Recent developments in the POWHEG BOX

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Standard Model @ LHC

Durham, 12 April 2011

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- Quick description of the method
- The `POWHEG BOX` framework
    - organization of the program
    - current version
- Already available processes
- Work in progress

The POWHEG method

[Nason, JHEP 0411:040,2004]

- POWHEG is a method to merge NLO calculations with Parton Showers:

NLO

✓ reduced scale dependence

✓ better description of high-p_T tails

PS

✓ Sudakov suppression in collinear regions

✓ parton $\rightarrow$ hadron corrections not needed

- In a nutshell, the method can be summarized by the following *master* formula:

$$d\sigma_{POW} = \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta(\Phi_n; k_T^{\min}) + \Delta(\Phi_n; k_T) \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} d\Phi_r \right\}$$

where

$$\bar{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int \left[R(\Phi_{n+1}) - C(\Phi_{n+1}) \right] d\Phi_r$$

$$\Delta(\Phi_n; k_T) = \exp\left\{ - \int \frac{R(\Phi_n, \Phi_r')}{B(\Phi_n)} \theta(k_T' - k_T)\, d\Phi_r' \right\}$$

and to avoid double-counting the subsequent emissions are p_T-*vetoed*.

- POWHEG is a method to merge NLO calculations with Parton Showers:

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- ✓ better description of high-p_T tails

PS
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- ✓ parton $\longrightarrow$ hadron corrections not needed

- In a nutshell, the method can be summarized by the following *master* formula:

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- General comments:
  - Accuracy: inclusive observables @NLO, first hard emission with full tree level ME, (N)LL resummation of collinear/soft logs, extra jets in the shower approximation:
    - if only interested in multijet shapes $\longrightarrow$ ME+PS (CKKW, MLM)
      if only interested in inclusive quantities $\longrightarrow$ NNLO
    - however, in both cases, it is still better than standalone SMC...
  - Main differences with respect to MC@NLO:
    - ✓ Events are positive weighted.
    - ✓ It does not depend from the parton-shower algorithm used.
  - Only when used with angular-ordered PS, a truncated shower should be included too. So far, negligible effects in neglecting it.

The POWHEG BOX framework

- Although it may look easy, the actual implementation of the algorithm is not straightforward. [Frixione,Nason,Oleari, JHEP 0711:070,2007]
- Our automation of the algorithm led to the POWHEG BOX package, which has been available for more than 1 year now.
- General features:
  - automation of the POWHEG algorithm using the FKS subtraction scheme.
  - all previous implementations and new ones included in a single and public framework.
  - it produces LHE files, ready to be showered.
  - can be used as a “black-box”, although all the details were carefully described.

[Alioli,Nason,Oleari,ER, JHEP 1006:043,2010]

- Other features:
  - we want to keep as much as possible the original goal of independence from the parton-shower. If needed, will try to refine the interface.
  - by default unweighted generation of events
  - for more complicated processes, it is also possible to generate weighted events.
    - $\hookrightarrow$ Useful to populate the high-pt tail for processes with steeply-falling cross section.
  - we will continue keeping our code completely available for interested theorists, and if you implement your process, we would be happy to include it in the repository.

Present status of the program: release 1.0

All available at

`http://powhegbox.mib.infn.it`

It became clear that especially for experimental collaborations there is the need to reference a version/release: since 2 weeks, repository is organized as follows:

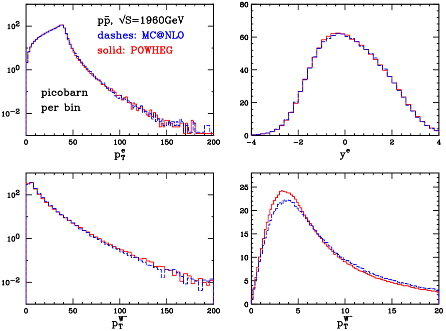
- `releases/POWHEG-BOX-1.0`
- `releases/POWHEG-BOX-1.0.#` $\rightarrow$ bug fixes after we collect some of them
- `trunk` $\rightarrow$ main development, and bug fixing as soon as a bug is found

- structure: main directory + process folders.
- for users: general user manual + shorter manuals in each subprocess directory (to describe specific settings) + template input files.
- although the important output is a LH event file (partonic events to be showered), template drivers for PYTHIA and HERWIG are also available.
- we tried to be as uniform as possible among different processes.

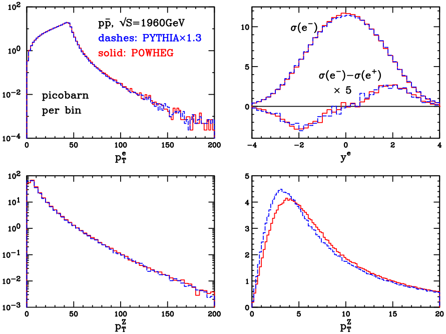
Single vector-boson production

[Alioli,Nason,Oleari,ER, JHEP 0807:060,2008]

- Originally standalone code, now also within the `POWHEG BOX` package.
- Important process for luminosity measurements and precision Physics (standard candle). Relevant also for tuning MC parameters.



