Stefano Frixione

Single-top theory

SM@LHC, Madrid, 10/4/2014

Thanks to: A. Papanastasiou, S. Prestel, P. Torrielli

As is the case for many other SM processes, there are two main classes of activities relevant to single top: increasing the purely-perturbative accuracy ($\longrightarrow$ NNLO, NLO+NLL), and improving the description of final states ($\longrightarrow$ NLO+PS)

I'll not even try to cover the former, since:

- I don't have the time
- I believe the scope of the latter is much broader, and more relevant to experimental analyses

Likewise, I'll not review the very significant and extensive literature on past parton-level results $\longrightarrow$

[5] B. W. Harris, E. Laenen, L. Phaf, Z. Sullivan and S. Weinzierl, *The fully differential single top quark cross section in next-to-leading order QCD*, *Phys. Rev.* **D66** (2002) 054024 [hep-ph/0207055].

[6] Z. Sullivan, *Understanding single-top-quark production and jets at hadron colliders*, *Phys. Rev.* **D70** (2004) 114012 [hep-ph/0408049].

[7] Z. Sullivan, *Angular correlations in single-top-quark and Wjj production at next-to-leading order*, *Phys. Rev.* **D72** (2005) 094034 [hep-ph/0510224].

[8] S. Zhu, *Next-to-leading order QCD corrections to $bg \to tW^-$ at the CERN Large Hadron Collider*, *Phys. Lett.* **B524** (2002) 283–288 [Erratum: *ibid* **B537** (2002) 351].

[9] J. Campbell, R. K. Ellis and F. Tramontano, *Single top production and decay at next-to-leading order*, *Phys. Rev.* **D70** (2004) 094012 [hep-ph/0408158].

[10] Q.-H. Cao and C. P. Yuan, *Single top quark production and decay at next-to-leading order in hadron collision*, *Phys. Rev.* **D71** (2005) 054022 [hep-ph/0408180].

[11] Q.-H. Cao, R. Schwienhorst and C. P. Yuan, *Next-to-leading order corrections to single top quark production and decay at Tevatron. 1: s-channel process*, *Phys. Rev.* **D71** (2005) 054023 [hep-ph/0409040].

[12] Q.-H. Cao, R. Schwienhorst, J. A. Benitez, R. Brock and C. P. Yuan, *Next-to-leading order corrections to single top quark production and decay at the Tevatron. 2: t-channel process*, *Phys. Rev.* **D72** (2005) 094027 [hep-ph/0504230].

[13] J. Campbell and F. Tramontano, *Next-to-leading order corrections to Wt production and decay*, *Nucl. Phys.* **B726** (2005) 109–130 [hep-ph/0506289].

and these do not include works on resummation...

[7] T. M. P. Tait, *The tW^- mode of single top production*, *Phys. Rev.* **D61** (2000) 034001 [arXiv:hep-ph/9909352].

[8] A. S. Belyaev, E. E. Boos and L. V. Dudko, *Single top quark at future hadron colliders: Complete signal and background study*, Phys. Rev. D **59** (1999) 075001 [arXiv:hep-ph/9806332].

[9] B. P. Kersevan and I. Hinchliffe, *A consistent prescription for the production involving massive quarks in hadron collisions*, JHEP **0609** (2006) 033 [arXiv:hep-ph/0603068].

[10] S. Zhu, *Next-to-leading order QCD corrections to $bg \to tW^-$ at the CERN Large Hadron Collider*, *Phys. Lett.* **B524** (2002) 283–288.

[11] J. Campbell and F. Tramontano, *Next-to-leading order corrections to Wt production and decay*, *Nucl. Phys.* **B726** (2005) 109–130 [arXiv:hep-ph/0506289].

[12] Q. H. Cao, *Demonstration of One Cutoff Phase Space Slicing Method: Next-to-Leading Order QCD Corrections to the tW Associated Production in Hadron Collision*, [arXiv:0801.1539 [hep-ph]].

[13] M. Beccaria *et. al.*, *A complete one-loop description of associated tW production at lhc and a search for possible genuine supersymmetric effects*, [arXiv:0705.3101 [hep-ph]].

[7] B. W. Harris, E. Laenen, L. Phaf, Z. Sullivan, and S. Weinzierl, *The Fully differential single top quark cross-section in next to leading order QCD*, *Phys. Rev.* **D66** (2002) 054024, [hep-ph/0207055].

[8] J. M. Campbell, R. K. Ellis, and F. Tramontano, *Single top production and decay at next-to-leading order*, *Phys. Rev.* **D70** (2004) 094012, [hep-ph/0408158].

[9] Q.-H. Cao, R. Schwienhorst, J. A. Benitez, R. Brock, and C. P. Yuan, *Next-to-leading order corrections to single top quark production and decay at the Tevatron: 2. t-channel process*, *Phys. Rev.* **D72** (2005) 094027, [hep-ph/0504230].

[10] J. Wang, C. S. Li, H. X. Zhu, and J. J. Zhang, *Factorization and resummation of t-channel single top quark production*, 1010.4509.

[11] N. Kidonakis, *Next-to-next-to-leading-order collinear and soft gluon corrections for t-channel single top quark production*, *Phys. Rev.* **D83** (2011) 091503, [1103.2792].

[12] P. Falgari, P. Mellor, and A. Signer, *Production-decay interferences at NLO in QCD for t-channel single-top production*, *Phys.Rev.* **D82** (2010) 054028, [1007.0893].

[13] P. Falgari, F. Giannuzzi, P. Mellor, and A. Signer, *Off-shell effects for t-channel and s-channel single-top production at NLO in QCD*, *Phys. Rev.* **D83** (2011) 094013, [1102.5267].

[14] M. Beccaria *et al.*, *A complete one-loop calculation of electroweak supersymmetric effects in t-channel single top production at LHC*, *Phys. Rev.* **D77** (2008) 113018, [0802.1994].

[15] J. M. Campbell, R. Frederix, F. Maltoni, and F. Tramontano, *Next-to-Leading-Order Predictions for t-Channel Single-Top Production at Hadron Colliders*, *Phys. Rev. Lett.* **102** (2009) 182003, [0903.0005].

[16] J. M. Campbell, R. Frederix, F. Maltoni, and F. Tramontano, *NLO predictions for t-channel production of single top and fourth generation quarks at hadron colliders*, *JHEP* **10** (2009) 042, [0907.3933].

[17] J. M. Campbell and R. K. Ellis, *Top-quark processes at NLO in production and decay*, 1204.1513.

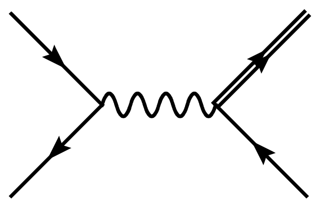
As is the case for many other SM processes, there are two main classes of activities relevant to single top: increasing the purely-perturbative accuracy ($\longrightarrow$ NNLO, NLO+NLL), and improving the description of the final states ($\longrightarrow$ NLO+PS)

I'll not even try to cover the former, since:

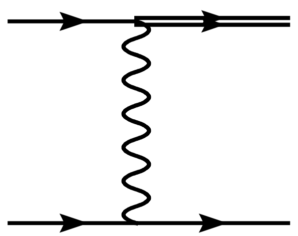
- I don't have the time
- I believe the scope of the latter is much broader, and more relevant to experimental analyses

Rather, I'll limit myself to recalling the basic physics ideas, and discuss some issues that may become relevant in the future

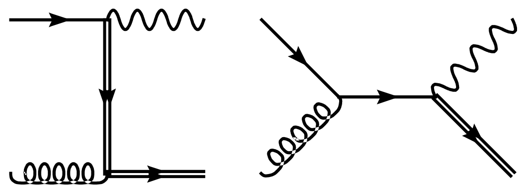
Production channels



s channel



t channel



Wt channel

The separation of the channels is based on the W virtuality.
It is naive at best, and strictly speaking plain wrong

