POWHEG and MiNLO in Vector Boson+jets

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Multiscale improved NLO basics

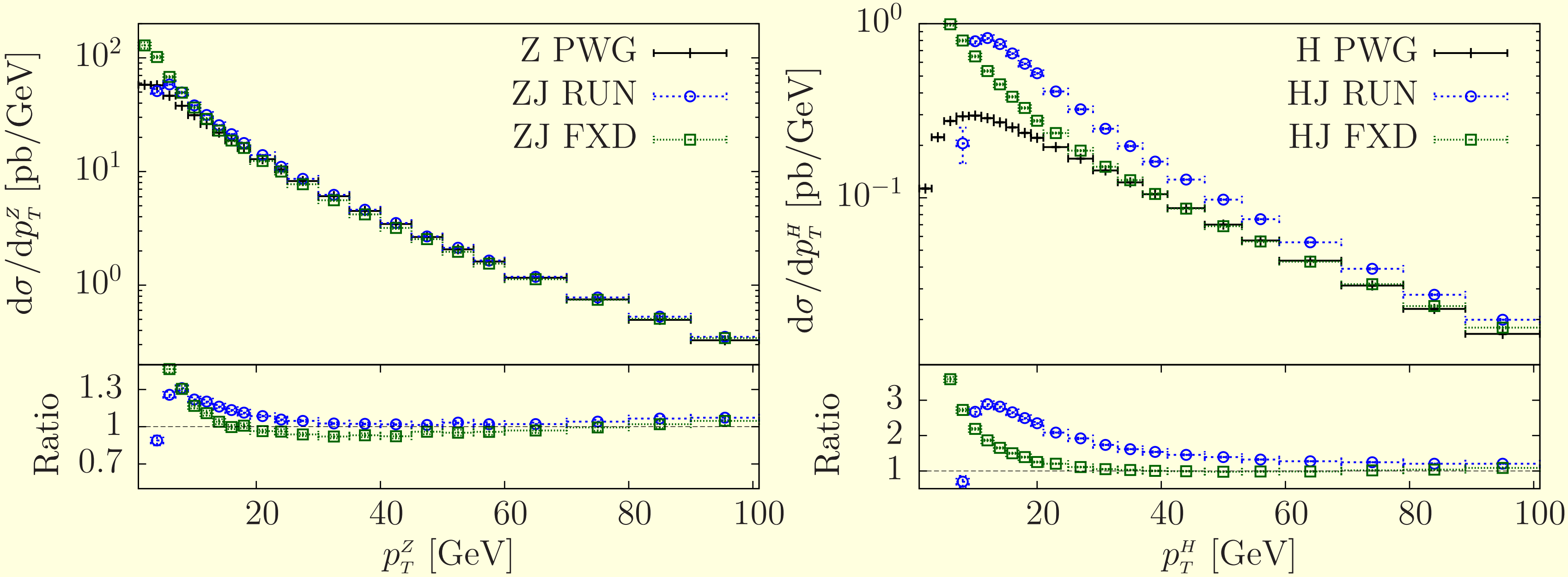
There are problems with the scale choice when implementing POWHEG for processes with associated jets. We first noticed them in V + jet production (Alioli,Oleari,Re,P.N. 2011). POWHEG generate events in two steps:

A) First a configuration for $V+1$ parton is generated, with a distribution proportional to the NLO cross section for the production of $V+1$ pseudo-parton (i.e. jet, according to an internal clustering procedure). This is the so called $\bar{B}$ function:

$$\bar{B} = B + V + \int R \mathrm{d}\Phi_{\mathrm{rad}}$$

B) Next, the kinematics of $V+2$ partons is generated, with a probability given by the POWHEG radiation formula (which is similar to the algorithm used by shower Monte Carlo programs to generate radiation). Notice that the $V+2$ parton configuration clusters back to the $V+1$ configuration generated at A (in the internal clustering scheme).

When considering cross sections involving associated jets, the scale choice becomes problematic.



Z/H `POWHEG` yields the LL resummed result for the $Z/H\ p_T$
Z/H J is the NLO calculation for the $Z/H\ p_T$
RUN is with scales set to the $Z/H\ p_T$
FXD is with scales set to the Z/H mass

At low p_T we trust better the Z/H `POWHEG` result. But the NLO result seems to break down already at relatively large transverse momenta (15-20 GeV for Z, 30-40 for the Higgs).

At relatively low p_T, large logarithms of p_T arise in the perturbative calculation, that spoil scale stability.

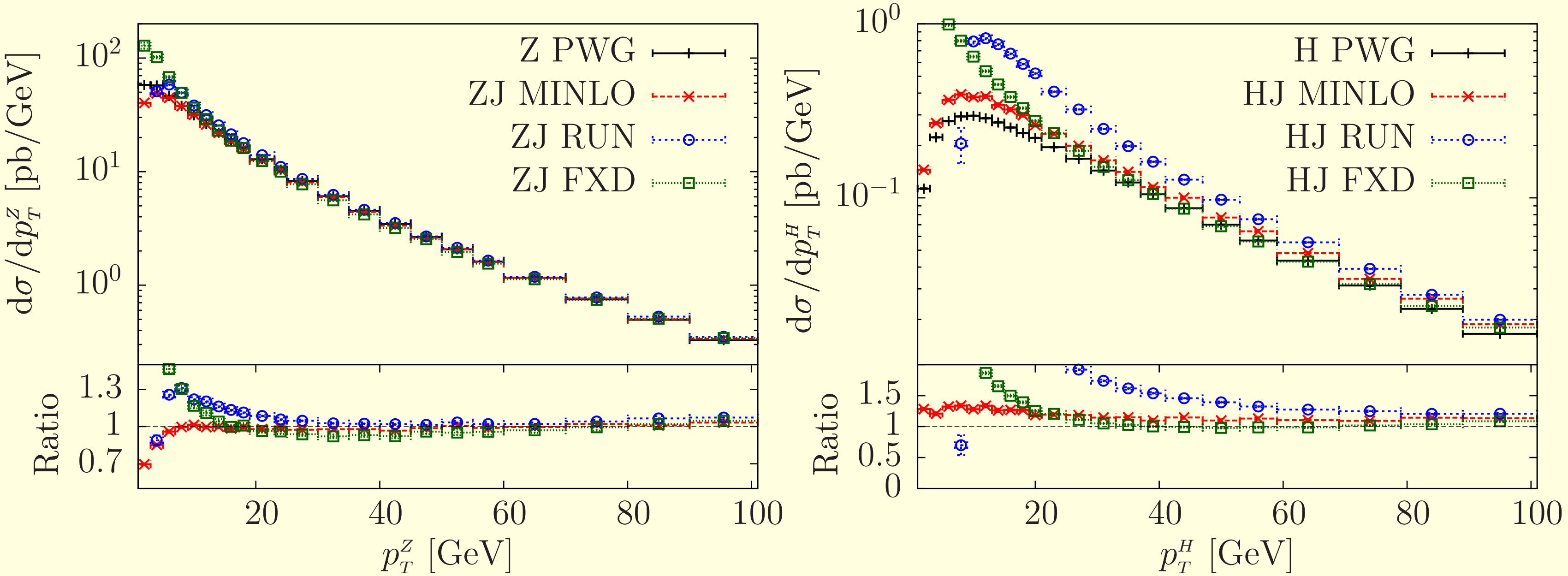
It is possible to organize the NLO result in such a way that these large logarithms are resummed. The starting point is the CKKW procedure, that, by choosing the factorization and renormalization scales in an appropriate way, and by providing Sudakov form factors, can resum the large logs.
`MiNLO` does the following:

A) NLO calculations are organized so that at the Born level, the CKKW procedure is used for assigning scales and Sudakov form factors

B) Virtual, collinear remnants and real terms are defined in such a way that

    i. overall NLO accuracy is preserved

    ii. The nice features of the CKKW procedure are preserved: Sudakov damping in singular regions (i.e. low Z/H p_T in the B + jet example), (N)LL accuracy preserved, etc.



By using the MiNLO prescription, the inclusive cross section remains well defined.

Accuracy of MiNLO for inclusive cross section

2nd MiNLO paper (Hamilton,Oleari,Zanderighi,P.N. 2012)

- In $B + \mathrm{jet}$: MiNLO accuracy is $< \alpha_s^{1.5}$ (relative to Born term) corrections
- With suitable modification, one can reach up to $< \alpha_s^2$ (i.e. NLO) accuracy
- In $B + 2\,\mathrm{jets}$: accuracy up to $< \alpha_s^{1.5}$ for 1-jet inclusive and (inductively) 2-jet inclusive corrections (conjectured)

Example in Higgs production:

	Inclusive	2 jets, $p_T > 25, \|y\| < 5$	$+\,\eta_{\mathrm{jj}} < 2.8, m_{\mathrm{jj}} > 400\,\mathrm{GeV}$
H	13.2	1.61	0.177
HJ	16.2	2.04	0.202
HJ-N	13.3	2.10	0.209
HJJ	17.8	2.41	0.239

where HJ-N is the “improved” MiNLO as in the 2nd MiNLO paper

To merge or not to merge

So: we have generators for B, BJ, BJJ (B=W,Z,H).
What do we use? Shall we merge them?
Not difficult to do; but there are several reasons not to do it:

- Difficulties in establishing rigorously a valid merging scale
- Trying to increase the accuracy of the MiNLO approach seems more promising (already done for $B + \mathrm{jet}$).
- It ain't interesting

So: if you are interested up to 1 jet, use the BJ 2nd MiNLO (it recovers NLO accuracy when used inclusively). If you are interested in two jets, use BJJ, and check it against the BJ one for inclusive quantities.

Besides: the generators are public code. Anybody interested can use them to build a merged sample, if he wants.

Difficulties in establishing rigorously a valid merging scale

Consider the B generator. We have

$$\int \mathrm{d}p_T \frac{\mathrm{d}\sigma(B)}{\mathrm{d}p_T} = \mathrm{NLO} \times (1 + \mathcal{O}(\alpha_s))$$

If we introduce a matching cut Q below which we use the B generato, and above which we use the BJ one, then

$$\int^{Q} \mathrm{d}p_T \frac{\mathrm{d}\sigma(B)}{\mathrm{d}p_T} = \mathrm{NLO} \times (1 + \mathcal{O}(\alpha_s)) - \int_{Q} \mathrm{d}p_T \frac{\mathrm{d}\sigma(B)}{\mathrm{d}p_T}$$

If Q is large ($\sim M_B$), the subtraction has $\mathrm{NLO} \times (1 + \mathcal{O}(\alpha_s))$ accuracy. But if $Q \ll M_B$ (isn't this what we want?) the accuracy is always less than that:

$$\frac{\mathrm{d}\sigma(B)}{\mathrm{d}p_T} = \alpha \frac{L}{p_T} + \alpha \frac{1}{p_T} + \alpha + \alpha^2 \frac{L^3}{p_T} + \alpha^2 \frac{L^2}{p_T} + \alpha^2 \frac{L}{p_T} + \alpha^2 \frac{1}{p_T} + \alpha^2 \qquad L = \log \frac{M_B}{p_T}$$

Unless we have control over up to the $1/p_T$ term, the accuracy of the result is $\mathrm{NLO} \times (1 + \mathcal{O}(L_Q^M \alpha_s))$, $L_Q = \log M_B/Q$, less than true NLO.

The Z2jet and W2jet generators

Several ZJJ generators: first by E.Re 2011 (originally interfaced to Black Hat). Since the Black Hat code is not public, in the 1st MiNLO paper we built new (Z/W)JJ generators using the MadGraphStuff MadGraph-POWHEG-BOX interface (Frederix, 2011), and the MCFM virtual amplitudes.

Later (Ellis,Campbell,Zanderighi,P.N.2013) we built the Z2jet and W2jet generators. These use MCFM also for the real graphs, and are much faster. The programs were extensively validated using ATLAS data (arXiv:1111.2690,arXiv:1201.1276)

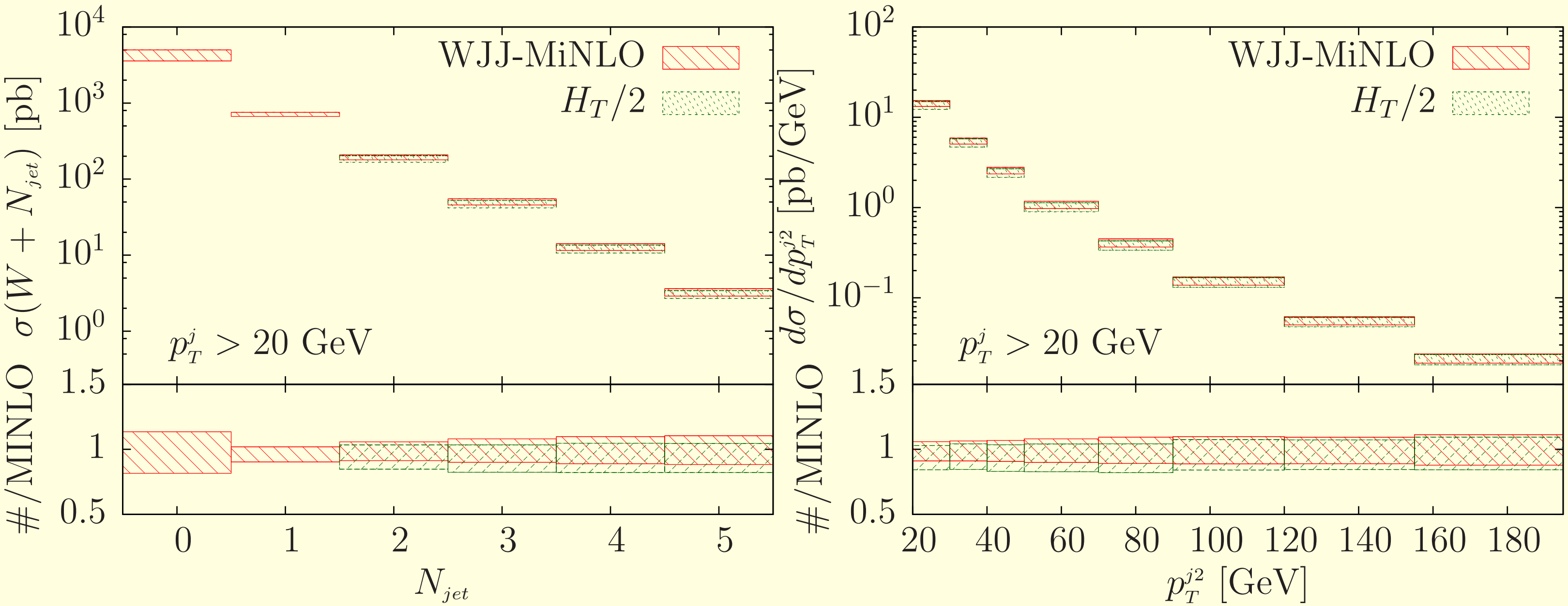
- Validation with MiNLO and $H_t/2$ scale choice.
- Solved problems arising with (rare) events near the singular region at the underlying Born level, being promoted to non-singular events after radiation (improvement in the POWHEG BOX separation of singular regions)
- Events that are near the singular region at the POWHEG level, even after radiation, may become hard after MPI: unless the generator maintains some validity near the singular regions, these effects cannot be properly modelled. In our case, MiNLO works, $H_t/2$ does not.

