POWHEG-BOX

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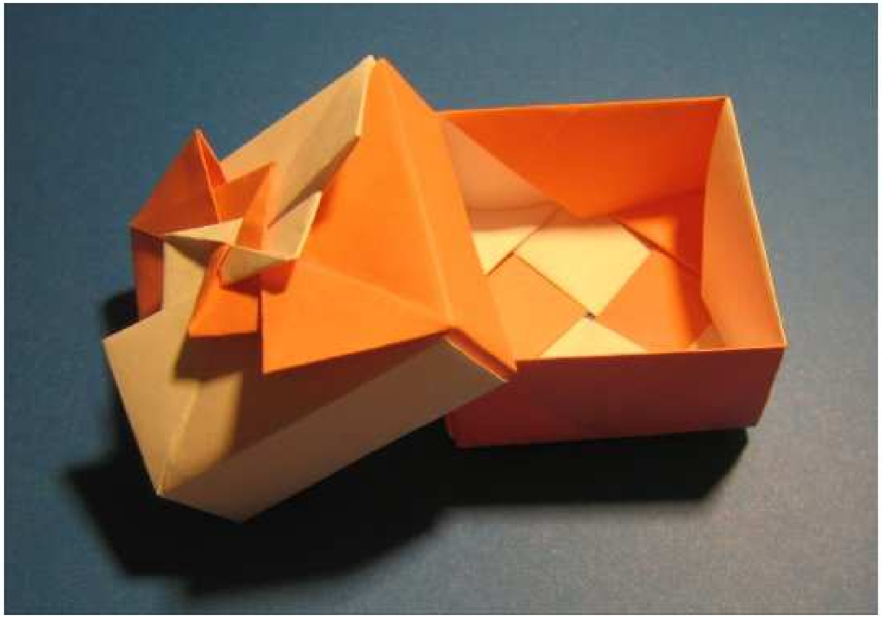
The POWHEG BOX



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

- History
- Highlight of recent developements
- `POWHEG BOX` and data

History

In the past (before 2002), NLO calculations were used to compute infrared safe observables, but could not be used to perform event generation.

`MC@NLO` (Frixione, Webber 2002): method for interfacing NLO calculations to parton showers. IR safe observables computed with `MC@NLO` have NLO accuracy (standard PS do not).

The `POWHEG` method (P.N. 2004) was conceived to overcome certain limitations in `MC@NLO`. Advantages:

- Separates the NLO calculation from the Shower stage
- It can generate positive weighted events
- Better treatment in the soft limit

Proof of concept for `POWHEG`:

- $hh \to ZZ$ (Ridolfi, P.N., 2006)
- $hh \to Q\bar{Q}$ (Frixione, Ridolfi, P.N., 2007)

Frixione, Oleari, P.N 2007: fully general formulation of the method.

Several other processes were added:

- $hh \to Z/W$ (Alioli, Oleari, Re, P.N., 2008)
- $hh \to H$ (gluon fusion) (Alioli, Oleari, Re, P.N., 2008)
- $hh \to t + X$ (single top) (Alioli, Oleari, Re, P.N., 2009)

Other `POWHEG` efforts started (`Herwig++` team), `Sherpa`,

- $hh \to Z/W$ (Hamilton,Richardson,Tully, 2008;)
- $hh \to H$, $hh \to HZ/W$ (Hamilton,Richardson,Tully, 2009)
- Höche, Krauss, Shönherr, Siegert, 2010 (`Sherpa`)

POWHEG BOX: general framework for implementing NLO processes in POWHEG, Alioli, Oleari, Re, P.N., 2010

Several processes implemented directly in the POWHEG BOX:

- VBF Higgs, (Oleari,P.N., 2009).
- $hh \to tW$ (E. Re, 2010)
- $hh \to Z + \mathrm{jet}$, (Alioli, Oleari, Re, P.N., 2010)
- Dijet production (Alioli, Hamilton,Oleari, Re, P.N., 2010)
- $hh \to W^+W^+ + X$ (Melia, Rontsch, Zanderighi, P.N., 2011)
- $hh \to t\bar{t} + \mathrm{jet}$ (Kardos, Papadopoulos, Trocsanyi, 2011) also (Alioli, Moch, Uwer, in preparation)
- $hh \to t\bar{t}H$ (Kardos, Papadopoulos, Trocsanyi, 2011)
- $hh \to Wb\bar{b}$, (Oleari, Reina 2011)
- $hh \to ZZ, WZ, W^+W^- \to 4l$ (Melia, Rontsch, Zanderighi, P.N., 2011)
- $hh \to tH^-$, in preparation (Klasen, Kovaric, Weydert, P.N.)
- $hh \to W^+W^+ + X$, EW (Jaeger, Zanderighi, 2011)

Remember: POWHEG is a method. Few independent POWHEG codes exist:

POWHEG efforts in:

- Herwig++ (Hamilton etal)
- Sherpa (Höche, Krauss, Schönherr, Siegert, 2011)
- Milano Bicocca (POWHEG BOX)
- others (POWHEG BOX)

POWHEG BOX is a freely available framework for producing POWHEG generators.
So: there are several groups of authors using the POWHEG BOX, some of them independent from the original authors of the framework.

Present organization of the POWHEG BOX: release 1.0

Since March 29 2011:

`http://powhegbox.mib.infn.it`	Web page
`svn://powhegbox.mib.infn.it`	svn repository
`trunk` (Main development)	
`releases/POWHEG-BOX-1.0`	
`releases/POWHEG-BOX-1.0.#`	Future bugfixes of release 1.0
tags/trunk00	Previous abandoned trunk
branches/	Restricted, stuff being developed

In a release, we try to put together, and render uniform, all features added to the framework for the implementation of various processes, and include all processes developed so far. However, since different processes may have different authors, this uniformity is not as tight as in standard PS releases.

In other words: the authors of a process are responsible for the relative code.

Automation

The POWHEG BOX automates all aspects of the calculation that have to do with interfacing a given NLO calculation to a shower. In other words:
given the Born phase space, the Born, the colour correlated Born, the spin correlated Born, the Born colour structure and the Virtual and Real matrix elements it builds a program to generate events in the Les Houches interface for user processes, that can be fed to Shower Monte Carlo programs that comply with it.

The inner working of the POWHEG BOX is documented to a considerable detail in the corresponding paper (Alioli, Oleari, Re, P.N. 2010), in the hope that other authors may partecipate in development.

Automation: interfacing with ME generators

Since automatic ME generators do exist, it is natural to attempt to construct interfaces of ME generators and the POWHEG BOX.

Very recently, an interface of MadGraph and the POWHEG BOX has been set up by Frederix Rikkert, C. Oleari and P.N., and a case study of this interface is under development. As soon as the study will be completed, the interface will be released in the public domain. Using this interface, a user needs only to supply the Born Phase space and the Virtual term.

An interface of HELAC-Oneloop and the POWHEG BOX is being developed by Garzelli, Kardos, Papadopoulos, Trocsanyi. Several processes in associated production with $t\bar{t}$; $t\bar{t}$ + jet and $t\bar{t}$ + Higgs already published. This should take also care of automating the virtual (but, will it become public?).

A remark: the POWHEG BOX is as public as something can be. We encourage develpers of programs that use the POWHEG BOX to make their code public.

