Top quark at colliders

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Introduction and Outline

- The top quark has a very large width ($\Gamma_t \simeq 1.5\,\mathrm{GeV} \gg \Lambda_{\mathrm{QCD}}$) and decays before it would form a meson: very clean laboratory for strong and electroweak interactions.

- What do we know: it has been discovered (!) (CDF/D∅, 1995) and its mass has been measured ($m_t = 172.5 \pm 2.3$ GeV).

- What do we need to explore further:
  $\longrightarrow$ strong and EW couplings ($\rightarrow t\bar{t}$ and single-top production);
  $\longrightarrow$ mass: precision needed to constrain M_H ($\rightarrow t\bar{t}$ production);
  $\longrightarrow$ Yukawa coupling to the Higgs boson ($\rightarrow t\bar{t}H$ production).

  Status of theoretical predictions and experimental measurements.

- The top laboratory is even richer:
  $\longrightarrow$ top-decays and polarization measurements.

- Main focus: hadron colliders.

The top quark in the Standard Model

The top quark gauge Lagrangian in the Standard Model (SM) is:

$$\mathcal{L}_{\rm gauge} = i\overline{Q_L}\not{D}Q_L + i\overline{t_R}\not{D}t_R + i\overline{b_R}\not{D}b_R$$

where the SM covariant derivative D^μ is:

$$D_\mu = \partial^\mu + ig_s G^a_\mu T^a + igW^i_\mu T^i + ig' B_\mu Y$$

in terms of the generators and gauge bosons of $SU(3)_{\rm color}$ (T^a, G^a_μ, g_s), $SU(2)_W$ (T^i, W^i_μ, g), and $U(1)_Y$ (Y, B_μ, g') gauge groups, while:

$$Z_\mu = \cos\theta_W W^3_\mu - \sin\theta_W B_\mu \quad , \quad A_\mu = \sin\theta_W W^3_\mu + \cos\theta_W B_\mu$$

in terms of θ_W, the Weinberg's angle.

In addition, the coupling to the Higgs boson field (H), upon SSB, is:

$$\mathcal{L}_{\rm Yukawa} = -y_t \bar{t}tH$$

with $\boxed{y_t = m_t/v}$ ($v = (\sqrt{2}G_F)^{-1/2} \simeq 246$ GeV).

When expressed in terms of mass eigenstates, the charged current interactions introduce flavor mixing in the SM:

$$\mathcal{L}_{W^\pm} = g W_\mu^- \sum_{i=u,c,t;j=d,s,b} V_{ij} \bar{q}_i \gamma^\mu q_j + \text{h.c.}$$

Where V_{ij} are the elements of the Cabibbo-Kobayashi-Maskawa matrix:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

V_{tj} $(j = d, s, b)$ parametrize the weak interactions of the top quark. Indeed, the top quark is intrinsically related to the origin of CP-violation in the SM:

$$3 \text{ generations} \longrightarrow \text{one complex phase in } V_{CKM}.$$

Assuming only 3 generations:

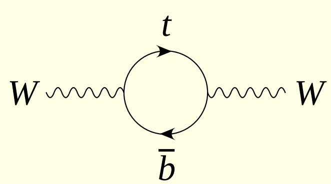
$$V_{CKM} = \begin{pmatrix} \cdots & \cdots & \cdots \\ 0.0048 - 0.014 & 0.037 - 0.043 & 0.9990 - 0.9992 \end{pmatrix}$$

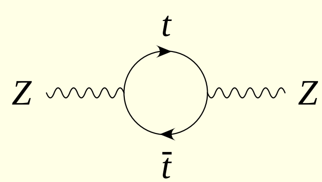
Add one more heavy generation: $\boxed{V_{tb} > 0.7}$ $\rightarrow$ much weaker bound.

Top mass and Electroweak Precision Physics

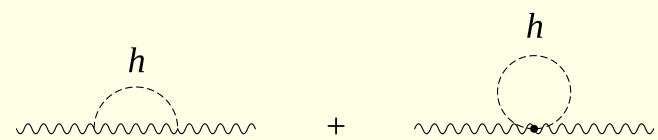
EW Radiative corrections depend on the top mass (m_t). Using the value measured at the Tevatron, EW precision fits can constrain the Higgs boson mass (M_H).

Both top quark and Higgs boson contributing to 1-loop W/Z propagators:





and



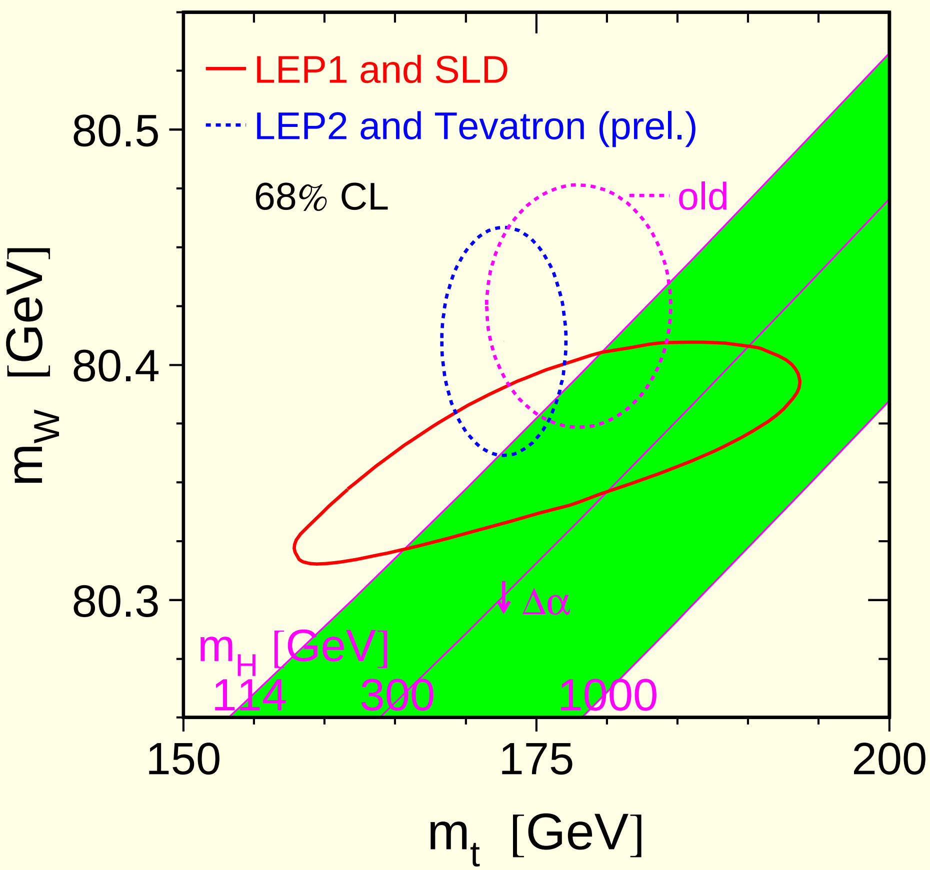
Assuming α, G_F and M_Z as inputs, M_W^2 at 1-loop is given by:

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2\theta_W} \frac{1}{1-\Delta r(m_t, M_H)}$$

where

$$\Delta r(m_t, M_H) \simeq c_t m_t^2 + c_H \ln\left(\frac{M_H^2}{M_Z^2}\right) + \cdots$$

M_H very sensitive to small variations of m_t (and M_W!)



