Production-decay interferences in t-channel single-top production at NLO in QCD

Pietro Falgari

ITF Utrecht

Terascale Alliance 4th Annual Workshop
Dresden, 1-3 December 2010

Based on **PF, P. Mellor, A. Signer** **[Phys. Rev. D82 (2010)]**
and work in preparation

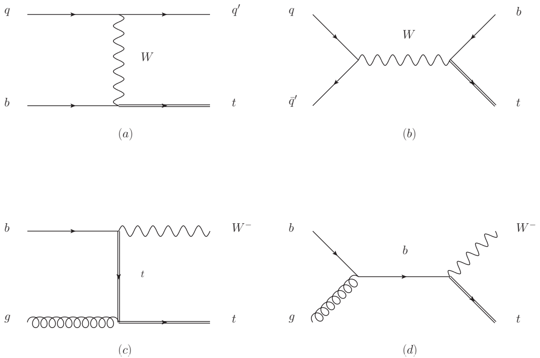
Why single top production?

- **observed last year by CDF and D0 at Tevatron**
  ... and large production rate expected at the LHC
- proceeds via electroweak interactions $\Rightarrow$ contains information on charged-current interactions of the top quark (and on possible anomalous couplings...)
- can be used the extract $|V_{tb}|$ $\Rightarrow$ test of unitarity of CKM matrix!
- probes the bottom-quark PDFs in the proton
  (usually computed from light-parton PDFs ...)
- important as a signal...but also as background to Higgs production channels

precise theoretical predictions necessary to make sense out of data!

Single-top production in the SM

In the Standard Model single top produced via three different channels
t-channel, **s-channel** and **associated** ***Wt*** **production**

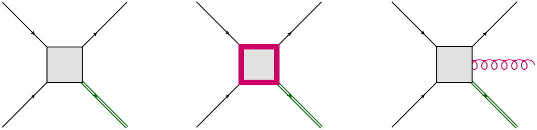


In this talk focus on *t*-channel single top production
(largest cross section at both Tevatron and LHC)

NOTE: in fact ***t*-channel and *s*-channel** can contribute to **same final state at NLO**
⇒ separation experimentally (and theoretically) not completely justified...

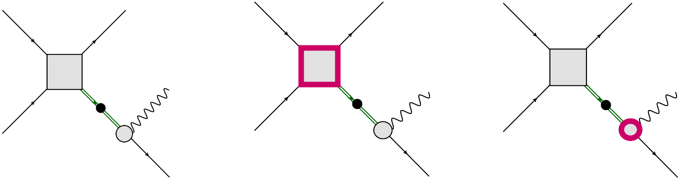
t-channel single top production

- **Stable-top approximation**: $qb \to q' t(m_t^2)$
  [**Bordes et al.; Stelzer et al.; Harris et al.; Sullivan et al.; Beccaria et al.;....**]



- **Narrow-width approximation**: $qb \to q' t(m_t^2) \to q' W^+ b$
  [**Campbell et all.; Cao et al.**]

$$\frac{1}{(p_t^2 - m_t^2)^2 + m_t^2 \Gamma_t^2} \sim \frac{\pi}{m_t \Gamma_t} \delta(p_t^2 - m_t^2)$$

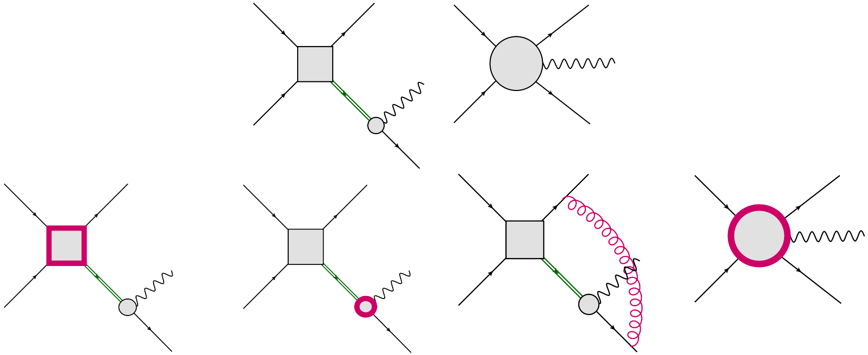


- **NLO/parton-shower matching** [**MC@NLO; POWHEG**]

