Top Quark Physics

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IN PURSUIT OF KNOWLEDGE

One of the six quarks & *heaviest* among all fundamental particles discovered so far

$$\begin{pmatrix} t_L^c \\ b_L^c \end{pmatrix}, \quad t_R^c$$

$$\Uparrow$$

$$Q = +\frac{2}{3} \Leftarrow \boxed{\text{Top Quark } (t)} \Rightarrow J = \frac{1}{2}$$

$$\Downarrow$$

$$m_t = 172.9 \pm 0.4 \text{ GeV}$$
$$\Gamma_t = 1.42^{+0.19}_{-0.15} \text{ GeV}$$

The particle was discovered in 1995 by CDF and D0 collaborations at Tevatran ($p\bar{p}$ collider, $\sqrt{s} = 1.8$ TeV).

Top quark in the Standard Model

Mass is generated via the mechanism of EWSB.

$$\mathcal{L}_{\text{Yukawa}} \supset y_t \, \bar{Q}_L \tilde{\Phi} t_R + \text{h.c.} = m_t \, (\bar{t}_L t_R + \bar{t}_R t_L)$$

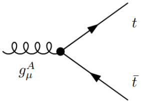
where, $m_t = \frac{1}{\sqrt{2}} y_t v \Rightarrow y_t \sim 1$.

Thus, the top-quark has the most *natural* mass among all fermions. It couples with the Higgs very strongly.

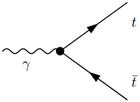
Has very short life time, decays before hadronization
$\tau_{\text{had}} \sim 1/\Lambda_{\text{QCD}} \sim 10^{-24}\ sec; \quad \tau_t \sim 10^{-25}\ sec$
$\Rightarrow$ no top-flavoured hadrons.

Plays important role in Higgs production and decay modes.

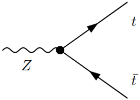
Top quark couplings



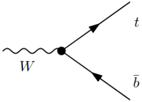
$$= -ig_s T^A \gamma^\mu,$$



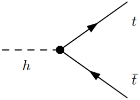
$$= -i\frac{2}{3}e\gamma^\mu.$$



$$= \frac{ig}{2\cos\theta_W}\gamma^\mu(v_t - a_t\gamma^5),$$



$$= ig\gamma^\mu(1-\gamma^5)V_{tb},$$



$$= y_t = \frac{\sqrt{2}m_t}{v}.$$

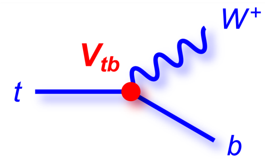
Top Quark Decay

Due to $m_t > m_W$, $t \to b + W$ is allowed. At NLO QCD and assuming $|V_{tb}| = 1$,

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{M_W^2}{m_t^2}\right) \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]$$

The phase space for decay is large and top decays before it can hadronise.

$m_t \sim 173$ GeV $\Rightarrow \Gamma_t \simeq 1.3$ GeV corresponding to a lifetime of 0.5×10^{-24} s.



Top Quark Decay

W polarization: Due to the large decay width the spin information is carried by its decay products. SM predicts that in top decay, W is mostly longitudinal. In the SM, neglecting the b-quark mass

$$F_0 = \frac{m_t^2}{m_t^2 + 2M_W^2} \approx 0.70\,,$$
$$F_L = \frac{2M_W^2}{m_t^2 + 2M_W^2} \approx 0.30\,,$$
$$F_R = 0\,.$$

where,

$$F_{0/L/R} = \frac{\Gamma_{0/L/R}}{\Gamma_0 + \Gamma_L + \Gamma_R}$$

For the finite b-quark mass, calculations at NNLO predict,
$F_0 = 0.687 \pm 0.005$; $F_L = 0.311 \pm 0.005$; $F_R = 0.0017 \pm 0.0001$

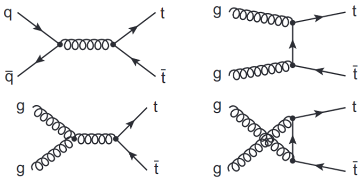
Any modification in tbW vertex would change this prediction. The information on W polarization can be obtained using angular distribution,

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos(\theta^*)} = \sin(\theta^*)^2 F_0 + \frac{3}{8}\left(1 - \cos(\theta^*)\right)^2 F_L + \frac{3}{8}\left(1 + \cos(\theta^*)\right)^2 F_R\,.$$

θ^* is angle between reverse momentum of decaying top and charged lepton momentum in W rest frame.

