LEPTON FLAVOUR VIOLATION, EXTRA GAUGE BOSONS & NEW PHYSICS SCALE

theory & phenomenology

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JOINT INSTITUTE FOR NUCLEAR RESEARCH

High Energy Physics 2006

- 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 (Sept. 1st 2007 start & 2008 first results)

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

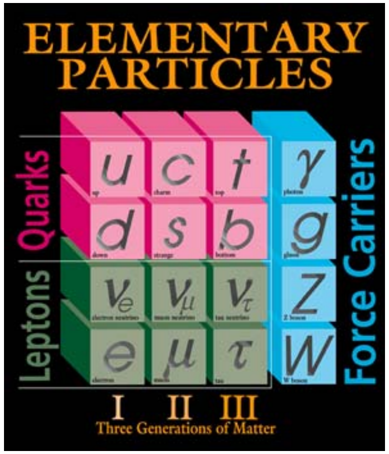
In the Standard Model

- 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

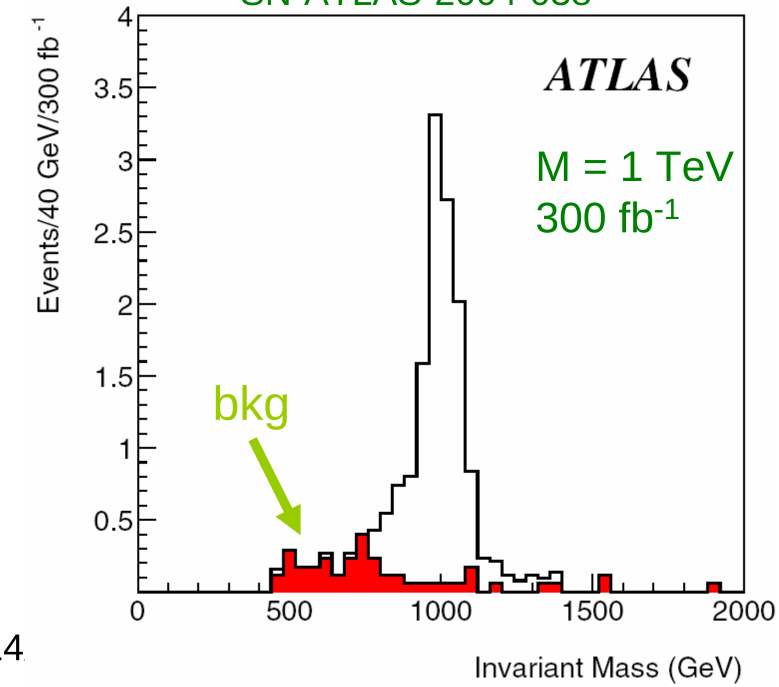
- Quark and lepton generations:
  - Why are there 3 generations? → Fermions composite?
  - Is there a lepto(n)-quark symmetry?
  - More than 3 generations of quarks & leptons?



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 ($gg \to$ Top $\overline{\text{Top}}$, $q\bar{q} \to$ Top $\overline{\text{Top}}$)
  via W exchange ($qb \to q'$ T) dominant for M_T > 700 GeV
- Decays: $T \to t\,Z$, $T \to t\,H$, $T \to b\,W$
  - cleanest is $T \to t\,Z \to b\,l\,\nu\,l^+\,l^-$
    main bkg is tbZ
    5σ signal up to ~1.0-1.4 TeV
  - $T \to t\,H \to b\,l\,\nu\,b\,\bar{b}$ < 5σ
  - $T \to b\,W \to b\,l\,\nu$
    main bkg is $t\,\bar{t}$
    5σ signal up to ~2.0-2.5 TeV

SN-ATLAS-2004-038

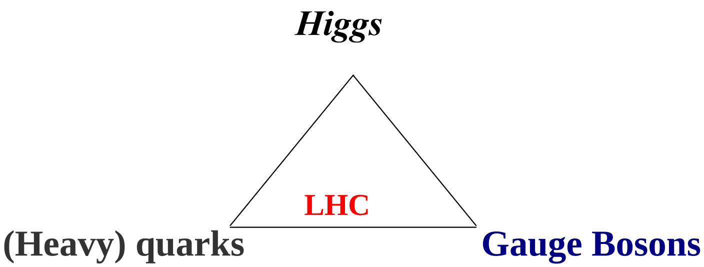


WHAT ONE CAN PRETEND ON

GUT (E_6)

Golden triangle

Minimal Triangle Union

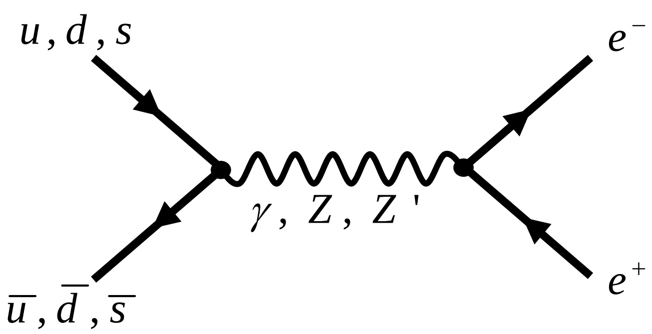


KGA ('02-'05)

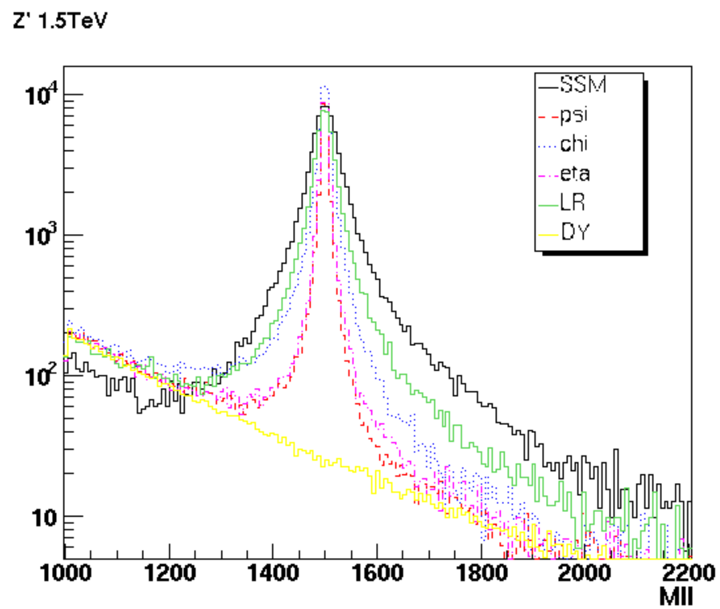
- Discovery
- Spectra $Z', W^{\pm'}, Z'', W^{\pm''}, \ldots$
- Origin (SO(10), E_6, …)
- Couplings: $g_{Z'}, g'_V, g'_A$
- $g_{Z'}$ universality
- Prediction $m_{\tilde{t}}, m_{higgs}$
- Little Higgs, Twin Higgs (?)

