Top quark physics at the LHC

IPM
October 17, 2007

Mojtaba Mohammadi

Top Quark properties

- Top quark, when it was discovered at Fermilab in 1995, completed the three generation structure of the SM and opened up the new field of Top quark physics.

- With the mass of 175 GeV/c2 , Top quark is the heaviest discovered elementary particle which breaks the electroweak gauge symmetry maximally among the other observed particles of the SM.

- Contrary to other quarks, Top quark decays rapidly via weak interaction without forming any hadronic bound state.

- Top quark almost exclusively decays to a W-boson and a b-quark.

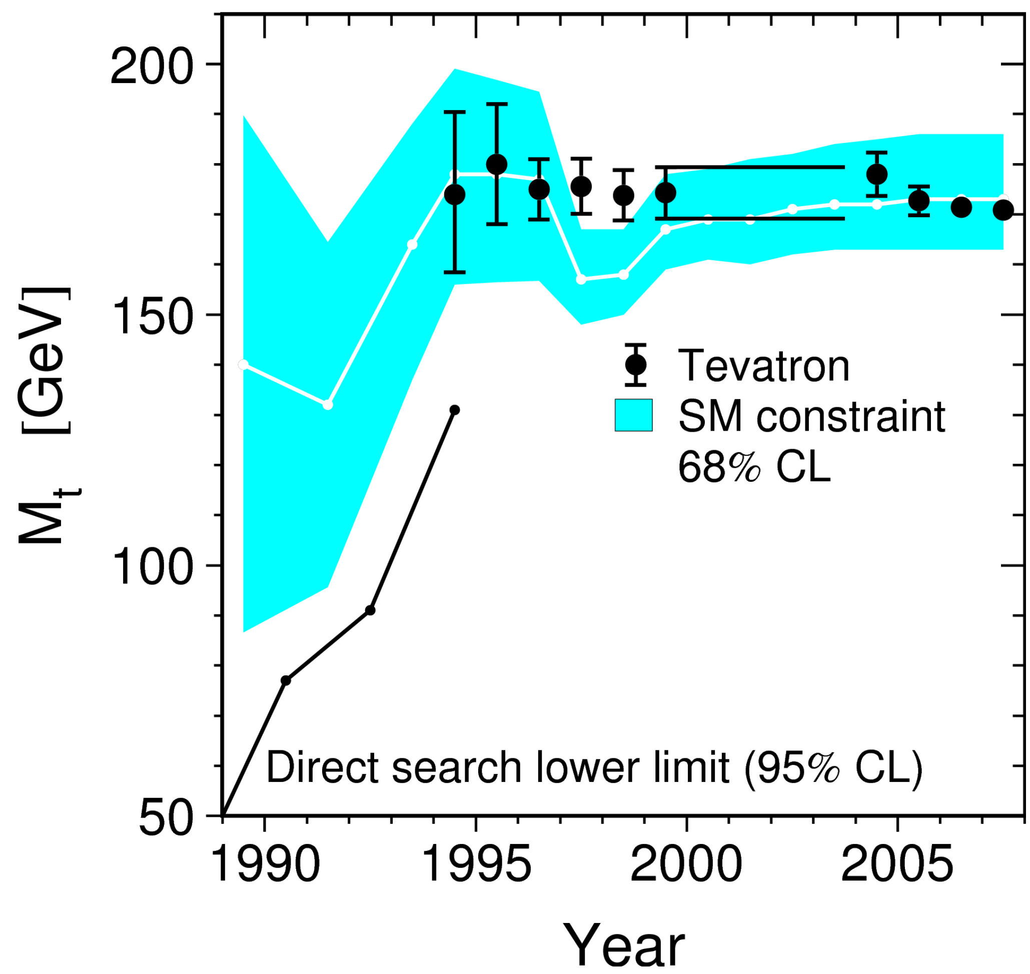
  $BR(t \rightarrow W+b) \sim 0.99$

Top quark

Since 1990:

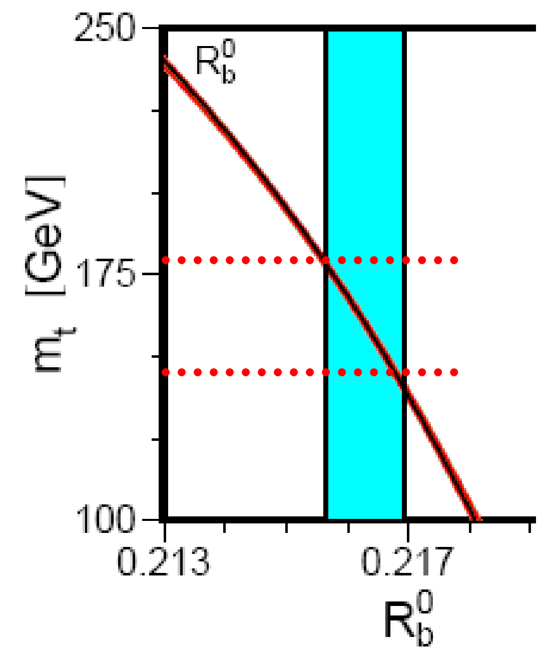
Prediction of the top quark mass

1995: Discovery at the Tevatron CDF, DØ



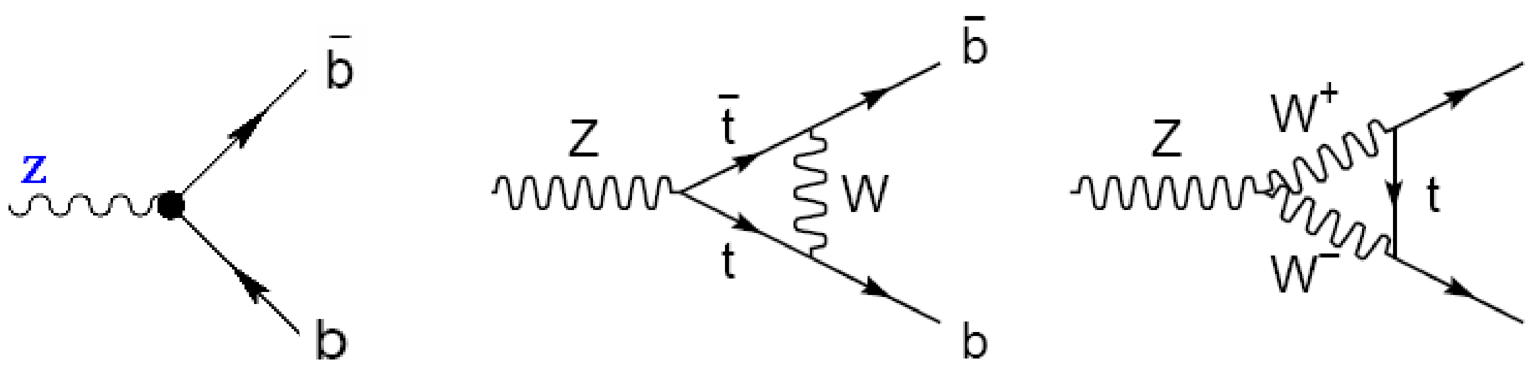
Top quark

Rb has a very strong sensitivity to top mass



$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to all\ hadrons)} = 0.21629 \pm 0.00066$$

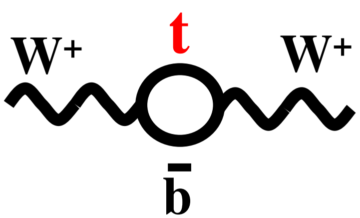
LEP,SLC



Importance of the top quark mass

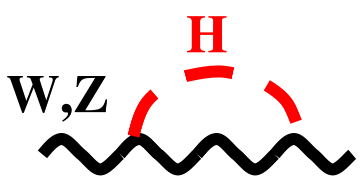
Tree level: $M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F Sin^2\theta_W}$ **1-loop correction:** $M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F Sin^2\theta_W}(1+\Delta r)$

- m_t enters quadratically in electroweak loop corrections



$(\Delta r)_{top} \propto (m_t^2 - m_b^2)$

- m_H only logarithmically



$(\Delta r)_{Higgs} \propto \log m_H/m_W$

All observables include the combined effect!

→ m_t plays a key role in precision test of the SM

- to predict the Higgs mass
- and once the Higgs is discovered to check the consistency of the model

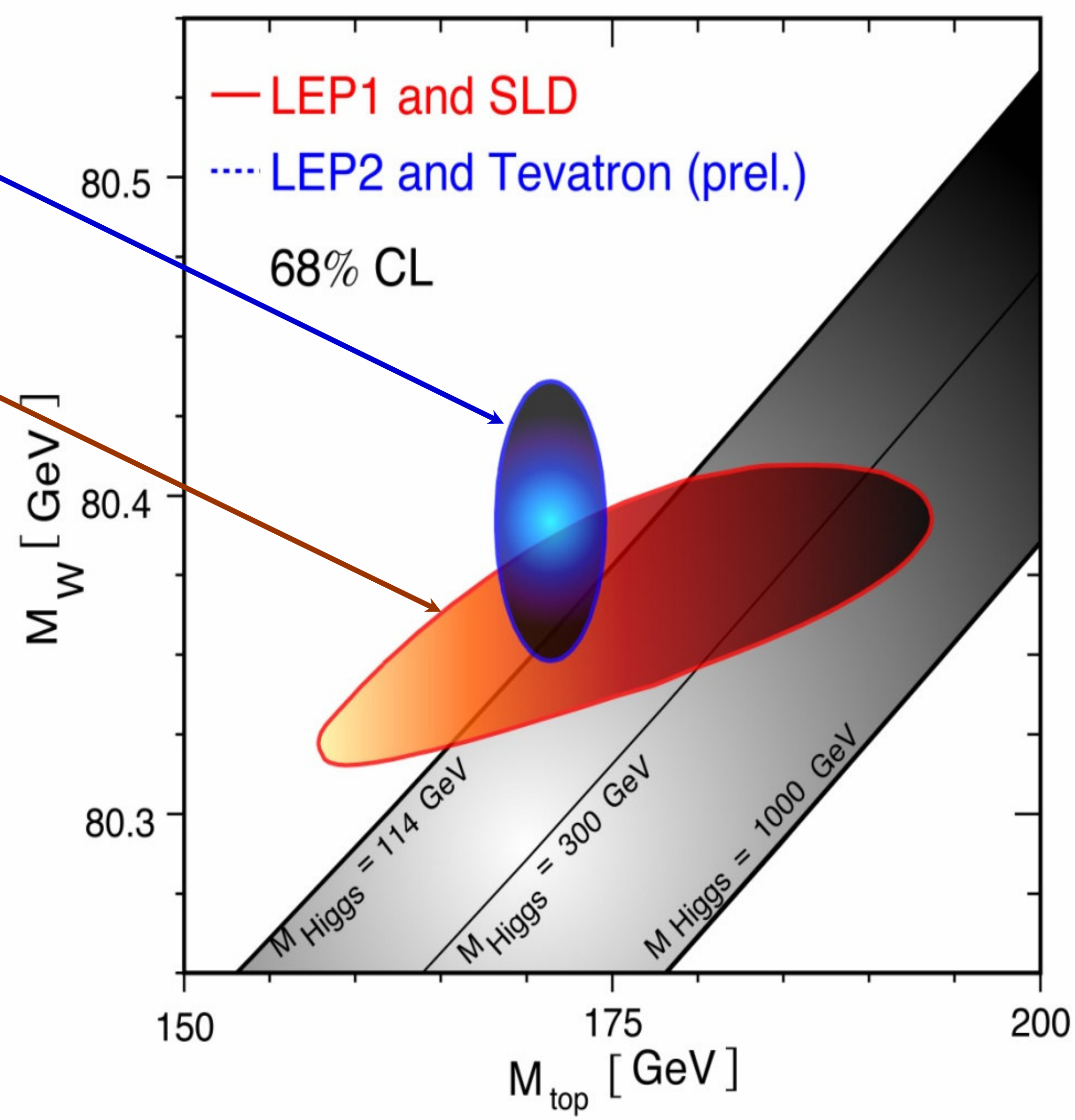
Importance of the top quark mass

Direct measurements:
LEP2 and Tevstron

Z-Pole measrements:
Constrain electroweak
radiative corrections
Allow to predict Mw
and Mtop within SM

