Top @ 2016

PRATISHRUTI SAHA
Sangam @ HRI
February, 2016

- What do we know about the top quark ?

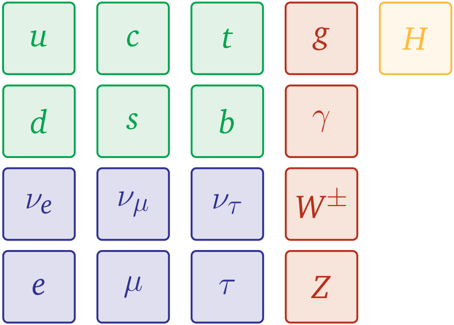
- What do we still not know about the top quark ?

- What can the top quark tell us about other stuff (*aka BSM*) ?

- What do we know about the top quark ?

- What do we still not know about the top quark ?
  - Properties that are predicted in the Standard Model but are yet to be tested experimentally.
  - Properties that are not predicted in the Standard Model - *if they exist*.
- What can the top quark tell us about other stuff (*aka BSM*) ?

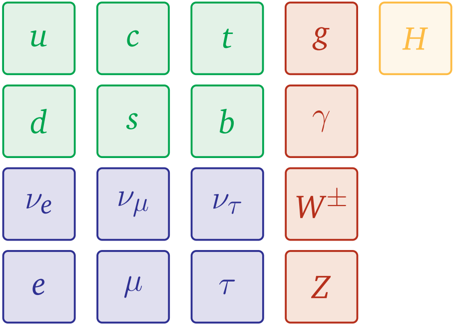
The Standard Model



u	c	t	g	H
d	s	b	γ	
ν_e	ν_μ	ν_τ	$W^\pm$	
e	μ	τ	Z	

The Standard Model

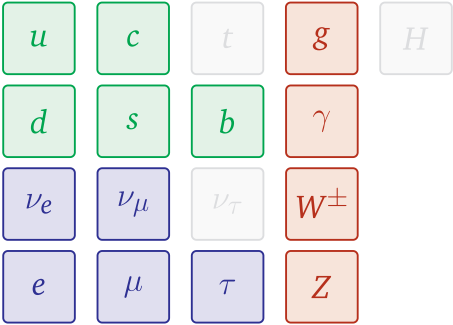
In 2016



u	c	t	g	H
d	s	b	γ	
ν_e	ν_μ	ν_τ	$W^\pm$	
e	μ	τ	Z	

The Standard Model

In 1994 ...



u	c	t	g	H
d	s	b	γ	
ν_e	ν_μ	ν_τ	$W^\pm$	
e	μ	τ	Z	

The Standard Model

$$\underbrace{SU(3)_C}_{\text{strong}} \times \underbrace{SU(2)_L \times U(1)_Y}_{\text{electroweak}}$$

		$SU(3)_C$	$SU(2)_L$	$U(1)_Y^*$	*Spin*
leptons	$\begin{pmatrix}\nu_e \\ e^-\end{pmatrix}_L$ $\begin{pmatrix}\nu_\mu \\ \mu^-\end{pmatrix}_L$ $\begin{pmatrix}\nu_\tau \\ \tau^-\end{pmatrix}_L$	SINGLET	DOUBLET	-1	1/2
	e_R μ_R τ_R	SINGLET	SINGLET	-2	1/2
quarks	$\begin{pmatrix}u \\ d\end{pmatrix}_L$ $\begin{pmatrix}c \\ s\end{pmatrix}_L$ $\begin{pmatrix}t \\ b\end{pmatrix}_L$	TRIPLET	DOUBLET	1/3	1/2
	u_R c_R t_R	TRIPLET	SINGLET	4/3	1/2
	d_R s_R b_R	TRIPLET	SINGLET	-2/3	1/2
gauge bosons	g	OCTET	SINGLET	0	1
	W, Z	SINGLET	TRIPLET	0	1
	γ	SINGLET	TRIPLET	0	1
	H	SINGLET	DOUBLET	1	0

$$^*Q = T_3 + \frac{Y}{2}$$

“The truth is out there …”

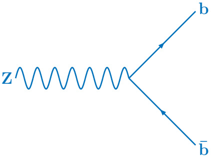
“The truth is out there ...”

- $Z \to b\bar{b}$ at LEP : R_b and $A_{FB}^{0,b}$

- Absence of FCNC’s

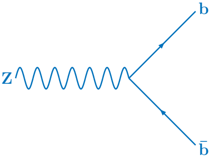
- Cancellation of Anomalies

$Z \to b\bar{b}$ @ LEP



$$i\frac{g}{2\cos\theta_W}\gamma_\mu(c_V - c_A\gamma_5)$$

$Z \to b\bar{b}$ @ LEP

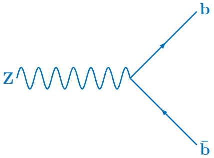


$$i \frac{g}{2\cos\theta_W} \gamma_\mu (c_V - c_A \gamma_5)$$

$$\Gamma(Z \to b\bar{b}) = \frac{1}{16\,\pi} \frac{g^2}{\cos\theta_W^2} (c_V^2 + c_A^2)\, M_Z$$

$$\begin{aligned} c_V &= T_{3L} - 2\,Q_b \sin^2\theta_W \\ c_A &= T_{3L} \end{aligned}$$

$Z \to b\bar{b}$ @ LEP



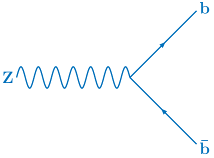
$$i \frac{g}{2\cos\theta_W} \gamma_\mu (c_V - c_A \gamma_5)$$

$$\Gamma(Z \to b\bar{b}) = \frac{1}{16\,\pi} \frac{g^2}{\cos\theta_W^2} (c_V^2 + c_A^2)\, M_Z$$

$$\begin{aligned} c_V &= T_{3L} - 2\,Q_b \sin^2\theta_W \\ c_A &= T_{3L} \end{aligned}$$

Without a partner, b_L would also be an $SU(2)_L$ singlet.

$Z \to b\bar{b}$ @ LEP



$$i\frac{g}{2\cos\theta_W}\gamma_\mu(c_V - c_A\gamma_5)$$

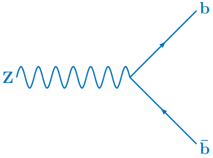
$$\Gamma(Z \to b\bar{b}) = \frac{1}{16\,\pi}\,\frac{g^2}{\cos\theta_W^2}\,(c_V^2 + c_A^2)\,M_Z$$

$$\begin{aligned} c_V &= T_{3L} - 2\,Q_b\sin^2\theta_W \\ c_A &= T_{3L} \end{aligned}$$

Without a partner, b_L would also be an $SU(2)_L$ singlet.

$$\Gamma(Z \to b\bar{b})_{singlet} \approx \frac{\Gamma(Z \to b\bar{b})_{doublet}}{13}$$

$Z \to b\bar{b}$ @ LEP

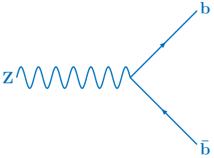


$$i\frac{g}{2\cos\theta_W}\gamma_\mu(c_V - c_A\gamma_5)$$

At LEP, by July 1994 :

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to hadrons)} = 0.2202 \pm 0.0020$$

$Z \to b\bar{b}$ @ LEP



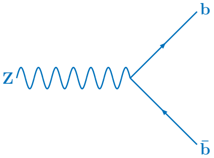
$$i\frac{g}{2\cos\theta_W}\gamma_\mu(c_V - c_A\gamma_5)$$

At LEP, by July 1994 :

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to hadrons)} = 0.2202 \pm 0.0020$$

Theory and experiment agreed provided b_L was considered to be the $T_{3L} = -\frac{1}{2}$ component of an $\mathrm{SU}(2)_\mathrm{L}$ doublet.

$Z \to b\bar{b}$ @ LEP



$$i\frac{g}{2\cos\theta_W}\gamma_\mu(c_V - c_A\gamma_5)$$

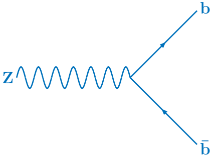
At LEP, by July 1994 :

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to hadrons)} = 0.2202 \pm 0.0020$$

Theory and experiment agreed provided b_L was considered to be the $T_{3L} = -\frac{1}{2}$ component of an $\mathrm{SU}(2)_\mathrm{L}$ doublet.

$\Rightarrow$ *the $T_{3L} = +\frac{1}{2}$ partner of b_L had to exist !*

$Z \to b\bar{b}$ @ LEP

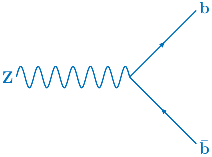


$$i\frac{g}{2\cos\theta_W}\gamma_\mu(c_V - c_A\gamma_5)$$

At LEP, by July 1994 :

$$A_{FB}^{0,b} \quad = \quad \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \quad = \quad 0.0967 \pm 0.0038$$

$Z \to b\bar{b}$ @ LEP



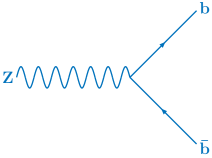
$$i\frac{g}{2\cos\theta_W}\gamma_\mu(c_V - c_A\gamma_5)$$

At LEP, by July 1994 :

$$A_{FB}^{0,b} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = 0.0967 \pm 0.0038$$

$$A_{FB}^{0,b} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b \qquad \mathcal{A}_e = \frac{2\,c_V^e\,c_A^e}{(c_V^e)^2 + (c_A^e)^2} \qquad \mathcal{A}_b = \frac{2\,c_V^b\,c_A^b}{(c_V^b)^2 + (c_A^b)^2}$$

$Z \to b\bar{b}$ @ LEP



$$i\frac{g}{2\cos\theta_W}\gamma_\mu(c_V - c_A\gamma_5)$$

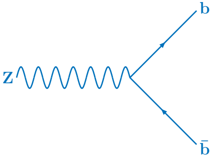
At LEP, by July 1994 :

$$A^{0,b}_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = 0.0967 \pm 0.0038$$

$$A^{0,b}_{FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b \qquad \mathcal{A}_e = \frac{2\,c^e_V\,c^e_A}{(c^e_V)^2 + (c^e_A)^2} \qquad \mathcal{A}_b = \frac{2\,c^b_V\,c^b_A}{(c^b_V)^2 + (c^b_A)^2}$$

$$T^b_{3L} = 0 \quad \Rightarrow \quad c^b_A = 0 \quad \Rightarrow \quad \mathcal{A}_b = 0 \quad \Rightarrow \quad A^{0,b}_{FB} = 0$$

$Z \to b\bar{b}$ @ LEP



$$i\frac{g}{2\cos\theta_W}\gamma_\mu(c_V - c_A\gamma_5)$$

At LEP, by July 1994 :

$$A_{FB}^{0,b} \quad = \quad \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \quad = \quad 0.0967 \pm 0.0038$$

$$A_{FB}^{0,b} \quad = \quad \frac{3}{4}\mathcal{A}_e\mathcal{A}_b \qquad \mathcal{A}_e \;=\; \frac{2\,c_V^e\,c_A^e}{(c_V^e)^2 + (c_A^e)^2} \qquad \mathcal{A}_b \;=\; \frac{2\,c_V^b\,c_A^b}{(c_V^b)^2 + (c_A^b)^2}$$

$$T_{3L}^b \;=\; 0 \quad \Rightarrow \quad c_A^b \;=\; 0 \quad \Rightarrow \quad \mathcal{A}_b \;=\; 0 \quad \Rightarrow \quad A_{FB}^{0,b} \;=\; 0$$

$A_{FB}^{0,b} \neq 0 \quad \Rightarrow \quad T_{3L}^b \neq 0.$ *b_L must have an $SU(2)_L$ partner !*

Absence of FCNC decays of the b

Suppose $b_L \equiv SU(2)_L$ singlet.

Absence of FCNC decays of the b

Suppose $b_L \equiv SU(2)_L$ singlet.

It could still have $U(1)_Y$ charge $\quad\Rightarrow\quad$ could have a coupling to the Z.

Would also couple to the W via its mixing with d and s quarks.

Absence of FCNC decays of the b

Suppose $b_L \equiv SU(2)_L$ singlet.

It could still have $U(1)_Y$ charge $\quad \Rightarrow \quad$ could have a coupling to the Z.

Would also couple to the W via its mixing with d and s quarks.

However, the GIM Mechanism would no longer work in the usual way.

$$\Rightarrow \quad b \rightarrow X\,\ell^+\,\ell^- \quad \text{no longer suppressed.}$$

Absence of FCNC decays of the b

Suppose $b_L \equiv SU(2)_L$ singlet.

It could still have $U(1)_Y$ charge $\quad\Rightarrow\quad$ could have a coupling to the Z.

Would also couple to the W via its mixing with d and s quarks.

However, the GIM Mechanism would no longer work in the usual way.

$$\Rightarrow \quad b \;\to\; X\,\ell^+\,\ell^- \quad \text{no longer suppressed.}$$

In such a scenario,

$$\frac{\Gamma(B \;\to\; X\,\ell^+\,\ell^-)}{\Gamma(B \;\to\; X\,\ell^+\,\nu_\ell)} \;\geqslant\; 0.12$$

[Kane and Peskin, 1981, [1]]

$$\Rightarrow \quad Br\,(\,B \;\to\; X\,\ell^+\,\ell^-\,) \;\geqslant\; 1.3 \times 10^{-2}$$

Absence of FCNC decays of the b

Suppose $b_L \equiv SU(2)_L$ singlet.

It could still have $U(1)_Y$ charge $\Rightarrow$ could have a coupling to the Z.

Would also couple to the W via its mixing with d and s quarks.