Heavy Gauge Bosons

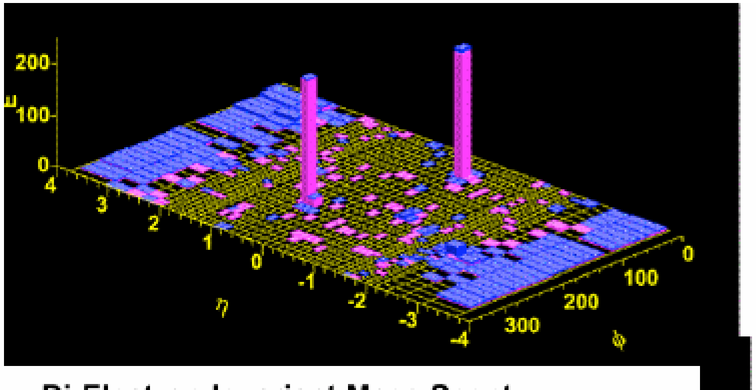
- Many extensions of the SM rely on larger symmetry groups (GUTs, string-inspired, little Higgs models, etc...)
  ➔ predict existence of new gauge bosons W' and Z'
- Production: s-channel



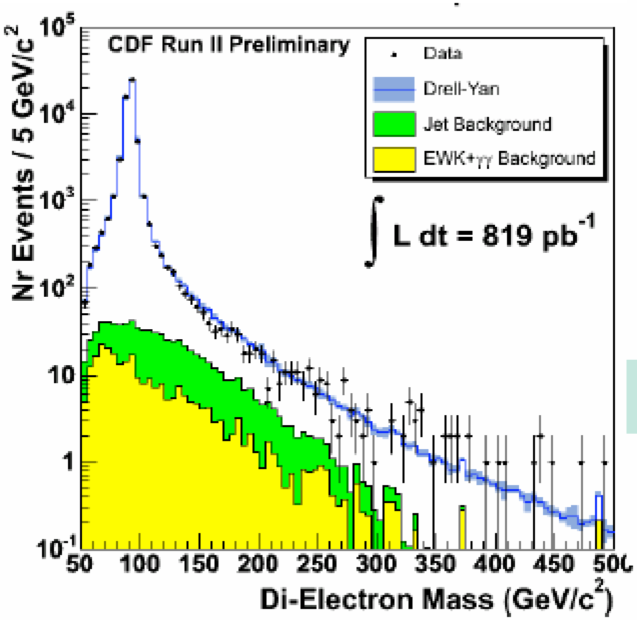
- Clean decay channels:
  - W' → $e\,\nu_e$ or $\mu\,\nu_\mu$
  - Z' → e^+e^- or $\mu^+\mu^-$
- Tevatron searches: M up to ~1 TeV
- Z' models considered:
  - Sequential SM (SSM) with same Z' couplings to fermions as for Z
  - Models based on different patterns of E6 symmetry breaking (ψ, χ and η)



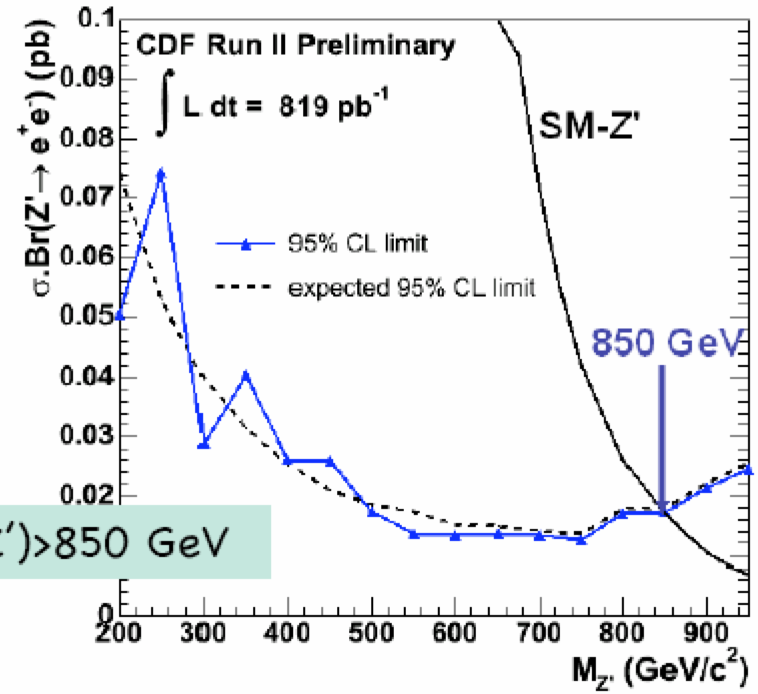
Search for Z' at the Tevatron



Di-Electron Invariant Mass Spectrum

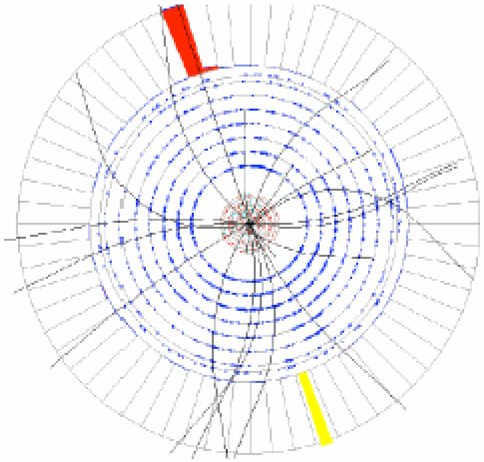


$$Z' \to e^+e^-$$



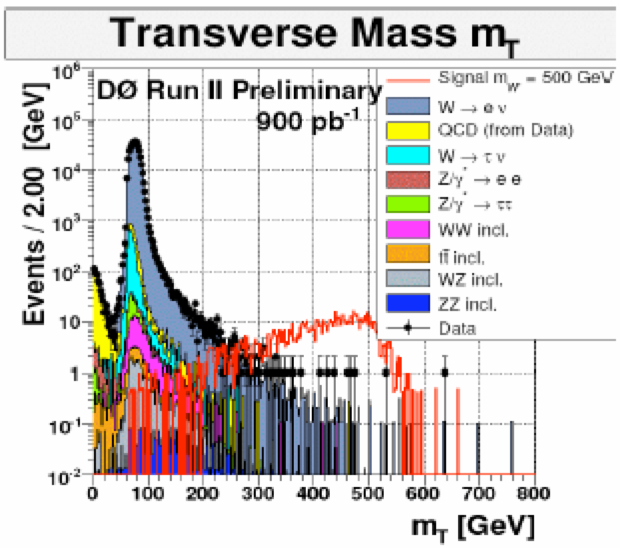
M(Z′)>850 GeV

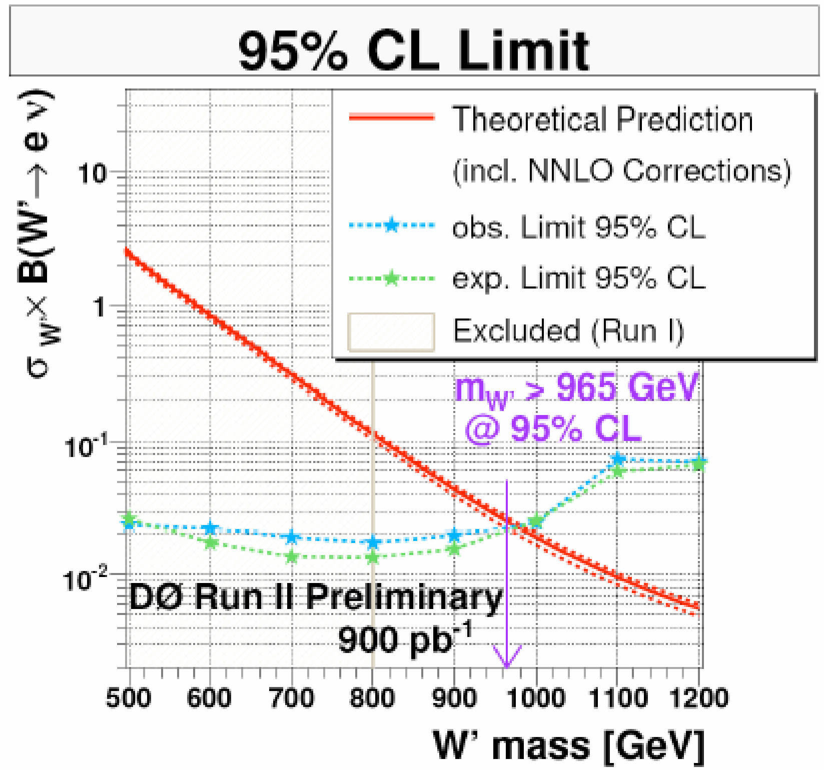
Search for W′ at TeVatron



W′→eν cand.