[W^- @ TeV]



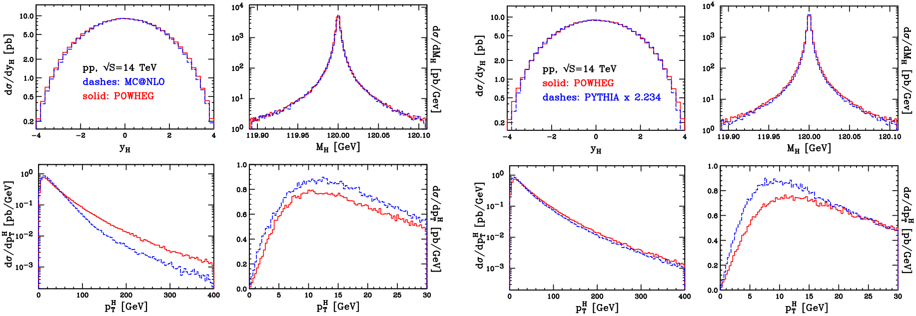
[Z @ TeV]

- Good agreement both at high and low-p_T with `MC@NLO`.
- `PYTHIA` ME corrections $\sim$ `POWHEG` (expected).
- `PYTHIA` standalone has a wrong normalization (expected).
- Reasonable agreement also with Tevatron data.

Higgs-boson production (gluon fusion)

[Alioli,Nason,Oleari,ER, JHEP 0904:002,2009]

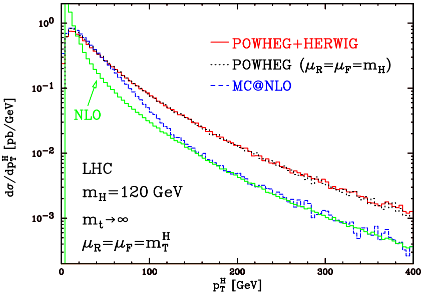
- Dominant production channel for SM Higgs-boson.
- Originally standalone code, now also within the POWHEG BOX package.

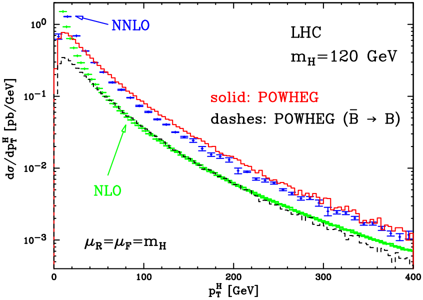


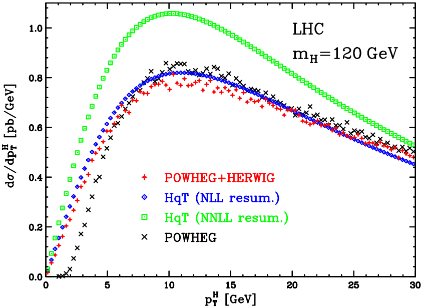
$m_H = 120$ GeV, @ LHC

- At low-p_{T}: agreement with MC@NLO, difference with PYTHIA
  - different prescription in Sudakov form factor (CMW)
- PYTHIA ME corrections $\sim$ POWHEG $\Rightarrow$ high-p_{T} agreement, after overall rescaling.
- POWHEG high-p_{T} tail harder wrt MC@NLO ...

Higgs-boson production (gluon fusion)



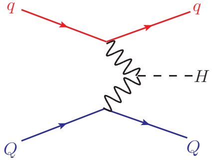




- difference with MC@NLO is understood: formally a NNLO mismatch, big because NLO is itself big ($\bar{B}/B \sim 1$).
- good agreement with NLL resummation (expected, but nontrivial).
- m_t dependence currently included as follows:

$$\bar{B} = \frac{B(m_t)}{B(m_t \to \infty)} \bar{B}(m_t \to \infty)$$

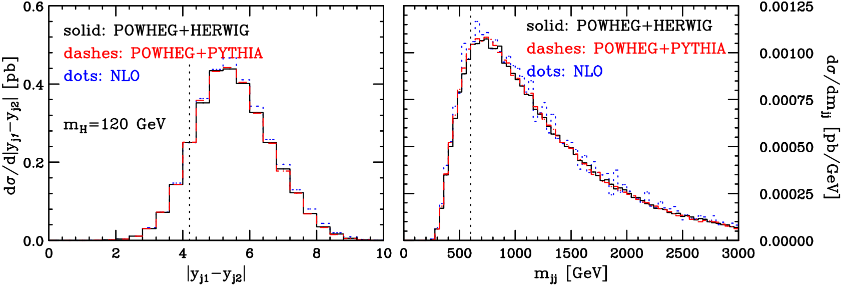
[Nason,Oleari, JHEP 1002:037,2010]