MiNLO versus $H_T/2$

We find good agreement between the two choices for all distributions considered by ATLAS (except of course for observables that are inclusive in the second jet, and cannot be computed with traditional scale choices).

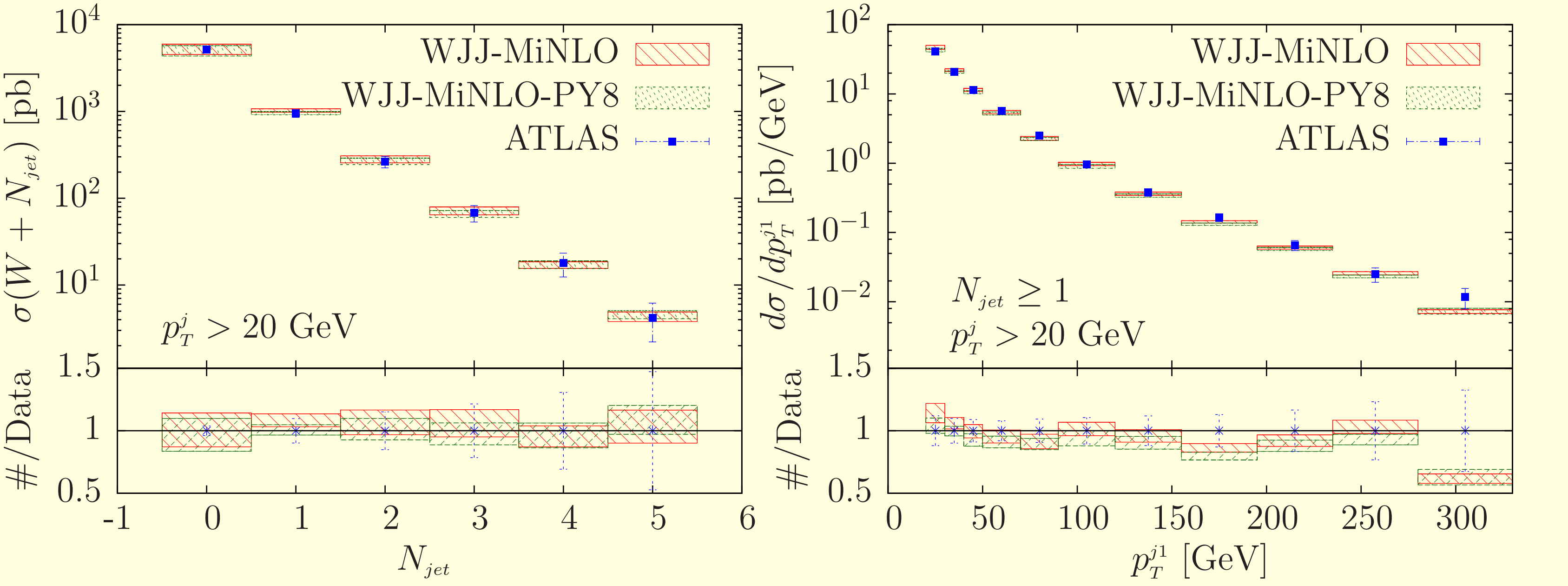
Notice: while some data bias in the $H_T/2$ choice cannot be excluded, this is not the case for MiNLO.

Two examples:

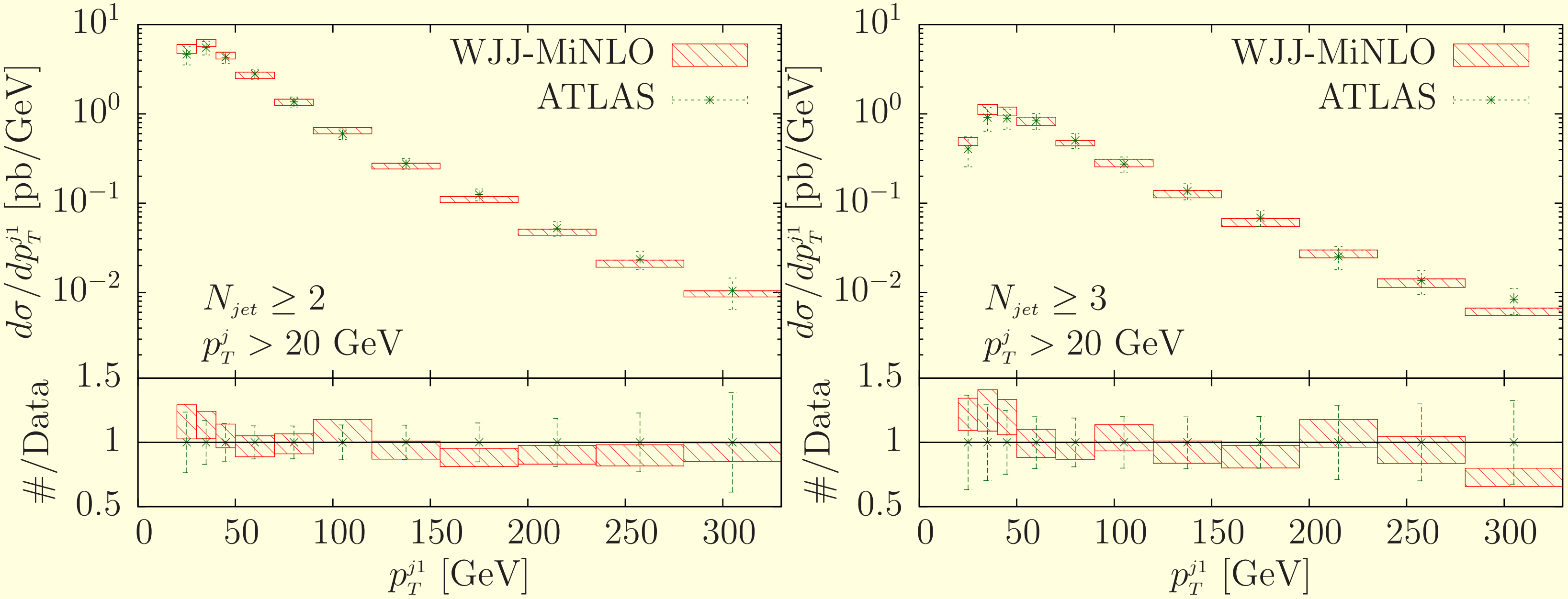


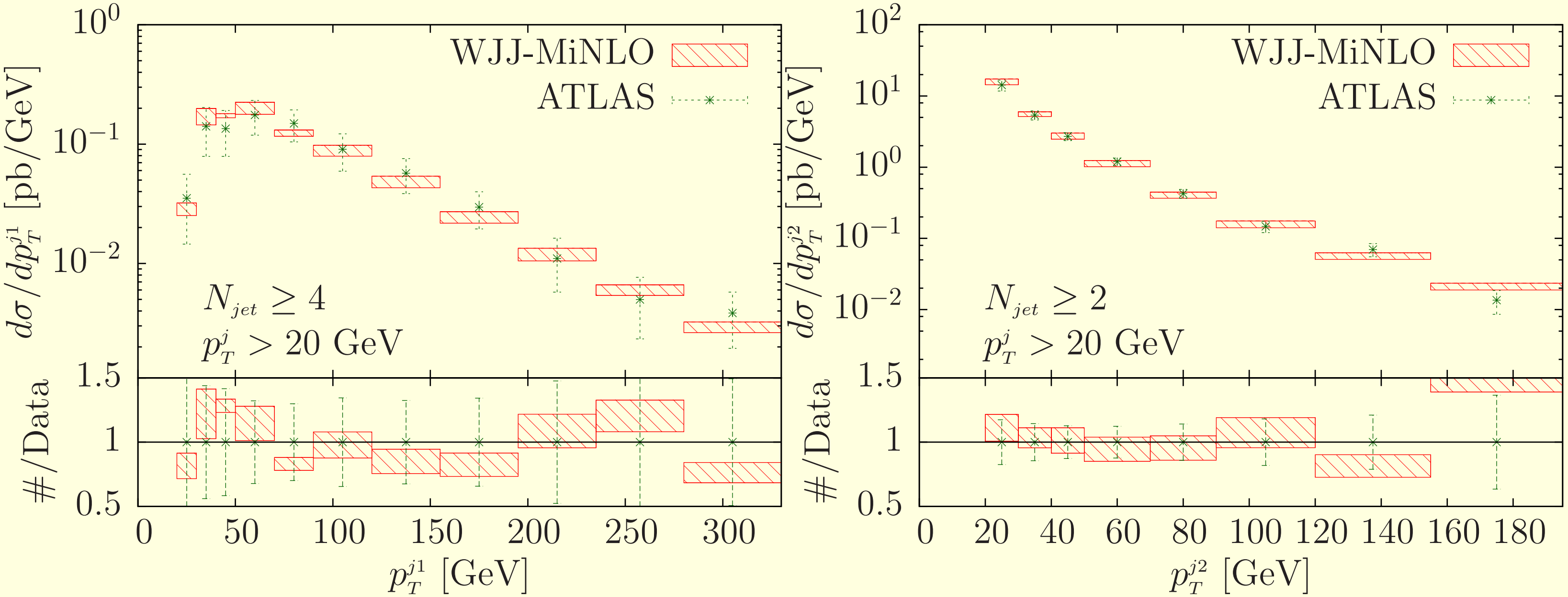
PYTHIA 6 versus PYTHIA 8

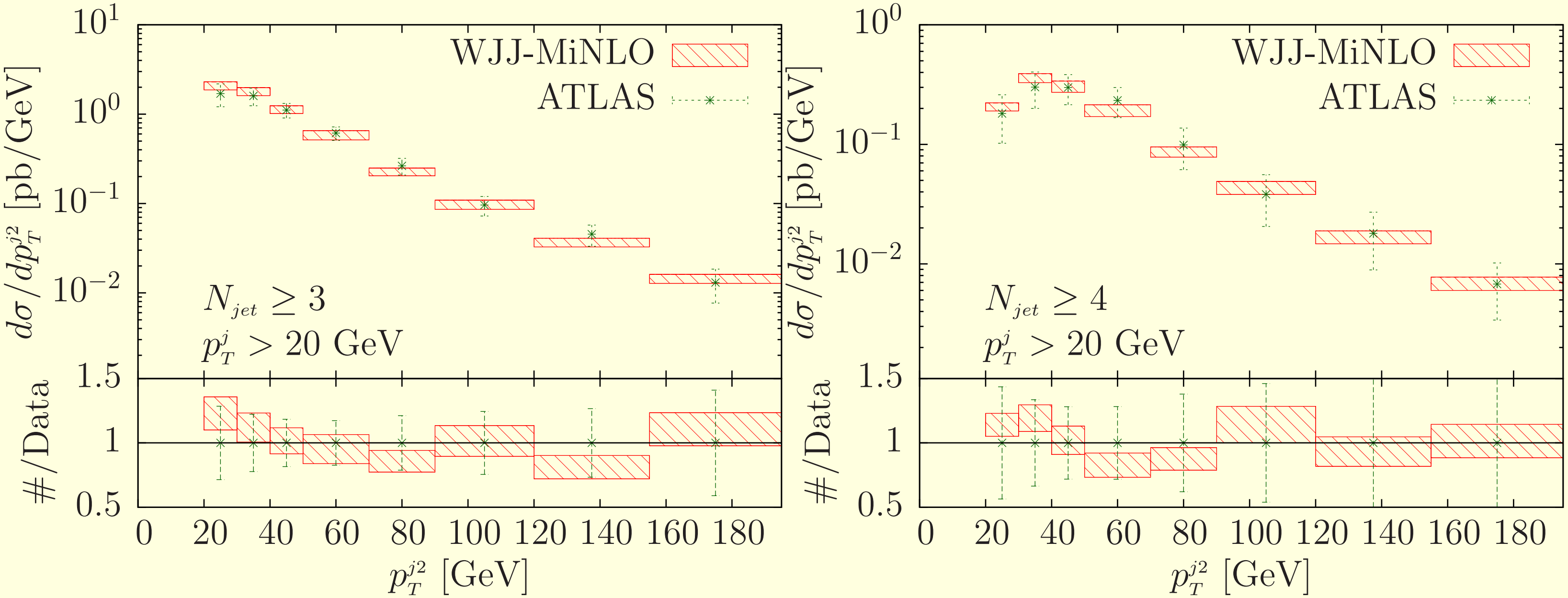
We have considered PYTHIA 8 showering for all observables. There are some differences, but the quality of the agreement with data is similar.

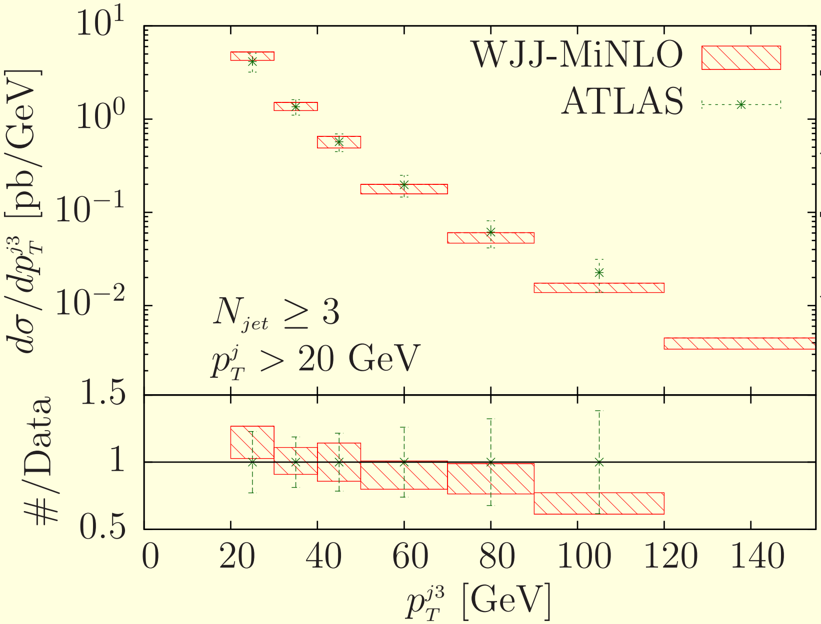


More distributions

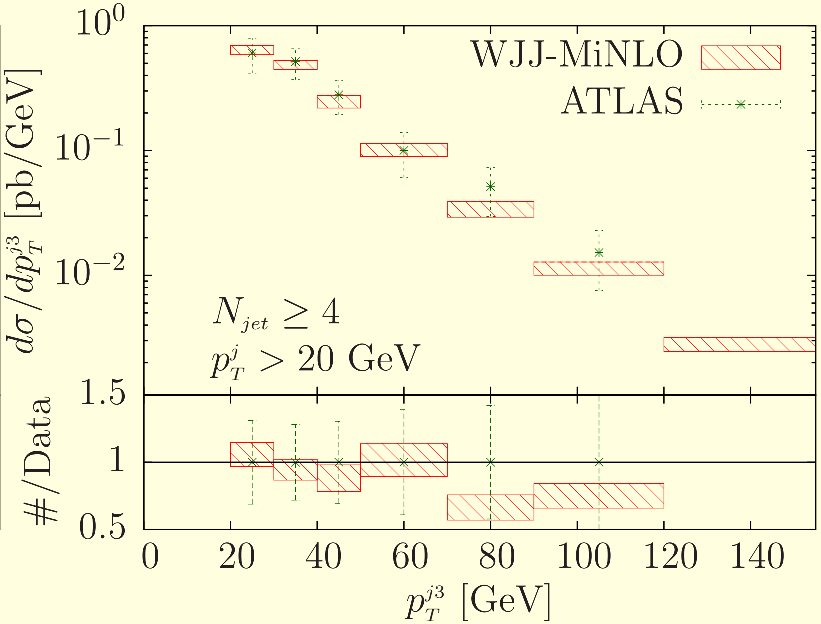



WJJ-MiNLO
ATLAS
$N_{jet} \geq 4$
$p_T^j > 20$ GeV
$d\sigma/dp_T^{j1}$ [pb/GeV]
#/Data
p_T^{j1} [GeV]
$N_{jet} \geq 2$
$p_T^j > 20$ GeV
$d\sigma/dp_T^{j2}$ [pb/GeV]
p_T^{j2} [GeV]

