Monte Carlo Tools for W & Z Production

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Monte Carlo Event Generators

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- Traditionally (imprecise) general-purpose tools

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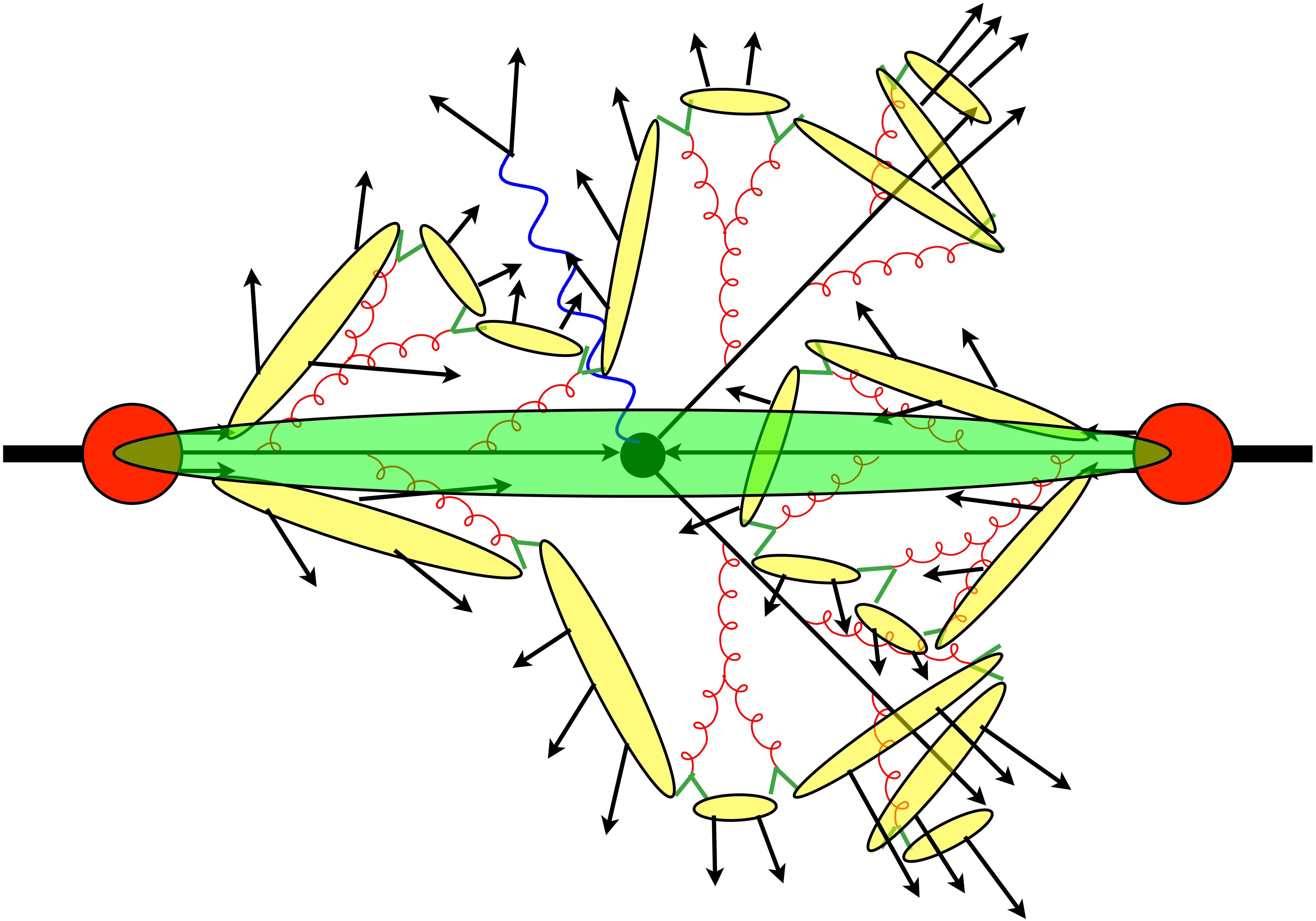
- Work in progress to make them more precise

Outline

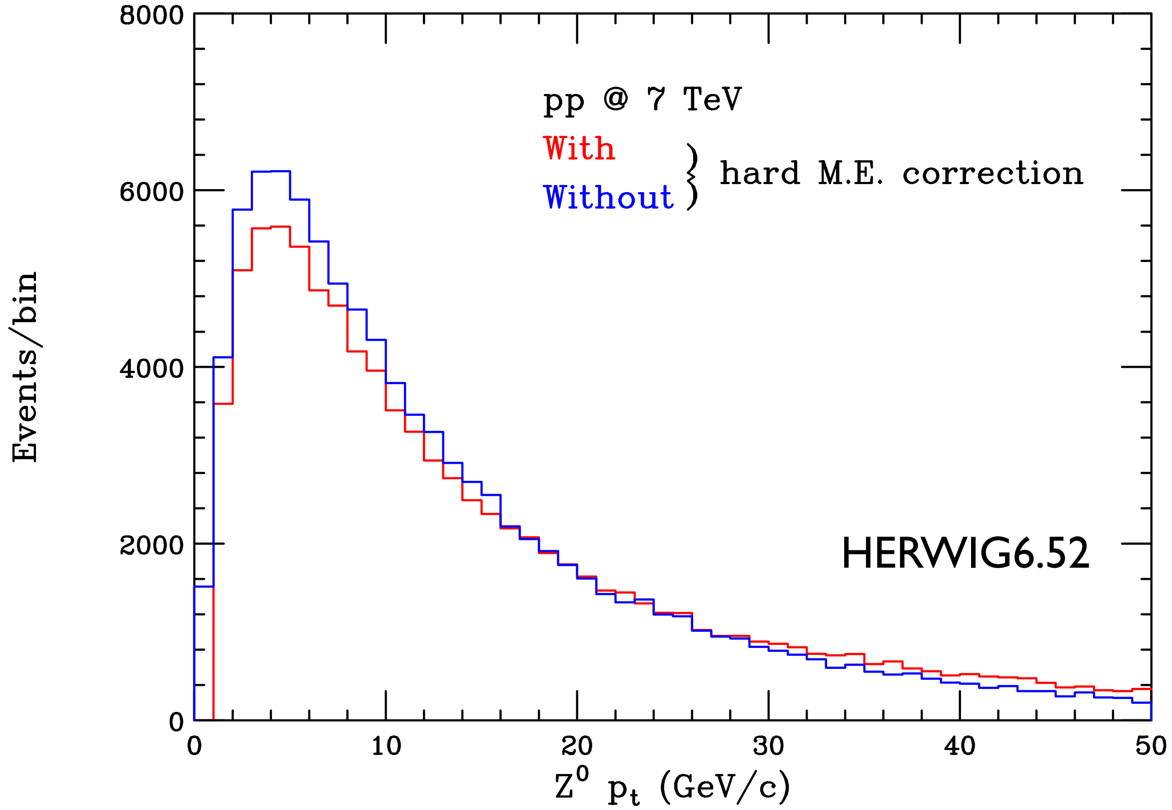
- Parton Shower Monte Carlo (PSMC)
- Matching PSMC to Next-to-Leading Order (NLOPS)
  - MC@NLO
  - POWHEG
- Merging PSMC with Multijet Matrix Elements (MEPS)
  - CKKW-L
  - MLM
- Combining MEPS with NLOPS (MENLOPS)
- Electroweak NLO + PSMC

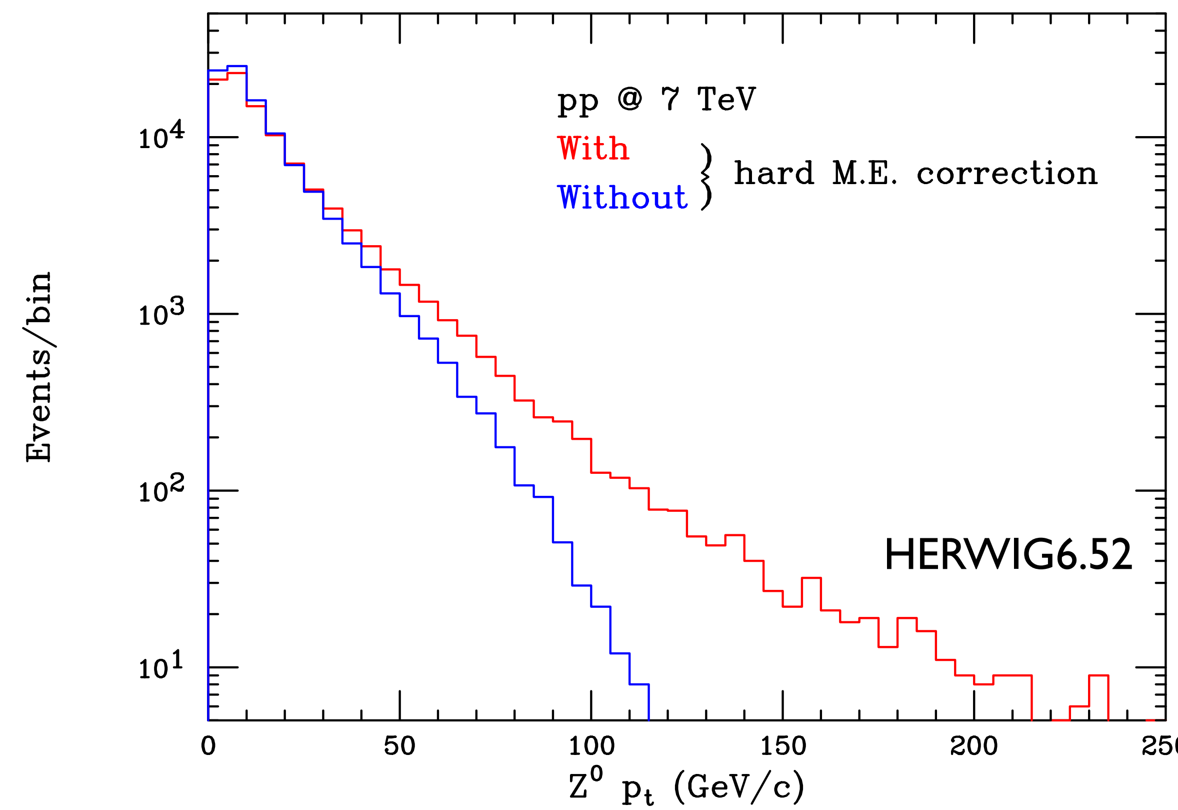
LHC Event Simulation

LHC Event Simulation



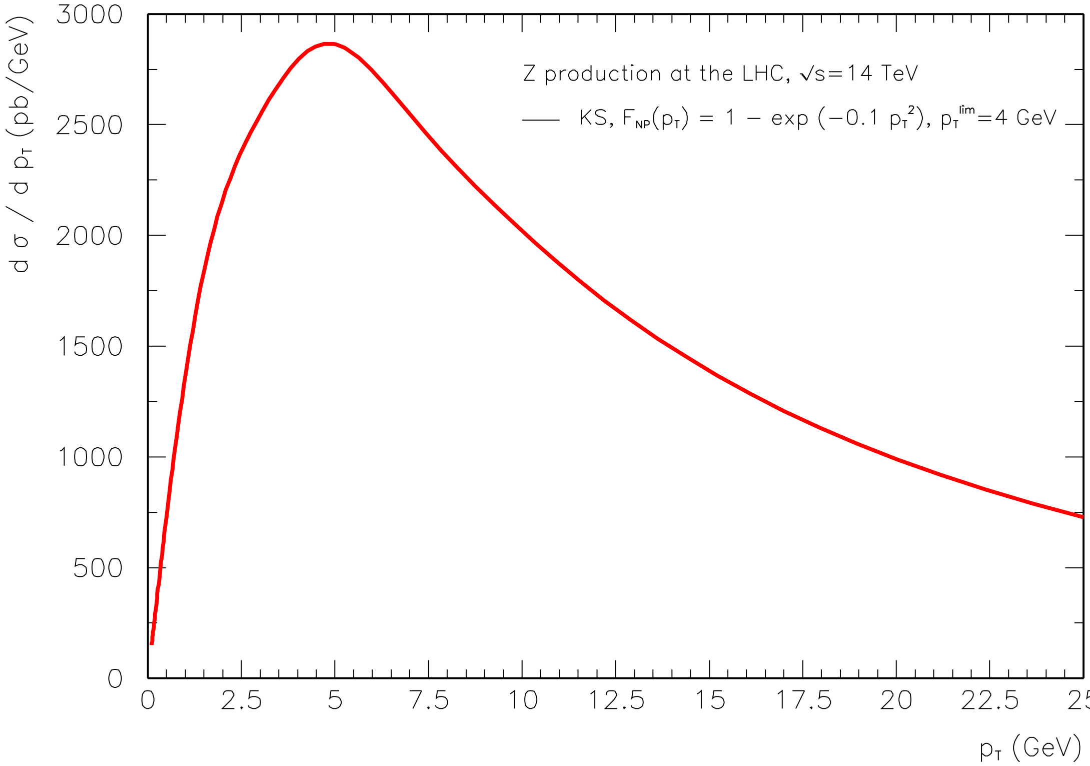
Parton Shower Monte Carlo



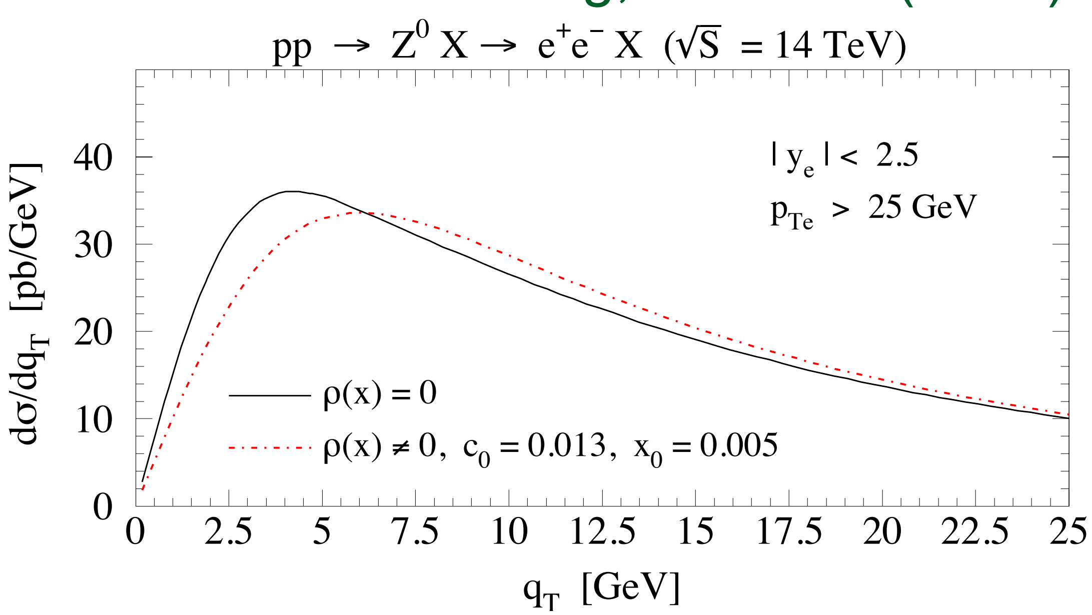


- Parton shower approximation
  - Bad for hard, wide-angle emission
- Hard matrix element correction: Z^0+parton
  - Not exact NLO

