Heavy quarks + jet production in Powheg

Simone Alioli
DESY Zeuthen

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in collaboration with S. Moch and P. Uwer

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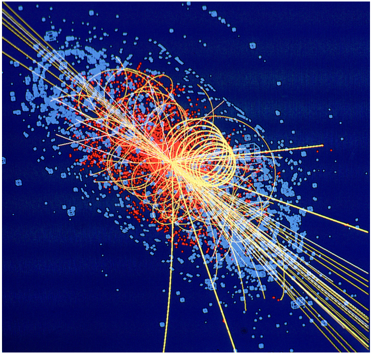
Outline



- The POWHEG method and the POWHEG−BOX
- $t\bar{t}$ + jet in the POWHEG−BOX
- Conclusions & Outlook

Motivations

SMC (LO+Shower)

- ✗ LO accuracy. Large dependence on μ_{R} and μ_{F}
- ✗ Extra emissions accurate only in soft/collinear approx.
- ✓ Sudakov suppression of soft/collinear emissions
- ✓ Realistic events in the output

NLO

- ✓ Accuracy up to a further order in α_{S}
- ✓ Reduced dependence on μ_{R} and μ_{F}
- ✗ Wrong shapes in the Sudakov region
- ✗ Parton level output only. Low final-state multiplicity.
- ✗ Numerical instability due to large cancellations

Try to merge benefits (and avoid drawbacks) of both approaches!

How to improve standard Shower Monte Carlo

✗ A K factor = $\frac{\sigma_{NLO}}{\sigma_{LO}}$ correction only improves inclusive quantities

✗ Including further real emissions may also accomodate shapes:

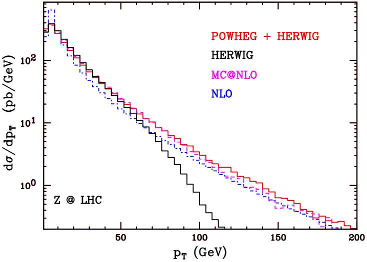
- ⇒ MEPS only has LO normalization
- ⇒ A matching prescription to avoid double-counting of radiation must be defined
- ⇒ Large uncertainty under scale variations due to the lack of virtual corrections

$$\alpha_S^n(f\mu) \approx \alpha_S^n(\mu)(1 - b_0\alpha_S(\mu)\log(f^2))^n \approx \alpha_S^n(\mu)(1 \pm n\alpha_S(\mu))$$

✓ Use full NLO calculation as "hard subprocess" for the SMC ⇒ NLO+PS

Many ideas to avoid double-counting, but two general method perform this merging for hadronic collisions fully tested

- MC@NLO [Frixione & Webber,JHEP 0206:029,2002]
- POWHEG [Nason,JHEP 0411:040,2004]
  [Frixione, Nason & Oleari, JHEP 0711:070,2007]

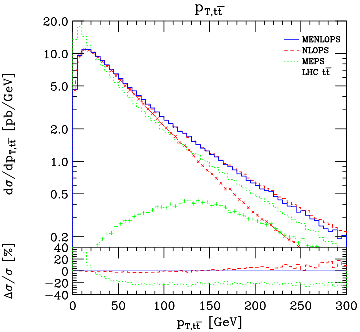


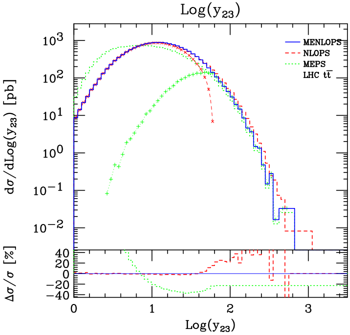
MC@NLO can now also be interfaced with PYTHIA and HERWIG++ showers.
POWHEG method adopted also in HERWIG++ and SHERPA programs.

A step further: ME+NLO+PS

✓ **Merging of NLO+PS with ME corrections. NLO accuracy can be reached reweighting ME+PS by a Φ_B-dependent $K-$factor.** [Nason& Hamilton, arXiv:1004.1764]
Very computer intensive evaluation: viable only for simple processes!

Approximate solution with available tools tested for W and $t\bar{t}$. Dubbed MENLOPS. Similar approach also implemented in SHERPA
[Hoche,Krauss,Schonherr&Siegert,arXiv:1009.1127]





- **NLO accuracy is maintained if fraction of ME+PS events is less than α_S.**

The POWHEG-BOX

The POWHEG–BOX [S.A., Nason,Oleari,Re, JHEP 1006:043,2010]

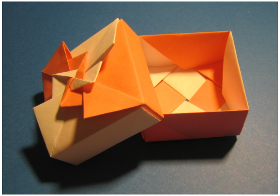
- Framework for the implementation of a POWHEG generator for a generic NLO process
- Practical implementation of the theoretical construction of the POWHEG general formulation presented in [Frixione,Nason,Oleari,JHEP 0711:070,2007]
- FKS subtraction approach automatically implemented, hiding all technicalities to the user
- Publicly available code at the webpage http://powhegbox.mib.infn.it

Available processes

- $Z/\gamma*, W^{\pm}$ production and decay
- $Z/\gamma*, W^{\pm}$ plus one jet production and decay
- Single-top production in the $s-$, $t-$ and $Wt-$ channel
- Higgs boson production in gluon and vector boson fusion
- Jet pair production
- Heavy-quark pairs production
- W^+W^+ plus two jets
- $Wb\bar{b}$, with massive b's and approximated decay
- ZZ, WW, WZ with Z/γ interference, off-shell effects and decays (in preparation)
- tH^- (in preparation)
- $t\bar{t}$ plus one jet , with approximated decay (this talk)

POWHEG is a method. Few independent codes implementing it are available:

- Herwig++, include also truncate showers (Hamilton,Richardson,Seymour *et al.*)
- Sherpa (Höche,Krauss,Schönerr,Siegert)
- POWHEG–BOX interfaced with HELAC–NLO (Kardos, Papadopoulos, Trocsanyi)
- POWHEG–BOX from the Milano-Bicocca group (Nason, Oleari, S.A., Re)



The POWHEG method was born to be PS independent.

- We follow this guideline, providing Les Houches event files, ready to be showered by any SMC.
- Ready to discuss/improve the LH interface, if needed for some generator.
- Interface to Rivet/AGile analysis frameworks under testing.
- Mailing list availaible at http://www.hepforge.org for announcements/contacting the authors

The POWHEG–BOX: issues with multileg processes

- Non trivial process definition when Born contributions are IR divergent. Need to introduce a process-defining cutoff.
- In a NLO computation is sufficient to ask that the observable $\mathcal{O}_n$ is infrared safe and that $\mathcal{O}_{n+1}$ vanish fast enough if two singular region are approached at the same time.
- POWHEG generates the Born process first, then it attaches radiation. Need to introduce a process-defining cutoff, but still not possible to generate an unweighted set of underlying Born configurations covering the whole phase space.
- Using an analysis cut $k_{\rm an}$ larger than the process defining cut $k_{\rm gen}$ is not enough because the shower can raise or lower the jet and recoiling momenta p_T^V independently. Results must not be sensitive to a decrease of the generation cut

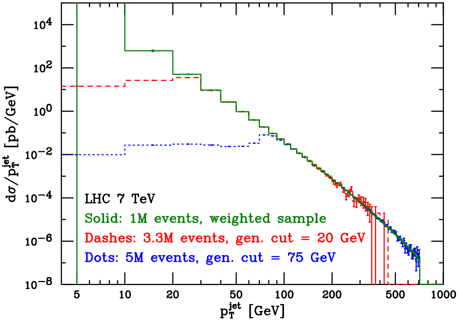
Two possible solutions implemented in POWHEG–BOX:

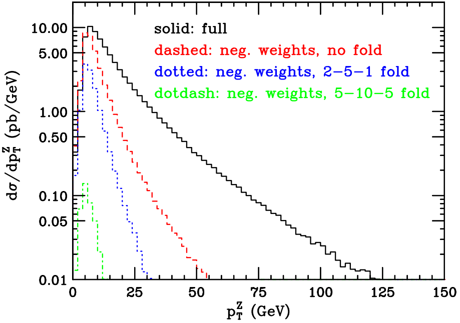
1. Use a generation cut much smaller than the analysis cut and consider its variations to asses the independence of results. Then combine different samples to get full phase space coverage, avoiding overlaps.
2. Generate weighted events, suppressing the divergence

$$\bar{B}_{\rm supp} = \bar{B} \times F(p_{\rm T}), \qquad F(p_{\rm T}) = \left(\frac{p_{\rm T}^2}{p_{\rm T}^2 + p_{\rm T,\,supp}{}^2} \right)^n$$

e.g. $n = 1$ **for** $V + 1$ **jet,** $n = 3$ **for Dijets. Then weigth events with** F^{-1}**.**

Generation cut and negative-weighted events



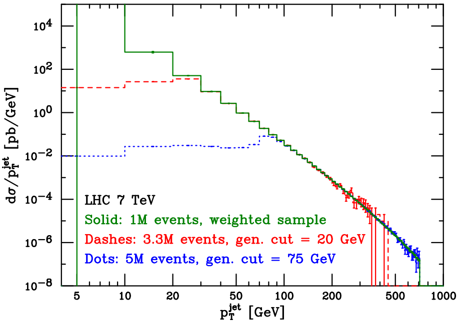


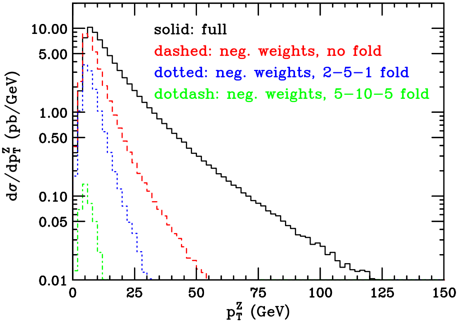
- **Negative values of** $\tilde{B}(\Phi_B, X) = B(\Phi_B) + V(\Phi_B) + \left|\frac{\partial \Phi_{\rm rad}}{\partial X}\right| [R(\Phi_B, \Phi_{\rm rad}) - C(\Phi_B, \Phi_{\rm rad})]$ **are expected in extreme regions of the phase-space. Only after integration over** $d\Phi_{\rm rad}$ **negative weights should disappear.**
- **Folding the radiative phase-space reduces the occurrence of negative weights, *e.g.***

$$\tilde{B}_{\rm folded}(\Phi_B, x_1, X_2, X_3) = \tilde{B}(\Phi_B, x_1, X_2, X_3) + \tilde{B}(\Phi_B, 1/2 + x_1, X_2, X_3)$$

- **Fully analogous to the negative weights in the $\mathcal{S}$ events in `MC@NLO`, but negative weights in the $\mathcal{H}$ event sample of `MC@NLO` cannot be reduced (due to shower approx. subtraction).**

Generation cut and negative-weighted events





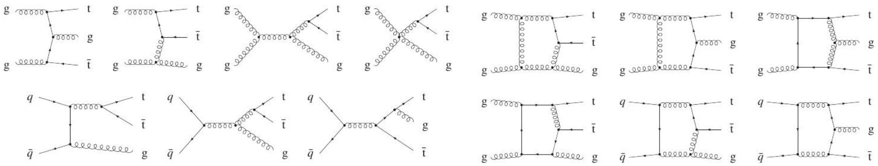
- Using signed events, weighted events or positive-weights only does not change the final results.
- Performance costs for obtaining positive-weighted events may be balanced if the analysys includes detector simulations and/or requires positive weights only.
- For multileg processes, or when virtual evaluation is costly, an high folding number allows to reduce the calls to the virtuals, while maintaining an adequate coverage of the real phase-space.

