NLO and Parton Showers: the POWHEG-BOX

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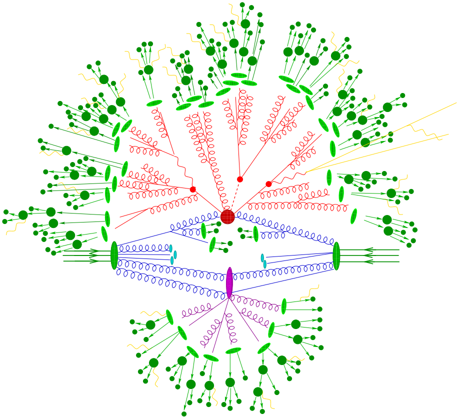
INTRODUCTION

High Energy Physics studies scattering and production of elementary constituents: leptons, quarks and gauge bosons. Hadronic collisions can be well summarized by this picture:



- Parton model
  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 and heavy hadrons decays ($\mu \approx \Lambda_{QCD}$)
- Multiple Particle Interactions - Underlying Event

Monte Carlo programs are computer codes able to simulate all these stages, starting from QCD, EW or BSM hard scatterings and dressing them with QCD effects.

SMC EVENT GENERATORS

SMC's output realistic events that can be used to set up analysis strategies, study acceptance cuts and/or signal detection efficiency.

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	PI0	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	PI0	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	PI0	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

SMC (LO+SHOWER)

- ✗ LO accuracy. Large dependence on $\mu_{\rm R}$ and $\mu_{\rm F}$
- ✗ 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 $\alpha_{\rm S}$
- ✓ Reduced dependence on $\mu_{\rm R}$ and $\mu_{\rm F}$
- ✗ Parton level output only. Low final-state multiplicity.
- ✗ Numerical instability due to large cancellations

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

IMPROVING SMC'S AND NLO

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

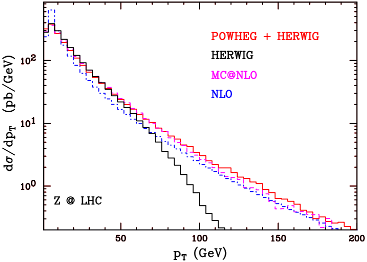
✗ Matrix element corrections added to obtain better shape predictions (*e.g.* CKKW, MLM)

- ⇒ Only add further real contributions (maintaining 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

Only two general method perform this merging for hadronic collisions avoiding double-counting:

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



✓ 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]
Not easy to evaluate! Approximate solution MENLOPS for W and $t\bar{t}$ implemented

NLO AND SMC FORMULAS

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

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

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

- Standard SMC's first emission:

$$d\sigma_{\tt SMC} = \overbrace{B(\Phi_n)}^{Born} d\Phi_n \left\{ \Delta_{\tt SMC}(t_0) + \Delta_{\tt SMC}(t) \overbrace{\frac{\alpha_{\rm S}(t)}{2\pi}\frac{1}{t} P(z)}^{\lim_{k_{\rm T}\to 0} R(\boldsymbol{\Phi}_{n+1})/B(\boldsymbol{\Phi}_n)} d\Phi_{\rm rad}^{\tt SMC} \right\}$$

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

POWHEG

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

✓ It yields the correct NLO cross section for inclusive quantities.

✓ No negative weights! $\bar{B} = B(\Phi_n) + V(\Phi_n) + \int [R(\Phi_n, \Phi_{\rm rad}) - C(\Phi_n, \Phi_{\rm rad})]\, d\Phi_{\rm rad} < 0$

only if 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 since for small k_T's

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

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

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

THE POWHEG−BOX [S.A., NASON,OLEARI,RE, ARXIV: 1002.2581]

- 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 followed, hiding all technicalities to the user
- Publicly available code

  http://powhegbox.mib.infn.it/~nason/POWHEG

  distributed according to the *"MCNET GUIDELINES for Event Generator Authors and Users "*
- Latest releases available trough

  `svn co [--revision n] svn://powhegbox.mib.infn.it/trunk/POWHEG-BOX`

The user should only communicate to the POWHEG−BOX the following informations:

- The number of legs in Born process `nlegborn`
  (*e.g.* `nlegborn`= 5 for $pp \to (Z \to e^+e^-) + j$)

- The list of flavour of Born and Real processes

  `flst_born(k=1..nlegborn,j=1..flst_nborn)`
  `flst_real(k=1..nlegreal,j=1..flst_nreal)`

  according to PDG conventions. Flavor defined incoming (outgoing) for incoming (outgoing) fermion lines, 0 for gluons (*e.g.* `[5,2,23,6,3,0]` for $b\,u \to Z\,t\,s\,g$)

- The Born phase space `Born_phsp(xborn)` for `xborn(1...ndims)` randoms, that sets : the Born Jacobian `kn_jacborn`, the Born momenta `kn_pborn,kn_cmpborn` in lab. and CM frames and the Bjorken x's `kn_xb1,kn_xb2`

- The inizialization of the couplings `init_couplings` and the setting of the scales `set_fac_ren_scales(muf,mur)`

- The Born squared amplitudes $\mathcal{B} = |\mathcal{M}|^2$, the color-ordered Born squared amplitudes $\mathcal{B}_{jk}$ and the helicity correlated Born squared amplitudes $\mathcal{B}_{k,\mu\nu}$, where k runs over all external gluons

  `setborn(p,bflav,born,bornjk,bornmunu)`

  for momenta `p(0:3,1:nlegborn)` and flavour string `bflav(1:nlegborn)`

- The Real squared amplitudes $\mathcal{R}$

  `setreal(p,rflav,amp2)`

  for momenta `p(0:3,1:nlegreal)` and flavour string `rflav(1:nlegreal)`

- The finite part of the interference of Born and virtual amplitude contributions $\mathcal{V}_{\rm b} = 2{\rm Re}\{\mathcal{B} \times \mathcal{V}\}$, after factorizing out $\mathcal{N} = \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \left(\frac{\mu_{\rm R}^2}{Q^2}\right)^\epsilon$

  `setvirtual(p(0:3,1:nlegborn),vflav(1:legborn),virtual)`

- The Born color structures in the large $N_{\rm c}$ limit, via the LH interface `borncolour_lh`

Common ingredients of any NLO calculation in a subtraction method

The POWHEG-BOX program takes care of evaluating

- ✓ The combinatorics, identifying of all the singular regions.
- ✓ The projection of real contributions over the singular regions
- ✓ The counterterms, built up from soft and collinear approximations of real emissions.
- ✓ The ISR and FSR phase space, according to the FKS parametrization of the singular region
- ✓ The NLO differential cross section.
  - BYPRODUCT: NLO distributions in the FKS subtraction scheme. Standard parton-level analysis provided, users can modify it or implement new one.