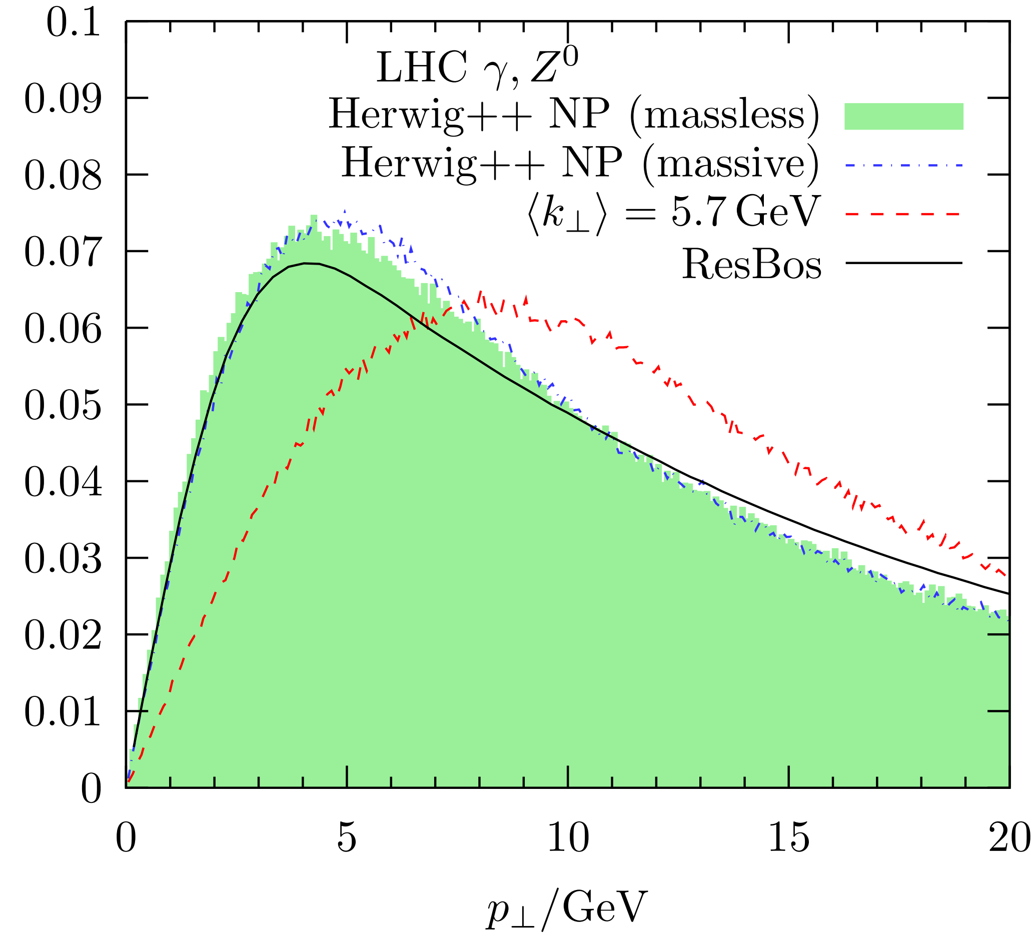
Comparison with resummed Z^0 p_T at LHC



A Kulesza & WJ Stirling, EPJC 20 (2001)349



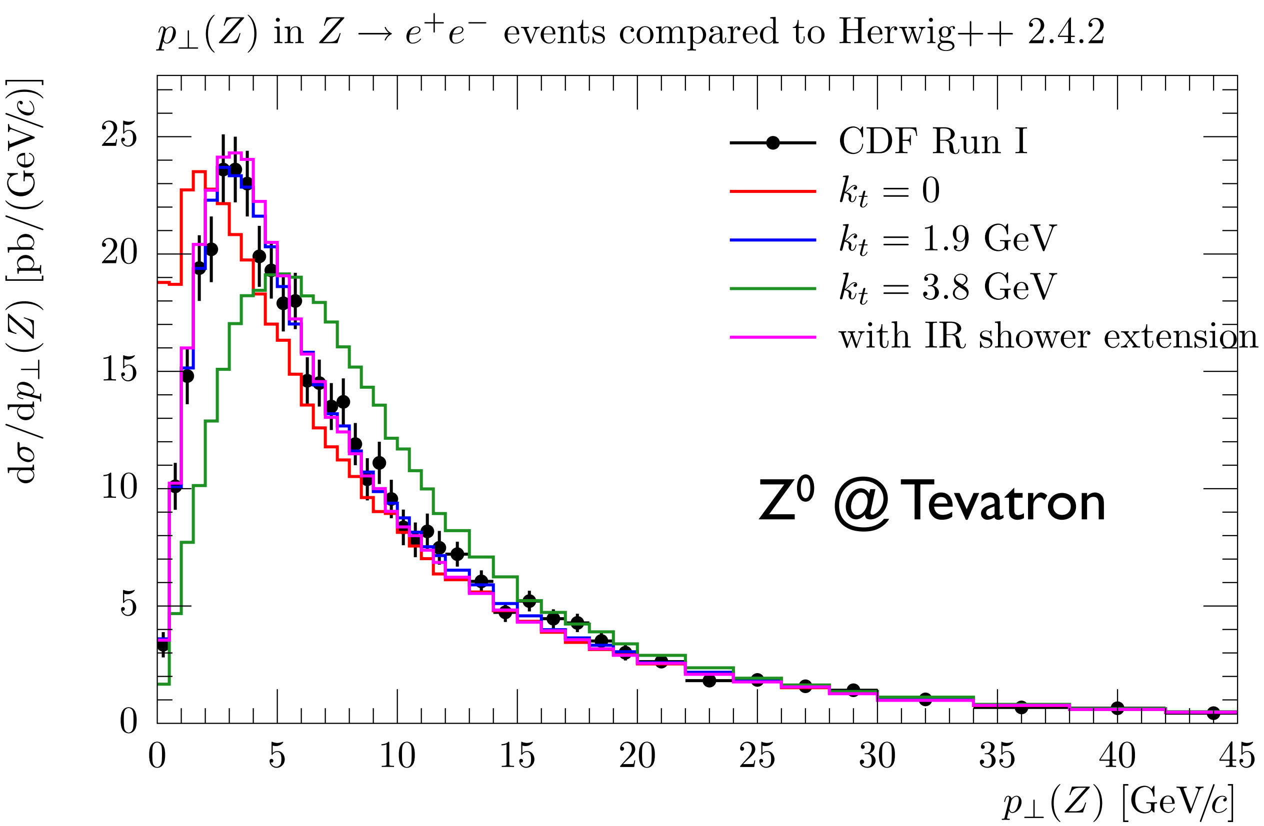
S Berge, P Nadolsky & F Olness, in arXiv:0709.3251

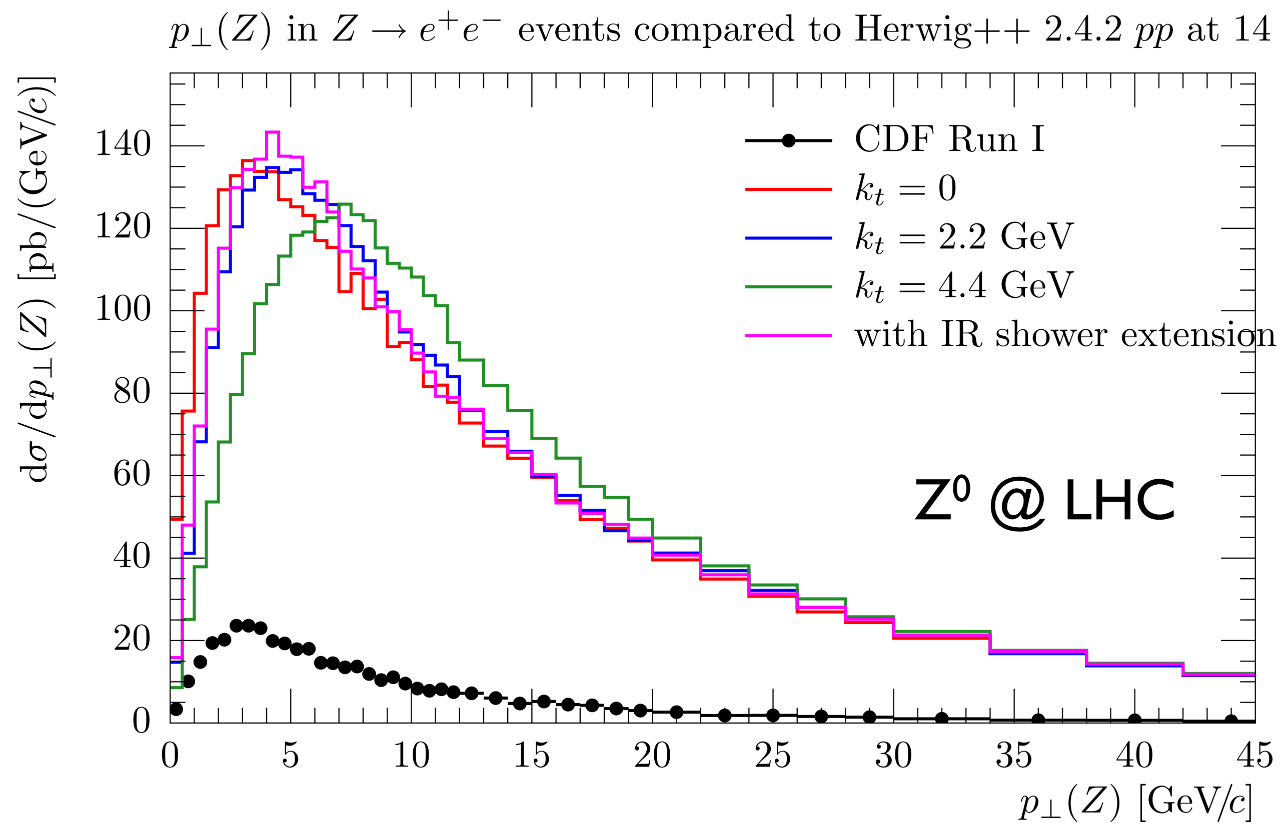


A Siodmok, S Gieseke & M Seymour, arXiv:0905.3455

- Slight broadening expected relative to Tevatron

"Intrinsic k_t"





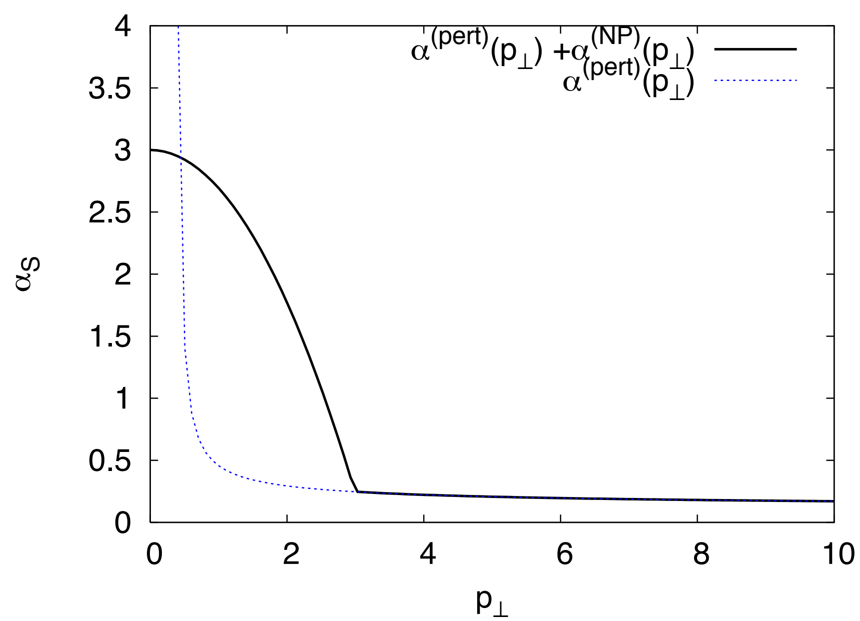


Figure 4: The optimal choice: "*quadratic*" interpolation with $\alpha_S(0) = 3$ and $p_{\perp 0} = 3\,\mathrm{GeV}$

- IR shower extension: extrapolate $\alpha_\mathrm{S}(p_\perp)$ to $p_\perp = 0$ non-perturbatively

Gieseke, Seymour & Siodmok, JHEP 06(2008)001

Parton Shower Monte Carlo

No (resolvable) emission One emission

$$d\sigma_{\rm MC} = \overbrace{B\left(\Phi_B\right)}^{\text{LO (Born)}}\, d\Phi_B \left[\Delta_{\rm MC}(0) + \frac{R_{\rm MC}\left(\Phi_B,\Phi_R\right)}{B\left(\Phi_B\right)}\,\Delta_{\rm MC}\left(k_T\left(\Phi_B,\Phi_R\right)\right)\, d\Phi_R\right]$$

- MC Sudakov form factor:

$$\Delta_{\rm MC}\left(p_T\right) = \exp\left[-\int d\Phi_R\,\frac{R_{\rm MC}\left(\Phi_B,\Phi_R\right)}{B\left(\Phi_B\right)}\,\theta\left(k_T\left(\Phi_B,\Phi_R\right)-p_T\right)\right]$$

- Unitarity:

$$\int d\sigma_{\rm MC} = \int B\left(\Phi_B\right)\, d\Phi_B$$

- Expanded to NLO:

$$d\sigma_{\rm MC} = \left[B\left(\Phi_B\right) - \int R_{\rm MC}\left(\Phi_B,\Phi_R\right) d\Phi_R\right] d\Phi_B + R_{\rm MC}\left(\Phi_B,\Phi_R\right) d\Phi_B\, d\Phi_R$$

MC@NLO

finite virtual

divergent

$$\begin{aligned}
\mathrm{d}\sigma_{\mathrm{NLO}} &= \left[B\left(\Phi_B\right)+V\left(\Phi_B\right)-\int\sum_i C_i\left(\Phi_B,\Phi_R\right)\mathrm{d}\Phi_R\right]\mathrm{d}\Phi_B+R\left(\Phi_B,\Phi_R\right)\mathrm{d}\Phi_B\,\mathrm{d}\Phi_R \\
&\equiv \left[B+V-\int C\,\mathrm{d}\Phi_R\right]\mathrm{d}\Phi_B+R\,\mathrm{d}\Phi_B\,\mathrm{d}\Phi_R
\end{aligned}$$

$$\begin{aligned}
\mathrm{d}\sigma_{\mathrm{MC}} &= B\left(\Phi_B\right)\mathrm{d}\Phi_B\left[\Delta_{\mathrm{MC}}(0)+\frac{R_{\mathrm{MC}}\left(\Phi_B,\Phi_R\right)}{B\left(\Phi_B\right)}\Delta_{\mathrm{MC}}\left(k_T\left(\Phi_B,\Phi_R\right)\right)\mathrm{d}\Phi_R\right] \\
&\equiv B\,\mathrm{d}\Phi_B\left[\Delta_{\mathrm{MC}}(0)+\left(R_{\mathrm{MC}}/B\right)\Delta_{\mathrm{MC}}\left(k_T\right)\mathrm{d}\Phi_R\right]
\end{aligned}$$

$$\begin{aligned}
\mathrm{d}\sigma_{\mathrm{MC@NLO}} &= \left[B+V+\int\left(R_{\mathrm{MC}}-C\right)\mathrm{d}\Phi_R\right]\mathrm{d}\Phi_B\left[\Delta_{\mathrm{MC}}(0)+\left(R_{\mathrm{MC}}/B\right)\Delta_{\mathrm{MC}}\left(k_T\right)\mathrm{d}\Phi_R\right] \\
&\quad+\left(R-R_{\mathrm{MC}}\right)\Delta_{\mathrm{MC}}\left(k_T\right)\mathrm{d}\Phi_B\,\mathrm{d}\Phi_R
\end{aligned}$$

