

Matching NLO QCD and Parton Showers: the POWHEG method

SIMONE ALIOLI

INFN & UNIVERSITY OF MILANO-BICOCCA

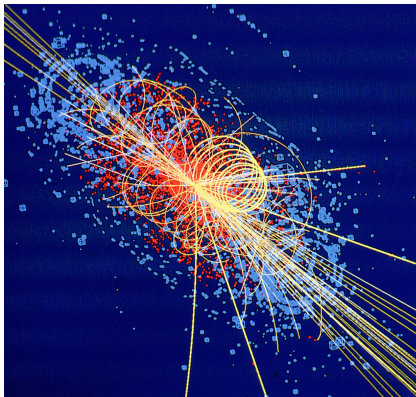


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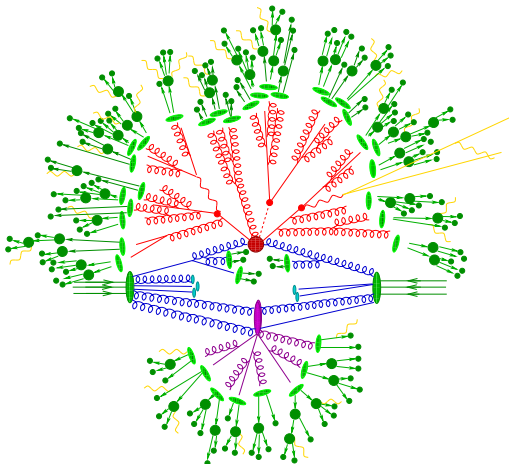
Summary

- (Brief) Introduction to Shower Monte Carlo programs
- The `POWHEG` method
- Applications & Results
- Conclusions & Future Outlooks



Introduction

Research in HEP studies scattering and production of elementary constituents: leptons, quarks and gauge bosons. In QCD quarks and gluons are not observed!



- Beam of hadrons = beam of partons
- Radiation off incoming partons (ISR)
- Primary hard scattering
($\mu \approx Q \gg \Lambda_{QCD}$)
- Radiation off outgoing partons (FSR)
($Q > \mu > \Lambda_{QCD}$)
- Hadronization ($\mu \approx \Lambda_{QCD}$)
- Multiple Particle Interactions - Underlying Event

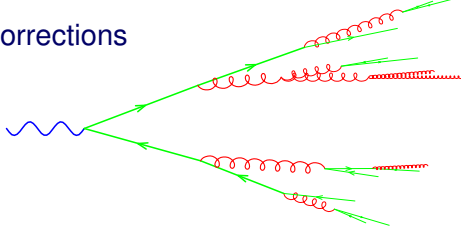
Introduction

Monte Carlo programs are computer codes able to include all the previous stages to simulate pQCD,EW or even BSM hard scatterings and dress them with QCD effects.
They output realistic events that can be used to set up **analysis** strategies!

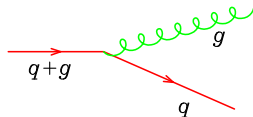
IHEP	ID	IDPDG	IST	MO1	MO2	DA1	DA2	P-X	P-Y	P-Z	ENERGY	MASS	V-X	V-Y	V-Z	V-C*T
30	NU_E	12	1	28	23	0	0	64.30	25.12	-1194.4	1196.4	0.00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
31	E+	-11	1	29	23	0	0	-22.36	6.19	-234.2	235.4	0.00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
230	PIO	111	1	155	24	0	0	0.31	0.38	0.9	1.0	0.13	4.209E-11	6.148E-11	-3.341E-11	5.192E-10
231	RHO+	213	197	155	24	317	318	-0.06	0.07	0.1	0.8	0.77	4.183E-11	6.130E-11	-3.365E-11	5.189E-10
232	P	2212	1	156	24	0	0	0.40	0.78	1.0	1.6	0.94	4.156E-11	6.029E-11	-4.205E-11	5.250E-10
233	NBAR	-2112	1	156	24	0	0	-0.13	-0.35	-0.9	1.3	0.94	4.168E-11	6.021E-11	-4.217E-11	5.249E-10
234	PI-	-211	1	157	9	0	0	0.14	0.34	286.9	286.9	0.14	4.660E-13	8.237E-12	1.748E-09	1.749E-09
235	PI+	211	1	157	9	0	0	-0.14	-0.34	624.5	624.5	0.14	4.056E-13	8.532E-12	2.462E-09	2.462E-09
236	P	2212	1	158	9	0	0	-1.23	-0.26	0.9	1.8	0.94	4.815E-11	1.893E-11	7.520E-12	3.252E-10
237	DLTABR--	-2224	197	158	9	319	320	0.94	0.35	1.6	2.2	1.23	4.817E-11	1.900E-11	7.482E-12	3.252E-10
238	PIO	111	1	159	9	0	0	0.74	-0.31	-27.9	27.9	0.13	-1.889E-10	9.893E-11	-2.123E-09	2.157E-09
239	RHO0	113	197	159	9	321	322	0.73	-0.88	-19.5	19.5	0.77	-1.888E-10	9.859E-11	-2.129E-09	2.163E-09
240	K+	321	1	160	9	0	0	0.58	0.02	-11.0	11.0	0.49	-1.890E-10	9.873E-11	-2.135E-09	2.169E-09
241	KL_1-	-10323	197	160	9	323	324	1.23	-1.50	-50.2	50.2	1.57	-1.890E-10	9.879E-11	-2.132E-09	2.166E-09
242	K-	-321	1	161	24	0	0	0.01	0.22	1.3	1.4	0.49	4.250E-11	6.333E-11	-2.746E-11	5.211E-10
243	PIO	111	1	161	24	0	0	0.31	0.38	0.2	0.6	0.13	4.301E-11	6.282E-11	-2.751E-11	5.210E-10

Experimentalists feed this output thought their detector simulation software to investigate **acceptance cuts** and/or to study signal detection **efficiency**.

