Monte Carlo Event Generation for the LHC

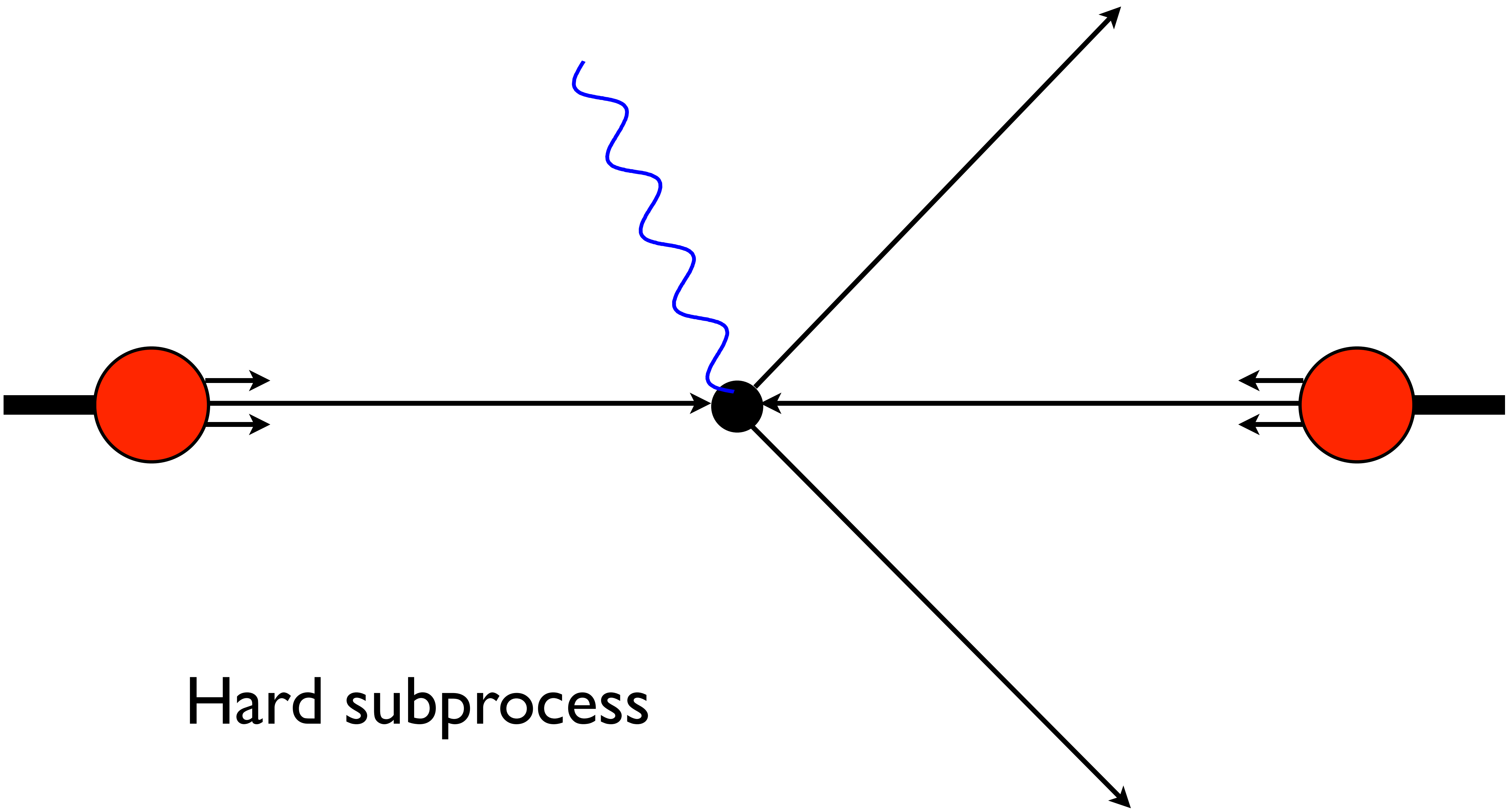
Bryan Webber
University of Cambridge

Monte Carlo Event Generators

- Traditionally (imprecise) general-purpose tools

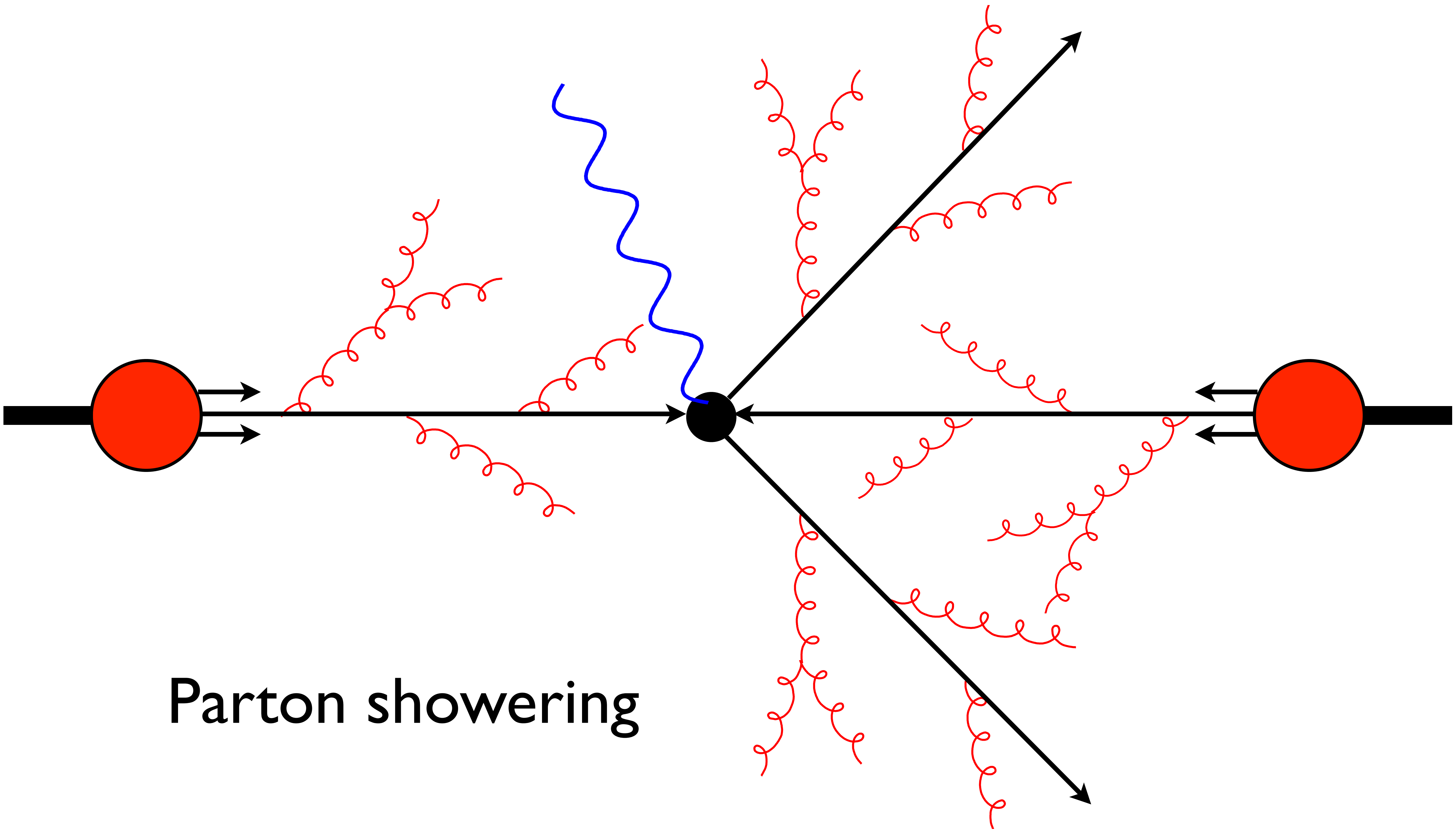
- Much recent work to make them more precise

LHC Event Simulation



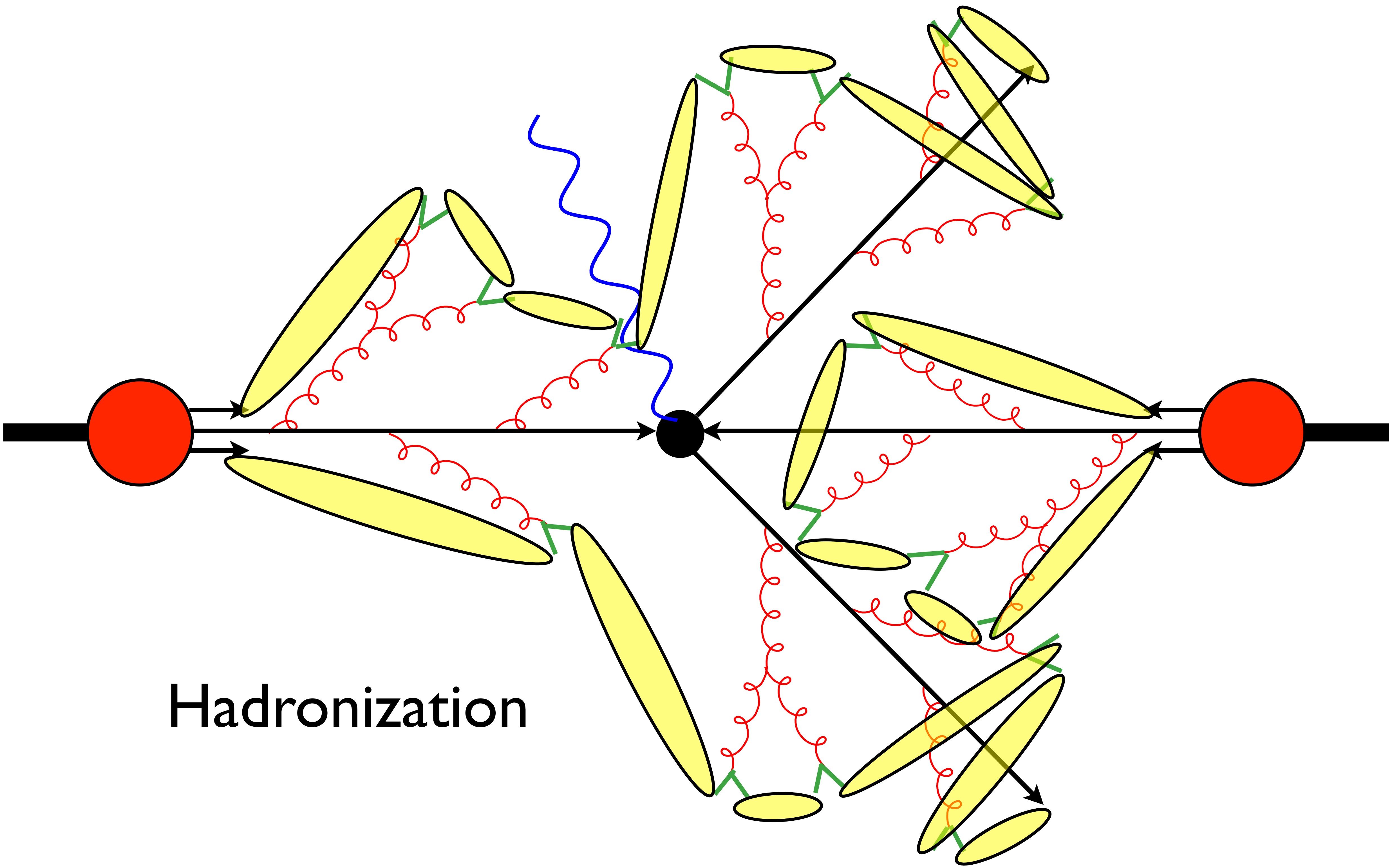
Hard subprocess

LHC Event Simulation



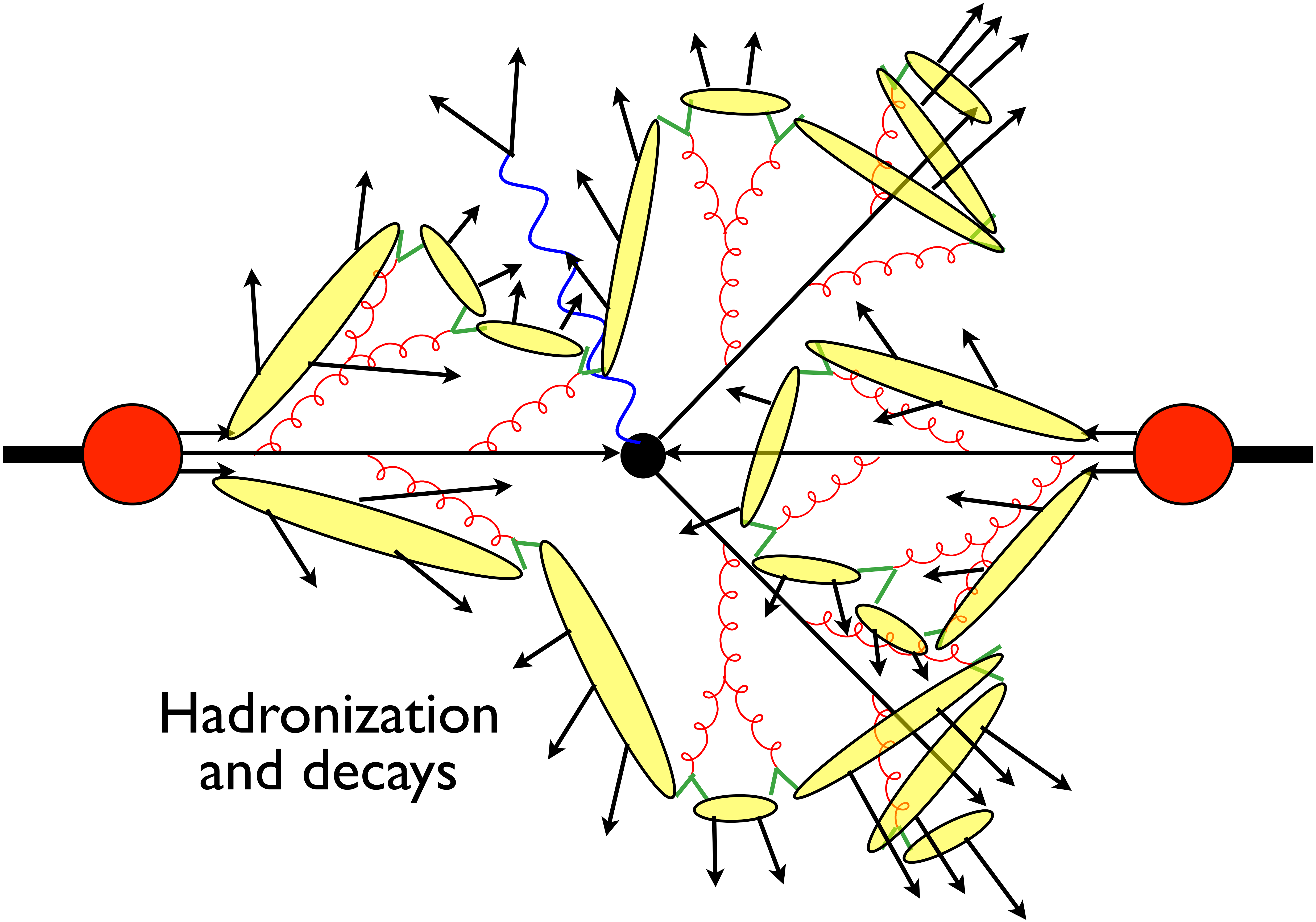
Parton showering

LHC Event Simulation

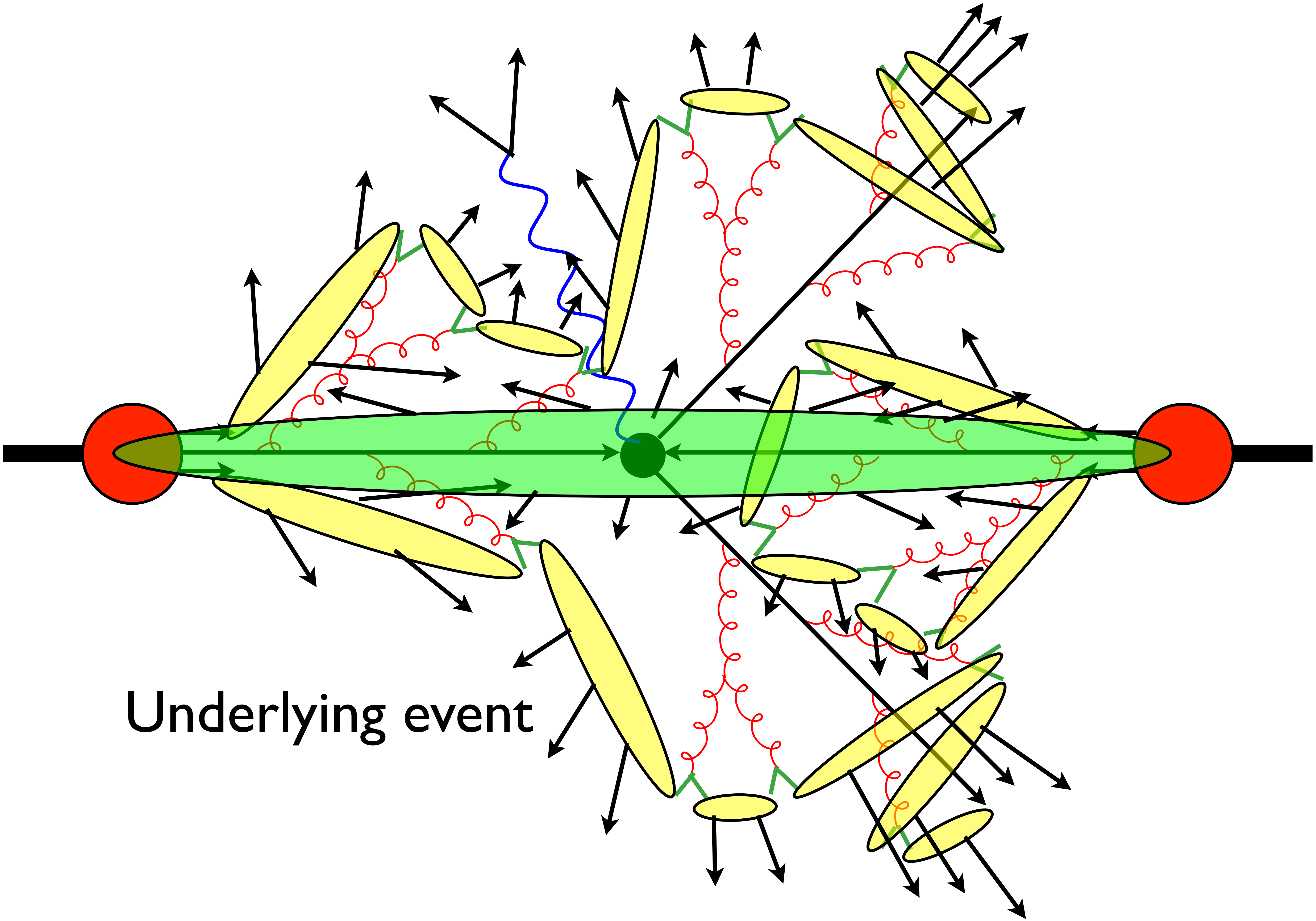


Hadronization

LHC Event Simulation



LHC Event Simulation



Underlying event

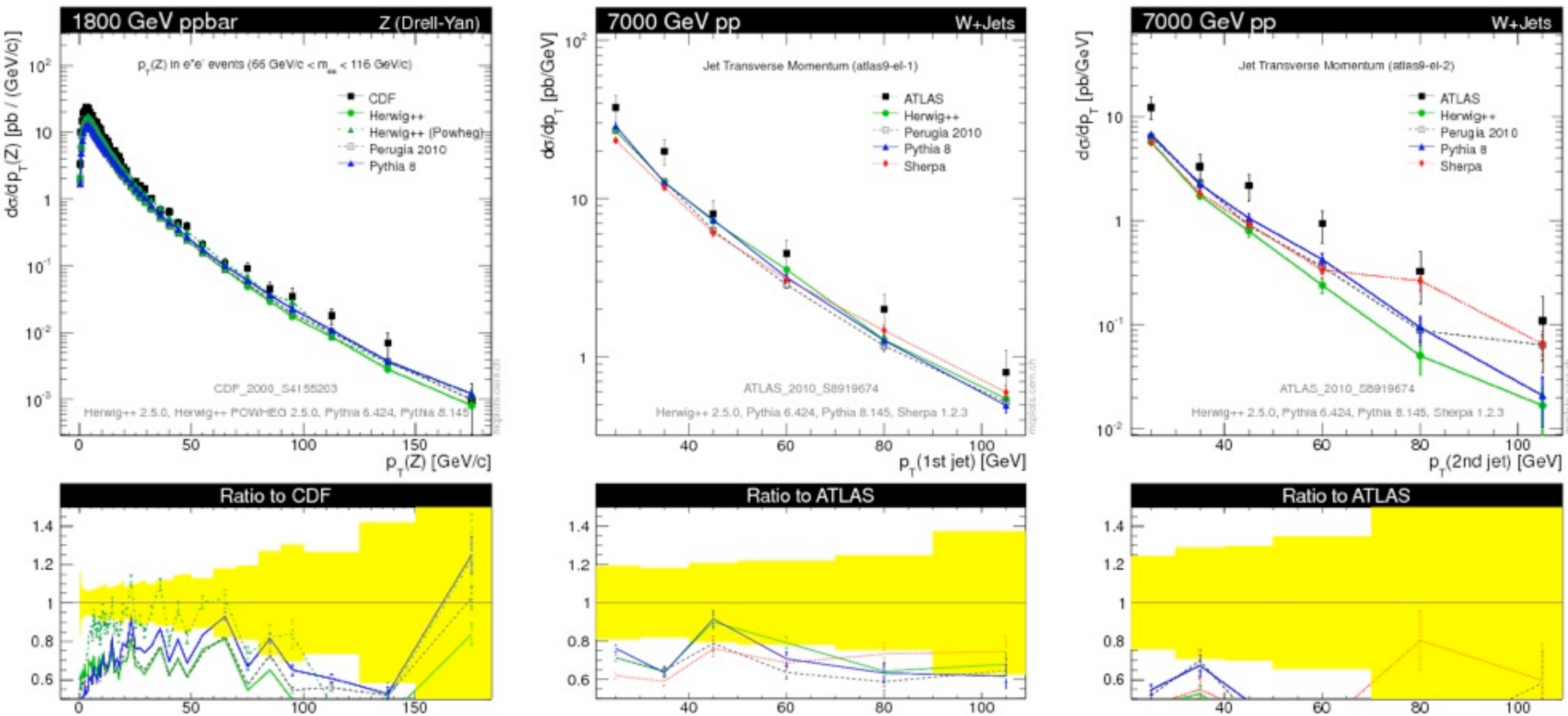
MC Event Generators

- **HERWIG** http://projects.hepforge.org/herwig/
  - Angular-ordered parton shower, cluster hadronization
  - v6 Fortran; Herwig++
- **PYTHIA** http://www.thep.lu.se/~torbjorn/Pythia.html
  - Dipole-type parton shower, string hadronization
  - v6 Fortran; v8 C++
- **SHERPA** http://projects.hepforge.org/sherpa/
  - Dipole-type parton shower, cluster hadronization
  - C++

"General-purpose event generators for LHC physics",
A Buckley et al., arXiv:1101.2599, to appear in Physics Reports

