QCD and Collider Phenomenology

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IPMU/KEK Lectures

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Lecture 3: Matching Fixed Order Matrix Elements with Parton Showers

ME-PS Matching

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

MC@NLO

Consider a simple one-dim. example:

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

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!

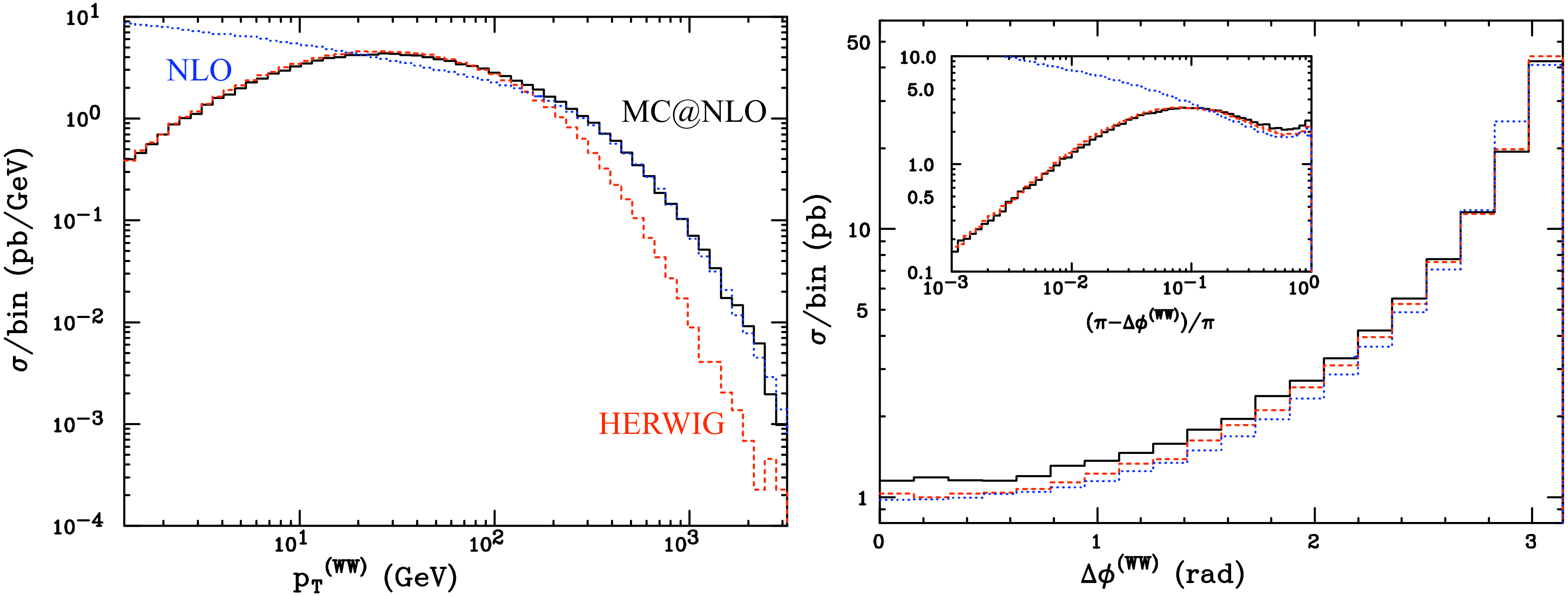
(But some can be negative “counter-events”)

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		7	7	×	$H_1H_2 \to t\bar{t} + X$
–1706		i	j	✓	$H_1H_2 \to (t \to) bl^+_i\nu_i(\bar{t} \to)\bar{b}l^-_j\bar{\nu}_j + X$
–2000–IC		7		×	$H_1H_2 \to t/\bar{t} + X$
–2000–IC		i		✓	$H_1H_2 \to (t \to) bl^+_i\nu_i/(\bar{t} \to)\bar{b}l^-_i\bar{\nu}_i + X$
–2001–IC		7		×	$H_1H_2 \to \bar{t} + X$
–2001–IC		i		✓	$H_1H_2 \to (\bar{t} \to)\bar{b}l^-_i\bar{\nu}_i + X$
–2004–IC		7		×	$H_1H_2 \to t + X$
–2004–IC		i		✓	$H_1H_2 \to (t \to) bl^+_i\nu_i + X$
–2600–ID	1	7		×	$H_1H_2 \to H^0W^+ + X$
–2600–ID	1	i		✓	$H_1H_2 \to H^0(W^+ \to) l^+_i\nu_i + X$
–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

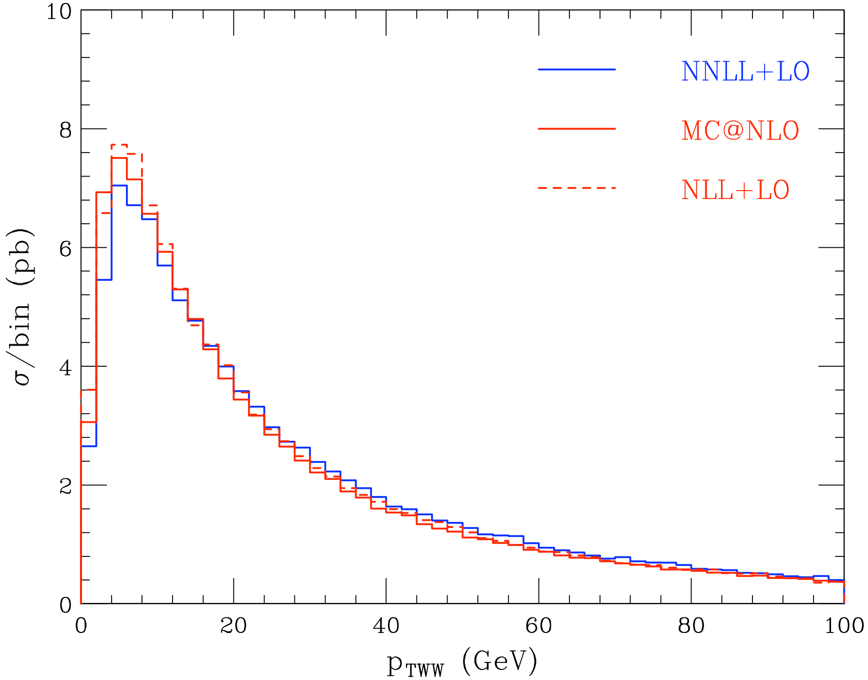
- WW production at LHC

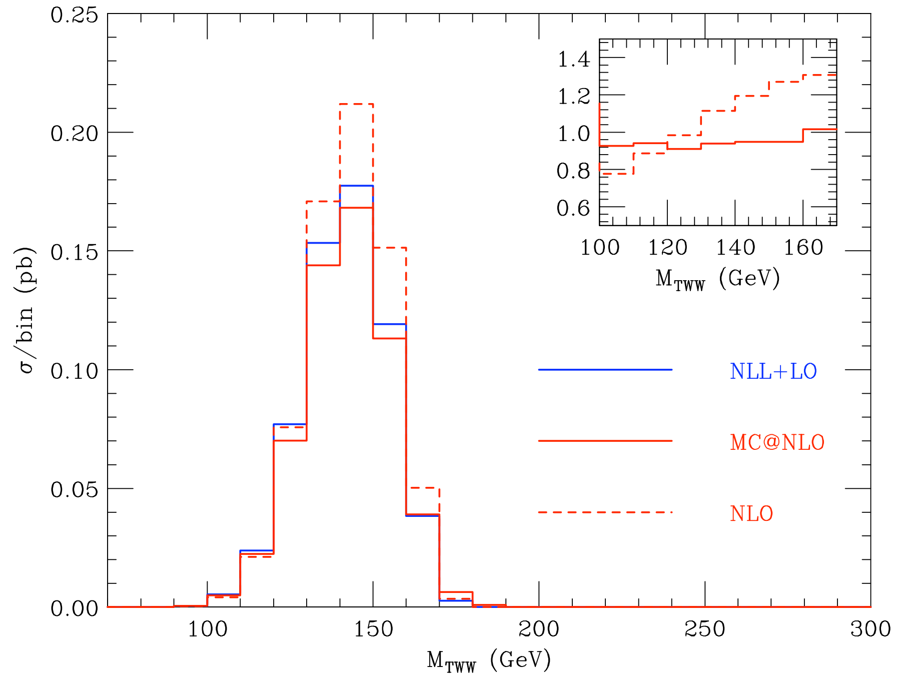


- Interpolates between MC & NLO in $\mathrm{p}_\mathrm{T}^{(\mathrm{WW})}$
- Above both at $\Delta\phi^{(\mathrm{WW})} \simeq 0$