Dominant QCD Corrections



Initial or final-state collinear or soft emissions (always with $k_T > \Lambda_{QCD}$) are **strongly enhanced**, due to the vanishing denominator in the propagator of the parent



$$\frac{1}{(q+g)^2 - m_q^2} = \frac{1}{2E_g E_q (1 - \beta_q \cos \theta_{qg})}$$

Soft divergence if $E_g \rightarrow 0$
collinear if $\theta_{qg} \rightarrow 0$ (only if $m_q = 0$)

- Shower algorithms evaluate all these enhanced contributions at **all** orders
- They give a description of hard collisions **up to** a distance scale $\approx 1/\Lambda_{QCD}$
- At larger distance perturbation theory breaks down and we need to rely on non-perturbative methods (*i.e.* lattice). Not feasible in case of complex system, only viable alternative are phenomenological **models of hadron formation**

SMC - NLO comparison

SMC

- Normalization only at the LO
- Poor description of the high p_T emissions (soft and collinear limit)
- LO dependence on μ_r and μ_f
- ★ Sudakov suppression of emissions in the low p_T region
- ★ (N)LL resummation of enhanced logarithms
- ★ Outputs realistic events with lepton and hadrons in the final state

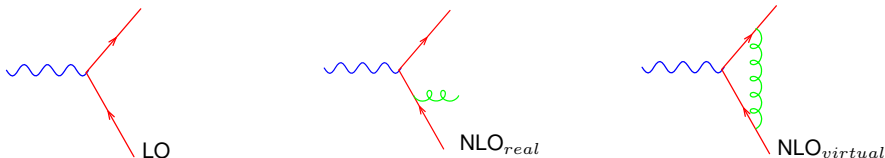
NLO

- ★ Total normalization at order α_s (NLO)
- ★ Accurate shapes at high p_T
- ★ Reduced dependence on μ_r and μ_f (due to the inclusion of virtuals)
- Wrong shapes in low p_T region
- Parton level output only. No way to get the high multiplicity of a realistic event.
- Sensible plots require numerical cancellations between positive and negative defined contributions: high instability

Try to merge benefits of both approaches!

Improving SMC's

- Shower Monte Carlo include LO hard subprocess only and takes account for further emissions in collinear/soft limits.
- A ***K factor*** correction could improve only few inclusive quantities
- Matrix element corrections were added to obtain **better shape predictions**. This corresponds to add further real contributions only.
A matching prescription to avoid double-counting must be defined (e.g. CKKW, MLM).



- Uncertainty in the overall normalization due to the lack of virtual corrections arises

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

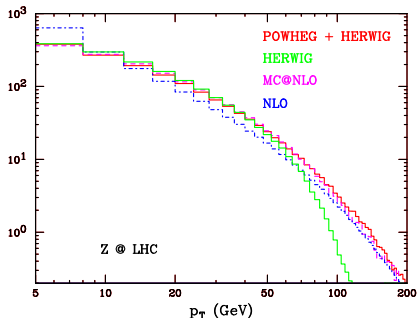
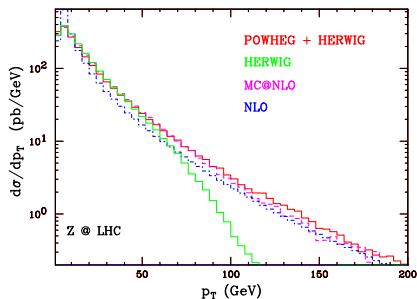
e.g. for $\mu = 100$ GeV and $\alpha_S = 0.12$,
varying $\mu \rightarrow \mu/2, 2\mu$, relative uncertainty is

$W + 1jet$	$W + 2jets$	$W + 3jets$
$\pm 12\%$	$\pm 24\%$	$\pm 36\%$

NLO + Parton Shower

To overcome this problem we should include full NLO calculation in SMC's, avoiding **double-counting** of radiation.

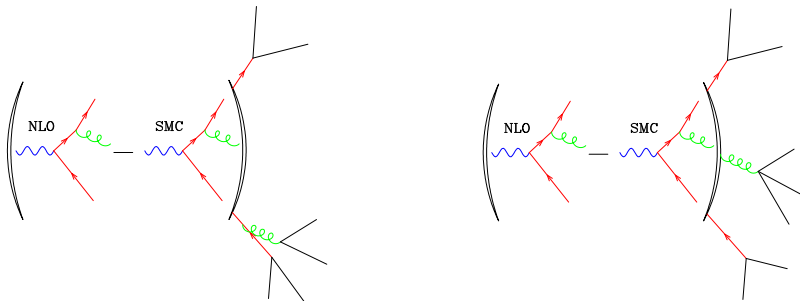
This would merge benefits of both approaches:



- Observables integrated over singular regions are reasonably described by both approaches
- At low p_T , exclusive observables, sensitive to IR singularities, are well described by SMC's (HERWIG)
⇒ NLO calculation fails in this region because large logarithms are not properly resummed
- If interested in high p_T (LHC, Tevatron) NLO calculation is more reliable
- NLO merged with parton shower (MC@NLO, POWHEG) works in both regions

These are the only two known and tested ways to perform this merging!

