POWHEG: status and perspectives

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HELMHOLTZ ASSOCIATION

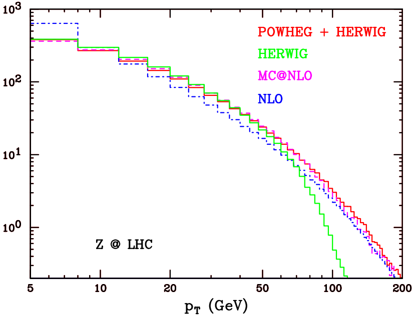
DESY

The POWHEG method

- SMC programs and higher order corrections have been considered complementary approaches for long time. Nowadays it is possible to merge them.
- Double counting of extra emission problem has been adressed and solved first by the MC@NLO approach [Frixione&Webber JHEP 0206:029,2002]
- POWHEG improves over it by being shower independent and by allowing the generation of positive weighted events only [Nason JHEP,2004]
- The resulting events have NLO accuracy and the correct Sudakov suppression

This is achieved by:

1. Generating hardest emission with full tree level matrix element and virtual corrections.
2. The shower generates subsequent emissions, performing (N)LL resummation of collinear/soft logs.
3. Vetoring emissions harder than the first.



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

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

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

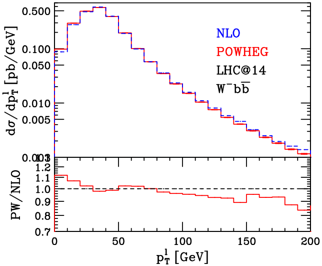
- Framework for the implementation of a POWHEG generator for a generic NLO process
- Practical implementation of the theoretical construction of the POWHEG general formulation presented in [Frixione,Nason,Oleari,JHEP 0711:070,2007]
- FKS subtraction approach automatically implemented, hiding all technicalities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

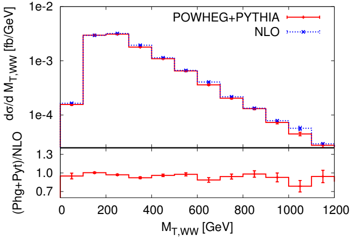
Included processes :

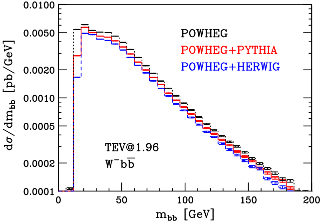
- $Z/\gamma*, W^{\pm}$ production and decay
- $Z/\gamma*, W^{\pm}$ plus one jet production and decay
- Single-top production in the $s-$, $t-$ and $Wt-$ channel (with approx. decay)
- Higgs boson production in gluon and vector boson fusion
- Jet pair production
- Heavy-quark pairs production (with approx. decay)
- W^+W^+ plus two jets
- $Wb\bar{b}$, with massive b's and approx. 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 approx. decay

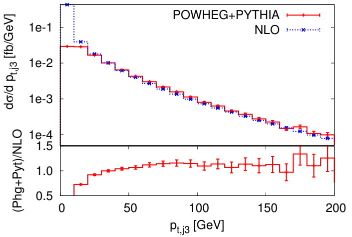
Recent additions: $Wb\bar{b}$ and W^+W^+jj

[Oleari,Reina ArXiv 1105.4488]
[Melia et al. Eur.Phys.J. C71 (2011) 1670]







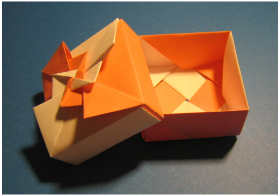


- **Many $2 \to 2$ and $2 \to 3$ processes already implemented, massless and massive.**
- **First $2 \to 4$ implementation in POWHEG: no more effort than the NLO calculation itself**

POWHEG BOX and other implementations

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

- Herwig++, include also truncated 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 shower independent.

- We follow this guideline, making the code publicly available and releasing Les Houches event files, ready to be showered by any SMC program.
- Ready to discuss/improve the LH interface, if needed for new SMC or for ME merging.
- Interface to Rivet/AGile analysis frameworks.
- Mailing lists availaible at http://www.hepforge.org for announcements/contacting the authors. Please subscribe if you are a POWHEG BOX user.

Validation

✓ The POWHEG BOX automatizes the inclusion of new processes

✗ However validation is still a demanding task!

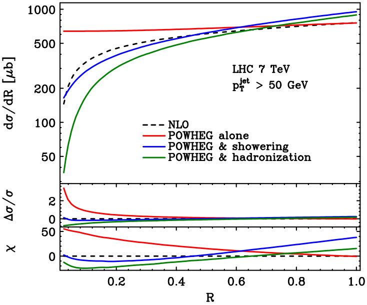
Why do we need it ?

- 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:
  - *a)* Check that these modifications reflect real physical effects not correctly accounted for at NLO.
  - *b)* Check that these modifications are compatible with (un)known higher-order corrections.

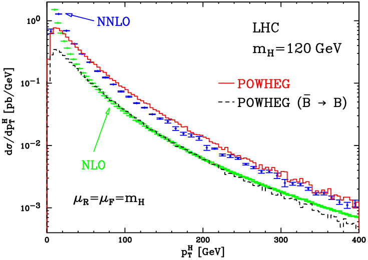
Validation

So:

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

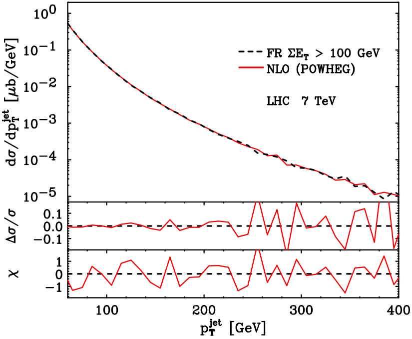


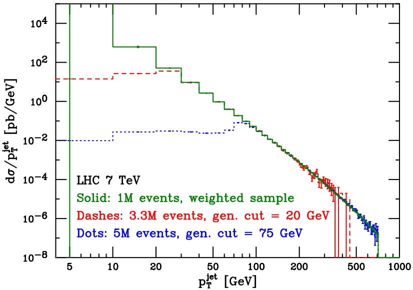
- Cross section dependence on jet radius is more phyiscal after showering and hadronization



