

the
POWHEG BOX

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QCD@LHC, August 21st 2012

Plan of the talk

- Status of the POWHEG BOX
- Automation
- Scales and PDF's uncertainties by reweighting
- New developments in NLO corrections to decays
- Multiscale Improved NLO

STATUS: powhegbox.mib.infn.it

Homepage of the POWHEG BOX

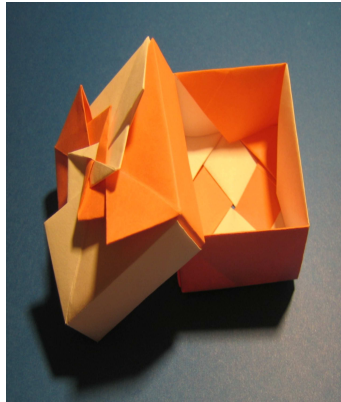
[http://powhegbox.mib.infn.it/Homepage of the POWHEG BOX](http://powhegbox.mib.infn.it/Homepage%20of%20the%20POWHEG%20BOX)

<http://powhegbox.mib.infn.it/>

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 [\[paper\]](#)

POWHEG-BOX/W
POWHEG-BOX/Z

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

POWHEG-BOX/Zj
POWHEG-BOX/Wj

- 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 [\[paper\]](#)

POWHEG-BOX/ST_sch
POWHEG-BOX/ST_tch

- Single-top production associated with a W boson, E. Re, *Eur. Phys. J.* **C71** (2011) 1547, arXiv:1009.2450 [\[paper\]](#)

POWHEG-BOX/ST_wtch_DR

POWHEG-BOX/ST_wtch_DS

- Higgs boson production in gluon fusion, S. Alioli, P. Nason, C. Oleari and E. Re, *JHEP* **0904** (2009) 002, arXiv:0812.0578 [\[paper\]](#)

POWHEG-BOX/gg_H

- Higgs boson production in vector boson fusion, P. Nason and C. Oleari, *JHEP* **1002** (2010) 037, arXiv:0911.5299 [\[paper\]](#)

POWHEG-BOX/VBF_H

- Jet pair production, S. Alioli, K. Hamilton, P. Nason, C. Oleari and E. Re, *JHEP* **1104** (2011) 081, arXiv:1012.3380 [\[paper\]](#)

POWHEG-BOX/Dijet

- Heavy-quark pair production, S. Frixione, P. Nason and G. Ridolfi, *JHEP* **0709** (2007) 126, arXiv:0707.3088 [\[paper\]](#)

POWHEG-BOX/hvq

- W+ W+ plus dijet production, T. Melia, P. Nason, R. Rontsch, G. Zanderighi, *Eur. Phys. J.* **C71** (2011) 1670, arXiv:1102.4846 [\[paper\]](#)

POWHEG-BOX/Wp_Wp_JJ

- ZZ, WZ and W+W- production, including Gamma/Z interference, singly resonant contributions and interference for identical leptons, T. Melia, P. Nason, R. Rontsch, G. Zanderighi, *JHEP* **1111** (2011) 078, arXiv:1107.5051 [\[paper\]](#)

POWHEG-BOX/WW
POWHEG-BOX/WZ
POWHEG-BOX/ZZ

- W b bbar production, C. Oleari and L. Reina, *JHEP* **1108** (2011) 061, arXiv:1105.4488 [\[paper\]](#)

POWHEG-BOX/Wbb

- NLO corrections to electroweak and QCD production of W+W+ plus two jets, B. Jager and G. Zanderighi, *JHEP* **1111** (2011) 055, arXiv:1108.0864 [\[paper\]](#)

POWHEG-BOX/VBF_Wp_Wp

- Higgs boson production in gluon fusion with quark mass and EW effects, E. Bagnaschi, G. Degrossi, P. Slavich, A. Vicini, arXiv:1111.2854 [\[paper\]](#)

POWHEG-BOX/gg_H_quark-mass-effects

- Combining NLO QCD and electroweak radiative corrections to W-boson production at hadron colliders in the POWHEG framework, C. Berniacci and D. Wackerroth, arXiv:1201.4804 [\[paper\]](#)

