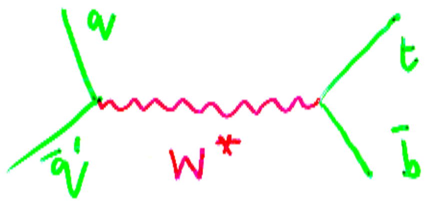
Effect of Kaluza-Klein Excited W in single top production

— A. Datta
P. J. O'Donnell
Xinmin Zhang
Z.-H. Lin
T. Huang

PLB 483, 203 (2000)
hep-ph/0001059.

- In the standard model (SM) single top is produced mainly thru' the processes:

a) 

s-channel W^* mode

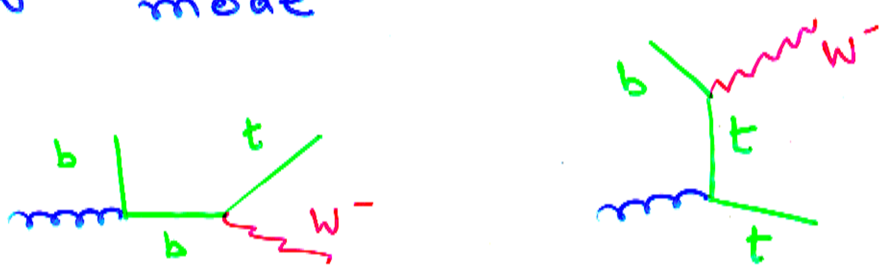
Cross section ~ 0·73 pb
(m_t = 175 GeV, $\sqrt{s}$ = 1·8 TeV)

b) 

W-gluon fusion : t-channel

Cross section ~ 1·7 pb (1·45 pb)

c) tW^- mode



Cross section ~ 0·15 pb

Experiment (DØ):
CDF

σ (W^* schannel $\equiv$ $p\bar{p} \to t b x$) < 39 pb (16 pb)   [DØ, CDF]

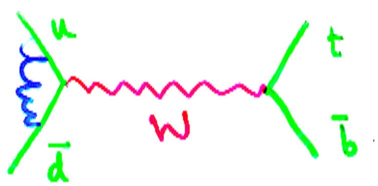
σ (W-gluon $\equiv$ $p\bar{p} \to t q b$) < 58 pb (15 pb)   [DØ, CDF]

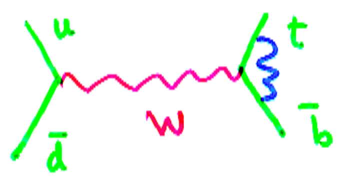
with $\simeq$ 90 pb^{-1} data from Run I between 1992-95

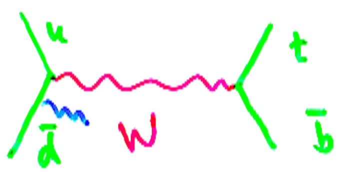
$\sqrt{s}$ = 1·8 TeV

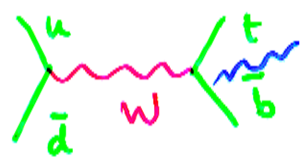
Theoretical Predictions

Have to include radiative corrections:









+ . . .

Cross section $\sigma = |V_{tb}|^2 \, f\,[\text{PDF}, \mu_{\text{Factorization}}, \mu_{\text{Renor}}]$
m_t

W^* s-channel : Less theoretical errors from better understood PDF in the relevant kinematical region

W-gluon fusion : Depends on gluon PDF with larger error
But has larger cross-section compared to W^* s-channel.

- In the SM $|V_{tb}|$ is already well known though it has not been directly measured

- $|V_{tb}|$ constrained from CKM unitarity

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix}_{Mass} = \underbrace{\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}}_{V_{CKM}} \begin{bmatrix} d \\ s \\ b \end{bmatrix}_{weak}$$

$$V_{CKM}^{\dagger} V_{CKM} = V_{CKM} V_{CKM}^{\dagger} = 1$$

$$|V_{tb}| = 0.9990 - 0.9993 \text{ (PDG)}$$

- Single top production can measure $|V_{tb}|$ directly

$$\sigma(p\bar{p} \to t\bar{b}X) \propto |V_{tb}|^2$$

Hence a measurement in $|V_{tb}|$ in single top, inconsistent with SM prediction, is a signal of new physics.

