LEPTON FLAVOUR VIOLATION, EXTRA GAUGE BOSONS & NEW PHYSICS SCALE

theory & phenomenology

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High Energy Physics 2007

- Some remarkable developments
- Theory
- Experiment

What have we learned and what are we going to learn

On Theory Side:

Progress in "practical theory/model"

- Impressive list in the Standard Model results
- Crucial beyond the Standard Model calculations

On Experimental Level:

- LEP2
- Tevatron
- LHC (2008 start & 2009 first results)

ILC (venue (?), phys. ideas (a lot))

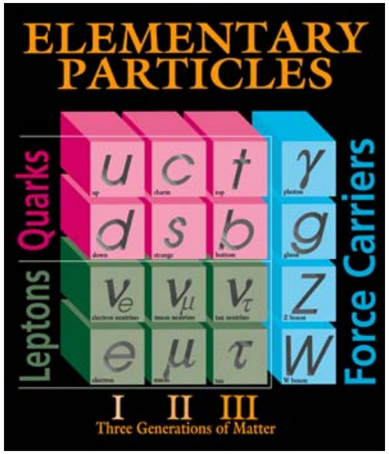
In the Standard Model

- Fundamental symmetries:
  - Are there more symmetries beyond $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$?
    → GUTs with larger symmetry group?
- ElectroWeak Symmetry Breaking (EWSB):

  solution: Higgs boson or other new particles with mass < 1 TeV
  - If Higgs ➔ *hierarchy problem:* fine tuning in rad. corr. to Higgs mass
  - *solution*: new physics at TeV scale (SUSY, Little Higgs, etc...)
  - If NO Higgs
    solution: new interactions (Top-color, etc...)

C.Hill, E.Simmons

- Quark and lepton generations:
  - Why are there 3 generations? → Fermions composite?
  - Is there a lepto(n)-quark symmetry?
  - More than 3 generations of quarks & leptons?



EXTRA GENERATIONS

- Collider effect: 4th generation coupled to Higgs doublet

$y > 1.5 \rightarrow$ Theory breaks down at the scale $\sim O(TeV)$

- Two constraints:

1. $\lambda < 0$ Destabilizing EW scale/Producing large field minima (quantum corrections)

2. Large $y \rightarrow$ Landau pole

- Extra generations: NEW CONTRIBUTIONS

$$16\pi^2 \frac{d\lambda}{dt} = 12\lambda^2 - 9g_2^2 - 3g_1^2 + 4\lambda \sum_f N_f y_f^2 - 4\sum_f N_f y_f^4$$

- Single top $V_{tb} > 0.68$ @ 95 % C.L. still allows for large 3d/4th generation mixing
- SM Vacuum Another Vacuum

Tunneling

Current age Universe $\left\{ P < 1 \Rightarrow \lambda(\mu) \leq \frac{4\pi^2}{3\ln(H/\mu)} \right\}$

IF NATURE DOES HAVE 4^{TH} GENERATIONS

↓

RICH SERIES OF NEW PHENOMENA

(EXPECTED AT COLLIDERS)

- ORDERING OF 4^{TH} GENERATIONS

  ↓ COULD PROCEED

  BY TEVATRON DISCOVERING THE HIGGS

- SUBDOMINANT HIGGS DECAYS

- DIRECT PRODUCTRION OF ν_4,'s, l_4's (TEVATRON) / Bgr. More detailed

- LHC: Q_4 readily produced and found
- LHC: rapidly verify that 4^{th} ***chiral*** generation does indeed exist.

- New effect: l_4's serve as **cold DM**

  (naively ruled out by direct detection)