S Frixione & BW, JHEP 06(2002)029

W^+W^-: MC@NLO vs Resummations

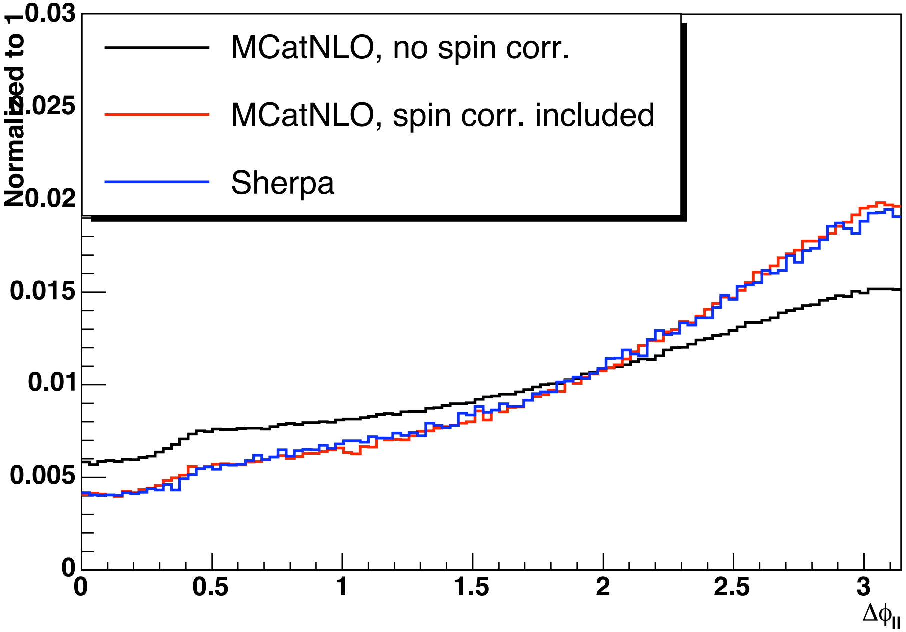


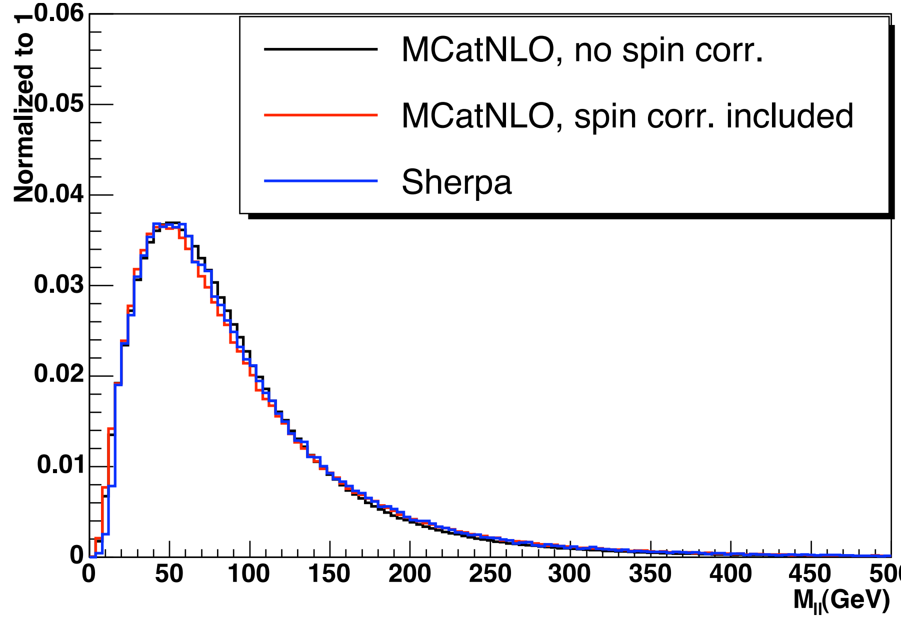


Plots from M. Grazzini JHEP 0601(2006)095

- Highly non-trivial test (of both computations) for *shapes* and *rates* !
- $M_{\rm TWW} = \sqrt{(E_{Tll} + \not{E}_T)^2 - (\mathbf{p}_{Tll} + \not{\mathbf{p}}_T)^2}$ where $E_{Tll} = \sqrt{\mathbf{p}_{Tll}^2 + m_{ll}^2}$ and $\not{E}_T \equiv \sqrt{\not{\mathbf{p}}_T^2 + m_{ll}^2}$ (Rainwater & Zeppenfeld)
- Cuts involved in definition of $M_{\rm TWW}$: $\Delta\phi_{l^+l^-} < \pi/4$, $M_{l^+l^-} < 35$ GeV, $p_{\rm Tmin}^{(l^+,l^-)} > 25$ GeV, $35 < p_{\rm Tmax}^{(l^+,l^-)} < 50$ GeV, $p_{\rm T}^{\rm WW} < 30$ GeV

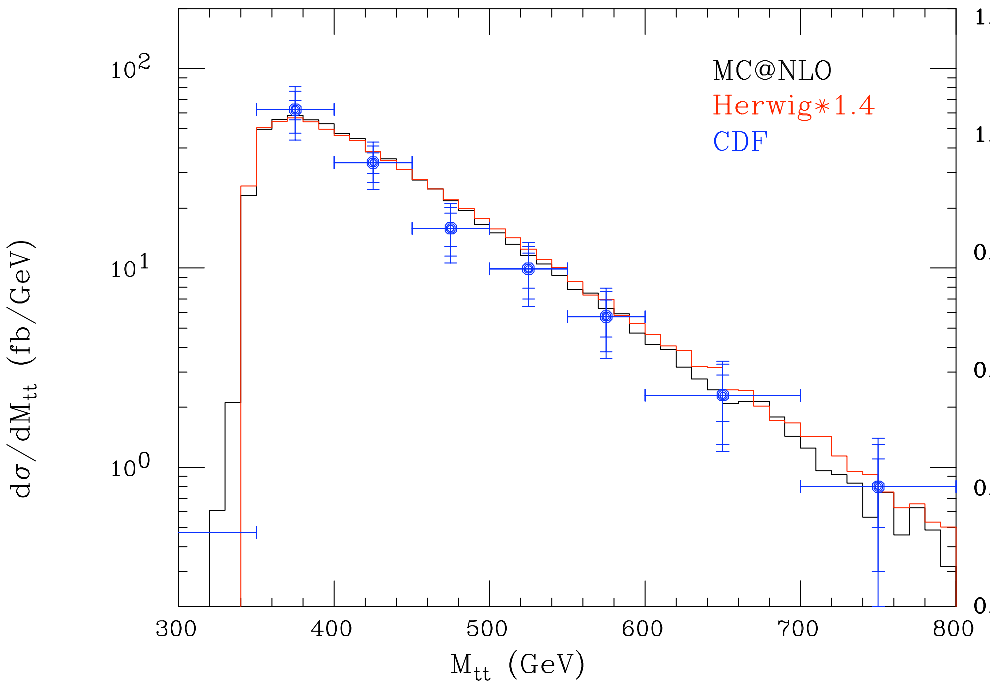
W^+W^- Spin Correlations

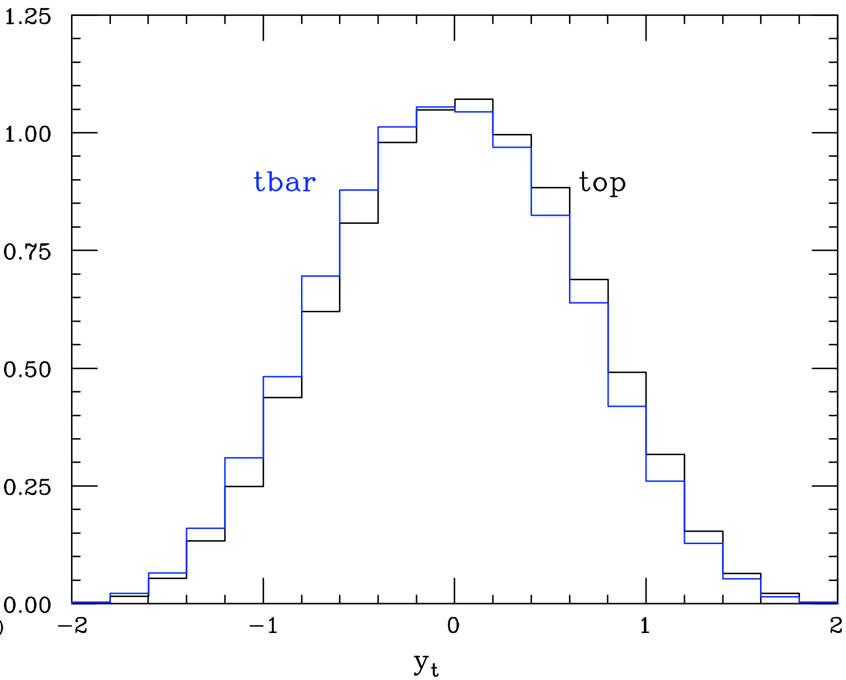




Plots from W. Quayle (preliminary)

