Single-Top in t-channel at NNLO

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in collaboration with

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Outline

Top quark physics

Single-Top Production

QCD corrections to t-channel Single-Top cross-section

Identikit

m_t	$\tau_t \simeq \frac{h}{\Gamma_t}$	$\tau_{had} \simeq \frac{h}{\Lambda_{QCD}}$	$\tau_{spinflip} \simeq h \left(\frac{\Lambda^2_{QCD}}{m_t}\right)^{-1}$

mass *theory*: convention-dependent parameter in the SM
experiments: $m_t^{exp} = 172.6 \pm 1.4 GeV$

spin *theory*: top quark is a spin-$1/2$ fermion
experiments: no dedicated experiment

- observed $t \to bW^+$ implies t is a fermion[1]
- $\sigma(t\bar{t})$ implies $s_t = 1/2$

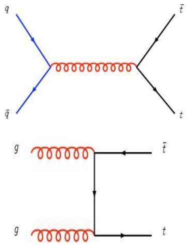
lifetime *theory*: $\tau_t = \simeq 5 \times 10^{-25} s < \tau_{had} \simeq 3 \times 10^{-24} s < \tau_{spinflip}$
$\Rightarrow$ Spin polarization and/or spin-spin correlation visible effects
experiments: $\Gamma_t \sim 1.3 GeV$ smaller than resolution at both Tevatron and LHC

Weak charge *theory*: top + bottom $\to SU(2)_W$ doublet $\begin{pmatrix} t \\ b \end{pmatrix}$
experiments: $|V_{tb}| \gg |V_{td}|, |V_{ts}|$ but no direct measurement of $|V_{tb}|$

[1] known b and W^+ spins + angular momentum conservation

Top Production

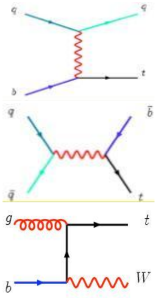
$t\bar{t}$ Pair Production



Hadronic production $\Rightarrow \mathcal{O}(\alpha_s^2)$(LO)

- $\sim$10pb at Tevatron
- $\sim$1nb at LHC

Single T Production



Weak production $\Rightarrow \mathcal{O}(\alpha_W^2)$(LO)

- $\sim$2 pb at Tevatron
- $\sim$300 pb at LHC

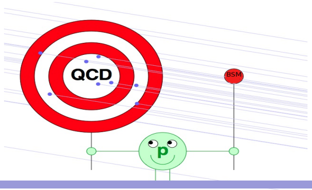
'Weak' cross-section greater than expected... thanks to PHASE SPACE!

Why studying Single Top?

- $\sigma_{singletop} \propto |V_{tb}|^2$ ⇒direct measurement of the *tbW* vertex

- source of polarized top quarks ⇒ structure of top *Charged Weak Interaction*
- possible window for BSM physics(ex. FCNC, top+charged SUSY Higgs boson, handness of the coupling, vector (extra W) resonances)
- it represents background to some important new physics processes ($p\bar{p} \to W^+H, p\bar{p} \to H \to W^+W^-$)

We need to compute $\sigma_{t(\bar{t})}$ as precisely as we can...
The most important are QCD corrections !!!
$\sigma_{t(\bar{t})} = \sigma_0 + \alpha_S \sigma_1 + \alpha_s^2 \sigma_2 + ...$



About t-channel...

In our analyses, we concentrate on t-channel...Why?

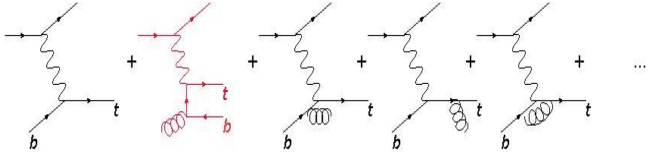
1. t-channel has the largest cross-section @LHC(Tevatron)!

$$\sigma_{t(\bar{t})}^{t-ch} > \sigma_{t(\bar{t})}^{s-ch}, \sigma_{t(\bar{t})}^{tW}$$

2. NLO QCD corrections are small ($\sim 5\%$), so $\sigma_{t(\bar{t})}^{t-ch}$ may become one of the most precisely predicted observables in Top Physics..