Non-factorizable and non-resonant contributions

Narrow-width approximation neglects off-shell configurations, production-decay interferences and background diagrams

More satisfactory solution is full calculation: $qb \rightarrow$ **anything** $\rightarrow q'W^+b$



much more involved than on-shell calculation!

+ requires gauge-invariant resummation of finite-width effects...

Non-factorizable and non-resonant contributions

Off-shell effects expected to be small ($\sim \Gamma_t/m_t$) for inclusive cross section
follows from large cancellations between virtual and real corrections
[**Fadin et al. 1994; Melnikov, Yakovlev 1994**]
$\Rightarrow$ **usually seen as justification to use narrow-width approximation**

However: no guarantee that cancellation still takes place when kinematical cuts on the final states are imposed or more exclusive observables are considered

Aim of our work:

- try to ascertain the effect of non-factorizable corrections on cross sections AND kinematical distributions
- develop a framework which systematically includes factorizable, non-factorizable AND background diagrams as an expansion in Γ_t/m_t
  $\Rightarrow$ **better than NWA but simpler than full calculation**
- how to identify and compute all the necessary terms (and only those!) at a given order in $\Gamma_t/m_t \Rightarrow$ suitable counting scheme

The Effective Theory approach

Consider a resonant unstable particle X (rather than on-shell) and use the small virtuality of X to build an expansion in $\delta \equiv (p_X^2 - M_X^2)/M_X^2 \ll 1 \Leftrightarrow$ pole approximation

Expansion implemented at the level of the Lagrangian $\Leftrightarrow$ **Effective Theory**
[**Beneke et al. 2003; Beneke et al. 2007**]

$$\mathcal{L}_{\rm EFT} = \Phi_X^\dagger \left(v \cdot D_s - \frac{\Delta_X}{2} \right) \Phi_X + C_P \Phi_X^\dagger \prod_i \xi_i + C_D \Phi_X \prod_j \phi_j + \ldots$$

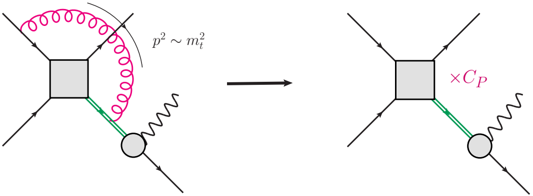
- Only low-virtuality modes ($p^2 \leq M_X^2 \delta$) are still dynamical: **resonant** (Φ_X), **collinear** (ξ_i, ϕ_i), **soft** ($D_s = \partial - igA_s$), ...
- Effects of **hard modes** ($p^2 \sim M_X^2$) encoded into matching coefficients C_P, C_D, Δ_X, ... extracted from **fixed-order on-shell matrix elements**
- Bilinear term for Φ_X resums finite-width effects: $\Delta_X = \mu_X^2 - \hat{M}_X^2$

NOTE: on-shell here means $p_X^2 = \hat{M}_X^2 + \Delta_X = M_X^2 - iM_X\Gamma_X \Rightarrow$ **gauge invariance**
(cf. with **complex-mass scheme** [**Denner et al. '99, Denner, Dittmaier 2006**])

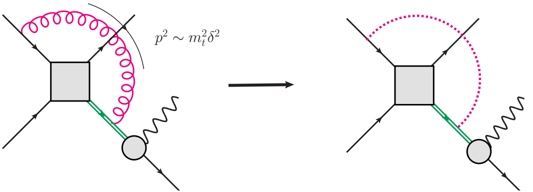
Effective-Theory approach: virtual corrections