New physics effects

Two approaches:

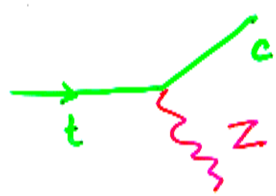
1. Model independent analysis:

a) $$L_{eff} = L_{SM} + \sum \frac{c_i^6 O_i^6}{\Lambda^2} + \cdots$$

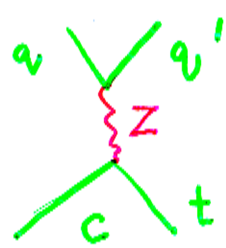
Constrain c_i's from available experiments

Predict effect on single top production.

b) There may be dim 4 anomalous top couplings



[FCNC term]



Contribution to t-channel single top production

2. Effects in specific models

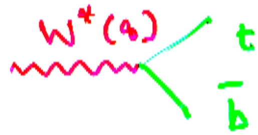
For eg: New models contain additional particles that can contribute to single top production.

Simple Example [From 1(a)]

$$\mathcal{O} = \bar{\Psi}_L \gamma_\mu \frac{\tau^a}{2} \Psi_L D_\nu F^{\mu\nu\, a}$$

$$\Psi_L = \begin{pmatrix} t \\ b \end{pmatrix}$$

(a)



(b)

$Z \to \bar{b} b$: $$\frac{-ig\gamma^\mu}{2\cos\theta_W}\left[g_L(1+\kappa_L)(1-\gamma_5) + g_R(1+\gamma_5)\right]$$

$$g_L = -\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$$

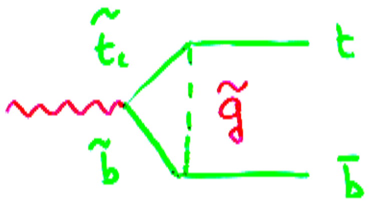
$$\kappa_L \simeq C_L\left(\frac{M_Z^2}{\Lambda^2}\right)\frac{\cos^2\theta_W}{2g g_L}$$

$W^+ \to \bar{t} b$: $$V_{tb}\left(\frac{-ig}{2\sqrt{2}}\right)\gamma^\mu\left[1 - \frac{C_L q^2}{g\Lambda^2}\right](1-\gamma_5)$$

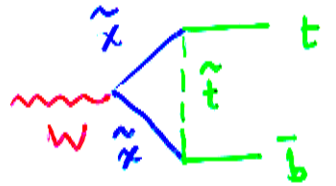
$$\frac{\delta W_{t\bar{b}}}{\delta Z_{b\bar{b}}} \sim \frac{q^2}{M_Z^2} \sim \frac{M_t^2}{M_Z^2}$$

Samples of Specific Models

Susy:



SUSY QCD

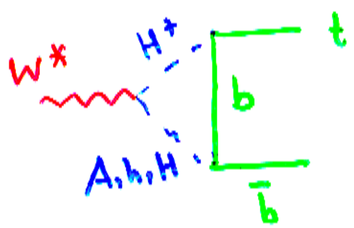


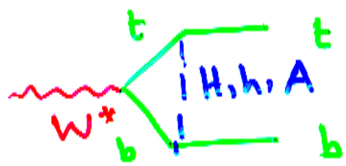
SUSY EW

+ . . . . .