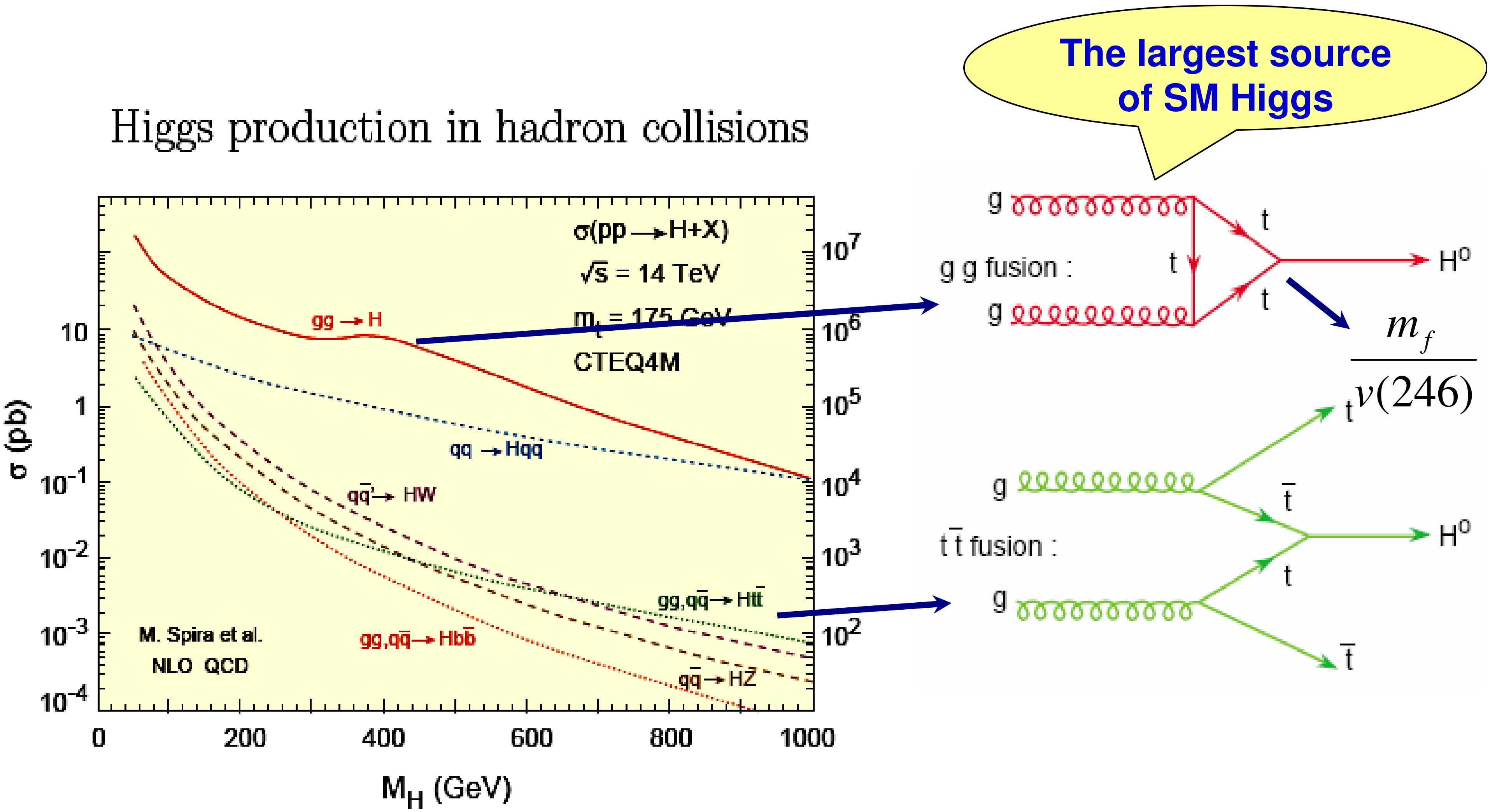
Good agreement:
Successful SM test

Both data sets prefer a
Light Higgs boson

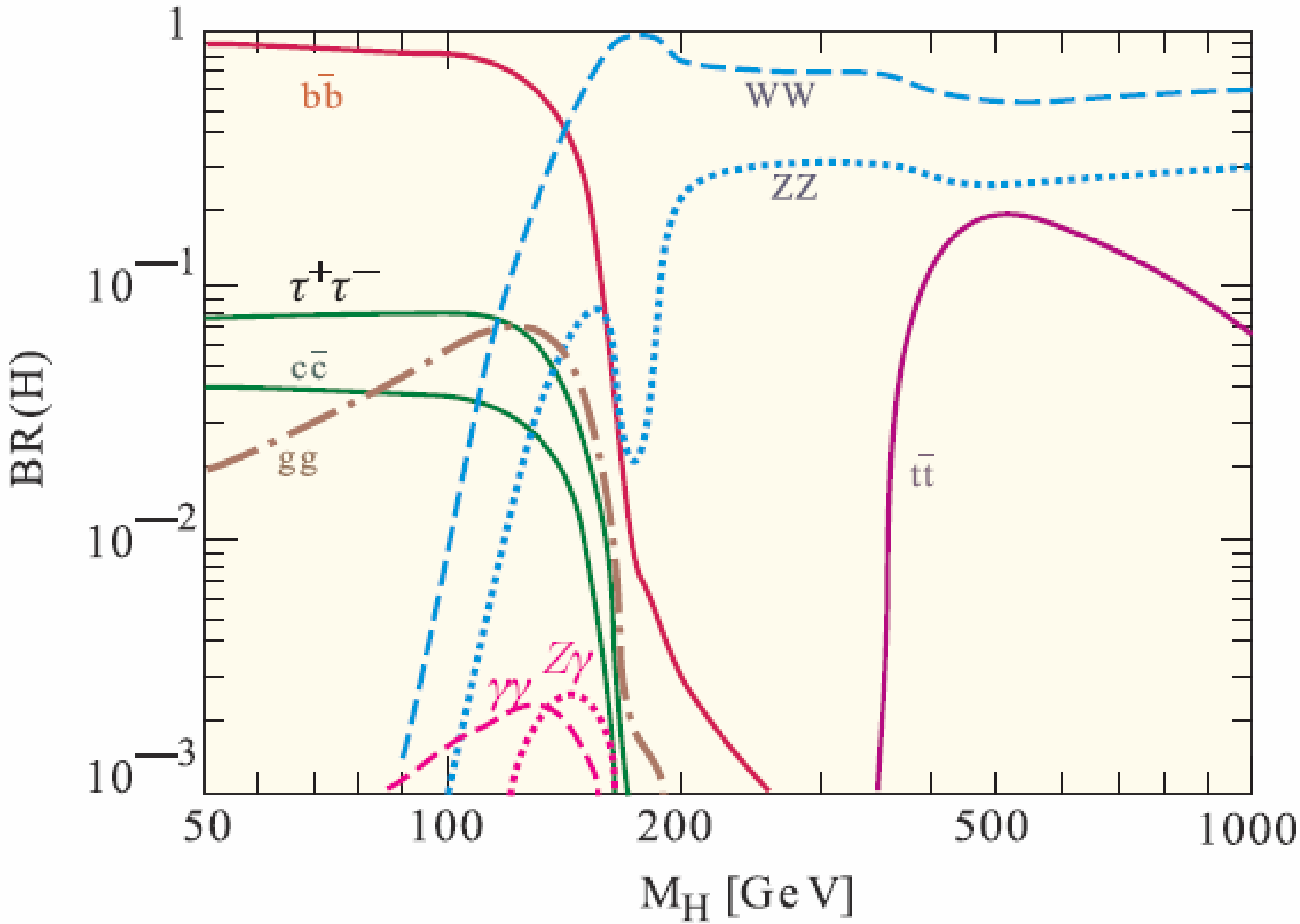


Top quark and Higgs boson

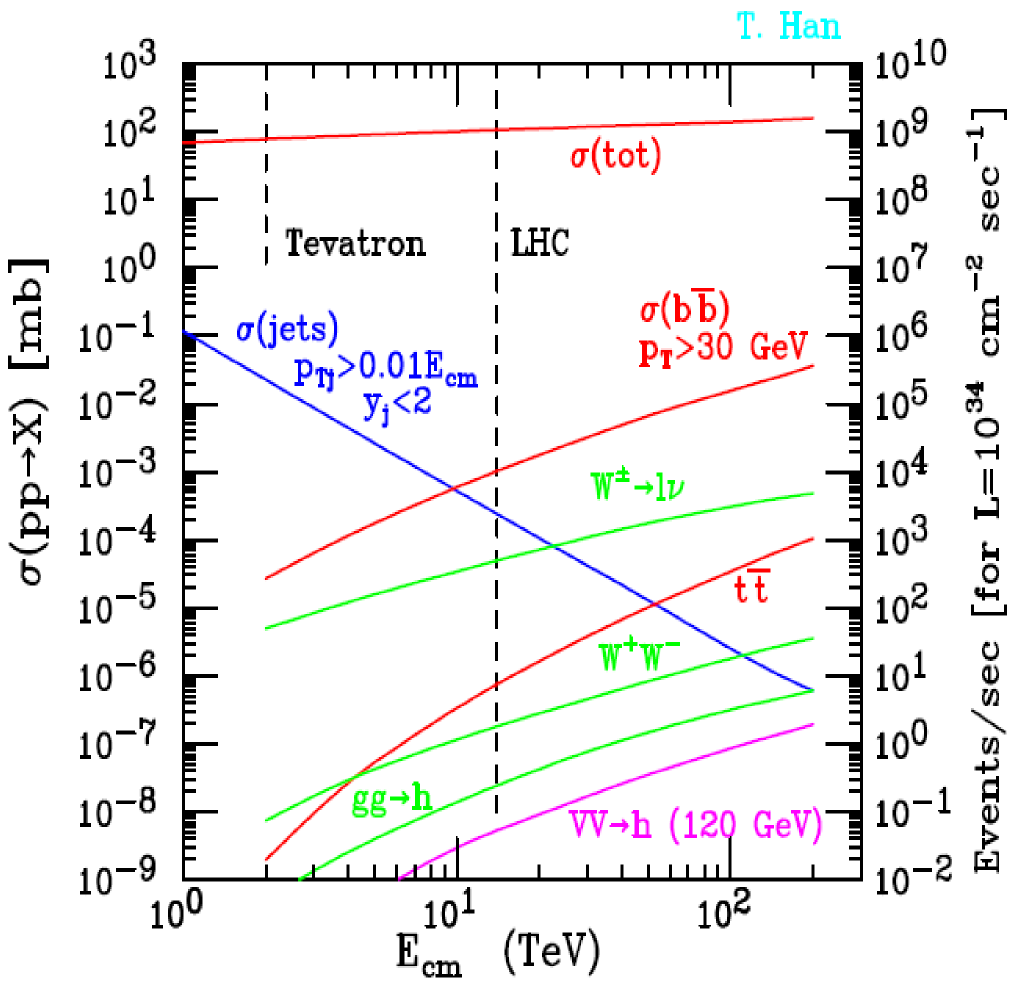
Top quark plays a key role in Higgs boson production



Top and Higgs



Cross Section of Various SM Processes



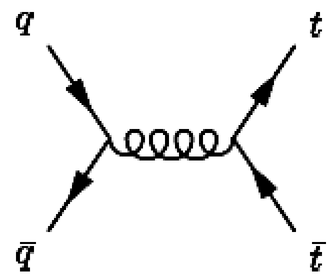
The LHC is a b, W, Z, top, Higgs, … factory!

The problem is to detect the events!

