Beyond the Standard Model

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EPS/HEP, Finnland, July 1999

- Introduction
  - Standard Model → the Higgs boson

    ↓ what we can learn from/about it?

- Supersymmetry
  - The MSSM Higgs sector: some peculiarities
  - complementarity of LEP, Tevatron & LHC in detecting the Higgs associated to electroweak symm.
  - Unification of couplings → 1st. exp. hint of SUSY?
  - SUSY → different scenarios ⇒ different signals

- Neutrino Oscillations → the first experimental evidence for physics BSM
  - Atmospheric & solar neutrinos

    ↳ ν mass matrix structure
  - Unification of couplings with $m_\nu \neq 0$ & mixing.

- Extra Dimensions
  - how to "see" E.D. in our 4d-world
  - gravity in E.D. → experimental signatures
  - Matter in E.D. (not so large E.D.)

Standard Model

gauge theory based on $G = SU(3)_c \times SU(2)_L \times U(1)_Y$

successful description of electroweak & strong int.

$\equiv$ effective theory valid up to scale

$$\Lambda_{eff} \lesssim M_{pl} \simeq 10^{19}\,\text{GeV}$$

where gravity becomes relevant

• presicion measurements:

confirm SM predictions to the level of radiative correct

but, mechanism of electroweak symmetry

remains unknown

in the SM $\longrightarrow$ origin of masses $\Leftrightarrow$ Higgs Boson

missing ingredient!

At present, experiments say little about

the Higgs $\longrightarrow$ loop corr領ec. to EW obs. dep. only on $\log(m_H$

Still, some information available

LEPEWWG '99

$m_H = 92^{+78}_{-45}$ GeV, $m_H \lesssim 245$ GeV @ 95% C.L

$\longrightarrow$ indirect data prefers a rather light Higgs

Before going BSM, although we know little about the Higgs in the SM, we can use it to have some hints on Λ_{eff}:

$$V(\phi) = -m^2 \phi^+\phi + \lambda(\phi)/_2 (\phi^+\phi)^2 \Longrightarrow \quad m_H^2 = 2\lambda v^2$$

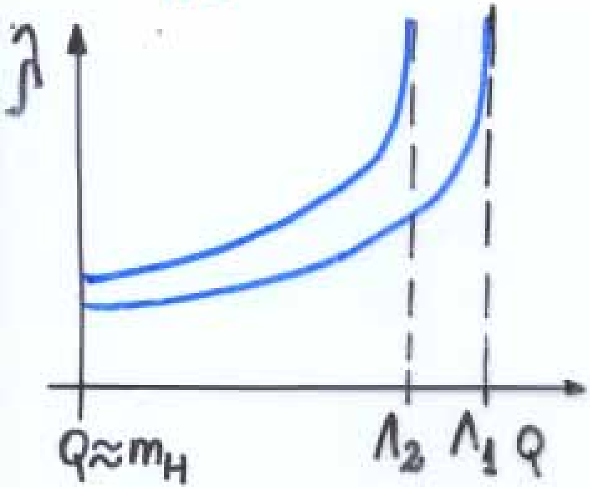
free param. but,

$v \equiv \langle\phi\rangle = 174$ GeV

$$d\lambda/_{\ln(Q^2/\Lambda^2)} = \frac{6}{16\pi^2}\Big(\underbrace{\lambda^2 + \lambda h_t^2}_{} - h_t^4\Big) + \text{elw. correc.}$$

not asymptotically free for sufficiently large Q^2

λ becomes too large strongly interact ($\simeq$ Landau pole)



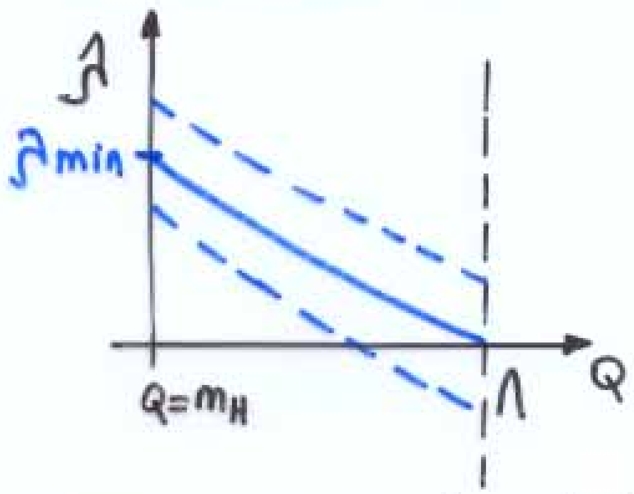
from requiring perturb. validity of the model up to scale Λ (or M_{Pl})

$$\lambda^{MAX}(\Lambda)/_{4\pi} \simeq 1$$

$$m_H^{MAX} = \sqrt{2\lambda^{MAX}}\, v$$

the part of β_λ indep of λ can drive $\lambda(Q)$ to negative values

destabilizing the electroweak minimum



$\lambda(Q) = 0$ for $Q = \Lambda$ determ $\lambda^{min}(Q = m_H)$

(stability assured)

and

$$m_H^{min} = \sqrt{2\lambda^{min}}\, v$$

strong M_t dep.

SM Higgs Boson:

Upper, Perturbative Bound and lower, Stability Bounds as a fc of the scale where new physics must appear

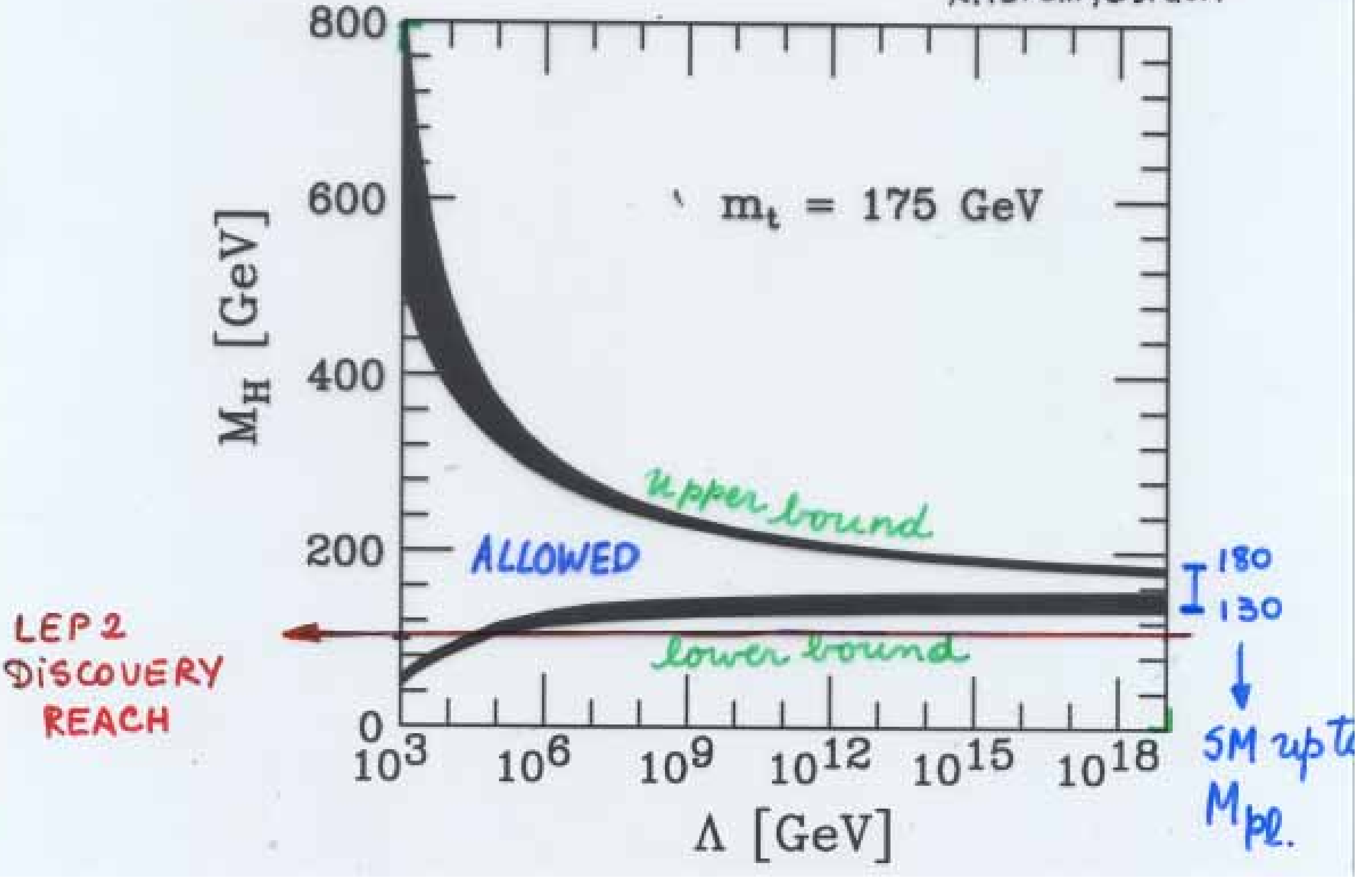
- If Higgs found at LEP: great!

$\Longrightarrow$ new physics most probably around the corner

- if $m_H \lesssim 130$ GeV

$\Longrightarrow$ new physics BSM should probably appear at $\Lambda \simeq 10^4 - 10^9$ GeV

Quiros (+Casas, Espino
Riesselmann (+Hambye)
Altarelli, Isidori



Three Higgs mass ranges of particular interest after LEP

i) $105\ \text{GeV} \lesssim m_H \lesssim 130\ \text{GeV}$

- above the LEP reach
- in the expected range of low energy SUSY
- demands $\Lambda_{eff} < M_{pl}$ $(\Lambda_{eff} \simeq 10^4 - 10^9\ \text{GeV})$

ii) $130\ \text{GeV} \lesssim m_H \lesssim 180\ \text{GeV}$

- consistent with $\Lambda = M_{pl}$ so the SM could be valid all the way up to the energy scale at which gravity enters

iii) $180\ \text{GeV} \lesssim m_H \lesssim 250\ \text{GeV}$

- still consistent with precision electroweak data
- implies $\Lambda_{eff} < M_{pl}$ $(\Lambda_{eff} \simeq 10^6 - 10^{19}\ \text{GeV})$

I & II $\longrightarrow$ good prospects to explore these ranges at the Tevatron if sufficient luminosity & efforts

I, II & III : possible at LHC

Prospects for SM Higgs Searches at the Tevatron

Higgs WG Studies (Fermilab '98-'99) (M. Roco's talk)

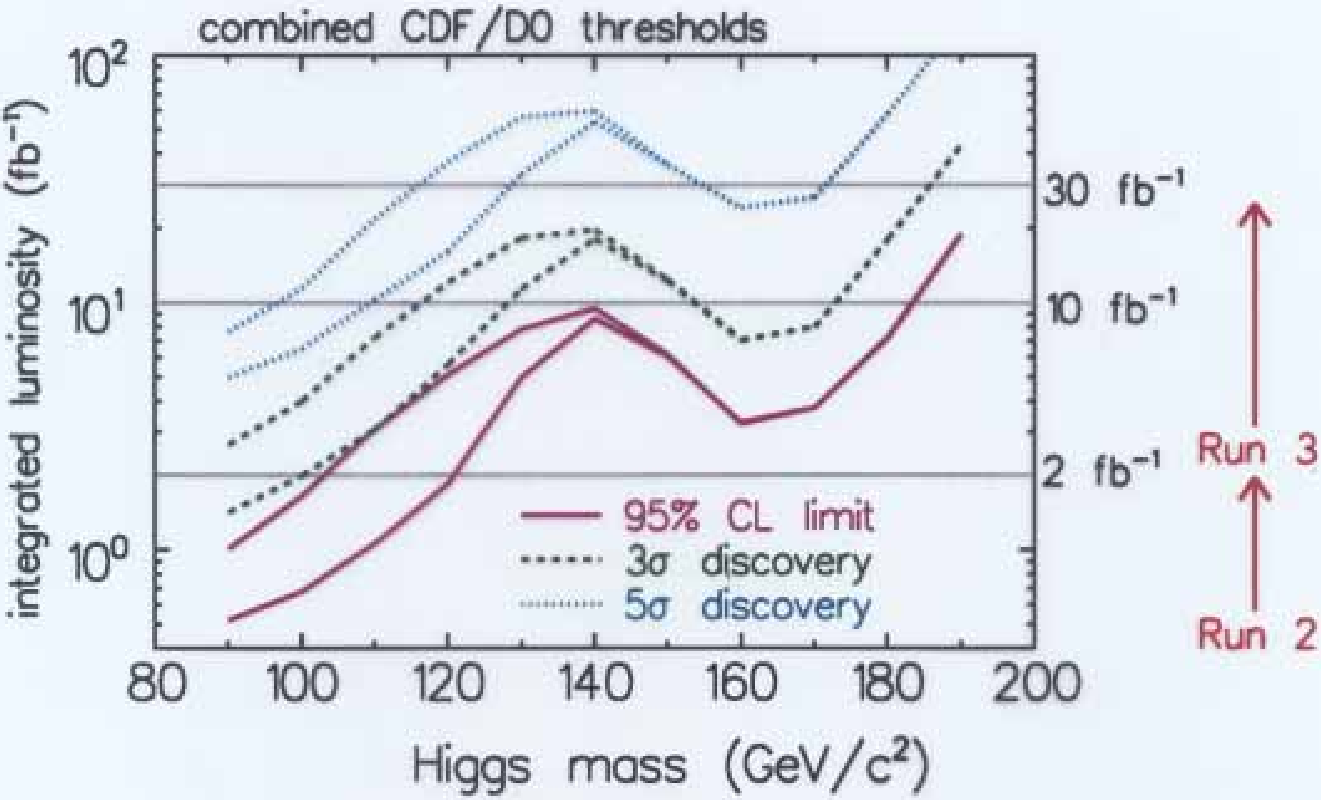
$m_{H_{SM}} \lesssim 130$ GeV $\longrightarrow p\bar{p} \xrightarrow{V^*} VH_{SM} \longrightarrow Vb\bar{b}$

with $V = W^{\pm}, Z \rightarrow$ leptonic decays

$m_{H_{SM}} \gtrsim 130$ GeV $\Longrightarrow$ $p\bar{p} \longrightarrow H_{SM} \longrightarrow WW^*$

$p\bar{p} \longrightarrow VH_{SM} \longrightarrow VWW^*$

Assume: $m_{b\bar{b}}$ resolution: 10%



results depend on optimization of analyses: w/wo NN

comparable to LEP mass reach with $\simeq 2$ fb^{-1} (excl.)