finite $\gtrsim 0$

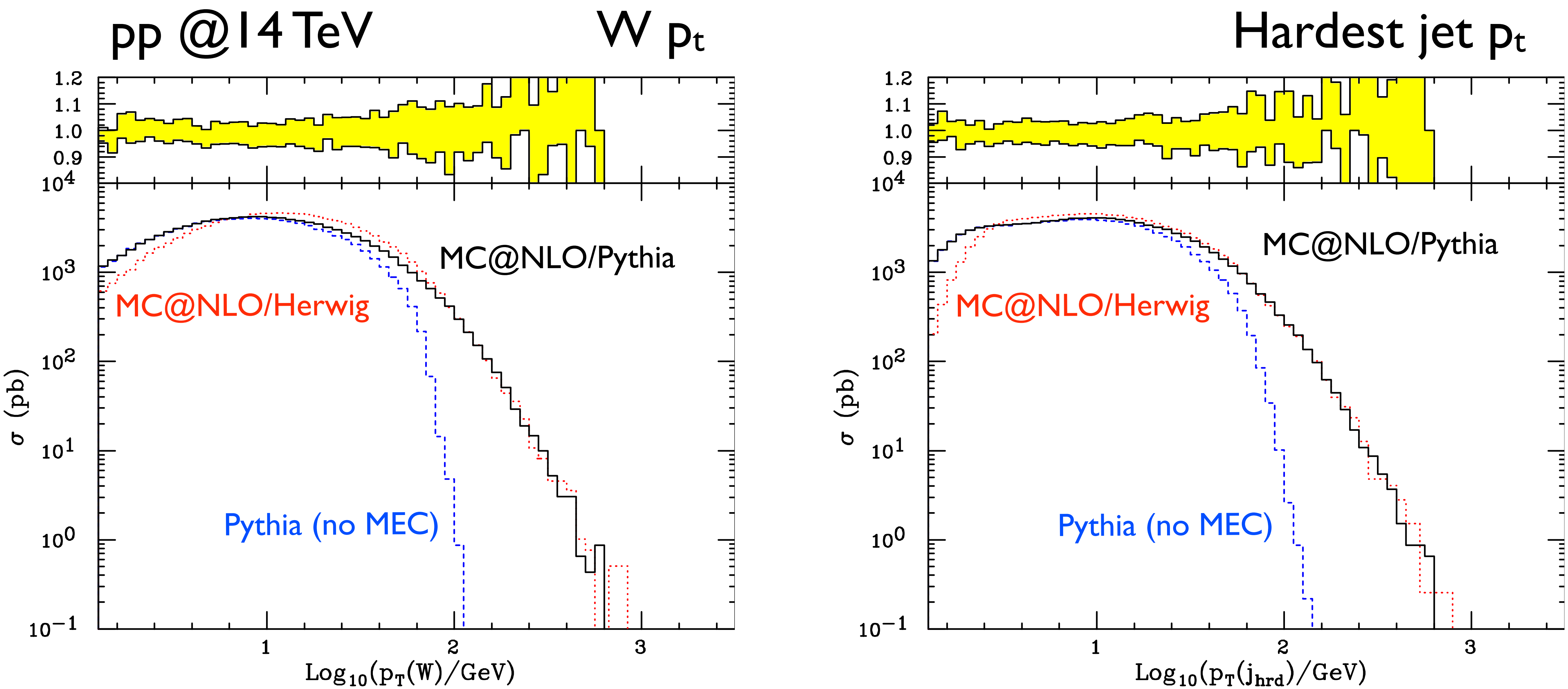
MC starting from no emission

MC starting from one emission

- Expanding gives NLO result

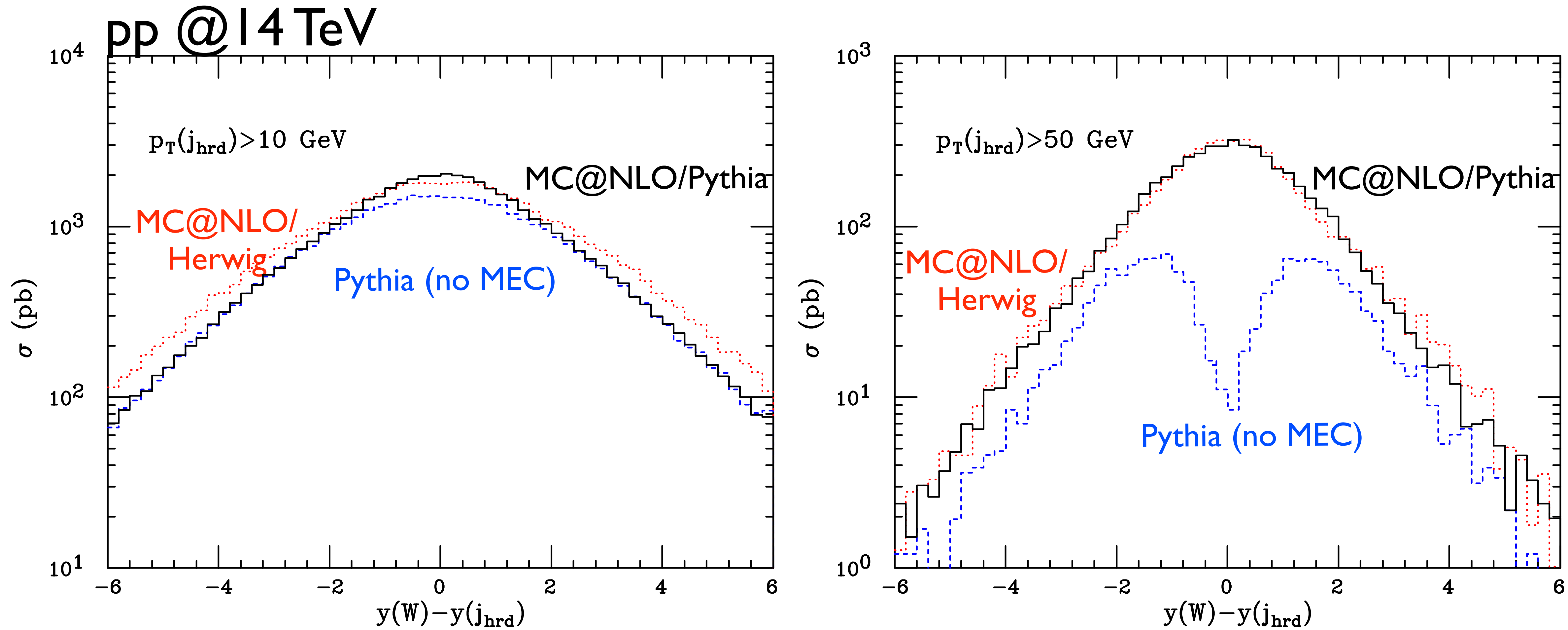
S Frixione & BW, JHEP 06(2002)029

MC@NLO



- MC@NLO is MC-specific

MC@NLO



- NLO is only LO at high p_t

S Frixione & P Torrielli, JHEP 04(2010)110

POWHEG

$$\mathrm{d}\sigma_{\mathrm{PH}} = \overline{B}\left(\Phi_B\right)\,\mathrm{d}\Phi_B\,\left[\Delta_R\left(0\right) + \frac{R\left(\Phi_B,\Phi_R\right)}{B\left(\Phi_B\right)}\,\Delta_R\left(k_T\left(\Phi_B,\Phi_R\right)\right)\,\mathrm{d}\Phi_R\right]$$

$$\overline{B}\left(\Phi_B\right) = B\left(\Phi_B\right) + V\left(\Phi_B\right) + \int\left[R\left(\Phi_B,\Phi_R\right) - \sum_i C_i\left(\Phi_B,\Phi_R\right)\right]\mathrm{d}\Phi_R$$

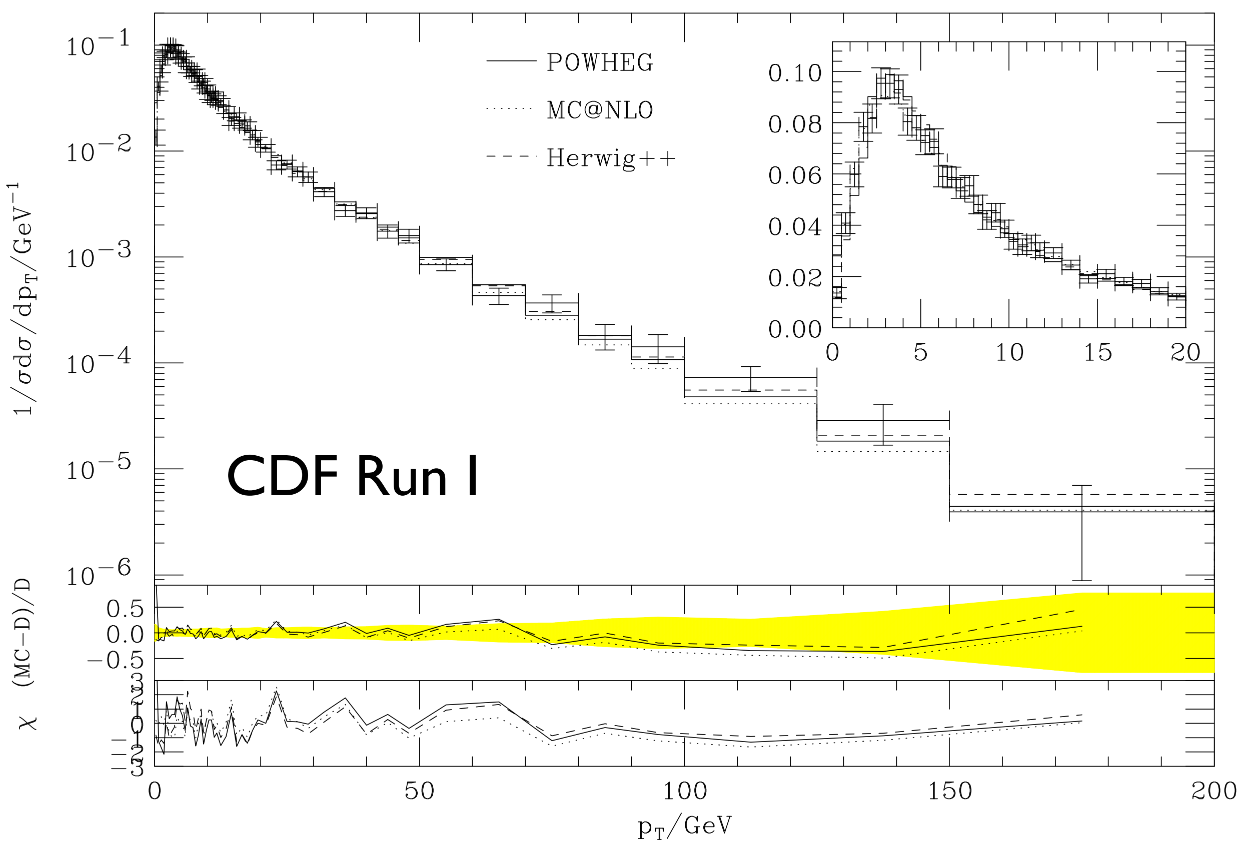
$$\Delta_R\left(p_T\right) = \exp\left[-\int \mathrm{d}\Phi_R\,\frac{R\left(\Phi_B,\Phi_R\right)}{B\left(\Phi_B\right)}\,\theta\left(k_T\left(\Phi_B,\Phi_R\right) - p_T\right)\right]$$

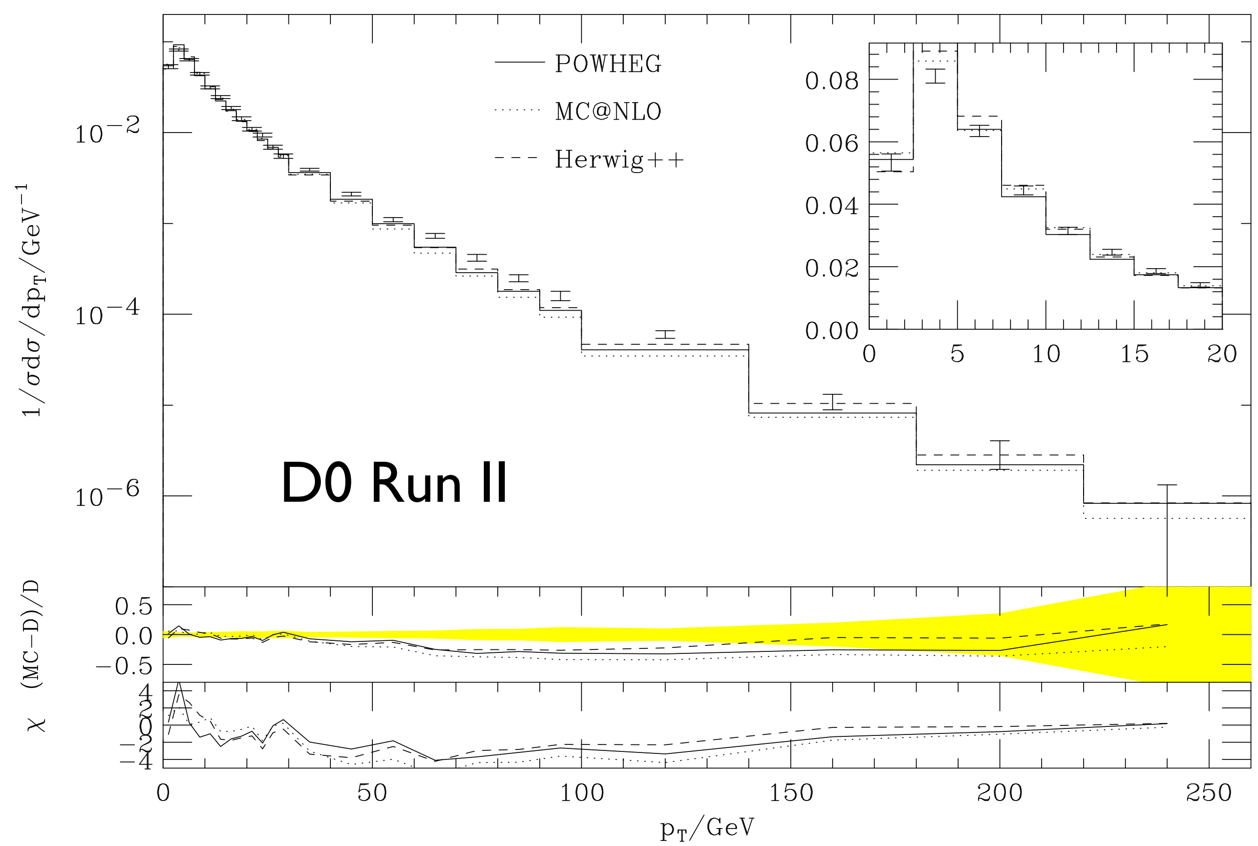
- NLO with no negative weights
- High p_t enhanced by $K = \overline{B}/B = 1 + \mathcal{O}(\alpha_{\mathrm{S}})$

arbitrary NNLO

P Nason, JHEP 11(2004)040

Z^0 @ Tevatron

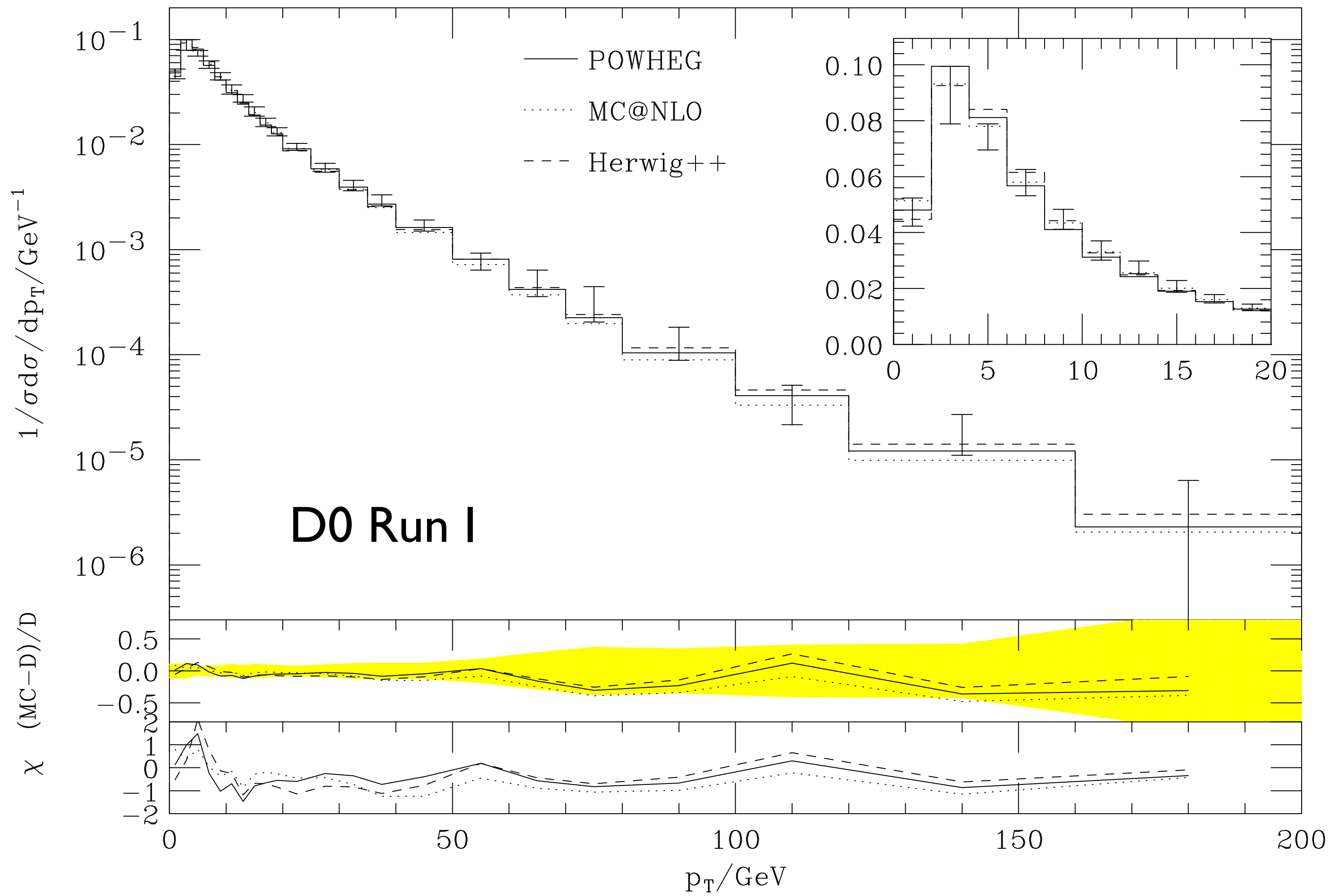




- NLO is only LO at high p_t

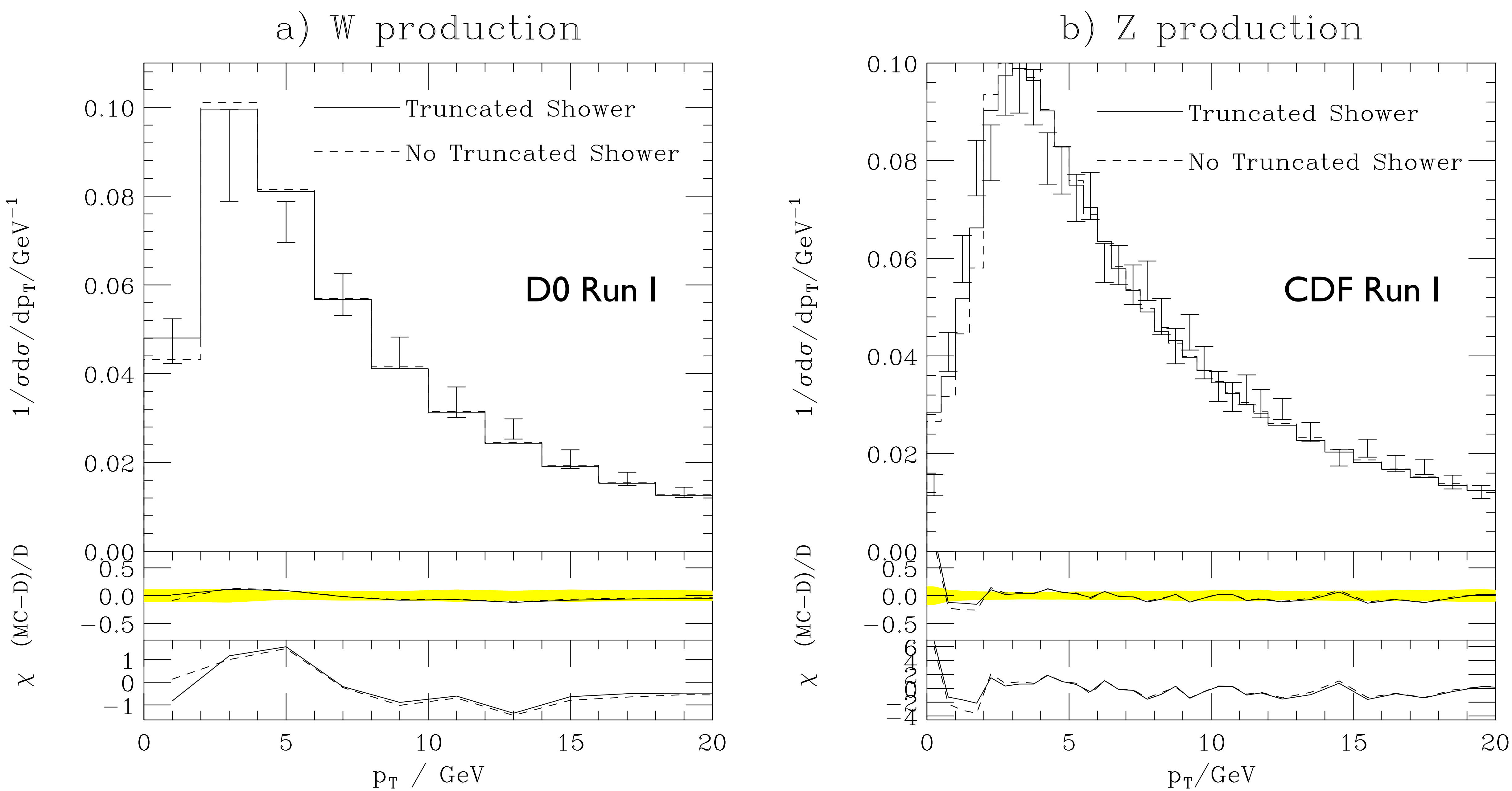
Hamilton, Richardson, Tully JHEP10(2008)015