- Second most important Higgs-boson production process.
- Main feature: colorless t-channel exchange $\rightarrow$ well separated jets, in opposite hemisphere, to reduce the background

jets: $p_T^j > 20\text{GeV}$, $|y^j| < 5$ kt, R=0.7

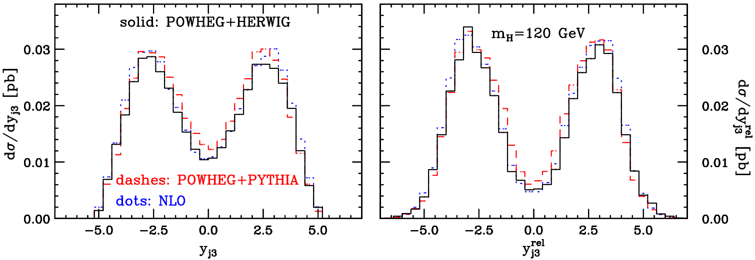
tagging jets: $p_T^{\text{tag}} > 30\text{GeV}$, $|y^{j1} - y^{j2}| < 4.2$, $y^{j1} \cdot y^{j2} < 0$, $m_{j_1 j_2} > 600\text{GeV}$



- typical backgrounds have QCD t-channel exchange: $t\bar{t}$, $WW + 2$ jets, $Z + 2$ jets. Very reduced with VBF cuts.
- good agreement between NLO and showered result for inclusive quantities.

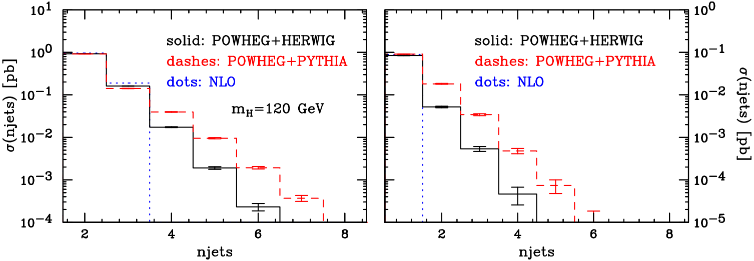
Higgs-boson production (VBF)

- jet activity mainly close to tagged jets ($y_{j3}^{\rm rel} = y_{j_3} - (y_{j_1} + y_{j_2})/2$)



- possible to study also the jet activity within the gap region:

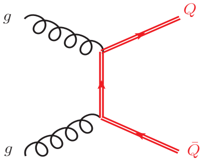
veto jets: $\min(y^{j1}, y^{j2}) < y^j < \max(y^{j1}, y^{j2})$



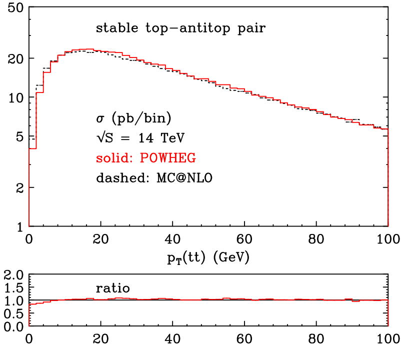
Heavy flavour pair production

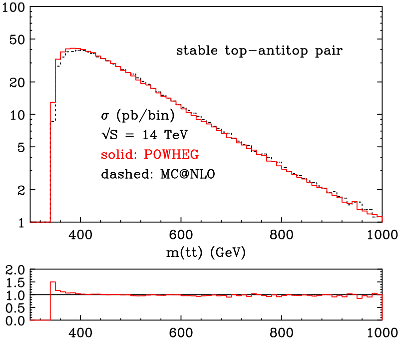
[Frixione,Nason,Ridolfi, JHEP 0709:126,2007]

- Originally standalone code, now also within the `POWHEG BOX` package.



- fundamental process, and also important background.
- implementation works also for $b\bar{b}$ and $c\bar{c}$.
- top decays generated with tree-level accuracy.



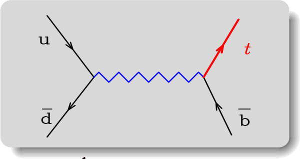


[Alioli,Nason,Oleari,ER, JHEP 0909:111,2009]

- Electroweak production of a top quark without its antiparticle.
  Observed recently at Tevatron (CDF and D0), under studied at LHC as well.
- Production channels are (traditionally) classified with respect to the virtuality of the W boson involved.
- All processes are relevant for a direct measure of V_{tb}.
- Probe directly the V-A structure of weak interactions:
  - $\hookrightarrow$ top-quark decays before hadronizing
  - $\hookrightarrow$ only left-handed charged-current interactions $\rightarrow$ spin correlation effects are seen as angular correlations in distributions involving its decay products

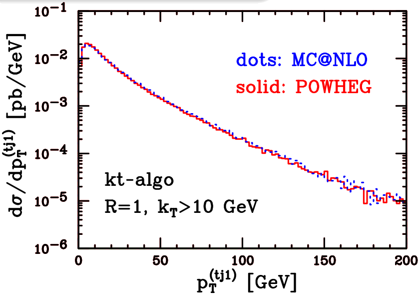
[Alioli,Nason,Oleari,ER, JHEP 0909:111,2009]

