Top: the importance of being single

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based on:
Campbell,Frederix,FM,Tramontano arXiv:0907.3933
Campbell,Frederix,FM,Tramontano arXiv:0903.0005
Outline

- Motivations for top physics
- Challenges and opportunities from single-top
- Anatomy of t-channel production
- Conclusions
Top Physics aims

I. Measure all properties (mass, couplings, spin) to establish *indirect* evidence for SM and BSM physics.

   - Precision EW and QCD;
   - Rare decays and anomalous couplings. Flavor Physics.
   - CP violation.

   - SM: \( ttH; tH \)
   - BSM: \( Z' \) and \( W' \) resonances;
   - SUSY: \( tH^+ \) and \( t \rightarrow bH^+ \) or stop \( \rightarrow tX \).

II. Use top as *direct* probe of the EWSB sector and BSM physics
Top as a link to BSM

The top quark dramatically affects the stability of the Higgs mass. Consider the SM as an effective field theory valid up to scale $\Lambda$:

$$m_H^2 = m_{H0}^2 - \frac{3}{8\pi^2} y_t \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

Putting numbers, I have:

$$(200 \text{ GeV})^2 = m_{H0}^2 + \left[ -(2 \text{ TeV})^2 + (700 \text{ GeV})^2 + (500 \text{ GeV})^2 \right] \left( \frac{\Lambda}{10 \text{ TeV}} \right)^2$$
Top as a link to BSM

\[ m_h^2 \sim (200 \text{ GeV})^2 \]

\[
(200 \text{ GeV})^2 = m_{H_0}^2 + \left[ -(2 \text{ TeV})^2 + (700 \text{ GeV})^2 + (500 \text{ GeV})^2 \right] \left( \frac{\Lambda}{10 \text{ TeV}} \right)^2
\]

Definition of naturalness: less than 90% cancellation:

\[ \Lambda_t < 3 \text{ TeV} \quad \Lambda_t < 9 \text{ TeV} \quad \Lambda_t < 12 \text{ TeV} \]

One can actually prove that this case in model independent way, i.e. that the scale associated with top mass generation is very close to that of EWSB =>

First new physics could be associated with top!!
Available solutions

There have been many different suggestions! Fortunately, we can say that they group in 1+3 large classes:

1. **Denial**: There is no problem. Naturalness is our problem not Nature’s. Pro’s: we’ll find the Higgs. Cons: that’s it.

2. **Weakly coupled model at the TeV scale**: Introduce new particles to cancel SM “divergences”.

3. **Strongly coupled model at the TeV scale**: New strong dynamics enters at ~1 TeV.

4. **New space-time structure**: Introduce extra space dimensions to lower the Planck scale cutoff to 1 TeV.

---

**Top**: t-tbar bound states, colorons.

**Top partners, new scalars/vectors possibly strongly coupled with top.**

**Top is the only natural quark**

**KK-excitations**
Both involve production of heavy colored states decaying through a chain into jets, leptons and $E_T$. 

Top as a template
Top as background

At the LHC, many measurements will need a good understanding and control of tt and single top events. A few examples:

- $gg \rightarrow H$ and $qq \rightarrow Hqq$ with $H \rightarrow WW$
- $tt$ in single top measurements
- $tt+$jets and $ttbb$ in $ttH$
- $tt+$jets in SUSY/UED searches (gluino pairs, stop pairs, $tH^+$....)
- .....
top pair vs single top production

* Strong process: (LO at $\alpha_s^2$):
  $\sim 10$ pb at Tevatron
  $\sim 1$ nb at the LHC14
* Top discovery mode.
* Weak Potential: $m_t$
* BSM Potential: Large

* Weak process: same diagrams as the top decay!
* “Surprising” large cross section:
  $\sim 3$ pb at Tevatron
  $\sim 300$ pb at the LHC14
* Weak Potential: CKM, anomalous couplings.
* BSM Potential: Large
Why single top is way cooler than ttbar?
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At least three reasons...
Reason #1: Teenager vs Newborn
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$t \text{ tbar}$
Reason #1: Teenager vs Newborn

- Born in 1995
- Good: We already know him well
- Bad: We ask him a lot!
Reason #1: Teenager vs Newborn

Top:
- Born in 1995
- Good: We already know him well
- Bad: We ask him a lot!