3. BSM: production of single top quarks by sizeable flavour-changing neutral currents, associated production of a top quark and charged Higgs boson in SUSY

$\sigma_{t(\bar{t})}^{t-ch} =$



t-channel: Status of the art

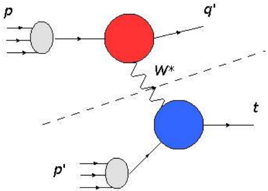
NLO QCD is fully explored ..

- NLO corrections ($\sim 5\%$ for LHC) for inclusive cross-section
- fully differential NLO cross-section
- NLO analyses including semi-leptonic top decays
- matching of NLO computation with parton shower MC
- EW corrections within the SM and MSSM ($\sim 1\%$)

$$\Downarrow$$

It's time for NNLO!!

Outline of the project-Ingredients : 1.a Structure function approach



$$d\sigma \propto \frac{1}{(Q^2+M_W^2)} MW_{\mu\nu}(x_1, Q^2, 0) \frac{1}{(Q^2+M_W^2)} MW^{\mu\nu}(x_2, Q^2, m_t^2) dQ^2 dW_1^2 dW_2^2 \quad (1)$$

$$\begin{aligned} MW_{\mu\nu}(x, Q^2, m^2) &= F_1(x, Q^2, m^2)\left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) \\ &+ \frac{F_2(x, Q^2, m^2)}{P\cdot q}\left(P_\mu - \frac{P\cdot q}{q^2}q_\mu\right)\left(P_\nu - \frac{P\cdot q}{q^2}q_\nu\right) \\ &- i\frac{F_3(x, Q^2, m^2)}{2P\cdot q}\epsilon_{\mu\nu\rho\sigma}P^\rho q^\sigma \\ &+ F_4(x, Q^2, m^2) q_\mu q_\nu + F_5(x, Q^2, m^2)(P_\mu q_\nu + P_\nu q_\mu) \quad (2) \end{aligned}$$

Outline of the project - Ingredients : 1.b Master QCD formula

$$d\sigma_X = \sum_{a,b} \int_{x_1}^{1} \int_{x_2}^{1} \frac{dz_1}{z_1} \frac{dz_2}{z_2} f_a(\frac{x_1}{z_1}, \mu_F^2) f_b(\frac{x_2}{z_2}, \mu_F^2) \times d\hat{\sigma}_{ab\to X}(z_1, z_2, \alpha_s(\mu_R^2), \frac{Q^2}{\mu_F^2} \frac{Q^2}{\mu_R^2}) \quad (3)$$

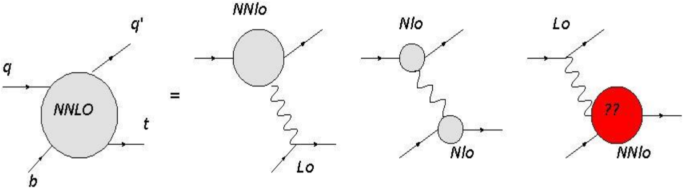
1. $f_a(x_1, \mu_F^2), f_b(x_2, \mu_F^2)$ are Parton Distribution Functions (from experimental data, but evolution from the theory)
2. $d\hat{\sigma}_{ab\to X}$ is the Coefficient Function, namely the partonic cross-section, describing the short distance interaction (from theory, it can be computed as expansion in α_s)

Combining eq.(1),(2) and (3), we obtain for $F_i(x, Q^2, m^2)$:

$$F_i(x, Q^2, m^2) = \sum_q \int_x^1 \frac{dz}{z} f_q(\frac{x}{z}, \mu_F^2) \times d\hat{\sigma}_{qV^*\to X}(z, \alpha_s(\mu_R^2), \frac{Q^2}{\mu_F^2} \frac{Q^2}{\mu_R^2}) \quad (4)$$

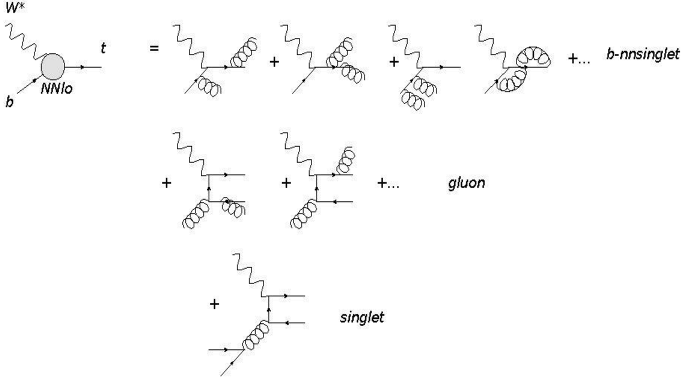
Outline of the project - Ingredients : 2.a Decomposition of $\mathcal{O}(\alpha_s^2)$ contribution $\hat{\sigma}^{(2)}$ to $\hat{\sigma}^{t-ch}_{t(\bar{t})}$ cross-section

