POWHEG-BOX

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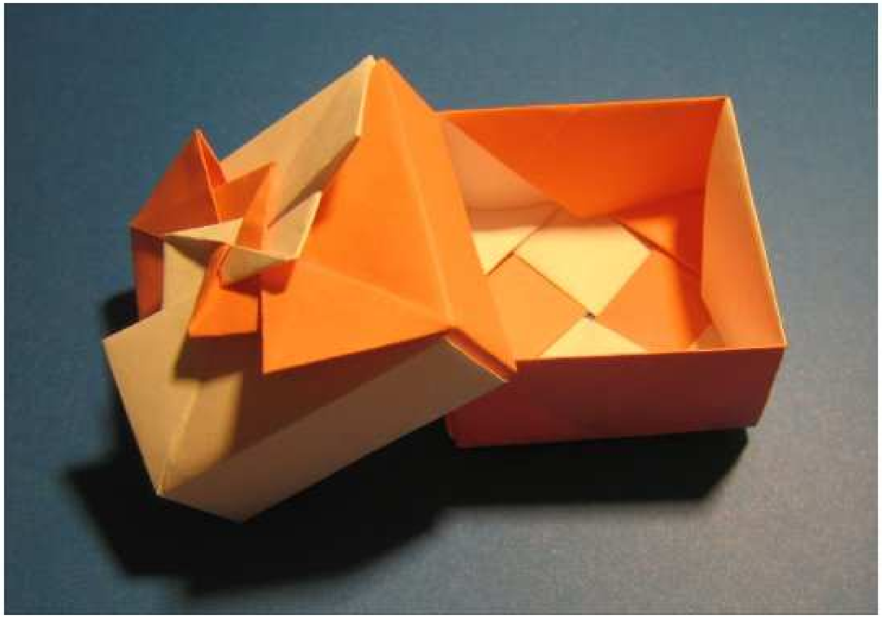
The POWHEG BOX



Project

The POWHEG BOX is a general computer framework for implementing NLO calculations in shower Monte Carlo programs according to the POWHEG method. It is also a library, where previously included processes are made available to the users. It can be interfaced with all modern shower Monte Carlo programs that support the Les Houches Interface for User Generated Processes.

Available Processes

- Single vector-boson production with decay, S. Alioli, P. Nason, C. Oleari and E. Re, *JHEP* **0807** (2008) 060, arXiv:0805.4802 [paper]
- Vector boson plus one jet production with decay, S. Alioli, P. Nason, C. Oleari and E. Re, *JHEP* **1101** (2011) 095, arXiv:1009.5594 [paper]

- Single-top production in the s- and t-channel, S. Alioli, P. Nason, C. Oleari and E. Re, *JHEP* **0909** (2009) 111, arXiv:0907.4076

Plan of the talk

- Status and developments
  - Automation
  - Studies on uncertainties - tuning
- Jets with the `POWHEG BOX`
  - practical item: interfacing to the shower
  - speculative item: more jet observables

Automation

`POWHEG BOX`: an automated framework for implementing any given NLO calculation as a POWHEG generator.
Thus, if one provides:

- The Born phase space
- The Born amplitude, (+Born colour correlated and spin correlated)
- The real amplitude
- The Virtual amplitude

the `POWHEG BOX` does all the rest. Recent processe implemented:
$W^+W^+ + X$, QCD, Melia, Röntsch, Zanderighi, P.N., 2011
$W^+W^+ + X$, EW, Jäger, Zanderighi, 2011
$Wb\bar{b}$, Oleari, Reina, 2011
ZZ, ZW, WW with leptonic decay, Melia, Röntsch, Zanderighi, P.N., 2011
$t\bar{t} + \mathrm{jet}$, Alioli, Moch, Uwer, 2011

Kardos, Papadopoulos and Trocsanyi are combining HELAC-nlo (Bevilacqua, Czakon, Garzelli, Hameren, Kardos, Papadopoulos, Pittau, Worek) an automated package for computing NLO cross sections, with the POWHEG BOX:

$t\bar{t}Z$ production, Garzelli, Kardos, Papadopoulos and Trocsanyi, 2011

$t\bar{t}H$ production, Garzelli, Kardos, Papadopoulos and Trocsanyi, 2011

$t\bar{t}+\mathrm{jet}$ production, Kardos, Papadopoulos and Trocsanyi, 2011

Our current effort (Oleari, P.N.):
MadGraph 4 interface (Rikkert Frederix).
Using this, the only items that are left to the user are

- The Born phase space
- The Virtual

`MCFM`: (Ciaran Williams, Campbell, Ellis) Build an interface to existing MCFM processes.

For the immediate future:
`GoSam`: (Cullen,Greiner,Heinrich,Luisoni,Mastrolia,Ossola,Reiter,Tramontano)
Public generator for virtual amplitudes;

After this, the only missing ingredient for a fully automated generator will be the Born phase space.

Uncertainties and tuning

Uncertainties: Shake the BOX as much as you can without breaking it! We have to vary all what can be varied, but maintaining formal NLO accuracy for inclusive quantities, and formal LL(NLL) accuracy in the shower aspect of POWHEG.

tuning: Within the variations allowed by the above procedure, see if we get a better description of data.

As of now, we (Hamilton, P.N.) are studying two kind of "parameters"

- Factorizatio and renormalization scales
- Separation of $R = R^s + R^f$.

The hardest emission in POWHEG has the form:

$$d\sigma = \underbrace{\bar{B}^s(\Phi_B) d\Phi_B \left[\Delta^s_{t_0} + \Delta^s_t \frac{R^s(\Phi)}{B(\Phi_B)} d\Phi_r \right]}_{S \text{ events}} + \underbrace{\left[\overbrace{R(\Phi) - R^s(\Phi)}^{R^f(\Phi)} \right] d\Phi}_{f \text{ events}}$$

where $R \Rightarrow R^s$ in the soft and collinear limit,

$$\bar{B}^s(\Phi_B) = B(\Phi_B) + \underbrace{\left[\underbrace{V(\Phi_B)}_{\text{infinite}} + \underbrace{\int R^s(\Phi)\, d\Phi_r}_{\text{infinite}} \right]}_{\text{finite}}$$

and

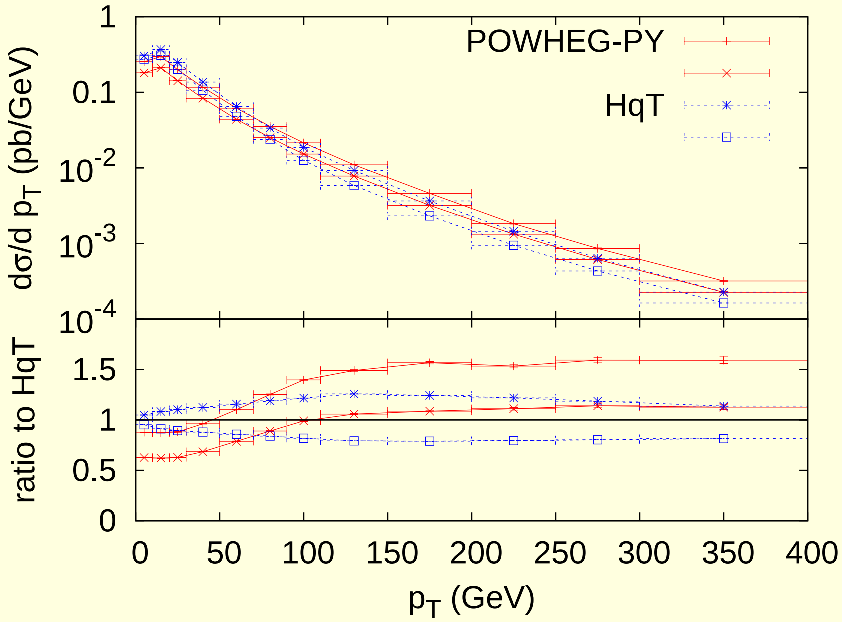
$$\Delta^s_t = \exp\left[- \int_{t_l} \frac{R^s}{B} d\Phi_r \theta(t(\Phi) - t_l) \right]$$

one can often choose $R^s = R$, $R^f = 0$, but other choices are possible.

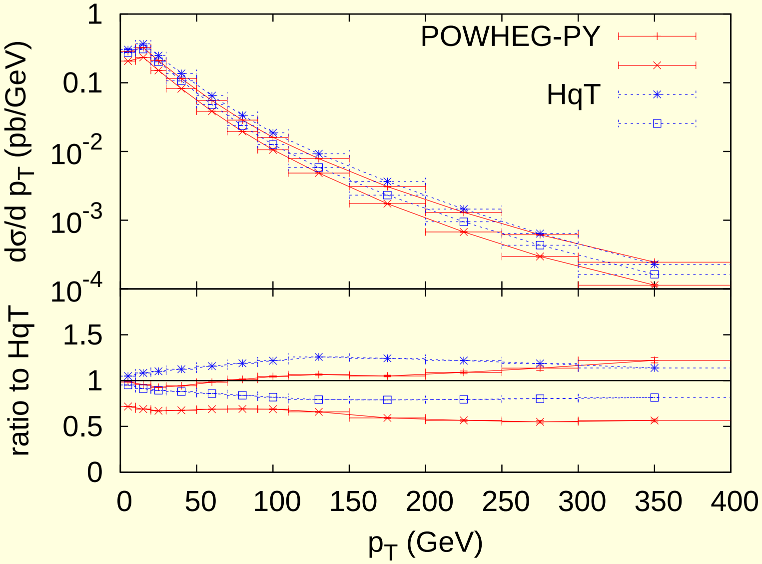
Choose

$$R^s = \frac{h^2}{p_T^2 + h^2}\, R\,, \quad R^f = \frac{p_T^2}{p_T^2 + h^2}\, R\,,$$

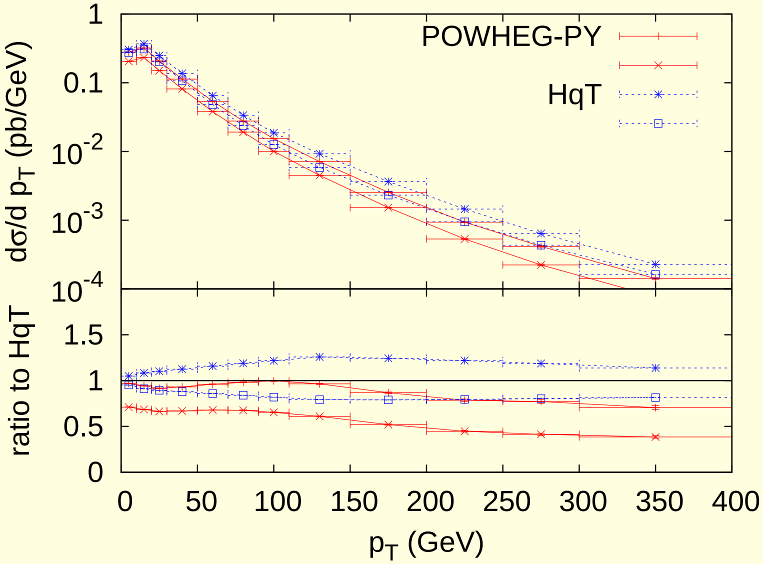
and there is freedom to vary h from a scale of the order of the basic hard process up to infinity. Example: Higgs production; tune output to HqT