- Subtract from the exact calculation the NLO expansion of the shower
- Correctly accounts for hard emissions at NLO
- Emissions at small p_T are treated no worse than in usual SMC's
- Several process implemented $pp \rightarrow \{V, VV, H + V, (gg \rightarrow)H, Q\bar{q}, Q\bar{Q}\}$



Nevertheless one has:

- To evaluate the NLO expansion of the shower: **different calculation for each SMC**
- To subtract from the SMC the difference between the exact NLO formula (**expressed in SMC kinematical variables**) and the SMC projected one: this difference may be negative

\Rightarrow **Some negative weighted events may appear (actually up to 20% for $b\bar{b}$!)**

POsitive Weight Hardest Emission Generator

[Nason,JHEP 0411:040,2004]

- It's a method to generate the **hardest emission first**, with **NLO accuracy**, independently from the subsequent shower.
- It generates events with positive weights only. **No negative weights** to handle.
- It can be interfaced with **any** SMC program (HERWIG,PYTHIA,SHERPA,...) which comply with the **Les Houches User Process Interface** and has the capability to veto emissions harder than the first (**SCALUP**). It is thus possible to compare different outputs.
- Can use existing NLO calculations with little effort. **No need to be a SMC expert** to implement them.

As far as the method is concerned, it guarantees:

- NLO accuracy of IR safe and integrated (over small k_T region) quantities.
- Double-log soft-collinear, single-log collinear, single-log soft large- N_c accuracy of the Sudakov form factor for the hardest emission.
- Subsequent emissions have the accuracy of the SMC one is interfaced to.

When interfaced to p_T ordered shower, **nothing else** to be done

When interfaced with **angular ordered** shower, need to restore color coherence of soft gluons at large angle.

- Pair up the nearest-in- p_T partons, generate an angular ordered shower from the largest angle to the angle between the paired partons (**truncated shower**), continue with angular ordered shower vetoing emission harder than the chosen one.

Implemented in recent versions of HERWIG++ [hep-ph/0612281, arXiv:0812.0529]

The same problem affects every angular ordered SMC, when the shower is started by a relatively complex Matrix Element.

Existing implementations

The POWHEG method had already been **successfully** tested in

- $pp \rightarrow ZZ$ [Nason and Ridolfi, JHEP 0608:077, 2006]
- $pp \rightarrow Q\bar{Q}$, $Q = c, b, t$ with spin correlations [Frixione, Nason and Ridolfi, JHEP 0709:126, 2007]
- $e^+e^- \rightarrow q\bar{q}$ [Latunde-Dada, Gieseke, Webber, JHEP 0702:051, 2007]
• $e^+e^- \rightarrow t\bar{t}$ with NLO top decay [Latunde-Dada, Eur.Phys.J.C58:543-554, 2008]
- $pp \rightarrow Z, W$ with spin correlations [SA, Nason, Oleari and Re, JHEP 0807:060, 2008]
[Hamilton, Richardson and Tully, JHEP 0810:015, 2008]
- $gg \rightarrow H$ [SA, Nason, Oleari, Re, arXiv:0812.0578], also in HERWIG++
- $pp \rightarrow W'$ [Latunde-Dada and Papaefstathiou, arXiv:0901.3685]
- $pp \rightarrow H + V$ [Hamilton, Richardson and Tully, arXiv: 0903.4345]
- $pp \rightarrow t + X$ (single top s and t -channel) **NEW (see E. Re talk)** [SA, Nason, Oleari and Re, 2009]
- $pp \rightarrow V + j$ **PRELIMINARY**, via the **POWHEG BOX**

Framework to build the POWHEG implementation of any NLO user supplied calculation.

How it works

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

$$V(\Phi_n) = \underbrace{\overbrace{V_b(\Phi_n)}^{\text{divergent}} + \int \overbrace{C(\Phi_n, \Phi_{\text{rad}})}^{\text{divergent}} d\Phi_{\text{rad}}}_{\text{finite}}$$

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

Standard SMC's:

$$d\sigma_{SMC} = \overbrace{B(\Phi_n)}^{\text{Born}} d\Phi_n \left\{ \Delta_{SMC}(t_0) + \Delta_{SMC}(t) \overbrace{\frac{\alpha_S(t)}{2\pi} \frac{1}{t} P(z)}^{\text{coll. limit of } R/B} d\Phi_{\text{rad}} \right\}$$

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

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

How it works

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

- It yields the **correct NLO cross section**, up to NNLO sub-leading $\mathcal{O}(\alpha_S)$ terms.
- No negative weights!** $\bar{B} = B(\Phi_n) + V(\Phi_n) + \int [R(\Phi_n, \Phi_{\text{rad}}) - C(\Phi_n, \Phi_{\text{rad}})] d\Phi_{\text{rad}} < 0$ only if NLO > LO, but perturbation expansion breaks down!

