LEPの精密測定と新しい物理

2001. 11. 5
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- $N_\nu = 3$

- 弱い相互作用のゲージ理論を検証

- 大統一理論・超対称性のヒント

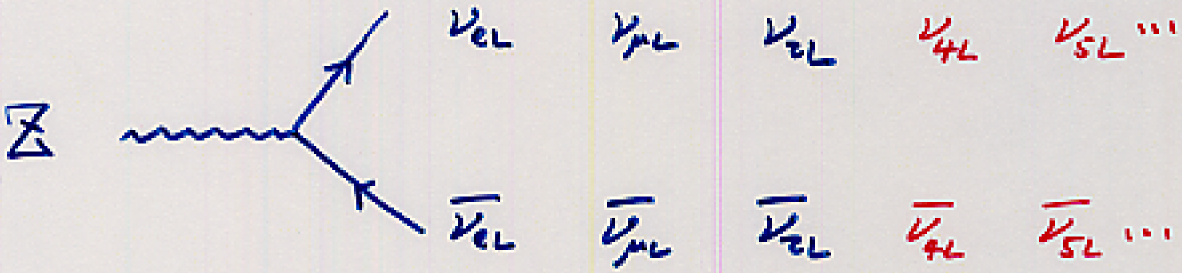
- 精密データを使い易い形で保存

- 三世代のクォークとレプトン

第一世代 $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ u_R d_R $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ e_R

第二世代 $\begin{pmatrix} c_L \\ s_L \end{pmatrix}$ c_R s_R $\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$ μ_R

第三世代 $\begin{pmatrix} t_L \\ b_L \end{pmatrix}$ t_R b_R $\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$ τ_R



$$\Gamma(Z \to \text{invisible mode}) \propto N_\nu$$

$$\left.\begin{aligned} &\sigma_h^0 = \frac{12\pi}{m_Z^2}\frac{\Gamma_e \Gamma_h}{\Gamma_Z^2} \\ &R_\ell = \frac{\Gamma_h}{\Gamma_\ell} \quad (\ell = e, \mu, \tau) \\ &\Gamma_Z \\ &m_Z \end{aligned}\right\} \Rightarrow \Gamma_Z = \Gamma_h + \Gamma_\ell + \underbrace{\Gamma_{inv.}}$$

$$\Downarrow$$

$$N_\nu = 2.9841 \pm 0.0083$$

* Degenerate 4'th generation with heavy Dirac ν_4.

$\Rightarrow \Delta S = 0.21$

* Vector-like families

BB宇宙論と素粒子論

$$\frac{{}^4He}{H} \propto \frac{\#n}{\#p}$$

平衡 $\displaystyle \frac{\#n}{\#p} = e^{-\frac{m_n-m_p}{T}} \approx e^{-\frac{1.3MeV}{T}}$

⇓

冷却 $G_F^2 T^5 < \sqrt{G_N(5{,}5+\frac{7}{4}N_\nu)}\,T^2$

$n \longleftrightarrow p$ 宇宙膨張

$N_\nu \nearrow \quad T \nearrow \quad \frac{\#n}{\#p} \nearrow \quad \frac{{}^4He}{H} \nearrow$

観測値 $\sim 0{,}25$

⇓

$N_\nu = 2 \sim 4$

⇓

* バリオン生成（物質宇宙の起源）
* ダークマター（銀河の主役）
* ダークエネルギー・宇宙定数（???）

・弱い相互作用のゲージ理論

自発的ゲージ対称性の破れ（ヒッグス機構）

→ m_W, m_Z, m_q, m_ℓ, …

→ 短距離・高振動部はゲージ対称性を保つ

⇓

高エネルギーの（未知の）物理に対する依存性がゲージ対称性によって制限される。

⇓

くり込み可能

⇓

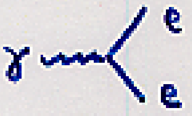
精密実験による検証。

v, g, g', …　$(g'/g = \tan\theta_W)$

$m_W \sim vg$

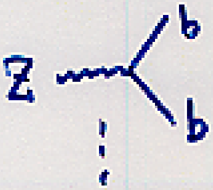
$m_Z \sim vg/\cos\theta_W$

$G_F \sim \frac{g^2}{m_W^2} \sim v^{-2}$

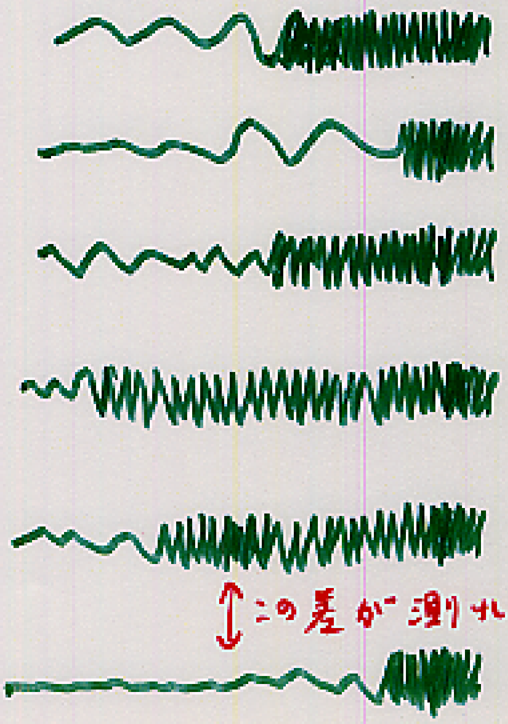


$\sim e = g\sin\theta_W$

$\sim \frac{g}{\cos\theta_W}$



$\sim \frac{g}{\cos\theta_W}$



低振動部←→高振動部はユニヴァーサル

↕ この差が測れる。

Precision Electroweak Data
(Lepton-Photon•2001)

	data	SM	pull	● 1998 data		
				SM	pull	
LEP 1						
line-shape & FB asym.:						
m_Z (GeV)	91.1867 ± 0.0021	—	—	—	—	
Γ_Z (GeV)	2.4952 ± 0.0023	2.4968	−0.7	2.4959	−0.8	
● σ_h^0(nb)	41.540 ± 0.037	41.476	1.7 ●	41.473	0.3	← QED
R_e	20.804 ± 0.050	20.744	1.2	20.746	0.7	
R_μ	20.785 ± 0.033	20.744	1.3	20.746	1.3	
R_τ	20.764 ± 0.045	20.791	−0.6	20.793	−0.7	
$A_{FB}^{0,e}$	0.0145 ± 0.0025	0.0165	−0.8	0.0162	−0.4	
$A_{FB}^{0,\mu}$	0.0169 ± 0.0013	0.0165	0.3	0.0162	0.1	
$A_{FB}^{0,\tau}$	0.0188 ± 0.0017	0.0165	1.4	0.0162	1.2	
τ polarization:						
A_τ	0.1439 ± 0.0042	0.1482	−1.0	0.1471	−0.9	
A_e	0.1498 ± 0.0048	0.1482	0.3	0.1471	0.2	
b and c quark results:						
R_b	0.21646 ± 0.00065	0.21597	0.8	0.21607	0.7	
R_c	0.1719 ± 0.0031	0.1721	−0.1	0.1720	0.3	
● $A_{FB}^{0,b}$	0.0990 ± 0.0017	0.1039	−2.9 ●	0.1031	−2.0	← QCD
● $A_{FB}^{0,c}$	0.0685 ± 0.0034	0.0743	−1.7 ●	0.0737	−0.6	
jet charge asymmetry:						
$\sin^2\theta_{eff}^{lept}$	0.2321 ± 0.0012	0.2314	0.9	0.2315	0.6	
SLC						
● A_{LR}^0	0.1513 ± 0.0021	0.1482	1.5 ●	0.1471	1.6	
A_b	0.922 ± 0.020	0.935	−0.6	0.935	−1.9	
A_c	0.670 ± 0.026	0.668	0.1	0.668	−0.5	
Tevatron + LEP 2						
● m_W (GeV)	80.451 ± 0.033	80.397	1.6 ●	80.372	0.9	
Parameters						
$1/\alpha(m_Z^2)$	128.936 ± 0.046	128.92	0.3	128.93	0.0	
$\alpha_s(m_Z)$	0.118 ± 0.002	0.118	0.0	0.118	0.0	
● m_t (GeV)	● 174.3 ± 5.1	● 176.3	−0.4	● 173.5	0.2	
m_H (GeV)	—	● 119	—	● 138	—	
χ^2_{tot} (d.o.f. = 22 − 4)			● 26.1		● 17.5	

Systematic approach to study quantum corrections

K.H. Ann.Rev.Nucl.Part.Sci. 48, 463 (1998)