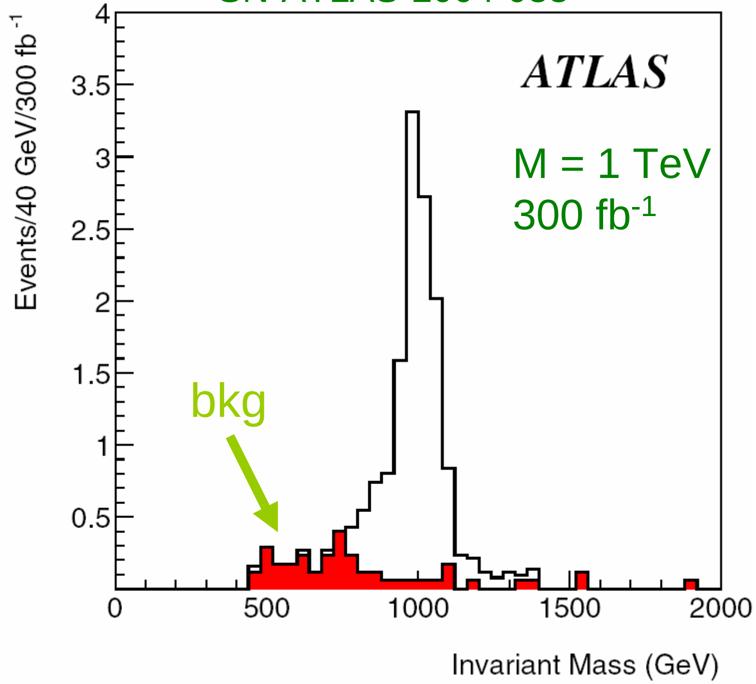
To avoid: either splitting with small Majorana mass

Z' coupling to $U(1)$ in SM

EWSB: Little Higgs

- Models with Higgs as pseudo-Goldstone boson from a broken global symmetry (SU(5) in “littlest Higgs model”)
  - Extra Q=2/3 heavy quark (T) and heavy gauge bosons (A_H, W_H, Z_H)
  - Quadratic divergences cancel top and VB divergences to Higgs mass
- Production: via QCD (gg → Top Top, qq → Top Top)
  via W exchange (qb → q' T) dominant for M_T > 700 GeV
- Decays: T → t Z, T → t H, T → b W
  - cleanest is T → t Z → b l ν l^+ l^-
    main bkg is tbZ
    5σ signal up to ~1.0-1.4 TeV
  - T → t H → b l ν b $\bar{b}$ < 5σ
  - T → b W → b l ν
    main bkg is t $\bar{t}$
    5σ signal up to ~2.0-2.5 TeV

SN-ATLAS-2004-038



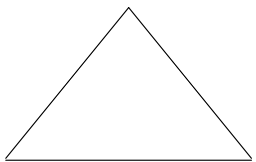
WHAT ONE CAN PRETEND ON

GUT (E_6)

Golden triangle

Minimal Triangle Union

Higgs



(Heavy) quarks **Gauge Bosons** **KGA ('02-'05)**

- Discovery
- Spectra $\boldsymbol{Z', W^{\pm'}, Z'', W^{\pm''}, \ldots}$
- Origin **(**SO(10), $\boldsymbol{E_6, \ldots}$**)**
- Couplings: $\boldsymbol{g_{Z'}, g'_V, g'_A}$
- $\boldsymbol{g_{Z'}}$ universality
- Prediction $\boldsymbol{m_{\tilde{t}}, m_{higgs}}$
- Little Higgs, Twin Higgs (?)

New coming Experiments

- **Not only discover NEW particles**
  predicted by modern models/theories

but also

- **Do measuring their couplings**

$\Downarrow$

Structure of Nature

Heavy quark physics & $Z', W'^{\pm}, H, A^0, H^{\pm}$

Our statement:

- Lepton flavor violation processes in heavy (top-) quark physics are rather dependent on effects of new physics (NP) due to additional heavy gauge bosons $Z', W'^{\pm}$, CP-even (h, H) and CP-odd (A^0) neutral and charged $(H^{\pm})$ Higgs particles.

- To study new effects due to extra gauge bosons and Higgs particles we will concentrate on physics at the energy scales $\Lambda > m_Z$. The interference effects in neutral channels $(\gamma, Z, Z', h, H, A^0)$ and in charged ones $(W, W'^{\pm})$ are included.

- The Tevatron RunII (till Sept. 2009) $\Rightarrow$ able to reach energy region where $Z', W'^{\pm}, h, H, A^0, H^{\pm}$ NP effects can be important

Where is the origin of Z' ?

- Minimal Extension of the SM

E_6 SUSY ?!

E_6 - Fermions and Extra Gauge Boson(s)

- Low Energy E_6 - Superstring

$$G_5 : SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$$

$$G_6 : SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\psi \times U(1)_\chi$$

- Abelian Z' Embedding in E_6 :

Breaking Pattern ↙

$$E_6 \supset SO(10) \times U(1)_\psi \supset SU(5) \times U(1)_\chi \times U(1)_\psi$$

$$SU(5) \supset SU(3)_c \times SU(2)_L \times U(1)_Y$$

Extended SU(N) & Z'

- Not Question: Where is Higgs?