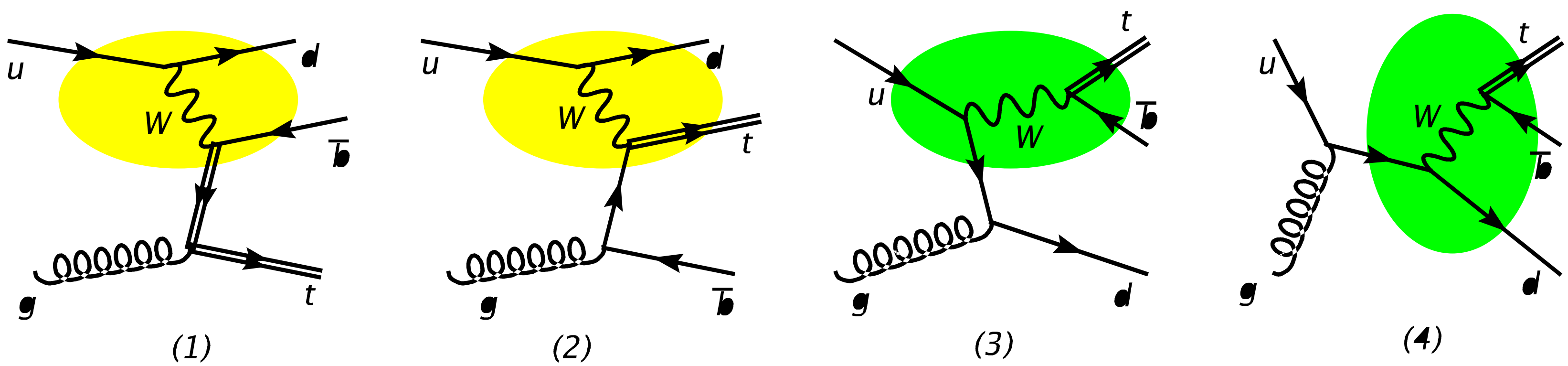
To put it simply: the idea of the separation is based on an amplitude-level idea. For it to be solid, it would need to be formulated at the level of squared amplitudes (i.e. of measurable quantities).
It is working OK at the LO, just because amplitudes do not interfere

Still, it does not make sense to all orders: this LO-inspired approach breaks down when higher orders are considered

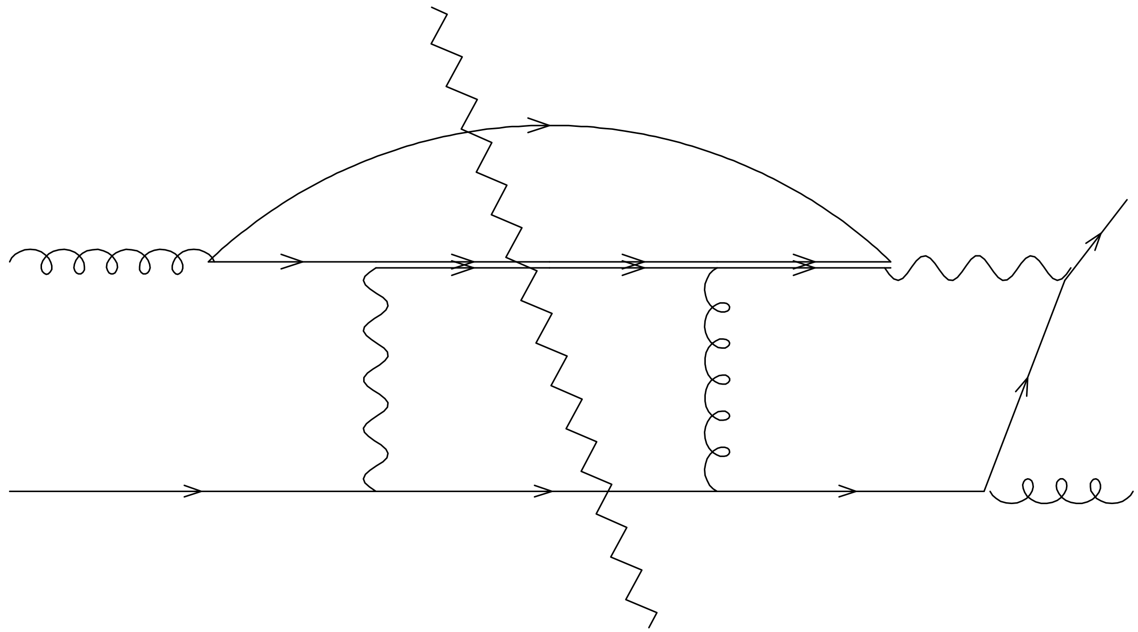
It is sort of fine in the case of Wt production (at least as long as one deals with *stable* t's and W's). Which is not much, since Wt production is not well defined beyond LO

s and t channels at the NLO

Take $ug \longrightarrow t\bar{b}d$:



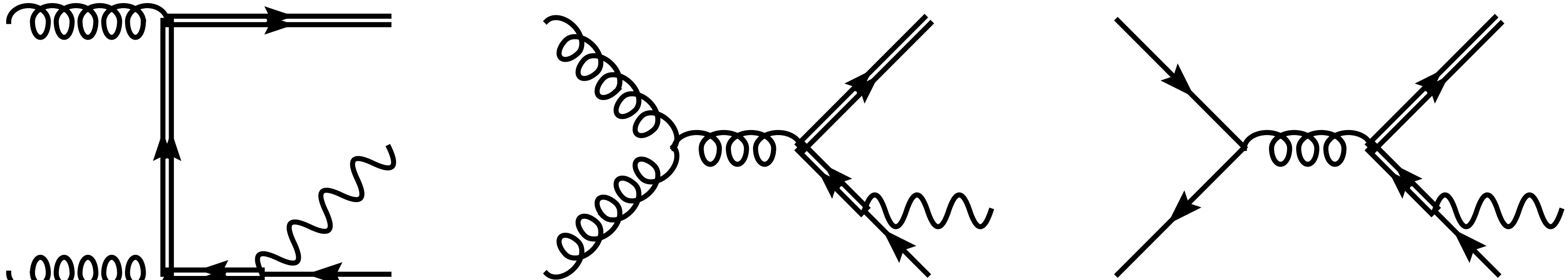
- Same initial and final states: s- and t-channel contributions interfere
- The day is saved by the fact that the interference is zero $(\mathrm{Tr}(\lambda^a) = 0)$
- At the next order, this is not longer the case



(this is a cut diagram: a t-channel amplitude on the left interferes with an s-channel amplitude on the right)

- We need not be too strict: just bear in mind that the separation between s and t channels is unphysical
- It can be given an operative meaning in perturbation theory, which clarifies immediately that it is of utmost importance to be conservative with theoretical systematics

As for Wt...



One just can't tell whether these diagrams are relevant to $t\bar{t}$ (with the t decay not drawn) or to Wt production

- $t\bar{t}$ and Wt production *interfere* at $\mathcal{O}(\alpha_W \alpha_S^2)$

Again, Wt production can be defined only in an operative manner
(Laenen, Motylinski, Webber, White, SF, 2008) $\longrightarrow$

DR: *Diagram removal:* eliminate all doubly-resonant diagrams

DS: *Diagram subtraction:* subtract locally $t\bar{t}$ contributions

PR: *Process removal:* do not include the contributions from processes which interfere with $t\bar{t}$

DR: Violation of gauge invariance. Very naive estimate:
$\Gamma_t^2 m_t^2/(m_t^2 - m_b^2)^2 \simeq 7 \cdot 10^{-5}$

DS: Restores gauge invariance, but does so by means of a procedure which is arbitrary. Error estimate similar to that for DR