Bottom:
- Just a few months old!
- Good: a whole new world to explore
- Bad: sleep deprivation...
Reason #2:
Single top comes in more shapes and forms!

*Theorist’s comments*
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Single top comes in more shapes and forms!

* “Drell-Yan” production mode.
* Tevatron is sizable (~1 pb), quite small at the LHC14 (~10 pb).
* Fully inclusive x-sec known at NNLO (leading Nc).
* Channel to search for new charged resonances (H⁺ or W').
  Four-fermion interactions.
* Final State: 2 b’s + W

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* “DIS” production mode.
  * Largest cross sections thanks to the t-channel W.
  * Sensitive to FCNC involving top. Four-fermion interactions.
  * b initiated
  * Final State: 1 or 2 b’s, W, forward jet

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* Associated production
* Sizable cross section (60 pb) at LHC14, but difficult.
* Template for tH⁺ production.
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* Interferes with ttbar at NLO: subtle definition.
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“No brainer”
“Interesting!”
“Challenging!!”
Example: Direct constraints on the 3rd row of CKM

Remember that $R$ is not so sensitive to $V_{tb}$ as we already know that $V_{tb} > V_{ts}, V_{td}$

$$R = \frac{\Gamma(t \rightarrow Wb)}{\Gamma(t \rightarrow Wq(=d,s,b))} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$
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On the other hand, single top is DIRECTLY sensitive to $V_{tb}, V_{ts}, V_{td}$:

\[
\sim |V_{td}|^2 \sigma_{d}^{t-ch} + |V_{ts}|^2 \sigma_{s}^{t-ch} + |V_{tb}|^2 \sigma_{b}^{t-ch}
\]

Enhancement due to large $d$ and $s$ densities

\[
\sim (|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2) \sigma^{s-ch}
\]

Signal becomes similar to $t$-channel (only 1 $b$-jet)
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$$\sigma_{1b-tag} = R \left\{ \sum_{i=b,s,d} |V_{ti}|^2 \sigma^{t-ch}_i + 2(|V_{td}|^2 + |V_{ts}|^2) \sigma^{s-ch} \right\}$$

$$\sigma_{2b-tag} = R |V_{tb}|^2 \sigma^{s-ch}$$

Enhancement due to large $d$ and $s$ densities

$$\sim (|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2) \sigma^{s-ch}$$

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Example: Direct constraints on the 3rd row of CKM

CDF

| $|V_{td}|$ vs $|V_{ts}|$ | $|V_{td}|$ vs $|V_{tb}|$ | $|V_{ts}|$ vs $|V_{tb}|$ |

DØ

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😊 All three 2→2 channels available in MC@NLO [Frixione et al.], w/ spin correlations!
😊 All MC implementations currently available for single top processes neglect $m_b$. 
Outline

• Motivations for top physics
• Challenges and opportunities from single-top
• Anatomy of t-channel production
• Conclusions
Deeper into t-channel...

• Both the t-channel as well as the Wt associated production have a (heavy) b quark in the initial state

\[ q \rightarrow q' \]
\[ b \rightarrow t \]

• There is an equivalent* description with a gluon splitting to b quark pairs

\[ q \rightarrow q' \]
\[ g \rightarrow W \rightarrow b \rightarrow t \]

*At all orders. At fixed order differences arise...
Collinear logarithms

- Both t-channel and Wt production are enhanced by a collinear logarithm.
- This results from integrating over a t-channel propagator.