Yield Question: Why HIGGS & TOP Are So Heavy?

Connection $\Downarrow$

New Extra Gauge Bosons: $Z', Z'', ..., W^{\pm'}, W^{\pm''}, ...$?!

- Tool: New Gauge Interactions

Third Generation Quarks $\swarrow$ Hill, Chivukula, Simmons

Sample: Extension of $SU(N) \to SU(N)_{3d} \times SU(N)_{1,2}$ Terning, Cohen

$\Downarrow$ Spontaneous Symmetry Breaking

Set of Massive SU(N) Gauge Bosons G

$\Downarrow$ Couplings

$g_1, \; g_2, \; g_3$ Different Strenghts

Low lying Neutral Sector $G: Z'$

Low lying Charged Sector $G: W^{\pm'}$

Lower bound $M_{Z'} \geq 850 \; GeV$ $t\bar{t}$ -Channel CDF LP2007, Daegu

Why we need Z'?

- Save the lower bound on lightest Higgs h
- And give an upper limit

MSSM: For $\tan\beta (= v_{up}/v_{down}) > 1$

$$\downarrow$$

$$m_h^2 < m_Z^2 \cos^2 2\beta + \delta_h$$

$\delta_h \Rightarrow$ Rising m_h as increase both m_{top} and $g_{Z'}$!

$$\delta_h \sim \frac{3}{2}\frac{m_{top}^4}{\pi^2 v^2}\log\frac{m_{\tilde{t}_1}\cdot m_{\tilde{t}_2}}{m_{top}^2} + 2 g_{Z'}^2 v^2 (Q_2 \cos^2\beta + Q_1 \sin^2\beta)^2$$

$$\Downarrow$$

$$m_h < 185 \;\; GeV$$

Extended Weak Interactions: Higgs & New Gauge Bosons

--------Higgs Mass Sum Rules-------

MSSM: $$M_{Z'} = \frac{m_h^2 - M_A^2 + \delta_{ZZ'} - \Delta_{\tilde{t}}}{M_{Z'} + M_H} + M_H$$

GAK, T. Morii

Phys. Lett. B (2002)

$$\begin{pmatrix} Z \\ Z' \end{pmatrix} \cong \begin{pmatrix} 1 & \frac{-\cos^3\phi\sin\phi}{x\cos\phi} \\ \frac{\cos^3\phi\sin\phi}{x\cos\phi} & 1 \end{pmatrix} \begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix}, \; \delta_{ZZ'} = M_{Z'}^2 - m_Z^2, \; x = \frac{u^2}{v^2} > 1$$

$$SU(2)_h \times SU(2)_l \times U(1)_Y$$
$$\downarrow u$$
$$SU(2)_L \times U(1)_Y$$
$$\downarrow v$$
$$U(1)_{em}$$

$$L \supset \frac{g^2}{M_{Z'}^2}\left(\frac{\cot\phi}{2}\right)^2 \left(\sum_{l:e,\mu,\tau} \bar{l}_L \gamma_\mu l_L\right)\left(\sum_q \bar{q}_L \gamma^\mu q_L\right)$$

What one can estimate?

- Lower bound on m_h
- Upper limit on $m_{\tilde{t}}$

1-loop SUSY top-quark correction:

$$\Delta_{\tilde{t}} = \left(\frac{N_c^{1/2} g \; m_t^2}{4\pi m_w \sin\beta} \right)^2 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)^2 < O\ (0.01\ TeV^2)$$

- NP breaking scale $u = \sqrt{x} v, \quad v = 246 GeV$

$$SU(2)_h \times SU(2)_l \times U(1)_Y$$
$$\downarrow u$$
$$SU(2)_L \times U(1)_Y$$
$$\downarrow v$$
$$U(1)_{em}$$

$$M_{Z'} \sim \alpha^{1/2} \Lambda_{\exp} \cot\phi / (2 \sin\theta)$$

$$ex., \quad \Lambda_{CDF} > \begin{cases} 3.7\ TeV,\ e^+e^-\ channel\ 95\%\ C.L. \\ 4.1\ TeV,\ \mu^+\mu^-\ channel\ 95\%\ C.L \end{cases}$$