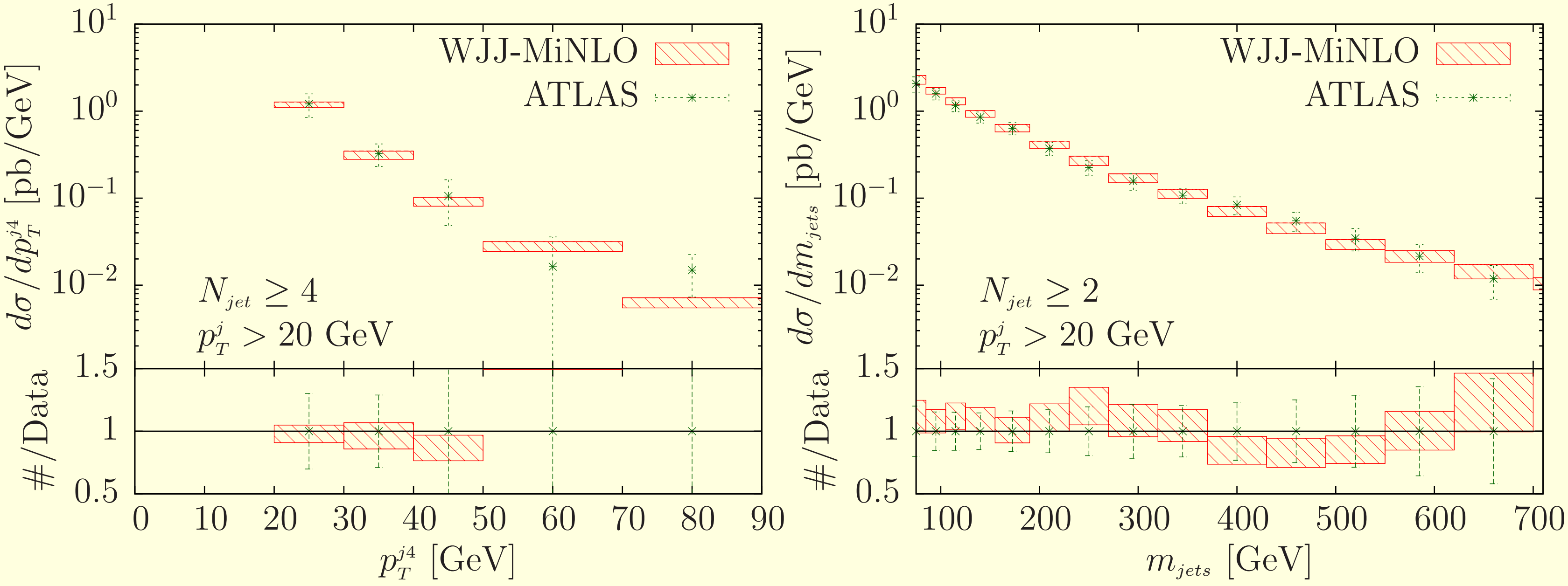

WJJ-MiNLO
ATLAS
$d\sigma/dp_T^{j2}$ [pb/GeV]
$N_{jet} \geq 3$
$p_T^j > 20$ GeV
$N_{jet} \geq 4$
$p_T^j > 20$ GeV
#/Data
p_T^{j2} [GeV]



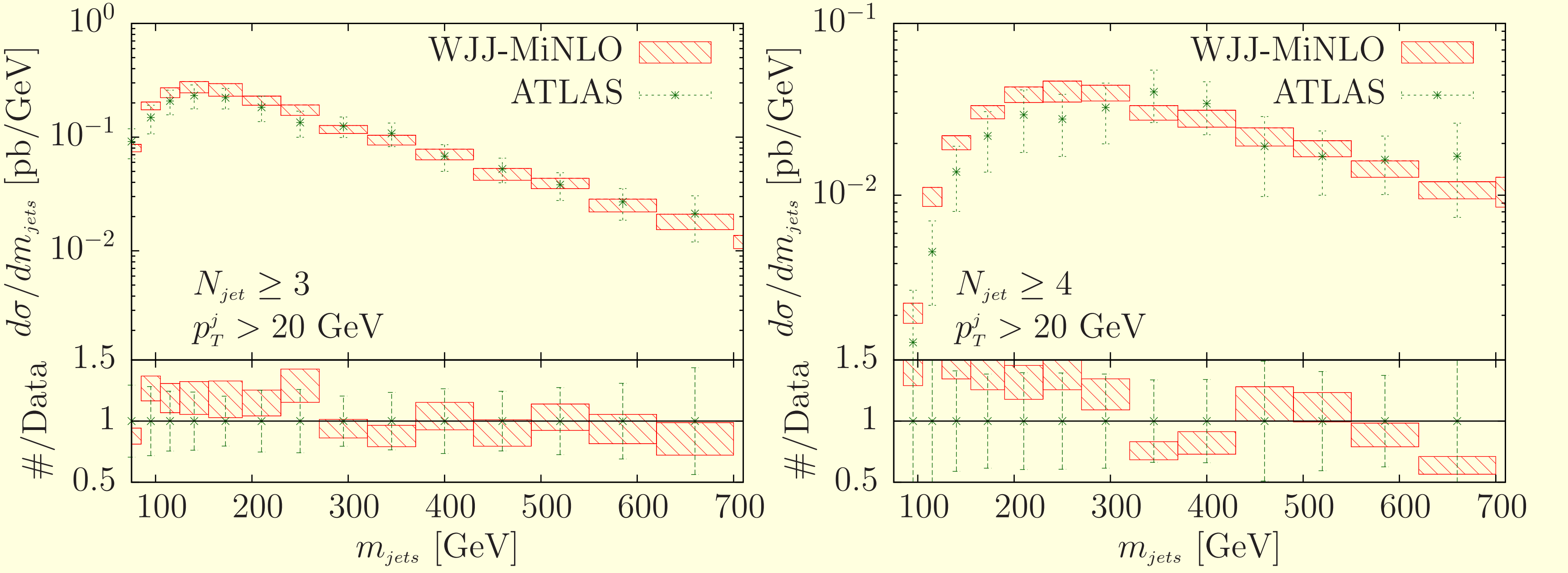
WJJ-MiNLO
ATLAS
$N_{jet} \geq 3$
$p_T^j > 20$ GeV
$d\sigma/dp_T^{j3}$ [pb/GeV]
#/Data
p_T^{j3} [GeV]

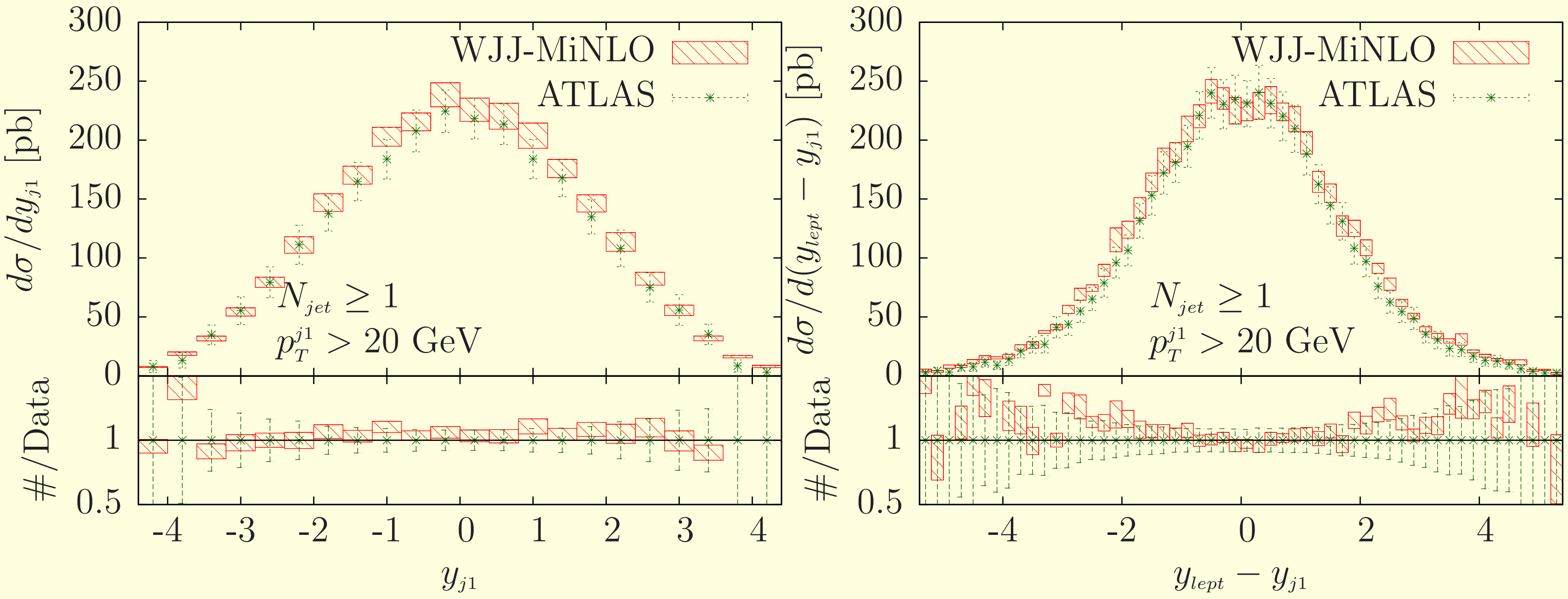


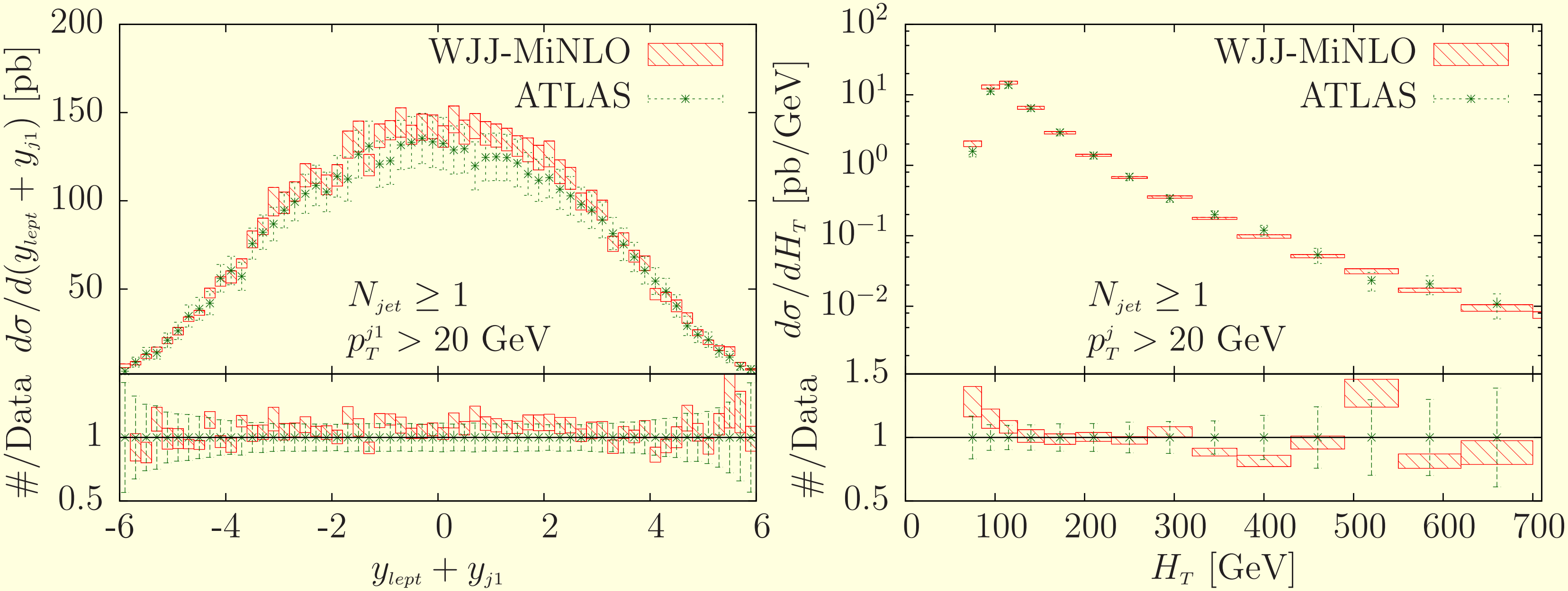
WJJ-MiNLO
ATLAS
$N_{jet} \geq 4$
$p_T^j > 20$ GeV
$d\sigma/dp_T^{j3}$ [pb/GeV]
#/Data
p_T^{j3} [GeV]