It also performs

- ✓ The calculation of upper bounds for an efficient generation of Sudakov-suppressed events
- ✓ The generation of hardest radiation, according to the POWHEG Sudakov
- ✓ The communication with a SMC program, either passing the generated events on-the-fly or storing them on a LesHouches events file.
- ✓ Simple standard analysis before and after shower and hadronization provided. Users can modify them or implement new ones.

THE POWHEG METHOD AND THE POWHEG−BOX

The POWHEG method had already been successfully tested in

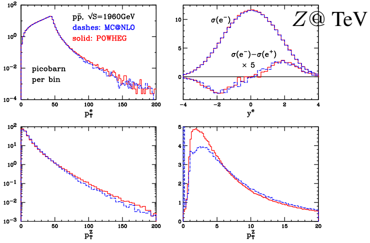
- $p \overset{(-)}{p} \to ZZ$ [Nason and Ridolfi,JHEP 0608:077,2006]
- $p \overset{(-)}{p} \to Q\bar{Q}\ ,\ \ Q = c, b, t$ with spin corr. [Frixione,Nason and Ridolfi,JHEP 0709:126,2007]
- $e^+e^- \to q\bar{q}$ [Latunde-Dada,Gieseke,Webber,JHEP 0702:051,2007]
  $e^+e^- \to t\bar{t}$ with NLO top decay [Latunde-Dada, Eur.Phys.J.C58:543-554,2008]
- $p \overset{(-)}{p} \to W'$ [Latunde-Dada and Papaefstathiou, arXiv:0901.3685]
- $p \overset{(-)}{p} \to H + V$ [Hamilton,Richardson and Tully, arXiv: 0903.4345]

The POWHEG−BOX is a package in evolution! Already available :

- $p \overset{(-)}{p} \to Z, W$ with spin correlations [S.A.,Nason,Oleari and Re,JHEP 0807:060,2008] HERWIG++ [Hamilton,Richardson and Tully, JHEP 0810:015,2008]

✗ $\sigma(q\bar{q}' \to W^\pm \to e^\pm \overset{(-)}{\nu_\ell}) = 0$ if $e \parallel q$

✓ Damping and introduction of remnants



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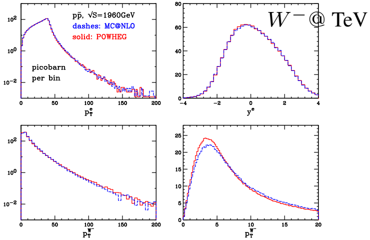

THE POWHEG-BOX: AVAILABLE PROCESSES

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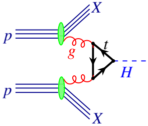
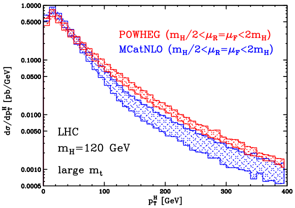


✗ $d\sigma_{\rm rad} \approx \frac{\bar{B}(\Phi_n)}{B(\Phi_n)} R(\mathbf{\Phi}_{n+1})\, d\mathbf{\Phi}_{n+1}$
$\approx \underbrace{\{1 + O(\alpha_S)\}}_{\approx 2 \text{ for } gg \to H} R(\mathbf{\Phi}_{n+1})\, d\mathbf{\Phi}_{n+1}$

✓ $R = \overbrace{R \times F}^{singular} + \overbrace{R \times (1 - F)}^{regular}$



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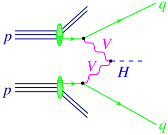

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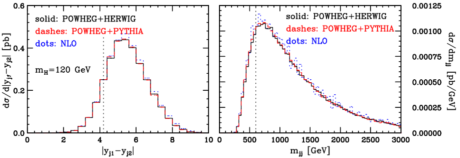

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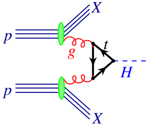

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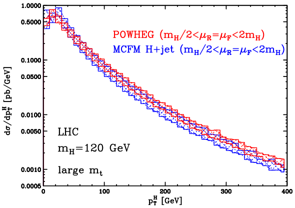

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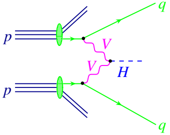

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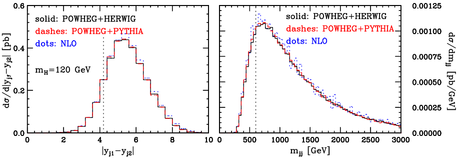

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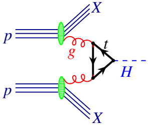

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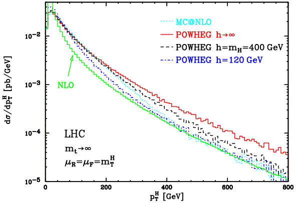

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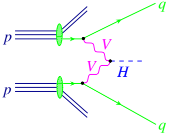

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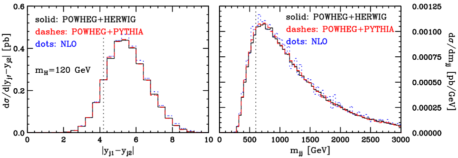

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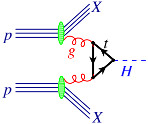

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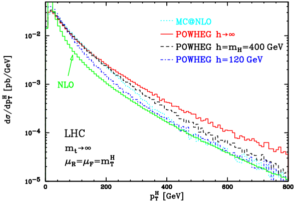

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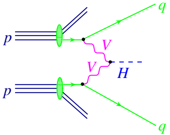

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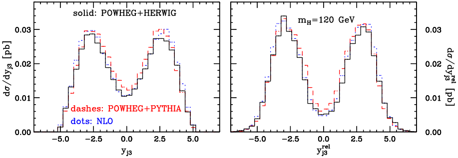
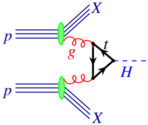


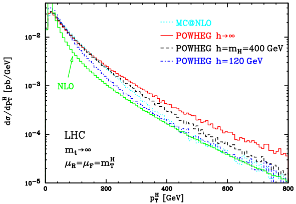
THE POWHEG-BOX: AVAILABLE PROCESSES

- $gg \to H$ [S.A.,Nason,Oleari,Re, JHEP 0904:002,2009]
  HERWIG++ [Hamilton,Richardson, Tully JHEP 0904:116,2009]

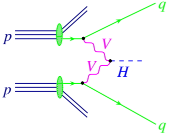


✗ $d\sigma_{\rm rad} \approx \frac{\bar{B}(\Phi_n)}{B(\Phi_n)} R(\mathbf{\Phi}_{n+1})\, d\mathbf{\Phi}_{n+1} \approx \underbrace{\{1 + O(\alpha_S)\}}_{\approx 2 \text{ for } gg\to H} R(\mathbf{\Phi}_{n+1})\, d\mathbf{\Phi}_{n+1}$