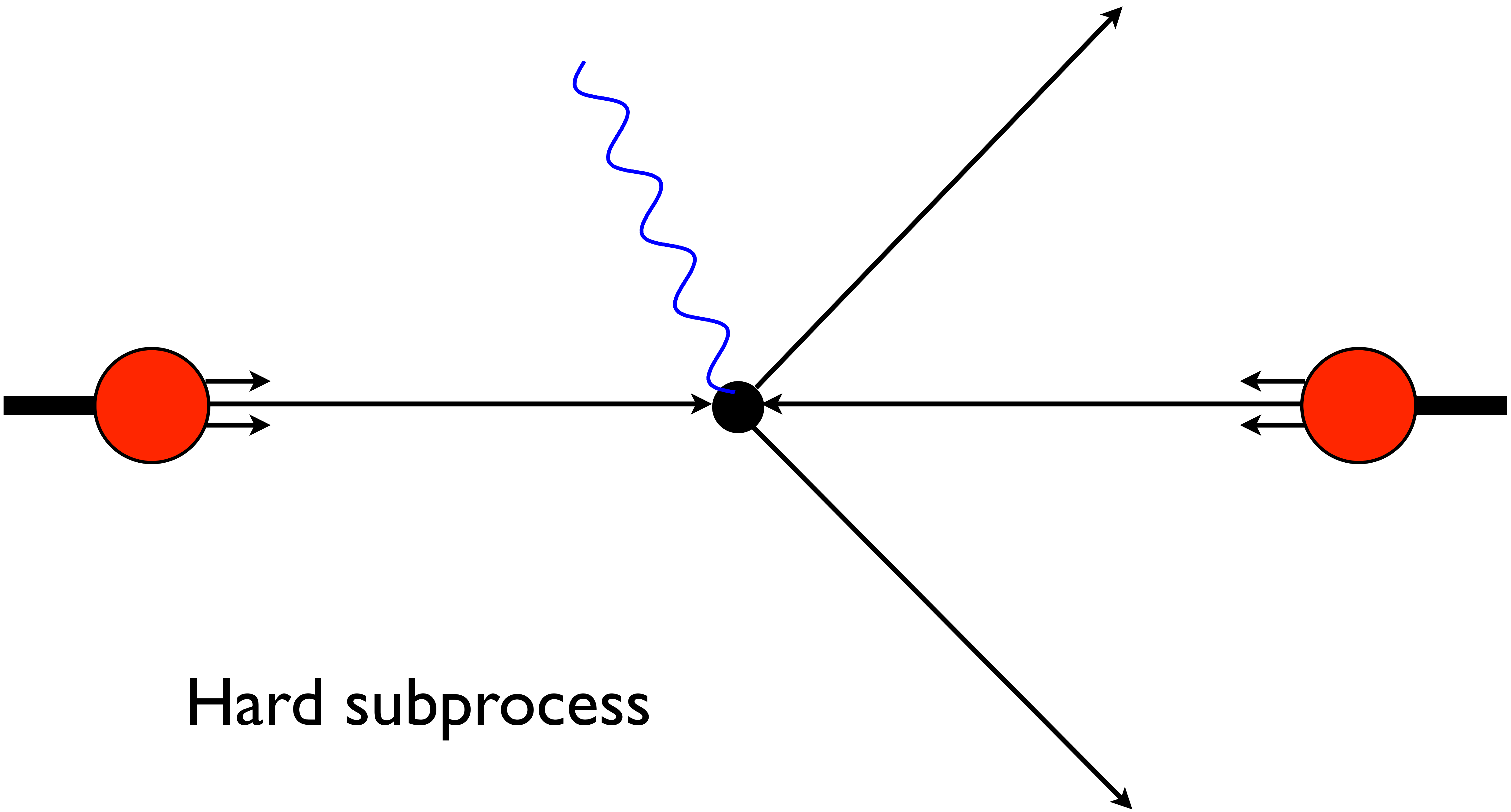
Parton Shower Monte Carlo

http://mcplots.cern.ch/



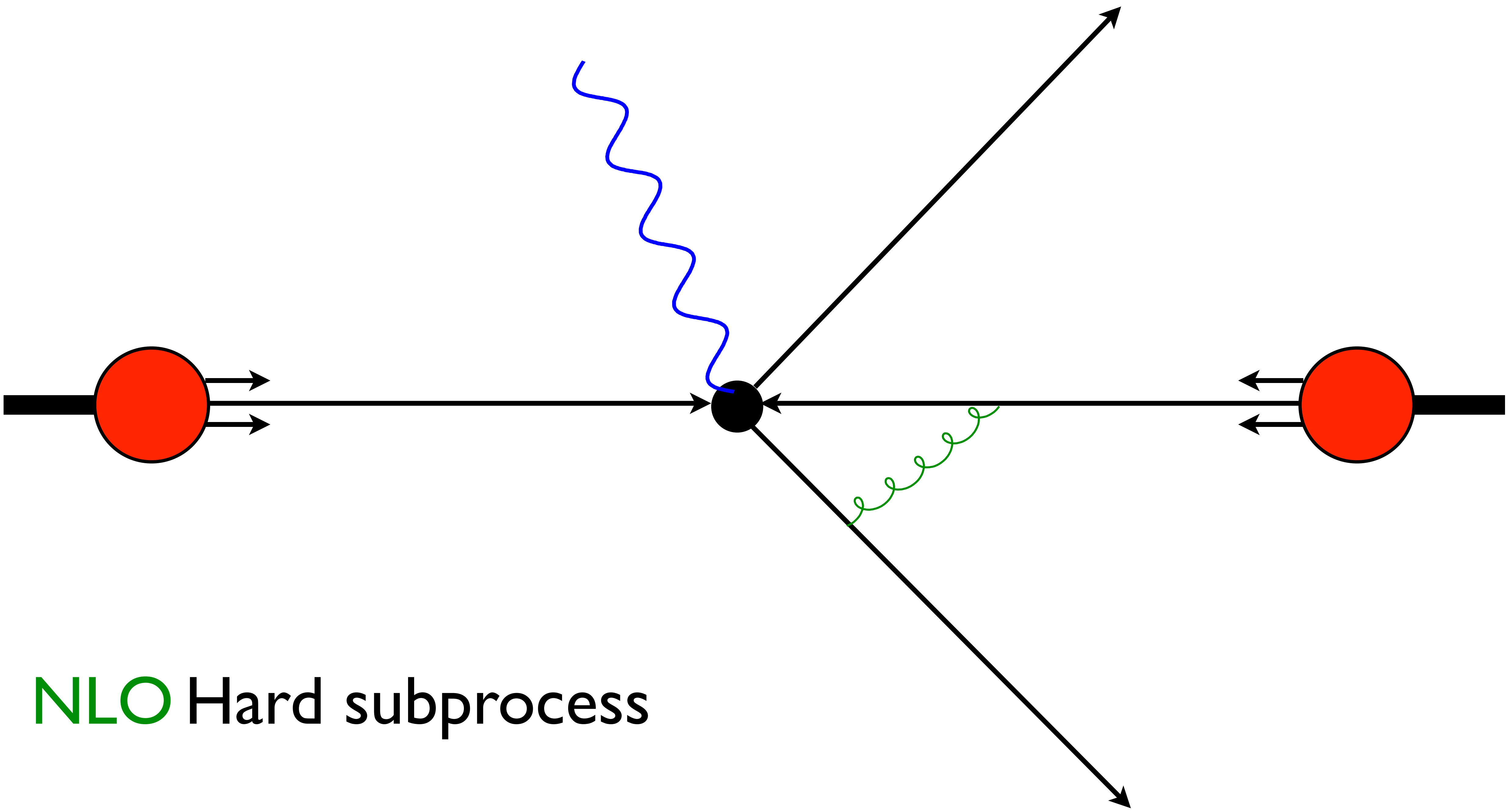
- Leading-order normalization
- Worse for high p_T and/or extra jets

LHC Event Simulation



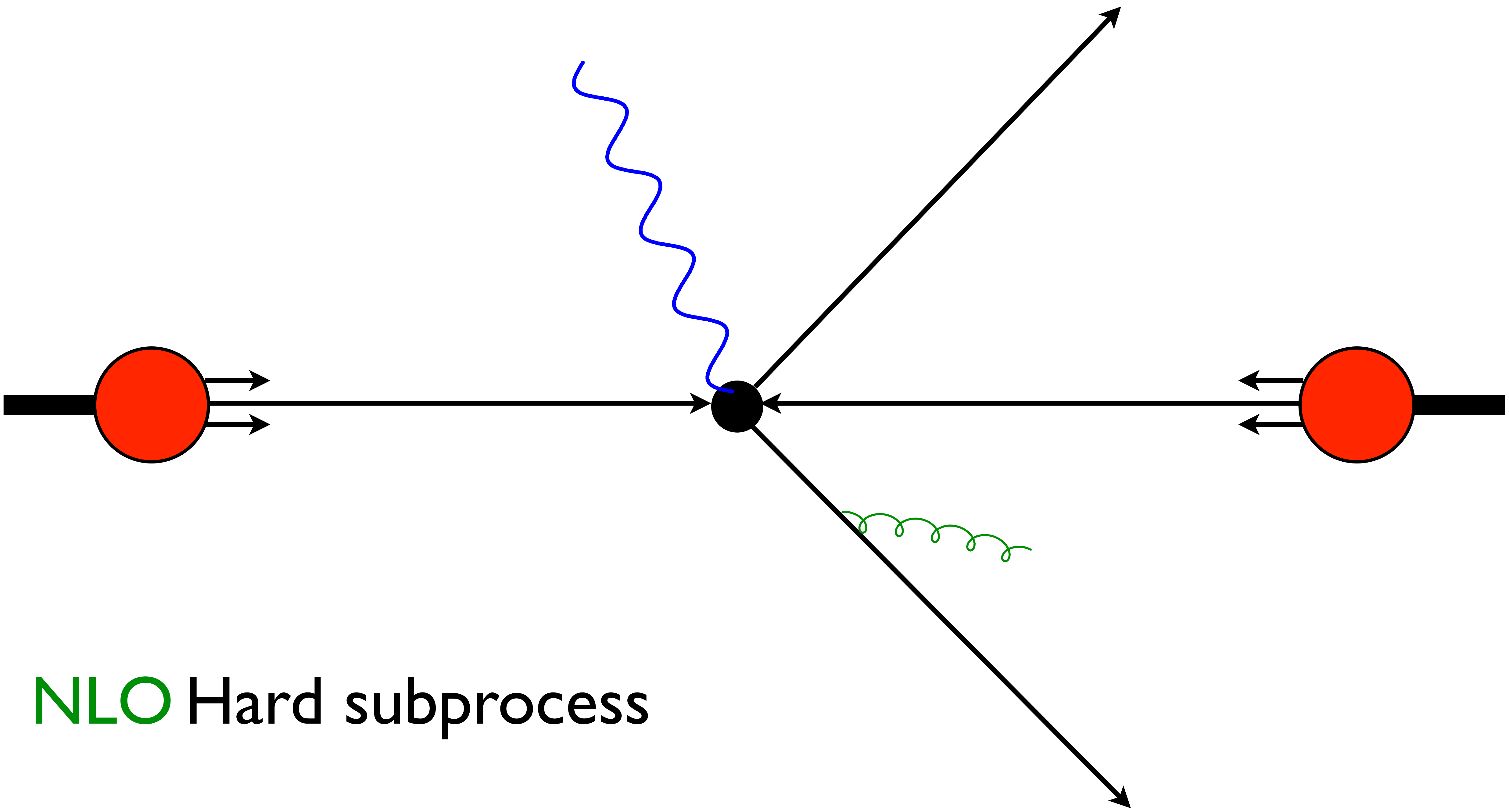
Hard subprocess

LHC Event Simulation



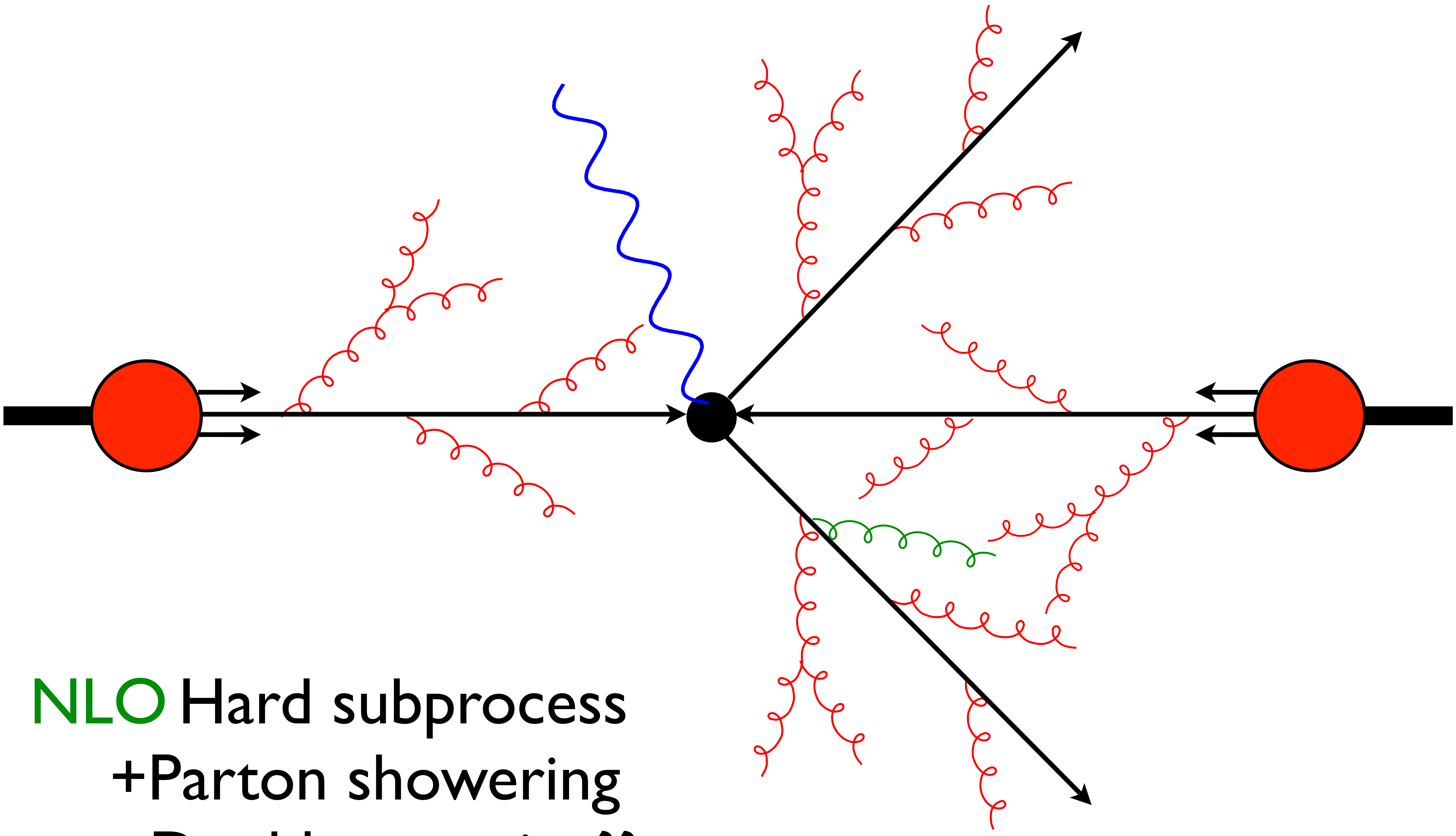
NLO Hard subprocess

LHC Event Simulation



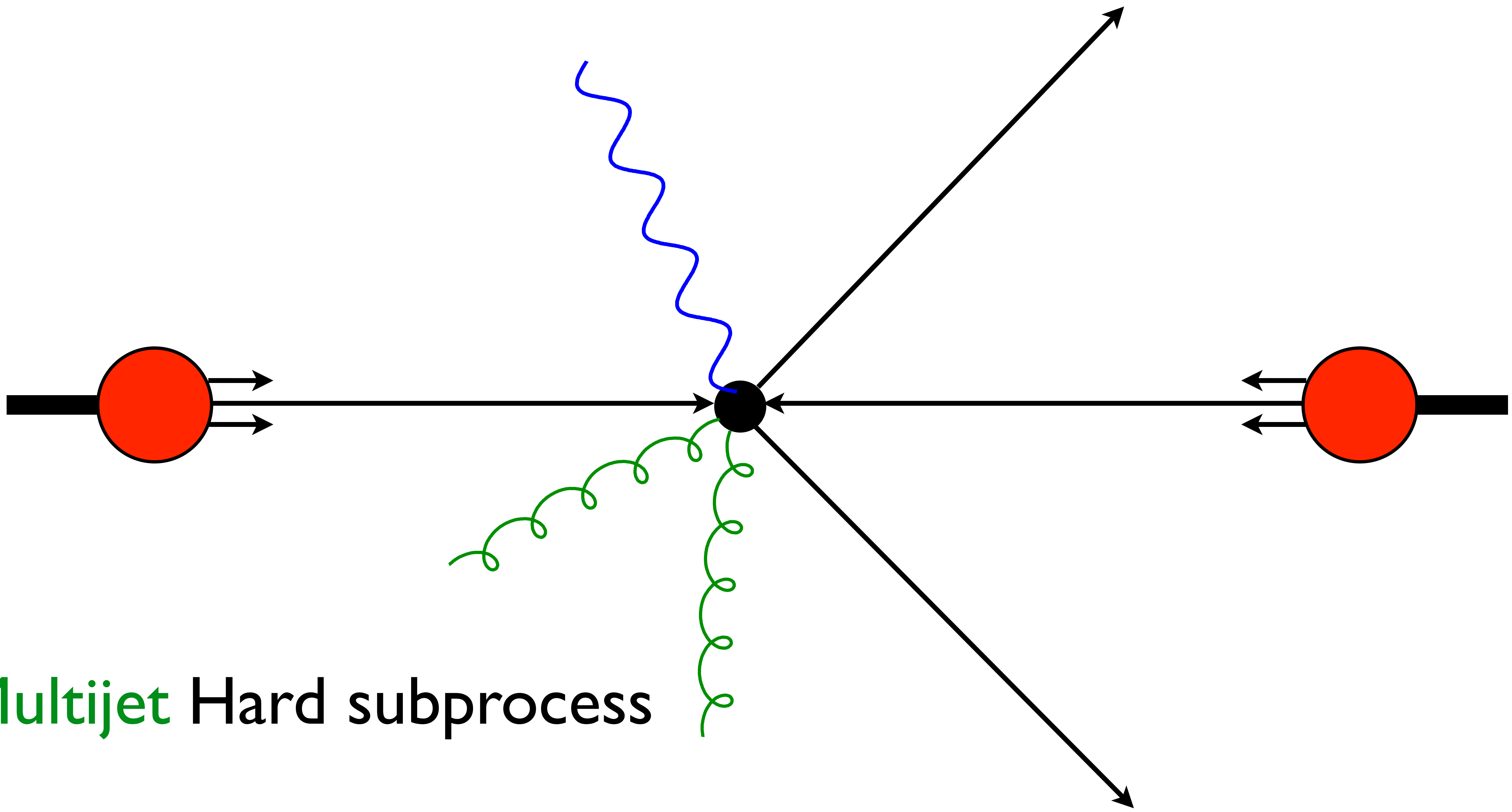
NLO Hard subprocess

LHC Event Simulation



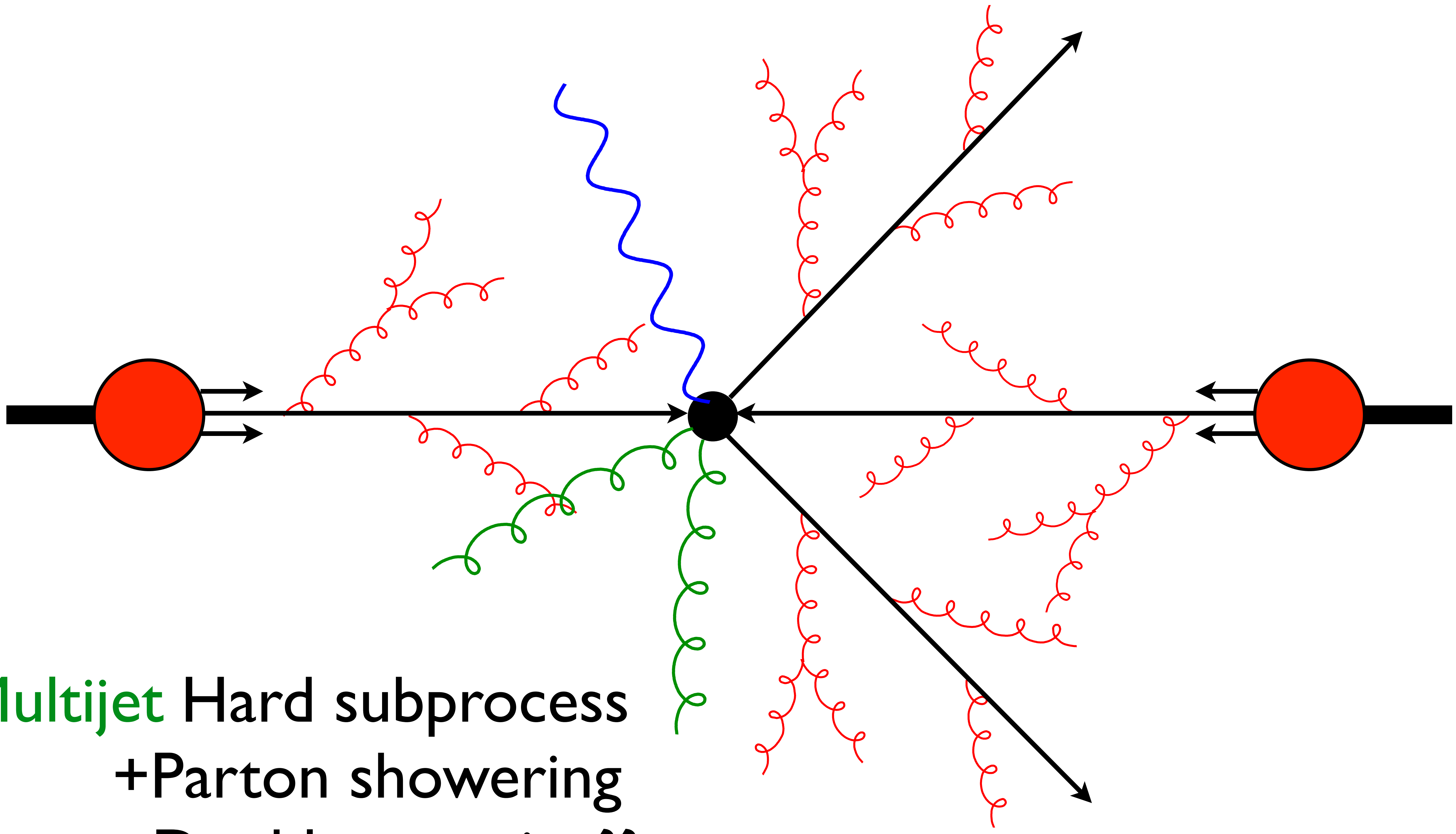
NLO Hard subprocess
+Parton showering
= Double counting??

LHC Event Simulation



Multijet Hard subprocess

LHC Event Simulation



Multijet Hard subprocess
+Parton showering
= Double counting??

Matching & Merging

- Two rather different objectives:
- Matching parton showers to NLO matrix elements, without double counting
  - MC@NLO — Frixione, BW
  - POWHEG — Nason
- Merging parton showers with LO n-jet matrix elements, minimizing jet resolution dependence
  - CKKW — Catani, Krauss, Kühn, BW
  - Dipole — Lönnblad
  - MLM merging — Mangano

(Also: matching NLO showers and matrix elements - see S Jadach et al., 1103.5015)

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)
- NLOPS case study: top production asymmetry

Parton Shower Monte Carlo

LO (Born) — No (resolvable) emission — One emission

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

- 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 matching

finite virtual

divergent

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

$$\equiv \left[B + V - \int C\, d\Phi_R\right] d\Phi_B + R\, d\Phi_B\, d\Phi_R$$

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

$$\equiv B\, d\Phi_B \left[\Delta_{\mathrm{MC}}(0) + (R_{\mathrm{MC}}/B)\, \Delta_{\mathrm{MC}}(k_T)\, d\Phi_R\right]$$

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

finite $\gtrless 0$

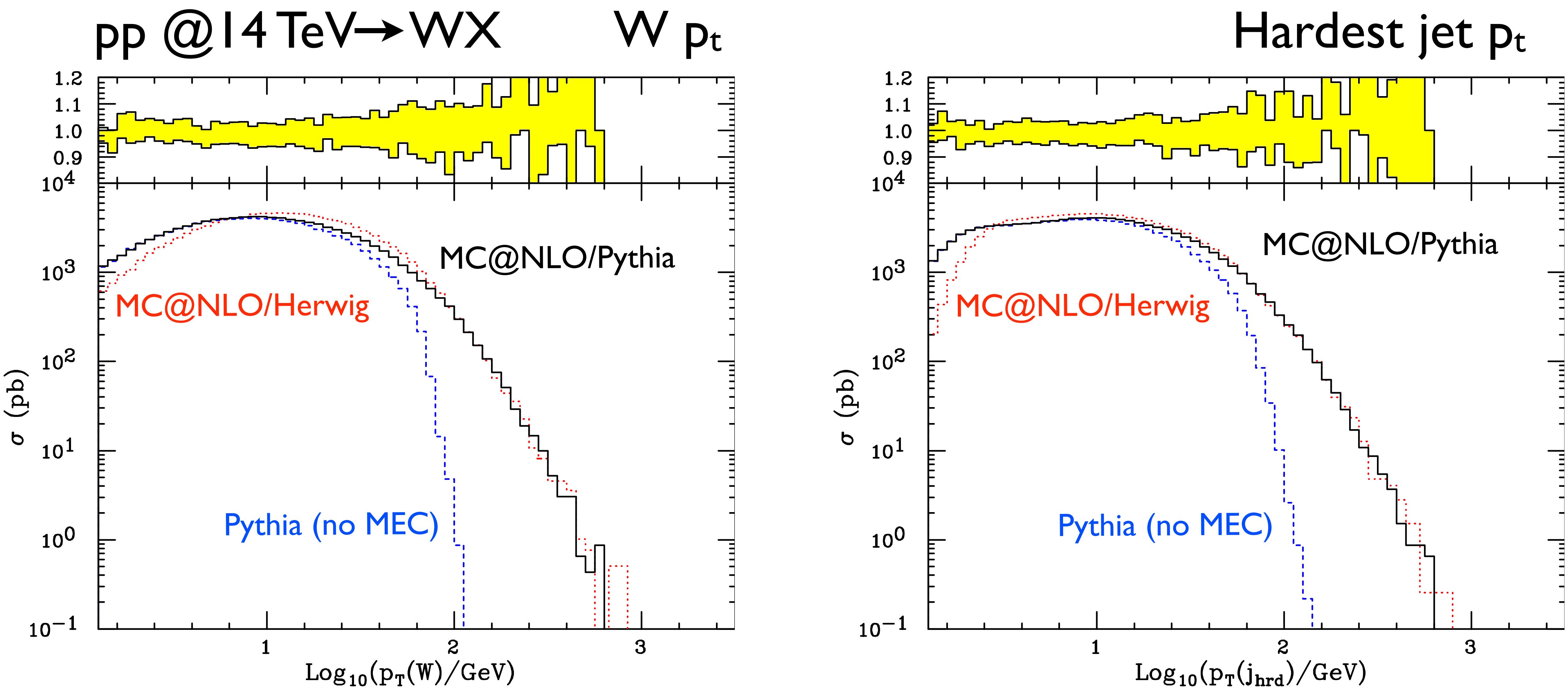
MC starting from no emission

MC starting from one emission

- Expanding gives NLO result

S Frixione & BW, JHEP 06(2002)029

MC@NLO matching

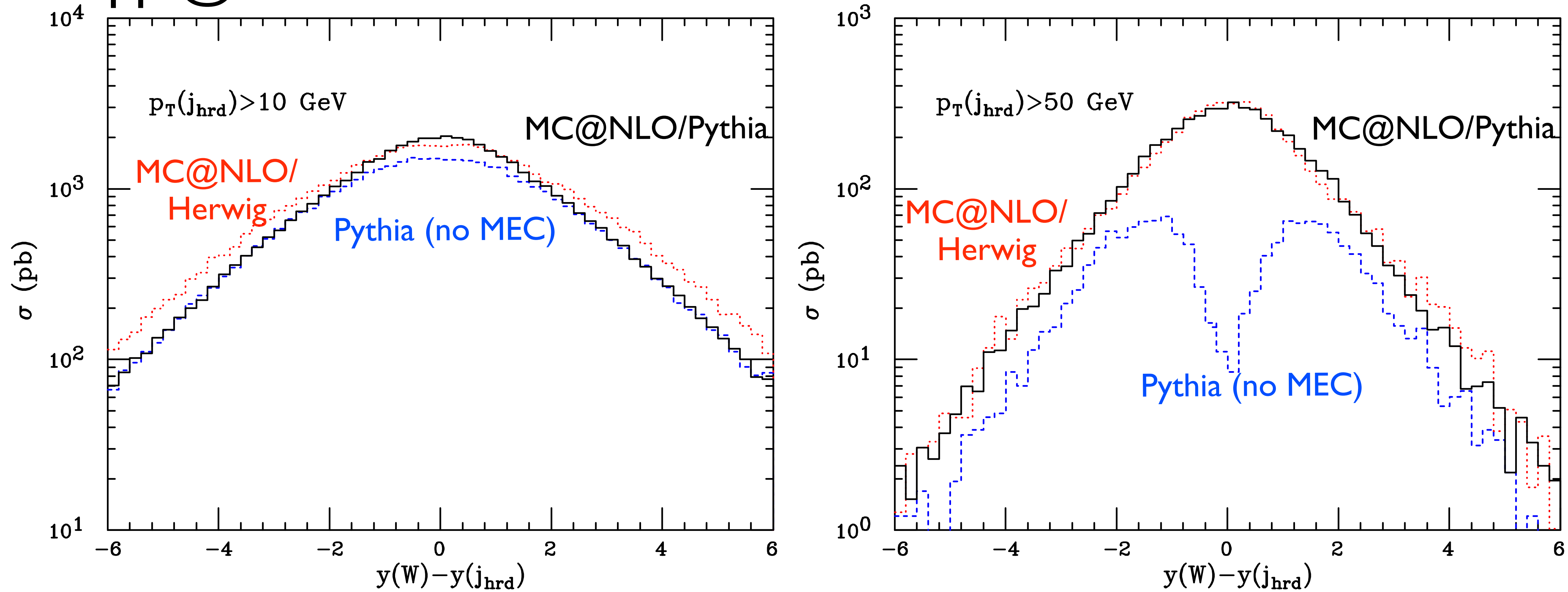


- MEC=Matrix Element Correction (not NLO)
- MC@NLO is MC-specific, but integral is NLO