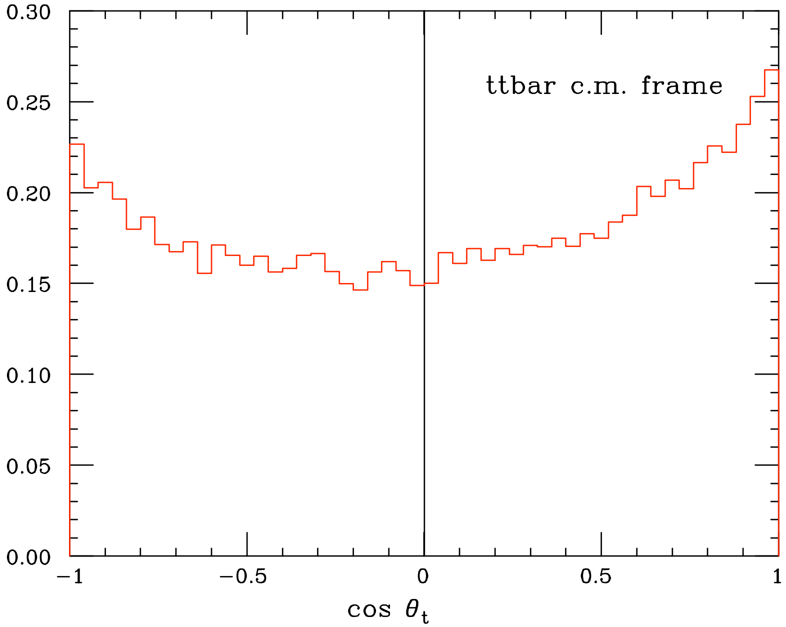
Top pair production at Tevatron

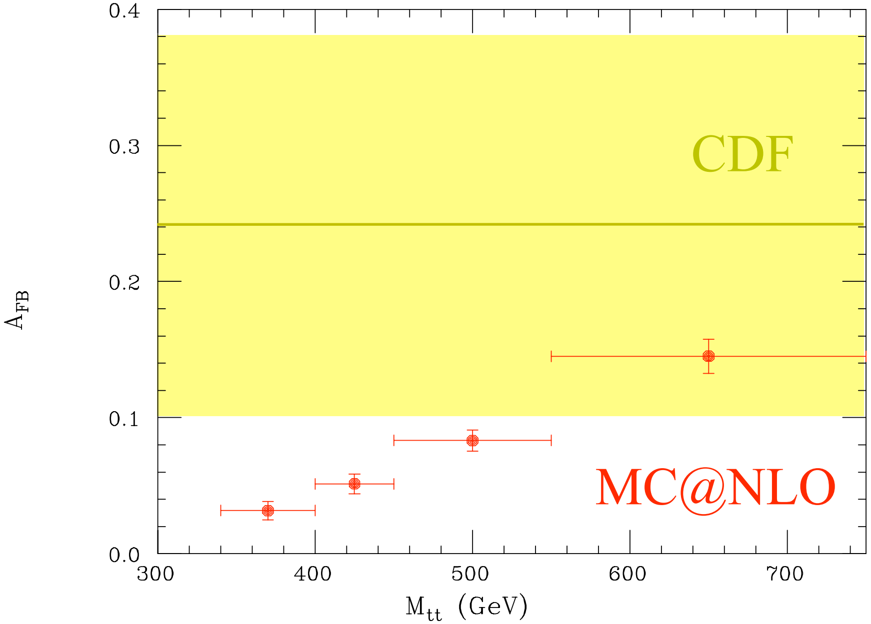




- Mass spectrum slightly softer than LO MC
- FB asymmetry: a purely NLO effect

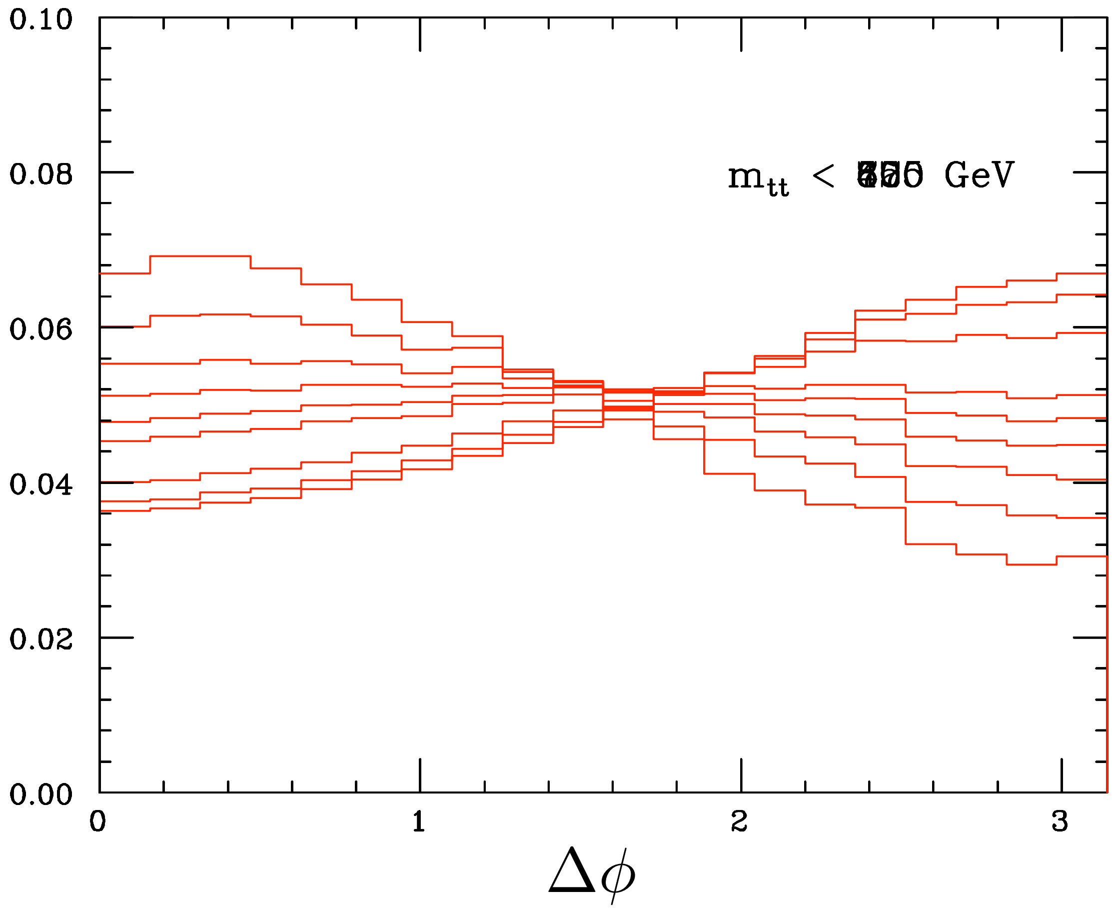
FB asymmetry in $t\bar{t}$ frame





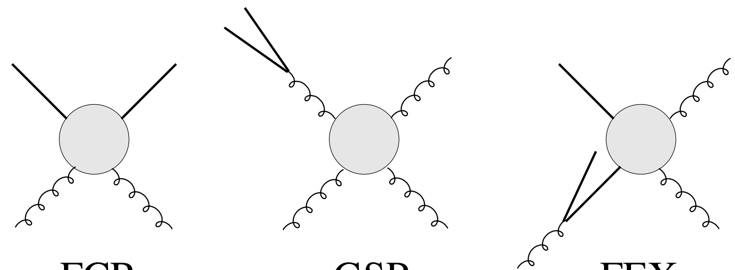
- Asymmetry increases strongly with invariant mass
- New physics should increase even more strongly

Dilepton correlation at LHC

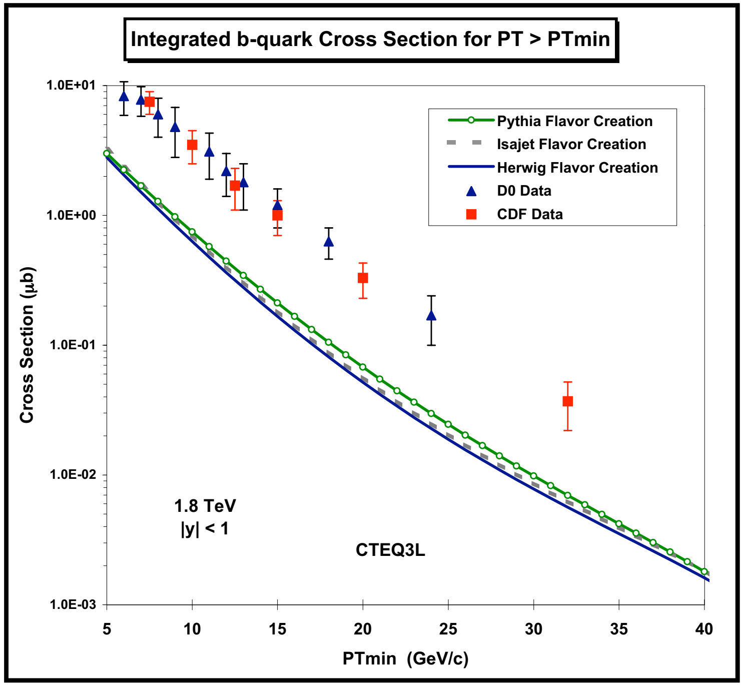


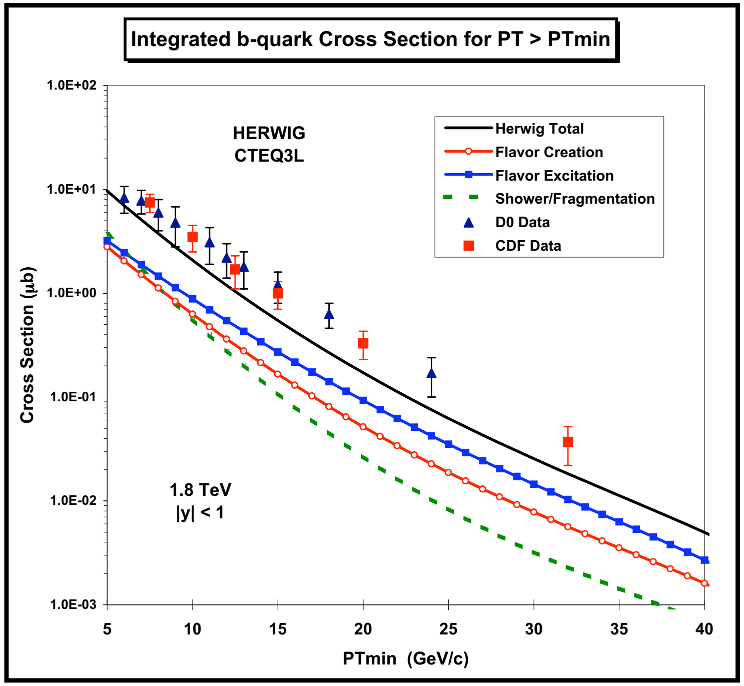
b Production: PS MC vs MC@NLO

- In parton shower MC's, 3 classes of processes can contribute:

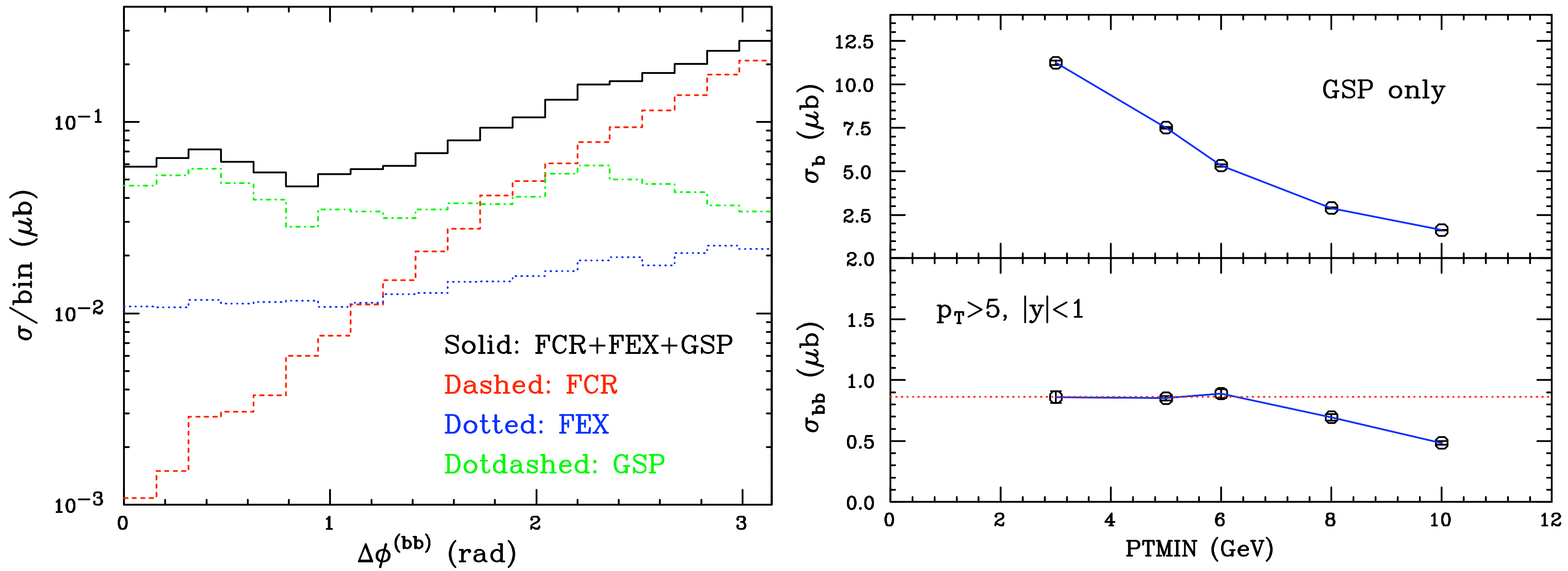


- All are needed to get close to data (RD Field, hep-ph/0201112):





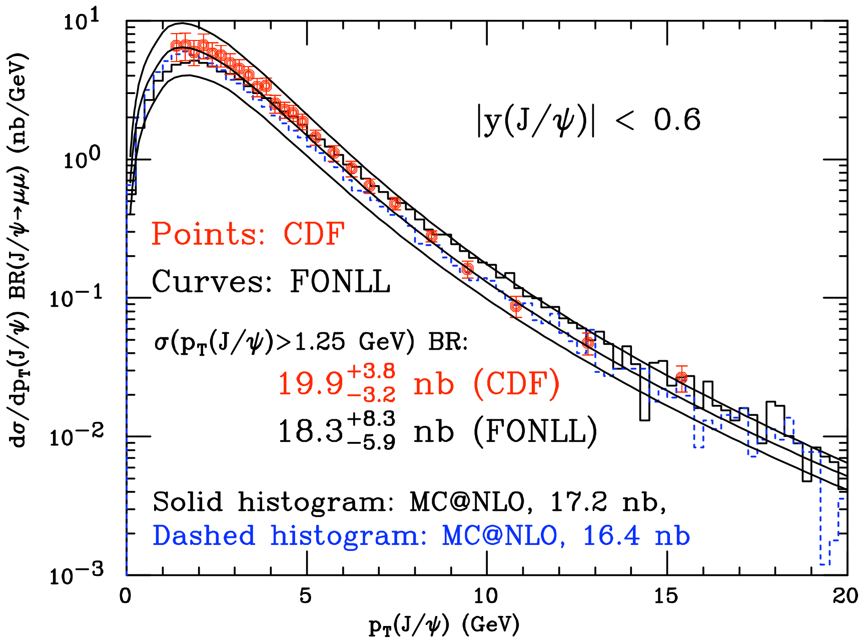
GSP and FEX contributions in HERWIG PS MC