"old": early Summer 2005

$$m_t = 178.0 \pm 4.3 \text{ GeV}$$

"new": late Summer 2005

$$m_t = 172.7 \pm 2.9 \text{ GeV}$$

$$\downarrow$$

Since Winter 2006:

$$m_t = 172.5 \pm 2.3 \text{ GeV}$$

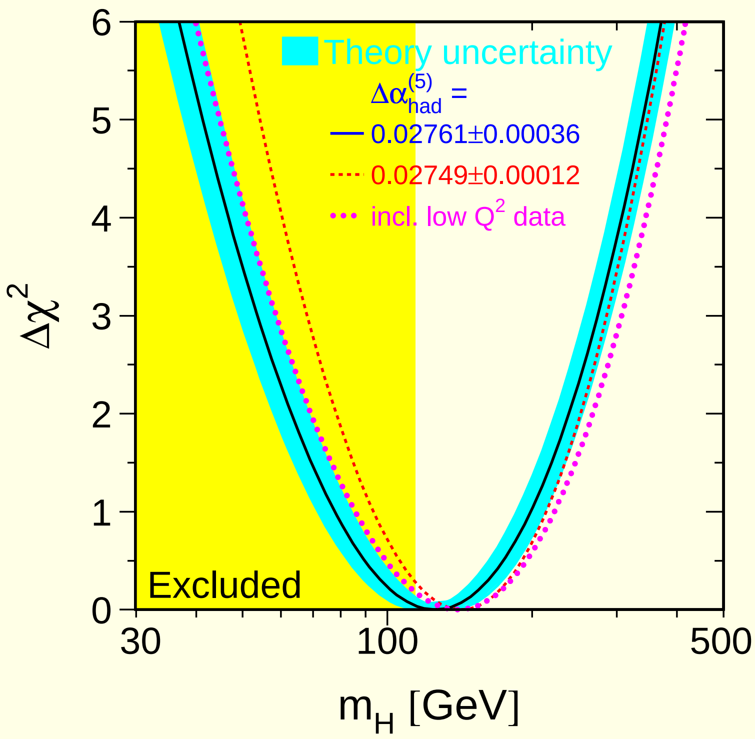
LEP1 and SLD $\longrightarrow$ indirect measurement (neutral-current data)

LEP2 and Tevatron $\longrightarrow$ direct measurement

shaded area $\longrightarrow$ SM relation between m_t and M_W as a function of M_H

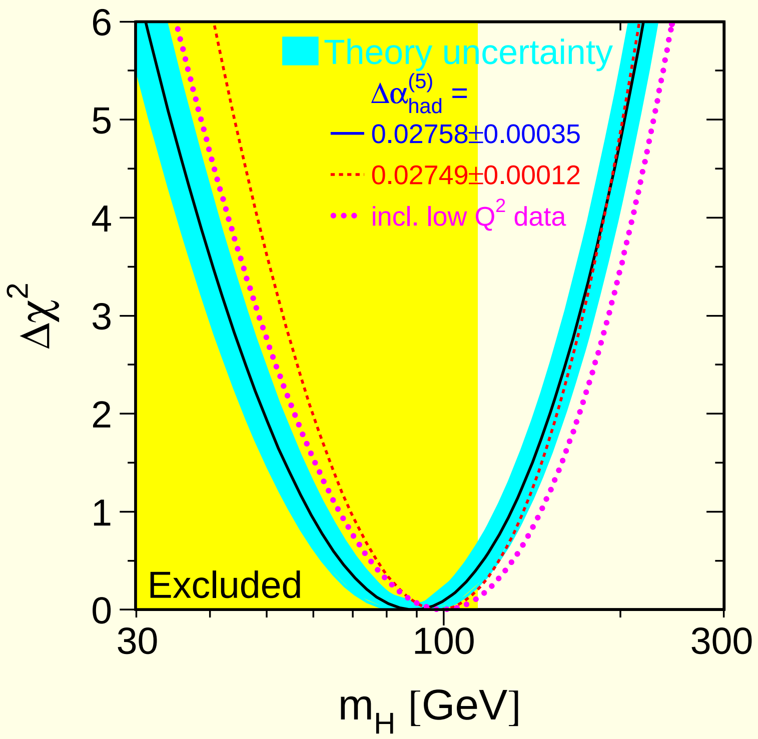
$\Delta\alpha$ $\longrightarrow$ additional theoretical uncertainty by varying α by 1σ.

as we can see from the famous blue-band plot ...



Before Summer 2005

$$\begin{cases} M_H = 117^{+67}_{-45} \ \text{GeV} \\ M_H < 251 \ \text{GeV} \ \ (95\% \text{ CL}) \end{cases}$$



Since Winter 2006

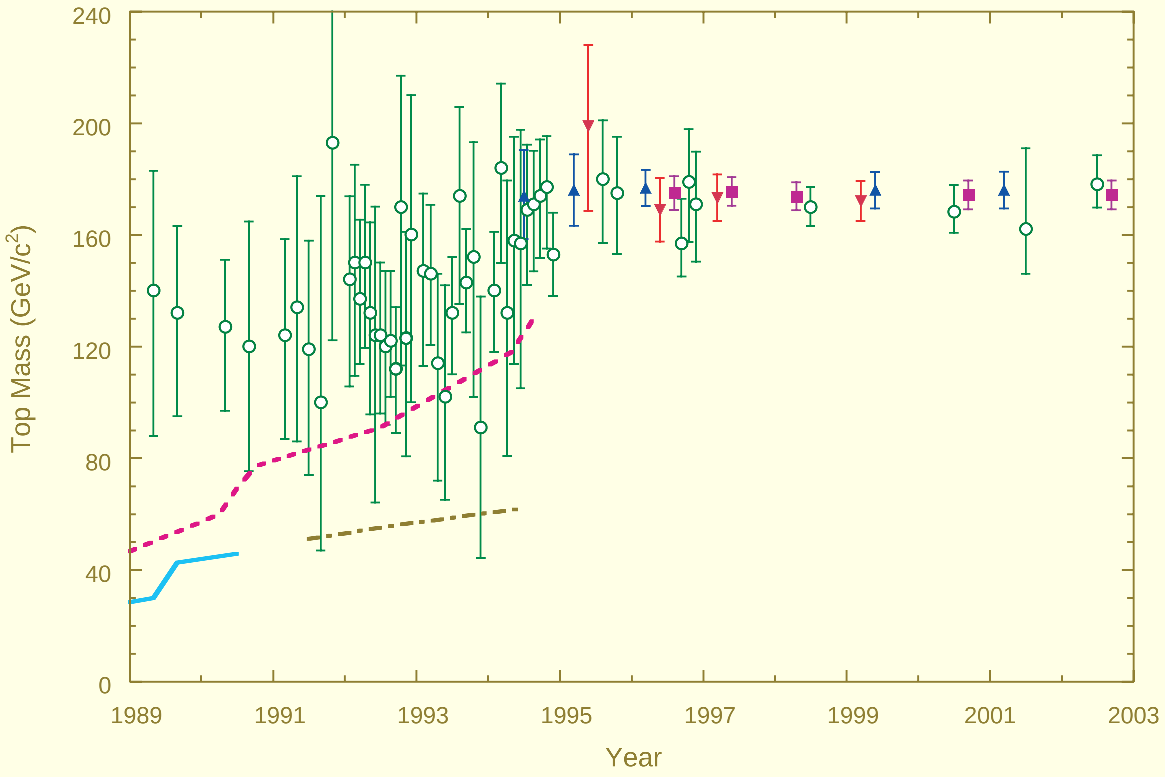
$$\begin{cases} M_H = 89^{+42}_{-30} \ \text{GeV} \\ M_H < 175 - 207 \ \text{GeV} \ \ (95\% \text{ CL}) \end{cases}$$

How accurately will we know m_t in the future?