\[
\frac{1}{t - m_b^2} \sim \frac{1}{p_T^2 + m_b^2}
\]

\[
t = (p_b - p_g)^2, \quad p_T^2 = p_{T,\bar{b}}^2
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- Contribution to the cross section:

\[
\int_{0}^{p_{T,max}^2} \frac{dp_T^2}{p_T^2 + m_b^2} = \log \left( \frac{p_{T,max}^2}{m_b^2} \right) + \ldots
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- Coefficient of the logarithm is:
Collinear logarithms

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Coefficient of the logarithm is:

AP splitting function $P_{g \rightarrow q\bar{q}}$ times matrix elements with splitting removed
Resummation into PDF

- Putting it together: \[ \frac{d\sigma(qg \to q't\bar{b})}{d\log p^2_{T,\text{max}}} \sim \left( \frac{\alpha_s}{2\pi} \right) \left[ \int \frac{dx}{x} P_{g\to qqf_{g}} \right] \times \hat{\sigma}(qb \to q't) \]

- But the first part resembles the evolution equation for a quark:
  \[ \frac{df_q}{d\log q^2} \sim \left( \frac{\alpha_s}{2\pi} \right) \int \frac{dx}{x} \left[ P_{g\to qqf_{g}} + P_{q\to qgf_q} \right] \]

- So when the logarithms really dominate, we can replace this description by: \[ \sigma(qg \to q't\bar{b}) \approx \sigma(qb \to q't) \]

- Scale of the bottom quark PDF should be related \( p_{T,\text{max}} \)

- At all orders both description should agree; otherwise, differ by:
  - evolution of logarithms in PDF: they are resummed
  - ranges of integration (obscured here)
  - approximation by large logarithm
# b-initiated processes

<table>
<thead>
<tr>
<th>Class</th>
<th>Process</th>
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<tr>
<td><strong>Top</strong></td>
<td>qb → tq (t-channel)</td>
<td>SM, top EW couplings and polarization, $V_{tb}$. Anomalous couplings. H+ : SUSY, 2HDM</td>
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Schemes

Two different ways of computing the same quantities:

1. It does not resum (possibly) large logs (⇒ norm. uncertainties)
2. Going NLO might be difficult.
3. Mass effects are there at any order in PT.
4. MC implementation with ME/PS merging a bit involved.

1. It resums initial state large logs in the b pdf, leading to more stable predictions
2. Going NLO (and NNLO) “easy”.
3. Mass effects are normally corrections and enter at higher orders.
4. Implementation in MC relies on mass effects given by the PS, which are presently not very accurate.

Let’s see a couple of examples...
Interference with $tt$ at NLO $\Rightarrow$ non trivial problem : definition of the process is at stake


However, interference is tamed with a (b-)jet veto $\Rightarrow$ sensitivity to low pt partons $\Rightarrow$ soft resummation $\Rightarrow$ MC with PS and with NLO needed.
Interference with tt at NLO ⇒ non trivial problem: definition of the process is at stake


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Diagram Removal:

\[ \hat{S}_{\alpha\beta} \]

Diagram Subtraction:

\[ \left( S_{\alpha\beta} + I_{\alpha\beta} + D_{\alpha\beta} - \tilde{D}_{\alpha\beta} \right) \]

Result: tW can be defined in

* a MC-friendly way
* (de facto) non-ambiguous way.

[Frixione, Laenen, Motylinski, Webber, White, 2008]
Interference with $tt$ at NLO ⇒ non trivial problem : definition of the process is at stake

[Tim Tait (2000), A. Belyaev & E. Boos (2001)]. First MC viable solution proposed

[Campbell, FM, Willenbrock, LH2005] and implemented in MCFM [Campbell, Tramontano, 2006].

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Upshot: 5F the most convenient choice to move the interference problem one order higher!
Scheme choice in Higgs production

\[ \sigma(p\bar{p} \to h_{SM} + X) \ [pb] \]
\[ \sqrt{s} = 2 \text{ TeV} \]
\[ M_t = 175 \text{ GeV} \]
CTEQ4M

Higgs Tevatron Workshop 1998
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Higgs Tevatron Workshop 1998
Scheme choice in Higgs production

Les Houches 03
HO corrections+
Scale choice!