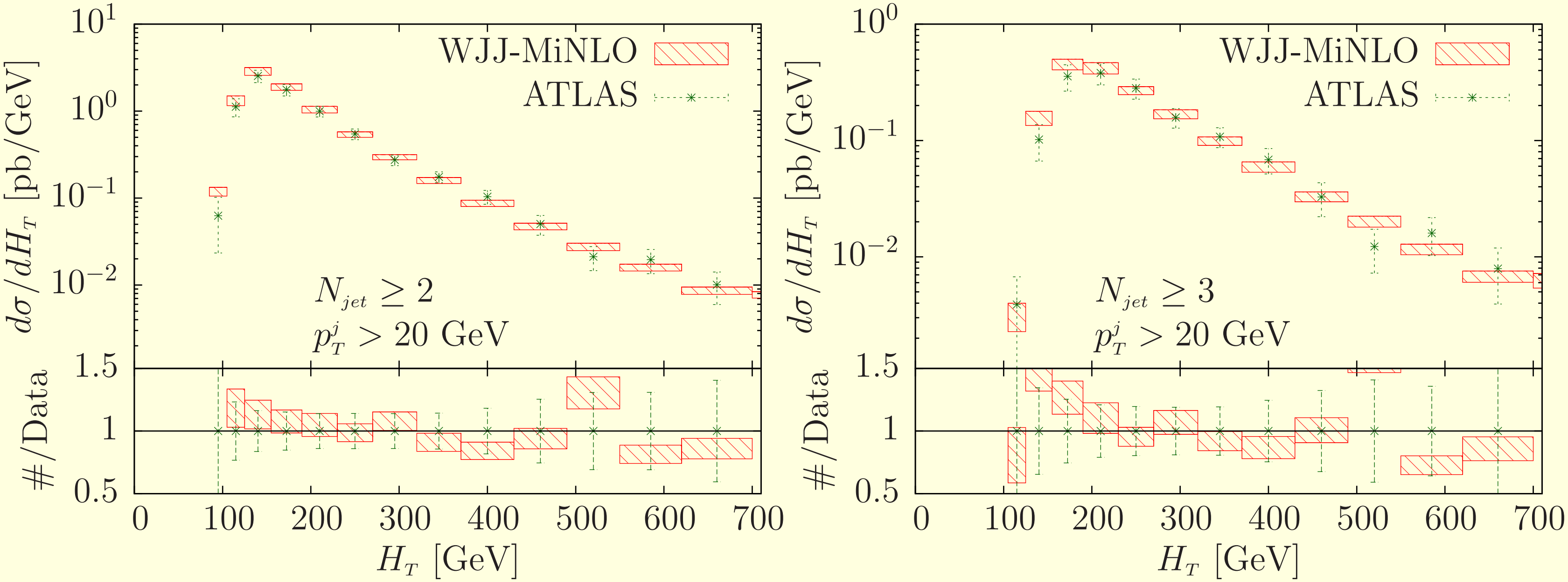


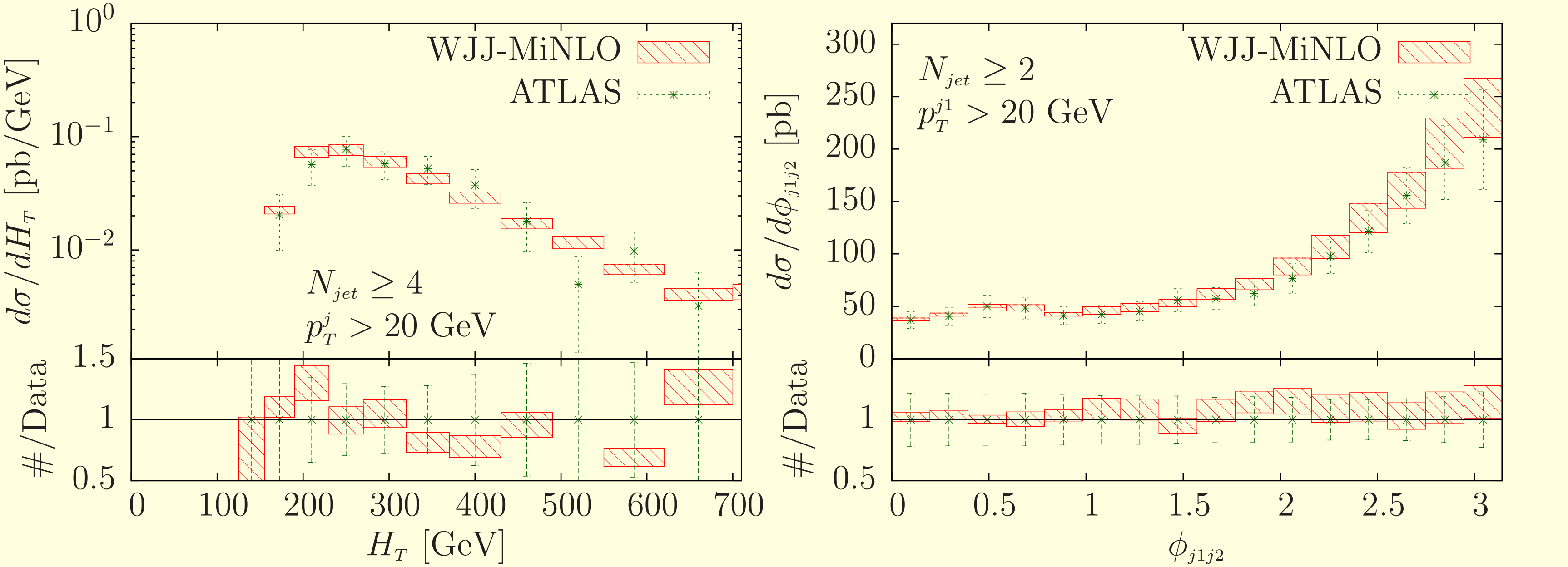
WJJ-MiNLO
ATLAS
$N_{jet} \geq 4$
$p_T^j > 20$ GeV
$d\sigma/dp_T^{j4}$ [pb/GeV]
#/Data
p_T^{j4} [GeV]
$N_{jet} \geq 2$
$p_T^j > 20$ GeV
$d\sigma/dm_{jets}$ [pb/GeV]
m_{jets} [GeV]


WJJ-MiNLO
ATLAS
$N_{jet} \geq 3$
$p_T^j > 20$ GeV
$N_{jet} \geq 4$
$p_T^j > 20$ GeV
$d\sigma/dm_{jets}$ [pb/GeV]
#/Data
m_{jets} [GeV]

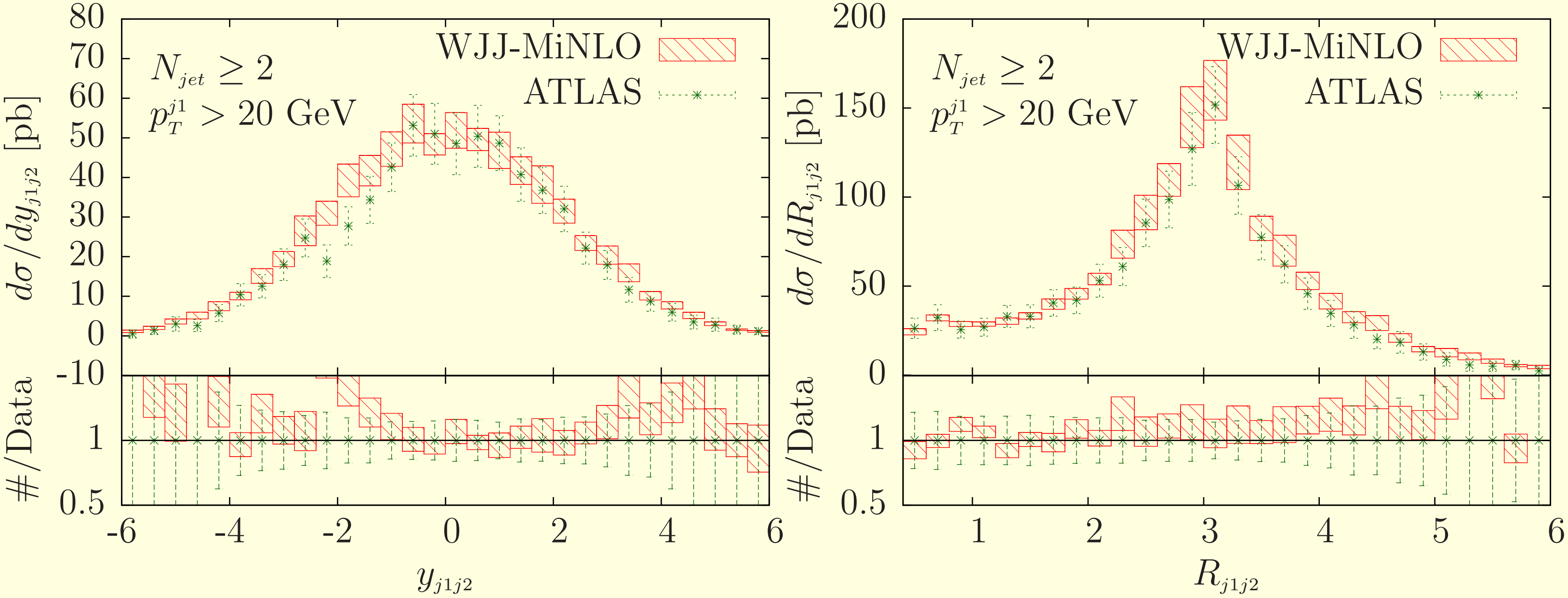

WJJ-MiNLO
ATLAS
$N_{jet} \geq 1$
$p_T^{j1} > 20$ GeV
$d\sigma/dy_{j1}$ [pb]
#/Data
y_{j1}
$d\sigma/d(y_{lept} - y_{j1})$ [pb]
$y_{lept} - y_{j1}$


WJJ-MiNLO
ATLAS
$N_{jet} \geq 1$
$p_T^{j1} > 20$ GeV
$d\sigma/d(y_{lept} + y_{j1})$ [pb]
#/Data
$y_{lept} + y_{j1}$
WJJ-MiNLO
ATLAS
$N_{jet} \geq 1$
$p_T^{j} > 20$ GeV
$d\sigma/dH_T$ [pb/GeV]
#/Data
H_T [GeV]


WJJ-MiNLO
ATLAS
$N_{jet} \geq 2$
$p_T^j > 20$ GeV
$N_{jet} \geq 3$
$p_T^j > 20$ GeV
$d\sigma/dH_T$ [pb/GeV]
#/Data
H_T [GeV]

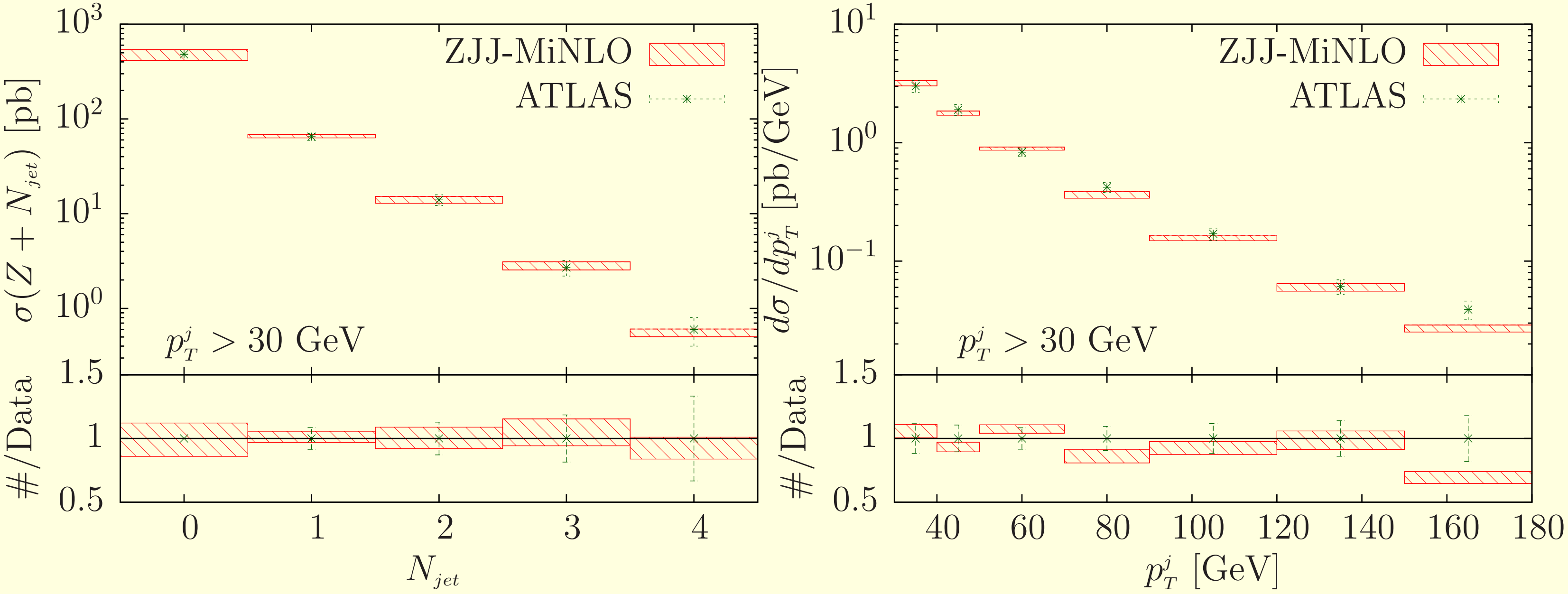


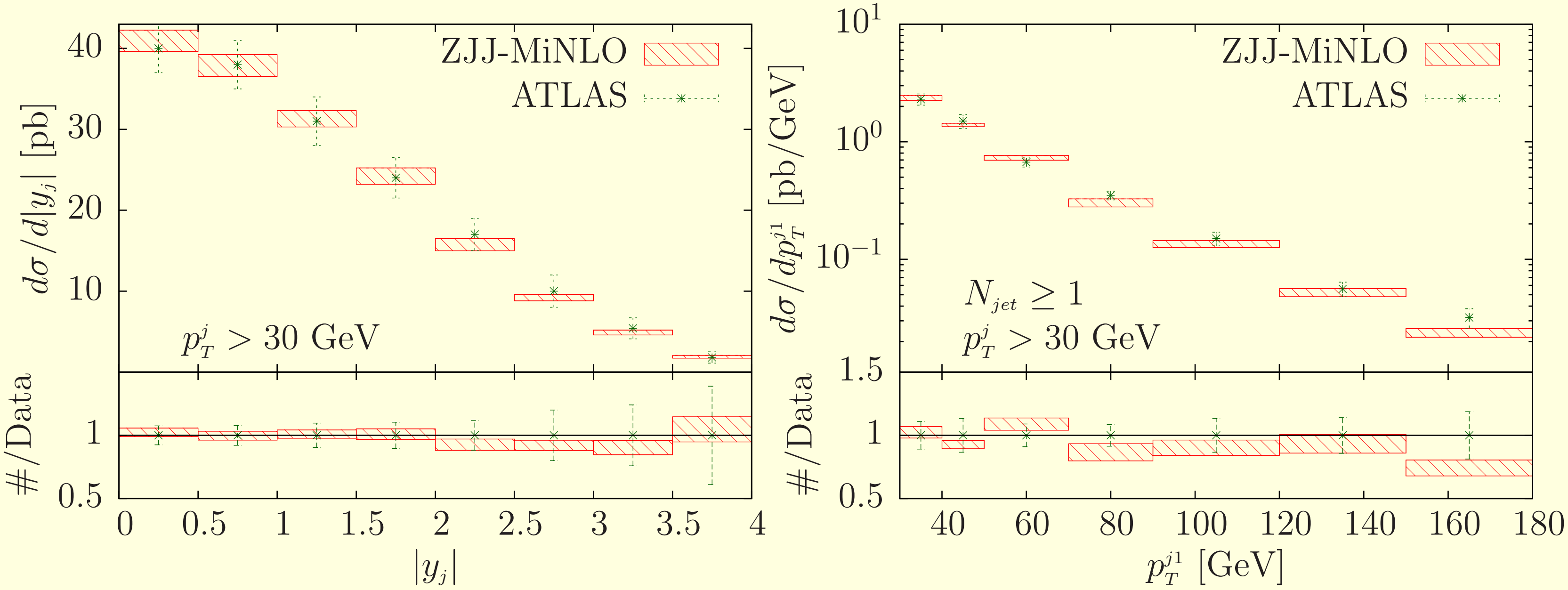
WJJ-MiNLO
ATLAS
$N_{jet} \geq 4$
$p_T^j > 20$ GeV
$d\sigma/dH_T$ [pb/GeV]
#/Data
H_T [GeV]
$N_{jet} \geq 2$
$p_T^{j1} > 20$ GeV
$d\sigma/d\phi_{j1j2}$ [pb]
ϕ_{j1j2}