$\simeq 10$ fb^{-1} (discov.)

here probe WWH & ZZH couplings

if $m_{H_{SM}} \lesssim 180$ GeV $\longrightarrow$ excl. with 10 fb^{-1}, 3σ disc. w/ 20 fb^{-1}

And 30 fb^{-1} $\Rightarrow$ 5σ disc. if $m_H \lesssim 115$-130 GeV

Beyond the Standard Model

• Precision measurements suggests (but does not demand) that any new physics lead to

- small corrections to precision electroweak observables
- be consistent with a light Higgs

  ⟨if $m_H \lesssim 130$ GeV → expects new physics at relatively low scales⟩

- does not lead to large contributions to FCNC

• Moreover, we would like to have a theory that

- leads to Unification of couplings (→ Unified theory)
- incorporates gravity
- leads to a technical solution to the hierarchy problem (why $M_{Pl} \gg M_W$)

  ⟨even if does not explain hierarchy, at least leads to stability under rad. corrections⟩

<u>SUPERSYMMETRY</u> → fulfills all these properties if $\Lambda^{SM}_{eff} \simeq 1$ TeV

↓

Symm. relating bosons & fermions

each SM particle → SUSY partner with opposite statistics

+ extended Higgs sector

The Higgs Sector in the MSSM

2 CP-even Higgs $\longrightarrow$ h, H

1 CP-odd Higgs $\longrightarrow$ A

1 charged Higgs $\longrightarrow$ $H^{\pm}$

mixing angle α

$\tan\beta \equiv v_2/v_1$

Tree level masses:

$$m_A^2 = m_1^2 + m_2^2$$

$$m_{H^\pm}^2 = m_A^2 + M_W^2$$

$$m_{h,H}^2 = \frac{1}{2}\left[m_A^2 + M_Z^2 \pm \sqrt{(m_A^2 + M_Z^2)^2 - 4 M_Z^2 m_A^2 \cos 2\beta} \right]$$

if $m_A^2 \gg M_Z^2 \longrightarrow m_h = M_Z |\cos 2\beta| \Longrightarrow m_h^{MAX.} = M_Z$

After radiative corrections

dominated by top & stop effects

<also sbottoms if large $\tan\beta$>

$$\underline{m_h \lesssim 130 \text{ GeV}}$$

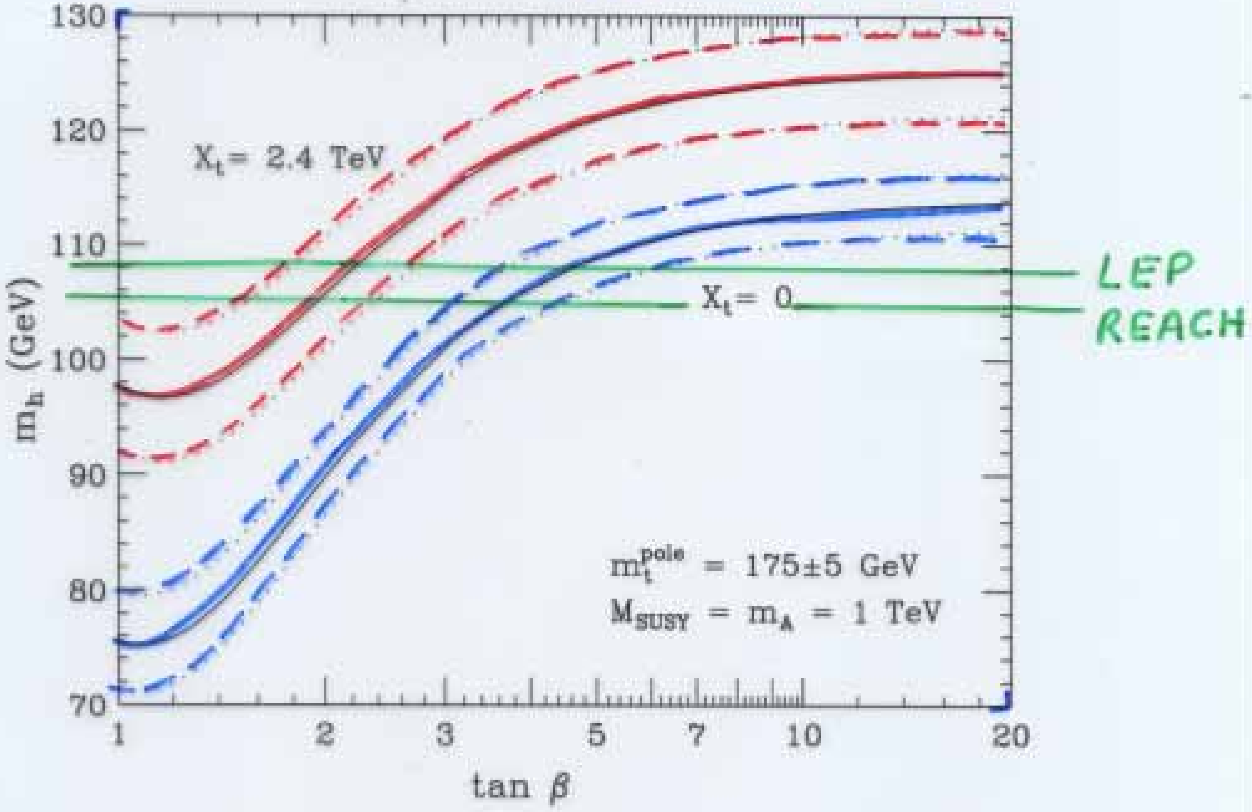
- large m_A limit
- $M_t = 175$ GeV
- MAXIMAL EFFECT of stop L-R mixing A_t, μ
- $M_{SUSY} \simeq 1$ TeV (m_Q, m_U)

Upper bound on m_h as a function of $\tan\beta$

for $M_t = 175 \pm 5$ GeV & max. or min. mixing effect from stop sector

Haber, Hempfling, Hoang
M.C., Quiros, Wagner (+Espinosa)

$X_t \equiv A_t - \mu/\tan\beta$
($\overline{MS}$ scheme)



- low $\tan\beta$ region ($\lesssim 2$) $\longrightarrow$ tested at LEP final run ($M_t \simeq 175$ GeV)
- if $M_{SUSY} \longrightarrow 2$ TeV $\quad m_h \longrightarrow \simeq +(3-4)$ GeV

Weiglein's talk

new two-loop diag. calc. Heinemeyer, Hollik, Weiglein

$\Rightarrow$ net finite two loop effects $m_h \longrightarrow +(3-4)$ GeV
dep on $\tan\beta$

1

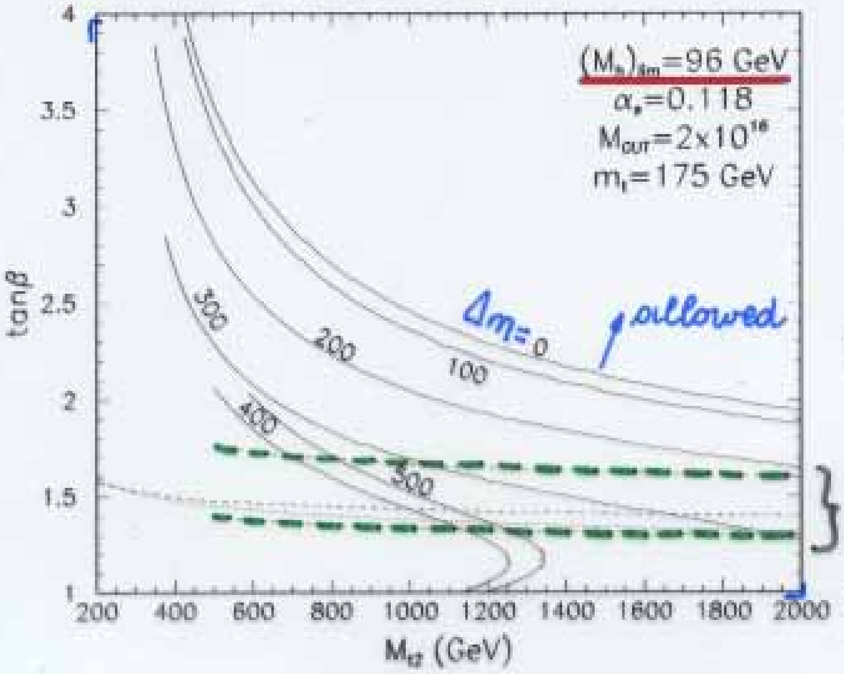
but also scheme dependent effects:
- leading log matching
- higher order uncertainties

M.C., Haber, Heinemeyer
Hollik, Weiglein, Wagner

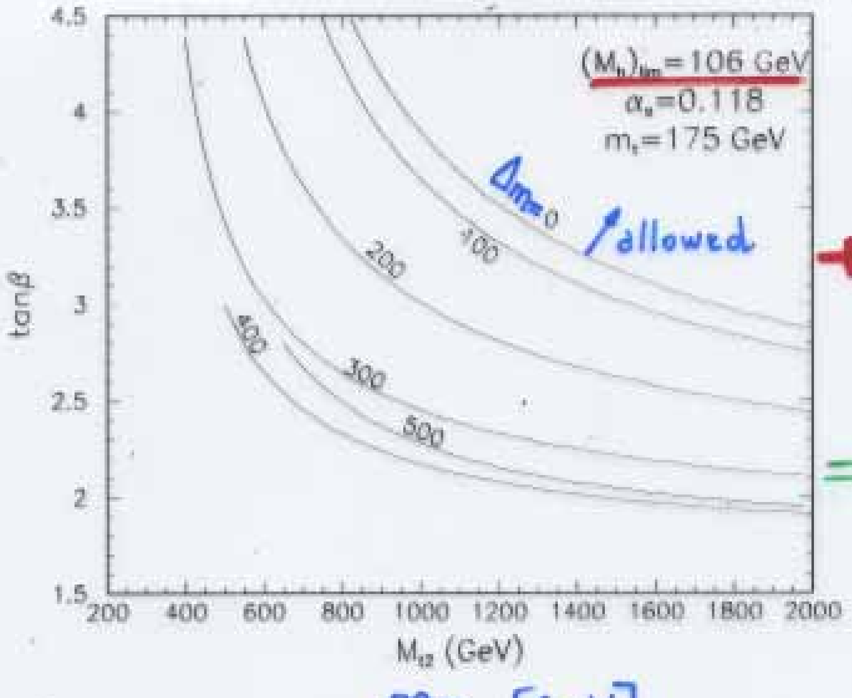
Lower bounds on $\tan\beta$ for near future (LEP)

lower bounds on SM-like Higgs $m_H = 98, 108$ GeV or its measurement, as a fc. of stop mass $m_{\tilde{t}_2}$ and for $\Delta m = m_{\tilde{t}_2} - m_{\tilde{t}_1} = 0 - 500$ GeV and

scanning over stop mix. $\sin 2\theta_{\tilde{t}} \downarrow (\sin 2\theta_{\tilde{t}})^{MAX}$



also top Yukawa coupling perturb. bound.



$\tan\beta$

$m_{\tilde{t}_2}$ [GeV]

QIR f. p. sol not allowed

$\Longrightarrow$ after LEP $\tan\beta \lesssim 2$ probed for any value of stop sector param (if $M_t \lesssim 175$ GeV)

M.C., Chankowski, Pokorski, Wagner '98

Figure 3: The same as Fig. 1, but for lower bounds on the Higgs boson mass of 96 GeV and 106 GeV.

$\Delta m = m_{\tilde{t}_2} - m_{\tilde{t}_1}$

$$\sin 2\theta_{\tilde{t}} = \frac{2 m_t (A_t - \mu/\tan\beta)}{m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2}$$

Neutral Higgs Boson Couplings to Fermions and Gauge Bosons

$$g_{hVV} = g_V\, m_V \sin(\beta-\alpha) \qquad\qquad V = W, Z$$

$$g_{HVV} = g_V\, m_V \cos(\beta-\alpha) \qquad\qquad g_V = \begin{cases} g & (V=W) \\ g/\cos\theta_W & (V=Z) \end{cases}$$

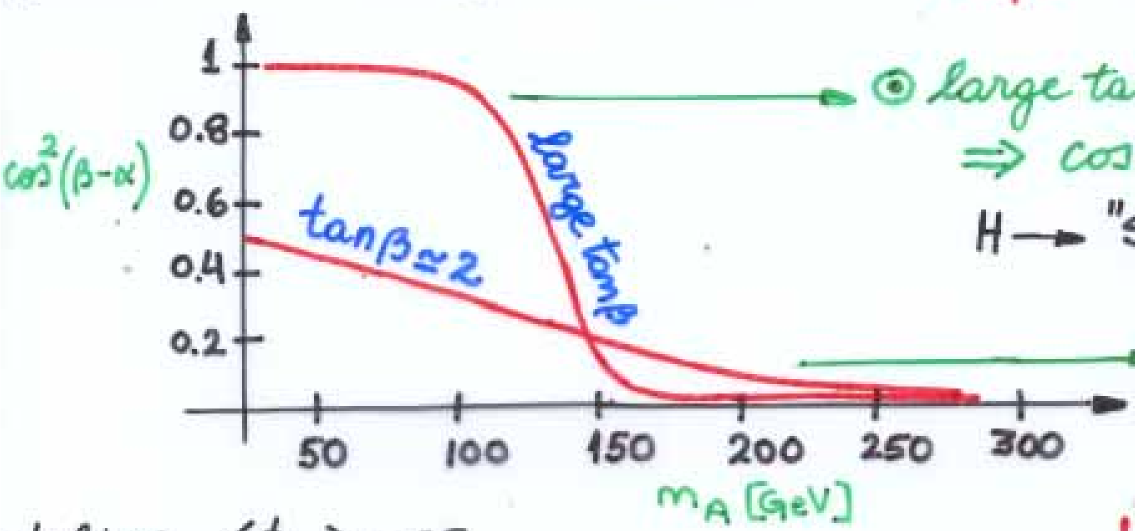
$$g_{hAZ} = \frac{g\,\cos(\beta-\alpha)}{2\cos\theta_W}$$

$$g_{HAZ} = \frac{-g\,\sin(\beta-\alpha)}{2\cos\theta_W}$$

(enhanced for large $\tan\beta$)

$$g_{ht\bar t} \propto \cos\alpha/\sin\beta \qquad g_{hb\bar b} \propto -\sin\alpha/\cos\beta \qquad g_{Ab\bar b} \propto \tan\beta$$

$$g_{Ht\bar t} \propto \sin\alpha/\sin\beta \qquad g_{Hb\bar b} \propto \cos\alpha/\cos\beta \qquad g_{At\bar t} \propto \cot\beta$$



⊙ large $\tan\beta$, low m_A
$\Rightarrow \cos(\beta-\alpha) \to 1$
$H \to$ "SM-like"

⊙ large m_A
$\sin(\beta-\alpha) \to 1$
$h \to$ SM-like
DECOUPLING LIMIT

define $\langle\phi_W\rangle = v$

$$\phi_W = h \sin(\beta-\alpha) + H\cos(\beta-\alpha)$$

couples to W, Z in SM way $\Longrightarrow$ EW ~~sym~~ symm.

