Progress in the POWHEG BOX

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Plan of the talk

- The `MiNLO` prescription
  - The choice of scale in NLO calculations
  - The `CKKW` prescription
  - The `MiNLO` prescription
  - Extending the `MiNLO` accuracy
- Recent progress in the `POWHEG BOX`: Reweighting, Parallelized runs, Electroweak processes, resonance decay, `MiNLO`, etc.
  Applications to the `Z2jj` and `W2jj` generators.

Scale choice in QCD processes

An NLO result looks like

$$R = B\alpha_s^N(\mu_R) + \left[N b_0 \log\frac{\mu_R^2}{Q^2} B + C \right] \alpha_s^{N+1}(\mu_R)$$

where μ_R dependence is shown explicitly. The μ_R dependence of the α_s^{N+1} coefficient is as required by RG invariance:

$$\frac{\partial R}{\partial \log \mu_R^2} = -N b_0\, \alpha_s^{N+1}(\mu_R)\, B + N b_0\, \alpha_s^{N+1}(\mu_R)\, B + \mathcal{O}(\alpha_s^{N+2})$$

If μ_R is largely different from the physical scales entering the process we expect unphysically large contributions.

Common practice: guess the magnitude of the "physical scale";
vary μ_R by a factor of two above and below this value

but also: refine the choice ($\mu_R = Q$ in $e^+e^- \to 3\,\mathrm{jets}$; why not $Q/3$?)
(bias to values of μ_R that reduce the NLO corrections unavoidable here)

Scale stability

It is always possible to choose the scale in such a way that the NLO correction vanishes. This value is also near a point where the scale dependence vanishes.

If μ_0 solves $Nb_0 \log \frac{\mu_0^2}{Q^2} B + C = 0$, then

$$\left[\frac{\partial R}{\partial \log \mu_R^2}\right]_{\mu_R=\mu_0} = -Nb_1 \alpha_s^{N+2}(\mu_R) B\,.$$

Stevenson (1981): solve $\frac{\partial R}{\partial \log \mu_R^2} = 0$ for μ_R (Principle of Minimal Sensitivity)

PMS (or μ_0) would certainly work if the scale logarithm was the only source of large NLO corrections ...

But we know there are others: large color factors, π^2 terms,
new channels opening up, large Sudakov double logarithms ...
By using PMS and the like we would end up resumming these large corrections as if they were RG logs.

BLM, PMC

It is true that the common use of the scale dependence to assess theoretical errors has limitations (for example, it does not work for conformal invariant theories, it is of no value in QED, where photon polarization corrections can be fully resummed, etc.). In QCD it seems to work well in practice, and it is simple.

Some (Brodsky, Lepage, Mackenzie (1983)) have suggested to resum all β function terms arising in NLO calculations (can be done exactly in QED), for example by choosing μ_R so that the n_f dependence of the C term is cancelled (b_0 contains an n_f term), or to resum all β function terms arising in NLO calculations (can be done exactly in QED), for example by choosing μ_R so that the n_f dependence of the C term is cancelled (b_0 contains an n_f term) (Brodsky, Lepage, Mackenzie (1983)), or to resum all non-conformal ($\beta \neq 0$) terms (Principle of Maximal Conformality, Brodsky, Giustino (2012)).

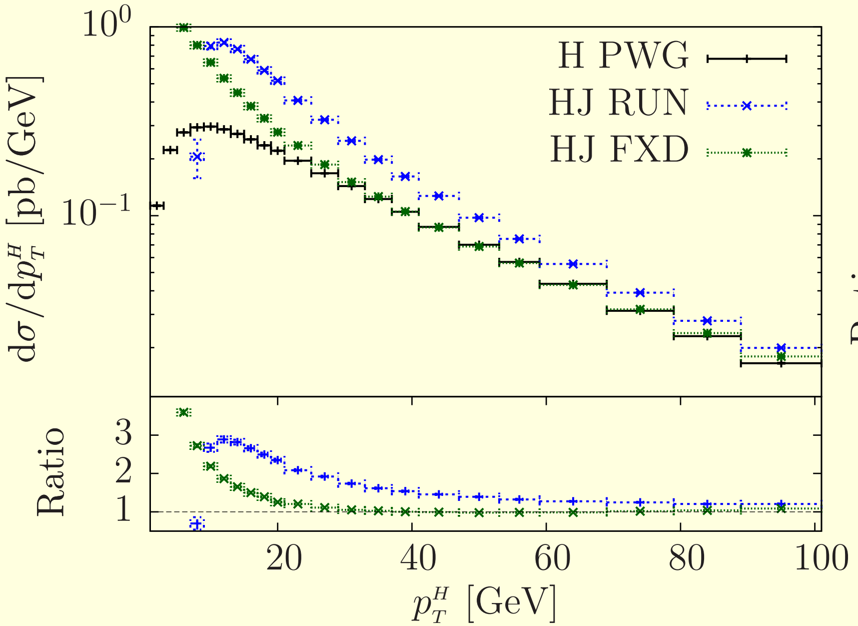
The present proposal is totally unrelated to these efforts; it only deals with the production of associated jets.

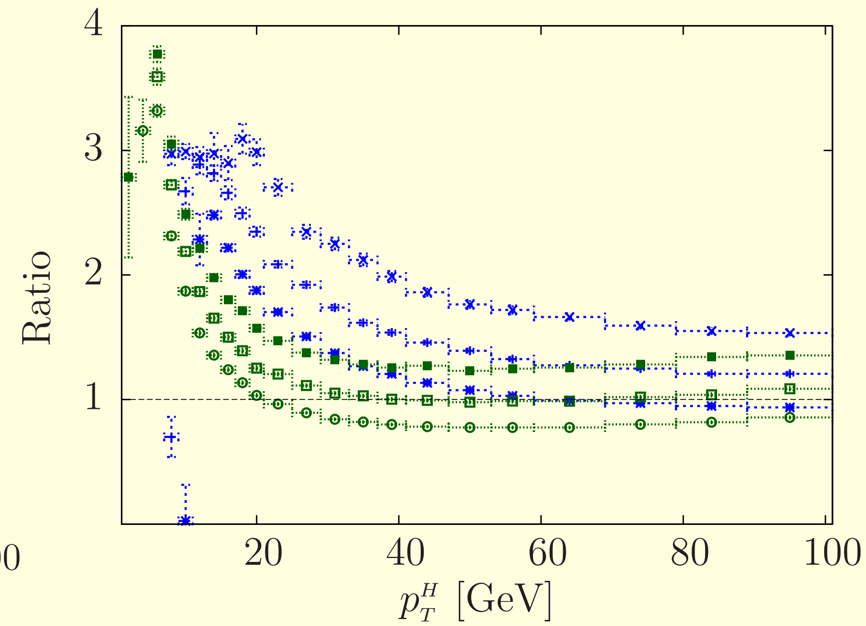
MiNLO:

- Assume only physically motivated scale (i.e. no PMS, BLM, PMC)
- Consider processes where many physical scales are present
- Focus on scales arising in collinear branching processes
  (will not consider small x scales.)

The problem we address is the choice of scales in the framework of processes with associated jets, near the kinematic region where it is most likely that associated jets are produced.

Consider $\mathrm{H} + \mathrm{jet}$ production. The jet will most likely have small p_T.
Two scales are present: the Higgs mass m_{H} and the p_T^{H}.
The choice of either scales leads to nearly incompatible results.





$M_{\mathrm{H}} = 120\,\mathrm{GeV}$ (perhaps we should upgrade our benchmark points ...)

H PWG: `POWHEG gg_H` generator interfaced with `PYTHIA`
HJ RUN: `HJ` NLO calculation with $\mu_R = \mu_F = p_{\mathrm{T}}^{\mathrm{H}}$
HJ FXD: `HJ` NLO calculation with $\mu_R = \mu_F = m_{\mathrm{H}}$

Ratio plots: ratio over H PWG

- Error bands obtained varying μ_R and μ_F by a factor of two above and below their common central value, with the constraint $\frac{1}{2} \leqslant \frac{\mu_R}{\mu_F} \leqslant 2$.
- Bands don't overlap at $p_T \lesssim 30\,\mathrm{GeV}$.
- NLO shapes differ from LL resummed result (`POWHEG`) at small p_T.

The M_{H} scale choice performs better. Can we find reasons to favour M_{H}? Or should we use some intermediate scale?
Scale choices in Matrix-Elements + Parton Shower approaches
(Catani,Krauss,Kuhn,Webber 2001): at leading order use $\alpha_s^2(M_{\mathrm{H}}^2) \times \alpha_s(p_T^{\mathrm{H}})$

Easy to argue that: p_T^{H} is right:

- Factorization scale: no jet $> p_T^{\mathrm{H}}$ in PDF evolution; $\mu_F = p_T^{\mathrm{H}}$.
- Virtuality of intermediated gluon $\lesssim p_T^{\mathrm{H}}$ by kinematics.
- Virtuality of initial gluons $\lesssim \mu_F = p_T^{\mathrm{H}}$.

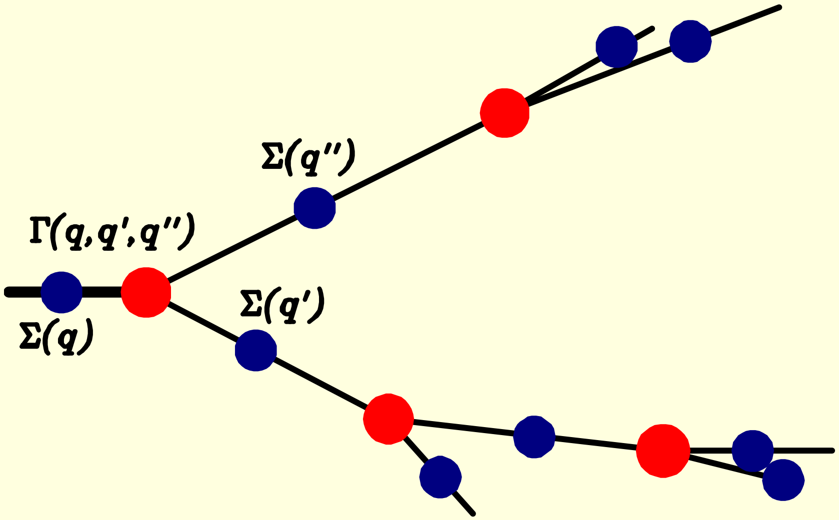
So: also $\mu_R = p_T^{\mathrm{H}}$. Does this contradict CKKW? (we will see it does not...)

CKKW: ME+PS matching

CKKW is a prescription for interfacing LO matrix element calculations with Parton Shower generators. Cannot fully review it here!

I only need to review CKKW in the context of IR finite field theories (like ϕ^3 in 6 dimentions, or Yukawa theories).

Shower basics:



Matrix elements computed in collinear approximation (Leading Log)
Splitting vertices computed using the Altarelli-Parisi approximation
Leading Log virtual corrections also included by inserting RG improved vertices and self-energy corrections.

At leading log: $\Gamma(q, q', q'') \approx \Gamma(q = \max(q, q', q''))$ (the largest scale), and

$$\Gamma(q)\left(\sqrt{\Sigma(q)}\right)^3 = \lambda(q)$$

So, virtual corrections are included by inserting in the squared amplitude:

- $\lambda^2(q)$ at each vertex (instead of λ^2), where q is the incoming virtuality
- $\Sigma(q')/\Sigma(q)$ in each intermediate line beginning at a scale q and ending at a scale q'. $\Sigma(q) = \Delta(q)$, "Sudakov" form factor.

CKKW basics:

- Use LO matrix elements, rather than LL approximation;
- Consider only configurations with the smallest relative transverse momentum $>Q_0$.
- Reconstruct a branching history from the kinematic of the event, using a clustering algorithm (for example, by recursively merging the pair of partons with smallest relative transverse momentum).
- Assign running couplings and Sudakov form factors as in the Parton Shower approximation to include LL virtual corrections.
- Feed the kinematics of the event to a parton shower to generate splittings with transverse momenta below Q_0.

What we learn: scale choice in the couplings is intertwined with the presence of the Sudakov form factors, that take care of large scale mismatch in nearby vertices. Scale assignment in multiscale processes must be complemented with the inclusion of Sudakov form factors.

The `MiNLO` approach

In order to deal with multi-scale processes, use the following strategy:

- Compute the Born term according to the CKKW prescription
- Include virtual and real corrections in such a way that
  - NLO accuracy is preserved
  - CKKW LL (NLL?) virtues are not spoiled

Problems to solve:

1. In CKKW, several renormalization scales are present in the Born term, in the argument of the coupling constant associated to each node of the branching history. The virtual correction coefficient is generally computed for a single renormalization scale.
2. CKKW requires a Q_0 scale. What do we choose in our case?
3. The Sudakov form factor in the Born term already contain terms of NLO order.
4. How do we chose the scales of the α_s's in the NLO term?

How to set μ_R

From:

$$R = B\alpha_s^N(\mu_R) + \left[N b_0 \log\frac{\mu_R^2}{Q^2} B + C \right]\alpha_s^{N+1}(\mu_R) =$$

So, if the scales in each α_s power in the Born term is different, we use

$$B\alpha_s(\mu_1)\ldots\alpha_s(\mu_n) + \left[\sum_{i=1}^{N} b_0 \log\frac{\mu_i^2}{Q^2} B + C \right]\alpha_s^{N+1}(\mu_R) =$$

$$B\alpha_s(\mu_1)\ldots\alpha_s(\mu_n) + \left[N b_0 \log\frac{\bar{\mu}}{Q^2} B + C \right]\alpha_s^{N+1}(\mu_R)$$

where $\bar{\mu}$ is the geometric average of $\mu_1\ldots\mu_N$. So: set μ_R to $\bar{\mu}$.