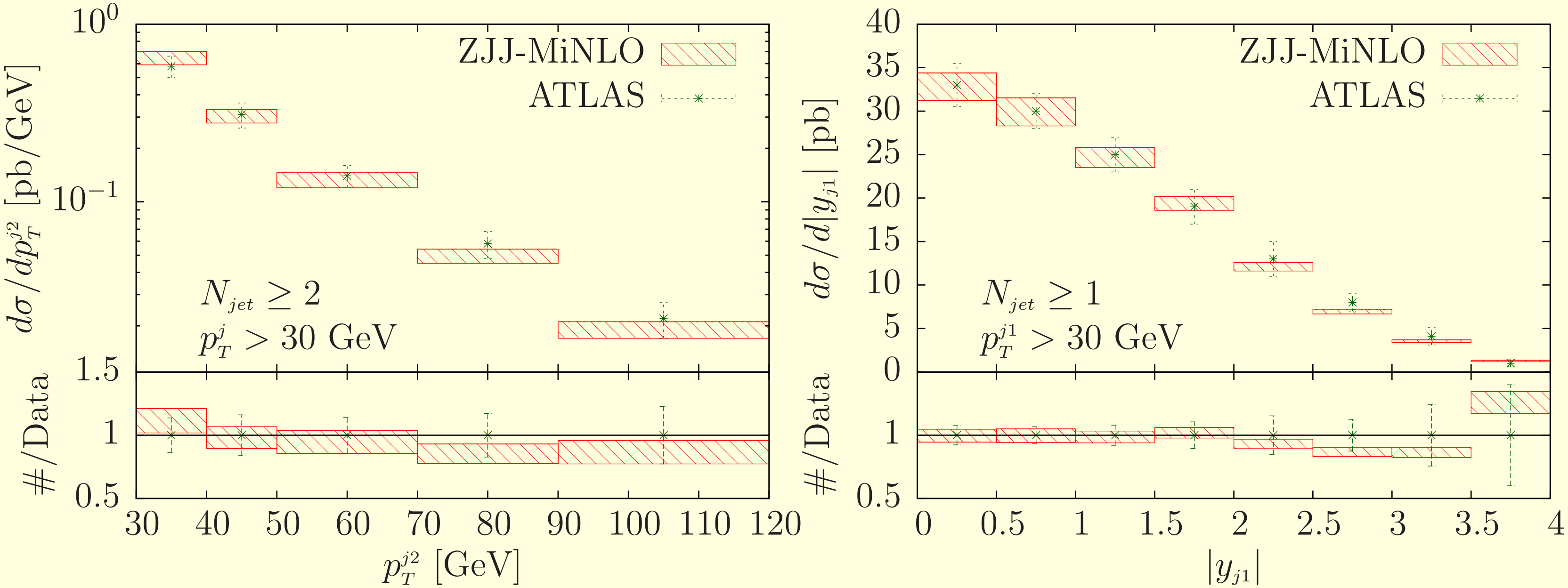


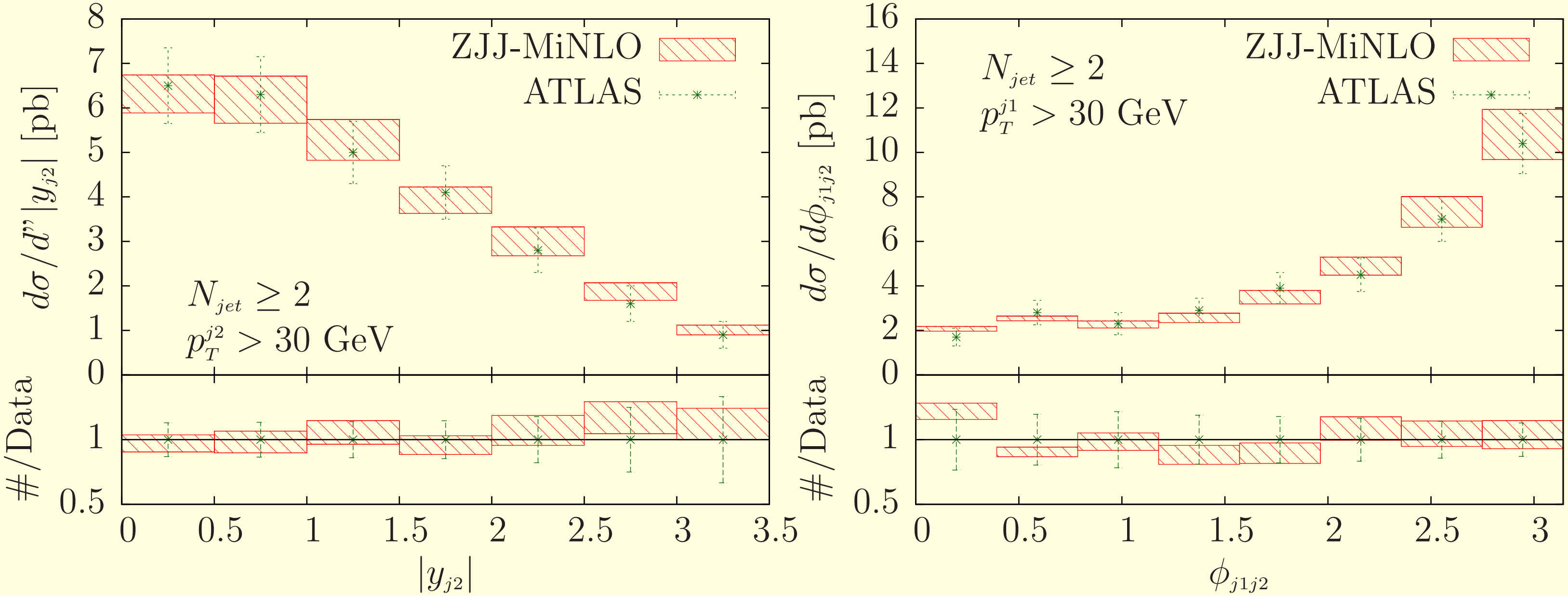
WJJ-MiNLO
ATLAS
$N_{jet} \geq 2$
$p_T^{j1} > 20$ GeV
$d\sigma/dy_{j1j2}$ [pb]
#/Data
y_{j1j2}
WJJ-MiNLO
ATLAS
$N_{jet} \geq 2$
$p_T^{j1} > 20$ GeV
$d\sigma/dR_{j1j2}$ [pb]
#/Data
R_{j1j2}

Z2jet results

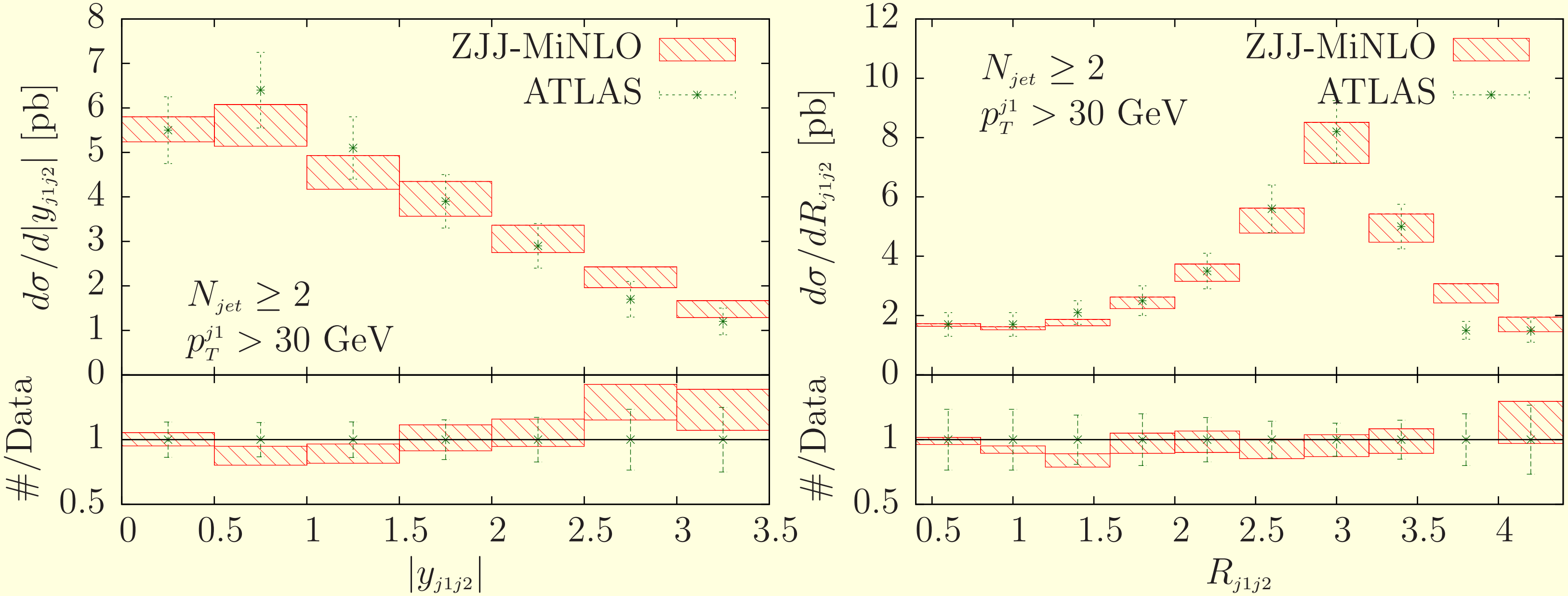



ZJJ-MiNLO
ATLAS
$d\sigma/d|y_j|$ [pb]
$p_T^j > 30$ GeV
#/Data
$|y_j|$
ZJJ-MiNLO
ATLAS
$d\sigma/dp_T^{j1}$ [pb/GeV]
$N_{jet} \geq 1$
$p_T^j > 30$ GeV
#/Data
p_T^{j1} [GeV]

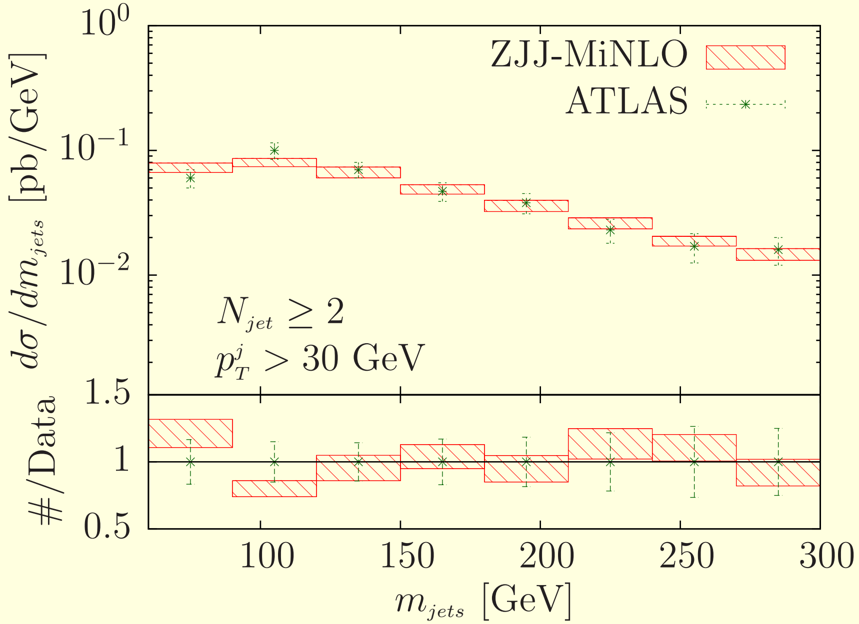

ZJJ-MiNLO
ATLAS
$N_{jet} \geq 2$
$p_T^j > 30$ GeV
$d\sigma/dp_T^{j2}$ [pb/GeV]
#/Data
p_T^{j2} [GeV]
$N_{jet} \geq 1$
$p_T^{j1} > 30$ GeV
$d\sigma/d|y_{j1}|$ [pb]
$|y_{j1}|$



ZJJ-MiNLO
ATLAS
$N_{jet} \geq 2$
$p_T^{j2} > 30$ GeV
$d\sigma/d"|y_{j2}|$ [pb]
#/Data
$|y_{j2}|$
ZJJ-MiNLO
ATLAS
$N_{jet} \geq 2$
$p_T^{j1} > 30$ GeV
$d\sigma/d\phi_{j1j2}$ [pb]
#/Data
ϕ_{j1j2}

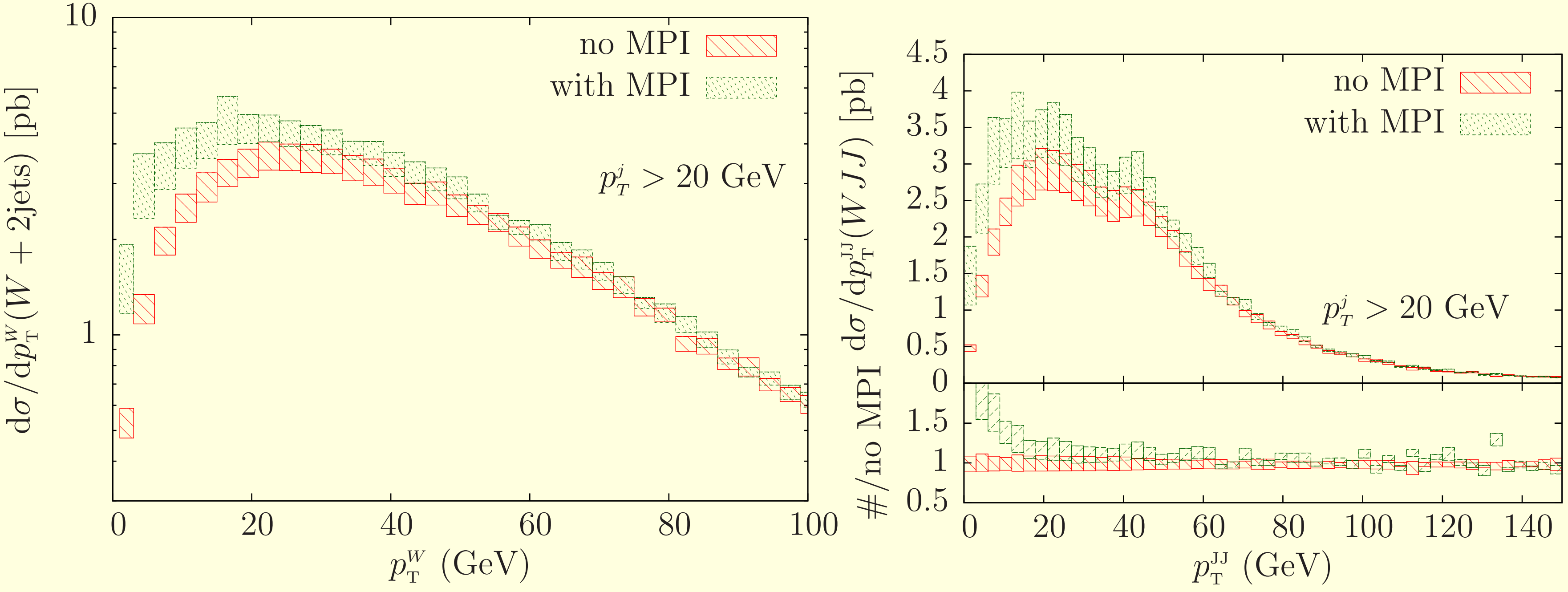


ZJJ-MiNLO
ATLAS
$N_{jet} \geq 2$
$p_T^{j1} > 30$ GeV
$d\sigma/d|y_{j1j2}|$ [pb]
#/Data
$|y_{j1j2}|$
$d\sigma/dR_{j1j2}$ [pb]
R_{j1j2}