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

MC@NLO matching

pp @14 TeV→WX



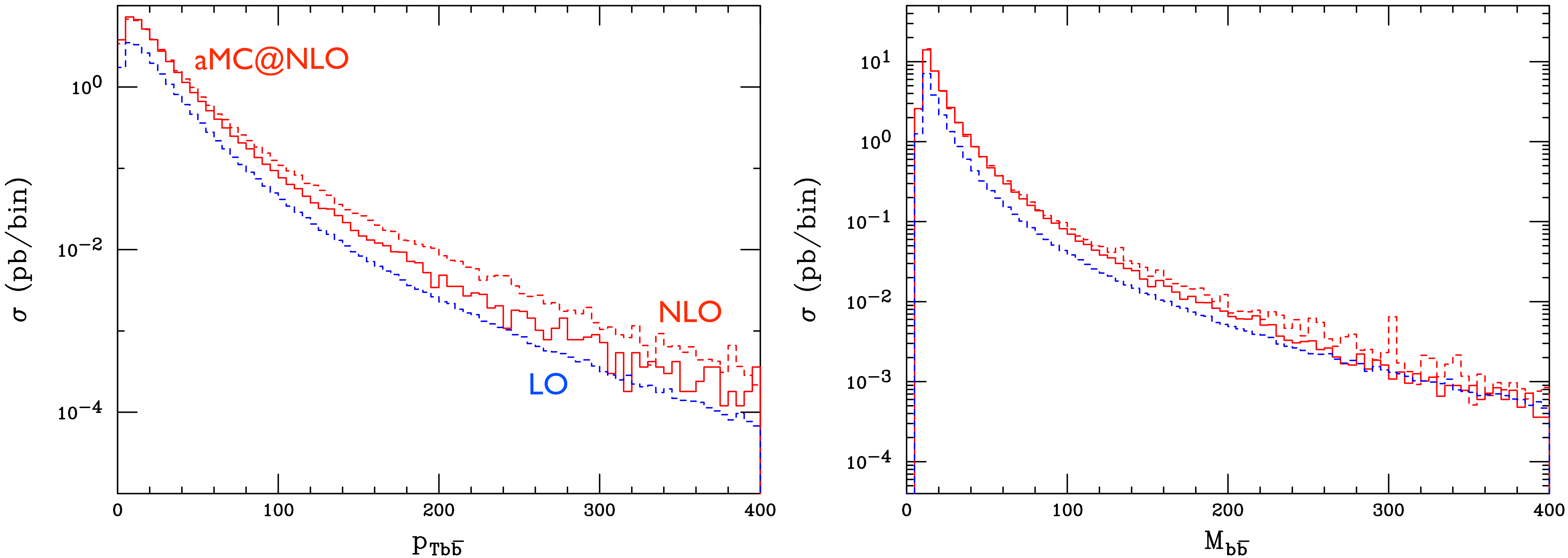
- NLO is only LO for high p_t jet

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

Automatic MC@NLO

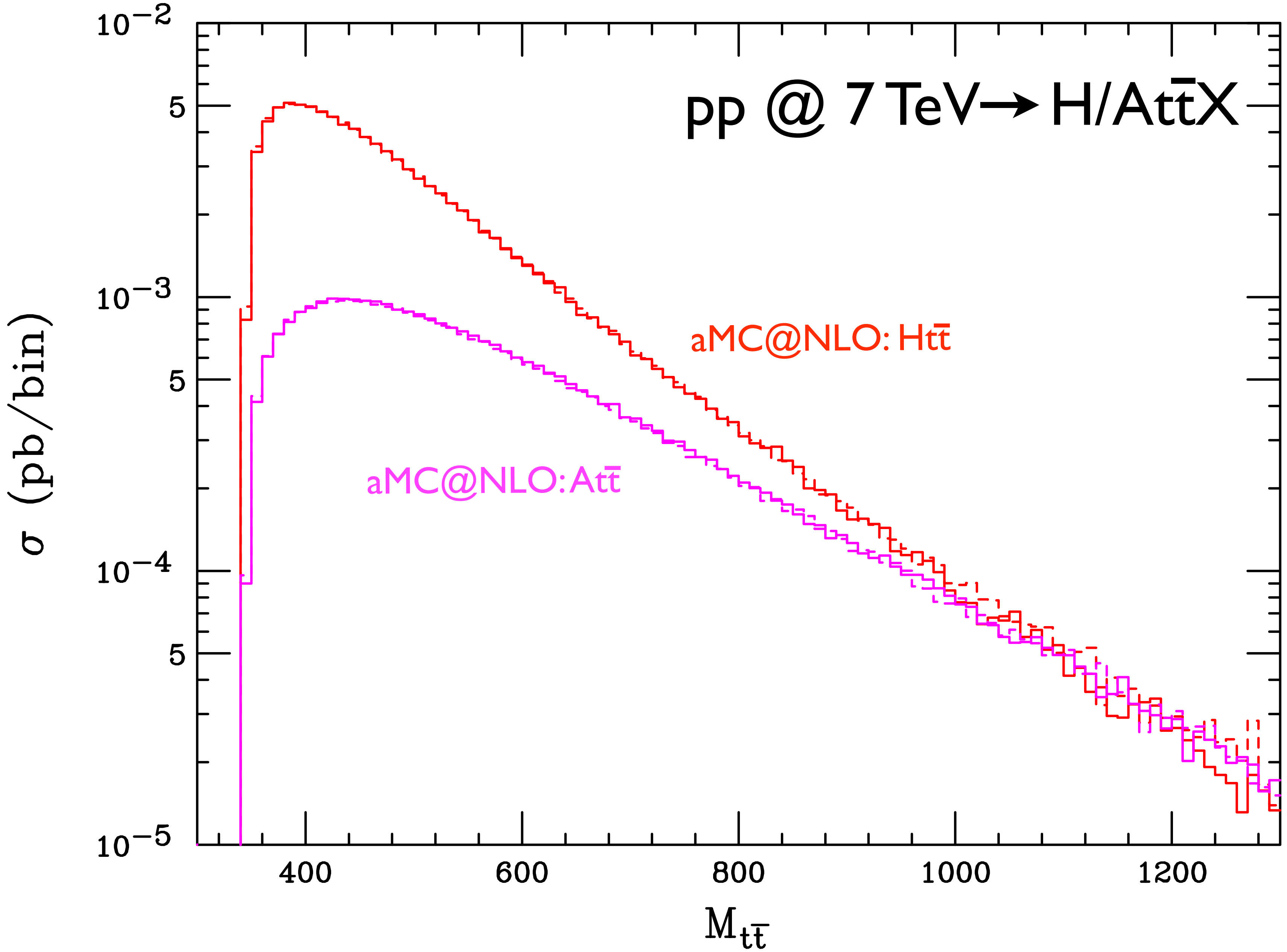
Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau, Stelzer, Torrielli

pp @ 7 TeV→$Wb\bar{b}X$



- $b\bar{b}$ distributions softer than NLO

Automatic MC@NLO



- Pseudoscalar distribution harder

POWHEG matching

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

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

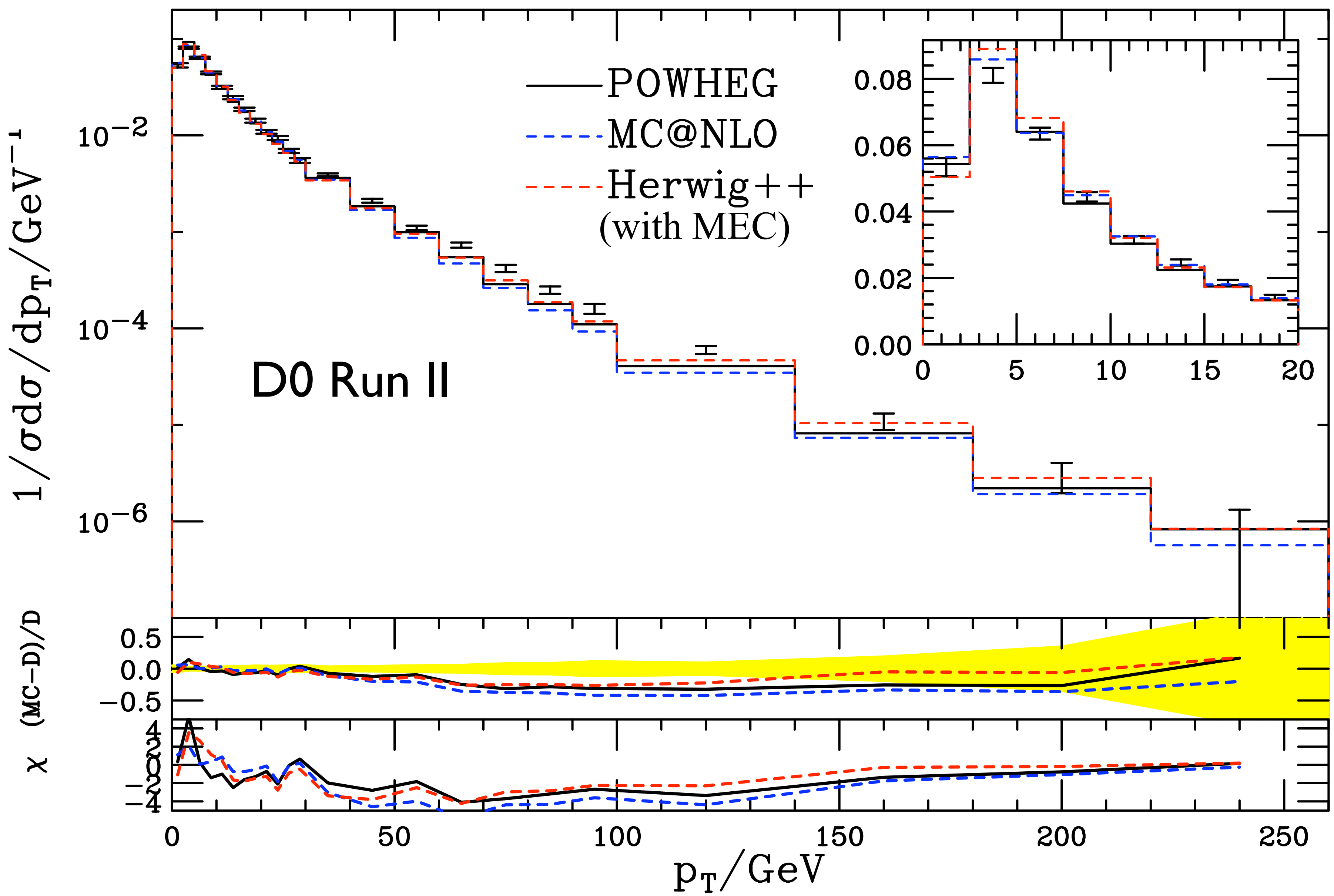
$$\Delta_R\left(p_T\right) = \exp\left[-\int \mathrm{d}\Phi_R\,\frac{R\left(\Phi_B,\Phi_R\right)}{B\left(\Phi_B\right)}\,\theta\left(k_T\left(\Phi_B,\Phi_R\right) - p_T\right)\right]$$

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

arbitrary, NNLO

P Nason, JHEP 11(2004)040

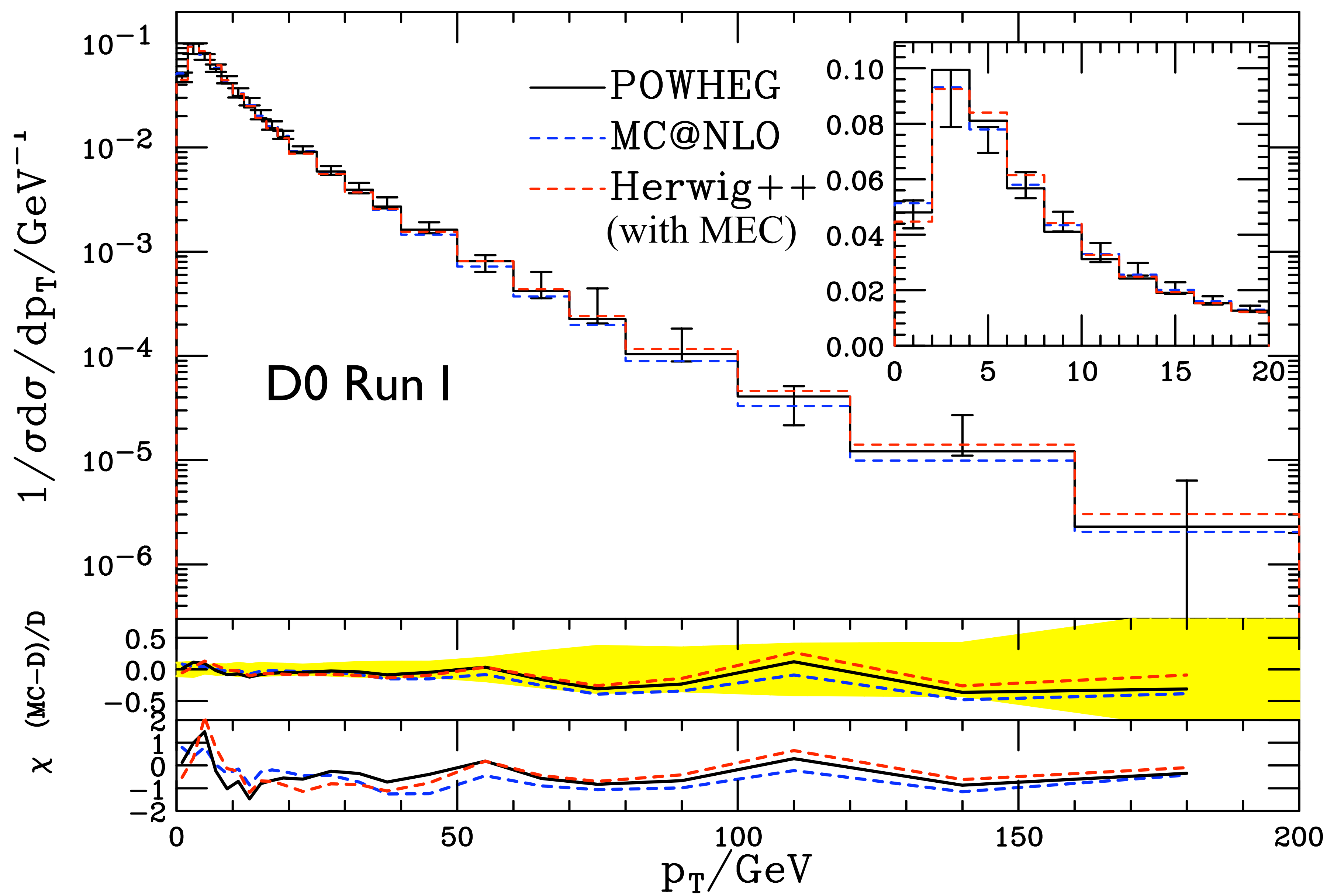
Z^0 at Tevatron



- NLO is only LO at high p_t

Hamilton, Richardson, Tully JHEP10(2008)015

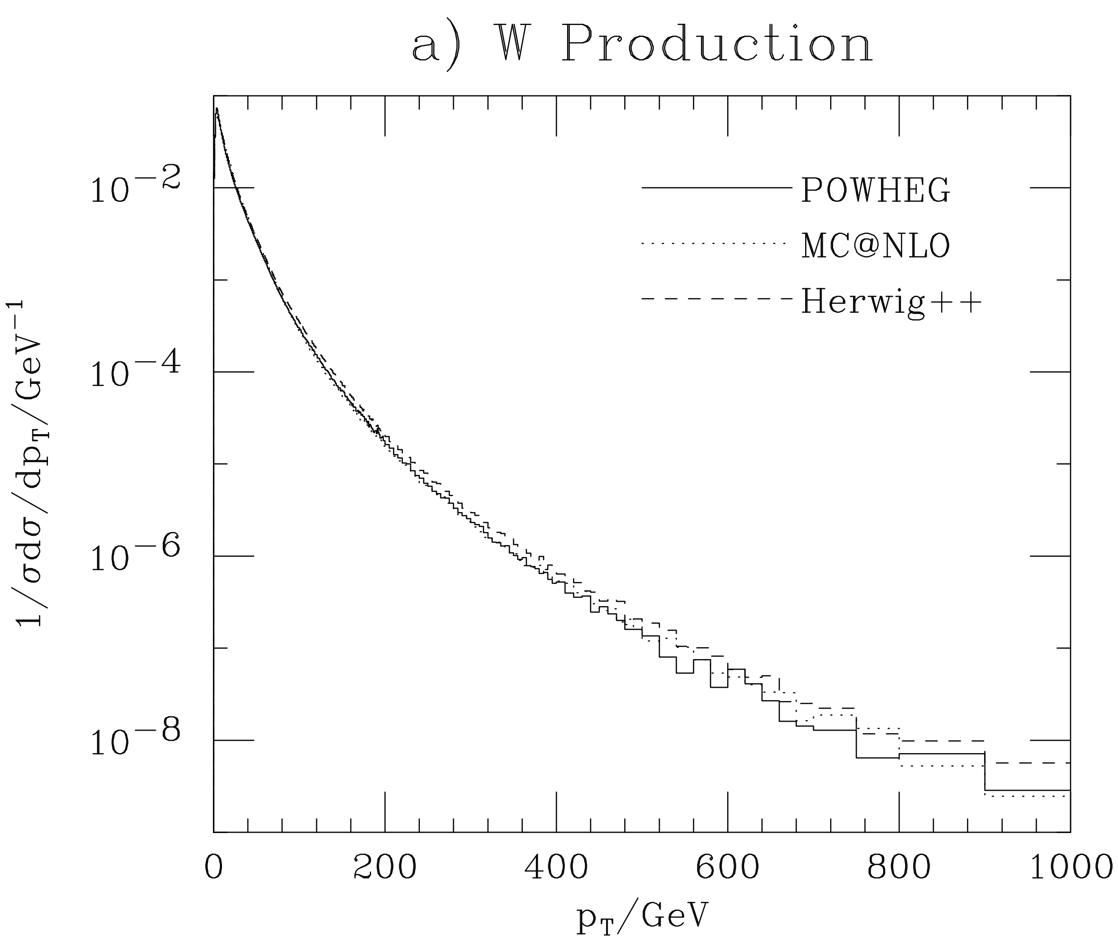
W at Tevatron

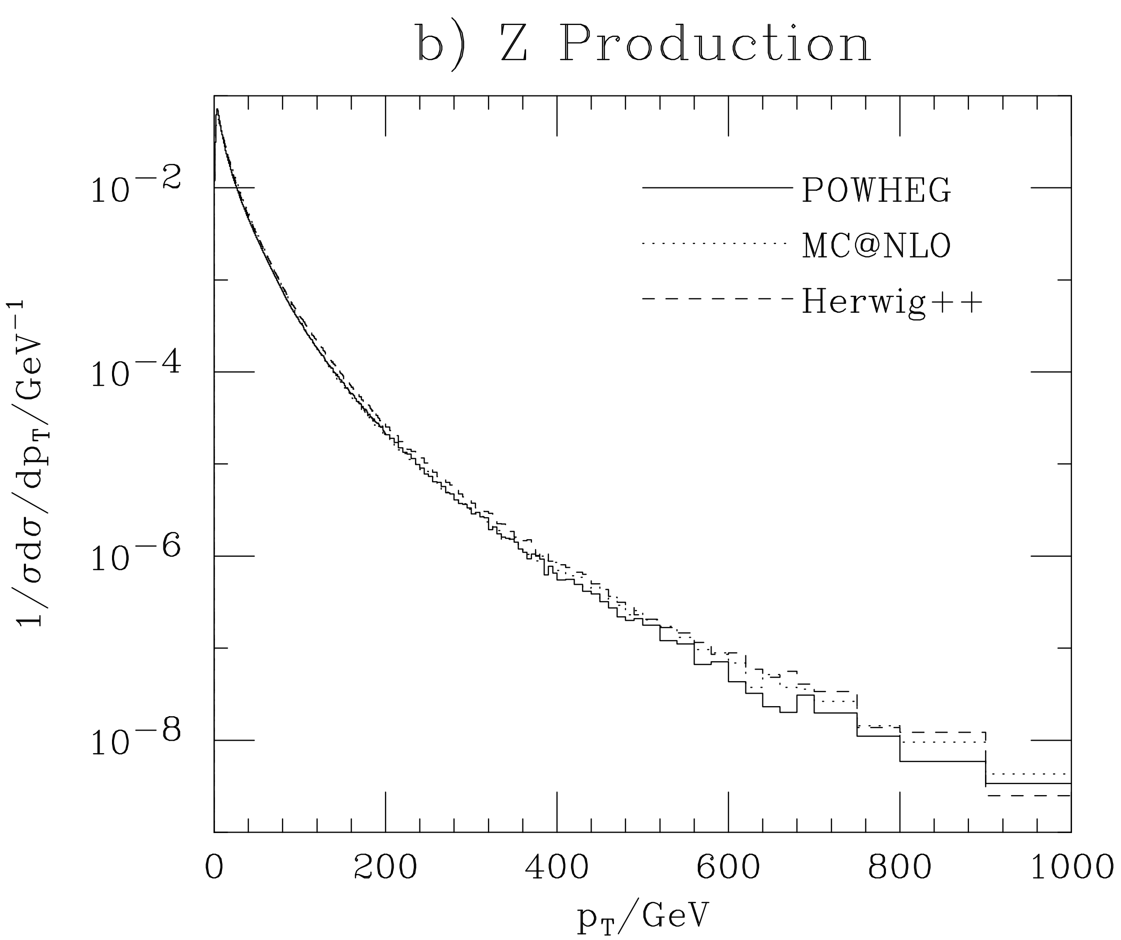


- All agree (tuned) at Tevatron

Hamilton, Richardson, Tully JHEP10(2008)015

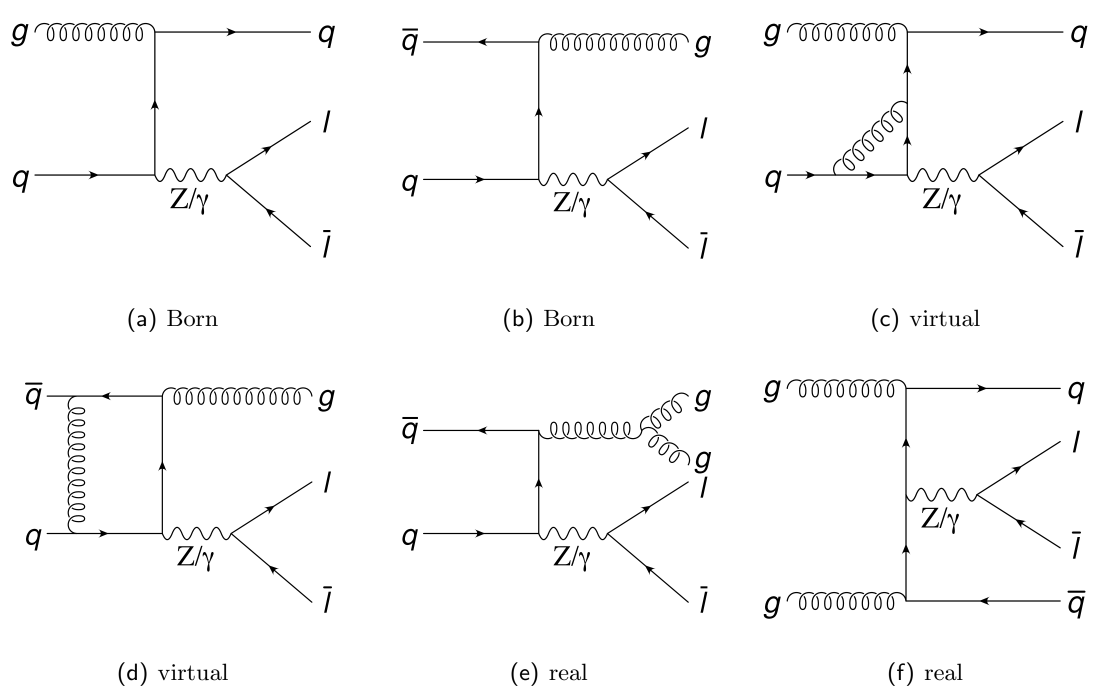
W & Z^0 at LHC (14 TeV)