- The Z-parameters

$Z \to f_\alpha \overline{f_\alpha}$ amplitudes

$$g_\alpha^f = \text{reference SM value} + \underbrace{(\cdots)\Delta\bar{g}_Z^2 + (\cdots)\Delta\bar{s}^2}_{\text{oblique corrections}} + \underbrace{\Delta g_\alpha^f}_{\text{vertex corrections}}$$

$$\begin{cases} \Delta\bar{g}_Z^2 = 0.00412\,\Delta T_Z \\ \Delta\bar{s}^2 = 0.00360\,\Delta S_Z - 0.00241\,\Delta T_Z \end{cases}$$

$$\begin{cases} \Delta S_Z = \Delta S + \Delta R - 0.064\, x_\alpha \\ \Delta T_Z = \Delta T + 1.49\,\Delta R - \dfrac{\Delta\delta_G}{\alpha} \end{cases}$$

$$x_\alpha = \frac{\frac{1}{\alpha(m_Z^2)} - 128.90}{0.09}$$

$\leftarrow$ corrections to μ-decay

Oblique parameters ΔS, ΔT, ΔR

$$\Delta R \sim \frac{1}{\bar{g}_Z^2(m_Z^2)} - \frac{1}{\bar{g}_Z^2(0)}$$

m_t, m_H dependence

$$\left.\begin{aligned} \Delta S &= (\Delta S)_{SM} + S_{new} \\ \Delta T &= (\Delta T)_{SM} + T_{new} \\ \Delta R &= (\Delta R)_{SM} + R_{new} \end{aligned}\right\} \text{oblique corrections}$$

$$\Delta g_\alpha^f = (\Delta g_\alpha^f)_{SM} + (\Delta g_\alpha^f)_{new} \quad \Big\}\ \text{vertex corrections}$$

only $\Delta g_L^b \neq 0$ in SM

12 distinctive corrections in MSSM

ν_e e_L e_R u_L u_R d_L d_R

ν_τ τ_L τ_R b_L b_R

- The W-mass

$$m_W = 80.402 \underbrace{- 0.288\,\Delta S + 0.448\,\Delta T + 0.337\,\Delta U}_{\text{obligua corrections}} + 0.012\, x_\alpha - 0.126\,\frac{\Delta\delta_G}{\alpha}$$

$Z \to f_\alpha \overline{f_\alpha}$ amplitudes

$$
\begin{aligned}
g_L^\nu &= 0.50214 + 0.453\,\Delta\bar{g}_Z^2 & & + \Delta g_L^\nu \\
g_L^e &= -0.26941 - 0.244\,\Delta\bar{g}_Z^2 & + 1.001\,\Delta\bar{s}^2 & + \Delta g_L^e \\
g_R^e &= 0.23201 + 0.208\,\Delta\bar{g}_Z^2 & + 1.001\,\Delta\bar{s}^2 & + \Delta g_R^e \\
g_L^u &= 0.34694 + 0.314\,\Delta\bar{g}_Z^2 & - 0.668\,\Delta\bar{s}^2 & + \Delta g_L^u \\
g_R^u &= -0.15466 - 0.139\,\Delta\bar{g}_Z^2 & - 0.668\,\Delta\bar{s}^2 & + \Delta g_R^u \\
g_L^d &= -0.42451 - 0.383\,\Delta\bar{g}_Z^2 & + 0.334\,\Delta\bar{s}^2 & + \Delta g_L^d \\
g_R^d &= 0.07732 + 0.069\,\Delta\bar{g}_Z^2 & + 0.334\,\Delta\bar{s}^2 & + \Delta g_R^d \\
g_L^b &= -0.42109 - 0.383\,\Delta\bar{g}_Z^2 & + 0.334\,\Delta\bar{s}^2 & + \Delta g_L^b
\end{aligned}
$$

SM : $(S, T, U, R, \Delta g_L^b) \sim$ functions $(m_t, m_H, \alpha, \alpha_s)$

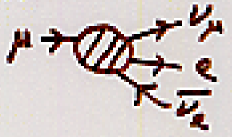
MSSM : $(S, T, U, R, \underbrace{12\,\Delta g_\alpha^f}, \underbrace{\Delta\delta_G}) \sim$ functions (MSSM parameters)

⇓

UPDATE

G.C.Cho + KH

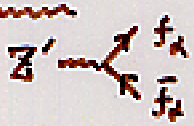
hep-ph/01



G.C.Cho + KH
NPB574, 623 (2000)
used CERN-EP/99-15 Data

Z′ models : $(+\underbrace{T_{\text{new}}}, \underbrace{\Delta g_\alpha^f})$

Z-Z′mixing



Triplet Higgs v.e.v. : (T_{new})

G.C.Cho, Y.Umeda + KH
NPB531, 65 (1998)

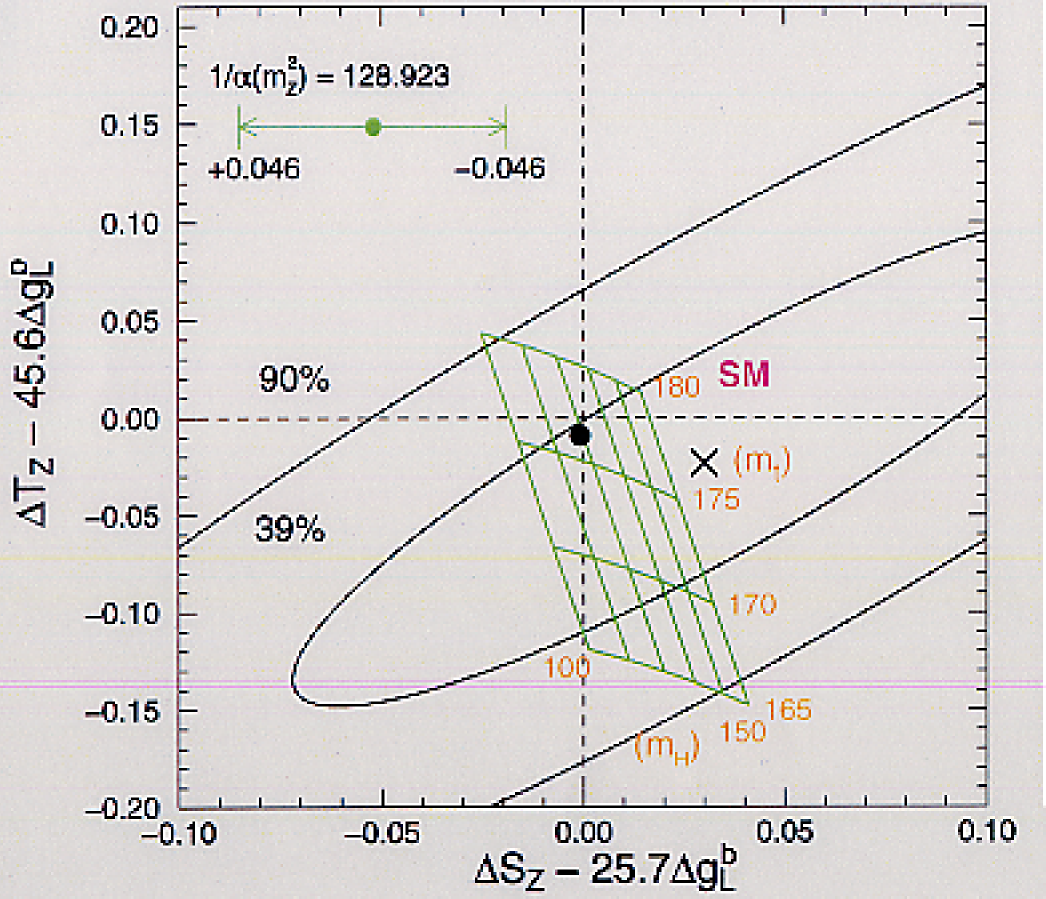
W′ models : $(+\underbrace{U_{\text{new}}}, \underbrace{\Delta\delta_G})$