Also $m_H^2 \cos^2(\beta-\alpha) + m_h^2 \sin^2(\beta-\alpha) = m_h^{2\,MAX} \lesssim 130$ GeV

$\Longrightarrow$ for large $\tan\beta$ always one CP-even Higgs with SM-like coupl. to W, Z and mass $\lesssim 130$ GeV

MSSM Higgs Search at LEP

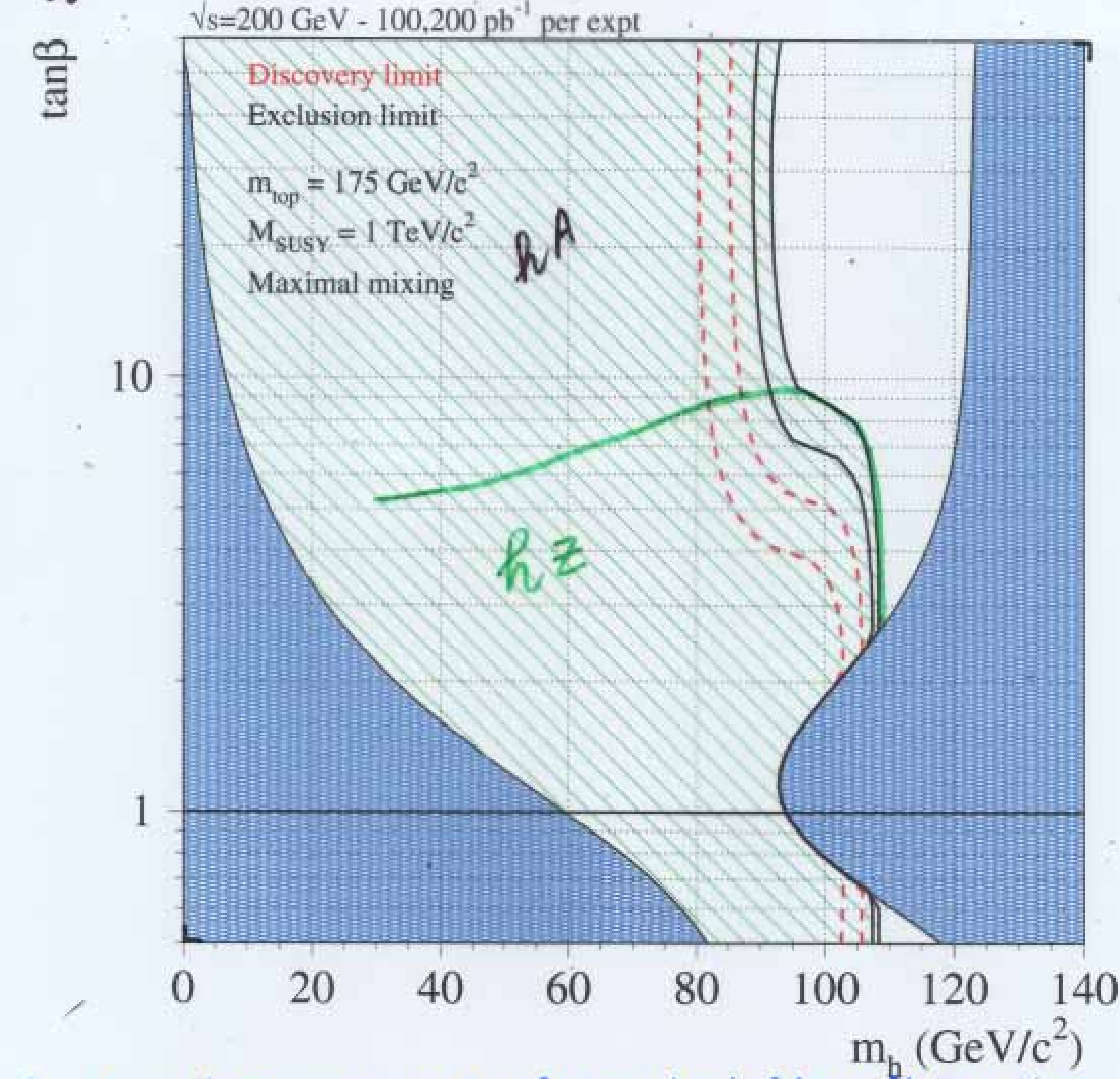
1) $e^+e^- \longrightarrow Z\underset{\downarrow}{h}$ $\quad \sigma(e^+e^- \to Zh) = \sin^2(\beta-\alpha)\, \sigma(e^+e^- \to ZH_{SM})$

$b\bar{b}/\tau^+\tau^-$ good channel @ large m_A
low $\tan\beta$ + low m_A

2) $e^+e^- \longrightarrow \underset{\downarrow}{h}A$ $\quad \sigma(e^+e^- \to hA) \propto \cos^2(\beta-\alpha)\, \sigma(e^+e^- \to ZH_{SM})$

$b\bar{b}b\bar{b}/\tau^+\tau^-b\bar{b}$ good channel @ large $\tan\beta$, low m_A

Complementary channels, but only (1) searches for ϕ_W Higgs with SM-like couplings to vector bosons



Benchmark → in general, the most difficult region

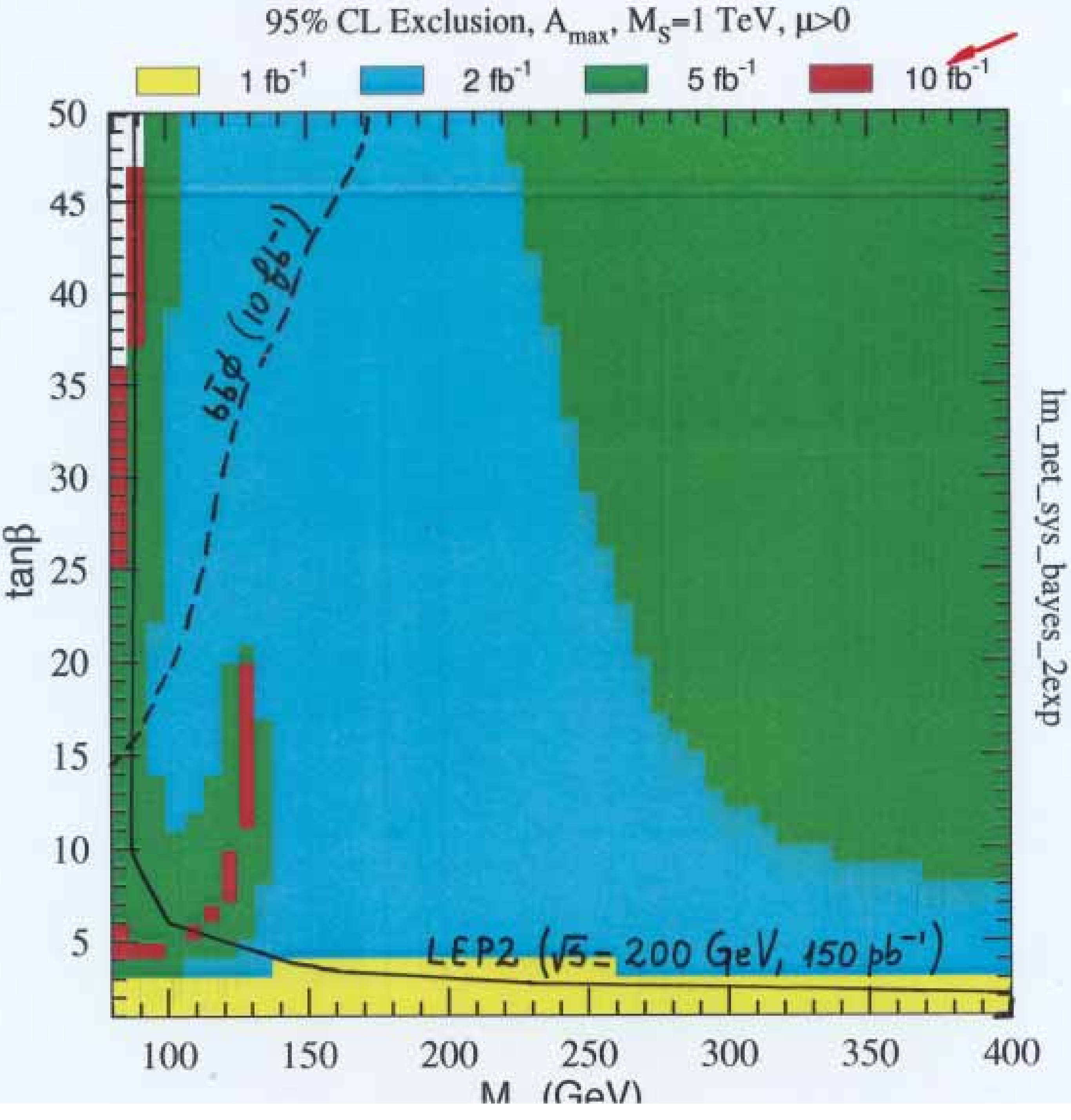
MSSM Higgs Searches at the Tevatron RUN II

$p\bar{p} \longrightarrow V\phi_W \longrightarrow V b\bar{b}$ $\quad V = W, Z \quad \phi_W = h, H$

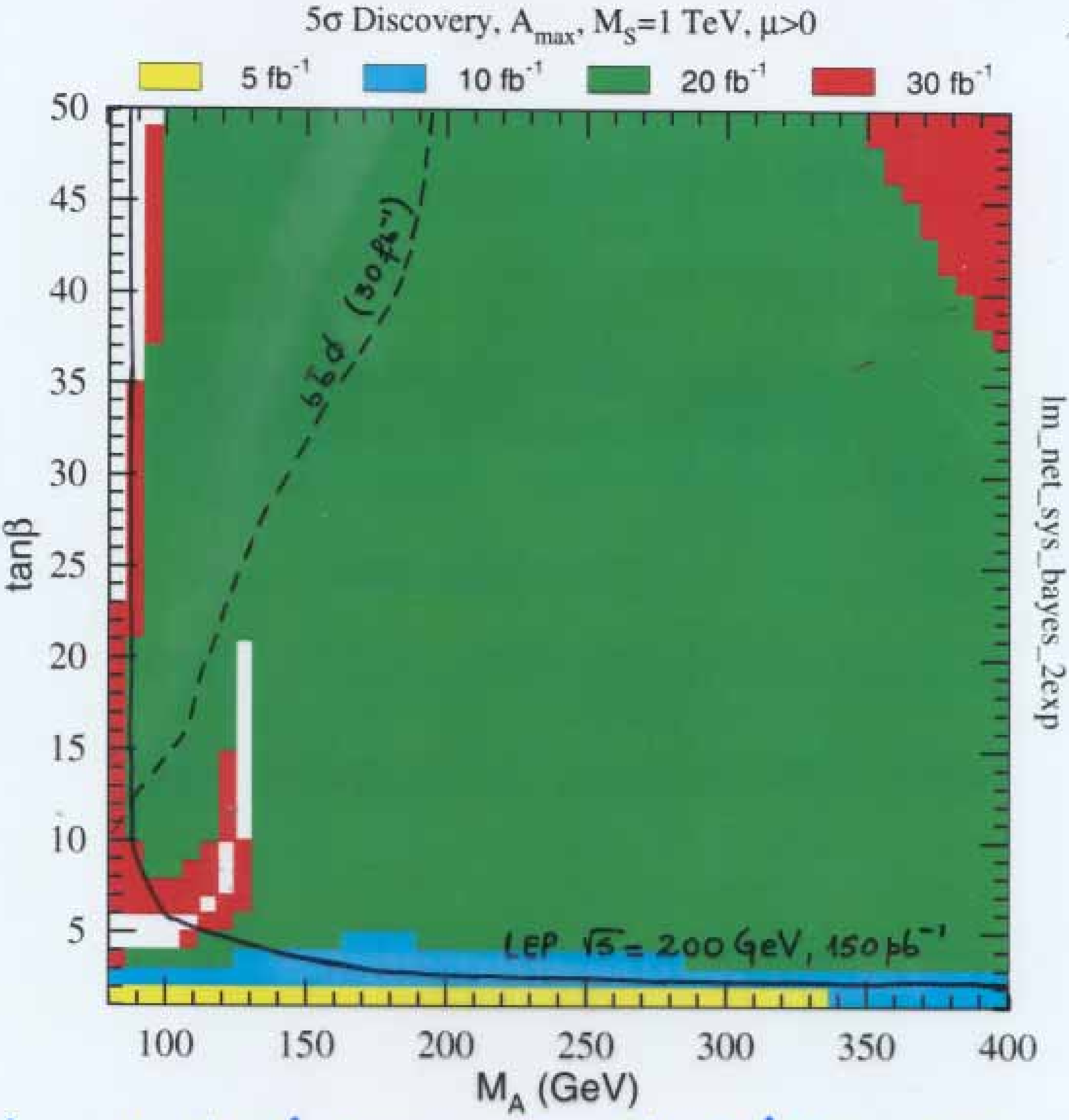
$$\left.\begin{aligned} \sigma(p\bar{p} \longrightarrow Vh) &= \sin^2(\beta-\alpha)\,\sigma_{SM} \\ \sigma(p\bar{p} \longrightarrow VH) &= \cos^2(\beta-\alpha)\,\sigma_{SM} \end{aligned}\right\} \Rightarrow \text{complementary}$$

and for large $\tan\beta$ → always one CP-even Higgs with SM-like couplings to vector bosons & mass $\lesssim 130$ GeV

- also $p\bar{p} \rightarrow b\bar{b}\phi \longrightarrow b\bar{b}b\bar{b}$ (ϕ non SM-like, $\tan\beta$ enh.)



$m_A - \tan\beta$ plane $\rightarrow$ 5σ Discovery Coverage at the Tevatron: $p\bar{p} \rightarrow V\phi_w \rightarrow Vb\bar{b}$



large part of parameter space for max. mixing: $\Rightarrow 5\sigma$ disc. with $20\,fb^{-1}$

$\left(\tilde{A}_t = \sqrt{6}\, M_S \;\&\; M_S = \mu = 1\,\text{TeV}\right)$

window for $m_A \simeq m_h|_{m_A \gg M_Z}$ ($\simeq 125$ GeV) & $\tan\beta = 5$-2

$\Rightarrow \cos^2(\beta-\alpha) \simeq \sin^2(\beta-\alpha) \simeq 0.5$ (if $\tan\beta \gtrsim 20 \Rightarrow m_h \simeq m_H$ comb

Peculiar regions of SUSY param. space
$\Rightarrow$ difficult coverage with golden/standard channels at different colliders.