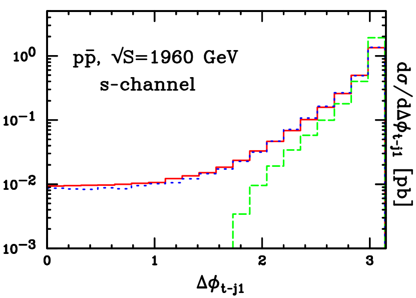
- Electroweak production of a top quark without its antiparticle.



s-channel

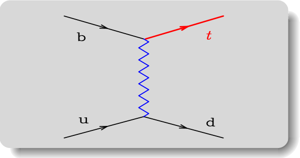
- Relatively large at TeV, negligible at LHC.
- Sensitive to a new intermediate particle (W').





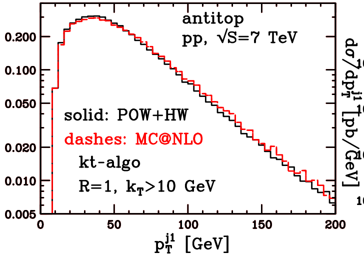
- Agreement with MC@NLO (expected).
- Differences with NLO in kinematics regions not covered by fixed-order.

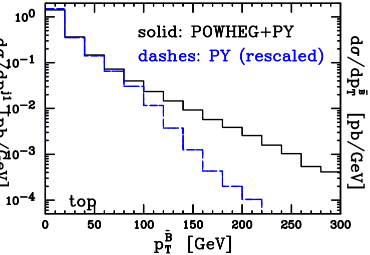
[Alioli,Nason,Oleari,ER, JHEP 0909:111,2009]



t-channel

- Dominant at TeV and LHC.
- Sensible to some new-physics models.
- Implemented in the 5-flavour scheme.

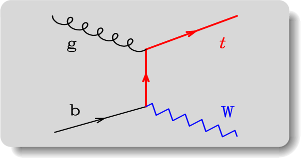




- well tested with MC@NLO.
- b-flavored jet not well described by standard MCs (expected: radiation only in the collinear approximation).
- Possible improvement: 4-flavour scheme. Relevant to describe with NLO accuracy the tagged b-jet, typical of single-top t-channel. Current POWHEG and MC@NLO are only LO accurate in this observable. Is it urgent?

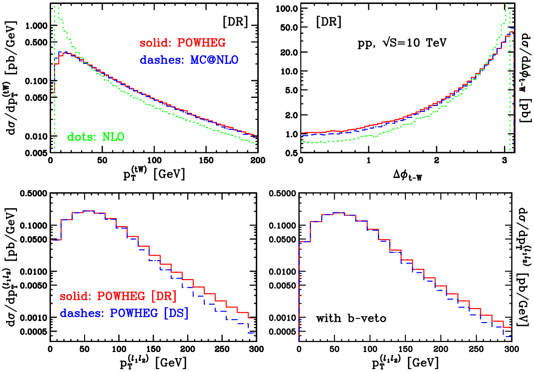
Single-top

[ER, EPJC 71:1547,2011]



Wt-channel

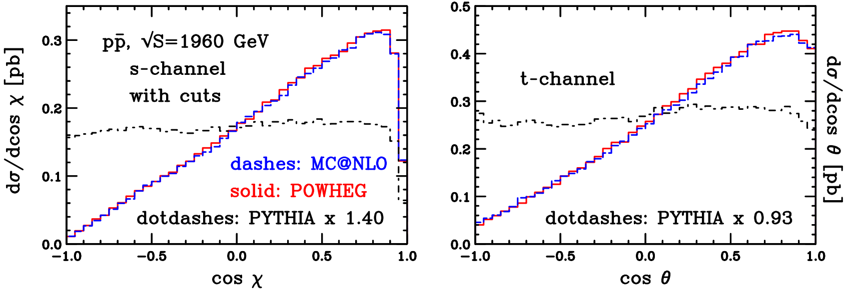
- Negligible at TeV, but relevant at LHC.
- Non trivial definition of NLO corrections. [interference with $t\bar{t}$ production, when $\bar{t} \to W\bar{b}$] $\hookrightarrow$ strictly speaking, it is not well defined, but an operative definition seems possible.



- Background for $H \to WW$
- Two prescriptions adopted (DR and DS), to quantify interference effects with $t\bar{t}$
- Very good agreement with MC@NLO
- Shown that the 2 approaches give very similar results when typical cuts are applied (here b-veto on second hardest b-hadron).
- More complete and realistic studies are also possible.

- For processes with tops, we generate the decay products with tree-level accuracy.

  [Frixione & al., JHEP 0704:081,2007]
- It is only LO accurate, but it should give good predictions for angular correlations.