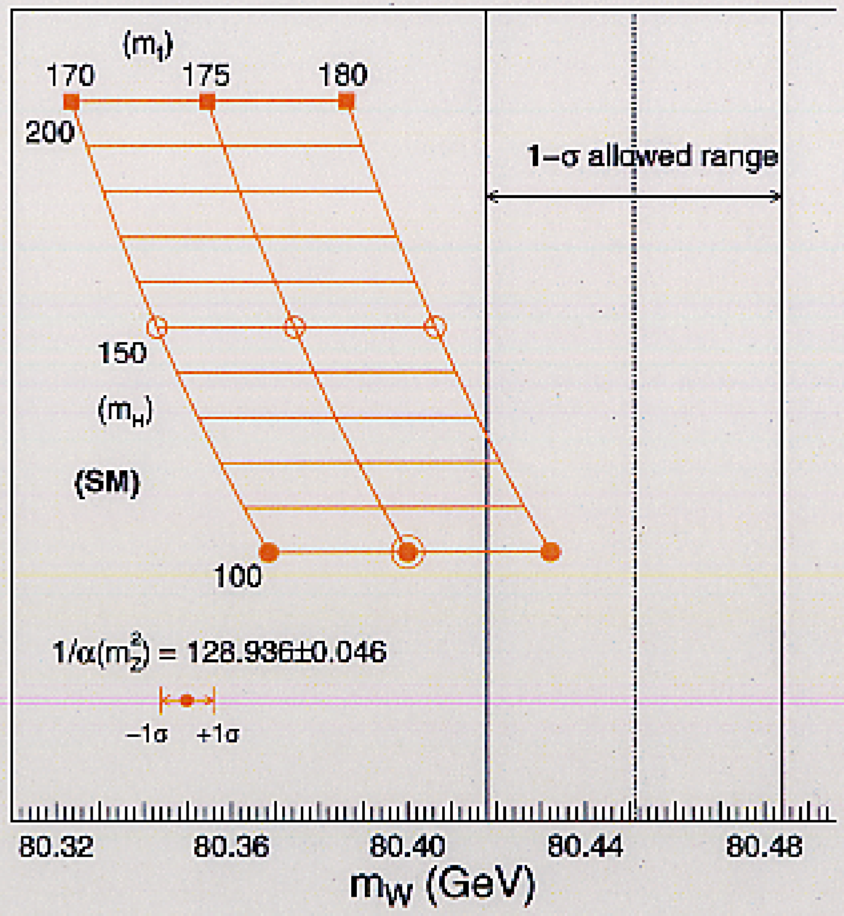
W-W′mixing

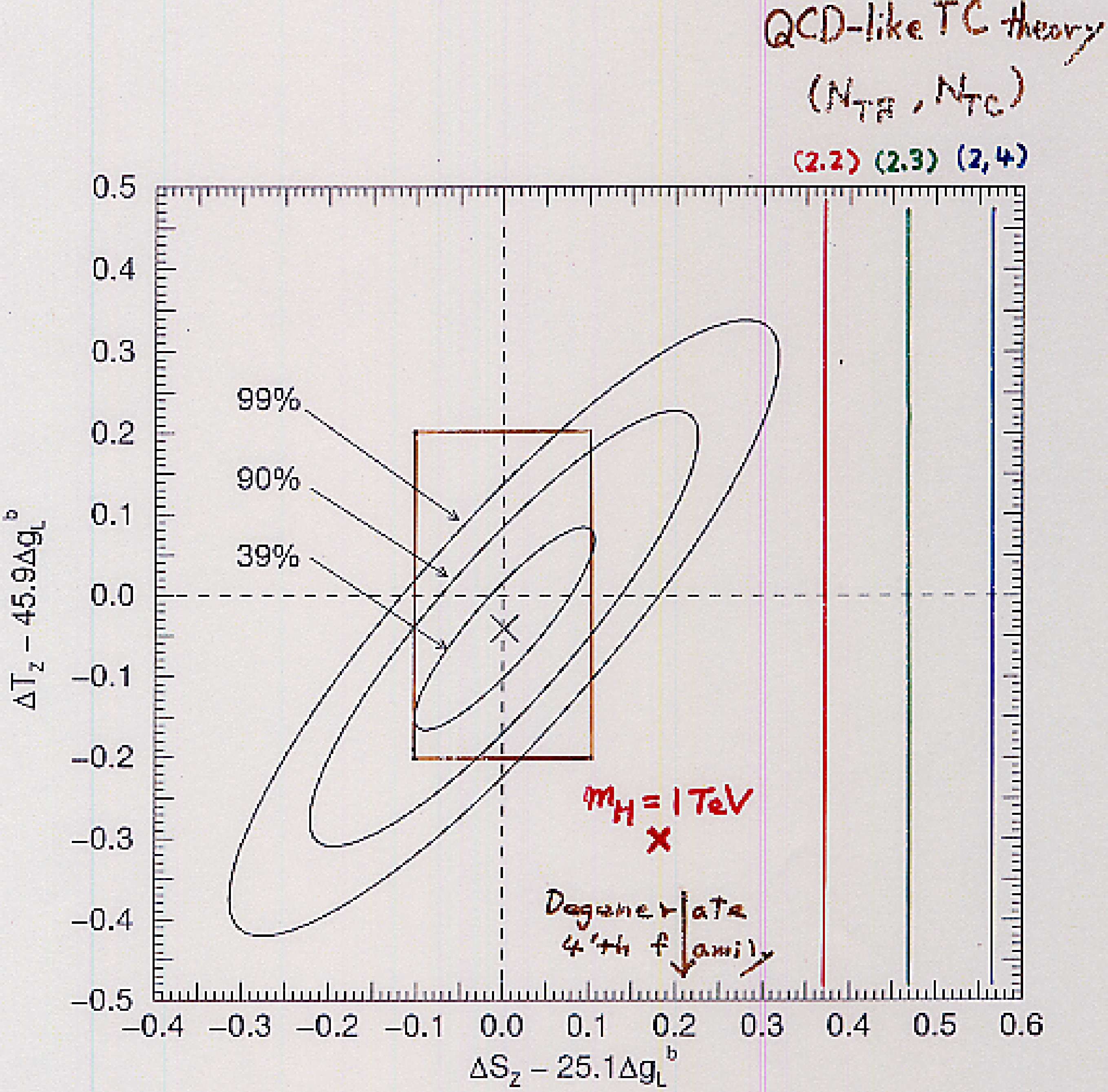
KH + S.Matsumoto
PLB424, 362 (1998)
E B478, 456 (2000)

TC models : $(S, T, U, \cdots)$

The SM prediction



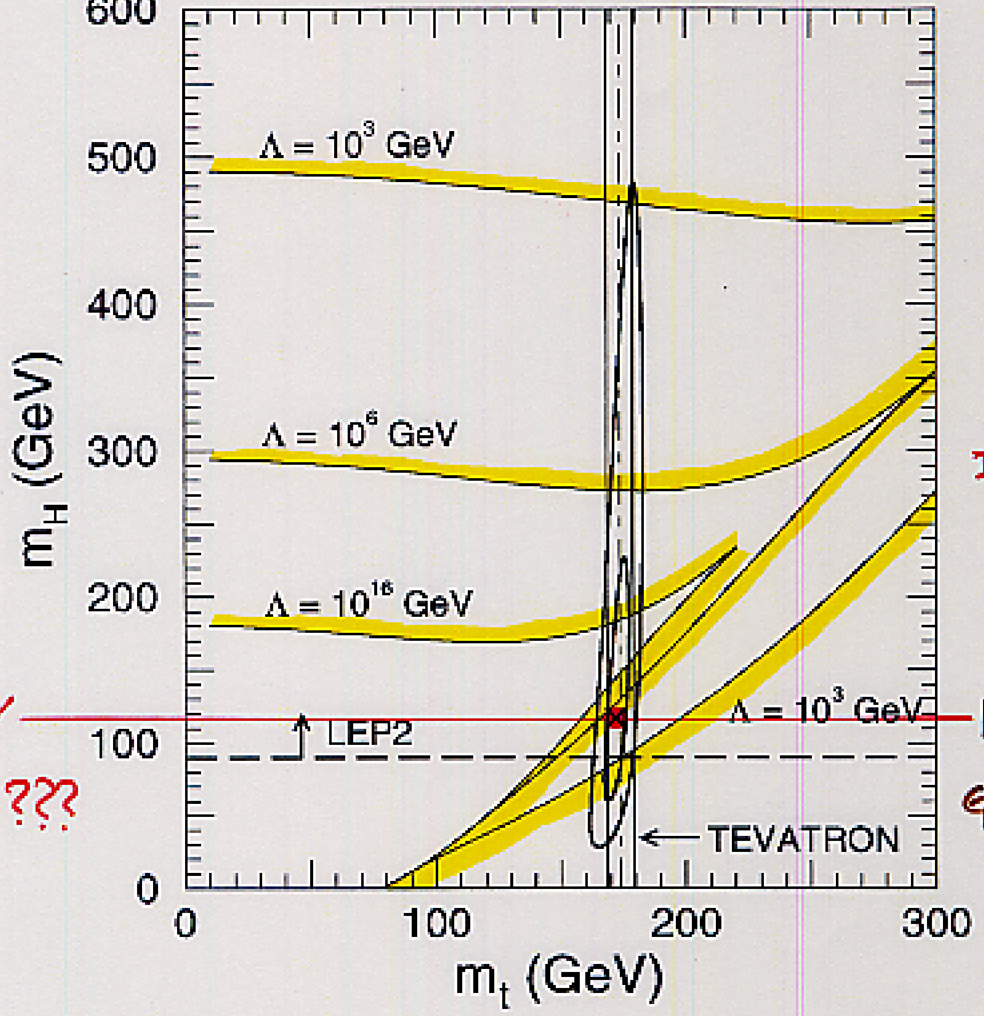




If m_H = 1 TeV
If TC-like theory
If 4'th generation

⇒ additional contribution with fine-tuning necessary.

⇒ A set of new particles.



$m_H = 115$ GeV

$\Lambda \lesssim 100$ TeV ???

If $m_H = 115$ GeV

$\Rightarrow \Lambda < 10^6$ GeV

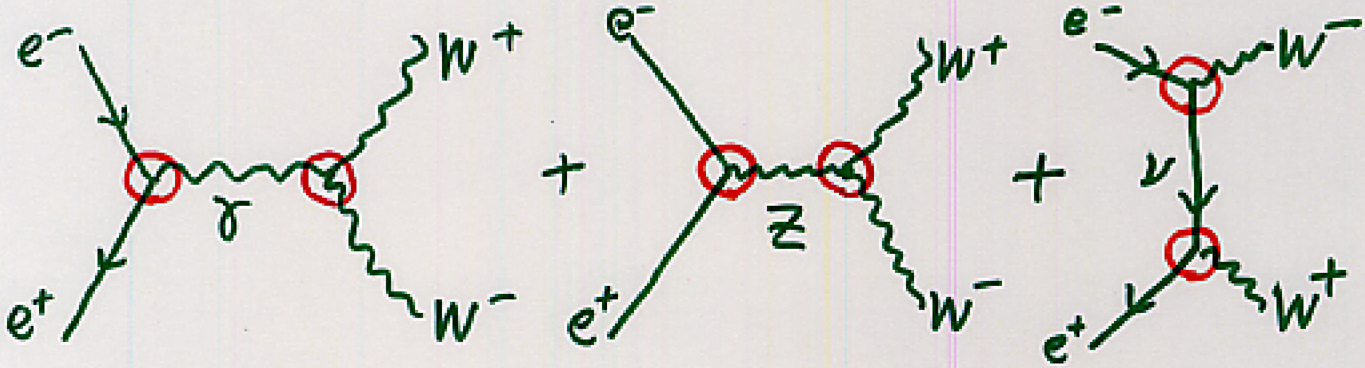
by

G.C. Cho

90% (39%) CL allowed region from precision experiments at LEP, SLC, Tevatron (Sep., 1999).
Also shown are the triviality (upper) bounds and the vacuum stability (lower) bounds for the Higgs boson mass.