$t\bar{t} + 1jet$ production

Motivations and available results:

- Top quark physics allows to study the EWSB mechanism, due to the larger mass
- Large fraction of inclusive $t\bar{t}$ events contains additional jet(s). Increasing relative importance of the $t\bar{t} + jet(s)$ sample at the LHC with respect to the TeVatron.
- Dominant background to Higgs production in VBF, for configurations that avoid the large rapidity gap between jets veto. Also important background for many SUSY signals.
- Fully exclusive NLO calculations have been performed: Dittmaier,Uwer and Weinzierl [Phys.Rev.Lett.98:262002,2007] for stable top-quarks and Melnikov and Shulze [Nucl.Phys.B840:129-159,2010] with unitarity methods and LO top-quark decay correlations included.
- Independent implementation of $t\bar{t} + j$ with POWHEG–BOX and HELAC–NLO by Kardos, Papadopoulos, Trocsanyi [arXiv:1101.2672]

Outline of the calculation

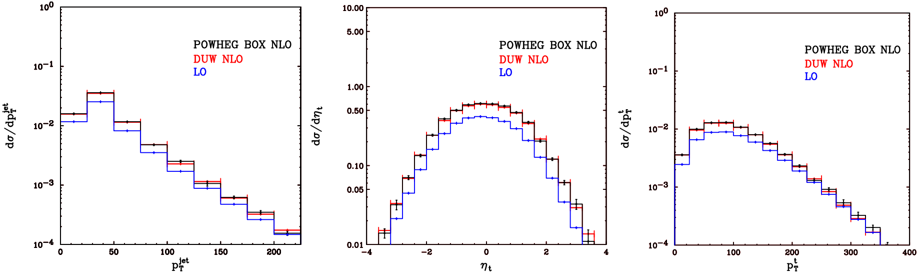


- **Color-correlated and Helicity-correlated Born amplitudes obtained modifying `MadGraph` routines**
- **Factorization in soft and collinear limits explicitly checked in double and quadruple precision.**
- **Binoth-LesHouches interface compliant library for virtuals from Dittmaier-Uwer-Weinzierl code:**
  - **Decompositon according to helicity and color structure times scalar functions depending on the external momenta only**
  - **Amplitudes evaluated analytically, then further manipulated with computer algebra programs and translated in C++ code**
  - **Reduction of up to 4 points tensor integrals performed with PV reduction**
  - **5-points tensor integrals reduced *à la* Denner-Dittmaier**
  - **Efficient caching system**

NLO comparisons

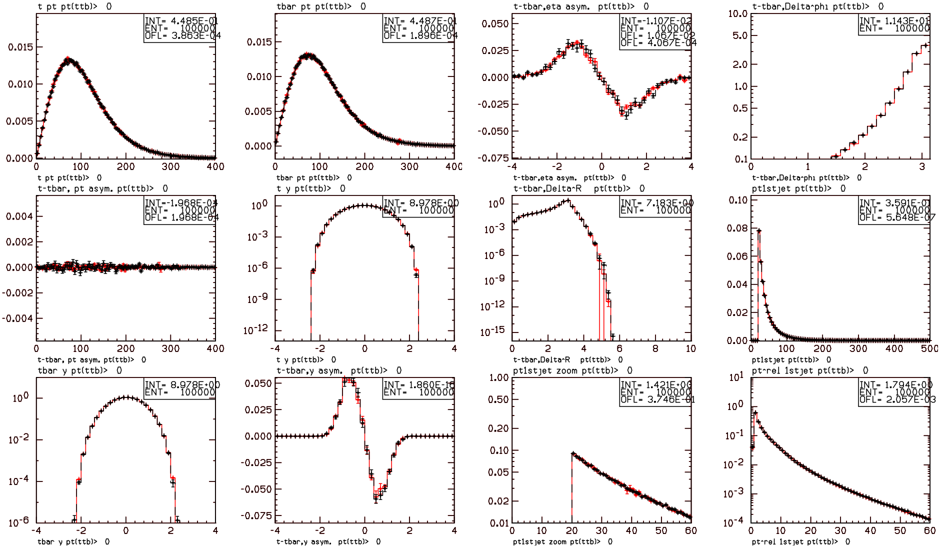
- **Non trivial check due to the different subtraction methods:**
  - **(Massive) Dipole subtraction in Dittmaier-Uwer-Weinzierl**
  - **FKS subtraction, extendend to deal with soft emissions out of massive colored particles, in `POWHEG–BOX`**

  Regularized (subtracted) reals and virtuals are different, but results independent from method chosen.
- **Fixed renormalization and factorization scales at $m_t = 174$ GeV, CTEQ6M pdf .**
- **Inclusive$-k_{\rm T}$ jet algo (Collins-Soper) $k_{\rm T} > 20$ GeV, $R = 1$ with E_t recombination scheme via FastJet. Comparisons for TeVatron $\sqrt{S} = 1.96\ {\rm TeV}$**
- **Top quarks always tagged, excluded from jet reconstruction**



NLO comparisons

- **Hundreds of distributions compared. Always perfect agreement found.**



Validation

- **The POWHEG−BOX eases the inclusion of new processes. However validation is still a demanding task!**

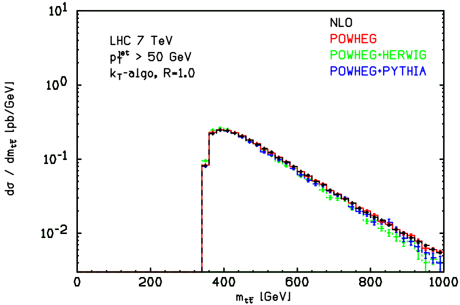
Why do we need validation of an automated code ?

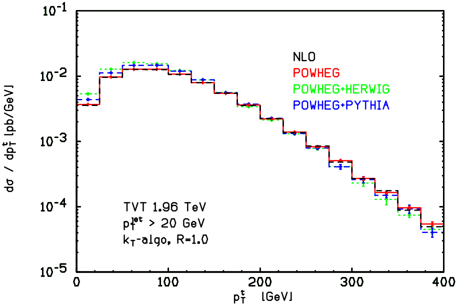
- **A NLO calculation has an unique output. If it is correct, then it is valid!**
- **In the POWHEG approach a choice is made on which corrections beyond NLO are included.**
- **These modify NLO predictions, sometimes also for very inclusive quantities.**
- **The purpose of validation is twofold:**
  - **Check that these modifications reflect real physics effects not accounted for at NLO.**
  - **Check that these modifications are compatible with (un)known higher-order corrections.**

Validation steps

- Pick a suitable set of distributions.
- Compare NLO and POWHEG results after the first emission (Les Houches Event File level). Explain similarities and differences.
- Shower the events. Compare POWHEG + PS results with LHEF and NLO ones. Explain the differences.
- Study the behaviour of POWHEG + PS with different PS and different tunings.

Examples: $t\bar{t} + 1jet$

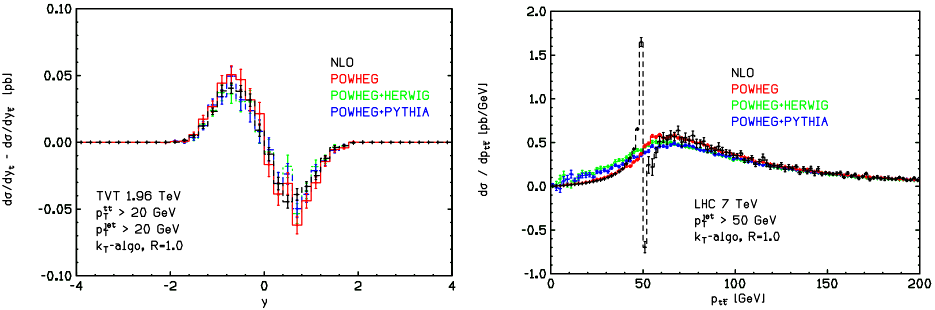




✓ **Inclusive quantities in good agreement**

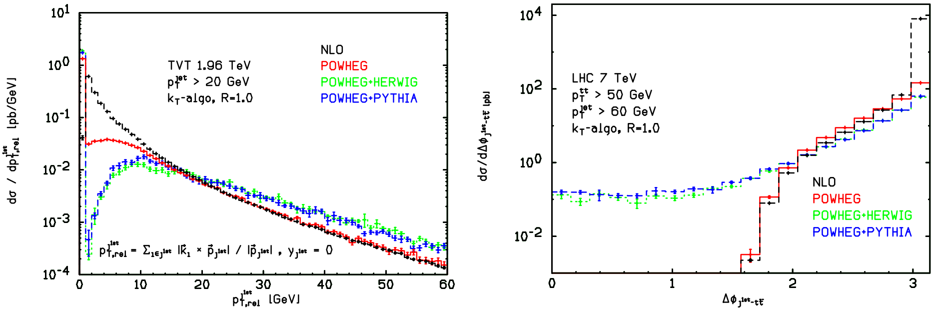
✓ **Shower effects well under control**

Examples: $t\bar{t} + 1jet$



- Spot out problems with fixed-order calculations: here sensitivity to p_T jet cut