- Suppression of Yukawa couplings

recall $g_{hb\bar{b}} \propto -\sin\alpha/\cos\beta$ $\quad g_{Hbb} \propto \cos\alpha/\cos\beta$

and $\sin\alpha\cos\alpha \propto M_{12}^2 \longrightarrow$ off diag. element of CP even Higgs mass matrix

If
$$M_{12}^2 \simeq -\left[m_A^2 + M_Z^2 - \frac{h_t^4 v^2}{8\pi^2 M_S^2}\left(3\mu^2 - \mu^2 A_t^2/M_S^2\right)\right]\sin\beta\cos\beta$$
$$+\left[\frac{h_t^4 v^2}{16\pi^2}\sin^2\beta\,\frac{\mu X_t}{M_S^2}\left\{\frac{A_t X_t}{M_S^2}-6\right\}+\frac{3h_t^2 M_Z^2}{32\pi^2}\frac{\mu X_t}{M_S^2}\right]\left(1+\lg\frac{M_S^2}{m_t^2}\cdot\frac{(4.5h_t^2-8g_3^2)}{16\pi^2}\right)$$
$\longrightarrow 0$

M.C., Mrenna, Wagner '98
$\langle X_t = A_t - \mu/\tan\beta \rangle$

$\Longrightarrow \sin\alpha = 0$ or $\cos\alpha = 0$ $\quad$ $\langle$dep. on M_{11}, M_{22} element

in each case

$g_{hb\bar{b}}$ or $g_{Hb\bar{b}}$, the one with SM-like couplings to $W, Z \longrightarrow 0$ & important consequences for Higgs searches

h or $H \longrightarrow b\bar{b}$ & $\tau^+\tau^-$ are diminished and

$\phi \longrightarrow gg,\ c\bar{c},\ \gamma\gamma,\ WW$ are enhanced over SM expectations

Baer, Wells, Loinaz
M.C., Mrenna, Wagner

$\langle$effect dep. on sign of μX_t & value of $|A_t|\rangle$

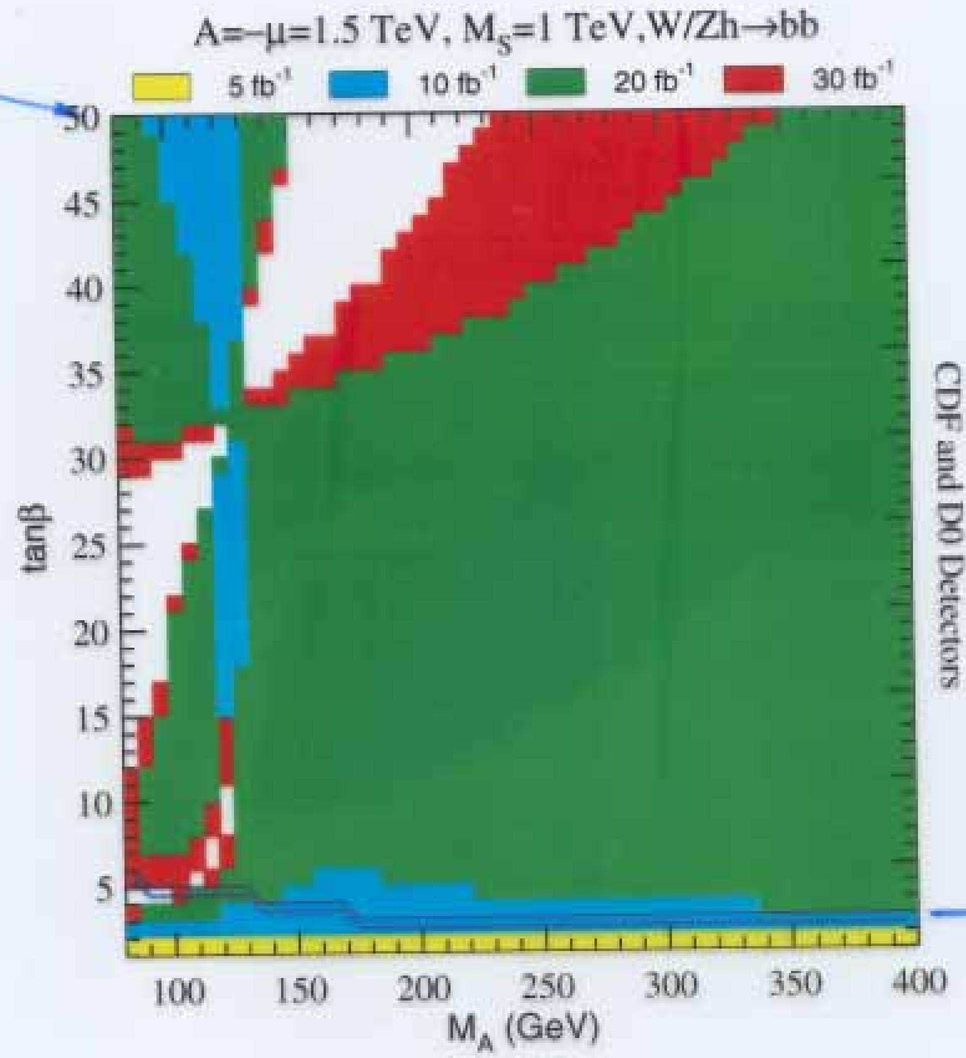
Important holes in the $\tan\beta - m_A$ plane coverage due to suppression of

h or $H \longrightarrow b\bar{b}$

M.C., Mrenna, Wagner.

Tevatron

$\sqrt{s} = 2$ TeV



LEP

but, this implies enhancement in

$BR(\phi \rightarrow \gamma\gamma)$ (also into $gg, c\bar{c}, WW$)

$\downarrow$ easier region for LHC

Complementarity of the Tevatron & LHC

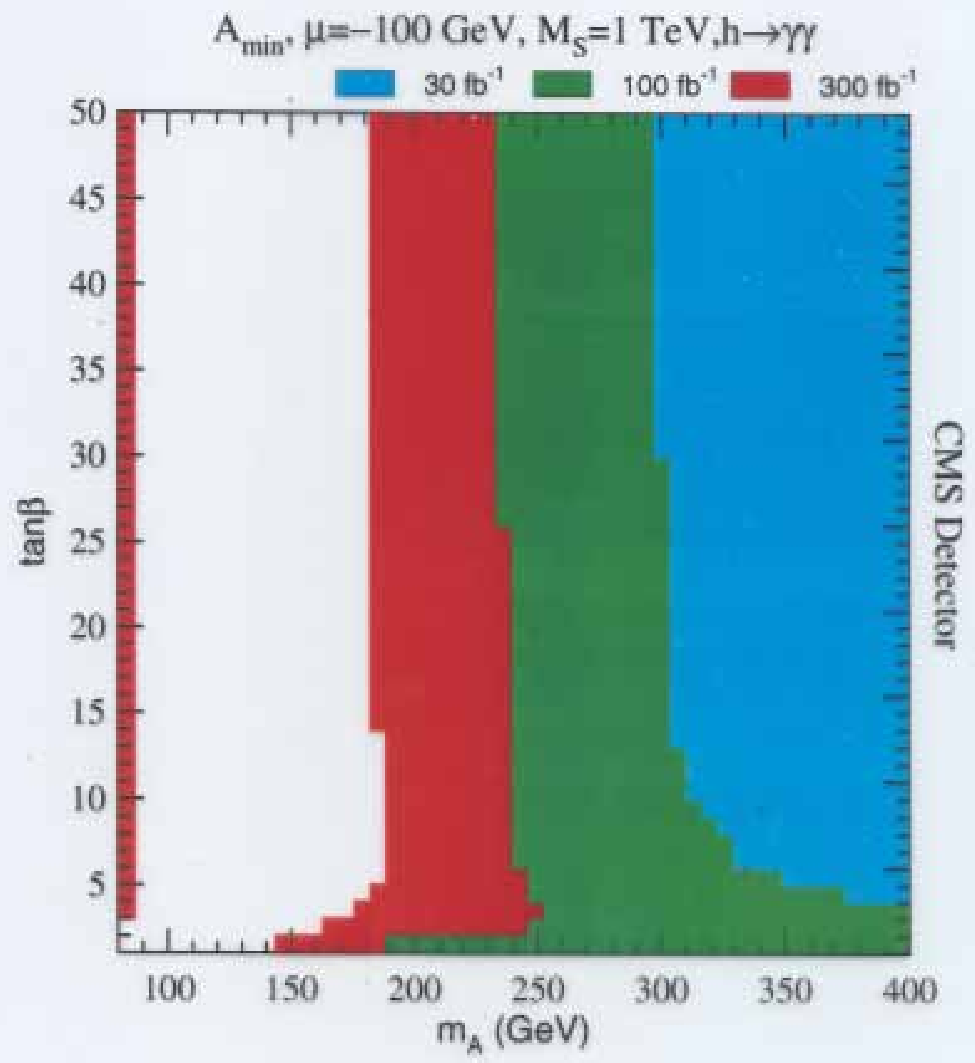
to search for the neutral CP-even Higgs responsable for electroweak symmetry breaking

M.C, Mrenna, Wagner

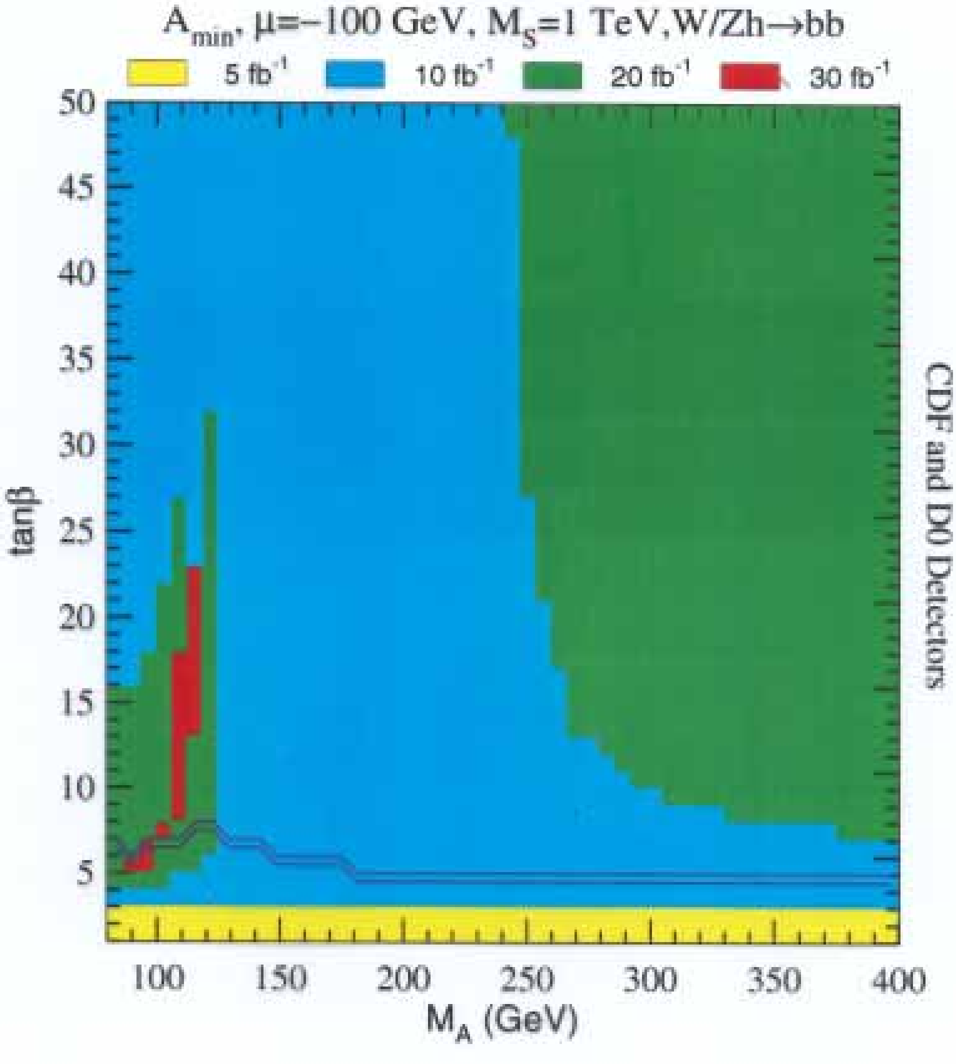
Tevatron : $V\phi \to Vb\bar{b}$ $(V = W, Z)$

LHC: $gg \to \phi \to \gamma\gamma + W\phi \to W\gamma\gamma + t\bar{t}\phi \to t\bar{t}\gamma\gamma$

i) $M_S = 1\,\text{TeV}$, $A_t = 0$, $\mu = -100\,\text{GeV}$ $M_t = 175\,\text{GeV}$



• for low m_A $g_{hb\bar{b}}$ enhanced $\Rightarrow BR(\phi \to \gamma\gamma)$ suppressed



A$_{min}$, μ=−100 GeV, M$_S$=1 TeV,W/Zh→bb
5 fb^{-1}
10 fb^{-1}
20 fb^{-1}
30 fb^{-1}
tanβ
M$_A$ (GeV)
CDF and D0 Detectors