$m_H \lesssim 200$ GeV favored by the electroweak precision measurements at LEP1/SLC, m_W at Tevatron/LEP2

WWγ/WWZ 結合の測定



ゲージ対称性 ⇒ WWγ/WWZ結合がユニーク

⇓ ⇓

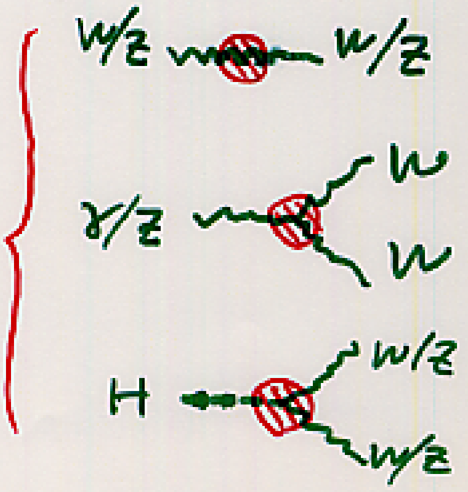
くり込み可能　　直接測定 @LEP2

⇓ ⇓

輻射補正によるテスト　　新しい物理探索のモデル

（精密実験）

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{f_i}{\Lambda^2} \underset{\Downarrow}{\underline{O_i^{(6)}}} + O\left(\frac{1}{\Lambda^4}\right)$$



精密電弱実験

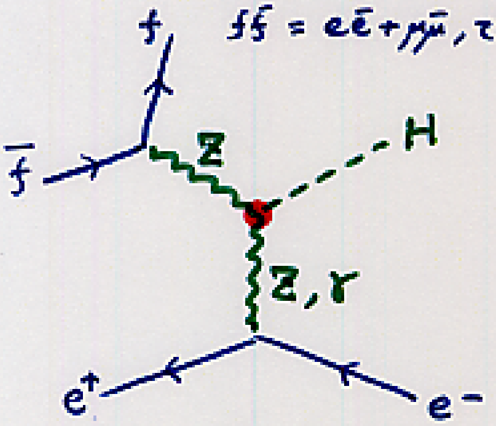
WZγ結合の精密測定

HVV結合の精密測定

How accurately can we measure the HVV couplings at a linear collider?

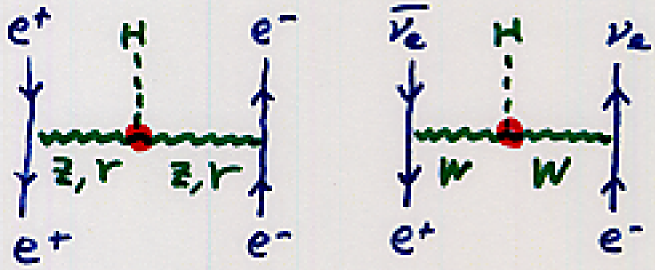
Kaoru Hagiwara (KEK)

2001. 10. 31
TsingHua U., ACFA LCWS IV



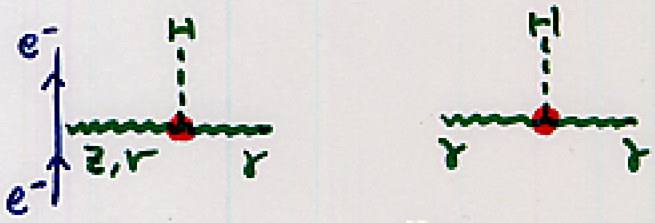
$f\bar{f} = e\bar{e} + \mu\bar{\mu}, \tau\bar{\tau}, \nu\bar{\nu}, u\bar{u}+d\bar{d}+s\bar{s}+c\bar{c}, b\bar{b}$

- KH + MLStong, ZPC 62, 99 (1994)
  - parametrization of HVV couplings
  - observables
- KH + S Ishihara + J Kamoshita + BA Kniehl, EPJC 14, 457 (2000)
  - optimal observables → error estimate
  - beam polarization, Z pol., b-charge etc

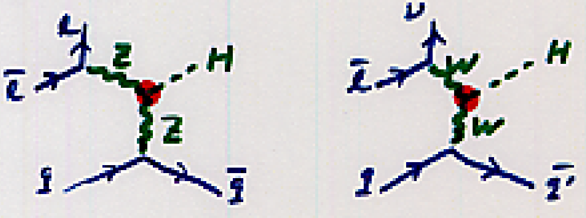


- KH + J Kamoshita + Y Uehara, in preparation
  - tagged e⁺, e⁻ information
  - beam polarization

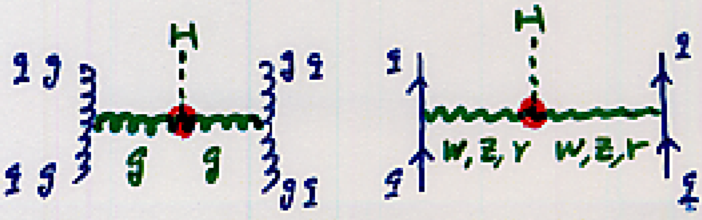
⇓
2001.10



- Bremsstrahling vs PLC



- Tevatron



- LHC

Table 6
Energy-dimension-six operators in the linear representation of the Higgs mechanism. The contribution of an operator to a particular vertex is denoted by an "X". In some cases an operator naively contributes to a vertex, yet that contribution does not lead to observable effects. In such cases the "X" is replaced by an "O"

													HVV			
$\mathcal{O}_i^{(6)}$	WW	ZZ	AZ	AA	WWZ	WWA	$WWWW$	$WWZZ$	$WWZA$	$WWAA$	$ZZZZ$	HH	HWW	HZZ	HZγ	Hγγ
$\mathcal{O}_{DW} = \mathrm{Tr}([D_\mu, \hat{W}_{\nu\rho}][D^\mu, \hat{W}^{\nu\rho}])$	X	X	X	X	X	X	X	X	X	X						
$\mathcal{O}_{DB} = -\frac{g'^2}{2}(\partial_\mu B_{\nu\rho})(\partial^\mu B^{\nu\rho})$		X	X	X												
$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$		X	X	X	X	X								x	x	x
$\mathcal{O}_{\Phi,1} = [(D_\mu\Phi)^\dagger\Phi][\Phi^\dagger(D^\mu\Phi)]$		X										x		x		
$\mathcal{O}_{WWW} = \mathrm{Tr}(\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}_\rho^\mu)$					X	X	X	X	X	X						
$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$	O	O	O	O	O	O	O	O	O	O			x	x	x	x
$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi$		O	O	O										x	x	x
$\mathcal{O}_W = (D_\mu\Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu\Phi)$					X	X	X	X	X				x	x	x	
$\mathcal{O}_B = (D_\mu\Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu\Phi)$					X	X								x	x	
$\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$												x				
$\mathcal{O}_{\Phi,3} = \frac{1}{3}(\Phi^\dagger\Phi)^3$																
$\mathcal{O}_{\Phi,4} = (\Phi^\dagger\Phi)[(D_\mu\Phi)^\dagger(D^\mu\Phi)]$	O	O										x	x	x		

WWZ/γ

大統一理論と超対称性のヒント

何故 $Q_p + Q_e$
$= 2Q_u + Q_d + Q_e = 0$?
何故 $\alpha_s > \alpha_w > \alpha$?