Examples: $t\bar{t} + 1jet$

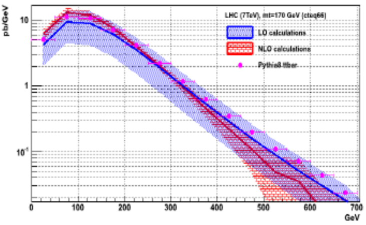


- **For more exclusive quantities kinematical constraints avoided: more realistic final states.**
- **However, results are more sensitive to analysis cuts: dependence on jet cuts may change the normalization**

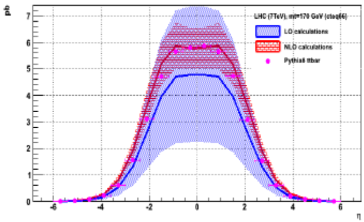
Comparisons with other codes

Comparison with Pythia8

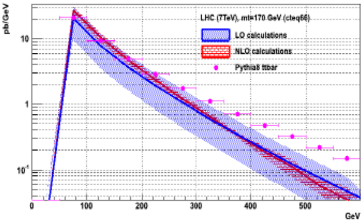
Top quark pT distribution



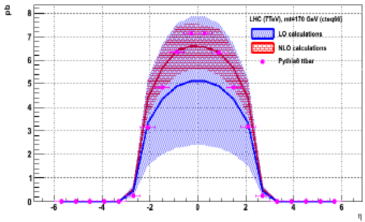
TOP quark η distribution



Jet pT distribution



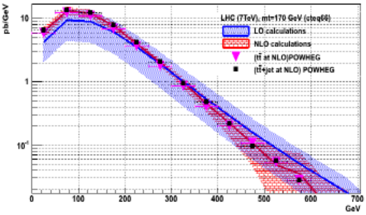
Jet η distribution



thanks to A. Irles

Comparison with POWHEG

Top quark pT distribution



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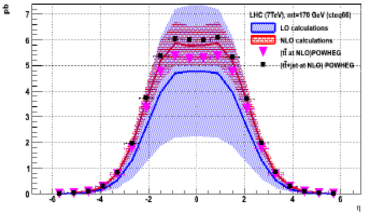
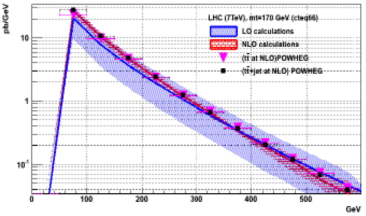
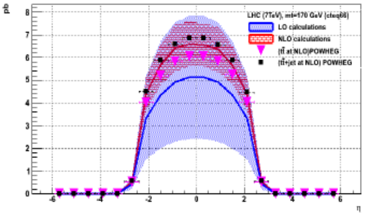


Jet pT distribution



Jet η distribution



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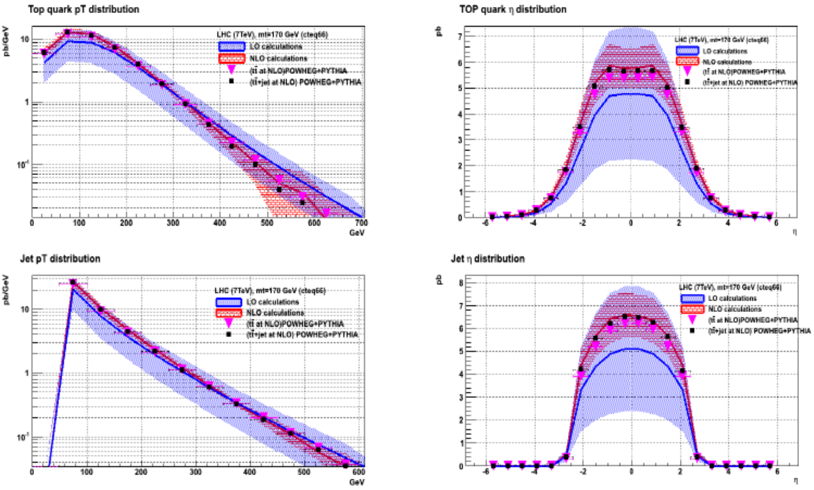
Comparisons with other codes

Comparison with POWHEG+Pythia8



thanks to A. Irles

Conclusions

Conclusions and Outlook

- The POWHEG–BOX allows the implementation of an arbitrary process in the FKS subtraction approach. Code is publicly available!
- Several processes already implemented into the POWHEG–BOX : it can be used as a tool to obtain NLO+SMC predictions.
- Inclusions of more complicated processes is work in progress: technical bottlenecks and limitations can be dealt with!
- Validation is still required, to understand underlying physics!

Outlook :

- $t\bar{t} + 1\ jet$ status: inclusion of top decay correlations and phenomenological studies at Tevatron and LHC are work in progress.
- More multileg processes are currently being implemented.
- Dedicated tuning of NLO+SMC results to data.
- Merging NLO+PS with ME corrections.
- Merging NLO+PS samples with different multiplicities: $t\bar{t}$, $t\bar{t} + jet$ ....

  Ad-hoc merging theoretically unappealing
  NLO exclusive samples merging proposal under investigation...

Thank you for your attention!

Extra slides

POWHEG master formula can be derived by simple considerations:

- **NLO calculation (subtraction method):** $d\Phi_{n+1} = d\Phi_n \, d\Phi_{\text{rad}} \qquad d\Phi_{\text{rad}} \div dt \, dz \, \frac{d\varphi}{2\pi}$

$$d\sigma_{\texttt{NLO}} = \left\{ B(\Phi_n) + V(\Phi_n) + \Big[\underbrace{\overbrace{R(\Phi_n, \Phi_{\text{rad}})}^{\text{divergent}} - \overbrace{C(\Phi_n, \Phi_{\text{rad}})}^{\text{divergent}}}_{\text{finite}} \Big] d\Phi_{\text{rad}} \right\} d\Phi_n$$

$$\underbrace{\int d\sigma_{\texttt{NLO}} \, d\Phi_{\text{rad}} = \bar{B}(\Phi_n)\,,}_{\substack{\text{Inclusive NLO cross section} \\ \text{at fixed underlying Born kinematics}}} \qquad V(\Phi_n) = \underbrace{\overbrace{V_b(\Phi_n)}^{\text{divergent}} + \overbrace{\int C(\Phi_n, \Phi_{\text{rad}}) \, d\Phi_{\text{rad}}}^{\text{divergent}}}_{\text{finite}}$$

POWHEG master formula can be derived by simple considerations:

- **Standard SMC's first emission:**

$$d\sigma_{\text{SMC}} = \overbrace{B(\Phi_n)}^{Born} \, d\Phi_n \left\{ \Delta_{\text{SMC}}(t_0) + \Delta_{\text{SMC}}(t) \overbrace{\frac{\alpha_S(t)}{2\pi} \frac{1}{t} P(z)}^{\lim_{k_T \to 0} R(\mathbf{\Phi}_{n+1})/B(\mathbf{\Phi}_n)} d\Phi_{\text{rad}}^{\text{SMC}} \right\}$$

$$\Delta_{\text{SMC}}(t) = \underbrace{\exp\left[- \int d\Phi'_{\text{rad}} \frac{\alpha_S(t')}{2\pi} \frac{1}{t'} P(z') \, \theta(t' - t) \right]}_{\text{SMC } Sudakov}$$

SMC Sudakov is the probability of not emitting at a scale greater than t (virtuality, angle, p_T^2)

- **POWHEG first emission**

$$d\sigma_{\texttt{POWHEG}} = \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta_{\texttt{POWHEG}}(\Phi_n, p_{\mathrm{T}}^{\mathrm{min}}) + \Delta_{\texttt{POWHEG}}(\Phi_n, k_{\mathrm{T}}) \frac{R(\Phi_n, \Phi_{\mathrm{rad}})}{B(\Phi_n)}\, \theta\left(k_{\mathrm{T}} - p_{\mathrm{T}}\right)\, d\Phi_{\mathrm{rad}} \right\}$$

The POWHEG method [Nason JHEP,2004] [Frixione,Nason,Oleari JHEP,2007]

- **POWHEG first emission**

$$d\sigma_{\texttt{POWHEG}} = \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta_{\texttt{POWHEG}}(\Phi_n, p_T^{\min}) + \Delta_{\texttt{POWHEG}}(\Phi_n, k_T) \frac{R(\Phi_n, \Phi_{\text{rad}})}{B(\Phi_n)}\, \theta\,(k_T - p_T)\; d\Phi_{\text{rad}} \right\}$$

✓ **NLO cross section for inclusive quantities.**

- **POWHEG first emission**

$$d\sigma_{\texttt{POWHEG}} = \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta_{\texttt{POWHEG}}(\Phi_n, p_{\mathrm{T}}^{\min}) + \Delta_{\texttt{POWHEG}}(\Phi_n, k_{\mathrm{T}}) \frac{R(\Phi_n, \Phi_{\mathrm{rad}})}{B(\Phi_n)}\, \theta\left(k_{\mathrm{T}} - p_{\mathrm{T}}\right)\, d\Phi_{\mathrm{rad}} \right\}$$

✓ **NLO cross section for inclusive quantities.**

✓ $\bar{B} = B(\Phi_n) + V(\Phi_n) + \int \left[R(\Phi_n, \Phi_{\mathrm{rad}}) - C(\Phi_n, \Phi_{\mathrm{rad}})\right]\, d\Phi_{\mathrm{rad}} < 0$

Negative weights where NLO $>$ LO, i.e. where perturbation expansion breaks down!

- **POWHEG first emission**

$$d\sigma_{\mathtt{POWHEG}} = \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta_{\mathtt{POWHEG}}(\Phi_n, p_T^{\min}) + \Delta_{\mathtt{POWHEG}}(\Phi_n, k_T) \frac{R(\Phi_n, \Phi_{\rm rad})}{B(\Phi_n)}\, \theta(k_T - p_T)\, d\Phi_{\rm rad} \right\}$$

✓ **NLO cross section for inclusive quantities.**

✓ $\bar{B} = B(\Phi_n) + V(\Phi_n) + \int [R(\Phi_n, \Phi_{\rm rad}) - C(\Phi_n, \Phi_{\rm rad})]\, d\Phi_{\rm rad} < 0$

Negative weights where NLO $>$ LO, i.e. where perturbation expansion breaks down!