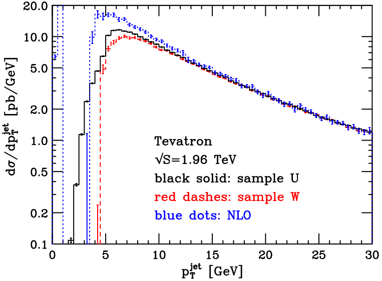


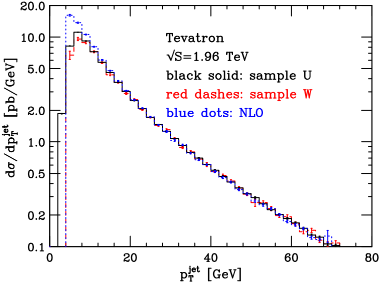
- Possible improvements: decay generation using POWHEG, OR implementation of the full NLO calculation with decay effects ($t\bar{t}$: Melnikov,Schulze, single-top: Falgari,Mellor,Signer).

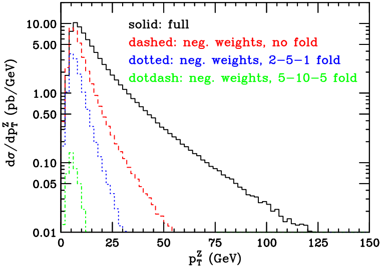
V+1jet

[Alioli,Nason,Oleari,ER, JHEP 1101:095,2011]

- First implemented process defined through a jet algorithm at LO.







- option 1: sharp cut on Z transverse momentum (here, $k_{T,cut} = 5$ GeV).
- option 2: generation of weighted events:

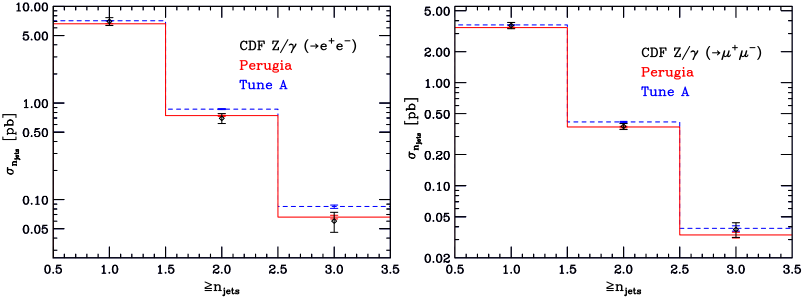
$$\bar{B} \to \bar{B} \times F(p_{T,Z}), \quad F(p_T) = \frac{p_T^2}{p_T^2 + k_{T,supp}^2}$$

(here, $k_{T,supp} = 10$ GeV, and $k_{T,cut} = 1$ GeV).

- Using F also helps in populating the high-p_t region more efficiently.

V+1jet, data comparison

- Samples of $\sim$ 1.3 million of positive weighted events.
- Direct comparison with CDF data (PRL 100:102001 (2008) - blessed data from CDF-QCD webpage): no K-factors, no parton-to-hadron corrections (not needed).
- Showered with `PYTHIA 6.4.21`, with Perugia 0 (p_{T}-ordered) and Tune A (Q^2-ordered).

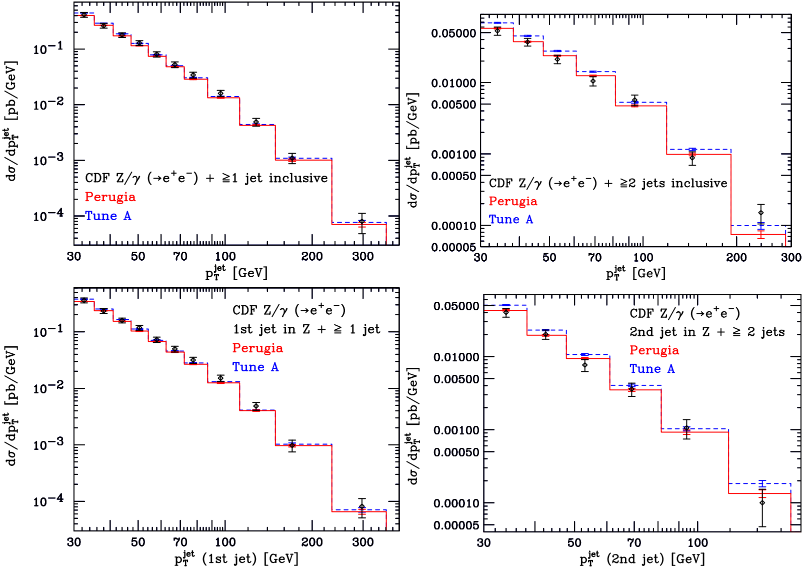


Comments:

- very good agreement.
- tune effect sizeable (and p_{T}-ordering gives better results, as expected).