$\Big\}$ ⇒ 大統一理論
⇓
大砂漠
⇓
軽いスカラー場(ヒッグス)の不安定性
⇓
超対称性

クォークとレプトン　は同じものの部分

グルオンと W, Z と光　は同じものの部分

例) SU(5)

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ h_5 \end{pmatrix} \begin{matrix} \nearrow \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} \text{重い} \ (10^{16}\,\mathrm{GeV}) \\ \updownarrow \\ \searrow \begin{pmatrix} h_4 \\ h_5 \end{pmatrix} \text{転い} \ (0\,\mathrm{GeV}) \end{matrix}$$

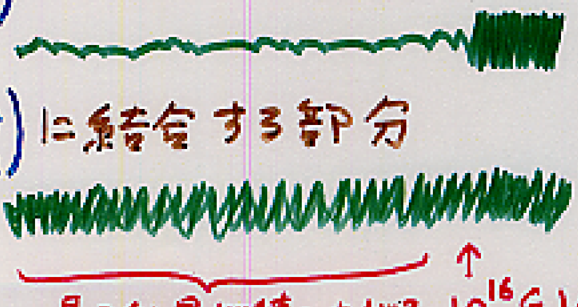
24ヶのゲージボソンの内、$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$ に結合する部分

← g_1, g_3　B, グルオン ←

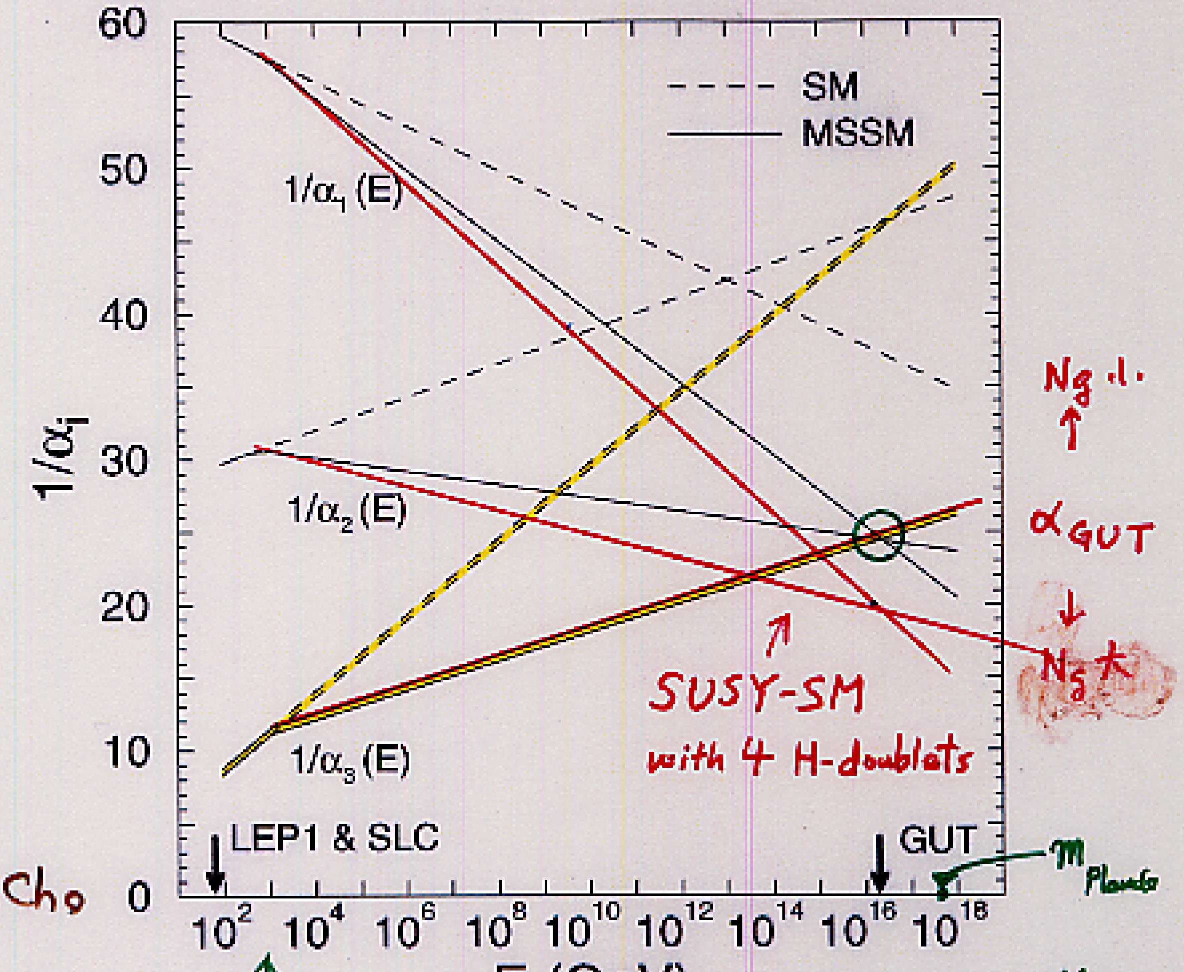
24ヶのゲージボソンの内、$\begin{pmatrix} h_4 \\ h_5 \end{pmatrix}$ に結合する部分

↙ g_2　W, B ←

↖ $\sin^2\theta_W$ ↖ $\frac{g_1}{g_2}$



Running gauge couplings in the SM and in the MSSM (Minimal Supersymmetric SM)



by G.C.Cho

$m_{GUT} \approx 2\times10^{16}$ GeV

new particles mass $\lesssim 1$ TeV

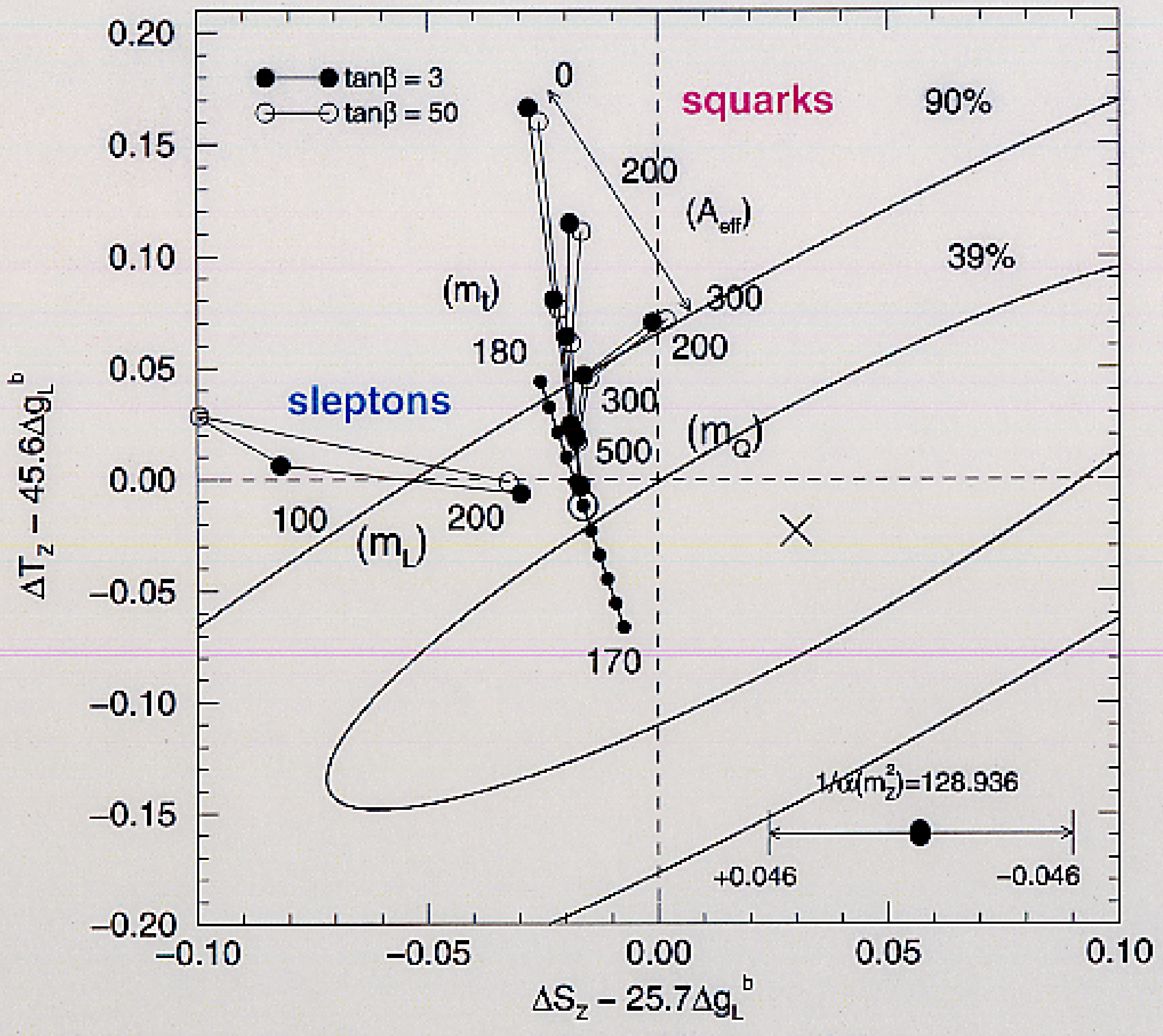
MSSM with 2 H-doublets is favored! FCNC OK.