W @ Tevatron



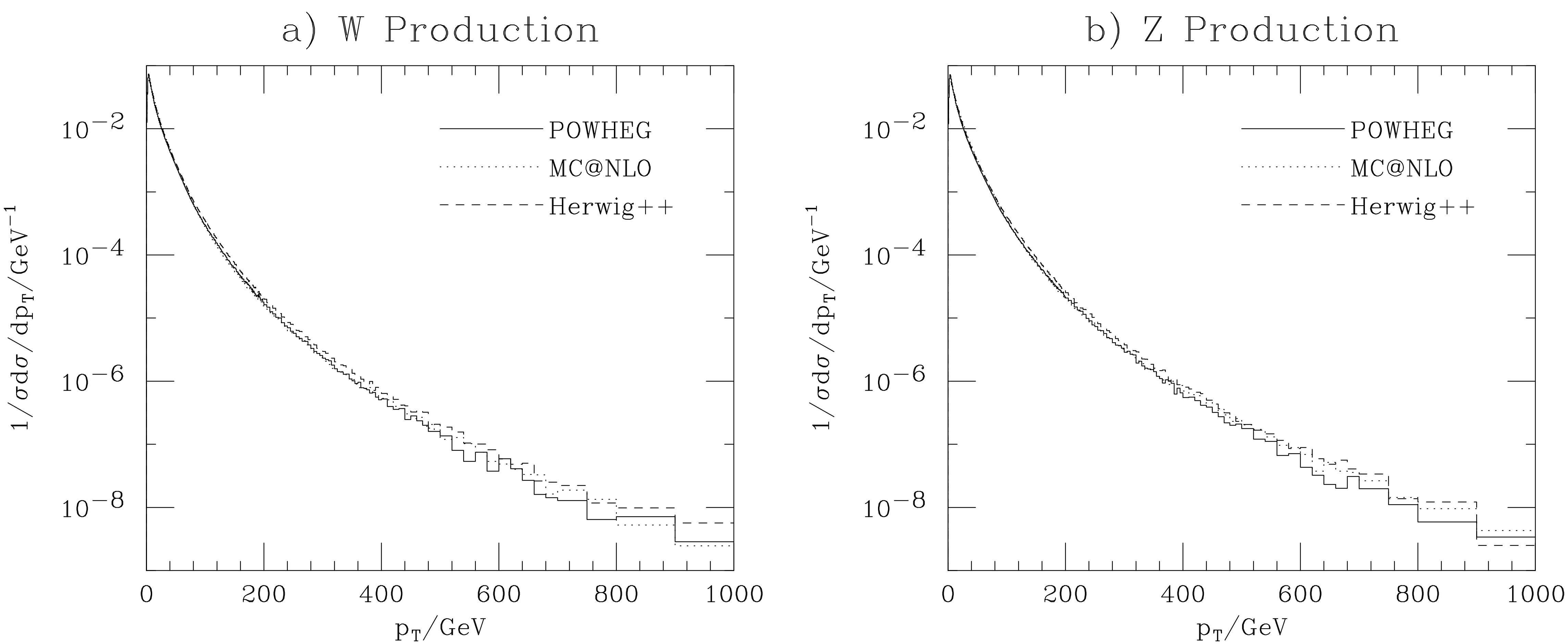
- All agree (tuned) at Tevatron

Truncated shower



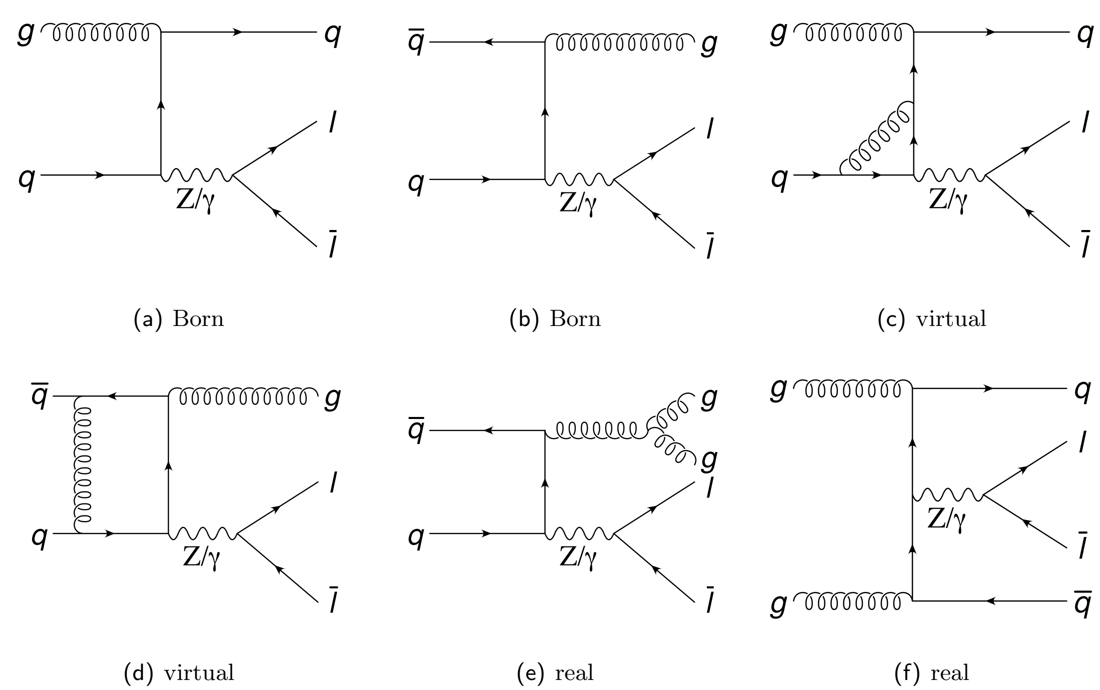
- Highest p_t emission not always first
  - must add ‘truncated’ shower at wider angles

W & Z^0 @ LHC (14 TeV)

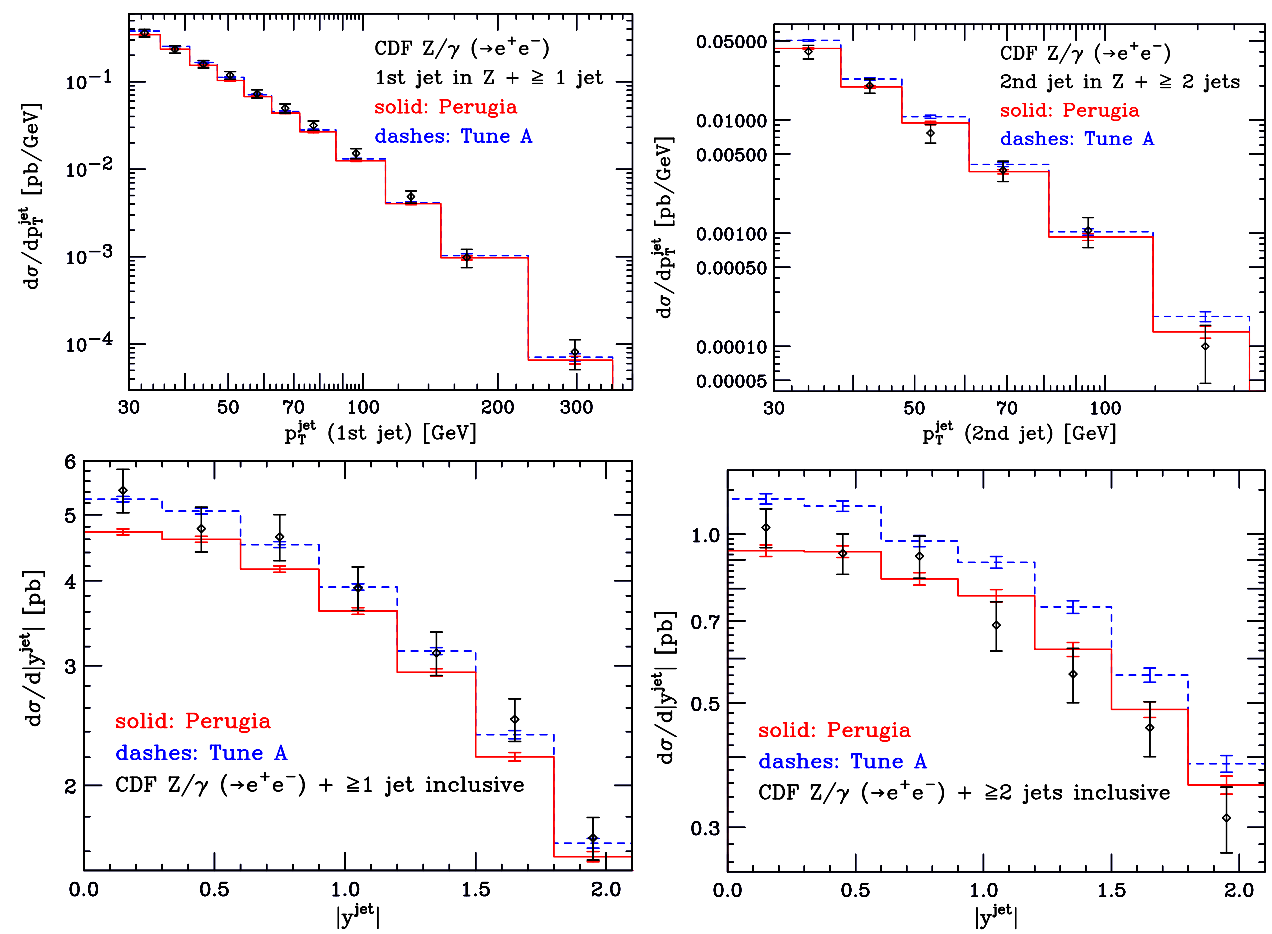


- Still in fair agreement at 14 TeV

Z^0 + jet POWHEG



Sample graphs



- Cut now needed on 'underlying Born' p_t of Z^0
- Good agreement with CDF (not so good with D0)
- First jet is now NLO, second is LO (times $\bar{B}$/B ...)

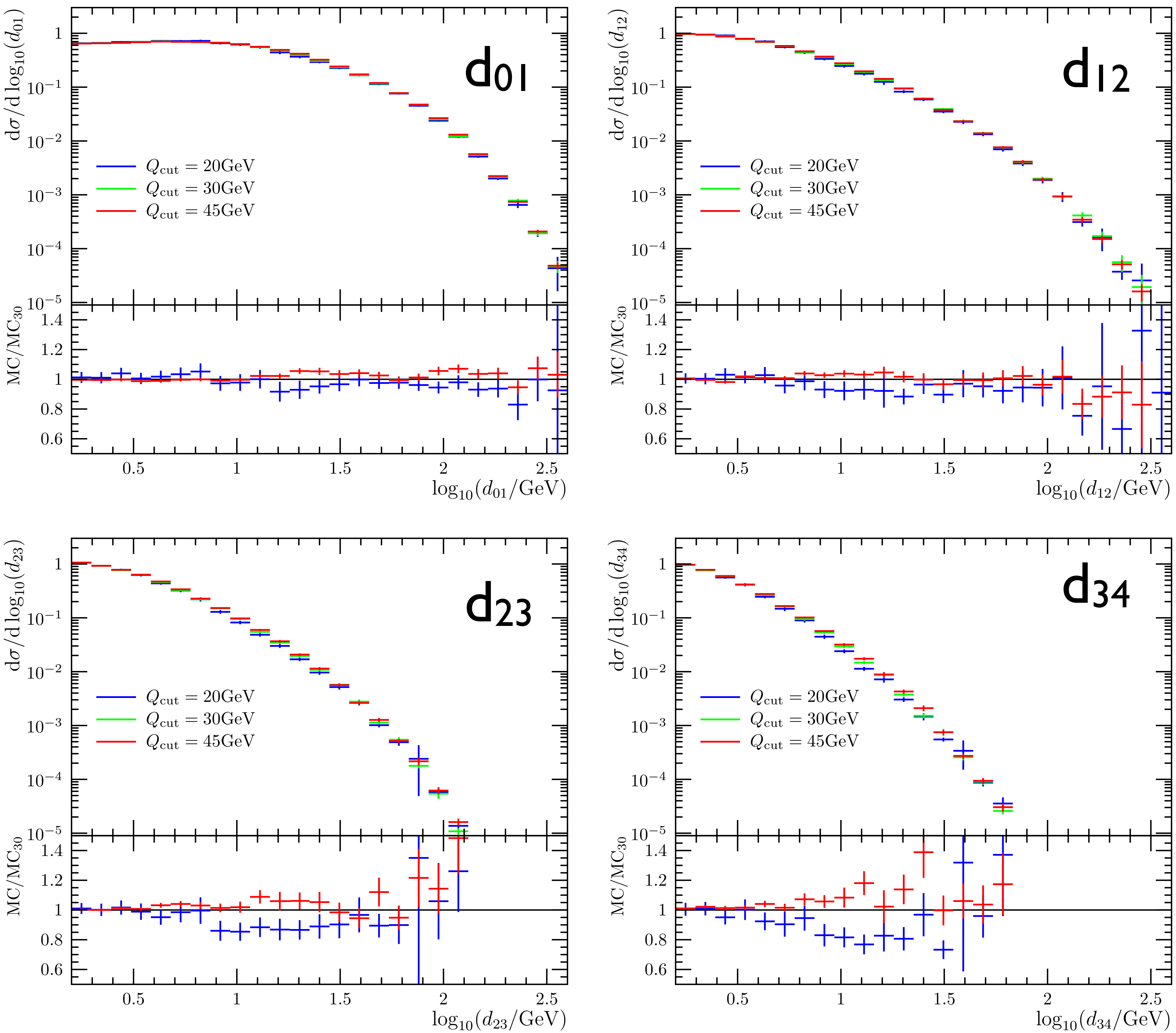
Alioli, Nason, Oleari, Re, 1009.5594

MEPS

- Objective: merge n-jet MEs with PSMC such that
  - Multijet rates for k_t-resolution > Q_{cut} are correct to LO
  - PSMC generates jet structure below Q_{cut}
  - Q_{cut} dependence cancels to NLL accuracy

CKKW: Catani et al., JHEP 11(2001)
-L: Lonnblad, JHEP 05(2002)063
MLM: Mangano et al., NP B632(2002)343