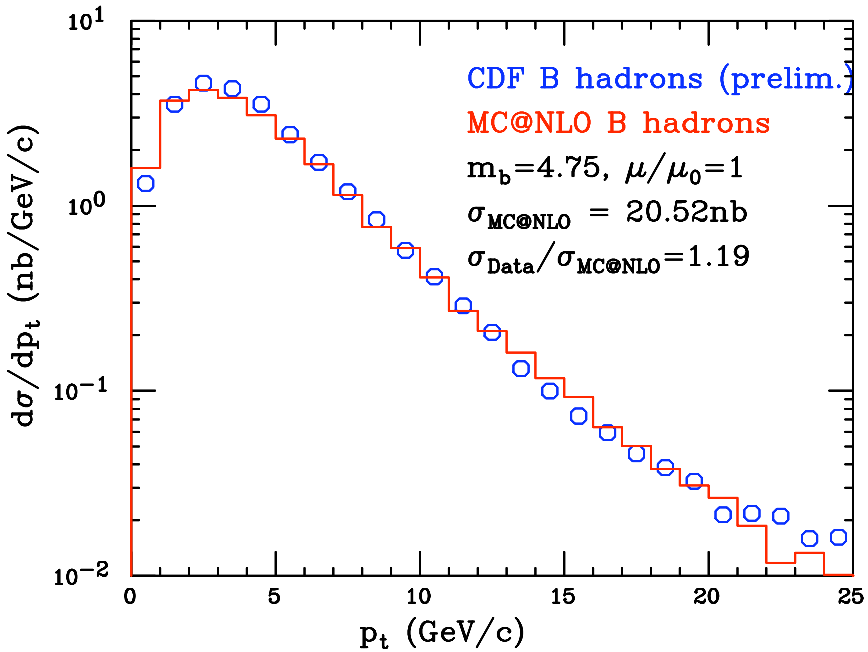


- GSP, FEX and FCR are complementary and all must be generated
  - GSP cutoff (PTMIN) sensitivity depends on cuts and observable
  - FEX sensitive to bottom PDF
  - GSP efficiency very poor, $\sim 10^{-4}$
- All these problems are avoided with MC@NLO!

MC@NLO: B Production at Tevatron

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



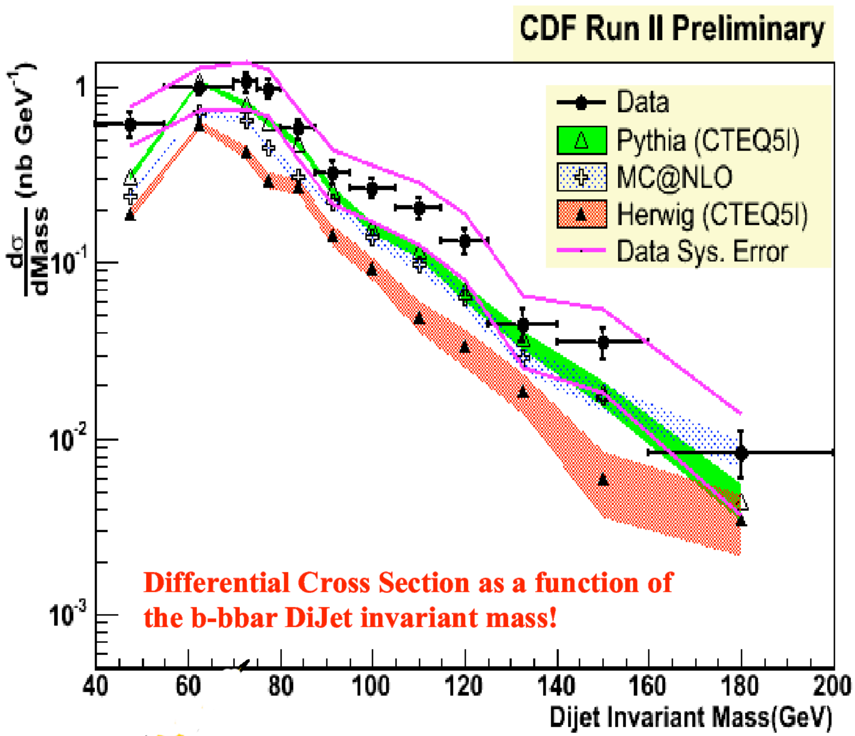


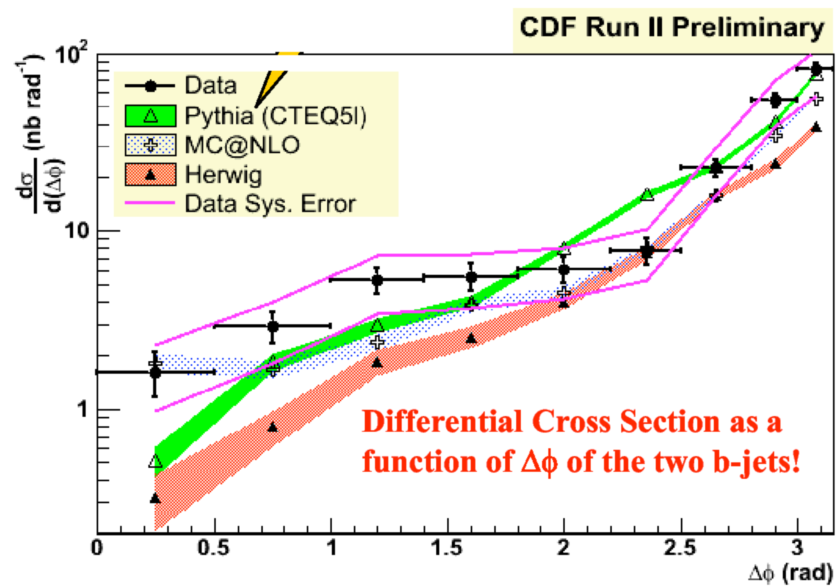
➡ Good agreement (and MC efficiency)

S Frixione, P Nason & BW, JHEP 0308(2003)007

M Cacciari et al., JHEP 0407(2004)033

MC@NLO Di-b Jet Production

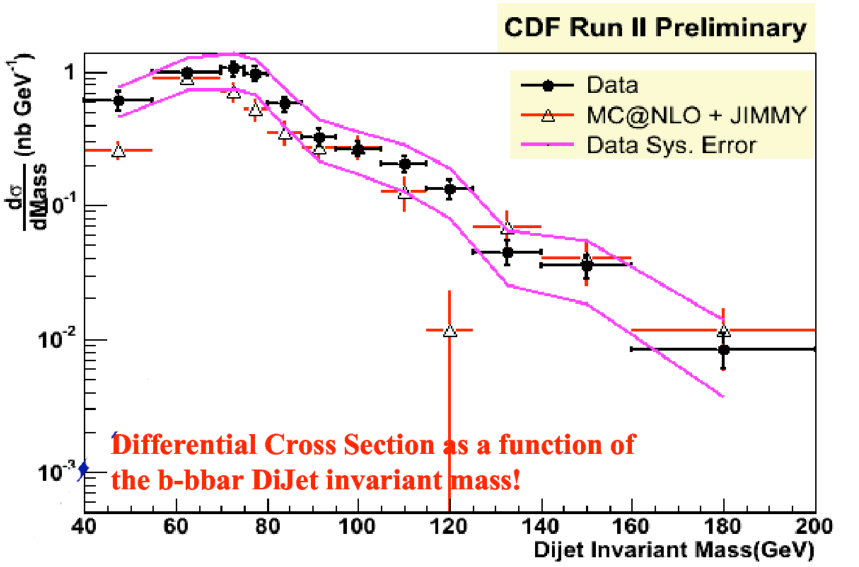


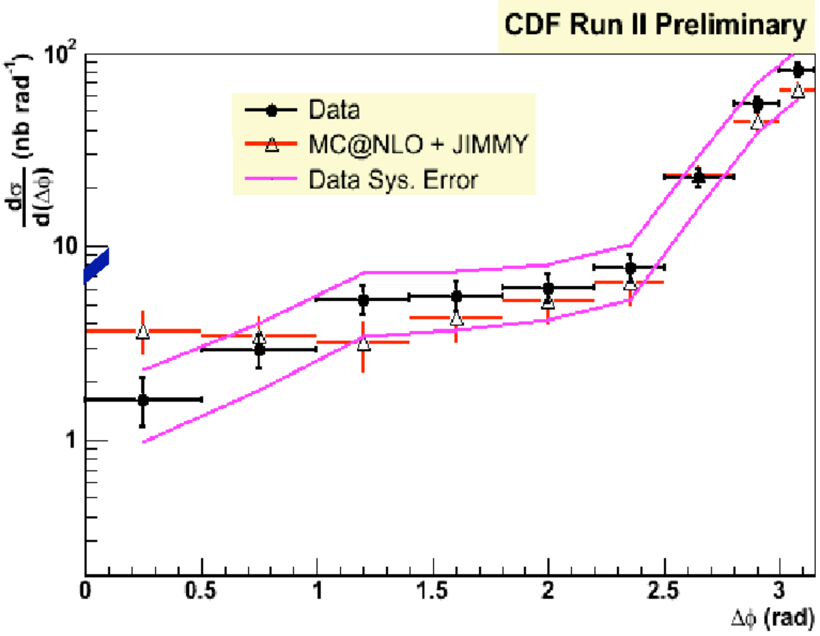


- These observables are very involved (b-jets at hadron level) and cannot be computed with analytical techniques;
- The underlying event in Pythia is fitted to data; default Herwig model (used in MC@NLO) does not fit data well (lack of MPI).