✓ $R = \overbrace{R \times F}^{singular} + \overbrace{R \times (1-F)}^{regular}$

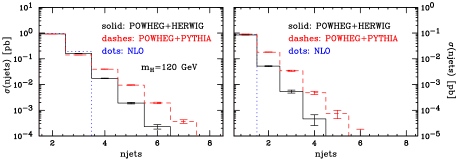


- $p\overset{(-)}{p} \to Hjj$ via WBF [Nason & Oleari JHEP 1002:037,2010]



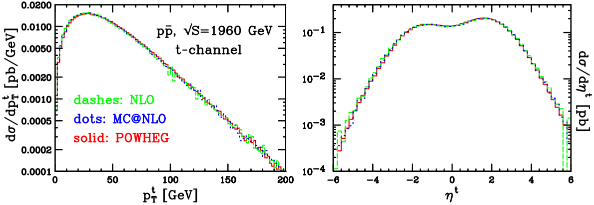
✗ POWHEG-BOX assumes graphs symmetrized w.r.t identical final state particles

✓ Tagging of parton lines

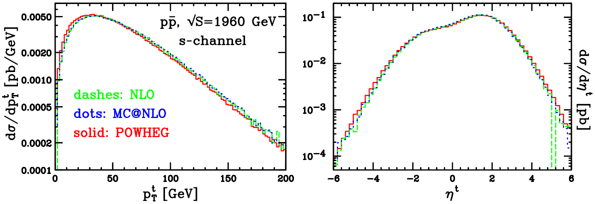


- $p \overset{(-)}{p} \to t + j$ (single top s and t-channel) [S.A.,Nason,Oleari and Re, JHEP 0909:111,2009]

- TeV, t-channel



- TeV, s-channel

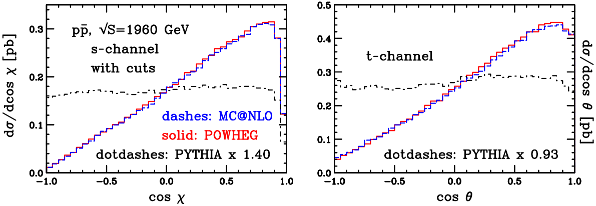


- Very good agreement with NLO and MC@NLO for inclusive quantities

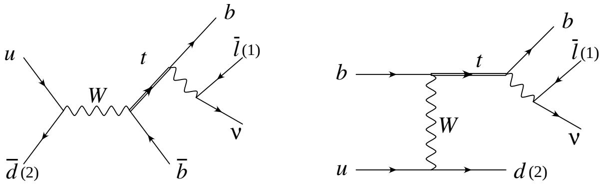
THE POWHEG−BOX: AVAILABLE PROCESSES

- $p\overset{(-)}{p} \to t + j$ (single top s and t-channel) [S.A.,Nason,Oleari and Re, JHEP 0909:111,2009]

- No NLO top decay, approx. spin correlations [Frixione et al. JHEP 0704:081,2007]

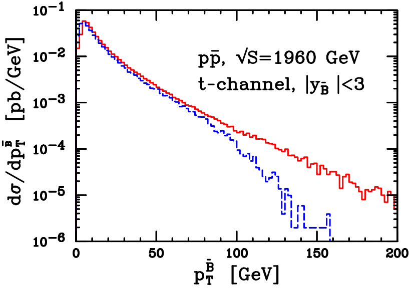


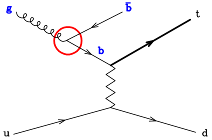
- Angles defined in top rest frame according to



- Cuts as in [hep-ph/0702198] to isolate leptons and an hardest central jet

- $p\overset{(-)}{p} \to t + j$ (single top s and t-channel) [S.A.,Nason,Oleari and Re, JHEP 0909:111,2009]

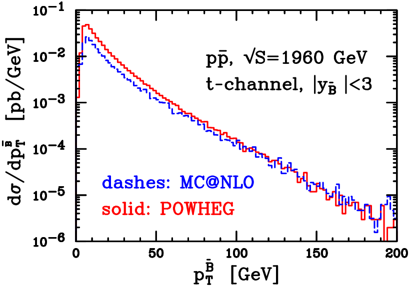


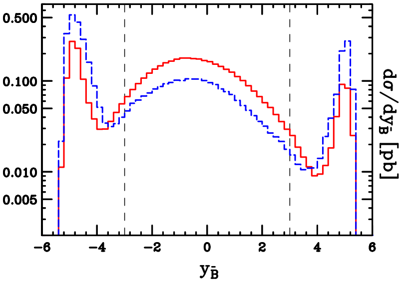


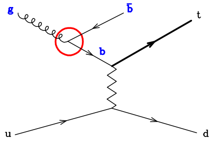
- ✗ Expected: in PYTHIA $g \to b\bar{b}$ only in the soft/coll. approximation (No ME corr. !)
- ✓ High$-p_{\rm T}$ agreement with MC@NLO
- ✗ No b mass in POWHEG & MC@NLO. Alternative: 4F$(2 \to 3)$ massive calculation of [Phys.Rev.Lett.102:182003,2009] + PS
- ✗ Known problem with initial-state heavy quarks in HERWIG. Fixed in HERWIG++

THE POWHEG-BOX: AVAILABLE PROCESSES

- $p\overset{(-)}{p} \to t + j$ (single top s and t-channel) [S.A.,Nason,Oleari and Re, JHEP 0909:111,2009]







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- ✗ Known problem with initial-state heavy quarks in HERWIG. Fixed in HERWIG++

THE POWHEG−BOX: Z PLUS JET

- Non trivial process definition because Born contributions are IR divergent
- 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. Accept $Z + 1\ jet$ as Born process only if $p_{\mathrm{T}}^{\mathrm{jet}} > p_{\mathrm{T}}^{\mathrm{Born}}$ Study the dependence of the results on this cutoff
- Merge consistently Z and $Z + 1\ jet$ samples, in order to obtain a description as smooth and accurate as possible.

How to build the merged sample :

✓ Pick a random event from the Z or $Z + 1\ jet$ samples according to the relative cross sections

✓ Shower and hadronize it with a chosen SMC program (HERWIG,PYTHIA)