E_T=265 GeV, MET 265 GeV





M(W′)>965 GeV

New coming Experiments

- **Not only discover NEW particles**

  predicted by modern models/theories

but also

- **Do measuring their couplings**

$\Downarrow$

Structure of Nature

Heavy Gauge Bosons: Z'

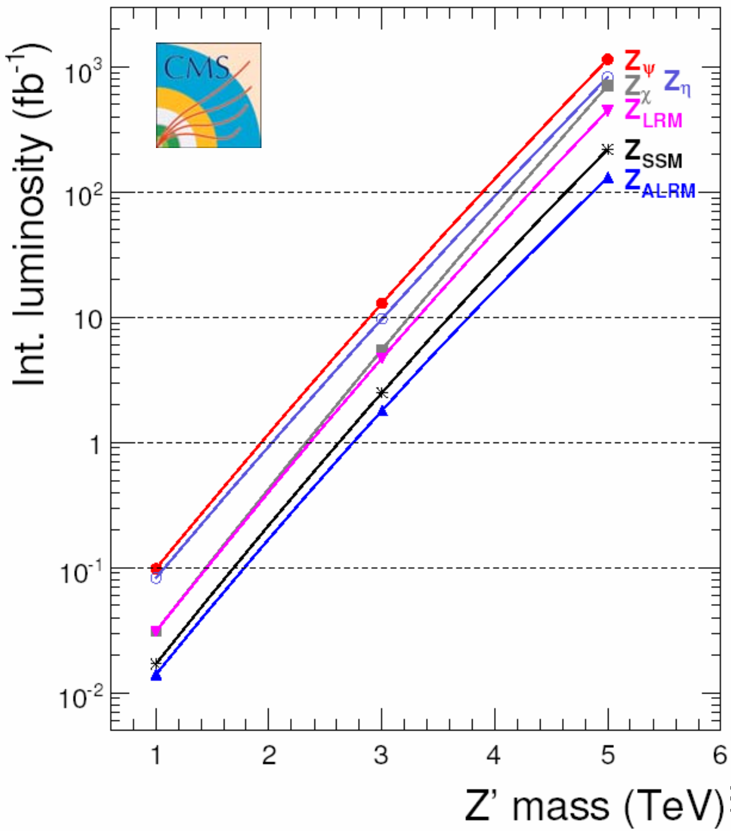
- Selection: pairs of isolated e or μ
- Bkg: dominated by dileptons from Drell-Yan
- 5σ discovery up to ~5 TeV (model dependent) for both ATLAS and CMS

Expt Issues:
- electronics saturation for high E e§ at CMS M(Z') ≥ 3 TeV ➔ correct
- muon bremsstrahlung ➔ isolation with tracks

