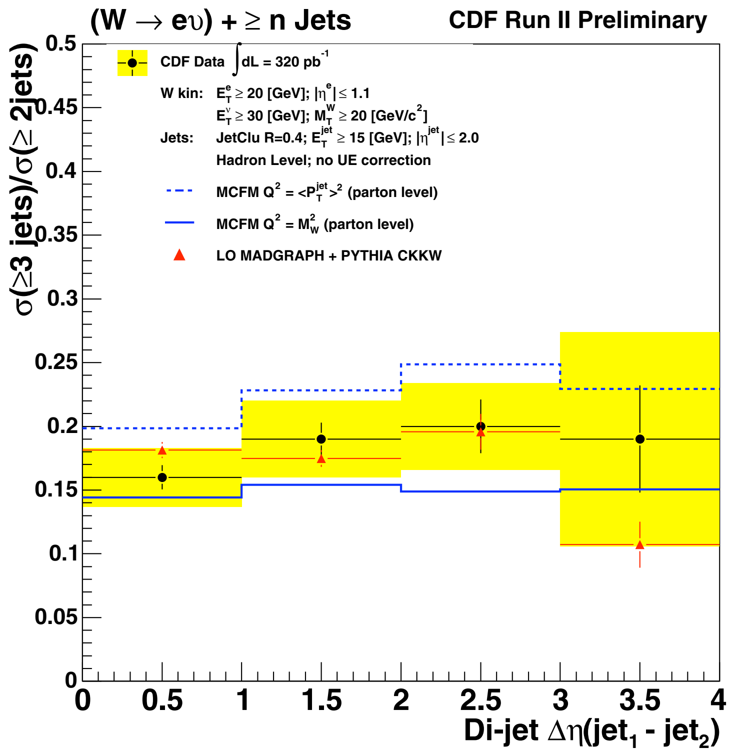
CKKW shower veto

- Shower n partons from “creation scales”
  - includes coherent soft emission
- Veto emissions at scales above Q_1
  - cancels leading (LL&NLL) Q_1 dependence



Comparisons with Tevatron data





from JM Campbell, JW Huston & WJ Stirling, Rept.Prog.Phys.70(2007)89

➡ M.E. + PYTHIA CKKW looks good

Dipole Matching

- Implemented in ARIADNE dipole MC
- Dipole cascade replaces parton shower
- Construct equivalent dipole history $\{p_{Ti}\}$
- Rejection replaces Sudakov weights
  - cascade from p_{Ti}, reject if $p_T > p_{Ti+1}$

L Lönnblad, JHEP05(2002)046

MLM Matching

- Use cone algorithm for jet definition:

$$R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

$$E_{Ti} > E_{Tmin}, \; R_{ij} > R_{min}$$

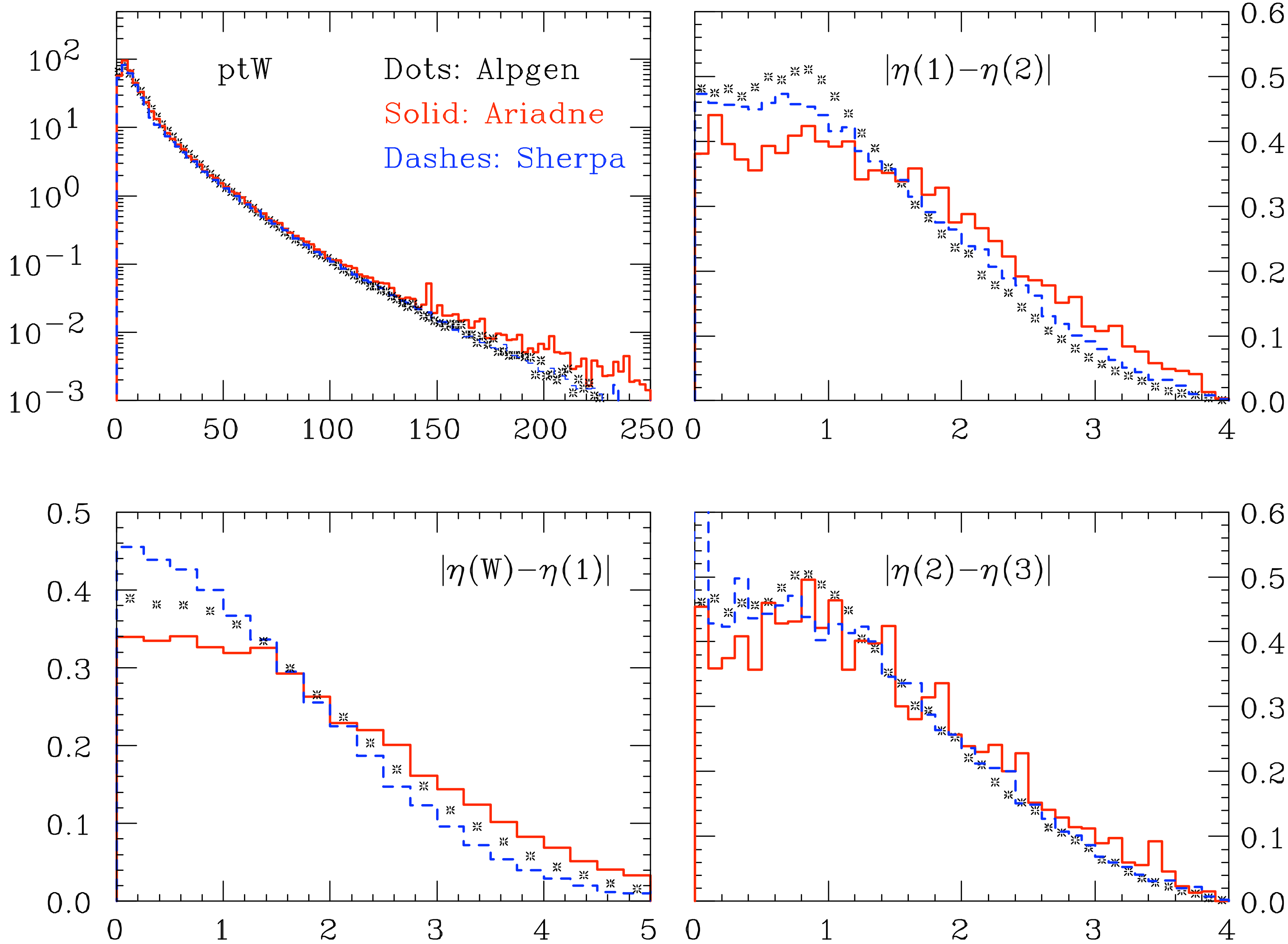
- Generate n-parton configurations with $E_{Ti} > E_{Tmin}, \; R_{ij} > R_{min}$ (no Sudakov weights)
- Generate showers (no vetos)
- Form jets using same jet definition
- Reject event if $n_{jets} \neq n_{partons}$