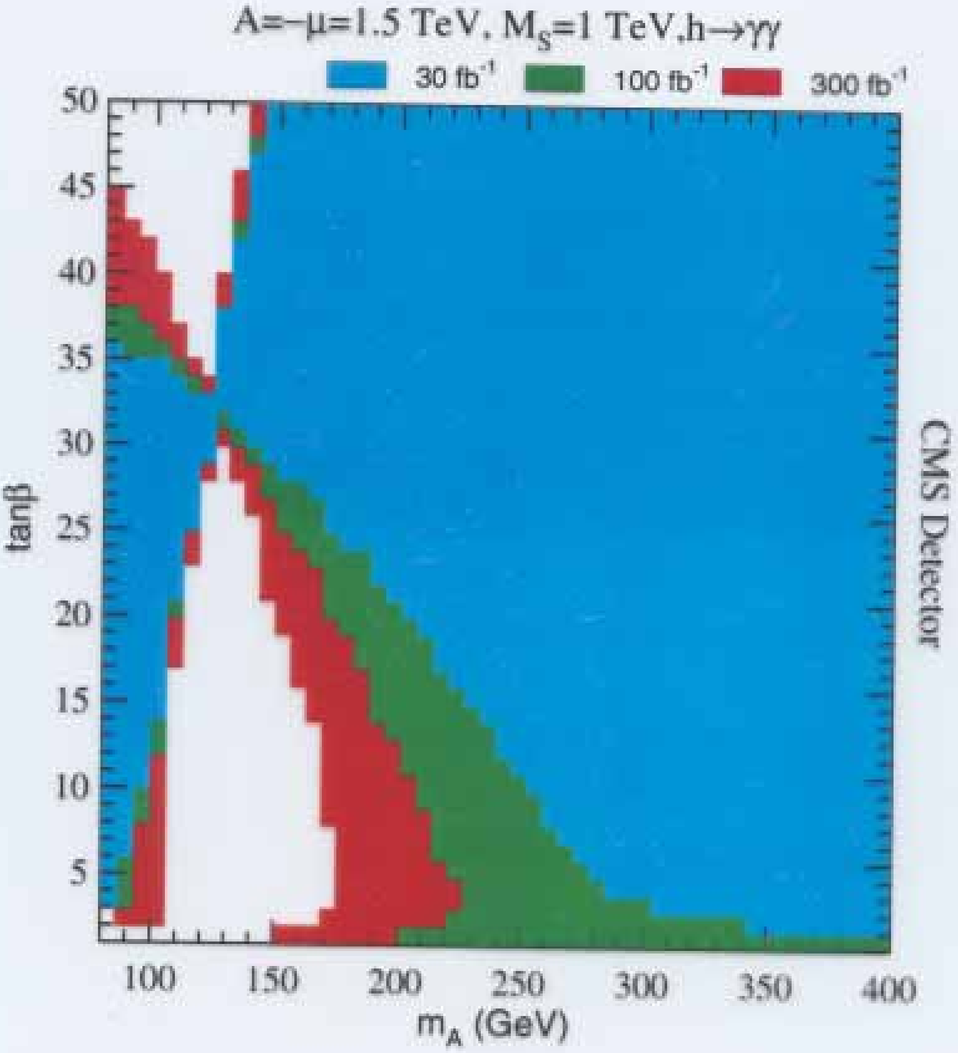
Complementarity between the Tevatron and LHC

case of suppressed $BR(\phi \to b\bar{b})$

$\Rightarrow$ enhancement in $BR(\phi \to \gamma\gamma)$

ii) $A_t = -\mu = 1.5$ TeV $\qquad M_S = 1$ TeV

M.C, Mrenna, Wagner



• Strong Modification of Higgs couplings to b quarks at large $\tan\beta$

$$\mathcal{L} = h_b H_1^0 b\bar{b} + \Delta h_b H_2^0 b\bar{b}$$

talk of Mahanthappa

SUSY effect $\neq 0$ even if heavy SUSY spectrum.

rad. corrections: modify relation between m_b measured and h_b

$$\Longrightarrow g_{Ab\bar{b}} \simeq h_b \sin\beta = \frac{m_b}{(1+\Delta_b) v} \tan\beta$$

$$\Delta_b = \frac{\Delta h_b}{h_b} \tan\beta$$

$$g_{hb\bar{b}} = \frac{-m_b \sin\alpha}{v \cos\beta}\left(1 + \frac{\Delta_b}{1+\Delta_b}\left(1 + \frac{1}{\tan\alpha \tan\beta}\right)\right)$$

$$g_{Hb\bar{b}} = \frac{m_b \cos\alpha}{v \cos\beta}\left(1 - \frac{\Delta_b}{1+\Delta_b}\left(1 - \tan\alpha/\tan\beta\right)\right)$$

M.C., Mrenna Wagner
Haber, Logan, Herrero

where

$$\Delta_b \propto \left[M_{\tilde{g}}\mu \frac{2\alpha_s}{3\pi} I(m^2_{\tilde{b}_i}, M^2_{\tilde{g}}) + A_t \mu \frac{h_t^4}{16\pi^2} I(m^2_{\tilde{t}_i}, \mu^2) \right] \tan\beta$$

Hall, Rattazzi, Sarid/Hempfling
M.C., Olechowski, Pokorski, Wagner
Bagger, Pierce, Matchev

large $m_A \Rightarrow g_{hbb} \equiv h_b^{SM} = m_b/v$ $\qquad v = 174$ GeV

$$g_{Ab\bar{b}} = g_{Hb\bar{b}} \sim h_b \sin\beta = \frac{m_b}{1+\Delta_b} \frac{\tan\beta}{v}$$

low $m_A \Longrightarrow h \longleftrightarrow H$

Always 2 Higgs bosons with enhanced $\tan\beta$ couplings & Δ_b effects! • important in $\phi b\bar{b}$ prod

• Effects of $\cancel{CP}$ in the MSSM Higgs sector

- soft SUSY parameter may be complex
  A_t, μ, $M_{1/2}$, μB
- $\cancel{CP}$ possible after radiative corrections
- main effect of $\cancel{CP}$ phases $\Rightarrow$ mixing between 3 neutral states

$$A,\ H_1^\circ,\ H_2^\circ \xrightarrow{CP} A,\ h,\ H$$
$$\xrightarrow{\cancel{CP}} H_1,\ H_2,\ H_3$$

Some regions of param. space, with sizeable $\cancel{CP}$ phases, large μ, A_t ($\gtrsim M_{SUSY}$)

$\Rightarrow$ drastic modifications to couplings of neutral Higgs bosons to vector bosons

Present bounds from LEP can be relaxed

EXAMPLE: LEP may be unable to see H_1 as light as 60-70 GeV if $g_{H_1 ZZ} \to 0$ & $g_{H_1 H_2 Z}$ not efficient ($m_{H_1} + m_{H_2}$ too heavy + coupling too weak)

then: direct detection of $g_{H_2 ZZ}$ possible at the edge

Pilaftsis, Wagner
Demir

$\downarrow$

Tevatron with 20-30 fb^{-1} can cover those windows left by LEP

Predictions from Minimal Unification

⟨neglecting GUT/string thresholds⟩

inputs: $1/\alpha_{em}(M_Z)$, $\sin^2\theta_W(M_Z)$, SUSY spectrum

$\rightarrow$ unification at $\alpha_G \simeq 0.04$ $M_{GUT} \simeq 2 \cdot 10^{16}$ GeV

$$\Longrightarrow \alpha_3(M_Z) = 0.127 - 4(\sin^2\theta_W - 0.2315) \pm 0.008$$

SUSY SPECTRUM

Recall:

Experimentally $\longrightarrow$ $\alpha_3(M_Z) \simeq 0.119 \pm 0.006$

Remarkable agreement between theory & experiment !!

Bardeen, M.C., Pokorski, Wagner
Langacker, Polonsky

T_{SUSY} dep. of $\alpha_3(M_Z)$ predictions

M_t [GeV]	$\sin^2\theta_W(M_Z)$	$T_{SUSY} = 1$ TeV	$T_{SUSY} = M_Z$
150	0.2321	0.116	0.125
170	0.2315	0.118	0.127
190	0.2305	0.122	0.131

$\alpha_3(M_Z)$

preferred values: $\alpha_3(M_Z) > 0.116$

Largest uncertainty in $\alpha_3(M_Z)$: from GUT scale physics

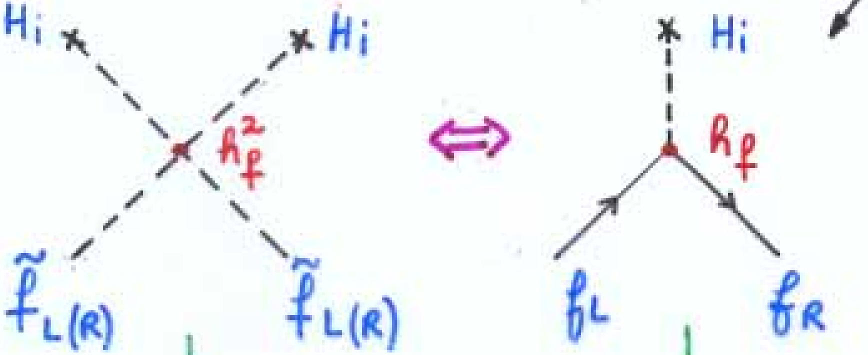
SUSY Breaking

- SUSY must be broken in nature, but ~~SUSY~~ mechanism not well understood yet.

- empirically: add all possible soft ~~SUSY~~ terms
  $\longrightarrow$ which preserve cancellation of quad. divergence

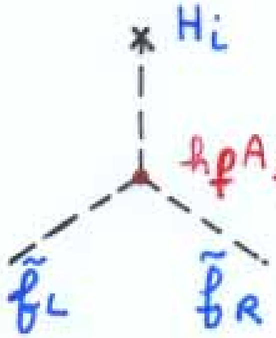
- Scalar masses $m_{\tilde{f}_{\not{SUSY}}} \Longrightarrow m^2_{\tilde{f}} = m^2_f + m^2_{\tilde{f}_{\not{SUSY}}}$

  $\swarrow$ SUSY



$\downarrow$ $m^2_{\tilde{f}} = h_f^2 v^2$ $\qquad$ $\downarrow$ $m_f = h_f v$

- Scalar left-right mixing terms A_f:



- Gaugino mass terms $\quad M_i\,(\lambda_i \lambda_i + \bar{\lambda}_i \bar{\lambda}_i)$

Finite set of soft ~~SUSY~~ param.: $m_{\tilde{f}_{\not{SUSY}}}, A_f, M_i$

$\Rightarrow$ wide range of possible values at high energies
⟨dep. on ~~SUSY~~ mechanism⟩

+ Renormalization Group evolution $\longrightarrow$ determine low energy values

$\Rightarrow$ Define SUSY MASS SPECTRUM

In general, ~~SUSY~~ spontaneously/dynam. in some new (hidden) sector at high energies, where some components of the new sector adquire v.e.v.

$\langle F \rangle \longrightarrow$ dim. m^2

• interaction between those components & MSSM superfields

$\Longrightarrow$ give rise to soft ~~SUSY~~ terms: $\tilde{m} \propto \frac{\langle F \rangle}{M}$

scale of transmission of ~~SUSY~~ (messenger scale)

- Two/Three main scenarios

I) Supergravity

$$\text{moduli fields } T, S \xleftrightarrow[\;1/M_{pl} \text{ interact.}\;]{} \text{MSSM fields}$$

(hidden sector)

$\downarrow$ adquire v.e.v.'s $\langle F_{S,T} \rangle \neq 0$

$$m_{\tilde{f}_{\cancel{SUSY}}} \propto \frac{\langle F_S \rangle}{M_{pl}} + \frac{\langle F_T \rangle}{M_{pl}} \propto m_{3/2} \longrightarrow \text{gravitino mass}$$

$$M_i \propto \frac{\langle F_S \rangle}{M_{pl}} \simeq M_{1/2} \qquad A_f \propto \frac{\langle F_{T,S} \rangle}{M_{pl}} \qquad B\mu \propto \frac{\langle F_T \rangle^2}{M_{pl}^2}$$

• boundary cond. at M_{pl} then RG ev. to $M_{weak} \simeq M_{SUSY}$

to have $m_{\tilde{f}_{\cancel{SUSY}}} \propto \frac{\langle F_{S,T} \rangle}{M_{pl}} \sim 1\,\text{TeV} \Rightarrow \sqrt{F_{S,T}} \simeq 10^{11}\,\text{GeV}$

Problems:

• sensitivity to UV physics • lack of predictivity

• sensitivity to flavour $\longrightarrow$ hard to suppress contrib. from

II) Gauge-mediated, low energy SUSY

Dine, Nelson + Shirman + Nir

Messenger Superfield Φ $\longleftrightarrow$ S (singlet, hidden sector) $\langle \tilde{S} \rangle \neq 0, \langle F_S \rangle \neq 0$

$\langle \phi$ (scalar), ψ (fermion) comp.$\rangle$

$\Phi \longleftrightarrow$ MSSM fields

coupling through gauge interactions

Messenger "transmits" $\cancel{\text{SUSY}}$ which receives from hidden sector

- Simplest version

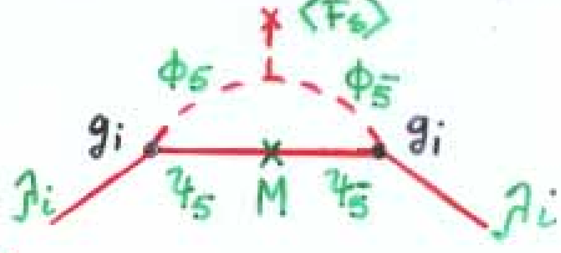
$$\Phi, \bar{\Phi} \longrightarrow 5, \bar{5} \text{ from } SU(5) \longrightarrow W \propto S \Phi \bar{\Phi}$$

$$m_{\psi_{mess.}} \propto \langle \tilde{S} \rangle \equiv M \qquad m^2_{\phi_{mess.}} \propto M^2 \pm \langle F_S \rangle$$

$\langle F_S \rangle / M \longrightarrow$ overall scale of SUSY particles

- Integrating out the messengers $\Rightarrow$ masses to MSSM ptles

- gauginos $\longrightarrow$ $M_i \simeq c_i N \dfrac{\alpha_i}{4\pi} \dfrac{\langle F_S \rangle}{M}$
  ⟨one-loop⟩



- scalars
  ⟨two-loops⟩ $m_{\tilde{f}_{SUSY}} \simeq \dfrac{2\langle F_S \rangle^2}{M^2} N \sum_{i=1,3} c_i^{\tilde{f}} \dfrac{\alpha_i^2}{(4\pi)^2}$

- $\cancel{\text{SUSY}}$ masses $\longrightarrow$ correlated to gauge couplings
- heavy particles dynamics ($>M$) does not affect SUSY spectrum
- if $M > \Lambda_{\text{FLAVOUR}}$ only Yukawa int. violate flavour
- if $M_i \sim 100$ GeV $\Rightarrow \langle F_S \rangle / M \sim 100$ TeV hence $m_{\tilde{G}} \simeq 10^{-14} \dfrac{M}{[\text{GeV}]}$

Soft ~~SUSY~~ parameters obey RG equations

$M_W \simeq M_{SUSY}$ — M (messengers) or M_{GUT} — $\Lambda_{Flavour}$ — M_{pl} — μ

$\Lambda = M, M_{GUT}, M_{pl}$

$$m^2_{\tilde{f}_{\cancel{SUSY}}}(\mu) \simeq -2\, c_i^f / b_i \left(\alpha_i^2(\mu) - \alpha_i^2(\Lambda)\right) \frac{M_i^2(\Lambda)}{\alpha_i^2(\Lambda)} + m^2_{\tilde{f}_{\cancel{SUSY}}}(\Lambda) + \text{Yuk. terms}$$

$$M_i(\mu) \simeq \alpha_i(\mu) \frac{M_i(\Lambda)}{\alpha_i(\Lambda)}$$

III) Interesting case : Anomaly mediated ~~SUSY~~

Randall, Sundrum
Giudice, Luty, Murayama, Rattazzi

- even if no soft ~~SUSY~~ terms at tree level, gravity generates them at quantum level

masses generated at loop level via effects of the superconformal anomaly $\Leftrightarrow$ μ (scale) dependence

$$M_i(\Lambda) \simeq b_i\, \alpha_i(\Lambda) \langle F_{T,S}\rangle / M_{pl} \longrightarrow M_i(\mu) \simeq b_i\, \alpha_i(\mu)\, m_{3/2}$$

$$m^2_{\tilde{f}_{\cancel{SUSY}}}(\mu) \propto - c_i^f / b_i \left(\alpha_i^2(\mu) - \alpha_i^2(\Lambda)\right) b_i^2\, m_{3/2}^2 + m^2_{\tilde{f}_{\cancel{SUSY}}}(\Lambda) + \text{Yukawa terms}$$

$$\longrightarrow m^2_{\tilde{f}_{\cancel{SUSY}}}(\mu) \propto - c_i^f\, b_i\, \alpha_i^2(\mu)\, m_{3/2}^2$$