⇓

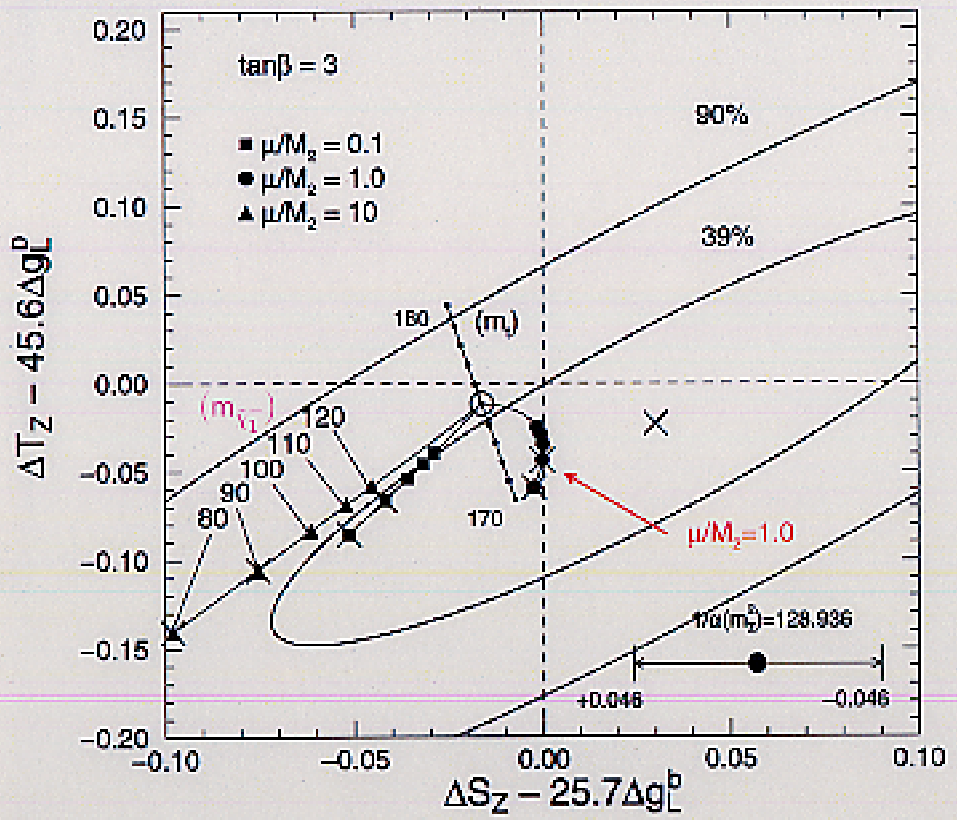
If some of them are sufficiently light, their effects may be detected by precision electroweak measurements of Z and W.

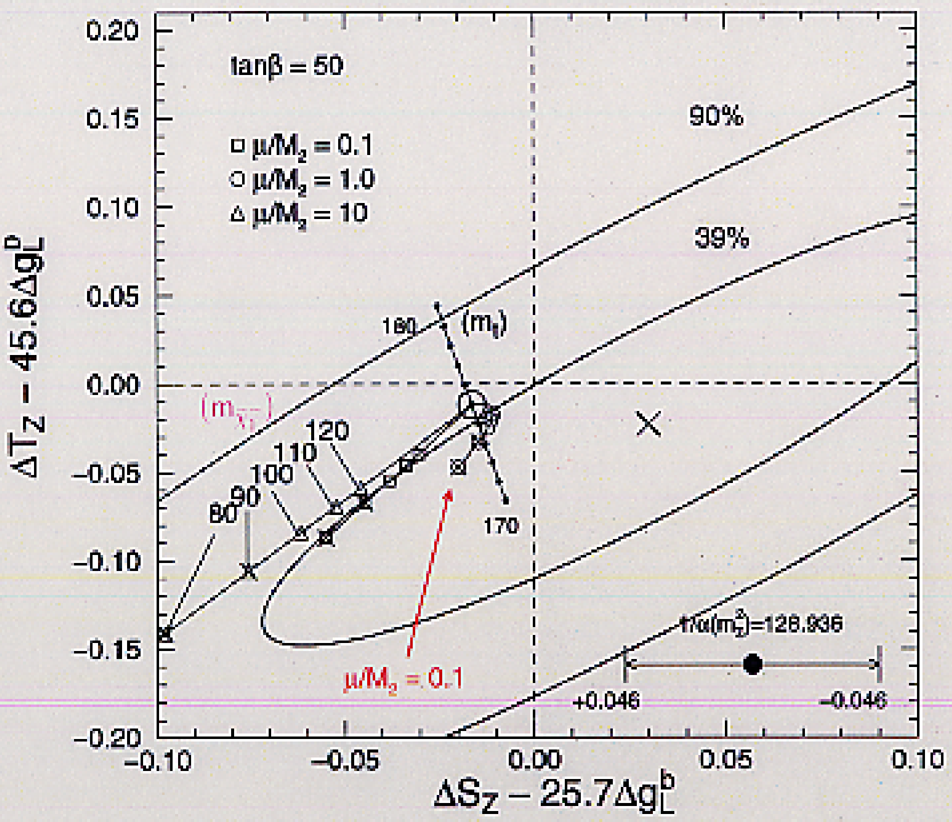
⇓

Sfermions

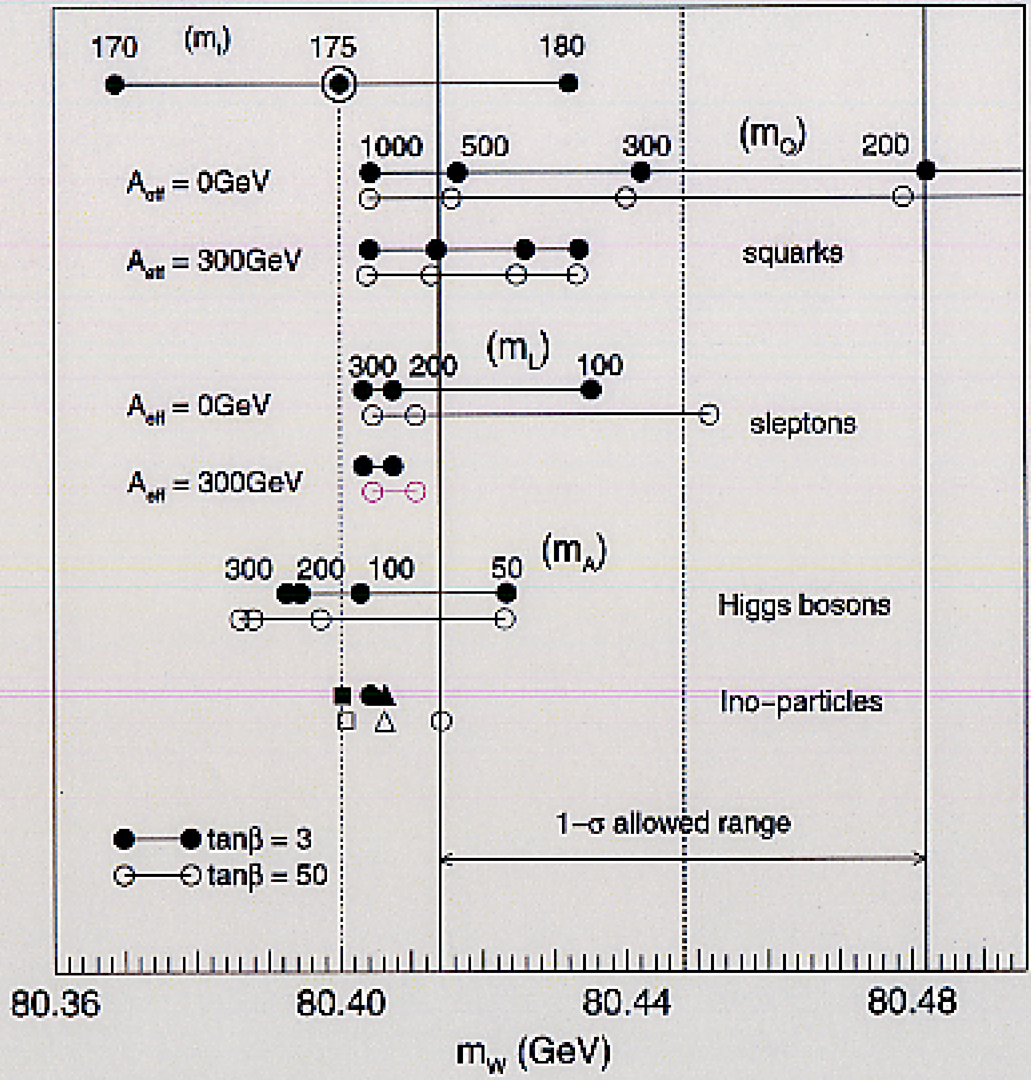

tanβ = 3
tanβ = 50
0
squarks
90%
200
(A_eff)
39%
(m_t)
300
180
200
sleptons
300
(m_Q)
500
100
200
(m_L)
170
1/α(m_Z^2)=128.936
+0.046
−0.046
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
−0.10
−0.05
0.00
0.05
0.10
ΔS_Z − 25.7Δg_L^b
ΔT_Z − 45.6Δg_L^b