POWHEG-BOX/W_ew_BW

- Electroweak corrections in single W production, L. Barze', G. Montagna, P. Nason, O. Nicrosini, F. Piccinini, arXiv:1202.0465 [\[paper\]](#)

POWHEG-BOX/W_ew_BMNNP

- NLO Higgs boson production plus one and two jets using the POWHEG BOX, MadGraph4 and MCFM, J.M. Campbell, R.K. Ellis, R. Frederix, P. Nason, C. Oleari, C. Williams, arXiv:1202.5475 [\[paper\]](#)

POWHEG-BOX/HJ
POWHEG-BOX/HJJ

- Associated production of charged Higgs bosons and top quarks with POWHEG, M. Klasen, K. Kovarik, P. Nason, C. Weydert, arXiv:1203.1341 [\[paper\]](#)

POWHEG-BOX/**

- Next-to-leading order QCD corrections to electroweak Zjj production in the POWHEGBOX, Barbara Jager, Steven Schneider, Giulia Zanderighi, arXiv:1207.2626 [\[paper\]](#)

POWHEG-BOX/VBF_Z

- Single-top t-channel hadroproduction in the four-flavour scheme with POWHEG and aMC@NLO, R. Frederix, E. Re, P. Torrielli, arXiv:1207.5391 [\[paper\]](#)

POWHEG-BOX/ST_tch_4f

In addition to the specific subprocess reference, the following papers should always be cited while using the POWHEG BOX:

- P. Nason, *JHEP* **0411** (2004) 040, hep-ph/0409146 [\[paper\]](#)
- S. Frixione, P. Nason and C. Oleari, *JHEP* **0711** (2007) 070, arXiv:0709.2092 [\[paper\]](#)
- S. Alioli, P. Nason, C. Oleari and E. Re, *JHEP* **1006** (2010) 043, arXiv:1002.2581 [\[paper\]](#)

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Notice: also EW corrections have being addressed recently in the POWHEG BOX framework, with multi photon emissions treated on the same ground as gluon emissions.

Other noticeable efforts:
 the **HELAC** team has implemented a merged **POWHEG-HELAC** framework (**POWHEL**) using the **POWHEG BOX**:
 $t\bar{t}W, t\bar{t}Z$ (Garzelli, Kardos, Papadopoulos, Trocsanyi, 2012)
 $t\bar{t}H$ (Garzelli, Kardos, Papadopoulos, Trocsanyi, 2011)
 $t\bar{t}j$ (Kardos, Papadopoulos, Trocsanyi, 2011)

Automation

The POWHEG BOX automates all aspects of the construction of the generator, except for the following:

- The Born phase space
- The Born matrix elements, including color correlated and spin correlated Born terms
- The real and virtual matrix elements
- The Born leading colour contributions, in order to assign colours to the user process partons.

In particular, the POWHEG BOX by itself knows nothing about the generation of matrix elements. On the other hands, it can be interfaced to existing programs for the generation of matrix elements, like in the HELAC case.

Available within the POWHEG BOX:

Interface to Madgraph: everything but the virtual and the Born phase space (R.Frederix, 2012):

`svn://powhegbox.mib.infn.it/trunk/POWHEG-BOX/MadGraphStuff`
Used to compute Hj and Hjj production, using the MCFM virtual matrix elements (Campbell, Ellis, Frederix, Oleari, Williams, P.N. 2012).

Being developed:

The **Gosam** program for the generation of virtual matrix elements (Cullen, Greiner, Heinrich, Luisoni, Matrolia, Ossola, Reiter, Tramontano, 2012) has been made public this year. An interface to the POWHEG BOX is under current development (Luisoni, Oleari, Tramontano, P.N.)

So: several alternatives for fully automated implementations; interfaces to dedicated (fast) hand-made implementations also available (MCFM).

Scales and pdf uncertainties

Scales and pdf uncertainties are difficult to compute, if one must generate new Monte Carlo samples for each PDF set and scales choice.

It is desirable to have, associated with each event, a set of weights corresponding to different PDF and scale choices.

The POWHEG BOX provided since some time a primitive pdf reweighting facility, and no scales reweighting of the kind that is available in aMC@NLO.

We have now implemented scale and pdf reweighting in the POWHEG BOX.
(Hamilton, Re, P.N.)