- Small corrections for $\tan\beta \gtrsim 1$
- Maximum $\pm 10\%$

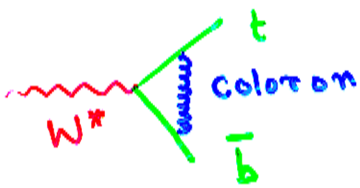
2-Higgs Doublet:





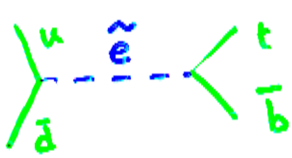
Maximum ~ 15%

Top color:



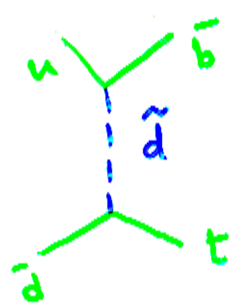
~ Small correction

R̸ SUSY:



Increase cross section

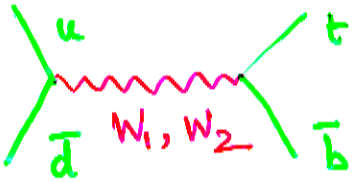
Does not interfere with SM



Interferes with SM

$\Delta\sigma = \pm$ depending on sign of couplings

- W' models



L-R symmetric models
Topflavor
ETC
W_{KK}

- Extra quarks

a) Fourth generation:

V_{tb} is no longer constrained

$$V_{tb} = 0.07 \to 0.993 \quad [PDG]$$

b) Extra b' quark (singlet) from E_6 GUT

$$\begin{bmatrix} d' \\ s' \\ b' \\ b'' \end{bmatrix}_M = \begin{bmatrix} V_{CKM} & & & V_{ub'} \\ & & & V_{cb'} \\ & & & V_{tb'} \\ U_d & U_s & U_b & U_{b'} \end{bmatrix}_{4\times4} \begin{bmatrix} d \\ s \\ b \\ b' \end{bmatrix}_G$$

Prediction: Decrease in the single top X-section

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

$$|V_{tb}|^2 \simeq 1 - |U_b|^2$$

- Measurement of V_{tb} therefore measures U_b

Extra Dim and W_{KK}

- Idea is we live in a universe with extra compact spatial dimensions : $D = 4+n$

- Extra dim can solve the hierarchy problem

$$M_W \ll M_{PL}$$

a) Gravity lives in all the extra dim but SM fields are localized on a 3D-brane

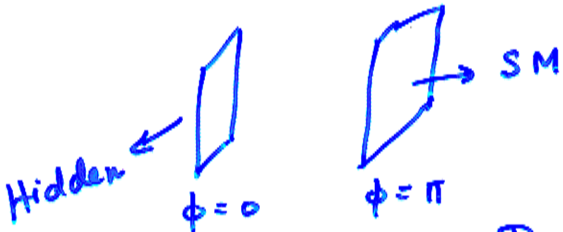
The fundamental scale of gravity

$$M_S \sim \text{TeV}$$

$$M_{Pl}^2 = V_n M_S^{n+2} \qquad V_n \sim R^n \to \text{volume factor}$$

b) Another scenario: Hierarchy generated by an exponential function in the bulk metric

$$ds^2 = e^{-2\sigma(\phi)} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\phi^2$$



Any field has a fundamental mass $m_0 \sim M_{PL}$

But on our brane it appears to have a physical mass $m_0' = m_0 e^{-kr_c\pi}$ $\sim$ TeV

Consequence : Any field living in the bulk will have Kaluza-Klein excited modes which may be detected (directly or indirectly) at colliders.

- If only gravity is allowed to live in the extra dimensions then there will be KK excitations of gravitons.

- Relax the fact that the SM fields are localized in extra dimensions

Some ~~(for)~~ of them may be able to propagate in some of the extra dimensions

$$\Downarrow$$

These SM fields will also have KK excitations.

In particular if W propagatio in some extra dim

$$\underset{\substack{\downarrow \\ \text{usual } W}}{W^0}, \underbrace{W^1, W^2 \ldots\ldots}_{\text{KK excited } W}$$

$W^0, W^1 \sim$ Models with extra W (with some differences).

To make quantitative predictions:

$$\mathcal{L}_{full} = \mathcal{L}(\phi_{SM}, f_{SM}, G_{SM}) + \mathcal{L}(\phi^{KK}, f^{KK}, G^{KK}) + \mathcal{L}_{gravity}(g, g^{KK})$$

$\mathcal{L}_{full}$ is unknown: Also no real models exist.

Simple model

- $D = 4 + n$ $\qquad n$?