$$h = \infty,\, \mu = M_H$$



$$h \approx M_H, \mu = M_H$$



$$h \approx M_H, \mu = \sqrt{M_H^2 + p_t^2}$$

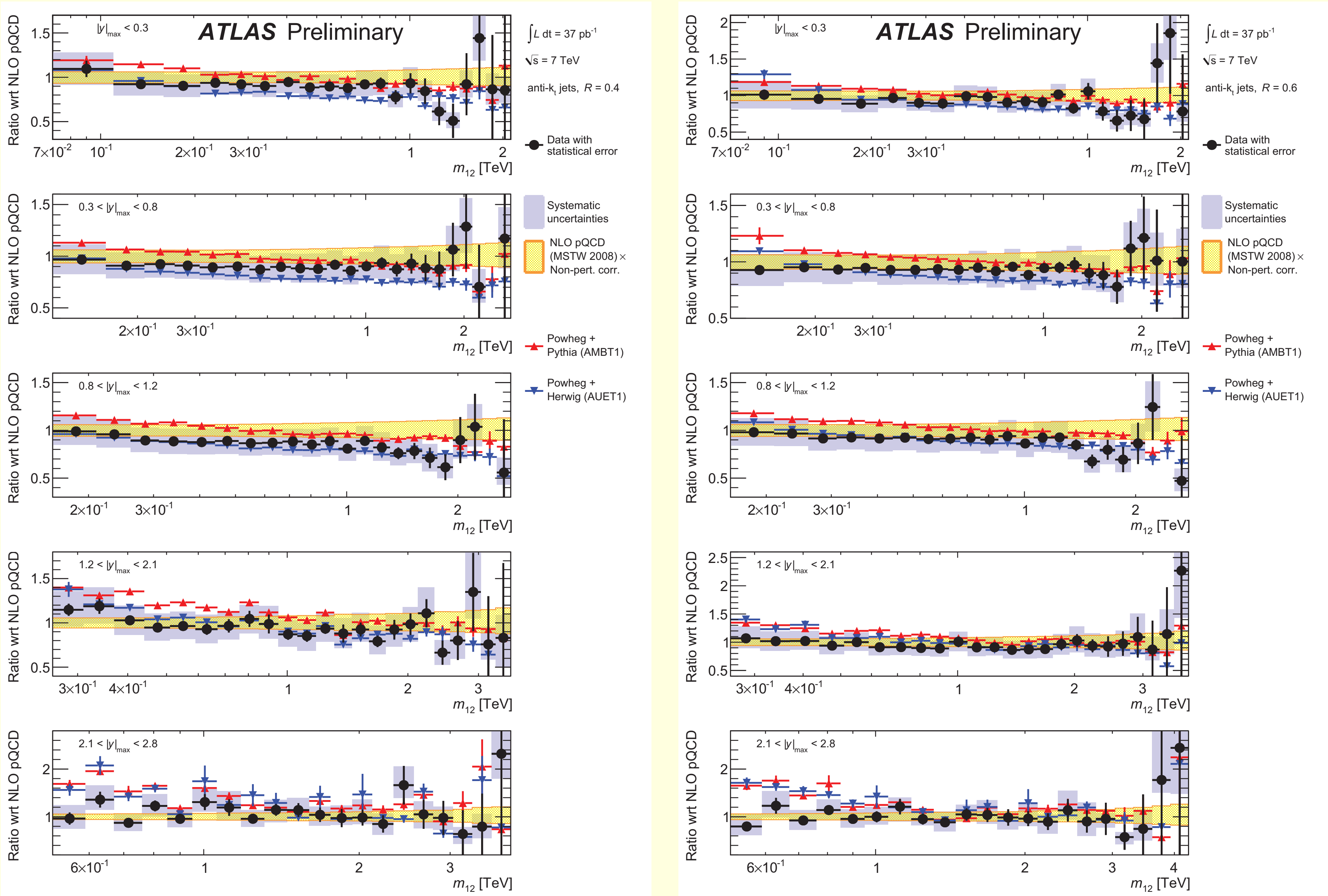
where the bands are obtained by varying the scales by a factor of 2 above and below the central value.

Jets with the POWHEG BOX

Dijet cross section available in the POWHEG BOX since the end of 2010.

2 topics:

- Practical item: problems that have arised in its usage
- ”Speculative” item: can we extend the scope of jet physics tests?



ATLAS Preliminary
∫L dt = 37 pb⁻¹
√s = 7 TeV
anti-k_t jets, R = 0.4
Data with statistical error
Systematic uncertainties
NLO pQCD (MSTW 2008) × Non-pert. corr.
Powheg + Pythia (AMBT1)
Powheg + Herwig (AUET1)
|y|max < 0.3
0.3 < |y|max < 0.8
0.8 < |y|max < 1.2
1.2 < |y|max < 2.1
2.1 < |y|max < 2.8
Ratio wrt NLO pQCD
m12 [TeV]
ATLAS Preliminary
∫L dt = 37 pb⁻¹
√s = 7 TeV
anti-k_t jets, R = 0.6

ATLAS 2011-047-v2: extensive study of inclusive jet and dijet production; comparisons with POWHEG and NLO QCD (+ pdf studies, etc.)
Lots of work also from our side in the past three monts or so ... Issues:

- NLO yellow band corrected for hadronization effects (using hadron/parton from PYTHIA)
- NO SCALE VARIATION in NLO band (only PDF and hadronization)
- Signal of problems at large y
- ATLAS generated the POWHEG sample using weighted events, in order to cover the 8 or more order of magnitude spanned by the cross section

Using POWHEG in this mode, interfaced to PYTHIA, causes rare events with large weight. Rare events with large weight are also present if HERWIG+Jimmy is used. These events lead to spikes in distributions.
The ATLAS people devised a do-it-yourself method to get rid of spikes.
We know understand the problem in the PYTHIA case, and have also found theoretically sound solutions. We do not find marked differences with respect to the ATLAS approach using our solutions.

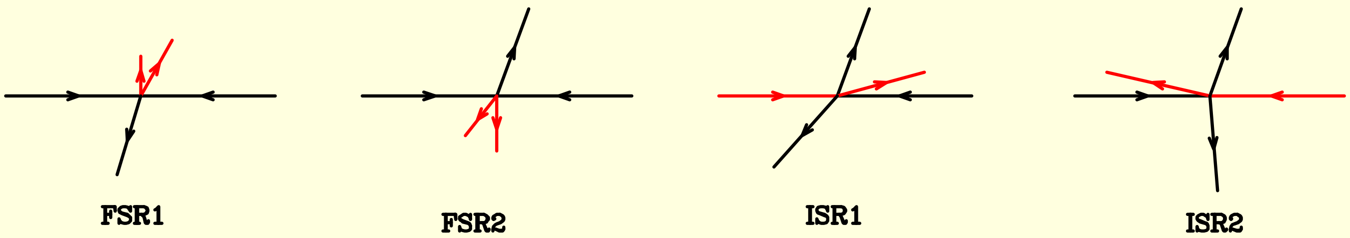
ATLAS also found a do-it-yourself method to get rid of spikes in the HERWIG+Jimmy case. Here we don't understand the problem well.

In PYTHIA a flag (mstp(86)=1) is used to have MPI with dijet, in order to avoid overcounting by having a secondary interaction harder than the jet in the primary process. It is unclear to us what to do with Jimmy in this case.

The large difference PYTHIA/HERWIG is also not understood at the moment.

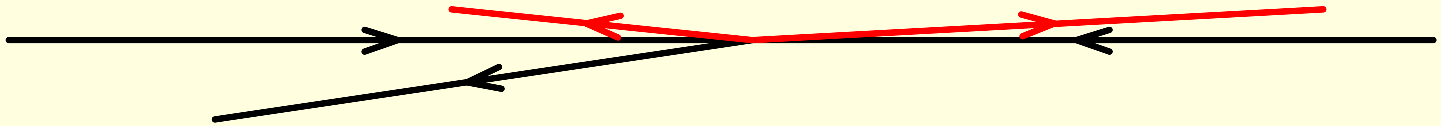
Origin of the problem:

POWHEG separates the real cross section for 3 parton production into the sum of 4 contributions:



so that $R = R_{\rm FSR1} + R_{\rm FSR2} + R_{\rm FSR3} + R_{\rm FSR4}$, with the requirement that each contribution is singular only in the appropriate singular region (notice that FSR1 and FSR2 are actually the same, and POWHEG combines them).

POWHEG generates radiation for each region, picks the hardest one, and passes the event to the Shower, instructing it not to produce any harder radiation. The separation of region is a soft one (i.e., it is not performed with theta functions, but with suppression factors) so that, when using the program in weighted event mode, events like



with a final state parton splitting into a large mass system, but all transverse momenta being in fact small. This event is passed with a large value of the shower theshold to PYTHIA, that can generate a high p_T MPI event on top of it. This event is very rare, but it has a large weight. When running in weighted event mode, the cross section is suppressed by a power of the pt before the splitting. The events are output with the inverse of this factor as a weight.

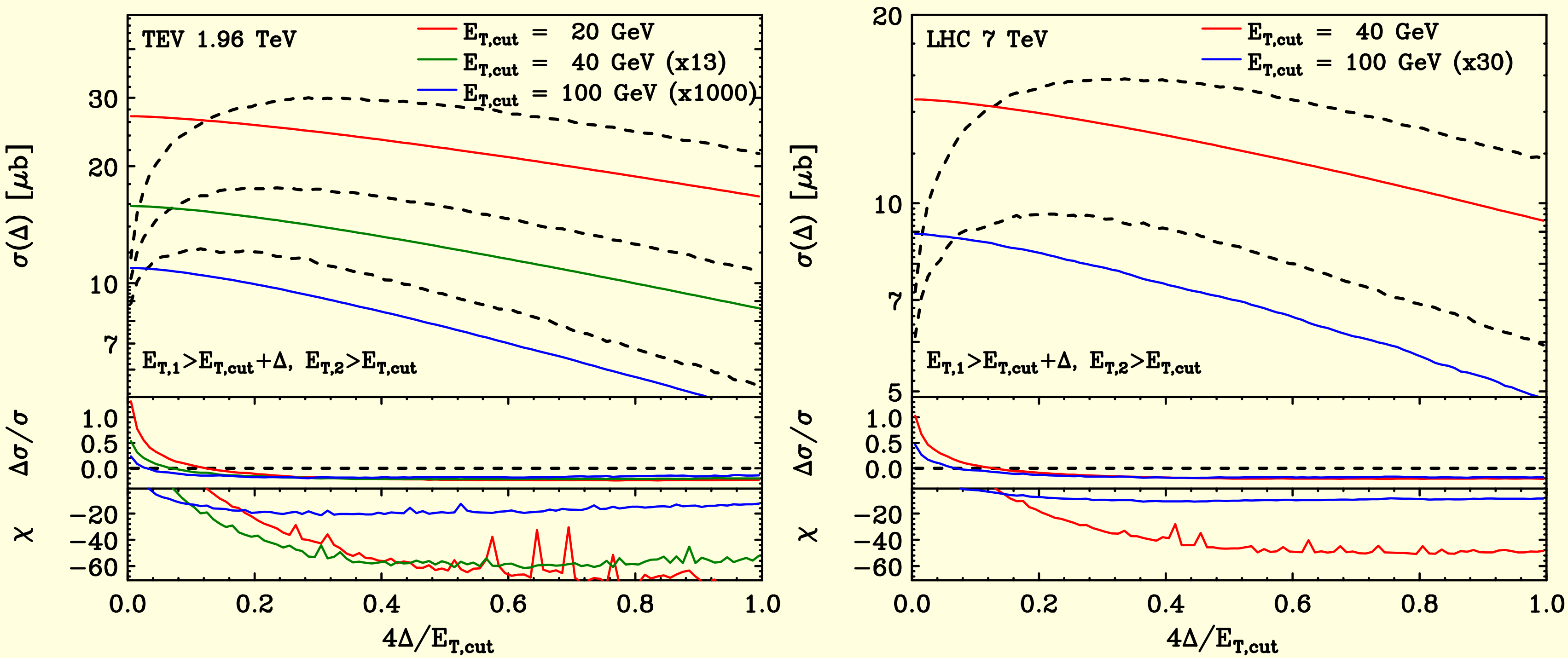
Remedies (besides Atlas do it yourself method):

- Limit SCALUP to the largest p_T of the initial parton
- Clusterize the LH event in p_T, limit SCALUP to the p_T of the smalles cluster
- Use hard theta functions to separate the regions
- Others, not yet attempted: improve drastically the separation of singular regions, also making it flavour dependent, etc.