However, the GIM Mechanism would no longer work in the usual way.

$\Rightarrow \quad b \to X \ell^+ \ell^-$ no longer suppressed.

In such a scenario,

$$\frac{\Gamma(B \to X \ell^+ \ell^-)}{\Gamma(B \to X \ell^+ \nu_\ell)} \geqslant 0.12$$

[Kane and Peskin, 1981, [1]]

$$\Rightarrow \quad Br\,(B \to X \ell^+ \ell^-) \geqslant 1.3 \times 10^{-2}$$

On the other hand, experimentally

$$Br\,(B \to X \ell^+ \ell^-) \leqslant 3.1 \times 10^{-3}$$

[CLEO Collaboration, 1987, [2]]

Absence of FCNC decays of the b

Suppose $b_L \equiv SU(2)_L$ singlet.

It could still have $U(1)_Y$ charge ⇒ could have a coupling to the Z.

Would also couple to the W via its mixing with d and s quarks.

However, the GIM Mechanism would no longer work in the usual way.

$$\Rightarrow \quad b \to X \ell^+ \ell^- \quad \text{no longer suppressed.}$$

In such a scenario,

$$\frac{\Gamma(B \to X \ell^+ \ell^-)}{\Gamma(B \to X \ell^+ \nu_\ell)} \geqslant 0.12$$

[Kane and Peskin, 1981, [1]]

$$\Rightarrow \quad Br\,(B \to X \ell^+ \ell^-) \geqslant 1.3 \times 10^{-2}$$

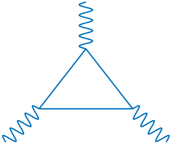
On the other hand, experimentally

$$Br\,(B \to X \ell^+ \ell^-) \leqslant 3.1 \times 10^{-3}$$

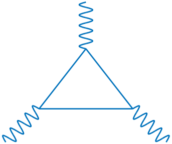
[CLEO Collaboration, 1987, [2]]

Five-quark model ruled out !

Anomaly Cancellation

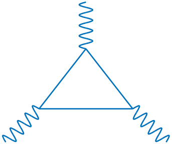


Anomaly Cancellation



Chiral coupling at any vertex ⇒ Violation of Gauge Invariance !

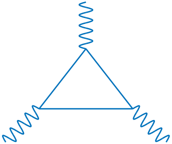
Anomaly Cancellation



Chiral coupling at any vertex ⇒ Violation of Gauge Invariance !

All such diagrams must evaluate to zero.

Anomaly Cancellation



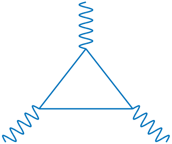
Chiral coupling at any vertex ⇒ Violation of Gauge Invariance !

All such diagrams must evaluate to zero.

$$T^{abc} \propto Tr\left[\zeta_i \, t^a \, \{t^b, t^c\}\right]$$

$$\begin{aligned} \zeta_i &= +1 \quad \text{for right-handed fermions} \\ &= -1 \quad \text{for left-handed fermions} \end{aligned}$$

Anomaly Cancellation



Chiral coupling at any vertex ⇒ Violation of Gauge Invariance !

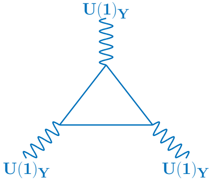
All such diagrams must evaluate to zero.

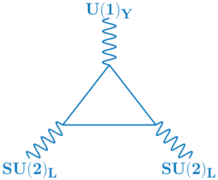
$$T^{abc} \;\propto\; Tr\,[\zeta_i\, t^a\,\{t^b, t^c\}]$$

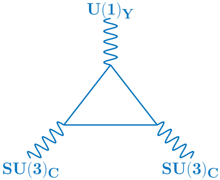
$$\begin{aligned}\zeta_i &= +1 \quad \text{for right-handed fermions}\\ &= -1 \quad \text{for left-handed fermions}\end{aligned}$$

f_L couplings $\equiv$ f_R couplings ⇒ anomalies cancel trivially for each fermion species.

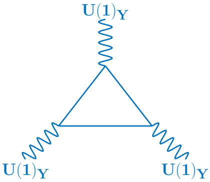
Anomaly Cancellation

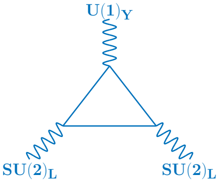


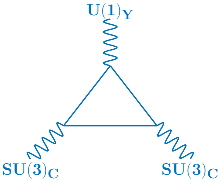




Anomaly Cancellation





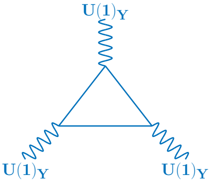


↑

In the SM : cancels for each generation of

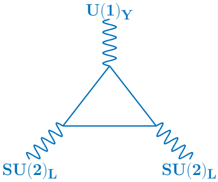
quarks and leptons.

Anomaly Cancellation



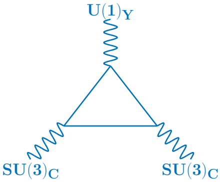
↑

In the SM : cancels for each generation of quarks and leptons.

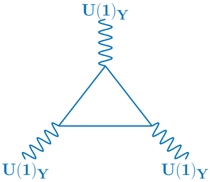


↑

In the SM : cancels separately for each generation of quarks and each generation of leptons.

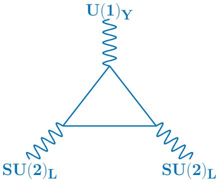


Anomaly Cancellation



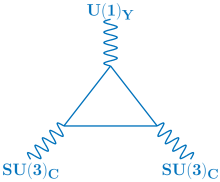
↑

In the SM : cancels for each generation of quarks and leptons.



↑

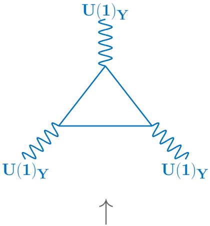
In the SM : cancels separately for each generation of quarks and each generation of leptons.



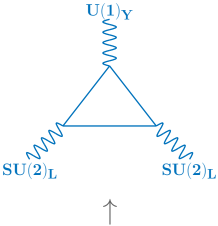
↑

In the SM : cancels separately for each generation of quarks.

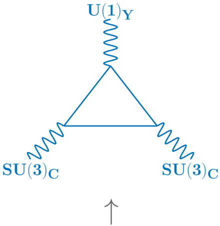
Anomaly Cancellation



In the SM : cancels for each generation of quarks and leptons.



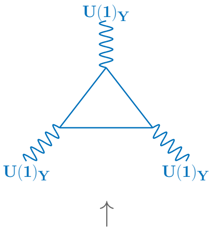
In the SM : cancels separately for each generation of quarks and each generation of leptons.



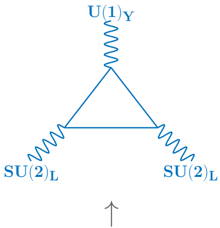
In the SM : cancels separately for each generation of quarks.

No top $\Rightarrow$ b_L is an $SU(2)_L$ singlet.

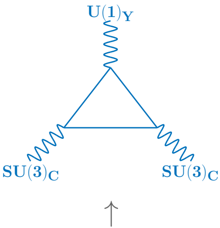
Anomaly Cancellation



In the SM : cancels for each generation of quarks and leptons.



In the SM : cancels separately for each generation of quarks and each generation of leptons.

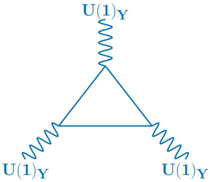


In the SM : cancels separately for each generation of quarks.

No top $\Rightarrow$ b_L is an $SU(2)_L$ singlet.

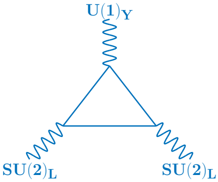
Would not arise for b.

Anomaly Cancellation



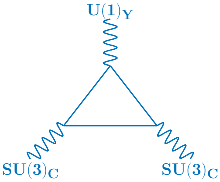
↑

In the SM : cancels for each generation of quarks and leptons.



↑

In the SM : cancels separately for each generation of quarks and each generation of leptons.



↑

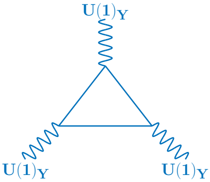
In the SM : cancels separately for each generation of quarks.

No top $\Rightarrow$ b_L is an $SU(2)_L$ singlet.

Would not arise for b.

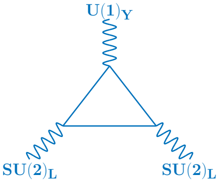
Would still cancel if $Y(b_L) = Y(b_R)$.

Anomaly Cancellation



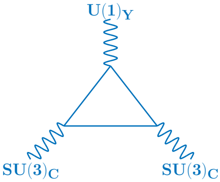
↑

In the SM : cancels for each generation of quarks and leptons.



↑

In the SM : cancels separately for each generation of quarks and each generation of leptons.



↑

In the SM : cancels separately for each generation of quarks.

No top ⇒ b_L is an $SU(2)_L$ singlet.

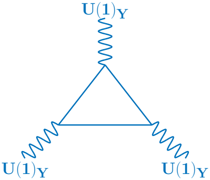
Cancellation would require

$Y(b_L) = Y(b_R)$
$Y(\tau_L) = Y(\tau_R)$
$T_{3L}(\tau_L) = T_{3L}(\tau_R)$

Would not arise for b.

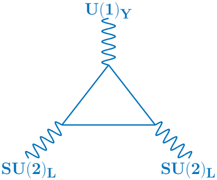
Would still cancel if $Y(b_L) = Y(b_R)$.

Anomaly Cancellation



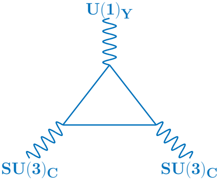
↑

In the SM : cancels for each generation of quarks and leptons.



↑

In the SM : cancels separately for each generation of quarks and each generation of leptons.

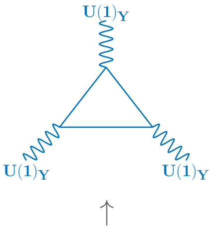


↑

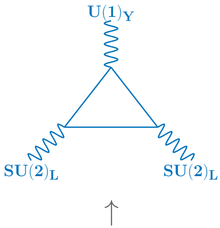
In the SM : cancels separately for each generation of quarks.

Experimentally, b has SM-like couplings !

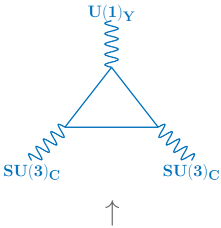
Anomaly Cancellation



In the SM : cancels for each generation of quarks and leptons.



In the SM : cancels separately for each generation of quarks and each generation of leptons.

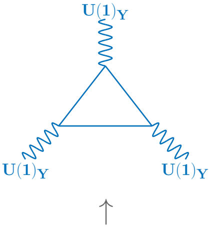


In the SM : cancels separately for each generation of quarks.

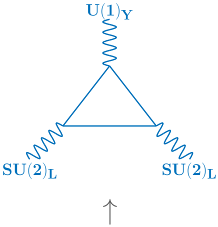
Experimentally, b has SM-like couplings !

Anomalies do not cancel !!

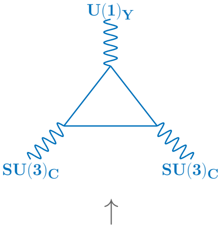
Anomaly Cancellation



In the SM : cancels for each generation of quarks and leptons.



In the SM : cancels separately for each generation of quarks and each generation of leptons.



In the SM : cancels separately for each generation of quarks.

Experimentally, b has SM-like couplings !

Anomalies do not cancel !!

The b-quark needs an "up-type" partner also with SM-like couplings.

Ergo …..

Ergo .....

the truth is DEFINITELY out there.

The story so far …

The story so far ...

- The top quark must exist.
- Its quantum numbers should be the same as those of the up or charm quark.
- Its mass can be anything.

The story so far ...

- The top quark must exist.
- Its quantum numbers should be the same as those of the up or charm quark.
- Its mass can be *anything ?*

The story so far ...

- The top quark must exist.
- Its quantum numbers should be the same as those of the up or charm quark.
- Its mass can be *anything ?*
    - Z decays had been studied in detail at the LEP. $Z \rightarrow t\bar{t}$ was not seen.
    - $Br\,(\,Z \rightarrow t\bar{t}\,) \approx 0$.

The story so far ...

- The top quark must exist.
- Its quantum numbers should be the same as those of the up or charm quark.
- Its mass can be *anything ?*
  - Z decays had been studied in detail at the LEP. $Z \rightarrow t\bar{t}$ was not seen.
  - $Br\,(\,Z \rightarrow t\bar{t}\,) \approx 0$.
  - The couplings were known.

The story so far ...

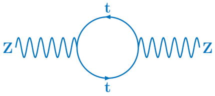
- The top quark must exist.
- Its quantum numbers should be the same as those of the up or charm quark.
- Its mass can be *anything ?*
  - Z decays had been studied in detail at the LEP. $Z \rightarrow t\bar{t}$ was not seen.
  - $Br\,(\,Z \rightarrow t\bar{t}\,) \approx 0.$
  - The couplings were known.
  - $\Gamma(Z \rightarrow t\bar{t}) \simeq 0 \qquad \Rightarrow \qquad m_t \gtrsim \dfrac{M_Z}{2}$

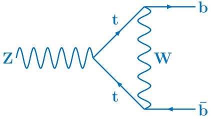
The story so far ...