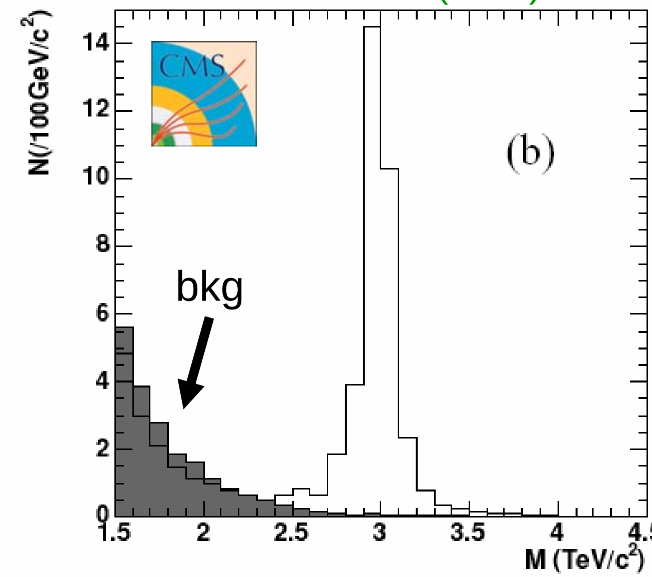
CMS PTDR 2006

Z' → ee

Luminosity needed for 5σ signal



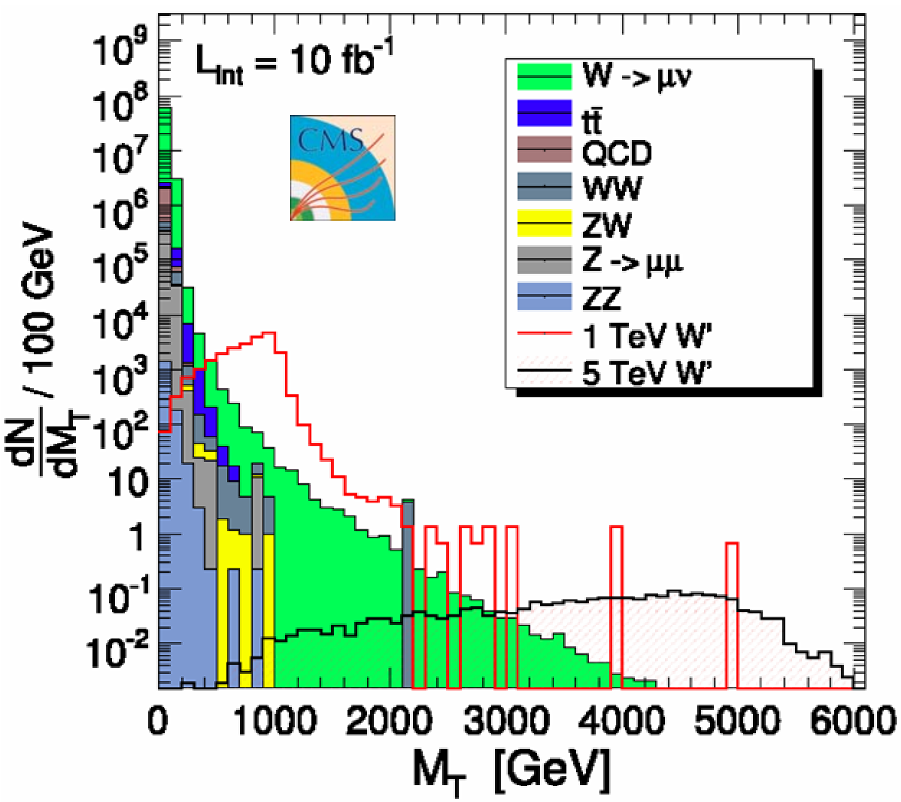
CMS PTDR Z' → ee (SSM) 30 fb^{-1}



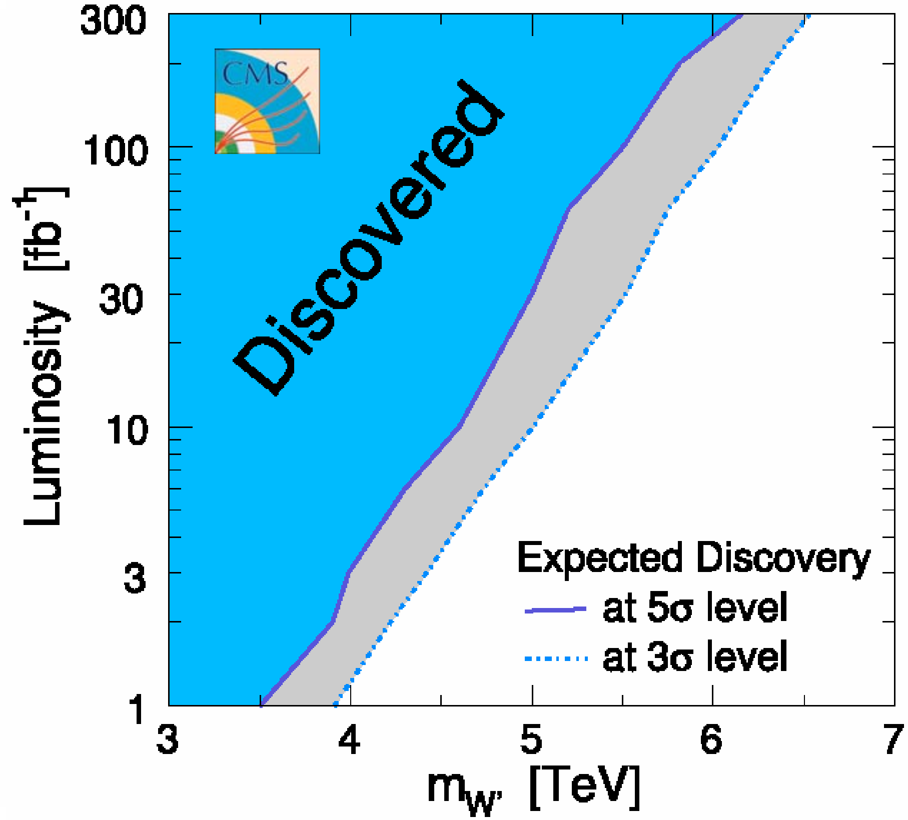
SSM Z' → ee	M = 1 TeV	M = 5 TeV
N signal	72020	0.58
N bkg	85.5	0.025
Significance	225	1.63

Heavy Gauge Bosons: W'

- Selection: one-muon event with track isolation around mu + missing transverse energy
- Background: mostly W → μ ν



CMS PTDR 2006



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

Our statement:

- Lepton flavor violation processes in 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 energy scales $\Lambda > m_Z$. The interference effects in neutral channels (γ, Z, Z', h, H, A^0) and in charged ones ($W, W'^{\pm}$) should be included.

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

Lepton-flavor universality

$$e\mu\tau - universality$$

$$\swarrow$$

$$\Gamma(W \to l\bar{\nu}_l) = \frac{G_F m_W^3}{6\sqrt{2}\pi}, \qquad l = e, \mu, \tau$$

While violation in $p\bar{p}$

$$\underbrace{UA(1) \qquad \mathrm{UA}(2)}_{\mathrm{W}\to e\bar{\nu}_l,\ W\to\mu\bar{\nu}_\mu}$$

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: $Z', Z'', \ldots, W^{\pm'}, W^{\pm''}, \ldots$?!

- 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 ICHEP'06 Moscow

Why we need Z'?

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

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

$$\swarrow$$

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

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

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

$$\Downarrow$$

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

Gauge bosons eigenstates

NP weak interactions: $SU(2)_h \times SU(2)_l$

$$\boldsymbol{A^\mu = \sin\theta(\cos\phi\, W_{3h}{}^\mu + \sin\phi\, W_{3l}{}^\mu) - \cos\theta\, X^\mu}$$

$$\boldsymbol{Z_1{}^\mu = \cos\theta(\cos\phi\, W_{3h}{}^\mu + \sin\phi\, W_{3l}{}^\mu) - \sin\theta\, X^\mu}$$

$$\boldsymbol{Z_2{}^\mu = -\sin\phi\, W_{3h}{}^\mu + \cos\phi\, W_{3l}{}^\mu}$$

$$\boldsymbol{W_1{}^{\mu\pm} = \cos\phi\, W_h{}^{\pm\mu} + \sin\phi\, W_l{}^{\pm\mu}}$$

$$\boldsymbol{W_2{}^{\pm\mu} = -\sin\phi\, W_h{}^{\pm\mu} + \cos\phi\, W_l{}^{\pm\mu}}$$

$$\boldsymbol{W_h{}^{\pm\mu} = (W_{1h}{}^\mu \pm i\, W_{2h}{}^\mu)/\sqrt{2}\ ,\quad W_l{}^{\pm\mu} = (W_{1l}{}^\mu \pm i\, W_{2l}{}^\mu)/\sqrt{2}}$$

Mixing angle ϕ: occasioned by $SU(2)_l \otimes SU(2)_h$

Extended covariant derivative

separation in standard and non-standard contributions

$$D^\mu = \partial^\mu - i\frac{g}{\cos\theta} Z_1{}^\mu (T_3 - Q\ \sin^2\theta) - i\ Z_2{}^\mu(-g_h \sin\phi\ T_{3h} + g_l \cos\phi\ T_{3l}) -$$

$$- ig(T_h{}^\pm + T_l{}^\pm)\ W_1{}^{\pm\mu} - ig(\cot\phi\ T_l{}^\pm - \tan\phi\ T_h{}^\pm)\ W_2{}^\pm$$

Effective q-l Contact Interactions & Experimental Data

$$L \supset \left[\begin{array}{l} \frac{1}{\Lambda_{LL}^2} g_0^2 (\bar{E}_L \gamma_\mu E_L)(\bar{Q}_L \gamma^\mu Q_L) + \frac{1}{\Lambda_{LL}^2} g_1^2 (\bar{E}_L \gamma_\mu \tau_a E_L)(\bar{Q}_L \gamma^\mu \tau_a Q_L) \\ \qquad + \frac{g_e^2}{\Lambda_{LR}^2} (\bar{e}_R \gamma_\mu e_R)(\bar{Q}_L \gamma^\mu Q_L) + \\ \qquad \left[\frac{1}{\Lambda_{LR}^2} (\bar{E}_L \gamma_\mu E_L) + \frac{1}{\Lambda_{RR}^2} (\bar{e}_R \gamma_\mu e_R) \right] \times \sum_{q:u,d} g_q^2 (\bar{q}_R \gamma^\mu q_R) \end{array} \right]$$

$$E_L = (\nu,\ e,\ \mu,\ \tau),\ \ Q_L = (up, down)_L$$

Λ_{ij} - *Scales of New Physics(NP)*

$\Lambda \to \Lambda_{(EXP)}$ Have to be determined from the Experiment

Where is Z'? Z' Embedding:

$$L \supset \frac{g^2}{M_{Z'}^2} \left(\frac{\cot\phi}{2} \right)^2 \left(\sum_{e,\mu,\tau} \bar{l}_L \gamma_\mu l_L \right) \left(\sum_q \bar{q} \gamma^\mu q \right),\ \ M_{Z'} \sim \sqrt{\alpha}\, \Lambda \cot\phi / (2 \sin\theta)$$

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)

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

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

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

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 $u = \sqrt{x}v, \quad v = 246 GeV$

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

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

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

Upper Limit on $(m_{\tilde{t}_1} . m_{\tilde{t}_2})$

- Decoupling Regime:

GAK, T. Morii

Phys. Rev. D (2003)

$$M_H^2 \cong M_A^2 + m_Z^2 \sin^2(2\beta) + \mu^2,$$

$$CP\ even\ mixing\ angle\ \tan\alpha \to -\cot\beta,\ \ M_A \gg m_Z$$

$$\Delta\left(m_{\tilde{t}}\right) < \left(B + M_H^*\right)\left(B - f\ C\right) + m_h^2 - m_Z^2(1-\sin^2 2\beta) + \mu^2$$

$$B \equiv B\left(x,\phi\right) = m_W\sqrt{x}/(\cos\phi\sin\phi)$$

$$f \equiv f\left(\phi\right) = \cot\phi\sqrt{2}/(2\sin\theta)$$

$$M_H^* = (M_A^2 + m_Z^2\sin^2 2\beta + \mu^2)^{1/2}$$

- Minimal value of $\Lambda_{\exp}$ is awaiting from Tevatron/LHC data analysis

$$C \equiv C_{\exp} < \Lambda_{\exp}$$

Dilepton Poduction

- Beyond the SM Lagrangian Density
- Summation over the flavor indices α, β

$$L_{NP} = \sum_{\alpha,\beta} c_{\alpha,\beta} (\bar{l}_i \Gamma_l l_j) \frac{1}{-q^2 + m^2} (\bar{q}^{\alpha} \Gamma_q q^{\beta}) + h.c.$$

$\Gamma = 1,\ \gamma_5,\ \gamma^{\mu},\ \gamma_5 \gamma_{\mu}$

$c_{\alpha,\beta}$ constants are more weak than the strong effective couplings

$c_{\alpha,\beta} < g_s^2 \sim 4\pi O(1)$

- New Physics (NP) associated with $(l_i l_j)$ flavor violation below NP scale

- $\Lambda_{NP} > (-q^2 + m^2)^{1/2} \sim m$ at $q^2 \ll m^2$

$D = 4 \quad \leftrightarrow \quad D = D + 2$

(SM) *hidden symmetry* NP

- Λ_{NP} is associated with the mass of new bosons as well

NP ideas

SM: $s = 1/2$ matter fields

$s = 1$ gauge (forces)

Scalars : neither matter nor force (just hidden)

NP gauge: neither matter … but force ?

NP SM: scalars & extra gauge

$\Downarrow$

origin ?

NP forces: mediated by scalars & gauge

Scalars - fundamental

$\Rightarrow$ ever discovered

Extra gauge - new force

“Small” and “Large” systems

- Stat. mech. & stochastic processes

Krylov &
N.Bogolyubov (1939)

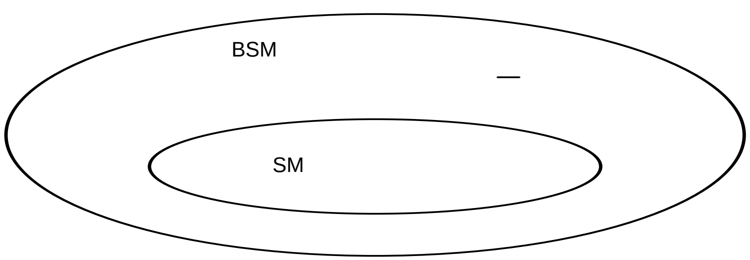
Weak action
“Small” $\leftarrow$ “Large”
Stochastic

Even interplay between systems
$\Downarrow$
Random fields, SUSY, + 2 dim

Parisi & Sourlas (1979)

Idea:	SM	Λ^{0}	d = D-2
	BSM	Λ^{-2}	d = D

New forces
Stochastic fields
$\swarrow$ Under $\tilde{s}(x)$



- Scalar case: $\phi(x) \rightarrow \phi_{\tilde{s}}(x,\tau)$ Stochastic field

$$\mu\, \partial_\tau \phi(x,\tau) = -\frac{\delta J\left[\phi(x,\tau)\right]}{\delta\phi(x,\tau)} + \tilde{s}(x), \quad \tilde{s}(x) = s(x) + P$$

stochastic operator

Bose - particle correlations with stochastic forces GAK ('98-'05)

$\tilde{s}(x)$ carries random stochastic history of "Large" system

$$\langle \tilde{s}(x)\, \tilde{s}(y) \rangle \sim c\ \exp(-z^2 \Lambda_{ch}^2), \quad z_\mu = (x-y)_\mu$$

- Both c and Λ_{ch} define influence of (quantum) noise on SM interactions
- SM feels an action of "Large" system

Model

$$\mu\ \partial_\tau \phi(x,\tau) = -\frac{\delta J\left[\phi(x,\tau)\right]}{\delta\phi(x,\tau)} + \tilde{s}(x), \quad \tilde{s}(x) = s(x) + P$$

$$L(\phi) \sim -\frac{1}{2}\phi(x)\triangle\phi(x) - \frac{1}{2}m^2\phi^2(x) + \frac{1}{4}\lambda\phi^4(x)$$

$$\left[\triangle + m^2 - \left(\lambda\phi^2 + \mu\partial_\tau\right)\right]\phi(x) = -\tilde{s}(x)$$

Energy averaged over random $\tilde{s}$:

$$E_{\tilde{s}} = \left\langle E(\phi)\,|\,\tilde{s}\right\rangle_{\tilde{s}} = \int D\tilde{s}\ \hat{E}(\tilde{s})\exp\left[-\int d^4x\ \tilde{s}^2(x)\right]$$

$$\hat{E}(\tilde{s}) = \ln\int D\phi\ \exp\left\{-\left[J(x) + \int d^4x\ \tilde{s}(x)\ \phi(x)\right]\right\}$$

Two-point Green's Function: $G_{\tilde{s}} \sim \int D\tilde{s}\ \phi(x)\ \phi(0)\exp\left[-\int d^4x\ \tilde{s}^2(x)\right]$

Green’s function level

Stochastic Eq.

$$\left[\triangle + m^2 - \left(\lambda\phi^2 + \mu\partial_\tau\right)\right]\phi(x) = -\tilde{s}(x)$$

may provide us with different framework to study the properties of scalar field theory.

equivalence

$$G_{\tilde{s}} \quad \rightleftharpoons \quad G_{\phi}$$

$$d = D \qquad\qquad d = D-2$$

in terms of superfield $\varphi\left(x,\vartheta\right) = \phi(x) + \bar{\vartheta}\psi(x) + \bar{\psi}(x)\vartheta + \vartheta\bar{\vartheta}\omega$

$$\int d^{D-2}x\, F\left(Y_j x, x^2\right) = \int d^D x\, d\vartheta\, F\left(Y_j x, x^2 + \vartheta\bar{\vartheta}\right), \quad \vartheta^2 = \bar{\vartheta}^2 = \vartheta\bar{\vartheta} + \bar{\vartheta}\vartheta = 0$$

↓

D-2 dim. vectors

Parisi & Sourlas

Effective Lagrangian

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

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

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

$\bullet \; Both \;\; \alpha_j^{(n)} \;\; and \;\; \Lambda \; parameterize\ effects\ of \;\; NP\, (beyond\ the\ SM)$

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

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

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

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

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

n=6 & n=8 effective operators

$\circ$ n = 6 $\quad O_j^{(6)\alpha\beta} = (\bar{\mu}\ \Gamma_j\ \tau)\ (\bar{q}^{\alpha}\ \Gamma_j\ q^{\beta})$

$$\Delta\ L^{(6)} = \sum_{j,\alpha,\beta} \frac{\alpha^{j}_{\alpha\beta}}{\Lambda^2} O_j^{(6)^{\alpha\beta}} + h.c.$$

$\circ$ n = 8 (Higgs sector included)

$$\Delta\ L^{(8)} = \sum_{\alpha',\beta',\alpha,\beta} \left[\frac{\alpha^{j}_{\alpha\beta,\alpha'\beta'}}{\Lambda^4} (\bar{L}_l^{\alpha'}\ \phi\ \Gamma_j\ l_R^{\beta'})(\bar{q}_l^{\alpha}\ \phi'\ \Gamma_j\ q_R^{\beta}) \right.$$

$$\left. + \frac{\tilde{\alpha}^{j}_{\alpha\beta,\alpha'\beta'}}{\Lambda^4} (\bar{L}_l^{\alpha'}\ \phi\ \Gamma_j\ l_R^{\beta'})(\bar{q}_R^{\beta}\ \phi'^{+}\ \Gamma_j\ q_l^{\alpha}) + h.c. \right]$$

$$\Rightarrow \sum_{\alpha\beta} \frac{<\phi>^2}{\Lambda^4} \alpha^{j(8)}_{\alpha\beta} (\bar{\mu}\ \Gamma_j\ \tau)(\bar{q}^{\alpha}\ \Gamma_j\ q^{\beta}),\ \ \Gamma_j = 1, \gamma_5 \qquad (Higgs?)$$