- But SM particles (some of them) are allowed to propagate in $4+1 = 5$ Dimension

- Fifth dim x_5 is a circle of radius R with the identification $x_5 \to -x_5$

  [x_5 is compactified on a S^1/Z_2 orbifold]

- We have a line segment of length πR with two boundaries at $x_5 = 0$ and $x_5 = \pi$

- Effect of gravity is neglected

$$\mathcal{L}_{5D} = -\frac{1}{4g_5^2} F_{MN}^2 + \sum_i \Big[(1 - \varepsilon^{\psi_i})\, i\, \bar{\Psi}_i \Gamma^M D_M \Psi_i$$

$$+ (1 - \varepsilon^{H_i}) |D_M H_i|^2 \Big]$$

$$+ \sum_i \Big[\varepsilon^{H_i} |D_\mu H_i|^2 + \varepsilon^{\psi_i}\, i\, \bar{\Psi}_i \sigma^\mu D_\mu \Psi_i \Big] \delta(x_5)$$

$\varepsilon^F = 1\ (0)$ if F living on boundary or bulk

$M = (\mu, 5)$

$g_5 \to$ 5D gauge coupling

The fields living in the bulk can be Fourier expanded

$$\phi_+(x_\mu, x_5) = \sum_{n=0}^{\infty} \cos\frac{n x_5}{R}\, \phi_+^n(x_\mu)$$

$$\phi_-(x_\mu, x_5) = \sum_{n=0}^{\infty} \sin\frac{n x_5}{R}\, \phi_-^n(x_\mu)$$

$$\left.\begin{array}{l} \phi_+(x_5) = +\phi(-x_5) \\ \phi_-(x_5) = -\phi(-x_5) \end{array}\right\}$$

$\phi_\pm^0$ are the usual SM fields

$\phi_\pm^n \rightarrow$ KK excitations of these fields.

$$\mathcal{L}^{ch} = \frac{1}{2} m_W^2 \left[W_a W^a + 2\sqrt{2}\, s \sum_{n=1}^{\infty} W_a W^{a(n)} \right]$$

$$+ \frac{1}{2} M_c^2 \sum_{n=1}^{\infty} n^2 W_a^{(n)} W_a^{(n)}$$

$$- \underline{\underline{g}}\, W_a J^a - \underline{\underline{g\sqrt{2}}}\, J_a^{KK} \sum_{n=1}^{\infty} W_a^{(n)}$$

$M_c = \frac{1}{R} \sim$ TeV

$$J_\mu = \bar{\psi}_L \gamma_\mu \frac{\tau^a}{2} \psi_L$$

$$J_\mu^{KK} = \varepsilon^{\psi_L} \bar{\psi}_L \gamma_\mu \frac{\tau^a}{2} \psi_L$$

$$\underline{M_{W_{KK}}^n = n M_c}$$

[① coupling of ψ to W, W' related by $\sqrt{2}$

② If ψ lives in bulk it does not couple to W_n^{KK} $n \geq 1$]

- Mixing between W_a^0, W_{KK}^1 [ignoring $W_{KK}^{n=2\ldots}$]

  Mixing $\sim \left(\frac{m_Z^2}{M_c^2}\right) \sim$ small if $M_c \sim$ TeV

Hence for single top production mixing effects can be neglected.

$$\sigma(\text{single top}) = f(\ldots_{SM}, M_c)$$

$\rightarrow$ no dependence on any mixing angle (This is different from other W' models)

Bounds on M_c

- EW precision observables: Depend on

a) which SM fields live on the extra dimensions and which fields are localized

b) Understanding the contribution of gravity induced processes (g_{KK}) to the electroweak observables.