$t\bar{t}$ Production

Dominated by QCD processes at hadron colliders.



At LO,

$$\sigma_{q\bar{q}\to t\bar{t}} = \frac{g_s^4}{108\pi s}\beta(3-\beta^2),$$

$$\sigma_{gg\to t\bar{t}} = \frac{g_s^4}{768\pi s}\left(31\beta^3 - 59\beta + (33 - 59\beta + (33 - 18\beta^2 + \beta^4))\log\frac{1+\beta}{1-\beta}\right)$$

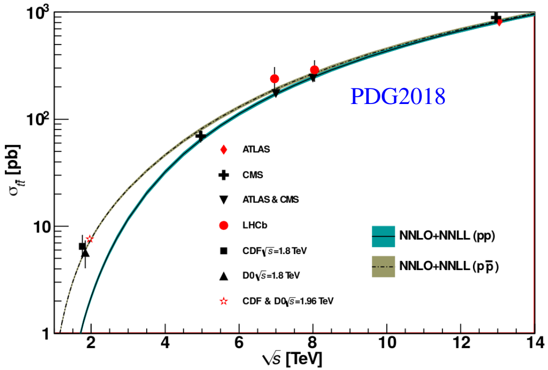
where $\beta = \sqrt{1 - 4m_t^2/s}$.
The hadronic cross section is dominated by the gg channel ($\sim 90\%$ of the coss section at the LHC).

$t\bar{t}$ Production

Higher order calculations are avaialble at NNLO+NNLL and at 13 TeV LHC

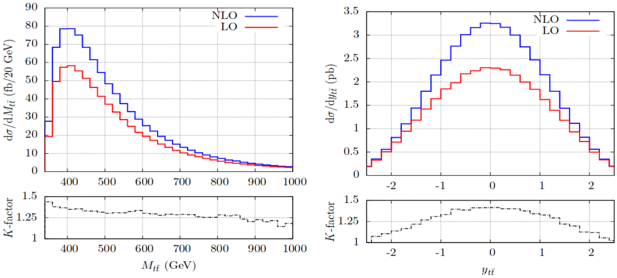
$$\sigma_{t\bar{t}} = 816^{+19.4}_{-28.6}\ \text{pb}$$

A very good agreement between theory and experiments.



$t\bar{t}$ Production

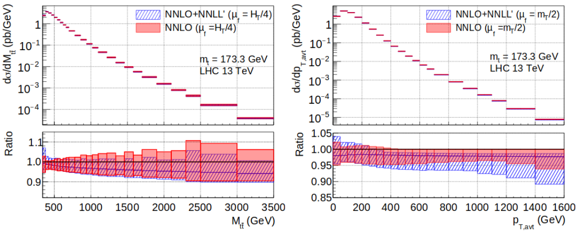
Importance of NLO QCD corrections in differential distributions.

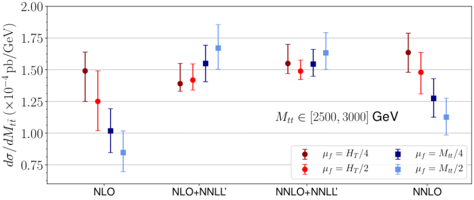


The corrections reach ∼ 40% in certain bins.

$t\bar{t}$ Production

Further higher order corrections are required to reduce the scale uncerainty in the boosted regime.





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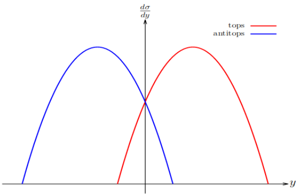
$t\bar{t}$ Production

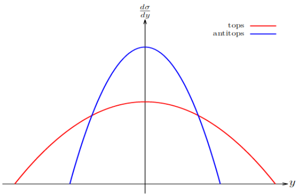
Charge asymmetries (like forward-backward asymmetries at Tevatron) are important probe of BSM at the LHC.

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}, \quad A_C = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)}$$

where, $\Delta|y| = |y_t| - |y_{\bar{t}}|$. A_{FB} works when intial states are not symmetric and a forward-backward direction can be defined. For Tevatron, $A_{FB}^{\text{SM}} = 7.24^{+1.04}_{-0.67}$ at NNLO QCD.