Charginos/Neutralinos



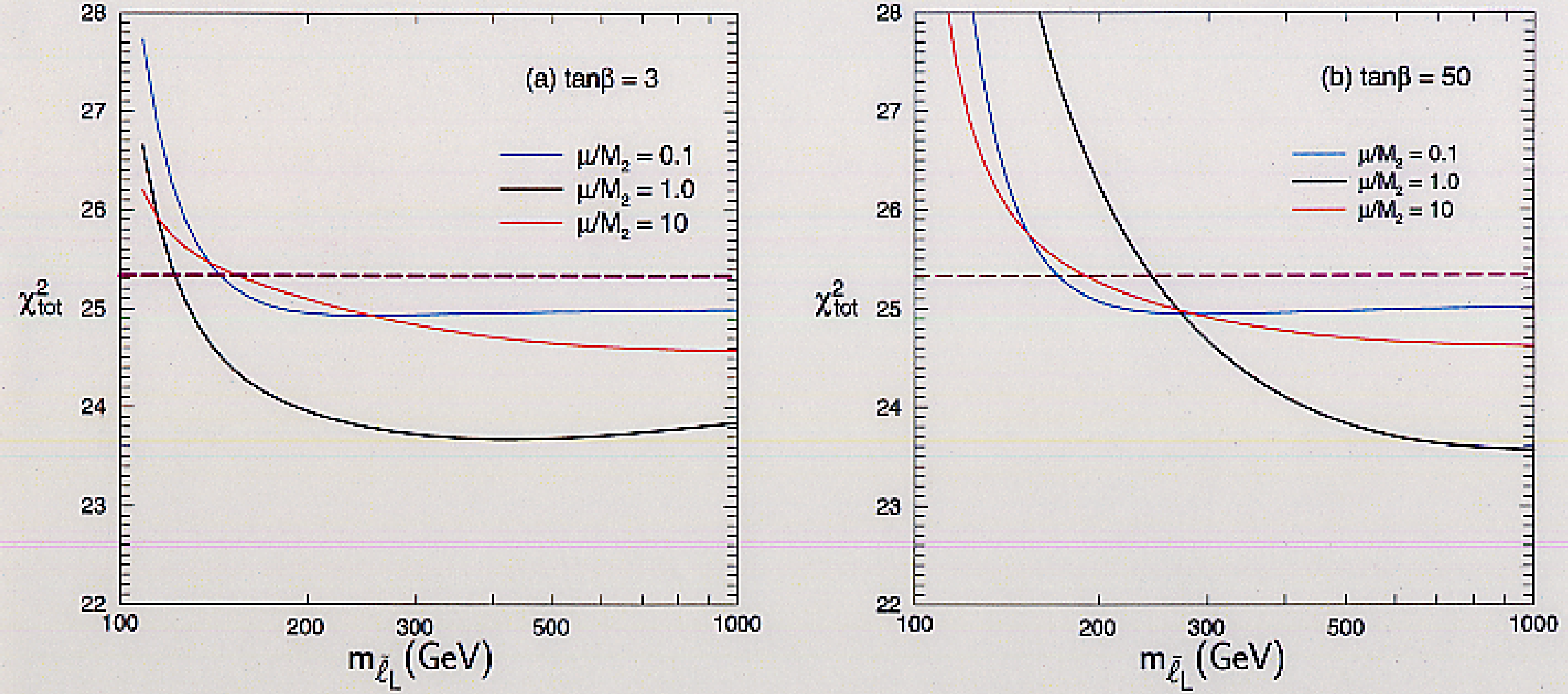


W-boson mass



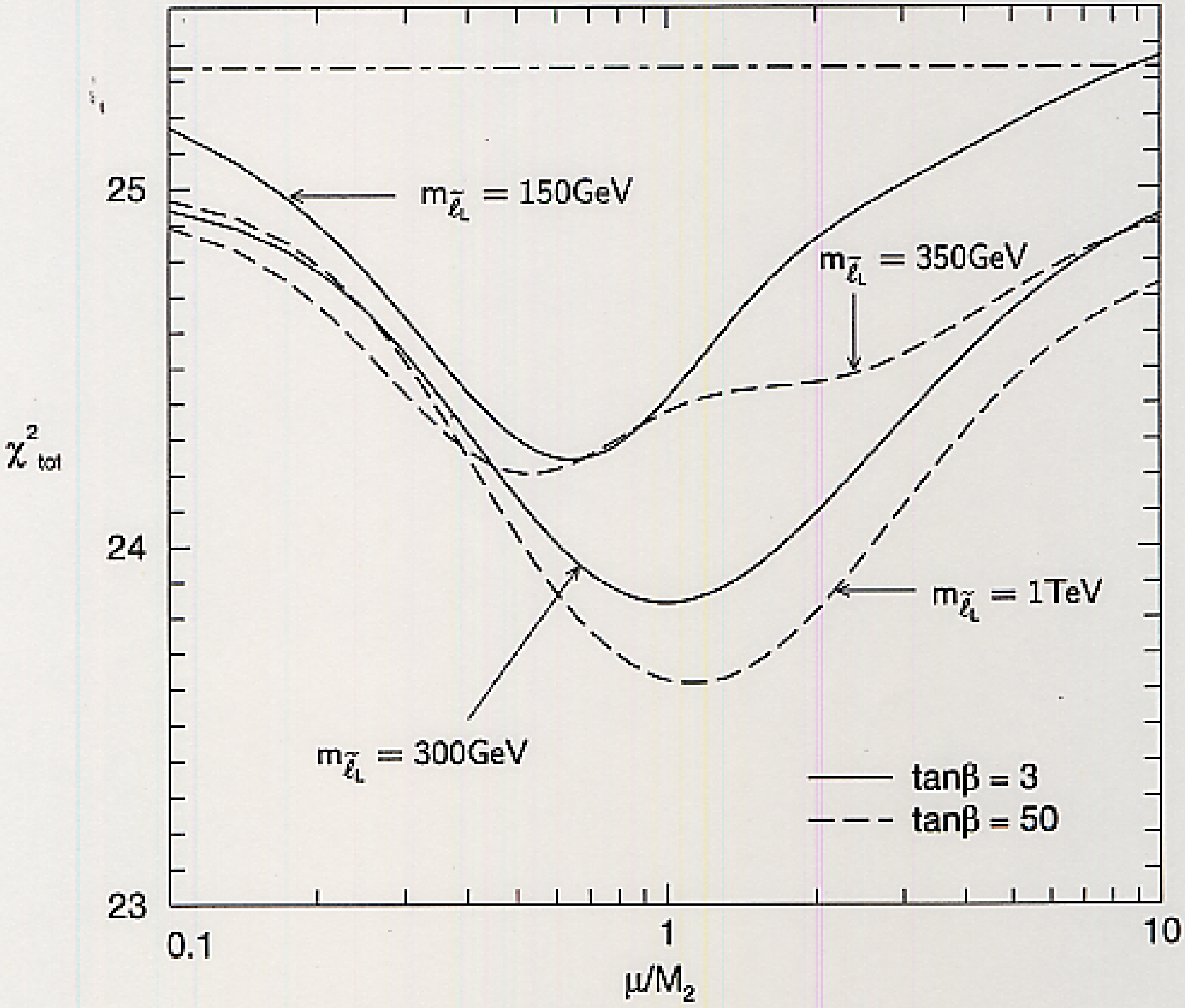
170
(m_t)
175
180
1000
500
300
$(m_{\tilde{Q}})$
200
A_{eff} = 0GeV
A_{eff} = 300GeV
squarks
300
200
$(m_{\tilde{L}})$
100
A_{eff} = 0GeV
sleptons
A_{eff} = 300GeV
300
200
100
50
(m_A)
Higgs bosons
Ino-particles
tanβ = 3
tanβ = 50
1−σ allowed range
80.36
80.40
80.44
80.48
m_W (GeV)