Effective Lagrangians, soft modes, hard matching coefficients... **Sounds complicated!**

In practice it boils down to computing loop integrals with the **method of regions** [**Beneke, Smirnov 1998**]



- **Hard region** ($q^2 \sim M_X^2$) yields the matching coefficients $\Rightarrow$ **factorizable corrections**

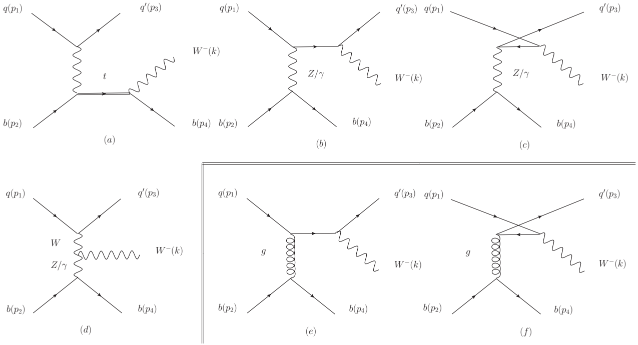


- **Soft region** ($q^2 \sim M_X^2\delta^2$) corresponds to loops in the effective-theory $\Rightarrow$ **non-factorizable corrections**

Tree-level amplitudes

$$q(p_1)b(p_2) \to q'(p_3)W^+(M_W^2)b(p_4) \to q'(p_3)l^+(p_5)\nu_l(p_6)b(p_4)$$

W decays in NWA

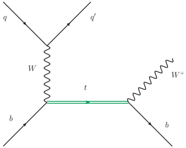


Systematically expand matrix element using the ET framework!

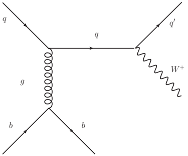
$$\underbrace{\frac{(p_W + p_b)^2 - m_t^2}{m_t^2} \sim \frac{\Gamma_t}{m_t} \sim \alpha_{ew} \sim \alpha_s^2}_{\delta}$$

Scaling of tree-level diagrams

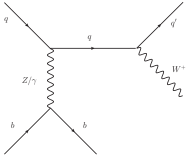
$$\mathcal{A}^{\text{tree}} = \delta_{31}\delta_{42}\Big(\underbrace{g_{ew}^3 A^{(3,0)}_{(-1)}}_{\text{EW res}} + \underbrace{g_{ew}^3 A^{(3,0)}_{(0)}}_{\text{EW non-res}} + \dots\Big) + T^a_{31}T^a_{42}\underbrace{g_{ew} g_s^2 A^{(1,2)}}_{\text{QCD}}\,.$$



$$\sim g_{ew}^3 \frac{1}{\Delta_t} \sim \delta^{1/2} \qquad \Delta_t \equiv (p_W + p_b)^2 - \mu_t^2$$