- depend only on low E param. $\longrightarrow$ high E effects cancell out
- inverted relation $M_3 : M_2 : M_1 \longrightarrow -10 : 1 : 3.3$

  $\Rightarrow$ wino LSP $\Rightarrow m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm}$

Problem: $b_{1,2} > 0 \Rightarrow m^2_{\tilde{\ell}} \longrightarrow$ NEGATIVE ! (Tachyons)

Randall, Sundrum ; Pomarol, Rattazzi ; Luty et al

Different ~~SUSY~~ Scenarios $\Rightarrow$ different experimental signatures expected

<u>GRAVITY-Mediated</u>: $\tilde{\chi}_1^0$ LSP $\Rightarrow \not{E}_T$

$\langle$ $\tilde{\chi}_1^0$ provides a CDM candidate $\rangle$

$\Longrightarrow$ combinations of jets + $\not{E}_T$, leptons + $\not{E}_T$
jets + leptons + $\not{E}_T$

<u>Gauge mediated</u>: $\tilde{G}$ LSP $\Longrightarrow \not{E}_T$

Thomas, Dimopoulos, Dine, Raby
Ambrosanio, Kane, Kribs
Martin, Mrenna

but $\not{E}_T$ signatures depend on decay length of NLSP $\longrightarrow$ $1/\Gamma \propto F^2/m_{NLSP}^5$ ($\sqrt{F} \leq 10^4$ GeV $\Rightarrow$ inside detector)

if $\tilde{\chi}_1^0$ NLSP $\longrightarrow \gamma\tilde{G}$, $h\tilde{G}$, $Z\tilde{G}$ (rarer decay)

distinctive signature: 2 hard photons + $\not{E}_T$
4 b jets + $\not{E}_T$

if $\tilde{\ell}_R$ NLSP $\longrightarrow \tau\tilde{G} \longrightarrow \tau + \not{E}_T$ (kink)
$\Downarrow$
($\tilde{\tau}_R$)

- if $\tilde{\tau}$ long lived $\Rightarrow$ charged tracks with no $\not{E}_T$!

<u>Anomaly mediated</u>: $\langle$ phenom.: under construction $\rangle$

- $\tilde{\chi}_1^0 \longrightarrow$ LSP and wino-like $\Rightarrow \chi_1^0, \chi_1^\pm$ almost degenerate

Giudice, Walls, Gherghetta
Feng, Moroi, Strassler, Randall, Su
Gunion, Mrenna

since $\Delta m \equiv m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \gtrsim m_{\pi^\pm}$

$\chi^\pm \rightarrow \tilde{\chi}_1^0 \, \pi^\pm$

$\longrightarrow$ difficult to trigger (very soft leptons/π's)

$\langle$ • if $\tilde{\nu}$ LSP $\Rightarrow \tilde{\chi}^+ \longrightarrow \tilde{\nu}\ell$ (lepton + $\not{E}_T$: helpful) $\rangle$

Evidence for Neutrino Masses and Mixings

$\Longrightarrow$ direct experimental indication for physics beyond the Standard Model

- SM extensions, preserving $SU(3)_C \times SU(2)_L \times U(1)_Y$

I) SM + 3 ν_R $\longrightarrow$ DIRAC masses $\rightarrow$ L conserved

$$\delta\mathcal{L}_{SM} = \bar{L}_L \lambda \phi \nu_R + h.c \longrightarrow v\, \bar{\nu}_L \lambda^\nu \nu_R \qquad \lambda^\nu \neq \mathbb{I}$$

mixing

$$\bar{\nu}_L m_D \nu_R \longrightarrow \bar{\nu}_L^{\,Diag} \underbrace{U_{\nu_L} m_D V^+_{\nu_R}}_{m_\nu^{DIAG}} \nu_R^{\,Diag}$$

define $V_{MNS} \equiv U_{\ell_L} U^+_{\nu_L}$ $\rightsquigarrow$ analogous to V_{CKM}

Maki, Nakagawa, Sakata '62

Problem: if $m_\nu \lesssim eV \Rightarrow \lambda_\nu / \lambda_{\ell^\pm} \ll 1$

II) Majorana masses $\rightarrow$ (SM + 3 ν_R $\longrightarrow$ heavy) $\not{L}$

$$\delta\mathcal{L}_{SM} = \bar{L}^c_L \phi^T \Lambda^{-1} \phi L_L + h.c. \longrightarrow \frac{v^2}{\Lambda} \nu_L^T h^\nu \nu_L$$

see-saw mechanism may provide this realization

$$\delta\mathcal{L}_{SM} = \left(\nu_R^T \frac{M_{\nu_R}}{2} \nu_R + \bar{\nu}_L \underbrace{\lambda^\nu v}_{m_D} \nu_R\right) + h.c$$

Yanagida, Gell-Mann, Ramond, Slansky

$\downarrow$ at scale M_N the ν_R decouples

$$\delta\mathcal{L}_{SM} = \nu_L^T \frac{m_\nu}{2} \nu_L + h.c$$

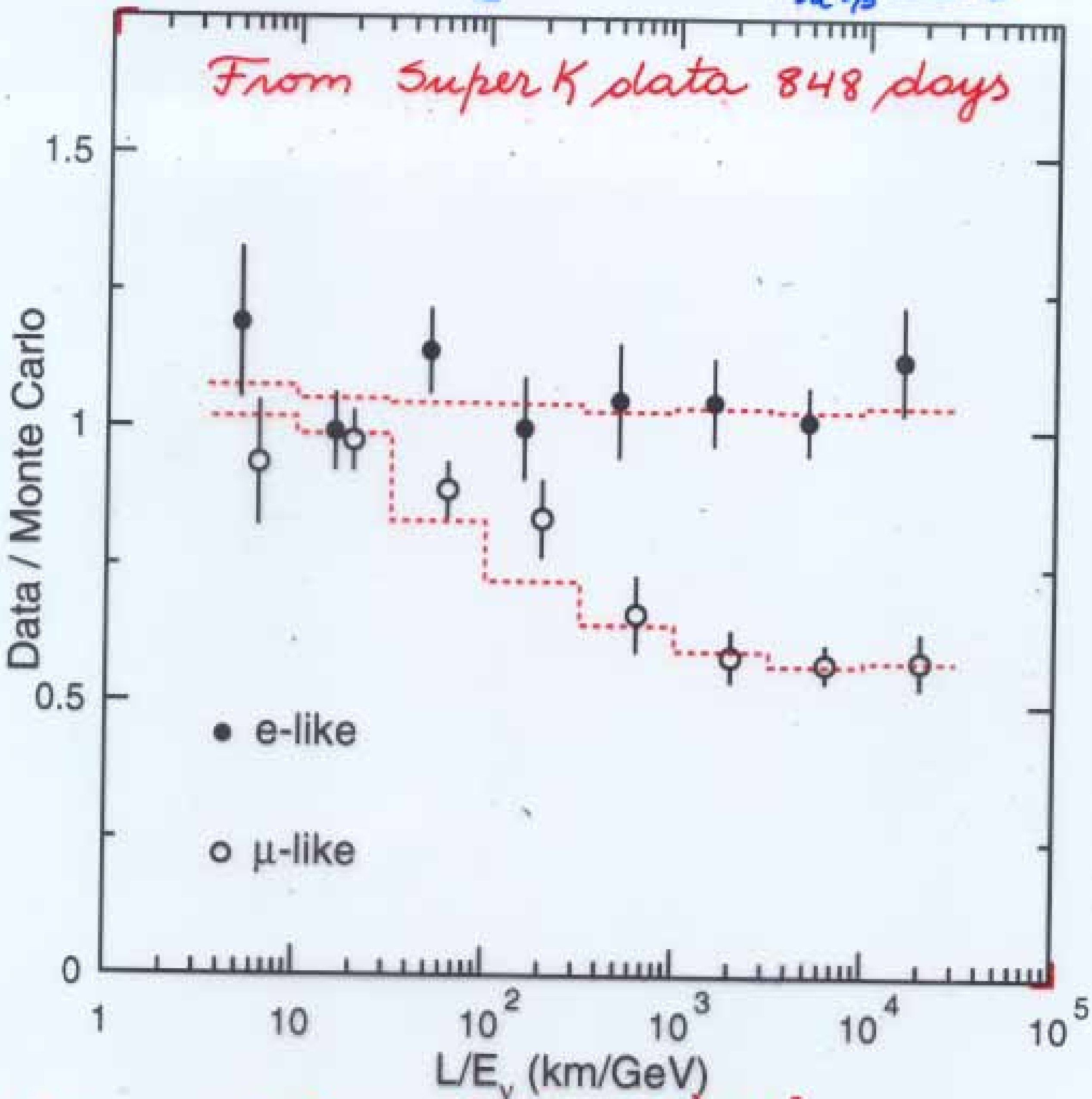
$$m_\nu = m_D M_{\nu_R}^{-1} m_D^T$$

$$m_\nu^{DIAG} = U_{\nu_L} m_\nu U^T_{\nu_L}$$

III) extra sterile ν's @ low energy

Hence,

$$\sin^2\left[\frac{1.27\ \delta m^2_{ATM}\ L}{E}\right] \Longrightarrow \begin{cases} E \ll \delta m^2 L \rightarrow \text{rapid osc. with variation of } L \,\&\, E,\quad P_{\nu_\alpha \nu_\beta} \rightarrow 0.5 \\ E \simeq \delta m^2 L \rightarrow \text{suppression in osc. dep. precisely on } L, E \\ E \gg \delta m^2 L \rightarrow \text{strong suppression},\quad P_{\nu_\alpha \nu_\beta} \rightarrow 0 \end{cases}$$



it follows: $\delta m^2_{ATM} \sim (10^{-2} - 10^{-3})\, eV^2$

$P_{\nu_\mu \nu_e}$ small $\Longrightarrow \theta_1$ small* $\quad P_{\nu_\mu \nu_\tau}$ large $\Longrightarrow 2\theta_2 \simeq \pi/2$

Best fit: $\delta m^2_{ATM} \simeq 3.5\, 10^{-3}\, eV^2$

Barger, Whisnant / Bilenky et. al
Barbieri et. al / Fogli et. al

$\theta_1 \simeq 0$ (min. $\nu_e \rightarrow \nu_\mu, \nu_\tau$)

$\theta_2 \simeq \pi/4$ (max $\nu_\mu \rightarrow \nu_\tau$)

II) Solar Neutrino Oscillations

Bahcall, Pinsonneault '98
Bahcall, Krastev, Smirnov '98

- Experiments sample different energy ranges and find different deficits in the ν_e flux from the SUN

<compare to expectations from SSM>

$$\left.\begin{array}{lll} pp \to d\, e^+ \nu_e & E_\nu < 0.42\,\mathrm{MeV} & \text{(majority)} \\ e^-\, {}^7Be \to \nu_e\, {}^7Li & E_\nu \simeq 0.86\,\mathrm{MeV} & \\ \left.\begin{array}{l} {}^8B \to {}^8Be\, e^+ \nu_e \\ {}^3He + p \to {}^4He\, e^+ \nu_e \end{array}\right\} & E_\nu < 15\,\mathrm{MeV} & \end{array}\right\} \text{Solar reactions \& Energies}$$

Process	Detector	E_ν [Mev]	data/SSM
$\nu_e\, {}^{71}Ga \to {}^{71}Ge\, e$	Gallex	> 0.23	0.60 ± 0.06
	Sage		0.52 ± 0.06
$\nu_e\, {}^{37}Cl \to {}^{37}Ar\, e$	Homestake	> 0.81	0.33 ± 0.03
$\nu_e\, e \longrightarrow \nu_e\, e$	Super K	> 6.5	0.47 ± 0.02
	Kamiokande		0.52 ± 0.06

- sub-leading oscillations

- oscillations prop. to δm^2_{ATM} go like $\sin^2 2\theta_1 \sim 0$ (small)

- now $\longrightarrow$ $\underline{L/E \propto \frac{10^{10}\,\mathrm{km}}{\mathrm{GeV}}}$ hence, to have

$$\Delta m_{SUN} \equiv \delta m^2_{SUN}\, L/E \simeq \pi/2 \implies \underline{\delta m^2_{SUN} \ll \delta m^2_{ATM}}$$

$$P(\nu_e \to \nu_e) = 1 - \cos^4\theta_1\, \sin^2 2\theta_3\, \sin^2 \Delta m_{SUN} \longrightarrow \text{VACUUM OSCILLATIONS}$$

to get large suppression $\longrightarrow \theta_3 \sim \pi/4$; $\delta m^2_{SUN} \sim 10^{-10}\, eV^2$

Solar Neutrino Oscillations → 3 solutions

- Vaccuum Oscillations (VO)

$$P_{\nu_e \nu_e} = 1 - \cos^4\theta_1 \sin^2 2\theta_3 \sin^2(1.27\, \delta m^2_{SUN} L/E)$$

- Matter Oscillations (MSW), large or small angle

⟨more involved modelling⟩

fits → Figs →

Solutions	$\sin^2 2\theta_3$	δm^2_{SUN}
VO	~ 1	$\sim 4.10^{-10}\,eV^2$
MSW (LA)	~ 1	$\sim 10^{-4} - 10^{-5}\,eV^2$
MSW (SA)	$\sim 10^{-2}$	$\sim 10^{-5}\,eV^2$

- other comparisons of VO vs MSW (LA or SA)

- Energy dependence $\quad \nu_e e \to \nu_e e \rightsquigarrow E_e[MeV]$

MSW (SA) gradual rise, MSW(LA) flat

VO → rise at $E_e > 12$ MeV natural

DATA SHOWS rise at $E_e \gtrsim 12$ MeV

- Seasonal dependence $\quad$ - Night-Day dep.