How to pick Q_0

Born term: pick the scale of the first clustering.
(Usual choice in CKKW for the highest multiplicity sample,
where we want that the parton shower generates all softer jets.)

In our case, a Born kinematic configuration with N partons will be associated with a virtual term with N partons, and with a real emission term with $N+1$ partons, where the softest clustering will yield N pseudopartons with the same kinematic configuration as the Born term. The integration of the softest cluster plays the role here of the further shower in ME+PS matching, i.e. it represent inclusive radiation that does not spoil the N jet structure. Q_0 is taken as the clustering scale for going from N to $N-1$ jets, i.e. the first clustering scale in the Born event, and the second clustering scale in the real event.

Remaining issues

The extra NLO terms present in the Sudakov form factor multiplying the Born term must be subtracted. We then have to decide what to use for the scales appearing in the powers of the coupling constant multiplying the NLO correction, and whether to include Sudakov form factors also in the NLO terms.

Guideline: treat the NLO term as much as possible as the Born term

By doing this we avoid spoiling the good LL features of the CKKW approach.

Notice that, in doing so, the real term has to be clustered once, and some (somewhat arbitrary) prescription has to be given for the choice of scale in the α_s^{N+1} power of α_s in the NLO terms.

Summary of the MiNLO prescription

We deal with a process of associated jet production, of order $N=m+n$, where n is the number of associated jets. For example, in Higgs plus 2 jets, $m=2$ and $n=2$.

1. Perform the k_T clustering of the partons in the event, determine the nodal scales $q_1 \ldots q_n$, the scale of the primary process Q, and eventualy the very first merging scale q_0 for the real process. Set $Q_0=q_1$.

2. n powers of the coupling constant will be evaluated at the scales $\mu_1 \ldots . \mu_n$, with $\mu_i = K_R q_i$. K_R is the renormalization scale factor, that will be varied between $1/2$ and 2 to study scale uncertainties. The remaining m powers of the strong coupling are evaluated at the primary process scale Q.

3. The (explicit) renormalization scale in the virtual term is set to

$$\mu_R = ((\mu_Q)^m \times \mu_1 \ldots \mu_n)^{\frac{1}{n+m}}.$$

   The factorization scale is taken equal to $K_F Q_0$, where K_F is the renormalization scale factor.

4. The Sudakov form factor are applied to all internal and external line of the branching skeleton. For real events, the branching skeleton after the first clustering is considered. External lines leaving a node at the scale q_i have a Sudakov form factor $\Delta_{f_i}(Q_0, q_i)$. Internal lines joining nodes i and j have the Sudakov form factor

$$\Delta_{f_{ij}}(Q_0, q_i)/\Delta_{f_{ij}}(Q_0, q_j),\ q_i > q_j$$

Note that the line leaving the node q_1 has no Sudakov:

$$\Delta(Q_0, q_1) = \Delta(Q_0, Q_0) = 1.$$

5. The subtraction of the NLO contribution already included in the Born term via the Sudakov form factor amounts to the replacement

$$B \Rightarrow B\left(1 - \sum_{ij}\left[\Delta^{(1)}_{f_{ij}}(Q_0, q_i) - \Delta^{(1)}_{f_{ij}}(Q_0, q_j)\right] - \sum_{l}\Delta^{(1)}_{f_l}(Q_0, q_i)\right)$$

the first sum runs over all pairs of nodes connected by a line, and l runs over external lines. $\Delta^{(1)}$ is the first order term in the expansion of Δ.

6. The $(N+1)^{\rm th}$ power of α_s multiplying the virtual, real and Sudakov subtraction term is taken equal to the average of the first N powers:

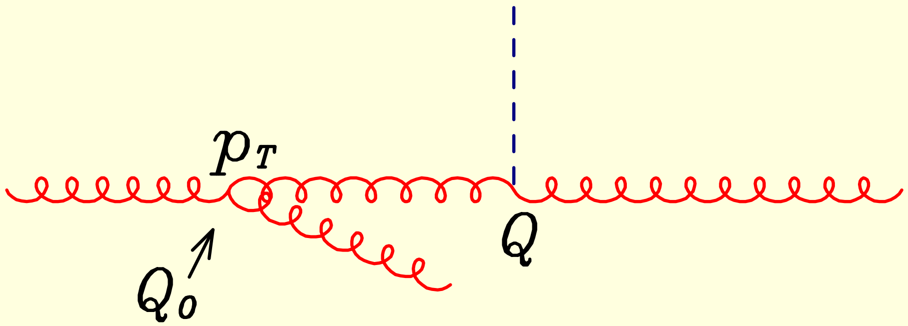
$$\alpha_s^{(N+1)} = \frac{1}{N}\left(\sum_{i=1}^{n} \alpha_s(\mu_i) + m\alpha_s(\mu_Q)\right).$$

The prescription at 6 is somewhat arbitrary, other options being possible.

Back to the HJ example

The CKKW factors amount to ($Q = M_{\rm H}$, $Q_0 = p_{\rm T}$)

$$F = \alpha_s^2(Q^2)\alpha_s(Q_0)\left\{\exp\left[-\frac{C_A}{\pi b_0}\left(\log\frac{\log\frac{Q^2}{\Lambda^2}}{\log\frac{Q_0^2}{\Lambda^2}}\left(\frac{1}{2}\log\frac{Q^2}{\Lambda^2}-\frac{\pi b_0}{C_A}\right)-\frac{1}{2}\log\frac{Q^2}{Q_0^2}\right)\right]\right\}^2$$



No Sudakov for external lines meeting at Q_0, and two identical Sudakov for the remaining gluon lines.

The red term in the exponent yields the factor $\left(\log\frac{Q^2}{\Lambda^2}/\log\frac{Q_0^2}{\Lambda^2}\right)^2$, and $\alpha_s^2(Q^2)\left(\log\frac{Q^2}{\Lambda^2}/\log\frac{Q_0^2}{\Lambda^2}\right)^2 = \alpha_s^2(Q_0^2)$.

So: no contradiction with intuitive reasoning
but Sudakov form factors cannot be forgotten!

MiNLO results

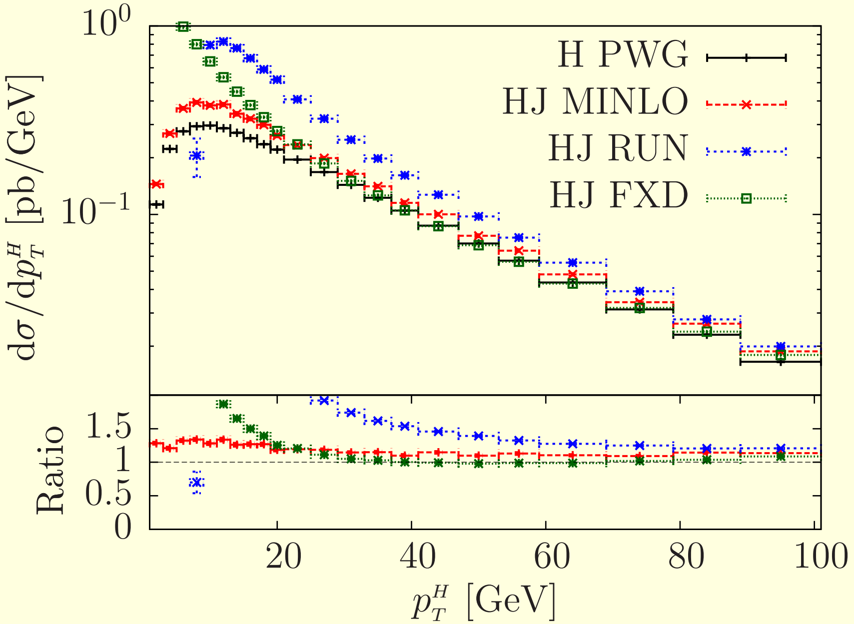
The MiNLO prescription has been implemented in the POWHEG BOX in a fully generic way, in such a way that it can be applied to any process. We have used the POWHEG-BOX as an NLO calculator for our studies.

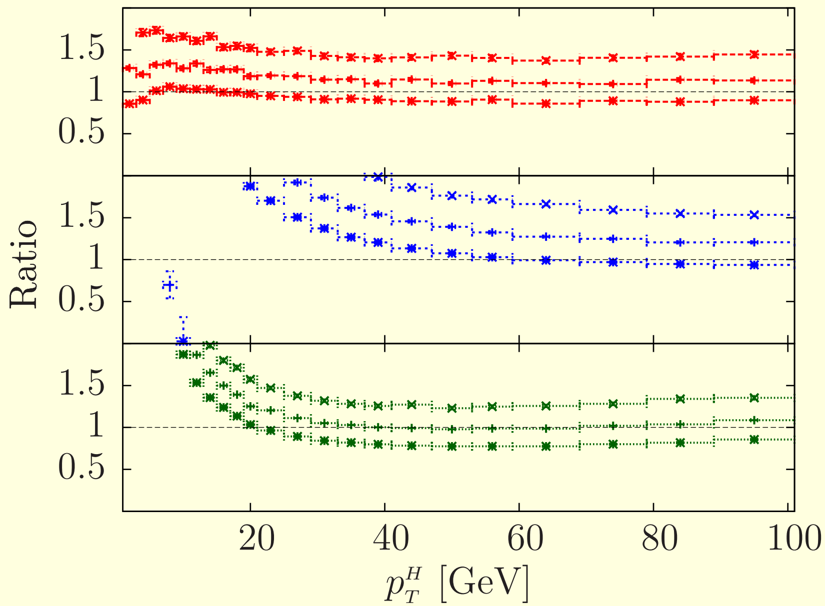
For simplicity, we have used a variant of the k_{T}-clustering procedure: for real emission events, the first clustering is performed using the internal POWHEG-BOX mapping of the real emission event into the underlying Born configuration.

We have considered Higgs plus up to 2 jets (Campbell, Ellis, Frederix, Oleari, Williams, P.N. 2012), and Z in association with up to 2 jets ($Z+J$, Alioli, Oleari, Re, P.N. 2011). For $Z+2J$, an implementation was built by us (Hamilton, Zanderighi, P.N.) using the MadGraphStuff interface of the POWHEG-BOX, and the virtual corrections from MCFM (see also Re, 2012).

For comparison we are also showing POWHEG results showered with PYTHIA6.

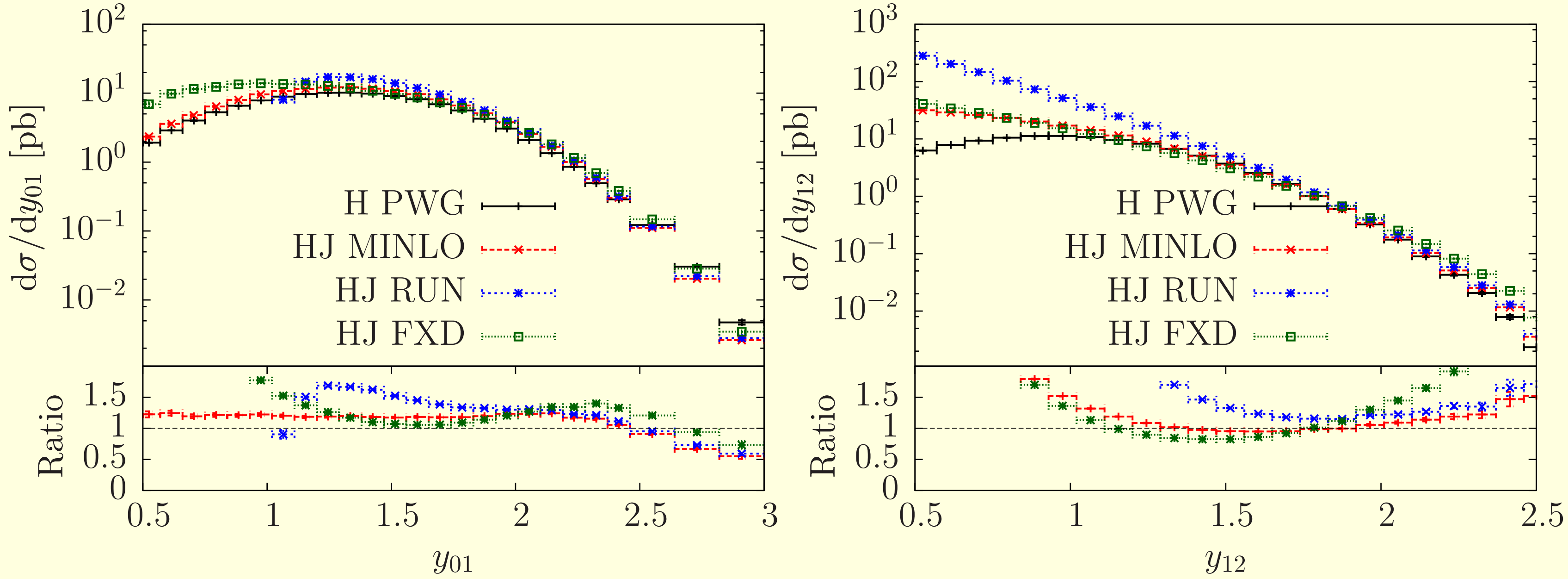
HJ results





- H PWG: the (showered) `gg_H POWHEG BOX` result.
- RUN and FXD need a generation cut (or Born suppression) at small p_{T}. The `MiNLO` result is instead FINITE (up to a cut-off $\approx\Lambda$)
- We can thrust the `MiNLO` result at small p_{T} only as a LO result (see the widening of the `MiNLO` uncertainty band at small p_{T}). However, at least we get a result that is sensible also at low p_{T} rather than divergent.