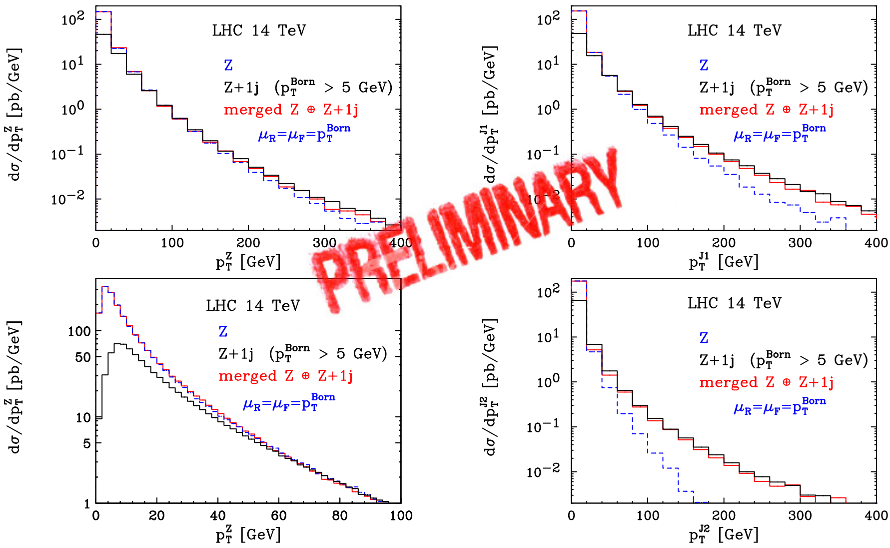
✓ Choose to retain the event according to a veto based on the $Z\ p_{\mathrm{T}}$ after shower and hadronization:

  - At high $p_{\mathrm{T}}(\gtrsim$ 30-40 $\mathrm{GeV})$ keep it only if it belongs to $Z + 1\ jet$ sample
  - At low $p_{\mathrm{T}}(\lesssim$ 10-12 $\mathrm{GeV})$ keep it only if it belongs to Z sample
  - In the intermediate region combine both with a smooth function

✗ If the veto is failed discard the event and pick another one

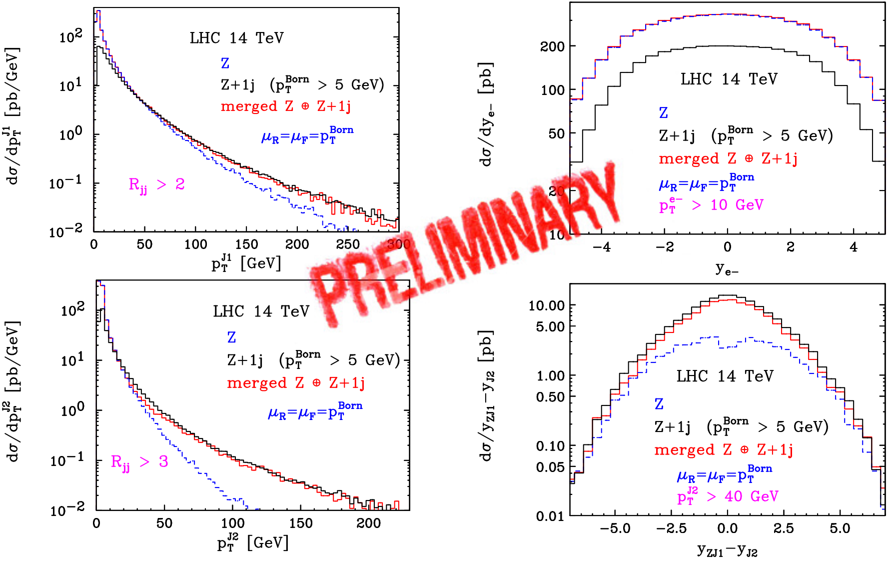
Merging Z and $Z+1$ jet samples

Results obtained with HERWIG shower & hadronization



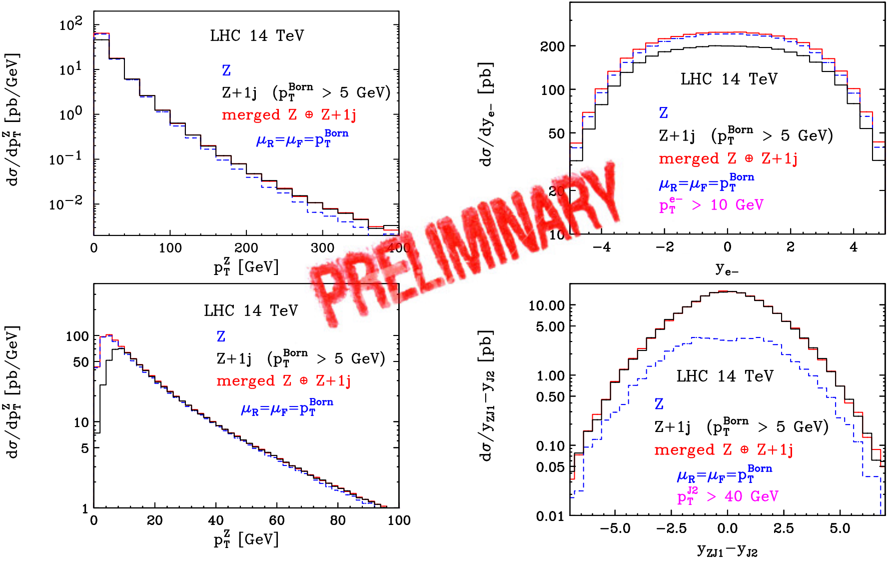
MERGING Z AND $Z + 1$ jet SAMPLES

Results obtained with HERWIG shower & hadronization



Merging Z and $Z + 1$ *jet* samples

Results obtained with PYTHIA shower & hadronization



CONCLUSIONS AND OUTLOOK

- POWHEG proved to be a valid method for implement NLO corrections in SMC's. SMC independent and with positive weighted events only
- A general framework, named POWHEG-BOX, for implementing an arbitrary process in the FKS subtraction approach has been released and is publicly available!
- Several process already implemented: single vector boson, Higgs via gluon and weak boson fusion, single top, heavy quarks
- $Z + jet$ production ready, merging with Z sample and comparison with D0 and CDF data in progress

Outlook :

- Single-top in the Wt channel (Re)
- MSSM $H^{\pm}t$ associated production (Weydert, Kovarik, Klasen, Nason)
- $W + jet$, $t\bar{t} + jet$, di-jet are next targets for the POWHEG − BOX.
- New problems may show up! So far the POWHEG method proved to be flexible enough to face them !
- Merging NLO+PS with ME corrections.

Thank you for your attention!

EXTRA SLIDES

NLO ACCURACY OF POWHEG FORMULA (1)

- Use the POWHEG formula

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

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

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

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

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

- 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

$$\int_{p_T^{\min}} d\Phi_{\rm rad} \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Delta(\Phi_n, k_T) \; = \; \int_{p_T^{\min}}^{\infty} dp'_T \int d\Phi_{\rm rad}\, \delta(k_T - p'_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Delta(\Phi_n, p'_T)$$

$$= - \int_{p_T^{\min}}^{\infty} dp'_T \Delta(\Phi_n, p'_T) \frac{d}{dp'_T} \int_{p_T^{\min}} d\Phi_{\rm rad}\, \theta(k_T - p'_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)}$$

$$= \int_{p_T^{\min}}^{\infty} dp'_T \frac{d}{dp'_T} \Delta(\Phi_n, p'_T) \; = \; 1 - \Delta(\Phi_n, p_T^{\min})$$