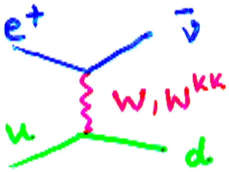
- Assuming all SM localized
- No gravity effects $\quad M_c \gtrsim 4$ TeV

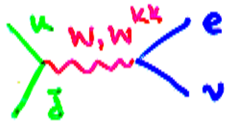
If above assumptions are not made M_c may be lower

At best we can assume $M_c \sim 1$ TeV (ballpark value)

Other bound

Use data on $e^+p \to \bar{\nu}\, X$ (HERA) [t-channel)





$p\bar{p} \to e^{\pm}\bar{\nu}$ (Tevatron) [s-channel]

Exchange of W^{KK} generate contact terms. For $q^2 \ll M_c^2$

$$\mathcal{L}_{contact} \sim \frac{g^2}{M_c^2}\, \bar{l}\gamma^\mu \Upsilon^a l\; \bar{q}\gamma^\mu \Upsilon^a q$$

M_c(HERA) $\left[\text{Fit to } \frac{d\sigma}{dx\,dQ^2}\right]$

$$M_c = \frac{g}{\sqrt{4\pi}}\Lambda \qquad [\Lambda \sim 3.5\text{ TeV}]$$

$$g \sim 1 \qquad M_c \gtrsim 1\text{ TeV}$$

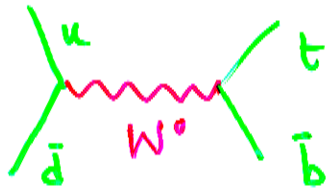
M_c(Tevatron) $\left[\text{Fit to } \frac{d\sigma}{dM_t} \quad M_t^2 = (e+\nu)^2,\; M_t \geq 140\text{ GeV}\right]$

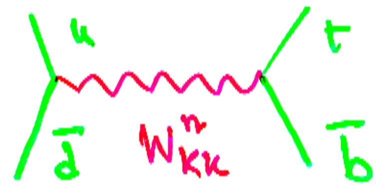
$$M_c \sim \frac{g}{\sqrt{4\pi}}\Lambda \qquad \Lambda \geq 2\text{TeV}$$

$$M_c \sim 1\text{TeV}$$

- Note these processes do not receive any effects from KK excited gravitons. Hence no gravity pollution of signal unlike bounds from EW observables.

Predictions for Singe top





Partonic level

$$\sigma = \sigma_{SM}\left[1 + 4\frac{A}{D} + 4\frac{C}{D}\right]$$

$$A = (s - M_W^2)(s - M_{W_{KK}}^2) + M_W M_{W_{KK}} \Gamma_W \Gamma_{W_{KK}}$$

$$D = (s - M_{W_{KK}}^2)^2 + (M_{W_{KK}} \Gamma_{W_{KK}})^2$$

$$C = (s - M_W^2)^2 + (M_W \Gamma_W)^2$$

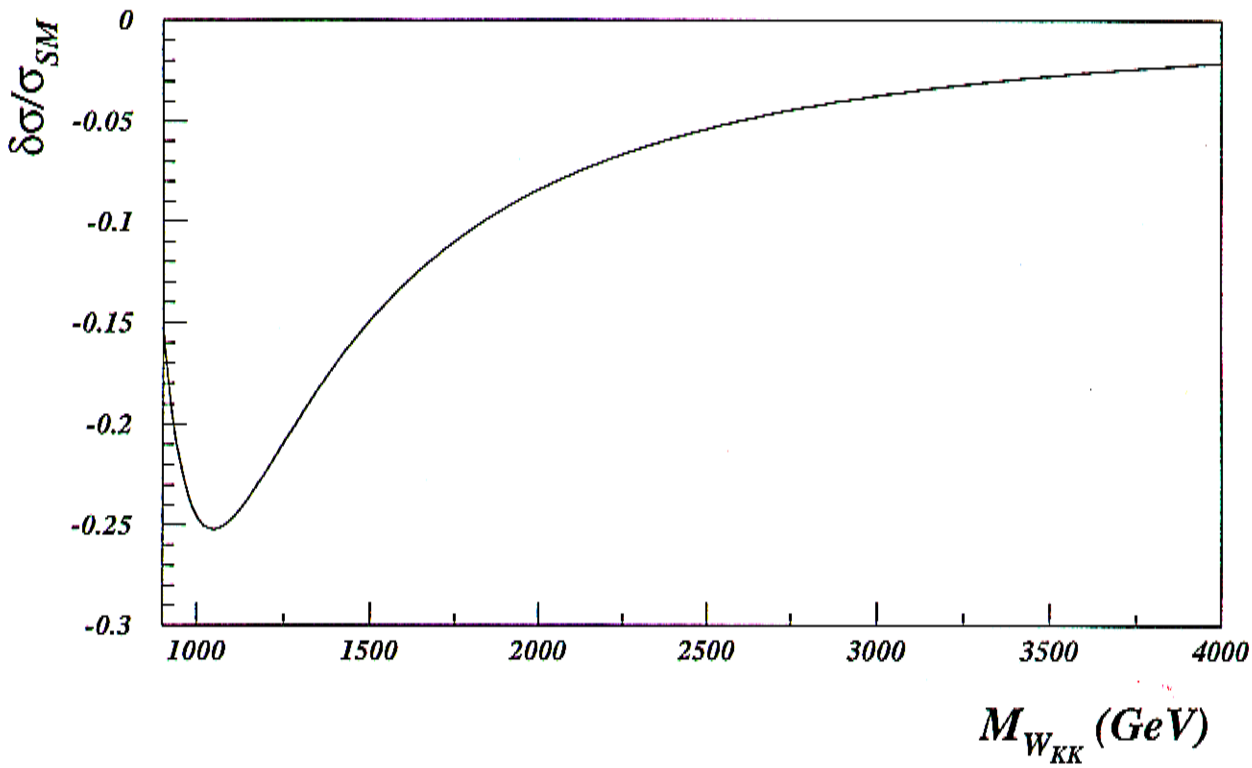
Note • Interference term $4\frac{A}{D}$ dominates the direct term $4\frac{C}{D}$ in the signal region