MC@NLO b-Jets: Improved Underlying Event

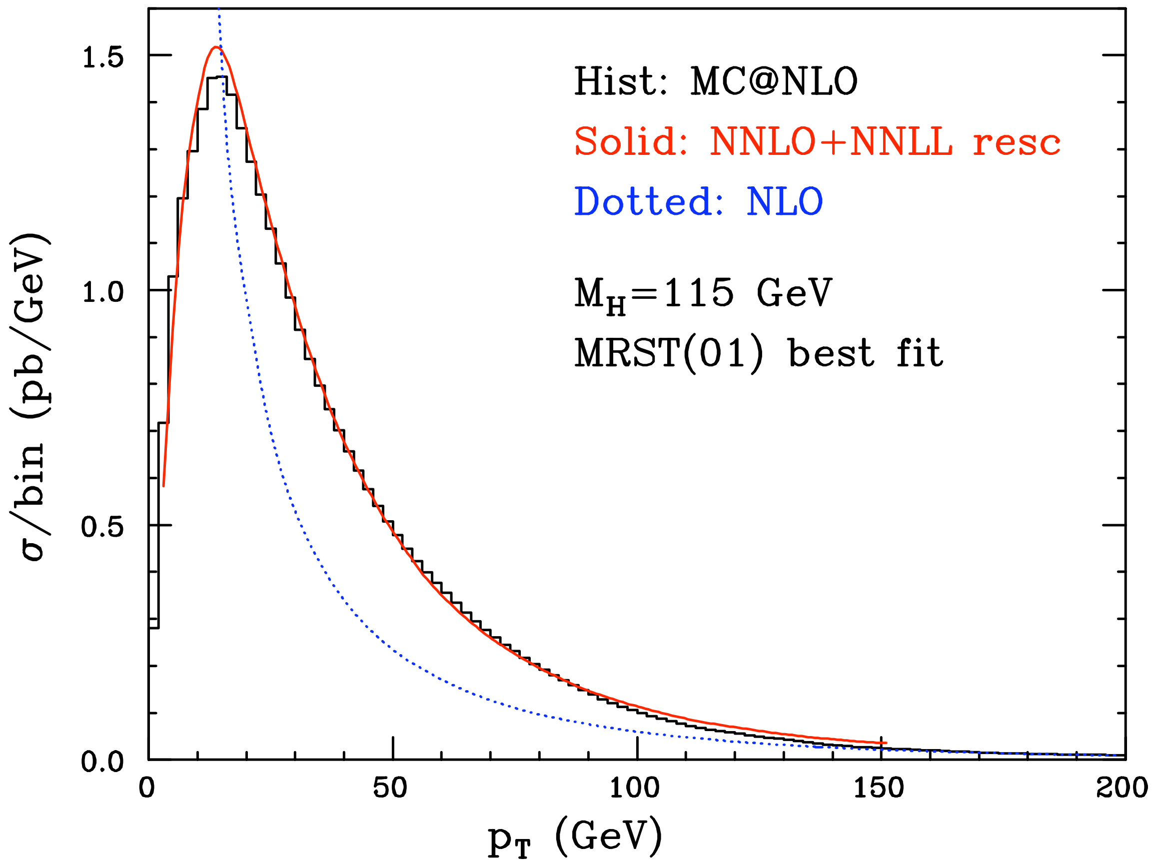
- The JIMMY underlying event model includes multiple parton interactions and interfaces to Herwig $\Rightarrow$ interfaces to MC@NLO





- The importance of the underlying event shows the necessity of embedding precise computations in a Monte Carlo framework.

MC@NLO: Higgs Production at LHC



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

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

POWHEG

Positive Weight Hardest Emission Generator

- Method to generate hardest emission first, with NLO accuracy, independent of PSEG
- Can be interfaced to any PSEG
- No negative weights
- Inaccuracies only affect next-to-hardest emission
- In principle, needs ‘truncated showers’

P Nason & G Ridolfi, JHEP08(2006)077

S Frixione, P Nason & G Ridolfi, JHEP09(2007)126

S Frixione, P Nason & C Oleari, JHEP11(2007)070

POWHEG

How it works (roughly)

In words: works like a standard Shower MC for the hardest radiation, with care to maintain higher accuracy.

Inclusive cross section $\Longrightarrow$ NLO inclusive cross section. Positive if $\mathrm{NL} < \mathrm{LO}$

$\Phi_n = \text{Born variables}$
$\Phi_r = \text{radiation vars.}$

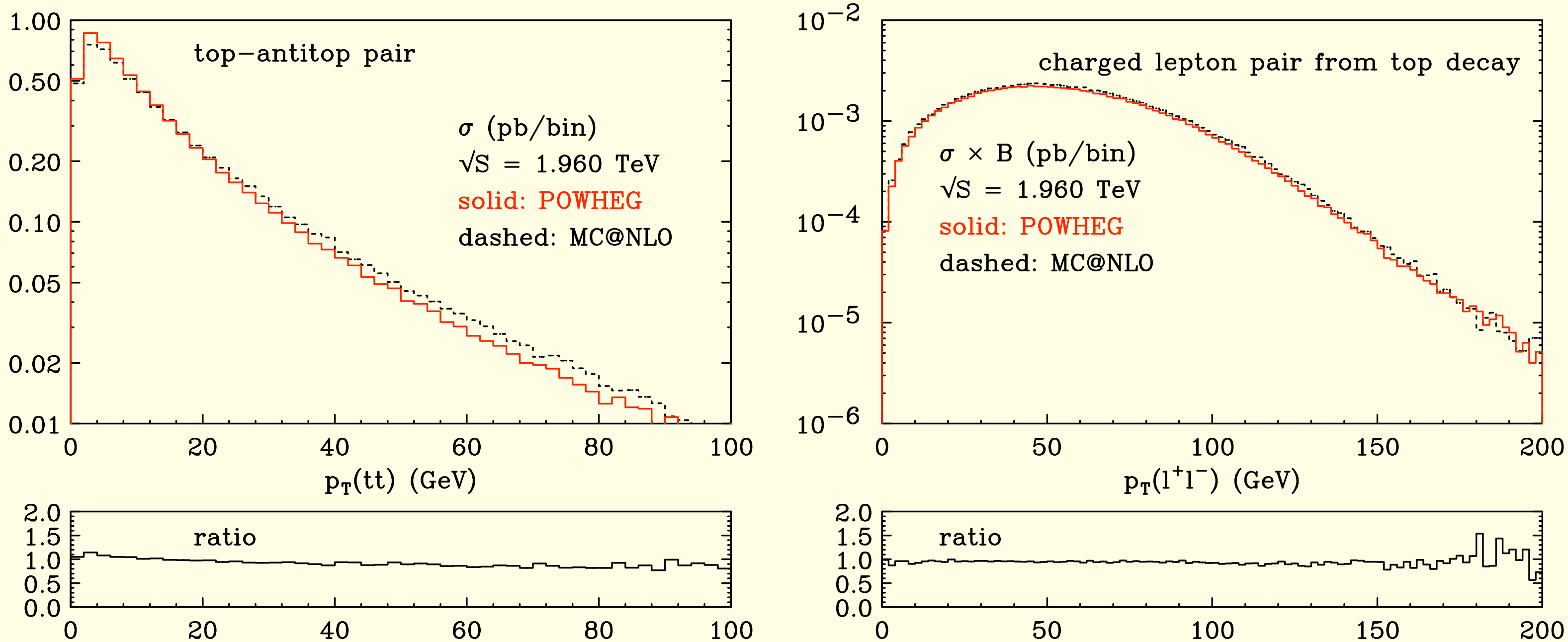
$$\bar{B}(\Phi_n) = B(\Phi_n) + \underbrace{\left[\overbrace{V(\Phi_n)}^{\text{INFINITE}} + \overbrace{\int R(\Phi_n, \Phi_r)\, d\Phi_r}^{\text{INFINITE}} \right]}_{\text{FINITE!}}$$

Sudakov form factor for hardest emission built from exact NLO real emission

$$\Delta_t = \exp\left[\underbrace{-\int \theta(t_r - t) \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} d\Phi_r}_{\text{FINITE because of } \theta \text{ function}} \right]$$

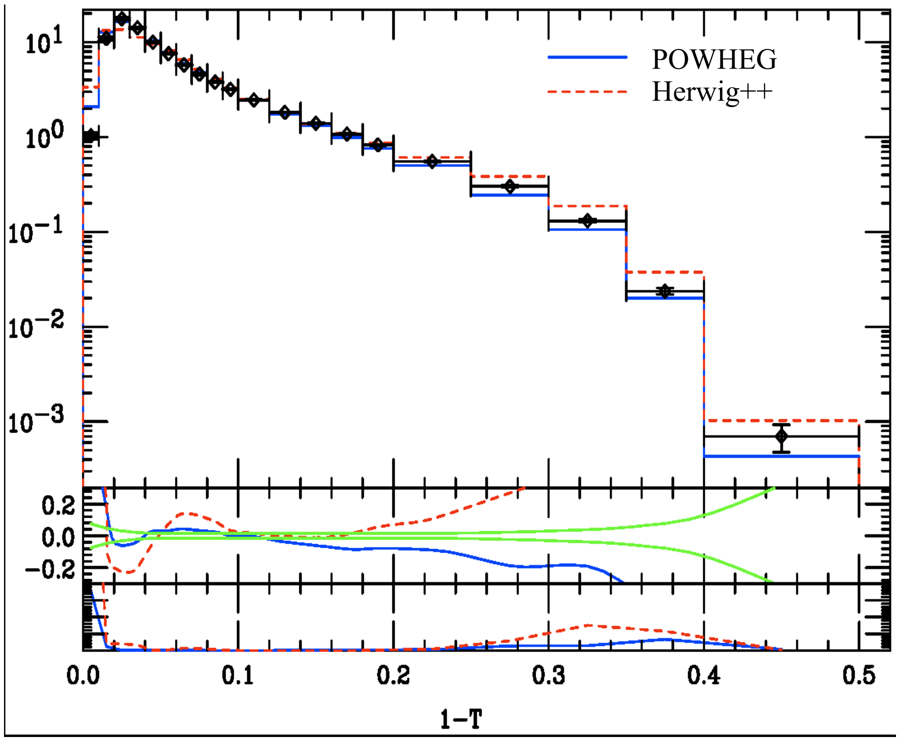
with $t_r = k_T(\Phi_n, \Phi_r)$, the transverse momentum for the radiation.

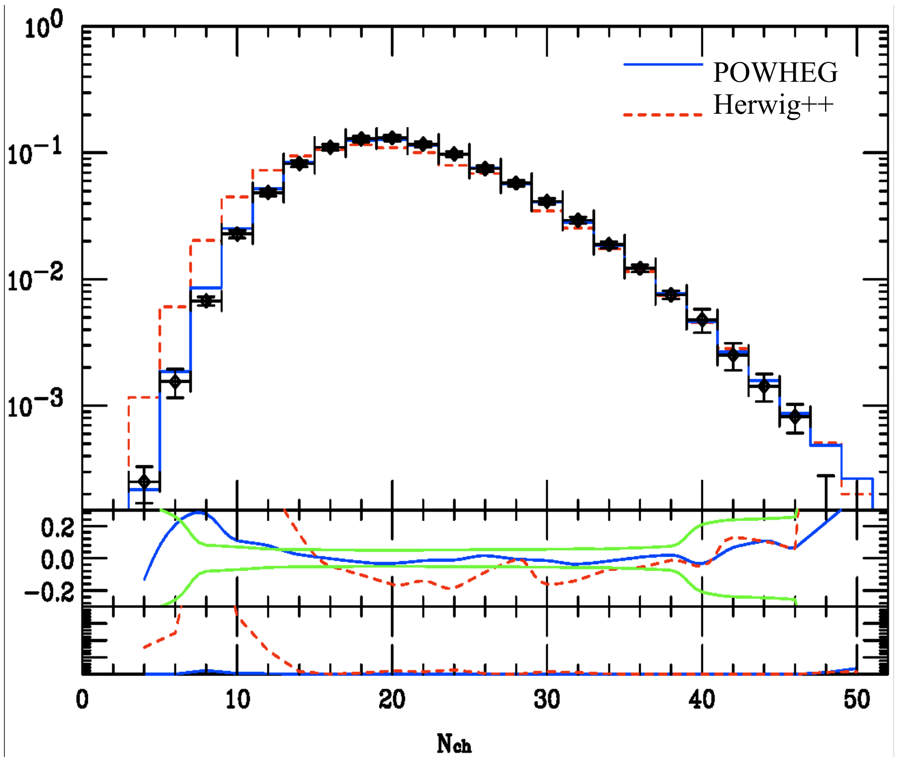
POWHEG and MC@NLO comparison: Top pair production