- The `MiNLO` result is tracked closely by the fixed scale NLO result down to $p_{\mathrm{T}} \approx 30$. We now explain this as due to the fact that the unphysical choice of a larger scale in the FXD result compensates the effect of the large Sudakov double logs.
- The fixed order results approach at low p_{T} a region where the large negative NLO Sudakov logarithm causes the full NLO correction to vanish. Under these conditions the scale uncertainty is reduced, leading to a fake impression of stability.



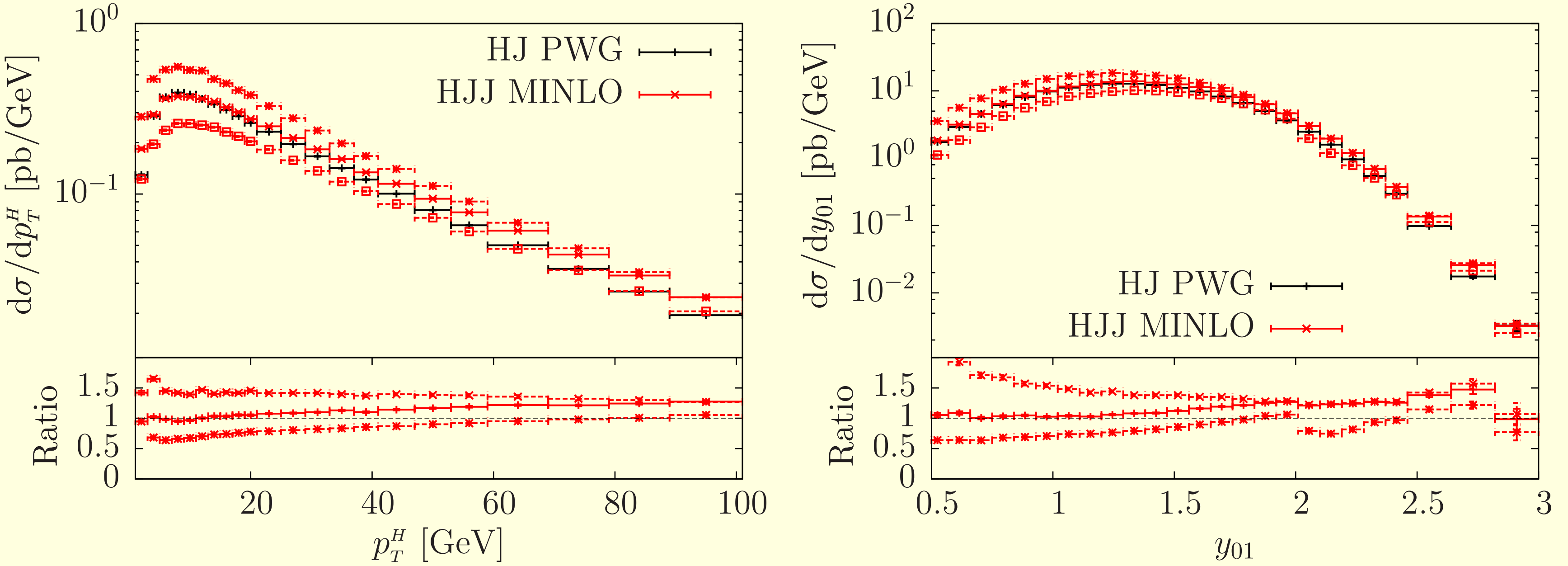
$y_{k,k+1} = \log_{10}(q_{k,k+1}/1\,\mathrm{GeV})$

$q_{k,k+1}$: k_{T} merging scale for going from a $(k+1)$-jet to a k-jet configuration.

The q_{01} scale is inclusive in the real radiation (that is clustered in the 12 step), and is thus well predicted by `MiNLO`, while the NLO result with standard scale choices are problematic.

The q_{21} scale: clustering the real radiation. RUN, FXD and `MiNLO` perform alike, none of them include resummed virtual effects for real radiation (but `POWHEG HJ` would perform well in all three cases!).

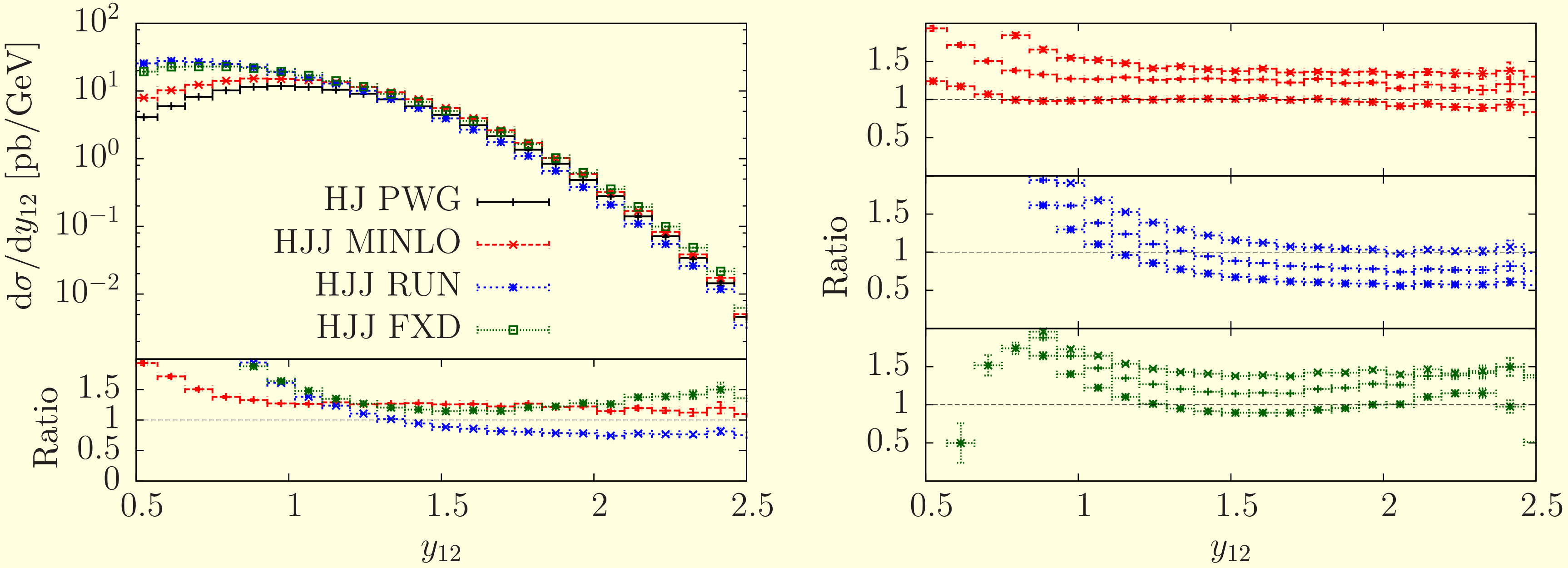
HJJ results



Notice: RUN and FXD scale results not available for these distributions.
The Born term alone is divergent, since it is integrated in the second jet with no restriction.

However: the `MiNLO` result is still sensible, and is sensible also at very low p_{T} (although with larger scale uncertainty: no longer NLO!)

The HJ PWG result here refers to the fully showered `HJ POWHEG` result, with the computation of the underlying Born improved with `MiNLO`.



Now: FXD: $\mu_R = \mu_F = m_{\mathrm{H}}$,

RUN: $\mu_R = \mu_F = \hat{H}_{\mathrm{T}} = \sqrt{M_{\mathrm{H}}^2 + p_{\mathrm{T}}^{H\,2}} + \sum_i p_{\mathrm{T}}^i$

y_{12} is predicted by all approaches; the `MiNLO` is qualitatively closer to the `HJ POWHEG` (showered) result.

Notice: $\hat{H}_{\mathrm{T}}$ band barely intersects the `MiNLO` band; better to choose $\hat{H}_{\mathrm{T}}/2$ as central value (as usually done in W/Z production)

The integrated result of HJJ in MiNLO is also fairly compatible with the inclusive H cross section. Why is it so?

We have the (so called!) Unitarity relation:

$$\Delta_i(Q_0, Q) + \sum_j \int dz \int_{Q_0}^{Q} \frac{dq^2}{q^2} \alpha_S(q^2) \, P_{ij}(z) \, \Delta_i(Q_0, q) = 1$$

since

$$\Delta_i(Q_0, q) = \exp\left[-\sum_j \int dz \int_{Q_0}^{q} \frac{dq'^2}{q'^2} \alpha_S(q'^2) \, P_{ij}(z) \right].$$

This implies that integrating over the final splittings in a Shower we get 1, so that integrating recursively the whole shower we get the inclusive cross section for the primary process. A property of this kind remains true in ME with CKKW improvements, but it is no longer exact. MiNLO inherits this property.

What is the real error on this procedure, in the MiNLO case?

(Hamilton,Oleari,Zanderighi,P.N. 2012)Focus upon $H/W/Z+1\,\mathrm{jet}$.The NNLL resummed the transverse momentum distribution of the vector boson is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y\mathrm{d}q_T^2}=\sigma_0\frac{\mathrm{d}}{\mathrm{d}q_T^2}\{[C\otimes f_A](x_A,q_T)\times[C\otimes f_B](x_B,q_T)\times\exp\mathcal{S}(Q,q_T)\}+R_f$$

$$\mathcal{S}(Q,q_T)=-\int_{q_T^2}^{Q^2}\frac{\mathrm{d}q^2}{q^2}\left[A(\alpha_s(q^2))\log\frac{Q^2}{q^2}+B(\alpha_s(q^2))\right],$$

$$A(\alpha_s)=\sum_{i=1}^{\infty}A_i\alpha_s^i,\qquad B(\alpha_s)=\sum_{i=1}^{\infty}B_i\alpha_s^i,\qquad R_f=\text{finite terms}$$

This formula yields the correct NLO $\mathrm{d}B/\mathrm{d}y$ when integrated over $\mathrm{d}q_T^2$.
To make contact with the MiNLO result, take explicitly $\mathrm{d}/\mathrm{d}q_T^2$, and get:

$$\sim\sigma_0\frac{1}{q_T^2}[\alpha_S,\alpha_S^2,\alpha_S^3,\alpha_S^3,\alpha_S^4,\alpha_S L,\alpha_S^2 L,\alpha_S^3 L,\alpha_S^4 L]\times\exp\mathcal{S}(Q,q_T)+R_f,$$

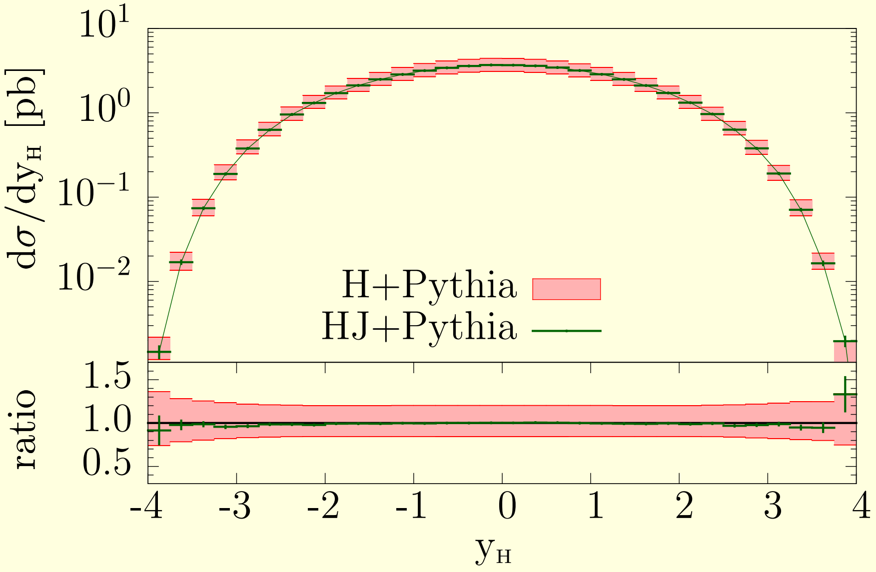
$(L=\log Q^2/q_T^2)$. We have: $\int\frac{\mathrm{d}q_T^2}{q_T^2}L^m\alpha_s^n\exp\mathcal{S}(Q,q_T)\approx[\alpha_s(Q^2)]^{n-\frac{m+1}{2}}$
Thus, if we drop all α^3 and higher terms, NLO accuracy upon integration is still preserved (worse term: $\alpha^3 L\to\alpha_s^2(Q)$, NNLO).
Same accuracy as in MiNLO! Only difference: B_2 term missing in MiNLO $\mathcal{S}$!