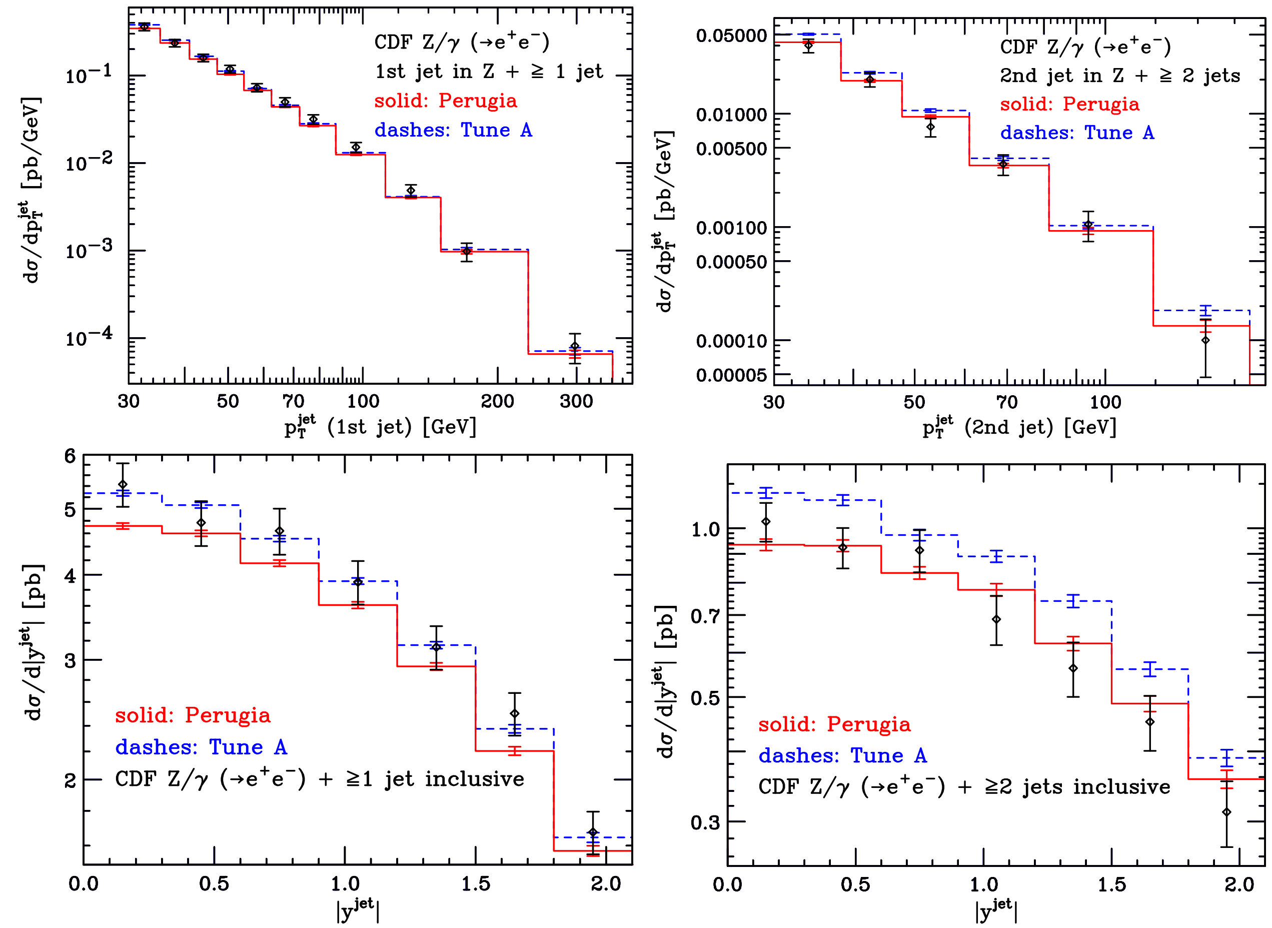


- Still in fair agreement at 14 TeV

Z^0 + jet POWHEG



Sample graphs



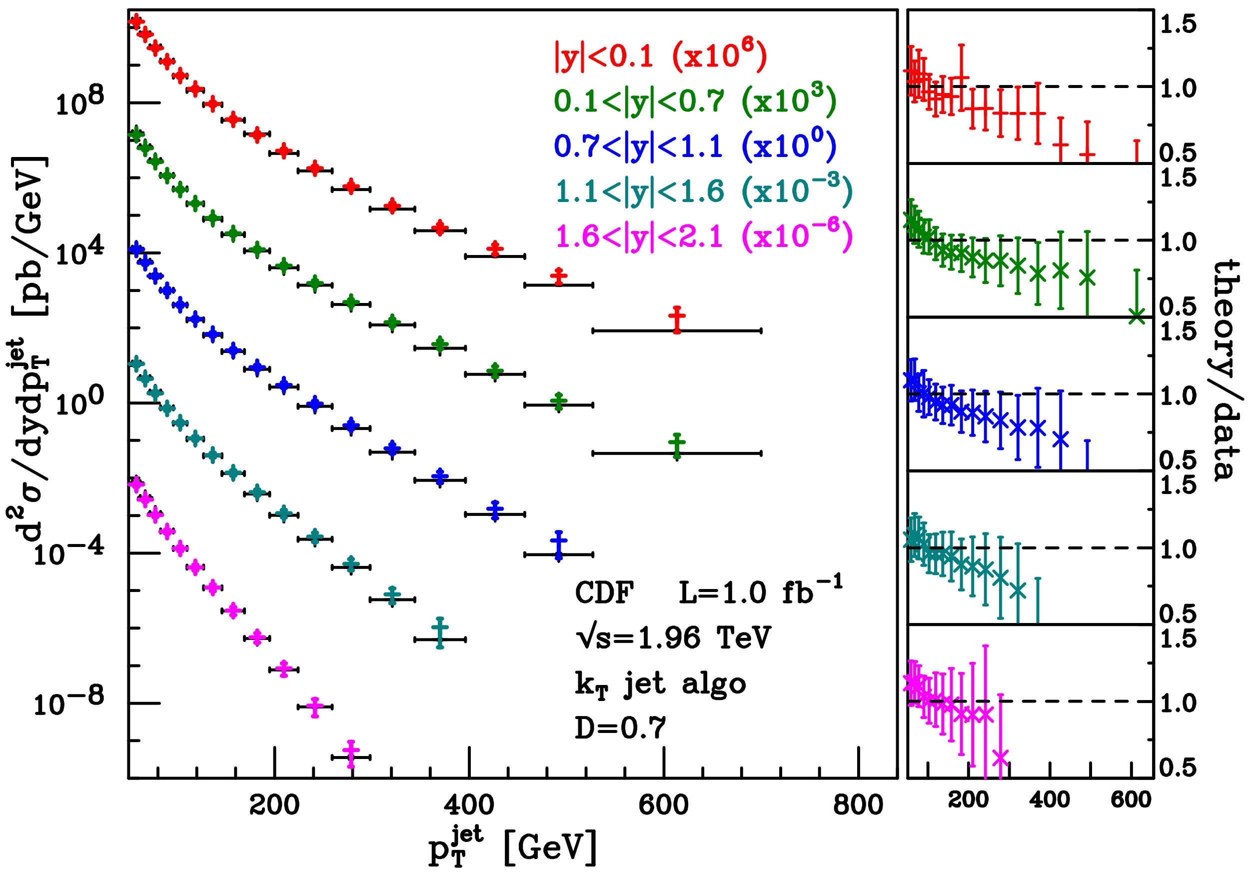
- Cut now needed on ‘underlying Born’ p_t of Z^0
- Good agreement with CDF (not so good with D0)
- First jet is now NLO, second is LO (times $\overline{B}$/B ...)

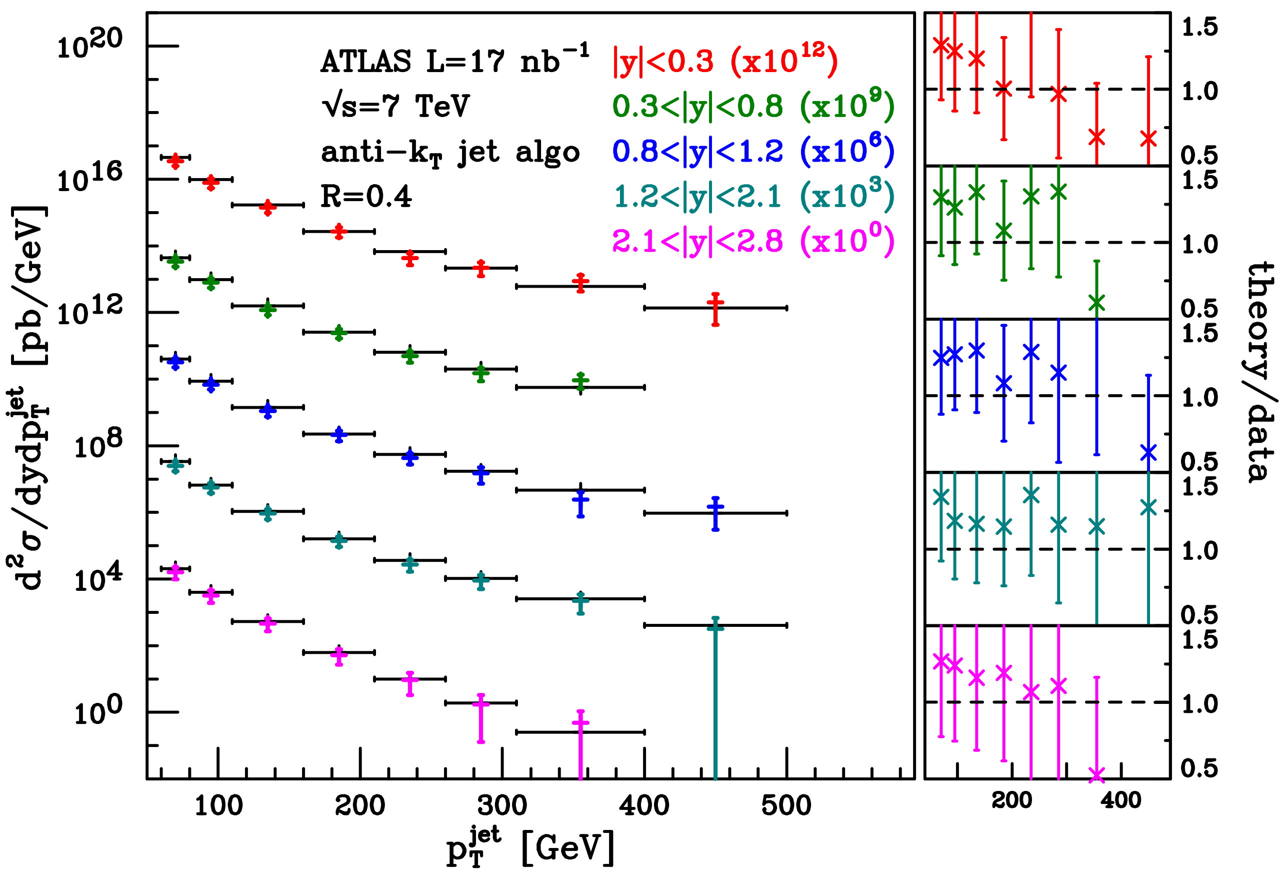
Alioli, Nason, Oleari, Re, JHEP01(2011)095

Dijet POWHEG

CDF

ATLAS





- Again, cut needed on 'underlying Born' jet p_t
- Good agreement with LHC at 7 TeV

Alioli, Hamilton, Nason, Oleari, Re, 1012.3380

MEPS merging

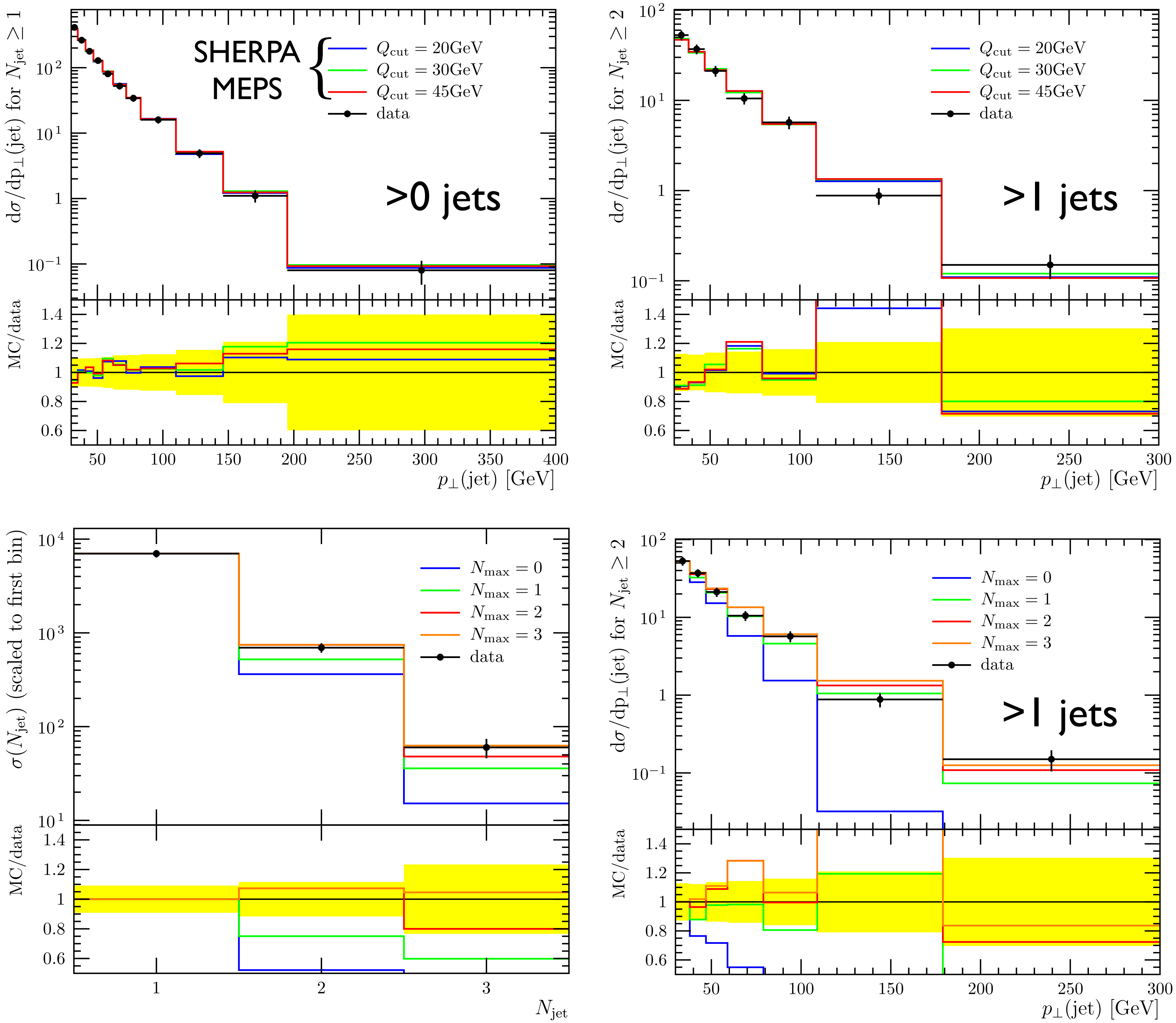
- Objective: merge LO n-jet MEs* with PSMC such that

  * ALPGEN or MadGraph, $n \leqslant N_{max}$

  - Multijet rates for resolution > Q_{cut} are correct to LO (up to N_{max})
  - PSMC generates jet structure below Q_{cut}
  - Q_{cut} dependence cancels to NLL accuracy

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

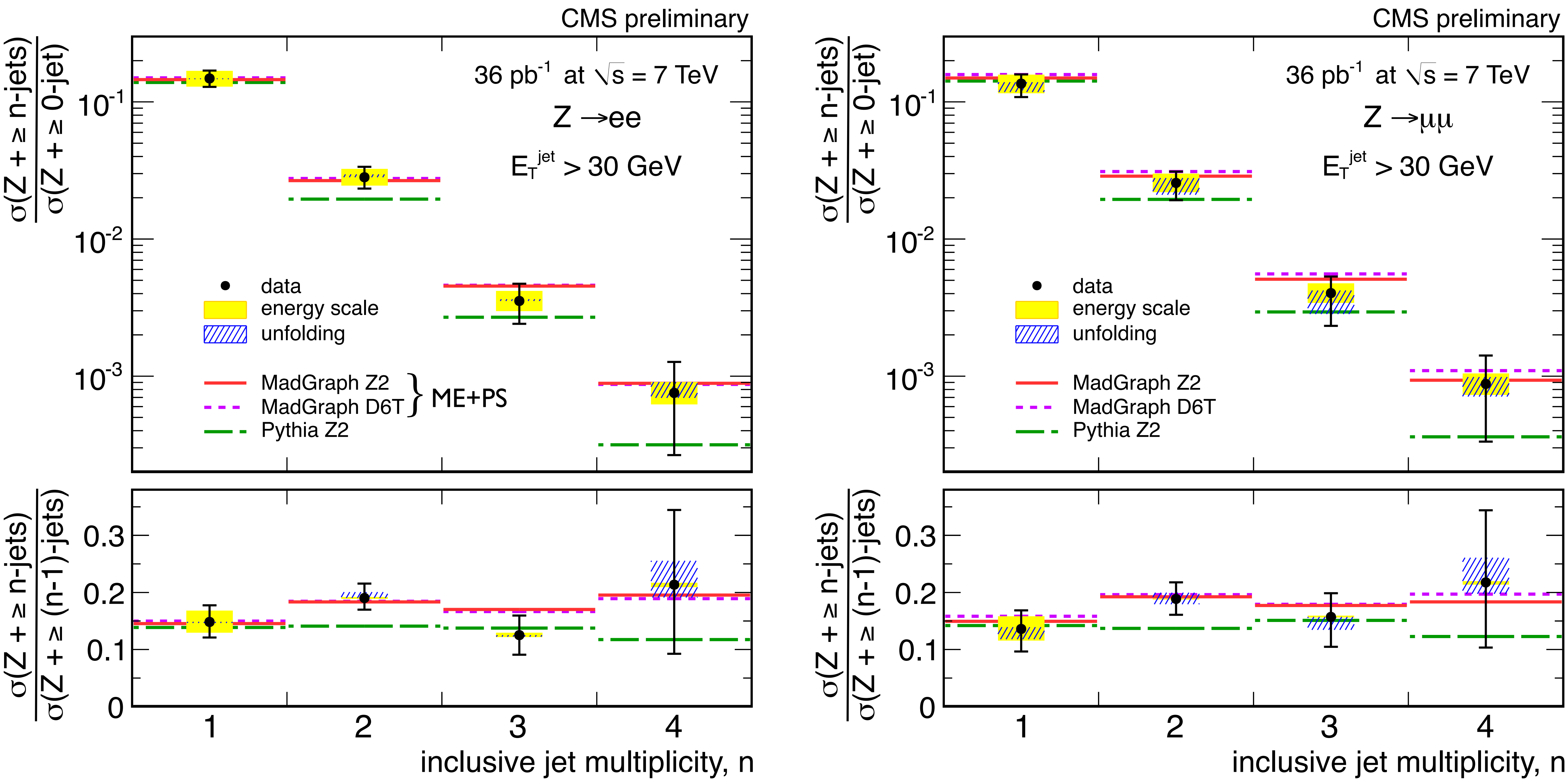
Z^0+jets at Tevatron



- 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

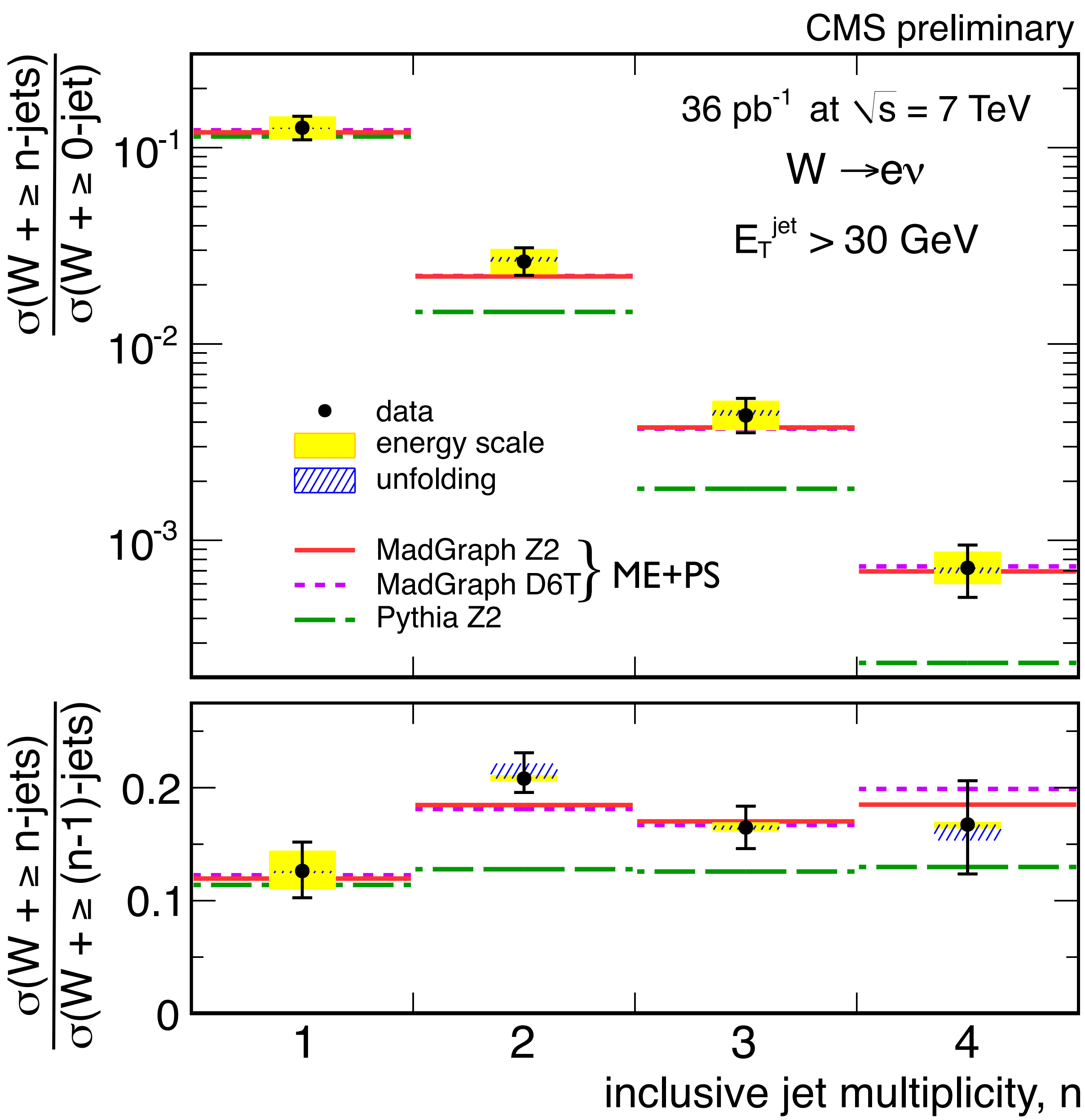
Z^0+jets at LHC (CMS)