$\Delta m_t \simeq 2$ GeV (Tevatron)

$\Delta m_t \simeq 1$ GeV (LHC)

A little bit of history . . .



green $\longrightarrow$ indirect fits

blue $\longrightarrow$ CDF

red $\longrightarrow$ DØ

violet $\longrightarrow$ World Average

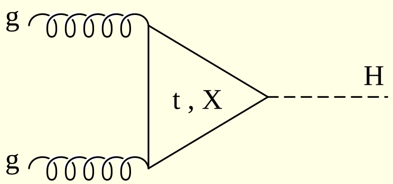
(direct searches)

(C. Quigg)

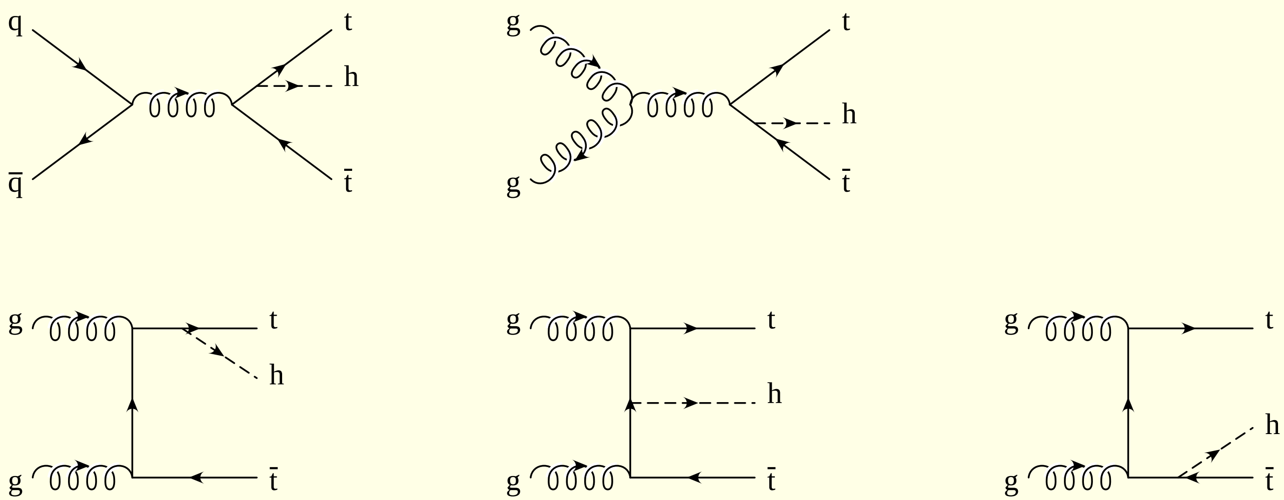
Top quark Yukawa coupling and more . . .

The SM Higgs boson couple to the top quark in two production modes:

$\longrightarrow$ gluon-gluon fusion: indirect determination of y_t.

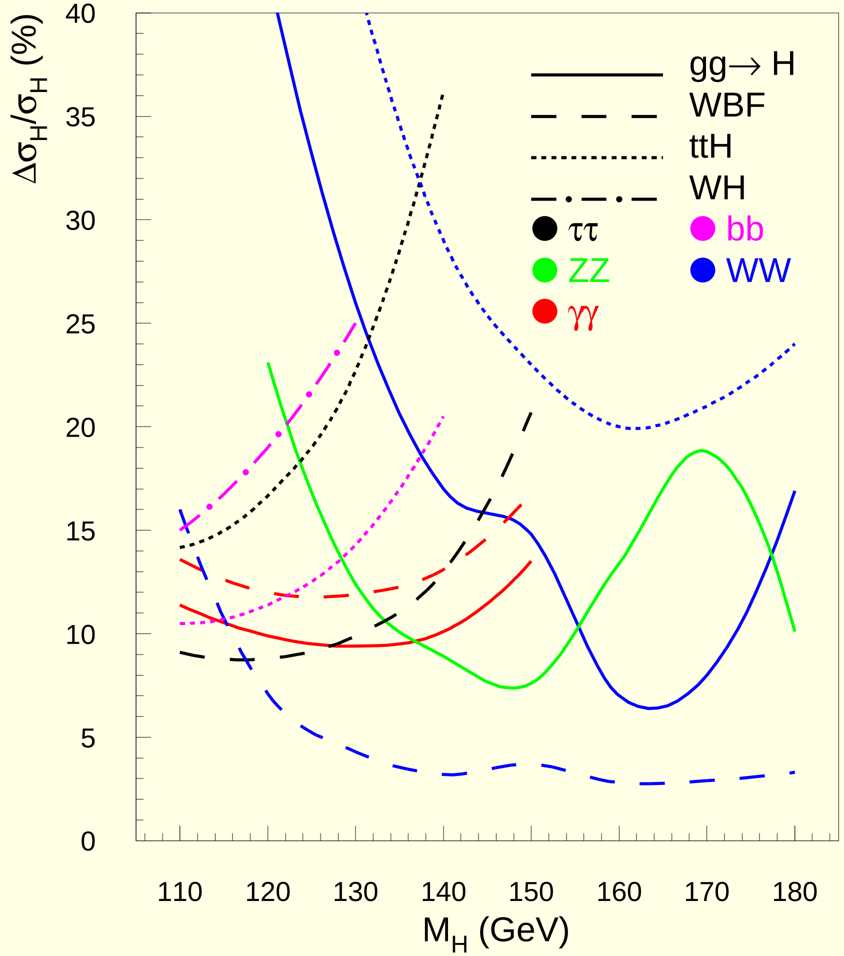


$\longrightarrow$ associated production with $t\bar{t}$ pair: direct determination of y_t.



Can the top Yukawa coupling be measured?

It comes from a more general strategy aimed at determining several couplings at once. Consider all accessible channels at the LHC:



- Below 130-140 GeV

  $gg \to H\ ,\ H \to \gamma\gamma, WW, ZZ$

  $qq \to qqH\ ,\ H \to \gamma\gamma, WW, ZZ, \tau\tau$

  $q\bar{q}, gg \to t\bar{t}H\ ,\ H \to b\bar{b}, \tau\tau$

- Above 130-140 GeV

  $gg \to H\ ,\ H \to WW, ZZ$

  $qq \to qqH\ ,\ H \to \gamma\gamma, WW, ZZ$

  $q\bar{q}, gg \to t\bar{t}H\ ,\ H \to WW$

($t\bar{t}H$: F.Maltoni, D.Rainwater, S.Willenbrock, A.Belyaev, L.R.)

Observing a given production+decay (p+d) channel gives a relation:

$$(\sigma_p(H)\mathrm{Br}(H \to dd))^{exp} = \frac{\sigma_p^{th}(H)}{\Gamma_p^{th}} \frac{\Gamma_d \Gamma_p}{\Gamma}$$

(in the narrow Higgs approximation).