$H^{\pm}$ Importance

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

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

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

- 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 $H^{\pm} \to t^{*} \, b \to W \, b \, b$

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

Intermediate Higgs

$$H^{\pm} \to W^{\pm}\ S(Ps) \to W^{\pm}\ l_i^-\ l_j^+, \qquad S = h, H; \quad Ps = A$$

$$m^2{}_{H^{\pm}} = \left(m_A^2 + m_W^2\right)\left(1+\xi\right)^2$$

$$\xi \sim \frac{N_c}{2\pi^2 v^2}\left(\frac{m_t^2 m_b^2}{m_A^2 + m_W^2}\right)\frac{1}{\sin^2 2\beta}\left(1 + \ln\frac{\tilde{M}^2}{m_t^2}\right)$$

Extended SU(2)

$$SU(2)_l \times SU(2)_h \times U(1)_Y \to SU(2)_{l+h} \times U(1)_Y \to U(1)_{em}$$

$b, t, ...$ $\qquad u \qquad v$

$\tau, \nu_\tau, ...$ $\qquad ?\,GeV \qquad 246\,GeV$

- Breakdown scales

u: composite scalar matrix field $\Sigma = \sigma + i\,\pi^a\,\tau^a$, $\quad Tr(\tau^a \tau^b) = \frac{1}{2}\delta^{ab}$

$$v : <\phi> = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

- Z'-boson origin and mixing angle $Z - Z'$: $\quad \begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} Z \\ Z' \end{pmatrix}$

$$E_6 \supset SO(10) \times U(1)_\psi,\ \mathrm{SO(10)} \supset \mathrm{SU(5)} \times \mathrm{U(1)}_\chi,\ \mathrm{SU(5)} \supset \mathrm{SU(3)}_c \times SU(2)_L \times U(1)_Y$$

Mixing angle: $0 < |\xi| < 5 \times 10^{-2}$

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 !

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

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

$$\downarrow$$

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

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

- ρ-Factor:

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

- Top-quark contribution (1-loop)

$$\rho_{top} = \frac{1}{1-\delta\rho_{top}}, \qquad \delta\rho_{top} = \frac{3G_F}{8\,2^{1/2}\pi^2} m_{top}^2 \approx 0.01$$

- ρ-Mixing effect

$$\rho_{mix} \approx 1 + \sin^2\xi \left(\frac{M_{Z_2}^2}{m_{Z_1}^2} - 1 \right)$$

- Upper limit on $|\xi|$

GAK, Phys.Rev. D (2005)

$$|\xi| < \frac{m_Z}{C^{\exp} - \Delta_M} \left(1 - \frac{1}{\rho_{mix}} \right)^{1/2}$$

LHC? New estimation is needed!

$C^{\exp}$: ***LEP*** $e^+e^- \to Z' \to \tau^+\tau^-$, ***Tevatron*** $\bar{p}p \to Z' \to e^+e^-, \mu^+\mu^-$

Experimental limits and window for $|\xi|$

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

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

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

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

- $\Delta_M = M_{Z'} - M_{Z_2}$ 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)

Gauge couplings sum

$$\frac{g^2}{g_h{}^2}+\frac{g^2}{g_l{}^2}=1, \quad g_h=\frac{g}{\cos\phi}, \quad g_l=\frac{g}{\sin\phi}, \quad g=\frac{e}{\sin\theta}$$

Free parameters: $g_h,\ g_l,\ x=u^2/v^2 \quad (v=246\,GeV)$

Physical case: $g_h > g_l \ \ (g_h{}^2 < 4\pi),\ \ x \geq 1$

Mass eigenstates
$$\begin{pmatrix} Z^0 \\ Z' \end{pmatrix} \cong \begin{pmatrix} 1 & -\frac{\cos^3\phi\sin\phi}{x\cos\theta} \\ \frac{\cos^3\phi\sin\phi}{x\cos\theta} & 1 \end{pmatrix} \begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix}$$

Lower bound on NP scale u:
$$\sqrt{x}=\frac{u}{v} > \Lambda^{\exp}\ \frac{\sqrt{\alpha}\cos\phi\ \sin\phi}{2\sin\theta\ m_W}$$

We found: $1.93 \leq \ \sqrt{x}=\frac{u}{v}\ \leq 2.07$ (expansion over $\sqrt{x}$ is available)

- **Decay** $t \to bH^+ (competes\ \ with\ t \to bW)$

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

$$\Gamma(t \to bH^+) = \frac{m_t^2}{4\pi v^2} F \Big\{ (|g_L|^2 + |g_R|^2)(1 + \frac{m_b^2}{m_t^2} - \frac{m_{H^+}^2}{m_t^2})$$

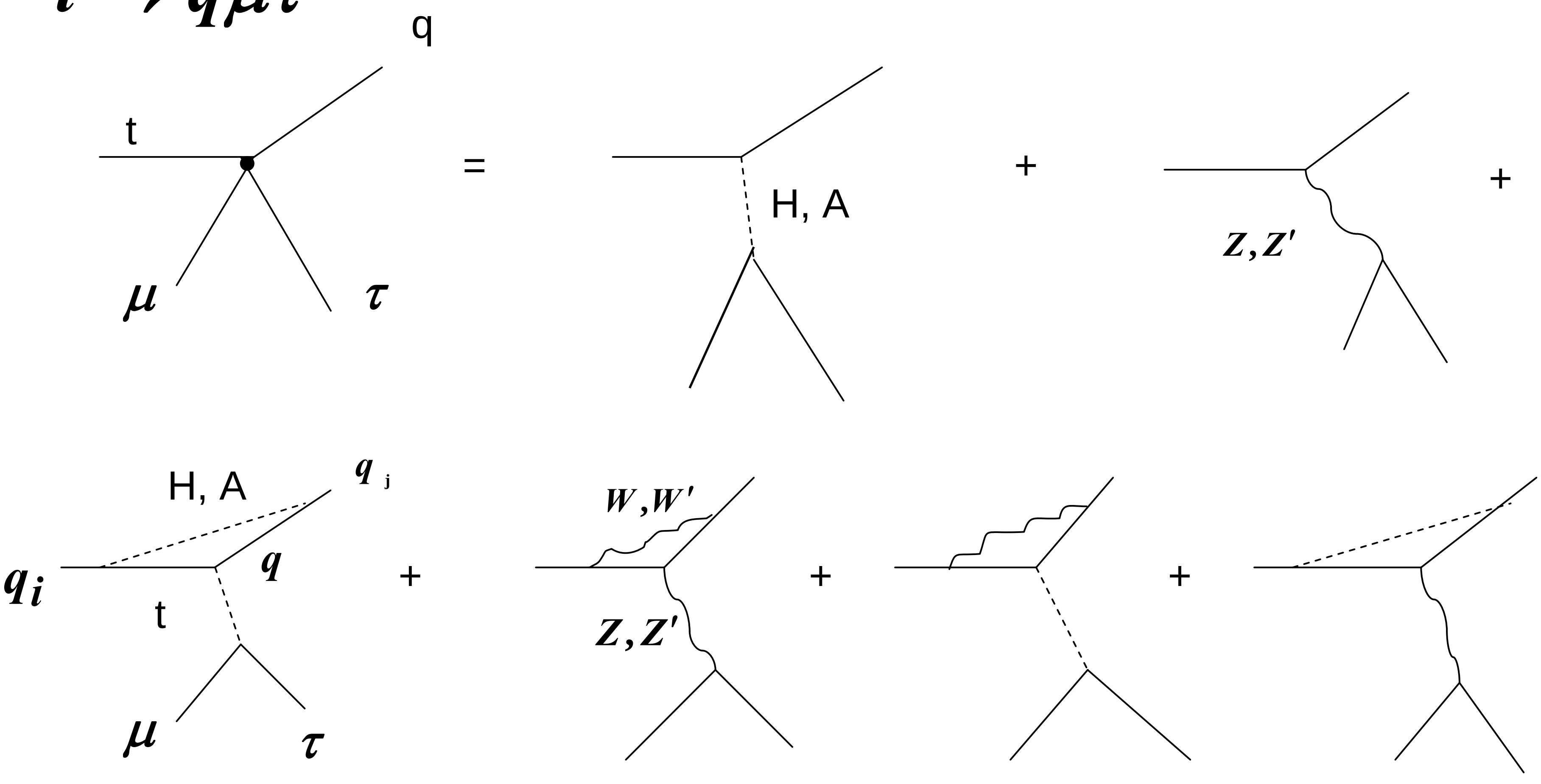
$$+ 4\,\mathrm{Re}\, g_L g_R^* \frac{m_b}{m_t} \Big\}$$