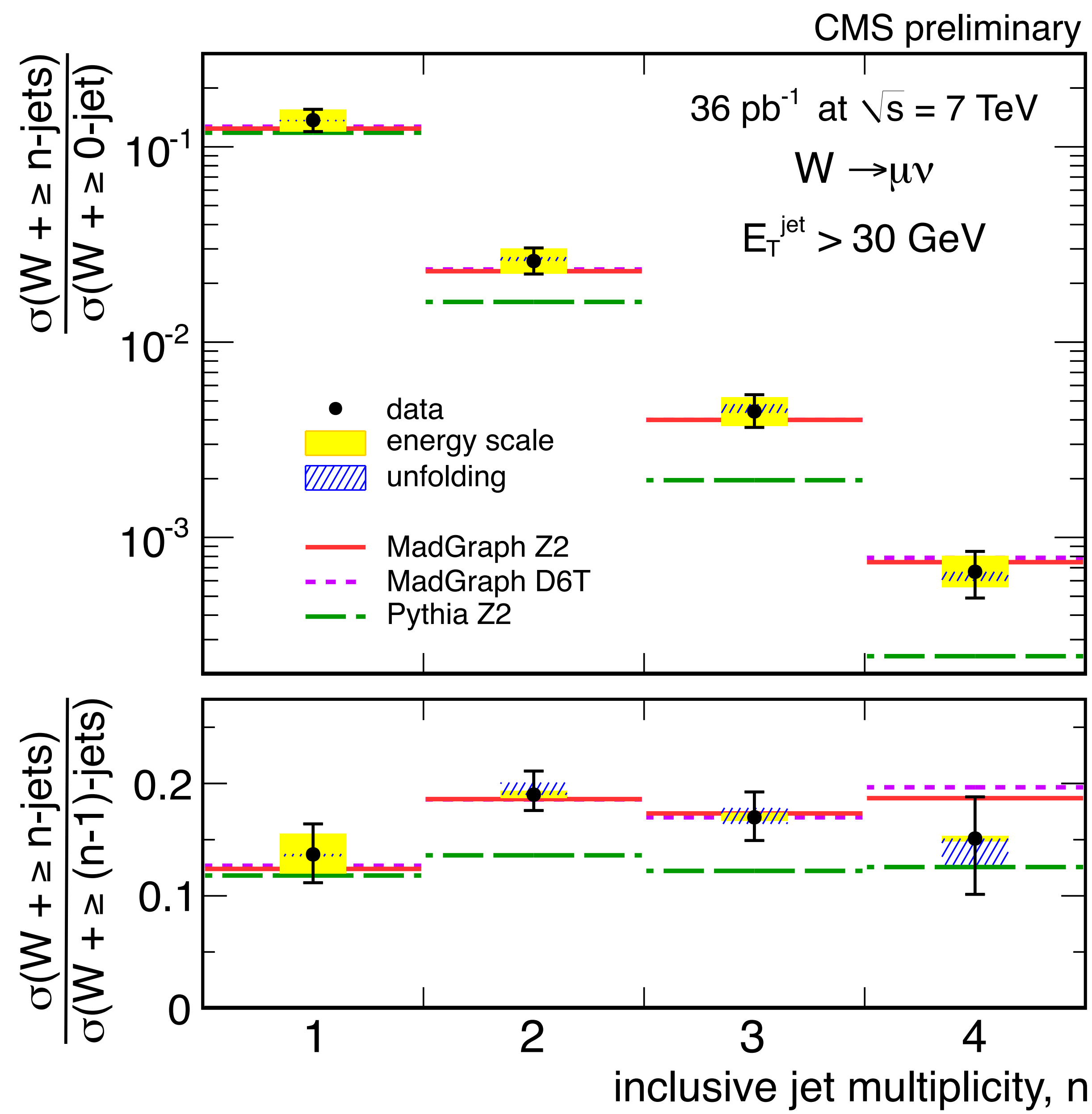


- Inclusive jet rates (anti-k_t-algorithm)
- "Very good agreement with predictions from ME+PS simulation, while PS alone starts to fail for njet ≥ 2"

V Ciulli, Moriond, 24/03/11

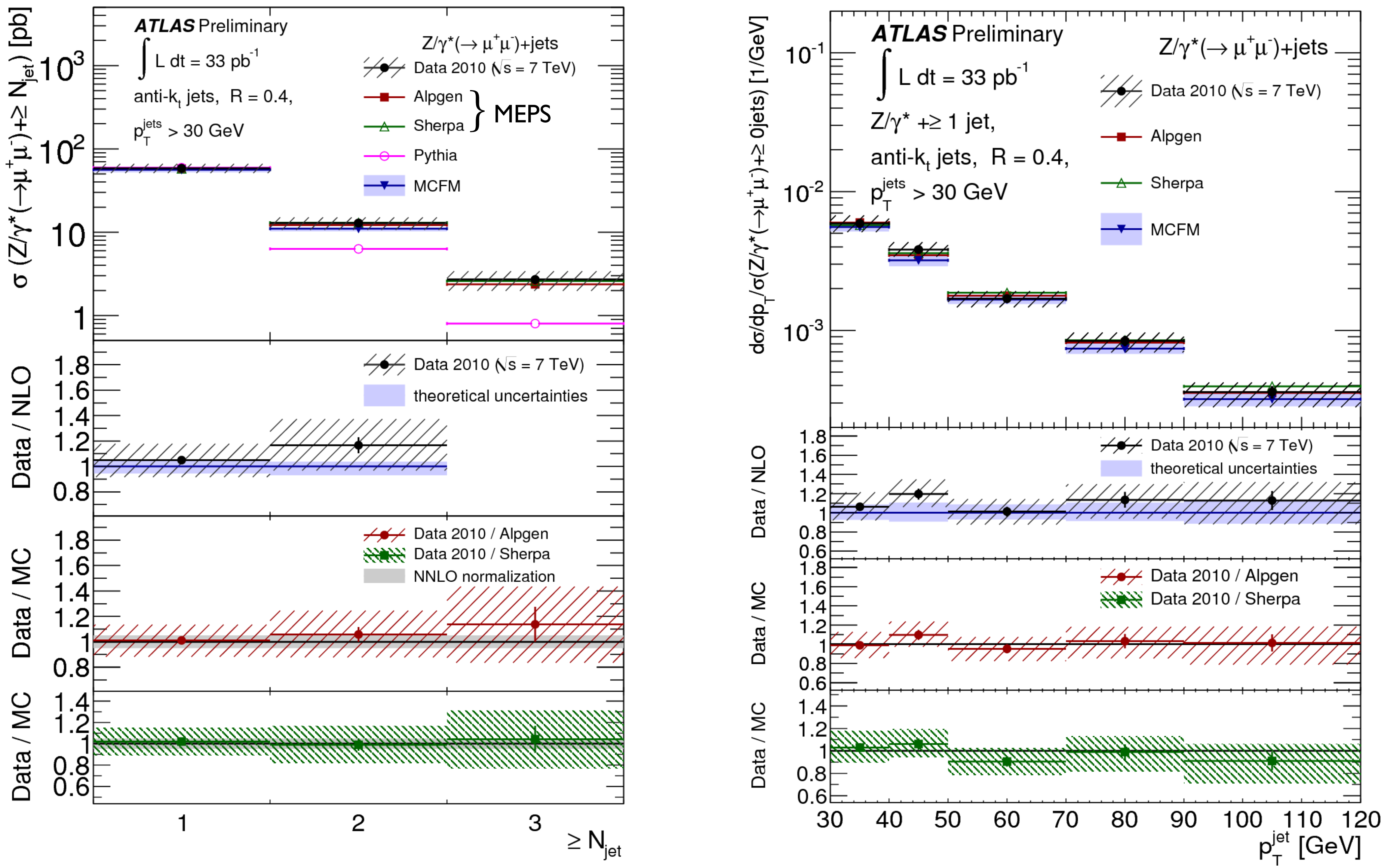
W+jets at LHC (CMS)





- Same conclusion as for Z^0

Z^0+jets at LHC (ATLAS)



- Same conclusion as CMS ...

N Makovec, Moriond, 24/03/11

Matching & Merging: MENLOPS

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

- Assume ≥ 2 jets have K-factor

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

- To retain NLO accuracy we need

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

- Therefore

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

Hamilton & Nason, JHEP06(2010)039

Hoeche, Krauss, Schonherr, Siegert, 1009.1127

MENLOPS

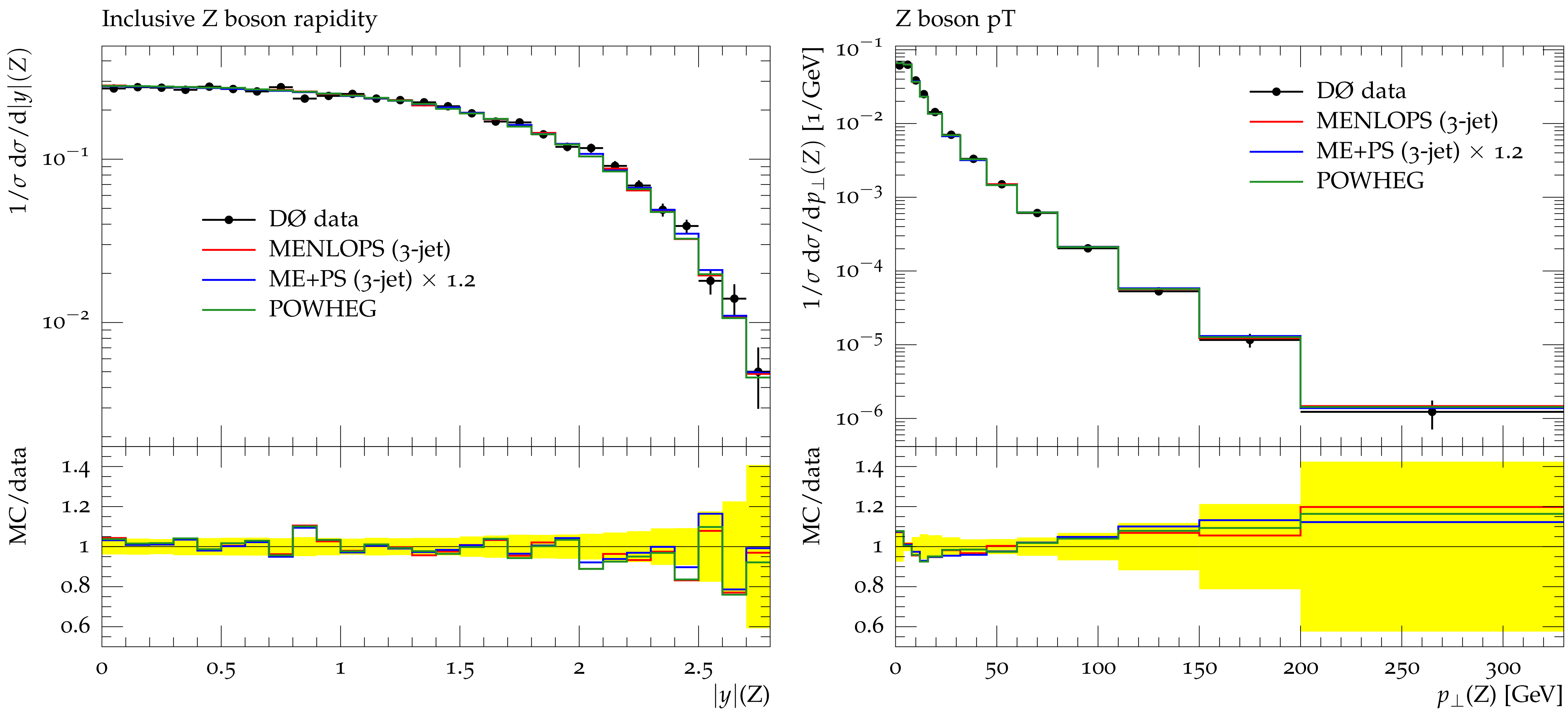
$$d\sigma_{\mathrm{TOT}} = d\sigma_{\mathrm{NLOPS}}(0\,\mathrm{jets}) + K_1\, d\sigma_{\mathrm{NLOPS}}(1\,\mathrm{jet}) + K_2\, d\sigma_{\mathrm{MEPS}}(\geq 2\,\mathrm{jets})$$

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

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

- 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

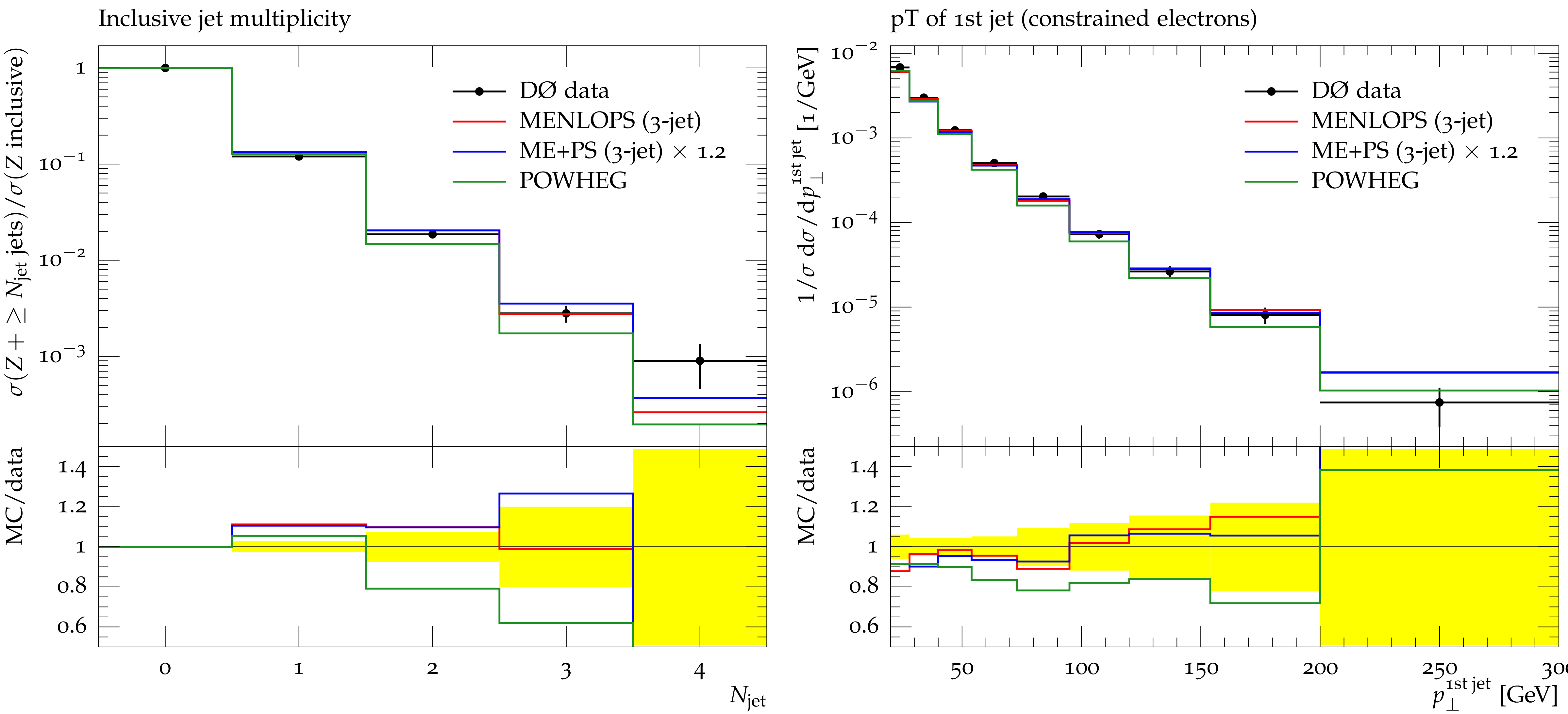
Z^0 at Tevatron



- All treatments agree (MEPS rescaled)

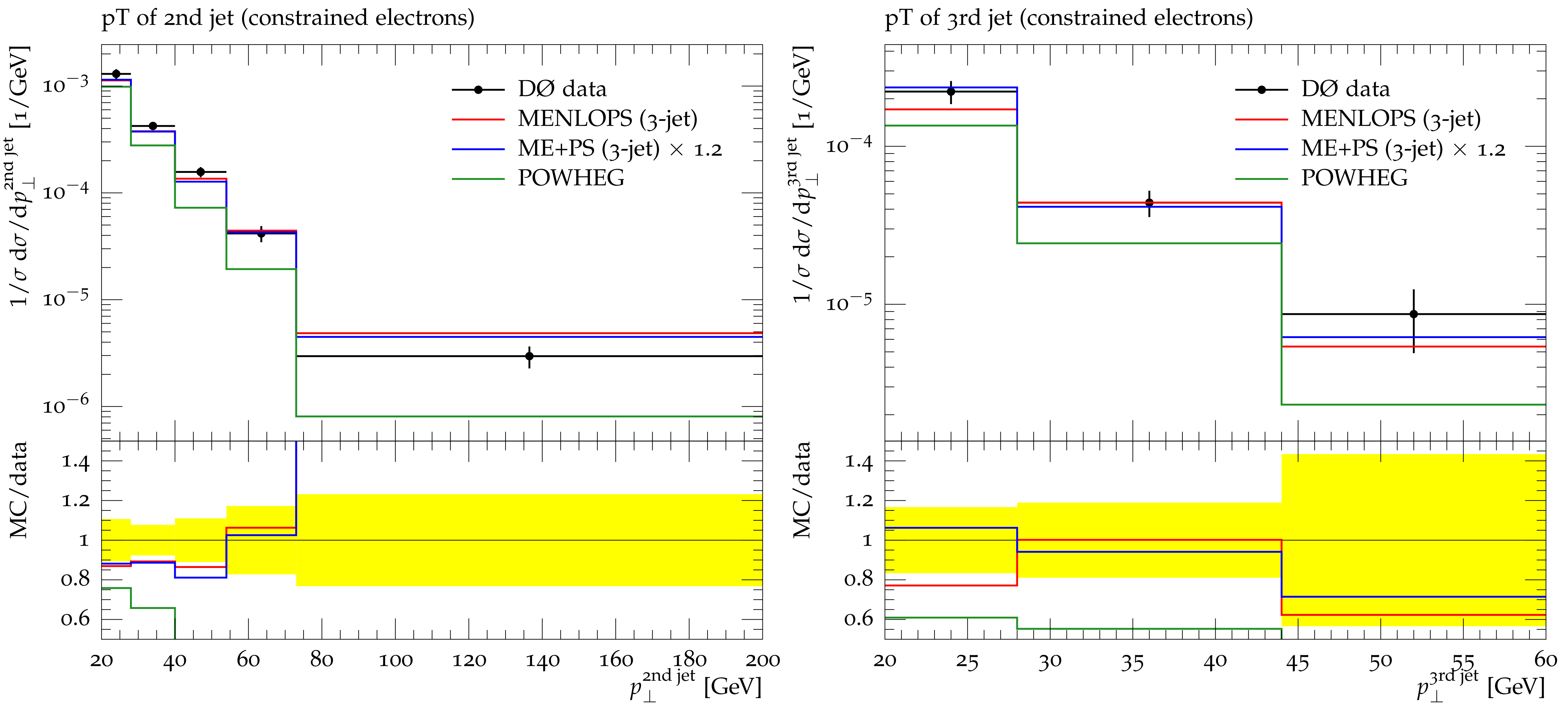
Hoeche, Krauss, Schonherr, Siegert, 1009.1127

Z^0+jets at Tevatron



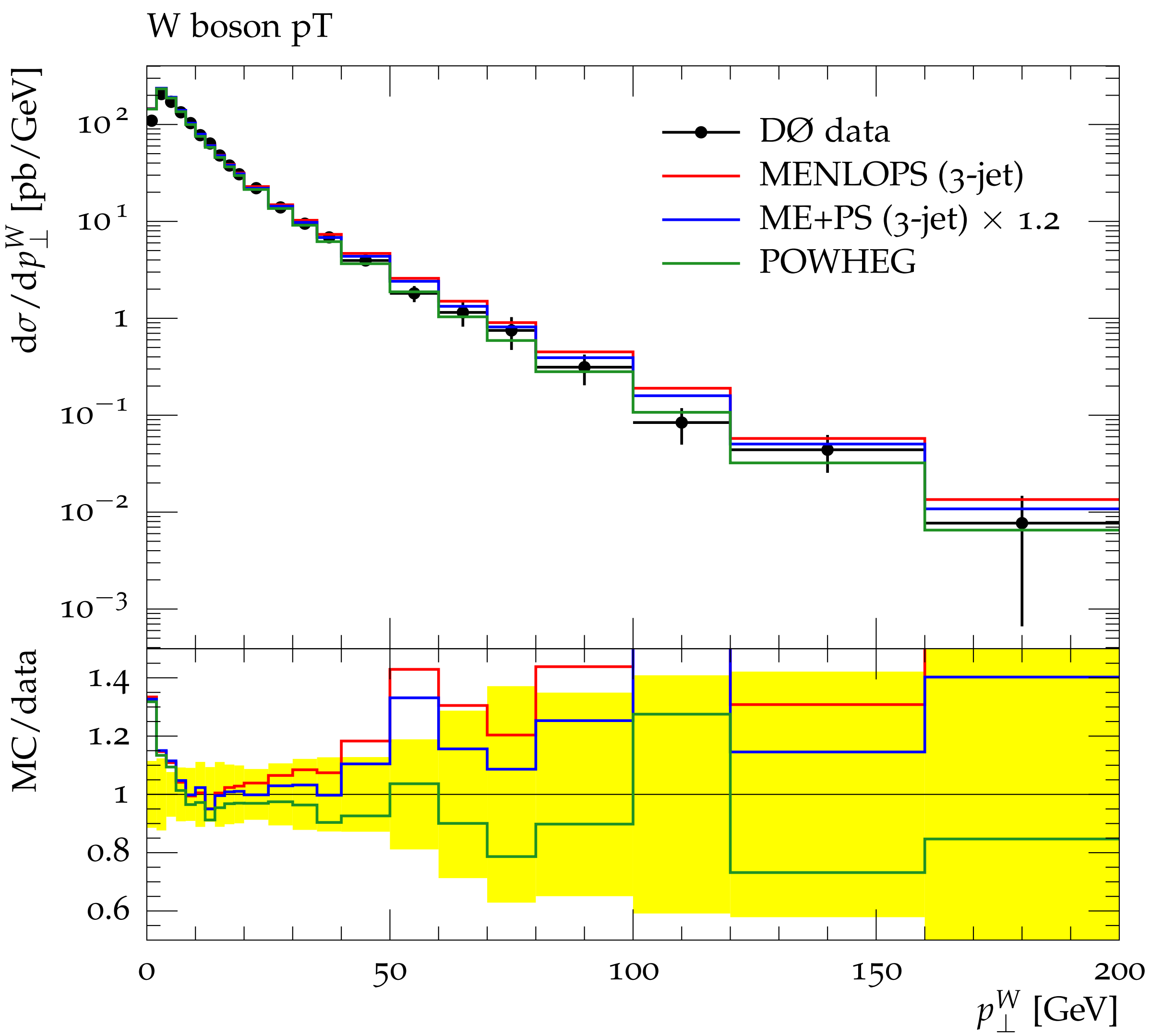
- MENLOPS good for N_{jet}=1,2,3 (no ME for 4)