Mixing $Z-Z'$

- Minimal Scheme

$$\begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} Z \\ Z' \end{pmatrix}$$

$\downarrow \xi - ?$ important !

$$|\xi| = \arctan\left(\frac{m_Z^2 - m_{Z_1}^2}{M_{Z_2}^2 - m_Z^2} \right)^{1/2}$$

$$\mathbf{M}_{Z'} \approx \Delta_{\mathbf{M}} + |\xi|^{-1} \sqrt{m_Z^2 - m_{Z_1}^2}, \quad |\xi| \neq 0 \quad \hookleftarrow$$

$$\downarrow$$

$$M_{Z'} - M_{Z_2}$$

$$g_Z = \frac{g}{\cos\Theta_W} \rho^{1/2}, \qquad \rho = \rho_{top} \cdot \rho_{mix}$$

- ρ -Factor:

$$\sin^2\Theta_W = \frac{1}{2} - \left[\frac{1}{4} - \frac{\pi\,\alpha(m_Z)}{2^{1/2} G_F \rho\, m_Z^2} \right]^{1/2}$$

Experimental limits and window for $|\xi|$

LEP: $C^{\exp}_{OPAL} = 0.355\, TeV; \qquad C^{\exp}_{ALEPH} = 0.365\, TeV$

Tevatron: $C^{\exp}_{CDF} = 0.345 \cot\phi\, TeV\ (e^+e^-), \quad C^{\exp}_{CDF} = 0.380 \cot\phi\, TeV\ (\mu^+\mu^-)$

Δ_M estimation: $M^2_{Z_2} - M^2_{Z'} \approx \frac{(\delta m^2)^2}{M^2_{Z'} - m^2_Z}, \quad \delta m^2 = \sin\Theta_W m^2_Z \left(1 - \frac{4}{3}\frac{1 - v_1^2/4v_2^2}{1 - v_1^2/v_2^2}\right)$

$$|\delta m|^2 < \frac{7}{12}\sin\Theta_W m^2_Z \Rightarrow \left(M^2_{Z_2} - M^2_{Z'}\right)^{1/2} < 2.3\, GeV$$

- $\Delta_M = M_{Z'} - M_{Z_2}$ Does not contribute to $|\xi|$!

Finally: $0 < |\xi| < 5\times 10^{-2}$ at $0 < \delta < 0.05, \quad \delta = \rho_{mix} - 1$ GAK, Phys.Rev.D (2005)

Effective Lagrangian

$$L_{eff} = L_{SM} + \sum_{n\geq 5}\sum_{j}\frac{\alpha_j^{(n)}}{\Lambda^{n-4}}O_j^{(n)} + L_{H^{\pm}}$$

$\bullet \Lambda > \mathrm{v} \; = \; 246\, GeV \;\; (decoupling\ scenario)$

$\bullet \Lambda \sim 1-10 \; TeV \;\; (\text{expected})$

$\bullet$ *Both* $\alpha_j^{(n)}$ *and* Λ *parameterize effects of NP (beyond the SM)*

$n = 6 \Rightarrow$ 4- fermion interplay + Z'

$n = 8 \Rightarrow$ 4-fermion interplay + Higgs + Z'

$$*\Gamma_{tot} = \Gamma(Q \to qW) + \Gamma(Q \to H^{+}b) + \Gamma(Q \to q\mu\tau) + \ldots \; q: d, s, b$$

$$\Gamma(Q \to q\mu\tau) < \frac{\Gamma(Q \to bW)}{C} - \sum_{q:d,s,b}\Gamma(Q \to qW) - \Gamma(Q \to H^{+}b),$$

$$if \;\; R = \frac{\Gamma(\mathrm{Q} \to bW)}{\Gamma_{tot}} > C = C^{\exp} < 1$$

$H^{\pm}$ Importance

$$Q \to H^{+} b \;\; (\bar{Q} \to H^{-} \bar{b}), \;\; H^{\pm} \to l \nu_l$$

- Eff. Couplings $QH^{\pm}b$:

$$\frac{g}{\sqrt{2} m_W} \left(m_b \tan\beta \, P_L + m_Q \cot\beta \, P_R \right)$$

- Eff. Couplings $H^{\pm} l \nu_l$:

$$\frac{g}{\sqrt{2} m_W} m_l \tan\beta \, P_L$$

Significant for either large and small $\tan\beta$

Large $\tan\beta \;\Rightarrow\; H^{\pm} \to l \nu_l$ more preferable than that of