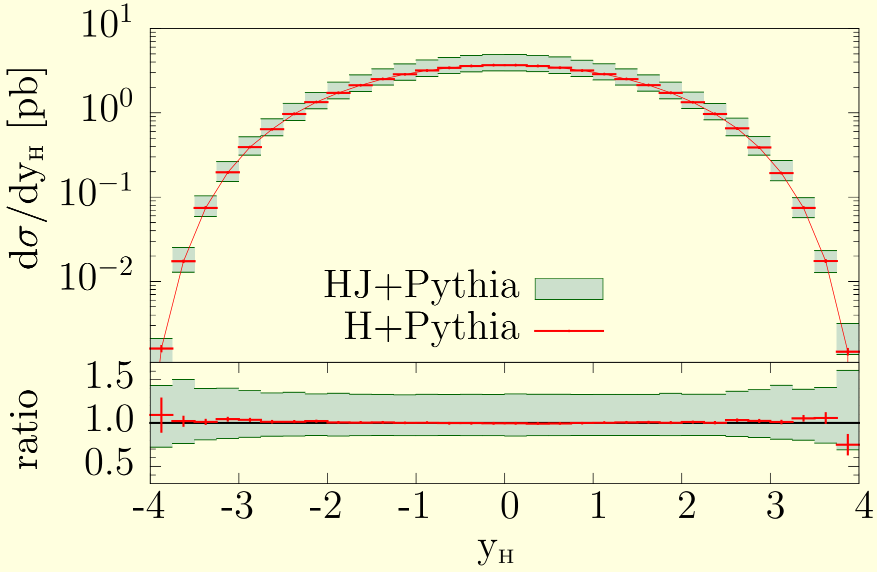
$$\sim\sigma_0\frac{1}{q_T^2}[\alpha_S,\alpha_S^2,\alpha_S^3,\alpha_S^3,\alpha_S^4,\alpha_S L,\alpha_S^2 L]\times\exp\mathcal{S}\times\exp\left[-\int_{q_T^2}^{Q^2}\frac{\mathrm{d}q^2}{q^2}B_2\alpha_S^2\right]$$

$$\Longrightarrow\frac{1}{q_T^2}[\alpha_S^3 L^2]\times\exp\mathcal{S}\Longrightarrow[\alpha_s(Q^2)]^{3-\frac{2+1}{2}}=[\alpha_s(Q^2)]^{1.5}$$

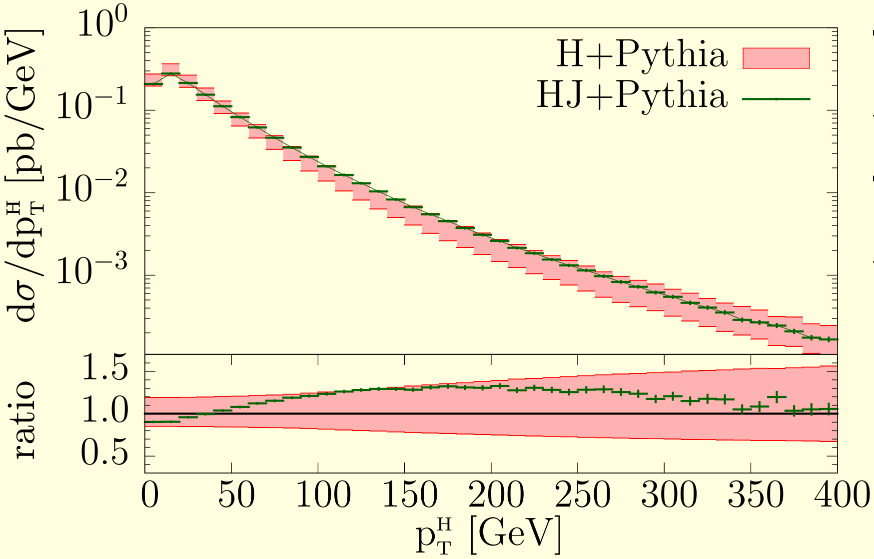
So, MiNLO yields an accuracy that is more than LO, but less than NLO, in the inclusive cross section, the neglected term having a power of α_S greater than 1 but less than 2.

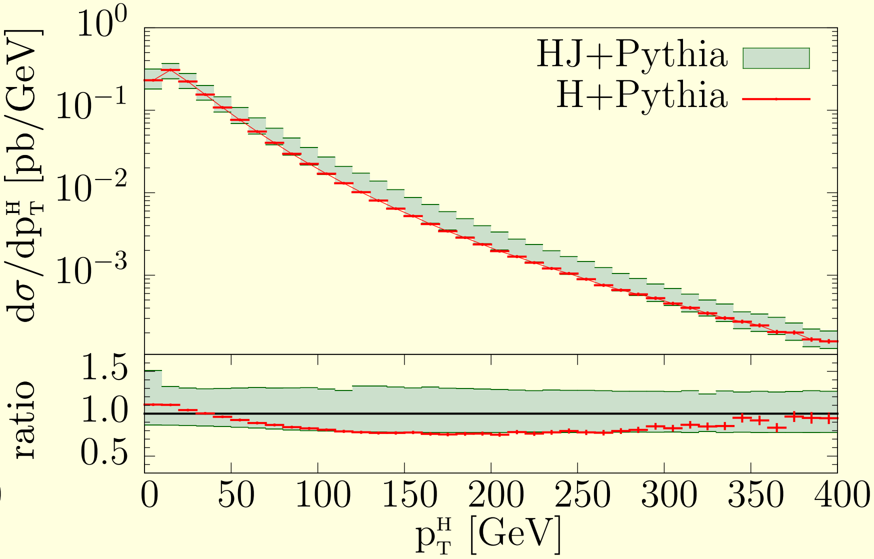
In case of $H/W/Z+1\,\mathrm{jet}$, it is in fact possible to modify the MiNLO Sudakov form factor by carefully including the B_2 term in such a way that integrating over the radiated jet we achieve NLO accuracy for inclusive $H/W/Z$ distributions. (Hamilton,Oleari,Zanderighi,P.N. 2012)





Using this method inclusive observables computed with the HJ generator match very well those computed with the H generator.

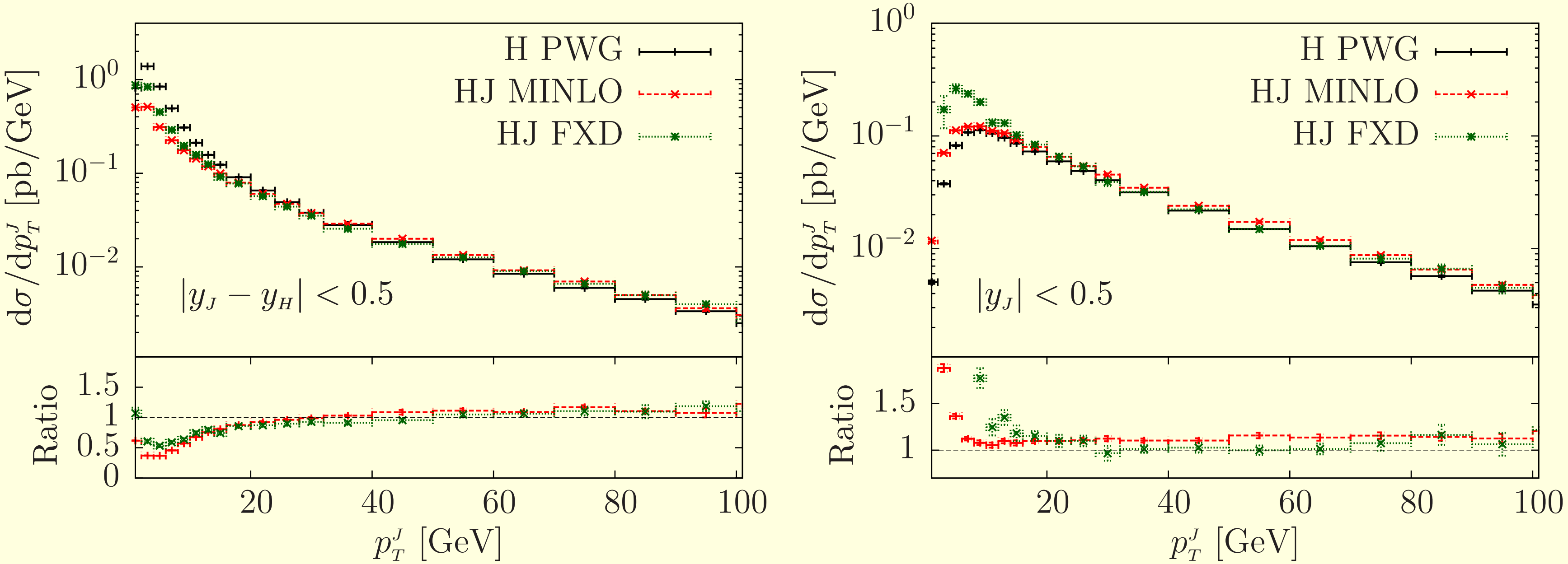

H+Pythia
HJ+Pythia
$d\sigma/dp_T^H$ [pb/GeV]
ratio
p_T^H [GeV]


HJ+Pythia
H+Pythia
$d\sigma/dp_T^H$ [pb/GeV]
ratio
p_T^H [GeV]

CAVEAT

When using MiNLO in NLO calculations, care is needed in understanding whether the observables we are considering are going to be improved.

Even apparently harmless observables sometimes may not satisfy the `MiNLO` requirement. An example (G.Salam): in `HJ`, the transverse momentum of the hardest jet found in a given rapidity interval around the Higgs rapidity.



Notice: hardest jet in given y range NOT insensitive to first merging ...

So: fixed order slightly better than `MiNLO` in left plot; right plot not so bad ...

MiNLO and NLO+PS

When MiNLO is used in standard fixed order calculations, by construction we expect an improvement for quantities that can be built out of the jet kinematics after the first clustering. MiNLO does not provide an improved description of the real radiation. Including by hand Sudakov form factors for the real radiation destroyes NLO accuracy.

On the other hand, NLO+PS methods do include these Sudakov effects, using appropriate methods that maintain NLO accuracy.

So, we expect the MiNLO method to be best suited in the MC+NLO context.

MiNLO and NNLO+PS

At the present stage, MiNLO for processes of 1 associated jet production of colour neutral systems (Higgs, W/Z, HW, etc), allows for full NLO accuracy for inclusive quantities involving and not involving the extra jet. It is possible (and not difficult) to extend the present framework in such a way that a true NNLO+PS generator is built, without the use of any matching scales.

In the example of Higgs production: the MiNLO HJ generator can be promoted to a NNLO+PS generator by simply reweighting the events with the factor

$$\frac{\mathrm{d}\sigma^{(\mathrm{NNLO})}}{\mathrm{d}y_{\mathrm{H}}} \Big/ \frac{\mathrm{d}\sigma^{(\mathtt{HJ})}}{\mathrm{d}y_{\mathrm{H}}} = 1 + \mathcal{O}(\alpha_S^2)$$

or with alternative procedures where the reweighting takes place mostl for events with $p_T^{(\mathrm{H})} \lesssim M_{\mathrm{H}}$.

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.

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 generator, 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.

Current merging approaches:

- SHERPA, [Hoeche, Krauss, Schonherr, Siegert, arXiv:1207.5030], traditional merging with matching scales.

- aMCNLO, [Frederix, Frixione, arXiv:1209.6215], traditional merging with matching scales; scales kept high to avoid above problems.

- [Platzer, arXiv:1211.5467], [Lönnblad, Prestel, arXiv:1211.7278], force unitarity by subtracting appropriate terms.

- GENEVA, [Alioli, Bauer, Berggren, Hornig, Tackmann, Vermilion, Walsh, Zuberi, arXiv:1211.7049], increase precision in LL resummation to reach accurate matching

POWHEG BOX progress

POWHEG BOX improvements: towards Version 2

Several enhancements of the original package have been introduced for particular processes. Now time to merge all these enhancements to head towards a new version of the framework:

1. Reweighting: a feature used to perform studies on scale variation and PDF dependence without the need to replicate the sample generation
2. Parallelized grid generation; for complex processes, for which grid adaptation is a bottleneck for the calculation, it is now possible to perform all steps in parallel, including grid adaptation.
3. In the framework of W and Z production including EW corrections (Barzè, Montagna, Nicrosini, Piccinini, 2012; +Vicini, 2013), an extension including the treatment of photons has been implemented
4. `MiNLO`
5. NLO corrections to decaying resonances

At the moment 1,2 and 4 are merged into a preliminary `Version-pre2-1`, and have been tested in the new `Z2jet` and `W2jet` generators.

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)

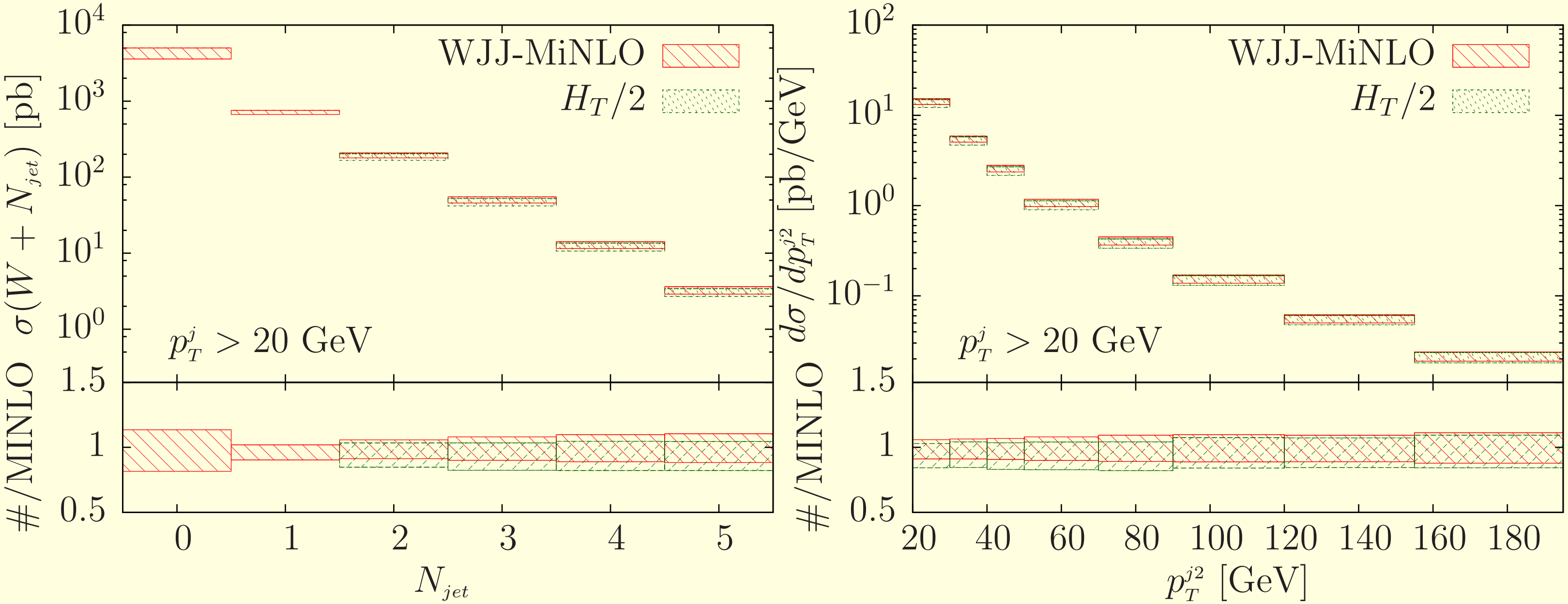
- Validation with MiNLO and $H_t/2$ scale choice.
- Solved problems arising with (rare) events near the singular region at the underlying Born level, being promoted to non-singular events after radiation (improvement in the POWHEG BOX separation of singular regions)
- Events that are near the singular 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.