✓ **Probability of not emitting with transverse momentum harder than p_T:**

$$\Delta_{\mathtt{POWHEG}}(\Phi_n, p_T) = \overbrace{\exp\left[-\int d\Phi'_{\rm rad} \frac{R(\Phi_n, \Phi'_{\rm rad})}{B(\Phi_n)} \theta\left(k_T(\Phi_n, \Phi'_{\rm rad}) - p_T\right) \right]}^{\mathtt{POWHEG}\ Sudakov}$$

The POWHEG method

[Nason JHEP,2004] [Frixione,Nason,Oleari JHEP,2007]

- **POWHEG first emission**

$$d\sigma_{\texttt{POWHEG}} = \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta_{\texttt{POWHEG}}(\Phi_n, p_T^{\min}) + \Delta_{\texttt{POWHEG}}(\Phi_n, k_T) \frac{R(\Phi_n, \Phi_{\rm rad})}{B(\Phi_n)}\, \theta\left(k_T - p_T\right)\, d\Phi_{\rm rad} \right\}$$

✓ **NLO cross section for inclusive quantities.**

✓ $\bar{B} = B(\Phi_n) + V(\Phi_n) + \int \left[R(\Phi_n, \Phi_{\rm rad}) - C(\Phi_n, \Phi_{\rm rad})\right]\, d\Phi_{\rm rad} < 0$

Negative weights where NLO $>$ LO, i.e. where perturbation expansion breaks down!

✓ **Probability of not emitting with transverse momentum harder than p_T:**

$$\Delta_{\texttt{POWHEG}}(\Phi_n, p_T) = \overbrace{\exp\left[-\int d\Phi'_{\rm rad} \frac{R(\Phi_n, \Phi'_{\rm rad})}{B(\Phi_n)} \theta\left(k_T(\Phi_n, \Phi'_{\rm rad}) - p_T\right)\right]}^{\texttt{POWHEG}\ Sudakov}$$

✓ **It has the same LL accuracy of a SMC. In the soft/collinear region $k_T \to 0$ and**

$$\frac{R(\Phi_n, \Phi_{\rm rad})}{B(\Phi_n)} d\Phi_{\rm rad} \approx \frac{\alpha_S(t)}{2\pi} \frac{1}{t} P(z)\, dt\, dz\, \frac{d\varphi}{2\pi} \quad \textbf{and} \quad \bar{B} \approx B\left(1 + \mathcal{O}(\alpha_S)\right)$$

The POWHEG method [Nason JHEP,2004] [Frixione,Nason,Oleari JHEP,2007]

- **POWHEG first emission**

$$d\sigma_{\texttt{POWHEG}} = \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta_{\texttt{POWHEG}}(\Phi_n, p_{\rm T}^{\rm min}) + \Delta_{\texttt{POWHEG}}(\Phi_n, k_{\rm T}) \frac{R(\Phi_n, \Phi_{\rm rad})}{B(\Phi_n)}\, \theta\left(k_{\rm T} - p_{\rm T}\right)\, d\Phi_{\rm rad} \right\}$$

✓ **NLO cross section for inclusive quantities.**

✓ $\bar{B} = B(\Phi_n) + V(\Phi_n) + \int \left[R(\Phi_n, \Phi_{\rm rad}) - C(\Phi_n, \Phi_{\rm rad})\right]\, d\Phi_{\rm rad} < 0$

Negative weights where NLO $>$ LO, i.e. where perturbation expansion breaks down!

✓ **Probability of not emitting with transverse momentum harder than $p_{\rm T}$:**

$$\Delta_{\texttt{POWHEG}}(\Phi_n, p_{\rm T}) = \overbrace{\exp\left[- \int d\Phi'_{\rm rad} \frac{R(\Phi_n, \Phi'_{\rm rad})}{B(\Phi_n)} \theta\left(k_{\rm T}(\Phi_n, \Phi'_{\rm rad}) - p_{\rm T}\right) \right]}^{\texttt{POWHEG}\ Sudakov}$$

✓ **It has the same LL accuracy of a SMC. In the soft/collinear region $k_{\rm T} \to 0$ and**

$$\frac{R(\Phi_n, \Phi_{\rm rad})}{B(\Phi_n)} d\Phi_{\rm rad} \approx \frac{\alpha_{\rm S}(t)}{2\pi} \frac{1}{t}\, P(z)\, dt\, dz\, \frac{d\varphi}{2\pi} \qquad \text{and} \qquad \bar{B} \approx B\left(1 + \mathcal{O}(\alpha_{\rm S})\right)$$

✓ **The accuracy of NLO is preserved in the hard region, since $\Delta_{\texttt{POWHEG}}(\Phi_n, p_{\rm T}) \approx 1$ and**

$$d\sigma_{\texttt{POWHEG}} \approx \frac{\bar{B}(\Phi_n)}{B(\Phi_n)} R(\Phi_n, \Phi_{\rm rad})\, d\Phi_n\, d\Phi_{\rm rad} \approx R(\Phi_n, \Phi_{\rm rad})\left(1 + \mathcal{O}(\alpha_{\rm S})\right)\, d\Phi_n\, d\Phi_{\rm rad}$$

The POWHEG method

- **Single out the singular part of real contribution** $R = R^{\text{sing.}} + R^{\text{remn.}}$

$$
\begin{aligned}
d\sigma &= \overbrace{\bar{B}_{\text{sing.}}(\Phi_n)}^{\text{NLO}}\, d\Phi_n \overbrace{\left\{ \Delta_{\text{sing.}}(t_0) + \Delta_{\text{sing.}}(t) \frac{R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}})}{B(\Phi_n)}\, d\Phi_{\text{rad}} \right\}}^{\text{sum to 1 by unitarity}} \\
&+ \underbrace{\left[R(\Phi_n, \Phi_{\text{rad}}) - R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}}) \right]}_{\text{NLO}} d\Phi_n\, d\Phi_{\text{rad}}
\end{aligned}
$$

$$
\bar{B}_{\text{sing}}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int \left[R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}}) - C(\Phi_n, \Phi_{\text{rad}}) \right]\, d\Phi_{\text{rad}}
$$

$$
\Delta_{\text{sing.}}(t) = \exp\left[-\int d\Phi'_{\text{rad}} \frac{R^{\text{sing.}}(\Phi_n, \Phi'_{\text{rad}})}{B(\Phi_n)} \theta\left(t' - t\right) \right]
$$

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$$+ \underbrace{\left[R(\Phi_n, \Phi_{\text{rad}}) - R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}}) \right]}_{\text{NLO}} d\Phi_n \, d\Phi_{\text{rad}}$$

$$\bar{B}_{\text{sing}}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int \left[R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}}) - C(\Phi_n, \Phi_{\text{rad}}) \right] d\Phi_{\text{rad}}$$

$$\Delta_{\text{sing.}}(t) = \exp\left[- \int d\Phi'_{\text{rad}} \frac{R^{\text{sing.}}(\Phi_n, \Phi'_{\text{rad}})}{B(\Phi_n)} \theta(t' - t) \right]$$

- **In POWHEG :** $R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}}) = F(\Phi_n, \Phi_{\text{rad}}) \times R(\Phi_n, \Phi_{\text{rad}})$**, with** $0 \leq F \leq 1$**, and** $F(\Phi_n, \Phi_{\text{rad}}) \to 1$ **in the soft/collinear limit.**

$F = 1$ **is the simplest choice, often adopted.**

The POWHEG method

- **Single out the singular part of real contribution** $R = R^{\text{sing.}} + R^{\text{remn.}}$

$$d\sigma = \overbrace{\bar{B}_{\text{sing.}}(\Phi_n)}^{\text{NLO}}\, d\Phi_n \overbrace{\left\{\Delta_{\text{sing.}}(t_0) + \Delta_{\text{sing.}}(t)\frac{R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}})}{B(\Phi_n)}\, d\Phi_{\text{rad}}\right\}}^{\text{sum to 1 by unitarity}}$$
$$+ \underbrace{\left[R(\Phi_n, \Phi_{\text{rad}}) - R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}})\right]}_{\text{NLO}} d\Phi_n\, d\Phi_{\text{rad}}$$

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  $F = 1$ **is the simplest choice, often adopted.**

- **In MC@NLO :** $R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}}) = R_{\text{SMC}}(\Phi_n, \Phi_{\text{rad}}^{\text{SMC}})$ **is the shower approximation of a real emission**

MC@NLO

$$d\sigma_{\mathtt{MC@NLO}} = \underbrace{\overbrace{\bar{B}_{\mathtt{SMC}}(\Phi_n)}^{\mathtt{MC@NLO}\ \mathcal{S}-\text{event}}} \, d\Phi_n \overbrace{\left\{ \Delta_{\mathtt{SMC}}(t_0) + \Delta_{\mathtt{SMC}}(t) \frac{R_{\mathtt{SMC}}(\Phi_n, \Phi_{\text{rad}}^{\mathtt{SMC}})}{B(\Phi_n)} \, d\Phi_{\text{rad}}^{\mathtt{SMC}} \right\}}^{\mathtt{SMC}}$$

$$+ \underbrace{\left[R(\Phi_n, \Phi_{\text{rad}}^{\mathtt{SMC}}) - R_{\mathtt{SMC}}(\Phi_n, \Phi_{\text{rad}}^{\mathtt{SMC}}) \right]}_{\mathtt{MC@NLO}\ \mathcal{H}-\text{event}} d\Phi_n \, d\Phi_{\text{rad}}^{\mathtt{SMC}}$$

$$\bar{B}_{\mathtt{SMC}}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int \left[R_{\mathtt{SMC}}(\Phi_n, \Phi_{\text{rad}}^{\mathtt{SMC}}) - C(\Phi_n, \Phi_{\text{rad}}^{\mathtt{SMC}}) \right] \, d\Phi_{\text{rad}}^{\mathtt{SMC}}$$

$$\Delta_{\mathtt{SMC}}(t) = \exp\left[- \int d\Phi'_{\text{rad}} \frac{R_{\mathtt{SMC}}(\Phi_n, \Phi'_{\text{rad}})}{B(\Phi_n)} \theta\left(t' - t\right) \right] \quad \Leftarrow \textbf{HERWIG or PYTHIA Sudakov!}$$