Top quark production at the LHC

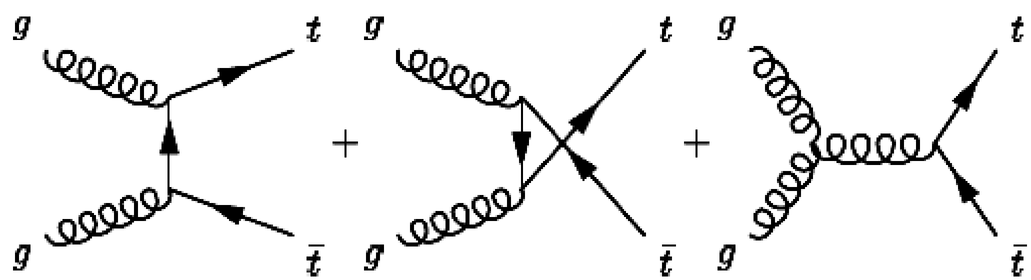
Top quarks are produced at the LHC mainly via Strong interactions in two sub-processes:

Quark-anti quark annihilation



$q\bar{q} \to t\bar{t}$

Gluon-gluon fusion,



$gg \to t\bar{t}$

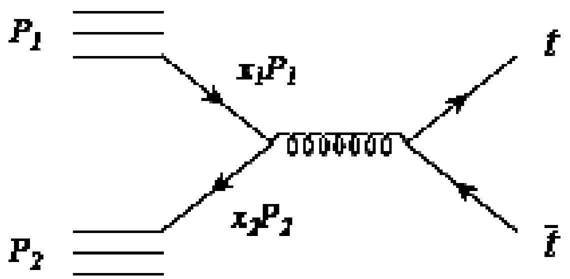
	Cross section (pb)	$q\bar{q} \to t\bar{t}$	$gg \to t\bar{t}$
LHC (pp, $\sqrt{S} = 14\ TeV$)	833	10%	90%

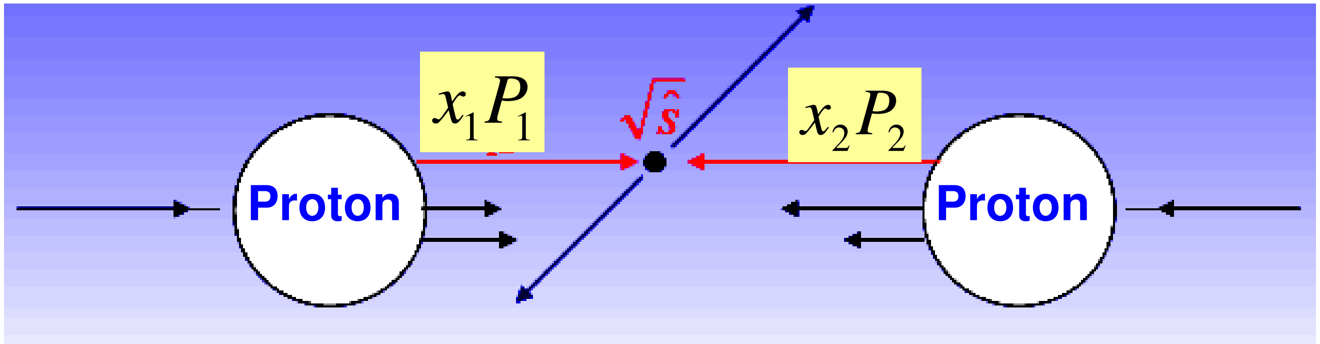
→ approx. 1 $t\bar{t}$-pair per second at $10^{33}/cm^2/s$

LHC is a top factory!

Top quark production at the LHC

- **Proton beam can be seen as beam of quarks and gluons with a wide band of energies**
- **The proton constituents (partons) carry only a fraction $0 \leq x \leq 1$ of the proton momentum**





center-of-mass energy (S):

$$S \equiv (P_1 + P_2)^2 \approx 2P_1.P_2 \ , \ \sqrt{S} = 14 \ TeV$$

Partonic center-of-mass:

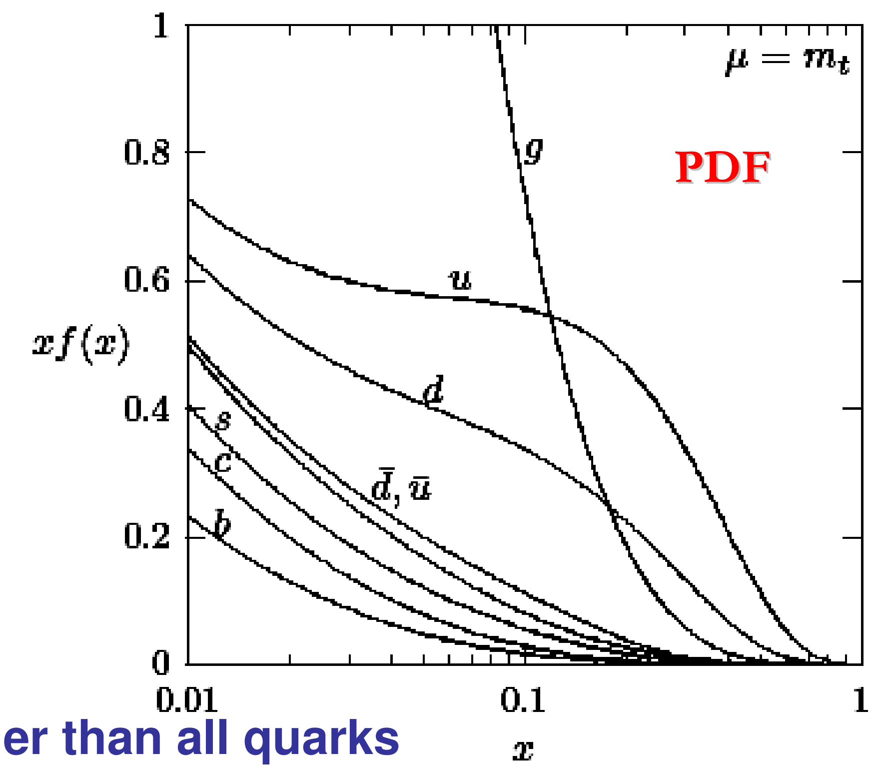
$$\hat{s} \equiv (x_1 P_1 + x_2 P_2)^2 \approx 2 x_1 x_2 P_1 P_2 = x_1 x_2 S$$

To produce a ttbar at rest:

$$\hat{s} \geq 4 m_{top}^2 \quad , x_1 x_2 = \frac{\hat{s}}{S} \geq \frac{4 m_{top}^2}{S}$$

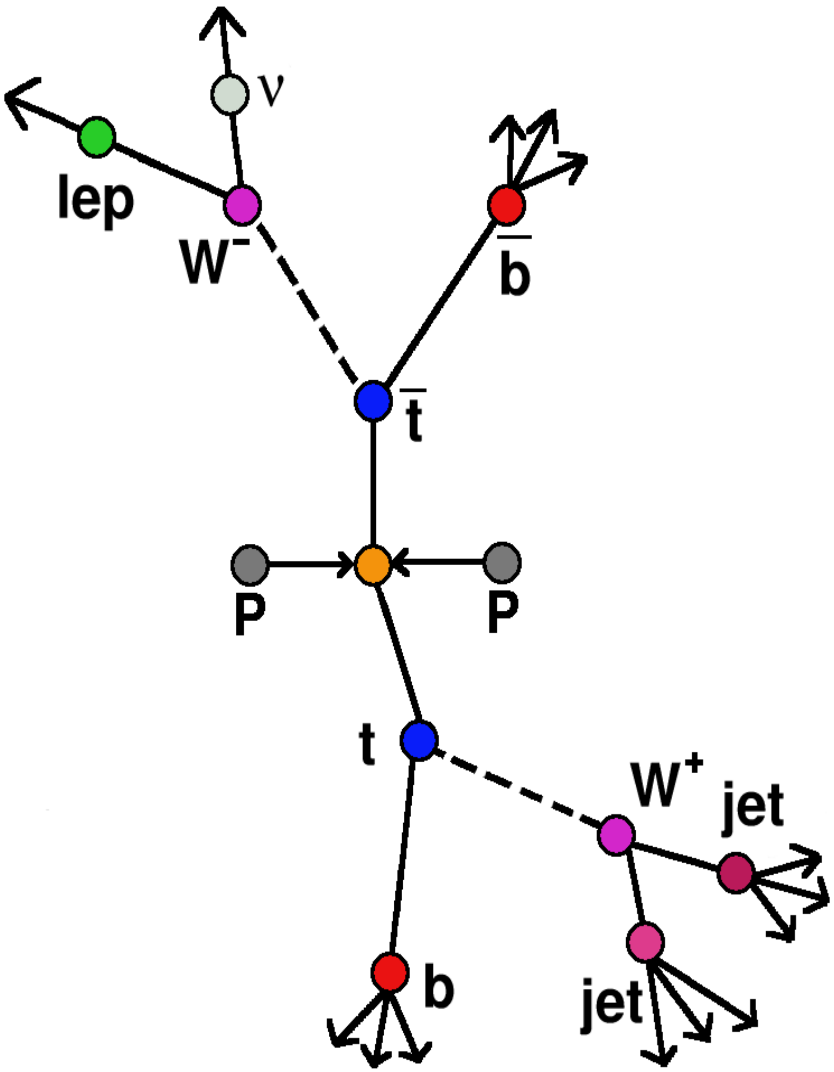
To estimate a typical value of x:

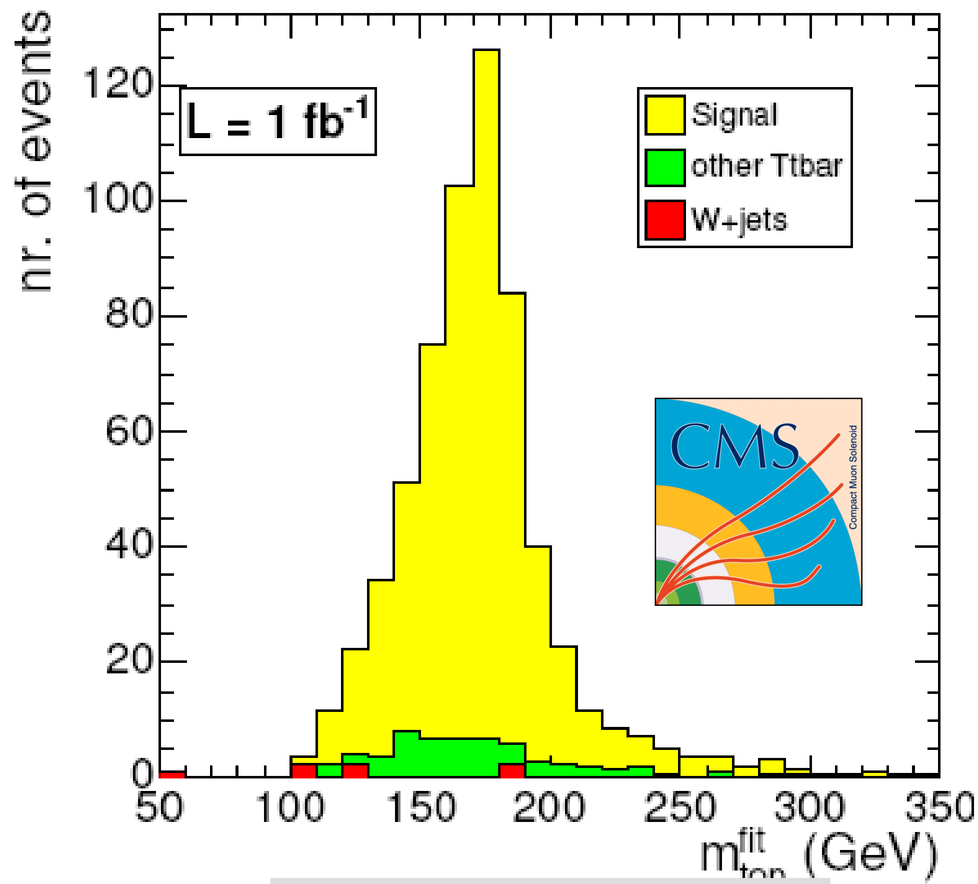
$$x_1 \approx x_2 = x \Rightarrow x \approx \frac{2 m_{top}}{\sqrt{S}} \approx 0.025$$



The gluon distribution function is much larger than all quarks

Top quark mass at the LHC





semi-leptonic
± 1.2 GeV

→ total top mass error ≤ 1 GeV possible with O(10 fb^{-1}) of well understood data

Top quark decays before hadronization via weak interaction therefore the spin information is transferred to its decay products

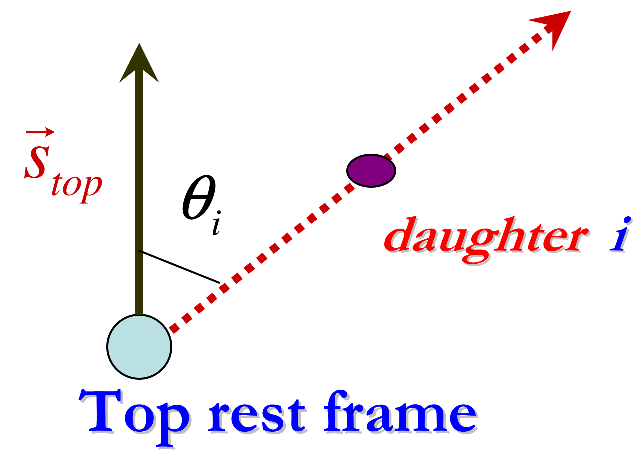
($Wb \rightarrow jjb\ / l\,\nu\, b$)

-We can determine the spin and polarization by looking at the angular distributions of its decay products

-Test SM couplings with clean probe

The angular distribution of the final particles:

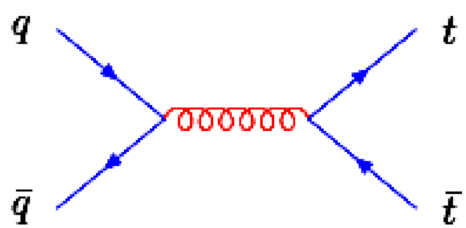
$$\frac{d\Gamma}{d\cos\theta_i} = \frac{1}{2}(1 + \alpha_i \cos\theta_i)$$



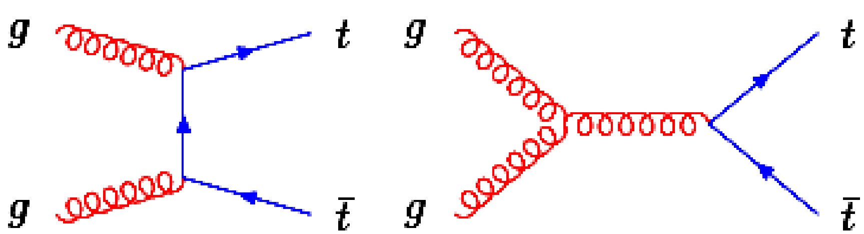
Particle	b-jet	W^+	l^+	$j_1=\bar{d}$-jet, $\bar{s}$-jet	$j_2=u$-jet, $\bar{c}$-jet	lej
α_i (LO)	-0.41	0.41	1	1	-0.31	0.51

Spin and polarization studies

Top quarks produced in ttbar pairs are scarcely polarized, therefore in order to study the spin and polarization of the top quarks the correlation between top spin and anti-top spin is considered.