$\texttt{MiNLO}$ 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).

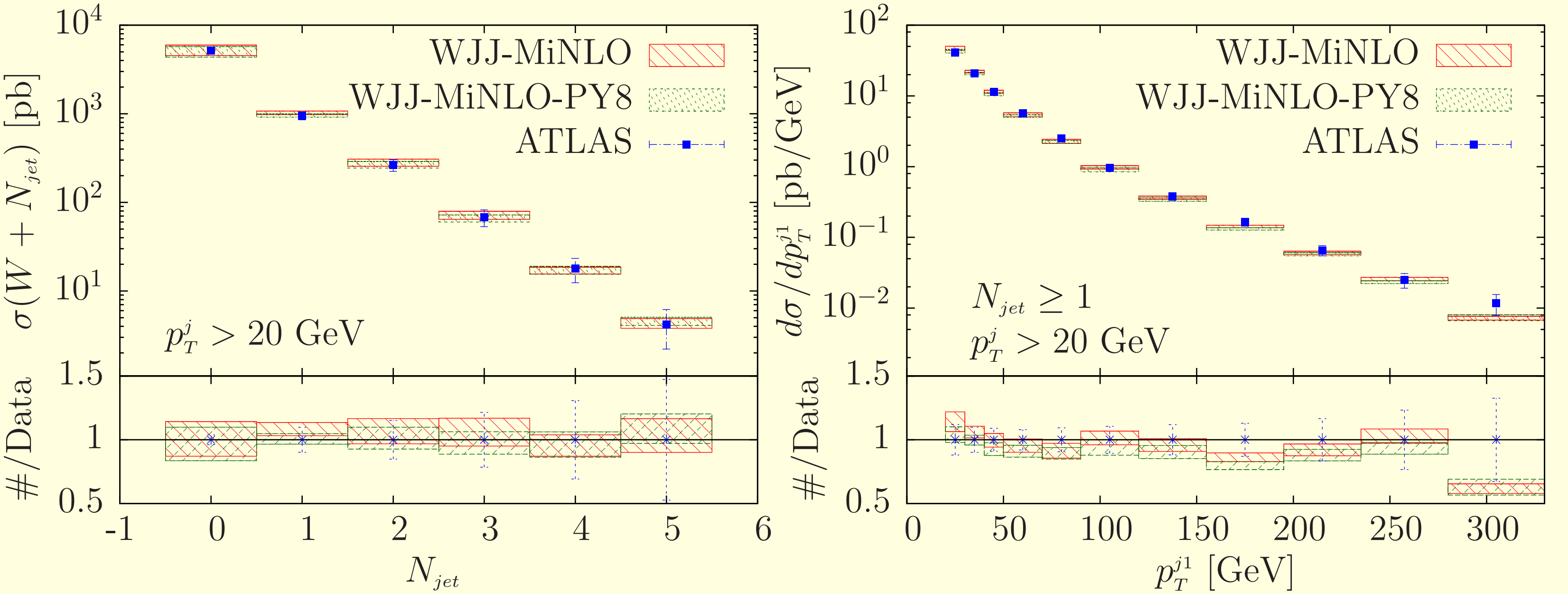
Notice: while some data bias in the $H_T/2$ choice cannot be excluded, this is not the case for $\texttt{MiNLO}$.

Two examples:

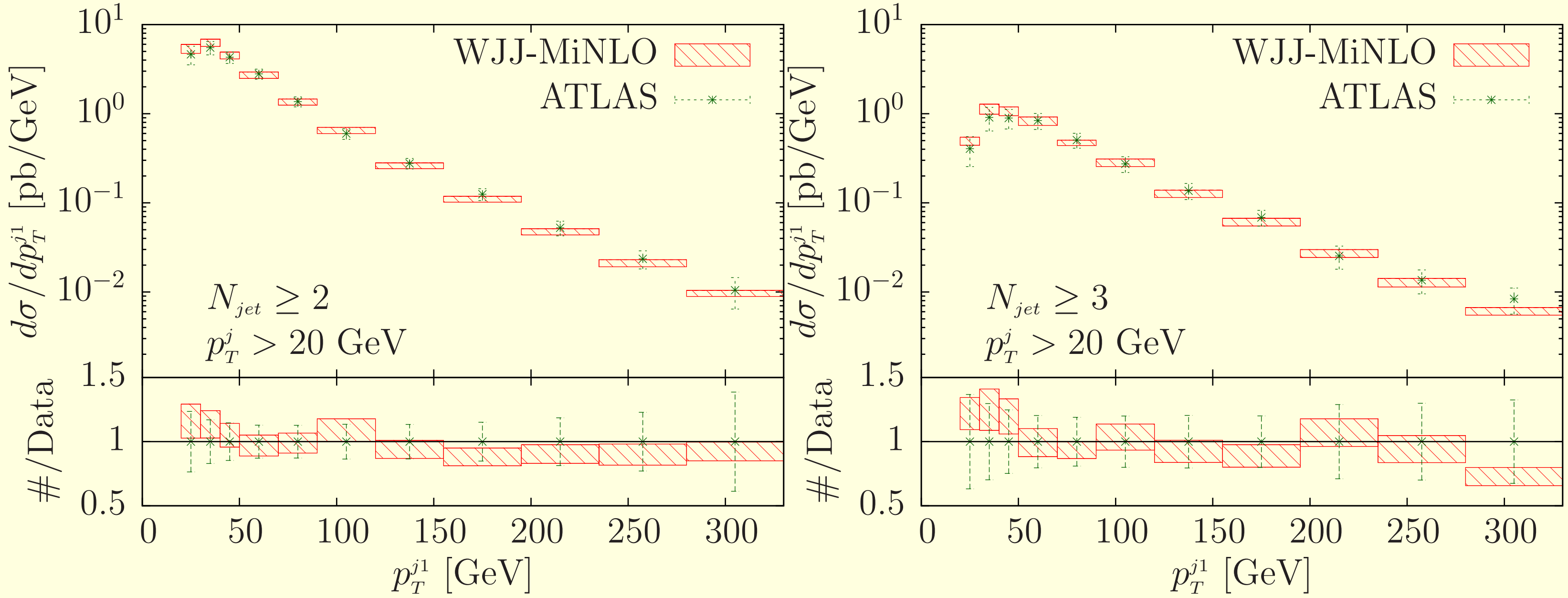


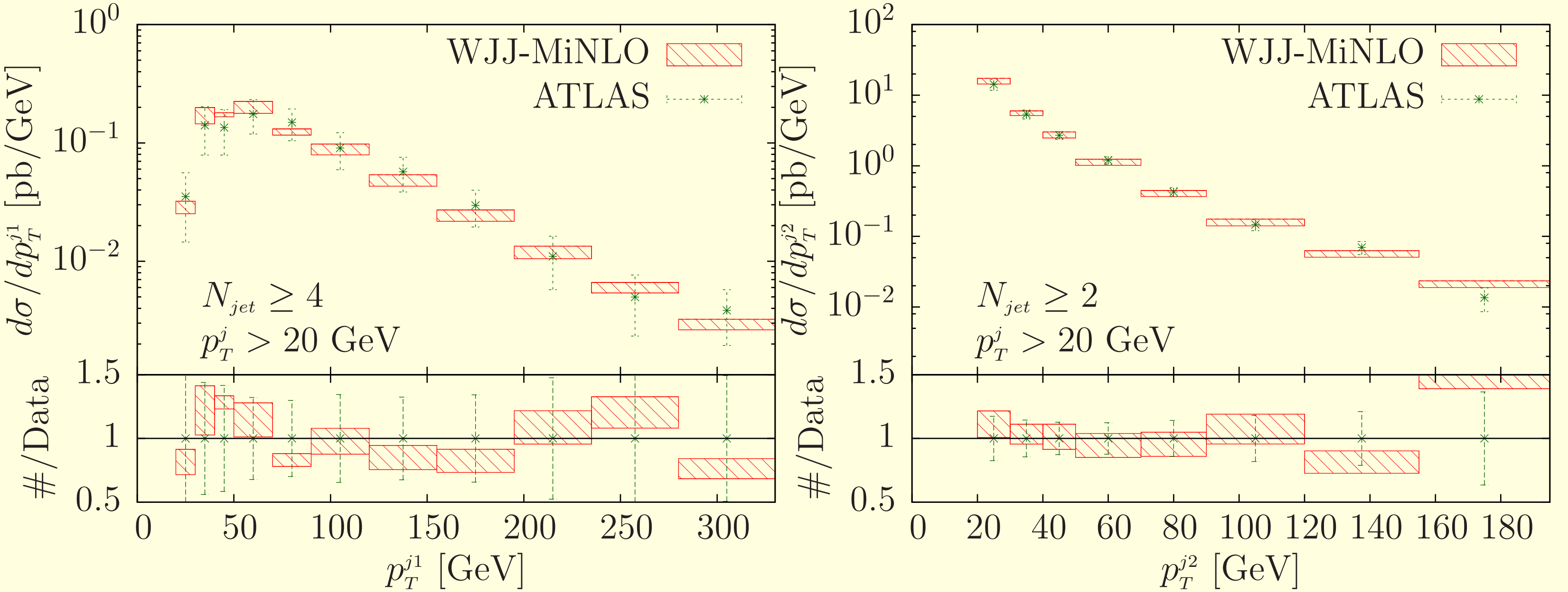
PYTHIA 6 versus PYTHIA 8

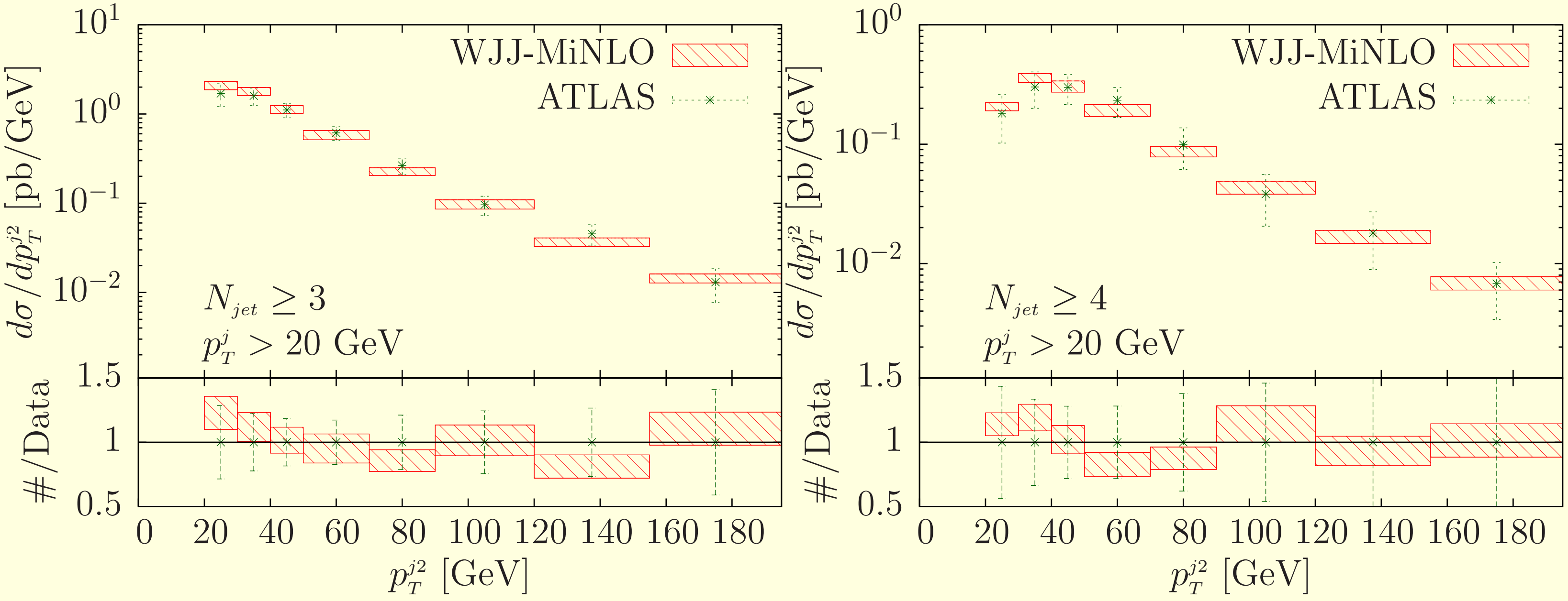
We have considered PYTHIA 8 showering for all observables. There are some differences, but the quality of the agreement with data is similar.