- Higgs boson high-p_T tail is enhanced by large contributions beyond NLO, but still in agreement with NNLO

- **Most frequently occuring hard scattering in hadronic collisions**
- **All ingredients knowns since late ’80s** [Nucl.Phys. B269 (1986)] [Phys. Rev.D 46 (1992)]
- **Check with Frixione&Ridolfi NLO code** [Nucl.Phys. B507 (1997)]





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

- **Weighted event generation**

$$W(p_{\rm T}) = \left(\frac{p_{\rm T}^2}{p_{\rm T}^2 + p_{{\rm T},\,{\rm supp}}{}^2}\right)^3$$

Dijets

- With symmetric cuts, the (IR safe) NLO cross sec. with $E_{T,1} > E_{T,\text{cut}} + \Delta$, $E_{T,2} > E_{T,\text{cut}}$ is patologic when $\Delta \to 0$.

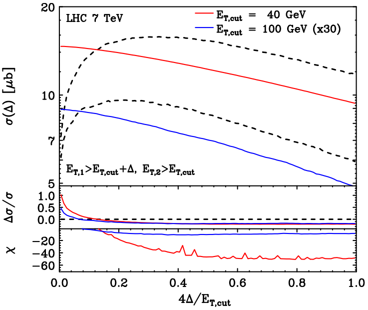
✗ It does not decrease reducing the available phase space

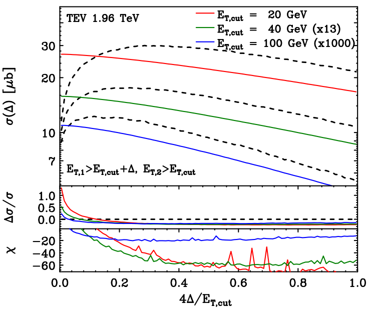
- Well known effect, already observed in [Nucl.Phys. B507 (1997), Phys.Rev. D56 (1997)]
- Truncation of perturbative expansion at NLO induces logarithmic Δ terms from unbalanced cancellation of soft gluons between reals and virtual contributions.
- Inclusion of soft gluons resummation fixes this anomalous behaviour

[Eur. Phys. J. C 23, 13 (2002)]

- Similar resummation performed by POWHEG:

- - - NLO — POWHEG





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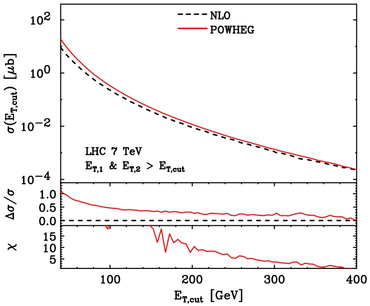
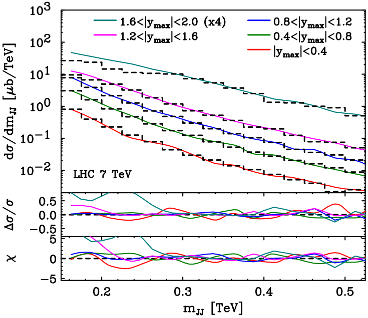
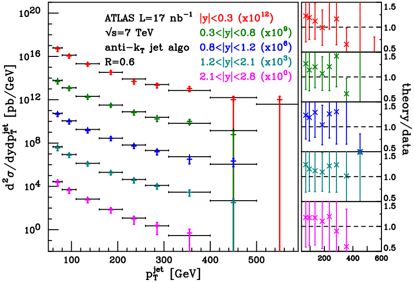
- Effects visible also in physical distributions: $E_T \approx \frac{m_{jj}}{2\cosh|y|}$ symmetric $E_{T,\text{cut}} = 40\text{GeV}$

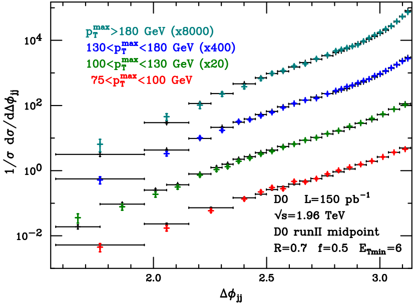


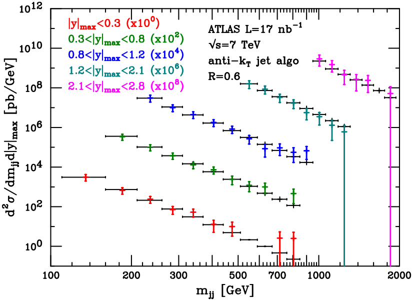


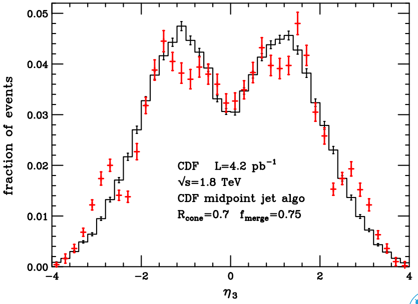
Comparison with LHC and TeV data

D0 [Phys. Rev. Lett. 94(2005) ,Phys.Lett. B693(2010)]
CDF [Phys.Rev.D50(1994),Phys.Rev.D75(2007)]
ATLAS [Eur.Phys.J.C71:1512(2011)]



