

Single-top production in the POWHEG formalism

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Sestri Levante, 8 June 2009

OUTLINE

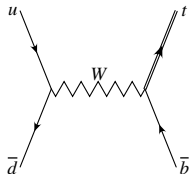
- (Quick) introduction on single-top hadroproduction
- (Some) details on the POWHEG implementation
- POWHEG results and comparisons with existing codes
- Top decay generation
- Conclusions

Aim: Show, with an example, how an implementation of a NLO calculation is included in the POWHEG scheme

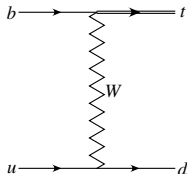
INTRODUCTION: PRODUCTION CHANNELS

Single-top production modes are classified with respect to the virtuality of the W boson involved: at the *leading* order we have

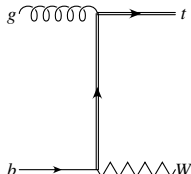
s-channel



t-channel



Wt-channel

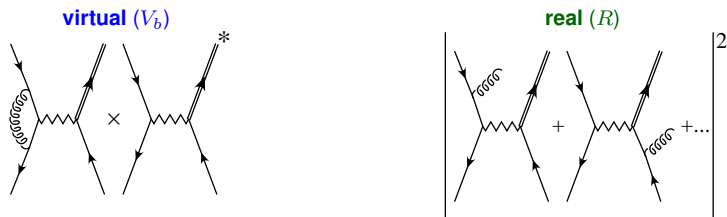


- relatively large at TeV, small at LHC
- **sensible to a new intermediate particle (W')**
 - All channels are relevant for a **direct measure of V_{tb}** (in a production process)
 - Top quarks are produced polarized \rightarrow direct probe of V-A structure of weak interactions \rightarrow angular correlations
 - with $Z + 1$ jet, it is the 1st in POWHEG with **both initial & final** state singularities (Born graphs have a massless outgoing leg)
- dominant at TeV and LHC
- **constrain b pdf** (up to now calculated)
- negligible at TeV but not at LHC
- non trivial definition of NLO corrections

In this talk, **ONLY** s and t -channel

NLO CORRECTIONS (1/3)

To calculate the NLO cross section, one needs real and virtual corrections:



Cancellation of soft and collinear singularities is taken into account with a subtraction scheme:

$$d\sigma_{NLO} = d\Phi_2 \underbrace{\left\{ B(\Phi_2) + V(\Phi_2) + [R(\Phi_3) - C(\Phi_3)] d\Phi_r \right\}}_{\bar{B}(\Phi_2)}$$

where

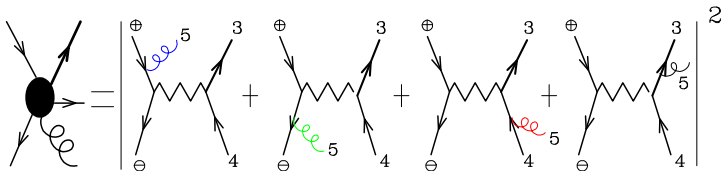
$$d\Phi_3 = d\Phi_2 d\Phi_r \quad , \quad V(\Phi_2) \equiv V_b(\Phi_2) + \int d\Phi_r C(\Phi_2, \Phi_r) .$$

C and Φ_r parametrization have to be chosen such that

- ① $R \rightarrow C$ when soft or collinear limit is approached $\Rightarrow \int d\Phi_r (R - C)$ is **finite**
- ② $\int d\Phi_r C$ is analytically computable \Rightarrow exact cancellation of IR poles $\Rightarrow V$ is **finite**

NLO CORRECTIONS (2/3)

As example, consider single-top s-channel $q\bar{q}$ real corrections:



$R_{q\bar{q}}$ is singular when

$$(k_5 k_{\oplus}) \rightarrow 0 \text{ (coll. } \oplus), (k_5 k_{\ominus}) \rightarrow 0 \text{ (coll. } \ominus), (k_5 k_4) \rightarrow 0 \text{ (coll. out)}$$

and when $k_5 \rightarrow 0$ (soft).