• Interference term is $-ve$

• $\sigma = f(\text{SM parametrs}, M_{W_{KK}})$

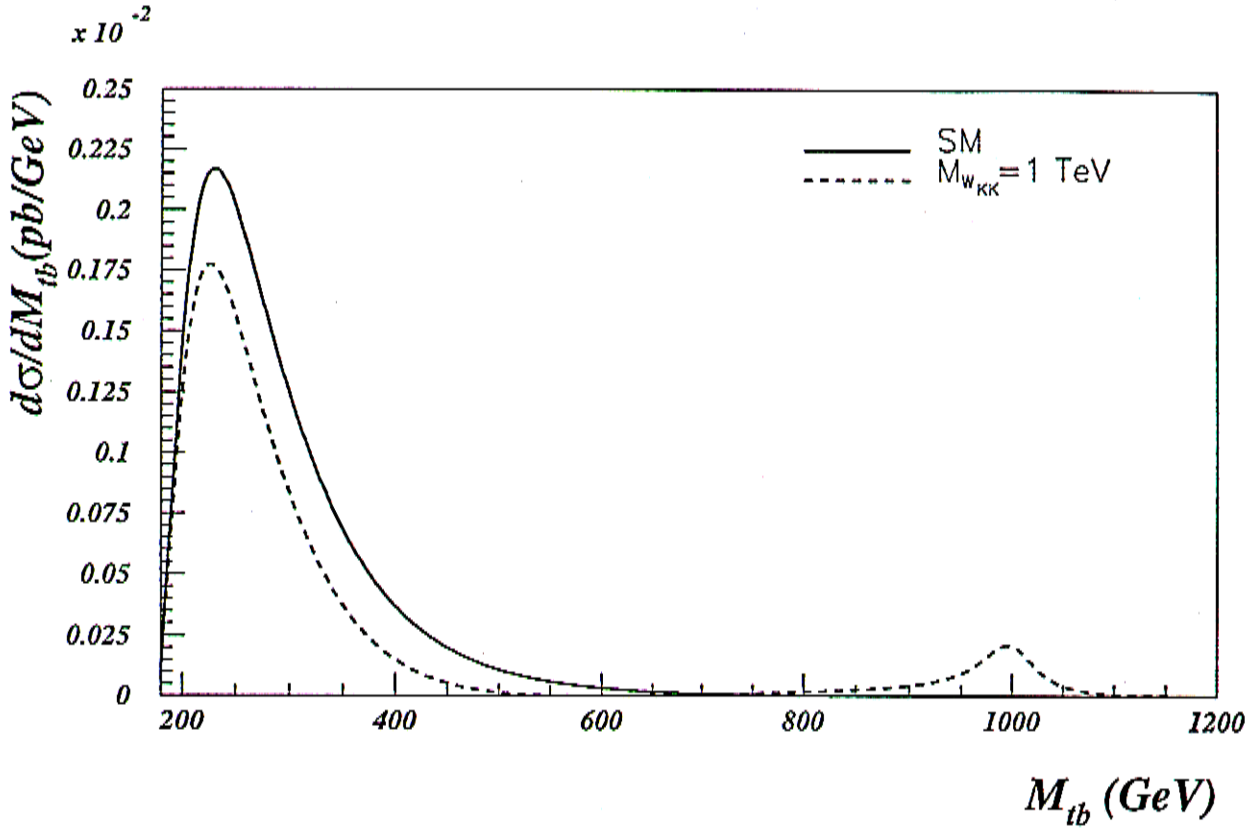
• Note $\Gamma_W \neq \Gamma_{W_{KK}}$. $W_{KK} \to t\bar{b}$ for onshell W_{KK} is allowed.