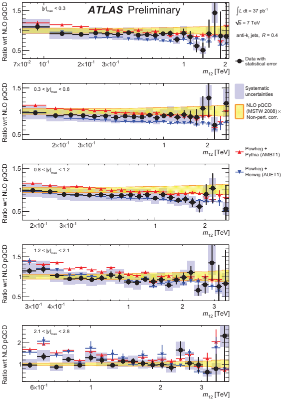


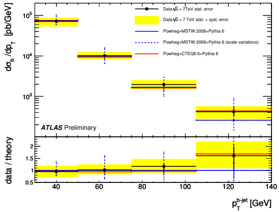


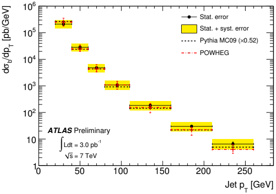


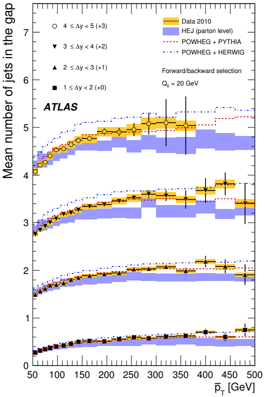
Dijets

- **Program already used in ATLAS-CONF-2011-038,-047,-056,-057 CMS-PAS-FWD-10-003,-006**







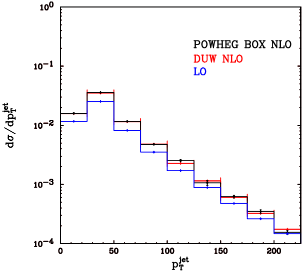


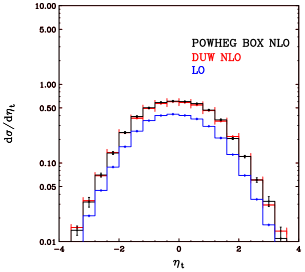
- **Directly comparable to data: no K-factor, no hadronization corrections needed.**
- **Discrepancies have been understood, interesting features under investigation**

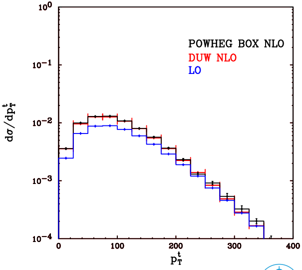
$t\bar{t} + 1jet$

[S.A.,Moch,Uwer, in preparation]

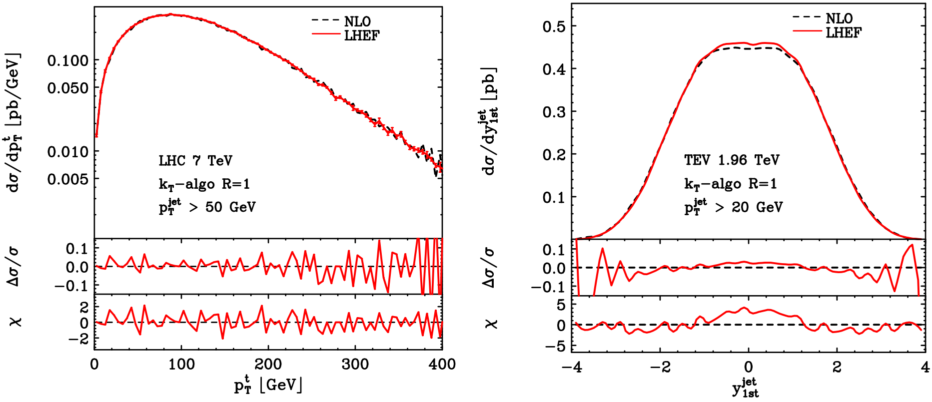
- **Large fractions of inclusive $t\bar{t}$ events contains additional jet(s)**
- **Dominant background to Higgs production in VBF, for configurations that avoid the large rapidity gap between jets veto. Also important background for many SUSY signals.**
- **Fully exclusive NLO calculation available: 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.**
- **Recent independent implementation with `POWHEG BOX` and `HELAC−NLO` by Kardos, Papadopoulos, Trocsanyi** [arXiv:1101.2672]
- **Validation against DUW code (Massive CS vs. FKS subtraction)**





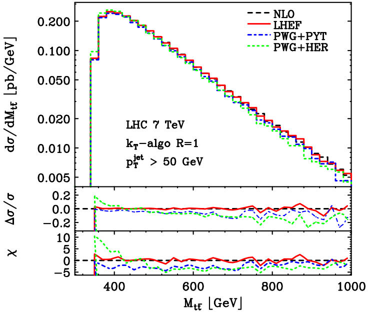


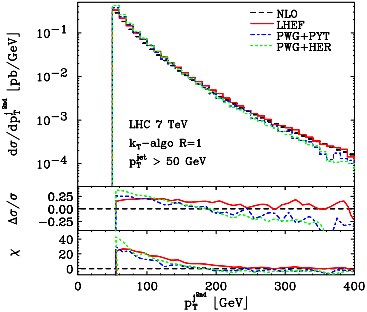
$t\bar{t} + 1jet$: first emission

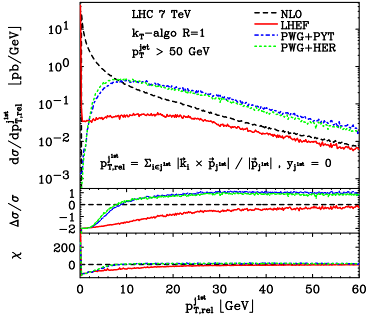


- ✓ **No major discrepancies found in inclusive quantities**
- ✓ **No extra enhancement in particular distributions**
- ✓ **Expected differences in regions where resummation is important**