$$\sim g_{ew} g_s^2 \sim \delta$$



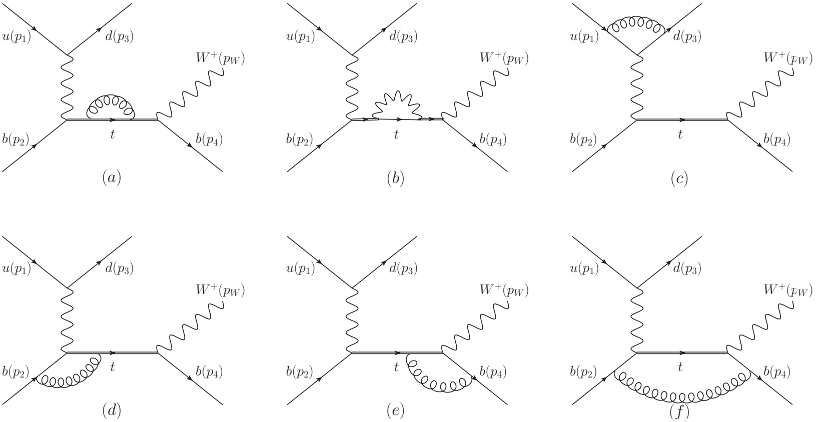
$$\sim g_{ew}^3 \sim \delta^{3/2}$$

$$M^{\text{tree}} = \underbrace{g_{ew}^6 \left|A^{(3,0)}_{(-1)}\right|^2}_{\sim\delta} + \underbrace{g_{ew}^6\, 2\,\text{Re}\left(A^{(3,0)}_{(-1)}\,[A^{(3,0)}_{(0)}]^*\right)}_{\sim\delta^2} + \underbrace{g_{ew}^2 g_s^4 \frac{C_F}{2N_c}\left|A^{(1,2)}\right|^2}_{\sim\delta^2} + \dots$$

Corrections of order $\delta^{1/2}$ vanish in squared matrix element due to colour!

NLO matrix element

Leading tree contribution $M^{\text{tree}} \sim \delta \Rightarrow$ compute all corrections of order $\delta^{3/2}$ (**NLO** approx.)
Arise from subset of one-loop resonant diagrams



Note: **before expansion in δ the subset of diagrams is gauge-dependent!**

Computation of soft and hard corrections

Expansion in soft and hard region dramatically simplifies loop integrals!

$$p_t^2 - \hat{m}_t^2 - 2p_t \cdot q + q^2 \quad \Rightarrow \quad q^2 - 2p_t \cdot q \qquad \text{if } q \sim m_t$$
$$\Rightarrow \quad \Delta_t - 2p_t \cdot q \qquad \text{if } q \sim m_t\delta \qquad (\Delta_t = p_t^2 - \mu_t^2)$$

finite-width effects resummed only in the soft region!

- **Soft corrections**(⇔non-factorizable corrections)

$$A^{(3,2)S}_{(-1)} = \frac{\alpha_s C_F}{2\pi}\left(-\frac{\Delta_t}{\mu m_t}\right)^{-2\epsilon}\left[\frac{1}{\epsilon}\left(1 - \ln\left(\frac{(s_{2t}-m_t^2)(s_{4t}-m_t^2)}{m_t^2 s_{24}}\right)\right) + 2 + \mathrm{Li}_2\left(1 - \frac{(s_{2t}-m_t^2)(s_{4t}-m_t^2)}{m_t^2 s_{24}}\right)\right] A^{(3,0)}_{(-1)}$$

- **Hard corrections**(⇔factorizable corrections)

coincide with 1-loop corr. for on-shell top production AND decay

⇒ EFT results contains on-shell corrections (NWA) and leading off-shell effects

Real corrections

How to expand real corrections in δ for arbitrary observables?

No obvious way... $\Rightarrow$ **be pragmatic and use full matrix element for real corrections**

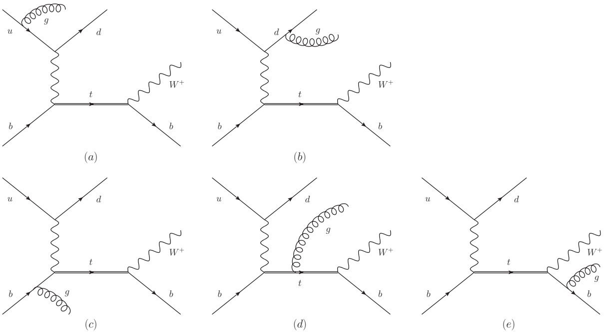
Cancellation of IR singularities requires some attention...