Near threshold, top and anti-top tend to have their spin aligned

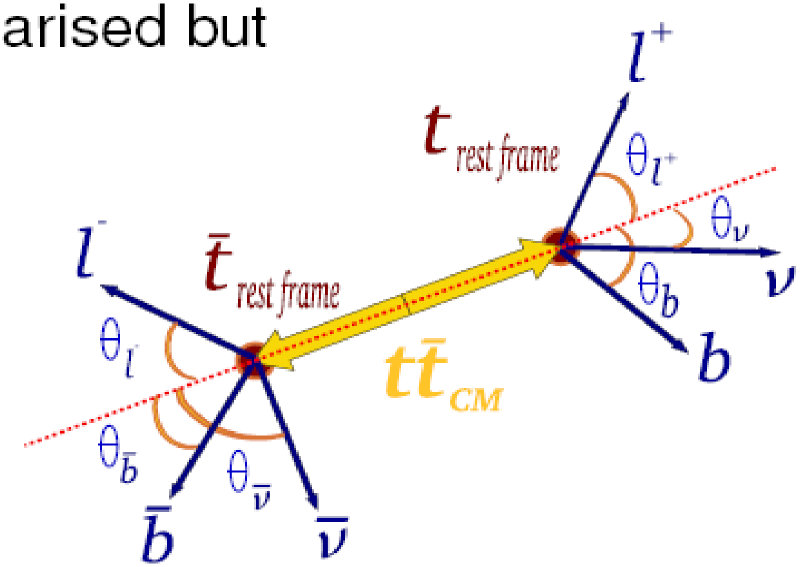


Near threshold, top and anti-top tend to have their spin opposite

G. Mahlon and S. Parke ,hep-ph/9512264

Spin and polarization studies

- $t\bar{t} \Rightarrow$ produced (almost) unpolarised but their spins are correlated



double distribution in helicity basis

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_X \, d\cos\theta_{\bar{X}'}} = \frac{1}{4}(1 + C\,\alpha_X \alpha_{\bar{X}'} \cos\theta_X \cos\theta_{\bar{X}'})$$

compare distribution of $\left[\begin{array}{l} X \text{ from } t \text{ decay} \\ \bar{X}' \text{ from } \bar{t} \text{ decay} \end{array}\right.$

$$C \equiv \frac{N(t_L\bar{t}_L + t_R\bar{t}_R) - N(t_L\bar{t}_R + t_R\bar{t}_L)}{N(t_L\bar{t}_L + t_R\bar{t}_R) + N(t_L\bar{t}_R + t_R\bar{t}_L)} = 0.332$$

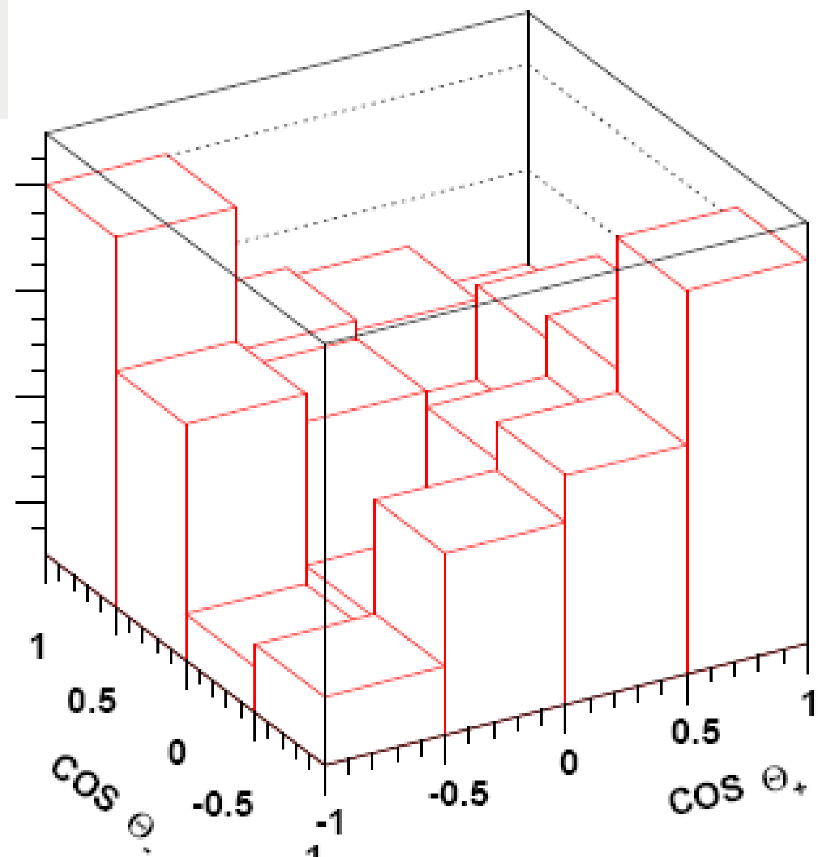
Spin and polarization studies

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_X \, d\cos\theta_{\bar{X}'}} = \frac{1}{4}(1 + C\,\alpha_X\alpha_{\bar{X}'}\cos\theta_X\cos\theta_{\bar{X}'})$$

compare distribution of [X from t decay; $\bar{X}'$ from $\bar{t}$ decay]

$$C \equiv \frac{N(t_L\bar{t}_L + t_R\bar{t}_R) - N(t_L\bar{t}_R + t_R\bar{t}_L)}{N(t_L\bar{t}_L + t_R\bar{t}_R) + N(t_L\bar{t}_R + t_R\bar{t}_L)} = 0.332$$

$$C = 0.332 \pm 0.023$$



Study of the W-polarization in Top quark decay

The W-boson from a top quark, t→W+b, can be produced with a longitudinal, left-handed or right-handed helicity. According to the SM expectation, the corresponding probabilities are as follows:

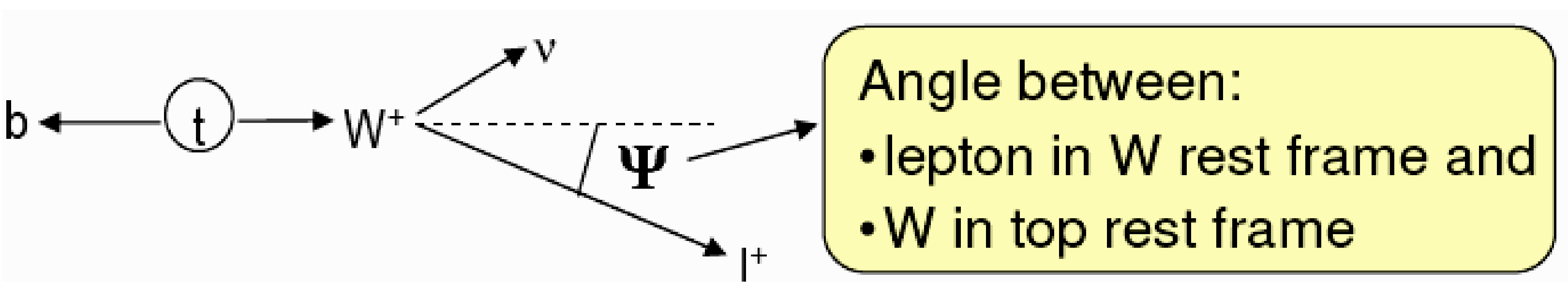
$$F_0 = \frac{M_{top}^2}{M_{top}^2 + 2M_W^2} = 0.703$$ → **Longitudinal**

$$F_L = \frac{2M_W^2}{M_{top}^2 + 2M_W^2} = 0.297$$ → **Left-handed**

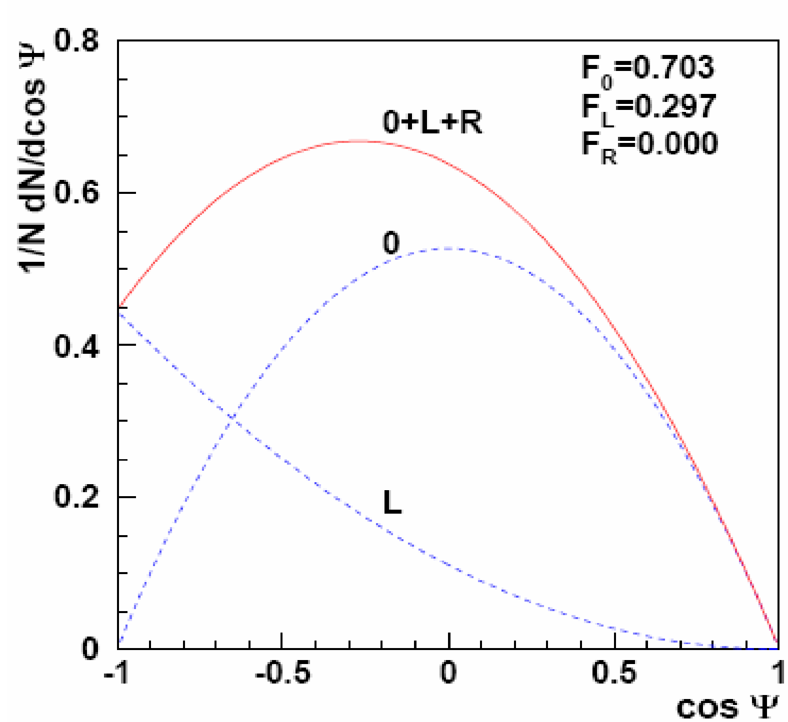
$$F_R = 0.000$$ → **Right-handed**

Consider t→Wb→l+n+b, This can be seen in angular distribution of the charged lepton coming from W boson in the rest frame of the W-boson:

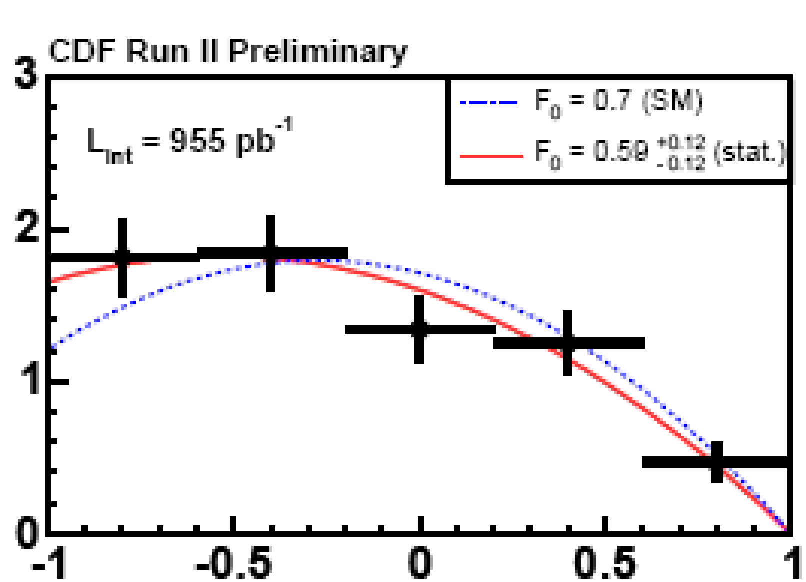
$$\frac{1}{N}\frac{dN}{d\cos\Psi} = \frac{3}{2}\left[F_0 \cdot \left(\frac{\sin\Psi}{\sqrt{2}}\right)^2 + F_L \cdot \left(\frac{1-\cos\Psi}{2}\right)^2 + F_R \cdot \left(\frac{1+\cos\Psi}{2}\right)^2 \right]$$