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

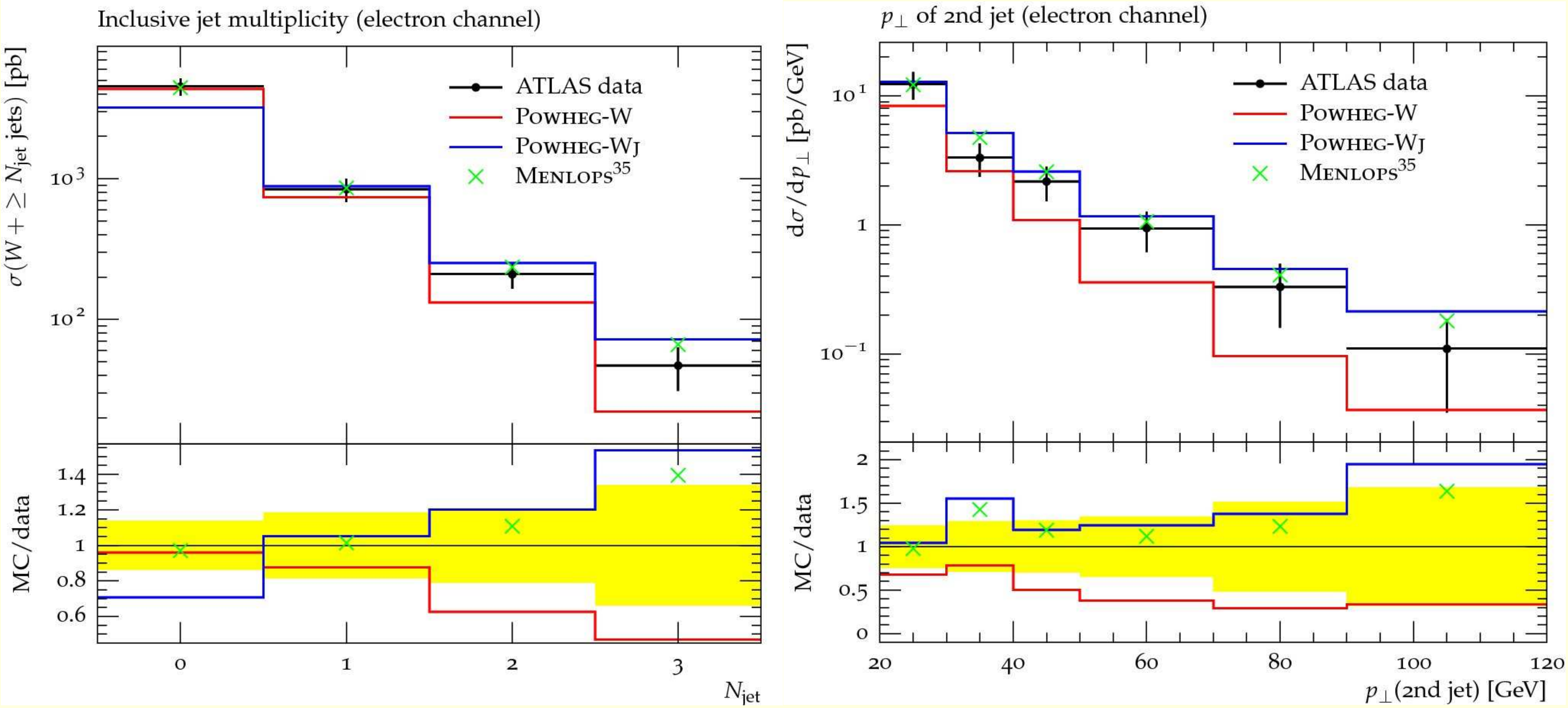
where (i) plays the role of the hard cross section, and (ii) the Shower Algorithm in a stadard Shower MC.
In principle, one can use the (ii) component to build an ME+PS generator without any matching scale. For example, in vector boson production:

- 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 $V + 2\,p$

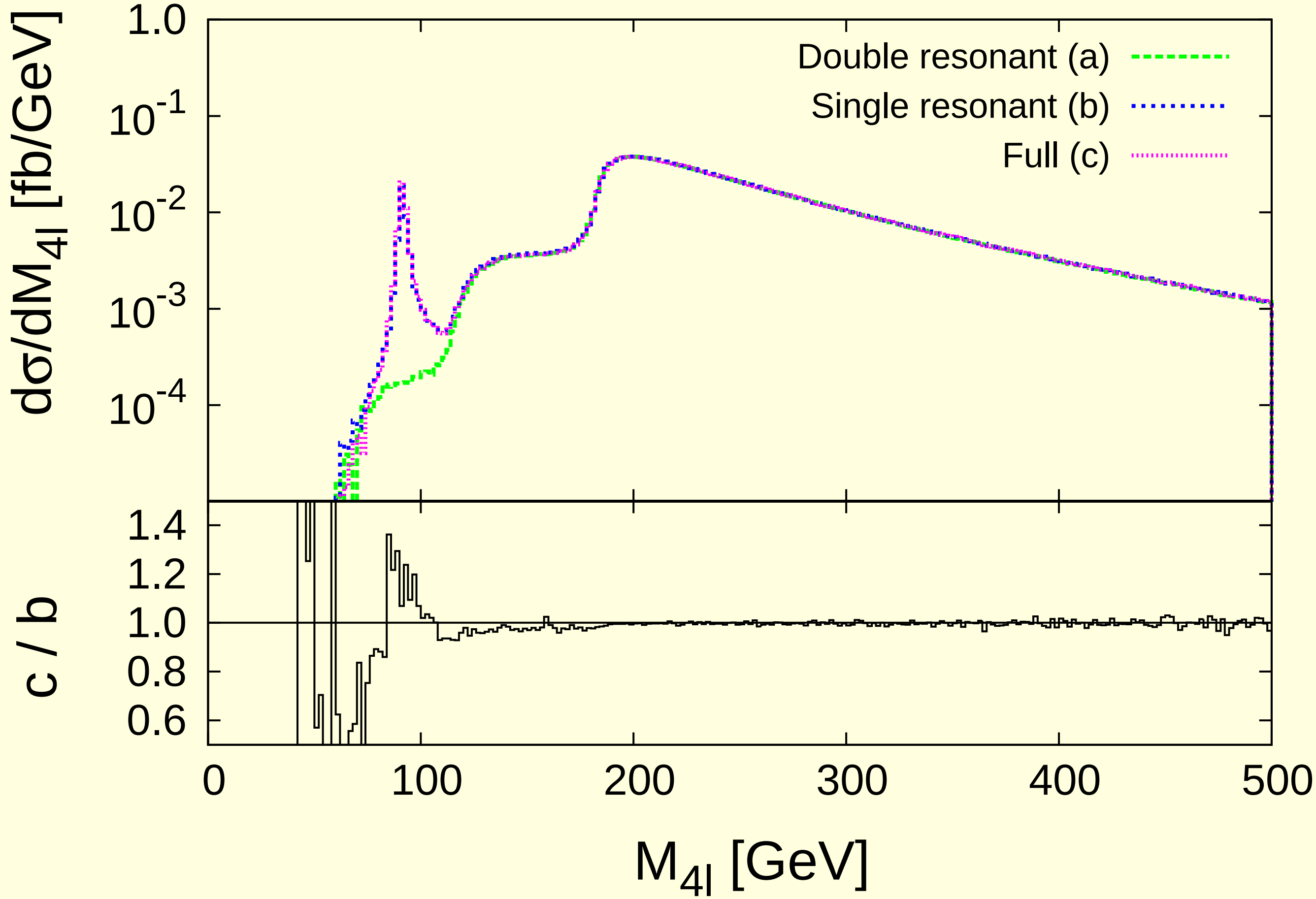
and so on. The output is analogous to what you would get in an ME+PS generator by sending the matching scale to zero.

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.

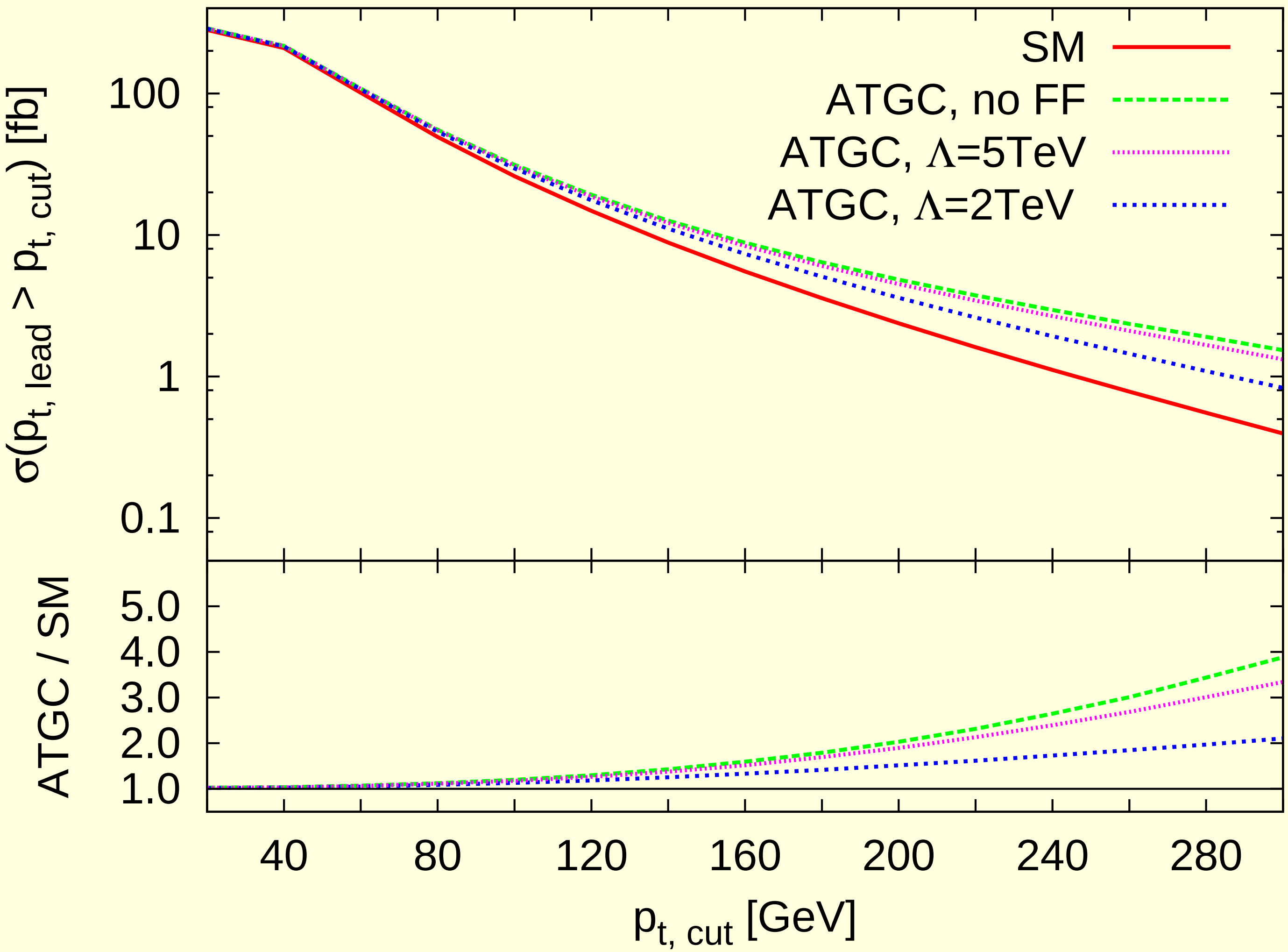
The next step is to improve again on this output by merging it with the output of the full NLO $V + j$ generator, in such a way that, in the hard jet region, this generator prevails, and in the small pt region, the first sample prevails. This works as a practical extension of ME+PS matching to NLO level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