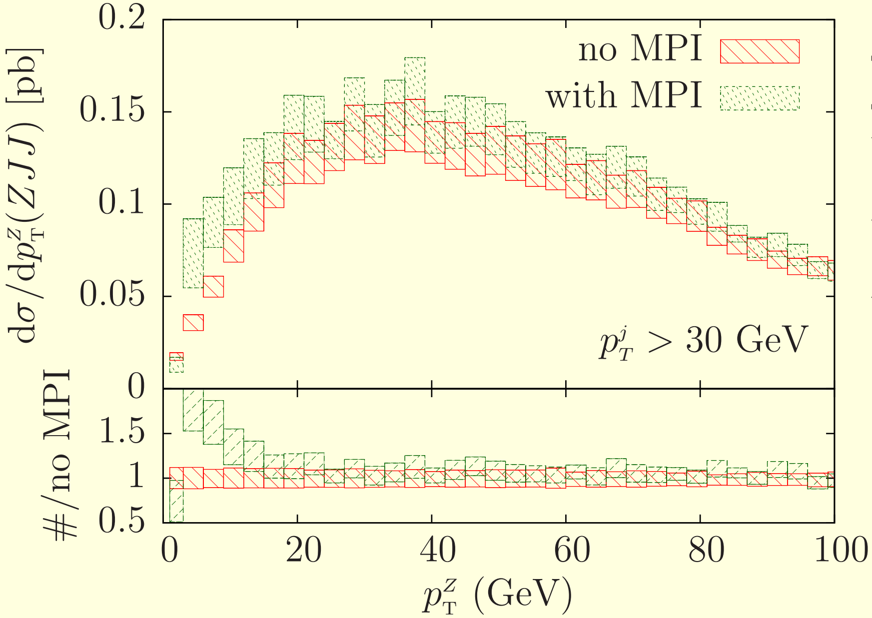


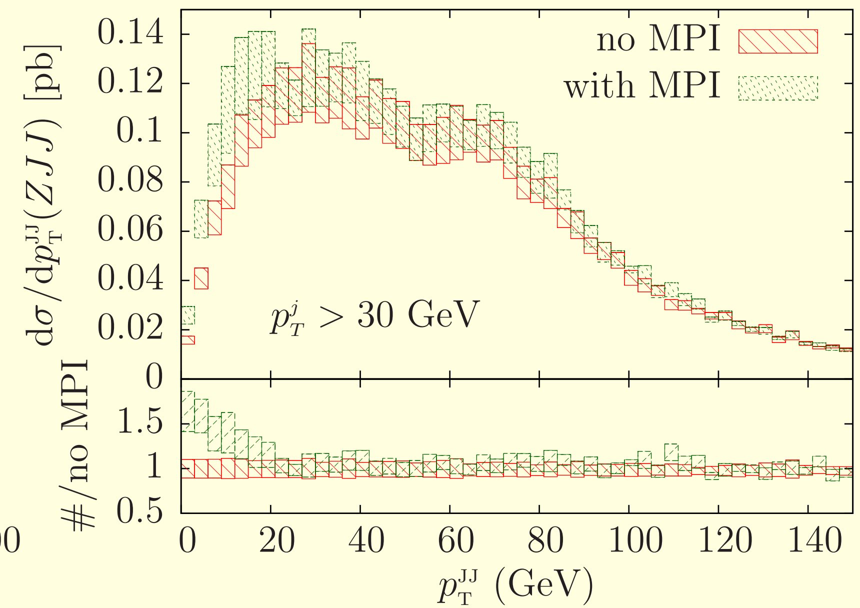
ZJJ-MiNLO
ATLAS
$d\sigma/dm_{jets}$ [pb/GeV]
10^0
10^{-1}
10^{-2}
$N_{jet} \geq 2$
$p_T^j > 30$ GeV
#/Data
1.5
1
0.5
100
150
200
250
300
m_{jets} [GeV]

MPI effect, PYTHIA 6, W2jet



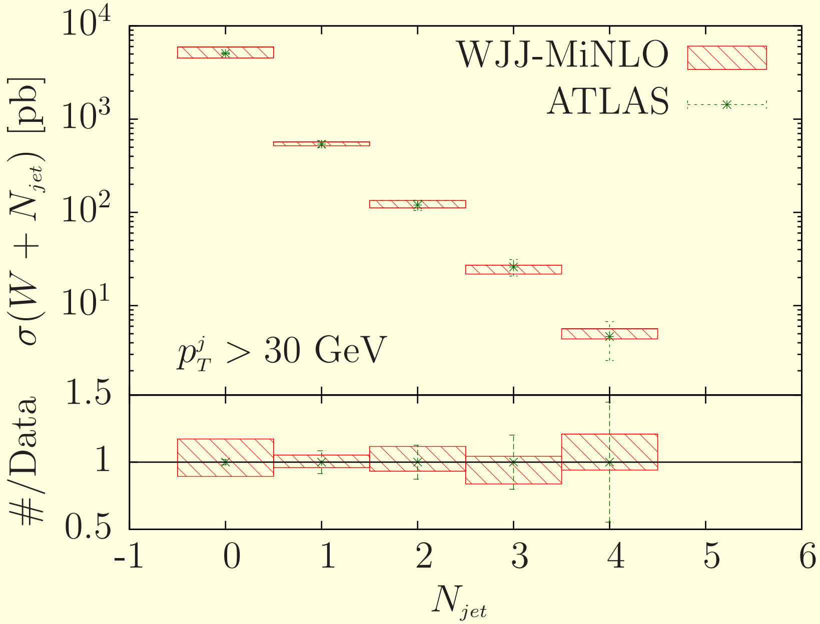
MPI effect, PYTHIA 6, Z2jet

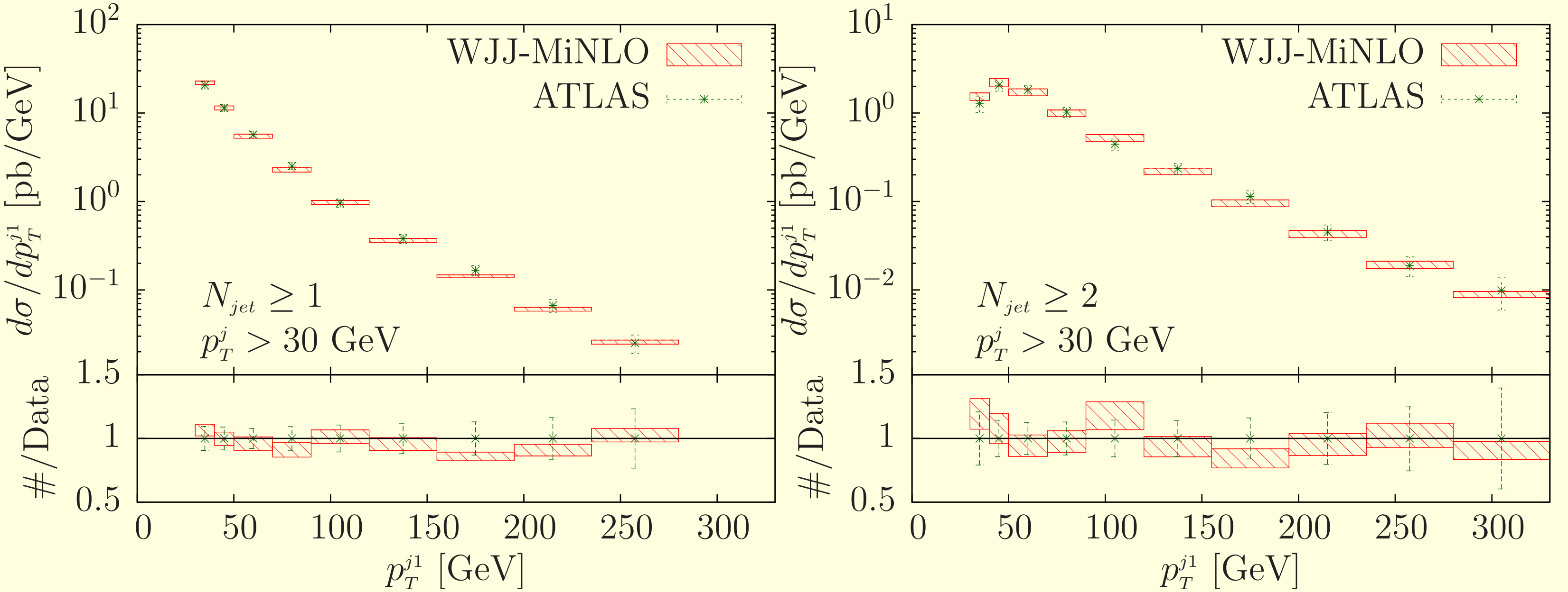


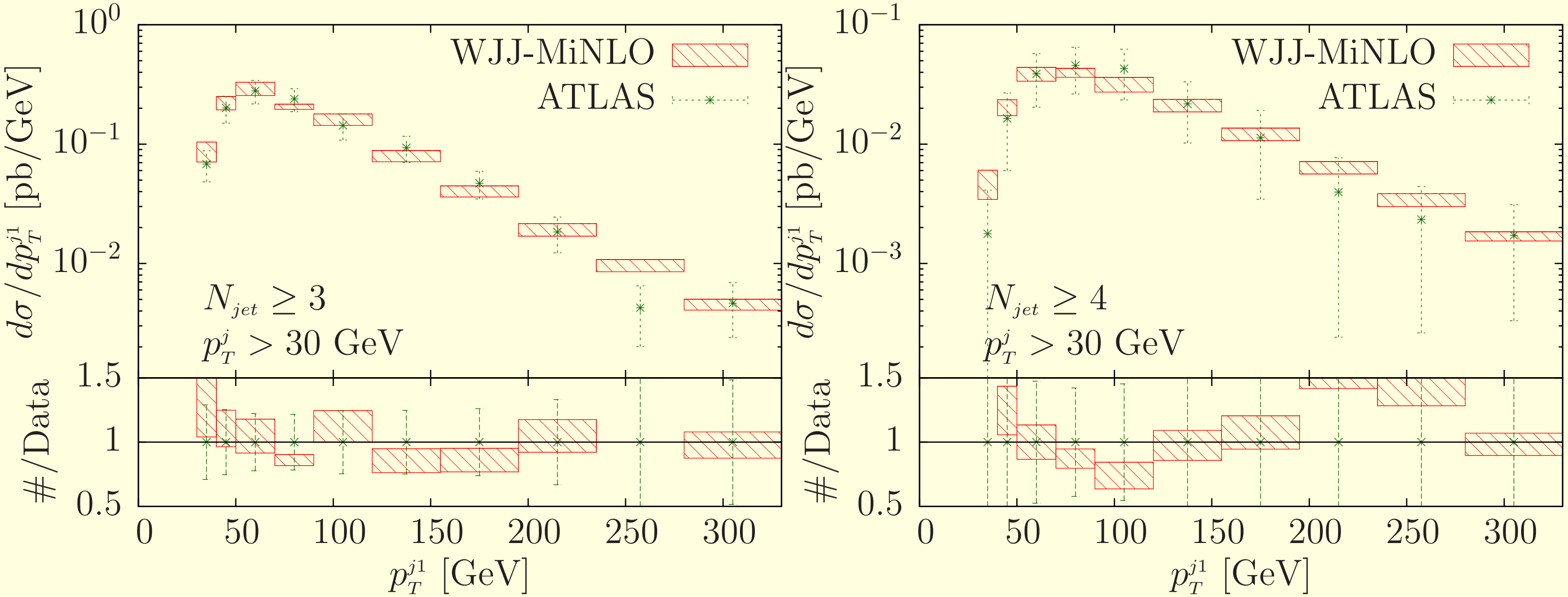


Smaller effect because $p_T^j > 30\,\mathrm{GeV}$ (going to 20 or smaller yields more sensitivity).