- ✗ **Dependence of PS algorithm and parametrization: need to express NLO calculation in $\Phi_{\text{rad}}^{\mathtt{SMC}}$ variables.**
- ✗ $R - R_{\mathtt{SMC}}$ **not singular only if** $R_{\mathtt{SMC}}$ **reproduces exactly all the singularities of** R**.**
  Issue: azimuthal dependence of collinear sing. neglected in most $R_{\mathtt{SMC}}$ **.**
- ✗ **Both** $\mathcal{S}$ **and** $\mathcal{H}$**-events can have negative weitghs!**

NLO accuracy of POWHEG formula (1)

- **Use the POWHEG formula**

$$d\sigma = \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta(\Phi_n, p_T^{\min}) + \Delta(\Phi_n, k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)}\, \theta(k_T - p_T^{\min})\, d\Phi_{\rm rad} \right\}$$

- **to calculate the expectation value of a generic observable** $< \mathcal{O} > =$

$$= \int \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta(\Phi_n, p_T^{\min}) O_n(\Phi_n) + \int_{p_T^{\min}} \Delta(\Phi_n, k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} O_{n+1}(\Phi_{n+1})\, d\Phi_{\rm rad} \right\}$$

$$= \int \bar{B}(\Phi_n)\, d\Phi_n \left\{ \left[\Delta(\Phi_n, p_T^{\min}) + \int_{p_T^{\min}} \Delta(\Phi_n, k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)}\, d\Phi_{\rm rad} \right] O_n(\Phi_n) \right.$$

$$\left. + \int_{p_T^{\min}} \Delta(\Phi_n, k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \left[O_{n+1}(\Phi_{n+1}) - O_n(\Phi_n) \right]\, d\Phi_{\rm rad} \right\}$$

- O_n, O_{n+1} **are the actual forms of** $\mathcal{O}$ **in the** $n, n+1$**-body phase space.**
- $\mathcal{O}$ **is required to be infrared-safe and to vanish fast enough when two singular regions are approached at the same time**

NLO accuracy of POWHEG formula (2)

- **Now observe that**

$$\int_{p_{\rm T}^{\rm min}} d\Phi_{\rm rad} \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Delta(\Phi_n, k_{\rm T}) = \int_{p_{\rm T}^{\rm min}}^{\infty} dp'_{\rm T} \int d\Phi_{\rm rad}\, \delta(k_{\rm T} - p'_{\rm T}) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Delta(\Phi_n, p'_{\rm T})$$

$$= - \int_{p_{\rm T}^{\rm min}}^{\infty} dp'_{\rm T} \Delta(\Phi_n, p'_{\rm T}) \frac{d}{dp'_{\rm T}} \int_{p_{\rm T}^{\rm min}} d\Phi_{\rm rad}\, \theta(k_{\rm T} - p'_{\rm T}) \frac{R(\Phi_{n+1})}{B(\Phi_n)}$$

$$= \int_{p_{\rm T}^{\rm min}}^{\infty} dp'_{\rm T} \frac{d}{dp'_{\rm T}} \Delta(\Phi_n, p'_{\rm T}) = 1 - \Delta(\Phi_n, p_{\rm T}^{\rm min})$$

- **Furthermore we can replace** $\bar{B}(\Phi_n) \approx B(\Phi_n)\,(1 + \mathcal{O}(\alpha_{\rm S}))$
- **and also** $\Delta(\Phi_n, k_{\rm T}) \approx 1 + \mathcal{O}(\alpha_{\rm S})$ **since** $[O_{n+1} - O_n] \to 0$ **at small** $k_{\rm T}$**'s**
- **The final result is (up to** $p_{\rm T}^{\rm min}$ **power-suppressed terms)**

$$\begin{aligned} < \mathcal{O} > &= \int d\Phi_n \bar{B}(\Phi_n)\, 1\, O_n(\Phi_n) \\ &+ \int 1 \frac{R(\Phi_{n+1})}{1} \left[O_{n+1}(\Phi_{n+1}) - O_n(\Phi_n)\right]\, d\Phi_{\rm rad} + \mathcal{O}(\alpha_{\rm S}) \end{aligned}$$

NLL accuracy of the POWHEG Sudakov Form Factor

Substitute $\alpha_{\rm S} \to A\left(\alpha_{\rm S}\left(k_{\rm T}^2\right)\right)$ in the Sudakov exponent, with

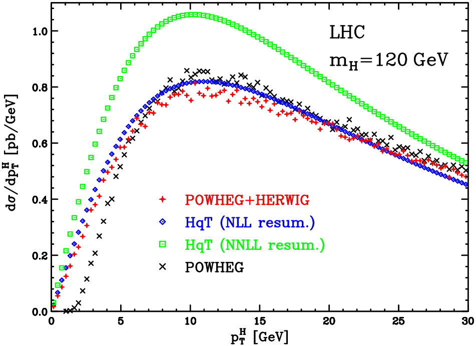
$$A(\alpha_{\rm S}) = \alpha_{\rm S}\left\{1 + \frac{\alpha_{\rm S}}{2\pi}\left[\left(\frac{67}{18} - \frac{\pi^2}{6}\right)C_{\rm A} - \frac{5}{9}n_{\rm f}\right]\right\}$$

and one-loop expression for $\alpha_{\rm S}$, to get NLL resummed results for process with up to 3 coloured partons at the Born level **[Catani,Marchesini and Webber Nucl.Phys.B349]**

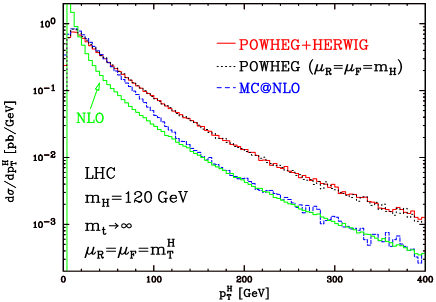
For > 3 coloured partons, soft NLL contributions exponentiates only in a matrix sense

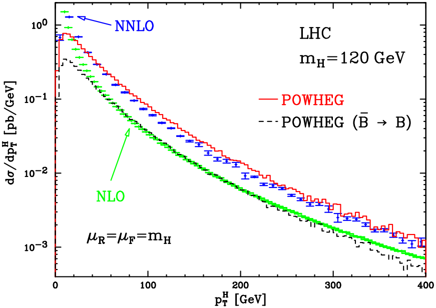
- **Need to diagonalize the colour structures**
- **Always possible to take the large N_c limit and get NLL**

Comparison with HqT program
[Bozzi,Catani,de Florian and Grazzini, Nucl.Phys.B737] $\Rightarrow$



High$-p_T$ behaviour





$$\bar{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int [R(\Phi_n,\Phi_{\rm rad}) - C(\Phi_n,\Phi_{\rm rad})]\; d\Phi_{\rm rad}$$

$$d\sigma = \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta(\Phi_n, p_T^{\rm min}) + \Delta(\Phi_n, p_T) \frac{R(\Phi_n,\Phi_{\rm rad})}{B(\Phi_n)}\, d\Phi_{\rm rad} \right\}$$

if $p_T >> 1 \quad \Rightarrow \quad \Delta(\Phi_n, p_T) \approx 1$ **and**

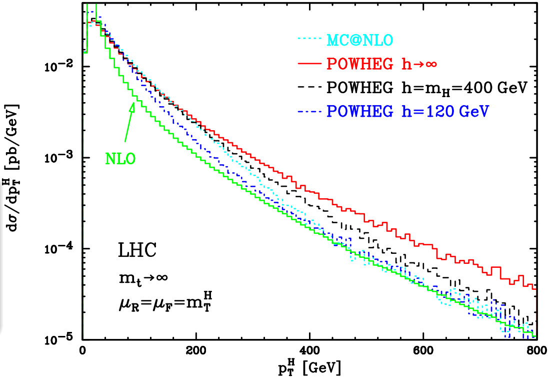
$$d\sigma_{\rm rad} \approx \frac{\bar{B}(\Phi_n)}{B(\Phi_n)} R(\Phi_n,\Phi_{\rm rad})\, d\Phi_n\, d\Phi_{\rm rad} \approx \underbrace{\{1+O(\alpha_S)\}}_{\approx 2 \text{ for } gg\to H} R(\Phi_n,\Phi_{\rm rad})\, d\Phi_n\, d\Phi_{\rm rad}$$

Better agreement with NNLO results, but still enough flexibility to get rid of this feature!

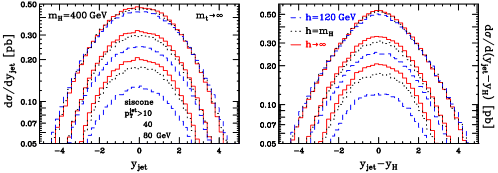
Reduction of real contribution entering the Sudakov FF

$$R = \underbrace{R \times F}_{singular} + \underbrace{R \times (1-F)}_{regular}$$
$$= R_{\bar{B}} + R_{\mathbf{reg}}$$

$F < 1, \quad F \to 1$ **when** $p_T \to 0$,
$F \to 0$ **when** $p_T \to \infty$
$\Rightarrow F = \frac{h^2}{p_T^2 + h^2}$

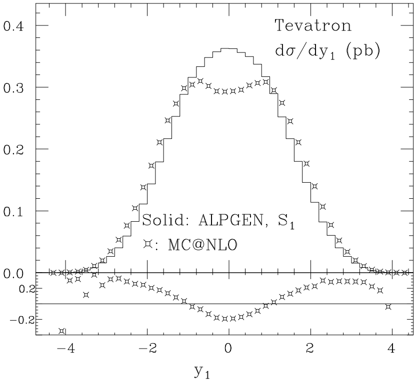


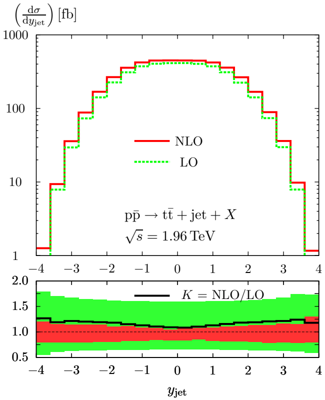
$$\sigma = \sigma_{\bar{B}} + \sigma_{\mathbf{reg}}$$
$$\sigma_{\bar{B}} = \int d\Phi_n \Big\{ B(\Phi_n) + V(\Phi_n) + \left[R_{\bar{B}}(\Phi_n, \Phi_{\rm rad}) - C(\Phi_n, \Phi_{\rm rad}) \right] d\Phi_{\rm rad} \Big\}$$
$$\sigma_{\mathbf{reg}} = \int R_{\mathbf{reg}}(\Phi_n, \Phi_{\rm rad})\, d\Phi_n\, d\Phi_{\rm rad}$$