- The top quark must exist.
- Its quantum numbers should be the same as those of the up or charm quark.
- Its mass can be *anything ?*
  - Z decays had been studied in detail at the LEP. $Z \to t\bar{t}$ was not seen.
  - $Br\,(\,Z \to t\bar{t}\,) \approx 0$.
  - The couplings were known.
  - $\Gamma(Z \to t\bar{t}) \simeq 0 \qquad \Rightarrow \qquad m_t \gtrsim \frac{M_Z}{2}$
  - LEP and the other experiments of the time had also measured a whole host of observables related to the EW theory.

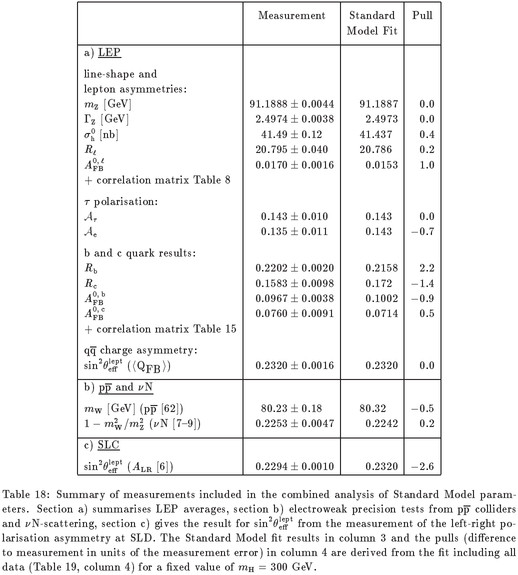
The story so far ...

- The top quark must exist.
- Its quantum numbers should be the same as those of the up or charm quark.
- Its mass can be *anything ?*
  - Z decays had been studied in detail at the LEP. $Z \to t\bar{t}$ was not seen.
  - $Br\,(\,Z \to t\bar{t}\,) \approx 0$.
  - The couplings were known.
  - $\Gamma(Z \to t\bar{t}) \simeq 0 \qquad \Rightarrow \qquad m_t \gtrsim \dfrac{M_Z}{2}$
  - LEP and the other experiments of the time had also measured a whole host of observables related to the EW theory.
  - Many of these quantities were sensitive to m_t (as well as m_H) through quantum corrections.





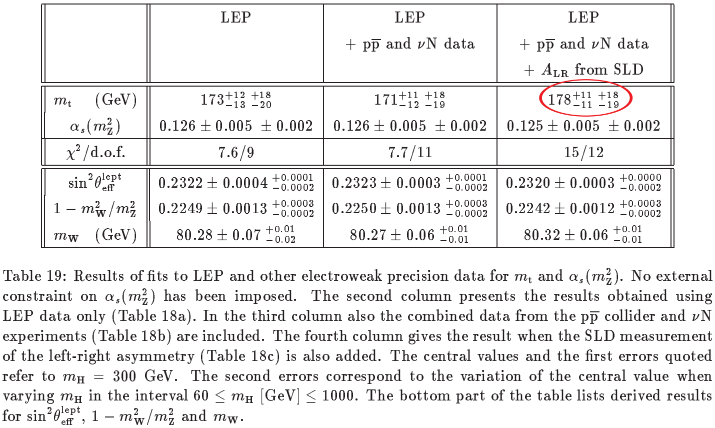
[ALEPH, DELPHI, L3, OPAL, 1994, [3]]



	Measurement	Standard Model Fit	Pull
a) LEP			
line-shape and lepton asymmetries:			
m_Z [GeV]	91.1888 ± 0.0044	91.1887	0.0
Γ_Z [GeV]	2.4974 ± 0.0038	2.4973	0.0
σ_h^0 [nb]	41.49 ± 0.12	41.437	0.4
R_ℓ	20.795 ± 0.040	20.786	0.2
$A_{FB}^{0,\ell}$	0.0170 ± 0.0016	0.0153	1.0
+ correlation matrix Table 8			
τ polarisation:			
$\mathcal{A}_\tau$	0.143 ± 0.010	0.143	0.0
$\mathcal{A}_e$	0.135 ± 0.011	0.143	-0.7
b and c quark results:			
R_b	0.2202 ± 0.0020	0.2158	2.2
R_c	0.1583 ± 0.0098	0.172	-1.4
$A_{FB}^{0,b}$	0.0967 ± 0.0038	0.1002	-0.9
$A_{FB}^{0,c}$	0.0760 ± 0.0091	0.0714	0.5
+ correlation matrix Table 15			
$q\overline{q}$ charge asymmetry:			
$\sin^2\theta_{eff}^{lept}$ ($\langle Q_{FB} \rangle$)	0.2320 ± 0.0016	0.2320	0.0
b) $p\overline{p}$ and νN			
m_W [GeV] ($p\overline{p}$ [62])	80.23 ± 0.18	80.32	-0.5
$1 - m_W^2/m_Z^2$ (νN [7–9])	0.2253 ± 0.0047	0.2242	0.2
c) SLC			
$\sin^2\theta_{eff}^{lept}$ (A_{LR} [6])	0.2294 ± 0.0010	0.2320	-2.6

Table 18: Summary of measurements included in the combined analysis of Standard Model parameters. Section a) summarises LEP averages, section b) electroweak precision tests from $p\overline{p}$ colliders and νN-scattering, section c) gives the result for $\sin^2\theta_{eff}^{lept}$ from the measurement of the left-right polarisation asymmetry at SLD. The Standard Model fit results in column 3 and the pulls (difference to measurement in units of the measurement error) in column 4 are derived from the fit including all data (Table 19, column 4) for a fixed value of $m_H = 300$ GeV.

[ALEPH, DELPHI, L3, OPAL, 1994, [3]]



	LEP	LEP + p$\bar{\mathrm{p}}$ and νN data	LEP + p$\bar{\mathrm{p}}$ and νN data + A_{LR} from SLD
m_{t} (GeV)	$173^{+12}_{-13}\,{}^{+18}_{-20}$	$171^{+11}_{-12}\,{}^{+18}_{-19}$	$178^{+11}_{-11}\,{}^{+18}_{-19}$
$\alpha_s(m_{\mathrm{Z}}^2)$	$0.126 \pm 0.005 \pm 0.002$	$0.126 \pm 0.005 \pm 0.002$	$0.125 \pm 0.005 \pm 0.002$
χ^2/d.o.f.	7.6/9	7.7/11	15/12
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$	$0.2322 \pm 0.0004\,{}^{+0.0001}_{-0.0002}$	$0.2323 \pm 0.0003\,{}^{+0.0001}_{-0.0002}$	$0.2320 \pm 0.0003\,{}^{+0.0000}_{-0.0002}$
$1 - m_{\mathrm{W}}^2/m_{\mathrm{Z}}^2$	$0.2249 \pm 0.0013\,{}^{+0.0003}_{-0.0002}$	$0.2250 \pm 0.0013\,{}^{+0.0003}_{-0.0002}$	$0.2242 \pm 0.0012\,{}^{+0.0003}_{-0.0002}$
m_{W} (GeV)	$80.28 \pm 0.07\,{}^{+0.01}_{-0.02}$	$80.27 \pm 0.06\,{}^{+0.01}_{-0.01}$	$80.32 \pm 0.06\,{}^{+0.01}_{-0.01}$

Table 19: Results of fits to LEP and other electroweak precision data for m_{t} and $\alpha_s(m_{\mathrm{Z}}^2)$. No external constraint on $\alpha_s(m_{\mathrm{Z}}^2)$ has been imposed. The second column presents the results obtained using LEP data only (Table 18a). In the third column also the combined data from the p$\bar{\mathrm{p}}$ collider and νN experiments (Table 18b) are included. The fourth column gives the result when the SLD measurement of the left-right asymmetry (Table 18c) is also added. The central values and the first errors quoted refer to $m_{\mathrm{H}} = 300$ GeV. The second errors correspond to the variation of the central value when varying m_{H} in the interval $60 \leq m_{\mathrm{H}}\ [\mathrm{GeV}] \leq 1000$. The bottom part of the table lists derived results for $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$, $1 - m_{\mathrm{W}}^2/m_{\mathrm{Z}}^2$ and m_{W}.

FERMILAB
A Department of Energy National Laboratory

NEWS RELEASE

News Release - March 2, 1995

NEWS MEDIA CONTACTS:
Judy Jackson, 708/840-4112 (Fermilab)
Gary Pitchford, 708/252-2013 (Department of Energy)
Jeff Sherwood, 202/586-5806 (Department of Energy)

Office of Public Affairs
P.O. Box 500
Batavia, IL 60510
630-840-3351
Fax 630-840-8780
E-Mail TOPQUARK@FNAL.GOV

PHYSICISTS DISCOVER TOP QUARK

Batavia, IL--Physicists at the Department of Energy's Fermi National Accelerator Laboratory today (March 2) announced the discovery of the subatomic particle called the top quark, the last undiscovered quark of the six predicted by current scientific theory. Scientists worldwide had sought the top quark since the discovery of the bottom quark at Fermilab in 1977. The discovery provides strong support for the quark theory of the structure of matter.

Two research papers, submitted on Friday, February 24, to Physical Review Letters by the CDF and DZero experiment collaborations respectively, describe the observation of top quarks produced in high-energy collisions between protons and antiprotons, their antimatter counterparts. The two experiments operate simultaneously using particle beams from Fermilab's Tevatron, world's highest energy particle accelerator. The collaborations, each with about 450 members, presented their results at seminars held at Fermilab on March 2.

"Last April, CDF announced the first direct experimental evidence for the top quark," said William Carithers, Jr., cospokesman, with Giorgio Bellettini, for the CDF experiment, "but at that time we stopped short of claiming a discovery. Now, the analysis of about three times as much data confirms our previous evidence and establishes the discovery of the top quark."

The DZero collaboration has discovered the top quark in an independent investigation. "The DZero observation of the top quark depends primarily on the number of events we have seen, but also on their characteristics," said Paul Grannis, who serves, with Hugh Montgomery, as DZero cospokesman. "Last year, we just did not have enough events to make a statement about the top quark's existence, but now, with a larger data sample, the signal is clear."

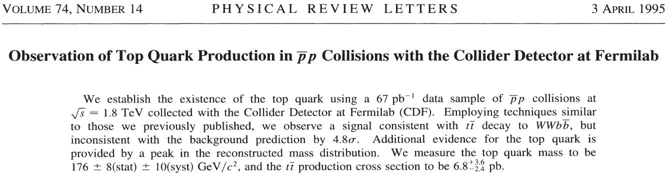
Physicists identify top quarks by the characteristic electronic signals they produce. However, other phenomena can sometimes mimic top quark signals. To claim a discovery, experimenters must observe enough top quark events to rule out any other source of the signals.

"This discovery serves as a powerful validation of federal support for science," said Secretary of Energy Hazel R. O'Leary. "Using one of the world's most powerful research tools, scientists at Fermilab have made yet another major contribution to human understanding of the fundamentals of the universe."

The Department of Energy, the primary steward of U.S. high-energy physics, provided the majority of funding for the research. The Italian Institute for Nuclear Physics and the Japanese Ministry of Education, Science and Culture made major contributions to CDF. Support for DZero came from Russia, France, India, and Brazil. The National Science Foundation contributed to both collaborations. Collaborators include scientists from Brazil, Canada, Colombia, France, India, Italy, Japan, Korea, Mexico, Poland, Russia, Taiwan, and the U.S.

"The discovery of the top quark is a great achievement for the collaborations," said Fermilab Director John Peoples, "and also for the men and women of Fermilab who imagined, then built, and now operate the Tevatron accelerator. We have much to learn about the top quark, and more of nature's best-kept secrets to explore. We look forward to beginning a new era of research with the Tevatron, making the best use of the world's highest-energy collider."

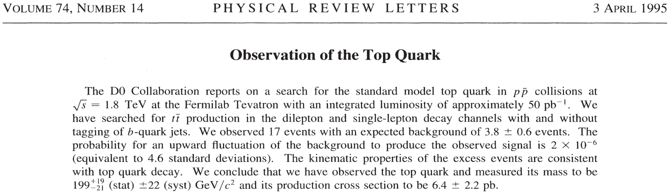
Fermilab, 30 miles west of Chicago, is a high-energy physics laboratory operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy.



VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of Top Quark Production in $\overline{p}p$ Collisions with the Collider Detector at Fermilab

We establish the existence of the top quark using a 67 pb^{-1} data sample of $\overline{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, but inconsistent with the background prediction by 4.8σ. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be $176 \pm 8(\text{stat}) \pm 10(\text{syst})$ GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.



VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of the Top Quark

The D0 Collaboration reports on a search for the standard model top quark in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron with an integrated luminosity of approximately 50 pb^{-1}. We have searched for $t\bar{t}$ production in the dilepton and single-lepton decay channels with and without tagging of b-quark jets. We observed 17 events with an expected background of 3.8 ± 0.6 events. The probability for an upward fluctuation of the background to produce the observed signal is 2×10^{-6} (equivalent to 4.6 standard deviations). The kinematic properties of the excess events are consistent with top quark decay. We conclude that we have observed the top quark and measured its mass to be 199^{+19}_{-21} (stat) ± 22 (syst) GeV/c^2 and its production cross section to be 6.4 ± 2.2 pb.

Top Quark Production

Top Quark Production

Has so far been studied only at hadron colliders – the Tevatron ($p\bar{p}$) and the LHC (pp).

Top Quark Production

Has so far been studied only at hadron colliders – the Tevatron ($p\bar{p}$) and the LHC (pp).

Two major production modes :

Top Quark Production

Has so far been studied only at hadron colliders – the Tevatron ($p\bar{p}$) and the LHC (pp).