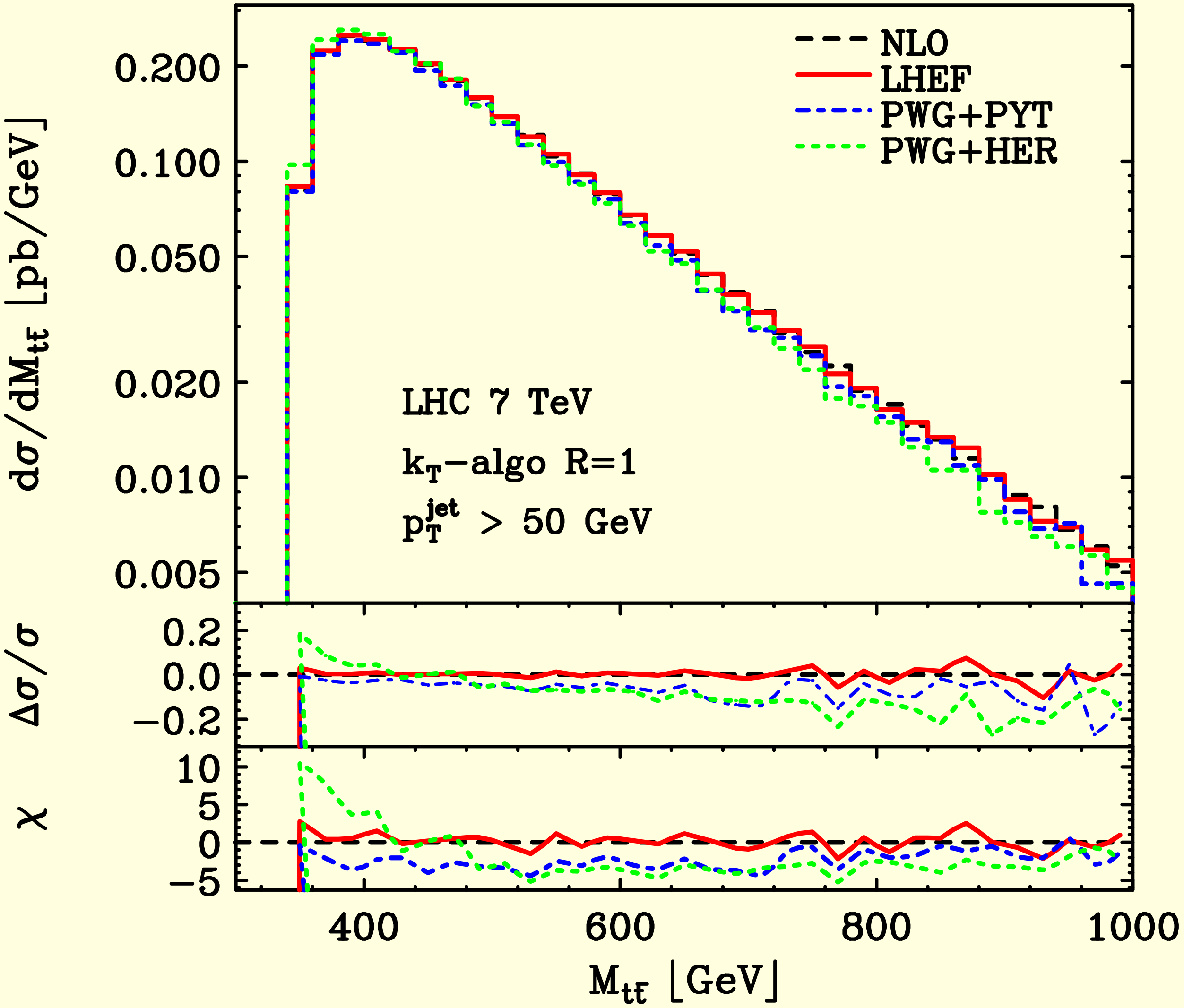
ZZ, W^+W^-, ZW: ME from Dixon, Kunszt, Signer 1998, as in MCFM (Campbell, Ellis, Williams 2011): Z/γ interference included, single resonant graphs included. We also added interference for identical fermions. In ZZ:



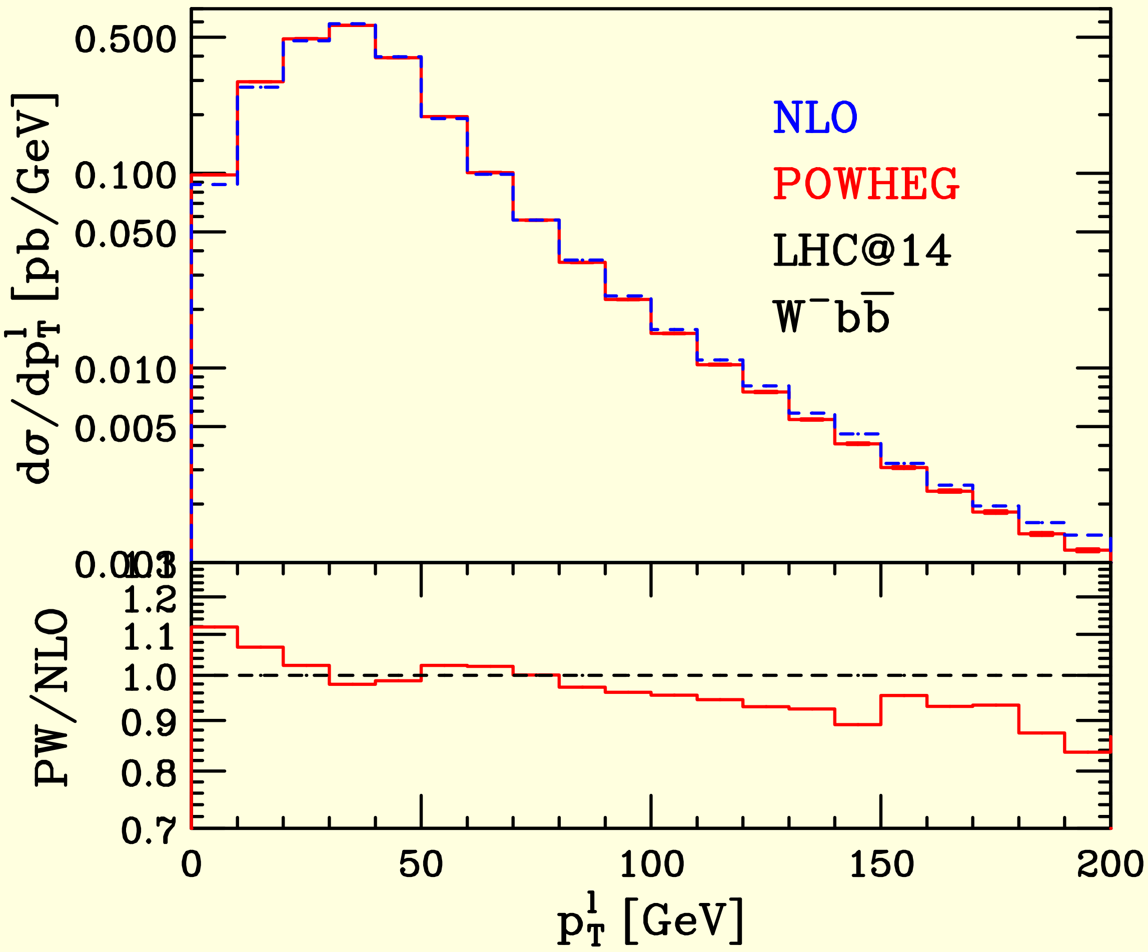
W^+W^-, anomalous couplings



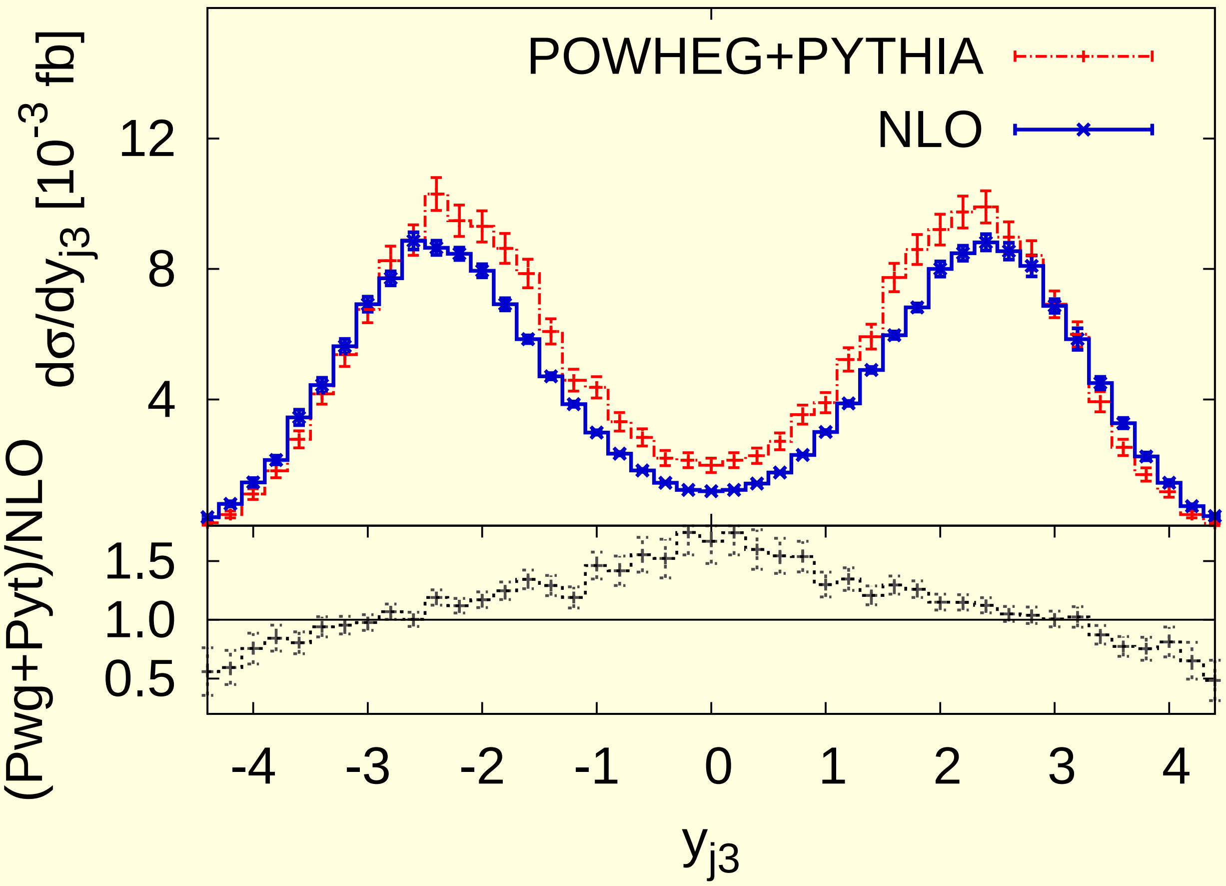
$t\bar{t}j$ production (Alioli, Moch, Uwer, 2011)



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



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



Comparison with data

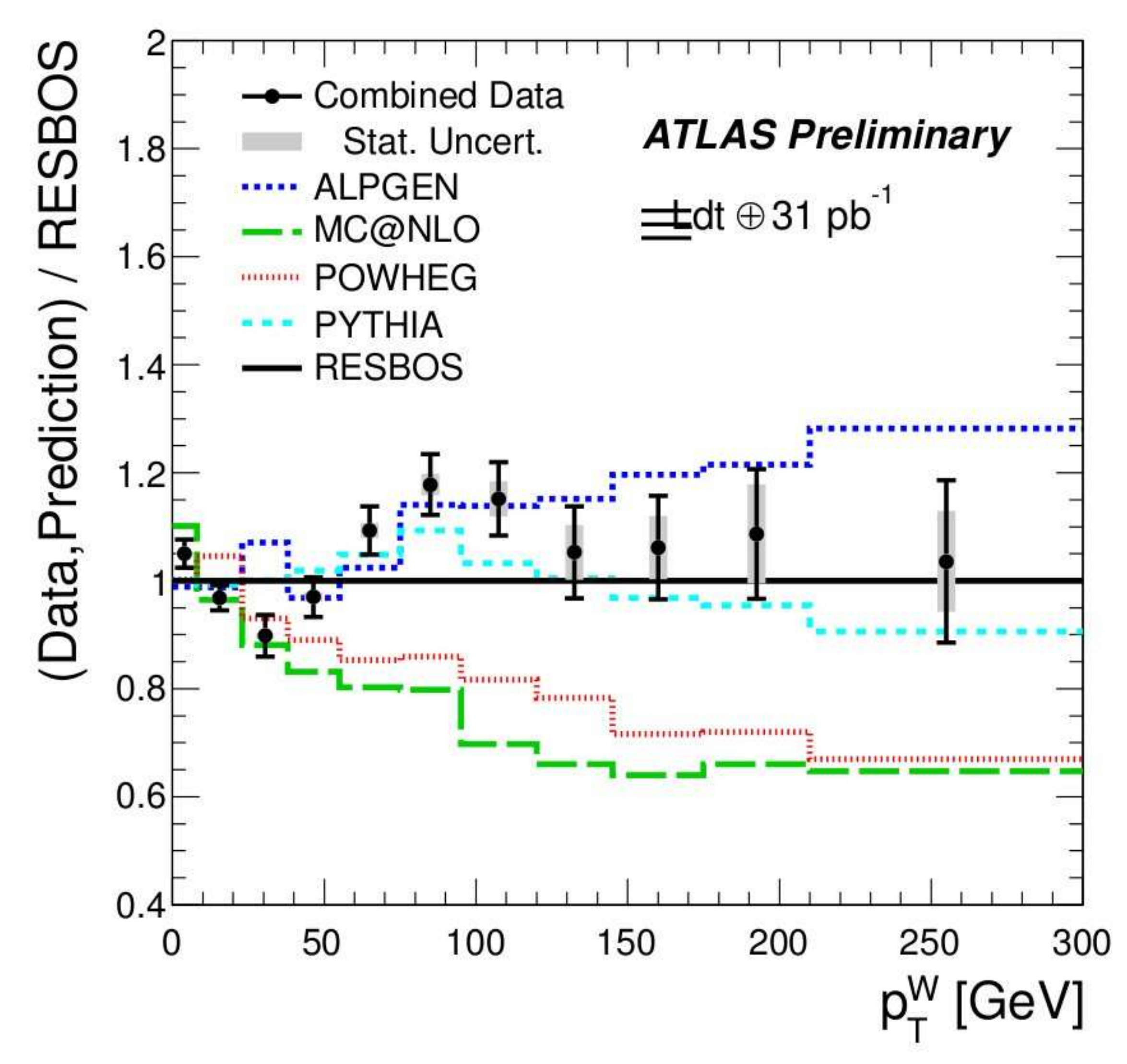
Experimental collaborations are using `POWHEG BOX` generators. Understanding the comparison with data will become an important part of our work.

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.