$F^{(2)}(x, Q^2, m_t^2)$ is the only piece left to complete the puzzle...
Indeed, at partonic level $d\hat{\sigma}^{(2)}_{qW^* \to t+X}$ is the only unknown part of NNLO coefficient function.



$$
\begin{aligned}
d\hat{\sigma}^{(2)} &= d\hat{\sigma}(q \to q' W^*)^{(2)} \times d\hat{\sigma}(bW^* \to t)^{(0)} \\
&+ d\hat{\sigma}(q \to q' W^*)^{(1)} \times d\hat{\sigma}(bW^* \to t)^{(1)} \\
&+ d\hat{\sigma}(q \to q' W^*)^{(0)} \times d\hat{\sigma}(bW^* \to t)^{(2)} \qquad (5)
\end{aligned}
$$

Outline of the project - Ingredients : 2.b Decomposition of $\mathcal{O}(\alpha_s^2)$ contribution $F_i^{(2)}(x, Q^2, m_t^2)$ to massive structure function $F_i(x, Q^2, m_t^2)$



$$F^{(2)}(x, Q^2, m_t^2) = F_q^{(2)}(x, Q^2, m_t^2) + F_g^{(2)}(x, Q^2, m_t^2) + F_s^{(2)}(x, Q^2, m_t^2)$$

Outline of the project-Ingredients : 3. Master Formula

1. $F_g^{(2)}(x, Q^2, m_t^2) + F_s^{(2)}(x, Q^2, m_t^2)$ can be extracted numerically from MC
2. $F_q^{(2)}(x, Q^2, m_t^2)$ is the real object of our guess!! It is known in 2 kinematical regions..

$Q^2 >> m_t^2 \Rightarrow F(x, Q^2, 0)$ $x \to 1 \Rightarrow F_{soft}(x, Q^2, m_t^2)$

$$F_q^{(k)}(x, Q^2, m_t^2) = F_{q,soft}^{(k)}(x, Q^2, m_t^2) + F_q^{(k)}(x, Q^2, 0) - F_{q,soft}^{(k)}(x, Q^2, 0) + R_q^{(k)}(x, Q^2, m_t)$$

R_q is the *finite part*, with the requirements:

massless $R_q^{(k)}(x, Q^2, m_t^2) \overset{m_t \to 0}{\to} 0$

soft $R_q^{(k)}(x, Q^2, m_t^2) \overset{x \to 1}{=} a(m_t) + (1-x)b(m_t) + \dots .$

If R_q is 'small'... $\Rightarrow$ our guess $F_{q,approx}^{(k)}(x, Q^2, m_t^2) = F_{q,soft}^{(k)}(x, Q^2, m_t^2) + F_q^{(k)}(x, Q^2, 0) - F_{q,soft}^{(k)}(x, Q^2, 0)$ is good!!

Outline of the project - NLO preliminary analyses

@NLO : full massive computation is still accessible...

1. checked $C^{(1)}(x, Q^2, m_t^2)$ results in literature by redoing full NLO computation for $d\hat{\sigma}_{qW^* \to t+X}$
2. implemented these results in a standalone MC code, to perform numerical phase space integration and convolution with PDFs, thus checking NLO results for $F^{(1)}(x, Q^2, m_t^2)$
3. performed analytically massless and soft limits on $C_q^{(1)}(x, Q^2, m_t^2)$
4. implemented this limits in our MC, to get $F^{(1)}_{q,soft}(x, Q^2, m_t^2)$, $F_q^{(1)}(x, Q^2, 0)$, $F^{(1)}_{q,soft}(x, Q^2, 0)$

$$R^{(1)}(x, Q^2, m_t^2) = F^{(1)}(x, Q^2, m_t^2) - F^{(1)}_{soft}(x, Q^2, m_t^2) - F^{(1)}(x, Q^2, 0) + F^{(1)}_{soft}(x, Q^2, 0)$$

... everything is known, so we can estimate $\mathcal{O}(R^{(1)})$...