$$\begin{aligned}
\sigma^{\mathrm{NLO}} &= \int d\Phi_n d\sigma_V + \int d\Phi_{n+1} d\sigma_R \\
&= \int d\Phi_n \left(d\sigma_V - \int d\Phi_1 d\sigma_{\mathrm{subt}} \right) + \int d\Phi_{n+1} (d\sigma_R - d\sigma_{\mathrm{subt}}) \\
&\sim \int d\Phi_n \underbrace{\left(d\sigma_V^{\mathrm{exp}} - \int d\Phi_1 d\sigma_{\mathrm{subt}}^{\mathrm{exp}} \right)}_{\text{expand in}\delta} + \int d\Phi_{n+1} (d\sigma_R - d\sigma_{\mathrm{subt}})
\end{aligned}$$

- expansion of $d\sigma_{\mathrm{subt}}$ guarantees exact cancellation of IR singularities in virtual corrections and subtraction term
- $\int d\Phi_1 d\sigma_{\mathrm{subt}}^{\mathrm{exp}}$ has Born kinematics $\Rightarrow$ clear what expansion parameter is
- $d\sigma_R - d\sigma_{\mathrm{subt}}$ still contains the full gauge-invariant set of Feynman diagrams

Calculation of real corrections

In practice use only subset of all real Feynam diagrams



+ resonant gluon-initiated processes

$$gb \Rightarrow q'bW^+\bar{q} \qquad qg \rightarrow q'bW^+\bar{b}$$

Note: strictly speaking not gauge invariant, but gauge violation suppressed by $g_s^2\Delta_t \sim \delta^{3/2} \lesssim 1\%$ compared to tree-level cross section

Results

NLO calculation implemented in two independent Montecarlo codes (**Catani-Seymour dipoles** and **FKS subtraction**)

$$PP(\sqrt{s} = 7\,\text{TeV}) \to J_b e^+ \nu_e + X \qquad X = \text{any number of } \textbf{light} \text{ jets}$$

- $m_t = 172\,\text{GeV}$
- MSTW2008NLO
- standard k_t jet algorithm ($D_{\text{res}} = 0.7$)
- $p_T(J_b) > 20\,\text{GeV}, p_T(e^+) > 25\,\text{GeV}$
- $\not{E}_t > 25\,\text{GeV}$
- $m_{\text{inv}} = \sqrt{(p(J_b) + p(e^+) + p(\nu_e))^2}$, $120\,\text{GeV} < m_{\text{inv}} < 200\,\text{GeV}$
- $\mu_R = \mu_F = m_t/2$
- **for each prediction show narrow-width approximation for comparison!**

Minimal set of cuts chosen here is just an example! can be easily and flexibly varied

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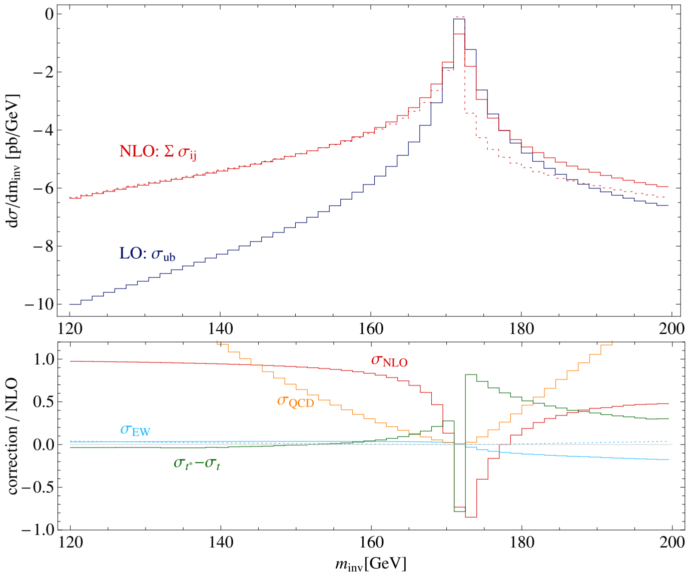
Total cross section