Two major production modes :

- $t\bar{t}$
- single top

Top Quark Production

Has so far been studied only at hadron colliders – the Tevatron ($p\bar{p}$) and the LHC (pp).

Two major production modes :

- $t\bar{t}$
  - driven by strong interactions
  - dominant ($pp \to t\bar{t}$ at $\sqrt{s} = 14$ TeV ~ 900 pb)
- single top

Top Quark Production

Has so far been studied only at hadron colliders – the Tevatron ($p\bar{p}$) and the LHC (pp).

Two major production modes :

- $t\bar{t}$
  - driven by strong interactions
  - dominant ($pp \to t\bar{t}$ at $\sqrt{s} = 14$ TeV ~ 900 pb)
- single top
  - driven (largely) by weak interactions
  - sub-dominant ($pp \to tX$ at $\sqrt{s} = 14$ TeV ~ 300 pb)

Top Quark Production

$t\bar{t}$ production

Top Quark Production

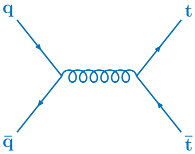
$t\bar{t}$ production

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

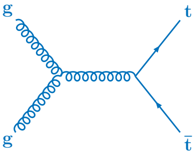
Top Quark Production

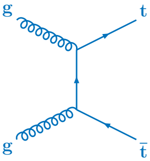
$t\bar{t}$ production

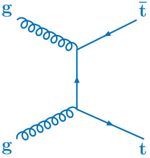
- $q\bar{q} \rightarrow t\bar{t}$



- $gg \rightarrow t\bar{t}$



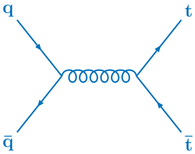




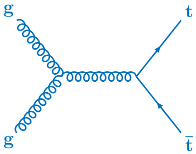
Top Quark Production

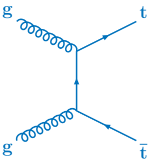
$t\bar{t}$ production

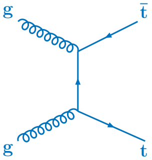
- $q\bar{q} \to t\bar{t}$: dominates when $\frac{2m_t}{\sqrt{s}}$ is large.



- $gg \to t\bar{t}$



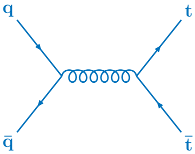




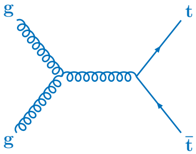
Top Quark Production

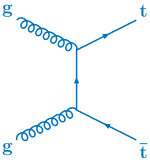
$t\bar{t}$ production

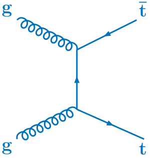
- $q\bar{q} \to t\bar{t}$: dominates when $\dfrac{2m_t}{\sqrt{s}}$ is large.



- $gg \to t\bar{t}$: dominates when $\dfrac{2m_t}{\sqrt{s}}$ is small.

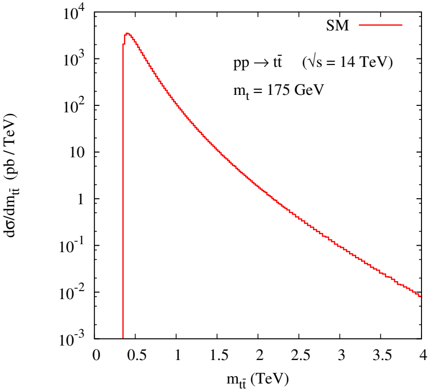






Top Quark Production

$t\bar{t}$ production

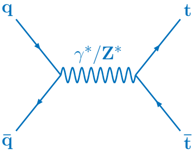


- The cross-section gets maximum contribution from near the threshold.
- At the threshold, $m_{t\bar{t}} = 2\,m_t = \sqrt{s\,x_1\,x_2}$
- If $\dfrac{2m_t}{\sqrt{s}}$ is large,
  the threshold corresponds to large x_1, x_2.
  $\Rightarrow$ *quark densities dominate*
- If $\dfrac{2m_t}{\sqrt{s}}$ is small,
  the threshold corresponds to small x_1, x_2.
  $\Rightarrow$ *gluon densities dominate*

Top Quark Production

$t\bar{t}$ production

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



⋆ contributes but only a miniscule amount

(weak couplings)

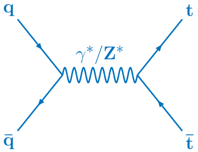
⋆ does not interfere with the gluon-mediated amplitude

($t\bar{t}$ pair in color-singlet configuration)

Top Quark Production

$t\bar{t}$ production

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

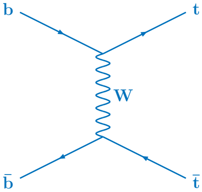


⋆ contributes but only a miniscule amount

(weak couplings)

⋆ does not interfere with the gluon-mediated amplitude

($t\bar{t}$ pair in color-singlet configuration)



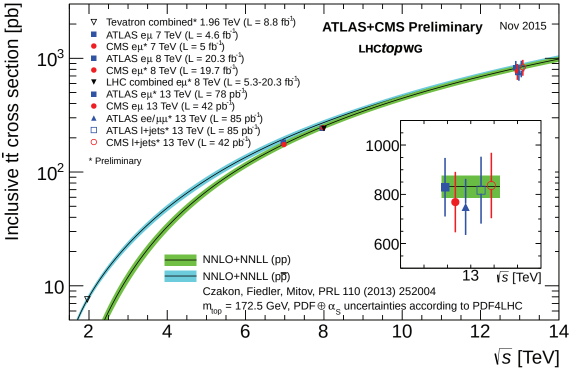
⋆ again, contributes only a miniscule amount

(weak couplings; small *b*-densities inside the proton)

Top Quark Production

$t\bar{t}$ production

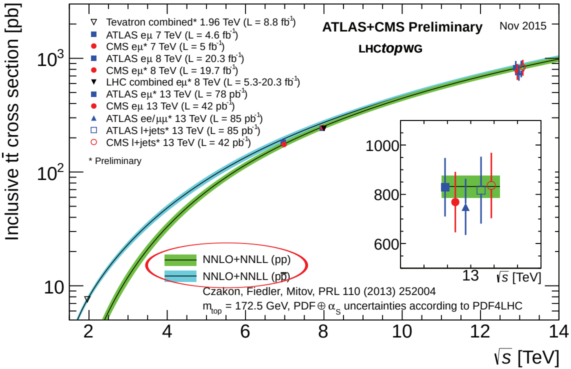
[LHC Top WG, 2015, [6]]



Top Quark Production

$t\bar{t}$ production

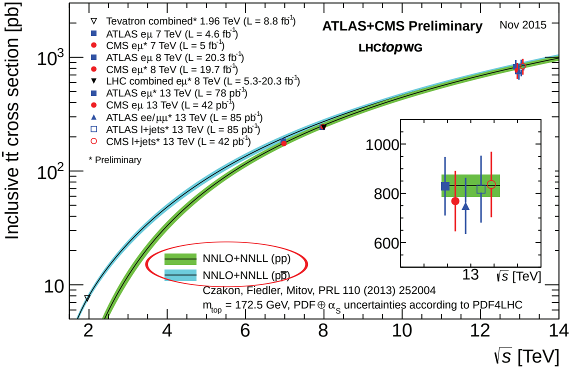
[LHC Top WG, 2015, [6]]



Top Quark Production

$t\bar{t}$ production

[LHC Top WG, 2015, [6]]

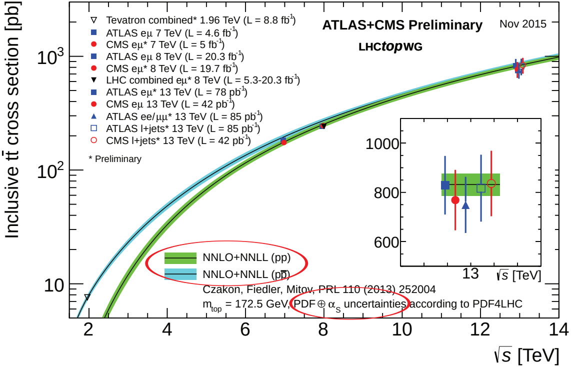


- The cross-section has been calculated to NNLO and beyond in the SM.

Top Quark Production

$t\bar{t}$ production

[LHC Top WG, 2015, [6]]

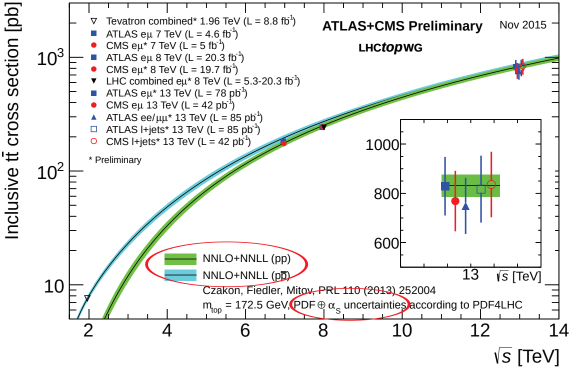


- The cross-section has been calculated to NNLO and beyond in the SM.

Top Quark Production

$t\bar{t}$ production

[LHC Top WG, 2015, [6]]

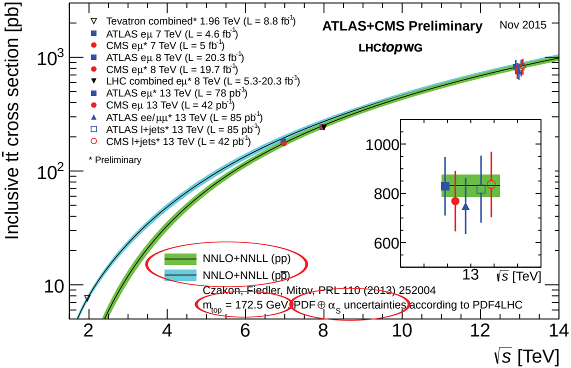


- The cross-section has been calculated to NNLO and beyond in the SM.
- As a result, the PDF and scale uncertainties are small and we have a robust prediction.

Top Quark Production

$t\bar{t}$ production

[LHC Top WG, 2015, [6]]

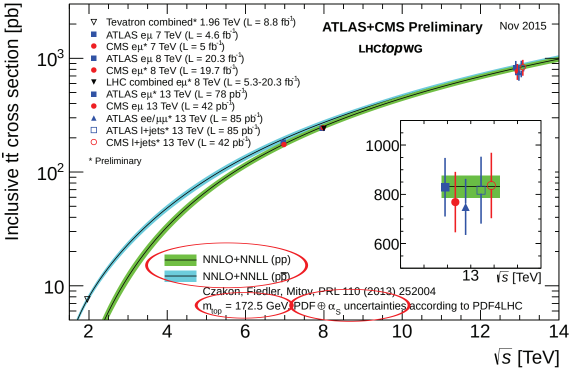


- The cross-section has been calculated to NNLO and beyond in the SM.
- As a result, the PDF and scale uncertainties are small and we have a robust prediction.

Top Quark Production

$t\bar{t}$ production

[LHC Top WG, 2015, [6]]

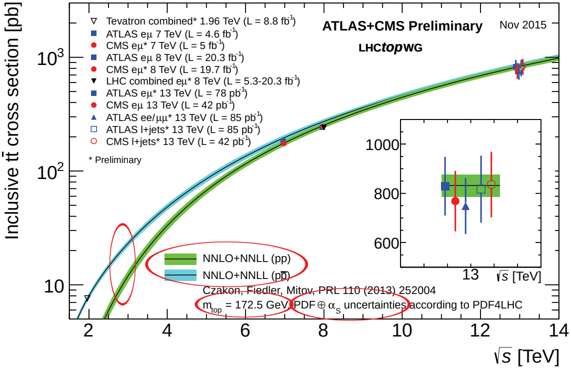


- The cross-section has been calculated to NNLO and beyond in the SM.
- As a result, the PDF and scale uncertainties are small and we have a robust prediction.
- The cross-section has a mass dependence.

Top Quark Production

$t\bar{t}$ production

[LHC Top WG, 2015, [6]]

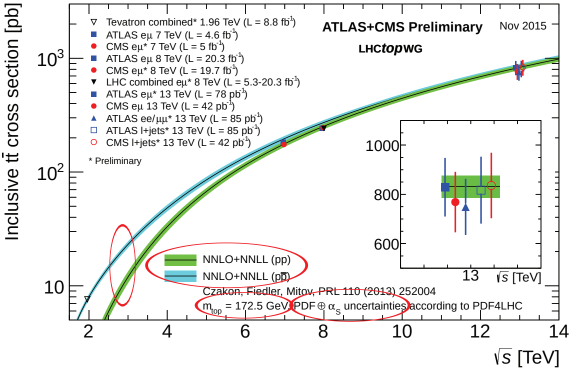


- The cross-section has been calculated to NNLO and beyond in the SM.
- As a result, the PDF and scale uncertainties are small and we have a robust prediction.
- The cross-section has a mass dependence.