Higgs Tevatron Workshop 1998
ACOT formalism

• Sensible way to combine the two approaches was formally identified some time ago: ACOT formalism [Aivazis, Collins, Olness & Tung, PRD50, 3102 (1994)]

• Roughly: use the bottom PDF ("5 flavor scheme", $2 \rightarrow 2$) when the "spectator b" is not important, otherwise keep it explicit ("4 flavor scheme", $2 \rightarrow 3$)

• But what to do in the intermediate region?

  • Deciding factor -- simpler to calculate with one less external leg

• All higher order calculations so far have been performed in the 5F ($2 \rightarrow 2$) scheme

• Terms from 4F ($2 \rightarrow 3$) enter at NLO. Properties of spectator b are only LO

• All calculations presented so far set $m_b=0$ in final state for simplicity
Need for matching in the $2 \to 2$ calculation

- At LO, no final state b quark
- At NLO, effects related to the spectator b only enter at this order and not well described by corresponding MC implementations
- "Effective NLO approximation": separate regions according to $p_T(b)$ and use (N)LO 5F ($2 \to 2$)+ shower below and LO 4F ($2 \to 3$) above
Need for matching in the $2 \rightarrow 2$ calculation

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- At NLO, effects related to the spectator $b$ only enter at this order and not well described by corresponding MC implementations
- “Effective NLO approximation”: separate regions according to $p_T(b)$ and use (N)LO 5F ($2 \rightarrow 2$) + shower below and LO 4F ($2 \rightarrow 3$) above

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- Ad hoc matching motivated by necessity, but theoretically unappealing.
- Done in a formally consistent way in MC@NLO (but with $m_b=0$)

NLO in the four-flavor scheme

- Use the 4-flavor (2 → 3) process as the Born and calculate NLO
- Much harder calculation due to two different masses and extra parton
- Spectator b for the first time at NLO
- Compare to 5F (2 → 2) to assess logarithms and applicability
- Starting point for future NLO+PS beginning at (2 → 3)
Checks of the calculation

- Real emission including subtraction terms checked against MadGraph & MadDipole
- Gauge invariance, CP, $m_t \leftrightarrow m_b$ symmetry
- Two different reduction schemes
- Most interesting check comes from crossing the whole calculation
  - Excellent agreement found

Setup

- Process implemented in the MCFM parton-level NLO code
- Use $m_t = 172$ GeV and $m_b = 4.5$ GeV
- For the 5F ($2 \rightarrow 2$) scheme, use regular PDF
- For 4F ($2 \rightarrow 3$) calculation, PDF’s need special treatment for consistency
  - the $b$ quark should not enter the evolution of the strong coupling or the PDF: MRST2004FF4
  - could also use a 5F PDF and pass to the 4F scheme using transition rules by Cacciari et al., JHEP05, 007 (1998)
- We use second option: CTEQ6.6 PDF set for both
Scale dependence

- Both schemes much improved from LO
- $5F (2 \rightarrow 2)$ only mildly sensitive to scales at NLO (use $m_t$ in what follows)
- $4F (2 \rightarrow 3)$ expected to be worse, but isn’t much
- Hardly a region of overlap between the two
- $4F (2 \rightarrow 3)$ prefers smaller scales than $m_t$, particularly at the Tevatron
Scale dependence 2 → 3

- Due to the near-factorization between the heavy and light quark lines we can vary the corresponding scales independently
- Expect smaller scale for heavy line due to $g \rightarrow b\bar{b}$ splitting

- Tevatron, LHC is similar
- Stronger dependence on heavy line, as expected
- Preference for scales smaller than $m_t$
- Choose central values:
  $$\mu_L = \frac{m_t}{2}, \quad \mu_H = \frac{m_t}{4}$$
t-channel best cross sections: $2\rightarrow 2$ vs $2\rightarrow 3$