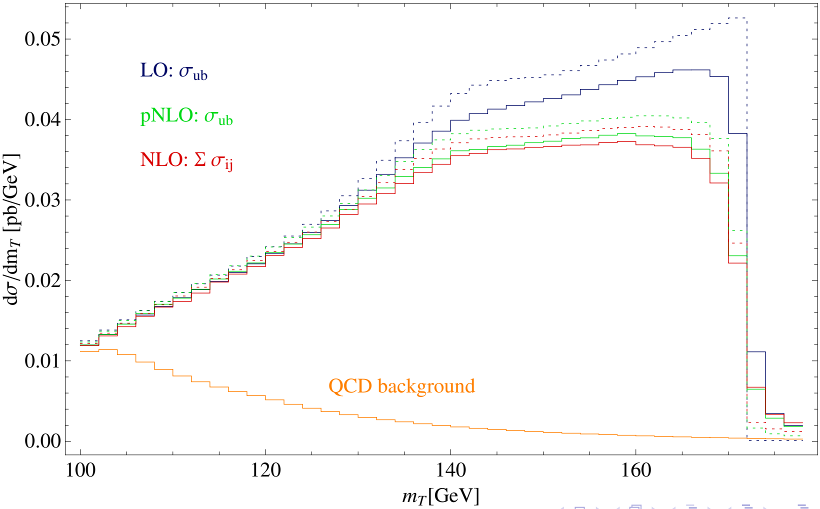
	NWA	FMS	$\Delta[\%]$
LO (pb)	2.6786(1)	2.519(1)	-6.5%
NLO (pb)	2.3079(1)	2.227(4)	-3.5%

Invariant-mass distribution: m_{inv}



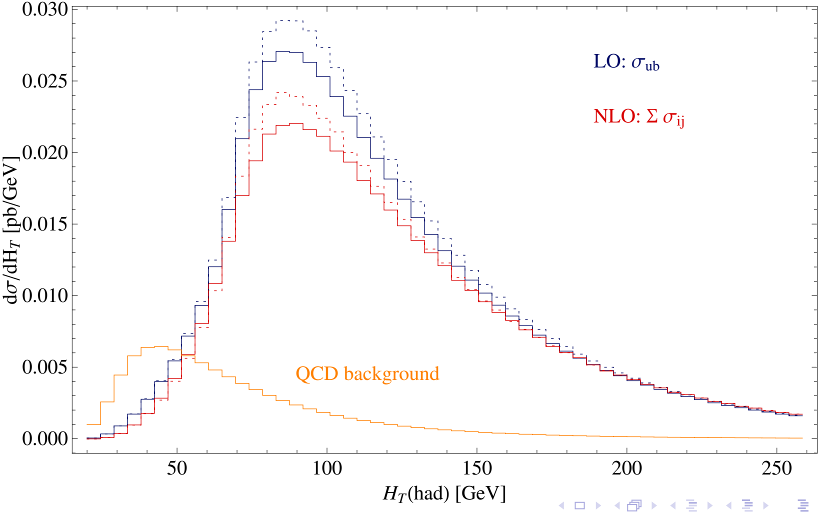
Top transverse mass m_T

$$m_T^2 = |p_T(J_b)|^2 + |p_T(e)|^2 + |p_T(\nu)|^2 - (\vec{p}_T(J_b) + \vec{p}_T(e) + \vec{p}_T(\nu))^2$$



Hadronic transverse energy

$$H_T(\text{had}) = |p_T(J_b)| + |p_T(J_l)|$$



Conclusions

- Effective-theory approach represents an economical way to include leading non-factorizable effects
- Formalism is completely general and can be easily adapted to other processes involving unstable particles
- For single-top production off-shell effects are generally small, but can be sizeable close to kinematic boundaries
- Size of non-factorizable corrections depends strongly on observable under consideration

What's next?

- include ***s*-channel production** processes
  [**PF, Giannuzzi, Mellor, Signer, in preparation**]
- ET approach is completely general
  $\Rightarrow$ can be applied to other processes, e.g. **top-pair production**