Associate to each channel $(\sigma_p(H) \times Br(H \to dd))$

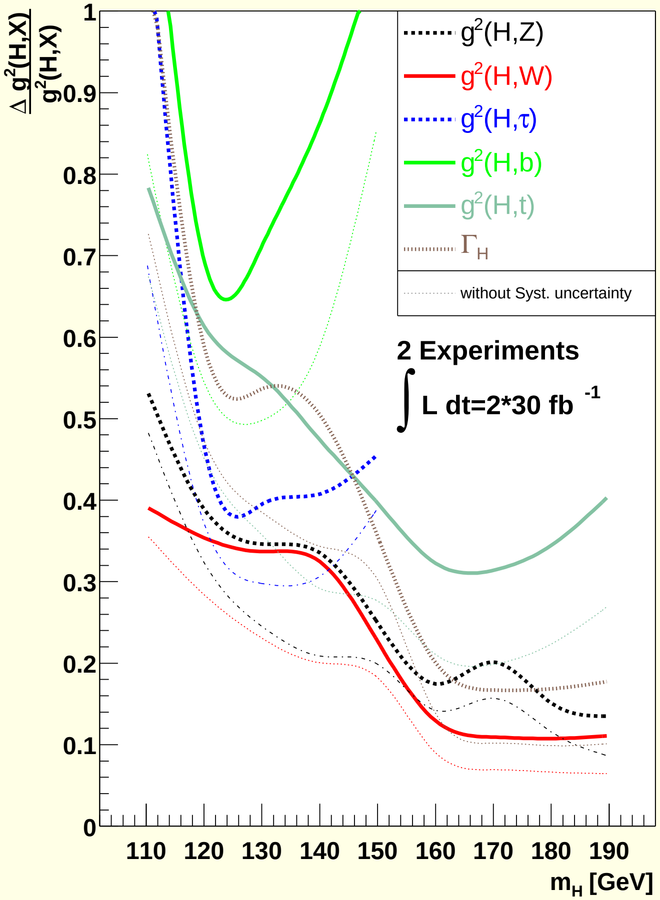
$$Z_d^{(p)} = \frac{\Gamma_p \Gamma_d}{\Gamma} \qquad \begin{cases} \Gamma_p \simeq g_{Hpp}^2 = y_p^2 \to \text{production} \\ \Gamma_d \simeq g_{Hdd}^2 = y_d^2 \to \text{decay} \end{cases}$$

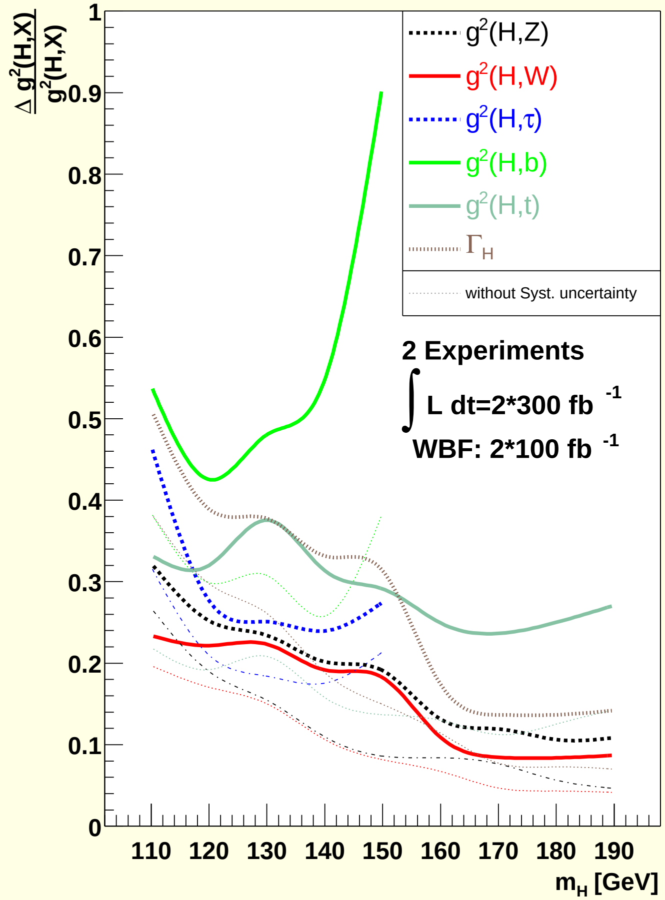
From LHC measurements, given the current simulated accuracies:

- Determine in a model independent way ratios of couplings at the $10 - 20\%$ level, for example:

$$\frac{y_t}{y_g} \quad \longleftrightarrow \quad \frac{\Gamma_t}{\Gamma_g} = \frac{Z_\tau^{(t)} Z_\gamma^{(w)}}{Z_\tau^{(w)} Z_\gamma^{(g)}}$$

- Determine individual couplings at the 10-30% level (under the assumption: $\Gamma = \Gamma_b + \Gamma_\tau + \Gamma_w + \Gamma_z + \Gamma_g + \Gamma_\gamma$)





Global χ^2 fit assuming

- $\longrightarrow$ $g^2(H,V) < g^2(H,V,SM) + 5\%$ $(V = W, Z)$
- $\longrightarrow$ new particles in loop production/decay modes
- $\longrightarrow$ unobservable decay modes

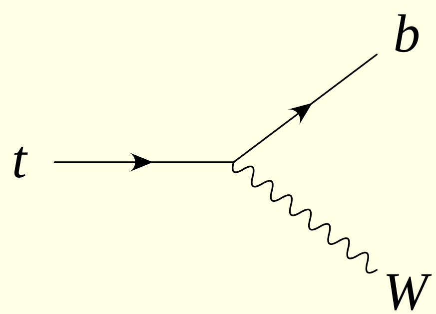
(M.Dührssen, S.Heinemeyer, H.Logan, D.Rainwater, G.Weiglein, D.Zeppenfeld, PRD 70 (2004) 113009)

Top quark decays

The top quark decays before it can form a bound state:

$\boxed{\tau_t \simeq 10^{-25} \text{ sec}}$ compared to $\boxed{\tau_{\text{QCD}} \simeq 10^{-24} \text{ sec}}$

and it decays predominantly as:



$$t \to bW^+ \quad \left\{ \begin{array}{l} W^+ \to l^+\nu_l \\ W^+ \to q\bar{q}' \end{array} \right.$$

It is instructive to derive the decay rate explicitely and see how the structure of the interaction constrains the helicity of the W-boson.

$$\Downarrow$$

The W coming from $t \to bW^+$ can only be (for $m_b \to 0$) either left-handed or longitudinal, never right-handed, because of angular momentum conservation.

How do you go calculating it ...

The decay amplitude for $t(p_t) \to b(p_b)W^+(p_W)$ comes straight from the top-quark EW Feynman rules:

$$\mathcal{A}(t \to bW^+) = -\frac{ig}{2\sqrt{2}}\, V_{tb}\bar{u}(p_b)\gamma^\mu(1-\gamma_5)u(p_t)\ \epsilon_\mu^{\lambda *}(p_W)$$

and the decay rate, for a given W-boson polarization, is calculated as:

$$\frac{1}{2m_t}\int d(PS_2)\overline{\sum}|\mathcal{A}(t \to bW^+)|^2$$

Assume the top-quark is unpolarized, to start with, and work in its rest frame. Then the momentum configuration can be parametrized as:

$$\begin{aligned}
p_t &= (m_t, 0, 0, 0) \\
p_W &= (E_W, 0, p\sin\theta_W^t, p\cos\theta_W^t) \\
p_b &= (E_b, 0, -p\sin\theta_W^t, -p\cos\theta_W^t)
\end{aligned}$$

with $E_W = \frac{m_t^2+M_W^2}{2m_t}$ and $p = \frac{m_t^2-M_W^2}{2m_t}$, while the W polarization vectors are:

$$\begin{aligned}
\epsilon_0 &= \frac{1}{M_W}\left(p, 0, E_W\sin\theta_W^t, E_W\cos\theta_W^t\right) \\
\epsilon_\pm &= \frac{1}{\sqrt{2}}\left(0, 1, \pm i\cos\theta_W^t, \mp\sin\theta_W^t\right)
\end{aligned}$$

Neglecting the mass of the b quark ($m_b \to 0$), one gets:

$$\overline{\sum} |\mathcal{A}(t \to bW^+)|^2 = \frac{g^2}{8} |V_{tb}|^2 \mathrm{Tr}\left[(\not{p}_t + m_t) \not{\epsilon}_\lambda^* (1 - \gamma_5) \not{p}_b \not{\epsilon}_\lambda \right]$$

and substituting the explicit polarization vectors one derives that:

$$\begin{aligned} \overline{\sum} |\mathcal{A}_-|^2 &= \frac{2 G_F m_t^4}{\sqrt{2}} |V_{tb}|^2 2x^2 (1 - x^2) \\ \overline{\sum} |\mathcal{A}_0|^2 &= \frac{2 G_F m_t^4}{\sqrt{2}} |V_{tb}|^2 (1 - x^2) \end{aligned}$$

for $x = \frac{M_W}{m_t}$, such that:

$$F_0 = \frac{\Gamma_0}{\Gamma_{\mathrm{tot}}} = \frac{1}{1 + 2x^2} = \frac{m_t^2}{m_t^2 + 2M_W^2} \simeq 0.70$$

Experimentally:

$$\begin{aligned} F_0 &= 0.74^{+0.22}_{-0.34} \text{ (stat+syst) (CDF)} \\ F_+ &< 0.27 \text{ at } 95\% \text{ c.l. (CDF)} \\ F_+ &< 0.25 \text{ at } 95\% \text{ c.l. (D}\emptyset\text{)} \end{aligned}$$

$\Gamma(t \to bW)$ also measure $|V_{tb}|$ ...

$$R_{tb} = \frac{\Gamma(t \to bW)}{\Gamma(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} =$$

Assuming unitarity ($|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$), R_{tb} measures $|V_{tb}|$.