Good agreement for all observable considered
(differences can be ascribed to different treatment of higher order terms)

POWHEG for $e^+e^- \rightarrow$ hadrons

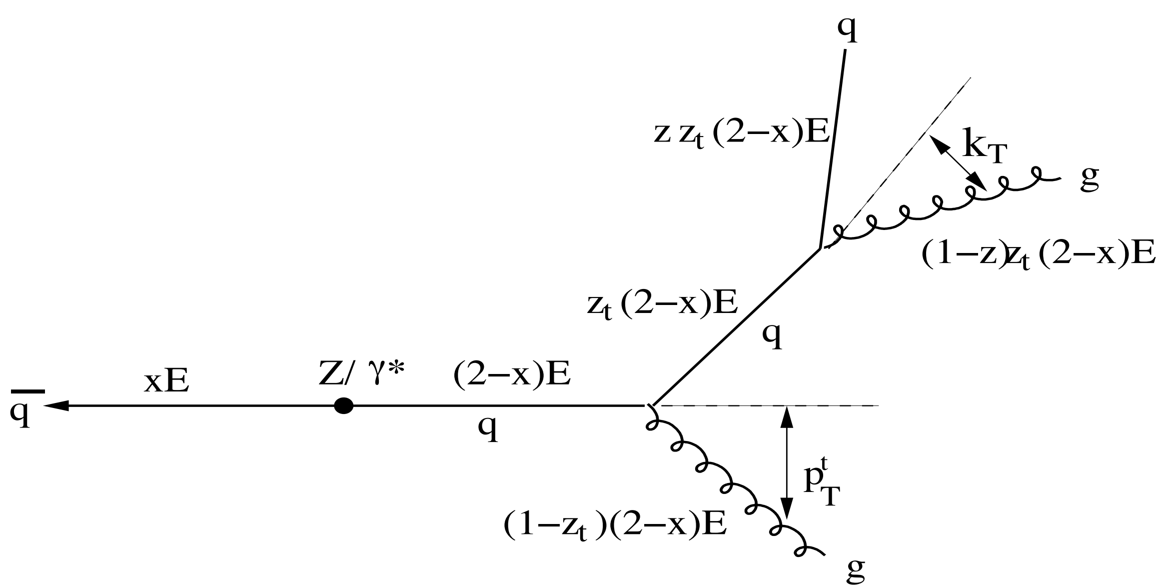




O Latunde-Dada, S Gieseke, BW, JHEP02 (2007) 051

Truncated Shower

- In angular-ordered shower, hardest emission is not necessarily the first
- Need to add softer, wider-angle emissions
- Checked for up to one such emission in e^+e^-



Effect of truncated shower

Observable	`Herwig++` ME	POWHEG with truncated shower	POWHEG w/o truncated shower
$1-T$	36.52	9.03	9.81
Thrust Major	267.22	36.44	37.65
Thrust Minor	190.25	86.30	90.59
Oblateness	7.58	6.86	6.28
Sphericity	9.61	7.55	9.01
Aplanarity	8.70	22.96	25.33
Planarity	2.14	1.19	1.45
C Parameter	96.69	10.50	11.14
D Parameter	84.86	8.89	10.88
M_{high}	14.70	5.31	6.61
M_{low}	7.82	12.90	13.44
M_{diff}	5.11	1.89	2.09
B_{max}	39.50	11.42	12.17
B_{min}	45.96	35.2	36.16
B_{sum}	91.03	28.83	30.58
B_{diff}	8.94	1.40	1.14
N_{ch}	43.33	1.58	10.08
$\langle\chi^2\rangle$/bin	56.47	16.96	18.49

Table 2: χ^2/bin for all observables we studied.

→ Small but beneficial effect

CKKW Matching

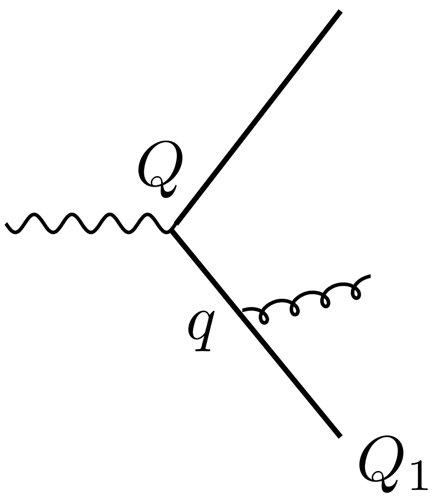
- Use Matrix Elements down to scale Q_1
- Use Parton Showers below Q_1
- Correct ME by reweighting
- Correct PS by vetoing
- Ensure that Q_1 cancels (to NLL)

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

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

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

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



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

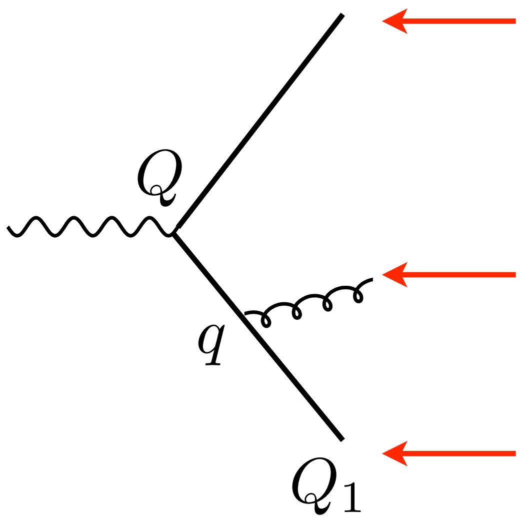
CKKW reweighting

- 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



shower from Q

shower from q

shower from Q, not q

Comparisons with Tevatron data

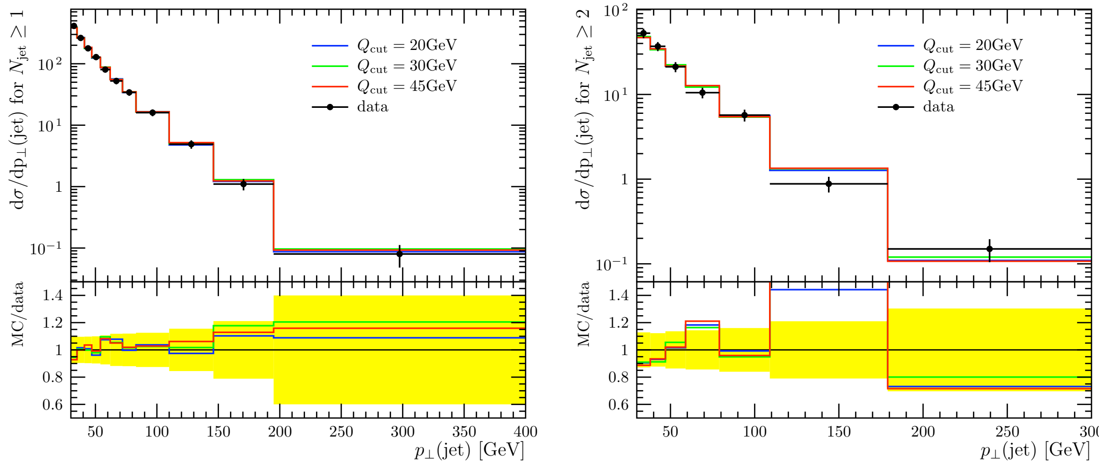


Figure 8: Jet p_T in $N_{\rm jet} \geq 1$ and $N_{\rm jet} \geq 2$ events compared to data from CDF [66].

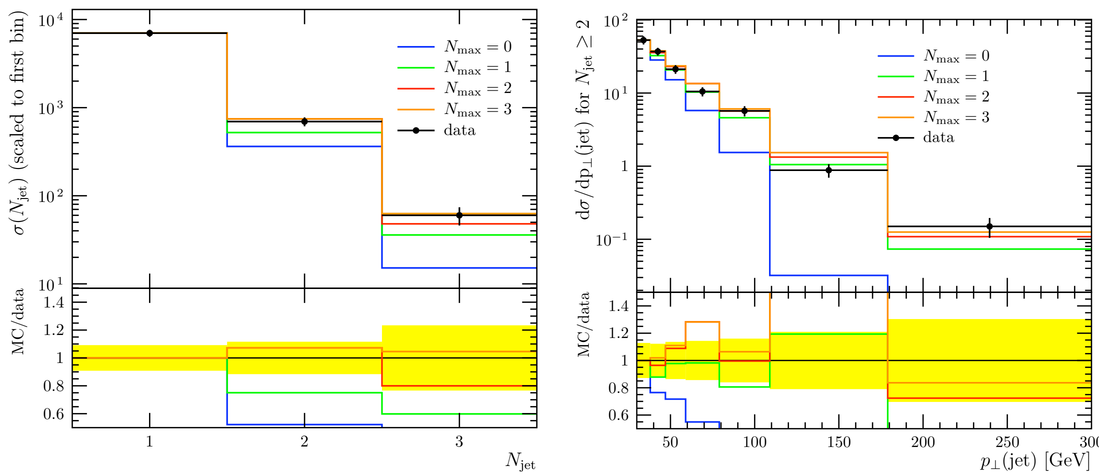


Figure 9: Jet multiplicity and jet p_T in $N_{\rm jet} \geq 2$ events compared to data from CDF [66].