All these remedies achieve the objective, and yield distributions that are compatible among each other (and with Atlas method).
We (Oleari, P.N.) are working to find a best recipe among these (i.e. the simplest one that does the job), to use as future default for the generation of events with jets.

POWHEG dijets and jet observables

Consider the example of dijet cross setion with symmetric cuts:

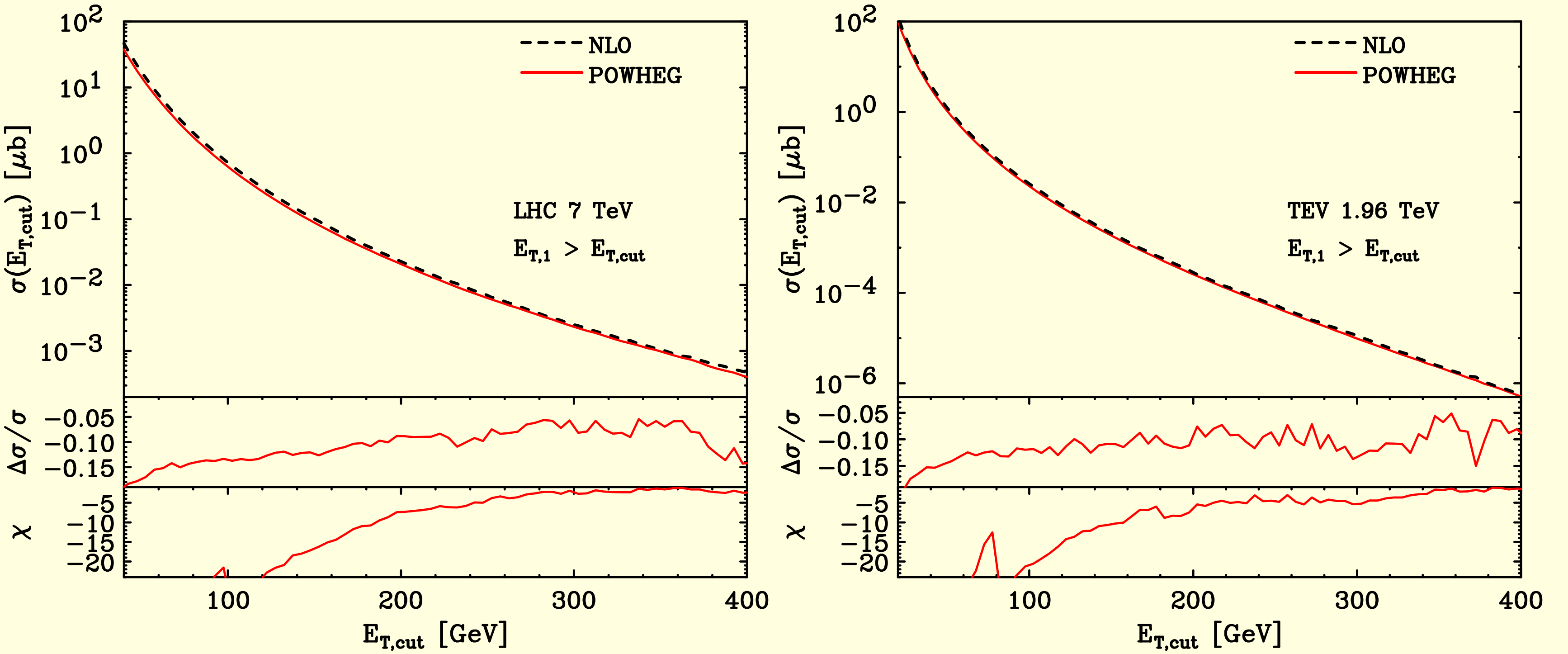


Clearly, the pure NLO calculation is unreliable when $\Delta = 0$.

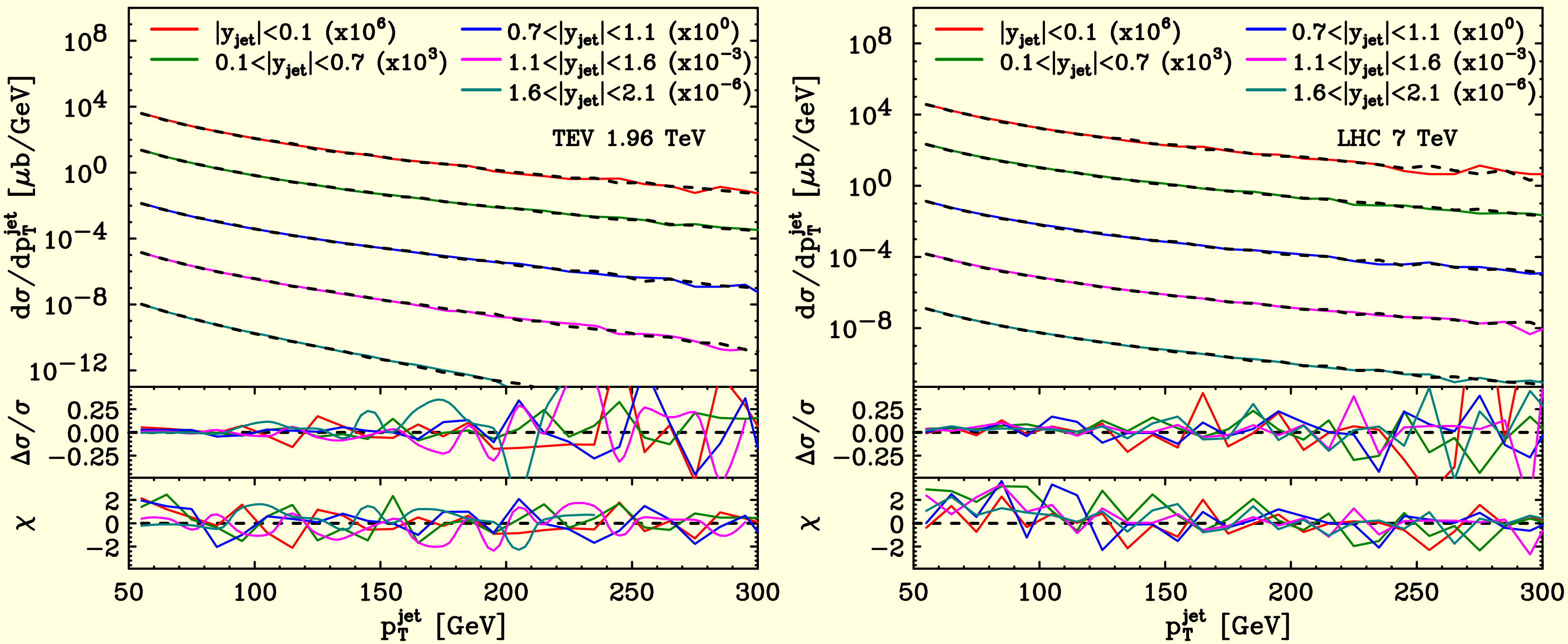
This was realized early by Frixione and Ridolfi, who noticed that the NLO cross section with symmetric cuts could even become negative.

However: the jet cross section with symmetric cuts is a perfectly acceptable IR safe observable. If it didn't turn negative perhaps we wouldn't have even noticed the problem.

Notice that even for large Δ a 10% difference between NLO and POWHEG remains. Cross section with a cut on the hardest jet:



On the other hand, the inclusive jet cross section at NLO and LHEF level agree:



Questions:

- Has jet analysis been biased by observables that yield better QCD fits?
- Is it possible to see these effects in data, looking also at IR safe variables that have problems in fixed order PQCD?

Conclusions

- Progress with automation; all elements falling into place
- The experimental community is asking for uncertainty bands; we look for recipes to provide them
- Jets: work in progress to polish the interface with the shower
- We need to now to what extent the NLO+PS dijet is better than NLO alone

Recent developments

NLO+PS (i.e. POWHEG and MC@NLO) do the following:

- Act as an extended Matrix Element Correction (MEC). Standard shower Monte Carlo implement MEC only for a limited set of processes (i.e. $2 \to 1$), while NLO+PS do this for generic processes. Thus, the hardest radiation from a given primary process is correct at LO in NLO+PS
- The integral of the bulk of the radiation region (typically when the hardest jet is collinear or soft, or is not there) has NLO accuracy.

Radiation beyond the hardest jet is accurate only in the collinear limit. Studies on merging NLO+PS and ME+PS have been carried out in the POWHEG BOX framework (Hamilton, P.N. 2010).

Now Alioli, Hamilton and Re are extending this study, in vector boson production, for merging NLO+PS V production and NLO+PS $V + J$ production, within the POWHEG BOX.

This uses the following facts:
The POWHEG BOX has two components:

i. Generation of the inclusive NLO cross section

ii. Generation of radiation

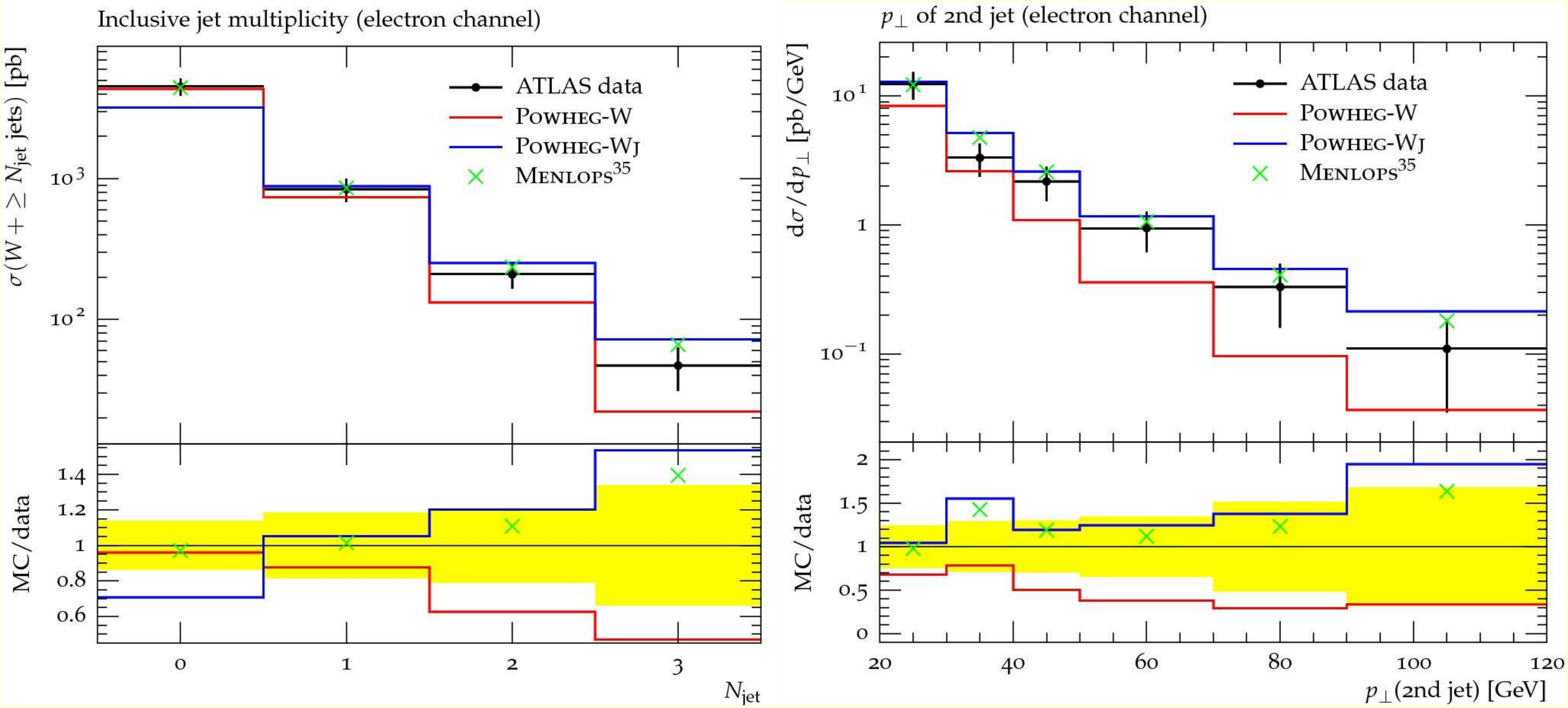
where (i) plays the role of the hard cross section, and (ii) the Shower Algorithm in a stadard Shower MC.
In principle, one can use the (ii) component to build an ME+PS generator without any matching scale. For example, in vector boson production:

- generate the Born configuration (i.e. V kinematics)
- feed it to (ii) in POWHEG BOX for V production: get $V + \mathrm{parton}$
- feed $V + \mathrm{parton}$ to (ii) in POWHEG BOX for $V + j$: get $V + 2p$

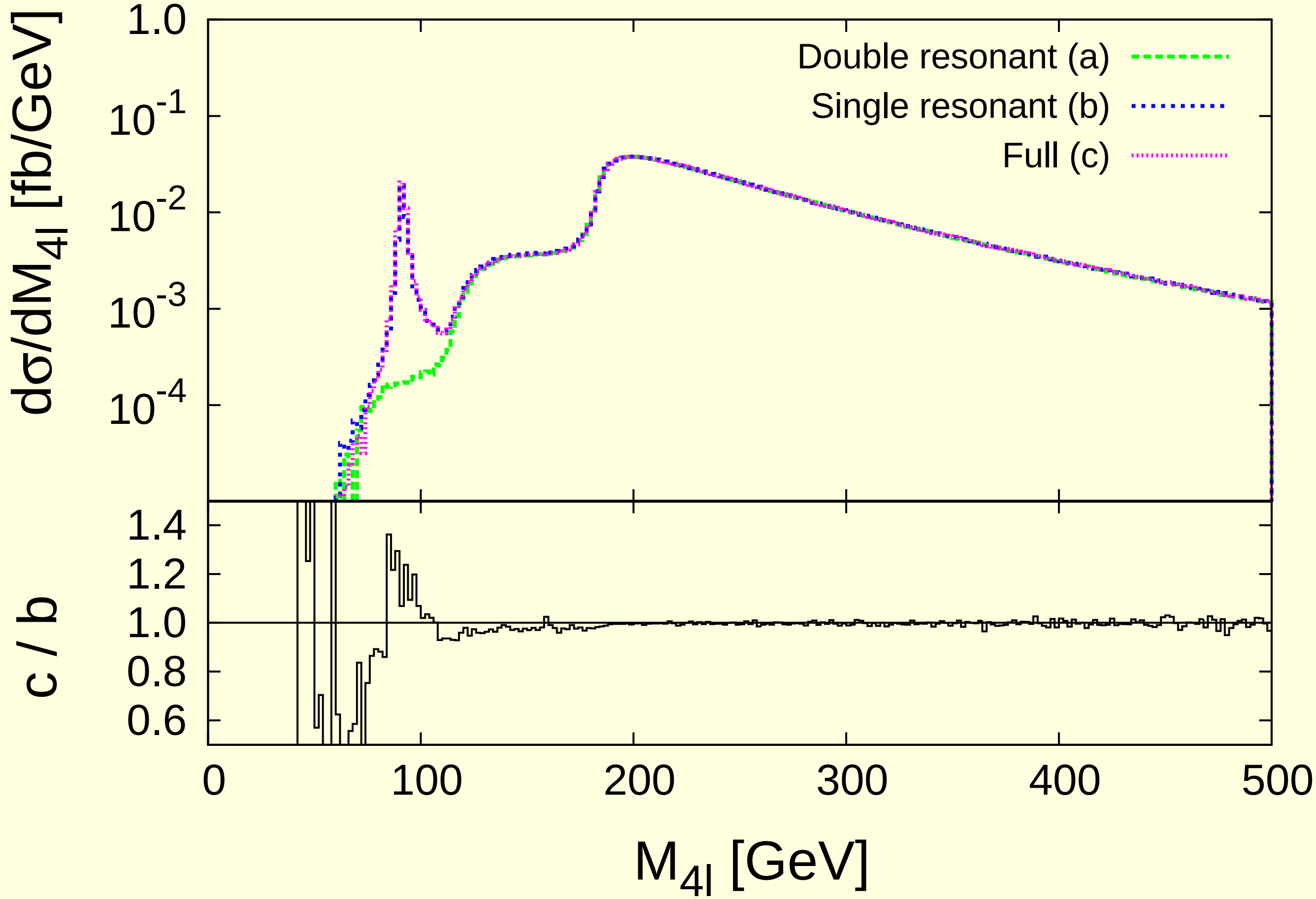
and so on. The output is analogous to what you would get in an ME+PS generator by sending the matching scale to zero.

Alioli, Hamilton and Re generate full NLO V production events with POWHEG, and feed them to the (ii) of $V + j$ code. This adds a second jet with ME accuracy, but maintains NLO accuracy for V production inclusive quantities.

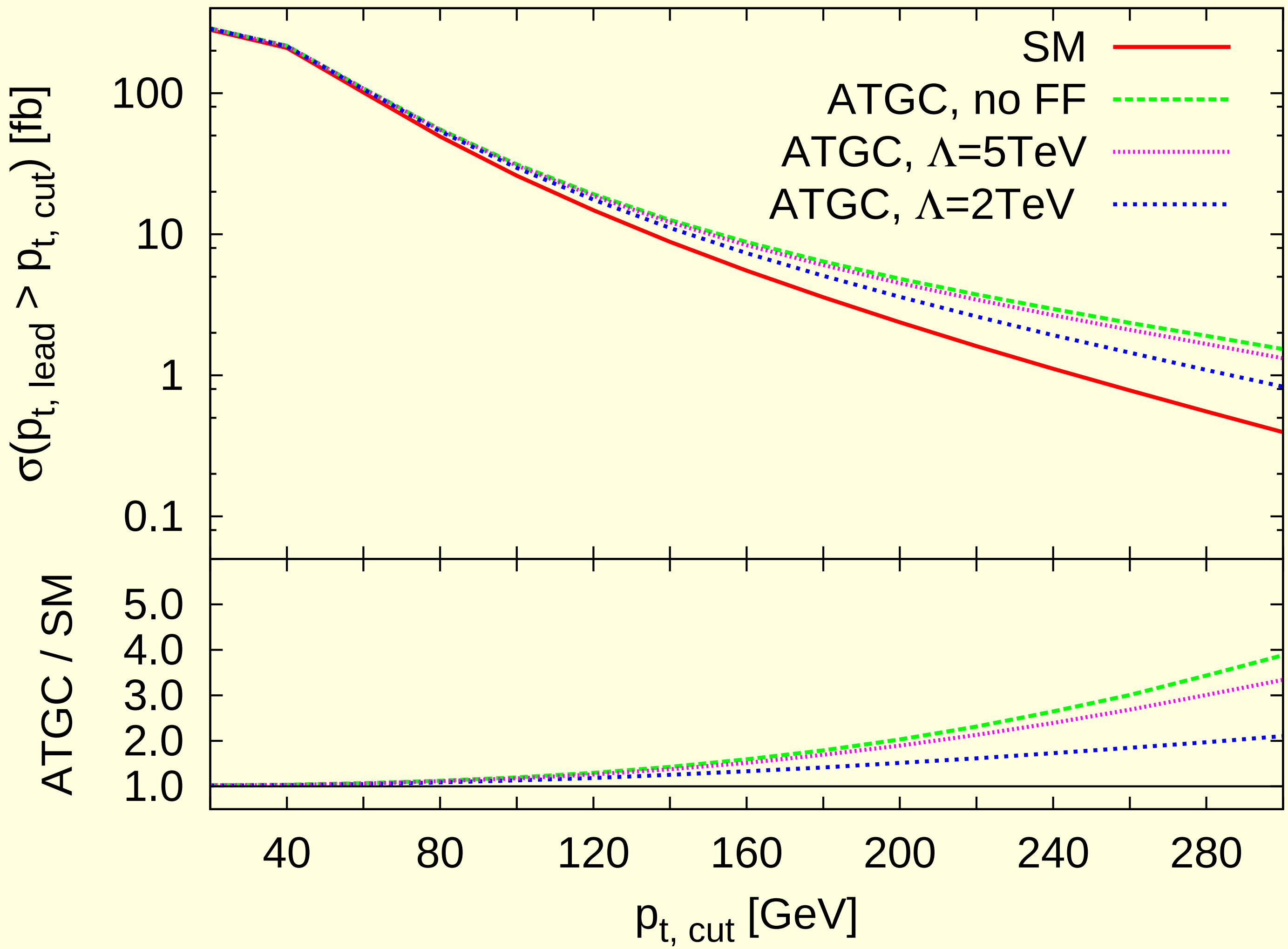
The next step is to improve again on this output by merging it with the output of the full NLO $V + j$ generator, in such a way that, in the hard jet region, this generator prevails, and in the small pt region, the first sample prevails. This works as a practical extension of ME+PS matching to NLO level for up to 1 extra jet in Z production, keeping LO matching for 2 jets.



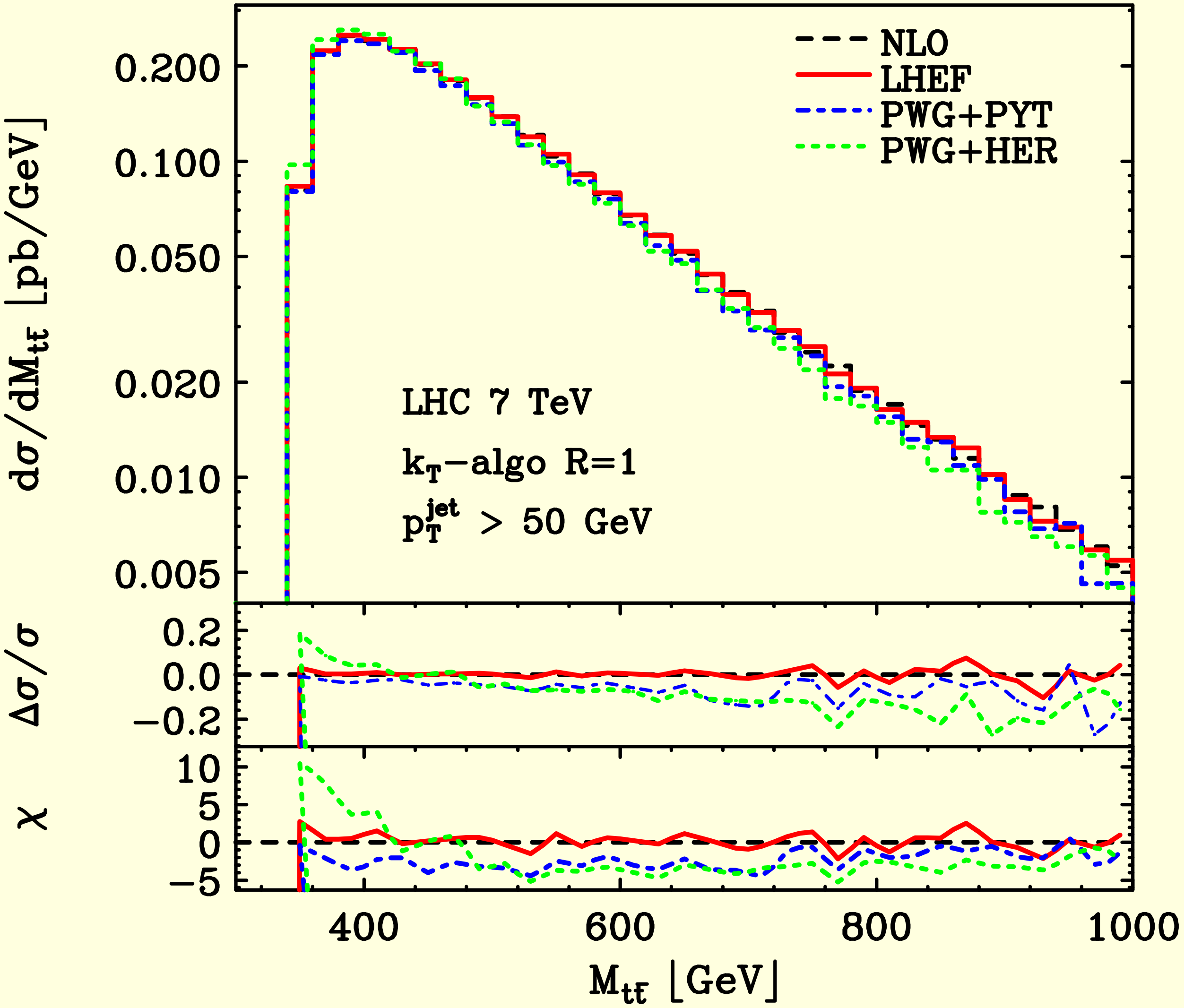
ZZ, W^+W^-, ZW: ME from Dixon, Kunszt, Signer 1998, as in MCFM (Campbell, Ellis, Williams 2011): Z/γ interference included, single resonant graphs included. We also added interference for identical fermions. In ZZ:



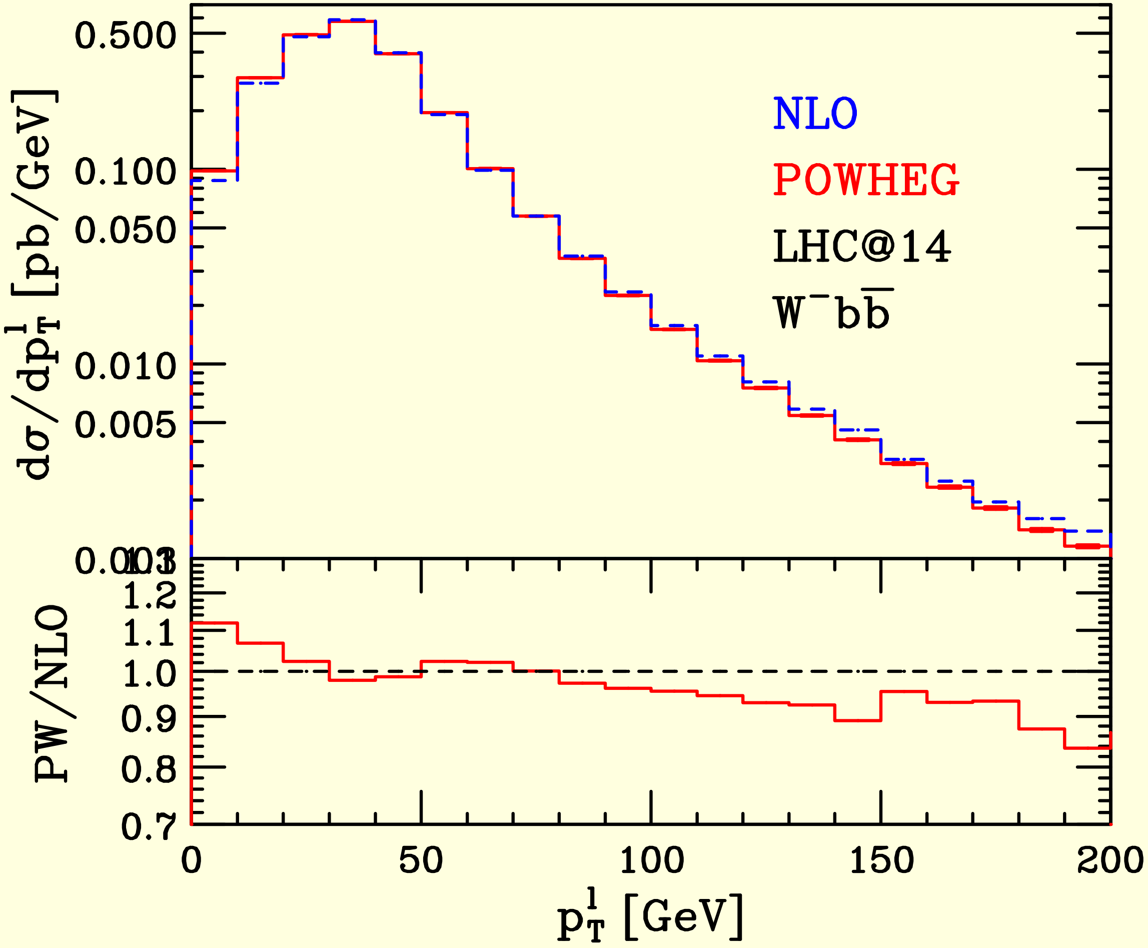
W^+W^-, anomalous couplings



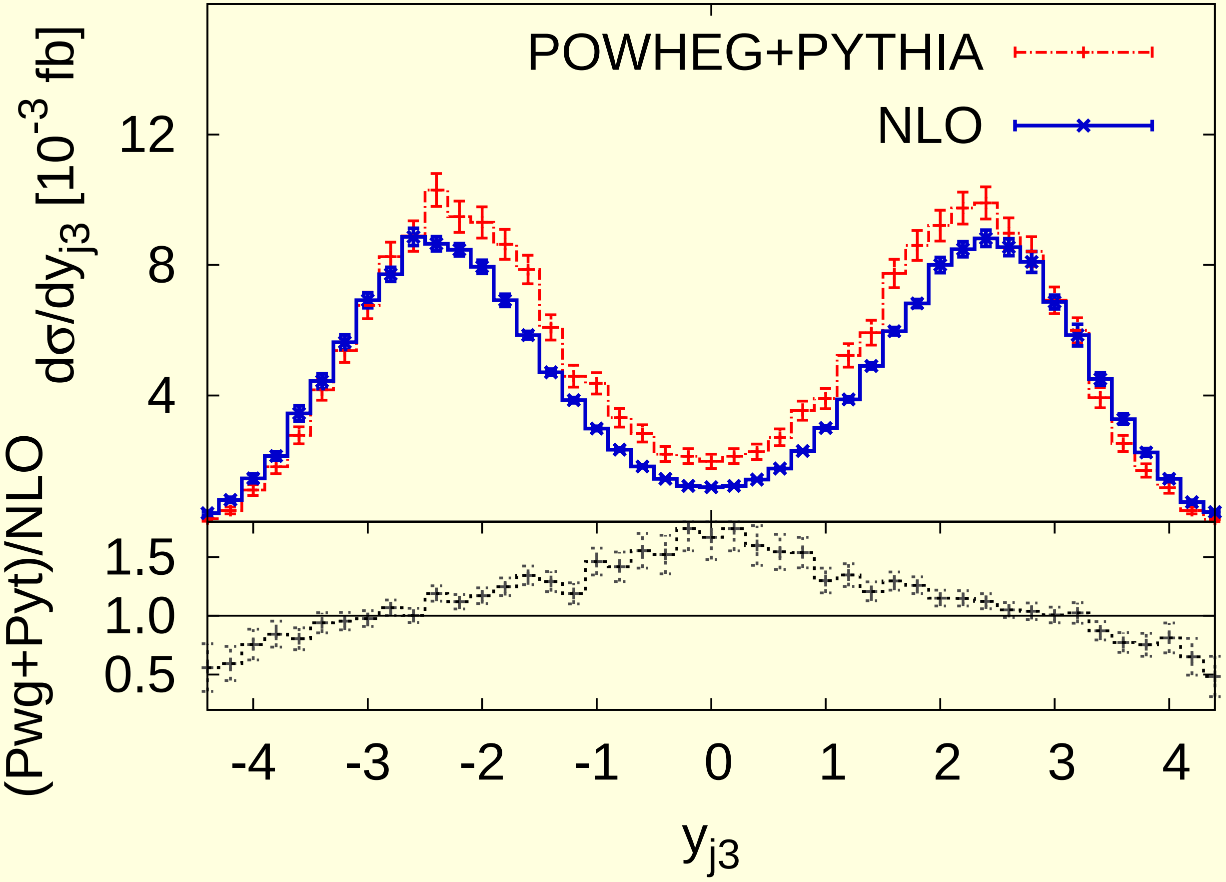
$t\bar{t}j$ production (Alioli, Moch, Uwer, 2011)



$Wb\bar{b}$ production (Oleari, Reina, 2011)



W^+W^+jj, Electro-Weak production, (Jäger, Zanderighi, 2011)



Comparison with data

Experimental collaborations are using POWHEG BOX generators. Understanding the comparison with data will become an important part of our work.

We did PS+NLO because it seemed to be a useful thing to do. Now is time to understand how is it going to be useful.

We are at a very early stage, but no clear pattern is seen at the moment.

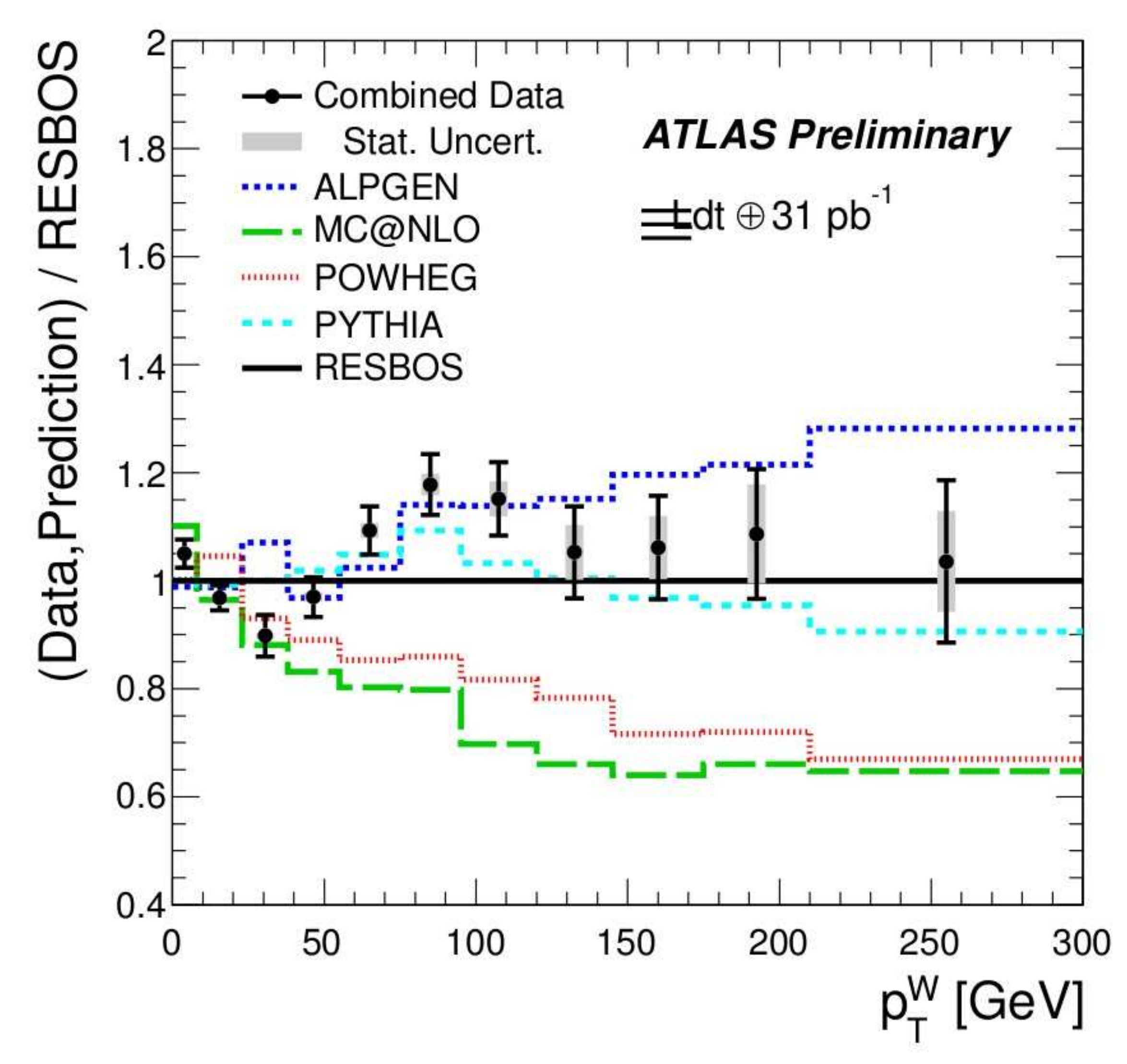
Instead, comparisons rise many questions that we need to answer.