Experimentally:

$$\left\{ \begin{array}{c} R_{tb} = 1.12^{+0.21+0.17}_{-0.19-0.13} \text{ (stat+syst) (CDF)} \\ R_{tb} > 0.61 \longrightarrow |V_{tb}| > 0.78 \text{ at 95\% c.l. (CDF)} \end{array} \right.$$

$$\left\{ \begin{array}{c} R_{tb} = 1.03^{+0.19}_{-0.17} \text{ (stat+syst) (D}\emptyset\text{)} \\ R_{tb} > 0.61 \longrightarrow |V_{tb}| > 0.78 \text{ at 95\% c.l. (D}\emptyset\text{)} \end{array} \right.$$

Polarized top quarks . . .

Even more interesting phenomena when decaying top-quarks are polarized (spin$=\pm\frac{1}{2}\hat{s}^\mu$, for a generic direction vector $\hat{s}^\mu$).

Using the same formalism introduced above, but now summing over W helicities and adding the $W^+ \to l^+\nu_l$ decay, one finds:

$$|\mathcal{A}|^2 = g^4|V_{tb}|^2 \frac{1}{[(p_t-p_b)^2-M_W^2]^2}(\bar{p}_t\cdot p_l\, p_b\cdot p_\nu) \propto (1+\cos\chi_l^t)$$

where $\bar{p}_t^\mu = p_t^\mu - m_t s^\mu$ and χ_l^t is the angle of the charge lepton in the top-quark c.o.m. frame.

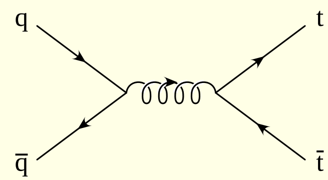
$\downarrow$

The second stage decay is 100% correlated to the parent top-quark!.

Top quark pair production: $q\bar{q}, gg \rightarrow t\bar{t}$

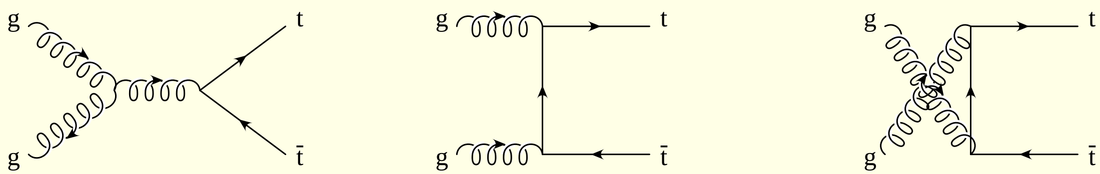
$q\bar{q} \rightarrow t\bar{t}$

leading contribution at the Tevatron



$gg \rightarrow t\bar{t}$

leading contribution at the LHC



<u>Tevatron</u>: $t\bar{t}$ pair produced close to kinematic threshold ($\hat{s} \simeq 4m_t^2$), henceforth large x dominated, while not so at the LHC.

Tevatron Run I discovered the top quark in $t\bar{t}$ production with $\simeq 100$ $t\bar{t}$ pairs. Run II has already accumulated larger statistics.
The LHC will be a top factory (≥ 8 millions top pairs/year/experiment).

The production rate of $t\bar{t}$ pairs at hadron colliders is a crucial test of top-quark strong interactions.

A precise theoretical understanding of the dynamics of $t\bar{t}$ pair production is mandatory to:

$\longrightarrow$ match the experimental precision coming from such huge statistics;

$\longrightarrow$ obtain a precision mass measurement ($\rightarrow$ see EW precision tests);

$\longrightarrow$ disentangle new physics (new production channels should give more $t\bar{t}$ pairs, new top-quark decay modes should give less).

$\downarrow$

Complete NLO calculation exists for total and differential cross-sections:

$\longrightarrow$ P. Nason, S. Dawson, R.K. Ellis, NPB 303 (1988) 607, NPB 327 (1989) 49;

$\longrightarrow$ W. Beenakker, H. Kuijf, W.L. van Neerven, J. Smith PRD 40 (1989) 54; (with R. Meng and G.A. Schuler) NPB 351 (1991) 507.

($\rightarrow$ see Practical NLO calculation)

Beyond NLO: various approximate all-order results exist.

Origin of large corrections ...

Large logarithmically-enhanced corrections arise in production cross-sections of high-mass systems near threshold ($\hat{s} = 4m_t^2$).

Consider the $t\bar{t}$ production cross-section in the form:

$$\hat{\sigma}_{ij}^{NLO}(\rho, m_t^2, \mu) = \frac{\alpha_s^2(\mu)}{m_t^2}\left\{c_{ij}^0(\rho) + 4\pi\alpha_s(\mu)\left[c_{ij}^1(\rho) + \bar{c}_{ij}^1(\rho)\ln\left(\frac{\mu^2}{m_t^2}\right)\right]\right\}$$

where $\rho = \frac{4m_t^2}{\hat{s}}$. The threshold behavior of the cross-section at LO is:

$$c_{q\bar{q}}^0(\rho) \overset{\beta\to 0}{\simeq} \frac{T_R C_F}{2N_c}\pi\beta \to 0 \quad , \quad c_{gg}^0(\rho) \overset{\beta\to 0}{\simeq} \frac{T_R}{N_c^2-1}\left(C_F - \frac{C_A}{2}\right)\pi\beta \to 0$$

(where $\beta = \sqrt{1-\rho}$), while at NLO is:

$$c_{q\bar{q}}^1(\rho) \xrightarrow{\beta\to 0} \frac{1}{4\pi^2}c_{q\bar{q}}^0(\rho)\left[\left(C_F - \frac{C_A}{2}\right)\frac{\pi^2}{2\beta} + 2C_F\ln^2(8\beta^2) - (8C_F + C_A)\ln(8\beta^2)\right]$$

$$c_{gg}^1(\rho) \xrightarrow{\beta\to 0} \frac{1}{4\pi^2}c_{gg}^0(\rho)\left[\frac{N_c^2+2}{N_c(N_c^2-2)}\frac{\pi^2}{4\beta} + 2C_A\ln^2(8\beta^2) - \frac{(9N_c^2-20)C_A}{N_c^2-2}\ln(8\beta^2)\right]$$

$$\bar{c}_{q\bar{q}}^1(\rho)\ln\left(\frac{\mu^2}{m_t^2}\right) \xrightarrow{\beta\to 0} \frac{1}{4\pi^2}c_{q\bar{q}}^0(\rho)\left[-2C_F\ln(4\beta^2)\ln\left(\frac{\mu^2}{m_t^2}\right) + \bar{C}_2\left(\frac{\mu^2}{m_t^2}\right)\right]$$

$$\bar{c}_{gg}^1(\rho)\ln\left(\frac{\mu^2}{m_t^2}\right) \xrightarrow{\beta\to 0} \frac{1}{4\pi^2}c_{gg}^0(\rho)\left[-2C_A\ln(4\beta^2)\ln\left(\frac{\mu^2}{m_t^2}\right) + \bar{C}_3\left(\frac{\mu^2}{m_t^2}\right)\right]$$

Threshold logarithms can be resummed via exponentiation: similar to Drell-Yan (DY), more complicated because of color structure.