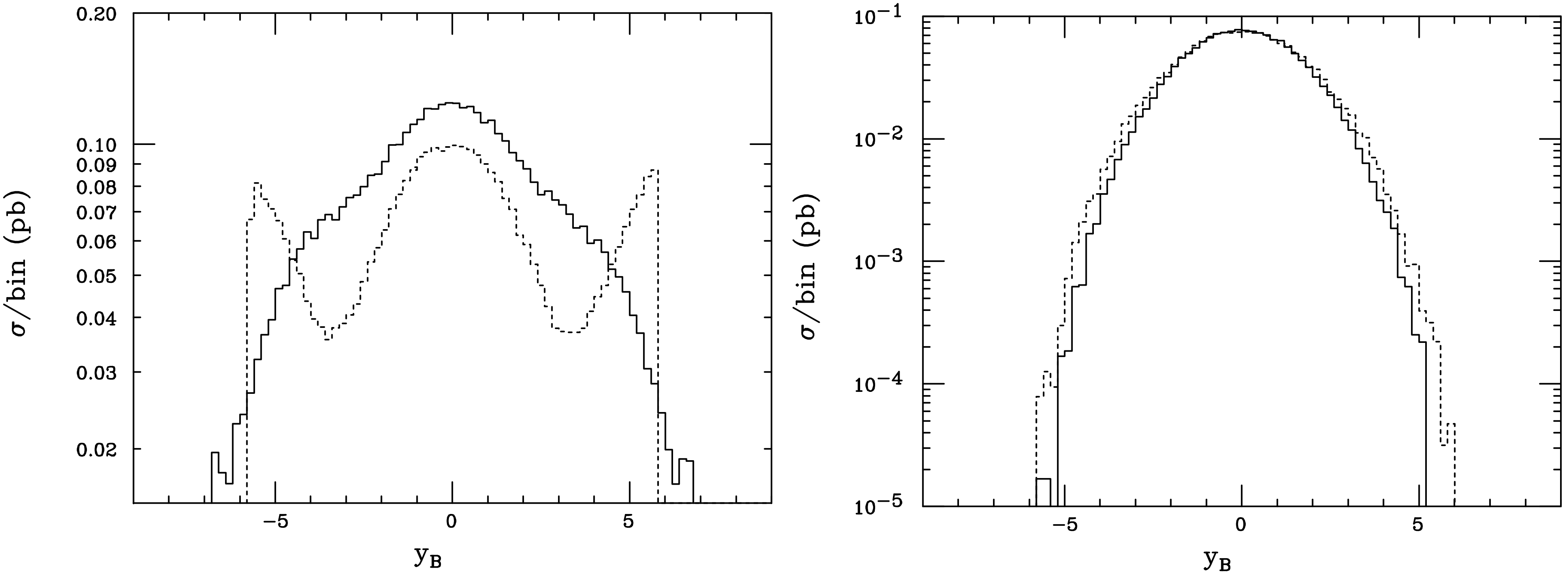
PR: Violation of renormalization group invariance. Leftover terms are not logarithmically enhanced, and can be estimated within a given NLO subtraction scheme

PR not suitable. DR and DS implemented in MC@NLO and POWHEG

Wt is meaningful *only* if DR−DS is small

This is the only way out if one doesn't want to compute $WWb(b)$

More troubles – t channel at NLO+PS

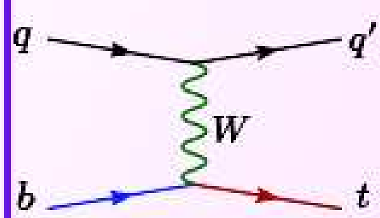


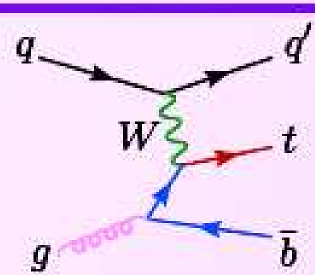
MC@NLO/HW++ (solid), MC@NLO/HW6 (dashed)

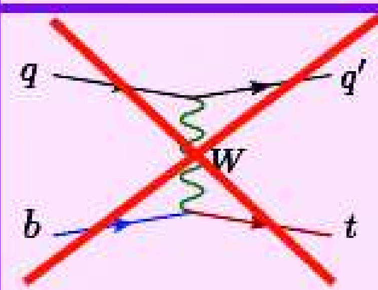
all p_T's (left), $p_T > 10$ GeV (right)

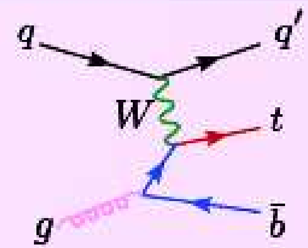
- Unphysical behaviour due to $bg \longleftarrow b$ HW6 backward evolution
- Disappears in tagging region, but nonetheless unpleasant, and the signal of a deficiency in the theoretical description

2 ways of making predictions

<table>
<tr><th colspan="2">5 flavour scheme</th><th colspan="2">4 flavour scheme</th></tr>
<tr><td colspan="2">massless b</td><td colspan="2">massive b</td></tr>
<tr><td colspan="2">PDF includes initial state b quarks</td><td colspan="2">No b quarks in PDF</td></tr>
<tr><td colspan="2">$\mathrm{Log}[m_b/\mu_F]$ resummed in PDF</td><td colspan="2">Finite terms correctly included</td></tr>
<tr><td colspan="2">Simpler calculation</td><td colspan="2">More involved prediction</td></tr>
<tr>
<td>