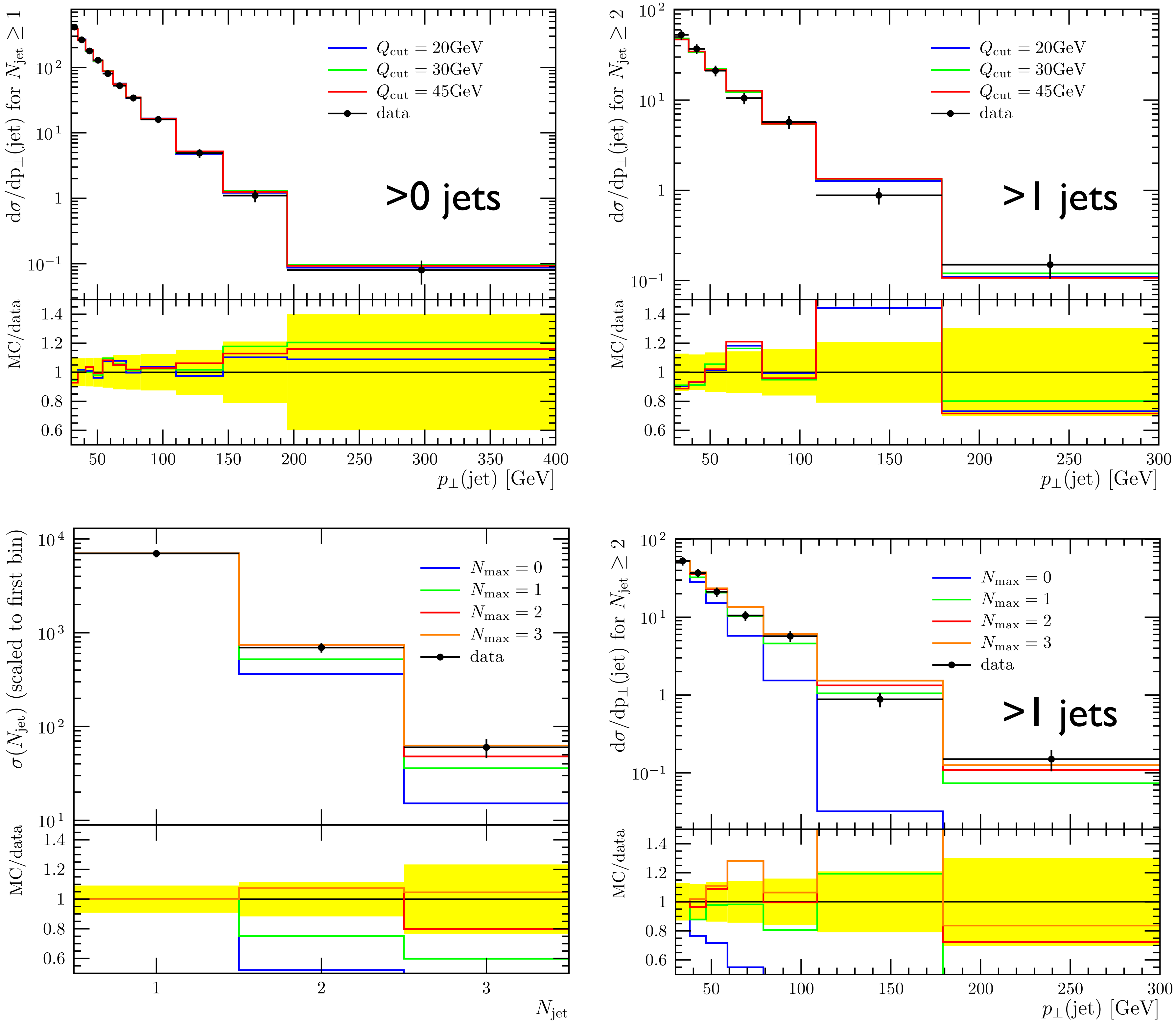
Z^0 MEPS @ Tevatron



- Differential jet rates (k_t-algorithm)

Hoeche, Krauss, Schumann, Siegert, JHEP05(2009)053

Z^0 MEPS @ Tevatron



- CDF run II data
- Jet p_t and N_{jets}
- Insensitive to Q_{cut}
- Insensitive to N_{max}>1

Hoeche, Krauss, Schumann, Siegert, JHEP05(2009)053

MENLOPS

$$d\sigma_{\mathrm{TOT}} = d\sigma_{\mathrm{NLOPS}}(0\,\mathrm{jets}) + K_1\, d\sigma_{\mathrm{NLOPS}}(1\,\mathrm{jet}) + K_2\, d\sigma_{\mathrm{MEPS}}(\geq 2\,\mathrm{jets})$$

- Assume ≥ 2 jets have K-factor

$$K_2 = \sigma_{\mathrm{NLOPS}}(\geq 1\,\mathrm{jets})/\sigma_{\mathrm{MEPS}}(\geq 1\,\mathrm{jets})$$

- To retain NLO accuracy we need

$$\sigma_{\mathrm{TOT}} = \sigma_{\mathrm{NLOPS}}(0\,\mathrm{jets}) + \sigma_{\mathrm{NLOPS}}(\geq 1\,\mathrm{jets})$$

- Therefore

$$K_1 = \frac{\sigma_{\mathrm{MEPS}}(1\,\mathrm{jet})}{\sigma_{\mathrm{MEPS}}(\geq 1\,\mathrm{jets})} \Big/ \frac{\sigma_{\mathrm{NLOPS}}(1\,\mathrm{jet})}{\sigma_{\mathrm{NLOPS}}(\geq 1\,\mathrm{jets})}$$

Hamilton & Nason, JHEP06(2010)039

Hoeche, Krauss, Schumann, Siegert, 1009.1127

MENLOPS

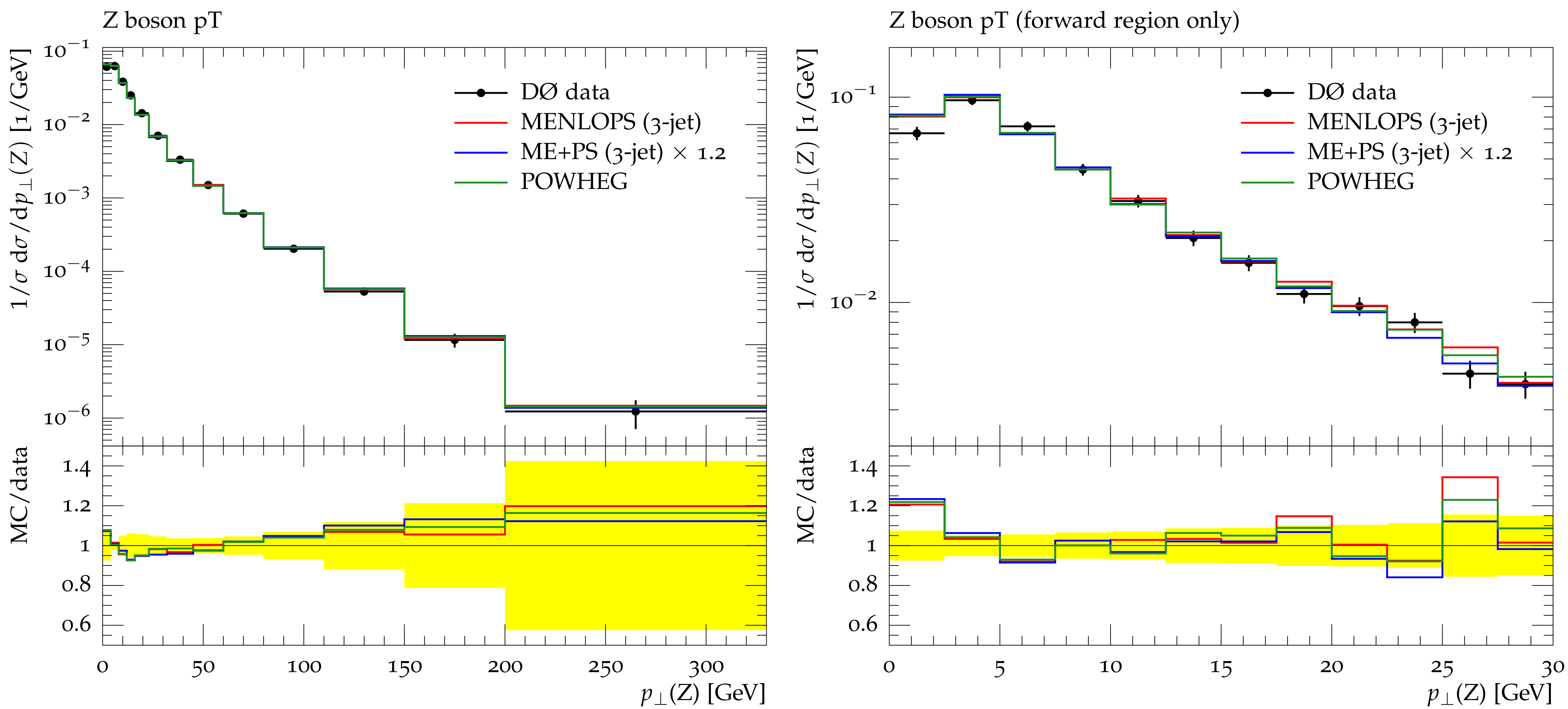
$$d\sigma_{\mathrm{TOT}} = d\sigma_{\mathrm{NLOPS}}(0\,\mathrm{jets}) + K_1\, d\sigma_{\mathrm{NLOPS}}(1\,\mathrm{jet}) + K_2\, d\sigma_{\mathrm{MEPS}}(\geq 2\,\mathrm{jets})$$

$$K_2 = \sigma_{\mathrm{NLOPS}}(\geq 1\,\mathrm{jets})/\sigma_{\mathrm{MEPS}}(\geq 1\,\mathrm{jets})$$

$$K_1 = \frac{\sigma_{\mathrm{MEPS}}(1\,\mathrm{jet})}{\sigma_{\mathrm{MEPS}}(\geq 1\,\mathrm{jets})} \Bigg/ \frac{\sigma_{\mathrm{NLOPS}}(1\,\mathrm{jet})}{\sigma_{\mathrm{NLOPS}}(\geq 1\,\mathrm{jets})}$$

- Choose Q_{cut} such that $\sigma_{\mathrm{MEPS}}(\geq 2\,\mathrm{jets}) \leq \mathcal{O}(\alpha_{\mathrm{S}})$
- Compute K_1, K_2 (in principle for each Born kinematics)
- Throw away MEPS 0- & 1-jet samples
- Replace them by NLOPS 0- & 1-jet samples

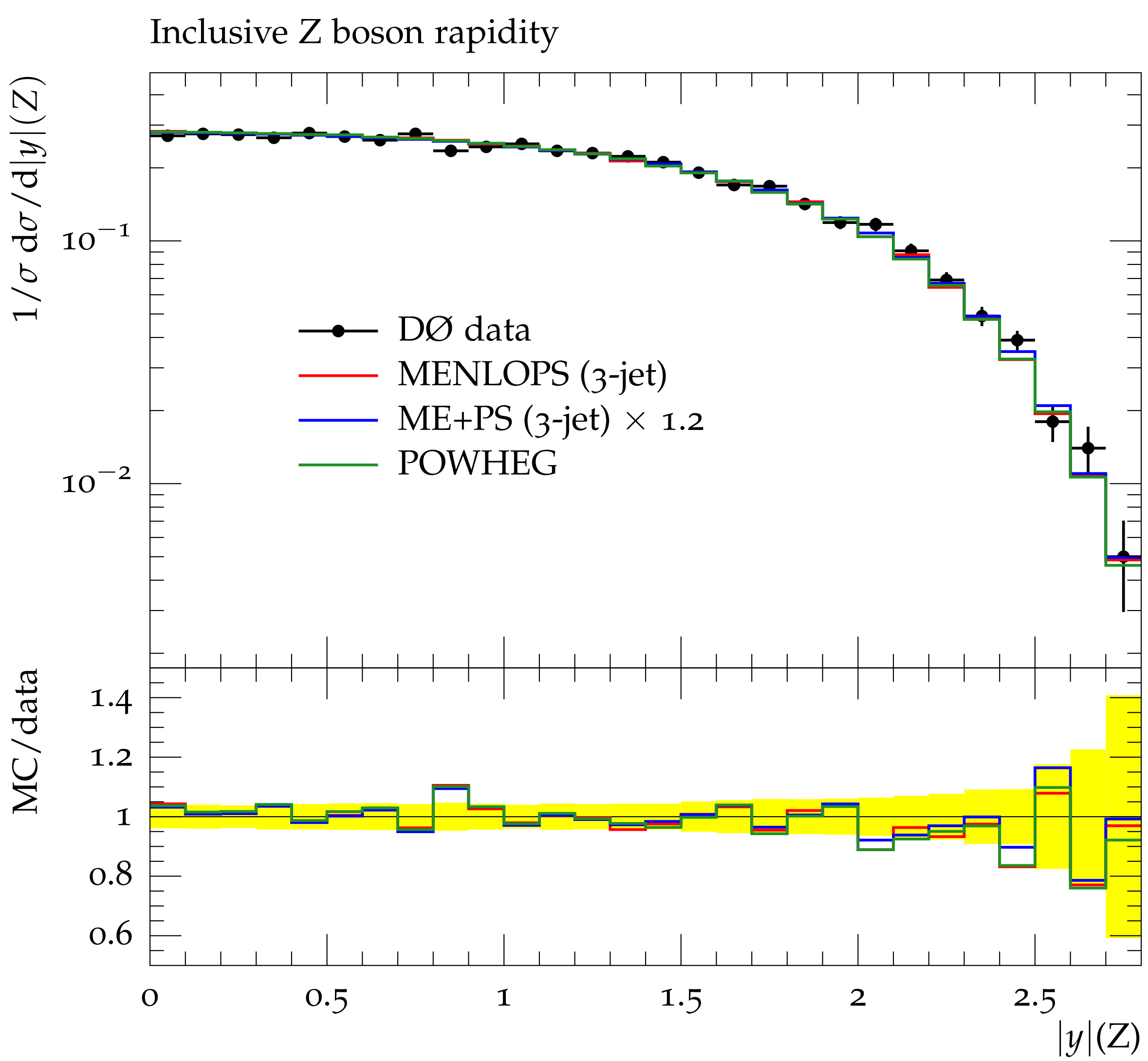
Z MENLOPS @ Tevatron

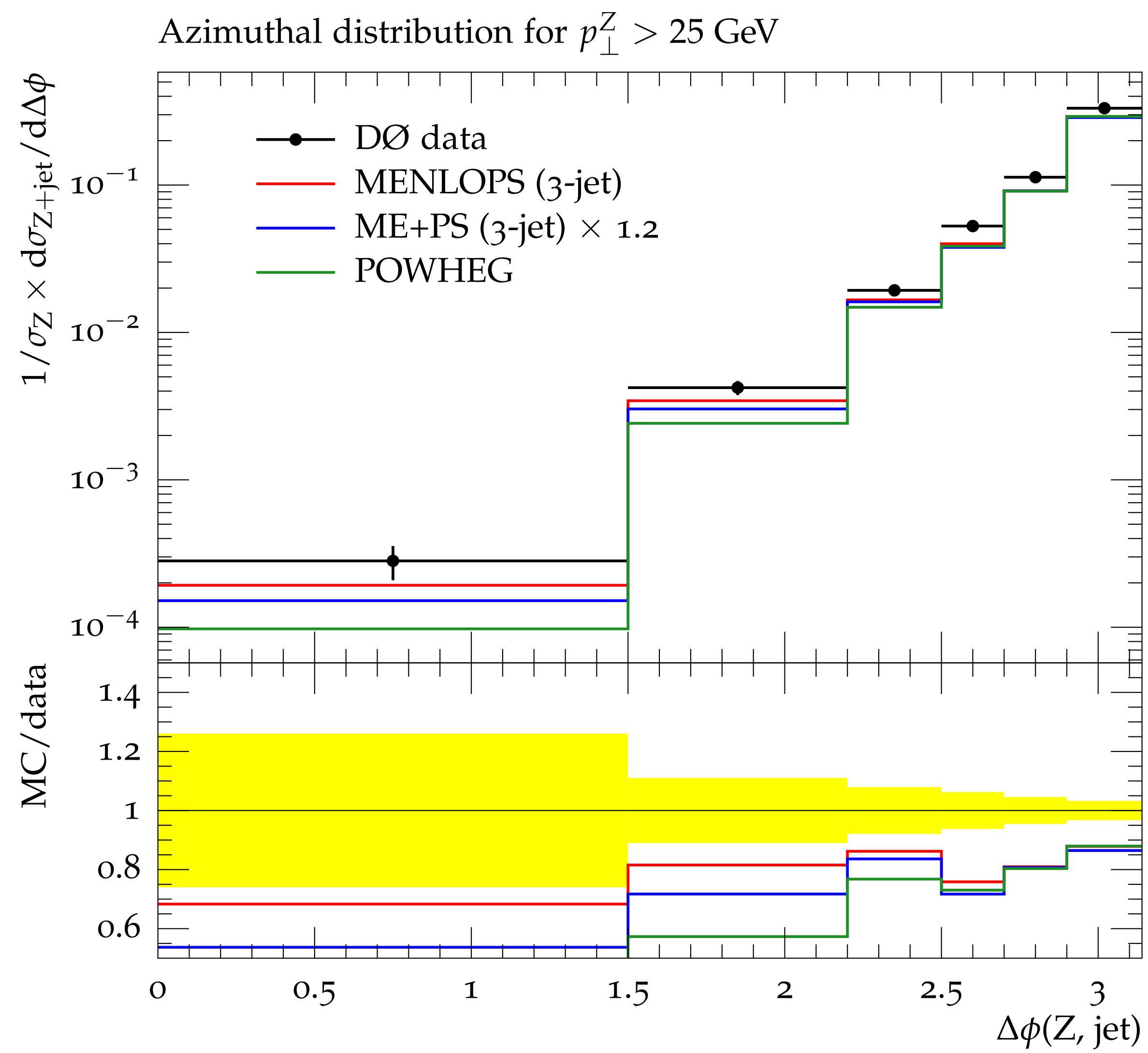


- All treatments agree (MEPS rescaled)