Top Quark Production

$t\bar{t}$ production

[LHC Top WG, 2015, [6]]

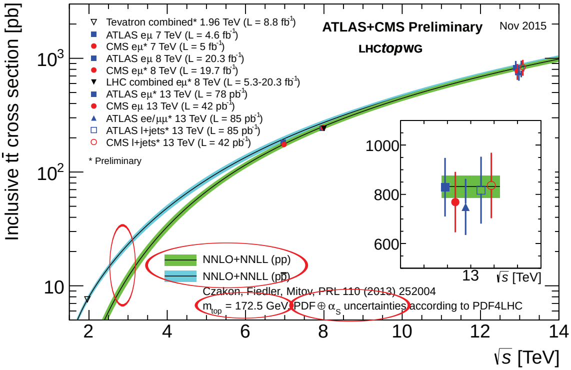


- The cross-section has been calculated to NNLO and beyond in the SM.
- As a result, the PDF and scale uncertainties are small and we have a robust prediction.
- The cross-section has a mass dependence.
- $p\bar{p}$ dominates for low $\sqrt{s}$: $q\bar{q} \to t\bar{t}$ & $\bar{q}$ densities in $\bar{p}$

Top Quark Production

$t\bar{t}$ production

[LHC Top WG, 2015, [6]]

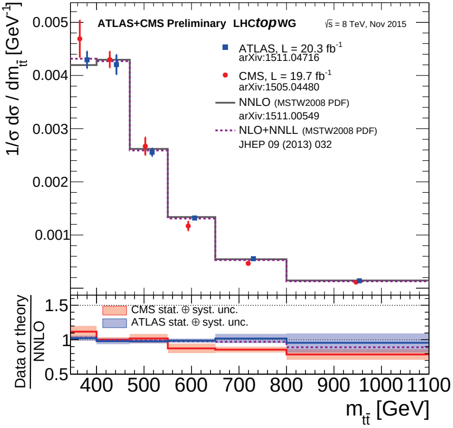


- The cross-section has been calculated to NNLO and beyond in the SM.
- As a result, the PDF and scale uncertainties are small and we have a robust prediction.
- The cross-section has a mass dependence.
- $p\bar{p}$ dominates for low $\sqrt{s}$: $q\bar{q} \to t\bar{t}$ & $\bar{q}$ densities in $\bar{p}$
- *Theory and experiment agree well !*

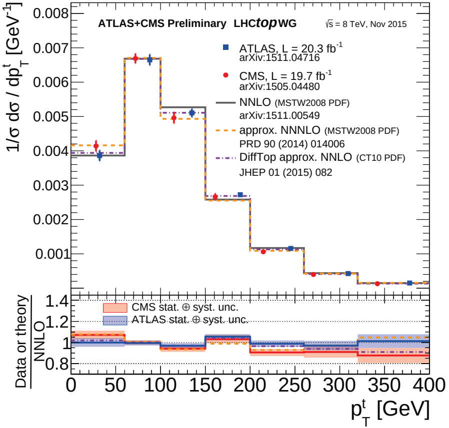
Top Quark Production

$t\bar{t}$ production

[LHC Top WG, 2015, [6]]



[LHC Top WG, 2015, [6]]



Top Quark Production

single top production

Top Quark Production

single top production

s-channel

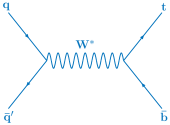
t-channel

tW-channel

Top Quark Production

single top production

s-channel



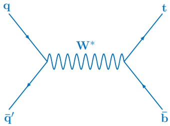
t-channel

tW-channel

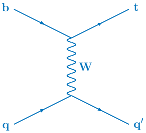
Top Quark Production

single top production

s-channel



t-channel

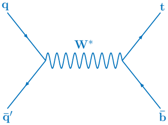


tW-channel

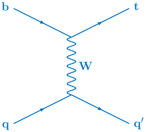
Top Quark Production

single top production

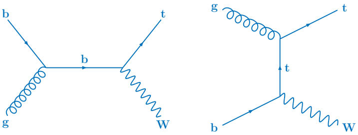
s-channel



t-channel



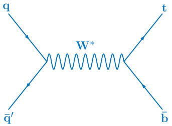
tW-channel



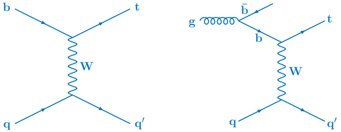
Top Quark Production

single top production

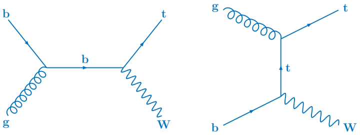
s-channel



t-channel



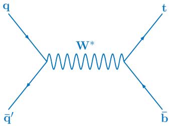
tW-channel



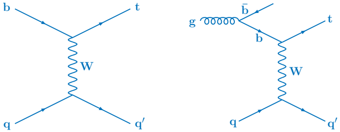
Top Quark Production

single top production

s-channel

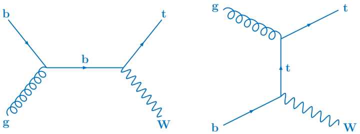


t-channel



Dominant at both the Tevatron and the LHC.

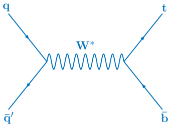
tW-channel



Top Quark Production

single top production

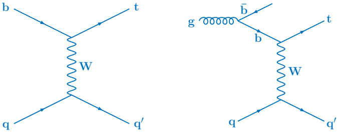
s-channel



Second most dominant process at the Tevatron.

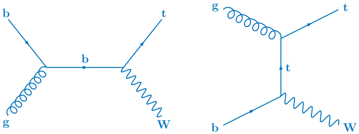
Loses out at the LHC due to low $\bar{q}$ densities inside the proton.

t-channel



Dominant at both the Tevatron and the LHC.

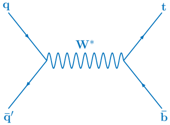
tW-channel



Top Quark Production

single top production

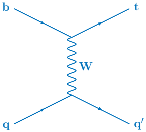
s-channel

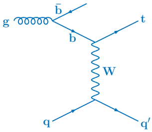


Second most dominant process at the Tevatron.

Loses out at the LHC due to low $\bar{q}$ densities inside the proton.

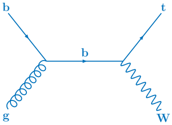
t-channel

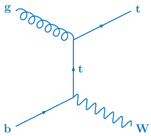




Dominant at both the Tevatron and the LHC.

tW-channel





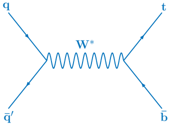
Very small at the Tevatron (two massive particles in the final state).

Second most dominant process at the LHC.

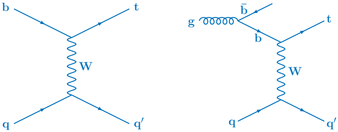
Top Quark Production

single top production

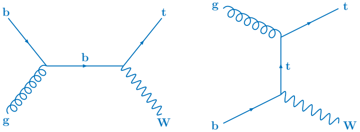
s-channel



t-channel



tW-channel



[Tait et al., 2000, [7]]

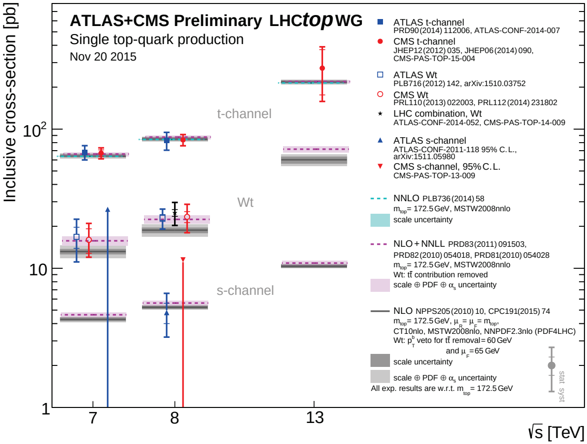
	Tevatron	LHC
s-channel	0.86 pb	11 pb
t-channel	2.4 pb	243 pb
tW-channel	0.088 pb	51 pb

$m_t = 175$ GeV; CTEQ4L, CTEQ4M PDFs

Top Quark Production

single top production

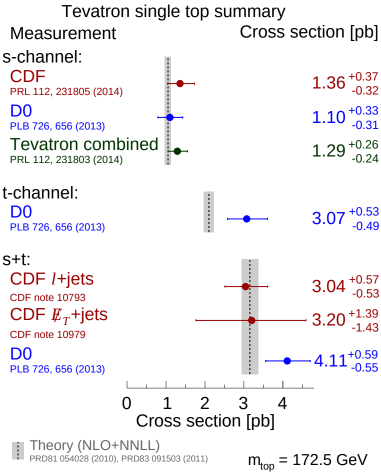
[LHC Top WG, 2015, [6]]



Top Quark Production

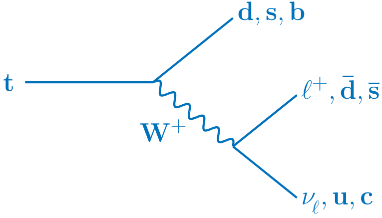
single top production

[Tevatron Electroweak WG, 2014, [8]]

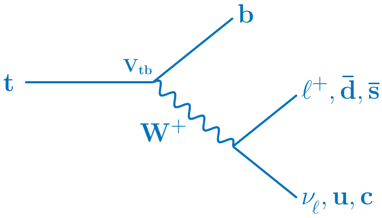


Top Quark Decay

Top Quark Decay



Top Quark Decay



$$V_{tb} = 0.999118^{+0.000024}_{-0.000014}$$

[CKM Fitter, 2015, [9]]

Top Quark Properties

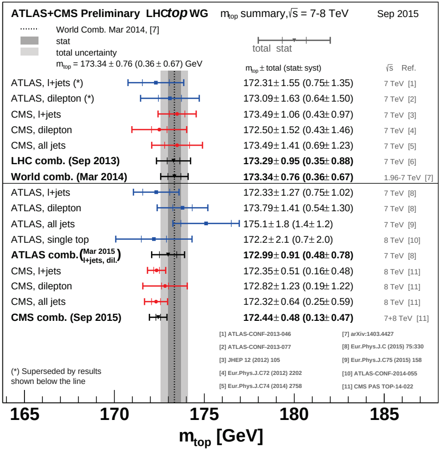
Top Quark Properties

- Mass

Top Quark Properties

Mass

[LHC Top WG, 2015, [6]]



Top Quark Properties

Width

SM (NNLO) : $\Gamma_t = 1.32$ GeV [Gao et al., 2013, [10]]

CDF : $1.10 < \Gamma_t < 4.05$ GeV at 68% confidence level [CDF, 2013, [11]]

CMS : $\Gamma_t = 1.36 \pm 0.02\ (\text{stat.})\ {}^{+0.14}_{-0.11}$ GeV [CMS, 2014, [12]]

Top Quark Properties

Width

SM (NNLO) : $\Gamma_t = 1.32$ GeV [Gao et al., 2013, [10]]

CDF : $1.10 < \Gamma_t < 4.05$ GeV at 68% confidence level [CDF, 2013, [11]]

CMS : $\Gamma_t = 1.36 \pm 0.02\ (\text{stat.})\ ^{+0.14}_{-0.11}$ GeV [CMS, 2014, [12]]

Charge

DØ : $Q_t = -4/3$ excluded at more than 5σ. [DØ, 2014, [13]]

ATLAS : $Q_t = 0.64 \pm 0.02\ (\text{stat.}) \pm 0.08\ (\text{syst.})$ [ATLAS, 2013, [14]]

$Q_t = -4/3$ excluded at more than 8σ.

Top FCNC Decays

Top FCNC Decays

$t \to uX, t \to cX$ $\qquad$ $(X \equiv \gamma, Z, g, H)$

Top FCNC Decays

$t \to uX, t \to cX \qquad\qquad (X \equiv \gamma, Z, g, H)$

Forbidden at the tree-level in the SM. (flavor universal couplings, unitarity of the CKM matrix)

Top FCNC Decays

$t \to uX, t \to cX$ $\qquad$ $(X \equiv \gamma, Z, g, H)$

Forbidden at the tree-level in the SM. (flavor universal couplings, unitarity of the CKM matrix)

Occur at the loop level ⇒ *small rates.*

Top FCNC Decays

$t \to uX,\ t \to cX \qquad\qquad (X \equiv \gamma, Z, g, H)$

Forbidden at the tree-level in the SM. (flavor universal couplings, unitarity of the CKM matrix)

Occur at the loop level ⇒ *small rates.*

	SM	Experimental	
$\mathcal{B}(t \to u\,\gamma)$	$\mathcal{O}(10^{-14})$	$< 1.3 \times 10^{-4}$	[CMS, 2015, [15]]
$\mathcal{B}(t \to c\,\gamma)$	$\mathcal{O}(10^{-14})$	$< 1.7 \times 10^{-3}$	[CMS, 2015, [15]]
$\mathcal{B}(t \to q\,Z)$	$\mathcal{O}(10^{-14})$	$< 5 \times 10^{-4}$	[CMS, 2015, [15]]
		$< 7 \times 10^{-4}$	[ATLAS, 2015, [16]]
$\mathcal{B}(t \to u\,g)$	$\mathcal{O}(10^{-10})$	$< 4 \times 10^{-5}$	[ATLAS, 2016, [16]]
$\mathcal{B}(t \to c\,g)$	$\mathcal{O}(10^{-10})$	$< 20 \times 10^{-5}$	[ATLAS, 2016, [16]]
$\mathcal{B}(t \to u\,H)$	$\mathcal{O}(10^{-17})$	$< 4.6 \times 10^{-3}$	[ATLAS, 2015, [16]]
$\mathcal{B}(t \to c\,H)$	$\mathcal{O}(10^{-15})$	$< 4.5 \times 10^{-3}$	[ATLAS, 2015, [16]]

Top FCNC Decays

$t \to uX, t \to cX$ $\qquad\qquad$ $(X \equiv \gamma, Z, g, H)$

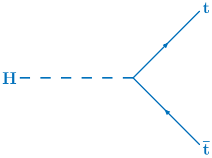
Forbidden at the tree-level in the SM. (flavor universal couplings, unitarity of the CKM matrix)

Occur at the loop level ⇒ *small rates.*

	SM	Experimental	
$\mathcal{B}(t \to u\gamma)$	$\mathcal{O}(10^{-14})$	$< 1.3 \times 10^{-4}$	[CMS, 2015, [15]]
$\mathcal{B}(t \to c\gamma)$	$\mathcal{O}(10^{-14})$	$< 1.7 \times 10^{-3}$	[CMS, 2015, [15]]
$\mathcal{B}(t \to qZ)$	$\mathcal{O}(10^{-14})$	$< 5 \times 10^{-4}$	[CMS, 2015, [15]]
		$< 7 \times 10^{-4}$	[ATLAS, 2015, [16]]
$\mathcal{B}(t \to ug)$	$\mathcal{O}(10^{-10})$	$< 4 \times 10^{-5}$	[ATLAS, 2016, [16]]
$\mathcal{B}(t \to cg)$	$\mathcal{O}(10^{-10})$	$< 20 \times 10^{-5}$	[ATLAS, 2016, [16]]
$\mathcal{B}(t \to uH)$	$\mathcal{O}(10^{-17})$	$< 4.6 \times 10^{-3}$	[ATLAS, 2015, [16]]
$\mathcal{B}(t \to cH)$	$\mathcal{O}(10^{-15})$	$< 4.5 \times 10^{-3}$	[ATLAS, 2015, [16]]

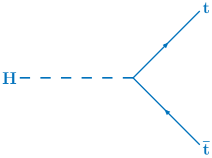
SM rates much lower than the current experimental reach.