In $q\bar{q} \to t\bar{t}$ at the LHC, the tops being correlated with q (valence quark), tend to be produced at larger rapidities than antitops. Since the cross section is dominated by gg channel, A_C is very small at the LHC. The data is consistent with the SM prediction (NLO QCD + NLO EW): $A_C = 0.0123 \pm 0.0005$.





$t\bar{t}$ Production

Top polarization and Spin correlation: Top quark polarization can be studied via the angular distribution of its decay products. This is possible because top quark decays before hadronization. The spins of top and antitop are correlated in $t\bar{t}$ production and this correlation is reflected in the angular correlation of decay products of top and antitop.

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos(\theta_1)\mathrm{d}\cos(\theta_2)} = \frac{1}{4}\left(1 + \alpha_1 P_1 \cos(\theta_1) + \alpha_2 P_2 \cos(\theta_2) - \alpha_1\alpha_2 A \cos(\theta_1)\cos(\theta_2)\right) ,$$

A is the measure of spin correlation between top and antitop, $A^{\mathrm{SM}} = 0.031 \pm 1\%$.

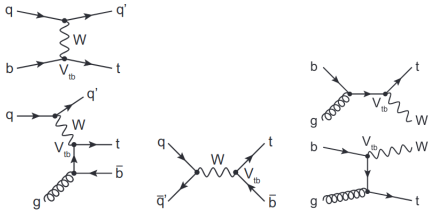
$$A = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

This quantity can also be used to probe BSM physics in the production mechanism, for example, models with colored scalars.

Single Top Production

Production is governed by electroweak processes: s-channel, t-channel and associated production with W

t-channel mediated by W boson has largest cross section ($\sim$ 1/3 of the pair production).



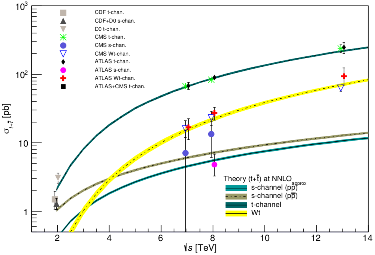
Directly sesitive to $|V_{tb}|$. It is also sensitive to W' boson in BSM models.

Single Top Production

The inclusive cross section

PDG2018

inclusive		LO	NLO	NNLO
8 TeV	$\sigma(t)$ [pb]	$2.498^{+0.17\%}_{-0.74\%}$	$3.382^{+2.36\%}_{-1.81\%}$	$3.566^{+0.95\%}_{-0.78\%}$
	$\sigma(\bar{t})$ [pb]	$1.418^{+0.12\%}_{-0.73\%}$	$1.922^{+2.37\%}_{-1.81\%}$	$2.029^{+1.07\%}_{-0.83\%}$
	$\sigma(t+\bar{t})$ [pb]	$3.916^{+0.15\%}_{-0.73\%}$	$5.304^{+2.36\%}_{-1.81\%}$	$5.595^{+0.99\%}_{-0.80\%}$
	$\sigma(t)/\sigma(\bar{t})$	$1.762^{+0.04\%}_{-0.01\%}$	$1.760^{+0.00\%}_{-0.02\%}$	$1.757^{+0.05\%}_{-0.12\%}$
13 TeV	$\sigma(t)$ [pb]	$4.775^{+2.69\%}_{-3.50\%}$	$6.447^{+1.39\%}_{-0.91\%}$	$6.778^{+0.76\%}_{-0.53\%}$
	$\sigma(\bar{t})$ [pb]	$2.998^{+2.69\%}_{-3.55\%}$	$4.043^{+1.33\%}_{-0.94\%}$	$4.249^{+0.69\%}_{-0.48\%}$
	$\sigma(t+\bar{t})$ [pb]	$7.772^{+2.69\%}_{-3.52\%}$	$10.49^{+1.36\%}_{-0.92\%}$	$11.03^{+0.74\%}_{-0.51\%}$
	$\sigma(t)/\sigma(\bar{t})$	$1.593^{+0.05\%}_{-0.01\%}$	$1.595^{+0.06\%}_{0.03\%}$	$1.595^{+0.07\%}_{-0.05\%}$