$H^{\pm} \to cs$ or $H^{\pm} \to Q^{*} \; b \to W \; b \; b$

A reduced rate in $Q \to H^{+} b \to e^{+} \nu_e b \Rightarrow$ signal the presence of $H^{\pm}$ itself

- Decay $Q_4 \to bH^+ (competes \quad with \;\; t \to bW)$

$$\Delta\ L_{H^+} \sim \frac{m_Q}{v} \bar{b} [(1-\gamma_5) g_L + (1+\gamma_5) g_R]\ Q$$

$$\Gamma(Q \to bH^+) = \frac{m_Q^2}{4\pi\ v^2} F \left\{ (|\ g_L\ |^2 + |\ g_R\ |^2)(1 + \frac{m_b^2}{m_Q^2} - \frac{m_{H^+}^2}{m_Q^2}) + \right.$$

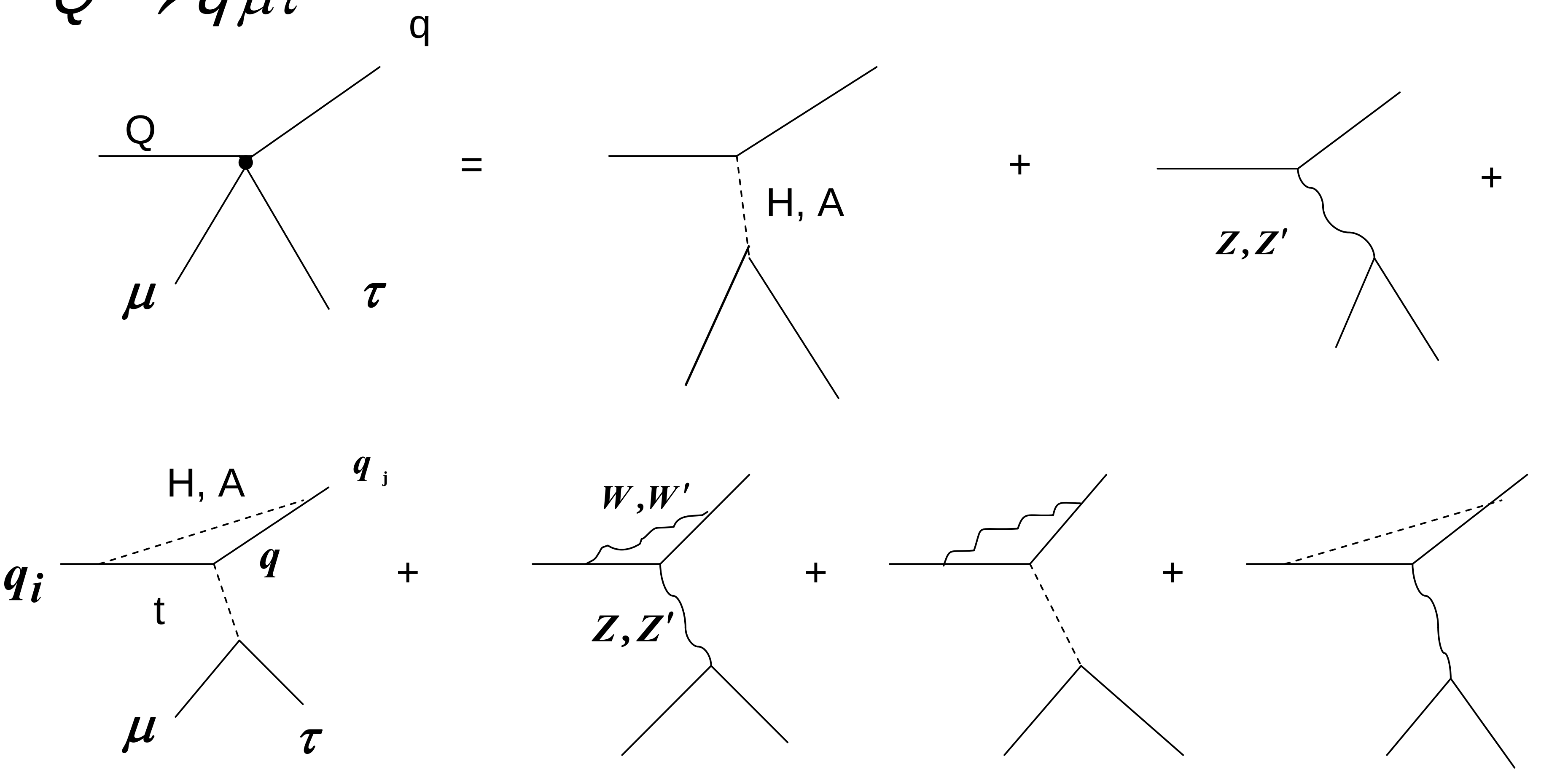
$$\left. + \ 4 \operatorname{Re} g_L g_R^* \frac{m_b}{m_Q} \right\}$$