S Hoeche, F Krauss, S Schumann & F Siegert, JHEP05(2009)053

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:

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

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

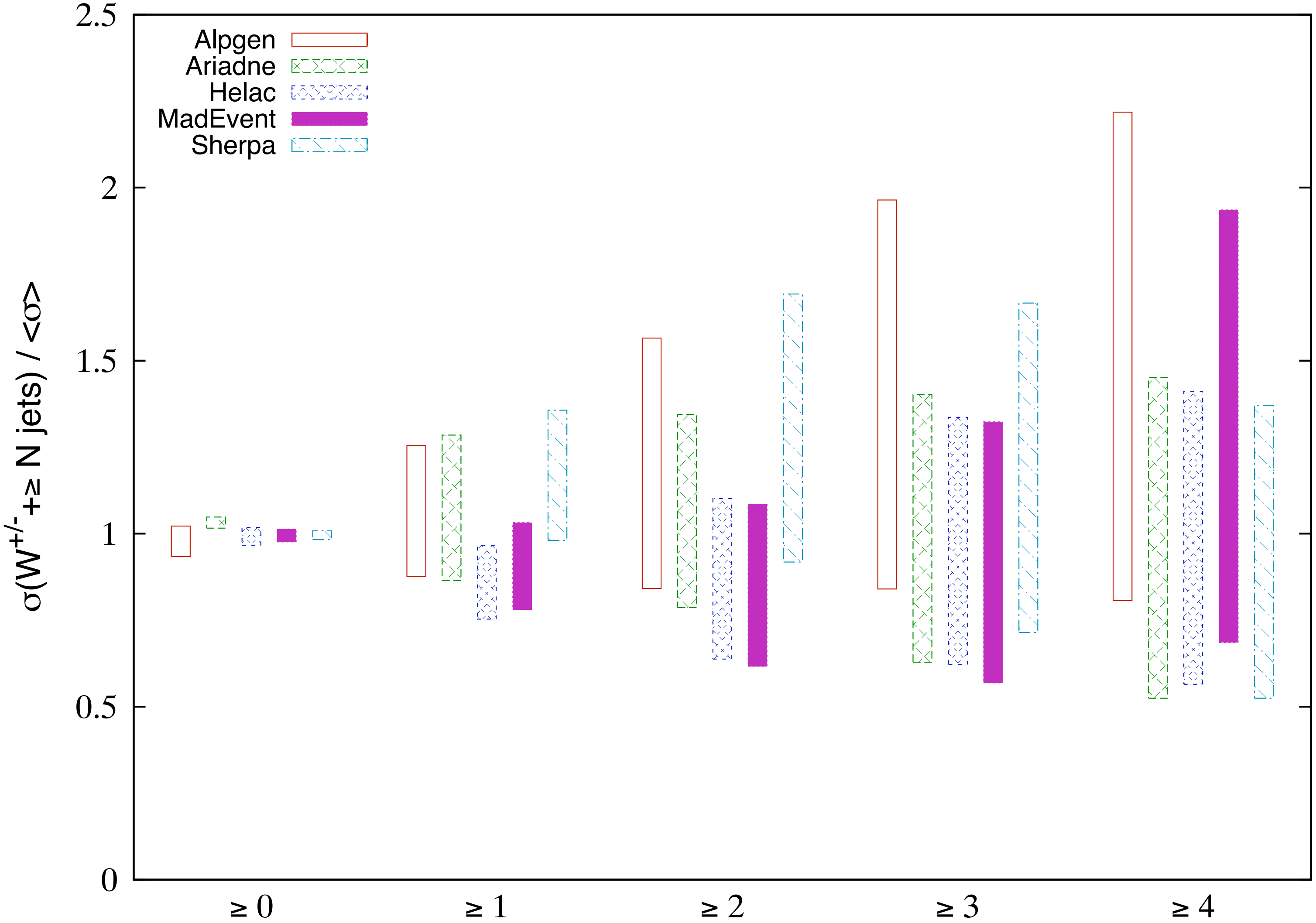
- Generate n-parton configurations with $E_{Ti} > E_{Tmin}, \ R_{ij} > R_{min}$ (no Sudakov weights)
- Generate showers (no vetos)
- Form jets using same jet definition
- Reject event if $n_{jets} \neq n_{partons}$

Comparisons

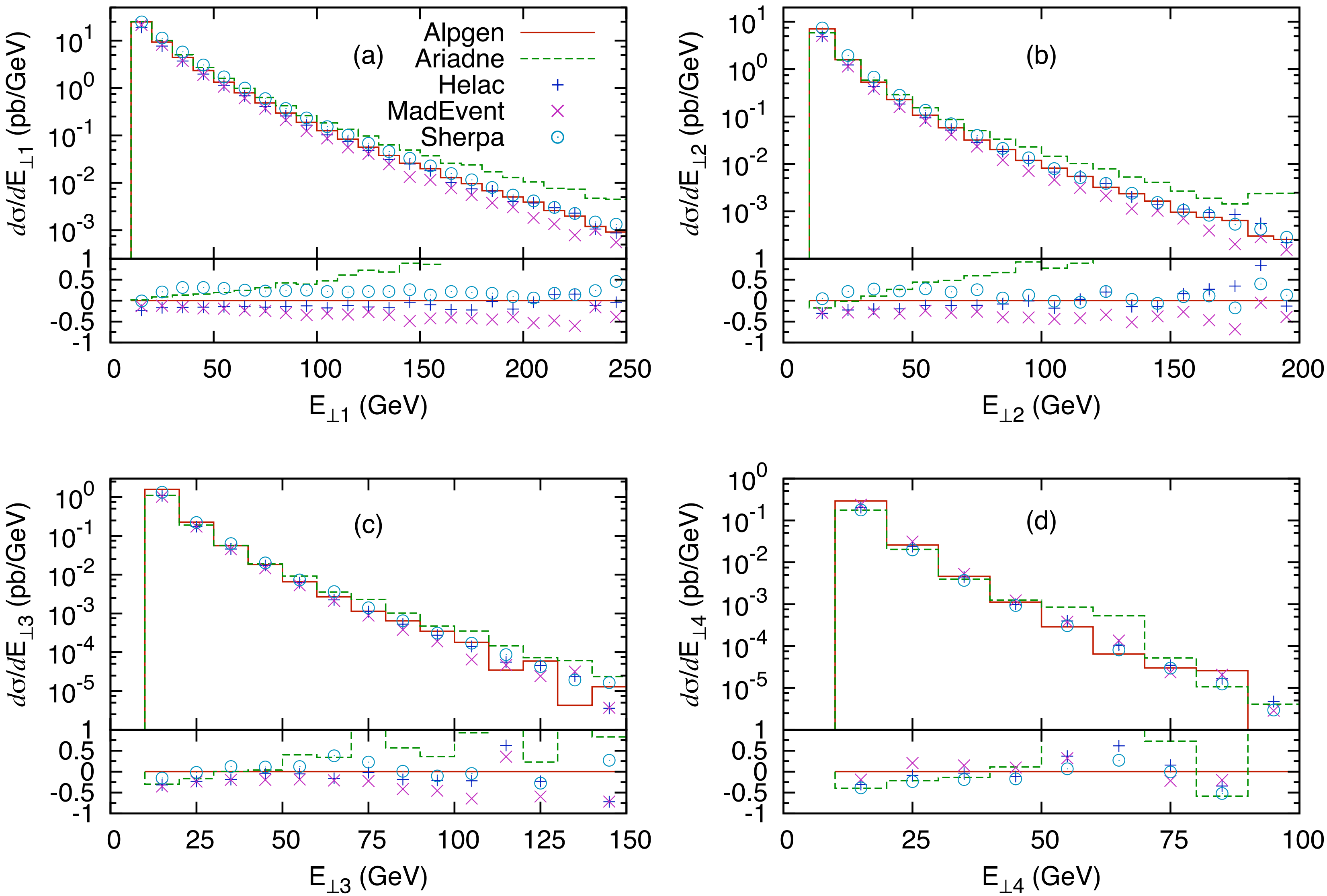
- ALPGEN: MLM matching
- ARIADNE: Dipole matching
- HELAC: MLM matching
- MadEvent: hybrid MLM/CKKW
- SHERPA: CKKW matching

J. Alwall el al., EPJC 53 (2008) 473

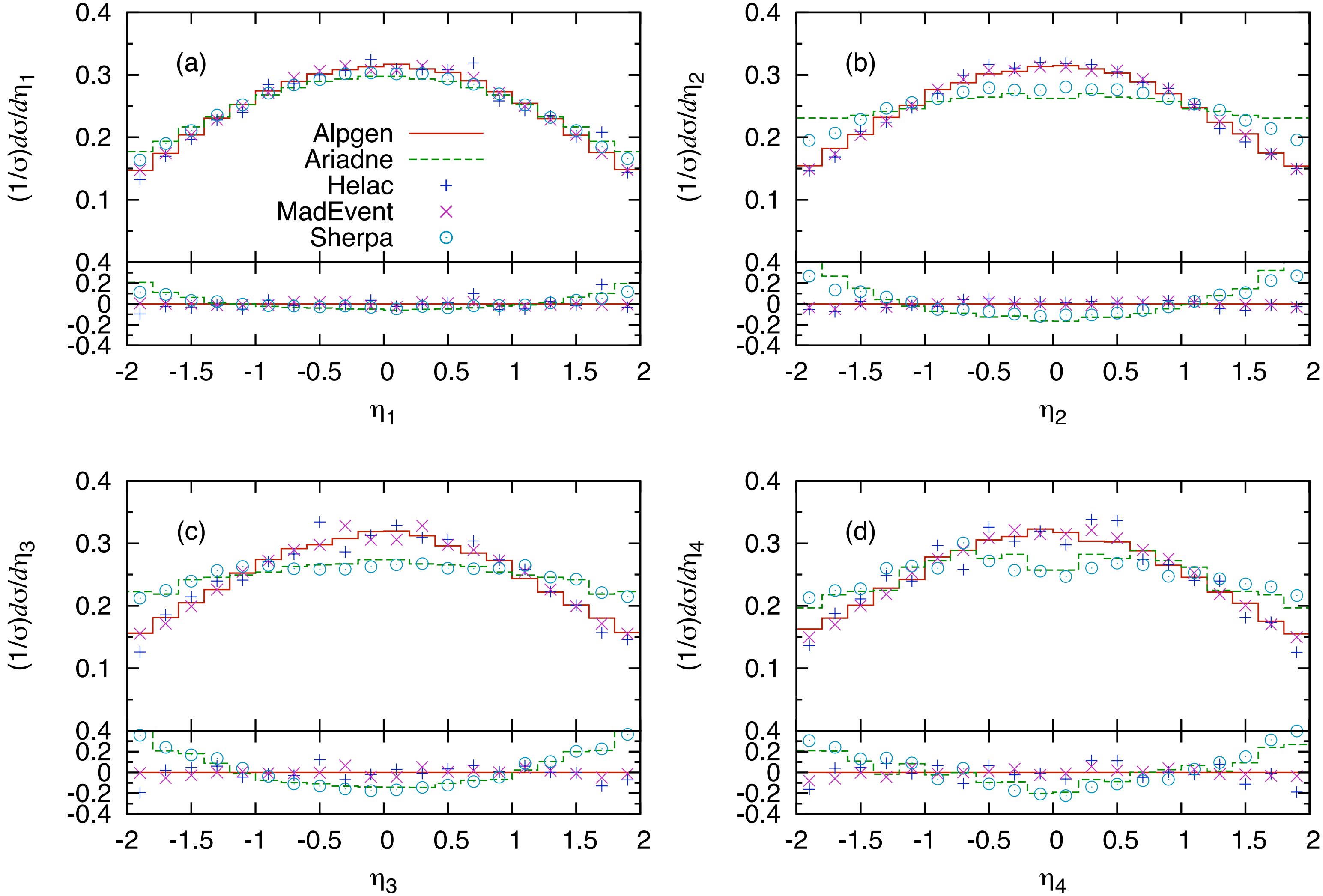
W + Multijets (Tevatron)