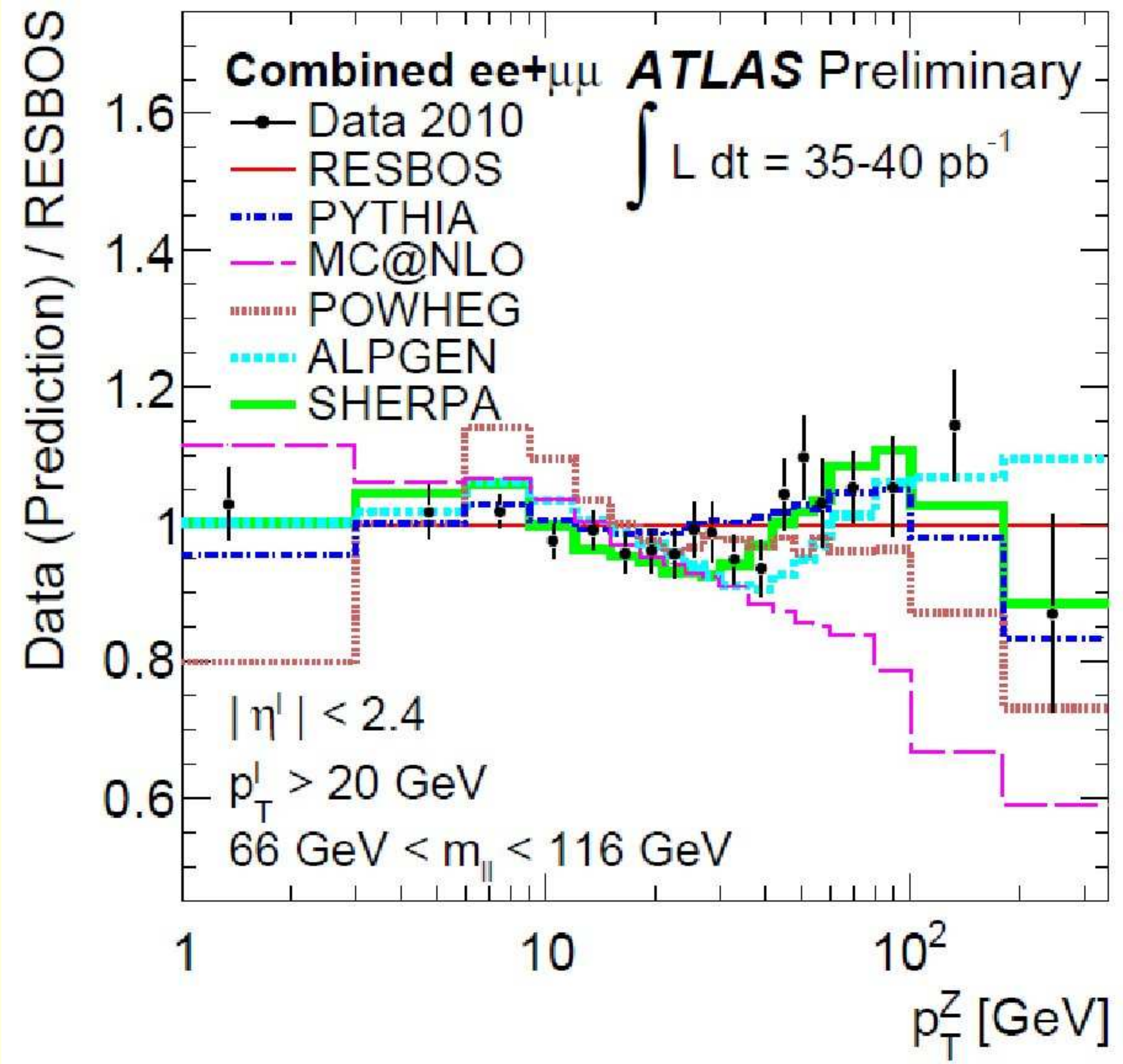


Questions:

are PYTHIA and ALPGEN rescaled by a K-factor?

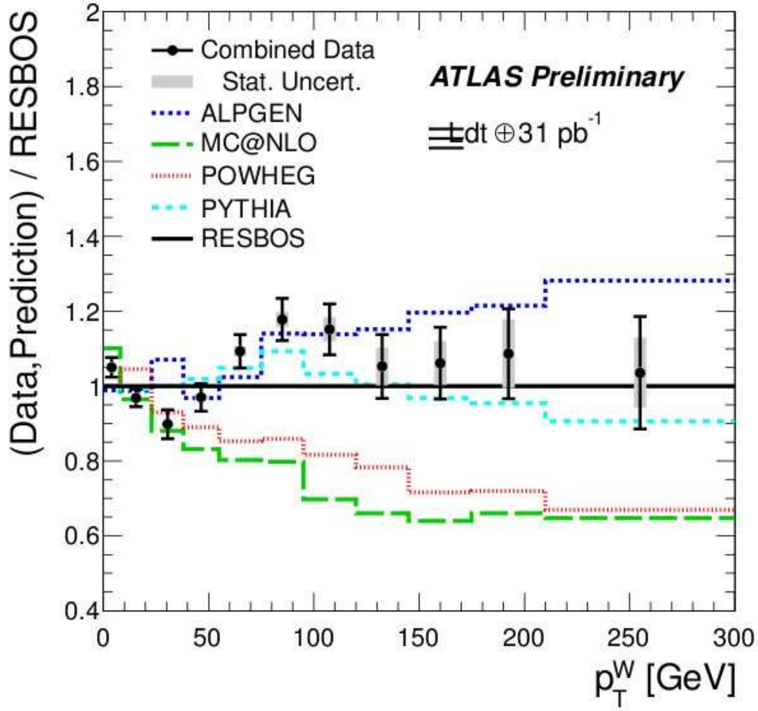
Why the disagreement at large p_T? They should all be the same.

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.

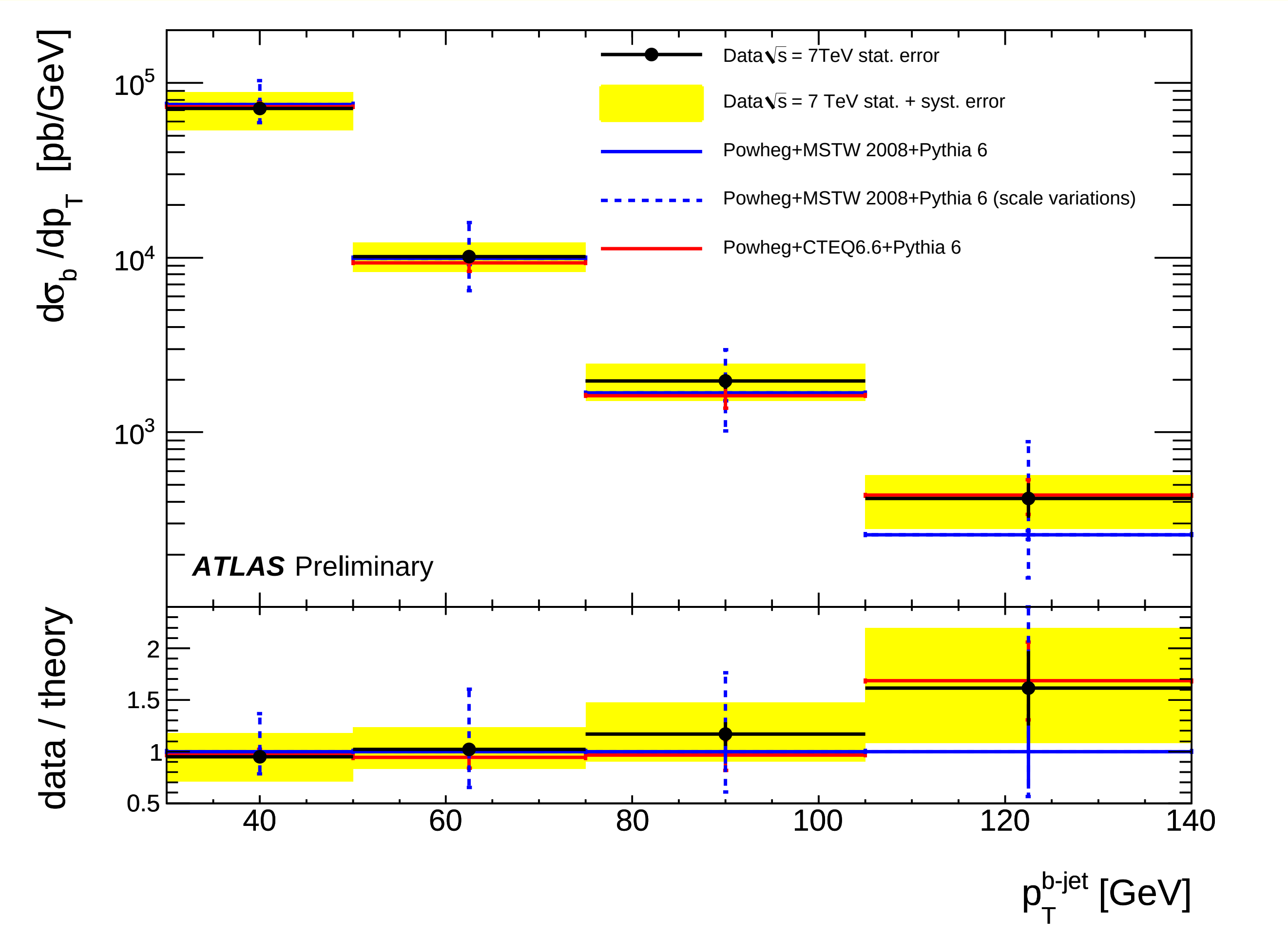


- $W \to \ell\nu$ and $Z \to \ell\ell$ cross section measurements use MC@NLO reweighted to match $p_{\mathrm{T}}^{W/Z}$ for LO Pythia, which agrees with the data because it has been tuned well to the Tevatron data.