How it works

Remember: the POWHEG BOX relies upon third parties matrix elements; it is difficult to track the coefficients of scale logs through them.

So we do the following multi-stage procedure:

- Include with each generated event the value of the random seed used to compute the last phase space point, and the value of the integrand.
- Read the event file; for each event set the random seed to the stored value (to get the same phase space point), and compute the integrand again, with the desired new scale values or pdf set. Store the same event in a new file, appending to it the new weight

$$\text{new weight} = \text{old weight} \times \frac{\text{new integrand}}{\text{old integrand}}$$

The procedure can be repeated as many times as one like, appending to each event as many new weights as one likes.

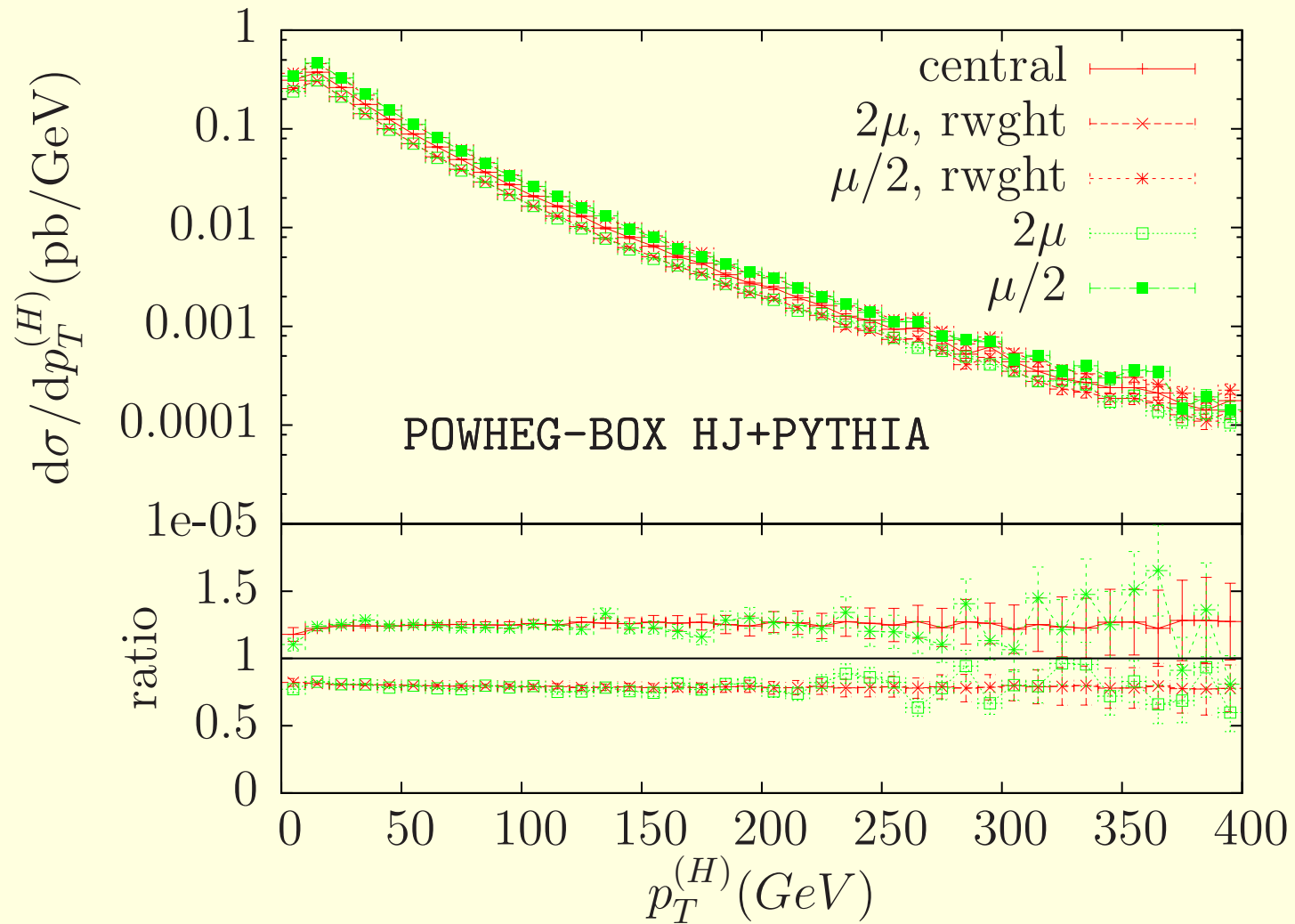
How it looks

```
<event>
 13 320000 1.00000E+00 7.55201E+01 -1.00000E+00 1.32196E-01
 21 -1 0 0 502 503 0.000000000E+00 0.000000000E+00 2.541357439E+02 2.541357439E+02 0.000000000E+00 0.00000E+00 9.000E+00
 21 -1 0 0 504 505 0.000000000E+00 0.000000000E+00 -4.038831662E+02 4.038831662E+02 0.000000000E+00 0.00000E+00 9.000E+00
 6 2 1 2 502 0 1.264725057E+02 -1.714959634E+01 1.426298903E+02 2.574639028E+02 1.722061913E+02 0.00000E+00 9.000E+00
 -6 2 1 2 0 505 -5.236398848E+01 3.168283322E+01 -1.387258735E+02 2.293473789E+02 1.720742951E+02 0.00000E+00 9.000E+00
 21 1 1 2 504 503 -7.410851721E+01 -1.453323688E+01 -1.536514390E+02 1.712076284E+02 1.907348633E-06 0.00000E+00 9.000E+00
 24 2 3 3 0 0 1.124848494E+02 -7.726549391E+00 2.893166297E+01 1.424214097E+02 8.206263407E+01 0.00000E+00 9.000E+00
 5 1 3 3 502 0 1.398765633E+01 -9.423046952E+00 1.136982273E+02 1.150424932E+02 4.800000000E+00 0.00000E+00 -1.000E+00
 -24 2 4 4 0 0 -5.945165693E+01 5.404154111E+01 -2.987203972E+01 1.178918093E+02 8.093918871E+01 0.00000E+00 9.000E+00