[Campbell, Frederix, FM, Tramontano, 0907.3933]

Uncertainties: scales, PDF, $m_t$ (1%), $m_b$(4%)

<table>
<thead>
<tr>
<th>$\sigma_{t\rightarrow t\bar{t}}^{NLO}$ ($t + \bar{t}$)</th>
<th>$2 \rightarrow 2$ (pb)</th>
<th>$2 \rightarrow 3$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron Run II</td>
<td>$1.96 \pm 0.05 \pm 0.20 \pm 0.06 \pm 0.05$</td>
<td>$1.87 \pm 0.16 \pm 0.18 \pm 0.06 \pm 0.04$</td>
</tr>
<tr>
<td>LHC (10 TeV)</td>
<td>$130^{+2}<em>{-2} +3</em>{-3} +2_{-2} +2_{-2}$</td>
<td>$124^{+4}<em>{-5} +2</em>{-3} +2_{-2} +2_{-2}$</td>
</tr>
<tr>
<td>LHC (14 TeV)</td>
<td>$244^{+5}<em>{-4} +5</em>{-6} +3_{-3} +4_{-4}$</td>
<td>$234^{+7}<em>{-9} +5</em>{-5} +3_{-3} +4_{-4}$</td>
</tr>
</tbody>
</table>
t-channel best cross sections : $2 \rightarrow 2$ vs $2 \rightarrow 3$

- Conservative combination of scale and PDF uncertainties
- PDF uncertainty dominant at Tevatron, but not at the LHC
- $b$-mass uncertainties at the same level as $t$-mass ones [Overseen in previous studies].
- Consistent at the Tevatron: logarithms not so important?
- For the LHC, the minor difference could point to either:
  - large logarithms being resummed
  - $b$-pdf’s might not be accurate...
  - Higher order corrections (NNLO for $2 \rightarrow 2$) important...
Fourth generation x secs.

The NLO $2\rightarrow 3$ massive calculation can be also used to make reliable predictions for $t'b$, $b't$ and $b't'$ cross sections.

It is interesting to see where the cross over between the QCD and the EW productions are at the LHC.

In these plots all the relevant CKM elements are set to one.
Top and light jet distributions

Some differences, but typically of the order of $\sim 10\%$ in the regions where the cross section is large.
Spectator b

- First NLO prediction for this observable
- Slightly softer in 4F ($2 \rightarrow 3$), particularly at the Tevatron
- Deviations up to ~ 20% : perturbatively quite stable
ME+PS comparison at LHC

pT and $\eta$ spectra of the spectator HQ from the $2 \rightarrow 3$ prediction are accurate and do not need any dangerous matching...

More work in progress with A. Giammanco, J. Bauer and R. Frederix.
Applications of the new NLO calculation

- Event though b quarks in the 4F (2 → 3) scheme are more forward and softer, we expect to see more b’s than in the 5F (2 → 2)
- In 5F (2 → 2) only a subset of real emission diagrams have a final state b quark
- Define “acceptance” as the ratio of events that have a central, hard b over inclusive cross section:

\[
\frac{\sigma(|\eta(b)| < 2.5, p_T(b) > 20 \text{ GeV})}{\sigma_{\text{inclusive}}}\
\]
- Very large scale dependence for 5F (2 → 2), effectively a LO quantity
- NLO 4F (2 → 3) much more stable
- Dramatic effect at the Tevatron, important at the LHC.
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![Graph showing acceptance as a function of $\mu/m_t$]
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![Graph showing acceptance as a function of \( \mu/m_t \)](graph.png)

Acceptance: \( \sigma(|\eta(b)|<2.5, p_T(b)>20 \text{ GeV})/\sigma \) in %

- 32% → D0 best
- 29% → best
- 17% → CDF
- 36% → best
- 27% → CMS
Consequences for single top observation?
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- Difficult to say a priori, but work in progress
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Measured \(t\) channel might go up, \(s\) channel might go down!!