There is a choice of $\Lambda_{\rm MC}$ for showering that is tied to $\Lambda_{\overline{\rm MS}}$: $\Lambda_{\rm MC} = 1.569\,\Lambda_{\overline{\rm MS}}$ (Catani, Marchesini, Webber, 1980)

My understanding is: PYTHIA does not use it, since it yields worse fits of the vector boson p_T. `POWHEG` uses it.
Can this be a partial cause of the difficulties? (i.e. the non perturbative model is insufficient to explain the spectrum at low p_T if one increases the perturbative accuracy of the LL resummation)

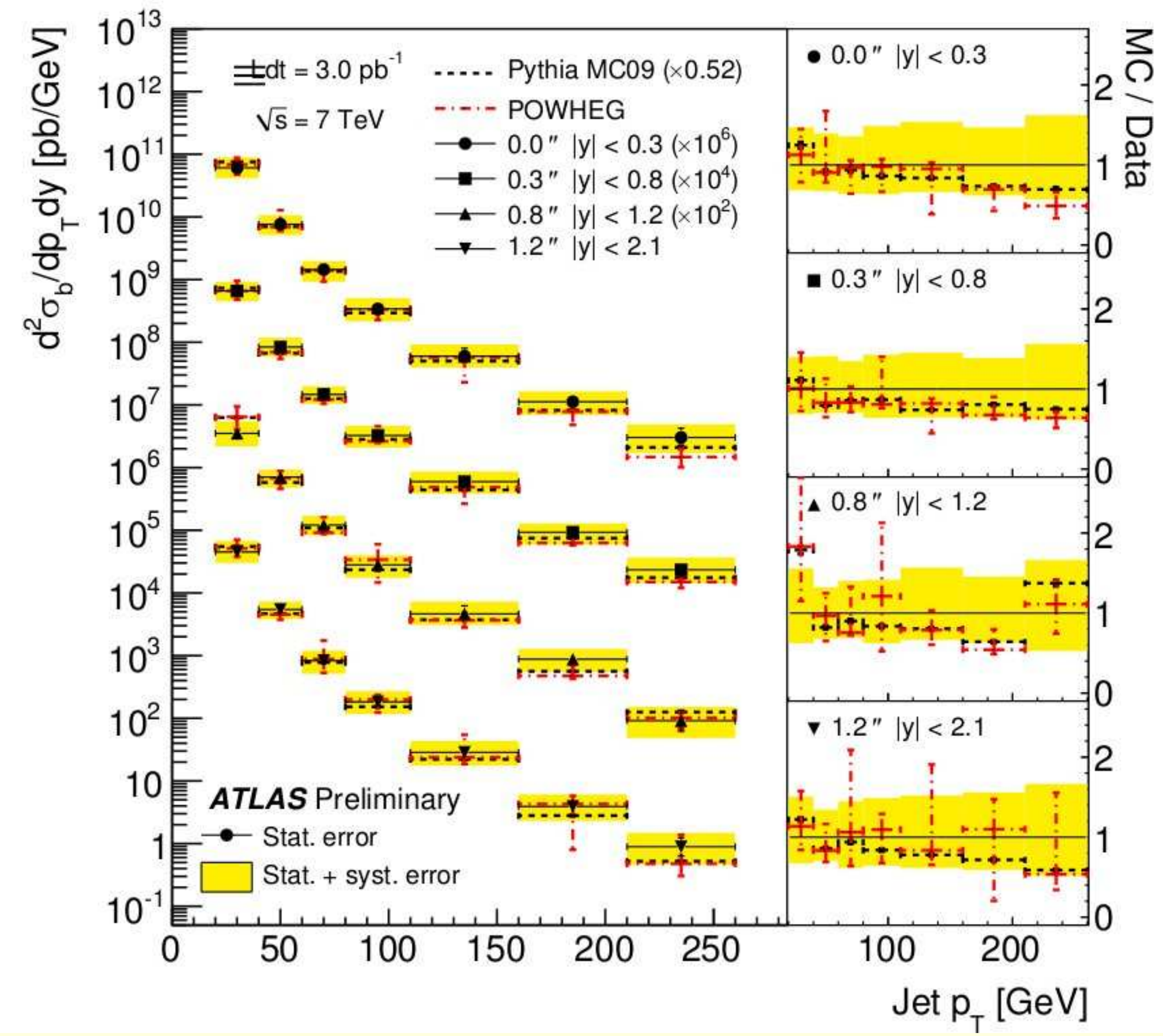
b-jets: Atlas note 2011-057; b jet cross section



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

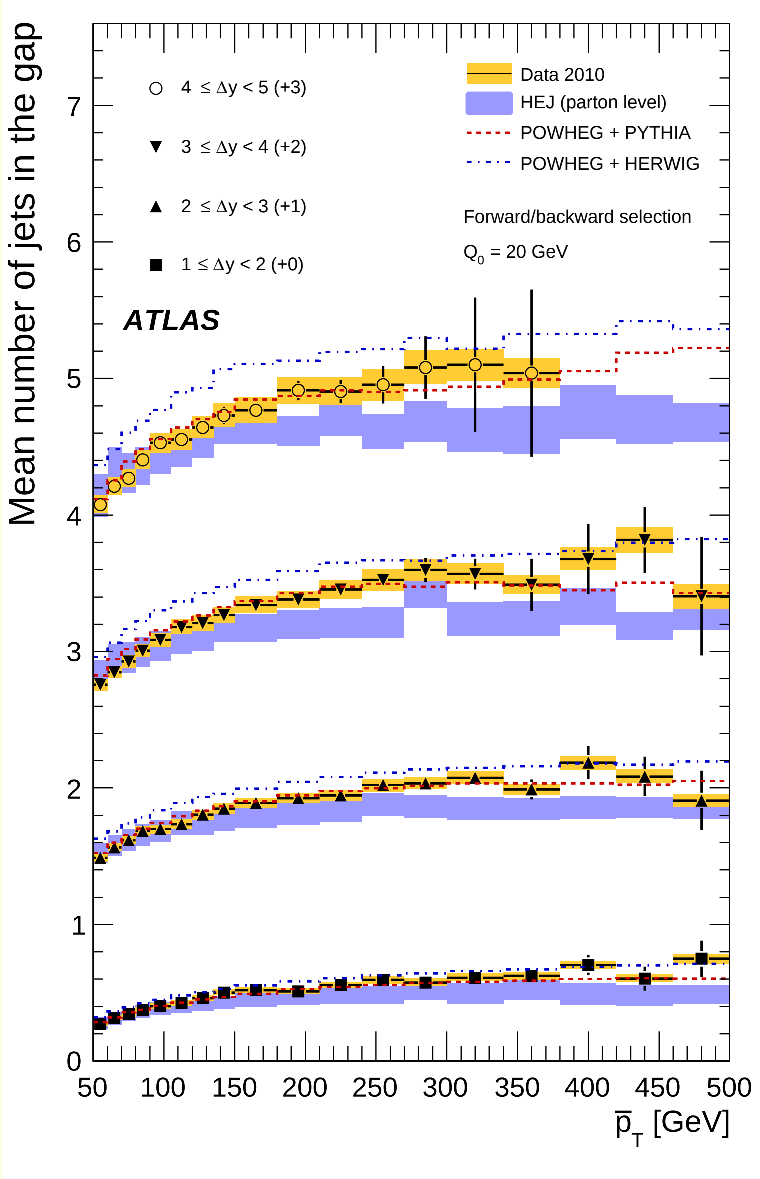
This is `POWHEG` Dijet; It works well, but the b is treated as massless in the Dijet program, and its cross section is controlled by the shower cutoff.