$t\bar{t} + 1jet$: showered results at the LHC

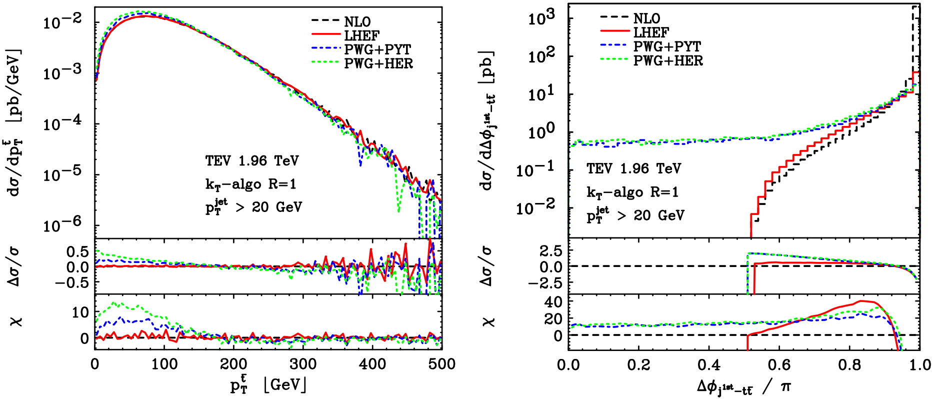






- ✓ **Total cross sections and inclusive distributions in good agreement. Shower effects under control!**
- ✓ **Result as expected fo exclusive quantities sensitive to shower effects**

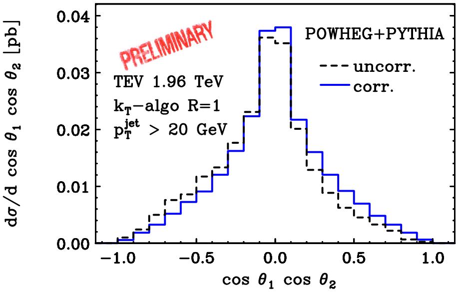
$t\bar{t} + 1jet$: showered results at the TeVatron

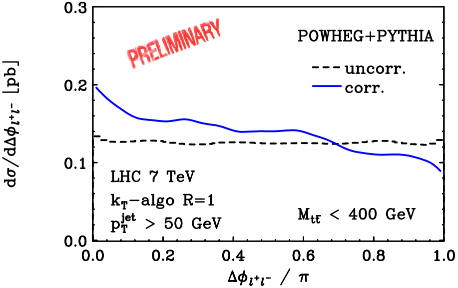


- For more exclusive quantities kinematical constraints avoided: more realistic final states.
- However, results are more sensitive to analysis cuts: dependence on jet cuts may change the normalization

$t\bar{t}+1jet$: spin correlation effects in top decays

- **LO spin correlations in top decays included *a posteriori*, reweighting events with full matrix element $pp \to (t \to b\ell^+\bar{\nu}_\ell)(\bar{t} \to \bar{b}\ell^-\nu_\ell)j(j)$** [Frixione et. al JHEP 0704 (2007)]
- **Top distributions unaffected by the inclusion of spin-correlated decays (no cuts!)**
- **Tiny effects in distributions of leptons coming from top quarks, visible both at Tevatron and at the LHC (enhanced in the low $M_{t\bar{t}}$ region)** [Mahlon&Parke, Phys.Rev. D81 (2010)]
- **May affects the normalization in case of stringent lepton cuts**





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!

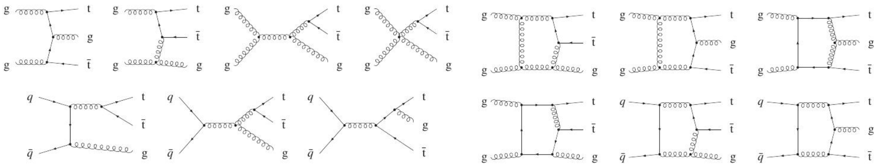
Outlook :

- More multileg processes currently being implemented.
- Interfacing to codes that perform automatic NLO calculations
- Dedicated tuning of NLO+SMC results to data.
- Merging NLO + Patron Shower with ME corrections and samples with different multiplicities:
  e.g. $t\bar{t}$, $t\bar{t} + jet$ ....

Thank you for your attention!

Extra slides

Outline of the calculation

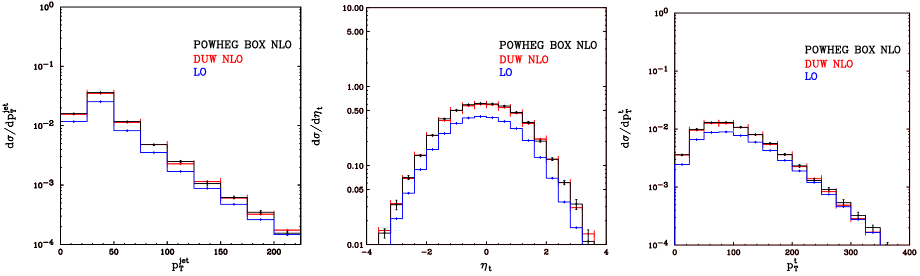


- Color-correlated and Helicity-correlated Born amplitudes obtained modifying `MadGraph` routines
- Factorization in soft and collinear limits explicitly checked in double and quadruple precision.
- Binoth-LesHouches interface compliant library for virtuals from Dittmaier-Uwer-Weinzierl code:
  - Decompositon 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