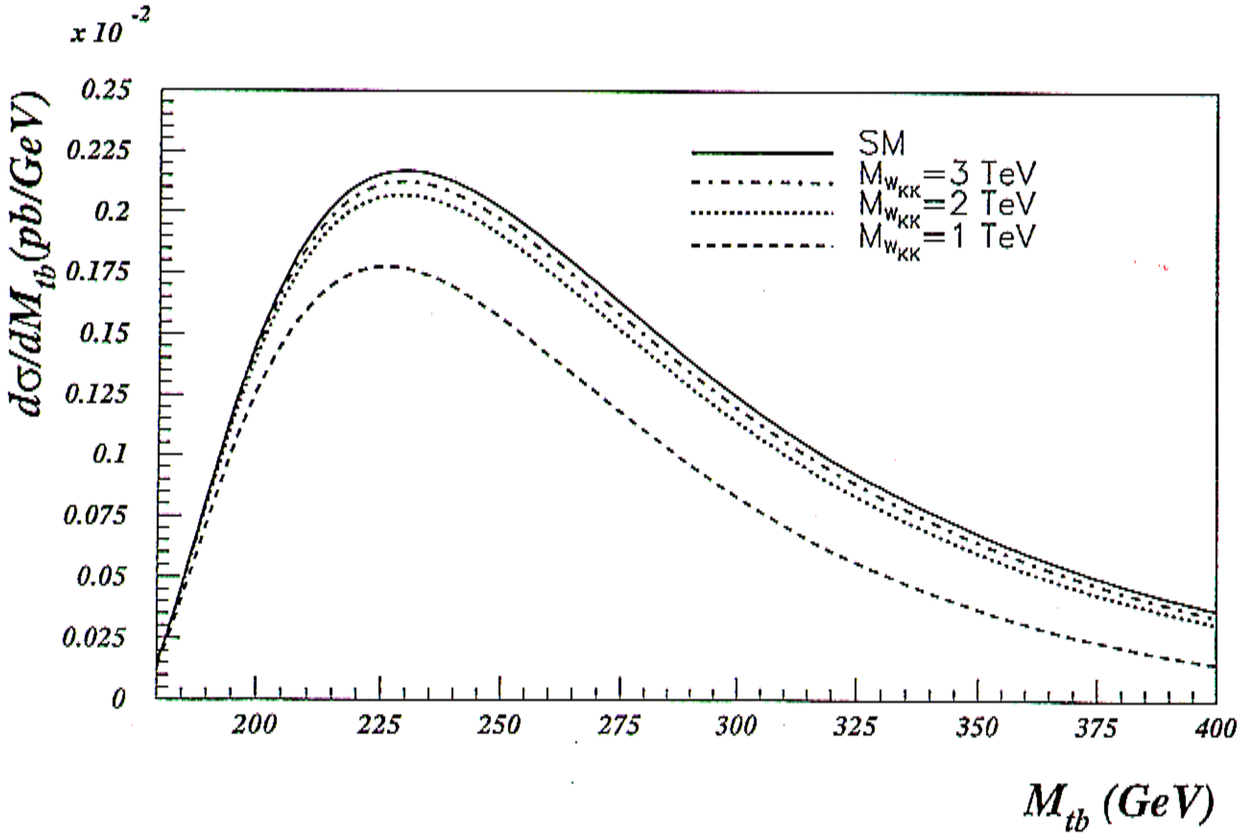
$$\Gamma_{W_{KK}} \sim \frac{M_{W_{KK}}}{M_W}\Gamma_W$$