Top-Higgs Yukawa Interaction

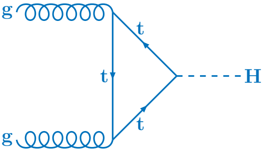


$$i\,\frac{m_t}{v}$$

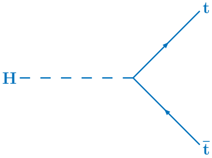
Top-Higgs Yukawa Interaction



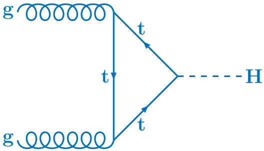
$$i\,\frac{m_t}{v}$$



Top-Higgs Yukawa Interaction

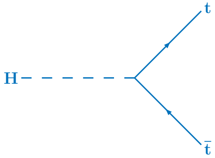


$$i\,\frac{m_t}{v}$$

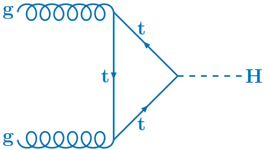


In principle, already tested in $\sigma(gg \to H)$.

Top-Higgs Yukawa Interaction



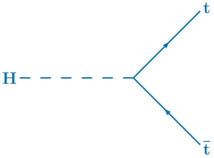
$$i\,\frac{m_t}{v}$$



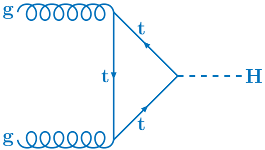
In principle, already tested in $\sigma(gg \rightarrow H)$.

In practice, $\sigma(gg \rightarrow H)$ is plagued by large theoretical (gluon PDFs) and experimental (all Higgs decay channels needed) uncertainties.

Top-Higgs Yukawa Interaction



$$i\,\frac{m_t}{v}$$

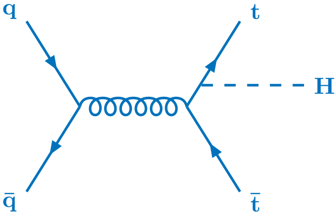


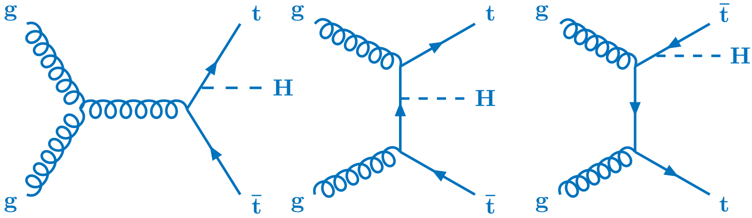
In principle, already tested in $\sigma(gg \to H)$.

In practice, $\sigma(gg \to H)$ is plagued by large theoretical (gluon PDFs) and experimental (all Higgs decay channels needed) uncertainties.

To measure the top-Higgs coupling : $p\,p \to t\,\bar{t}\,H$

Top-Higgs Yukawa Interaction

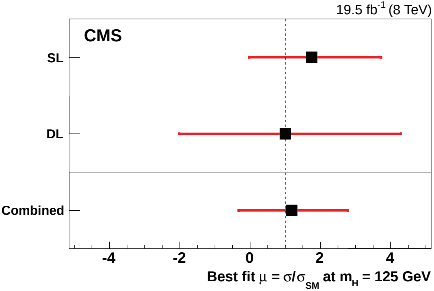




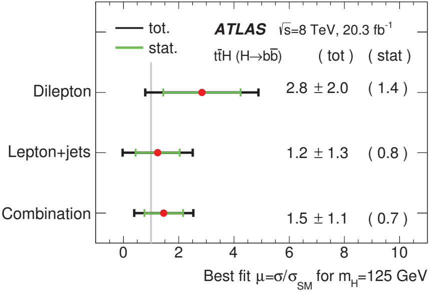
Top-Higgs Yukawa Interaction

$\sigma(pp \to t\bar{t}H)$ at $\sqrt{s} = 8$ TeV ~ 130 pb

[CMS, 2015, [17]]



[ATLAS, 2015, [18]]



But is it a purely scalar coupling ? Or is there a pseudo-scalar component ?

What do we know about the top ?

- Mass
- Width
- Electric Charge
- Strong Couplings
- Weak Couplings
- Production Cross-Section ($t\bar{t}$, single-t)
- Dominant Decays
- Rare Decays
- Yukawa Couplings

- Mass ✓
- Width
- Electric Charge
- Strong Couplings
- Weak Couplings
- Production Cross-Section ($t\bar{t}$, single-t)
- Dominant Decays
- Rare Decays
- Yukawa Couplings

- Mass ✓
- Width ✓
- Electric Charge
- Strong Couplings
- Weak Couplings
- Production Cross-Section ($t\bar{t}$, single-t)
- Dominant Decays
- Rare Decays
- Yukawa Couplings

- Mass ✓
- Width ✓
- Electric Charge ✓
- Strong Couplings
- Weak Couplings
- Production Cross-Section ($t\bar{t}$, single-t)
- Dominant Decays
- Rare Decays
- Yukawa Couplings

- Mass ✓
- Width ✓
- Electric Charge ✓
- Strong Couplings ✓
- Weak Couplings
- Production Cross-Section ($t\bar{t}$, single-t)
- Dominant Decays
- Rare Decays
- Yukawa Couplings

- Mass ✓
- Width ✓
- Electric Charge ✓
- Strong Couplings ✓
- Weak Couplings ✓
- Production Cross-Section ($t\bar{t}$, single-t)
- Dominant Decays
- Rare Decays
- Yukawa Couplings

- Mass ✓
- Width ✓
- Electric Charge ✓
- Strong Couplings ✓
- Weak Couplings ✓
- Production Cross-Section ($t\bar{t}$, single-t) ✓
- Dominant Decays
- Rare Decays
- Yukawa Couplings

- Mass ✓
- Width ✓
- Electric Charge ✓
- Strong Couplings ✓
- Weak Couplings ✓
- Production Cross-Section ($t\bar{t}$, single-t) ✓
- Dominant Decays ✓
- Rare Decays
- Yukawa Couplings

Mass	✓
Width	✓
Electric Charge	✓
Strong Couplings	✓
Weak Couplings	✓
Production Cross-Section ($t\bar{t}$, single-t)	✓
Dominant Decays	✓
Rare Decays	?
Yukawa Couplings	

Mass	✓
Width	✓
Electric Charge	✓
Strong Couplings	✓
Weak Couplings	✓
Production Cross-Section ($t\bar{t}$, single-t)	✓
Dominant Decays	✓
Rare Decays	?
Yukawa Couplings	?

What do we still not know about the top ?

The top quark appears to behave exactly as per the SM prescription.

The top quark appears to behave exactly as per the SM prescription.

Yes, but only upto the energy scales that have been probed.
Beyond this we do not know.

The top quark appears to behave exactly as per the SM prescription.

Yes, but only upto the energy scales that have been probed.
Beyond this we do not know.

Even at the energy scales that have supposedly been probed, BSM physics could be hiding - *small couplings, does not couple to the first 2 generations, does not couple to gluons.*

What can the top tell us about other stuff ?

New Physics in the Top Sector

New Physics in the Top Sector

Couples to a $t\bar{t}$ pair

e.g. $Z_{\mathcal{H}}$, $g_{\mathcal{H}}$, $H_{\mathcal{H}}$.

($\mathcal{H}$ → *heavy*)

New Physics in the Top Sector

Would contribute to top pair production.

(*provided it also couples to* u, d *quarks & gluons*)

Couples to a $t\bar{t}$ pair

e.g. $Z_{\mathcal{H}}$, $g_{\mathcal{H}}$, $H_{\mathcal{H}}$.

($\mathcal{H} \rightarrow$ *heavy*)

New Physics in the Top Sector

Would contribute to top pair production.

(*provided it also couples to u, d quarks & gluons*)

Couples to a $t\bar{t}$ pair

e.g. $Z_{\mathcal{H}}$, $g_{\mathcal{H}}$, $H_{\mathcal{H}}$.

($\mathcal{H} \rightarrow$ *heavy*)

Would appear as a resonance in the $m_{t\bar{t}}$ spectrum at $m_{t\bar{t}} = M_{\mathcal{H}}$

New Physics in the Top Sector

Couples to a $t\bar{t}$ pair

e.g. $Z_{\mathcal{H}}$, $g_{\mathcal{H}}$, $H_{\mathcal{H}}$.

($\mathcal{H} \rightarrow$ *heavy*)

Would contribute to top pair production.

(*provided it also couples to* u, d *quarks & gluons*)

New particles coupling to gluons would easier to spot.

($t\bar{t}$ *production is dominated by* $gg \rightarrow t\bar{t}$.)

Would appear as a resonance in the $m_{t\bar{t}}$ spectrum at $m_{t\bar{t}} = M_{\mathcal{H}}$

New Physics in the Top Sector

Couples t and another particle

e.g. $W_{\mathcal{H}}$, $H^{+}_{\mathcal{H}}$,

flavor-changing $Z_{\mathcal{H}}$.

($\mathcal{H} \rightarrow$ *heavy*)

New Physics in the Top Sector

Would contribute to top decay provided it also couples to other SM particles.

(*Top can only decay into particles lighter than itself; any BSM lighter than the top ought to have been spotted by now.*)

Couples t and another particle

e.g. $W_{\mathcal{H}}$, $H^{+}_{\mathcal{H}}$,

flavor-changing $Z_{\mathcal{H}}$.

($\mathcal{H} \rightarrow$ *heavy*)

New Physics in the Top Sector

Would contribute to top decay provided it also couples to other SM particles.

(*Top can only decay into particles lighter than itself; any BSM lighter than the top ought to have been spotted by now.*)

Would contribute to single top production, provided it couples to light quarks.

Couples t and another particle

e.g. $W_{\mathcal{H}}$, $H^{+}_{\mathcal{H}}$,

flavor-changing $Z_{\mathcal{H}}$.

($\mathcal{H} \to$ *heavy*)

New Physics in the Top Sector

Would contribute to top decay provided it also couples to other SM particles.

(*Top can only decay into particles lighter than itself; any BSM lighter than the top ought to have been spotted by now.*)

Would contribute to single top production, provided it couples to light quarks.

Couples t and another particle

e.g. $W_{\mathcal{H}}$, $H^{+}_{\mathcal{H}}$,

flavor-changing $Z_{\mathcal{H}}$.

($\mathcal{H} \to$ *heavy*)

Could contribute to other heavy BSM particles decaying to the top.

New Physics in the Top Sector

Would contribute to top decay provided it also couples to other SM particles.

(*Top can only decay into particles lighter than itself; any BSM lighter than the top ought to have been spotted by now.*)

Would contribute to single top production, provided it couples to light quarks.

Couples t and another particle

e.g. $W_{\mathcal{H}}$, $H^{+}_{\mathcal{H}}$,

flavor-changing $Z_{\mathcal{H}}$.

($\mathcal{H} \to$ *heavy*)

Could lead to a resonance in the m_{tX} spectrum at $m_{tX} = M_{\mathcal{H}}$.

Could contribute to other heavy BSM particles decaying to the top.

New Physics in the Top Sector

New physics in rare top decays.

New Physics in the Top Sector

$t \to \{u, c\}\ \{\gamma, Z, g, H\}$

(Loop-supressed in the SM.)

New physics in rare top decays.

New Physics in the Top Sector

$t \to \{u, c\}\ \{\gamma, Z, g, H\}$

(Loop-supressed in the SM.)

Can get contributions from
$t \to \{u, c\}\ \{V^0_{\mathcal{H}}, S^0_{\mathcal{H}}\}$.

New physics in rare top decays.

New Physics in the Top Sector

$t \to \{u, c\} \{\gamma, Z, g, H\}$

(Loop-supressed in the SM.)

$t \to bW^+$
$W^+ \to u\bar{b}; W^+ \to c\bar{b}$

(CKM supressed in the SM.)

Can get contributions from
$t \to \{u, c\} \{V^0_{\mathcal{H}}, S^0_{\mathcal{H}}\}$.

New physics in rare top decays.

New Physics in the Top Sector

$t \to \{u, c\}\ \{\gamma, Z, g, H\}$

(Loop-supressed in the SM.)