Hoeche, Krauss, Schumann, Siegert, 1009.1127

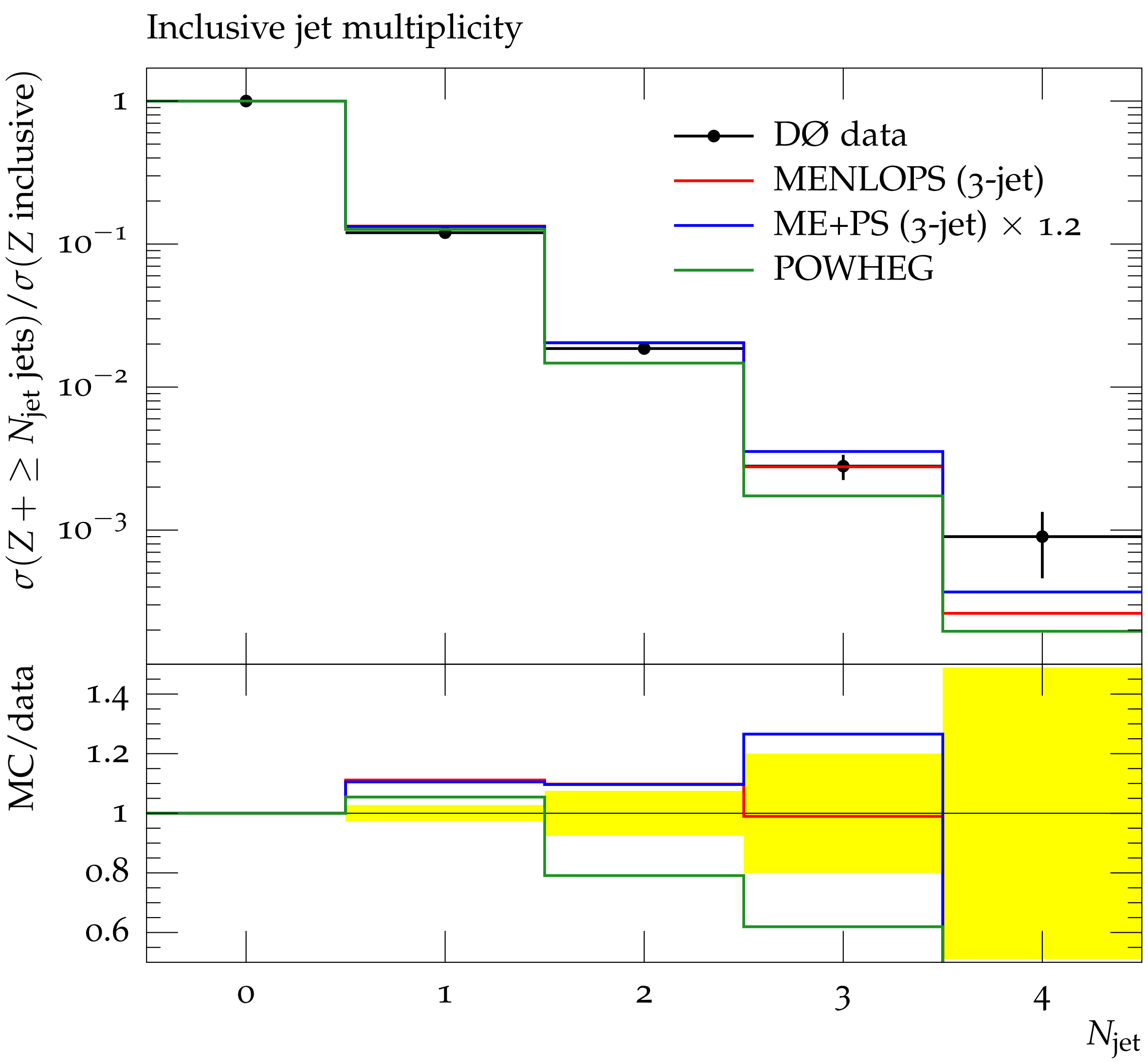
Z MENLOPS @ Tevatron

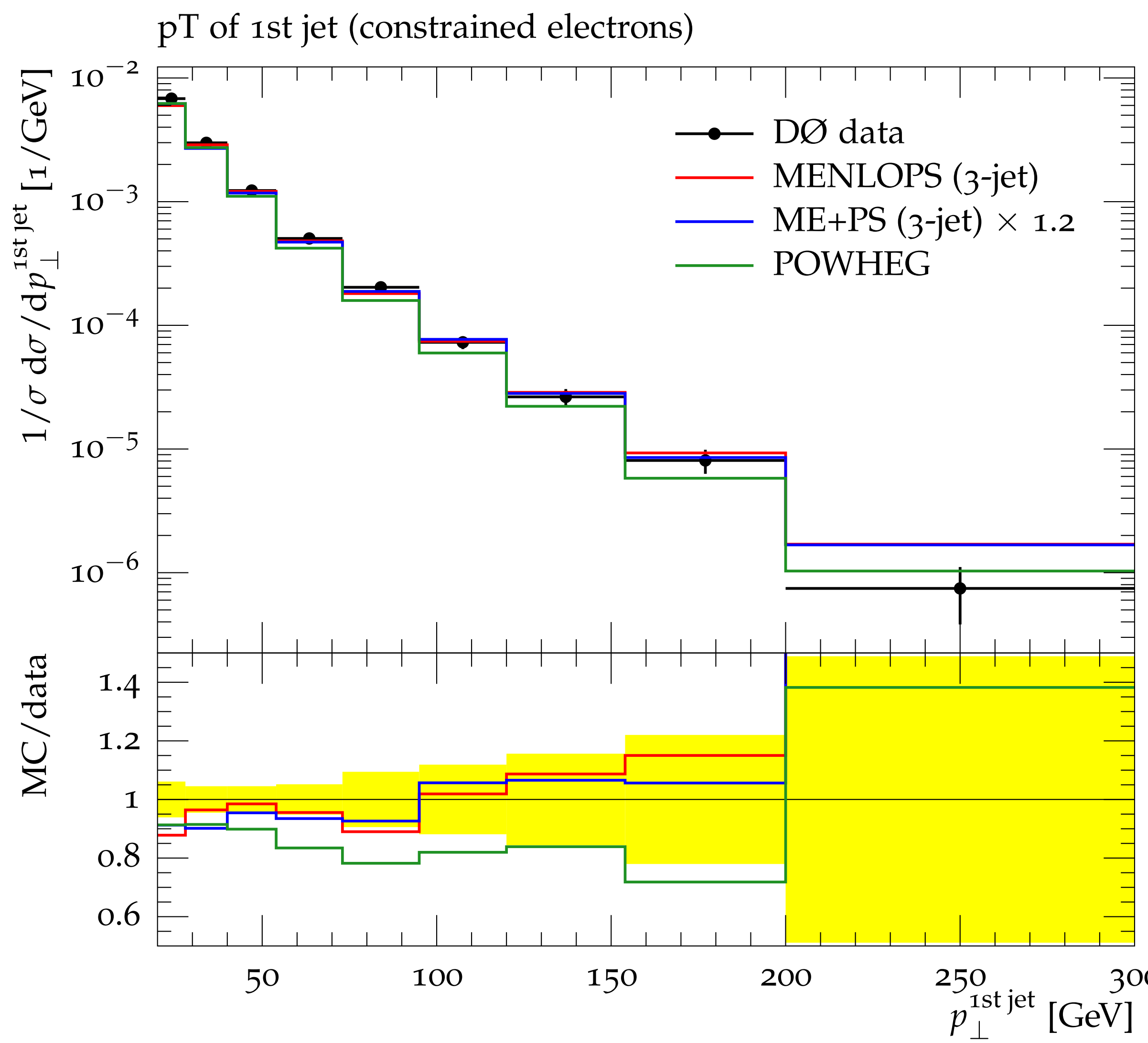




- MENLOPS best for $\Delta\phi(Z, \text{jet})$

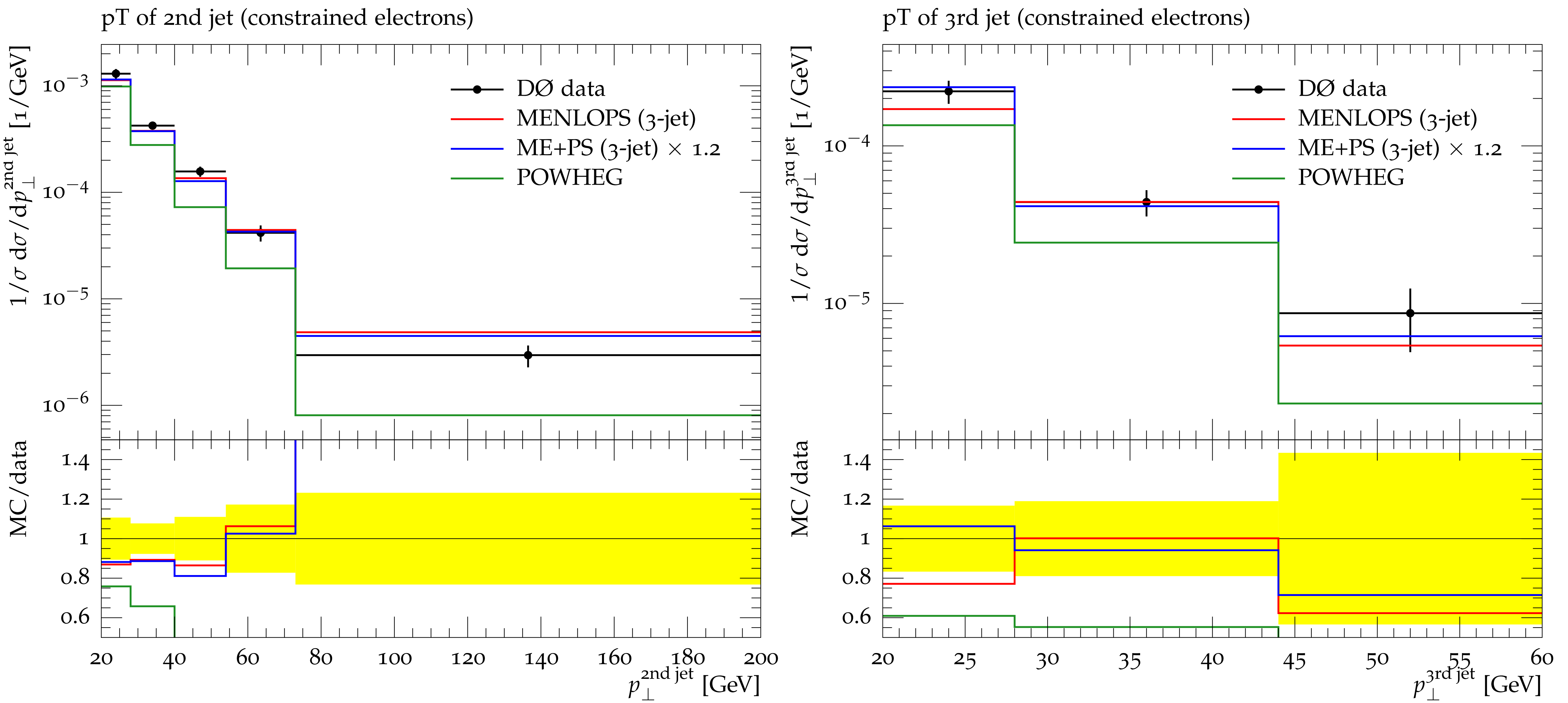
Z MENLOPS @ Tevatron





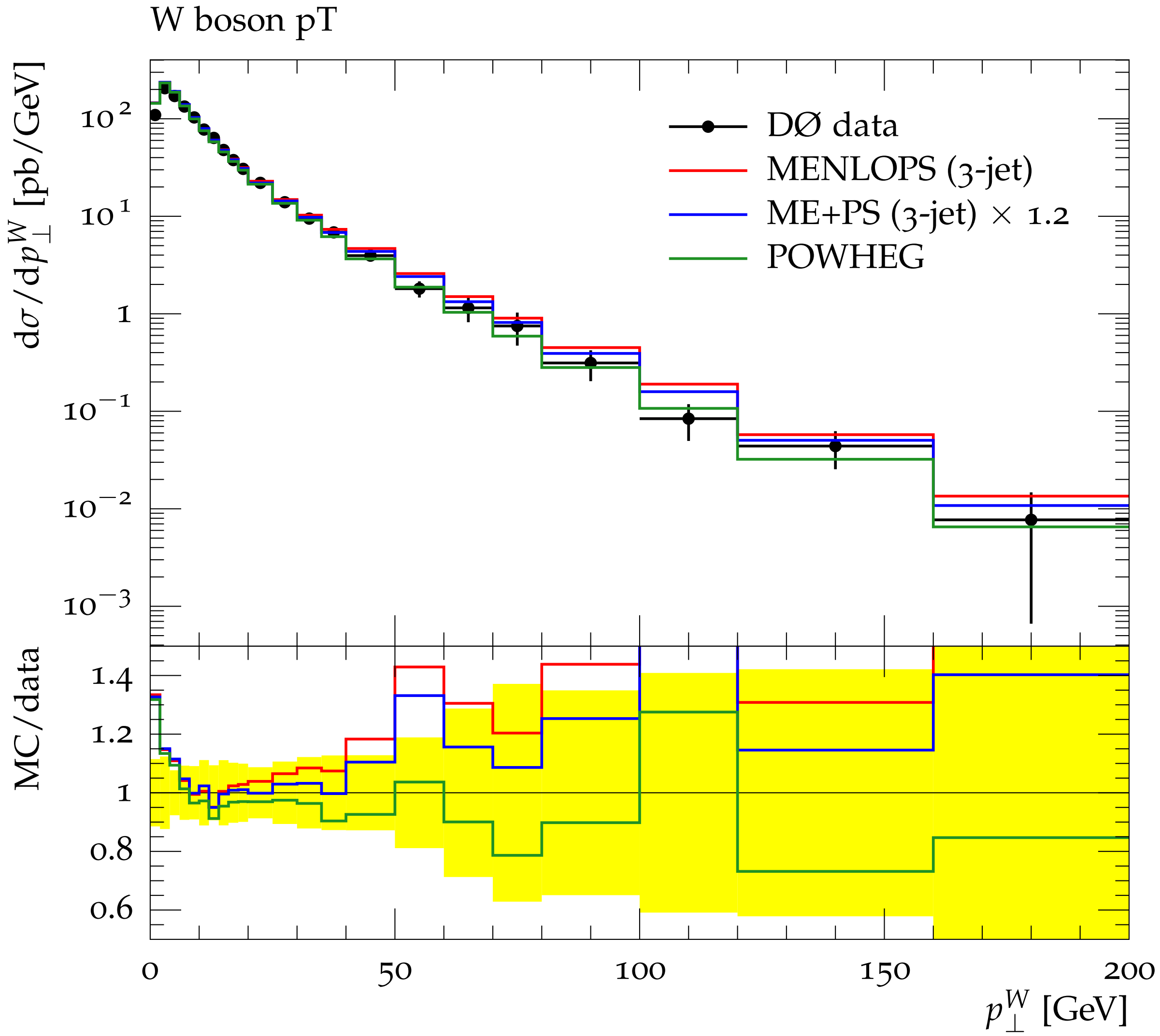
- MENLOPS good for N_{jet}=1,2,3 (no ME for 4)