Study of the W-polarization from CDF at Fermilab



CDF



$$F_0 = 0.59 \pm 0.12\,(stat) \pm 0.07\,(syst)$$

$$F_R < 0.10\ with\ 95\,\%\ C.L$$

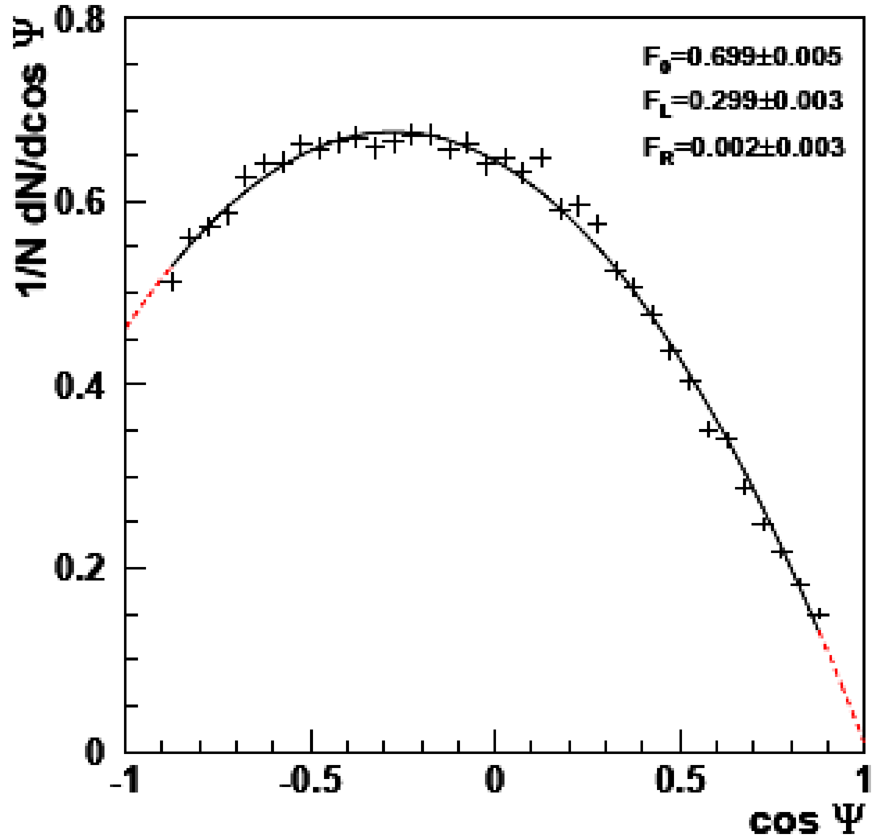
In agreement with SM prediction

hep-ex/0705.2966

Study of the W-polarization in ATLAS

Results of 10fb^{-1} data:

	Semileptonic (±stat±syst)
F_L	$0.299 \pm 0.003 \pm 0.024$
F_0	$0.699 \pm 0.005 \pm 0.023$
F_R	$0.002 \pm 0.003 \pm 0.012$



W-polarization will be measured very precisely at the LHC, the analysis is systematically dominated.

Study of the Wtb vertex

A model independent extension of the SM is to introduce new interactions:

Most general *Wtb* vertex

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_L P_L + V_R P_R)\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\,(g_L P_L + g_R P_R)\,t\,W_{\mu}^{-} + \text{h.c.}$$

$V_L \equiv V_{tb} \sim 1$ (within SM)

$V_R, g_R, g_L \Rightarrow$ anomalous couplings

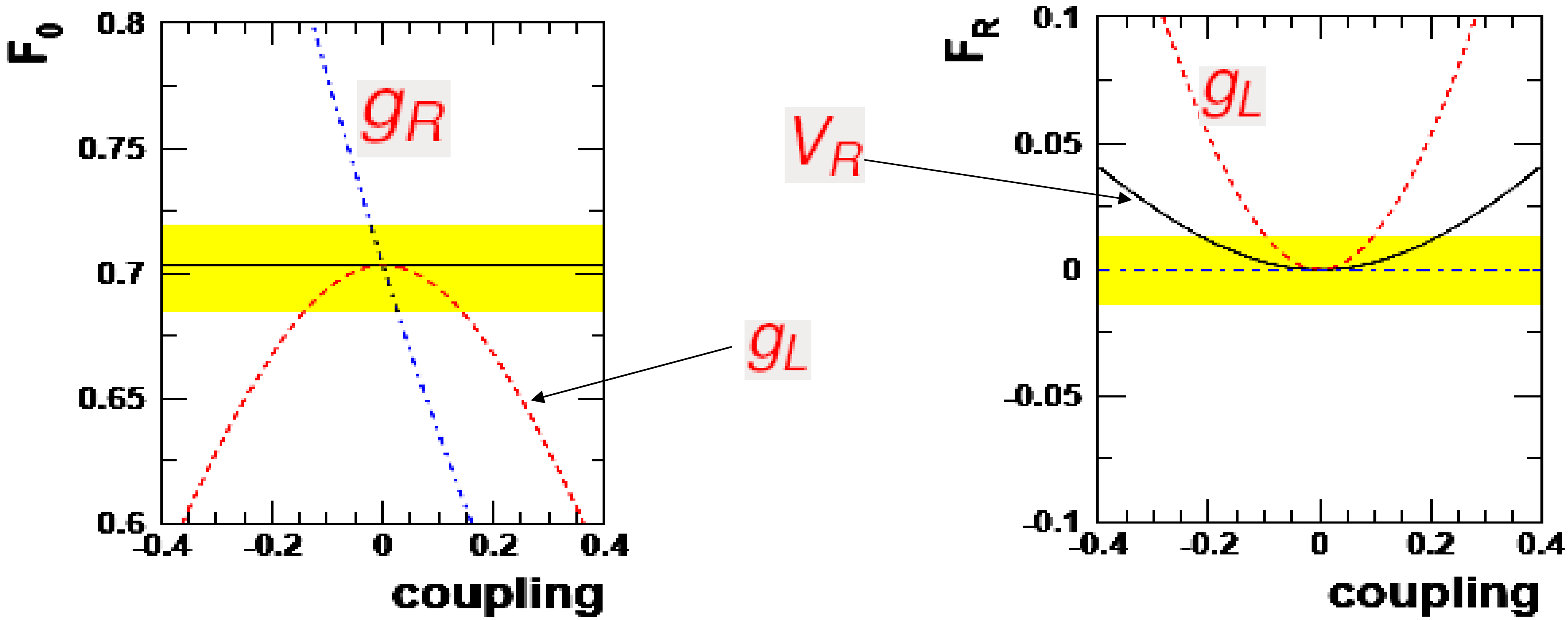
$$Tevatron \rightarrow -0.18 < g_L < 0.55 \;,\; -0.24 < g_R < 0.25$$

$$LHC \rightarrow -0.052 < g_L < 0.097 \;,\; -0.12 < g_R < 0.13$$

M. Beneke et al., *Top Quark Physics*, hep-ph/0003033

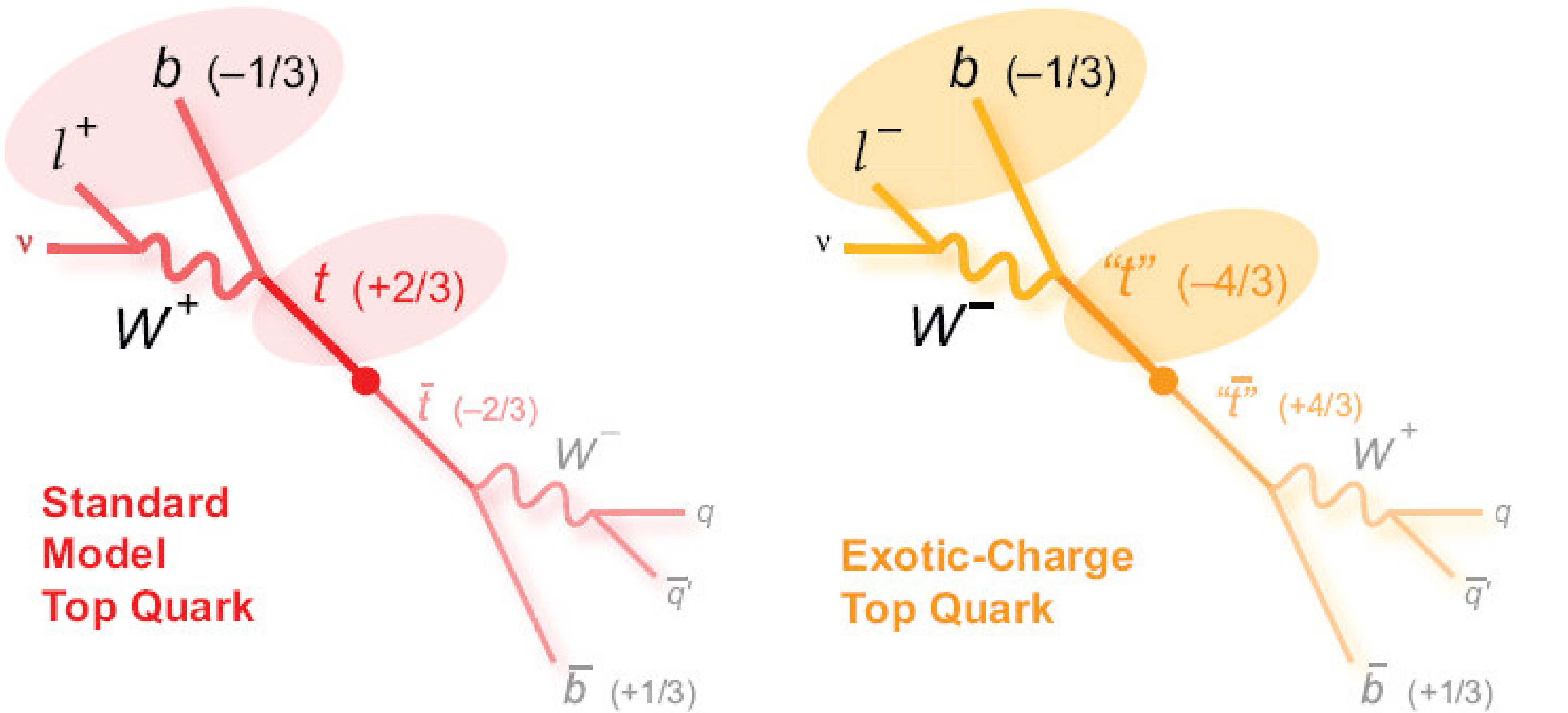
W-Polarization can be used to test the Wtb vertex

Presence of anomalous couplings → deviation in W-helicity fractions



$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_L P_L + V_R P_R)\,t\;W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\,(g_L P_L + g_R P_R)\,t\;W_{\mu}^{-} + \text{h.c.}$$

Top charge



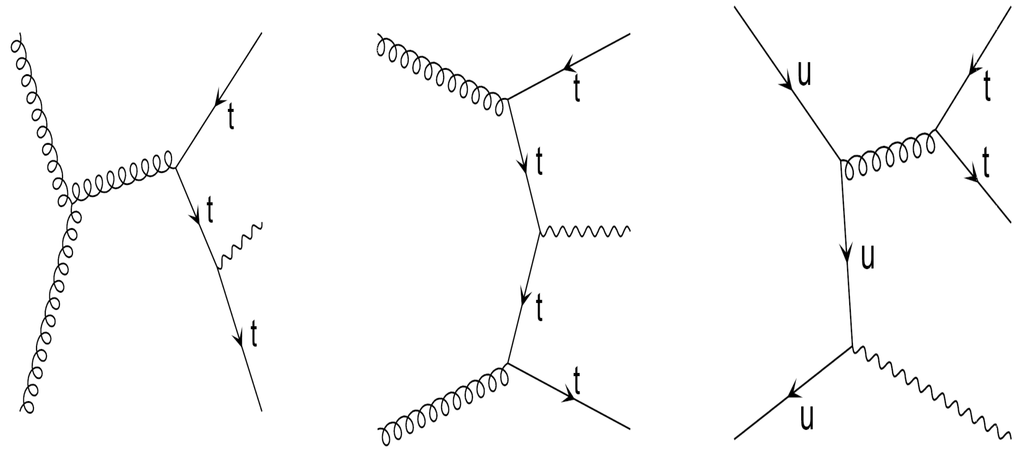
b (–1/3)
l+
ν
t (+2/3)
W+
t̄ (–2/3)
W–
q
q̄'
b̄ (+1/3)
Standard Model Top Quark
b (–1/3)
l–
ν
"t" (–4/3)
W–
"t̄" (+4/3)
W+
q
q̄'
b̄ (+1/3)
Exotic-Charge Top Quark