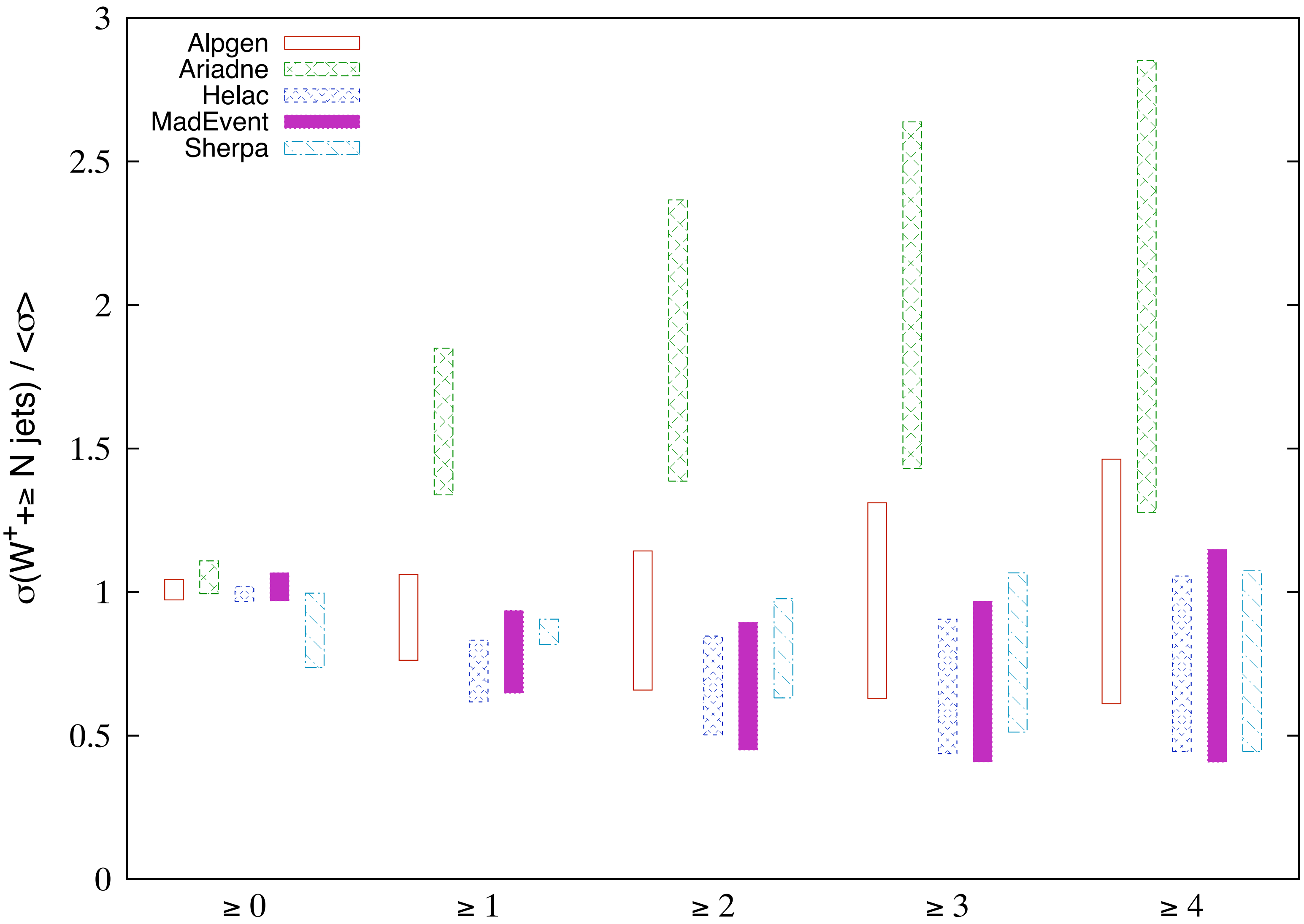
W + Multijets (Tevatron)



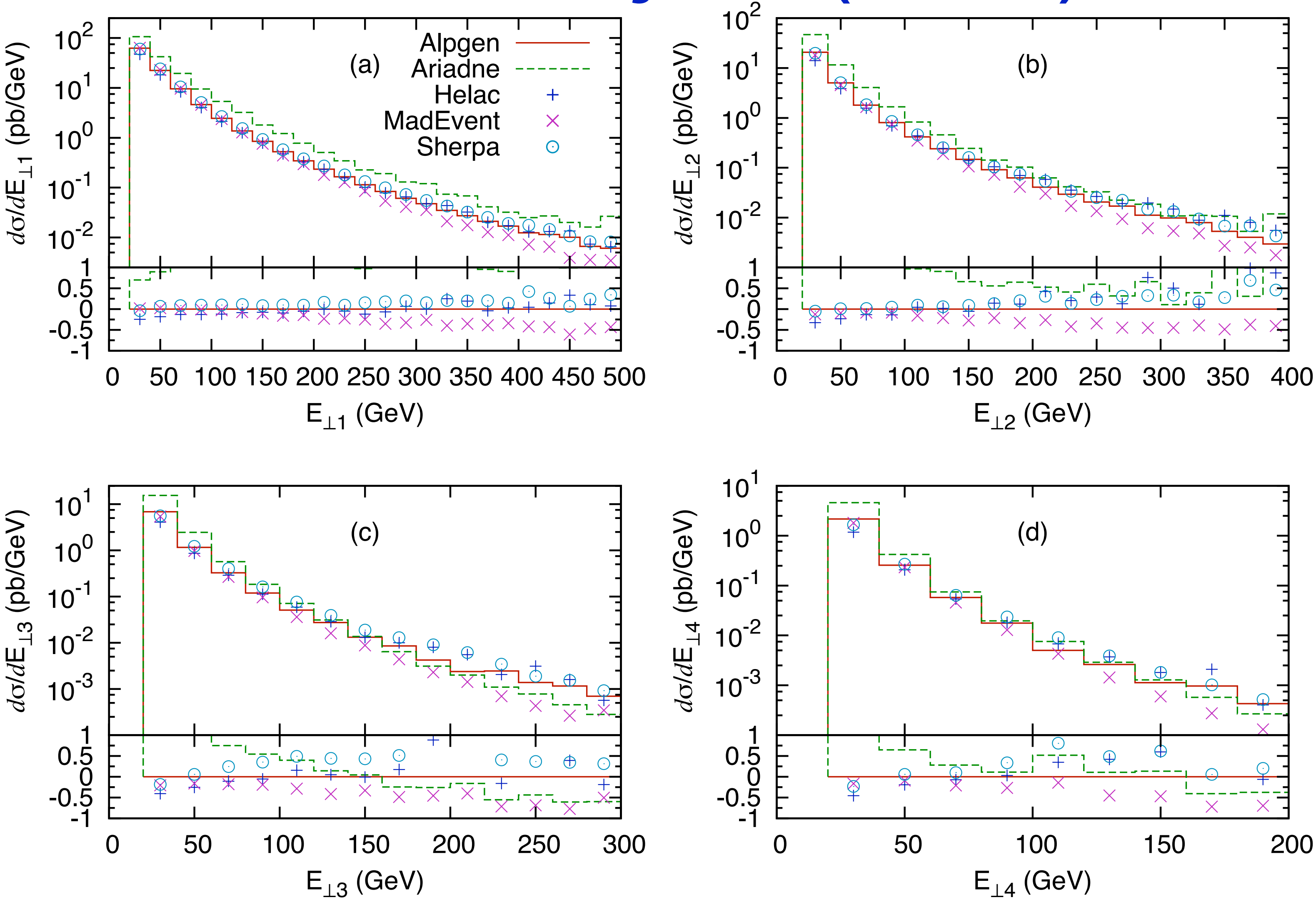
W + Multijets (Tevatron)



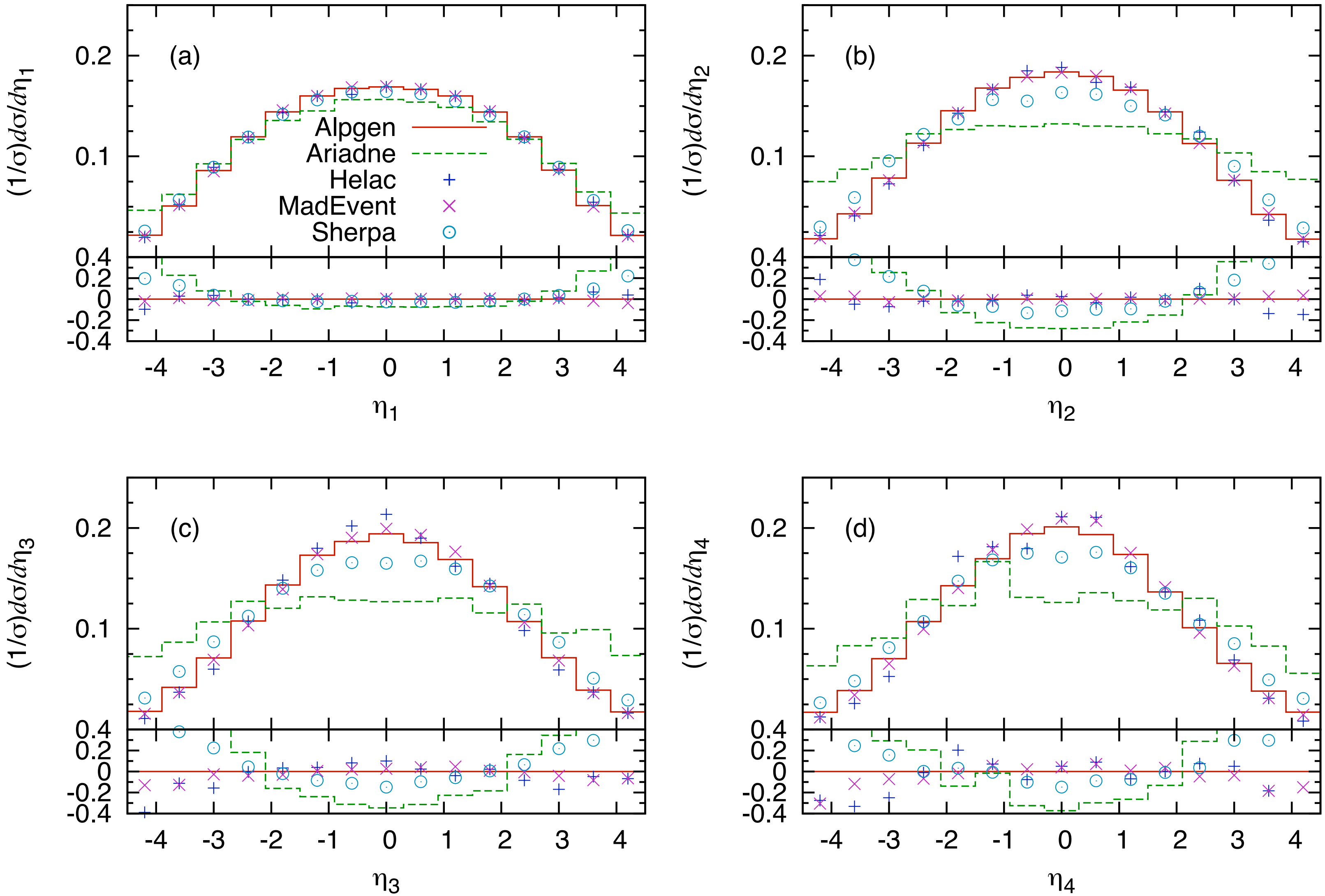
W + Multijets (LHC)



W + Multijets (LHC)



W + Multijets (LHC)



Summary of Lecture 3

- 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 POWHEG method looks promising
- Several options for LO multijets
  - reasonably consistent
  - spread indicates uncertainties (?)
- Field still very active
  - NLO matching for jets, spin correlations,...
  - building multijet matching into event generators