- Furthermore we can replace $\bar{B}(\Phi_n) \approx B(\Phi_n)\,(1 + \mathcal{O}(\alpha_S))$
- and also $\Delta(\Phi_n, k_T) \approx 1 + \mathcal{O}(\alpha_S)$ since $[O_{n+1} - O_n] \to 0$ at small k_T's
- The final result is (up to $p_T^{\min}$ power-suppressed terms)

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

$$d\sigma_{\texttt{MC@NLO}} = \overbrace{\bar{B}_{\texttt{SMC}}(\Phi_n)}^{\texttt{MC@NLO}}\, d\Phi_n \overbrace{\left\{\Delta_{\texttt{SMC}}(t_0) + \Delta_{\texttt{SMC}}(t)\frac{R_{\texttt{SMC}}(\Phi_n,\Phi_{\rm rad}^{\texttt{SMC}})}{B(\Phi_n)}\, d\Phi_{\rm rad}^{\texttt{SMC}}\right\}}^{\texttt{SMC}}$$

$$+ \underbrace{\left[R(\Phi_n,\Phi_{\rm rad}^{\texttt{SMC}}) - R_{\texttt{SMC}}(\Phi_n,\Phi_{\rm rad}^{\texttt{SMC}})\right]}_{\texttt{MC@NLO}} d\Phi_n\, d\Phi_{\rm rad}^{\texttt{SMC}}$$

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

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

- ✓ NLO accuracy for IR safe observables
- ✓ Exclusive observables are described no worse than in usual (N)LL SMC's
- ✗ Dependence of PS algorithm. Need to express NLO calulation in $\Phi_{\rm rad}^{\texttt{SMC}}$ variables
- ✗ $R - R_{\texttt{SMC}}$ not singular only if $R_{\texttt{SMC}}$ reproduces exactly all the singularities of R. Issue: azimuthal dependence of collinear sing. usually neglected in $R_{\texttt{SMC}}$.
- ✗ $\bar{B}_{\texttt{SMC}}$ may be negative ! Negative weighted events

MC@NLO DIP IN HARDEST RADIATION

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

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

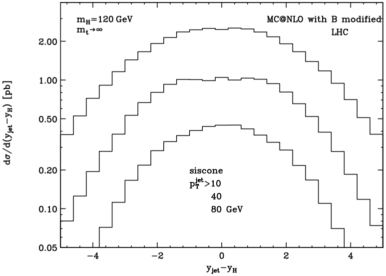
$$\bar{B}_{\texttt{HW}}(\Phi_n) = B(\Phi_n)+V(\Phi_n)+\int\left[R_{\texttt{HW}}(\Phi_n,\Phi_{\rm rad})-C(\Phi_n,\Phi_{\rm rad})\right]\,d\Phi_{\rm rad}$$

At high $p_{\rm T}$ the cross section goes as

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

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

The dip seems to disappear



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

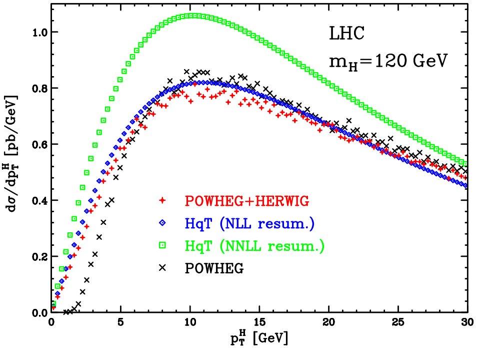
$$A(\alpha_S) = \alpha_S \left\{1 + \frac{\alpha_S}{2\pi}\left[\left(\frac{67}{18} - \frac{\pi^2}{6}\right)C_A - \frac{5}{9}n_f\right]\right\}$$

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]

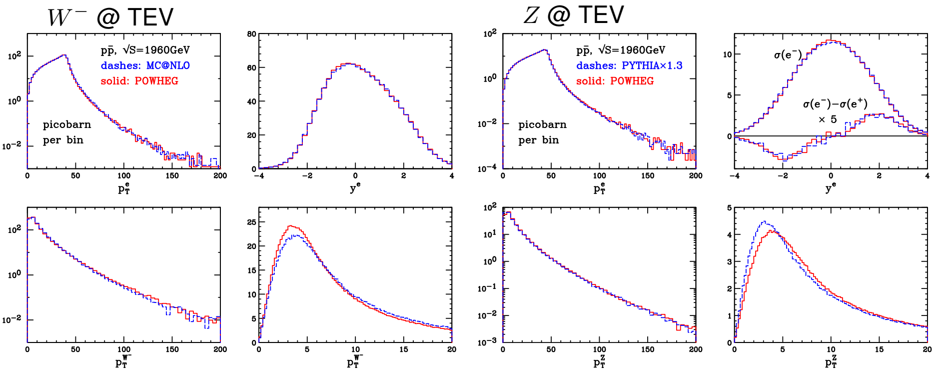
For > 3 coloured partons, soft NLL contributions exponentiates only in a matrix sense

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

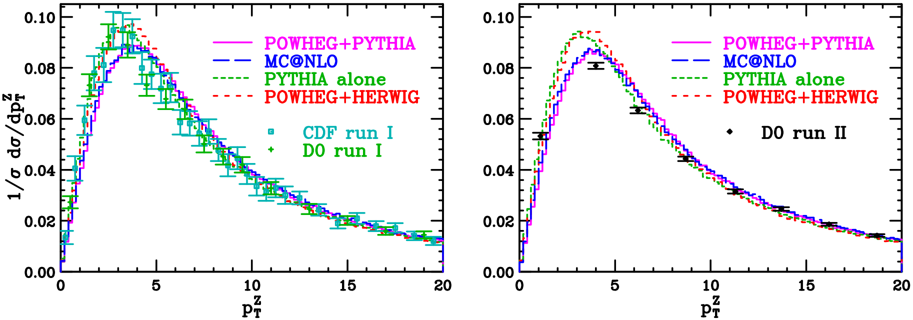
Comparison with HqT program [Bozzi,Catani,de Florian and Grazzini, Nucl.Phys.B737] $\Rightarrow$



SINGLE VECTOR BOSON PRODUCTION AND DECAY - TEVATRON RESULTS



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

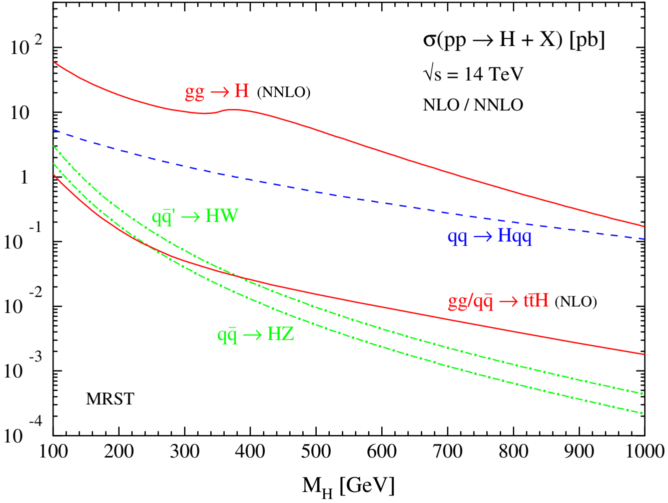


- Interesting processes for luminosity measurements, to estimate SM background to new physics,etc. Very clean signal thanks to decay modes $Z \to \ell^+\ell^-$
- Intrinsic p_T 2.5 GeV
- POWHEG+PYTHIA $\sim$ MC@NLO POWHEG+HERWIG $\sim$ PYTHIA
- Sensitivity to long distance effects: hadronization model and p_T smearing