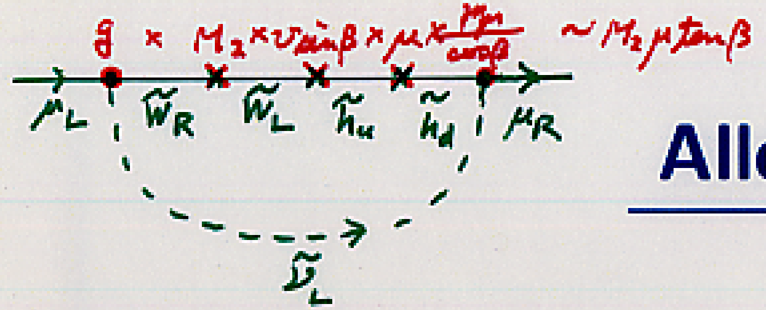
Light chargino & slepton



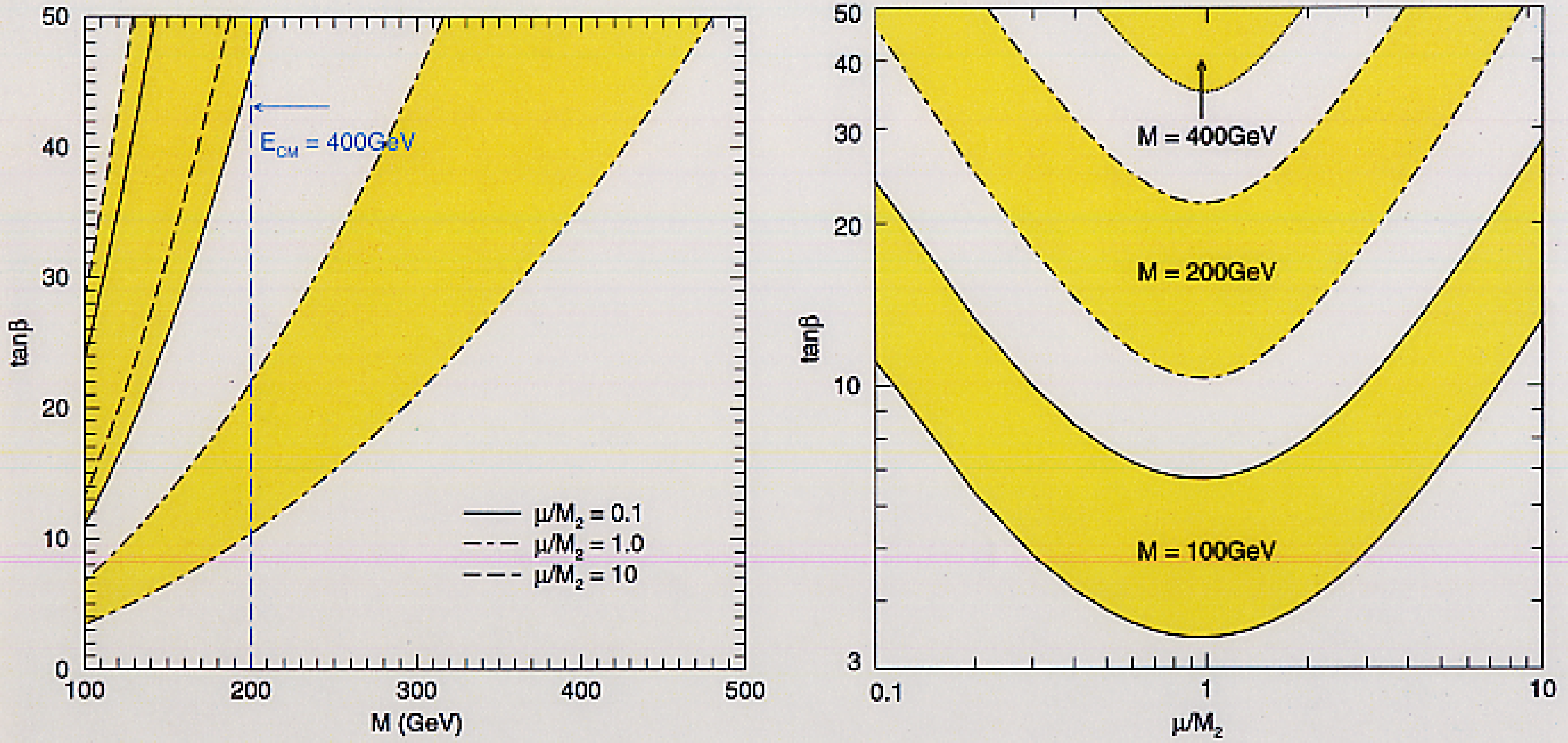
$\mu/M_2 \sim 1$ is favored from the EW precision data

χ^2(SUSY) $<$ χ^2(SM)


χ^2_{tot}
25
24
23
0.1
1
10
μ/M_2
$m_{\tilde{\ell}_L} = 150\mathrm{GeV}$
$m_{\tilde{\ell}_L} = 350\mathrm{GeV}$
$m_{\tilde{\ell}_L} = 1\mathrm{TeV}$
$m_{\tilde{\ell}_L} = 300\mathrm{GeV}$
$\tan\beta = 3$
$\tan\beta = 50$



Allowed region [2] from μ g-2



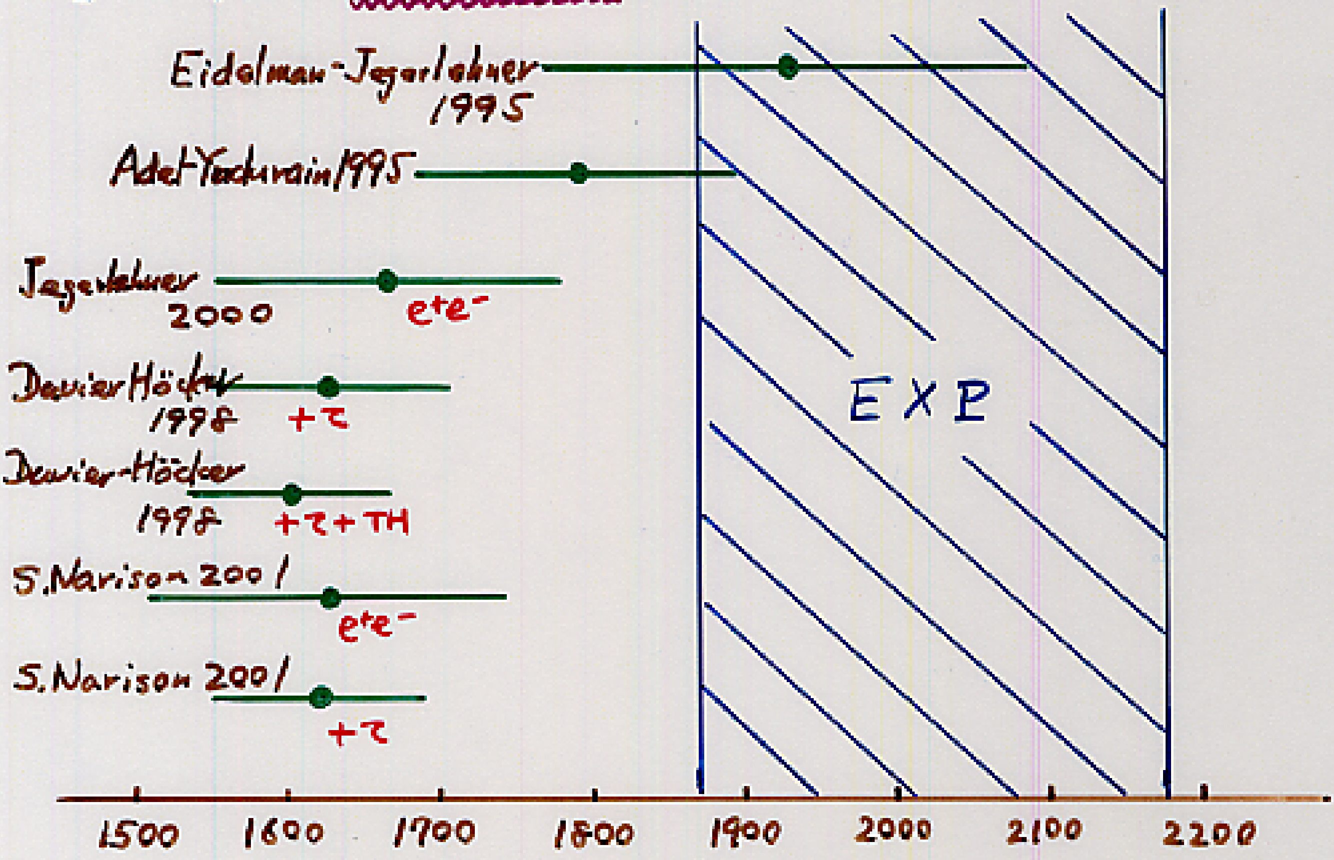
case for $m_{\tilde{\chi}_1^-} = m_{\tilde{\mu}_L} = m_{\tilde{\mu}_R}$

GCCho + KH, hep-ph/0105037
PLB

$(g-2)_\mu$

BNL: E821; H.N. Brown et al, hep-ex/0102017

$$\frac{g-2}{2} = (116\,592\,\underset{\sim\sim\sim\sim\sim\sim\sim\sim}{023 \pm 151}) \times 10^{-11}$$



- Recent theoretical estimates are consistent.
- Use of τ-decays in I=1 channel + $\underset{\sim\sim\sim}{\text{CVC}}$ reduces error.

error ? → Babar BELLE physics

- E821 error may be reduced to half soon ...

Evidence or hint of New Physics ?

$$\delta a_\mu [\text{EXP} - \text{SM}] \approx 400 \pm 150$$

$$\times 10^{-11}$$

精密データの保存

LEP Electroweak Working Group

http://lepewwg.web.cern.ch/LEPEWWG/.

LEPの4実験グループが共同作業により、個々の実験データを総合し、模型依存性を最小限に留める形で公表し、保存した。

⇓

- 外の研究者が独自の解析を行える。
- 新しい理論による解析ができる。
- 新現象との整合性が将来にわたって検証できる。

LEPの精密測定と新しい物理

2001. 11. 5
LEPシンポジウム@東大
KEK 萩原薫

- $N_\nu = 3$ ⇒ 3世代のクォーク・レプトン ⇒フレーバーの物理
  ⇒ 宇宙論と素粒子論 ⇒ダークマター
  ダークエナジー
  物質宇宙の起源
- 弱い相互作用のゲージ理論を検証
  - 輻射補正 ⇒ $m_t = 150 \sim 200$ GeV ⇒ 一致！
  ⇒ ヒッグスボソンは2重項 ⇒素粒子模型
  ⇒ $113\ \text{GeV} \lesssim m_{H_{SM}} \lesssim 200\ \text{GeV}$ ⇒新しい物理を示唆
  制限
  ⇒「ゲージ対称性を自発的に破る機構の解明」が素粒子実験の最大の課題となる。⇒LHC, LC
  - $WW\gamma / WWZ$ 結合の検証 ⇒「新しい物理」探索のモデル
- 大統一理論・超対称性のヒント
  - $\alpha_1(\mu) = \alpha_2(\mu) = \alpha_3(\mu)$ at $\mu \sim 10^{16}$ GeV
  IF $m_{SUSY} \lesssim 1$ TeV
  - $m_H \lesssim 200$ GeV はSUSY-GUTの予言と合う
  - $m_t \sim 175$ GeV は「輻射補正による対称性の破れ」のアイデアと合う
  - $m_{SUSY} < 1$ TeV のシグナル？ ⇒$(g-2)_\mu$ ？
- 精密データを使い易い形で保存
  - 今後何10年も「新しい物理のテスト」の場であり続けるだろう。