Frixione-Kunszt-Signer subtraction scheme:

- 1 Split $R_{q\bar{q}}$ into terms singular in *one region only*
- 2 Choose a parametrization of Φ_T suited for each region
→ use variables such that coll. and soft limits are **manifest**
- 3 Perform the subtraction using *plus distributions* in the coll. and soft variables
- 4 Add the integral of the subtracted terms to V_b
→ poles **cancel**

NLO CORRECTIONS (3/3)

- ① We split R as

$$R_{q\bar{q}} = R_{q\bar{q}}^{\oplus} + R_{q\bar{q}}^{\ominus} + R_{q\bar{q}}^{out}$$

where

$$R_{q\bar{q}}^{\oplus} = R_{q\bar{q}} \frac{d_{\oplus,5}^{-1}}{d_{\oplus,5}^{-1} + d_{\ominus,5}^{-1} + d_{4,5}^{-1}}, \quad R_{q\bar{q}}^{\ominus} = R_{q\bar{q}} \frac{d_{\ominus,5}^{-1}}{d_{\oplus,5}^{-1} + d_{\ominus,5}^{-1} + d_{4,5}^{-1}},$$

$$R_{q\bar{q}}^{out} = R_{q\bar{q}} \frac{d_{4,5}^{-1}}{d_{\oplus,5}^{-1} + d_{\ominus,5}^{-1} + d_{4,5}^{-1}} \quad \text{and } d_{ij} = (k_i k_j).$$

- ② We parametrize Φ_r^{out} in terms of $\{\xi, y, \phi\}$: in the CM frame

$$k_5^0 = \xi \frac{\sqrt{s}}{2} \quad (\xi \rightarrow 0 \Rightarrow \text{soft}), \quad \cos(\vec{k}_5, \vec{k}_4) = y \quad (y \rightarrow 1 \Rightarrow \text{coll. out}).$$

Similarly for Φ_r^{in} , but variables have different meanings

- ③ The integral

$$\int d\Phi_r^{out}(\xi, y, \varphi) \left\{ \frac{1}{\xi} \left(\frac{1}{\xi} \right)_+ \left(\frac{1}{1-y} \right)_+ [\xi^2(1-y) R_{q\bar{q}}^{out}] \right\}$$

is **finite** ! Similarly for $R_{q\bar{q}}^{\oplus}$ and $R_{q\bar{q}}^{\ominus}$

Note that $[\xi^2(1-y) R_{q\bar{q}}^{out}]$ is NOT singular \rightarrow action of plus distribution is well defined

GENERATION OF HARDEST RADIATION (1/2)

- We have to generate the hardest emission according to the POWHEG master formula:

$$d\sigma_{POW} = \bar{B}(\Phi_2) d\Phi_2 \left\{ \Delta(k_T^{min}) + \Delta(k_T) \frac{R^{in}(\Phi_2, \Phi_r)}{B(\Phi_2)} d\Phi_r^{in} \theta(k_T^{in}(\Phi_3) - k_T^{min}) \right. \\ \left. + \Delta(k_T) \frac{R^{out}(\Phi_2, \Phi_r)}{B(\Phi_2)} d\Phi_r^{out} \theta(k_T^{out}(\Phi_3) - k_T^{min}) \right\}$$

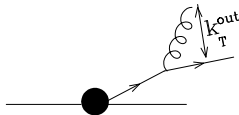
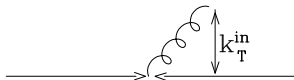
where the Sudakov form factors are

$$\Delta(k_T) = \Delta_{in}(k_T) \Delta_{out}(k_T)$$

$$\Delta_{in}(k_T) = \exp \left\{ - \int d\Phi_r^{in} \frac{R_{q\bar{q}}^{\oplus} + R_{gq} + R_{q\bar{q}}^{\ominus} + R_{qg}}{B} \theta(k_T^{in}(\Phi_3) - k_T) \right\}$$

$$\Delta_{out}(k_T) = \exp \left\{ - \int d\Phi_r^{out} \frac{R_{q\bar{q}}^{out}}{B} \theta(k_T^{out}(\Phi_3) - k_T) \right\}$$

and k_T 's in the Sudakov integral measure the radiation hardness for ISR or FSR. We choose



- We generate separately ISR and FSR (*highest k_T bid technique*)

GENERATION OF HARDEST RADIATION (2/2)

- The k_T of the real emission is distributed as the exact differential of the Sudakov factor. For FSR:

$$\text{Pr}_{out}(p_T) dp_T \equiv \left[\int d\Phi_r^{out} \Delta_{out}(k_T) \frac{R_{q\bar{q}}^{out}}{B} \delta(k_T(\Phi_3) - p_T) \right] dp_T = d\Delta_{out}(p_T)$$

To generate the radiation, we need to solve $\Delta_{out}(k_T) = r$ ($r \in [0, 1]$) with respect to k_T and then construct (at fixed k_T) the other radiation variables