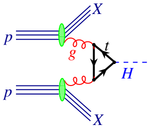
$\Downarrow$

Sensible parameter tuning needed to fully accommodate data

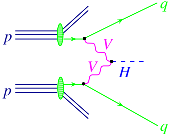
Higgs boson production at the LHC



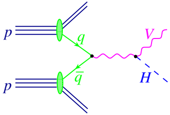
Gluon fusion



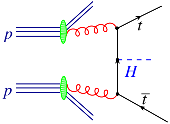
Weak-Boson Fusion



Higgs Strahlung



Associated $t\bar{t}H$



Gluon fusion - Outline of calculations

- Lowest order process is loop induced

$$\mathcal{B}_{gg} = \frac{\alpha_S^2}{\pi^2}\frac{G_F\,M^2}{576\sqrt{2}}\left|\frac{3}{2}\sum_Q \tau_Q\Big[1+(1-\tau_Q)f(\tau_Q)\Big]\right|^2 , \qquad \tau_Q = 4m_Q^2/M^2$$

where the sum runs over the heavy flavours circulating in the loop (only top quark in our analysis). The function f is given by

$$f(\tau_Q) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau_Q}} & \tau_Q \geq 1\,, \\ -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{(1-\tau_Q)}}{1-\sqrt{(1-\tau_Q)}}\right) - i\pi\right]^2 & \tau_Q < 1. \end{cases}$$

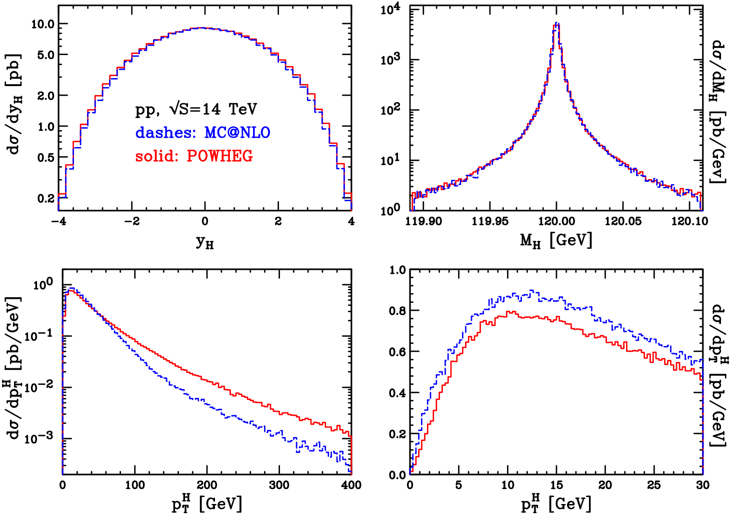
- Width is rapidly increasing with mass. $\delta(M^2 - m_H^2) \rightarrow \frac{1}{\pi}\frac{M^2\,\Gamma_H/m_H}{(M^2-m_H^2)^2+(M^2\,\Gamma_H/m_H)^2}$
- We retain full m_t dependence at L0, $m_t \rightarrow \infty$ approximation for NLO via

$$\mathcal{L}_{eff} = -\frac{\alpha_S}{12\pi v} H G_a^{\mu\nu} G_{\mu\nu}^a \left[1 + \frac{11}{4}\frac{\alpha_S}{\pi} + \mathcal{O}(\alpha_S^2)\right] , \qquad v = (\sqrt{2}G_F)^{-\frac{1}{2}} = 246 \text{ GeV}$$

Good approx. even over $t\bar{t}$ threshold $\Rightarrow$ Bulk of NLO corr. due to collinear/soft gluons
$\Rightarrow$ Breaks down in presence of high-p_T jet(s)

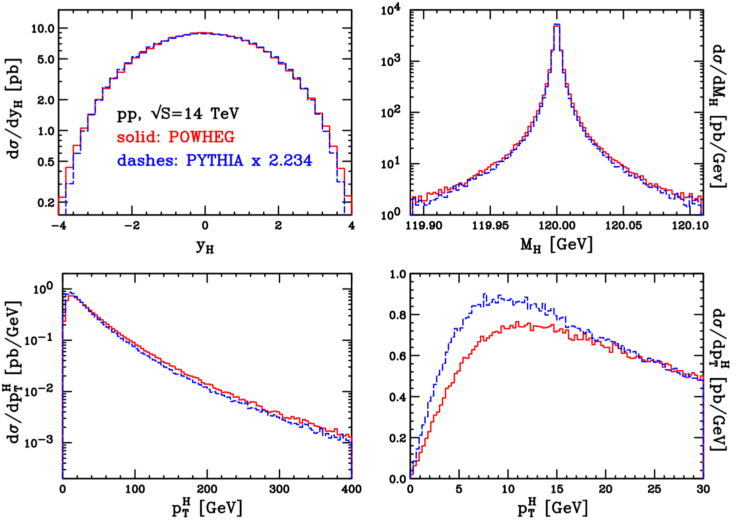
- Subtraction perfomed in FKS framework $\Rightarrow$ Coll. and soft limits of real matrix elements are used to regulate IR divergent real contributions by means of $()_+$ distributions

HIGGS BOSON PRODUCTION AT THE LHC - $gg \to H$



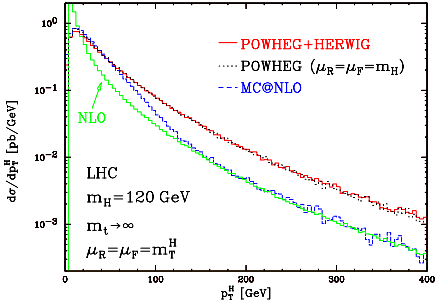
Differences in high (MC@NLO) and low-p_{T} (PYTHIA) regions at the LHC.

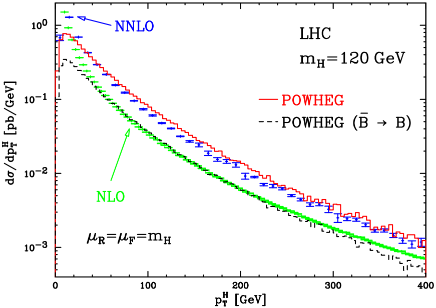
HIGGS BOSON PRODUCTION AT THE LHC - $gg \to H$



Differences in high (MC@NLO) and low-p_{T} (PYTHIA) regions at the LHC.