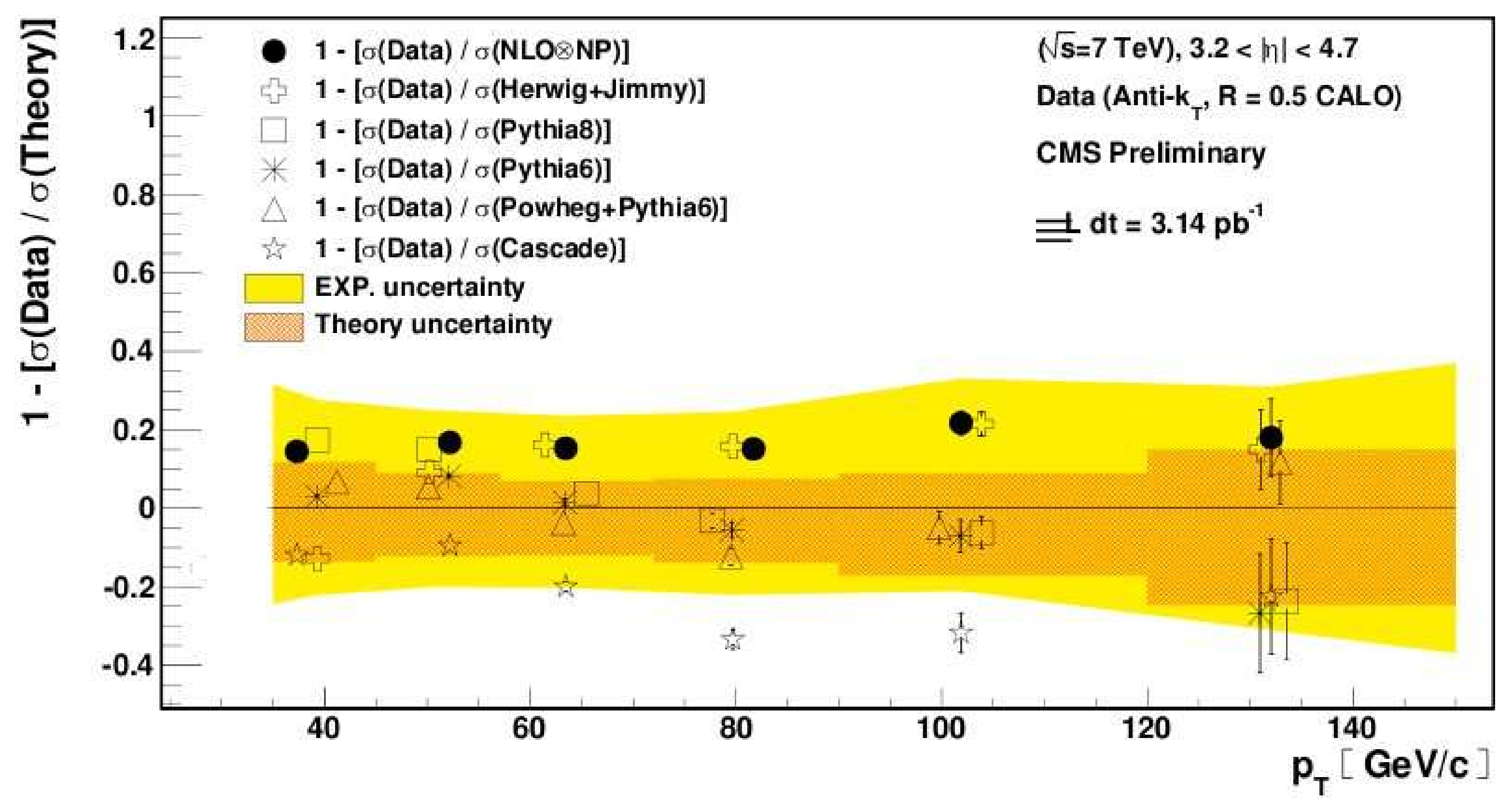
ATLAS 2011-038,
Dijet with a jet veto

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

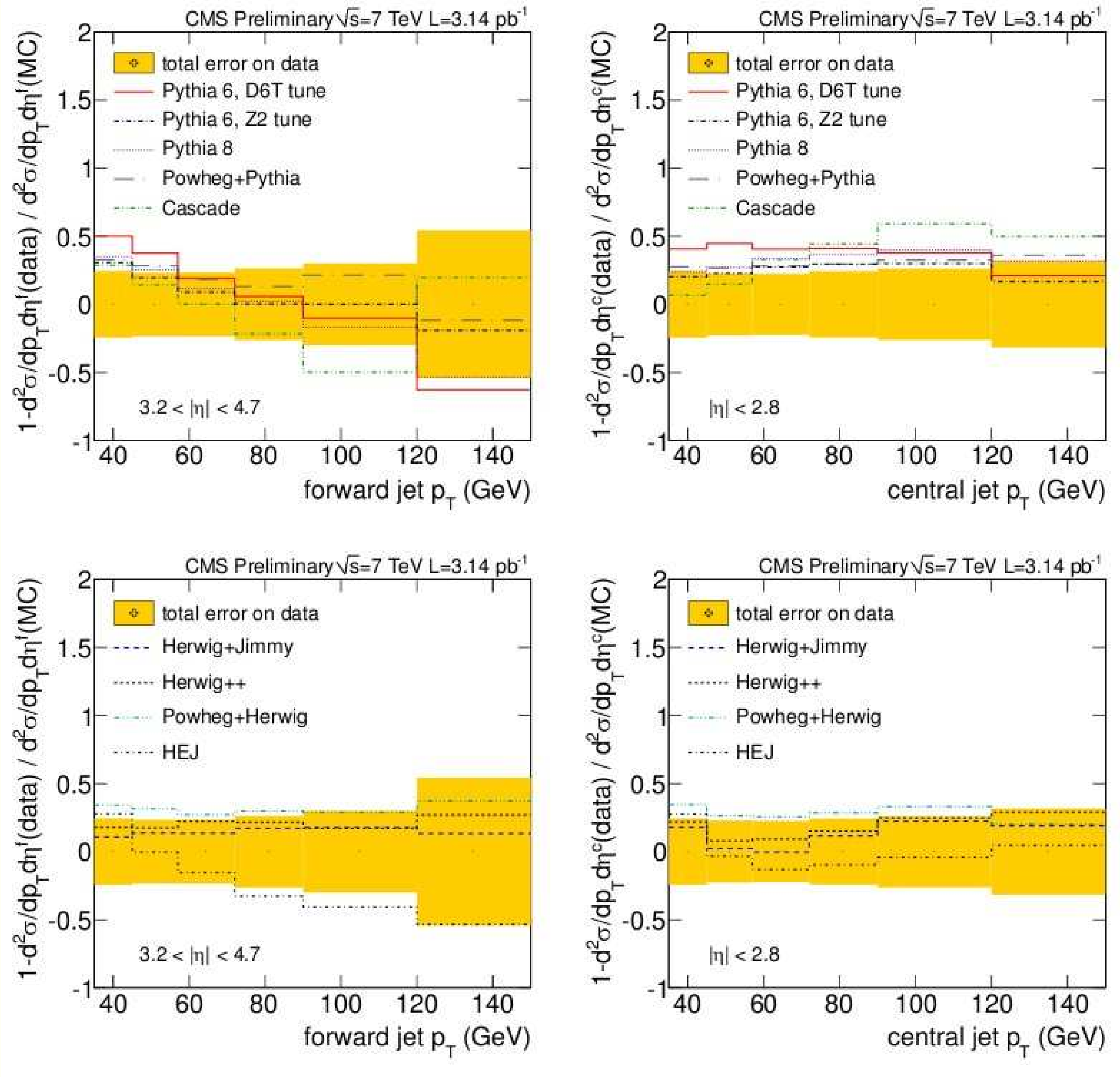
Here HEJ has no shower interface (Andersen, Smillie+Lonblad, 2011)