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

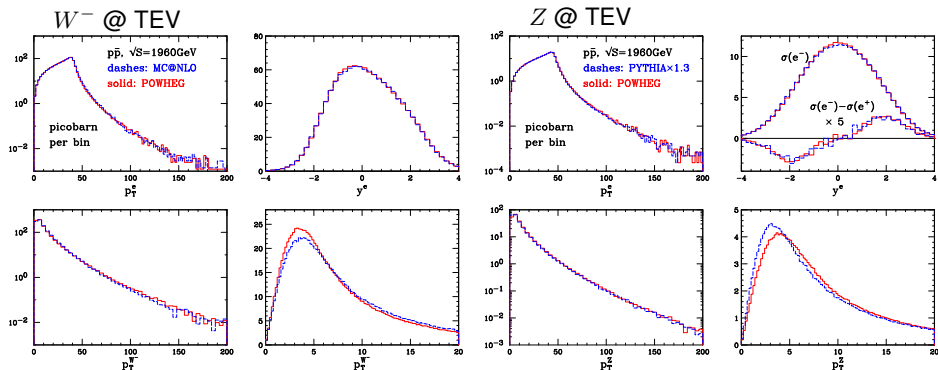
- Probability of not emitting with transverse momentum harder than p_T .
It has the same **LL accuracy** of a SMC's since at small k_T 's

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

- The large k_T 's accuracy is preserved since $\Delta_{\text{POWHEG}}(\Phi_n, p_T) \approx 1$ and

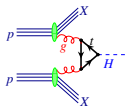
$$d\sigma_{\text{POWHEG}} \approx \frac{\bar{B}(\Phi_n)}{B(\Phi_n)} R(\Phi_n, \Phi_{\text{rad}}) d\Phi_n d\Phi_{\text{rad}} \approx R(\Phi_n, \Phi_{\text{rad}}) (1 + \mathcal{O}(\alpha_S)) d\Phi_n d\Phi_{\text{rad}}$$

Applications: Single vector boson production

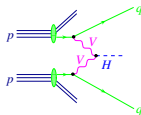


- Good agreement **both** at high and low p_T
- PYTHIA includes hard ME corrections in a POWHEG-like fashion.
but with **wrong** normalization !
- Similar results @LHC [SA,Nason,Oleari and Re,JHEP 0807:060,2008]
- Public code <http://moby.mib.infn.it/~nason/POWHEG>

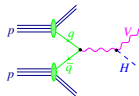
Applications: Higgs boson production via gluon fusion



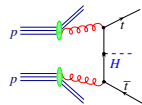
Gluon fusion



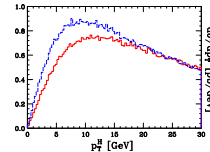
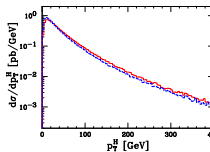
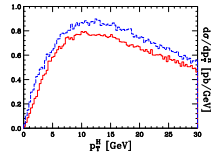
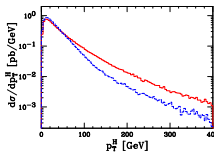
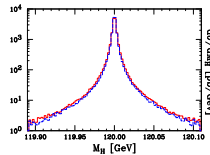
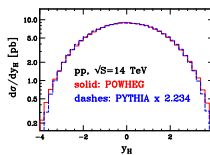
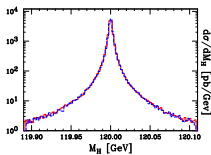
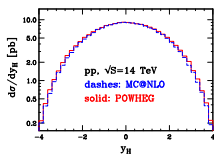
Weak-Boson Fusion



Higgs Strahlung

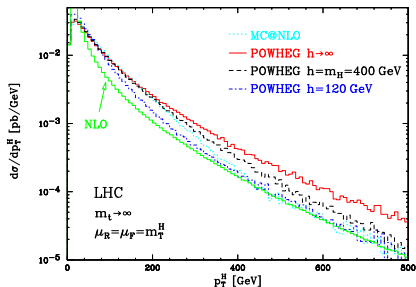
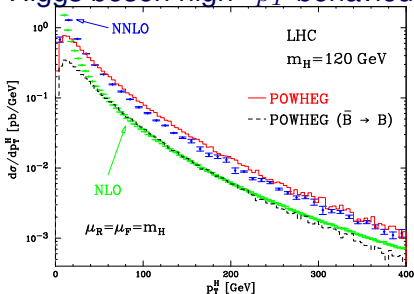


$t\bar{t}H$



Differences in **high** (MC@NLO) and **low- p_T** (PYTHIA) regions at the LHC.

Higgs boson high- p_T behaviour



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

Better agreement to NNLO this way, but enough flexibility to get rid of this feature!

$$\begin{aligned} \sigma &= \sigma_{\bar{B}} + \sigma_{\text{reg}} & R &= \underbrace{R \times F}_{\text{singular}} + \underbrace{R \times (1 - F)}_{\text{regular}} & F &= \frac{h^2}{p_T^2 + h^2} \\ \sigma_{\bar{B}} &= \int d\Phi_n \left\{ B(\Phi_n) + V(\Phi_n) + [R_{\bar{B}}(\Phi_n, \Phi_{\text{rad}}) - C(\Phi_n, \Phi_{\text{rad}})] d\Phi_{\text{rad}} \right\} \\ \sigma_{\text{reg}} &= \int R_{\text{reg}}(\Phi_n, \Phi_{\text{rad}}) d\Phi_n d\Phi_{\text{rad}} \end{aligned}$$

The POWHEG BOX: Z plus jet case study

- We built a framework for the implementation of a POWHEG generator for **any NLO process**
- FKS subtraction approach followed, but hiding all technicalities to the user
- Non trivial test with $Z + j$ production performed. Both ISR and FSR present!