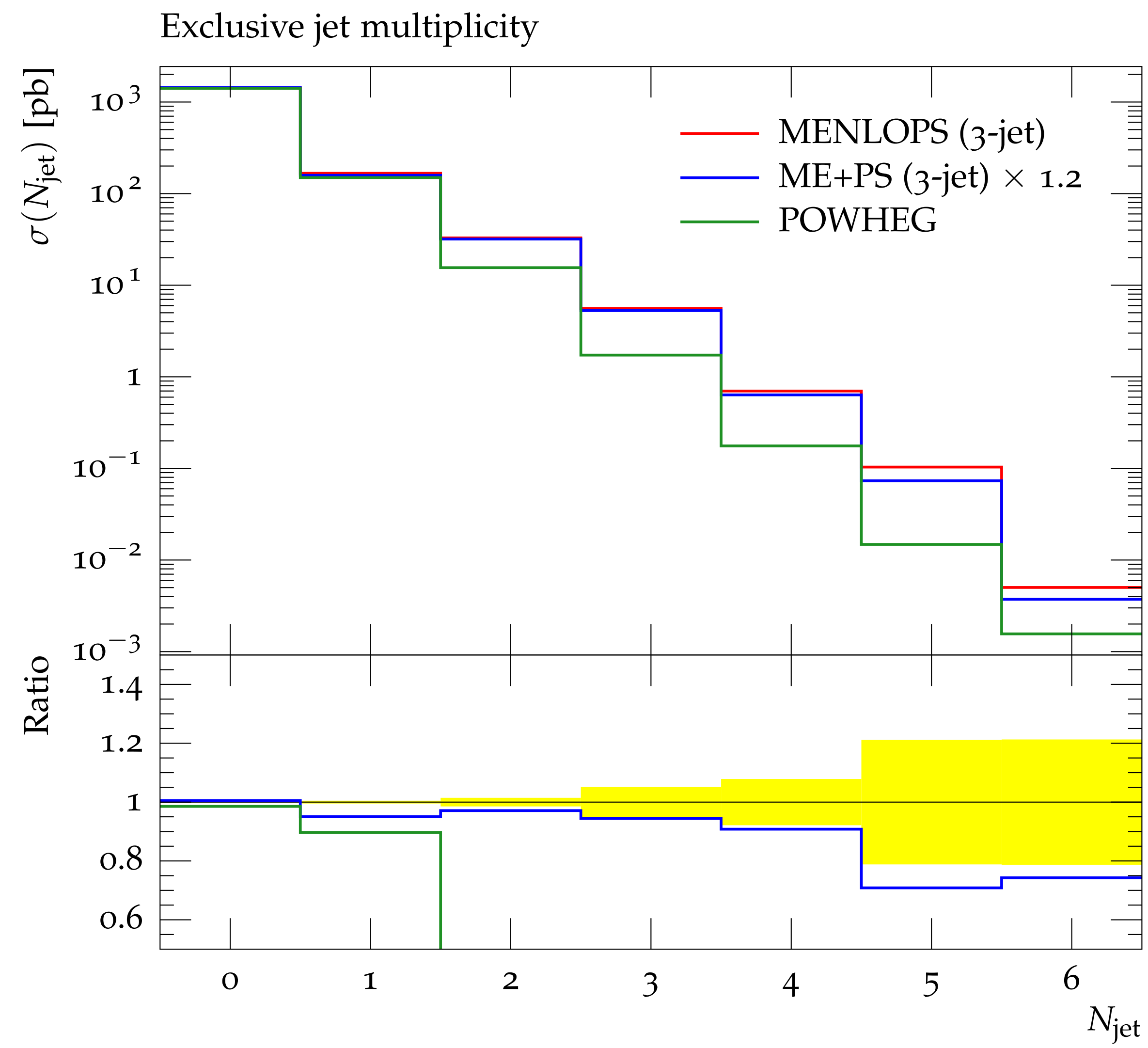
Z^0+jets at Tevatron



- MENLOPS best for jets 2 & 3

W(+jets) at Tevatron

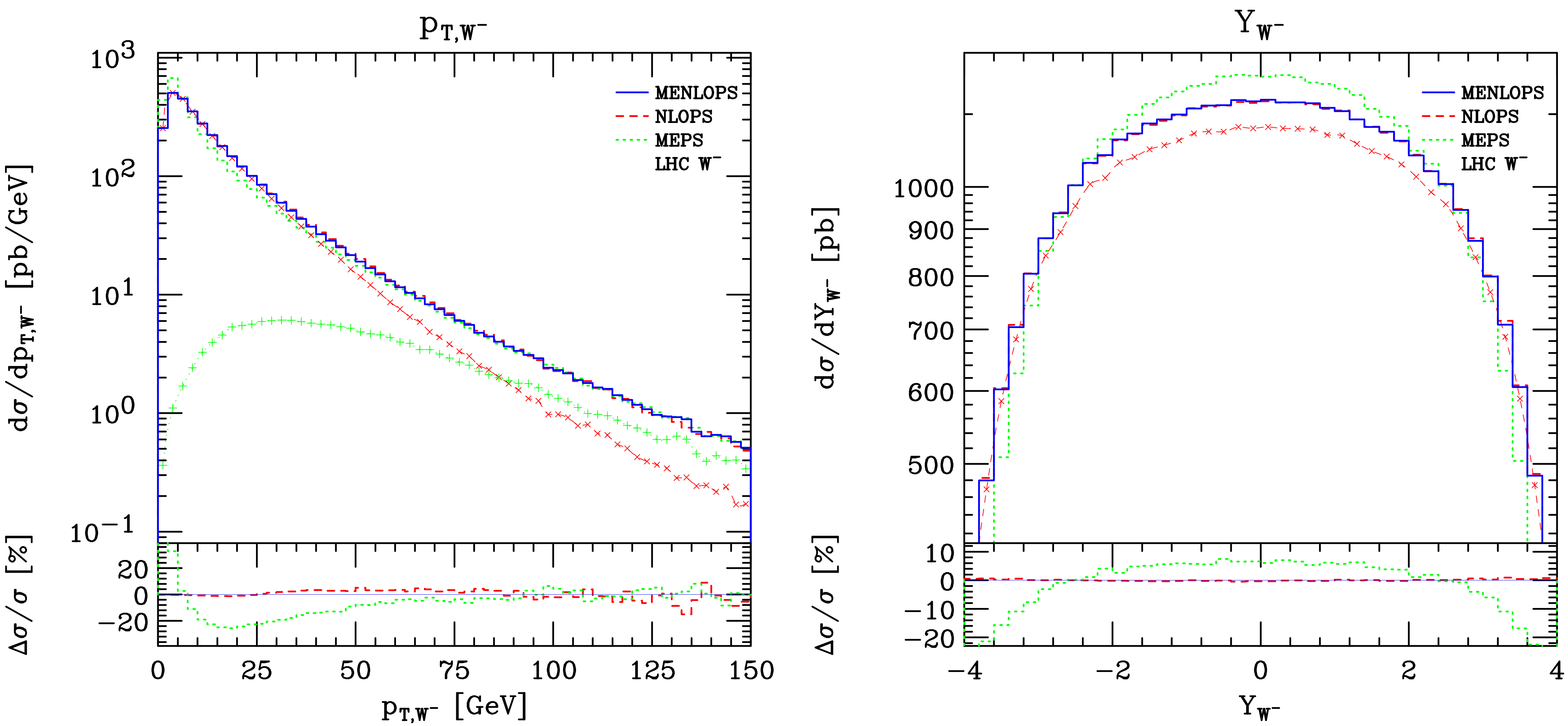




- POWHEG best for $p_t(W)$, lacks ME for $N_{jet}>1$

Hoeche, Krauss, Schonherr, Siegert, 1009.1127

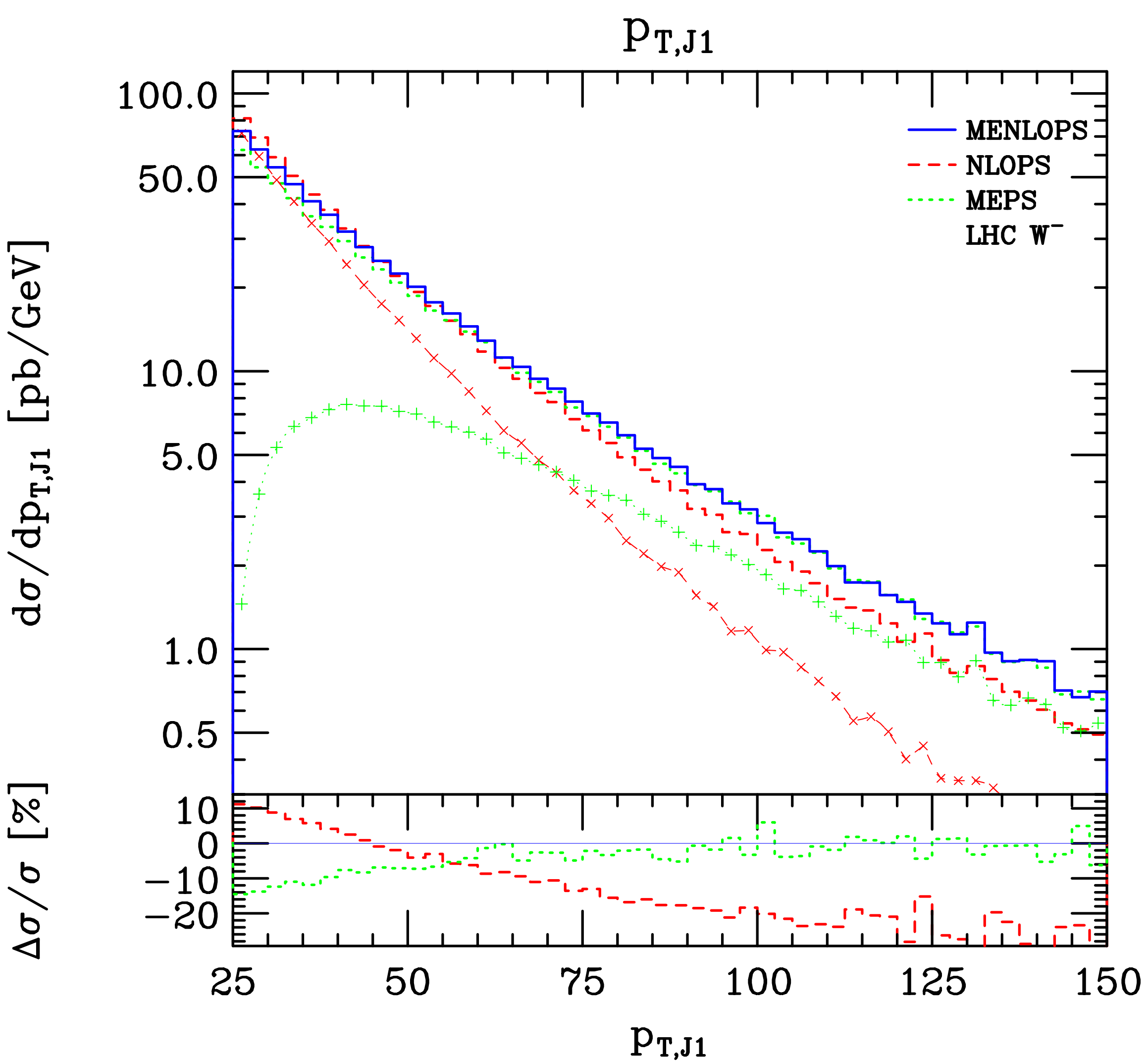
W at LHC (14 TeV)

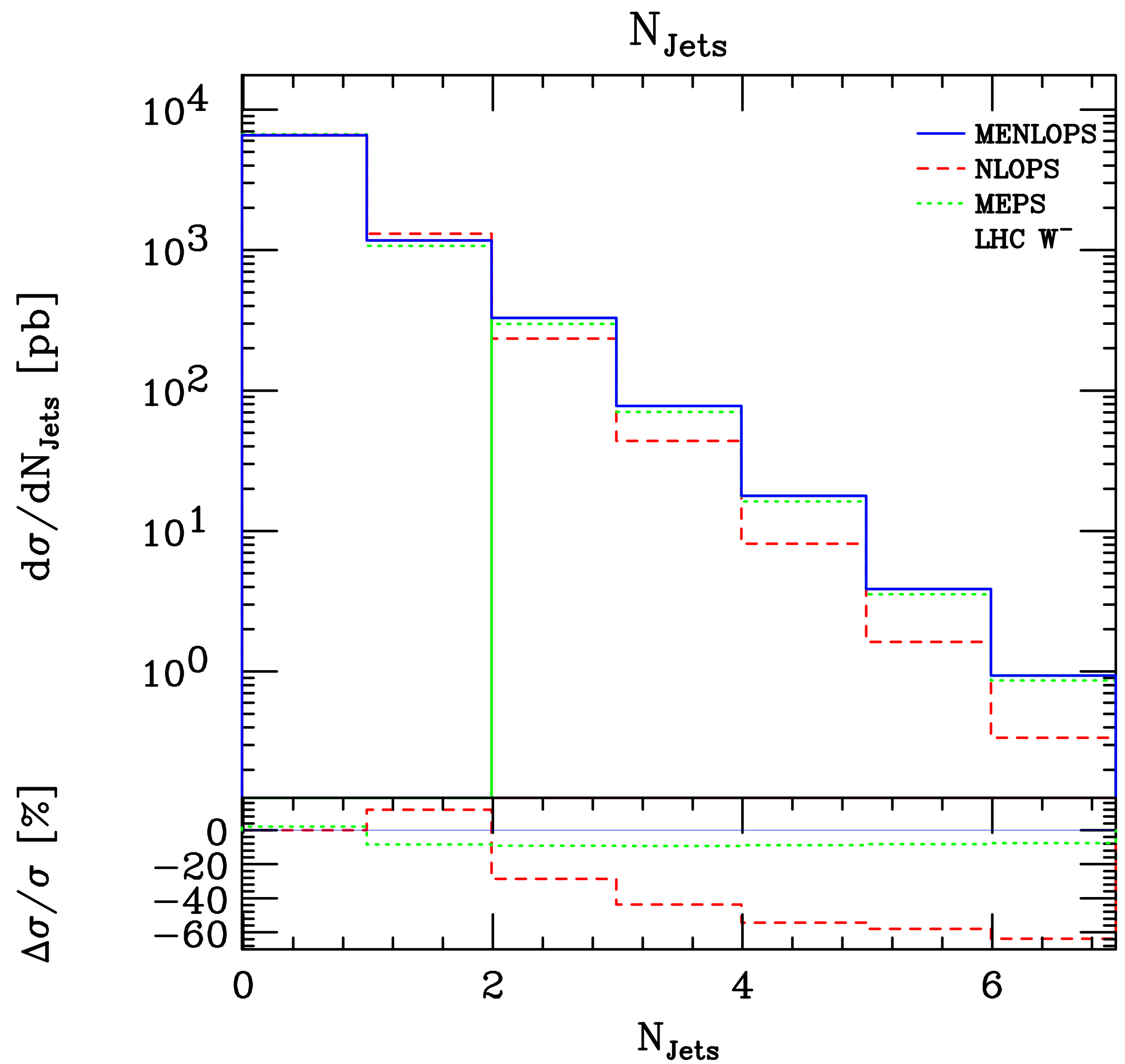


- Dashes are NLOPS & MEPS shapes
- Crosses are contributions to MENLOPS

Hamilton & Nason, JHEP06(2010)039

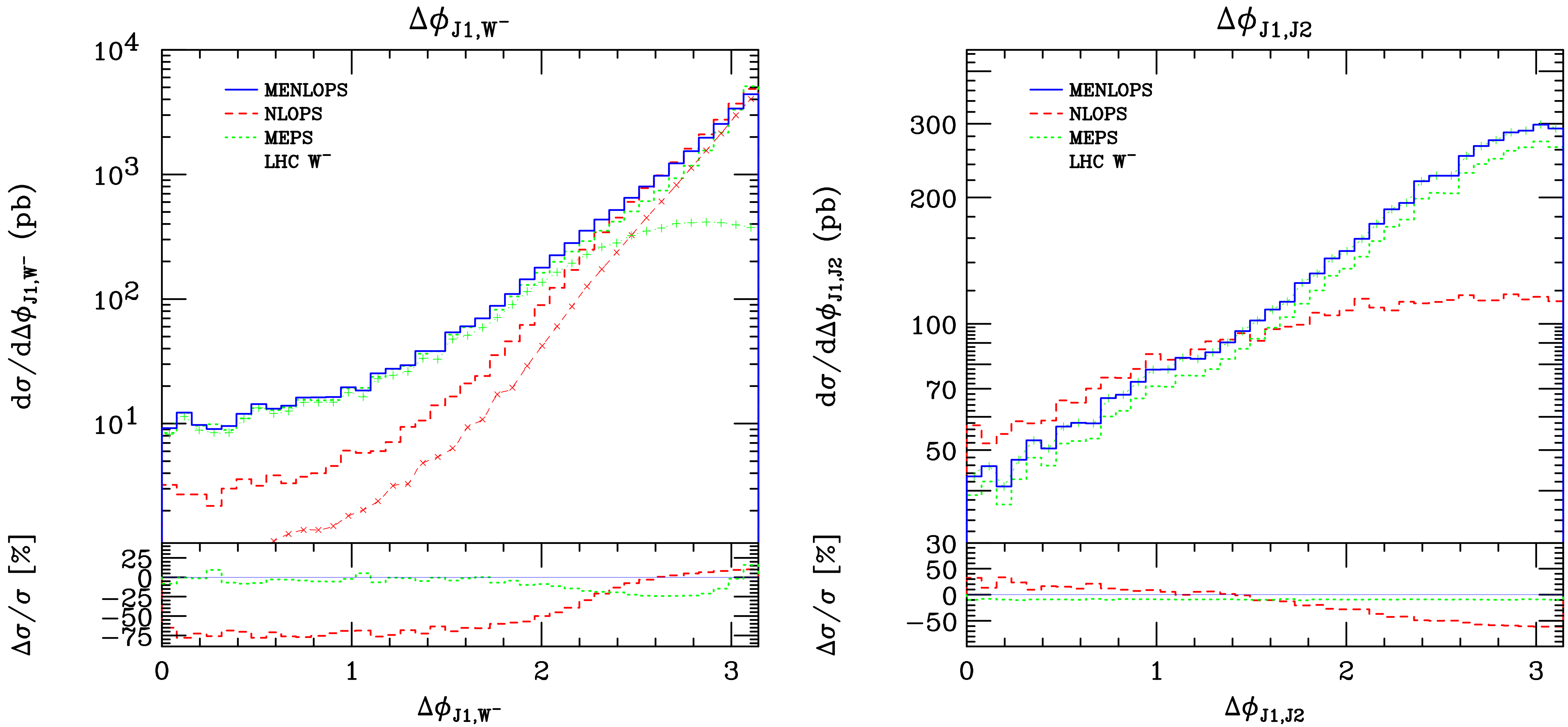
W+jets at LHC (14 TeV)





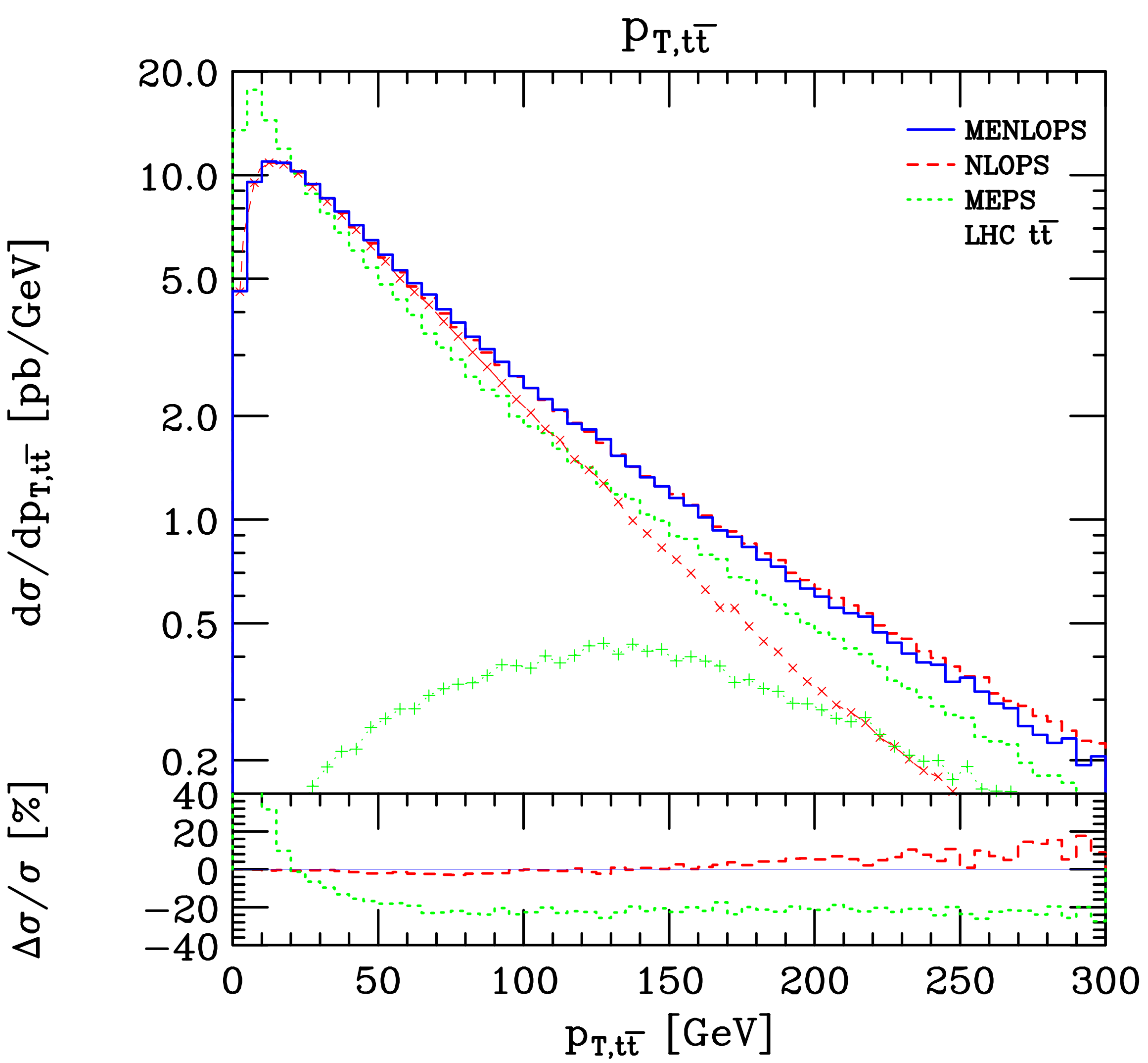
- NLOPS low for N_{jets}>1

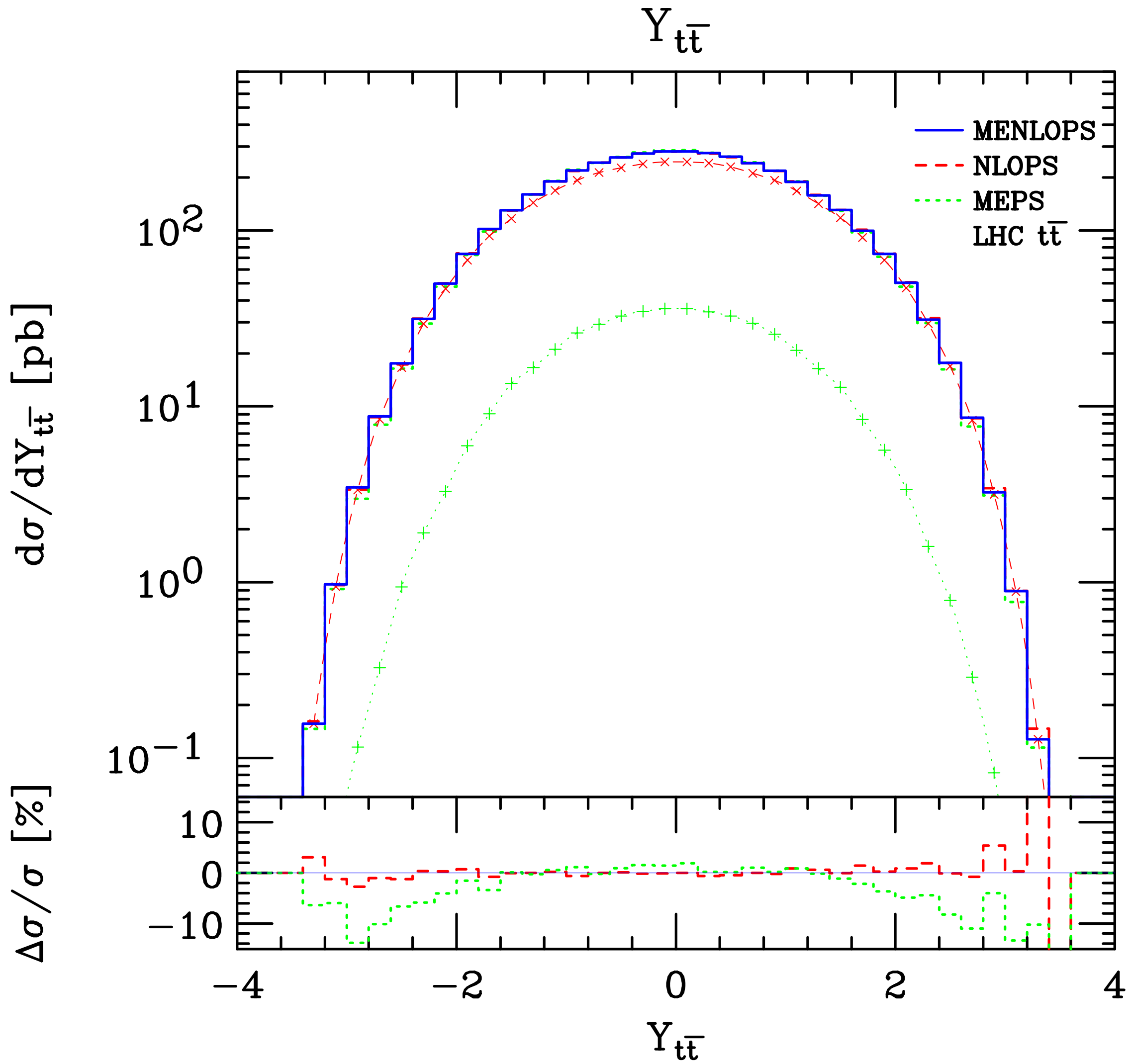
W+jets at LHC (14 TeV)



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

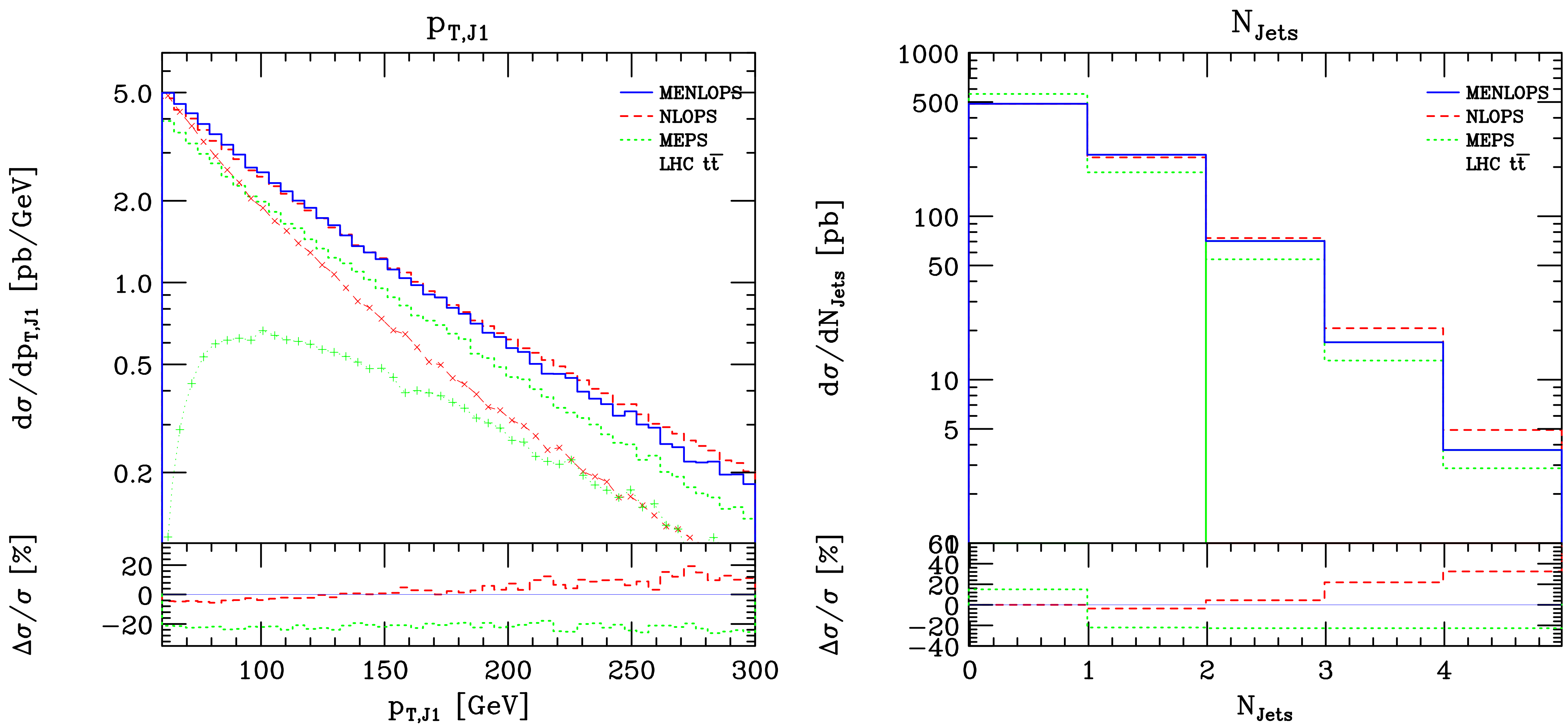
Top at LHC (14 TeV)





- See later for importance of $Y_{t\bar{t}}$

Top at LHC (14 TeV)