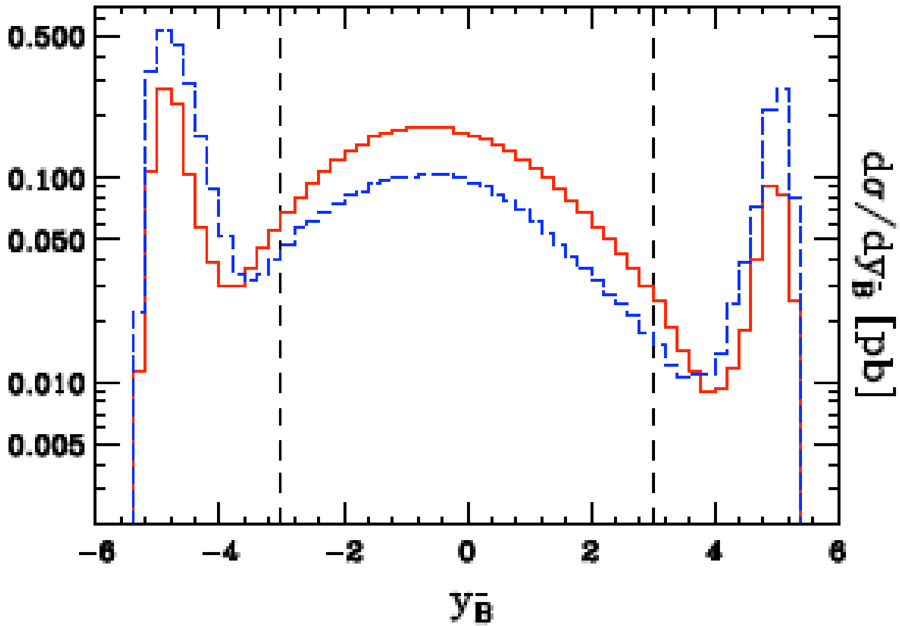
leading order</td>
<td>

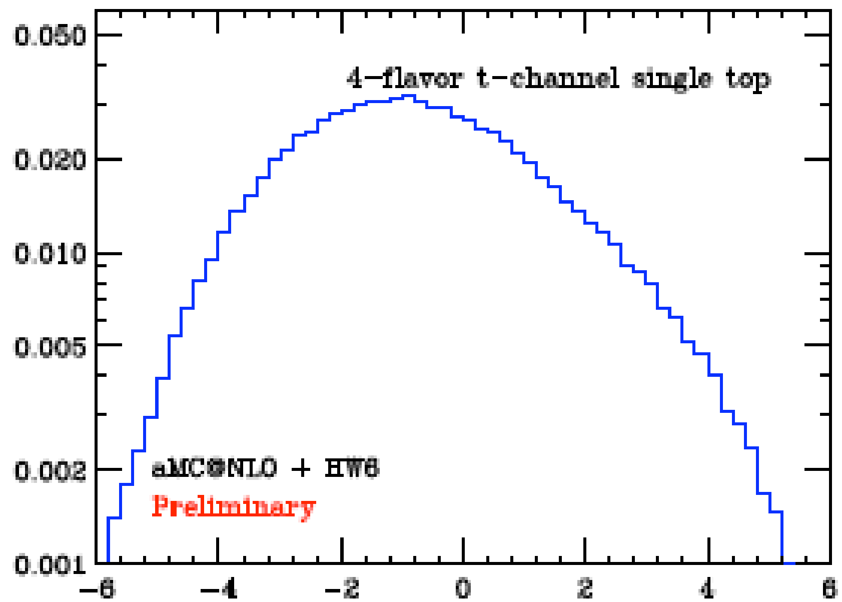
(contribution to) NLO</td>
<td>

Does not exist</td>
<td>

(part of) leading order</td>
</tr>
</table>

Descriptions are equivalent when including all orders in perturbation theory





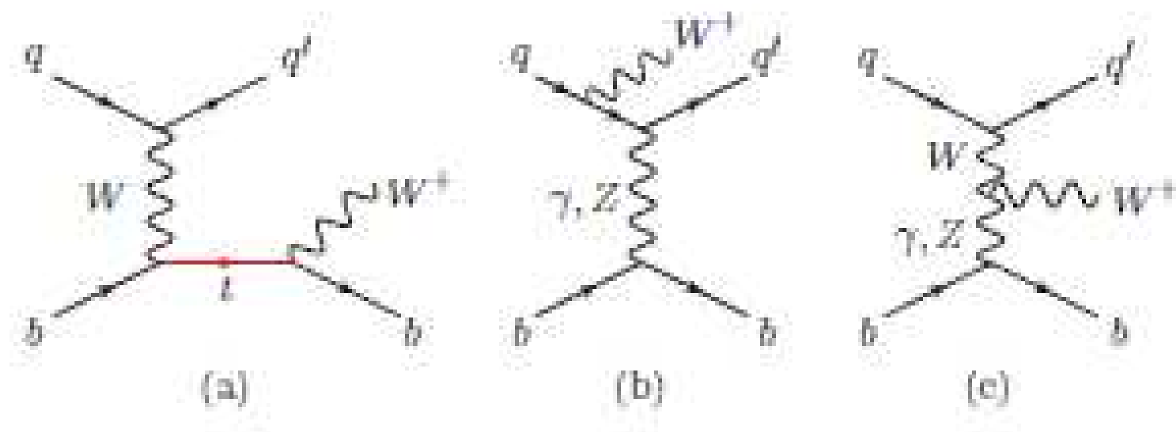
red: POWHEG, blue: MC@NLO
both with HW6, 5FS
(Alioli, Nason, Oleari, Re, 2009)

4FS with HW6
MadGraph5_aMC@NLO, preliminary

- By working in the 4FS, one bypasses the HW6 problem
  (MC@NLO and POWHEG in Frederix, Re, Torrielli, 2012)
- Mostly academic now for phenomenology, but has the virtue of exposing general features of the 4FS vs 5FS comparisons
  (see e.g. Maltoni, Ridolfi, Ubiali, 2012)

Although we are capable of taking production and decay spin correlations into account within NLO+PS approaches, we can try and be more ambitious, and consider:

$$pp \longrightarrow W^+ J_b J_{light} + X$$



Indeed, this is a definitely doable calculation in view of what automated codes can do with stable tops

$\longrightarrow$

	Process	Syntax	Cross section (pb)	
	Single-top		LO 13 TeV	NLO 13 TeV
f.1	$pp \to tj$ (t-channel)	`p p > tt j $$ w+ w-`	$1.520 \pm 0.001 \cdot 10^{2}\ {}^{+9.4\%}_{-11.9\%}\ {}^{+0.4\%}_{-0.6\%}$	$1.563 \pm 0.005 \cdot 10^{2}\ {}^{+1.4\%}_{-1.8\%}\ {}^{+0.4\%}_{-0.6\%}$
f.2	$pp \to t\gamma j$ (t-channel)	`p p > tt a j $$ w+ w-`	$9.956 \pm 0.014 \cdot 10^{-1}\ {}^{+6.4\%}_{-8.8\%}\ {}^{+0.9\%}_{-1.0\%}$	$1.017 \pm 0.003 \cdot 10^{0}\ {}^{+1.3\%}_{-1.2\%}\ {}^{+0.8\%}_{-0.9\%}$
f.3	$pp \to tZj$ (t-channel)	`p p > tt z j $$ w+ w-`	$6.967 \pm 0.007 \cdot 10^{-1}\ {}^{+3.5\%}_{-5.5\%}\ {}^{+0.9\%}_{-1.0\%}$	$6.993 \pm 0.021 \cdot 10^{-1}\ {}^{+1.6\%}_{-1.1\%}\ {}^{+0.9\%}_{-1.0\%}$
f.4	$pp \to tbj$ (t-channel)	`p p > tt bb j $$ w+ w-`	$1.003 \pm 0.000 \cdot 10^{2}\ {}^{+13.8\%}_{-11.5\%}\ {}^{+0.4\%}_{-0.5\%}$	$1.319 \pm 0.003 \cdot 10^{2}\ {}^{+5.8\%}_{-5.2\%}\ {}^{+0.4\%}_{-0.5\%}$
f.5*	$pp \to tbj\gamma$ (t-channel)	`p p > tt bb j a $$ w+ w-`	$6.293 \pm 0.006 \cdot 10^{-1}\ {}^{+16.8\%}_{-13.5\%}\ {}^{+0.8\%}_{-0.9\%}$	$8.612 \pm 0.025 \cdot 10^{-1}\ {}^{+6.2\%}_{-6.6\%}\ {}^{+0.8\%}_{-0.9\%}$
f.6*	$pp \to tbjZ$ (t-channel)	`p p > tt bb j z $$ w+ w-`	$3.934 \pm 0.002 \cdot 10^{-1}\ {}^{+18.7\%}_{-14.7\%}\ {}^{+1.0\%}_{-0.9\%}$	$5.657 \pm 0.014 \cdot 10^{-1}\ {}^{+7.7\%}_{-7.9\%}\ {}^{+0.9\%}_{-0.9\%}$
f.7	$pp \to tb$ (s-channel)	`p p > w+ > t b~, p p > w- > t~ b`	$7.489 \pm 0.007 \cdot 10^{0}\ {}^{+3.5\%}_{-4.4\%}\ {}^{+1.9\%}_{-1.4\%}$	$1.001 \pm 0.004 \cdot 10^{1}\ {}^{+3.7\%}_{-3.9\%}\ {}^{+1.9\%}_{-1.5\%}$
f.8*	$pp \to tb\gamma$ (s-channel)	`p p > w+ > t b~ a, p p > w- > t~ b a`	$1.490 \pm 0.001 \cdot 10^{-2}\ {}^{+1.2\%}_{-1.8\%}\ {}^{+1.9\%}_{-1.5\%}$	$1.952 \pm 0.007 \cdot 10^{-2}\ {}^{+2.6\%}_{-2.3\%}\ {}^{+1.7\%}_{-1.4\%}$
f.9*	$pp \to tbZ$ (s-channel)	`p p > w+ > t b~ z, p p > w- > t~ b z`	$1.072 \pm 0.001 \cdot 10^{-2}\ {}^{+1.3\%}_{-1.5\%}\ {}^{+2.0\%}_{-1.6\%}$	$1.539 \pm 0.005 \cdot 10^{-2}\ {}^{+3.9\%}_{-3.2\%}\ {}^{+1.9\%}_{-1.5\%}$

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro [MadGraph5_aMC@NLO], to appear