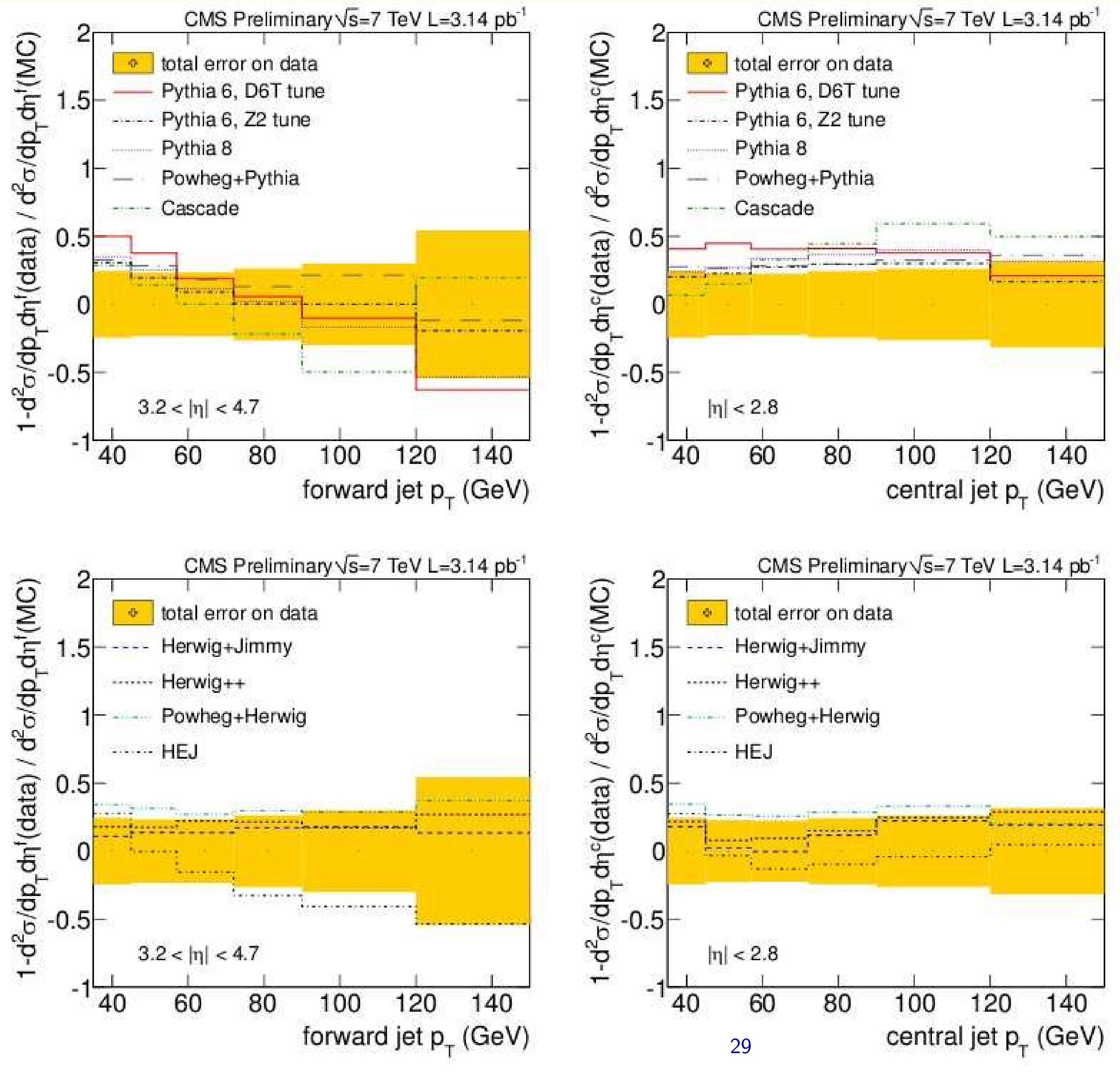


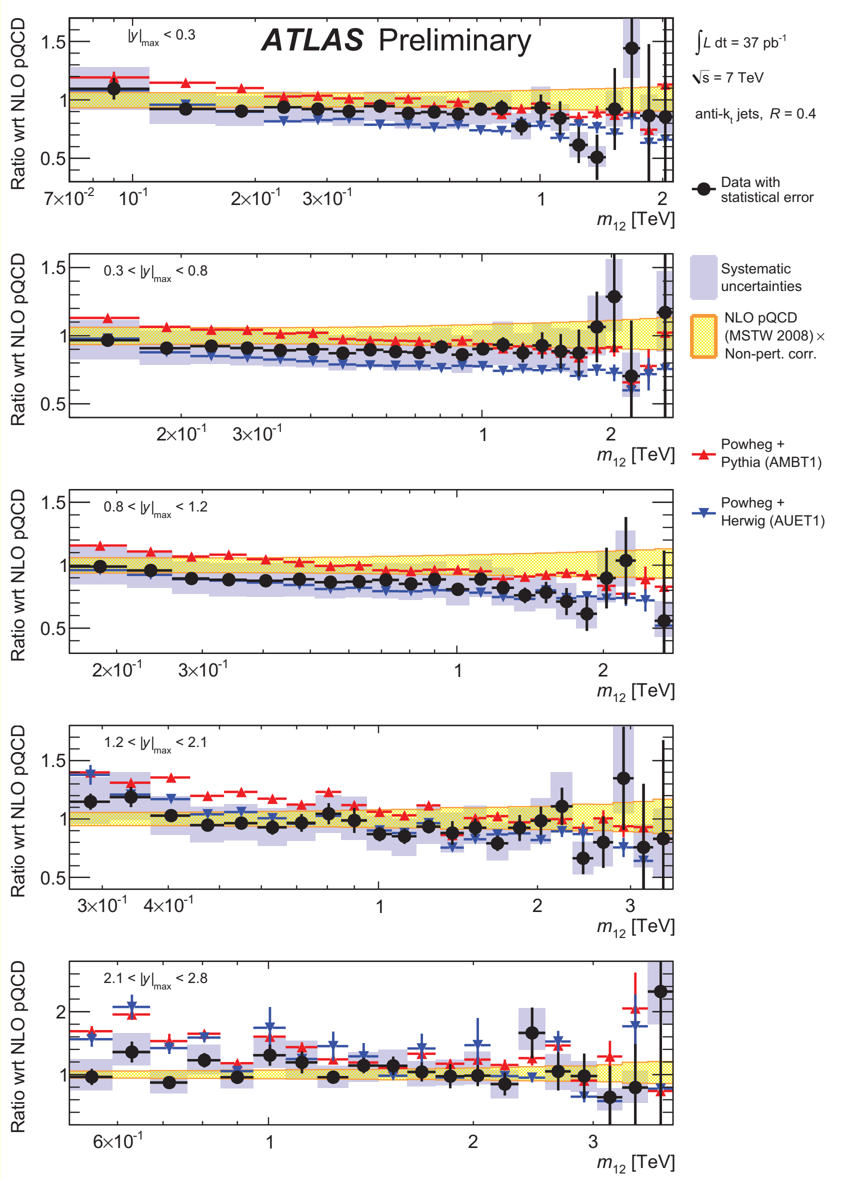
CMS PAS FWD-10-003, inclusive forward jets

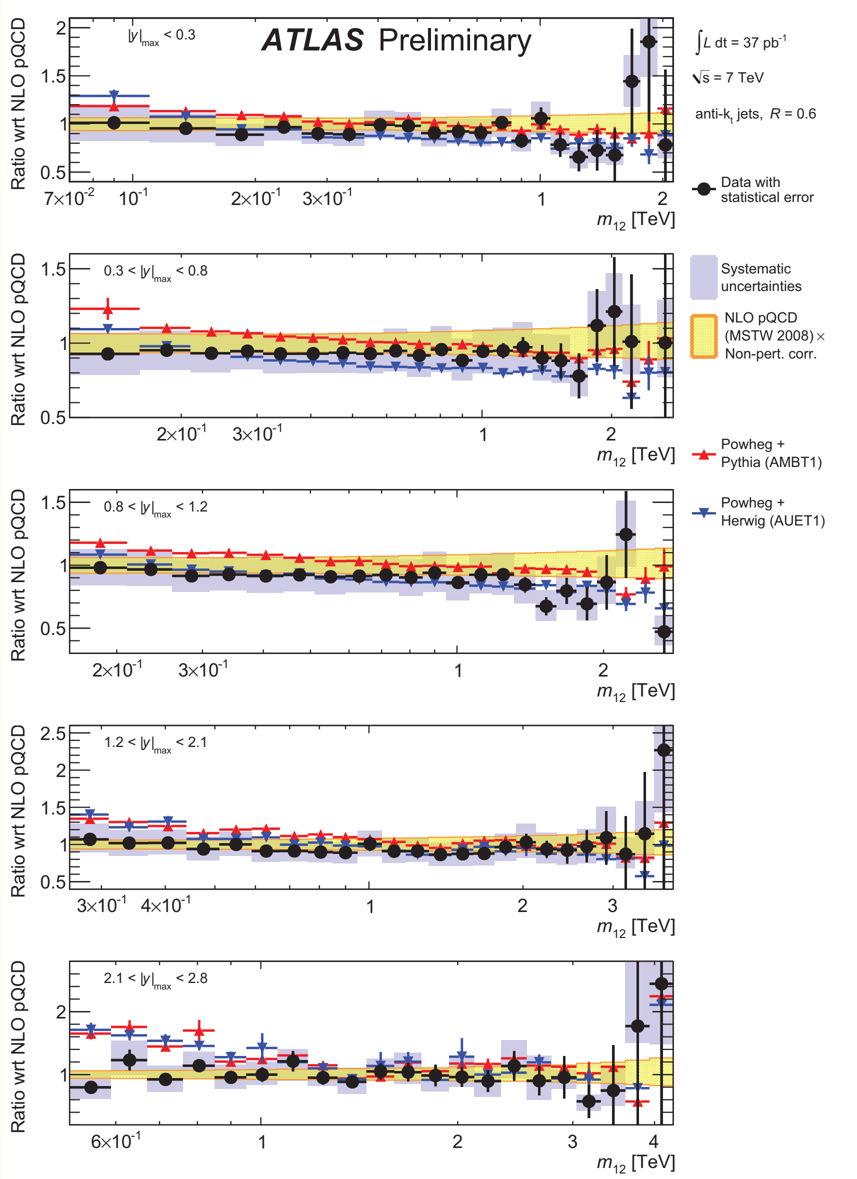


CMS PAS FWD-10-006, one forward + one central jet




CMS Preliminary √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
3.2 < |η| < 4.7
|η| < 2.8
1-d2σ/dpTdηf(data) / d2σ/dpTdηf(MC)
1-d2σ/dpTdηc(data) / d2σ/dpTdηc(MC)
forward jet pT (GeV)
central jet pT (GeV)
Herwig+Jimmy
Herwig++
Powheg+Herwig
HEJ


ATLAS Preliminary
∫L dt = 37 pb⁻¹
√s = 7 TeV
anti-kt 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-kt jets, R = 0.6
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 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.

Other general open questions for jet studies:
Can we do new studies with PS+NLO?
Has jet physics been biased by what works at fixed order?

Conclusions

- New processes are being added
- Complex processes are feasible (W^+W^+jj: 30 sec. per virtual point).
- Automation level grows
- Interesting studies in merging NLO+PS multijet samples
- Comparison with data, and direct interaction with the experimental community is becoming a must. Better communication will avoid lots of problems.
- Interaction with Shower expert is becoming mandatory. At some point, a way to address tuning issues in the MC+PS framework must be found.

Backup

NLO+PS (in POWHEG language)

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

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

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 Φ_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 $t = t_{\mathtt{powheg}}$
- The event is passed to a SMC, imposing no radiation with $t > t_{\mathtt{powheg}}$.

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.

$gg\,,\;\; q\bar{q}\,,\;\; qg$ components in $t\bar{t}$ production

The fraction of gg, $q\,\bar{q}$, qg components is a scheme dependent (i.e. $\overline{\mathrm{MS}}$) and scale dependent concept (it is scheme independent only at LO).

In `POWHEG`:
LHEF events represent production events including the hardest radiation.
In `MC@NLO`:
LHEF $\mathcal{H}$ events include the hardest radiation; $\mathcal{S}$ events do not
(hardest radiation generated down the shower by `HERWIG`)
The qg fraction in `MC@NLO` (in $\mathcal{H}$ events) is there to correct the qg fraction induced by HERWIG when showering $\mathcal{S}$ events.

So: the two don't need to agree, and do not necessarily agree with the NLO fractions. For example, the qg fraction can be made negative by a suitable choice of scale in NLO. Not so in `POWHEG`.

The $\overline{\mathrm{MS}}$, scale dependent, NLO gg fraction can be extracted only from the NLO calculation (for example, in `POWHEG`, at the NLO analysis level, if on)