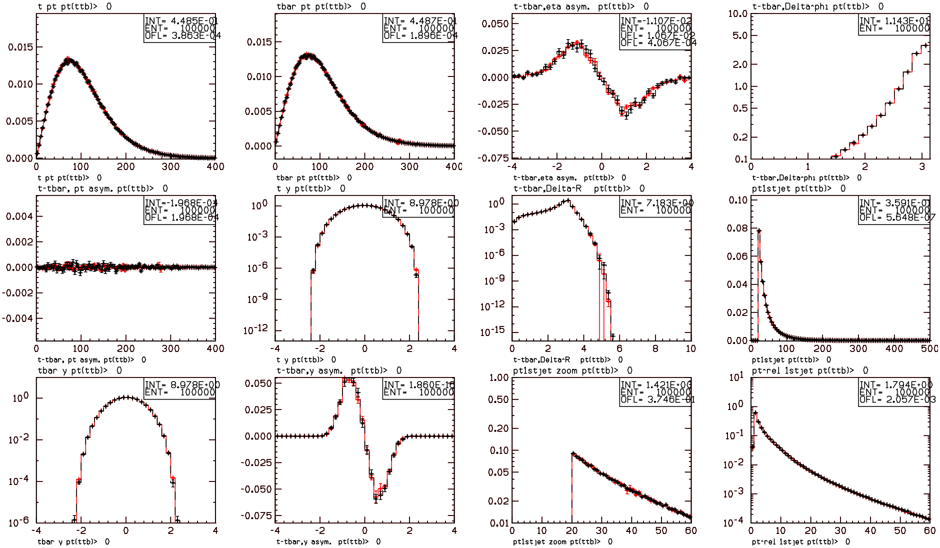
- Non trivial check due to the different subtraction methods:
  - (Massive) Dipole subtraction in Dittmaier-Uwer-Weinzierl
  - FKS subtraction, extendend to deal with soft emissions out of massive colored particles, in `POWHEG BOX`

  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$-k_{\mathrm{T}}$ jet algo (Collins-Soper) $k_{\mathrm{T}} > 20$ GeV, $R = 1$ with E_t recombination scheme via FastJet. Comparisons for TeVatron $\sqrt{S} = 1.96 \, \mathrm{TeV}$
- Top quarks always tagged, excluded from jet reconstruction

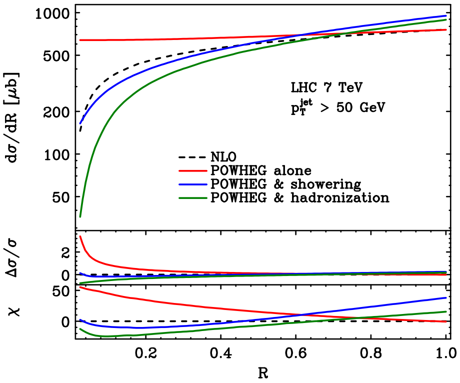


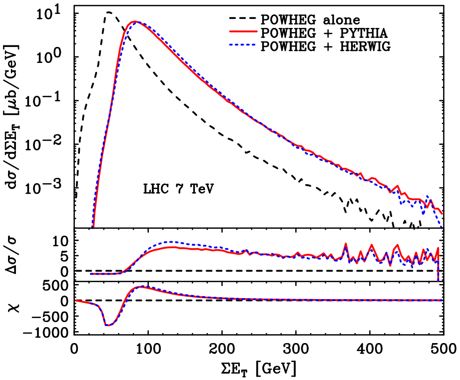
NLO comparisons

- Hundreds of distributions compared. Always perfect agreement found.



Dijets

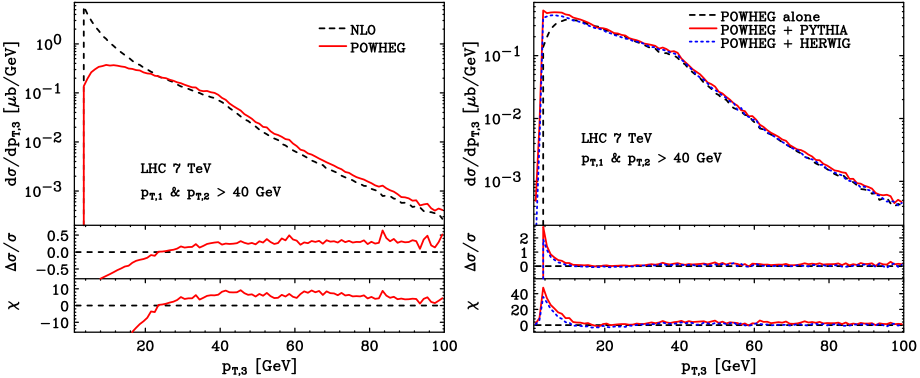




- Study of dependence on jet radius: NLO shows a logarithmic divergence for small R, not present in bare POWHEG result. POWHEG result is still unphysical, since only first emission is included. Only after shower and hadronization one get the correct behaviour.
- Large shower and hadronization effects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

Dijets

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



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_{an} larger than the process defining cut k_{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

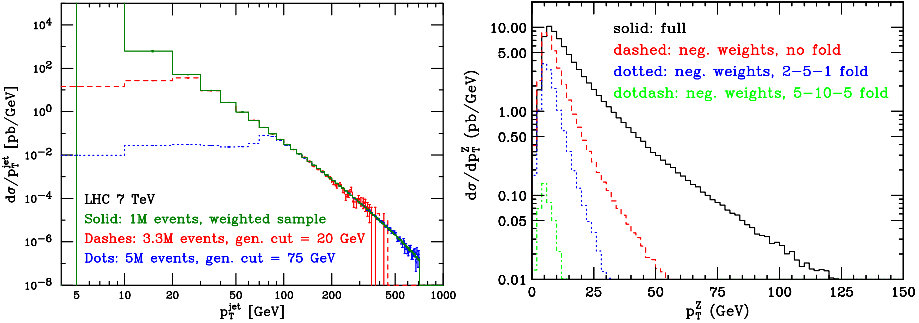
Two possible solutions implemented in POWHEG BOX:

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

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

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

Generation cut and negative-weighted events

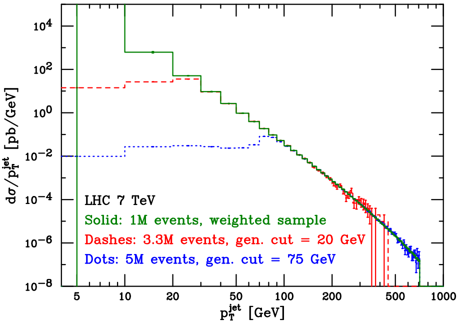


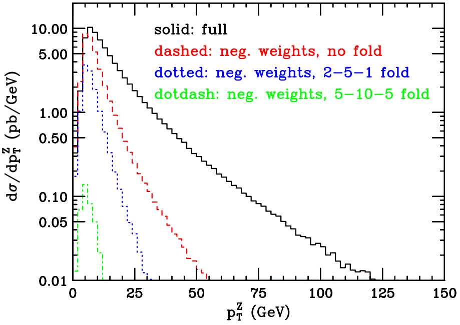
- **Negative values of** $\tilde{B}(\Phi_B, X) = B(\Phi_B) + V(\Phi_B) + \left|\frac{\partial\Phi_{\rm rad}}{\partial X}\right| [R(\Phi_B, \Phi_{\rm rad}) - C(\Phi_B, \Phi_{\rm rad})]$ **are expected in extreme regions of the phase-space. Only after integration over** $d\Phi_{\rm rad}$ **negative weights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

The POWHEG method

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

POWHEG master formula can be derived by simple considerations:

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

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

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

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

POWHEG master formula can be derived by simple considerations:

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

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

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

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

- **POWHEG first emission**

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

- **POWHEG first emission**

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

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

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

- **POWHEG first emission**

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

✓ **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!

The POWHEG method

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

- **POWHEG first emission**

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

✓ **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!

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

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

The POWHEG method

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

- **POWHEG first emission**

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

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

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

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

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

- **POWHEG first emission**

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

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

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

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

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

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

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

$$
\begin{aligned}
d\sigma &= \overbrace{\bar{B}_{\text{sing.}}(\Phi_n)}^{\text{NLO}}\, d\Phi_n \overbrace{\left\{\Delta_{\text{sing.}}(t_0) + \Delta_{\text{sing.}}(t)\frac{R^{\text{sing.}}(\Phi_n,\Phi_{\text{rad}})}{B(\Phi_n)}\, d\Phi_{\text{rad}}\right\}}^{\text{sum to 1 by unitarity}} \\
&+ \underbrace{\left[R(\Phi_n,\Phi_{\text{rad}}) - R^{\text{sing.}}(\Phi_n,\Phi_{\text{rad}})\right]}_{\text{NLO}} d\Phi_n\, d\Phi_{\text{rad}} \\
\bar{B}_{\text{sing}}(\Phi_n) &= B(\Phi_n) + V(\Phi_n) + \int \left[R^{\text{sing.}}(\Phi_n,\Phi_{\text{rad}}) - C(\Phi_n,\Phi_{\text{rad}})\right]\, d\Phi_{\text{rad}} \\
\Delta_{\text{sing.}}(t) &= \exp\left[-\int d\Phi'_{\text{rad}} \frac{R^{\text{sing.}}(\Phi_n,\Phi'_{\text{rad}})}{B(\Phi_n)}\theta\left(t'-t\right)\right]
\end{aligned}
$$

The POWHEG method

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

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

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

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

- **In POWHEG :** $R^{\text{sing.}}(\Phi_n,\Phi_{\text{rad}}) = F(\Phi_n,\Phi_{\text{rad}}) \times R(\Phi_n,\Phi_{\text{rad}})$**, with** $0 \le F \le 1$**, 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** $R = R^{\text{sing.}} + R^{\text{remn.}}$

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

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

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

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

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

$F = 1$ **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

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

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

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

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

- ✗ **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**

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

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

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

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

$$< \mathcal{O} > \; = \int d\Phi_n \bar{B}(\Phi_n)\, 1\, O_n(\Phi_n)$$

$$+ \int 1 \frac{R(\Phi_{n+1})}{1} \left[O_{n+1}(\Phi_{n+1}) - O_n(\Phi_n) \right] d\Phi_{\mathrm{rad}} + \mathcal{O}(\alpha_{\mathrm{S}})$$

NLL accuracy of the POWHEG Sudakov Form Factor

Substitute $\alpha_S \to A\left(\alpha_S\left(k_T^2\right)\right)$ in the Sudakov exponent, with

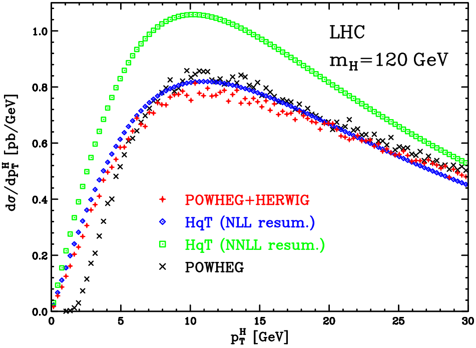
$$A(\alpha_S) = \alpha_S \left\{ 1 + \frac{\alpha_S}{2\pi} \left[\left(\frac{67}{18} - \frac{\pi^2}{6} \right) C_A - \frac{5}{9} n_f \right] \right\}$$

and one-loop expression for α_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]

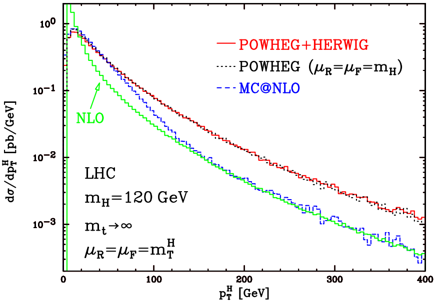
For > 3 coloured partons, soft NLL contributions exponentiates only in a matrix sense