HIGGS BOSON HIGH$-p_T$ BEHAVIOUR





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

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

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

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

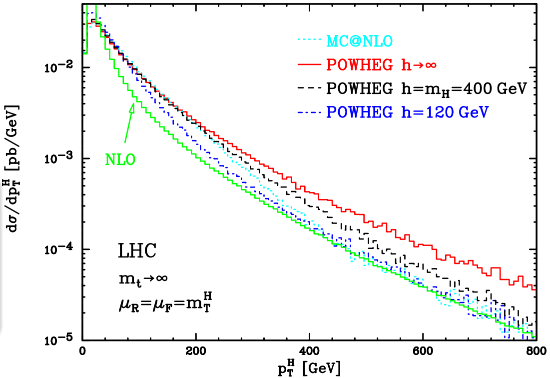
$F < 1, \quad F \to 1$ when $p_{\text{T}} \to 0$,
$F \to 0$ when $p_{\text{T}} \to \infty$

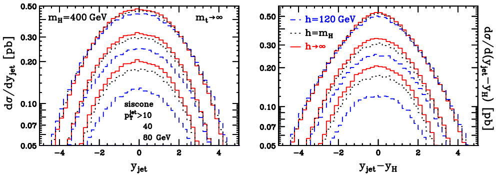
$$\Rightarrow F = \frac{h^2}{p_T^2 + h^2}$$

$$\sigma = \sigma_{\bar{B}} + \sigma_{\text{reg}}$$

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

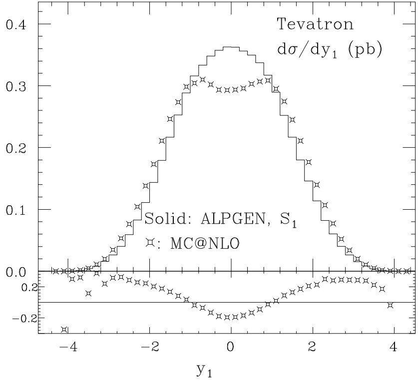
$$\sigma_{\text{reg}} = \int R_{\text{reg}}(\Phi_n, \Phi_{\text{rad}})\, d\Phi_n\, d\Phi_{\text{rad}}$$

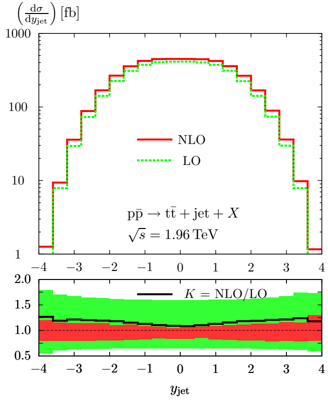




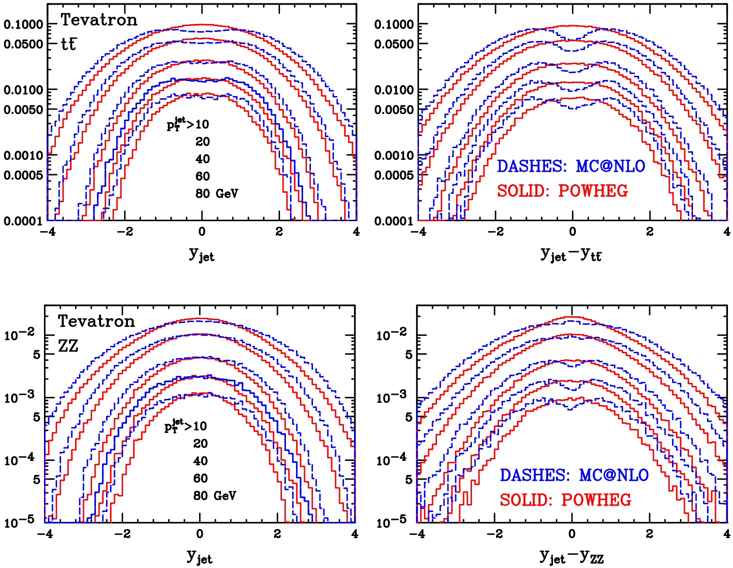
HARDEST JET RAPIDITY DIP

- 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 $p\bar{p} \to t\bar{t} + jet$ shows no dip too
  [Dittmaier,Uwer and and Weinzierl, arXiv:0810.0452]