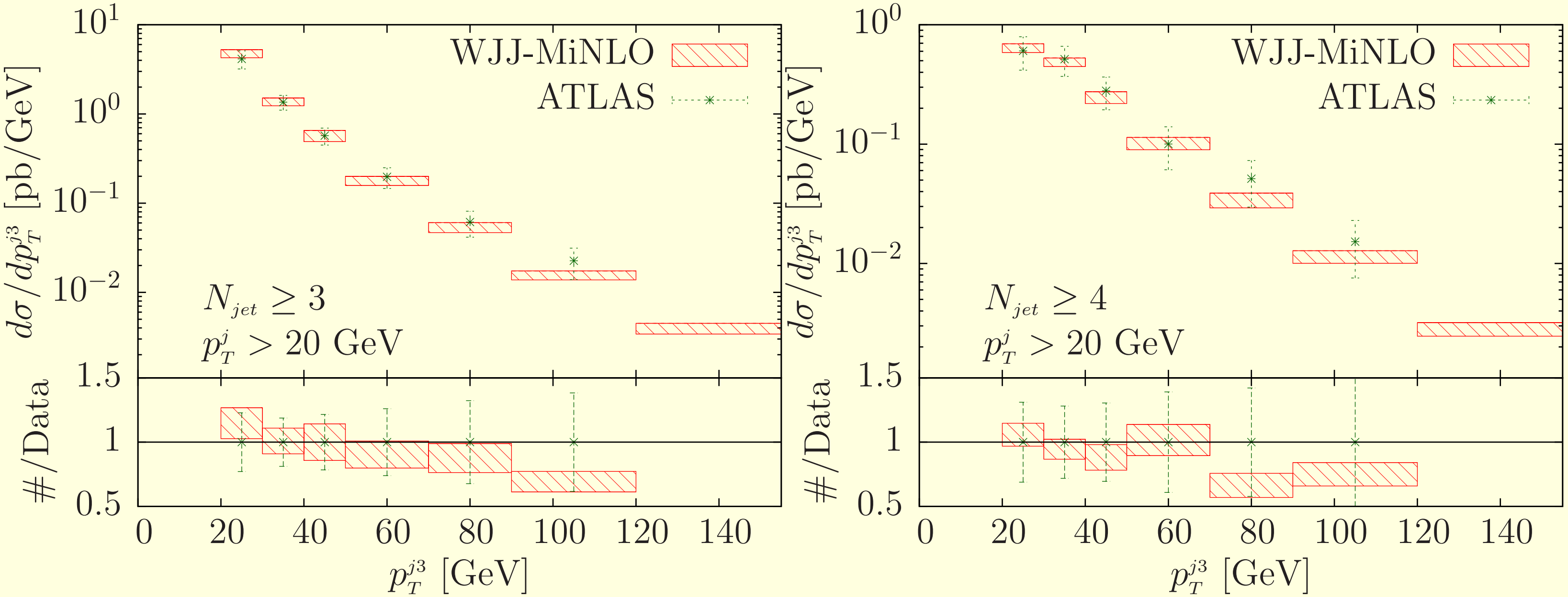
More distributions



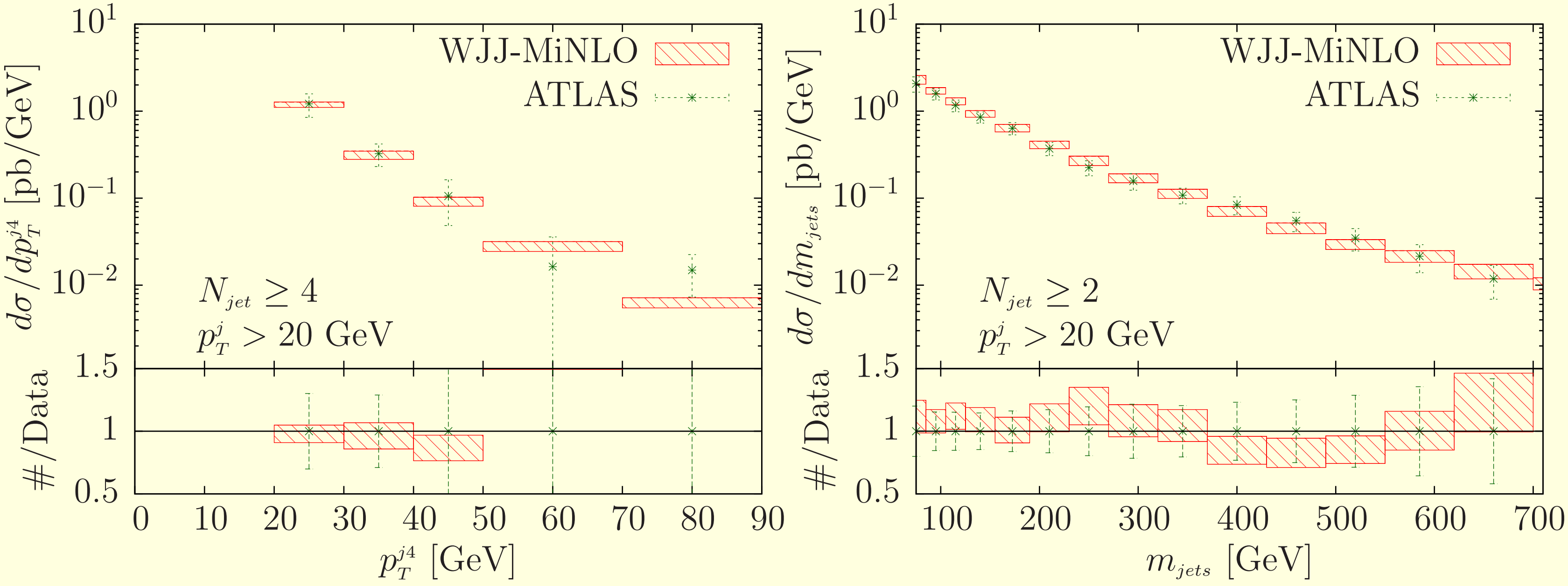

WJJ-MiNLO
ATLAS
$N_{jet} \geq 4$
$p_T^j > 20$ GeV
$d\sigma/dp_T^{j1}$ [pb/GeV]
#/Data
p_T^{j1} [GeV]
$N_{jet} \geq 2$
$p_T^j > 20$ GeV
$d\sigma/dp_T^{j2}$ [pb/GeV]
p_T^{j2} [GeV]



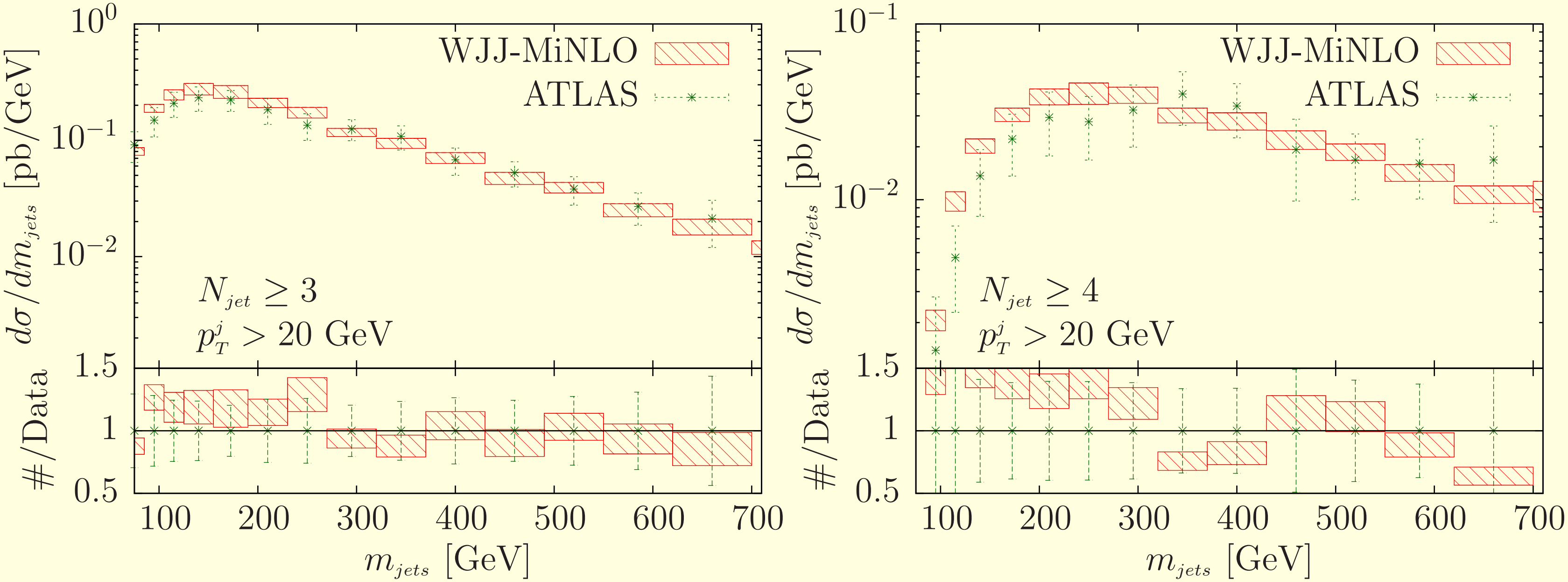
WJJ-MiNLO
ATLAS
$d\sigma/dp_T^{j2}$ [pb/GeV]
$N_{jet} \geq 3$
$p_T^j > 20$ GeV
$N_{jet} \geq 4$
$p_T^j > 20$ GeV
#/Data
p_T^{j2} [GeV]



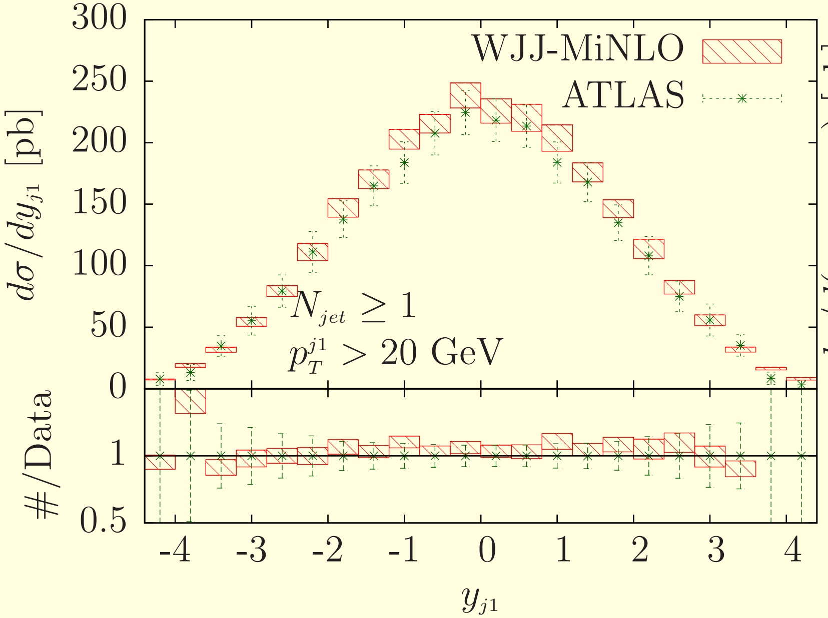
WJJ-MiNLO
ATLAS
$N_{jet} \geq 3$
$p_T^j > 20$ GeV
$d\sigma/dp_T^{j3}$ [pb/GeV]
#/Data
p_T^{j3} [GeV]
WJJ-MiNLO
ATLAS
$N_{jet} \geq 4$
$p_T^j > 20$ GeV
$d\sigma/dp_T^{j3}$ [pb/GeV]
#/Data
p_T^{j3} [GeV]



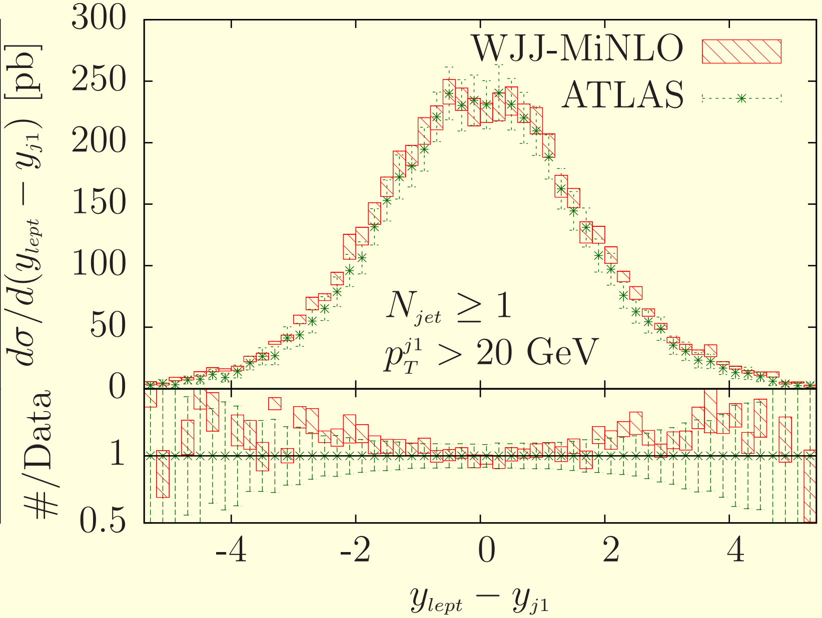
WJJ-MiNLO
ATLAS
$N_{jet} \geq 4$
$p_T^j > 20$ GeV
$d\sigma/dp_T^{j4}$ [pb/GeV]
#/Data
p_T^{j4} [GeV]
$N_{jet} \geq 2$
$p_T^j > 20$ GeV
$d\sigma/dm_{jets}$ [pb/GeV]
m_{jets} [GeV]