Process		Syntax	Cross section (pb)	
Single Higgs production			LO 13 TeV	NLO 13 TeV
g.1	$pp \to H$ (HEFT)	`p p > h`	$1.593 \pm 0.003 \cdot 10^{1}$ $^{+34.8\%}_{-26.0\%}$ $^{+1.2\%}_{-1.7\%}$	$3.261 \pm 0.010 \cdot 10^{1}$ $^{+20.2\%}_{-17.9\%}$ $^{+1.1\%}_{-1.6\%}$
g.2	$pp \to Hj$ (HEFT)	`p p > h j`	$8.367 \pm 0.003 \cdot 10^{0}$ $^{+39.4\%}_{-26.4\%}$ $^{+1.2\%}_{-1.4\%}$	$1.422 \pm 0.006 \cdot 10^{1}$ $^{+18.5\%}_{-16.6\%}$ $^{+1.1\%}_{-1.4\%}$
g.3	$pp \to Hjj$ (HEFT)	`p p > h j j`	$3.020 \pm 0.002 \cdot 10^{0}$ $^{+59.1\%}_{-34.7\%}$ $^{+1.4\%}_{-1.7\%}$	$5.124 \pm 0.020 \cdot 10^{0}$ $^{+20.7\%}_{-21.0\%}$ $^{+1.3\%}_{-1.5\%}$
g.4	$pp \to Hjj$ (VBF)	`p p > h j j $$ w+ w- z`	$1.987 \pm 0.002 \cdot 10^{0}$ $^{+1.7\%}_{-2.0\%}$ $^{+1.9\%}_{-1.4\%}$	$1.900 \pm 0.006 \cdot 10^{0}$ $^{+0.8\%}_{-0.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.5	$pp \to Hjjj$ (VBF)	`p p > h j j j $$ w+ w- z`	$2.824 \pm 0.005 \cdot 10^{-1}$ $^{+15.7\%}_{-12.7\%}$ $^{+1.5\%}_{-1.0\%}$	$3.085 \pm 0.010 \cdot 10^{-1}$ $^{+2.0\%}_{-3.0\%}$ $^{+1.5\%}_{-1.1\%}$
g.6	$pp \to HW^{\pm}$	`p p > h wpm`	$1.195 \pm 0.002 \cdot 10^{0}$ $^{+3.5\%}_{-4.5\%}$ $^{+1.9\%}_{-1.5\%}$	$1.419 \pm 0.005 \cdot 10^{0}$ $^{+2.1\%}_{-2.6\%}$ $^{+1.9\%}_{-1.4\%}$
g.7	$pp \to HW^{\pm}j$	`p p > h wpm j`	$4.018 \pm 0.003 \cdot 10^{-1}$ $^{+10.7\%}_{-9.3\%}$ $^{+1.2\%}_{-0.9\%}$	$4.842 \pm 0.017 \cdot 10^{-1}$ $^{+3.6\%}_{-3.7\%}$ $^{+1.2\%}_{-1.0\%}$
g.8*	$pp \to HW^{\pm}jj$	`p p > h wpm j j`	$1.198 \pm 0.016 \cdot 10^{-1}$ $^{+26.1\%}_{-19.4\%}$ $^{+0.8\%}_{-0.6\%}$	$1.574 \pm 0.014 \cdot 10^{-1}$ $^{+5.0\%}_{-6.5\%}$ $^{+0.9\%}_{-0.6\%}$
g.9	$pp \to HZ$	`p p > h z`	$6.468 \pm 0.008 \cdot 10^{-1}$ $^{+3.5\%}_{-4.5\%}$ $^{+1.9\%}_{-1.4\%}$	$7.674 \pm 0.027 \cdot 10^{-1}$ $^{+2.0\%}_{-2.5\%}$ $^{+1.9\%}_{-1.4\%}$
g.10	$pp \to HZj$	`p p > h z j`	$2.225 \pm 0.001 \cdot 10^{-1}$ $^{+10.6\%}_{-9.2\%}$ $^{+1.1\%}_{-0.8\%}$	$2.667 \pm 0.010 \cdot 10^{-1}$ $^{+3.5\%}_{-3.6\%}$ $^{+1.1\%}_{-0.9\%}$
g.11*	$pp \to HZjj$	`p p > h z j j`	$7.262 \pm 0.012 \cdot 10^{-2}$ $^{+26.2\%}_{-19.4\%}$ $^{+0.7\%}_{-0.6\%}$	$8.753 \pm 0.037 \cdot 10^{-2}$ $^{+4.8\%}_{-6.3\%}$ $^{+0.7\%}_{-0.6\%}$
g.12*	$pp \to HW^{+}W^{-}$ (4f)	`p p > h w+ w-`	$8.325 \pm 0.139 \cdot 10^{-3}$ $^{+0.0\%}_{-0.3\%}$ $^{+2.0\%}_{-1.6\%}$	$1.065 \pm 0.003 \cdot 10^{-2}$ $^{+2.5\%}_{-1.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.13*	$pp \to HW^{\pm}\gamma$	`p p > h wpm a`	$2.518 \pm 0.006 \cdot 10^{-3}$ $^{+0.7\%}_{-1.4\%}$ $^{+1.9\%}_{-1.5\%}$	$3.309 \pm 0.011 \cdot 10^{-3}$ $^{+2.7\%}_{-2.0\%}$ $^{+1.7\%}_{-1.4\%}$
g.14*	$pp \to HZW^{\pm}$	`p p > h z wpm`	$3.763 \pm 0.007 \cdot 10^{-3}$ $^{+1.1\%}_{-1.5\%}$ $^{+2.0\%}_{-1.6\%}$	$5.292 \pm 0.015 \cdot 10^{-3}$ $^{+3.9\%}_{-3.1\%}$ $^{+1.8\%}_{-1.4\%}$
g.15*	$pp \to HZZ$	`p p > h z z`	$2.093 \pm 0.003 \cdot 10^{-3}$ $^{+0.1\%}_{-0.6\%}$ $^{+1.9\%}_{-1.5\%}$	$2.538 \pm 0.007 \cdot 10^{-3}$ $^{+1.9\%}_{-1.4\%}$ $^{+2.0\%}_{-1.5\%}$
g.16	$pp \to Ht\bar{t}$	`p p > h t t~`	$3.579 \pm 0.003 \cdot 10^{-1}$ $^{+30.0\%}_{-21.5\%}$ $^{+1.7\%}_{-2.0\%}$	$4.608 \pm 0.016 \cdot 10^{-1}$ $^{+5.7\%}_{-9.0\%}$ $^{+2.0\%}_{-2.3\%}$
g.17	$pp \to Htj$	`p p > h tt j`	$4.994 \pm 0.005 \cdot 10^{-2}$ $^{+2.4\%}_{-4.2\%}$ $^{+1.2\%}_{-1.3\%}$	$6.328 \pm 0.022 \cdot 10^{-2}$ $^{+2.9\%}_{-1.8\%}$ $^{+1.5\%}_{-1.6\%}$
g.18	$pp \to Hb\bar{b}$	`p p > h b b~`	$4.983 \pm 0.002 \cdot 10^{-1}$ $^{+28.1\%}_{-21.0\%}$ $^{+1.5\%}_{-1.8\%}$	$6.085 \pm 0.026 \cdot 10^{-1}$ $^{+7.3\%}_{-9.6\%}$ $^{+1.6\%}_{-2.0\%}$
g.19	$pp \to Ht\bar{t}j$	`p p > h t t~ j`	$2.674 \pm 0.041 \cdot 10^{-1}$ $^{+45.6\%}_{-29.2\%}$ $^{+2.6\%}_{-2.9\%}$	$3.244 \pm 0.025 \cdot 10^{-1}$ $^{+3.5\%}_{-8.7\%}$ $^{+2.5\%}_{-2.9\%}$
g.20*	$pp \to Hb\bar{b}j$	`p p > h b b~ j`	$7.367 \pm 0.002 \cdot 10^{-2}$ $^{+45.6\%}_{-29.1\%}$ $^{+1.8\%}_{-2.1\%}$	$9.034 \pm 0.032 \cdot 10^{-2}$ $^{+7.9\%}_{-11.0\%}$ $^{+1.8\%}_{-2.2\%}$