Traditional to work in moment space, or Mellin-transformed space, or N-space. The Mellin-transformed cross-section of $\sigma(\rho, m_t^2)$ is defined as:

$$\hat{\sigma}_N(m^2) = \int_0^1 d\rho \rho^{N-1} \hat{\sigma}(\rho, m^2)$$

The threshold region corresponds to the $N \to \infty$ limit and threshold corrections have the following structure:

$$\hat{\sigma}_N^{LO} \left[1 + \sum_{n=1}^{\infty} \alpha_s^n \sum_{m=1}^{2n} c_{n,m} \ln^m N \right]$$

In DY this structure can be organized in a radiative factor $\Delta_{DY,N}$ of exponential form:

$$\begin{aligned} \Delta_{DY,N}(\alpha_s) &= \exp\left[\sum_{n=1}^{\infty} \alpha_s^n \sum_{m=1}^{n+1} G_{nm} \ln^m N \right] \\ &= \exp\left[\underbrace{\ln N g_{DY}^{(1)}(\alpha_s \ln N)}_{LL} + \underbrace{g_{DY}^{(2)}(\alpha_s \ln N)}_{NLL} + \underbrace{\alpha_s g_{DY}^{(3)}(\alpha_s \ln N)}_{NNLL} + \cdots \right] \end{aligned}$$

Generalization to $t\bar{t}$ production complicated by:

- $\longrightarrow$ $q\bar{q}$ and gg initial states;
- $\longrightarrow$ soft-gluon emission from both initial and final states: color exchange in the hard subprocess.

The resummed cross-section (N-space) can be cast into the form:

$$\hat{\sigma}_{ij}^{(res)} = \sum_{\mathbf{I},\mathbf{J}} M^{\dagger}_{ij,\mathbf{I},N} [\Delta_{ij,N}]_{\mathbf{I},\mathbf{J}} M_{ij,\mathbf{J},N}$$

where the sum is extended to all possible color states $\mathbf{I}$ and $\mathbf{J}$. $[\Delta_{ij,N}]_{\mathbf{I},\mathbf{J}}$ is the radiation factor, a matrix in the space of color states, and contains all the resummed soft logarithms.

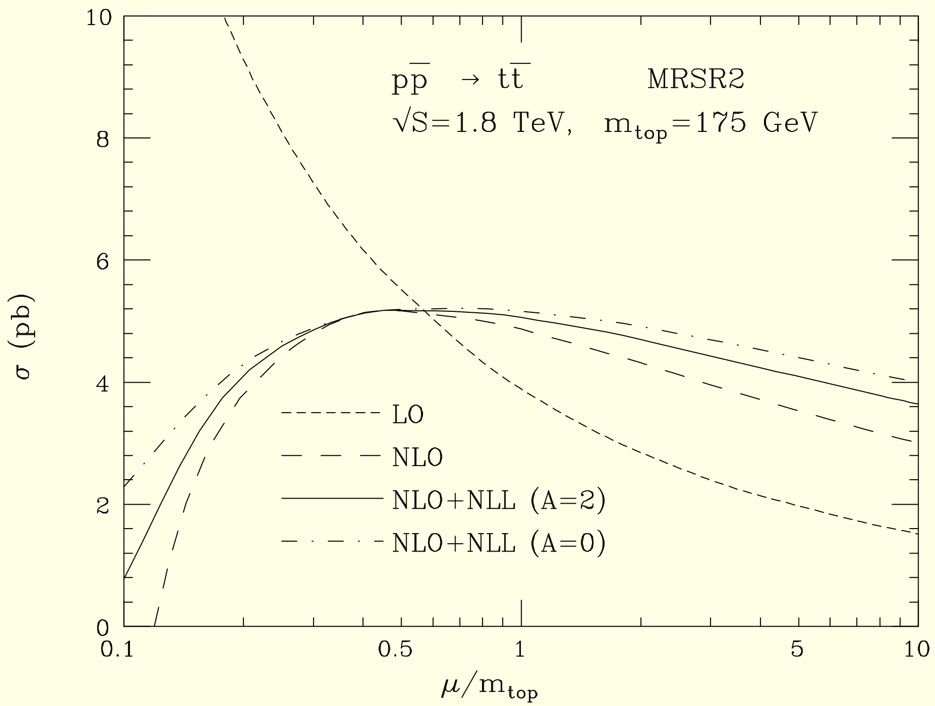
Formalism proposed by:

- $\longrightarrow$ N. Kidonakis, G. Sterman, PLB 387 (1996) 867, NPB 478 (1996) 273

and implemented in:

- $\longrightarrow$ R. Bonciani, S. Catani, M. Mangano, P. Nason, NPB 529 (1998) 424
- $\longrightarrow$ N. Kidonakis, R. Vogt, PRD 68 (2003) 1140014
- $\longrightarrow$ M. Cacciari, S. Frixione, M. Mangano, P. Nason, JHEP 04 (2004) 68

Back to the plot we saw in “Practical NLO calculation”:



(R. Bonciani, S. Catani, M. Mangano, P. Nason, NPB 529 (1998) 424)

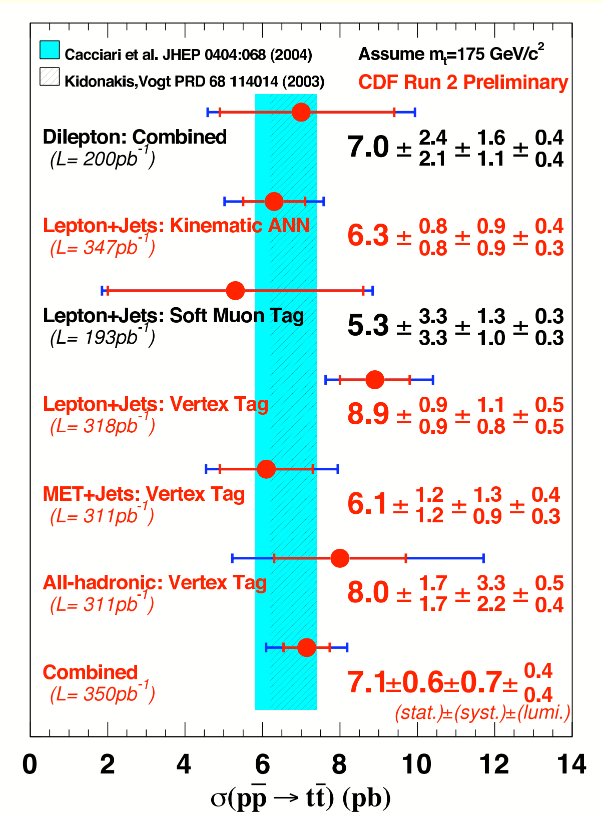
NLO $\longrightarrow$ scale uncertainty $\simeq \pm 10\%$