W2jet, $p_T^j > 30\,\mathrm{GeV}$




WJJ-MiNLO
ATLAS
$N_{jet} \geq 1$
$p_T^j > 30$ GeV
$N_{jet} \geq 2$
$p_T^j > 30$ GeV
$d\sigma/dp_T^{j1}$ [pb/GeV]
#/Data
p_T^{j1} [GeV]



WJJ-MiNLO
ATLAS
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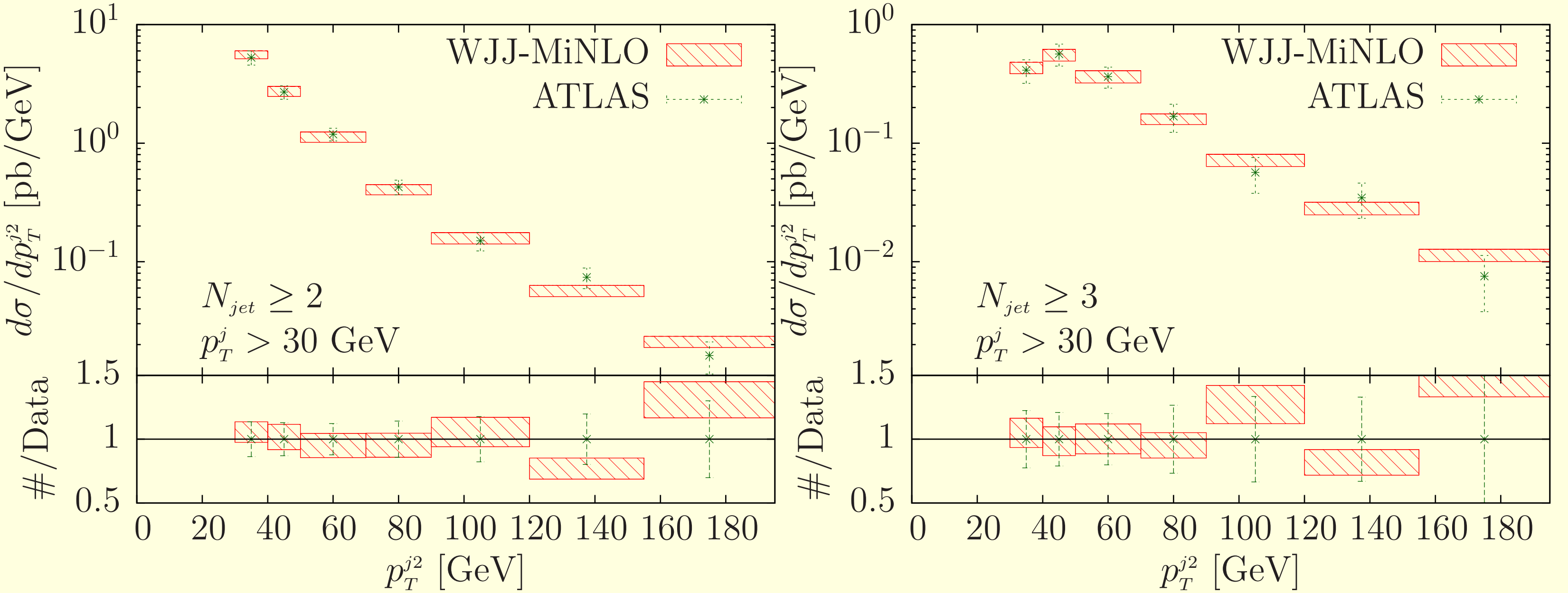
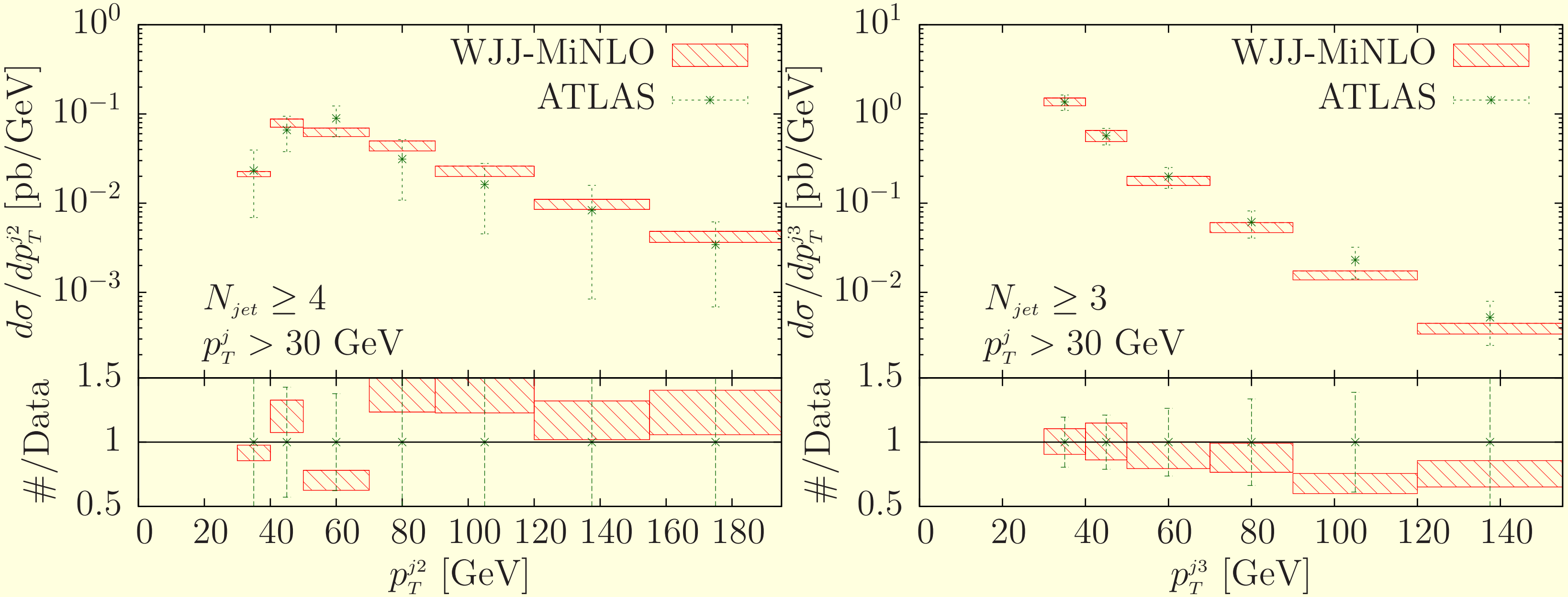
$p_T^j > 30$ GeV
$N_{jet} \geq 4$
$p_T^j > 30$ GeV
$d\sigma/dp_T^{j1}$ [pb/GeV]
#/Data
p_T^{j1} [GeV]


WJJ-MiNLO
ATLAS
$N_{jet} \geq 2$
$p_T^j > 30$ GeV
$d\sigma/dp_T^{j2}$ [pb/GeV]
#/Data
p_T^{j2} [GeV]
$N_{jet} \geq 3$
$p_T^j > 30$ GeV
$d\sigma/dp_T^{j2}$ [pb/GeV]
#/Data
p_T^{j2} [GeV]


WJJ-MiNLO
ATLAS
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$p_T^j > 30$ GeV
$d\sigma/dp_T^{j2}$ [pb/GeV]
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p_T^{j2} [GeV]
WJJ-MiNLO
ATLAS
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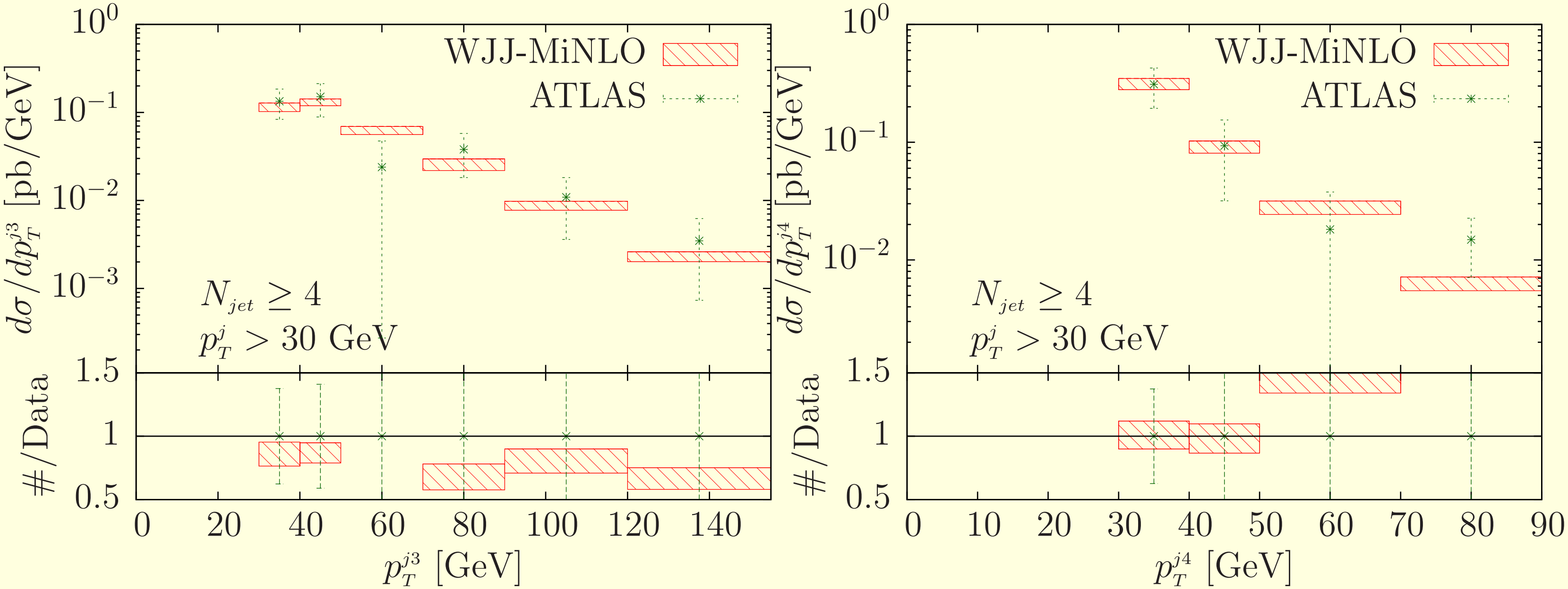
$p_T^j > 30$ GeV
$d\sigma/dp_T^{j3}$ [pb/GeV]
#/Data
p_T^{j3} [GeV]


WJJ-MiNLO
ATLAS
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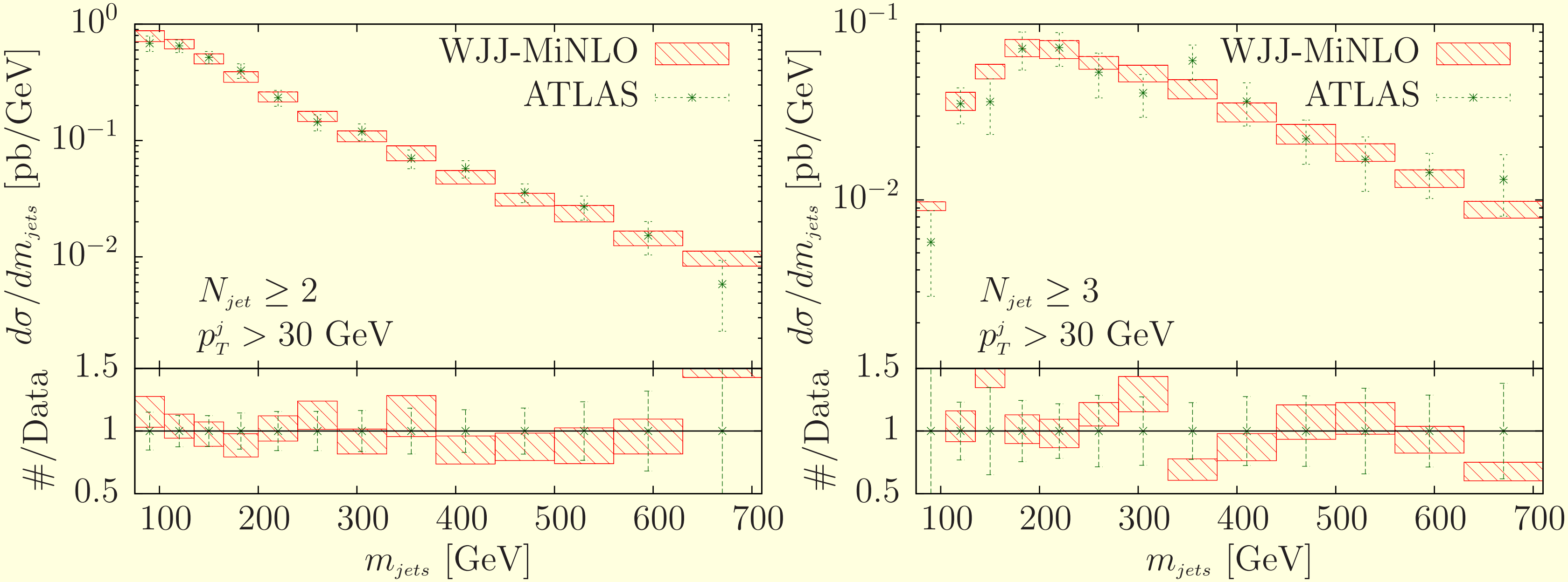
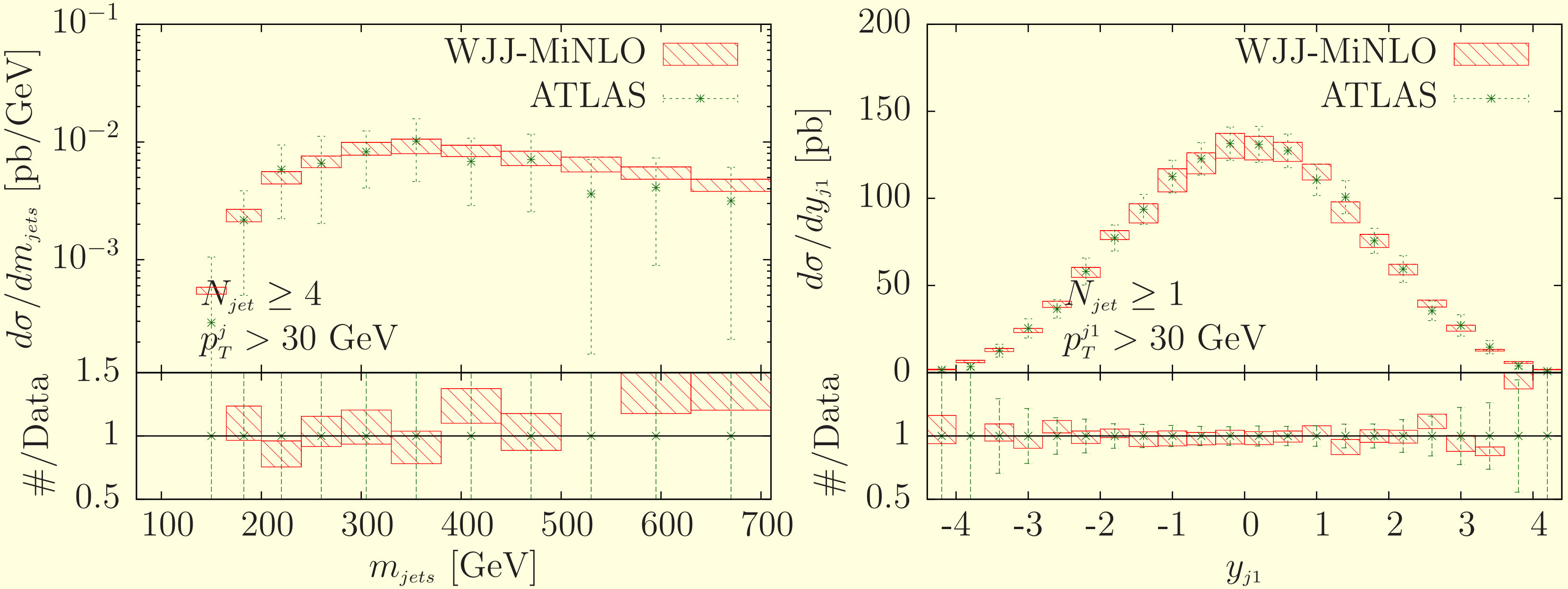
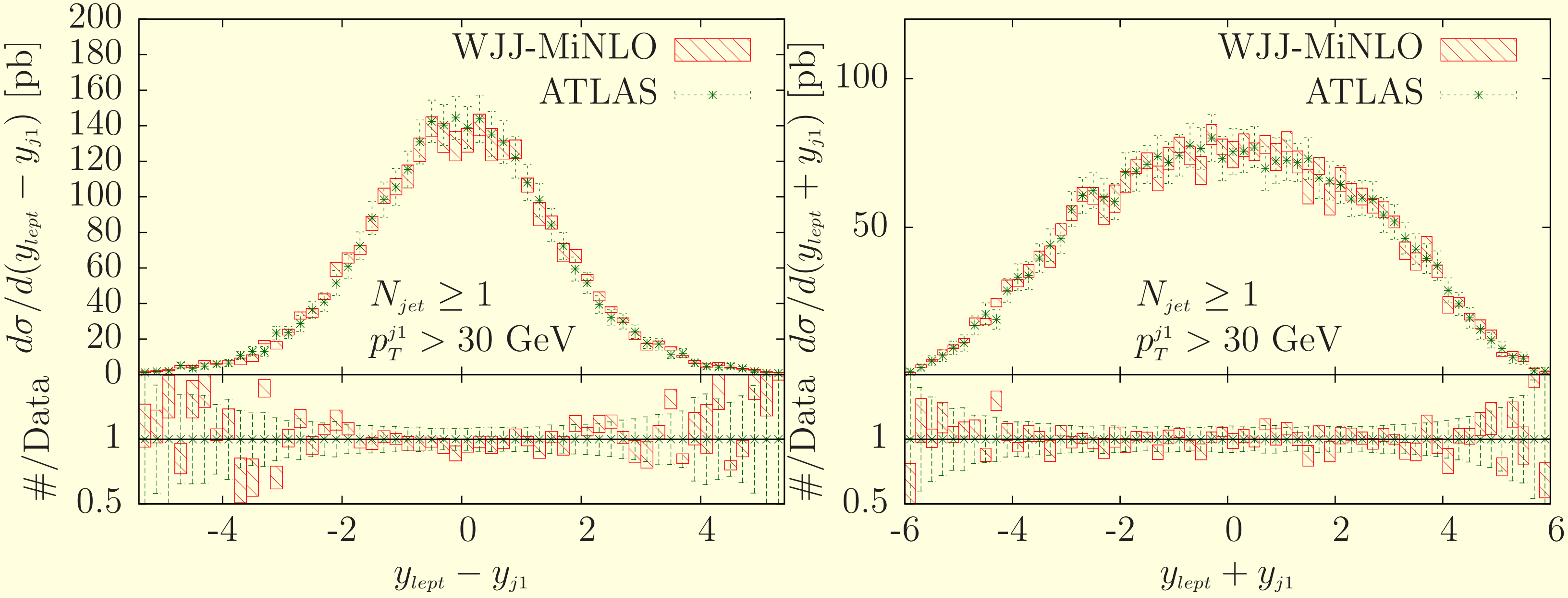
$p_T^j > 30$ GeV
$d\sigma/dp_T^{j3}$ [pb/GeV]
#/Data
p_T^{j3} [GeV]
$d\sigma/dp_T^{j4}$ [pb/GeV]
p_T^{j4} [GeV]