- Surprisingly, NLOPS is harder here

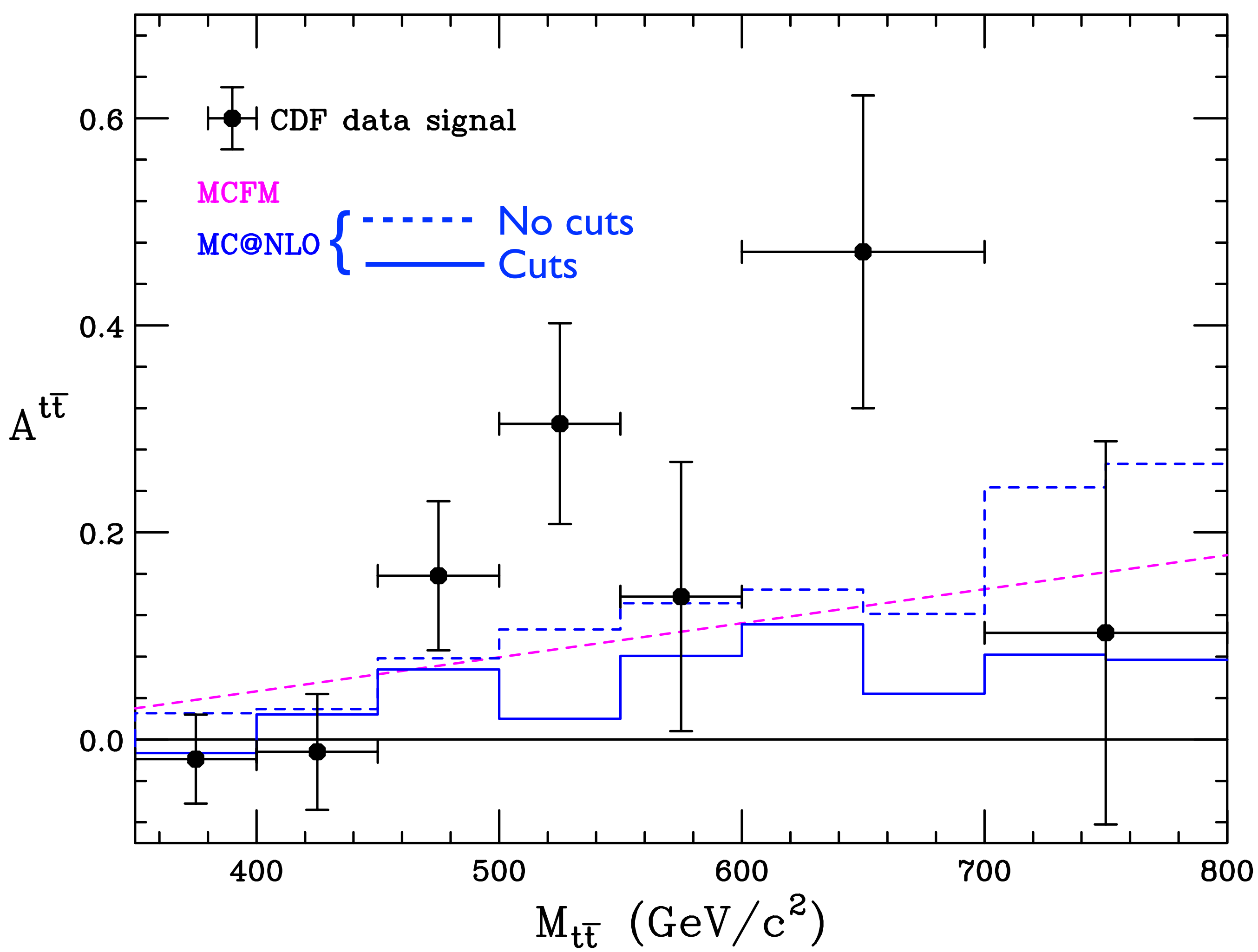
Forward-backward asymmetry in top quark production

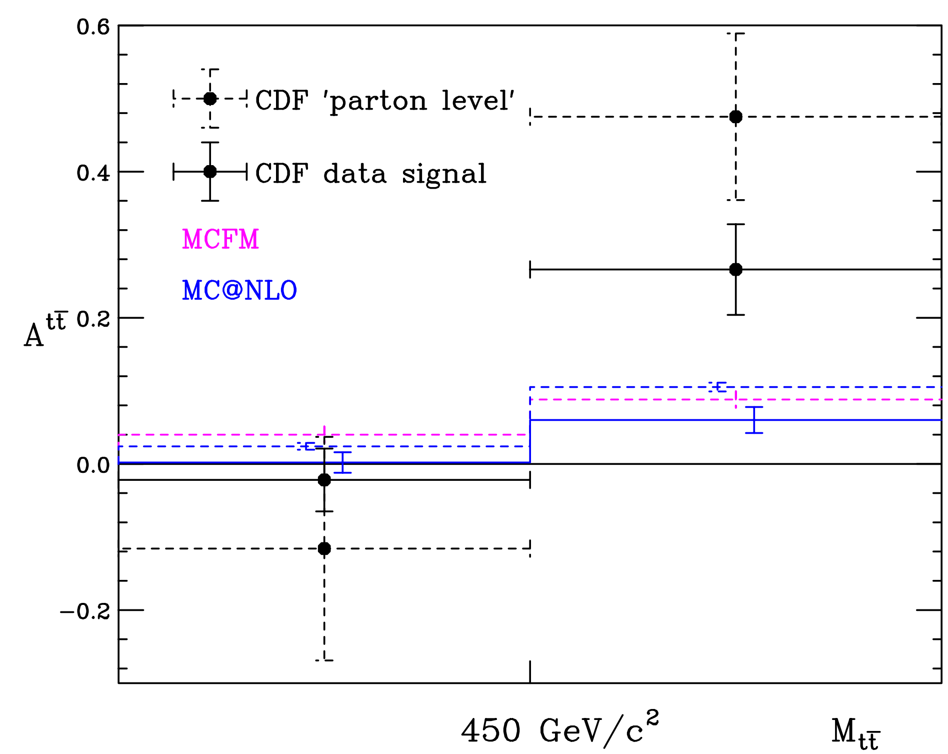
- CDF reports a large effect, increasing with $t\bar{t}$ invariant mass
- SM predicts a smaller NLO effect
- MC@NLO and MCFM in good agreement

CDF, 1101.0034

$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

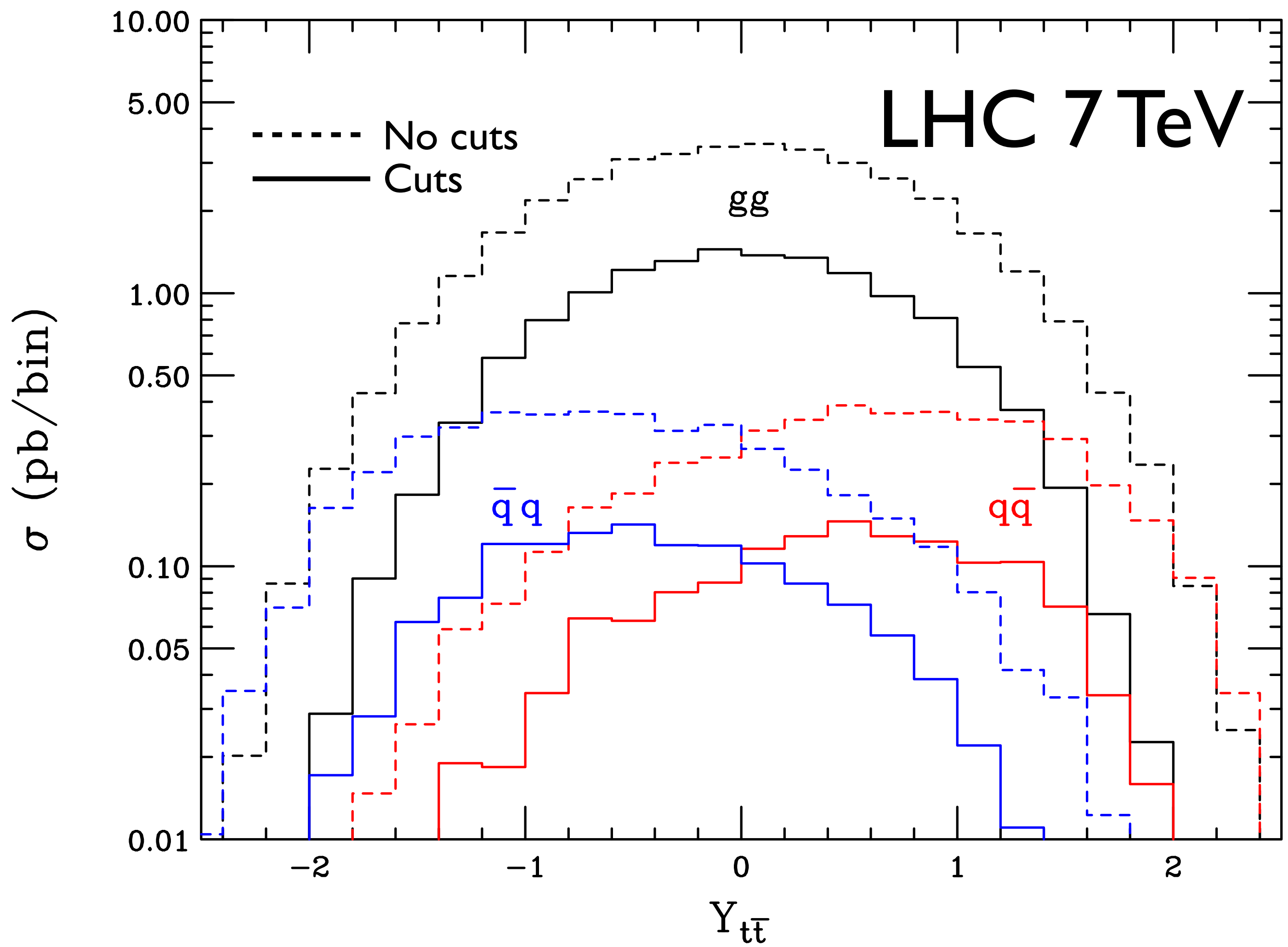
$$\Delta y = y_t - y_{\bar{t}}\ , \quad Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}})$$





Top quark asymmetry at LHC

- LHC is a pp collider ➡ no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- SM effect is small (plots show MC truth for 2 fb^{-1})



$$\Delta y = y_t - y_{\bar{t}} \ , \quad Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}})$$

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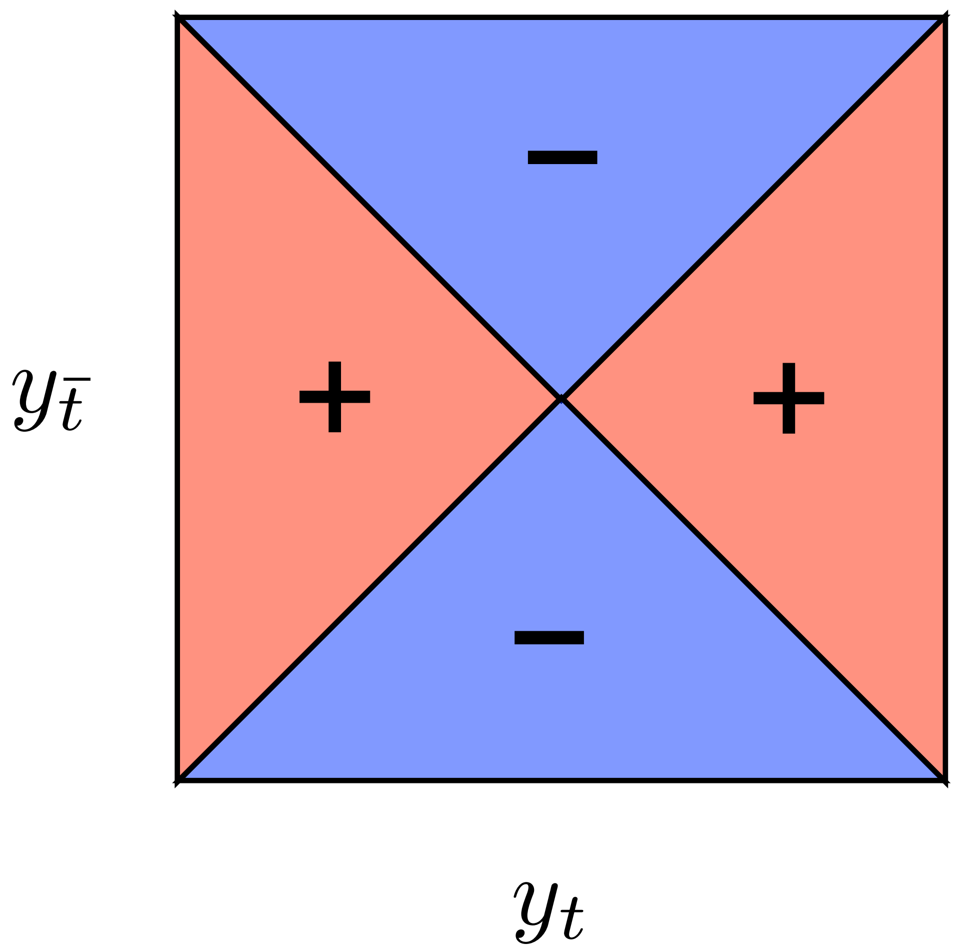
- Rapidity correlation should be as shown below



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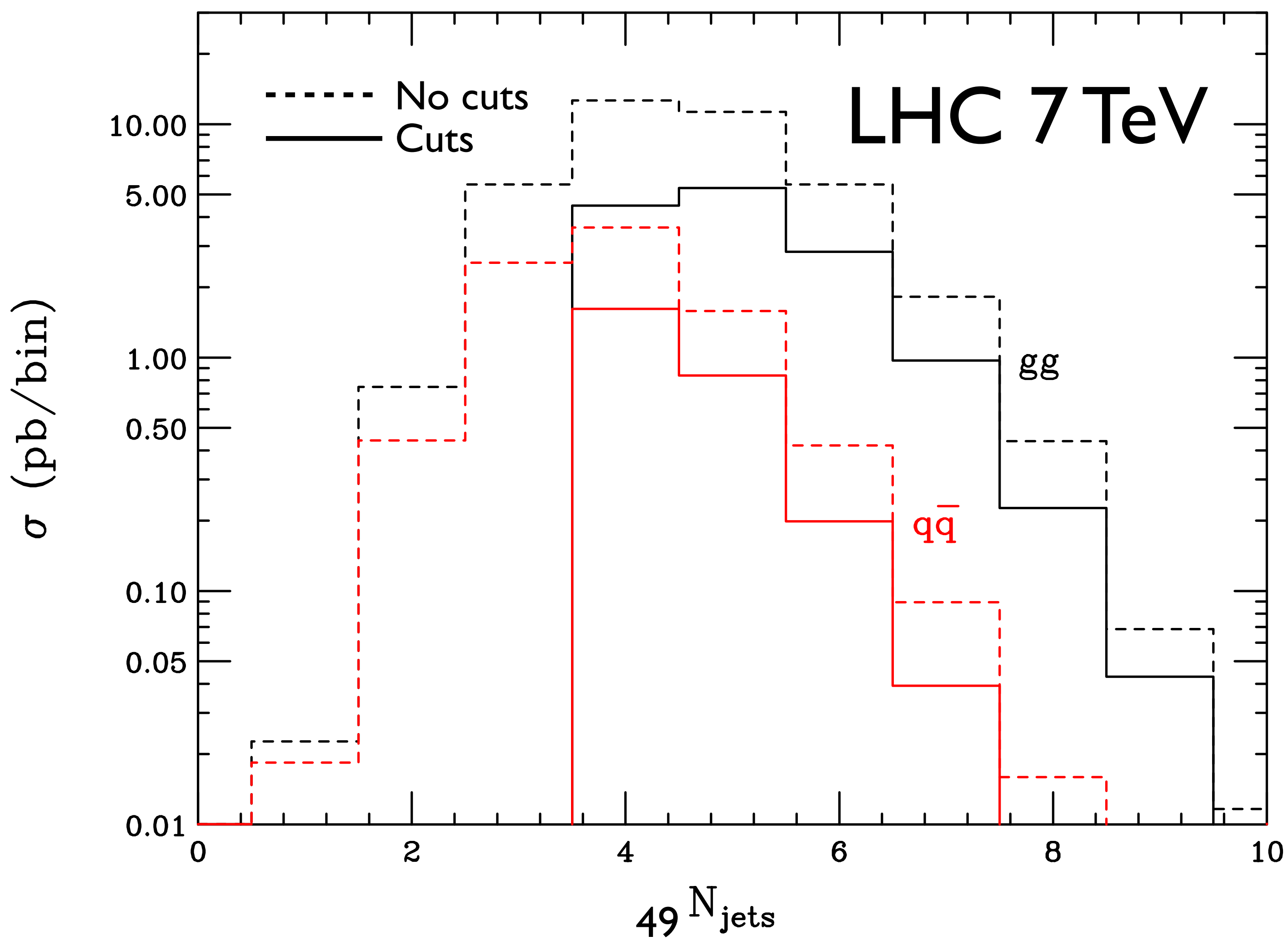
Top quark asymmetry at LHC

- LHC cuts assumed:
  - 1 charged lepton and at least 4 jets (inc. 2 b's) with $p_T > 20\,\mathrm{GeV/c}\,, \quad |\eta| < 2.5$
  - Missing $E_T > 20\,\mathrm{GeV}$
- 4 jet cut reduces gg contribution



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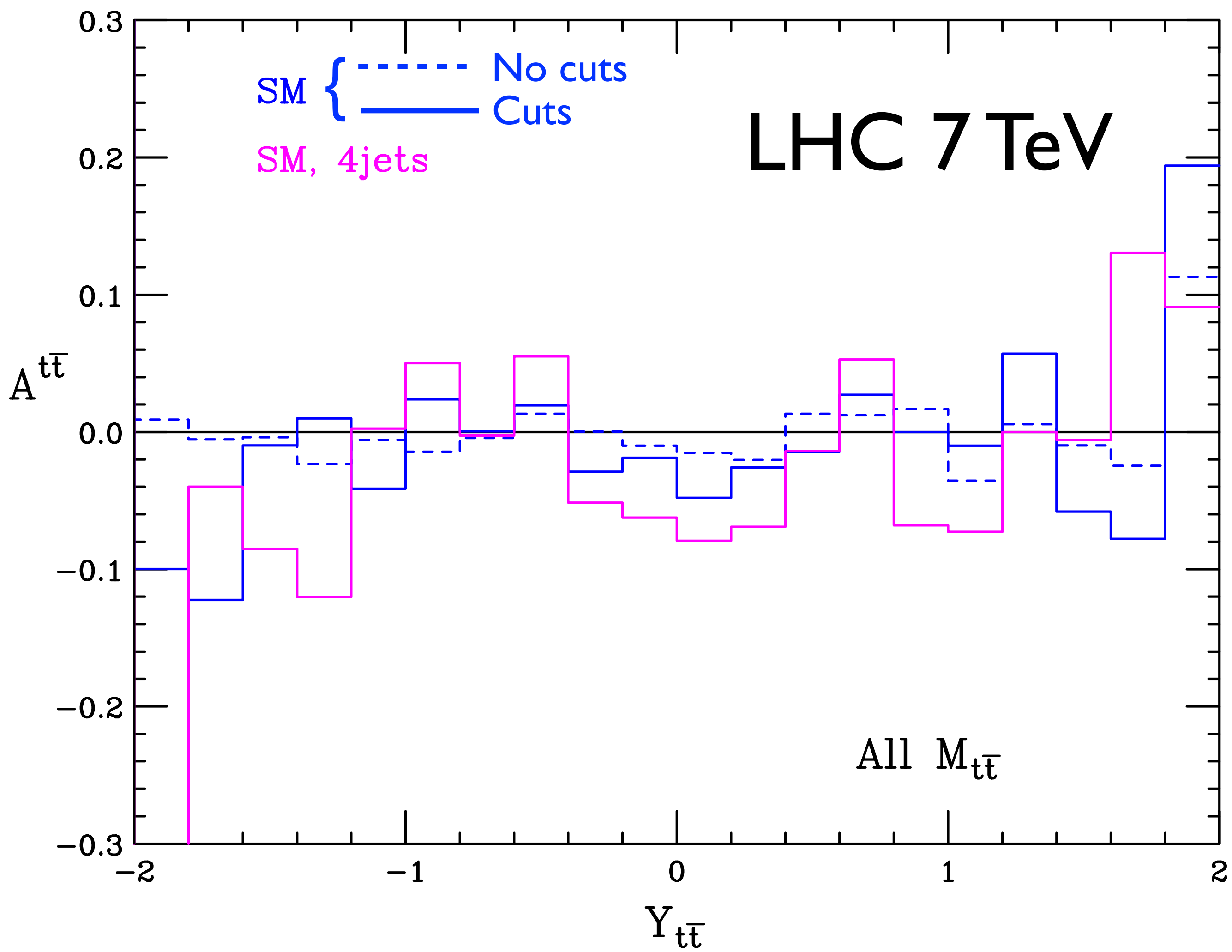

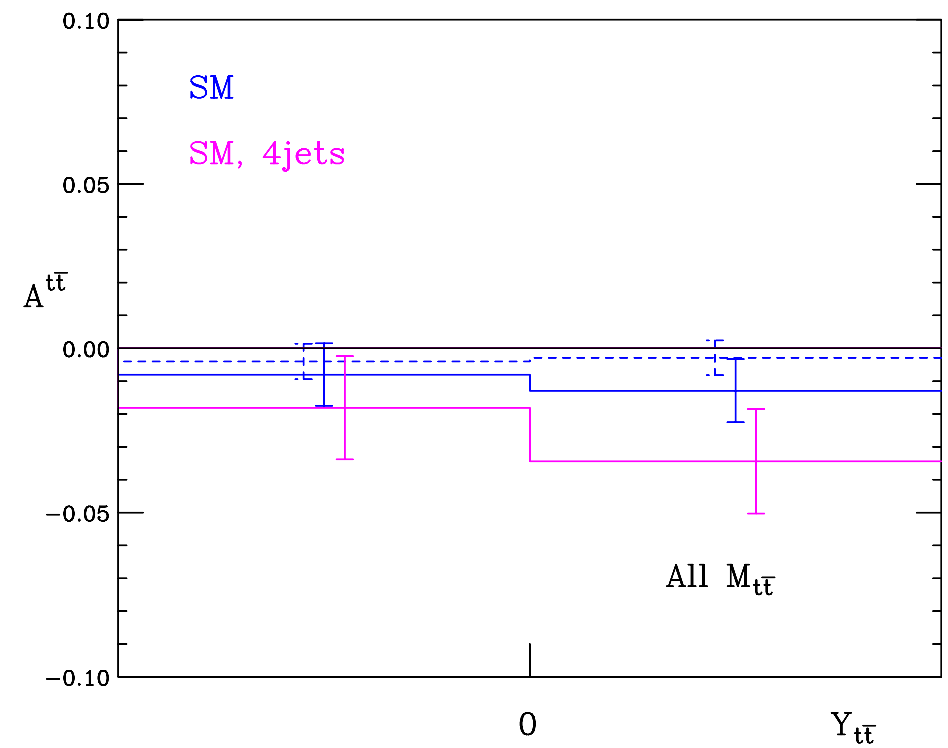

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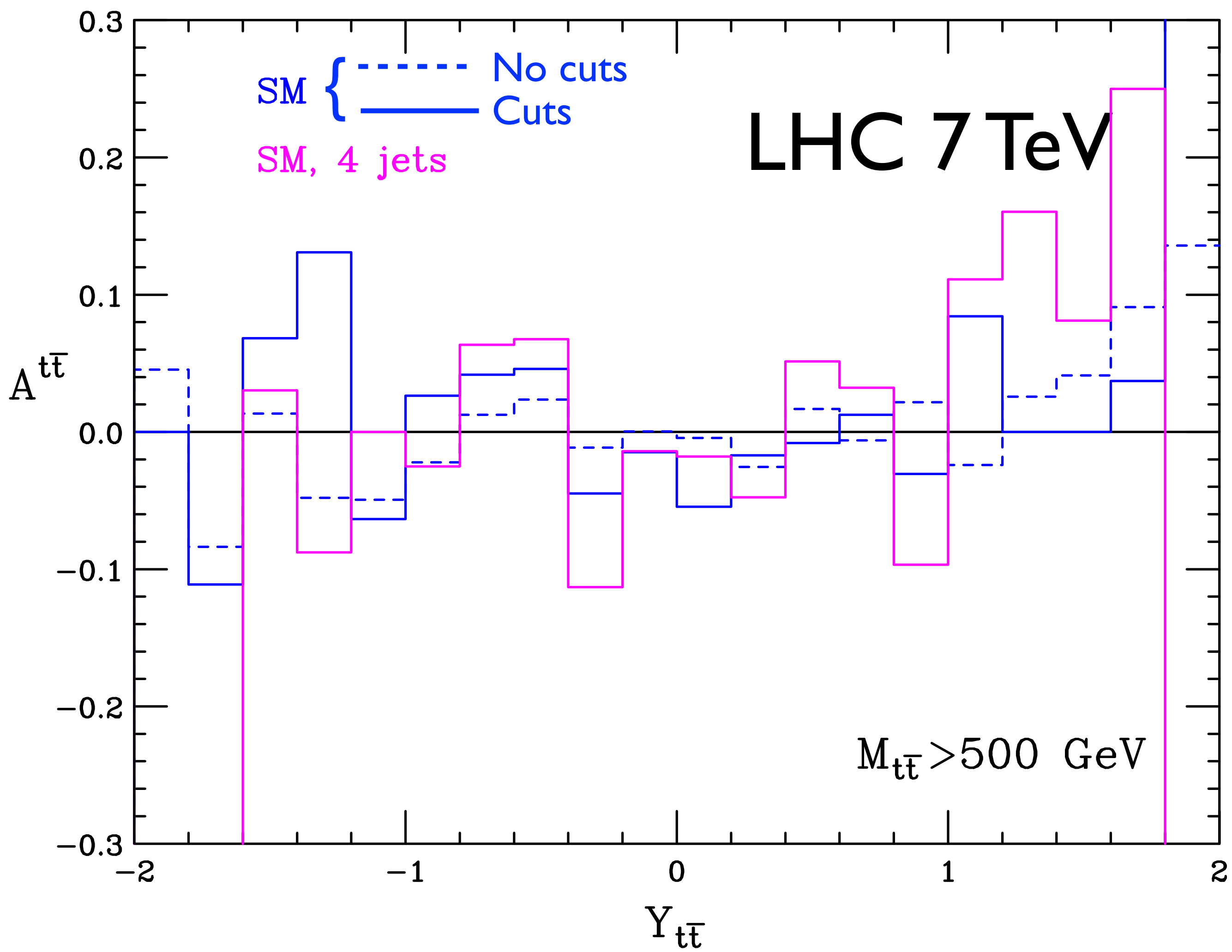