$$F = \frac{\{[m_Q^2 - (m_{H^+} + m_b)^2][m_Q^2 - (m_{H^+} - m_b)^2]\}^{1/2}}{2m_Q}$$

$$g_L = \tan\beta, \quad g_R = (m_b / m_Q) \cot\beta (\to 0)$$

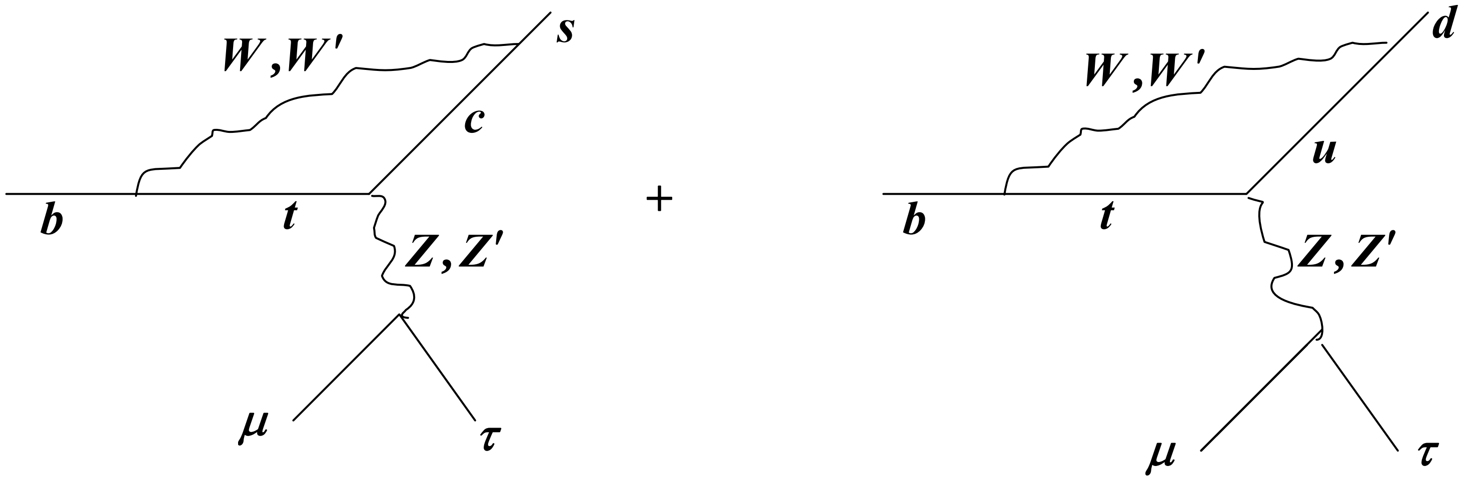
$$\Gamma(Q \to bH^+) \approx \frac{m_Q^3}{8\pi\ v^2} \beta_{H^+}^2 \tan^2\beta, \quad \beta_{\mathrm{H}^+} = 1 - \frac{m_{H^+}^2}{m_Q^2}$$

$$Q \to q\mu\tau$$



+ …

One-loop effect in $t \to q\mu\tau$



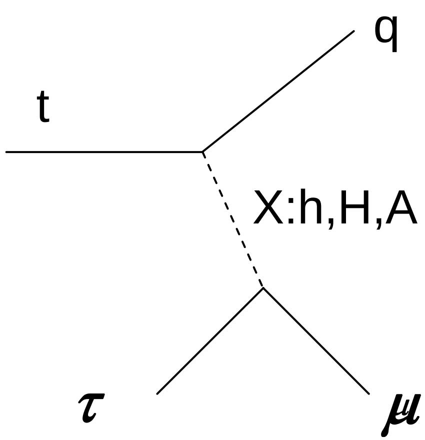
$$\Gamma(t \to q\mu\tau) = \Gamma_0(1 + \delta\, c_W + \delta\, c_{W'}),\ \ q = c, u$$