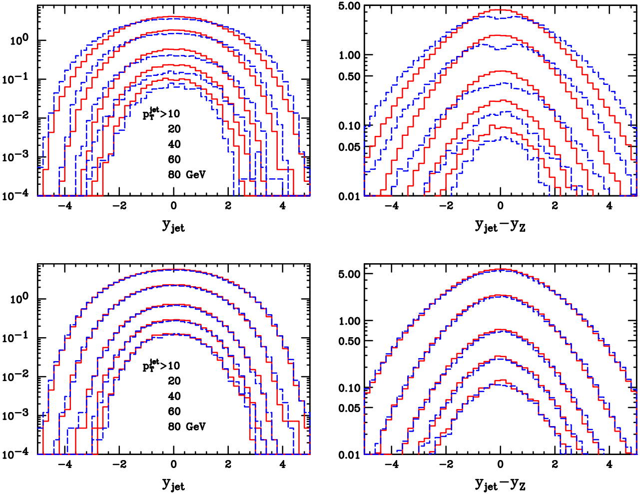




Hardest jet rapidity and rapidity difference



HARDEST JET - Z RAPIDITY DIFFERENCE @ TEV



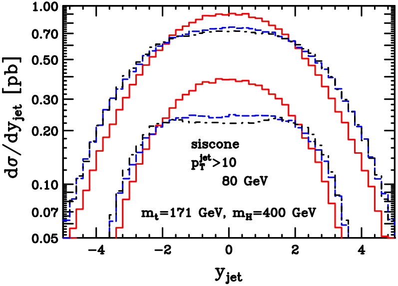
POWHEG + HERWIG

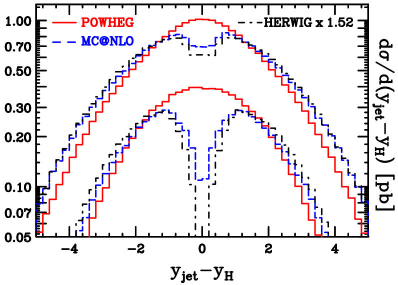
MC@NLO

POWHEG + PYTHIA

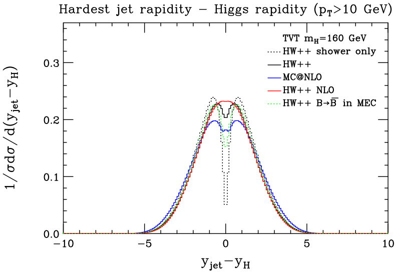
PYTHIA × 1.3

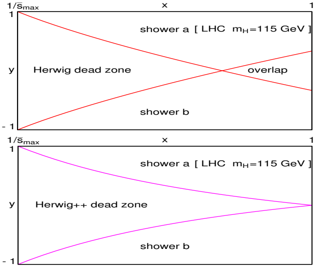
HARDEST JET - HIGGS BOSON RAPIDITY DIFFERENCE



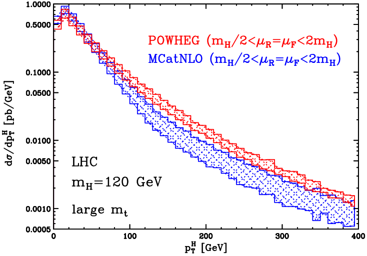


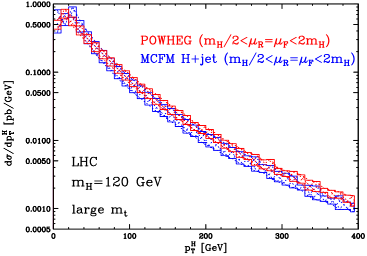
- Similar results from Hamilton, Richardson and Tully [ArXiv:0903.4345]

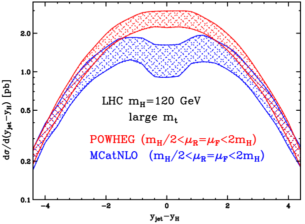


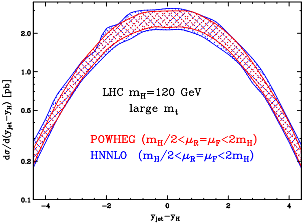


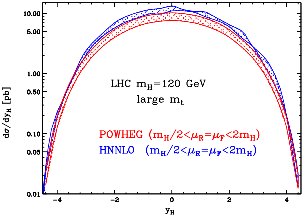
SCALES DEPENDENCE











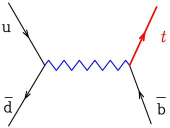
- NNLO results obtained using HNNLO [Catani and Grazzini, arXiv:0802.1410]

SINGLE TOP PRODUCTION

- *Single-Top* production is the EW production of a *top* quark without its antiparticle
- Production channels are classified according to the virtuality of the vector boson involved

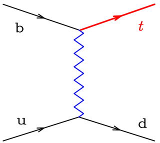
s-CHANNEL

- Predominant at TeV, negligible at LHC
- Sensible to new physics (W' exchange)



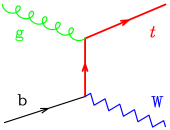
t-CHANNEL

- Dominant both at TeV and LHC
- Direct constraint on b *pdf* (otherwise generated via perturbative evolution)



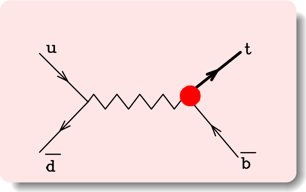
Wt ASSOCIATED PRODUCTION

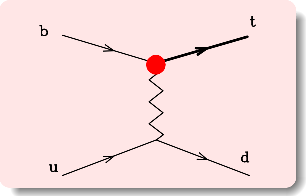
- Negligible at TeV, but relevant at LHC
- Non-trivial definition of NLO corrections (interference with $t\bar{t}$ production, if $\bar{t} \to W\bar{b}$)

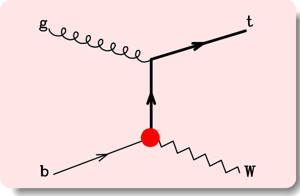


Single Top production

- All channels allow V_{tb} to be measured without assuming unitarity of CKM (V_{tb} in a production process)



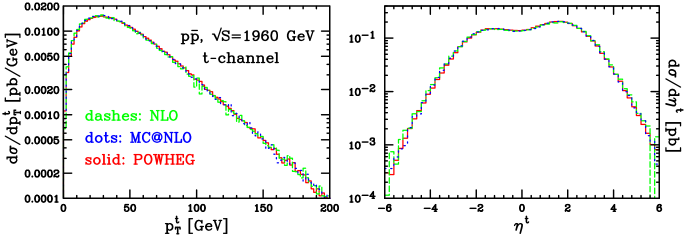




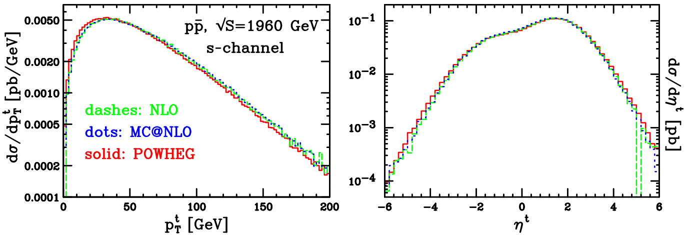
- Direct probe of V-A structure of weak interactions via spin correlation effects
  - $\Rightarrow$ *top*-quark decays before hadronizing
  - $\Rightarrow$ Only left-handed charged current involved
- First `POWHEG` implementation with both ISR and FSR
  - $\Rightarrow$ Simplest because LO is finite without cuts (EW process)
- FKS subtraction scheme adopted
- Only *top*-quark considered massive $\Rightarrow b$ massless, 5-flavour *pdf*s
- Up to now only s- and t-channels implemented
- *A posteriori* inclusion of *top* decay, including spin correlation effects

Results for Single Top: POWHEG vs. MC@NLO vs. NLO

- TeV, t-channel

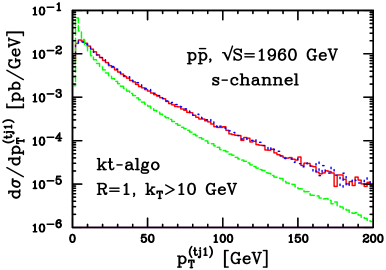


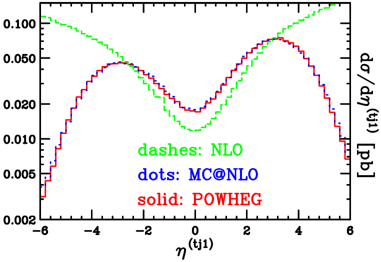
- TeV, s-channel



- Very good agreement with NLO and MC@NLO for inclusive quantities

RESULTS FOR SINGLE TOP: POWHEG VS. MC@NLO VS. NLO





- Sudakov suppression for ISR and FSR in more exclusive quantities
- Difference in the (tj_1) high-$p_{\rm T}$ tail due to the $p_{\rm T}$ imbalance from multiple emissions and to the *top*-jet clustering
- Relative momentum inside the hardest jet

$$p_{\rm T}^{\rm rel} = \sum_{i \in j_1} \frac{\left| \vec{k}_i \times \vec{p}_{j_1} \right|}{|\vec{p}_{j_1}|}$$

in the $y_{j_1} = 0$ frame