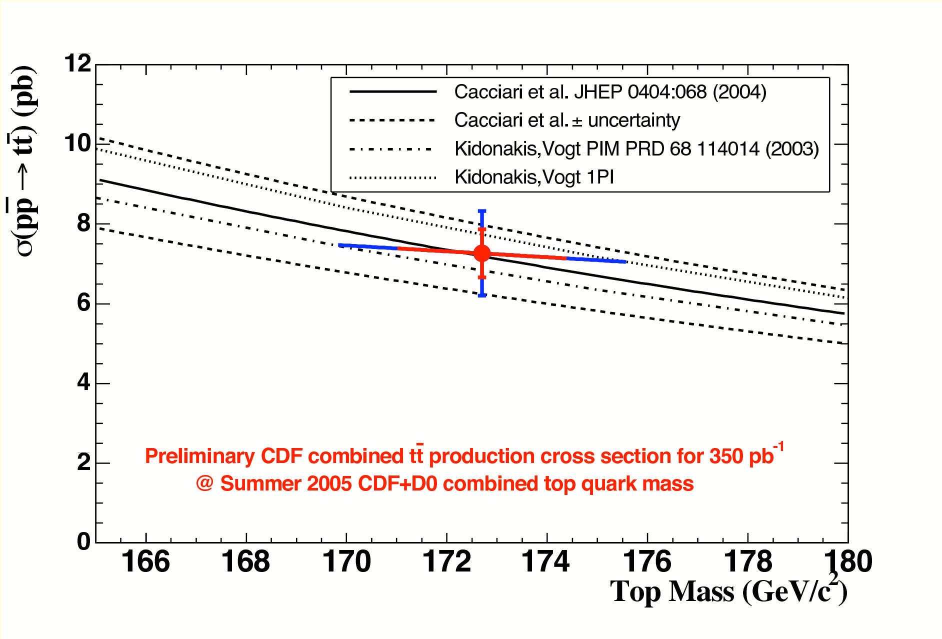
NLO+NNL $\longrightarrow$ scale uncertainty $\simeq \pm 5\%$

Including PDF uncertainty: $\simeq \pm 15\%$ residual uncertainty in theoretical prediction.

(M. Cacciari, S. Frixione, M. Mangano, P. Nason, JHEP 04 (2004) 68)

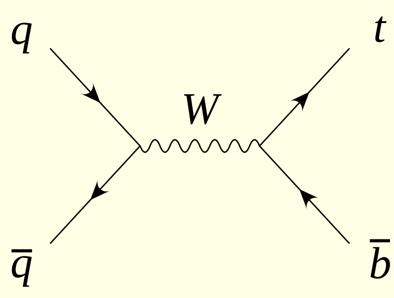
comparing to experimental results . . .

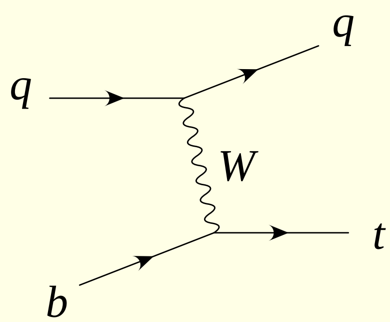


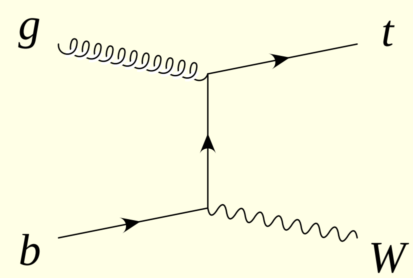


NLO and resummation of soft corrections crucial to match the $t\bar{t}$ cross-section measurement so closely.

Single top production: measuring V_{tb}



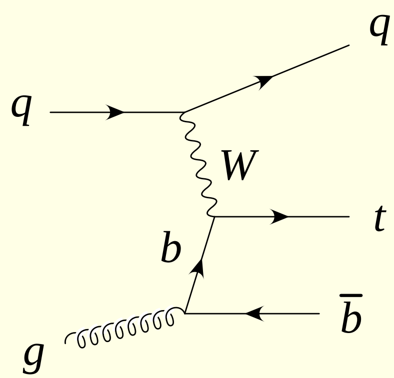


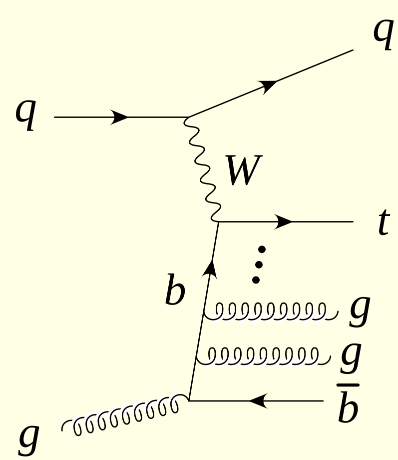


s-channel $\quad$ t-channel $\quad$ Wt associated prod.

- t-channel dominated both at the Tevatron and at the LHC.
- Wt associated production: LHC only.
- s-channel and t-channel have distinct signatures ($2b$ vs $1b$ tag). Important because s- and t-channels are:
  - $\rightarrow$ sensitive to different kinds of new physics (s-channel more sensitive to new resonances, t-channel more sensitive to new couplings);
  - $\rightarrow$ sensitive to different theoretical approaches (t-channel calculated using a b-quark density $\rightarrow$ 5FNS).

On the issue of a b-quark density ...





→ Large collinear logarithms of the form $\ln\left(\frac{m_t^2}{m_b^2}\right)$ arise at each order in α_s from $g \to b\bar{b}$ splitting (when integrating over the phase space of the final state on-shell b-quark).

→ Switch to perturbative expansion in $\alpha_s \ln\left(\frac{m_t^2}{m_b^2}\right)$ instead of α_s.

→ Resum powers of $\alpha_s \ln\left(\frac{m_t^2}{m_b^2}\right)$ (appearing from further gluon emission at all orders in α_s) by defining a b-quark PDF evolved through DGLAP equation.

→ measuring single-top production in t-channel could be an important cross-check of $b(x, \mu)$.

How to measure V_{tb}? Use two cross-sections:

$$\sigma_{t\bar{t}}^{exp} = \sigma_{t\bar{t}}^{th} \, \mathrm{Br}(t \to bW)^2$$

to measure $\mathrm{Br}(t \to bW)$ and then

$$\sigma_{t}^{exp} = \sigma_{t}^{th} |V_{tb}|^2 \, \mathrm{Br}(t \to bW)$$

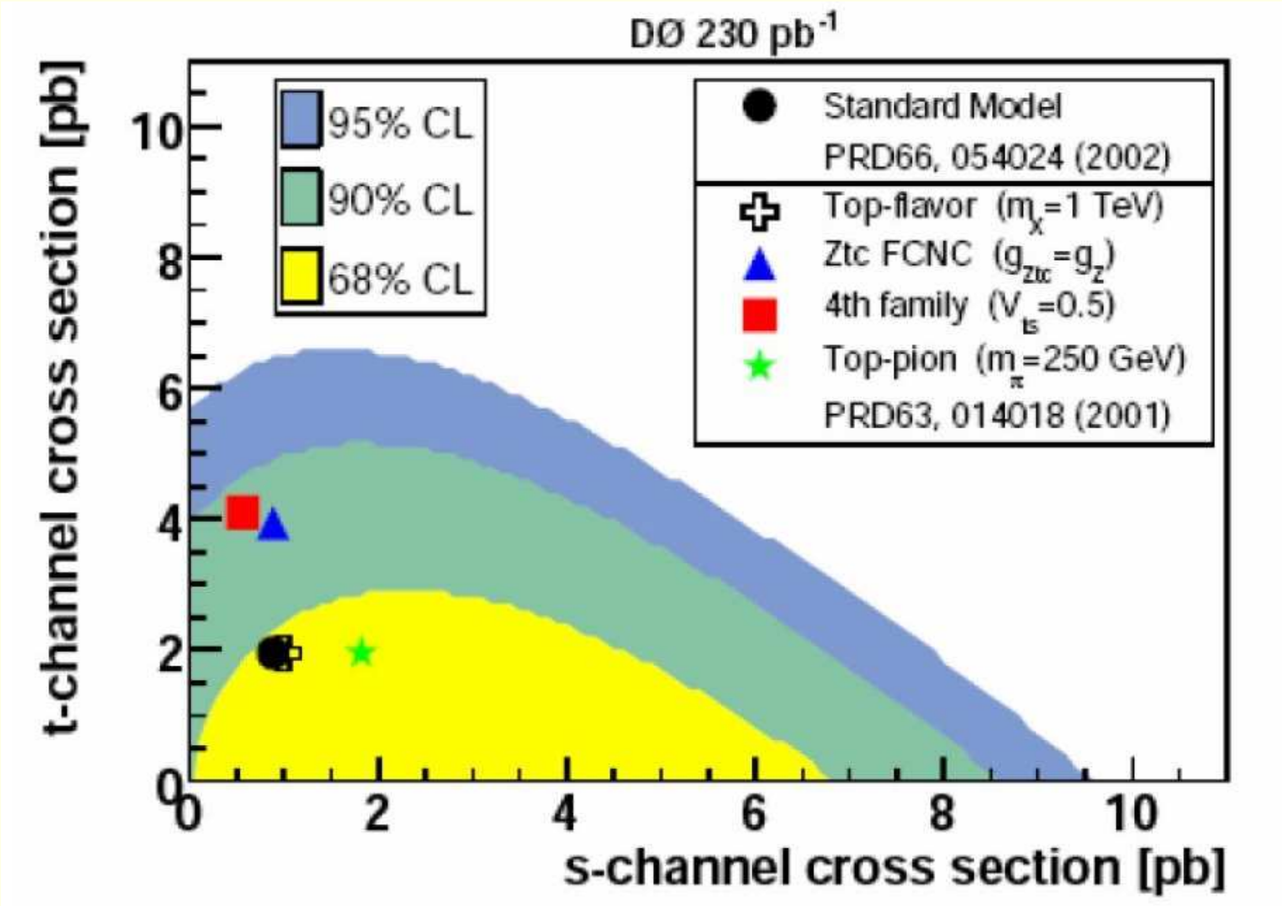
to extract V_{tb}.

NLO QCD corrections calculated for total cross section and distributions:

- → M.C. Smith, S. Willenbrock, PRD 54 (1996) 6696;
- → T. Stelzer, Z. Sullivan, S. Willenbrock, PRD 56 (1997) 5919;
- → T. Stelzer, Z. Sullivan, S. Willenbrock, PRD 58 (1998) 0904021;
- → B. W. Harris, E. Laenen, L. Phaf, Z. Sullivan, S. Weinzierl, PRD 66 (2002) 054024
- → Z. Sullivan, PRD 70 (2004) 114012
- → J. Campbell, R. K. Ellis, F. Tramontano, PRD 70 (2004) 094012
- → Q.-H. Cao, R. Schwienhorst, C.-P. Yuan, PRD 71 (2005) 054023

Tevatron: closing in on single-top production . . .

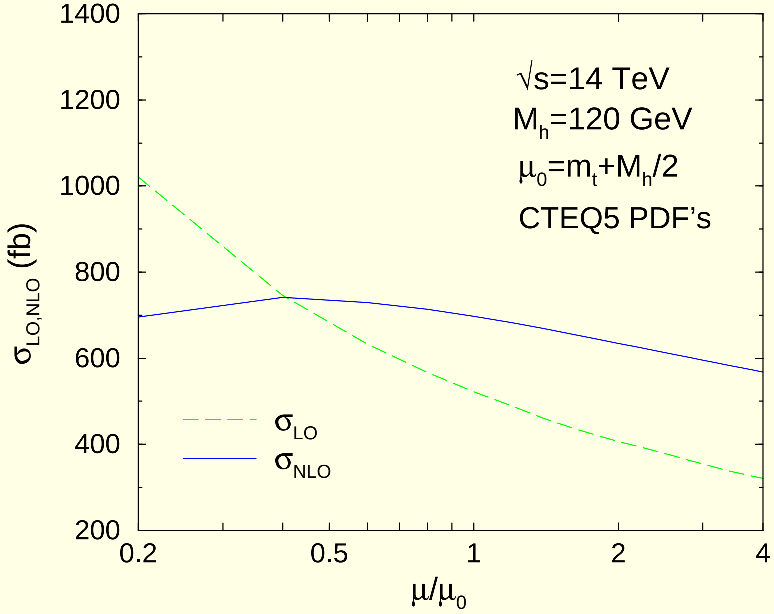
	Theory	CDF	DØ
s-channel	(0.88 ± 0.14) pb	< 13.6 pb	< 6.4 pb
t-channel	(1.98 ± 0.30) pb	< 10.1 pb	< 5.0 pb

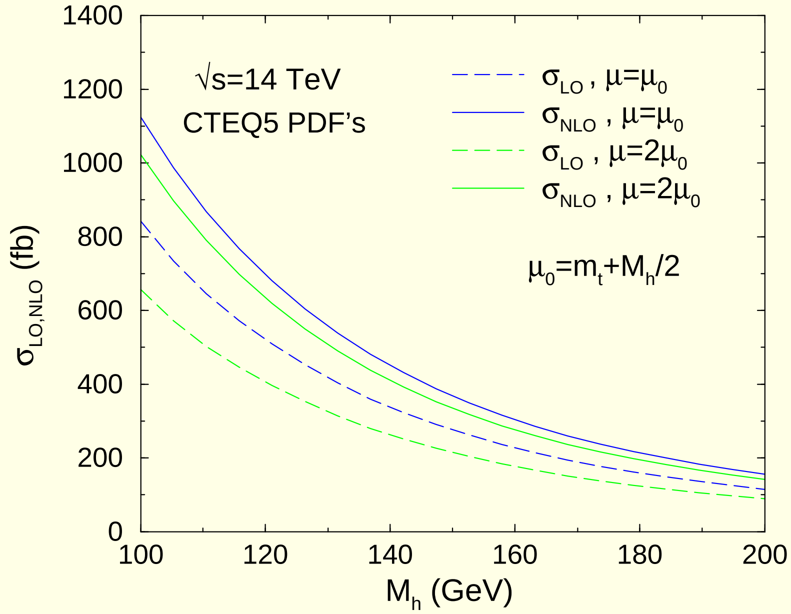


$t\bar{t}H$ associated production: determining y_t.

Small cross-section, but very neat signal. Probably not within the kinematic reach of the Tevatron, but very important at the LHC for discovery and direct determination of the top-quark Yukawa coupling y_t.

Complete NLO calculation available: scale uncertainty reduced to $\simeq 15\%$





⟶ W.Beenakker, S.Dittmaier, M.Krämer, B.Plümper, M.Spira, P.M.Zerwas (PRL 87(2001), NPB 653(2003))

⟶ S.Dawson, L.R., D.Wackeroth (PRL 87(2001), PRD 65(2002))

⟶ S.Dawson, C.Jackson, L.H.Orr, L.R., D.Wackeroth (PRD 67(2003), PRD 68(2003))

Conclusions

- Top-quark physics at hadron colliders constitutes a unique laboratory to test both strong and electroweak interactions.
- Its large mass makes the top quark a special candidate to explore spontaneous symmetry breaking. Moreover: m_t strongly influence the bound on M_H from precision electroweak fits.
- All main production modes (single-top, $t\bar{t}$ pairs, $t\bar{t}H$ associated production) are known at NLO in QCD, and large threshold corrections have been resummed when needed.
- We expect crucial developments both at the Tevatron and at the LHC:
  $\longrightarrow$ Tevatron: single-top discovery ($V_{tb}, \ldots$);
  $\longrightarrow$ LHC: measurement of y_t via $t\bar{t}H$ production.
- We did not discuss top-quark physics at a high energy e^+e^- collider (ILC). For the most updated studies, see "Report of the 2005 Snowmass Top/QCD Working Group, hep-ph/0601112.