 -5 1 4 4 0 505 7.087668448E+00 -2.235870789E+01 -1.088538338E+02 1.114555696E+02 4.800000000E+00 0.00000E+00 1.000E+00
 -11 1 6 6 0 0 4.753838319E+01 -4.076446196E+01 3.024215238E+01 6.954298683E+01 5.110000000E-04 0.00000E+00 1.000E+00
 12 1 6 6 0 0 6.494646617E+01 3.303791257E+01 -1.310489409E+00 7.287842286E+01 0.000000000E+00 0.00000E+00 -1.000E+00
 11 1 8 8 0 0 -1.056933235E+01 2.227732252E+01 -5.038255908E+01 5.609271026E+01 5.110000000E-04 0.00000E+00 -1.000E+00
 -12 1 8 8 0 0 -4.888232458E+01 3.176421859E+01 2.051051936E+01 6.179909906E+01 0.000000000E+00 0.00000E+00 1.000E+00
#rwgt 1 1 236.22329425426454 1 14 0
#new weight,renfact,facfact,pdf1,pdf2 1.0905908061313441 0.5000000000000000 0.5000000000000000 21100 21100 lha
#new weight,renfact,facfact,pdf1,pdf2 0.91488851756586331 1.0000000000000000 0.5000000000000000 21100 21100 lha
#new weight,renfact,facfact,pdf1,pdf2 1.2187689698521500 0.5000000000000000 1.0000000000000000 21100 21100 lha
#new weight,renfact,facfact,pdf1,pdf2 1.0697449892035478 1.0000000000000000 2.0000000000000000 21100 21100 lha
#new weight,renfact,facfact,pdf1,pdf2 0.83614889468182263 2.0000000000000000 1.0000000000000000 21100 21100 lha
#new weight,renfact,facfact,pdf1,pdf2 0.88271219160050818 2.0000000000000000 2.0000000000000000 21100 21100 lha
</event>
```

The **#rwgt** line contains the integrand and random number seeds, and is generated in the first run.

The **#new weight ...** lines are generated in subsequent (**cheep!**) runs, where only a single call to the cross section is made for each event.

Example: reweighted compared to direct



The reweighting code is in

```
svn://powhegbox.mib.infn.it/trunk/POWHEG-BOX/ReweightingStuff
```

with instruction on how to apply it to specific processes. It will be merged with the main POWHEG BOX files as soon as we are confident that it does what is needed (need feedback from experimental collaborations).