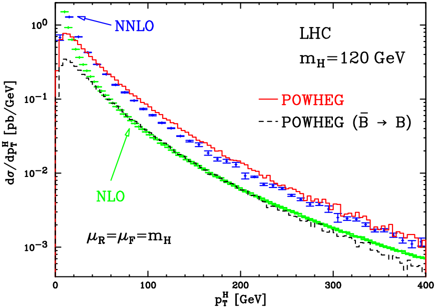
- **Need to diagonalize the colour structures**
- **Always possible to take the large N_c limit and get NLL**

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



High $-p_{\rm T}$ behaviour





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

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

if $p_{\rm T} >> 1 \quad \Rightarrow \quad \Delta(\Phi_n, p_{\rm T}) \approx 1$ **and**

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

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

Reduction of real contribution entering the Sudakov FF

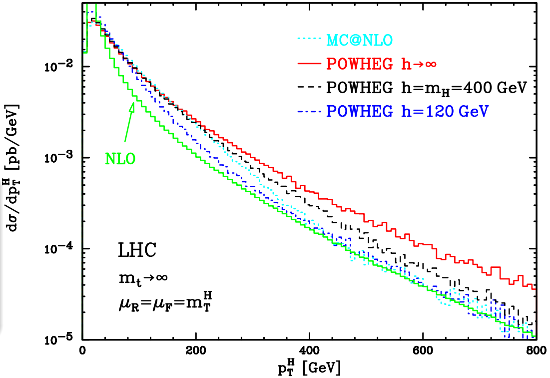
$$
\begin{aligned}
R &= \overbrace{R \times F}^{\color{red}{singular}} + \overbrace{R \times (1-F)}^{\color{blue}{regular}} \\
&= R_{\bar{B}} + R_{\mathbf{reg}}
\end{aligned}
$$

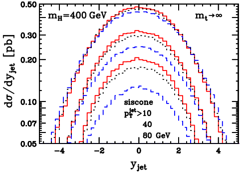
$F < 1, \qquad F \to 1$ **when** $p_{\mathrm{T}} \to 0,$

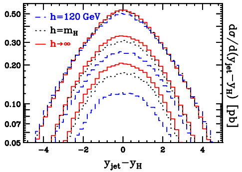
$F \to 0$ **when** $p_{\mathrm{T}} \to \infty$

$$\Rightarrow \quad F = \frac{h^2}{p_T^2 + h^2}$$

$$
\begin{aligned}
\sigma &= \sigma_{\bar{B}} + \sigma_{\mathbf{reg}} \\
\sigma_{\bar{B}} &= \int d\Phi_n \Big\{ B(\Phi_n) + V(\Phi_n) + \\
&\quad [\, R_{\bar{B}}(\Phi_n, \Phi_{\mathrm{rad}}) - C(\Phi_n, \Phi_{\mathrm{rad}}) \,]\, d\Phi_{\mathrm{rad}} \Big\} \\
\sigma_{\mathbf{reg}} &= \int R_{\mathbf{reg}}(\Phi_n, \Phi_{\mathrm{rad}}) \, d\Phi_n \, d\Phi_{\mathrm{rad}}
\end{aligned}
$$



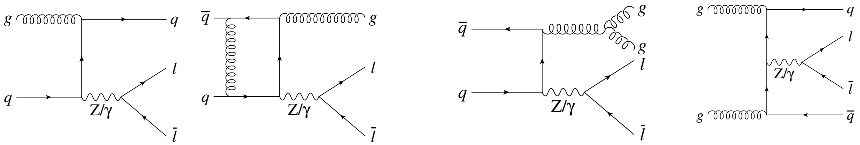




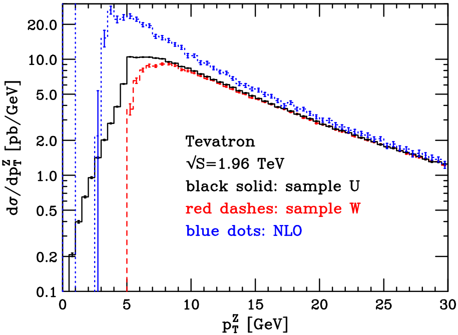
Vector boson plus jet production and decay

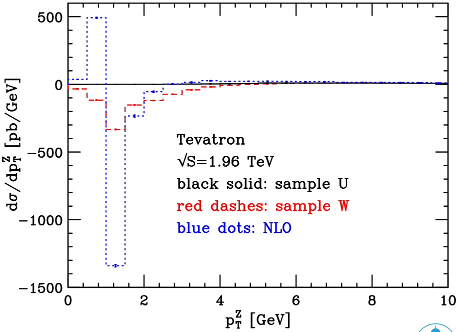
S.A., P.Nason, C.Oleari, E.Re [JHEP 1101:095,2011]

- **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

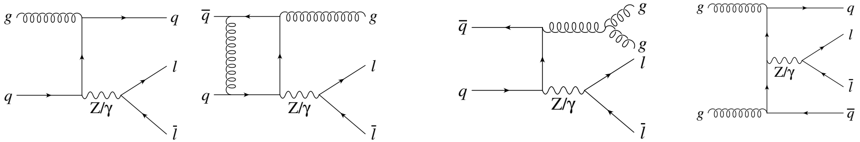




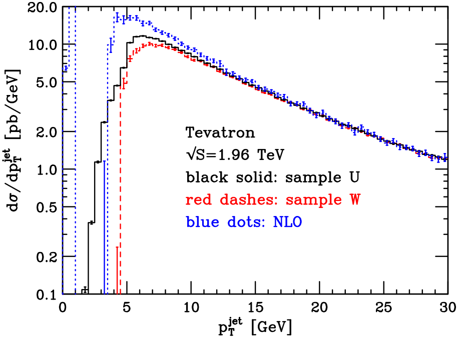
Vector boson plus jet production and decay