Top charge

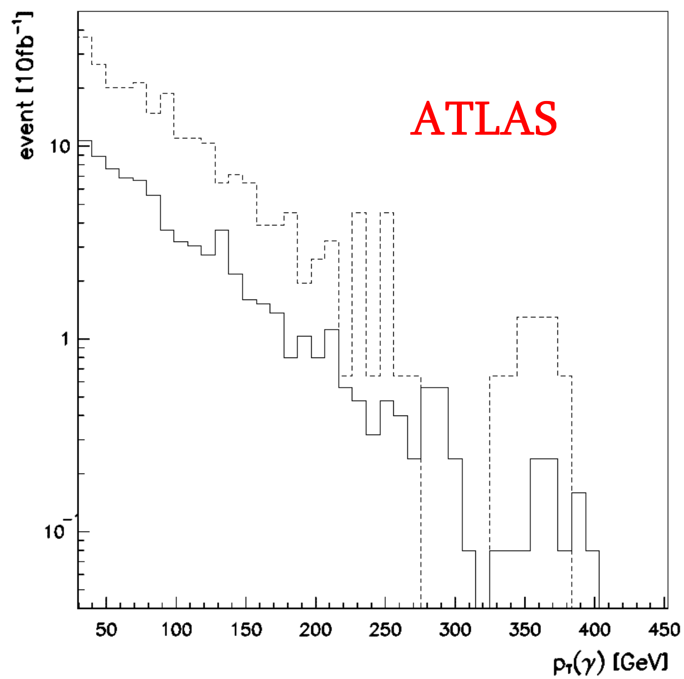
Radiative production :

pp→ttγ

σ proportional to $|Q_{top}|^2$



$$\frac{\sigma(pp \to t\bar{t}\gamma, |Q_{top}| = 4/3e)}{\sigma(pp \to t\bar{t}\gamma, |Q_{top}| = 2/3e)} \sim 4$$

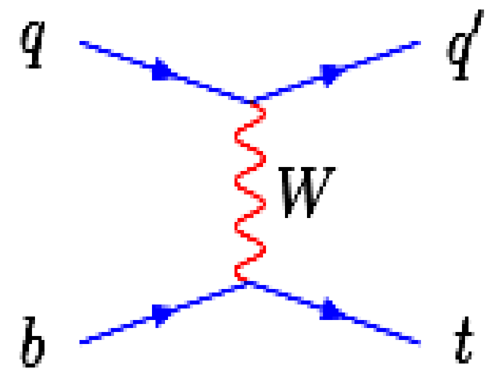


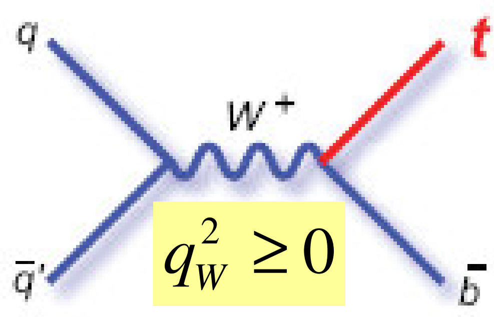
Electroweak (Single) top quark production

Another source of top quark at the LHC is Single top quark production. Top quarks are produced via electroweak interaction. Single top quarks are produced via three processes which can be listed by the virtuality of the involved W-boson:

t-channel, W-boson is space-like
cross section = 245 pb, the largest source of Single top

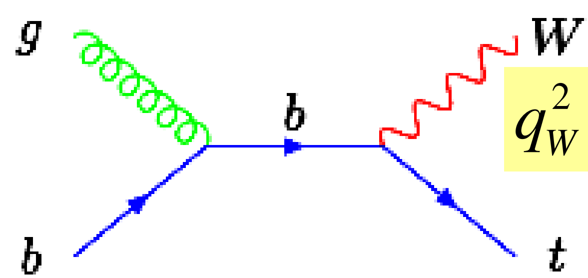
$q_W^2 \leq 0$





$q_W^2 \geq 0$

s-channel, W-boson is time-like
cross section = 10 pb



$q_W^2 = M_W^2$

tW-channel, W-boson is real
cross section = 60 pb

Single Top Quark at Tevatron

The D0 collaboration at Tevatron claimed the first evidence for discovery of single top in December of 2006. In the D0 search, the t-channel and s-channel Single top events are combined to one single top signal. According to the SM the cross section of **t+s** channel single top at Tevatron with the center of energy of 1.96 TeV is:

$$\sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 2.9 \pm 0.4 \text{ pb}$$

← *SM prediction*

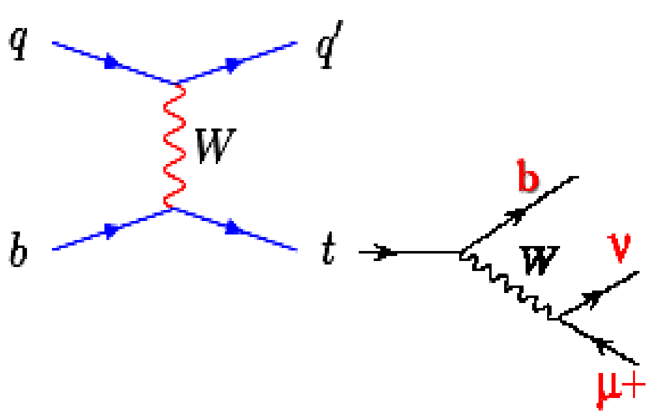
The measured cross section by D0 is:

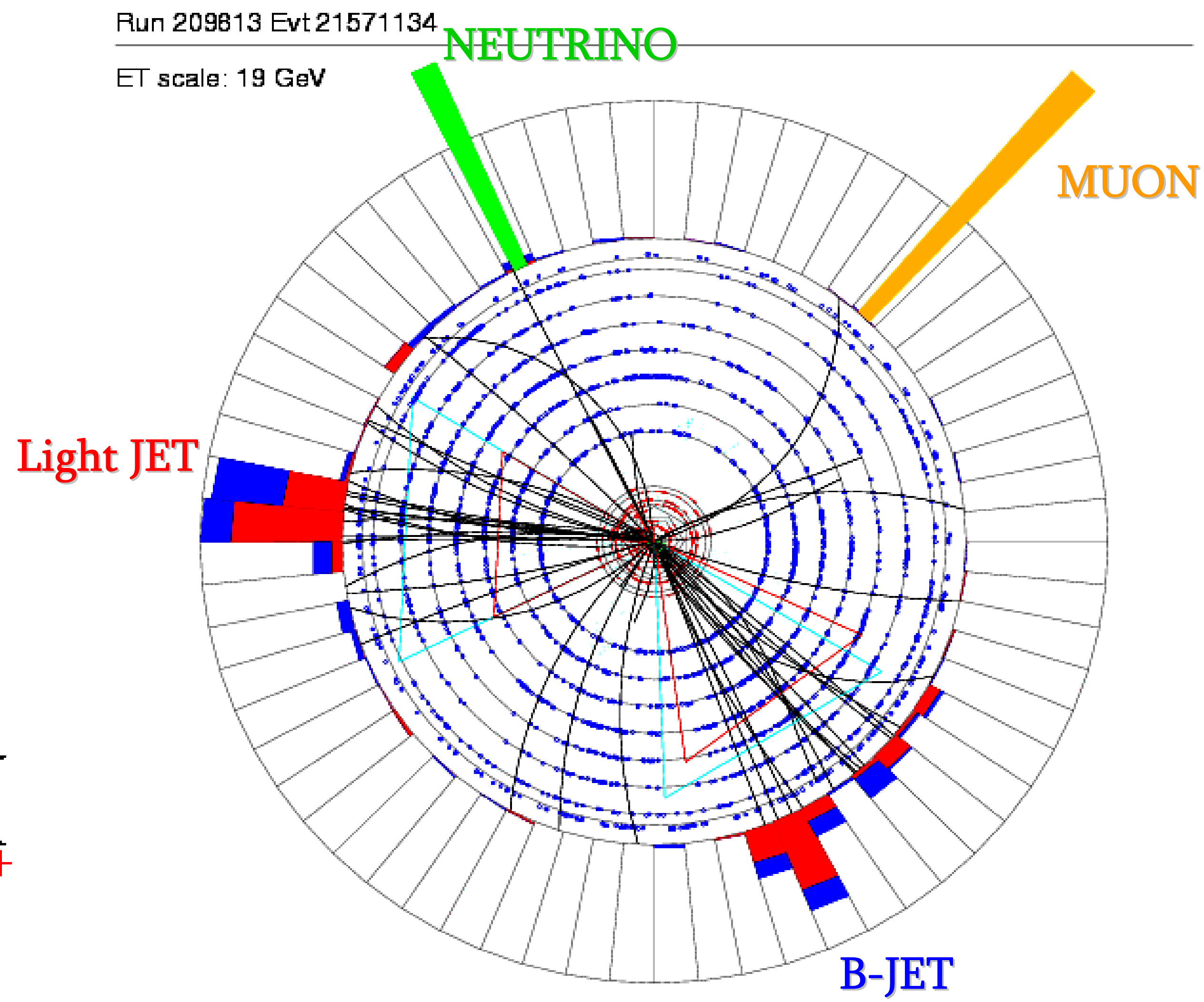
$$\sigma(p\bar{p} \rightarrow tqb + X, tb + X) = 4.2^{+1.8}_{-1.4} \text{ pb}$$

This result is consistent with the SM. The Signal Significance of this discovery is 3.4 which means that the probability that the events considered as signal are due to background fluctuation is 0.035%.

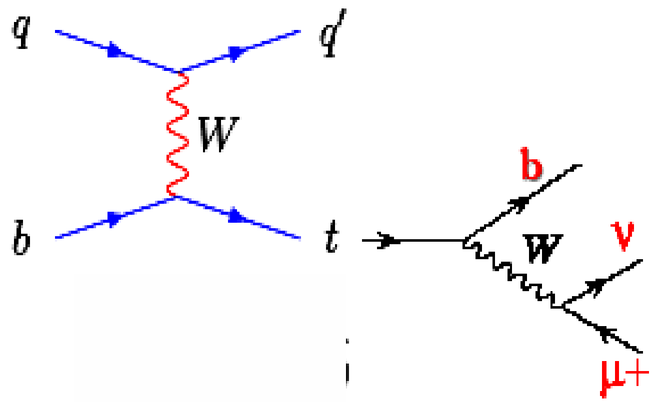
CDF has not claimed the discovery of Single Top yet.

One t-channel single top event at CDF

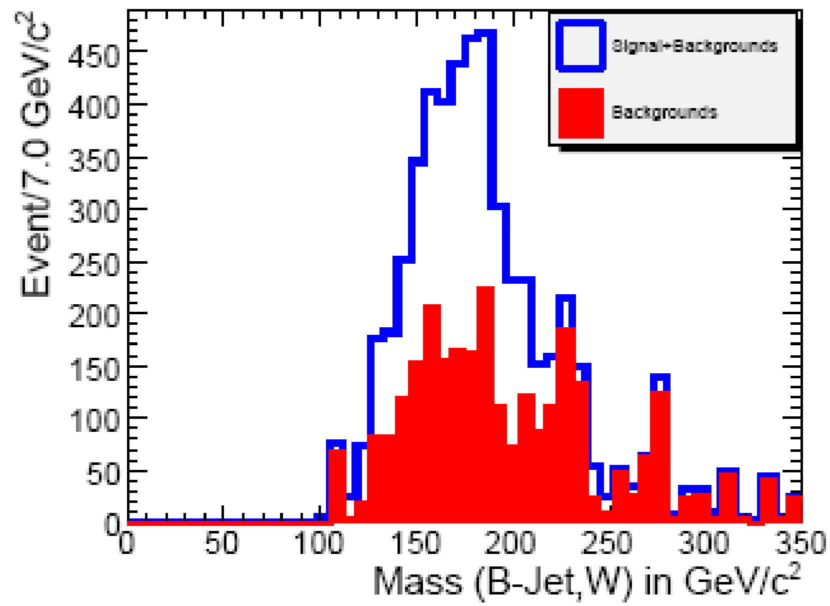




Single Top Quark at LHC



$$\frac{N_S}{N_B} = 1.34 \quad , \quad S = \frac{N_S}{\sqrt{N_S + N_B}} = 37.$$



After including uncertainties

↓

10.1

$$\frac{\Delta\sigma_t}{\sigma_t} = 10\% \;\; , \frac{\Delta V_{tb}}{V_{tb}} \approx 5\% \; @ \, 10\, fb^{-1}$$

Single top quark production as a window to Physics Beyond SM

☒ The cross sections of single top processes are proportional to $|V_{tb}|^2$.
These processes provide the only way to measure directly V_{tb} .