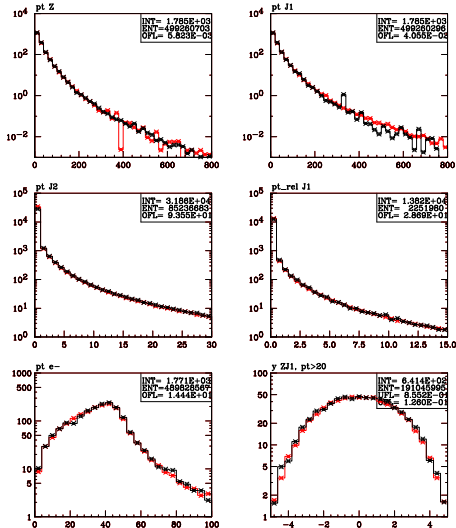
The user is asked to supply

- The Born phase space (in his/her variables)
- The list of flavour of Born and Real processes (e.g. $u \bar{d} \rightarrow W^+ c \bar{c}$)
- The Born squared amplitudes $\mathcal{B} = |\mathcal{M}|^2$
- The color ordered Born squared amplitudes \mathcal{B}_{ij}
- The helicity correlated Born squared amplitudes $\mathcal{B}_{k,\mu\nu}$, where k runs over all external gluons
- The Real squared amplitudes \mathcal{R}
- The finite part of the virtual amplitude contribution \mathcal{V}_b

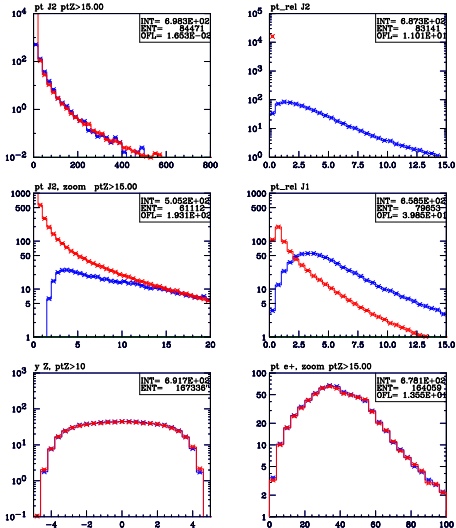
Common ingredients of any NLO calculation in the subtraction method

The POWHEG BOX: Z plus jet case study

NLO - MCFM at the LHC



NLO - POWHEG + HERWIG



Conclusions and future prospects

- POWHEG is a valid method for implement NLO corrections in SMC's.
- It is independent from the SMC.
- It outputs positive weighted events only , just as traditional SMC's.
- It is quite easy to implement, can use existing NLO computations.
- Some process already implemented, more to come.

We encourage people to work on it!

- We published all formulas and tricks to make it easy for other people to write the POWHEG implementation of its own NLO calculation.
- A general framework, named POWHEG BOX, for implementing an arbitrary process is almost complete, ready to be released!

EXTRA SLIDES

NLO accuracy of POWHEG formula

$$\begin{aligned}
 d\sigma &= \bar{B}(\Phi_n) d\Phi_n \left\{ \Delta(\Phi_n, p_T^{\min}) + \Delta(\Phi_n, k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} d\Phi_{\text{rad}} \right\} \\
 \langle O \rangle &= \int \bar{B}(\Phi_n) d\Phi_n \left\{ \Delta(\Phi_n, p_T^{\min}) O_n(\Phi_n) + \int \Delta(\Phi_n, k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} O_{n+1}(\Phi_{n+1}) d\Phi_{\text{rad}} \right\} \\
 &= \int \bar{B}(\Phi_n) d\Phi_n \left\{ \left[\Delta(\Phi_n, p_T^{\min}) + \int \Delta(\Phi_n, k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} d\Phi_{\text{rad}} \right] O_n(\Phi_n) \right. \\
 &\quad \left. + \int \Delta(\Phi_n, k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} [O_{n+1}(\Phi_{n+1}) - O_n(\Phi_n)] d\Phi_{\text{rad}} \right\} \\
 \int d\Phi_{\text{rad}} \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Delta(\Phi_n, k_T) &= \int_{p_T^{\min}}^{\infty} dp_T \int d\Phi_{\text{rad}} \delta(k_T - p_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Delta(\Phi_n, p_T) \\
 &= - \int_{p_T^{\min}}^{\infty} dp_T \Delta(\Phi_n, p_T) \frac{d}{dp_T} \int d\Phi_{\text{rad}} \Theta(k_T - p_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \\
 &= \int_{p_T^{\min}}^{\infty} dp_T \frac{d}{dp_T} \Delta(\Phi_n, p_T) = 1 - \Delta(\Phi_n, p_T^{\min}) \\
 \bar{B}(\Phi_n) &\approx B(\Phi_n) (1 + \mathcal{O}(\alpha_S)) \quad \Delta(\Phi_n, k_T) \approx 1 + \mathcal{O}(\alpha_S) \text{ since } [O_{n+1} - O_n] \rightarrow 0 \text{ at small } k_T \\
 \langle O \rangle &= \int d\Phi_n \bar{B}(\Phi_n) 1 O_n(\Phi_n) + \int 1 \frac{R(\Phi_{n+1})}{1} [O_{n+1}(\Phi_{n+1}) - O_n(\Phi_n)] d\Phi_{\text{rad}} + \mathcal{O}(\alpha_S)
 \end{aligned}$$