$t \to bW^+$
$W^+ \to u\bar{b}; W^+ \to c\bar{b}$

(CKM supressed in the SM.)

New physics in rare top decays.

Can get contributions from $t \to \{u, c\}\ \{V^0_{\mathcal{H}}, S^0_{\mathcal{H}}\}$.

Can get contributions from $t \to b\ \{V^+_{\mathcal{H}}, S^+_{\mathcal{H}}\}$.

New Physics in the Top Sector

$$t \to \{u, c\}\ \{\gamma, Z, g, H\}$$

(Loop-supressed in the SM.)

$$t \to bW^+$$
$$W^+ \to u\bar{b}; W^+ \to c\bar{b}$$

(CKM supressed in the SM.)

Can get contributions from $t \to \{u, c\}\ \{V^0_{\mathcal{H}}, S^0_{\mathcal{H}}\}$.

New physics in rare top decays.

Can get contributions from $t \to b\ \{V^+_{\mathcal{H}}, S^+_{\mathcal{H}}\}$.

Consider

$$t \to c\, V^0_{\mathcal{H}},\ V^0_{\mathcal{H}} \to b\, \bar{b}$$
$$i.e. \quad t \to b\, \bar{b}\, c$$

New Physics in the Top Sector

$t \to \{u, c\}\ \{\gamma, Z, g, H\}$

(Loop-supressed in the SM.)

$t \to bW^+$
$W^+ \to u\bar{b}; W^+ \to c\bar{b}$

(CKM supressed in the SM.)

Can get contributions from
$t \to \{u, c\}\ \{V^0_{\mathcal{H}}, S^0_{\mathcal{H}}\}$.

New physics in rare top decays.

Can get contributions from
$t \to b\ \{V^+_{\mathcal{H}}, S^+_{\mathcal{H}}\}$.

Consider
$t \to c\, V^0_{\mathcal{H}},\ V^0_{\mathcal{H}} \to b\, \bar{b}$
$i.e. \quad t \to b\, \bar{b}\, c$

Consider
$t \to b\, V^+_{\mathcal{H}},\ V^+_{\mathcal{H}} \to c\, \bar{b}$
$i.e. \quad t \to b\, \bar{b}\, c$

New Physics in the Top Sector

$t \to \{u, c\}\ \{\gamma, Z, g, H\}$

(Loop-supressed in the SM.)

$t \to bW^+$
$W^+ \to u\bar{b}; W^+ \to c\bar{b}$

(CKM supressed in the SM.)

New physics in rare top decays.

Can get contributions from
$t \to \{u, c\}\ \{V^0_{\mathcal{H}}, S^0_{\mathcal{H}}\}$.

Can get contributions from
$t \to b\ \{V^+_{\mathcal{H}}, S^+_{\mathcal{H}}\}$.

Consider
$t \to c\, V^0_{\mathcal{H}},\ V^0_{\mathcal{H}} \to b\, \bar{b}$
i.e. $\quad t \to b\, \bar{b}\, c$

⟵ Different Physics;

Identical Signature ⟶

Consider
$t \to b\, V^+_{\mathcal{H}},\ V^+_{\mathcal{H}} \to c\, \bar{b}$
i.e. $\quad t \to b\, \bar{b}\, c$

New Physics in the Top Sector

$$t \to \{u, c\}\ \{\gamma, Z, g, H\}$$

(Loop-supressed in the SM.)

$$t \to bW^+$$
$$W^+ \to u\bar{b};\, W^+ \to c\bar{b}$$

(CKM supressed in the SM.)

Can get contributions from
$t \to \{u, c\}\ \{V^0_{\mathcal{H}}, S^0_{\mathcal{H}}\}$.

New physics in rare top decays.

Can get contributions from
$t \to b\ \{V^+_{\mathcal{H}}, S^+_{\mathcal{H}}\}$.

Consider
$t \to c\, V^0_{\mathcal{H}},\ V^0_{\mathcal{H}} \to b\, \bar{b}$
i.e. $t \to b\, \bar{b}\, c$

$\longleftarrow$ Off-shell contribution
in the decay :

$m_{f_1 f_2}$ *does not help !* $\longrightarrow$

Consider
$t \to b\, V^+_{\mathcal{H}},\ V^+_{\mathcal{H}} \to c\, \bar{b}$
i.e. $t \to b\, \bar{b}\, c$

New Physics in the Top Sector

$$t \to \{u, c\}\ \{\gamma, Z, g, H\}$$

(Loop-supressed in the SM.)

$$t \to bW^+$$
$$W^+ \to u\bar{b};\, W^+ \to c\bar{b}$$

(CKM supressed in the SM.)

Can get contributions from $t \to \{u, c\}\ \{V^0_{\mathcal{H}}, S^0_{\mathcal{H}}\}$.

New physics in rare top decays.

Can get contributions from $t \to b\ \{V^+_{\mathcal{H}}, S^+_{\mathcal{H}}\}$.

Consider
$t \to c\, V^0_{\mathcal{H}},\ V^0_{\mathcal{H}} \to b\, \bar{b}$
i.e. $t \to b\, \bar{b}\, c$

$\longleftarrow$ Single top production from b, c initial states : $\longrightarrow$

heavily supressed !!

Consider
$t \to b\, V^+_{\mathcal{H}},\ V^+_{\mathcal{H}} \to c\, \bar{b}$
i.e. $t \to b\, \bar{b}\, c$

New Physics in the Top Sector

New Physics in the Top Sector

Spoiler Alert !

New Physics in the Top Sector

If t_L is involved in a BSM coupling, so is b_L – can be (severely) constrained by flavor physics.

(B-meson decays, oscillations)

Spoiler Alert !

New Physics in the Top Sector

If t_L is involved in a BSM coupling, so is b_L – can be (severely) constrained by flavor physics.

(B-meson decays, oscillations)

In the NP couples to the first two generations of quarks – gets constrained by dijet data.

(of which we have a huge amount)

Spoiler Alert !

New Physics in the Top Sector

If t_L is involved in a BSM coupling, so is b_L — can be (severely) constrained by flavor physics.

(B-meson decays, oscillations)

In the NP couples to the first two generations of quarks — gets constrained by dijet data.

(of which we have a huge amount)

Spoiler Alert !

In the NP does not couple to the first two generations of quarks — sets up FCNC processes.

(which cannot be large)

New Physics in the Top Sector

If t_L is involved in a BSM coupling, so is b_L — can be (severely) constrained by flavor physics.

(B-meson decays, oscillations)

In the NP couples to the first two generations of quarks — gets constrained by dijet data.

(of which we have a huge amount)

Spoiler Alert !

NP that contributes to decay will typically also contribute to single top production.

($m_{\mathcal{H}} \sim 500$ GeV won't do.)

In the NP does not couple to the first two generations of quarks — sets up FCNC processes.

(which cannot be large)

Looking For : New Physics in the Top Sector

Looking For : New Physics in the Top Sector

Productions cross-sections
$(\sigma \cdot \mathcal{B})$

Looking For : New Physics in the Top Sector

Productions cross-sections
$(\sigma \cdot \mathcal{B})$

Kinematic distributions :
$m_{t\bar{t}}, p_T, \eta, m_{tX}$

Looking For : New Physics in the Top Sector

Productions cross-sections

$(\sigma \cdot \mathcal{B})$

Kinematic distributions :

$m_{t\bar{t}}$, p_T, η, m_{tX}

Angular distributions

Looking For : New Physics in the Top Sector

Productions cross-sections

$(\sigma \cdot \mathcal{B})$

Kinematic distributions :

$m_{t\bar{t}}, p_T, \eta, m_{tX}$

Angular distributions

Polarization

Looking For : New Physics in the Top Sector

Productions cross-sections

$(\sigma \cdot \mathcal{B})$

Kinematic distributions :

$m_{t\bar{t}}$, p_T, η, m_{tX}

Angular distributions

Polarization

Spin Correlation

Looking For : New Physics in the Top Sector

Productions cross-sections
$(\sigma \cdot \mathcal{B})$

→

Likely to get affected.
(unless there is destructive interference)

Kinematic distributions :
$m_{t\bar{t}}, p_T, \eta, m_{tX}$

Angular distributions

Polarization

Spin Correlation

Looking For : New Physics in the Top Sector

Productions cross-sections ($\sigma \cdot \mathcal{B}$) → Likely to get affected.
(unless there is destructive interference)

Kinematic distributions : $m_{t\bar{t}}, p_T, \eta, m_{tX}$ → Heavy intermediate particle

Angular distributions

Polarization

Spin Correlation

Looking For : New Physics in the Top Sector

Productions cross-sections $(\sigma \cdot \mathcal{B})$ → Likely to get affected. (unless there is destructive interference)

Kinematic distributions : $m_{t\bar{t}}, p_T, \eta, m_{tX}$ → Heavy intermediate particle

Angular distributions → Nature of the couplings $(S, V, T, \not{P}, \cancel{CP})$

Polarization

Spin Correlation

Looking For : New Physics in the Top Sector

Productions cross-sections ($\sigma \cdot \mathcal{B}$) → Likely to get affected. (unless there is destructive interference)

Kinematic distributions : $m_{t\bar{t}}, p_T, \eta, m_{tX}$ → Heavy intermediate particle

Angular distributions → Nature of the couplings ($S, V, T, \not{P}, \not{CP}$)

Polarization → Specific to the top. Nature of the couplings ($\not{P}, \not{CP}$)

Spin Correlation → Specific to the top. Nature of the couplings ($\not{P}, \not{CP}$)

Looking For : New Physics in the Top Sector

Forward-Backward Asymmetry

$$A_{FB}^{t\bar{t}} = \frac{N(\cos\theta_t > 0) - N(\cos\theta_t < 0)}{N(\cos\theta_t > 0) + N(\cos\theta_t < 0)}$$

Looking For : New Physics in the Top Sector

Forward-Backward Asymmetry

$$A_{FB}^{t\bar{t}} \quad = \quad \frac{N(\cos\theta_t > 0) \ - \ N(\cos\theta_t < 0)}{N(\cos\theta_t > 0) \ + \ N(\cos\theta_t < 0)}$$

- Often considered an indicator of parity violation.
- Not always so
  - *$e^+ e^-$ scattering in pure QED is FB asymmetric* *(t-channel propagator)*.
  - *SM contribution to $A_{FB}^{t\bar{t}}$ comes from QCD.*

Looking For : New Physics in the Top Sector

Forward-Backward Asymmetry

$$A_{FB}^{t\bar{t}} = \frac{N(\cos\theta_t > 0) - N(\cos\theta_t < 0)}{N(\cos\theta_t > 0) + N(\cos\theta_t < 0)}$$

- Often considered an indicator of parity violation.
- Not always so
  - *$e^+ e^-$ scattering in pure QED is FB asymmetric* *(t-channel propagator)*.
  - *SM contribution to $A_{FB}^{t\bar{t}}$ comes from QCD.*

- Around 2009-10, at the Tevatron :
  Observed $A_{FB}^{t\bar{t}} \sim 15\%$
  SM Expectation : $A_{FB}^{t\bar{t}} \sim 5\%$
- Later :
  More data collected at Tevatron – *observed $A_{FB}^{t\bar{t}}$ decreased*;
  SM calculations revised (EW corrections incorporated) – *expected $A_{FB}^{t\bar{t}}$ increased.*
- Now : Data and theory consistent within error bars.

Looking For : New Physics in the Top Sector

Forward-Backward Asymmetry

$$A_{FB}^{t\bar{t}} = \frac{N(\cos\theta_t > 0) - N(\cos\theta_t < 0)}{N(\cos\theta_t > 0) + N(\cos\theta_t < 0)}$$

- Often considered an indicator of parity violation.
- Not always so
  - *$e^+ e^-$ scattering in pure QED is FB asymmetric* *(t-channel propagator)*.
  - *SM contribution to $A_{FB}^{t\bar{t}}$ comes from QCD.*

- Not feasible at the LHC :

  symmetric initial state ⇒ *statistically, any asymmetry gets washed out*.

- Around 2009-10, at the Tevatron :
  Observed $A_{FB}^{t\bar{t}} \sim 15\%$
  SM Expectation : $A_{FB}^{t\bar{t}} \sim 5\%$

- Later :
  More data collected at Tevatron – *observed $A_{FB}^{t\bar{t}}$ decreased*;
  SM calculations revised (EW corrections incorporated) – *expected $A_{FB}^{t\bar{t}}$ increased.*

- Now : Data and theory consistent within error bars.

Looking For : New Physics in the Top Sector

Polarization

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

($\uparrow$, $\downarrow$: helicity)

Looking For : New Physics in the Top Sector

Polarization

$$P_t \quad = \quad \frac{N(\uparrow) \; - \; N(\downarrow)}{N(\uparrow) \; + \; N(\downarrow)}$$

($\uparrow, \downarrow$: helicity)

- $\Gamma_t \approx 2$ GeV $\quad \Rightarrow \quad \tau_t \approx 0.33 \times 10^{-24}\ s$
- $\Lambda_{QCD} = 200$ MeV $\quad \Rightarrow \quad \tau_{had} = 3.3 \times 10^{-24}\ s$
- *The top quark decays before it can hadronize !*
- P_t can be inferred from the angular distributions of the decay products.