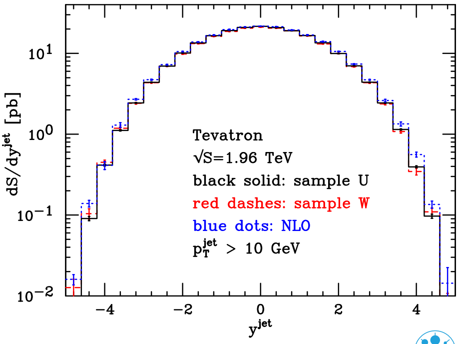
S.A., P.Nason, C.Oleari, E.Re [JHEP 1101:095,2011]

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



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

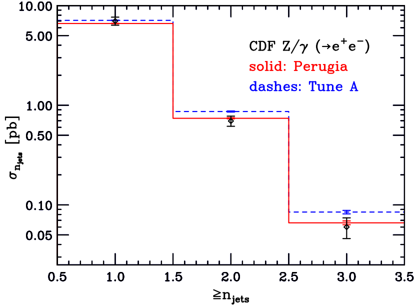


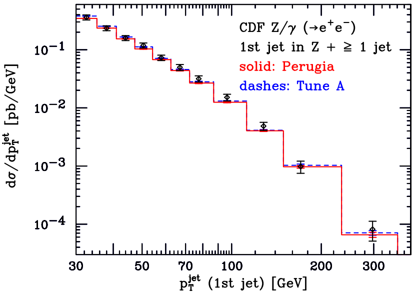


Comparison with $Z + 1j$ TeVatron data - e channel

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

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





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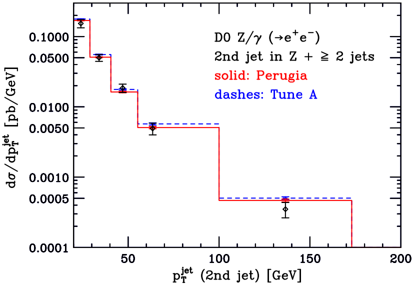
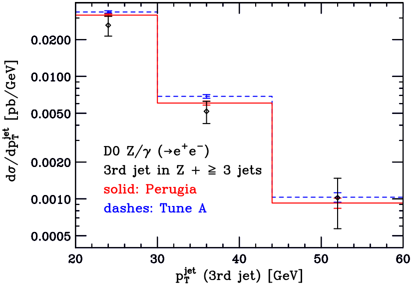
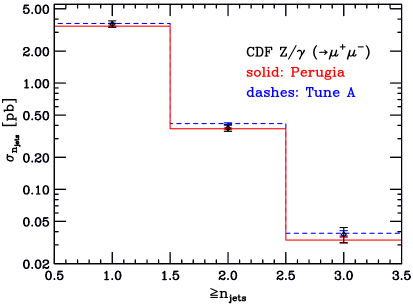


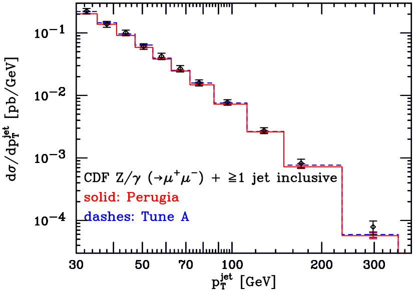


Comparison with $Z + 1j$ TeVatron data - μ channel

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

- **CDF cuts:** $66\ \text{GeV} < M_{\mu\mu} < 116\ \text{GeV},\ p_T^\mu > 25\ \text{GeV},\ |\eta^\mu| < 1.0,\ |y^{\text{jet}}| < 2.1,$ $p_T^{\text{jet}} > 30\ \text{GeV},\ \Delta R_{\mu,\,\text{jet}} > 0.7$
- **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**





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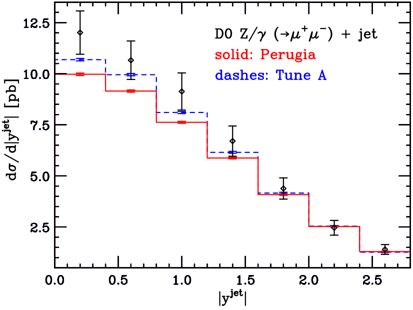
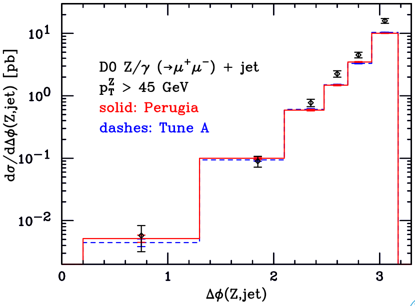
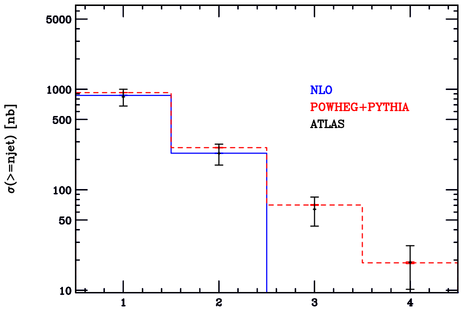
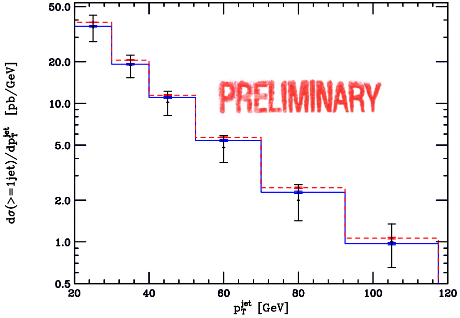




Comparison with $W + 1jet$ LHC data

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 $R = 0.4$**