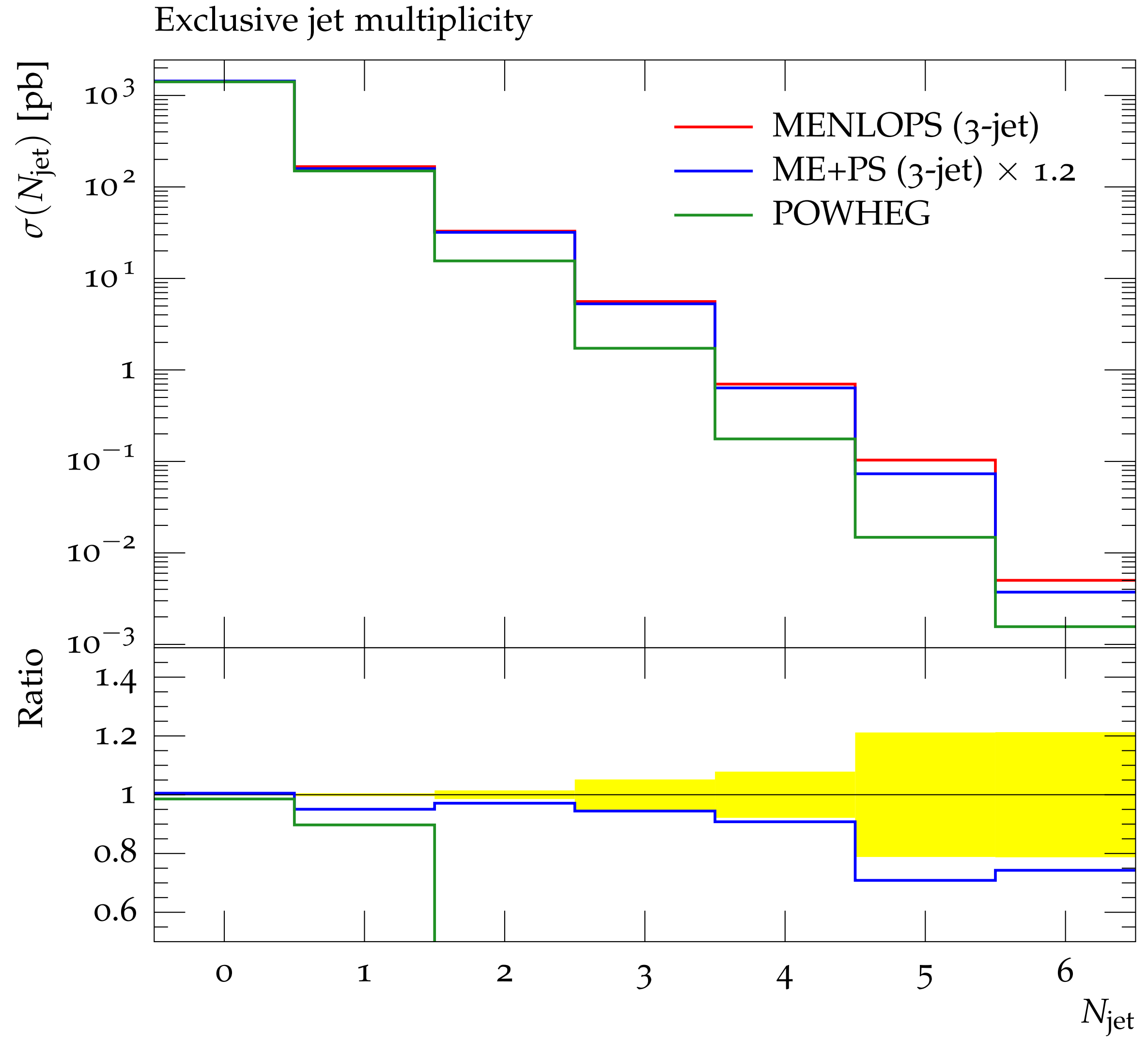
Z MENLOPS @ Tevatron



- MENLOPS best for jets 2 & 3

W MENLOPS @ Tevatron

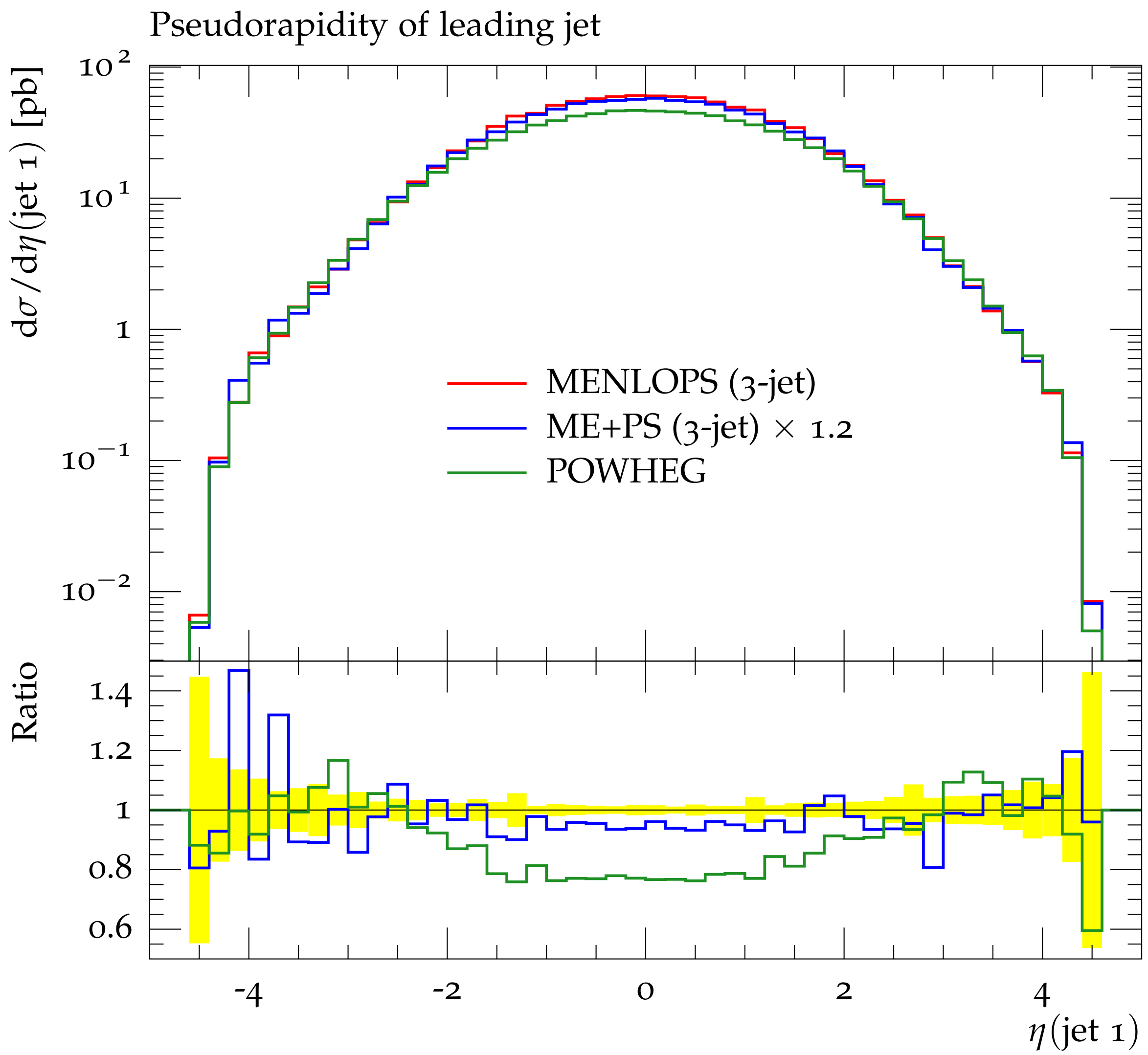


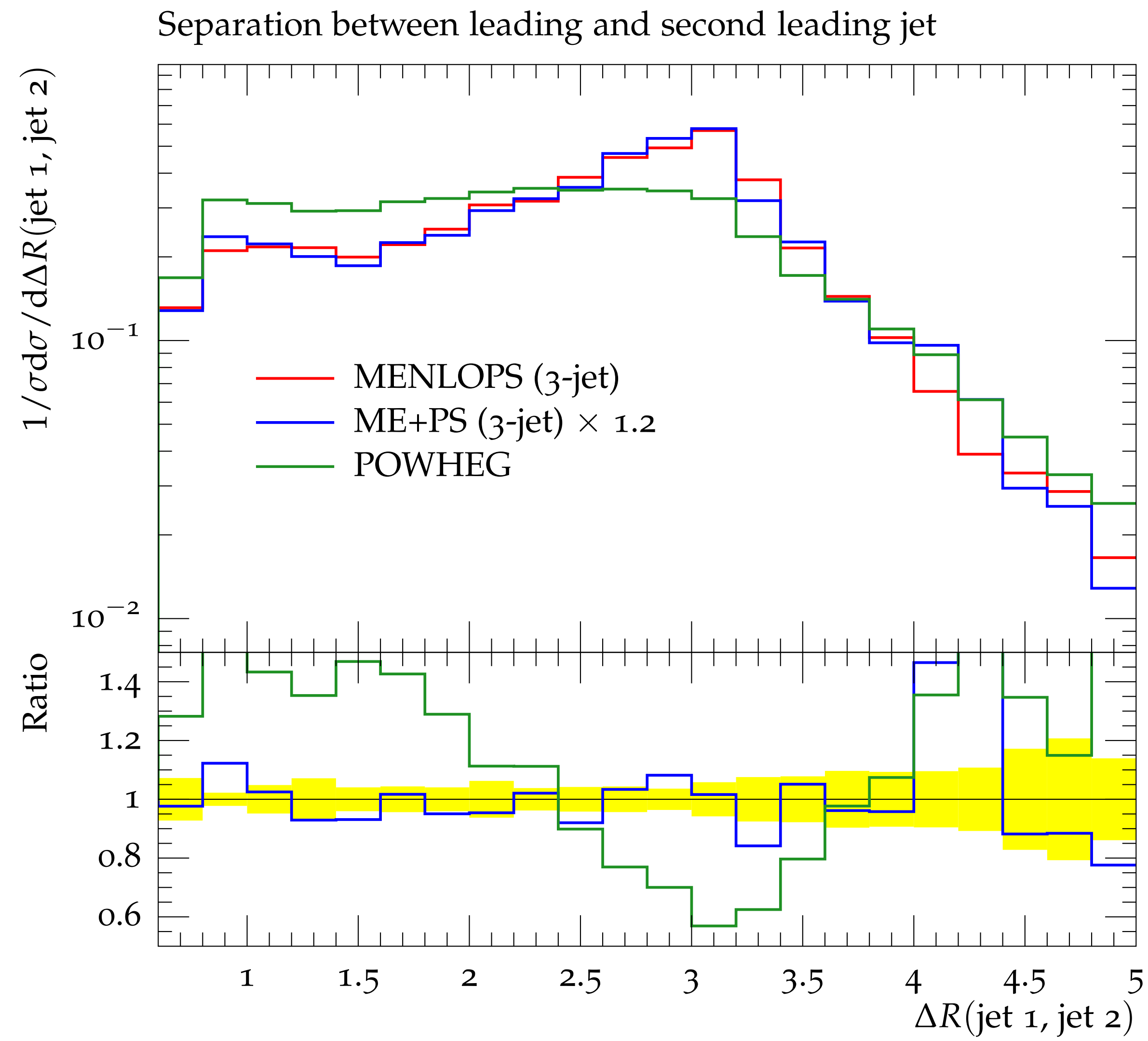


- POWHEG best for $p_t(W)$, lacks ME for $N_{jet}>1$

Hoeche, Krauss, Schumann, Siegert, 1009.1127

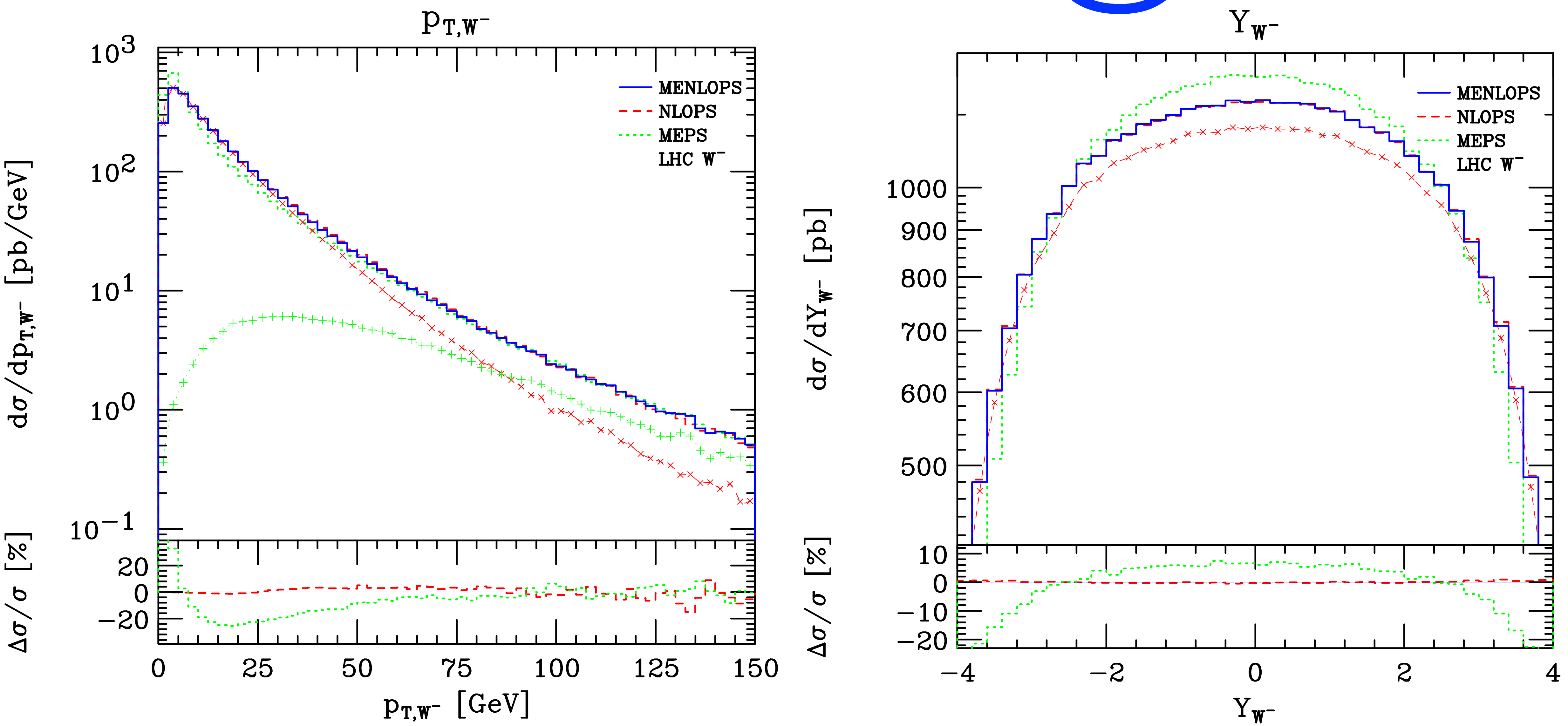
W MENLOPS @ Tevatron





- Again, POWHEG lacks ME for 2nd jet

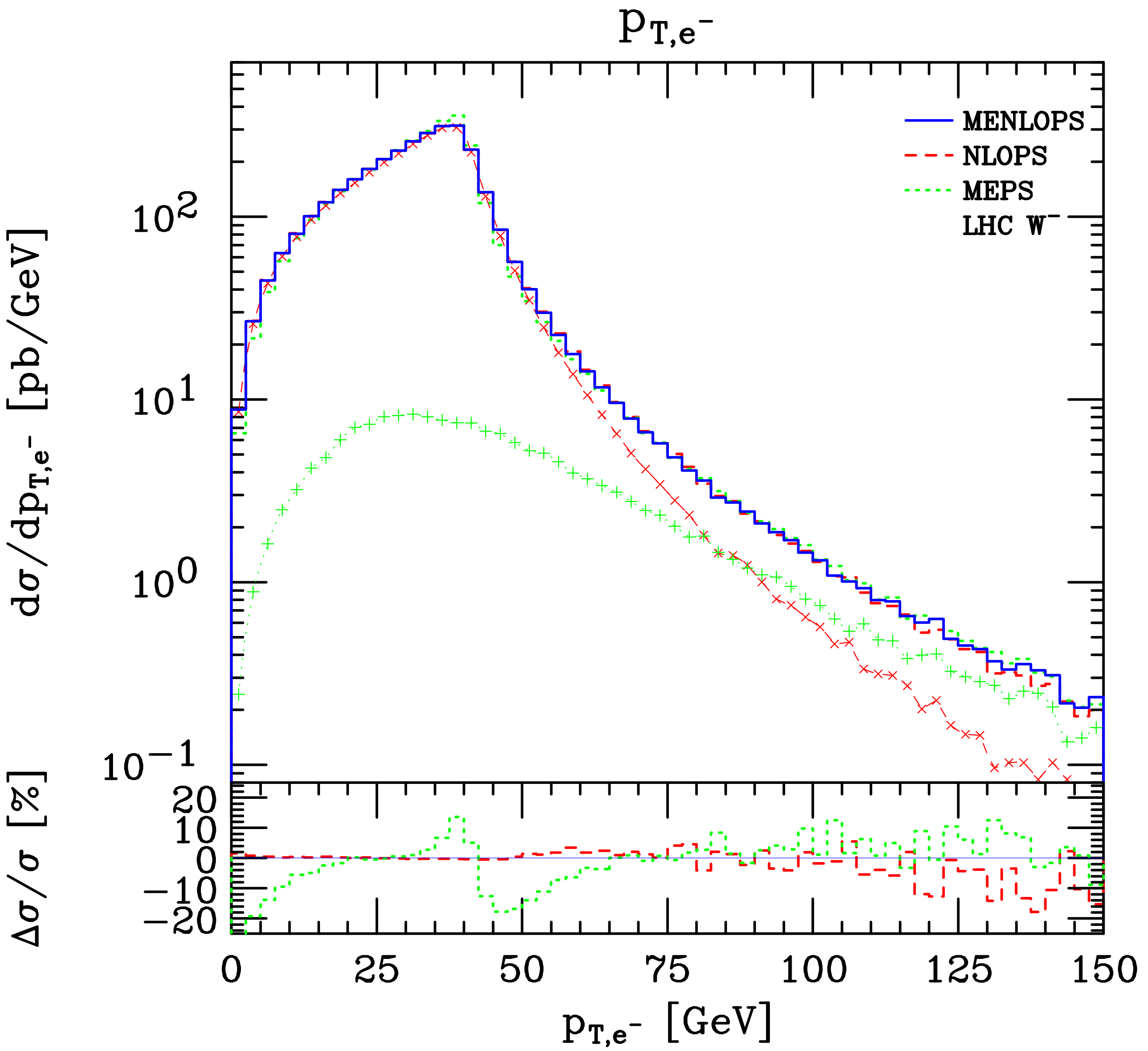
W MENLOPS @ LHC

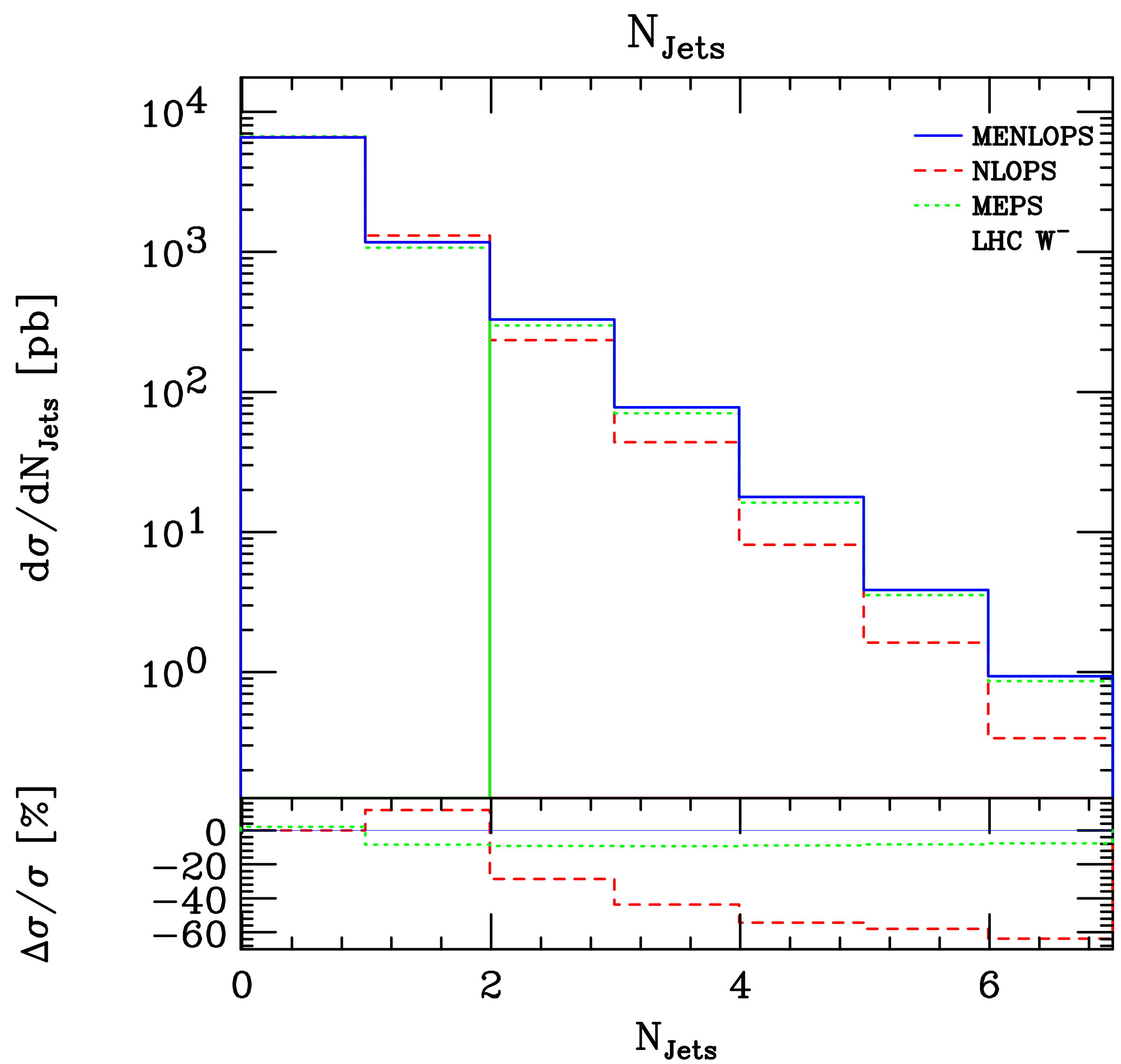


- Dashes are NLOPS & MEPS shapes
- Crosses are contributions to MENLOPS

Hamilton & Nason, JHEP06(2010)039

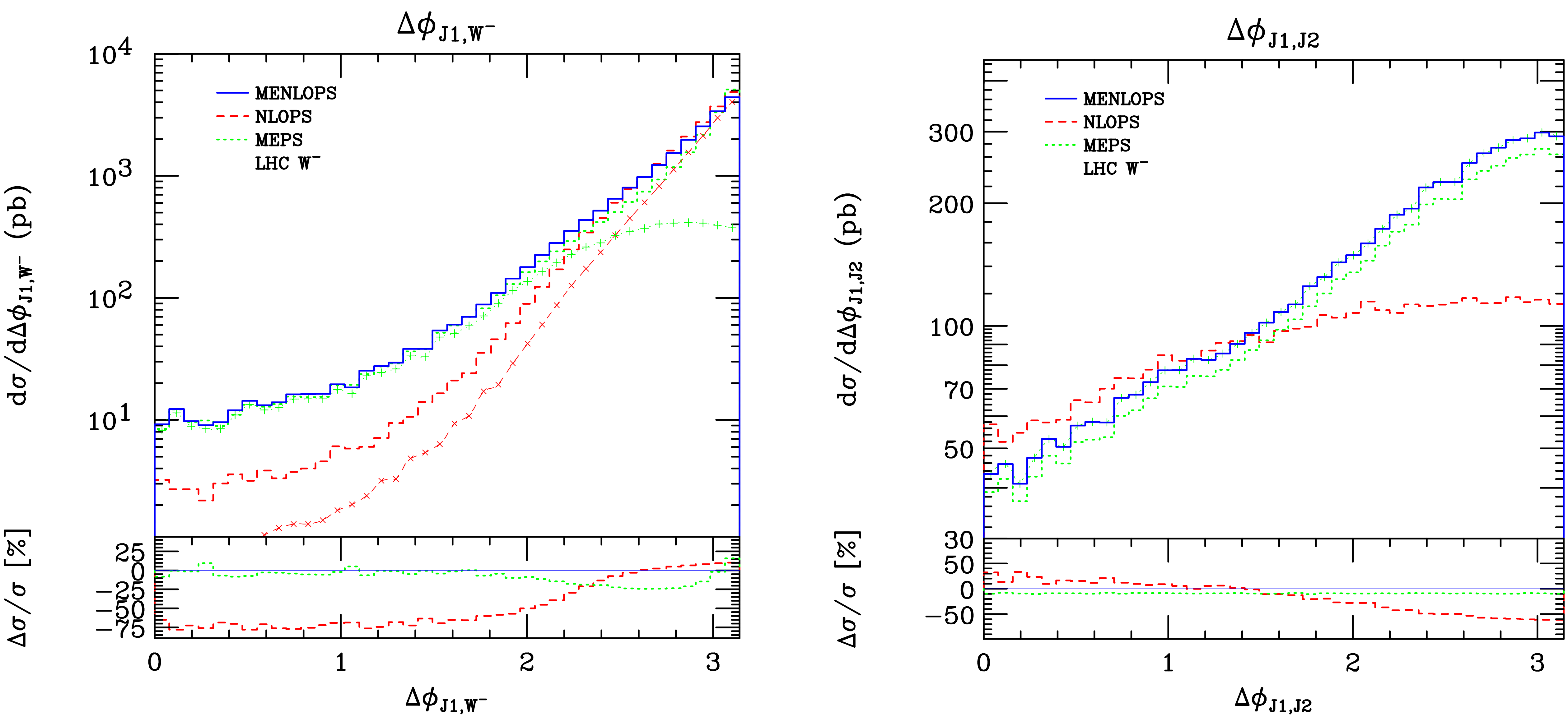
W MENLOPS @ LHC