Comparisons

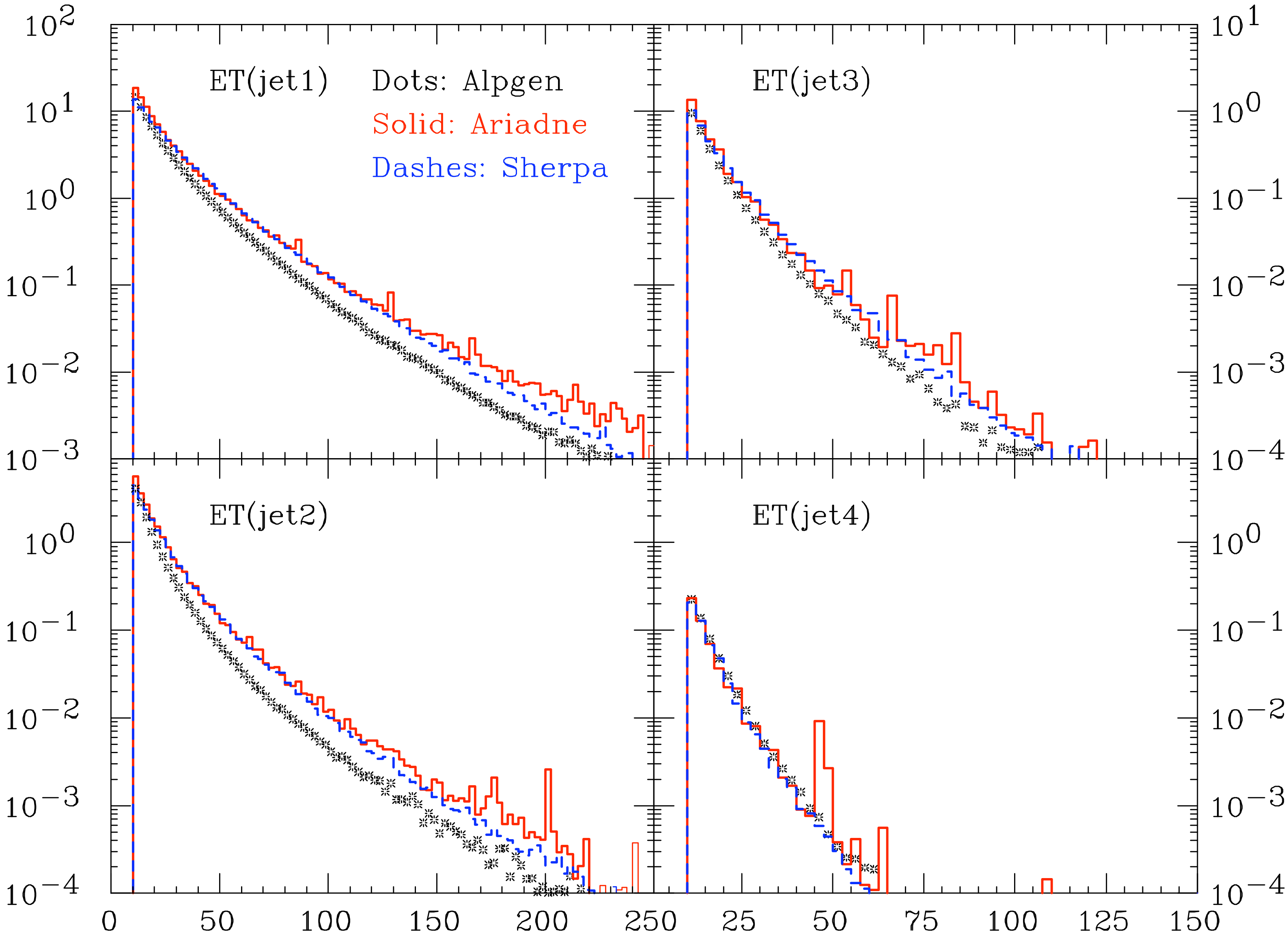
- ALPGEN: MLM matching
- ARIADNE: Dipole matching
  - problems with $g \longrightarrow q\bar{q} \;\Rightarrow$ not yet for LHC
- SHERPA: CKKW