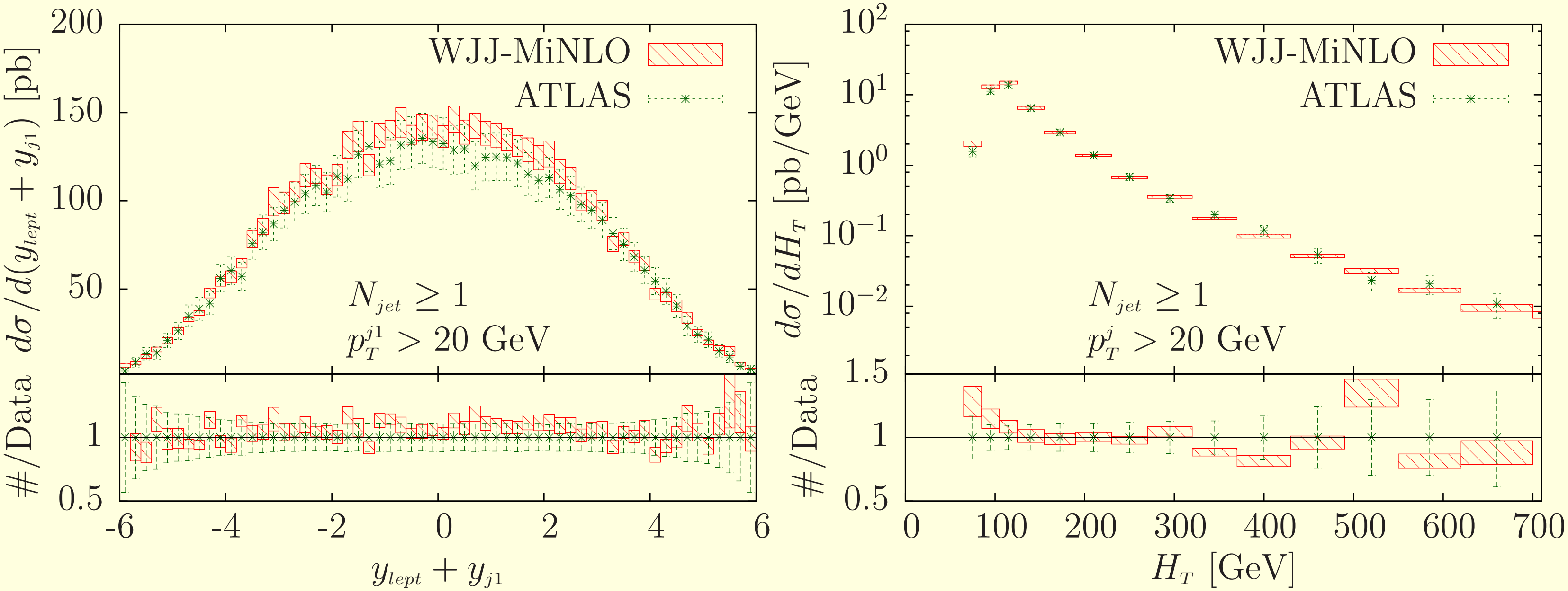
WJJ-MiNLO
ATLAS
$d\sigma/dm_{jets}$ [pb/GeV]
$N_{jet} \geq 3$
$p_T^j > 20$ GeV
#/Data
m_{jets} [GeV]
$N_{jet} \geq 4$
$p_T^j > 20$ GeV



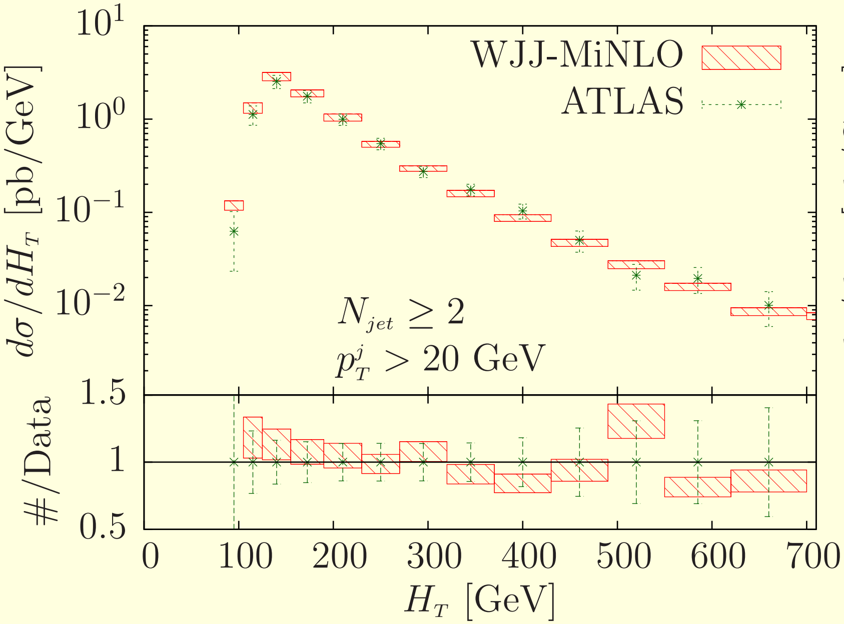
300
250
200
150
100
50
0
WJJ-MiNLO
ATLAS
$d\sigma/dy_{j1}$ [pb]
$N_{jet} \geq 1$
$p_T^{j1} > 20$ GeV
#/Data
1
0.5
-4
-3
-2
-1
0
1
2
3
4
y_{j1}



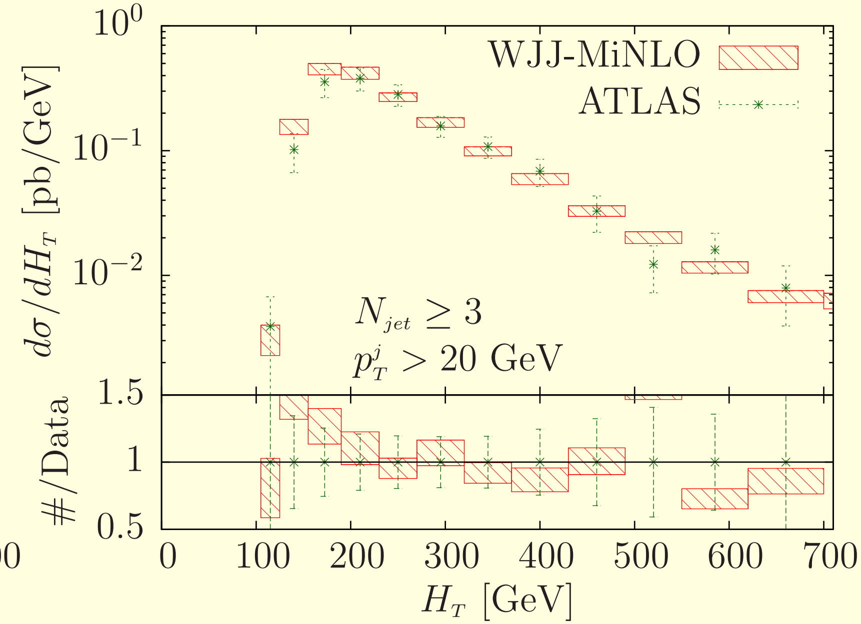
300
250
200
150
100
50
0
WJJ-MiNLO
ATLAS
$d\sigma/d(y_{lept} - y_{j1})$ [pb]
$N_{jet} \geq 1$
$p_T^{j1} > 20$ GeV
#/Data
1
0.5
-4
-2
0
2
4
$y_{lept} - y_{j1}$



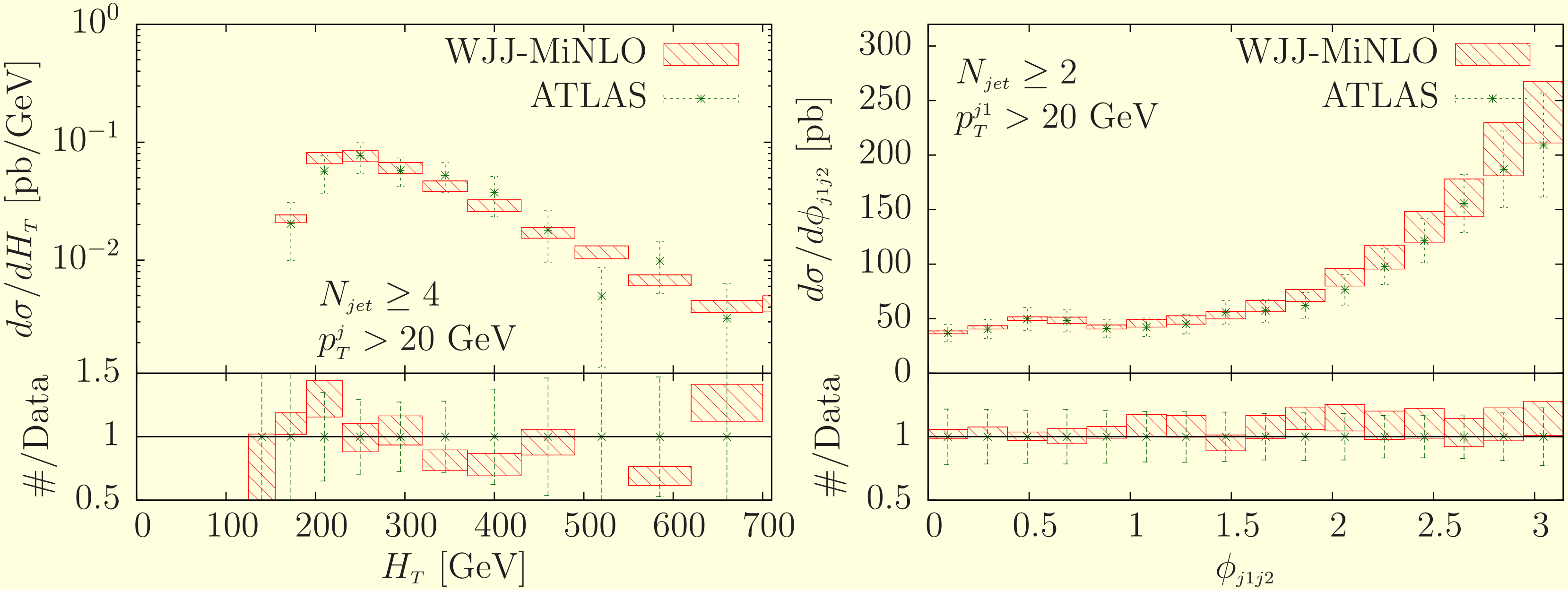
WJJ-MiNLO
ATLAS
$N_{jet} \geq 1$
$p_T^{j1} > 20$ GeV
$d\sigma/d(y_{lept} + y_{j1})$ [pb]
#/Data
$y_{lept} + y_{j1}$
$N_{jet} \geq 1$
$p_T^{j} > 20$ GeV
$d\sigma/dH_T$ [pb/GeV]
H_T [GeV]

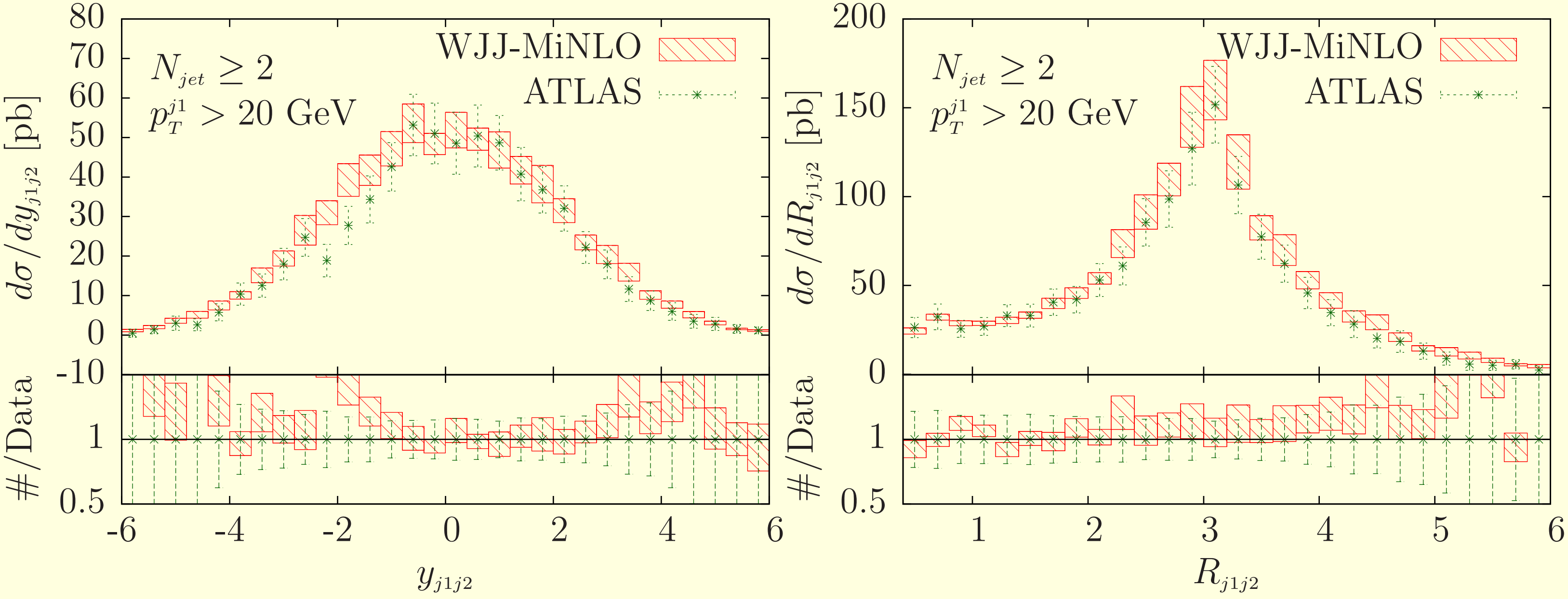


WJJ-MiNLO
ATLAS
$N_{jet} \geq 2$
$p_T^j > 20$ GeV
$d\sigma/dH_T$ [pb/GeV]
#/Data
H_T [GeV]



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


WJJ-MiNLO
ATLAS
$d\sigma/dH_T$ [pb/GeV]
$N_{jet} \geq 4$
$p_T^j > 20$ 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}
$d\sigma/dR_{j1j2}$ [pb]
R_{j1j2}

Conclusions

- Our study aimed at choosing in a proper way μ_R and μ_F in an NLO calculation. We concluded that one MUST include Sudakov form factors in order to do that, and developed the `MiNLO` prescription.