CKM entry	Value	Source
$\|V_{ud}\|$	0.97377 ± 0.00027	Nuclear β decay [7]
	0.9746 ± 0.0019	$n \to p e^- \bar{\nu}_e$ [7]
	0.9728 ± 0.0030	$\pi^+ \to \pi^0 e^+ \nu_e$ [62]
	0.97378 ± 0.00027	average
$\|V_{us}\|$	0.2234 ± 0.0024	$K \to \pi l^+ \nu_l$ [7,34,63]
	0.2220 ± 0.0033	τ decays [52]
	$0.2226 {}^{+0.0026}_{-0.0014}$	$K^+/\pi^+ \to \mu^+ \nu_\mu$, V_{ud} [7,53–55]
	0.226 ± 0.005	Hyperon decays [64–66]
	0.2230 ± 0.0015	average
$\|V_{cd}\|$	0.213 ± 0.022	$D \to \pi l \bar{\nu}_l$ [7]
	0.230 ± 0.011	$\nu d \to c X$ [7]
	0.227 ± 0.010	average
$\|V_{cs}\|$	0.957 ± 0.095	$D \to K l \bar{\nu}_l$ [7]
	$0.94 {}^{+0.35}_{-0.29}$	$W^+ \to c\bar{s}$ [7]
	0.974 ± 0.013	$W^+ \to$ had., V_{uj}, V_{cd}, V_{cb} [29,30]
$\|V_{cb}\|$	0.0392 ± 0.0016	$B \to D^* l \bar{\nu}_l$ [7,67]
	0.0417 ± 0.0007	$b \to c l \bar{\nu}_l$ [7,67]
	0.0413 ± 0.0006	average
$\|V_{ub}\|$	0.0039 ± 0.0006	$B \to \pi l \bar{\nu}_l$ [7,67]
	0.0045 ± 0.0003	$b \to u l \bar{\nu}_l$ [7,67]
	0.0044 ± 0.0003	average
$\|V_{tb}\|/\sqrt{\sum_q \|V_{tq}\|^2}$	> 0.78	$t \to bW/qW$ [68,69]
$\|V_{tb}\|$	> 0.68 ; ≤ 1	$p\bar{p} \to tb + X$ [70]

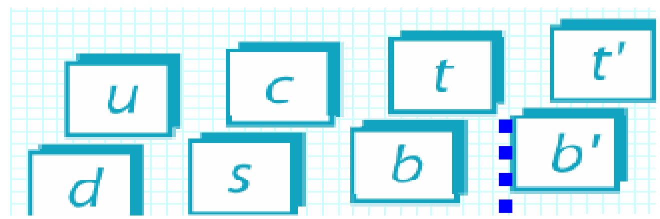
Unitatrity of the CKM matrix

$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$$

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

$$|V_{tb}| = 0.9991 \text{ to } 0.9994$$

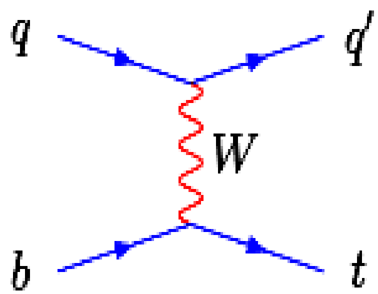
Fourth Generation

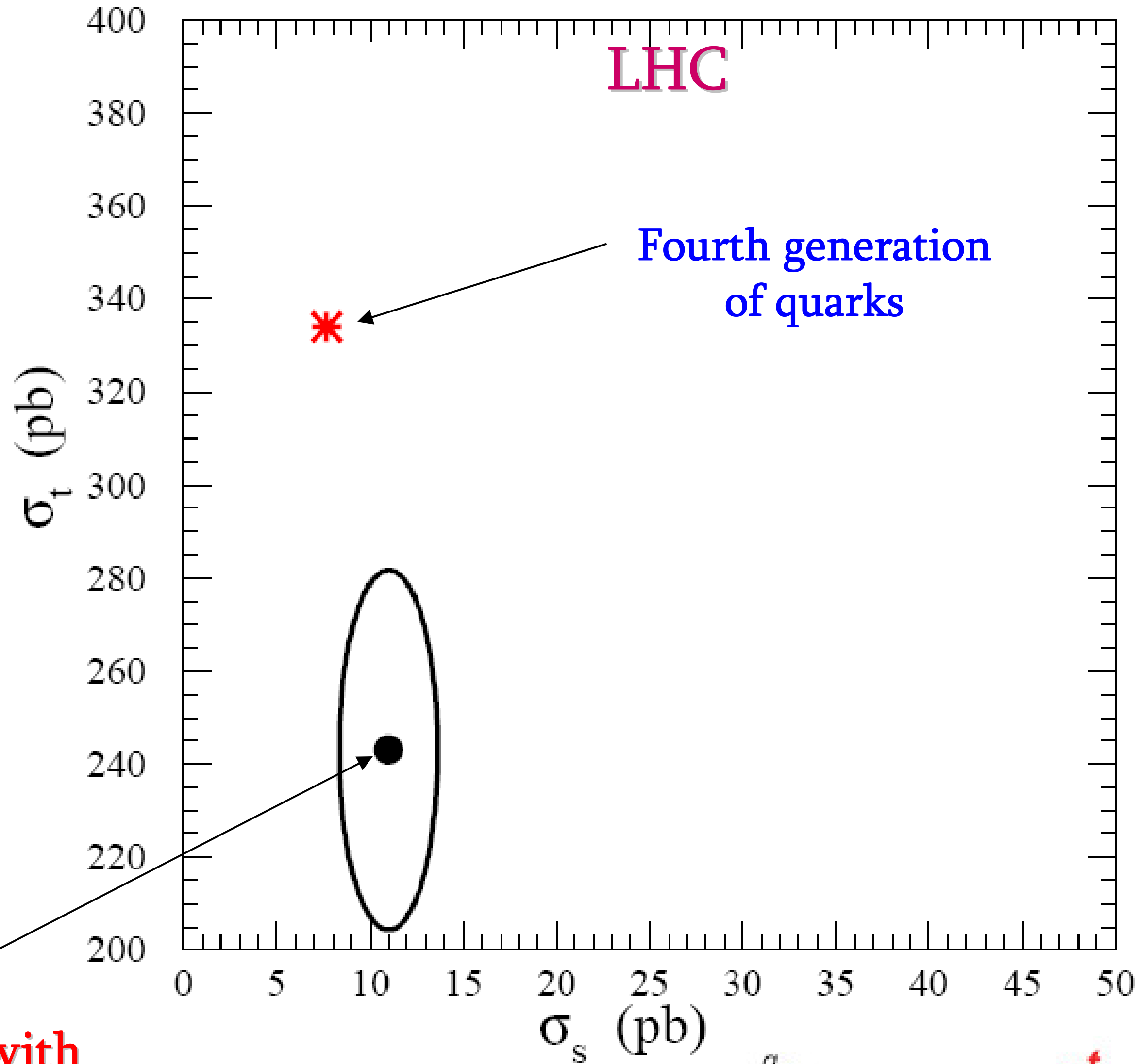


$$\begin{vmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{vmatrix}$$

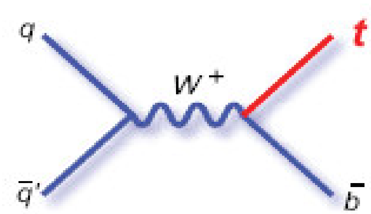
Vtb deviates Considerably from 1

The rates of the s- and t-channel modes are sensitive to different types of new physics.





SM prediction with theoretical uncertainty

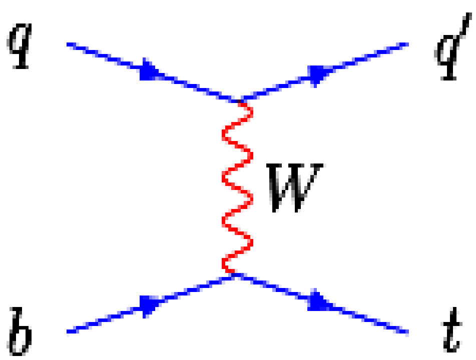


PRD63, 014018 (2001) [hep-ph/0007298]

Spin correlation in t-channel Single top quark

☒The t-channel single top quark production provides the possibility to study the spin and polarization of one isolated quark.

Because single top quarks are produced via weak interaction, they are highly polarized.



spin 4-vector

$$\sigma \propto |M|^2 \propto ((P_t - m_{top} S).P_{q'})(P_b.P_q)$$

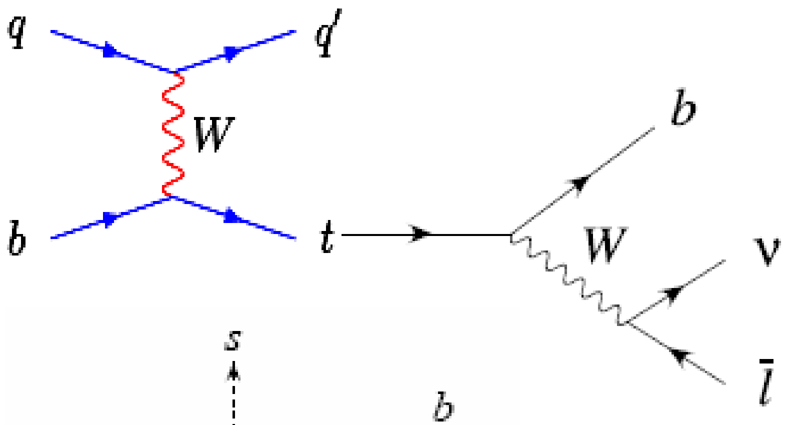
In top rest frame→ $S = (0, \hat{s})$ where s is unit vector which defines the spin quantization axis.

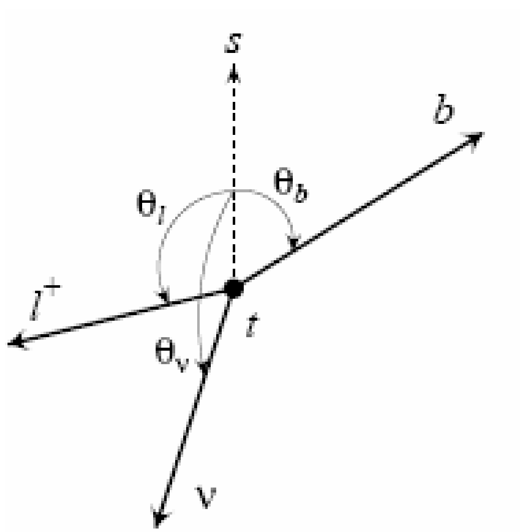
In top rest frame, the spin of the top is aligned with the momentum direction of the light Quark in the final state (q’)

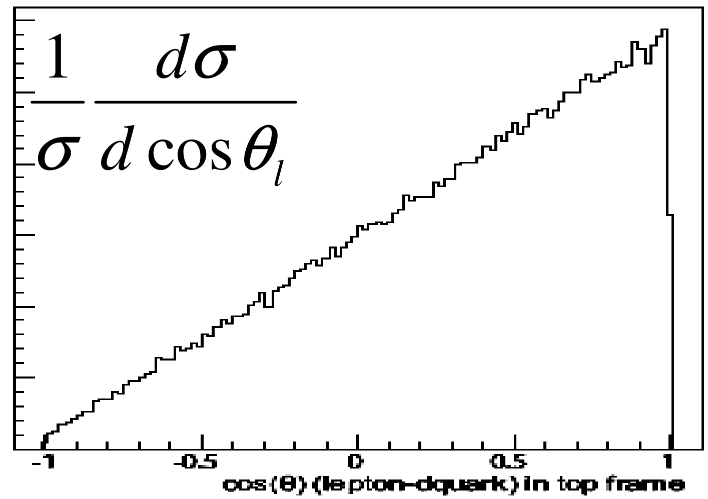
Spin correlation in t-channel Single top quark