Resonance decays in NLO+PS

NLO+PS generators usually include NLO corrections only to the production process. Thus, for example, in W production with subsequent W decay to hadrons, no NLO corrections are included in W decays.

In $t\bar{t}$ production, the NLO correction to the $t \rightarrow Wb$ decays is not included, and in case the W decays hadronically, the corresponding NLO correction is also not included.

Some shower generators are capable to include approximate NLO effects in t and W decays (for example, Pythia8).

Given (for example) a W decayed into a $q\bar{q}$ pair on the Les Houches interface, they shower them including MEC (i.e. such that the rotational averaged $q\bar{q}g$ matrix element is correct; some reasonable rotational correlation with the initial $q\bar{q}$. are also maintained.)

Virtual corrections divide out in a branching ratio, so that they cancel upon rotational average. In this sense, they are partially included.

Several NLO results including NLO corrections to top decays are available in the literature (Melnikov and Schulze; Bernreuther and Si; Campbell and Ellis)

So, the POWHEG BOX has been upgraded to deal with NLO corrections in decays. This upgrade is being applied to the MCFM NLO results for $t\bar{t}$ and single top production (Campbell, Ellis, P.N., current work).

Need to modify several aspects of the POWHEG BOX:

- In the POWHEG BOX, processes are represented by a string of flavours:
 $3 -3 11 -12 -11 12 5 -5$ is $q\bar{q} \rightarrow e \bar{\nu} \bar{e} \nu b \bar{b}$. Now we need to add
 resonance information: $q\bar{q} \rightarrow (t \rightarrow b (W^+ \rightarrow \bar{e} \nu)) (\bar{t} \rightarrow b (W^- \rightarrow e \bar{\nu}))$ is
 $3 -3 6 -6 24 -24 11 -12 -11 12 5 -5$
 $0 0 0 0 3 4 6 6 5 5 3 4$
- Real processes are different, depending upon the origin of the radiated
 parton, whether it is from production or resonances. So:
 $3 -3 6 -6 24 -24 11 -12 -11 12 5 -5 0$
 $0 0 0 0 3 4 6 6 5 5 3 4 0,3,4$, 3 independent contributions!
 For hadronic W 's, the radiated parton may also come from the W 's.

When requesting a real matrix element to MCFM, we invoke the appropriate routine (production or decay), depending upon the value of the pointer to a resonance of the radiated parton.

- POWHEG defines and underlying Born for each real emission kinematics. Now the underlying Born is different if the radiation comes from a resonance. In FSR, the underlying Born is such that the **whole final state system recoiling from the splitting pair of partons** is boosted to conserve total energy and momentum. Now, if a resonance is radiating, the recoil system is formed only by the partons belonging to the resonance, and this subset of parton is boosted to **conserve the resonance 4-momentum**.
- The soft terms, to be added to the virtual term, must be computed in the **resonance rest frame**, if they arise from real graphs where the radiation comes from a resonance.

The POWHEG BOX also implements an automatic subtraction scheme for NLO calculations. All these aspects must be update for resonance treatment.

These extensions have all been completed. They are designed to be fully general, and they are being applied to the $t\bar{t}$ and single top processes.

Interface to Shower

- With **no NLO corrections to decays** (but exact NLO spin correlations): can be interfaced to shower as before.
- With **NLO corrections to decays**: POWHEG generates the hardest radiation, whether it comes from production or decay. The shower should not generate anything harder, neither in production nor in decays.

Les Houches user process allows to veto radiation in production, by setting the variable **scalup**. The shower treats resonance decays independently.

Must go beyond Les Houches:

Pythia 8 has methods for vetoing the shower off a resonance, allowing for a great deal of flexibility. It is desirable that future interface accords will take account of these needs.