@physical Top mass

m_t	F_{m_t}	$F_{m_t,a}$	R	R/F_{m_t}
172.	41.848819	41.8501376	-0.0013186	-0.000031508655 $<$ MC error

Outline of the project - NNLO.. work in progress!

$$
\begin{aligned}
F^{(2)}_{q,approx}(x,Q^2,m_t^2) &= F^{(2)}_{q,soft}(x,Q^2,m_t^2) + F^{(2)}_{q}(x,Q^2,0) - F^{(2)}_{q,soft}(x,Q^2,0) \\
F^{(2)}_{approx}(x,Q^2,m_t^2) &= F^{(2)}_{q,approx}(x,Q^2,m_t^2) + F^{(2)}_{g}(x,Q^2,m_t^2) + F^{(2)}_{s}(x,Q^2,m_t^2) \qquad (6)
\end{aligned}
$$

1. is $C^{(2)}(x,Q^2,0)$ is known in literature $\rightarrow$ massless approximation $F^{(2)}_{q}(x,Q^2,0)$ is straight obtained with our MC
2. $F^{(2)}_{g}(x,Q^2,0) + F^{(2)}_{s}(x,Q^2,0)$ to be extracted numerically from existing MC
3. $F^{(2)}_{soft}(x,Q^2,m_t^2)$ and $F^{(2)}_{soft}(x,Q^2,0)$ have to be taken from *soft resummation*...

Soft resummation @NNLO

$$
\begin{aligned}
\frac{d^2\hat{\sigma}^{(2)}}{dt\,du} = F^B \frac{\alpha_s^2(\mu_R^2)}{\pi^2} \Bigg\{ & \frac{1}{2} c_3^2 \left[\frac{\ln^3(s_4/m_t^2)}{s_4}\right]_+ + \left[\frac{3}{2} c_3\, c_2 - \frac{\beta_0}{4} c_3 + C_F \frac{\beta_0}{8}\right] \left[\frac{\ln^2(s_4/m_t^2)}{s_4}\right]_+ \\
& + \left[c_3\, c_1 + c_2^2 - \zeta_2\, c_3^2 - \frac{\beta_0}{2} T_2 + \frac{\beta_0}{4} c_3 \ln\left(\frac{\mu_R^2}{m_t^2}\right) + \frac{3}{2} C_F\, K - \frac{3}{16} C_F\, \beta_0 + 4\Gamma^{(1)}_{S\,12}\, \Gamma^{(1)}_{S\,21}\right] \left[\frac{\ln(s_4/m_t^2)}{s_4}\right]_+ \\
& + \Bigg[c_2\, c_1 - \zeta_2\, c_3\, c_2 + \zeta_3\, c_3^2 + \frac{\beta_0}{4} c_2 \ln\left(\frac{\mu_R^2}{s}\right) - \frac{\beta_0}{2} C_F \ln^2\left(\frac{m_t^2 - t}{m_t^2}\right) - \frac{\beta_0}{2} C_F \ln^2\left(\frac{m_t^2 - u}{m_t^2}\right) \\
& - C_F\, K \ln\left(\frac{(m_t^2 - u)(m_t^2 - t)}{m_t^4}\right) + B^{(2)} + 3D^{(2)} + C_F \frac{\beta_0}{4} \ln^2\left(\frac{\mu_F^2}{s}\right) - C_F\, K \ln\left(\frac{\mu_F^2}{s}\right) \\
& + \frac{3\beta_0}{8} C_F \ln^2\left(\frac{m_t^2}{s}\right) - C_F\left(\frac{K}{2} - \frac{3}{16}\beta_0\right) \ln\left(\frac{m_t^2}{s}\right) + 2\Gamma^{(2)}_{S\,11} + \left(4\, \Gamma^{(1)}_{S\,12}\, \Gamma^{(1)}_{S\,21} + 4\, (\Gamma^{(1)}_{S\,11})^2\right) \ln\left(\frac{m_t^2}{s}\right)\Bigg] \left[\frac{1}{s_4}\right]_+ \Bigg\}
\end{aligned}
$$

just a matter of disentanglement ...

Conclusion

- Top Physics
- Single Top Production
- QCD corrections for Single Top Production in t-channel
  1. Ingredients
  2. NLO preliminary analyses... our guess looks promising!
  3. NNLO strategy

NNLO first result for CHARGED DIS structure functions $F^{(2)}(x, Q^2, m_t^2)$ in a couple of month!

..thank you for your attention