V+1jet, data comparison

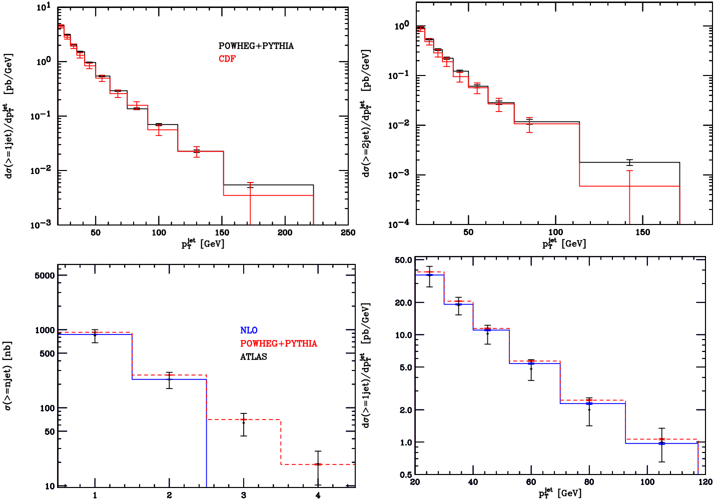
Upper panel: PRL (1.7 fb^{-1}). Lower panel: blessed data from CDF webpage (2.5 fb^{-1}).



- 1^{st} jet has full NLO+PS accuracy, 2^{nd} jet has tree-level full ME accuracy.

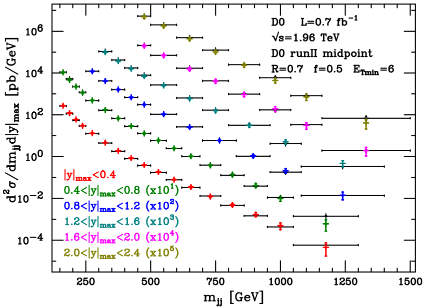
V+1jet, validation of W+1jet

[PRELIMINARY]

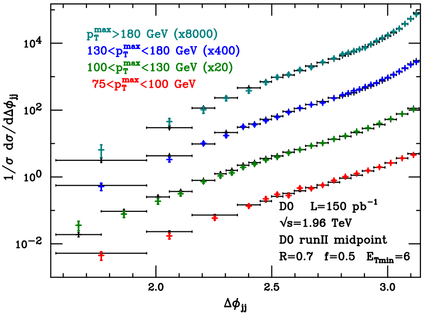


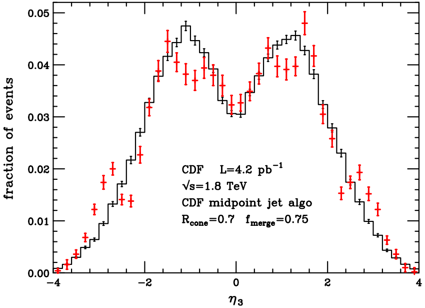
- cuts as described in Phys.Rev.D77:011108,2008 [CDF] and arXiv:0711.4044 [ATLAS].
- showered events with p_T-ordered PYTHIA (Perugia 0 tune).
- Validation finished, code soon public.

Dijets



[Alioli,Hamilton,Nason,Oleari,ER, arXiv:1012.3380]



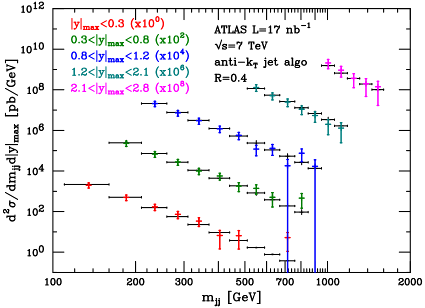


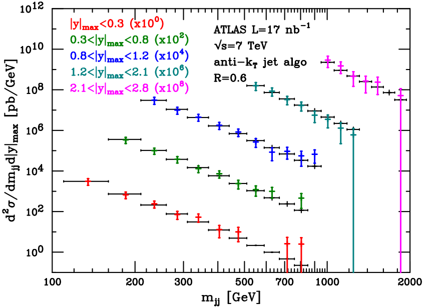
- Most frequent hard scattering in hadronic collisions.
- NLO has been checked against results by Frixione-Ridolfi.
- good agreement with D0 data.
- 5M weighted events, $k_{T,cut} = 1$ GeV,

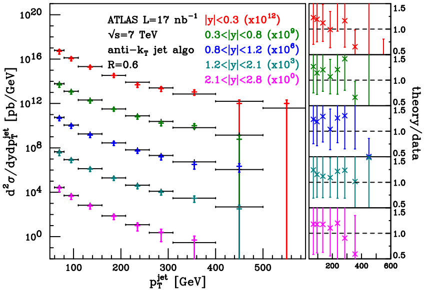
$$F(p_T) = \left(\frac{p_T^2}{p_T^2 + (600)^2}\right)^3$$

, folded integration.