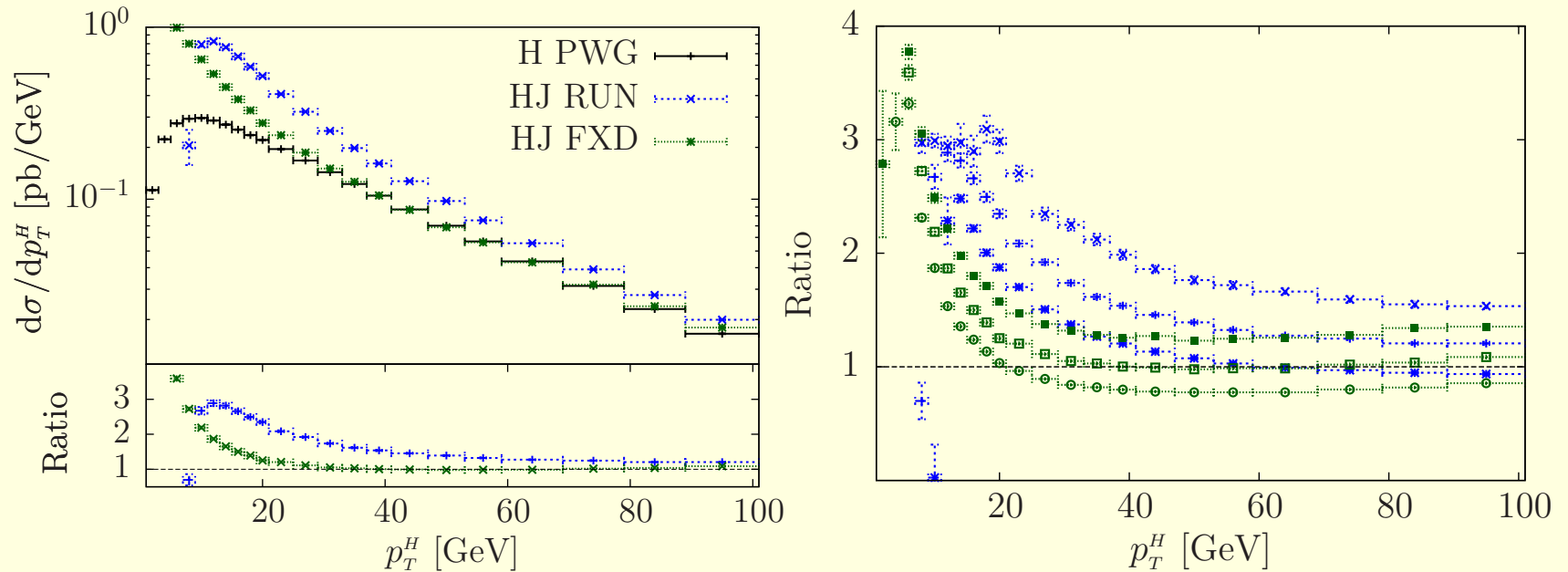
MINLO: Multi-scale Improved NLO

The MINLO procedure (Hamilton, Zanderighi, P.N. 2012) has been implemented and made public in the POWHEG BOX:

```
svn://powhegbox.mib.infn.it/trunk/POWHEG-BOX/MINLO
```

The purpose of this procedure is to improve the NLO computation of the inclusive cross section in the POWHEG BOX when regions of the phase space with widely different scales are approached.

The MINLO procedure achieves this by a suitable choices of the factorization and renormalization scales, and by exponentiating large Sudakov logarithms.