Single top: g.17

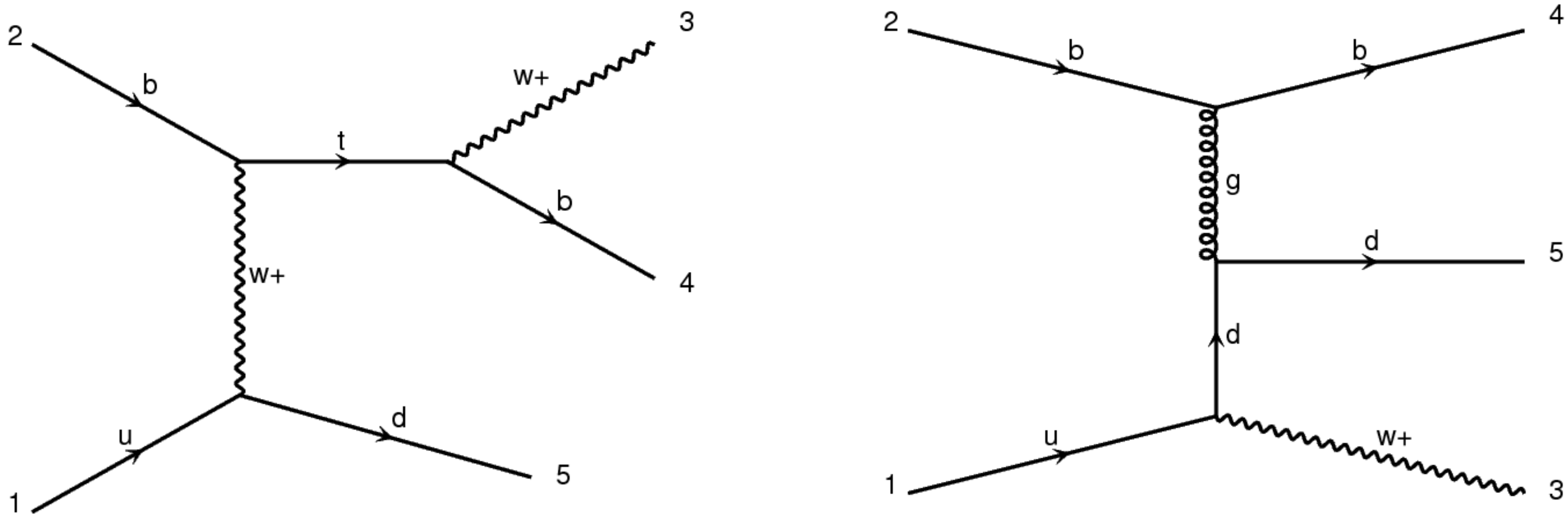
Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro [MadGraph5_aMC@NLO], to appear

	Process	Syntax	Cross section (pb)			
	Multiple Higgs production		LO 13 TeV		NLO 13 TeV	
h.1	$pp \to HH$ (Loop improved)	`p p > h h`	$1.772 \pm 0.006 \cdot 10^{-2}$	${}^{+29.5\%}_{-21.4\%}$ ${}^{+2.1\%}_{-2.6\%}$	$2.763 \pm 0.008 \cdot 10^{-2}$	${}^{+11.4\%}_{-11.8\%}$ ${}^{+2.1\%}_{-2.6\%}$
h.2	$pp \to HHjj$ (VBF)	`p p > h h j j $$ w+ w- z`	$6.503 \pm 0.019 \cdot 10^{-4}$	${}^{+7.2\%}_{-6.4\%}$ ${}^{+2.3\%}_{-1.6\%}$	$6.820 \pm 0.026 \cdot 10^{-4}$	${}^{+0.8\%}_{-1.0\%}$ ${}^{+2.4\%}_{-1.7\%}$
h.3	$pp \to HHW^{\pm}$	`p p > h h wpm`	$4.303 \pm 0.005 \cdot 10^{-4}$	${}^{+0.9\%}_{-1.3\%}$ ${}^{+2.0\%}_{-1.5\%}$	$5.002 \pm 0.014 \cdot 10^{-4}$	${}^{+1.5\%}_{-1.2\%}$ ${}^{+2.0\%}_{-1.6\%}$
h.4*	$pp \to HHW^{\pm}j$	`p p > h h wpm j`	$1.922 \pm 0.002 \cdot 10^{-4}$	${}^{+14.2\%}_{-11.7\%}$ ${}^{+1.5\%}_{-1.1\%}$	$2.218 \pm 0.009 \cdot 10^{-4}$	${}^{+2.7\%}_{-3.3\%}$ ${}^{+1.6\%}_{-1.1\%}$
h.5*	$pp \to HHW^{\pm}\gamma$	`p p > h h wpm a`	$1.952 \pm 0.004 \cdot 10^{-6}$	${}^{+3.0\%}_{-3.0\%}$ ${}^{+2.2\%}_{-1.6\%}$	$2.347 \pm 0.007 \cdot 10^{-6}$	${}^{+2.4\%}_{-2.0\%}$ ${}^{+2.1\%}_{-1.6\%}$
h.6*	$pp \to HHHW^{\pm}$	`p p > h h h wpm`	$3.989 \pm 0.009 \cdot 10^{-7}$	${}^{+3.9\%}_{-3.8\%}$ ${}^{+2.2\%}_{-1.7\%}$	$4.590 \pm 0.012 \cdot 10^{-7}$	${}^{+1.8\%}_{-1.7\%}$ ${}^{+2.2\%}_{-1.7\%}$
h.7	$pp \to HHZ$	`p p > h h z`	$2.701 \pm 0.007 \cdot 10^{-4}$	${}^{+0.9\%}_{-1.3\%}$ ${}^{+2.0\%}_{-1.5\%}$	$3.130 \pm 0.008 \cdot 10^{-4}$	${}^{+1.6\%}_{-1.2\%}$ ${}^{+2.0\%}_{-1.5\%}$
h.8*	$pp \to HHZj$	`p p > h h z j`	$1.211 \pm 0.001 \cdot 10^{-4}$	${}^{+14.1\%}_{-11.7\%}$ ${}^{+1.4\%}_{-1.1\%}$	$1.394 \pm 0.006 \cdot 10^{-4}$	${}^{+2.7\%}_{-3.2\%}$ ${}^{+1.5\%}_{-1.1\%}$
h.9*	$pp \to HHZ\gamma$	`p p > h h z a`	$1.397 \pm 0.003 \cdot 10^{-6}$	${}^{+2.4\%}_{-2.5\%}$ ${}^{+2.2\%}_{-1.7\%}$	$1.604 \pm 0.005 \cdot 10^{-6}$	${}^{+1.7\%}_{-1.4\%}$ ${}^{+2.3\%}_{-1.7\%}$
h.10*	$pp \to HHHZ$	`p p > h h h z`	$2.735 \pm 0.006 \cdot 10^{-7}$	${}^{+3.9\%}_{-3.7\%}$ ${}^{+2.2\%}_{-1.7\%}$	$3.154 \pm 0.007 \cdot 10^{-7}$	${}^{+1.7\%}_{-1.6\%}$ ${}^{+2.2\%}_{-1.7\%}$
h.11*	$pp \to HHZZ$	`p p > h h z z`	$2.309 \pm 0.005 \cdot 10^{-6}$	${}^{+3.9\%}_{-3.8\%}$ ${}^{+2.2\%}_{-1.7\%}$	$2.754 \pm 0.009 \cdot 10^{-6}$	${}^{+2.3\%}_{-2.0\%}$ ${}^{+2.3\%}_{-1.7\%}$
h.12*	$pp \to HHZW^{\pm}$	`p p > h h z wpm`	$3.708 \pm 0.013 \cdot 10^{-6}$	${}^{+4.8\%}_{-4.5\%}$ ${}^{+2.3\%}_{-1.7\%}$	$4.904 \pm 0.029 \cdot 10^{-6}$	${}^{+3.7\%}_{-3.2\%}$ ${}^{+2.2\%}_{-1.6\%}$
h.13*	$pp \to HHW^{+}W^{-}$ (4f)	`p p > h h w+ w-`	$7.524 \pm 0.070 \cdot 10^{-6}$	${}^{+3.5\%}_{-3.4\%}$ ${}^{+2.3\%}_{-1.7\%}$	$9.268 \pm 0.030 \cdot 10^{-6}$	${}^{+2.3\%}_{-2.1\%}$ ${}^{+2.3\%}_{-1.7\%}$
h.14	$pp \to HHt\bar{t}$	`p p > h h t t~`	$6.756 \pm 0.007 \cdot 10^{-4}$	${}^{+30.2\%}_{-21.6\%}$ ${}^{+1.8\%}_{-1.8\%}$	$7.301 \pm 0.024 \cdot 10^{-4}$	${}^{+1.4\%}_{-5.7\%}$ ${}^{+2.2\%}_{-2.3\%}$
h.15	$pp \to HHtj$	`p p > h h tt j`	$1.844 \pm 0.008 \cdot 10^{-5}$	${}^{+0.0\%}_{-0.6\%}$ ${}^{+1.8\%}_{-1.8\%}$	$2.444 \pm 0.009 \cdot 10^{-5}$	${}^{+4.5\%}_{-3.1\%}$ ${}^{+2.8\%}_{-3.0\%}$