Dijets







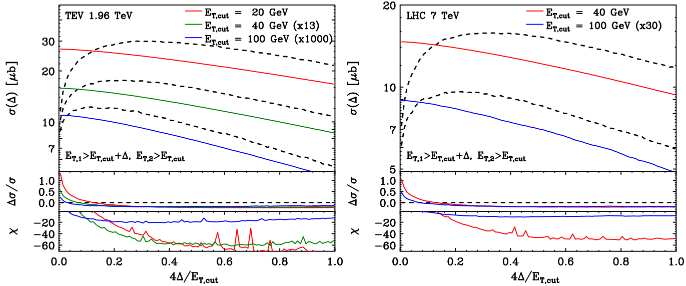
- 5M weighted events, $k_{T,cut} = 1$ GeV,
  $F(p_T) = \left(\frac{p_T^2}{p_T^2 + (200)^2}\right)^3$, folded integration.
- when comparing with first ATLAS data [Eur.Phys.J.C71:1512(2011)], we found good agreement.
- instead, as shown yesterday, with more recent data sizeable disagreement, especially in m_{jj} with R=0.6.
- Problem is currently under study.

Inclusive dijet processes and the role of cuts

- Most inclusive measurement: total cross section, it depends on the cuts used.
- Despite its simplicity, nontrivial QCD effects take place also when considering $\sigma(\Delta)$, where

$$E_{T,2} > E_{T,cut} \quad E_{T,1} > E_{T,cut} + \Delta$$

- From simple considerations on phase space, we expect $\sigma'(\Delta) < 0$, instead NLO prediction has a peak.



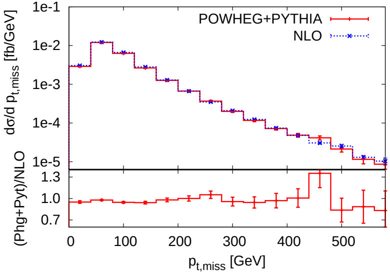
- As observed by Frixione-Ridolfi, and later studied thoroughly by Banfi-Dasgupta, NLO curve alone is “wrong” when symmetric cuts ($\Delta \to 0$) are applied:

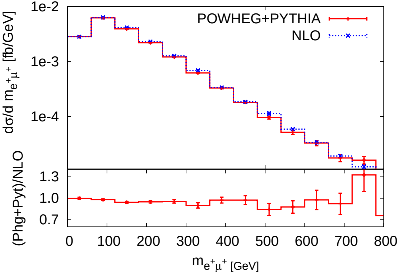
> peak and suppression at low Δ because of a $-\Delta \log \Delta$ term, arising from unbalanced cancellation of soft-collinear emissions.

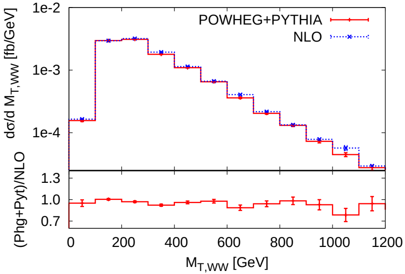
- Full analytic resummation is possible and restore correct behaviour (BD). Resummation performed by the shower works well too (here `POWHEG` first emission).

W^+W^+jj

[Melia,Nason,Rontsch,Zanderighi, arXiv:1102.4846]







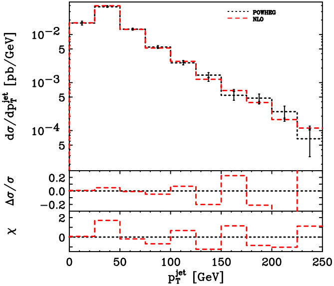
- relevant because background to new-Physics processes with same-sign leptons, missing energy and 2 jets.
- virtual corrections computed using state-of-the-art tecnique (d-dimensional unitarity)
- cuts:

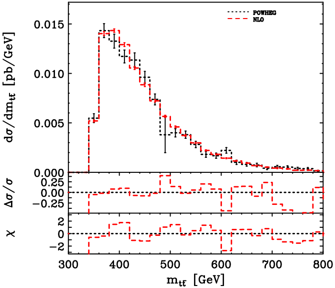
$$p_{t,l^+} > 20 \text{ GeV}, p_{t,\text{miss}} > 30 \text{ GeV}, |\eta_{l^+}| < 2.4$$

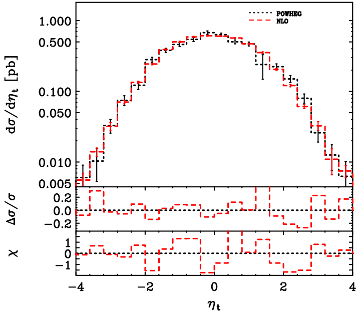
- some improvements in the BOX code. Looks promising in view of other recent NLO computations.