- We can not perform the Sudakov integral analytically \rightarrow veto technique
- We choose a simple upper bounding function for the integrand R/B :

$$\frac{R^{out}(\Phi_2, \Phi_r)}{B(\Phi_2)} d\Phi_r \leq U^{out}(\xi, y) d\xi dy d\phi$$

$$U^{out}(\xi, y) = N^{out} \frac{\alpha_S(k_T^{out})}{\xi(1-y)}$$

- N^{out} is found by probing the radiation phase space

- 1 We generate k_T according to the differential of

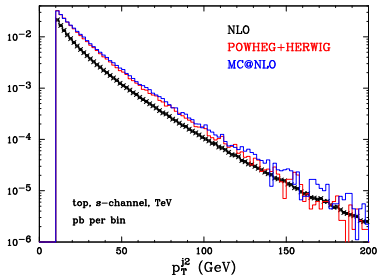
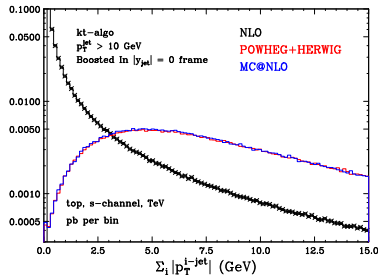
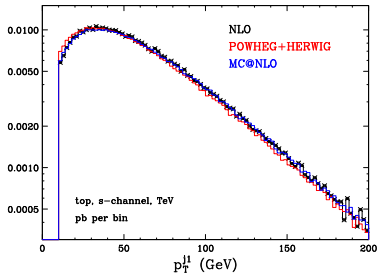
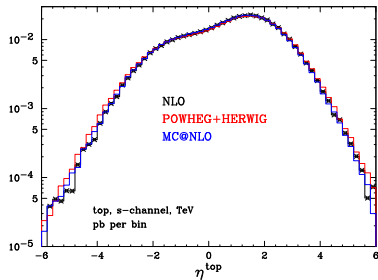
$$\Delta_{out}^U(k_T) = \exp \left[- \int U^{out}(\xi, y) d\xi dy d\phi \theta(k_T^{out}(\Phi_3) - k_T) \right]$$

- 2 We pick a random number r' and keep the generated kinematics if

$$r' < \frac{(R^{out}/B)}{U^{out}}$$

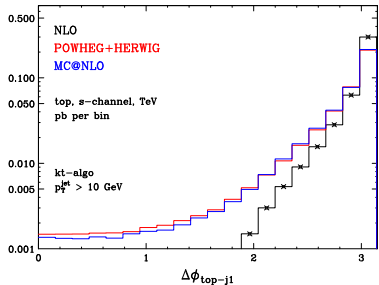
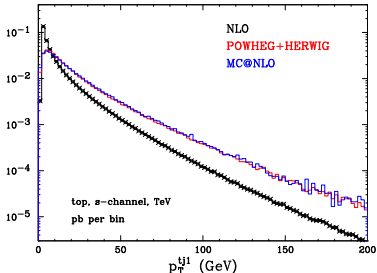
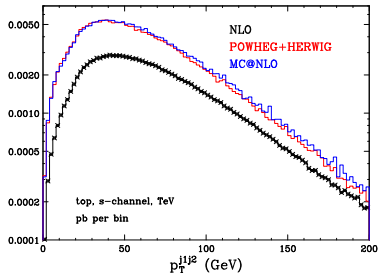
Otherwise we lower k_T

RESULTS: s -CHANNEL (1/2)



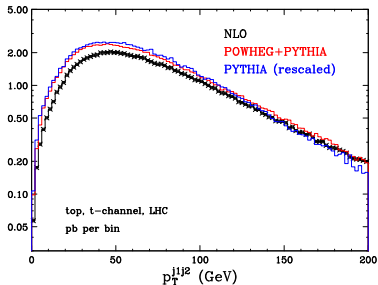
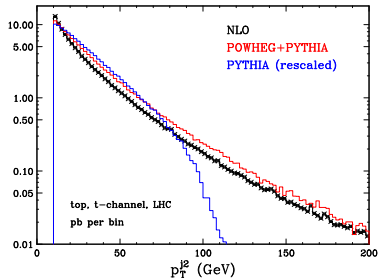
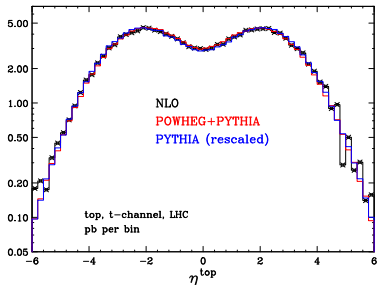
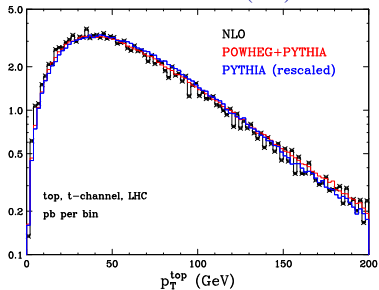
- Good agreement with NLO and MC@NLO for inclusive quantities
- Lower figures show expected differences with NLO