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

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

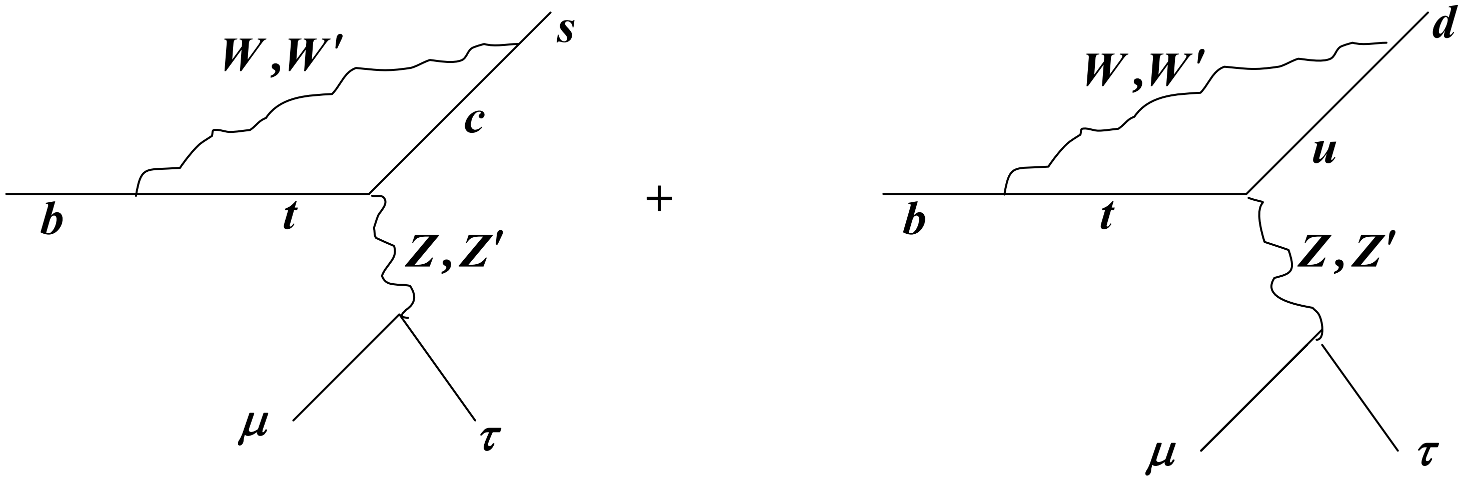
$$\Gamma(t \to bH^+) \approx \frac{m_t^3}{8\pi v^2} \beta_{H^+}^2 \tan^2\beta,\ \ \beta_{\mathrm{H}^+} = 1 - \frac{m_{H^+}^2}{m_t^2}$$

$t \to q\mu\tau$



+ …

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 $W' \to c\bar{s}$.

SM decay $t \to b + leptons$

- $t \to b + leptons, \quad b \to u l \nu, \quad \mu \to e \nu \bar{\nu}$

"W mass" $\Rightarrow$ "invariant mass" of a lepton pair

$$\Gamma_0(t \to bW) = \frac{m_t^3}{8\pi v^2} |V_{tb}|^2 \lambda^{1/2}(1, x_b^{1/2}, x_W^{1/2})[(1-x_b)^2 + (1+x_b)x_W - 2x_W^2]$$

$$x_j = m_j^2 / m_t^2, \quad j = b, W$$

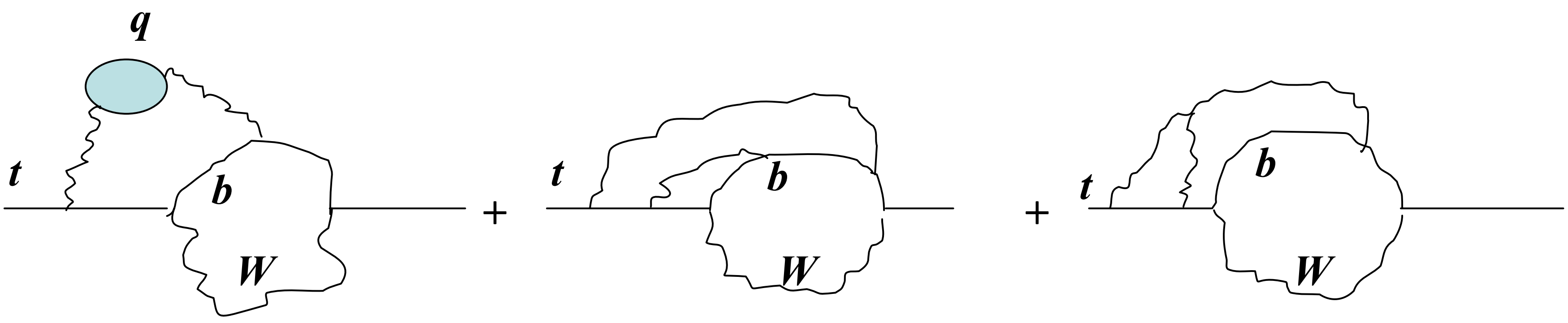
$\circ\, \alpha_s$ *Corrections*

$$\Gamma(t \to bW) = \Gamma_{0|_{x_W, x_b < 1}} [y_0 + \frac{\alpha_s}{\pi} y_1 + \frac{\alpha_s^2}{\pi^2} y_2]$$

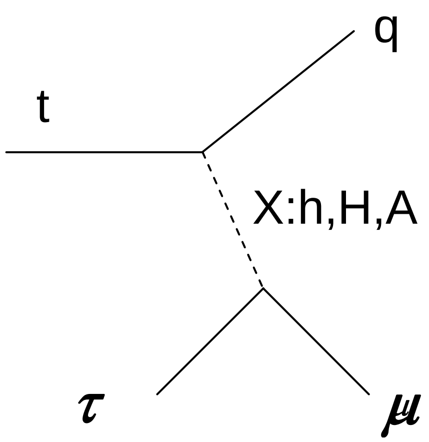
$$y_0 = 1 - x_W^2(3 - 2x_W), \quad x_W = 0.213 \text{ expansion parameter}$$

$$O(\alpha_s): y_1 = C_F[(\frac{5}{4} - \frac{\pi^2}{3}) + \frac{3}{2}x_W + x_W^2(\pi^2 - 6 + \frac{3}{2}\ln x_W) + O(x_W^3 \ln x_W)]$$