From Ryan Rice talk at EPS: PYTHIA and ALPGEN seem to work better than POWHEG and MC@NLO.

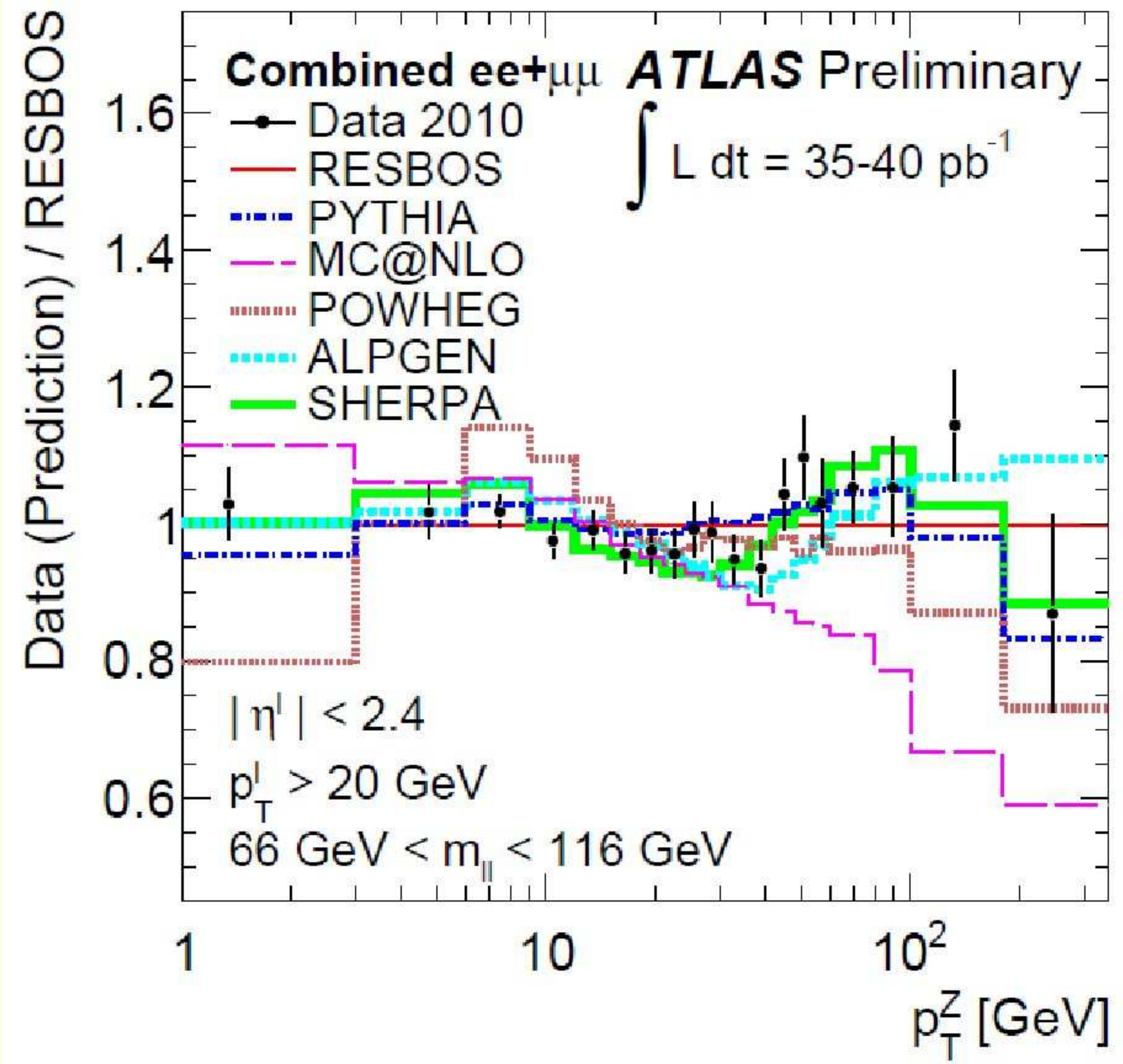
Questions:

are PYTHIA and ALPGEN rescaled by a K-factor?

Why the disagreement at large p_T? They should all be the same.

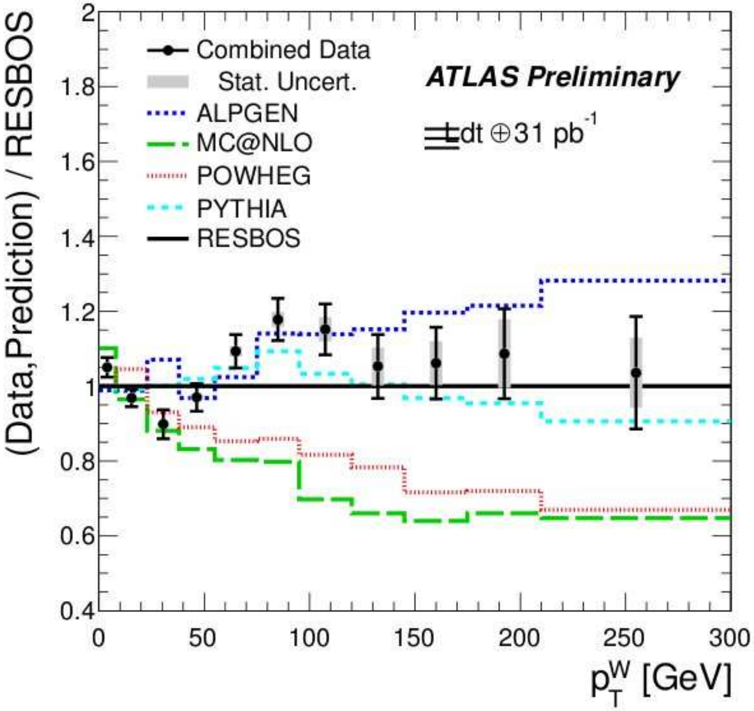


L Kashif, PLHC



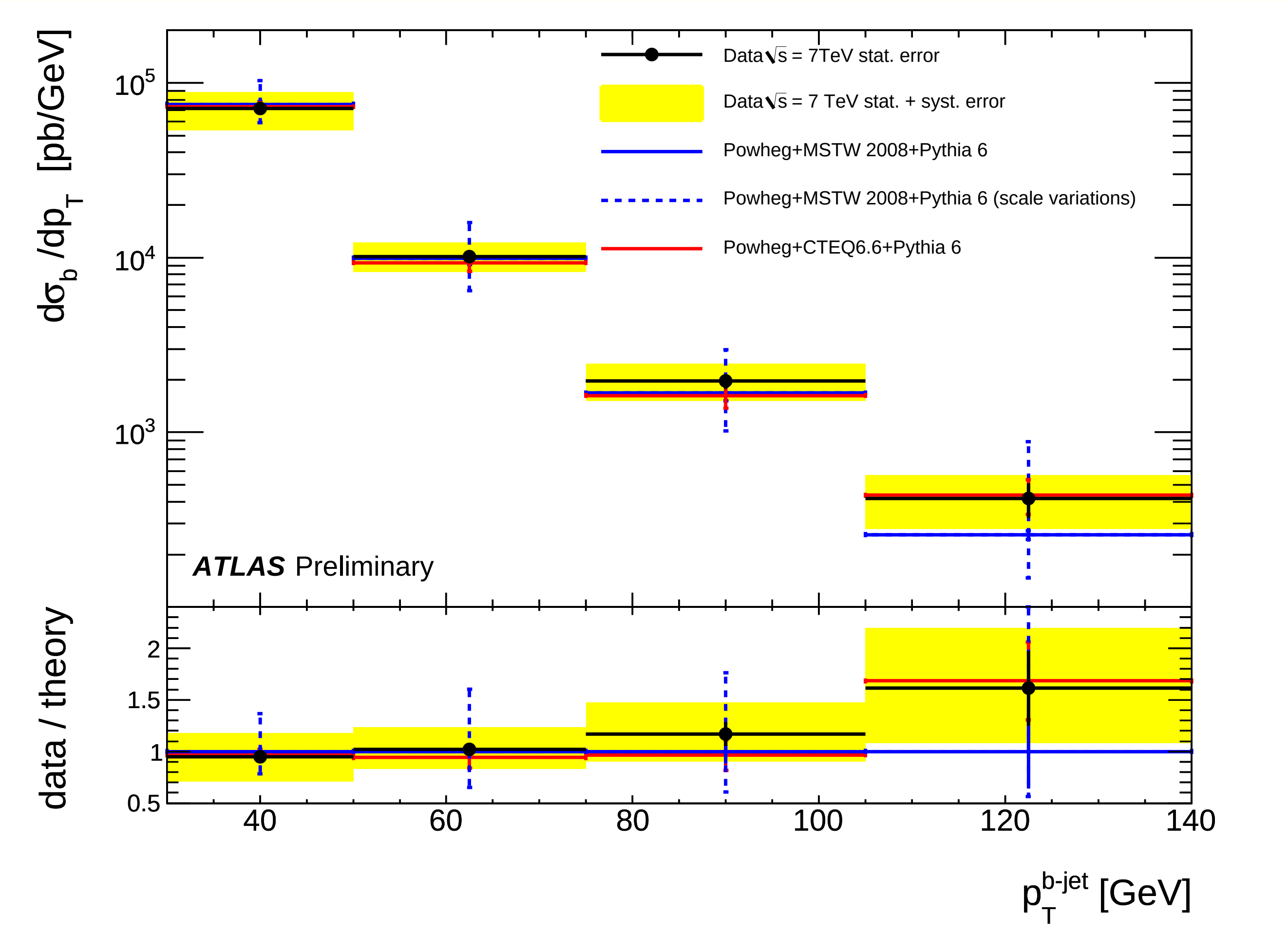
W, Z boson p_{T} reweighting

- The modeling of $d\sigma/dp_{\mathrm{T}}^{W/Z}$ can have significant effects on the expected efficiency and acceptance.
- NLO generators MC@NLO and POWHEG have deficits at high $p_{\mathrm{T}}^{W/Z}$.
- NLO effects are important at high $p_{\mathrm{T}}^{W/Z}$ because the W/Z is polarized by higher order QCD.



- $W \to \ell\nu$ and $Z \to \ell\ell$ cross section measurements use MC@NLO reweighted to match $p_{\mathrm{T}}^{W/Z}$ for LO Pythia, which agrees with the data because it has been tuned well to the Tevatron data.