S Höche el al., hep-ph/0602031

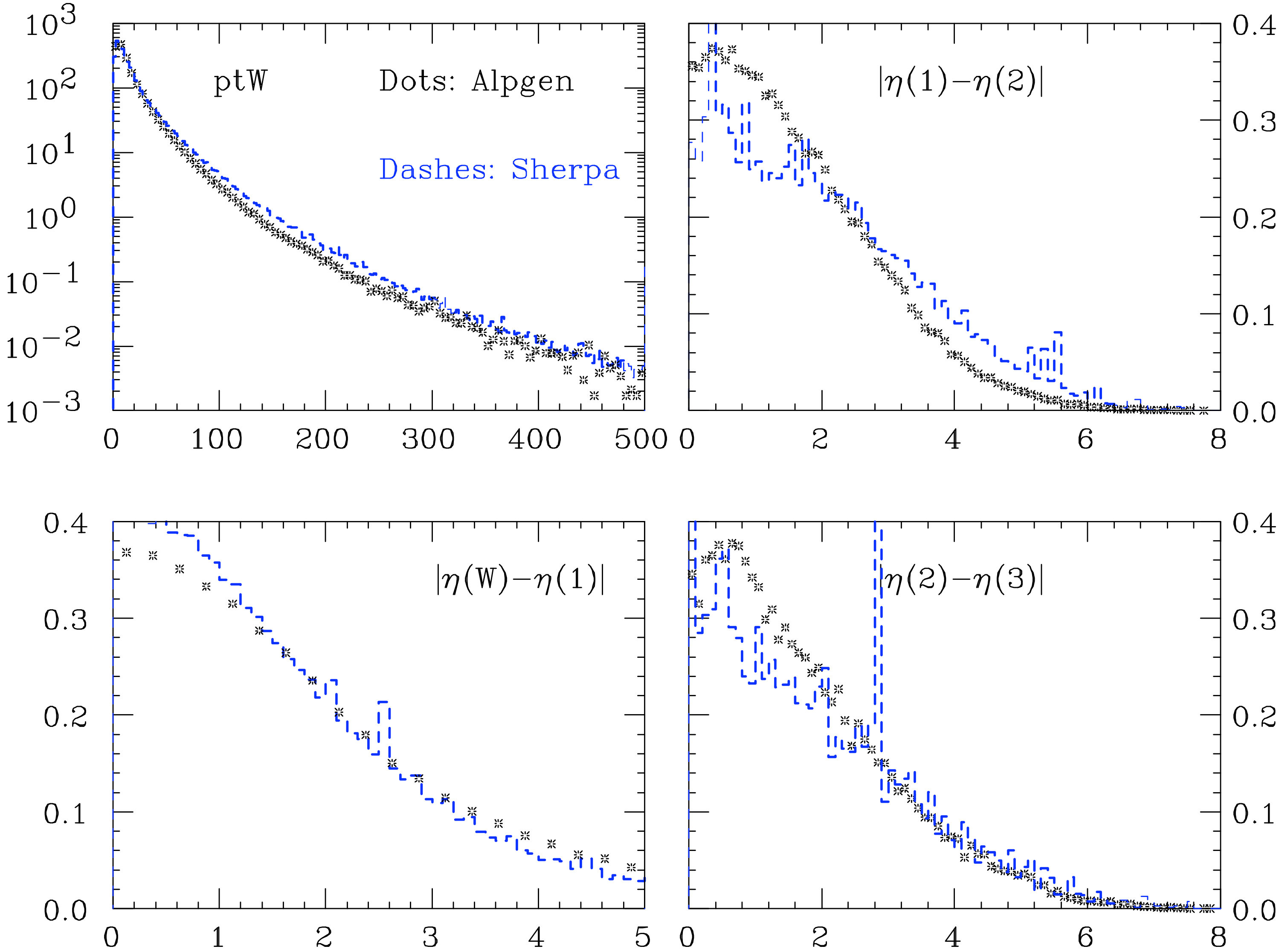
W + Multijets (Tevatron)