$$\delta\, c_W = \frac{g^2}{32\pi^2} \ln \frac{m}{m_W} [|V_{ud} V_{tb}^*|(1 - \frac{m_u m_t}{2m_W^2}) + |V_{cs} V_{tb}^*|(1 - \frac{m_c m_t}{2m_W^2})]$$

$$\delta\, c_{W'} = \frac{g'^2}{32\pi^2} \ln \frac{m'}{m_{W'}} [|V_{ud} V_{tb}^*|(1 - \frac{m_u m_t}{2m_{W'}^2}) + |V_{cs} V_{tb}^*|(1 - \frac{m_c m_t}{2m_{W'}^2})]$$

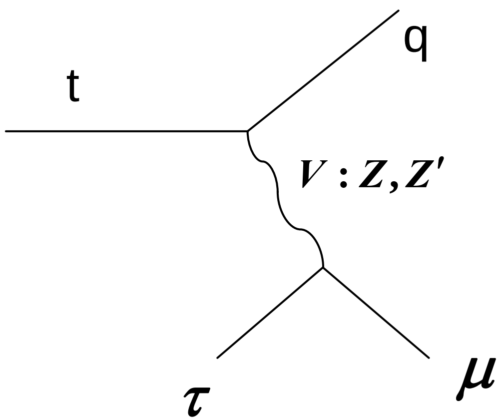
- *If* $W'^{\pm}$ is discovered in hadron colliders it will most likely be found through $W' \to t\bar{b}$ or $W' \to c\bar{s}$.

•SCALAR AND PSEUDOSCALAR (HIGGS) CONTRIBUTIONS



$$\Gamma_0 = \frac{m_t^5}{96\pi\Lambda^4} < \frac{m_t^5}{96\pi(-q^2 + m_X^2)^2}$$

Z, Z' CONTRIBUTIONS



$$\Gamma_0 = \frac{m_t^5}{24\pi\Lambda^4} < \frac{m_t^5}{24\pi(-q^2 + m_V^2)^2}$$

NP scale Λ lower bound

$$\Lambda > \left\{ \frac{m_t^5 (1 + \sum_{V:\, W,\, W'} \delta\, c_V)}{24\pi a[\Gamma(t \to bW)(\frac{1}{C} - \frac{1}{|V_{tb}|^2}) - \Gamma(t \to bH^+)]} \right\}^{\frac{1}{4}}$$

Upper limit on $\tan\beta$

$$\tan^2\beta < \left(\frac{|V_{tb}|^2}{C} - 1 \right)(1 + 2x_W)(\frac{1 - x_W}{1 - x_{H^+}}),\ x_j = \frac{m^2{}_j}{m^2{}_t},\ j = W, H^+,\ x_{H^+} > x_W$$

- The model predicts small $\tan\beta$
- The only case $m_{H^+} \approx m_t - m_b \Rightarrow \tan\beta$ enhancement

Result

The lower bounds on NP ($\boldsymbol{Z', H, A^0}$) scales

$$\Lambda_{Z'} > 275\, GeV, \quad \Lambda_{H(A^0)} > 195\, GeV \;\; for\ \tan\beta = 2$$

and

$$\Lambda_{Z'} > 347\, GeV, \quad \Lambda_{H(A^0)} > 245\, GeV \;\; for\ \tan\beta = 3$$

Used:
$$m_{H^+} = 165\, GeV, \; m_{H^\pm} > 78.6\, GeV \;\; (95\%\ C.L.)\;\; LEP$$
$$BR(H^\pm \to \tau\nu_\tau) + BR(H^\pm \to c\bar{s}) = 1$$

$$\frac{\Gamma(t \to bW)}{|V_{tb}|^2} \cong 1.42\, GeV$$ (SM + radiative corrections included)

INSTEAD OF CONCLUSION

- No convincing sign of New Physics with Q_4, $\boldsymbol{Z'}$, $\boldsymbol{W}^{\pm'}$ yet
- Tevatron started Run IIB expects 4-8 fb^-1 by 2009, still some new results may come
- We are all waiting eagerly for start and first Beyond the Standard Model New Physics results from LHC