$M_{W_{KK}} \sim 1$ TeV

$$\frac{\Delta\sigma}{\sigma} = -\ 25\%$$


x 10^-2
dσ/dM_tb (pb/GeV)
0.25
0.225
0.2
0.175
0.15
0.125
0.1
0.075
0.05
0.025
0
SM
M_W_KK = 1 TeV
200
400
600
800
1000
1200
M_tb (GeV)


x 10^-2
dσ/dM_tb (pb/GeV)
0.25
0.225
0.2
0.175
0.15
0.125
0.1
0.075
0.05
0.025
0
SM
M_W_KK = 3 TeV
M_W_KK = 2 TeV
M_W_KK = 1 TeV
200
225
250
275
300
325
350
375
400
M_tb (GeV)

Comparison with other Models

- General Statement: All models with extra W' can affect significantly the W^* s-channel process

- The W-gluon channel gets small corrections (t-channel)

Other popular W' models

General structure: Two $W's$ (W_l, W_h)

Mass eigenstates W_1, W_2

$$W_1 = c\,W_l - s\,W_h \qquad W_2 = s\,W_l + c\,W_h$$

$$s = \sin\phi \,, \quad c = \cos\phi \qquad \phi \to \text{mixing angle}$$

$$\sigma_{singletop} = \sigma(\phi, M_h, SM)$$

Left-Right Symmetric Models

$$G \equiv SU(2)_L \times SU(2)_R \times U(1)_Y$$

a) Explains $\cancel{P}$ at low energy

b) Generate neutrino masses naturally

c) $G \subset SO(10)$ GUT

W_L, W_R

$$\mathcal{L} = \bar{q}'_L \gamma_\mu q_L W_L \,, \quad \bar{q}'_R \gamma^\mu q_R W_R$$

- Interference between Left & Right handed terms $\to 0$ (m_q)

- Small mixing angle ($M_{W_R} \sim$ Tev)

- Small contribution to single top cross section

- Top flavor:

$$SU(2)_h \times SU(2)_\ell \times U(1)_Y$$

$$\begin{array}{cc} \downarrow & \downarrow \\ \text{heavy family} & \text{light family} \\ W_h & W_\ell \end{array}$$

$\Delta\sigma_{\text{single top}}$ can be $+15\%$

- Non-commuting ETC

$$G \to G_{TC} \times SU(2)_h \times SU(2)_\ell \times U(1)_Y$$

Large +ve corrections $\sim 25\%$

- Non-unified std model:

$$G = SU(2)_q \times SU(2)_\ell \times U(1)_Y$$

Large −ve corrections to W^* s channel process is possible $\sim -25\%$

- KK excited W

Large −ve corrections possible.

If $V_{tb} < 1$ [fourth generation, extra b' quark etc]

Both s-channel W^* and W-gluon fusion modes will be affected. (decrease in cross section)

- These models may have dramatic effects in measurements at B factories. [sbZ coupling]
$\sin 2\beta (B \to J/\psi K_S) \neq \sin 2\beta (B^0 \to \bar{D} D)$

W_{KK} has very small effect in B factory measurements.

Summary

- Presence of Kaluza-Klein excited W affects the s-channel W^* mechanism for single top production
- For $M_{WW} \sim 1$ TeV the prediction is a large decrease of σ which should be observable
- A large negative correction to $p\bar{p} \to t\bar{b}X$ only (but not in W-gluon fusion) may indicate presence of a W^{KK}.

—