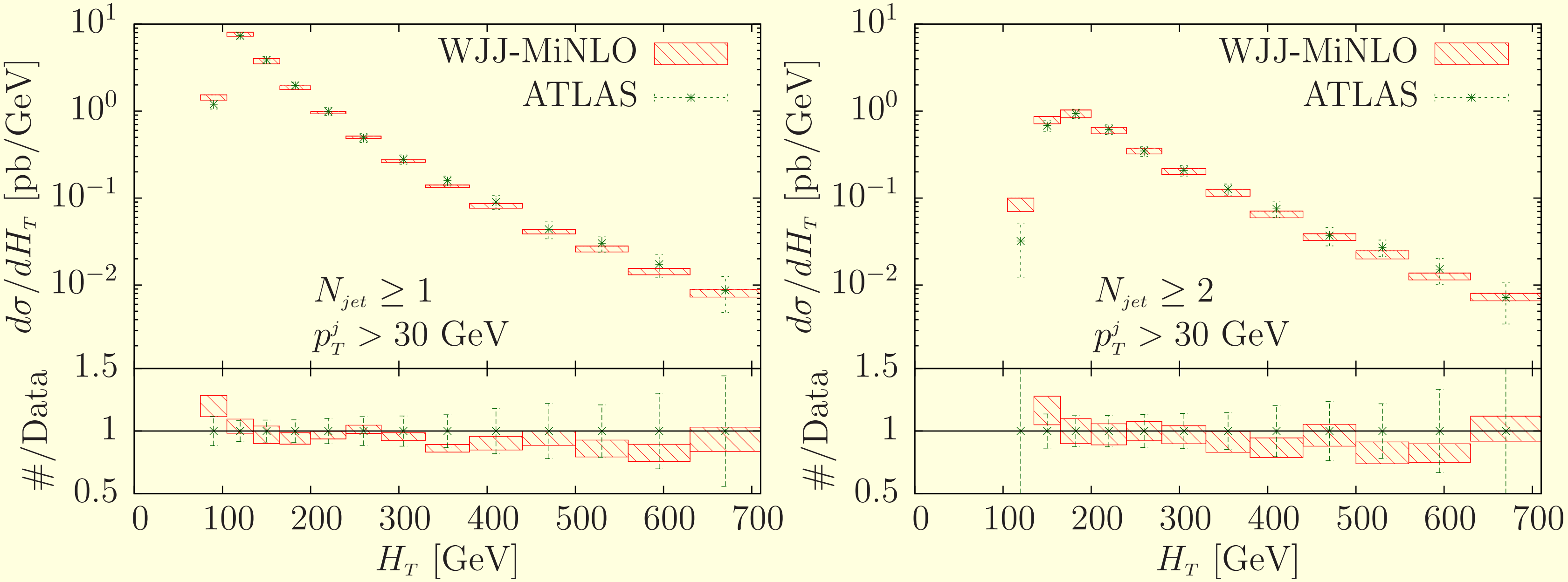

WJJ-MiNLO
ATLAS
$N_{jet} \geq 2$
$p_T^j > 30$ GeV
$d\sigma/dm_{jets}$ [pb/GeV]
#/Data
m_{jets} [GeV]
$N_{jet} \geq 3$
$p_T^j > 30$ GeV

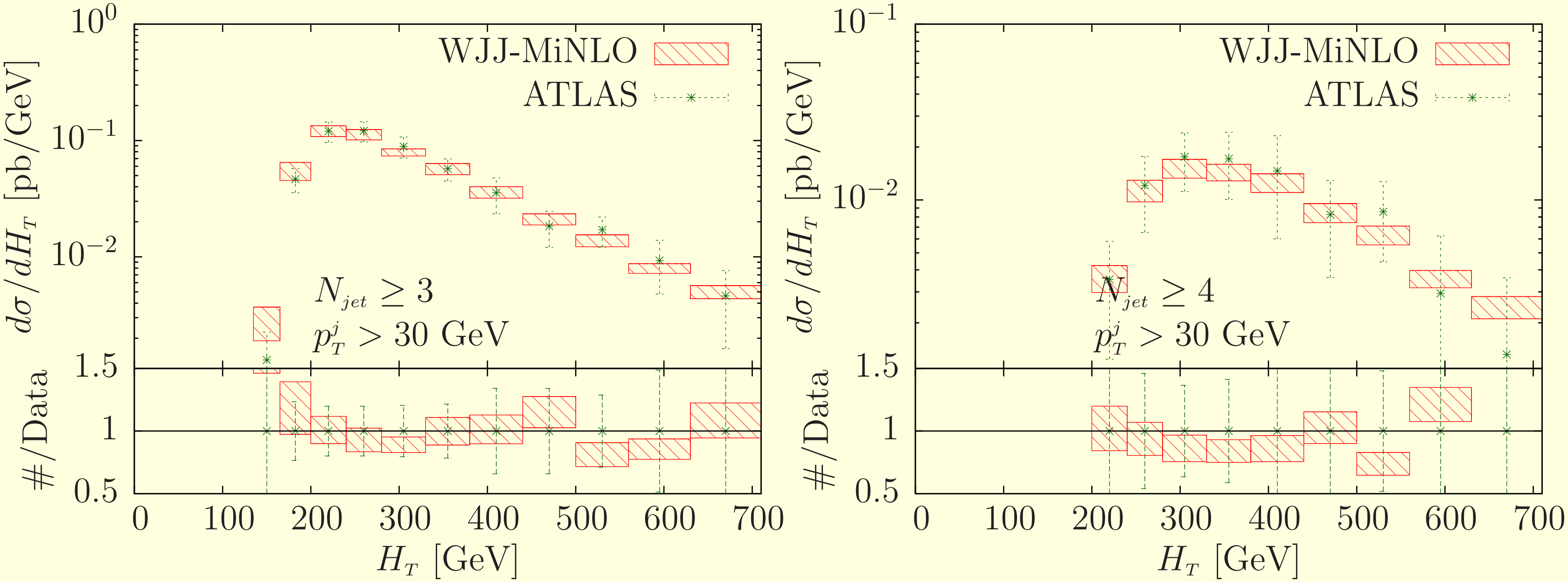


WJJ-MiNLO
ATLAS
$d\sigma/dm_{jets}$ [pb/GeV]
$N_{jet} \geq 4$
$p_T^j > 30$ GeV
#/Data
m_{jets} [GeV]
WJJ-MiNLO
ATLAS
$d\sigma/dy_{j1}$ [pb]
$N_{jet} \geq 1$
$p_T^{j1} > 30$ GeV
#/Data
y_{j1}

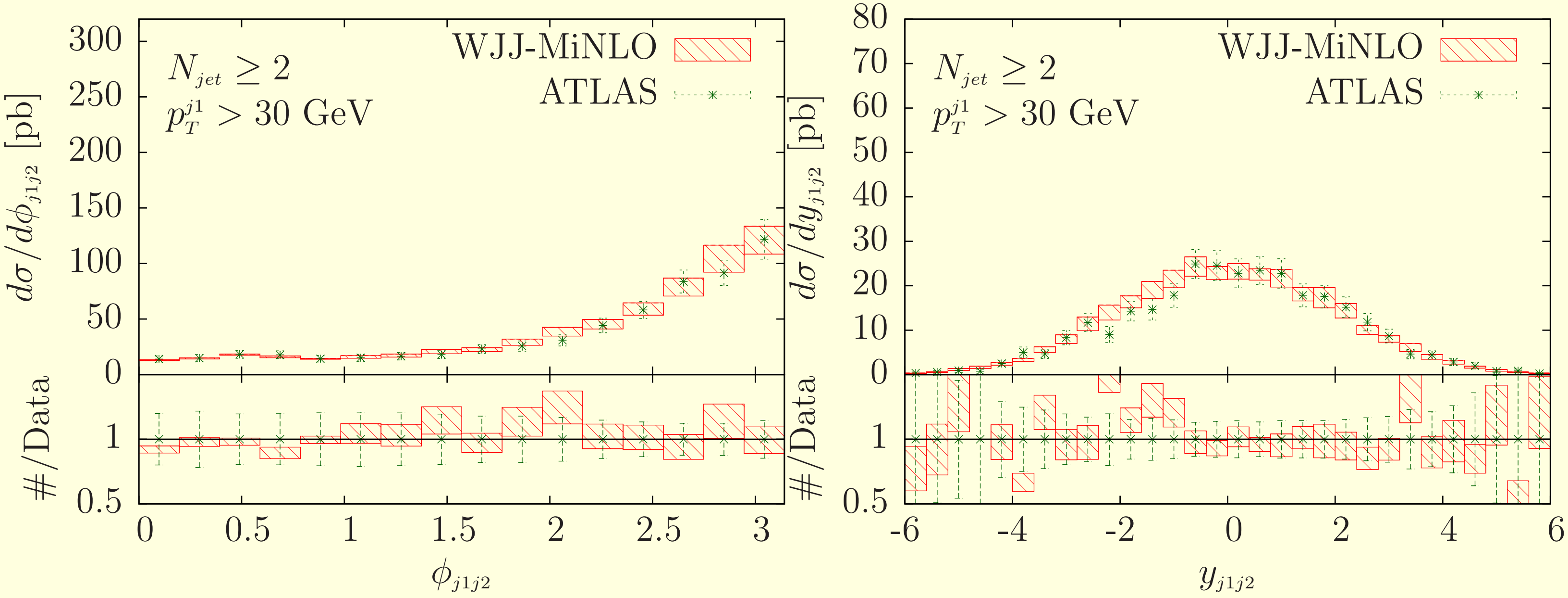


WJJ-MiNLO
ATLAS
$N_{jet} \geq 1$
$p_T^{j1} > 30$ GeV
$d\sigma/d(y_{lept} - y_{j1})$ [pb]
#/Data
$y_{lept} - y_{j1}$
$d\sigma/d(y_{lept} + y_{j1})$ [pb]
$y_{lept} + y_{j1}$

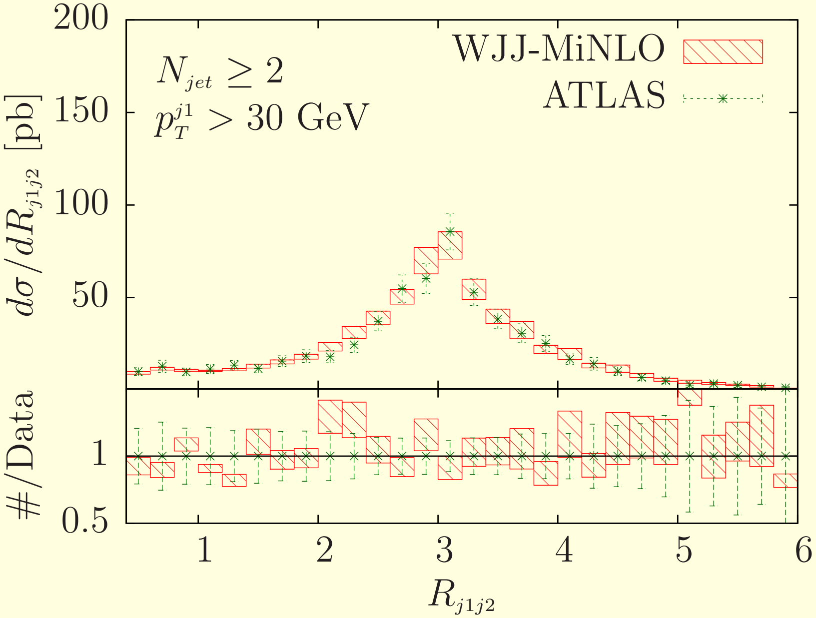

WJJ-MiNLO
ATLAS
$N_{jet} \geq 1$
$p_T^j > 30$ GeV
$d\sigma/dH_T$ [pb/GeV]
#/Data
H_T [GeV]
$N_{jet} \geq 2$
$p_T^j > 30$ GeV



WJJ-MiNLO
ATLAS
$N_{jet} \geq 3$
$p_T^j > 30$ GeV
$d\sigma/dH_T$ [pb/GeV]
#/Data
H_T [GeV]
$N_{jet} \geq 4$
$p_T^j > 30$ GeV



$N_{jet} \geq 2$
$p_T^{j1} > 30$ GeV
WJJ-MiNLO
ATLAS
$d\sigma/d\phi_{j1j2}$ [pb]
#/Data
ϕ_{j1j2}
$d\sigma/dy_{j1j2}$ [pb]
y_{j1j2}



$N_{jet} \geq 2$
$p_T^{j1} > 30$ GeV
WJJ-MiNLO
ATLAS
$d\sigma/dR_{j1j2}$ [pb]
#/Data
R_{j1j2}
200
150
100
50
1
0.5
1
2
3
4
5
6