Looking For : New Physics in the Top Sector

Polarization

$$P_t \quad = \quad \frac{N(\uparrow) \; - \; N(\downarrow)}{N(\uparrow) \; + \; N(\downarrow)}$$

($\uparrow, \downarrow$: helicity)

- $\Gamma_t \approx 2$ GeV $\quad \Rightarrow \quad \tau_t \approx 0.33 \times 10^{-24}\ s$
- $\Lambda_{QCD} = 200$ MeV $\quad \Rightarrow \quad \tau_{had} = 3.3 \times 10^{-24}\ s$
- *The top quark decays before it can hadronize !*
- P_t can be inferred from the angular distributions of the decay products.

$$\frac{d\,\sigma}{d\cos\theta_i^*} \; , \; \frac{d\,\sigma}{d\phi_i}$$

e.g.

$$\frac{1}{\sigma}\,\frac{d\,\sigma}{d\cos\theta_i^*} \;=\; \frac{1}{2}\,(1 \;+\; P_t\,\alpha_i\,\cos\theta_i^*)$$

θ_i^* : measured in the top rest frame

α_i : ‘spin analyzing power’ of the particle i

Looking For : New Physics in the Top Sector

Polarization

$$P_t \quad = \quad \frac{N(\uparrow) \; - \; N(\downarrow)}{N(\uparrow) \; + \; N(\downarrow)}$$

($\uparrow, \downarrow$: helicity)

- $\Gamma_t \approx 2$ GeV $\quad \Rightarrow \quad \tau_t \approx 0.33 \times 10^{-24}\, s$
- $\Lambda_{QCD} = 200$ MeV $\quad \Rightarrow \quad \tau_{had} = 3.3 \times 10^{-24}\, s$
- *The top quark decays before it can hadronize !*
- P_t can be inferred from the angular distributions of the decay products.

- *Genuine indicator of parity violating couplings.*

$$\frac{d\,\sigma}{d\cos\theta_i^*} \;,\; \frac{d\,\sigma}{d\phi_i}$$

e.g.

$$\frac{1}{\sigma}\,\frac{d\,\sigma}{d\cos\theta_i^*} \;=\; \frac{1}{2}\,(1 \;+\; P_t\,\alpha_i\; \cos\theta_i^*)$$

θ_i^* : measured in the top rest frame

α_i : ‘spin analyzing power’ of the particle i

Looking For : New Physics in the Top Sector

Spin Correlation

$$\kappa_{t\bar{t}} \quad = \quad \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

($\uparrow, \downarrow$: helicity)

Looking For : New Physics in the Top Sector

Spin Correlation

$$\kappa_{t\bar{t}} = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

($\uparrow, \downarrow$: helicity)

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_i^* \, d\cos\theta_{\bar{j}}^*} = \frac{1}{4}\left(1 + P_t\,\alpha_i\,\cos\theta_i^* + P_{\bar{t}}\,\alpha_{\bar{j}}\,\cos\theta_{\bar{j}}^* + \kappa_{t\bar{t}}\,\alpha_i\,\alpha_{\bar{j}}\,\cos\theta_i^*\,\cos\theta_{\bar{j}}^*\right)$$

θ_i^* : measured in the top rest frame $\theta_{\bar{j}}^*$: measured in the anti-top rest frame

α_i : ‘spin analyzing power’ of the particle i

Looking For : New Physics in the Top Sector

Spin Correlation

$$\kappa_{t\bar{t}} \quad = \quad \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

($\uparrow, \downarrow$: helicity)

$$\frac{1}{\sigma}\,\frac{d^2\sigma}{d\cos\theta_i^*\;d\cos\theta_{\bar{j}}^*} \quad = \quad \frac{1}{4}\left(1 + P_t\,\alpha_i\;\cos\theta_i^* + P_{\bar{t}}\,\alpha_{\bar{j}}\;\cos\theta_{\bar{j}}^* + \kappa_{t\bar{t}}\,\alpha_i\,\alpha_{\bar{j}}\;\cos\theta_i^*\;\cos\theta_{\bar{j}}^*\right)$$

θ_i^* : measured in the top rest frame $\quad$ $\theta_{\bar{j}}^*$: measured in the anti-top rest frame

α_i : 'spin analyzing power' of the particle i

In the SM :

$P_t, P_{\bar{t}} \;\approx\; 0$ (arise only from EW contributions)

$\kappa_{t\bar{t}} \;\neq\; 0$

Looking For : New Physics in the Top Sector

Points to Ponder

Looking For : New Physics in the Top Sector

Points to Ponder

- BSM contributions can affect both top production and decay.

Looking For : New Physics in the Top Sector

Points to Ponder

- BSM contributions can affect both top production and decay.
- The only observables are the decay products.

Looking For : New Physics in the Top Sector

Points to Ponder

- BSM contributions can affect both top production and decay.
- The only observables are the decay products.
- If a deviation from the SM is seen - what is it a sign of ?

Looking For : New Physics in the Top Sector

Points to Ponder

- BSM contributions can affect both top production and decay.
- The only observables are the decay products.
- If a deviation from the SM is seen - what is it a sign of ?
  - *New physics in the production mechanism ?*
  - *New physics in the decay ?*

Looking For : New Physics in the Top Sector

Points to Ponder

- BSM contributions can affect both top production and decay.
- The only observables are the decay products.
- If a deviation from the SM is seen - what is it a sign of ?
  - *New physics in the production mechanism ?*
  - *New physics in the decay ?*
- Way out ?

Looking For : New Physics in the Top Sector

Points to Ponder

- BSM contributions can affect both top production and decay.

- The only observables are the decay products.

- If a deviation from the SM is seen - what is it a sign of ?
  - *New physics in the production mechanism ?*
  - *New physics in the decay ?*

- Way out ?
  - *Construct observables carefully.*
  - *Compare and correlate multiple observables.*

Summary

Summary

- The existence of the top quark was anticipated well before it was discovered.
- In the 20 years since its discovery, many of the properties of the top quark have been studied in detail.

Summary

- The existence of the top quark was anticipated well before it was discovered.
- In the 20 years since its discovery, many of the properties of the top quark have been studied in detail.
- So far, the top quark has shown no non-standard behaviour.
- However, physics Beyond the Standard Model ought to exist.

Summary

- The existence of the top quark was anticipated well before it was discovered.

- In the 20 years since its discovery, many of the properties of the top quark have been studied in detail.

- So far, the top quark has shown no non-standard behaviour.

- However, physics Beyond the Standard Model ought to exist.

- The top might well be our window to the New (Physics) World.

Summary

- The existence of the top quark was anticipated well before it was discovered.
- In the 20 years since its discovery, many of the properties of the top quark have been studied in detail.
- So far, the top quark has shown no non-standard behaviour.
- However, physics Beyond the Standard Model ought to exist.
- The top might well be our window to the New (Physics) World.
- Run 2 of the LHC has only just begun.

Summary

- The existence of the top quark was anticipated well before it was discovered.
- In the 20 years since its discovery, many of the properties of the top quark have been studied in detail.
- So far, the top quark has shown no non-standard behaviour.
- However, physics Beyond the Standard Model ought to exist.
- The top might well be our window to the New (Physics) World.
- Run 2 of the LHC has only just begun.
- *The game is afoot !*

References

[1] G. L. Kane and M. E. Peskin, Nucl. Phys. B **195**, 29 (1982).

[2] A. Bean *et al.* [CLEO Collaboration], Phys. Rev. D **35**, 3533 (1987).

[3] ALEPH and DELPHI and L3 and OPAL and LEP Electroweak Working Group Collaborations, CERN-PPE-94-187, C94-07-20, ICHEP (1994).

[4] F. Abe *et al.* [CDF Collaboration], Phys. Rev. Lett. **74**, 2626 (1995).

[5] S. Abachi *et al.* [D0 Collaboration], Phys. Rev. Lett. **74**, 2632 (1995).

[6] The LHC Top Working Group, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG

[7] T. M. P. Tait and C. P. Yuan, Phys. Rev. D **63**, 014018 (2000).

[8] The Tevatron Electroweak Working Group, http://tevewwg.fnal.gov/singleTop/

[9] The CKM Fitter Group,
http://ckmfitter.in2p3.fr/www/results/plots_eps15/num/ckmEval_results_eps15.html

[10] J. Gao *et al.*, Phys. Rev. Lett. **110**, 042001 (2013).

[11] T. A. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **111**, 202001 (2013).

[12] V. Khachatryan *et al.* [CMS Collaboration], Phys. Lett. B **736**, 33 (2014).

References

[13] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **98**, 041801 (2007).

[14] G. Aad *et al.* [ATLAS Collaboration], JHEP **1311**, 031 (2013).

[15] V. Khachatryan *et al.* [CMS Collaboration], arXiv:1511.03951 [hep-ex];
S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **112**, 171802 (2014).

[16] G. Aad *et al.* [ATLAS Collaboration], JHEP **1512**, 061 (2015);
G. Aad *et al.* [ATLAS Collaboration], Eur. Phys. J. C **76**, no. 2, 55 (2016);
G. Aad *et al.* [ATLAS Collaboration], Eur. Phys. J. C **76**, no. 1, 12 (2016).

[17] V. Khachatryan *et al.* [CMS Collaboration], Eur. Phys. J. C **75**, no. 6, 251 (2015).

[18] G. Aad *et al.* [ATLAS Collaboration], Eur. Phys. J. C **75**, no. 7, 349 (2015).

Additional Reading :

[1] Sally Dawson - TASI Lectures 2002 (http://quark.phy.bnl.gov/∼dawson/talks.html)
[2] Mark Kruse - Thesis (http://www-cdf.fnal.gov/physics/new/top/thesis.html)
[3] J. A. Aguilar-Saavedra & Co.
[4] W. Bernreuther & Co.
[5] R. Godbole, S. D. Rindani & Co.
[6] G. Mahlon, S. J. Parke & Co.

Glossary

- LEP : Large Electron Positron Collider; $e^+ e^-$ collider at CERN; operated during 1989-2000 in the same tunnel that now houses the LHC; started at $\sqrt{s} = M_Z = 91$ GeV and went up to $\sqrt{s} = 209$ GeV.

- CLEO : The particle detector attached to the Cornell Electron Storage Ring (CESR); CESR collided e^+ and e^- at $\sqrt{s} \approx 10$ GeV; aimed at studying B-mesons; operated during 1979-2008; CESR is pronounced “Ceaser”; CLEO is short for Cleopatra. ☺

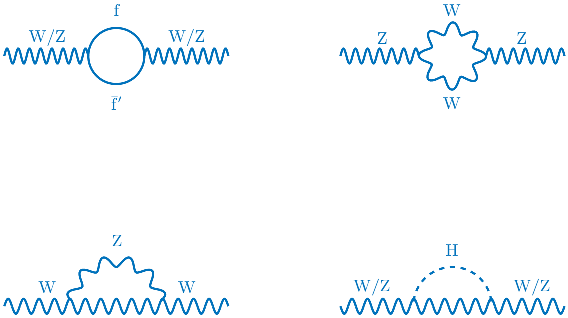
- SLC : Stanford Linear Collider; $e^+ e^-$ linear collider at SLAC; operated during 1989-1998; $\sqrt{s} = M_Z$; used polarized electrons.

- Tevatron : $p\bar{p}$ collider at Fermilab; operated during 1987-2011; $\sqrt{s} = 1.8$ TeV (Run I) and 1.96 TeV (Run II).

Thank You !

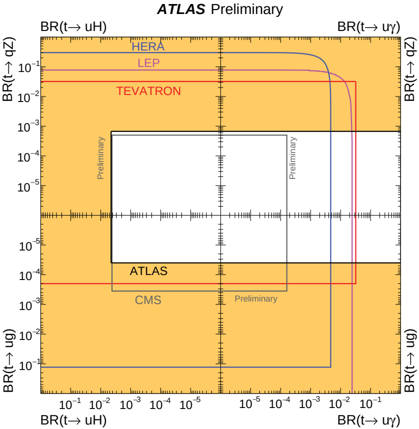
Backup Slides

$$\rho = \frac{M_W^2}{M_Z^2 \cos\theta_W^2}$$

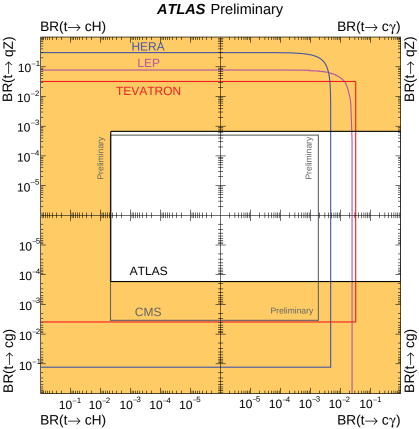


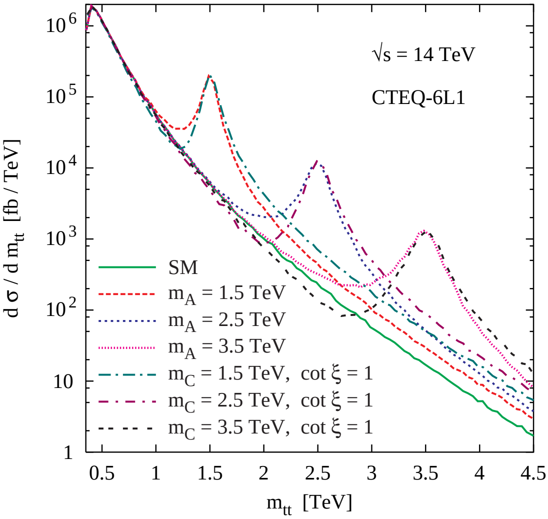
Top FCNC Decays

[ATLAS, 2015, [19]]



[ATLAS, 2015, [19]]





[Choudhury et al., 2007, [20]]

References for Backup Slides

[19] The ATLAS Collaboration,
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP/

[20] D. Choudhury, R. M. Godbole, R. K. Singh and K. Wagh, Phys. Lett. B **657**, 69 (2007).