⟨$\sin^2(1.27\, \delta m^2_{SUN} L/E)$ dep on L⟩

⇒ ALL solutions possible, large mix. angle ones preferred

more data needed

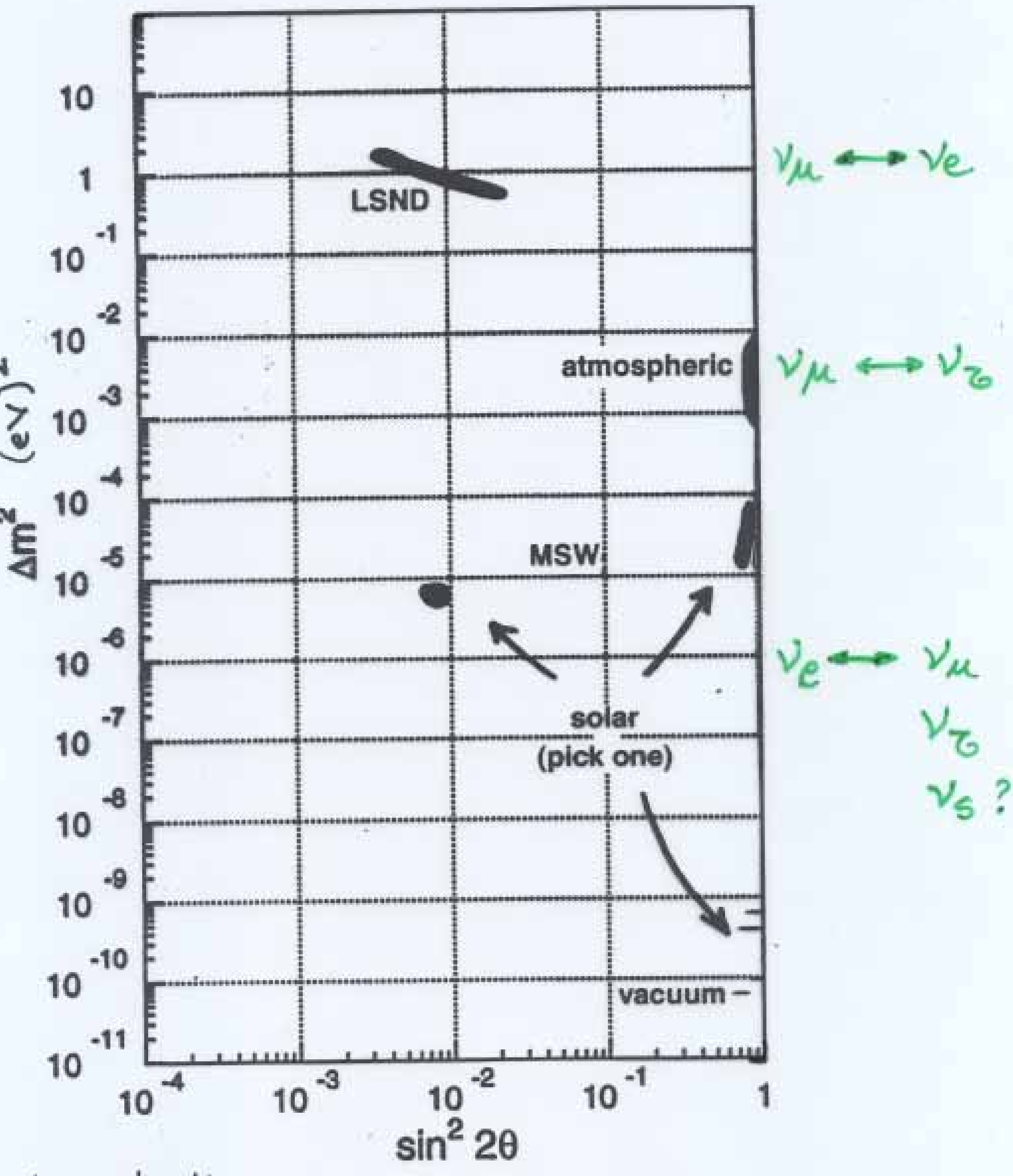
III) Reactor/Accelarator Neutrinos : no oscillations

but in LSND → ν_e ($\bar{\nu}_e$) appearance

$0.3 \gtrsim \delta m^2 [eV^2] > 2$, small mixing angle

• if confirmed ⇒ 4 ν's needed → to explain 3 indep. δm^2

Summary of evidence



Hata, Langacker '97
Bahcall, Krastev, Smirnov '98
SuperK '99

Barger (SUSY '99)

Reconstruction of V_{MNS} (lepton/ν mixing matrix) possible from data (except phases & solar sol.)

Barbieri et. al '98
Barger, Whisnant '98
Bilenky et. al. '98

$$V_{MNS} \simeq \begin{pmatrix} c_3 & s_3 & 0 \\ -s_3 c_2 & c_2 c_3 & s_2 \\ s_2 s_3 & -s_2 c_3 & c_2 \end{pmatrix} \quad \text{with } \vartheta_1 \sim 0 \text{ (approx.)}$$

hence, reconstruct ν mass matrix in the basis in which mixing is all in ν sector.

given $m_\nu^{DIAG} \equiv (m_1, m_2, m_3)$ for $c_2 = s_2 = 1/\sqrt{2}$ $\vartheta_2 = \pi/4$

$$\Rightarrow m_\nu = \begin{pmatrix} c_3^2 m_1 + s_3^2 m_2 & c_3 s_3 (m_2 - m_1)/\sqrt{2} & c_3 s_3 (m_1 - m_2)/\sqrt{2} \\ & (s_3^2 m_1 + c_3^2 m_2 + m_3)/2 & \\ c_3 s_3 (m_1 - m_2)/\sqrt{2} & -(s_3^2 m_1 + c_3^2 m_2 - m_3)/2 & (s_3^2 m_1 + c_3^2 m_2 + m_3)/2 \end{pmatrix}$$

symmetric

- Different solar ν oscillation solutions Altarelli, Feruglio Jezabek, Sumino

* Small mixing angle $\longrightarrow s_3 \sim 0,\ c_3 \sim 1$

+ degenerate neutrinos: $|m_1| \sim |m_2| \sim |m_3| \sim \mathcal{O}(eV)$

$\longrightarrow$ excluded via $\nu 0\beta\beta$ decay $\longrightarrow |m_1| \lesssim 0.2\,eV$

recall: $0\nu\beta\beta$ decay det. by $\nu_e \nu_e$ element of m_ν matrix

$$|m_\nu^{ee}| = |c_1^2 c_3^2 m_1 + c_1^2 s_3^2 m_2 e^{i\phi_2} + s_1^2 m_3 e^{i\phi_3}| < 0.2\,eV$$

Baudis et a
hepex/990201

* Large mixing angle $\longrightarrow s_3^2 \sim 1/2 \sim c_3^2$ (MSW or VO)

$\equiv$ bimaximal mixing

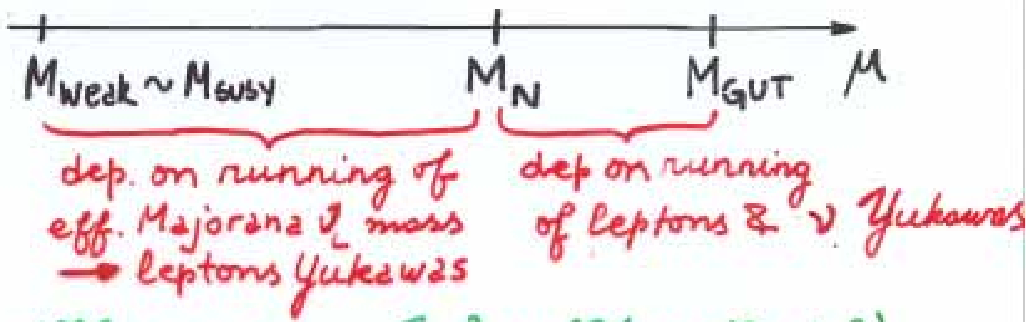
$|m_\nu^{ee}| = \left|\frac{m_1 + m_2}{2}\right| \Rightarrow$ Degenerate ν's with $|m_i| \sim 2\,eV$

$\longrightarrow$ possible $\longrightarrow m_1 \sim -m_2$

* hierarchical ν's : $m_3 \gg m_2 > m_1 \longrightarrow$ LMA or SMA ✓

- Low energy structure of ν mass matrix "defined" but, are sol. stable under quantum correc.?

GUT's with see-saw mech. →



- Are small mass differences $\delta m^2 \sim \mathcal{O}(10^{-10}\, eV^2)$ stable under RG evol. from $M_{Weak} \longrightarrow M_N, M_{GUT}$?

$$\delta m_\nu / m_\nu \sim \mathcal{O}\left(h_{\mu,\tau}^2 / 16\pi^2 \ln M_N / M_{Weak} \right) \sim \mathcal{O}(10^{-5}) \Rightarrow \delta m_\nu^2 \sim 10^{-5} m_\nu^2$$

$\Longrightarrow$ Degenerate neutrinos ($m_{\nu_i} \sim eV$) and VO ($\delta m^2 \sim 10^{-10} eV^2$) difficult to achieve

- MSW ($\delta m^2 \gtrsim 10^{-5} eV^2$) → easier to achieve

Ellis, Lola '99
Casas et al '99

- Unification of Couplings & hierarchical ν's

- new effect : ν Yukawa effects between M_G and M_N

- b-τ Unification?

Alternatives: Altarelli, Feruglio; Albright, Barr; Raby et al; Nomura, Yanagida; Fritzsch, Xing ...

given mass matrices in a unified model (at M_{GUT})

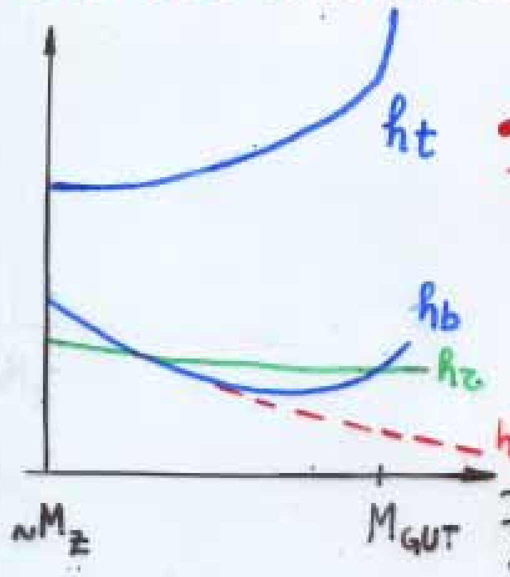
$$M_D = \begin{pmatrix} c & 0 \\ 0 & 1 \end{pmatrix} \qquad m_L = \begin{pmatrix} x^2 & x \\ x & 1 \end{pmatrix} \qquad m_D^\nu = B \begin{pmatrix} y^2 & y \\ y & 1 \end{pmatrix}$$

b-τ Unif. $\Leftrightarrow$ $m_D^{33}(M_{GUT}) = m_L^{33}(M_{GUT})$

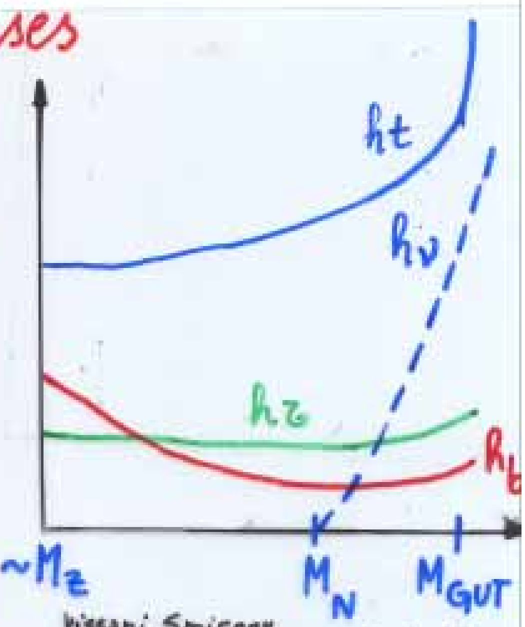
but "x" generates a mismatch between the value $m_\tau(M_{GUT})$ [extrapolated from $m_\tau(m_\tau)$] & $m_L^{33}(M_{GUT})$

$\Longrightarrow$ Due to ν Yukawa effects, this mismatch at

• In the absence of neutrino masses



• with non-zero neutrino mass $\longrightarrow$



Ramond et. al.
Barger et. al.
M.C, Pokorski, Wagner

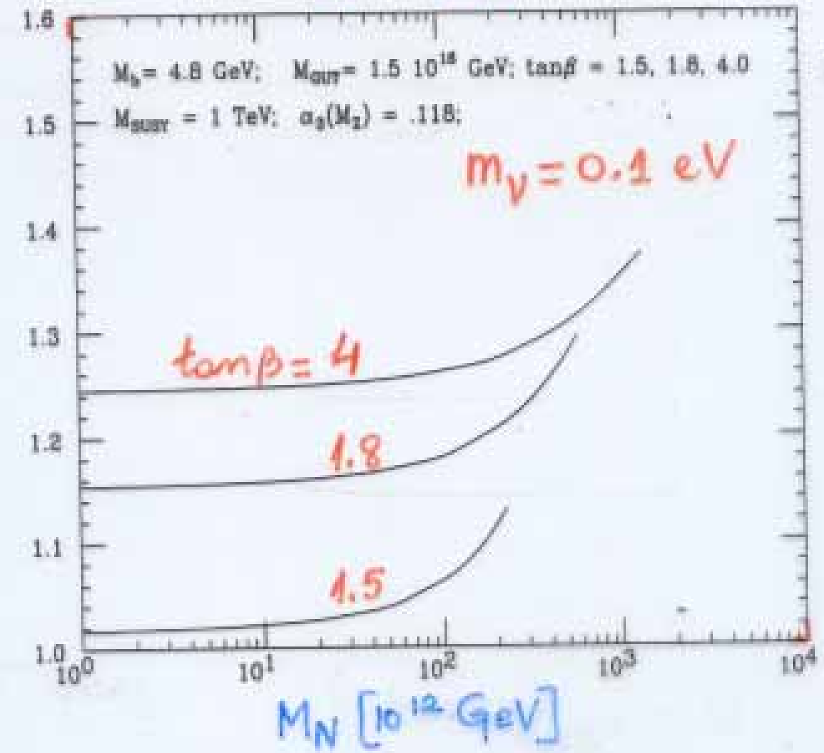
Vissani, Smirnov
Brignole, Murayama, Rattazzi

large h_ν has same effect on m_τ as h_t has on m_b

low $\tan\beta \longrightarrow$ unif. with small h_ν possible [M_{top} IR fixed point sol.]

if h_ν sizeable $\longrightarrow$ unif. difficult [without $\ell^\pm/\nu$ mixing]

M.C, Ellis, Lola, Wagner



$m_{\tilde\tau}/m_b\,(M_{GUT})$

no mixing effect

$h_\nu^2 \propto m_\nu M_N$

After taking into account $\ell^\pm/\nu$ mixing effects, unif. $\Rightarrow$

$$\tilde{m}_\tau(M_{GUT})/m_b(M_{GUT}) = (1+x^2)\sqrt{2/(1+\xi_N^2)}$$

max. mix: $\sin^2 2\theta_2 \simeq 1$ used $\Rightarrow y = (x-\xi_N)/(1+\xi_N x)$

b-τ Unification $\Rightarrow$ intermediate $\tan\beta \simeq 3-10$

$M_N \sim 10^{12}-10^{14}$ GeV ; $\sin^2 2\theta_2 \simeq 1 \Rightarrow$ NEW sol. interm $\tan\beta$