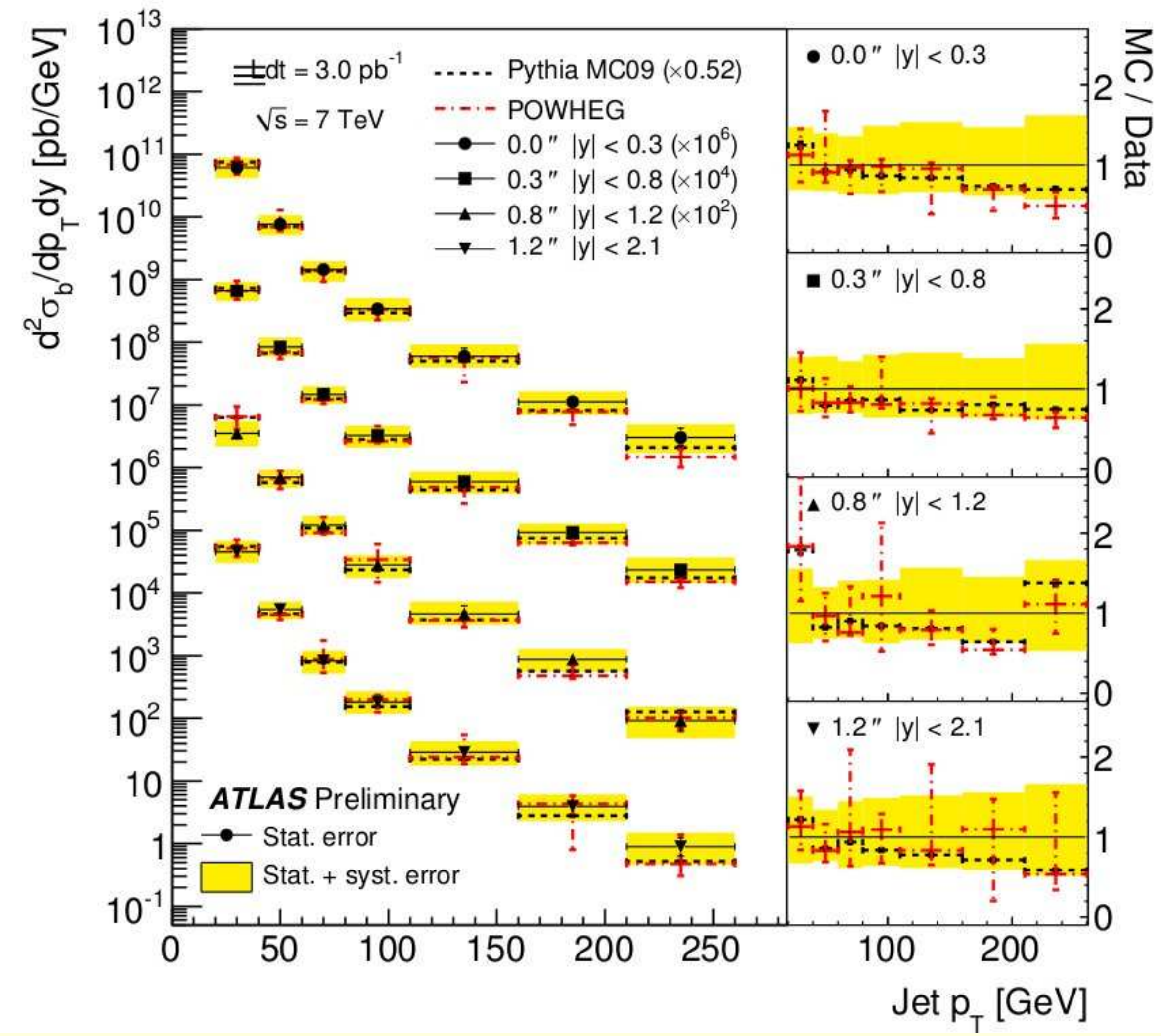
b-jets: Atlas note 2011-057; b jet cross section



POWHEG seems to be doing well, but which generator? Dijet or hvq?
They quote the POWHEG BOX ... It is probably Frixione, Ridolfi, P.N.2007

Atlas conf. note 2011-056: dijets of b jets

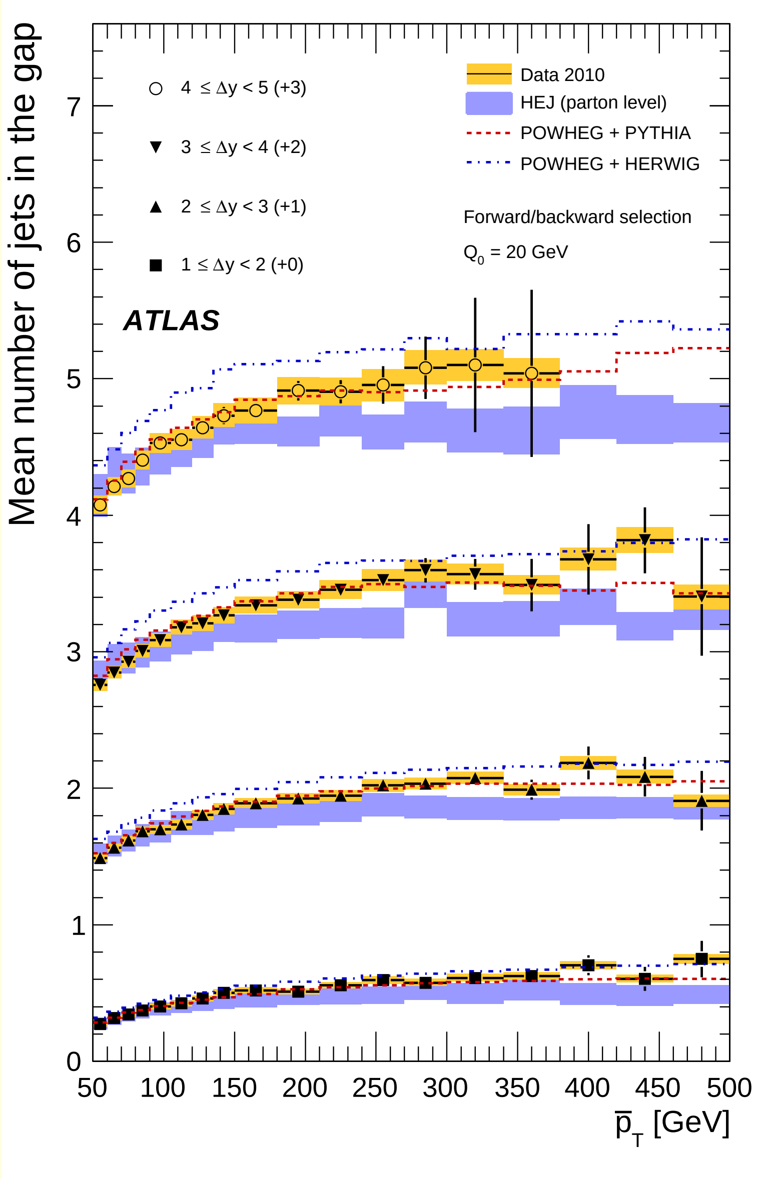
This is `POWHEG` Dijet; It works well, but the b is treated as massless in the Dijet program, and its cross section is controlled by the shower cutoff.



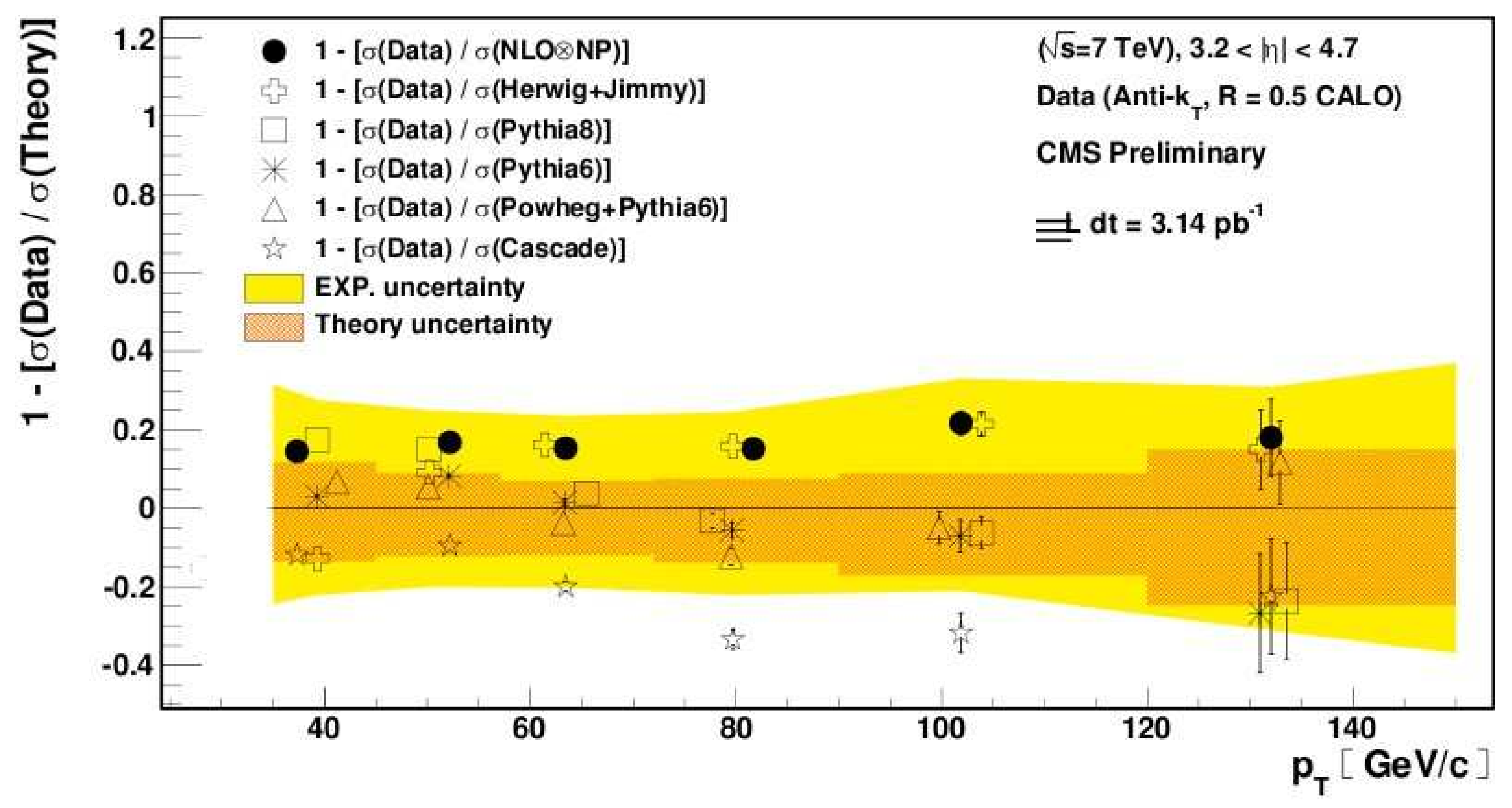
ATLAS 2011-038,
Dijet with a jet veto

HEJ (Andersen, Smillie 2010) is designed to deal with this type of configurations (high energy regime). POWHEG does nothing to resum the relevant logarithms.