Single top: h.15

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro [MadGraph5_aMC@NLO], to appear

$W^+ J_b J_{light}$ is easier than other processes we have already computed, but:



EW $\mathcal{O}(g_W^3)$ and QCD $\mathcal{O}(g_W g_S^2)$ amplitudes interfere, but the interference $\mathcal{O}(\alpha_W^2 \alpha_S)$ is zero. This is not true:

- At higher orders and in the 4FS scheme
- With more complicated final states
- Even with a non-diagonal CKM matrix!

Bottom line. We can study the t-channel EW production:

$$pp \longrightarrow W^+ J_b J_{light} + X$$

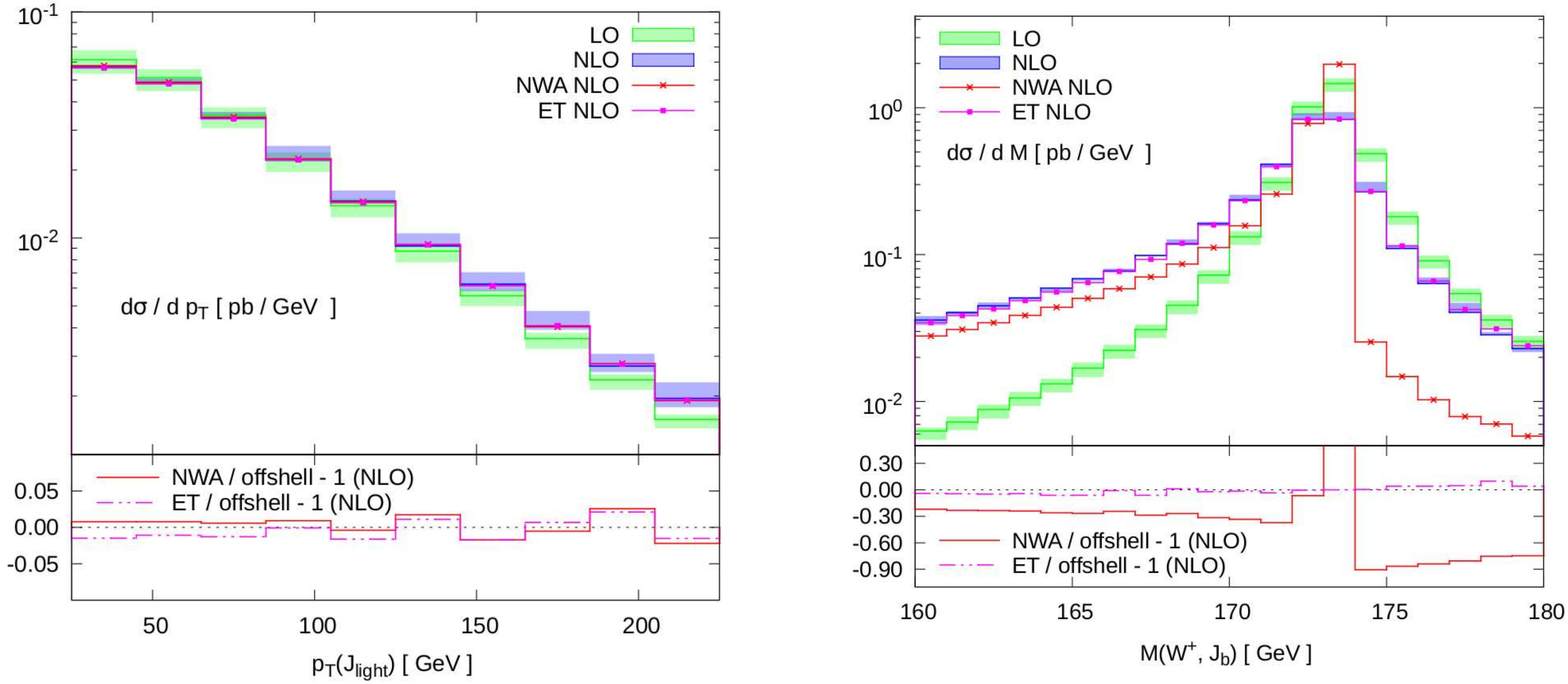
but we are lucky. Anything a tad more complicated would require one to consider *both* QCD (to $\mathcal{O}(\alpha_W^3)$) *and* EW (to $\mathcal{O}(\alpha_W^2 \alpha_S)$) corrections simultaneously

We start with parton-level NLO results

(Papanastasiou, Frederix, Hirschi, Maltoni, SF, 2013 – MadGraph5_aMC@NLO)

$p_T(J_b) > 25$ GeV	$p_T(J_{\rm light}) > 25$ GeV
$\lvert\eta(J_b)\rvert < 4.5$	$\lvert\eta(J_{\rm light})\rvert < 4.5$
$140 < M(W^+, J_b) < 200$ GeV	

These cuts (note that on the b-jet) enhance the resonant contributions, and allow one to assess how approximate computations behave