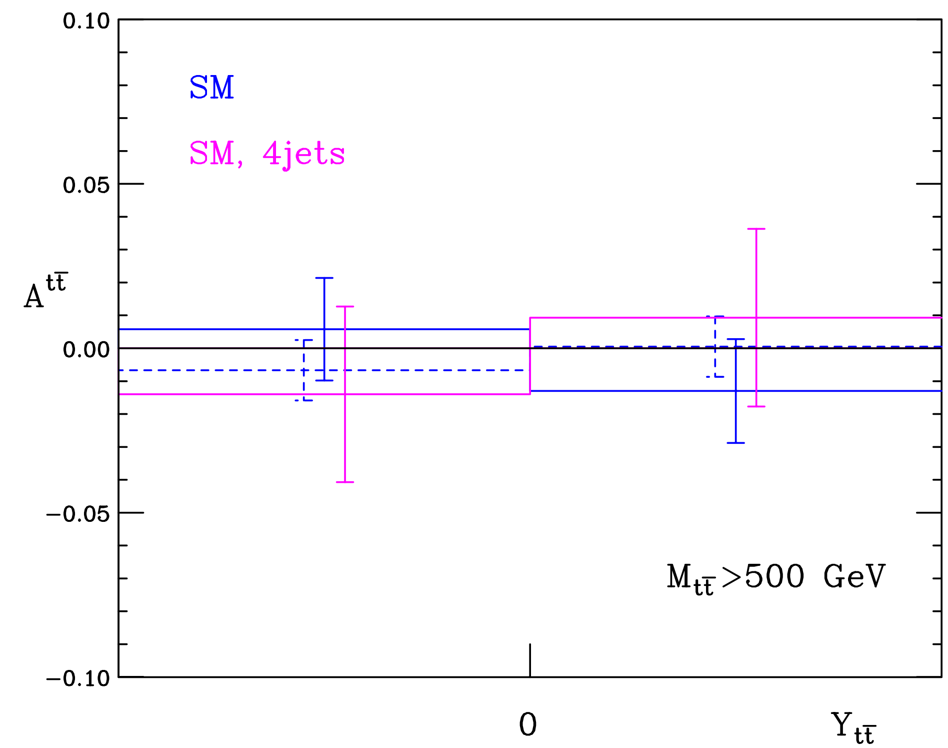

Forward-backward asymmetry in top quark production (2)

- CDF reports a large effect, increasing with $t\bar{t}$ invariant mass
- Suppose this is new physics
- Model it by reweighting $q\bar{q}$ contribution

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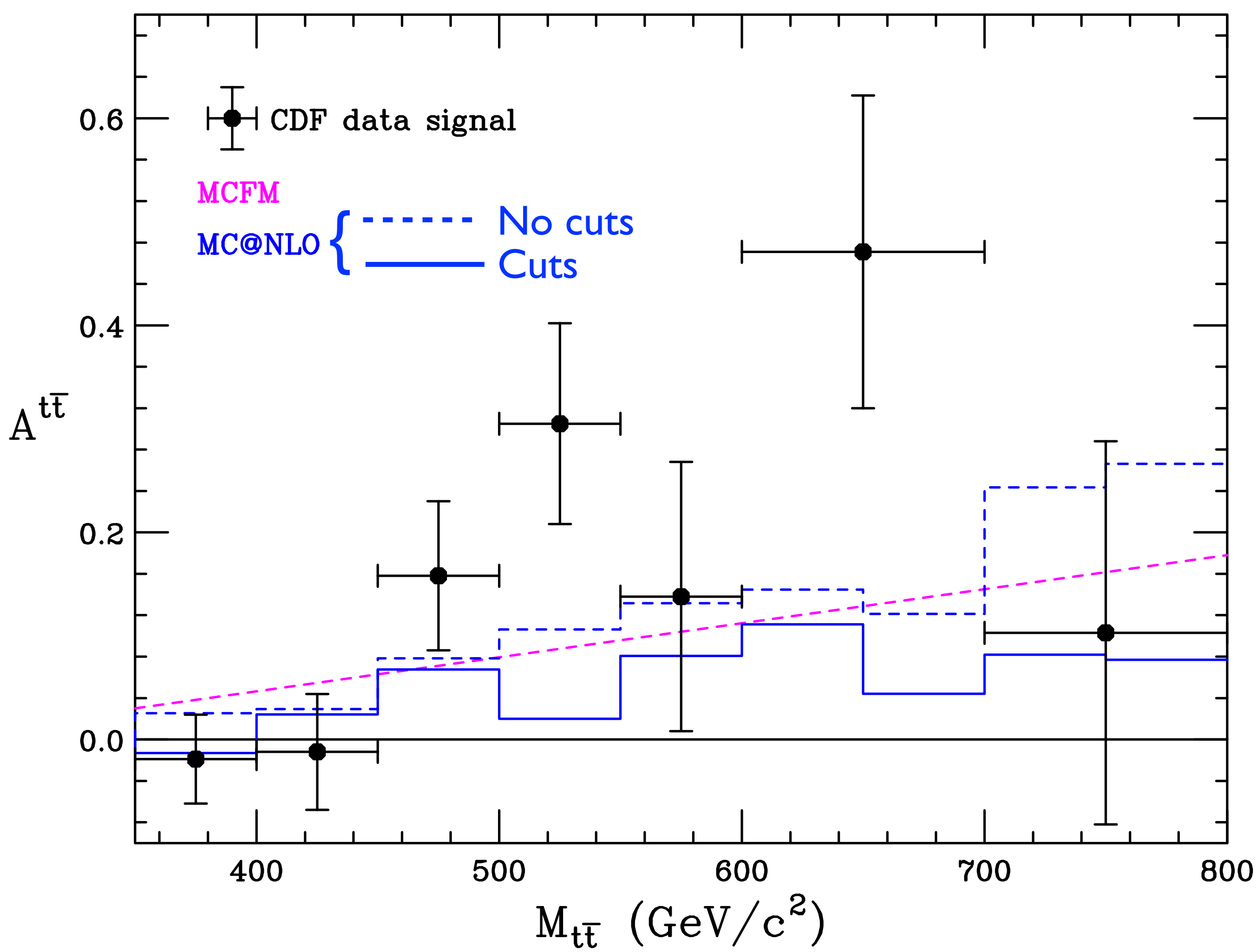

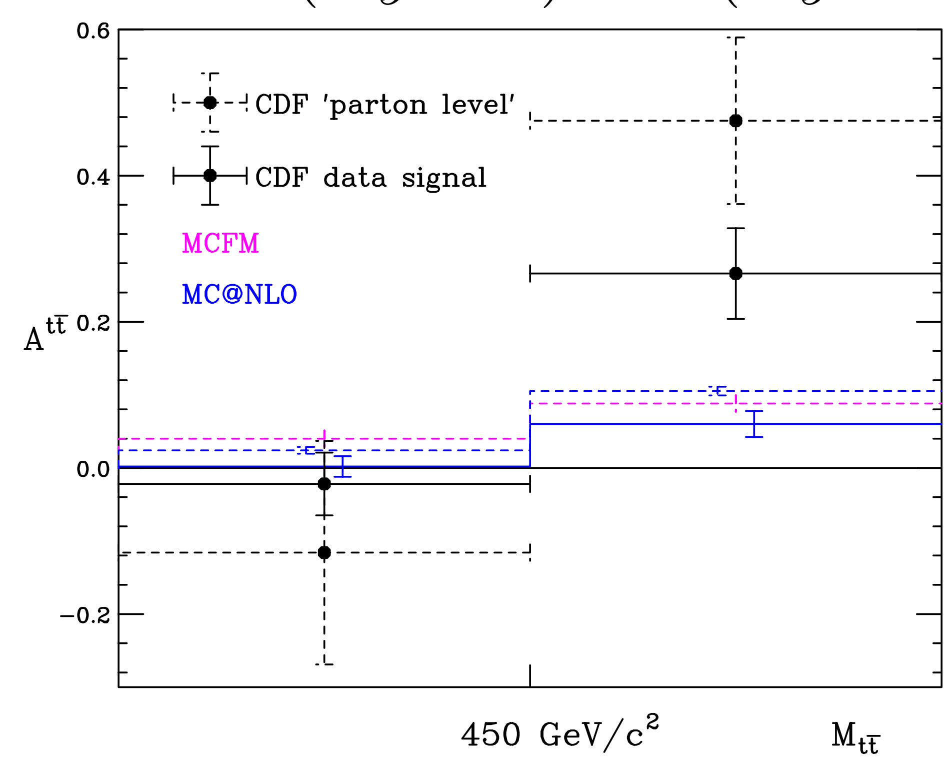

Forward-backward asymmetry in top quark production (2)

- CDF reports a large effect, increasing with $t\bar{t}$ invariant mass
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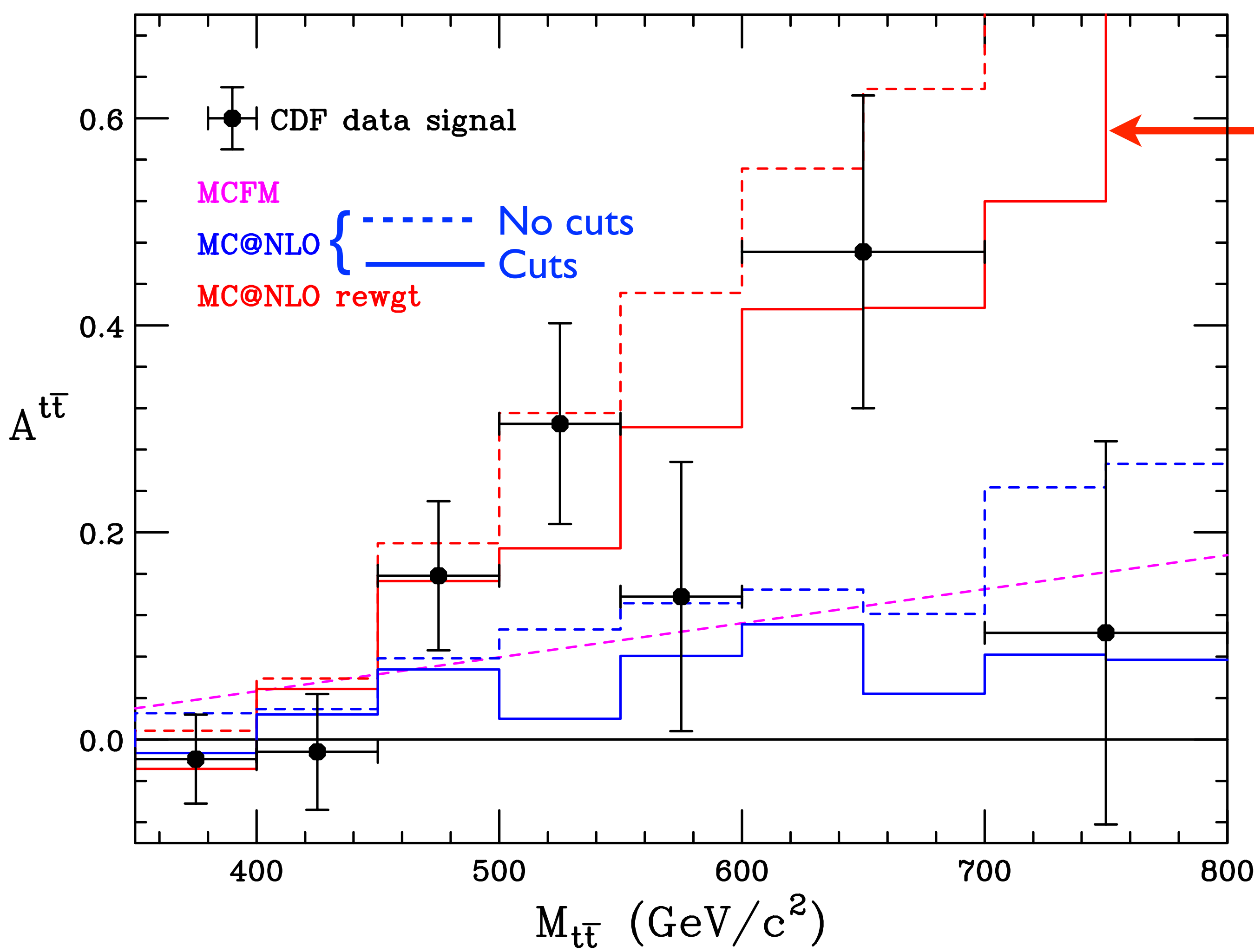
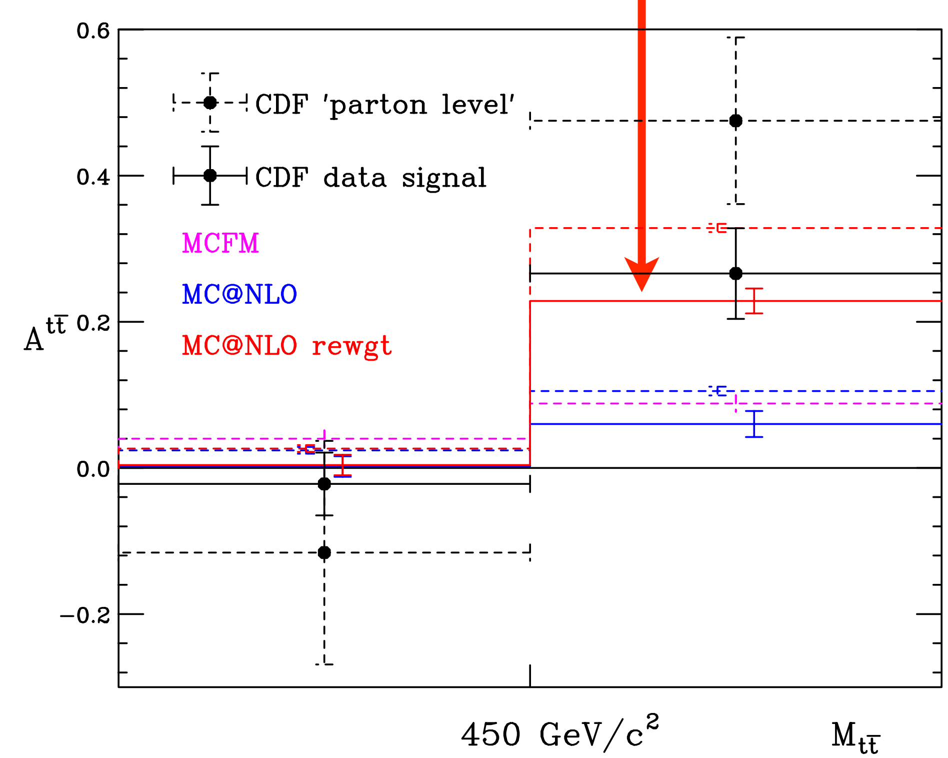
- Model it by reweighting $q\bar{q}$ contribution by: $1 + f(M_{t\bar{t}})\tanh(\Delta y/2)$

$$\simeq 1 + f(M_{t\bar{t}})\beta_t^* \cos\theta_t^*$$



$$f(M_{t\bar{t}}) = M_{t\bar{t}}/200 - 2$$



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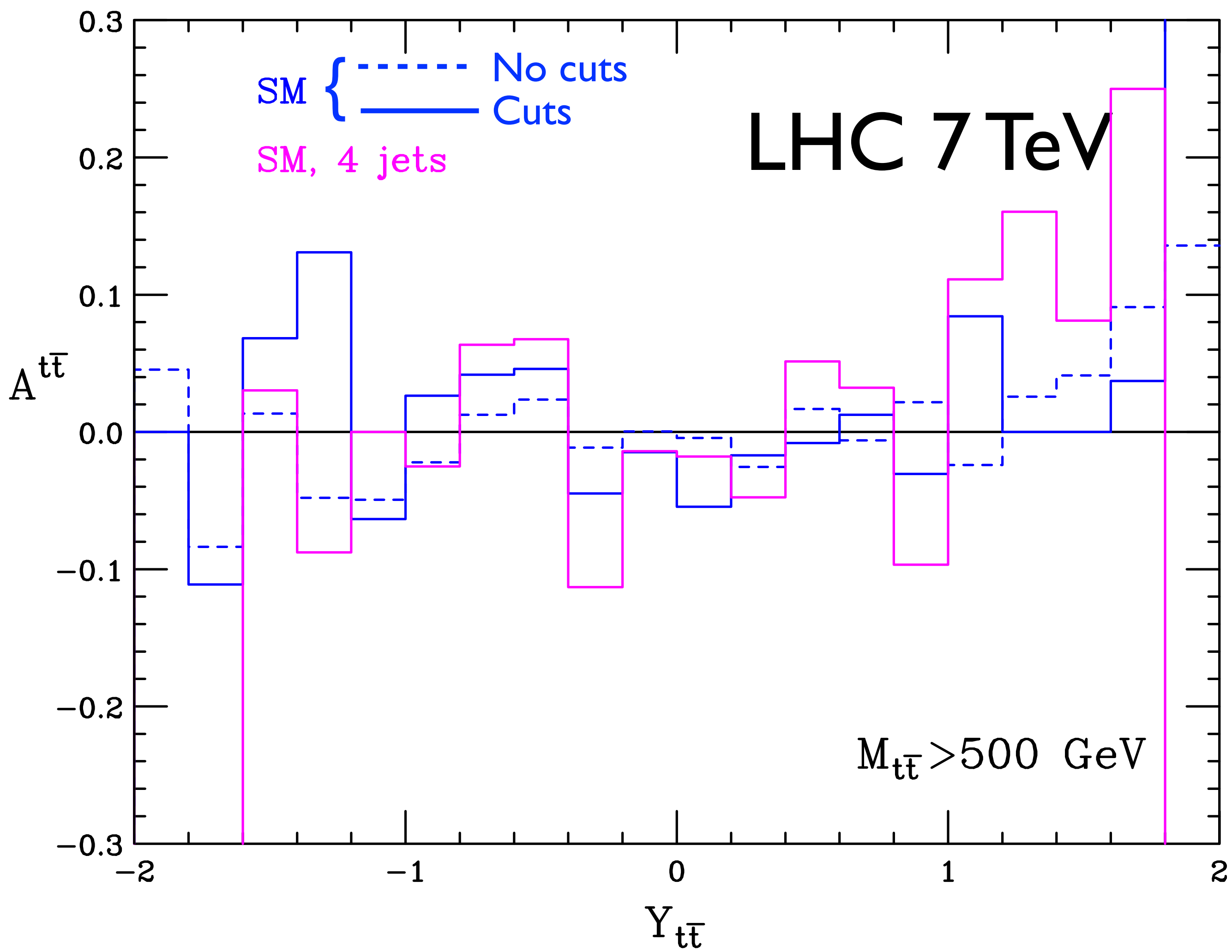
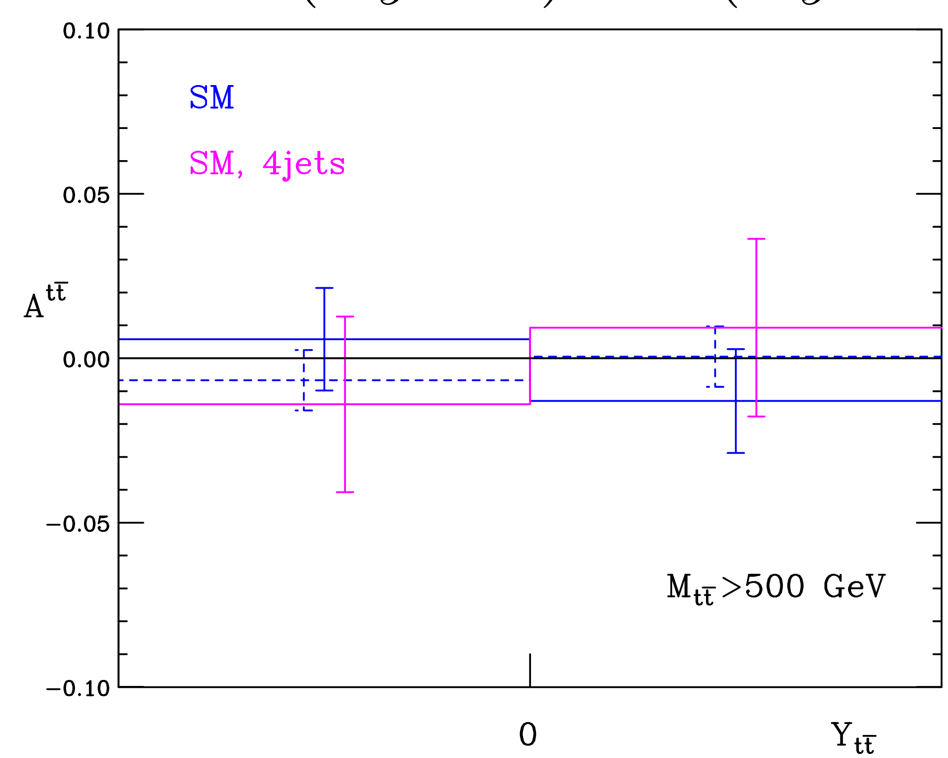
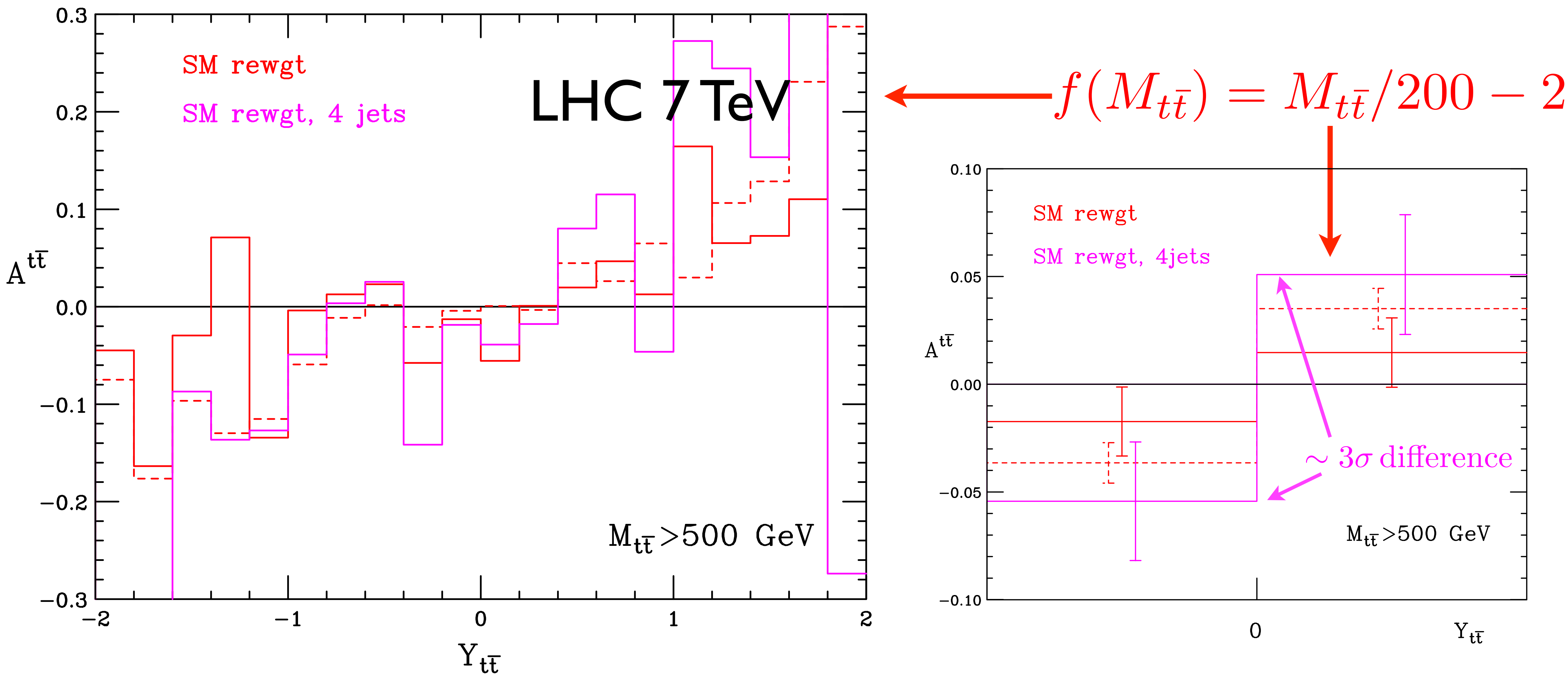




CDF top asymmetry at LHC?

- LHC is a pp collider ➡ no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- Model CDF effect by reweighting SM by: $1 + f(M_{t\bar{t}})\tanh(\Delta y/2)$
  $\simeq 1 + f(M_{t\bar{t}})\beta_t^* \cos\theta_t^*$



Conclusions

- Event generators continue to improve
- Many processes now reliable to NLO
- Multijets included to LO
- Multijets to NLO in progress
- Look for $t\bar{t}$ asymmetry at LHC!