- NLOPS low for $N_{jets}>1$

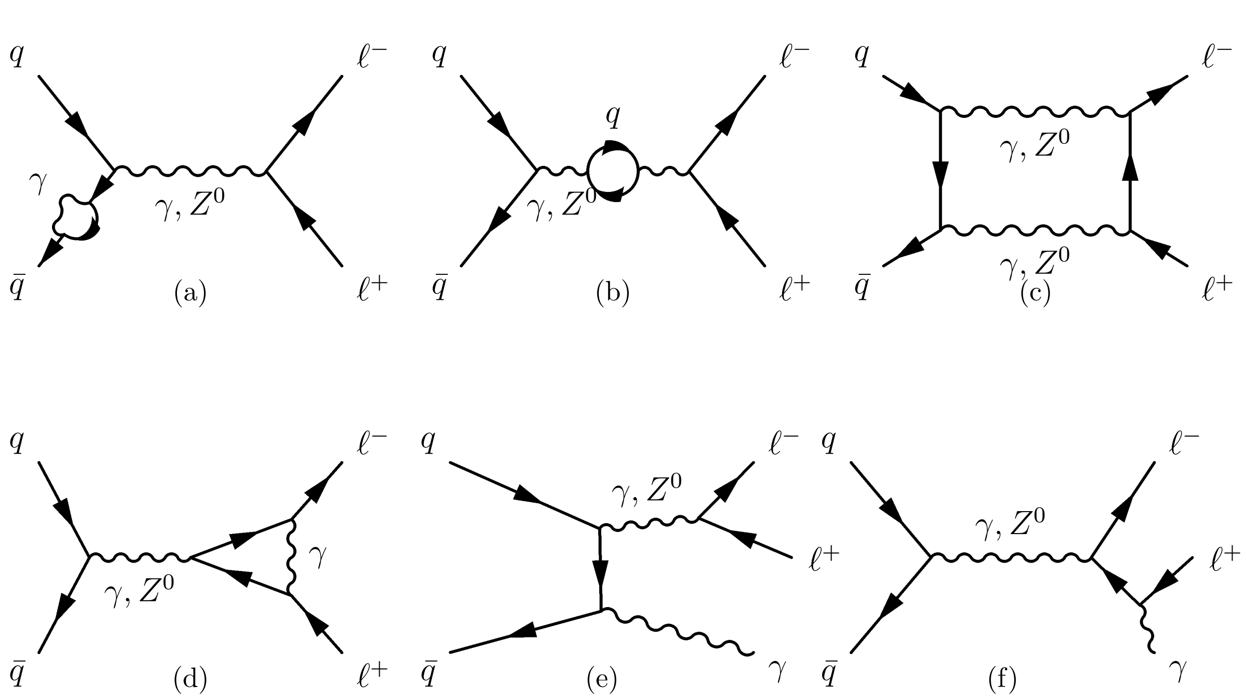
W MENLOPS @ LHC



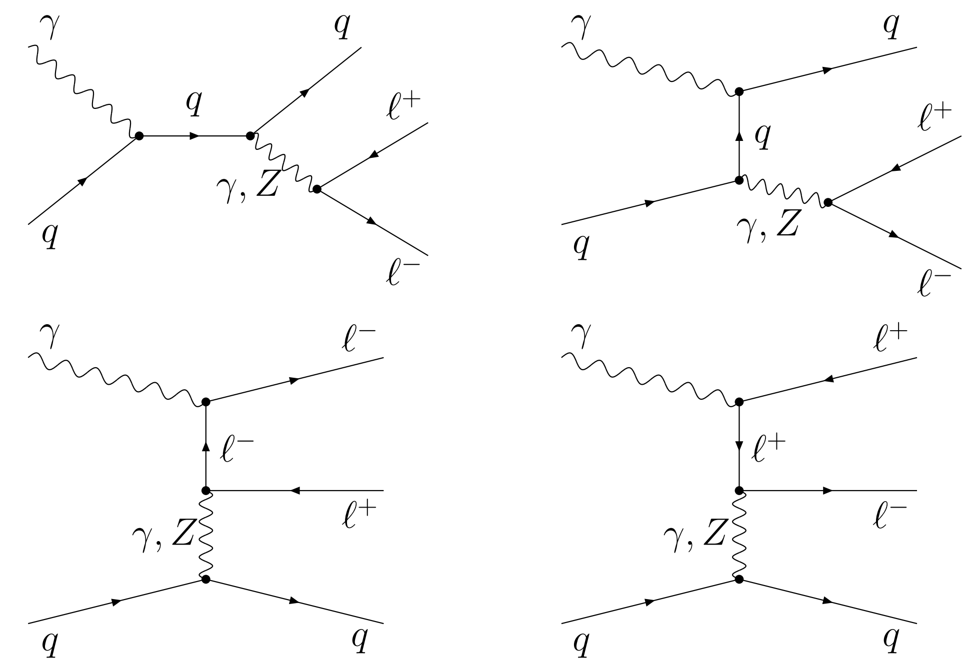
- Again MEPS dominates at small $\Delta\phi_{J1,W^-}$

Electroweak NLO

Sample graphs



Quark-induced



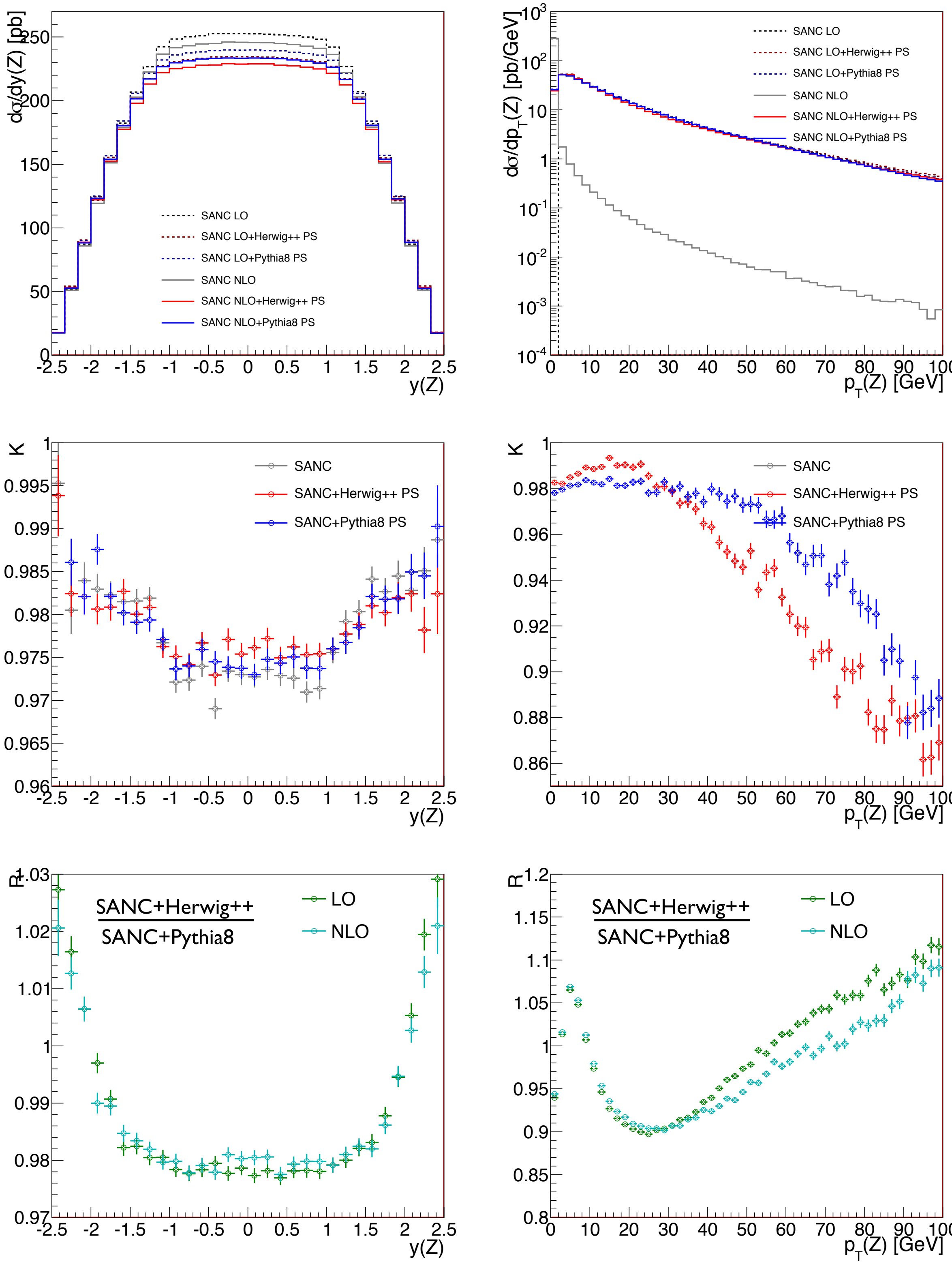
Photon-induced

- Need photon-in-proton PDF

SANC: Andonov et al., CPC 181(2010)305

Electroweak NLO+PSMC

Richardson, Sadykov, Sapronov, Seymour, Skands, 1011.5444



- SANC + LOPS only
- Significant differences between Herwig & Pythia
- Needs extension to SANC+ NLOPS

Conclusions

- PSMC & NLO successfully combined
- V+jets reliable to LO
- V+jets NLO in progress
- QCD+EW NLO coming