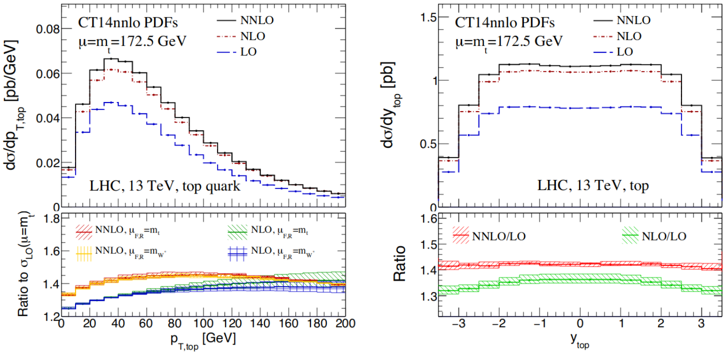


In the s-channel, the NLO corrections are ~ 35%; NNLO corrections ~ 7%; scale uncertainties are also reduced.

The meaurement of inclusive cross section at LHC ⇒
$|V_{tb}| = 1.05 \pm 0.07(exp) \pm 0.02(th)$.

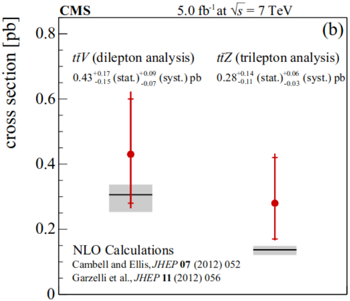
Single Top Production

The NNLO corrections (in the s-channel) reach up to 10% in kinematic distributions.



Associated Production: $t\bar{t} + X$

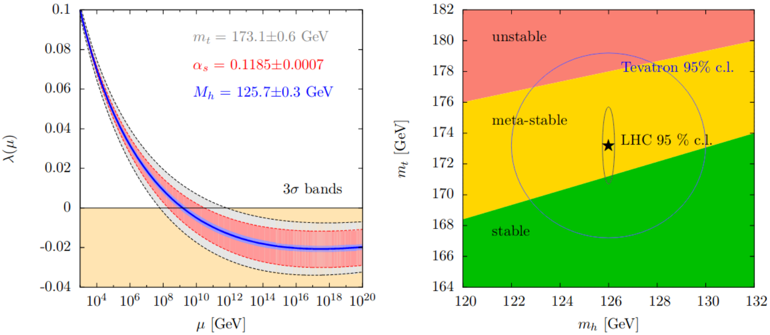
Many of them have already been observed.
ttH: information on $|y_t|$
ttγ: em coupling of top quark
ttZ: coupling of Z with top
ttW: coupling of W with top (Edited: No you don't probe coupling of top with W. Why ?)
tHj: sign of $|y_t|$



Top Quark Mass (m_t)

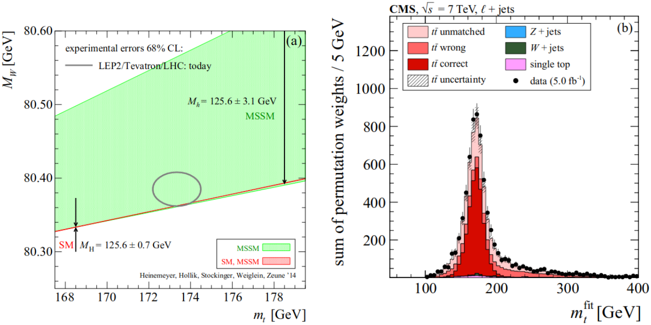
A precise measurement of top-quark mass is requird. It affects effective Higgs potential via quantum corrections.

$$\mu\frac{d\lambda}{d\mu} = \frac{1}{16\pi^2}\left(\frac{3g'^4}{8} + \frac{3g^2g'^2}{4} + \frac{9g^4}{8} - 6y_t^4 - \lambda(3g'^2 + 9g^2 - 12y_t^2) + 24\lambda^2\right)$$



Top Quark Mass (m_t)

Testing the consistency of the SM via W-mass.



At the collider we can measure m_t very precisely through invariant mass of the top decay products. From a theoretical point-of-view, this mass is closer to the pole mass (mass defined in on-shell scheme). Pole mass for quarks can never be determined with accuracy better than Λ_{QCD}. The other pssibility is to use $\overline{\text{MS}}$ scheme and $m_t \to m_t(\mu_R)$ (running mass).