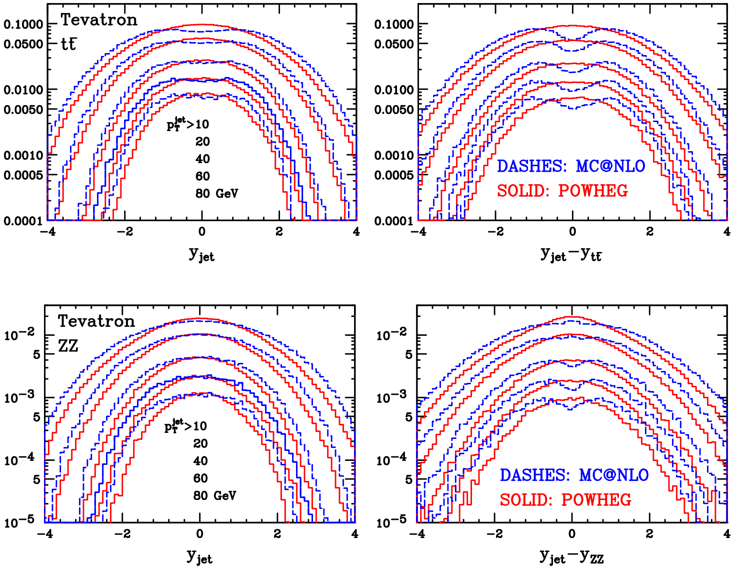
Hardest jet rapidity dip

- **ALPGEN vs. MC@NLO comparative study for $t\bar{t}$ productions**
  [Mangano,Moretti,Piccinini and Treccani, JHEP 0701:013]
- **ALPGEN has better high jet multiplicity (Exact ME), but only LO normalization**
- **MC@NLO is correct at NLO, but shows a dip in the hardest jet rapidity distribution**
- **NLO calculation of $p\bar{p} \rightarrow t\bar{t} + jet$ shows no dip too**
  [Dittmaier,Uwer and and Weinzierl, arXiv:0810.0452]

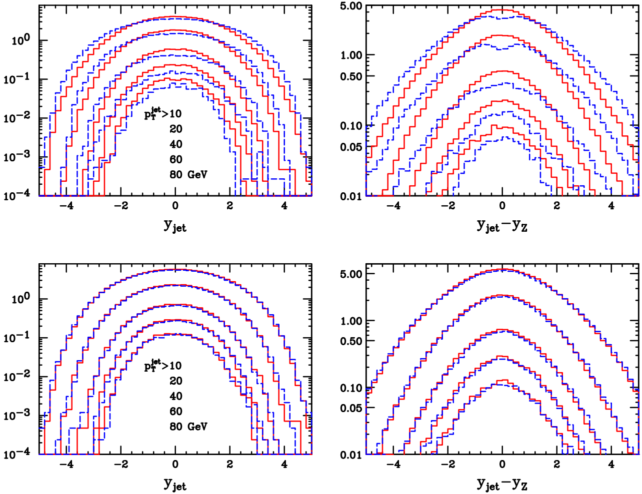




Hardest jet rapidity and rapidity difference



Hardest jet - Z rapidity difference @ TEV



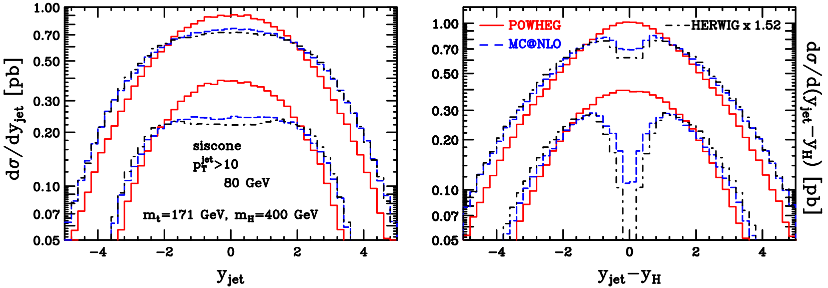
POWHEG + HERWIG

MC@NLO

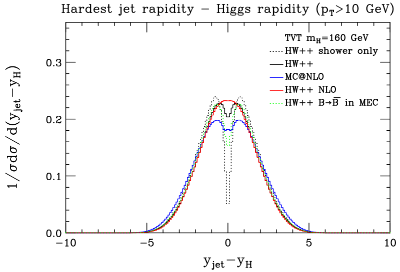
POWHEG + PYTHIA

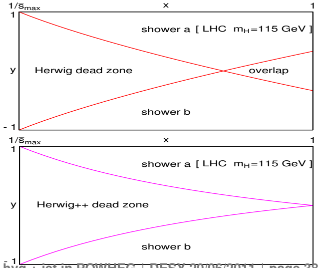
PYTHIA $\times 1.3$

Hardest jet - Higgs boson rapidity difference



- **Similar results from Hamilton, Richardson and Tully [ArXiv:0903.4345]**





MC@NLO dip in hardest radiation

$$\Delta_{\text{HW}}(t) = \exp\left[-\int d\Phi'_{\text{rad}} \frac{R_{\text{HW}}(\Phi_n,\Phi'_{\text{rad}})}{B(\Phi_n)}\theta\left(t'-t\right)\right] \Leftarrow \textbf{HERWIG Sudakov!}$$

$$d\sigma_{\text{MC@NLO}} = \bar{B}_{\text{HW}}(\Phi_n)\, d\Phi_n \left\{\Delta_{\text{HW}}(t_0) + \Delta_{\text{HW}}(t)\frac{R_{\text{HW}}(\Phi_n,\Phi_{\text{rad}})}{B(\Phi_n)}\, d\Phi_{\text{rad}}\right\} + \left[R(\Phi_n,\Phi_{\text{rad}}) - R_{\text{HW}}(\Phi_n,\Phi_{\text{rad}})\right]\, d\Phi_n\, d\Phi_{\text{rad}}$$

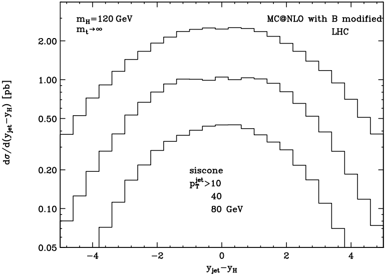
$$\bar{B}_{\text{HW}}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int \left[R_{\text{HW}}(\Phi_n,\Phi_{\text{rad}}) - C(\Phi_n,\Phi_{\text{rad}})\right]\, d\Phi_{\text{rad}}$$

At high p_{T} the cross section goes as

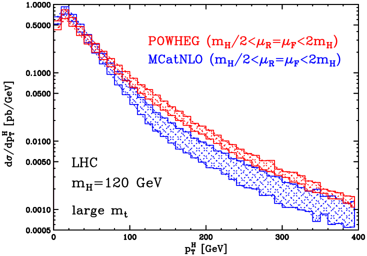
$$d\sigma_{\text{MC@NLO}} \approx \left(\frac{\bar{B}_{\text{HW}}(\Phi_n)}{B(\Phi_n)} - 1\right) R_{\text{HW}}(\Phi_n,\Phi_{\text{rad}})d\Phi_n d\Phi_{\text{rad}} + R(\Phi_n,\Phi_{\text{rad}})d\Phi_n d\Phi_{\text{rad}}$$

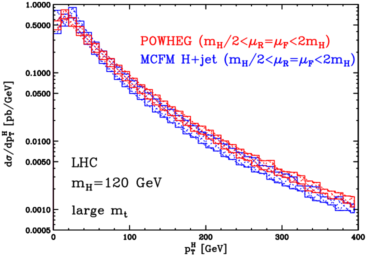
Test : Replace $\bar{B}_{\text{HW}}(\Phi_n)$ with $B(\Phi_n)$ in generation of $\mathbb{S}$-type events

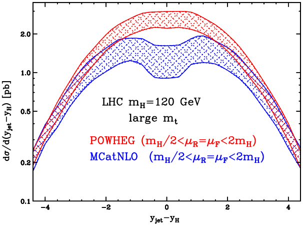
The dip seems to disappear

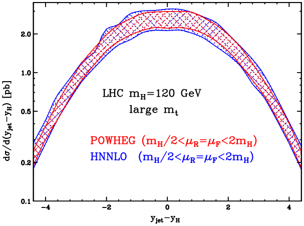


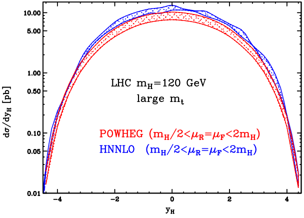
Scales dependence









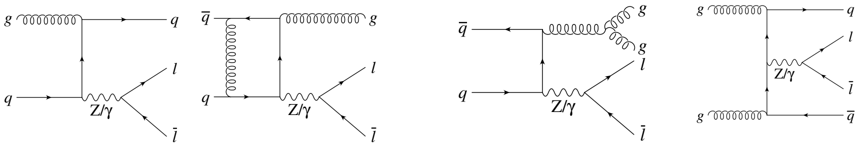


- **NNLO results obtained using HNNLO** **[Catani and Grazzini, arXiv:0802.1410]**

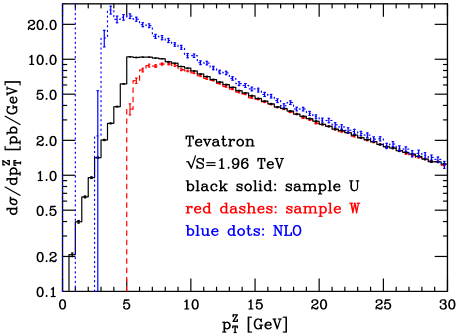
Vector boson plus jet production and decay