\[\begin{align*}
  q & \rightarrow W & t & \rightarrow e^+ \\
  \bar{q}' & \rightarrow \bar{b} & \bar{b} & \rightarrow q'
\end{align*}\]
s and t channel separation at CDF

- CDF has published separated results for the cross sections based on the 17% acceptance.
- Could this explain (at least part of) this 2 sigma deviation?
- CDF single top groups are addressing this issue
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CDF note 9716
Lesson from the $2\to3$ t-channel calculations

i. Single top (multivariate) analyses rely heavily on the MC's for the expected signal (and to a less extent background) distributions.

ii. We should always keep in mind that the adjective “NLO” can only be meaningfully associated to an observable NOT to a calculation!!

iii. In any case, the effect of theoretical uncertainites (scale and PDF uncertainites) on the analysis should be always estimated in situ.

iv. Single top can also be thought as a template to other difficult searches at the LHC.
Conclusions

🌟 Top physics is rich and exciting. Top offers also one of the most promising windows on New Physics.

🌟 Single top offers unique and exciting opportunities for testing the SM and probing new physics at the Tevatron and even more at the LHC.

🌟 Theory and MC’s under continuous improvement to match the needs of the experimental analyses (which are more demanding than those of ttbar!) : t-channel example!

🌟 A lot of work and fun ahead...
TOP QUARK

Discovered at Fermilab in 1995, the TOP QUARK is as short-lived as it is massive. Weighing in at a hefty 175 GeV, its lifetime, a mere $10^{-24}$ second, is the briefest of the six quarks. Top Quarks are an enigmatic particle whose personal life is sought after by thousands of physicists.

Acrylic felt with gravel fill for maximum mass.

$9.75$ plus shipping

...remember that you can always get one all for you!!
NLO MC at the Tevatron

[Chioli, Nason, Oleari, Re: 0907.4076]

Shower for initial states HQ needs to be corrected in HERWIG and in general improved! Work in progress...

[M. Seymour et al.]

😊 All MC implementations currently available for single top processes neglect $m_b$. 
Indirect evidence for the existence of particles not yet detected can be inferred from quantum corrections. At tree level $m_W = m_Z \cos \theta_W$. At one loop:

$$m_W^2 \left( 1 - \frac{m_W^2}{m_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_F} \left( 1 + \Delta r \right)$$

$$\Delta r_{\text{top}} = -\frac{3\alpha \cos^2 \theta_W}{16\pi} \frac{m_t^2}{\sin^4 \theta_W} \frac{m_Z^2}{m_W^2}$$

$$\Delta r_{\text{Higgs}} = +\frac{11\alpha}{48\pi \sin^2 \theta_W} \log \frac{m_H^2}{m_W^2}$$
Beyond the SM precision measurements can be also very useful. For instance in SUSY, the corrections to the Higgs mass are given by:

$$\Delta M^2 \simeq G_F m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$$

In fact top effects can be really important in theories like SUSY: Large and negative 1-loop corrections can turn the Higgs mass parameters negative and even trigger ESWB.
Similar behavior in WQ : 2→1 vs 2→2

[Campbell, FM, Mangano, Tramontano, in progress]

Conjecture: “Universal behaviour” for the scale dependence of the 5F and 4F calculations.
Similar behavior in $WQ : 2\rightarrow 1$ vs $2\rightarrow 2$

- $p_T$ spectrum of the spectator HQ unchanged
- no call for resummation
- the $2\rightarrow 2$ prediction for the spectator theoretically solid.

[Campbell, FM, Mangano, Tramontano, in progress]
t-channel single top at Tevatron

D0 has used samples obtained by COMPHEP+Pythia with a “hard pt matching” that are in good agreement with the $2 \rightarrow 3$ NLO predictions.

[Frederix, FM, Schwienhorst, Les Houches 2009]
NLO MC at the LHC

NLOwPS : MC@NLO

Konstantinov et al., CMS AN-2009/024

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