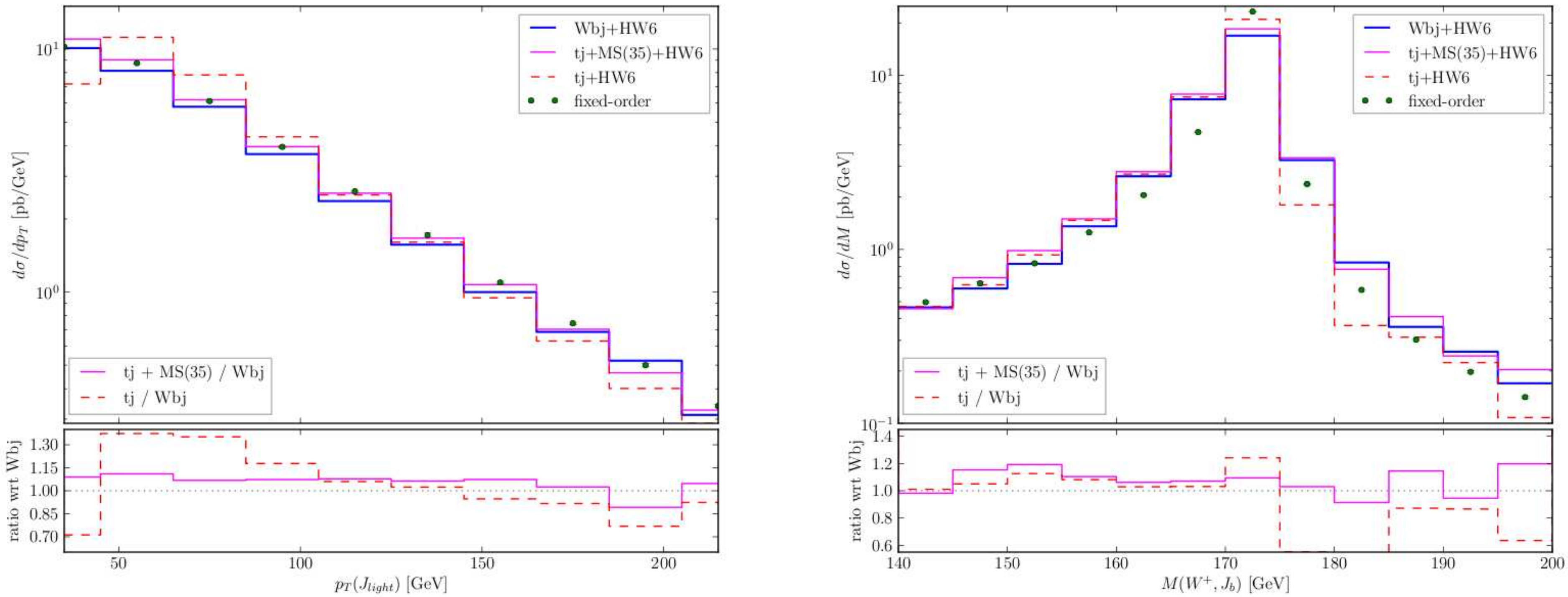
- LO and NLO: $W^+ J_b J_{light}$ production, $\mathcal{O}(\alpha_W^3)$ and $\mathcal{O}(\alpha_W^3 \alpha_S)$
- NWA NLO: MCFM (Campbell, Ellis, Tramontano), tj production, hep-ph/0408158 and 1204.1513
- ET NLO: pole expansion (Falgari, Mellor, Signer, 1007.0893)

Short summary

- It is incorrect to claim that the NWA is universally valid: for observables sensitive to $M(W^+J_b)$ it fails miserably
- Pole expansion does much better; deviations w.r.t. the full calculation only start to show up in the tail e.g. of $p_T^{(rel)}(J_b)$
- Therefore, it exists a class of observables for which off-shell effects are much more important than NLO corrections to decay; this conclusion should be largely independent of the production process

How about shower effects?

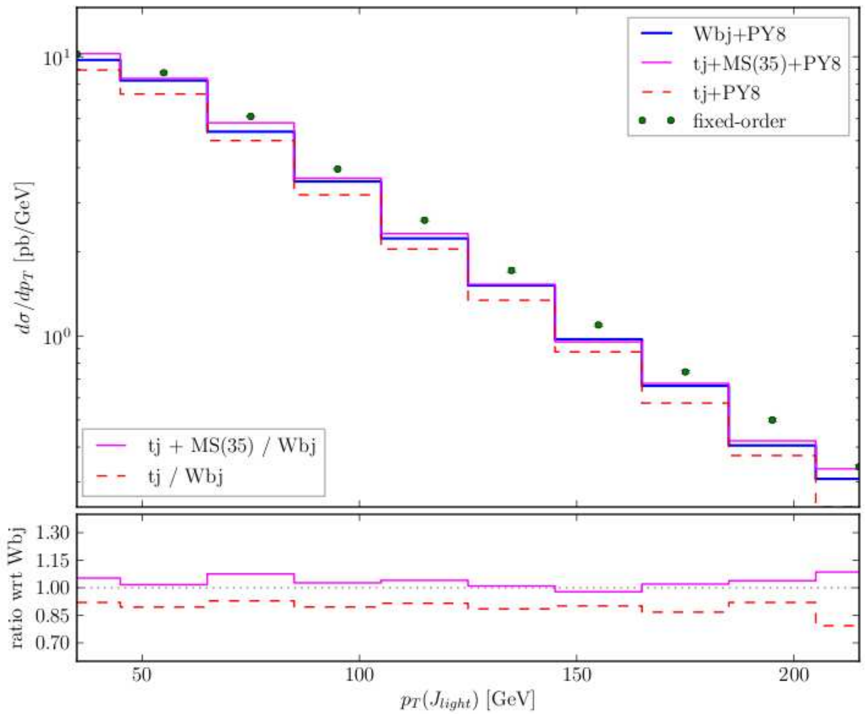
MadGraph5_aMC@NLO with HW6 - preliminary

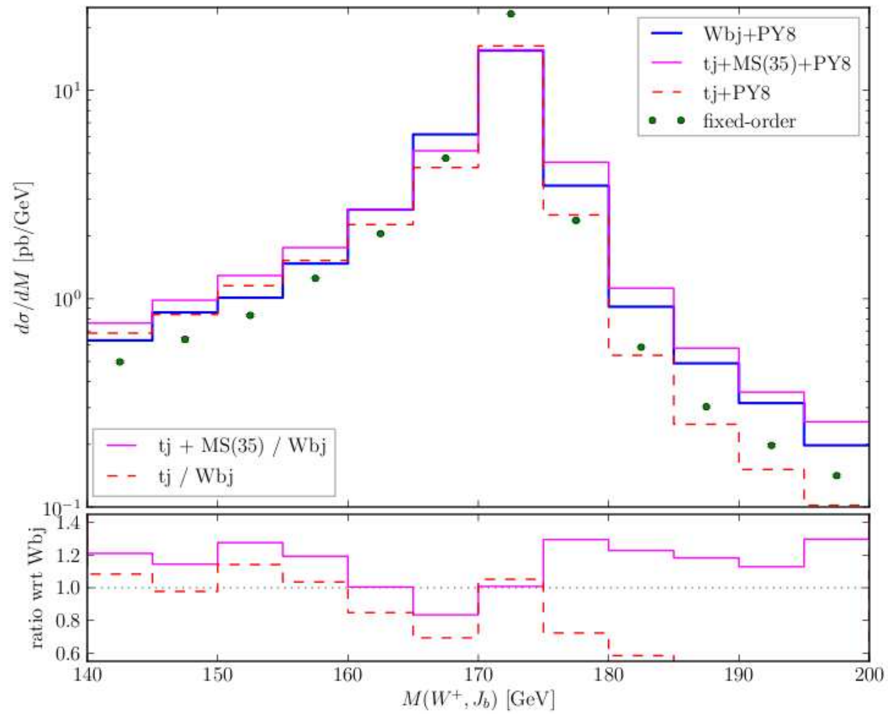


Papanastasiou, Prestel, Torrielli, SF, in preparation

- Blue: $W^+ J_b J_{light}$ NLO+PS
- Green dots: $W^+ J_b J_{light}$ NLO (same as before)
- Magenta: tj NLO+PS with spin correlations (MadSpin)
- Red dashed: tj NLO+PS without spin correlations

MadGraph5_aMC@NLO with PY8 - preliminary





Papanastasiou, Prestel, Torrielli, SF, in preparation

- Blue: $W^+ J_b J_{light}$ NLO+PS
- Green dots: $W^+ J_b J_{light}$ NLO (same as before)
- Magenta: tj NLO+PS with spin correlations (MadSpin)
- Red dashed: tj NLO+PS without spin correlations

The bad news

- Shower effects can be very large, typically for m_{top}-related quantities
- Differences induced by different showers are also non-negligible. For example, $M(W^+J_b)$ with PY8 is broader than with HW6
- NLO+PS predictions for $M(W^+J_b)$ are broader than fixed-order ones (i.e., further smearing), and thus farther away from NWA

The good news

- tj+spin correlations is within 25% of the full calculation. What has been done so far is not so bad after all. The level of the agreement is PSMC dependent

Conclusions

- Accurate theoretical predictions are crucial for single-top physics. Even when NNLO parton-level results will be available, computations matched to showers will be essential

- NLO+PS simulations with stable tops (5FS and 4FS) well established

- NLO+PS simulations with decayed tops are becoming available thanks to automated tools. It's important to compare them to data

- Will soon be able to explore a mixed QCD-QED expansion scenario