RESULTS: s -CHANNEL (2/2)



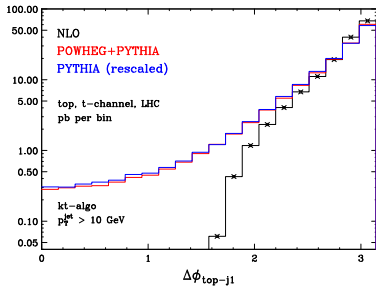
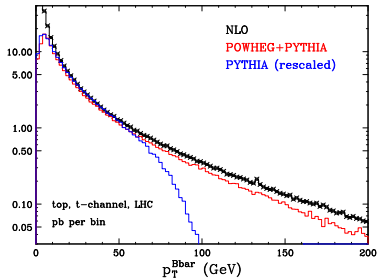
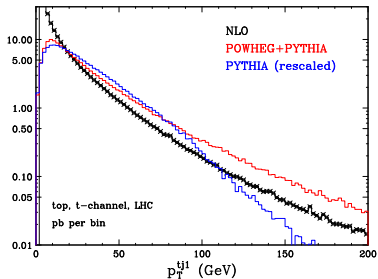
- Shape effects from shower multiple emissions
- Sudakov suppression at small values of p_T^{tj1} (vs. NLO divergence)
- Shower populates phase space regions that can not be filled by NLO calculation

RESULTS: t -CHANNEL (1/2)



- Good agreement with NLO and MC@NLO for inclusive quantities
- Effect of NLO matrix elements in p_T^{j2} : in PYTHIA, extra emissions **only in the collinear approximation**

RESULTS: t -CHANNEL (2/2)



- Shape effects from shower multiple emissions
- Sudakov suppression at small values of p_T^{tj1} and $p_T^{\bar{b}}$ (vs. NLO divergence)
- NLO matrix elements effects in $p_T^{\bar{b}}$: POWHEG includes $g \rightarrow b\bar{b}$ NOT ONLY in the collinear limit
- Shower populates phase space regions that can not be filled by NLO calculation

TOP DECAY

We can include angular correlation effects of top decay products as follows:

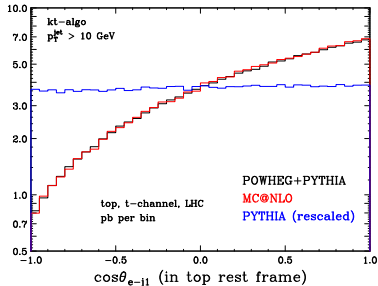
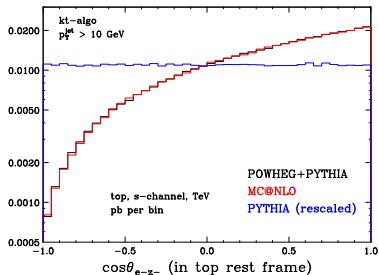
- We generate the decay products kinematics Φ_{dec} according to

$$d \Pr_{dec}(\Phi_{dec} \leftarrow \Phi_{undec}) = \frac{1}{\text{Br}} \frac{\mathcal{M}_{dec}(\Phi_{undec}, \Phi_{dec})}{\mathcal{M}_{undec}(\Phi_{undec})} d\Phi_{dec}$$

- We use again a veto technique:

$$\frac{\mathcal{M}_{dec}(\Phi_{undec}, \Phi_{dec})}{\mathcal{M}_{undec}(\Phi_{undec})} \leq N_{dec} U_{dec}(\Phi_{dec})$$

- Shapes are **in agreement** with MC@NLO. Large **differences** with respect to MC's that don't include these effects
- Loop effects in top decay are **NOT included**



CONCLUSIONS

- With single-top and $Z + 1jet$, the POWHEG method have been tested extensively
- POWHEG-BOX is almost ready to be released \rightarrow more users can implement NLO computations in this framework
- On the “experimental” side, POWHEG (as MC@NLO) can be used for realistic phenomenological studies (cuts effect, backgrounds estimate, signals isolation,...)