NLL accuracy of the POWHEG Sudakov Form Factor

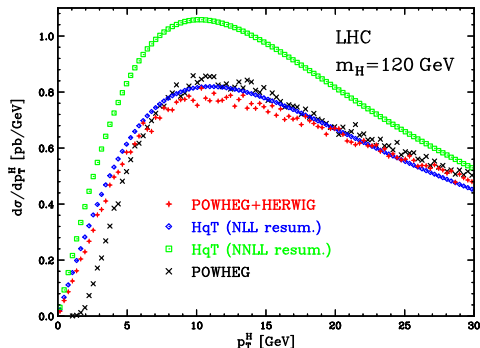
$$\Delta_t^{\text{POWHEG}} = \exp \left\{ - \int_t^{Q^2} \frac{dk_T^2}{k_T^2} \frac{\alpha_S(c k_T^2)}{\pi} \left[A \log \frac{E^2}{k_T^2} + B \right] \right\} \quad c \approx 1$$

$$\Delta_t^{NLL} = \exp \left\{ - \int_t^{Q^2} \frac{dk_T^2}{k_T^2} \frac{\alpha_S(k_T^2)}{\pi} \left[\left(A_1 + A_2 \frac{\alpha_S(k_T^2)}{\pi} \right) \log \frac{E^2}{k_T^2} + B \right] \right\} \quad DDT$$

[Catani, Marchesini and Webber Nucl.Phys.B349]

$$\alpha_S \rightarrow A(\alpha_S(k_T^2)),$$

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



Resummation performed with HqT

[Bozzi, Catani, de Florian and Grazzini, Nucl.Phys.B737]

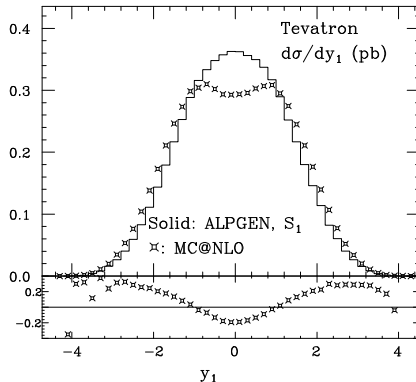
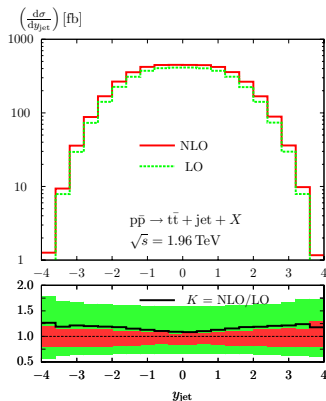
Hardest jet rapidity dip

- ALPGEN vs. MC@NLO comparison study for $t\bar{t}$ productions

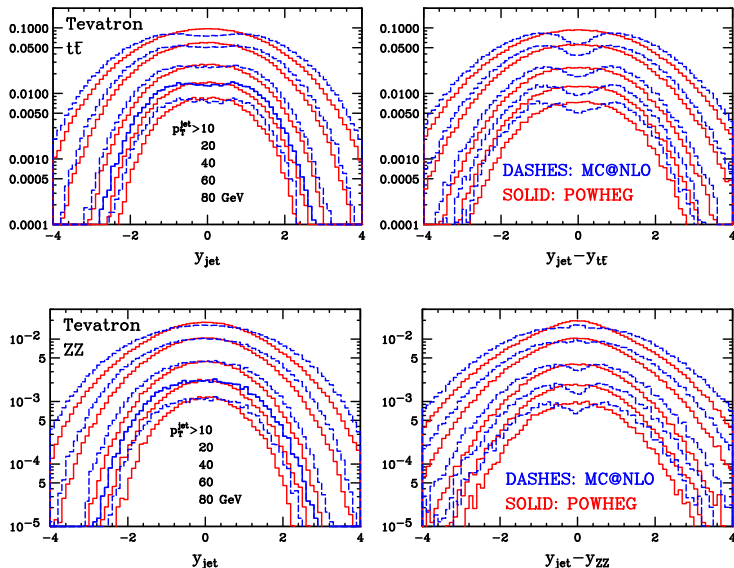
[Mangano,Moretti,Piccinini and Treccani, JHEP 0701:013]

- ALPGEN has better high jet multiplicity (Exact ME), but wrong normalization
- MC@NLO is correct at NLO, but shows a dip in the hardest jet rapidity distribution
- NLO calculation of $p\bar{p} \rightarrow t\bar{t} + 1jet$ shows no dip too