$t\bar{t}$ + 1 jet

Full implementation in [Kardos, Papadopoulos, Trocsanyi, arXiv:1101.2672], using HELAC.
Here I show some result from [Alioli,Moch,Uwer, in preparation]



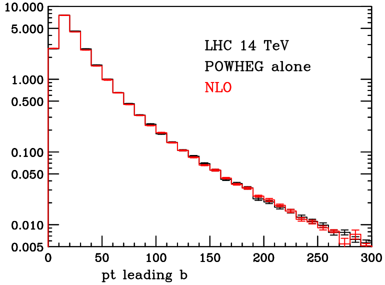


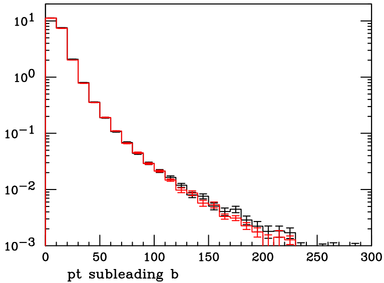


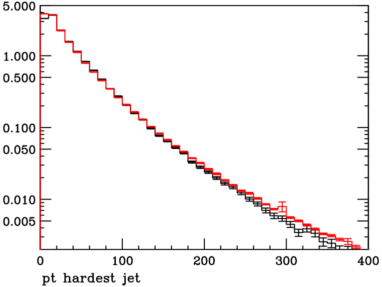
- Important because a significant fraction of $t\bar{t}$ events have an extra jet.
- For inclusive quantities, NLO and POWHEG hardest emission coincide up to NNLO contributions. However, agreement is good.
- Understanding the effect of the showering part is work in progress.

$Wb\bar{b}$

[Oleari,Reina, in preparation]







- irreducible background of WH process.
- full b-mass effects included.
- here jets with anti-kt algo, $p_T^{min} = 5$ GeV, $R = 0.4$.

Conclusions

- many $2 \to 2$ SM processes are available within the `POWHEG BOX` package. Together with other `POWHEG` implementations it is already possible to simulate almost all $2 \to 2$ SM processes with NLO+PS accuracy.
- $2 \to 3$ implementations are work in progress, and a $2 \to 4$ implementation was already possible.
- Understand the origin of the disagreement with dijets data is work in progress.
- In general, the validation of the code will be demanding for more complicated processes: matching with different shower algorithms (and need of more refined interfaces), need of complete truncated showers when using `HERWIG`, dedicated tuning, are problems that we will try to address.

Outlooks:

- Many interesting processes yet to be implemented (V+multijets, heavy flavours with jets, exact mass effects in Higgs gluon fusion).
- Interfacing to modern codes for virtual corrections.
- Further studies and improvements are possible, for example `MENLOPS`.

Backup

POWHEG generation cut: 5 GeV. PDF set: CTEQ6M.

CDF

Midpoint algo, cone radius $R = 0.7$, merging/splitting fraction 0.75.

- $Z(\to e^+e^-) + j$: (h/p $\sim 10\%$)

$$66\ \mathrm{GeV} < M_{ee} < 116\ \mathrm{GeV},\quad p_T^e > 25\ \mathrm{GeV},\quad |\eta^{e1}| < 1.0,\quad |\eta^{e2}| < 1.0 \text{ or } 1.2 < |\eta^{e2}| < 2.8,$$
$$|y^{\mathrm{jet}}| < 2.1,\quad p_T^{\mathrm{jet}} > 30\ \mathrm{GeV},\quad \Delta R_{e,\,\mathrm{jet}} > 0.7\,.$$

- $Z(\to \mu^+\mu^-) + j$

$$66\ \mathrm{GeV} < M_{\mu\mu} < 116\ \mathrm{GeV},\quad p_T^\mu > 25\ \mathrm{GeV},\quad |\eta^\mu| < 1.0,$$
$$|y^{\mathrm{jet}}| < 2.1,\quad p_T^{\mathrm{jet}} > 30\ \mathrm{GeV},\quad \Delta R_{\mu,\,\mathrm{jet}} > 0.7\,.$$

D0

D0 Run II iterative seed-based cone algo, cone radius $R = 0.5$, merging/splitting fraction 0.5.

- $Z(\to e^+e^-) + j$: (h/p $\sim 5\%$)

$$65\ \mathrm{GeV} < M_{ee} < 115\ \mathrm{GeV},\quad p_T^e > 25\ \mathrm{GeV},\quad |\eta^e| < 1.1 \text{ or } 1.5 < |\eta^e| < 2.5,$$
$$|y^{\mathrm{jet}}| < 2.5,\quad p_T^{\mathrm{jet}} > 20\ \mathrm{GeV}\,.$$

- $Z(\to \mu^+\mu^-) + j$: (h/p $< 4\%$)

$$65\ \mathrm{GeV} < M_{\mu\mu} < 115\ \mathrm{GeV},\quad p_T^\mu > 15\ \mathrm{GeV},\quad |\eta^\mu| < 1.7,$$
$$|y^{\mathrm{jet}}| < 2.8,\quad p_T^{\mathrm{jet}} > 20\ \mathrm{GeV},\quad \Delta R_{\mu,\,\mathrm{jet}} > 0.5\,.$$