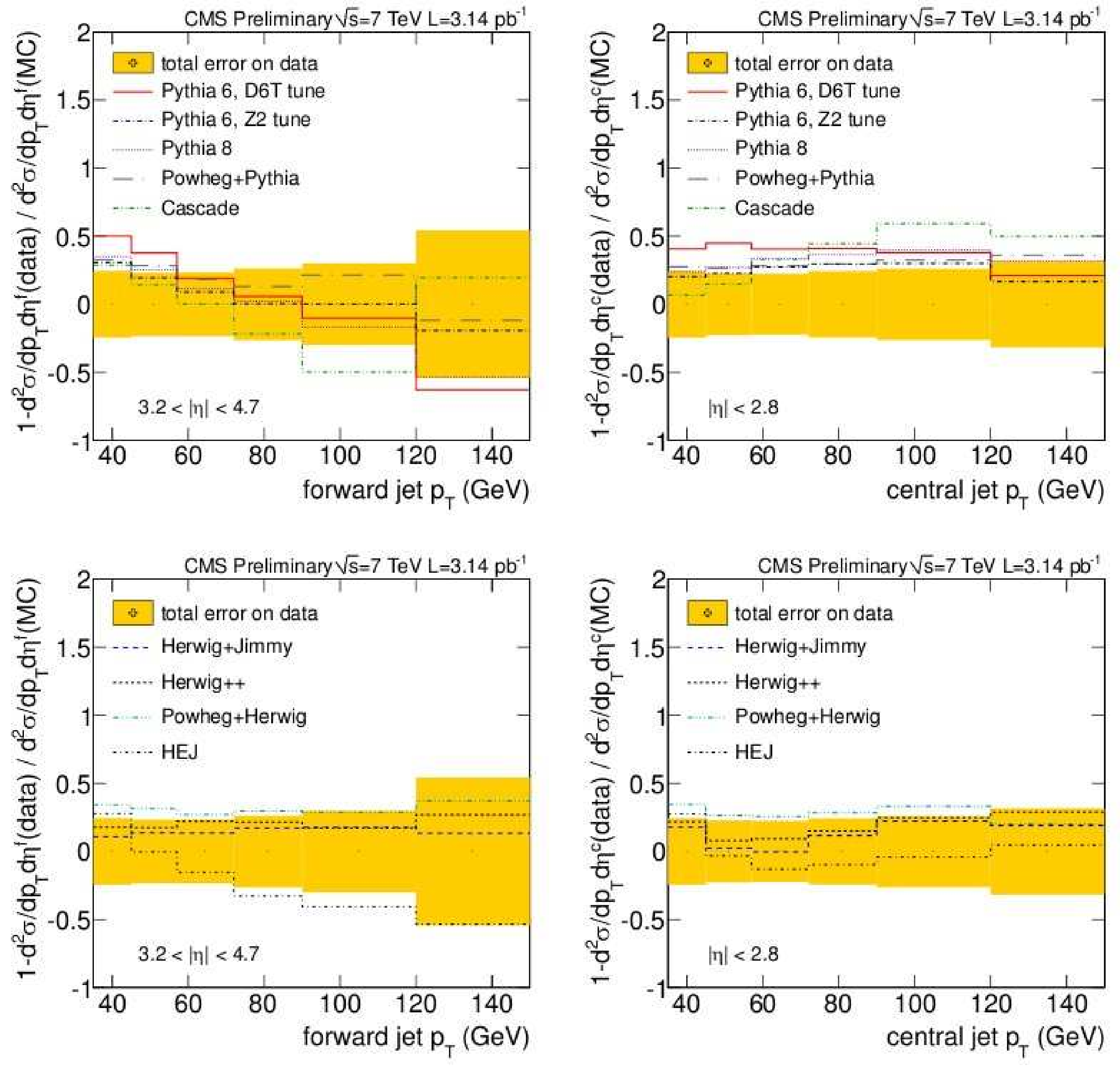
Here HEJ has no shower interface (Andersen, Smillie+Lonblad, 2011)

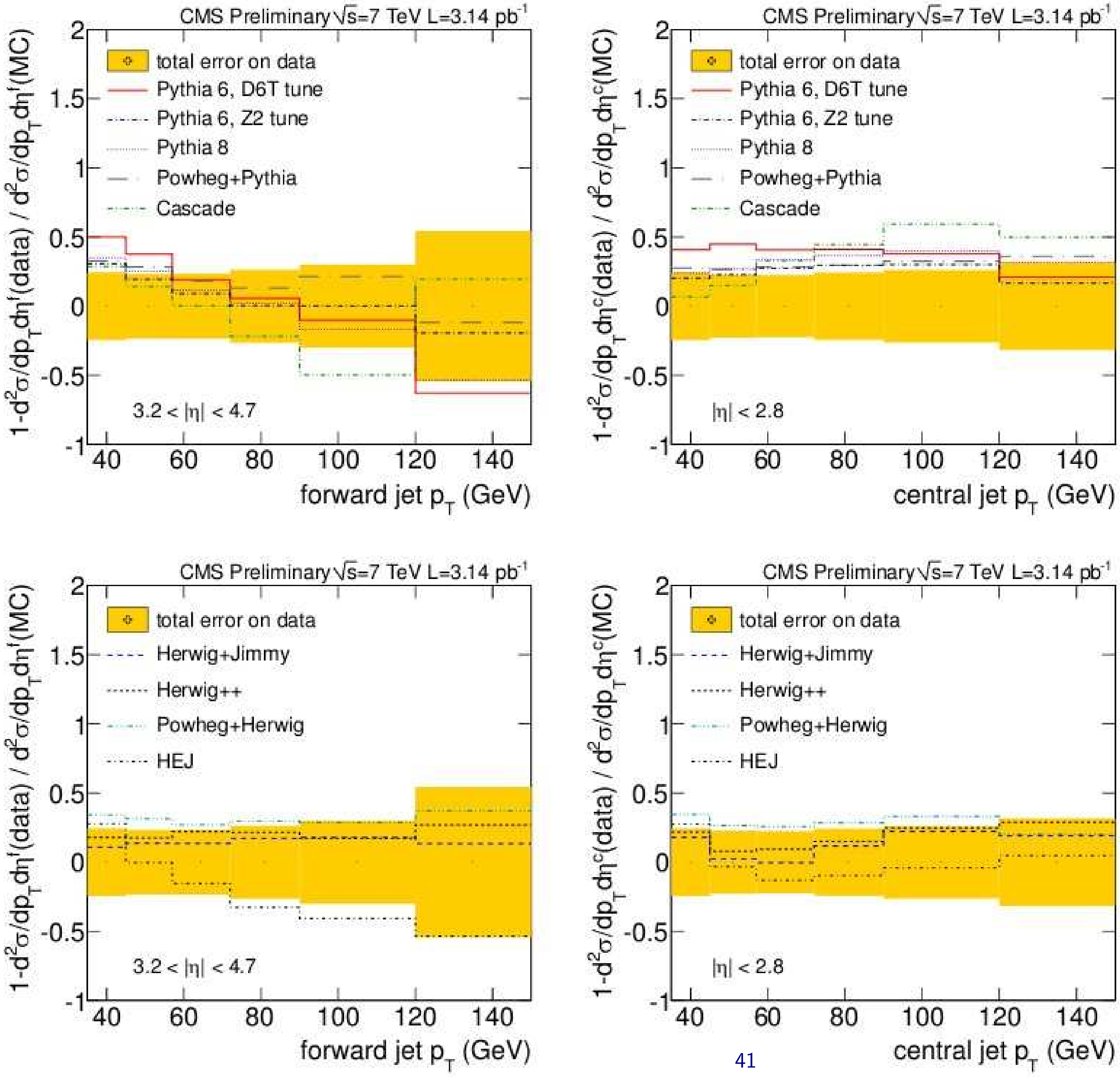


CMS PAS FWD-10-003, inclusive forward jets



CMS PAS FWD-10-006, one forward + one central jet





CMS Preliminary $\sqrt{s}$=7 TeV L=3.14 pb^{-1}
total error on data
Pythia 6, D6T tune
Pythia 6, Z2 tune
Pythia 8
Powheg+Pythia
Cascade
Herwig+Jimmy
Herwig++
Powheg+Herwig
HEJ
3.2 < |η| < 4.7
|η| < 2.8
$1-d^2\sigma/dp_T d\eta^f(\mathrm{data}) / d^2\sigma/dp_T d\eta^f(\mathrm{MC})$
$1-d^2\sigma/dp_T d\eta^c(\mathrm{data}) / d^2\sigma/dp_T d\eta^c(\mathrm{MC})$
forward jet p_T (GeV)
central jet p_T (GeV)

NLO+PS (in POWHEG language)

Hardest radiation: as in PS, but corrected up to NLO:

$$d\sigma = \overbrace{\bar{B}^s(\Phi_B)}^{\text{NLO!}} d\Phi_B \left[\overbrace{\Delta^s_{t_0}}^{P_0} + \overbrace{\Delta^s_t \frac{R^s(\Phi)}{B(\Phi_B)} d\Phi_r}^{P(\Phi_r)} \right] + \overbrace{[R(\Phi) - R^s(\Phi)]}^{\text{ME correction}} d\Phi$$

where $R \Rightarrow R^s$ in the soft and collinear limit,

$$\bar{B}^s(\Phi_B) = B(\Phi_B) + \underbrace{\left[\underbrace{V(\Phi_B)}_{\text{infinite}} + \underbrace{\int R^s(\Phi)\, d\Phi_r}_{\text{infinite}} \right]}_{\text{finite}}$$

The Born cross section is replaced by the inclusive cross section at fixed underlying Born

and

$$\Delta^s_t = \exp\left[- \int_{t_l} \frac{R^s}{B} d\Phi_r \theta(t(\Phi) - t_l) \right]$$

so that

$$\Delta^s_{t_0} + \int \Delta^s_t \frac{R^s(\Phi)}{B(\Phi_B)} d\Phi_r = 1 \,(\text{Unitarity})$$

In MC@NLO: $R^s d\Phi_r = R^{\rm MC} d\Phi_r^{\rm MC}$

Furthermore:

in MC@NLO the phase space parametrization $\Phi_B,\ \Phi_r \Rightarrow \Phi$ is the one of the Shower Monte Carlo. We have:

$$\underbrace{\bar{B}^s(\Phi_B)d\Phi_B}_{\substack{\text{provided by }\texttt{MCatNLO}\\ \mathcal{S}\text{ event}}} \left[\underbrace{\Delta^s_{t_0} + \Delta^s_t \frac{R^s(\Phi)}{B(\Phi_B)} d\Phi_r}_{\text{generated by }\texttt{HERWIG}} \right] + \underbrace{\left[R(\Phi) - R^s(\Phi)\right] d\Phi}_{\substack{\text{provided by }\texttt{MCatNLO}\\ \mathcal{H}\text{ event}}}$$

More synthetically

$$\texttt{MCatNLO}\ \mathcal{S} = \frac{\bar{B}^s(\Phi_B)}{B(\Phi_B)} \times \texttt{HERWIG}\ \text{basic process}$$

$$\texttt{MCatNLO}\ \mathcal{H} = R(\Phi) - R^s(\Phi)\ \text{fed through}\ \texttt{HERWIG}$$

In POWHEG: $R^s d\Phi_r = R F(\Phi)$

where $0 \leqslant F(\Phi) \leqslant 1$, and $F(\Phi) \Rightarrow 1$ in the soft or collinear limit.
$F(\Phi) = 1$ is also possible, and often adopted.
The parametrization $\Phi_B, \Phi_r \Rightarrow \Phi$ is within POWHEG, and there is complete freedom in its choice.

$$\underbrace{\bar{B}^s(\Phi_B) d\Phi_B}_{\texttt{POWHEG}} \left[\underbrace{\Delta^s_{t_0} + \Delta^s_t \frac{R^s(\Phi)}{B(\Phi_B)} d\Phi_r}_{\texttt{POWHEG}} \right] + \underbrace{\left[R(\Phi) - R^s(\Phi) \right] d\Phi}_{\texttt{POWHEG}}$$

All the elements of the hardest radiation are generated within POWHEG

Recipe

- POWHEG generates an event, with $t = t_{\mathrm{powheg}}$
- The event is passed to a SMC, imposing no radiation with $t > t_{\mathrm{powheg}}$.

Separation of Hardest event generator and Shower

In P.N. 2004 it was shown that the separation is possible if

- One can veto radiation harder than the hardest event in the Shower. (required feature in Les Houches Interface for User Processes).
- In case of angular ordered showers (the only kind of parton shower that fully preserve soft coherence in the double log region), and only in this case, a new type of vetoed shower must be included to maintain soft coherence (named vetoed truncated showers in P.N. 2004).
  In p_T ordered dipole showers (that also implement soft coherence) this problem does not arise, and no truncated showers are needed.

Not including truncated showers when needed, is like assuming total distructive coherent interference, the leftover coupling to the colour of the primary parton being neglected. This bears some analogy with PYTHIA's implementation of coherence in the old shower model, where configurations from the virtuality ordered shower were vetoed if not ordered in angles.