H PWG: POWHEG `gg_H` generator interfaced with PYTHIA, $M_H = 120 \text{ GeV}$

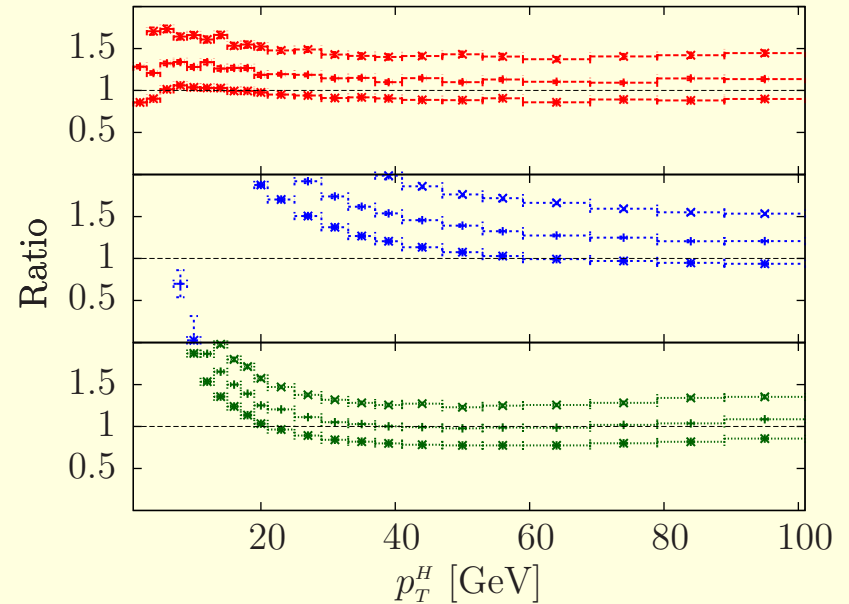
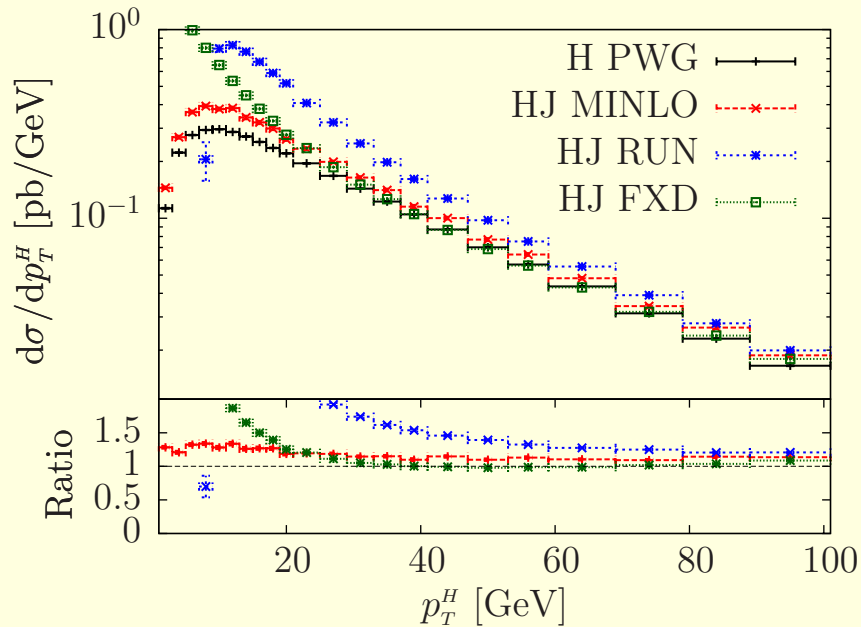
HJ RUN: HJ NLO calculation with $\mu_R = \mu_F = p_T^H$

HJ FXD: HJ NLO calculation with $\mu_R = \mu_F = m_H$. (Ratios 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 $\frac{1}{2} \leq \frac{\mu_R}{\mu_F} \leq 2$.
- Bands don't overlap at $p_T \lesssim 30 \text{ GeV}$.
- NLO shapes differ from LL resummed result (POWHEG) at small p_T .

In the standard POWHEG implementation of Hj production, the NLO computation of the Hj cross section suffers from large uncertainties due to scale choices, and, furthermore, does not have a good match with the H production POWHEG generator at small transverse momenta. This problem is easily tracked back to the fact that the Hj NLO calculation does not attempt to resum large logarithms of the jet transverse momentum, not even at the LO level.

MINLO HJ result



- 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.

Thus:

- The MINLO approach improves POWHEG implementation involving associated jet production, in the singular phase space region.
- It provides a better match with the corresponding lower multiplicity process (for example, Hjj matches Hj when approaching the one jet region, and Hj matches H when approaching the no-jet region).
- It eases considerably the construction of matched samples with different jet multiplicities.

Further work in this direction is in progress, for finding simple criteria for matching MINLO-POWHEG samples of different multiplicities.

Conclusions and prospects

- The list of POWHEG BOX processes increases steadily.
- A facility for event reweighting, in order to determine scale and pdf uncertainties, has been set up.
- The POWHEG BOX has been extended, to allow for the inclusion of NLO corrections to decay processes.
- The MINLO procedure yields a considerable improvement of the generators near the singular regions, allowing for better matching among samples with different jet multiplicity.