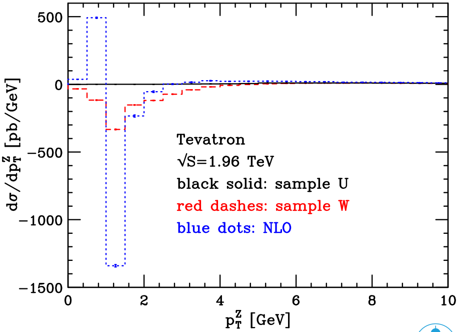
S.A., P.Nason, C.Oleari, E.Re [JHEP 1101:095,2011]

- **Full calculation for $W^{\pm}, Z/\gamma + 1\ jet$ with decays. Virtuals from MCFM**



- **Validation: $k_{\rm gen} = 5{\rm GeV}$ in U sample, $k_{\rm gen} = 1{\rm GeV}$ and $p_{\rm T,\,supp} = 10{\rm GeV}$ in W**





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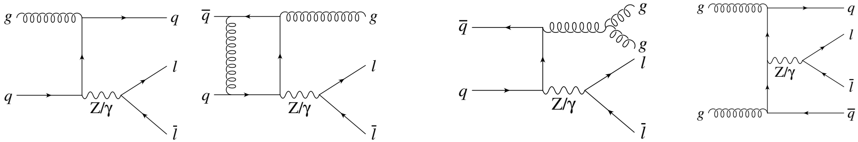

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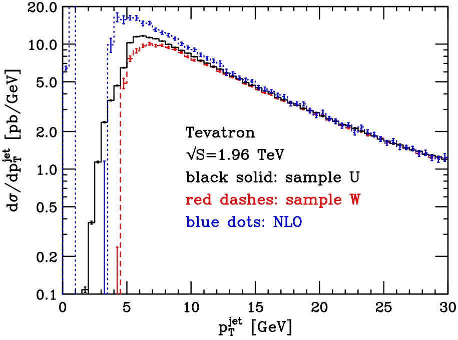
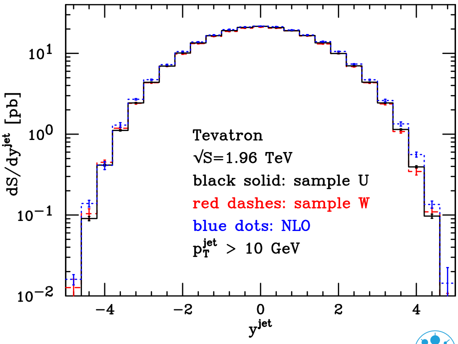
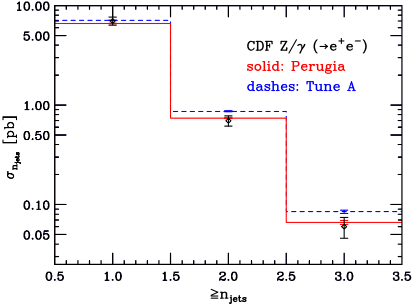


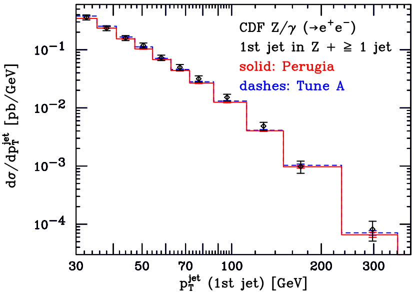


Comparison with $Z + 1j$ TeVatron data - e channel

$Z/\gamma\ (\to e^+e^-) + 1jet$ [Phys.Rev.Lett. 100 (2008) 102100, Phys.Lett. B678 (2009) 45-54]

- **CDF cuts:** $66\text{ GeV} < M_{ee} < 116\text{ GeV},\ p_T^e > 25\text{ GeV},\ |\eta^{e_1}| < 1.0,\ 1.2 < |\eta^{e_2}| < 2.8,$ $|y^{\rm jet}| < 2.1,\ p_T^{\rm jet} > 30\text{ GeV},\ \Delta R_{e,\,\rm jet} > 0.7$
- **D0 cuts:** $65\text{ GeV} < M_{ee} < 115\text{ GeV},\ p_T^e > 25\text{ GeV},\quad |\eta^e| < 1.1 \text{ or } 1.5 < |\eta^e| < 2.5\,,$ $|y^{\rm jet}| < 2.5\,,\ p_T^{\rm jet} > 20\text{ GeV}$
- **Good agreement without any parton-to-hadron correction factor**
- **A dedicated tuning may improve the remaining disagreements**





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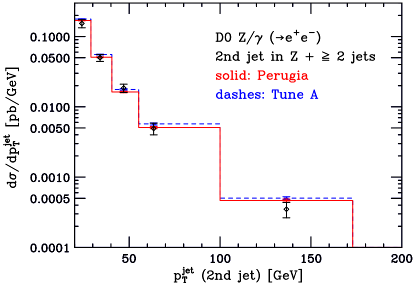

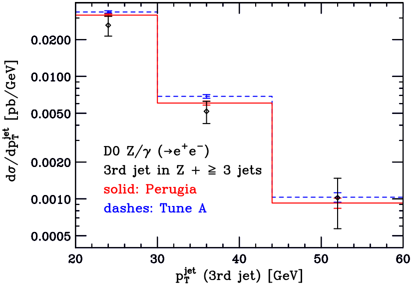

Comparison with $Z + 1j$ TeVatron data - μ channel

$Z/\gamma\ (\to \mu^+\mu^-) + 1jet$ [Phys.Lett. B65 (2008) 112-119, Phys.Lett. B669 (2008) 278-286]

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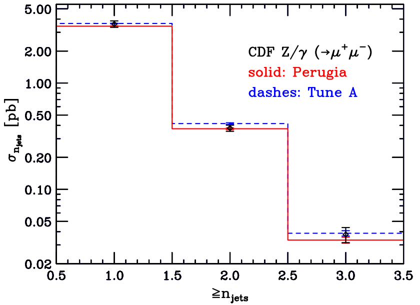
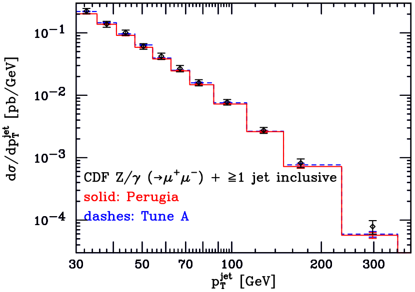
  $p_T^{\text{jet}} > 30\ \text{GeV},\ \Delta R_{\mu,\text{jet}} > 0.7$
- **D0 cuts:** $65\ \text{GeV} < M_{\mu\mu} < 115\ \text{GeV},\ p_T^\mu > 15\ \text{GeV},\ |\eta^\mu| < 1.7,\ |y^{\text{jet}}| < 2.8,$
  $p_T^{\text{jet}} > 20\ \text{GeV},\ \Delta R_{\mu,\text{jet}} > 0.5$
- **Good agreement without any parton-to-hadron correction factor**
- **A dedicated tuning may improve the small disagreements**





Comparison with $Z + 1j$ TeVatron data - μ channel

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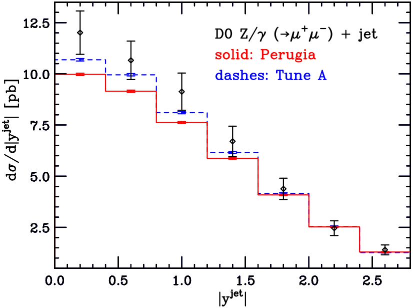
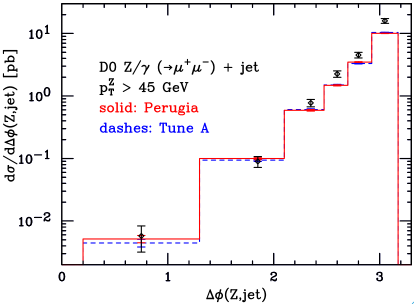
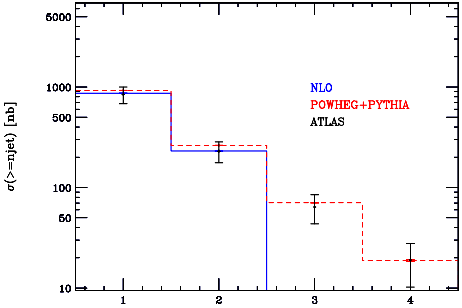
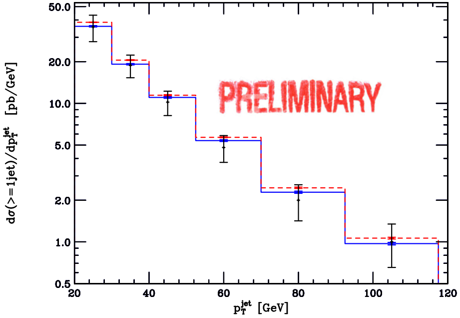




Comparison with $W + 1jet$ LHC data

ATLAS [ArXiv:1012.5382]





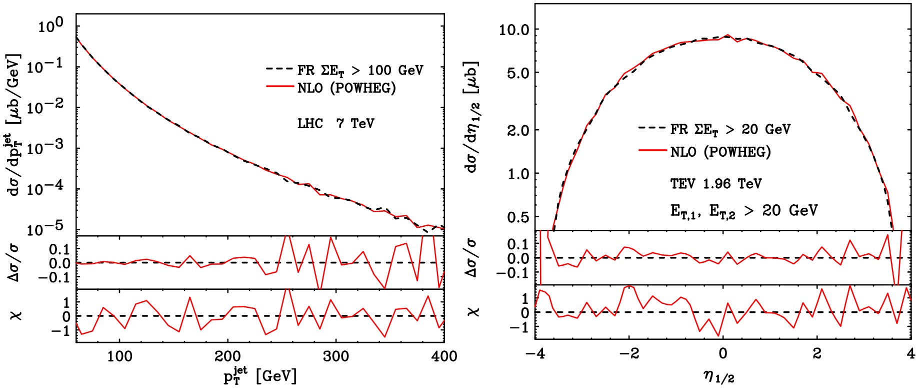
- **Combined** W^+ **and** W^- **sample. Results with** $L = 1.\ \mathrm{pb}^{-1}$ **at LHC** $7\ \mathrm{TeV}$
- **Events showered with `PYTHIA` Perugia0 tune.**
- **No attempt to perform theoretical uncertainties evaluation of scale/pdf variations yet**
- **Electron and muon channels**
- **Clustering according to anti**$-kt$ **algorithm with** $R = 0.4$