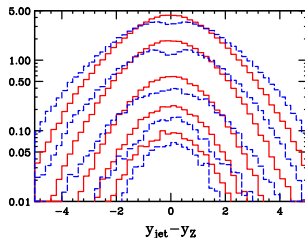
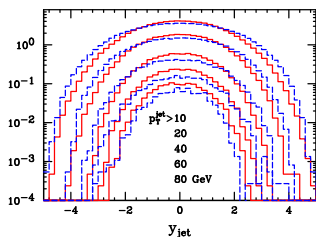
[Dittmaier,Uwer and Weinzierl, arXiv:0810.0452]



Hardest jet rapidity and rapidity difference

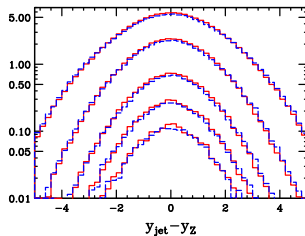
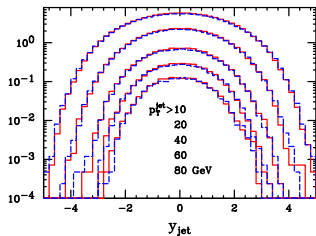


Hardest jet - Z rapidity difference @ TEV



POWHEG + HERWIG

MC@NLO



POWHEG + PYTHIA

PYTHIA $\times 1.3$

MC@NLO dip in hardest radiation

$$\begin{aligned}\Delta_{\text{HW}}(t) &= \exp \left[- \int d\Phi'_{\text{rad}} \frac{R_{\text{HW}}(\Phi_n, \Phi'_{\text{rad}})}{B(\Phi_n)} \Theta(t' - t) \right] \quad \Leftarrow \text{HERWIG Sudakov!} \\ d\sigma_{\text{MC@NLO}} &= \bar{B}_{\text{HW}}(\Phi_n) d\Phi_n \left\{ \Delta_{\text{HW}}(t_0) + \Delta_{\text{HW}}(t) \frac{R_{\text{HW}}(\Phi_n, \Phi_{\text{rad}})}{B(\Phi_n)} d\Phi_{\text{rad}} \right\} + \\ &\quad [R(\Phi_n, \Phi_{\text{rad}}) - R_{\text{HW}}(\Phi_n, \Phi_{\text{rad}})] d\Phi_n d\Phi_{\text{rad}} \\ \bar{B}_{\text{HW}}(\Phi_n) &= B(\Phi_n) + V(\Phi_n) + \int [R_{\text{HW}}(\Phi_n, \Phi_{\text{rad}}) - C(\Phi_n, \Phi_{\text{rad}})] d\Phi_{\text{rad}}\end{aligned}$$

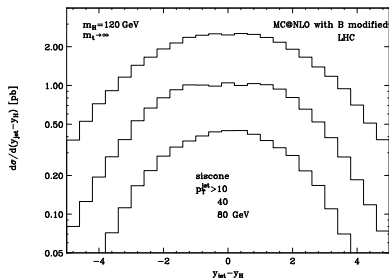
At high p_T the cross section goes as

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

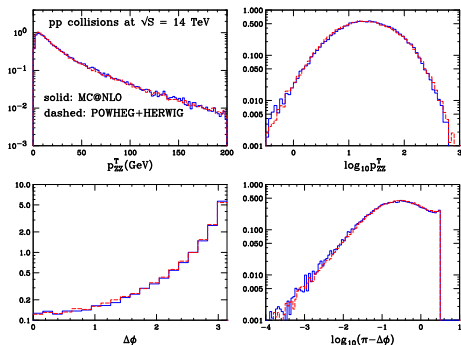
Test :
Replace $\bar{B}_{\text{HW}}(\Phi_n)$ with $B(\Phi_n)$ in
generation of \mathbb{S} -type events

The dip disappears

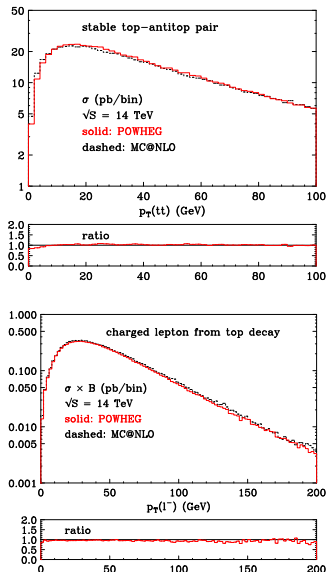
More studies needed to fully clarify the
issue.



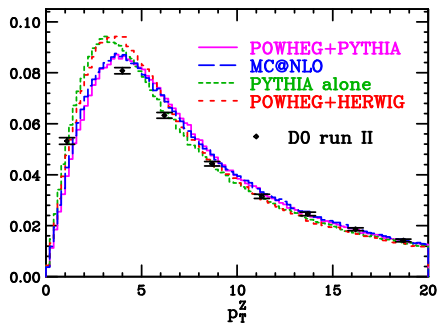
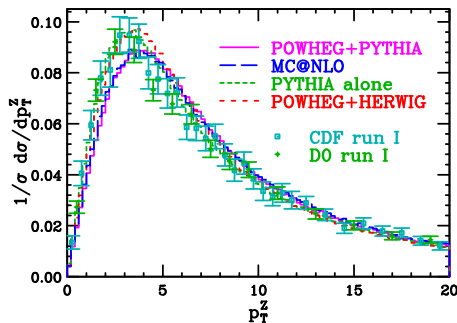
- Results in accord with MC@NLO in both cases