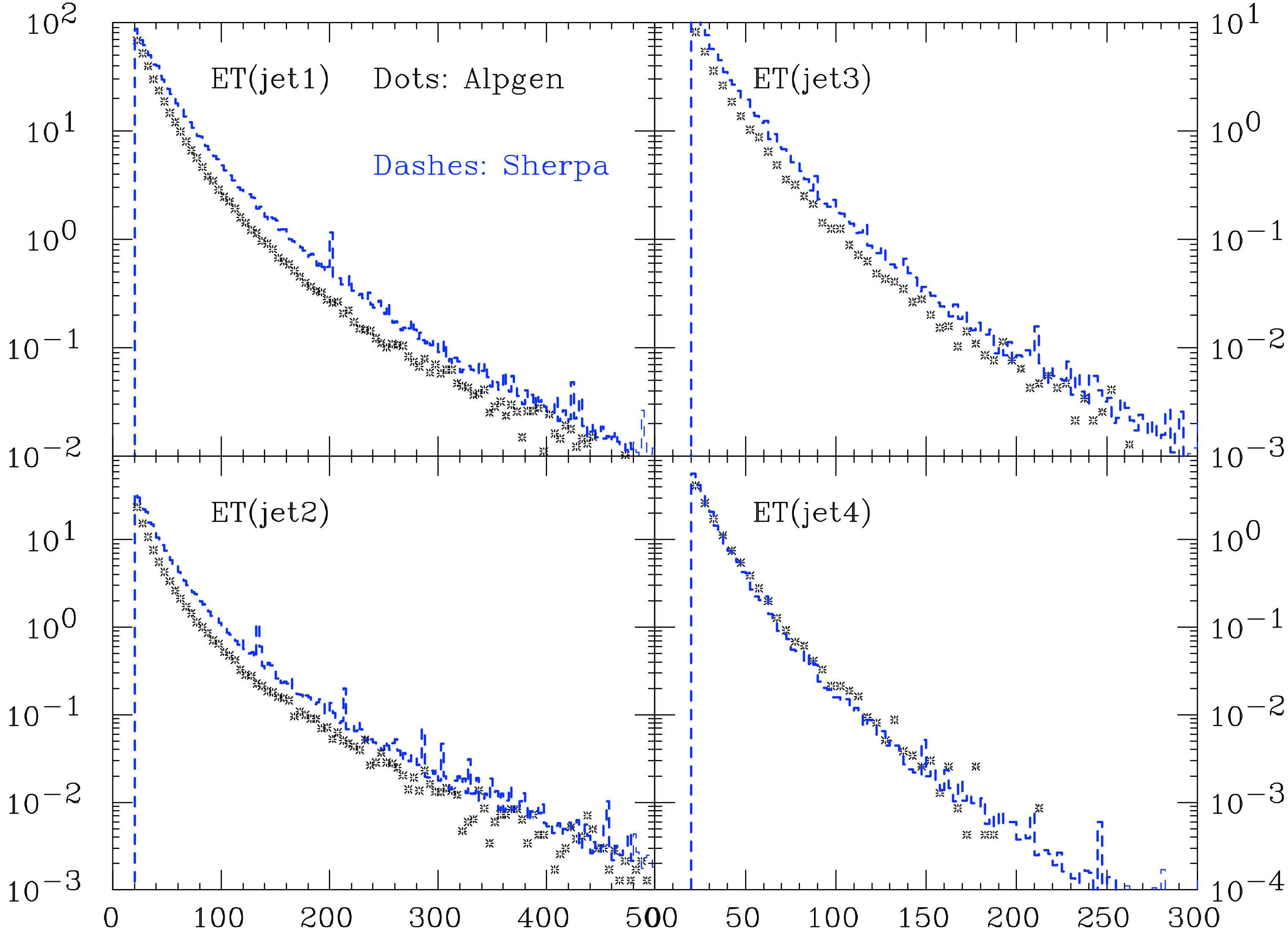
W + Multijets (Tevatron)



W + Multijets (LHC)



W + Multijets (LHC)



Summary

- Matching Parton Showers to Matrix Elements comes in different forms:
  - matching to NLO for better precision
  - matching to LO for multijets
- MC@NLO is main scheme for NLO matching
  - newer Nason method looks promising:

    P Nason & G Ridolfi, JHEP08(2006)077 + refs therein
- Several options for LO multijets
  - reasonably consistent
  - spread indicates uncertainties (?)
- Field still very active
  - NLO matching for jets, spin correlations,...
  - building multijet matching into OO generators