Dijets

S.A., K.Hamilton, P.Nason, C.Oleari, E.Re [arXiv:1012.3380]

- **Most frequently occuring hard scattering in hadronic collisions**
- **Straightforward implementation and comparison with Frixione&Ridolfi NLO code**

[Nucl.Phys. B507 (1997)]



- **Fractional difference and difference over stat. error defined as**

$$\frac{\Delta\sigma}{\sigma} = \frac{\sigma_1 - \sigma_2}{\sigma_2}, \qquad \chi = \frac{\sigma_1 - \sigma_2}{\sqrt{\delta\sigma_1^2 + \delta\sigma_2^2}}$$

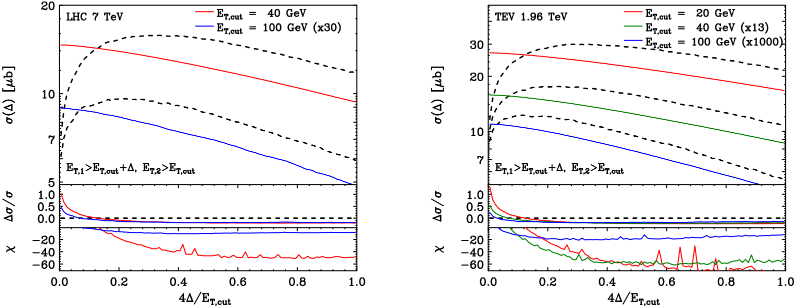
Dijets

- Issues when symmetric cuts are applied: albeit IR finite the NLO cross sec. with $E_{T,1} > E_{T,\text{cut}} + \Delta, \quad E_{T,2} > E_{T,\text{cut}}$ is ill defined when $\Delta \to 0$.

✗ It does not decrease reducing the available phase space

- Well known effect, first observed in [Nucl.Phys. B507 (1997), Phys.Rev. D56 (1997)]
  Truncation of perturbative expansion at NLO induces a $-\Delta \log(\Delta)$ term from unbalanced cancellation of soft gluons between reals and virtual contributions.
- Inclusion of soft gluons resummation fixes this anomalous behaviour
  [Eur. Phys. J. C 23, 13 (2002)]

- Similar resummation performed by `POWHEG`: - - - NLO — POWHEG



DESY

Dijets

- **Issues when symmetric cuts are applied: albeit IR finite the NLO cross sec. with** $E_{T,1} > E_{T,\text{cut}} + \Delta,\quad E_{T,2} > E_{T,\text{cut}}$ **is ill defined when** $\Delta \to 0$**.**

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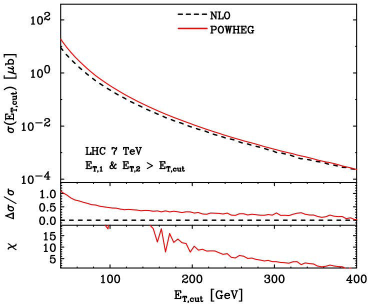
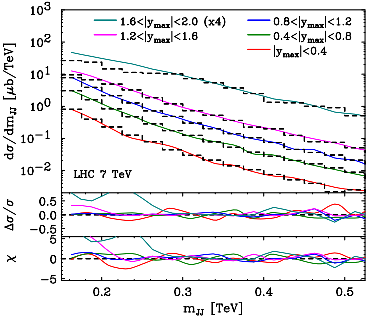
- **Inclusion of soft gluons resummation fixes this anomalous behaviour**
  [Eur. Phys. J. C 23, 13 (2002)]

- **Effects visible also in physical distributions:**

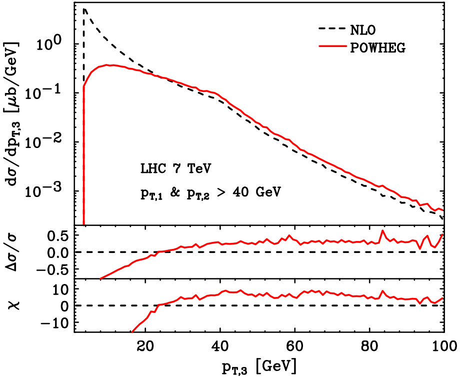
symmetric $E_{T,\text{cut}} = 40\text{GeV}$

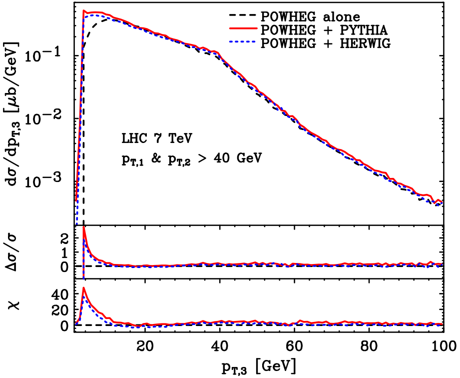




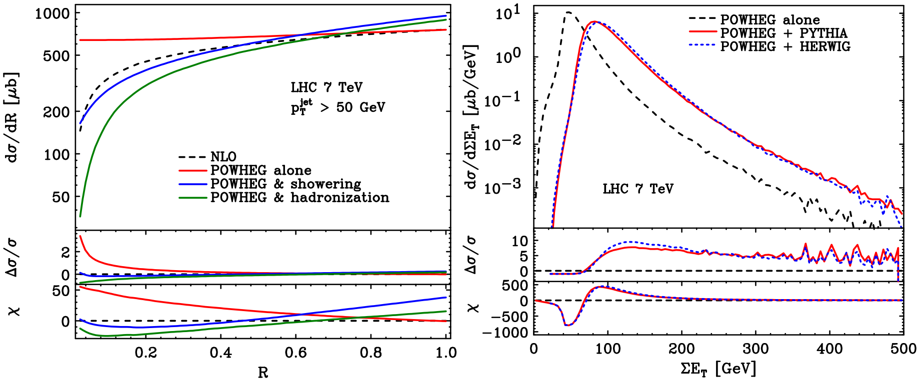
Dijets

- **Exclusive observables show the expected pattern at the various stage of the simulation: NLO, bare `POWHEG`, `POWHEG` + shower.**





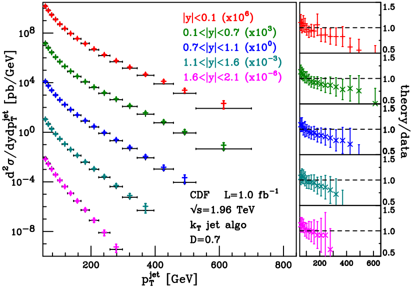
Dijets

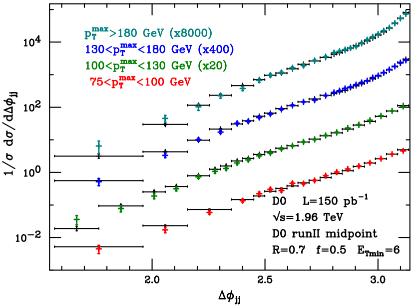


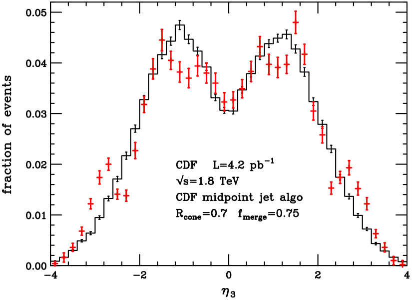
- **Study of dependence on jet radius: NLO shows a logarithmic divergence for small R, not present in bare POWHEG result. POWHEG result is still unphysical, since only first emission is included. Only after shower and hadronization one get the correct behaviour.**
- **Large shower and hadronization effects for particular observables: $50\mathrm{GeV}$ shift for total transverse-energy spectrum at LHC.**

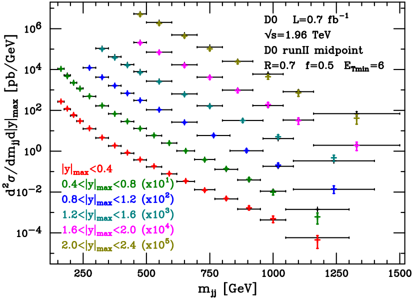
Comparison with TeVatron Dijet data

D0 [Phys. Rev. Lett. 94(2005) ,Phys.Lett. B693(2010)]
CDF [Phys.Rev.D50(1994),Phys.Rev.D75(2007)]



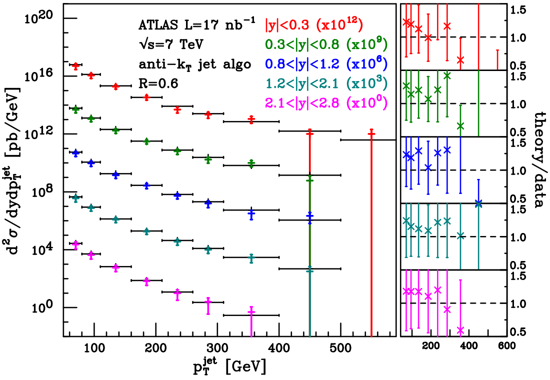


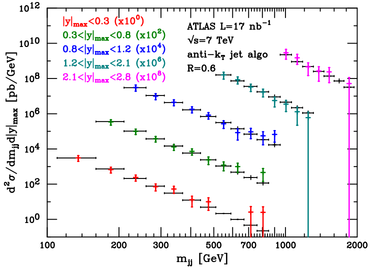


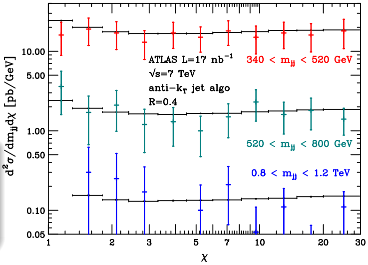


Comparison with ATLAS Dijet data

ATLAS [Eur.Phys.J.C71:1512(2011)]







- **Clustering with anti$-k_T$ jet algo $R = 0.4 - 0.6$**
- **Events showered with PYTHIA** Perugia0 Tune, MPI on
- **Angular variable $\chi = \exp(|y_1 - y_2|)$**