- No evidence for effects of the missing truncated shower



Single vector boson: comparison with TEV data

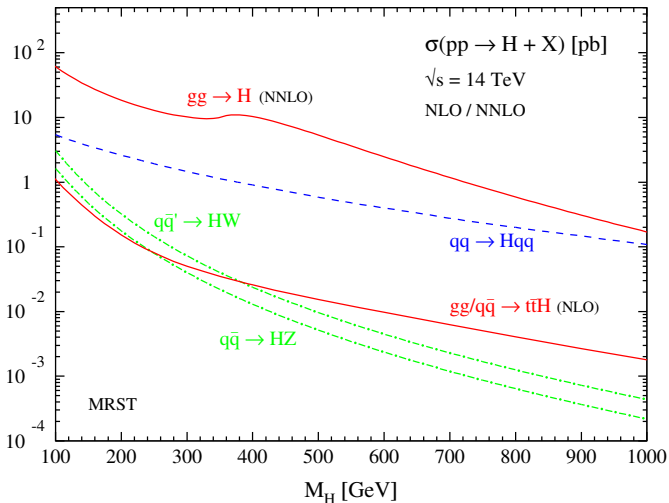


- Intrinsic p_T 2.5 GeV
- POWHEG+PYTHIA \sim MC@NLO POWHEG+HERWIG \sim PYTHIA
- Sensitivity to long distance effects: hadronization model and p_T smearing

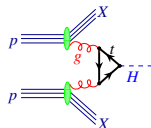


Sensible parameter tuning needed to fully accommodate data

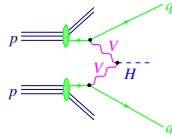
Higgs boson production at the LHC



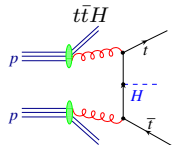
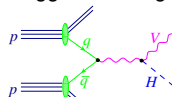
Gluon fusion



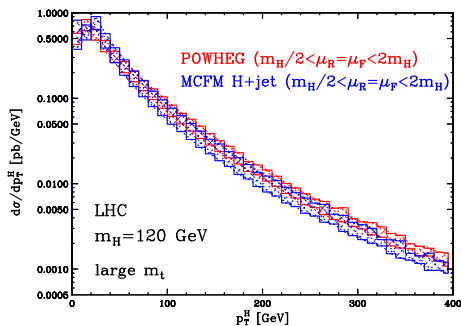
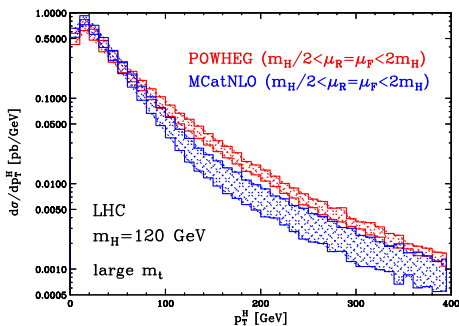
Weak-Boson Fusion



Higgs Strahlung

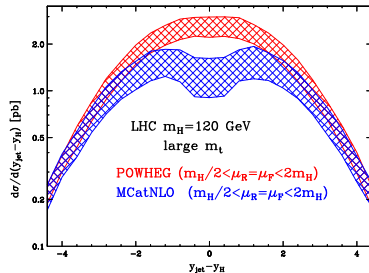
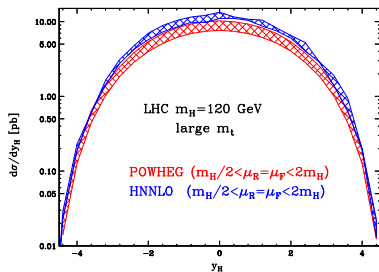


Scales dependence



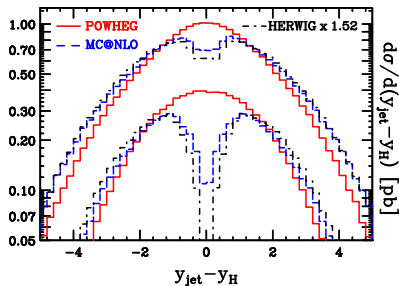
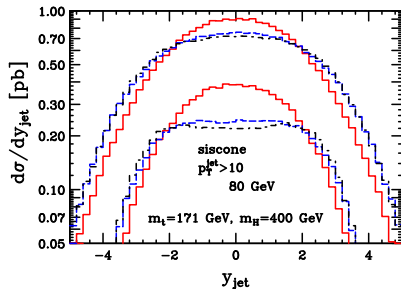
- In MC@NLO (and in $gg \rightarrow H$ at the NLO) high- p_T distribution receives **real** order contributions of order $\alpha_S^3(\mu)$ **only**
- Due to $\bar{B} \times R / B$ factor, the high- p_T distribution in POWHEG starts from contributions of order $\alpha_S^2(\mu) \alpha_S(p_T)$.
- The $gg \rightarrow H + jet$ NLO calculation (MCFM) has up to $\alpha_S^4(\mu)$ contributions, but **also virtuals** are included, so there is a lower scale dependence

Scales dependence - Hardest jet rapidity dip



NNLO results obtained using HNNLO

[Catani and Grazzini, arXiv:0802.1410]



Single top production