$O(\alpha_s^2)$:

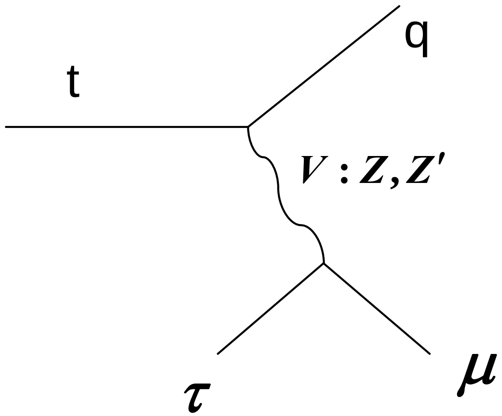


•SCALAR AND PSEUDOSCALAR (HIGGS) CONTRIBUTIONS



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

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

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

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 (Z', H, A^0) scales

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

and

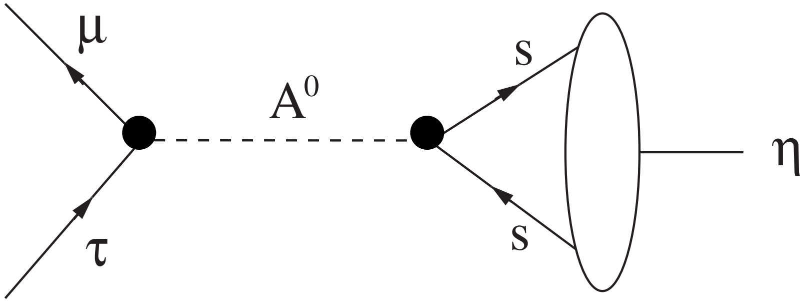
$$\Lambda_{Z'} > 347\,GeV, \quad \Lambda_{H(A^0)} > 245\,GeV \;\; for\; \tan\beta = 3$$

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)

$\tau \to \mu$

- Higgs mediated model predicts a process …



$$Br(\tau \to \mu\eta) = 8.4 \times 10^{-7} \times \left(\frac{\tan\beta}{60}\right)^{2} \times \left(\frac{M_A}{100\text{GeV}}\right)^{-4}$$

$$Br(\tau \to \mu\eta) : Br(\tau \to \mu\gamma) : Br(\tau \to 3\mu)$$

$$= 8.4 : 1.5 : 1$$

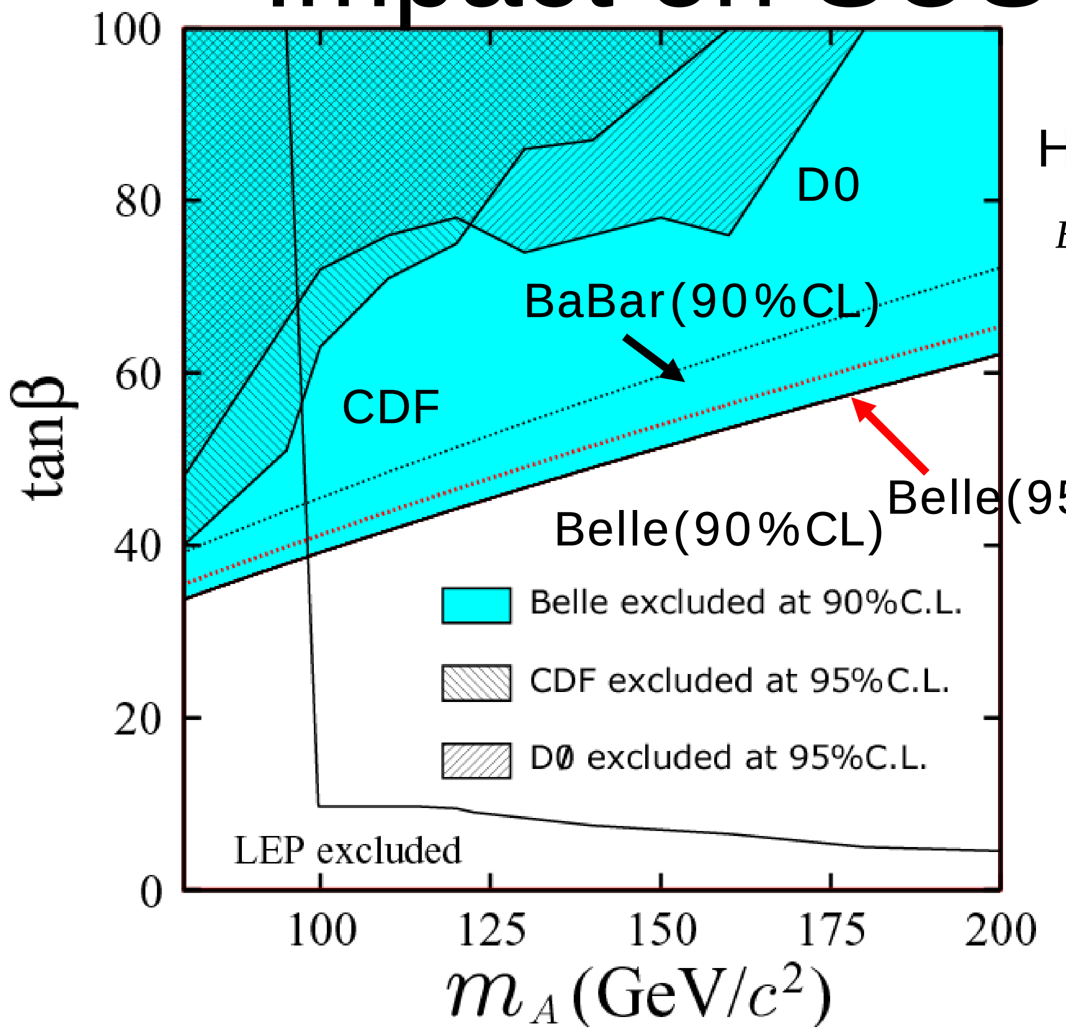
PRD 66, 057301 (2002).

In the case of Higgs mediated model,

MSher

$\tau \to \mu\eta$ decay may be observed earlier than $\tau \to \mu\gamma$.

Impact on SUSY of $\tau \rightarrow \mu + \eta$



Higgs mediated model predicts

$$Br(\tau \rightarrow \mu\eta) = 8.4 \times 10^{-7} \times \left(\frac{\tan\beta}{60}\right)^2 \times \left(\frac{M_A}{100\text{GeV}}\right)^{-4}$$

CDF
- $\phi \rightarrow \tau\tau$ search

D0
- $\phi \rightarrow \tau\tau$ search

Short comments

- Different rate production $\tau : \mu : e$

$$t \to q\ e^+\ \mu^-$$

$$q\ e^+\ \tau^-$$

$$q\ \mu^+\ \tau^- \to q\ \mu^+\ \mu^-\ \mu^-\ \mu^+$$

- Particularly sensitive probe in flavor physics at small $\tan\beta$ scenario
- NP signature: an excess in $l_i\,\bar{l}_j$ production
- LHC: either find new effects or constrain parameters of the model
- Large $\sin^2\phi \Rightarrow$ NP effects to heavy fermions and heavy gauge bosons will be large.
- The effect of NP to di-lepton pair production does not significantly depend on the angle $\phi \Rightarrow$ model constrain.
- H, A^0, Z' contribution can produce an excess in the production rate of $l_i\,\bar{l}_j \Rightarrow$ cannot be mistaken at the LHC

INSTEAD OF CONCLUSION

- No convincing sign of New Physics with $\boldsymbol{Z'},\ \boldsymbol{W}^{\pm'}$ 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