- We realized that in `MiNLO`, when integrating out m jets in a process with N associated jets, we get a fair description of the corresponding process with $N-m$ associated jets.

- In particular, integrating out one jet in processes with one associated jet, we get a description that includes the NLO corrections, but with errors of relative order $\sqrt{\alpha}$.

- By improving certain features of the Sudakov form factor, the $\mathcal{O}(\alpha)$ error can be eliminated, and one reaches full NLO accuracy in processes characterized by the production of a neutral system with one associated jet.

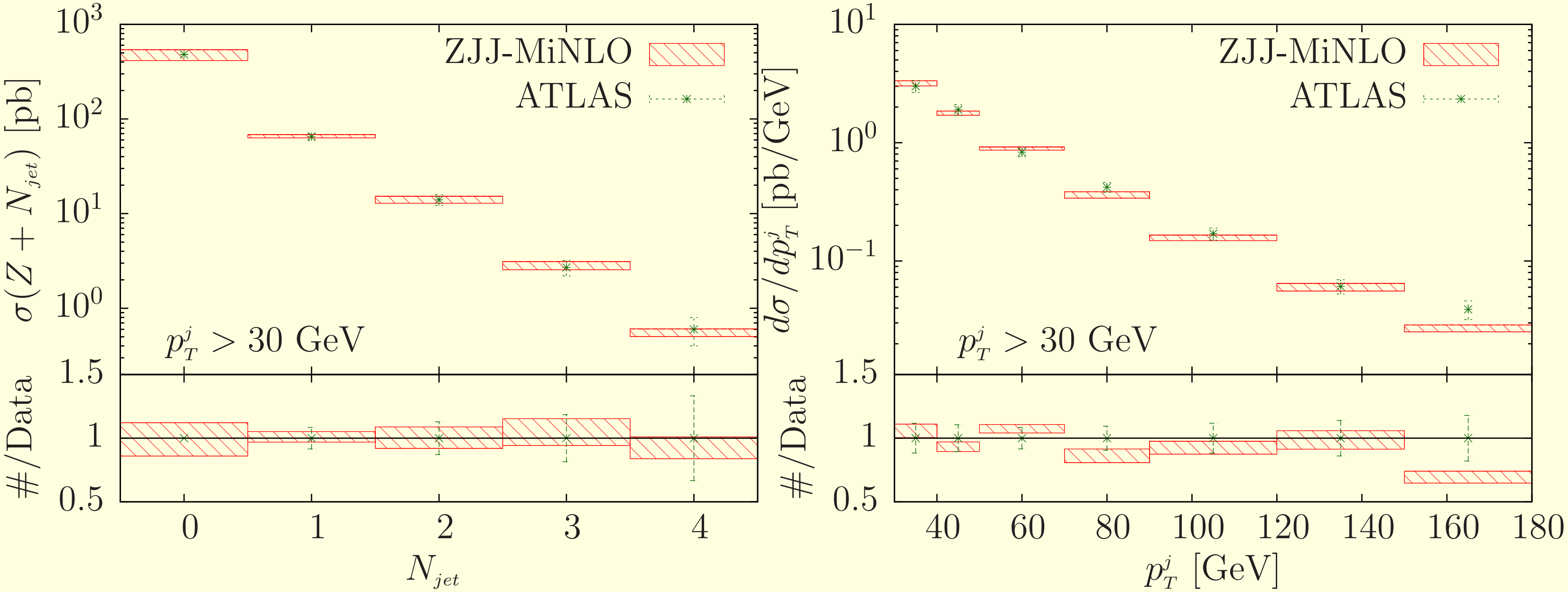
- The MiNLO prescription in processes with one associated jet opens up the possibility of building NNLO+PS generators for processes of hadronic production of a (color) neutral system, like H, W, Z, HW, etc.

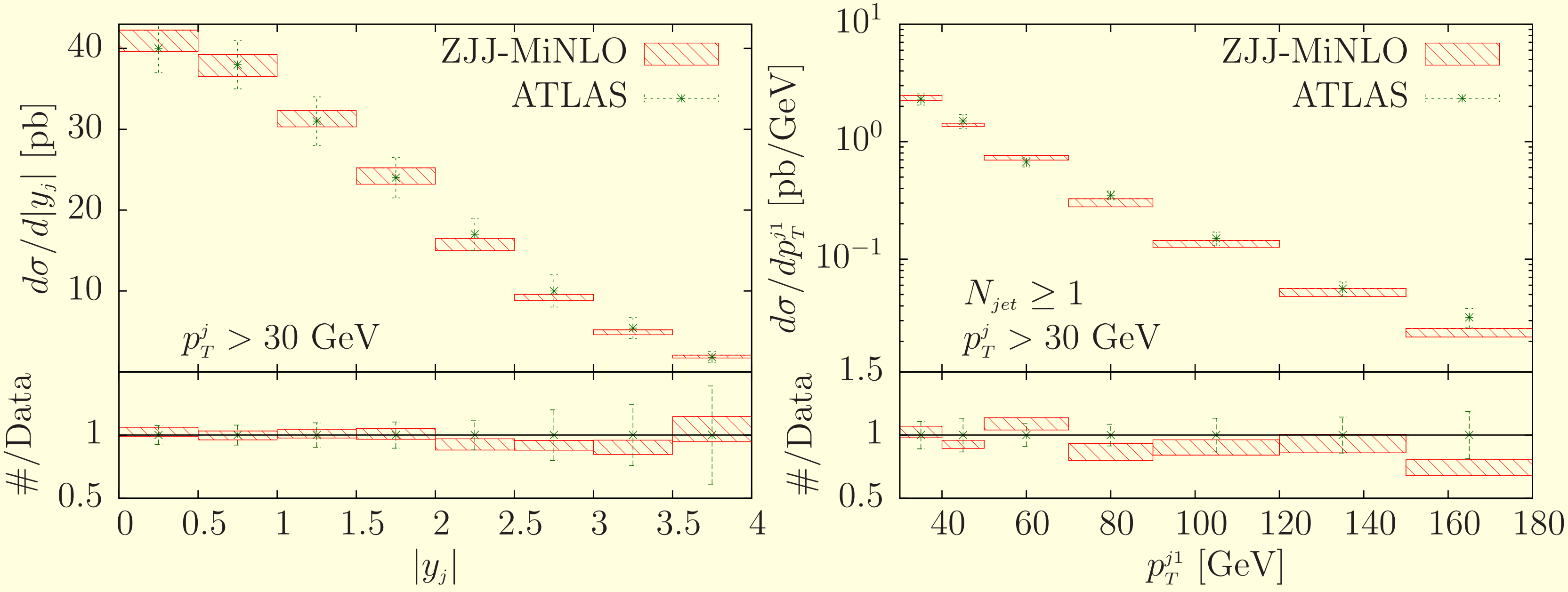
- Whether the MiNLO prescription can be generalized in order to constitute a general solution to the "Merging wihtout merging scale" problem is a subject of current study.

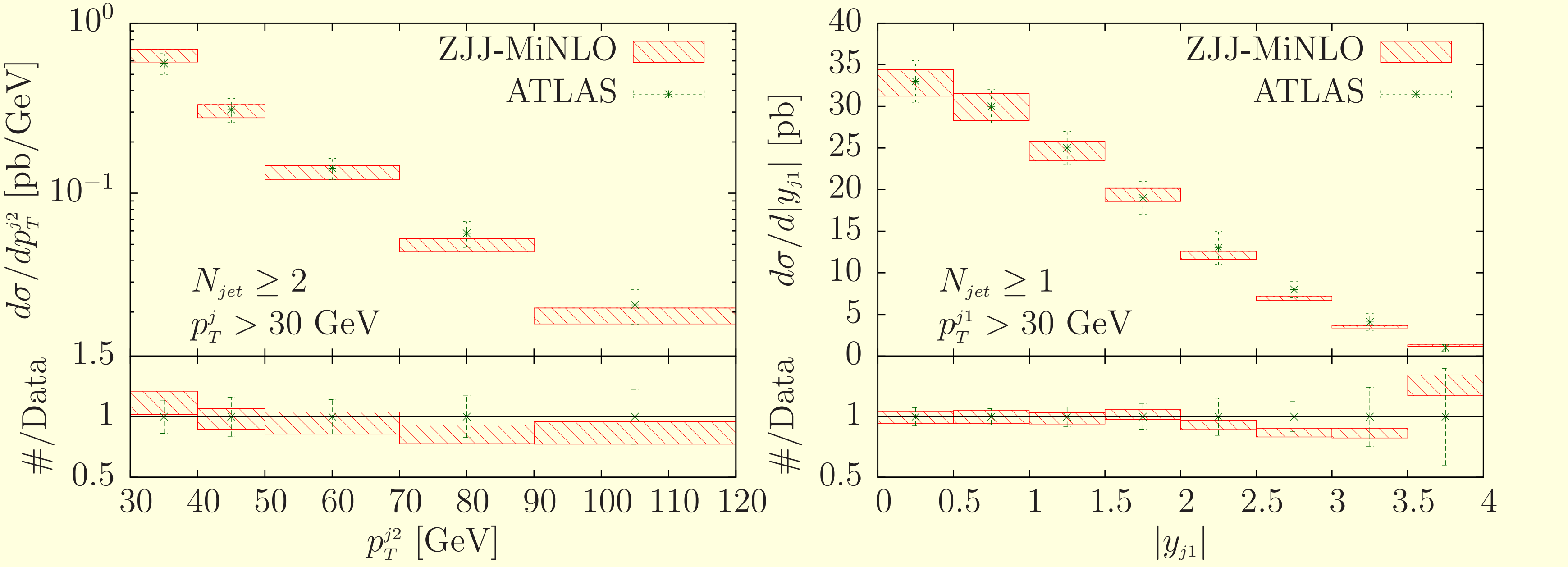
The `MiNLO` prescription is included in the `POWHEG BOX` framework, within a sub-package that can be used to implement a set of new features (reweighting, parallelized grid computation) that will form at some point the Version 2 of the `POWHEG BOX` package.

Backup slides

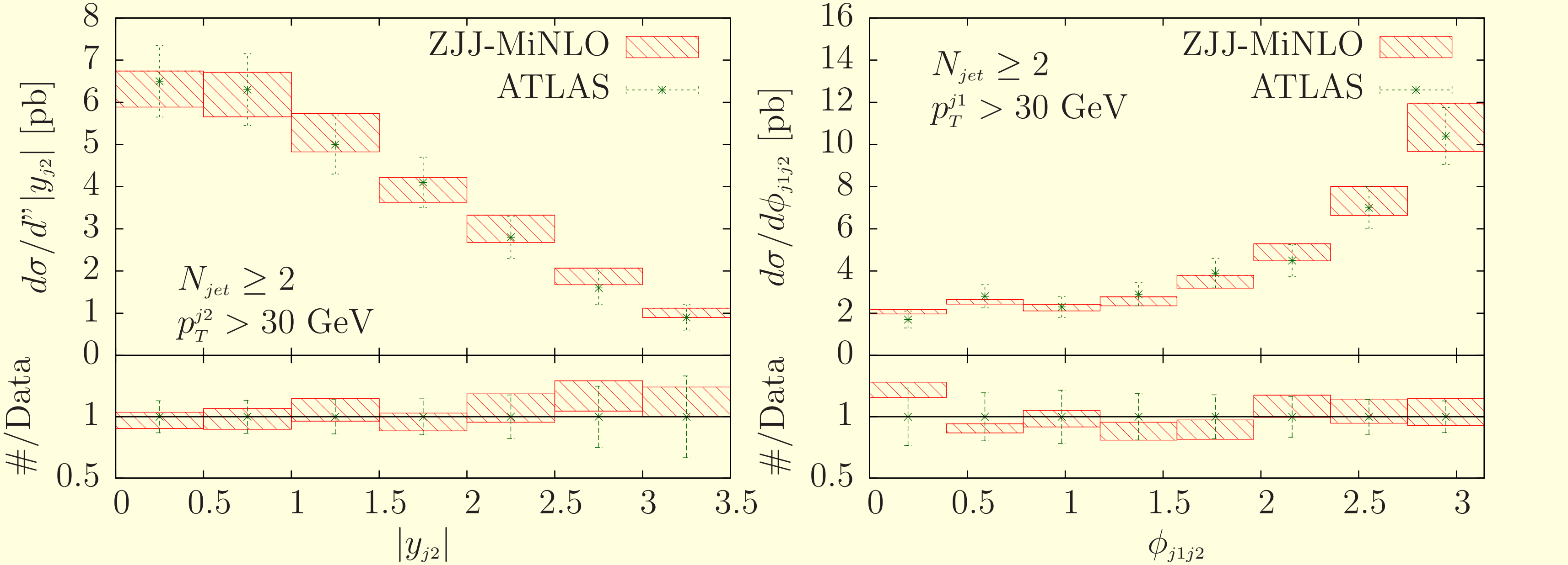
Z2jet results




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



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}

BACKUP