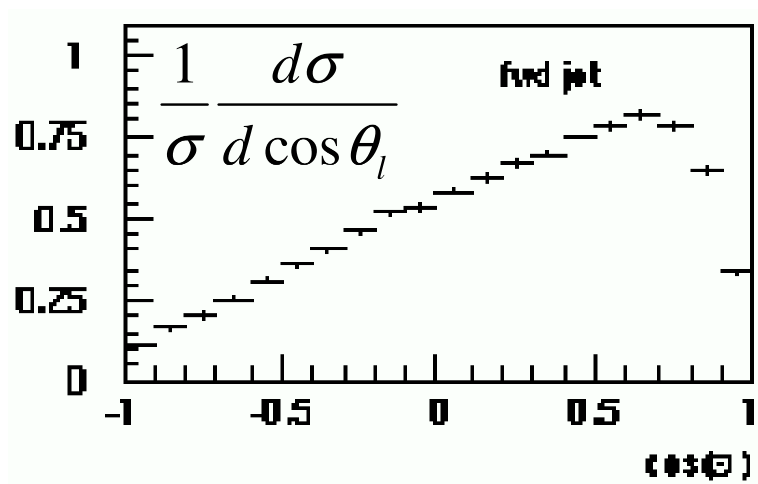
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i} = \frac{1}{2}(1+\alpha_i\cos\theta_i)$$

$$\alpha_l(SM)=1\ ,\ \ \alpha_b(SM)=-0.41$$









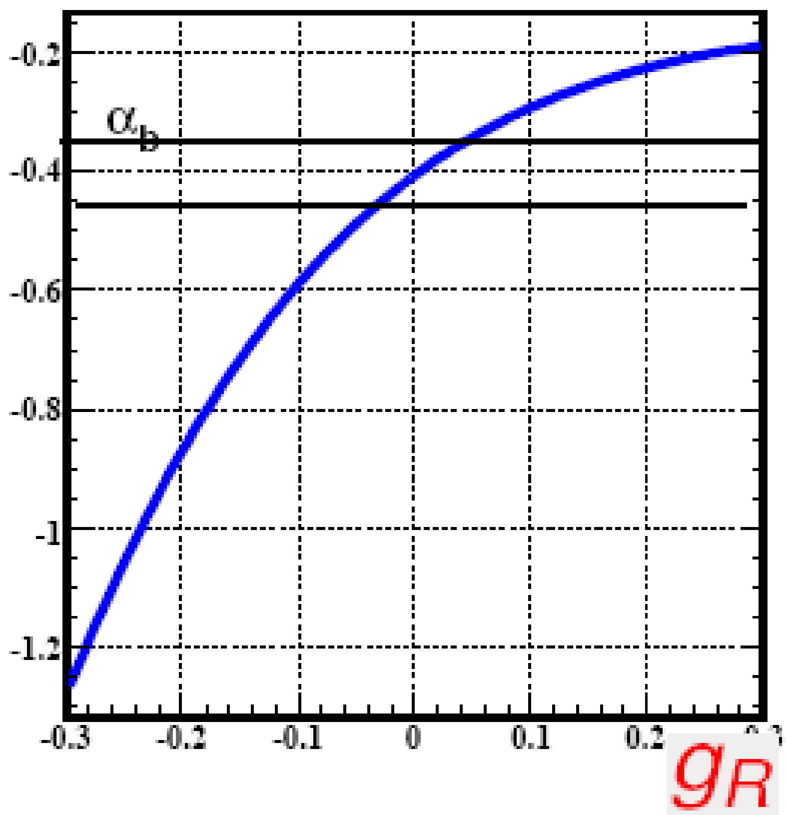
5% uncertainty on α

M. Beneke et al., *Top Quark Physics*, hep-ph/0003033

Single top quark production as a window to Physics Beyond SM

Non-SM top interactions

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_L P_L + V_R P_R)\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\,(g_L P_L + g_R P_R)\,t\,W_{\mu}^{-} + \text{h.c.}$$



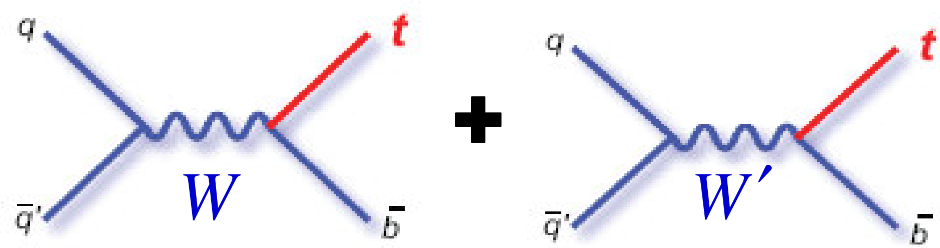
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i} = \frac{1}{2}(1+\alpha_b\cos\theta_b)$$

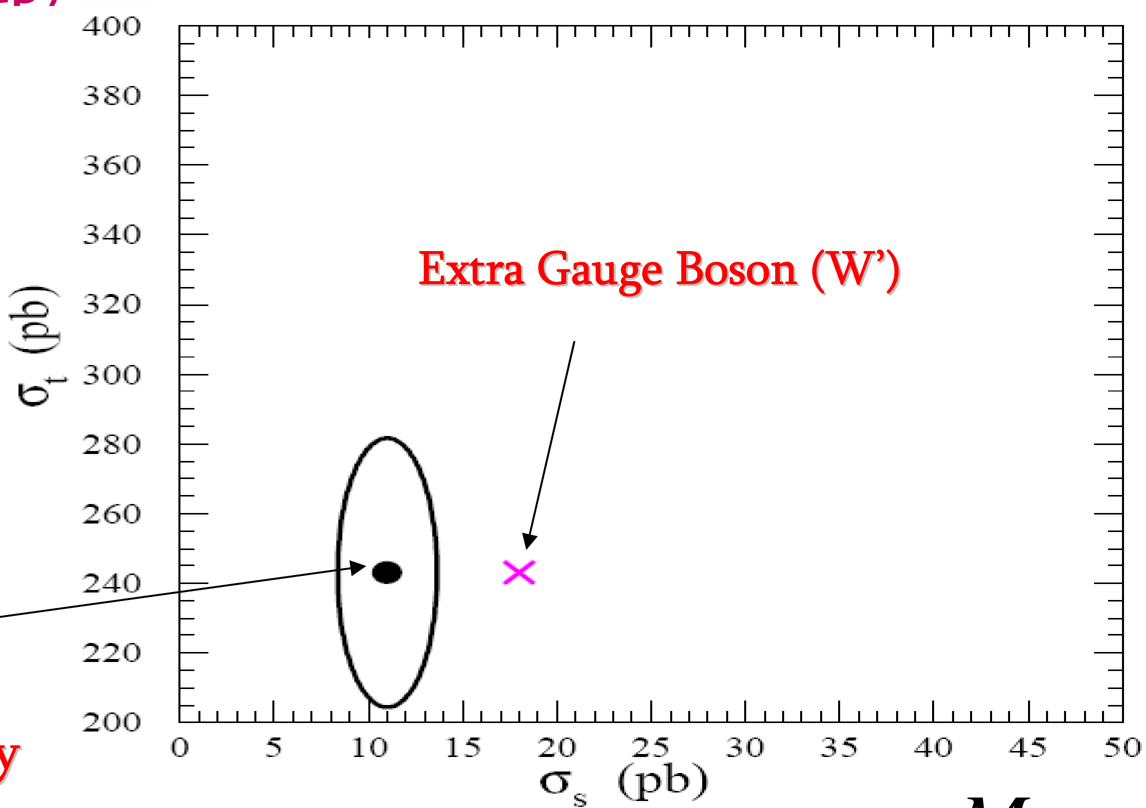
At the LHC the uncertainty on α is 5%

Single top quark production as a window to Physics Beyond SM

Extra Gauge Boson

Some BSM theories
(LH,ED …) predict
new gauge bosons (W’,Z’)
(Larger gauge group)





SM prediction with
theoretical uncertainty

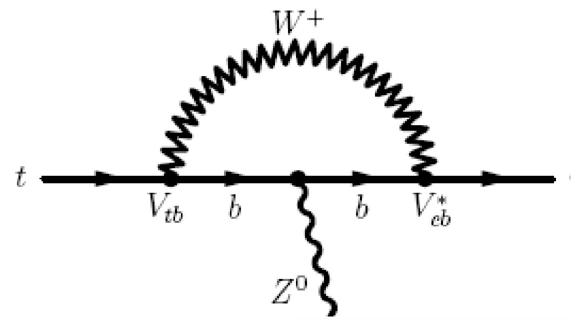
$$M_{W'} \approx 1\ TeV$$

PRD63, 014018 (2001) [hep-ph/0007298]

FCNC (Flavor Changing Neutral Current)

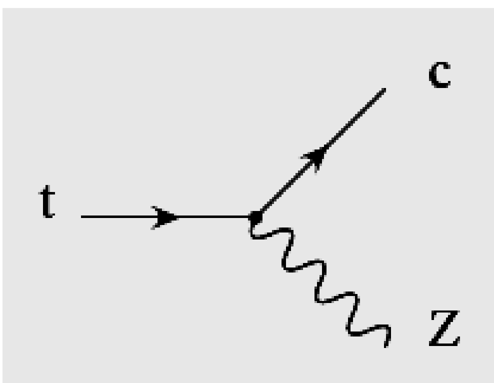
$$BR(t \to W + b) \cong 0.99$$

$$BR(t \to Z + c) \sim 10^{-10}$$



In SM, at tree level is impossible

$$Experiment \Rightarrow BR(t \to Z + c) < 0.33$$

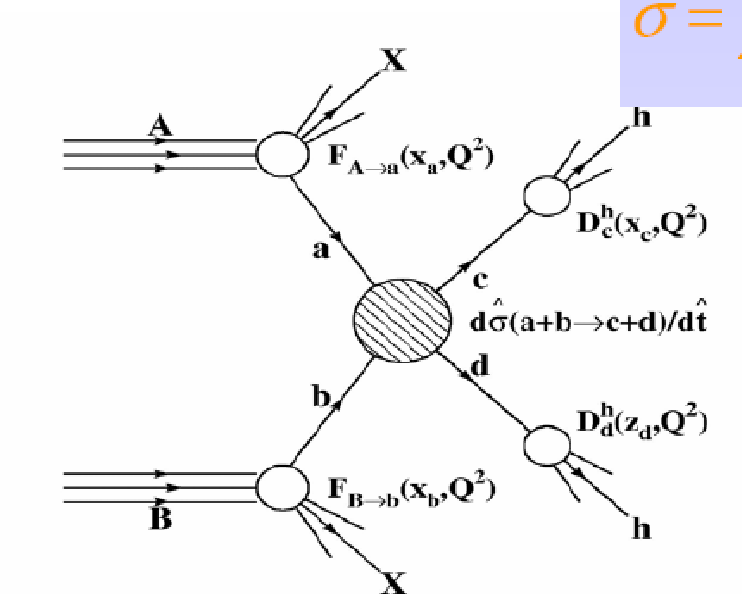


$$\frac{g}{\cos\theta_W}\left(\kappa_R^{Ztc}\bar{t}\gamma_\mu P_R c + \kappa_L^{Ztc}\bar{t}\gamma_\mu P_L c\right)Z^\mu + h.c.$$

$$k_L^{Ztc} < 0.41 @ 95\% C.L$$

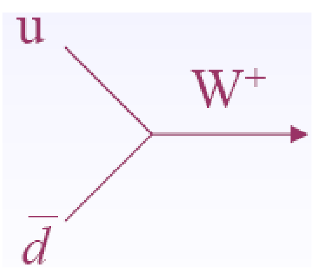
Cross Section Calculation

$$\sigma = \sum_{a,b} \int dx_a \, dx_b \, f_a(x_a, Q^2) \, f_b(x_b, Q^2) \, \hat{\sigma}_{ab}(x_a, x_b)$$



- **sum over initial states a,b**
- **$f_i(x_i,Q^2)$ = parton density functions**

- **Example: W production in leading order**



$\sigma(pp\to W) \approx 150 \text{ nb} \approx 2\cdot 10^{-6}\, \sigma_{tot}$

Luminosity

Rate of produced events for a given process

$$N = \sigma L$$

σ cross section [barn = 10^{-24} cm^2]
L luminosity [1/cm^2/s]

- **luminosity depends on machine parameters: number of protons stored, beam focus at the interaction point, …**
- **luminosity should be high to achieve acceptable rates for rare processes**

Comparison of colliders:

- 10^{31}/cm^2/s LEP
- $2 \cdot 10^{32}$/cm^2/s Tevatron Run II design
- 10^{33}/cm^2/s LHC initial phase (≈ 3 years)
- 10^{34}/cm^2/s LHC design luminosity (> 2010)

$$10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1} = 1\ \mathrm{nb}^{-1}\ \mathrm{s}^{-1} \approx 10\ \mathrm{fb}^{-1}/\mathrm{year}$$