$M_N[10^{13}$ GeV]	1	10	20	50	70	150	250	400
$\tan\beta = 1.5$	0.13	0.15	0.17	0.21	0.23			
$\tan\beta = 1.8$	0.39	0.40	0.40	0.41	0.42	0.43	0.44	
$\tan\beta = 4.0$	0.50	0.50	0.50	0.50	0.50	0.51	0.52	0.52

Table 5: *Values of x leading to $b-\tau$ Yukawa coupling unification for $m_\nu = 0.03$ eV, for different choices of $\tan\beta$ and M_N.*

$M_N[10^{13}$ GeV]	1	10	20	50	70	150	250	400
$\tan\beta = 1.5$	-0.77	-0.73	-0.69	-0.62	-0.58			
$\tan\beta = 1.8$	-0.44	-0.43	-0.42	-0.40	-0.39	-0.37	-0.35	
$\tan\beta = 4.0$	-0.34	-0.33	-0.33	-0.32	-0.32	-0.31	-0.30	-0.29

Table 6: *Values of y leading to $b-\tau$ Yukawa coupling unification for $m_\nu = 0.03$ eV, for different choices of $\tan\beta$ and M_N.*

$M_N[10^{12}$ GeV]	1	10	50	80	100	200	400	800
$\tan\beta = 1.49$	0.13	0.14	0.17	0.18	0.20	0.26		
$\tan\beta = 1.8$	0.39	0.39	0.40	0.41	0.41	0.43	0.45	
$\tan\beta = 4.0$	0.50	0.50	0.50	0.50	0.50	0.51	0.52	0.54

Table 7: *Values of x leading to $b-\tau$ Yukawa coupling unification for $m_\nu = 0.1$ eV, for different choices of $\tan\beta$ and M_N.*

$M_N[10^{12}$ GeV]	1	10	50	80	100	200	400	800
$\tan\beta = 1.49$	-0.76	-0.75	-0.70	-0.66	-0.62	-0.52		
$\tan\beta = 1.8$	-0.44	-0.43	-0.42	-0.41	-0.40	-0.37	-0.33	
$\tan\beta = 4.0$	-0.34	-0.34	-0.33	-0.33	-0.32	-0.31	-0.29	-0.26

Table 8: *Values of y leading to $b-\tau$ Yukawa coupling unification for $m_\nu = 0.1$ eV, for different choices of $\tan\beta$ and M_N.*

M.C, Ellis, Lola, Wagner

b-τ unification in the presence of ν masses and maximal mixing ($\sin^2 2\theta = 1$)

Extra Dimensions (E.D.)

Physical Motivations: ⟨some similar to SUSY⟩

I) Strings ⟶ indicate the existence of 6-7 extra dim

- they must be there, we do not know at what scale
- they should be compact (small)

 - if seen by SM particles $\Longrightarrow$ they should be quite small
   $R \lesssim 10^{-17}\,\mathrm{cm} \sim 1/\mathrm{TeV}$

 - if not seen by SM particles
   only gravity $\Longrightarrow$ can be larger (Bakas' talk.)
   $R \lesssim 1\,\mathrm{mm}$

II) hierarchy problem: big difference $M_{weak} \longleftrightarrow M_{pl}$

⟨≡ why gravity is so weak⟩

extra dim. ⟶ lower the value of M_{pl} Arkani-Hamed, Dimopoulos, Dvali

If $M_{pl}^{fund.} \sim \mathcal{O}(1\,\mathrm{TeV})$ ⟨needed if to be detected @ colliders⟩

$\Longrightarrow$ partial sol. to hierarchy problem

⟨not completely: why R is so large?⟩

- No SUSY needed, in pple

  but strings ⟶ SUSY needed to stabilize vacua

III) unification of gauge forces at low scales $\mathcal{O}(1/R)$ "possible" Dienes, Dudas, Gherghetta

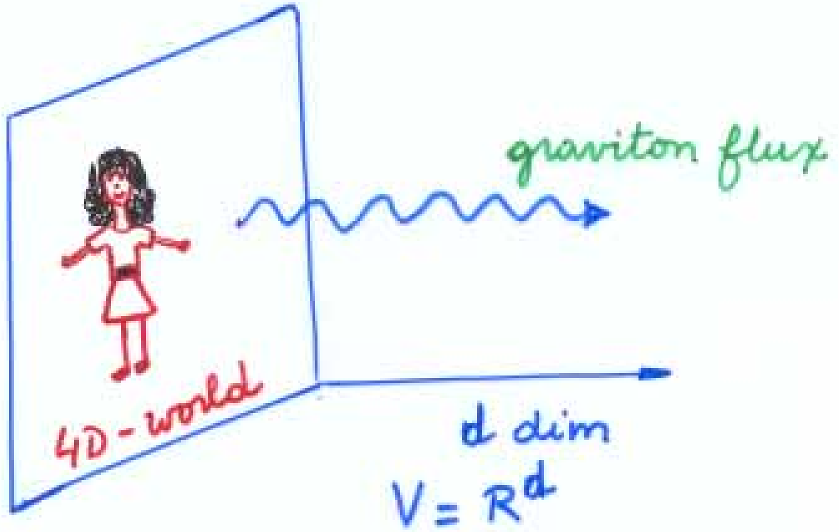
IV) some new possibilities for ~~SUSY~~ scenarios

Delgado, Dimopoulos, Pomarol, Quiros

- How to "see" extra dim. in our 4-D world?

if large extra dim. exist, then we live in 4-D wall (brane)
& only gravity propogates in extra dim.

Arkani-Ahmed, Dimopoulos, Dvali



$V = R^d$

the way we can see this in 4-D-world:

SM particles + graviton + tower of extra massive excitation
⟨Kaluza-Klein modes of the graviton

the way we can probe extra dim.

$\Rightarrow$ by "measuring" effects of these graviton KK modes at colliders

- missing energy lost by graviton emission
- virtual graviton mediated processes

- KK modes in 4D $\longrightarrow$ lower the fundamental planck scale $M_{pl}^{fund} \ll M_{pl}$

how much, dep. on the size and number of the extra dim.

What is a KK mode?

Any extra dim. must be compact

4 dim. x_0, x_1, x_2, x_3

R_d = radius of compactification in direction y_d

circular topology of extra dim.

$$\phi(x, y_i + 2\pi R_i) = \phi(x, y_i)$$

and

$$\phi(x,y) = \frac{1}{\sqrt{V_d}} \sum_{n=-\infty}^{\infty} \tilde{\phi}_n(x)\, e^{iny/R}$$

hence, if $d=1$ (d = # of E.D.)

$$S = \int d^4x \int dy\, (\partial_A \phi)^* \partial_A \phi = \sum_n \int d^4x \left[\partial_\mu \tilde{\phi}_n^* \partial_\mu \tilde{\phi}_n + \frac{n^2}{R^2} \tilde{\phi}_n^* \tilde{\phi}_n \right]$$

5D $\longrightarrow$ 4D : SM particles + graviton (identified with $n=0$)

+ tower of massive excitations with mass $\frac{n^2}{R^2}$

$\Downarrow$

mass of KK excitations $\equiv$ momentum in the extra dim.

$$q^2 = q_0^2 - \vec{q}^{\,2} - q_y^2 = 0 \Longrightarrow \underbrace{q_\mu q^\mu}_{4D} = q_y^2 = n^2/R^2$$

we call mass to the imbalance betwen measured energies & momentum in 4-D = mom. in extra. dim.

- generalization to more dimensions

$$\left(M_{KK}^{n_1, n_2, \ldots n_d}\right)^2 = n_1^2/R_1^2 + n_2^2/R_2^2 + \ldots + n_d^2/R_d^2$$

• Lowering the Planck Scale

- if gravity can penetrate extra dimensions

$\longrightarrow$ Newton's law will be modified

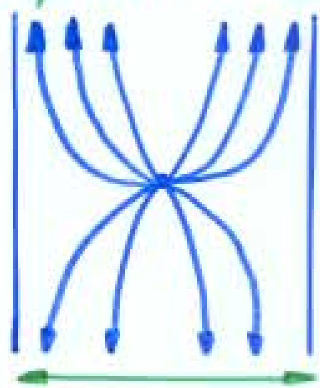
in 4 + d

$$\vec{G} \simeq \frac{m_1 . m_2}{(M_{pl}^{fund})^{2+d}} \frac{\hat{r}}{r^{2+d}}$$

but, macroscopically we see

$$\vec{G} \sim \frac{1}{M_{pl}^2} \frac{m_1 . m_2 \, \hat{r}}{r^2}$$

hence, extra dim. must be compact and the gravity flux is confined in the extra dimensions



2R = diamete

For $r << R$

$$\vec{G} = \frac{m_1 . m_2 \quad \hat{r}}{(M_{pl}^{fund})^{2+d} \, r^{2+d}}$$

For $r \gg R$

$$\vec{G} = \frac{m_1 . m_2 \quad \hat{r}}{(M_{pl}^{fund})^{2+d} \, R^d \, r^2}$$

continuity

$$\Longrightarrow \underline{\underline{M_{pl}^2 = (M_{pl}^{fund})^{2+d} R^d}} \longrightarrow \text{or } R^d = R_1 . R_2 \cdots R_d$$

scale at which gravity becomes strong.

• Newton law tested up to $r \gtrsim 1mm \longrightarrow \underline{\underline{R < r^{tested} \simeq 1mm}}$.

- alternative derivation of $M_{pl}^{fund.}$

$\Longrightarrow$ Newton's law in 4-D with $\underline{\underline{N_d}}$ KK modes of the graviton

I) Number of KK excitations produced with energy E
$\Rightarrow M_{KK} \leq E$

$d=1 \longrightarrow M_{KK} \longrightarrow 1/R\,,\ 2/R \cdots\ n_1/R \leq E \ \Rightarrow N_{d=1} = n_1 = ER$

$d=2 \longrightarrow M_{KK}^2 \longrightarrow 1/R_1^2\,,\ 1/R_2^2\,,\ 1/R_1^2 + 1/R_2^2\,, \cdots\ n_1^2/R_1^2 + n_2^2/R_2 \leq E^2$

hence $N_{d=2} \propto \sum_{n_1,n_2} \Big|_{n_1^2+n_2^2 \leq E^2R^2} \sim \int^{ER} dx_1\, dx_2 = (ER)^2$

generalizing, # of KK modes if d dim: $\underline{\underline{N_d \simeq (ER)^d}}$

Gravitational force between 2 ptles at distance $r < R$

$$\vec{G} = \frac{m_1 m_2\ \hat{r}}{M_{pl}^2\ r^2}\, N_d(M_{KK} < E) \qquad \text{with } E = 1/r$$

$$\vec{G} = \frac{m_1 . m_2\ \hat{r}\ R^d}{M_{pl}^2\ r^2\ r^d} \equiv \frac{m_1 . m_2\ \hat{r}}{\left(M_{pl}^{fund}\right)^{2+d}\ r^{2+d}}$$

- if $M_{pl}^{fund} \sim M_{STRING} \sim \mathcal{O}(M_{GUT})$ using $\left(M_{pl}^{fund}\right)^{2+d} = M_{pl}^2/R^d$

$\Longrightarrow d=1 \longrightarrow R \sim 10^{-23}\text{cm} \qquad d>1 \longrightarrow R$ even smaller

- if $M_{pl}^{fund} \sim \mathcal{O}(1\,\text{TeV})$

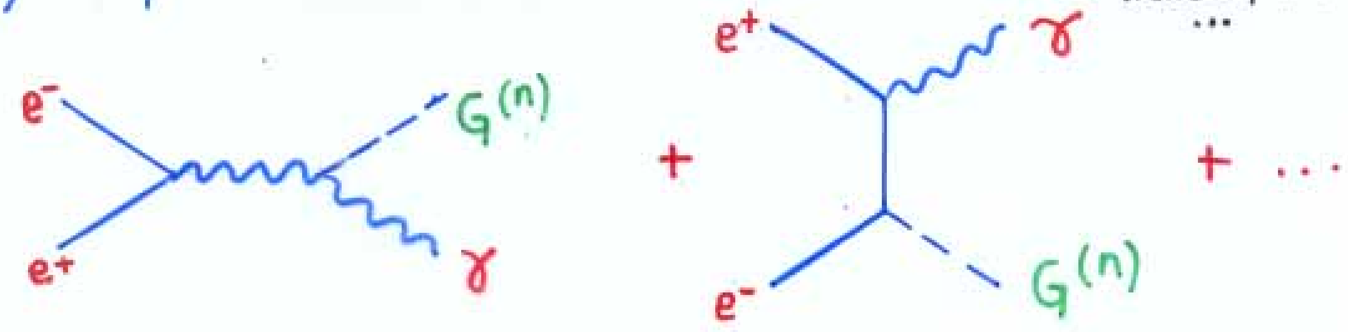
$d=1 \longrightarrow R \simeq 10^{15}\text{cm} \longrightarrow$ excluded

$d=2 \longrightarrow R \simeq 1\,\text{mm} \longrightarrow$ Testable, allowed

Search for Extra Dimensions at Colliders

Giudice, Rattazzi, Wells
Mirabelli, Perelstein, Peskin
Han, Lykken, Zhang
Hewett, Rizzo
...

I) Lepton Colliders



signal: $e^+e^- \longrightarrow \gamma + \not{E}$

each graviton extremely weakly coupled, but effective coupling constant $\propto E^2/M_{pl}^2 \; N_d$

$$\Longrightarrow \sigma/\sigma_{SM} \propto \frac{E^{2+d} \; R^d}{M_{pl}^2} = \left(\frac{\sqrt{s}}{M_{pl}^{fund}}\right)^{2+d}$$

(larger d ⟶ more difficult it becomes)

- if $M_{pl}^{fund} \sim 1$ TeV & $d = 2 \Longrightarrow \sim 10^{30}$ gravitons @ LEP2.

Backgrounds ⟶ $e^+e^- \to Z\gamma \to \nu\bar{\nu}\gamma$ (cut in $E_\gamma < E_\gamma^Z - \Delta$)

Sensitivity (5σ) @ LEP ($\sqrt{s} = 200$ GeV, $\mathcal{L} = 4 \times 500\,pb^{-1}$) and
LC ($\sqrt{s} = 1$ TeV, $\mathcal{L} = 200\,fb^{-1}$)

d	Max M_{pl}^{fund} @ LEP [TeV]		Max M_{pl}^{fund} @ LC [TeV]
2	1.3		4.1 - 5.7
3	1.0	($\simeq$ 15% worse	3.1 - 4.0
4	0.8	if $\sqrt{s} = 190$ GeV	2.5 - 3.0
5	0.65	$\mathcal{L} = 4 \cdot 150\,pb^{-1}$)	2.0 - 2.4

Giudice, Rattazzi, Wells

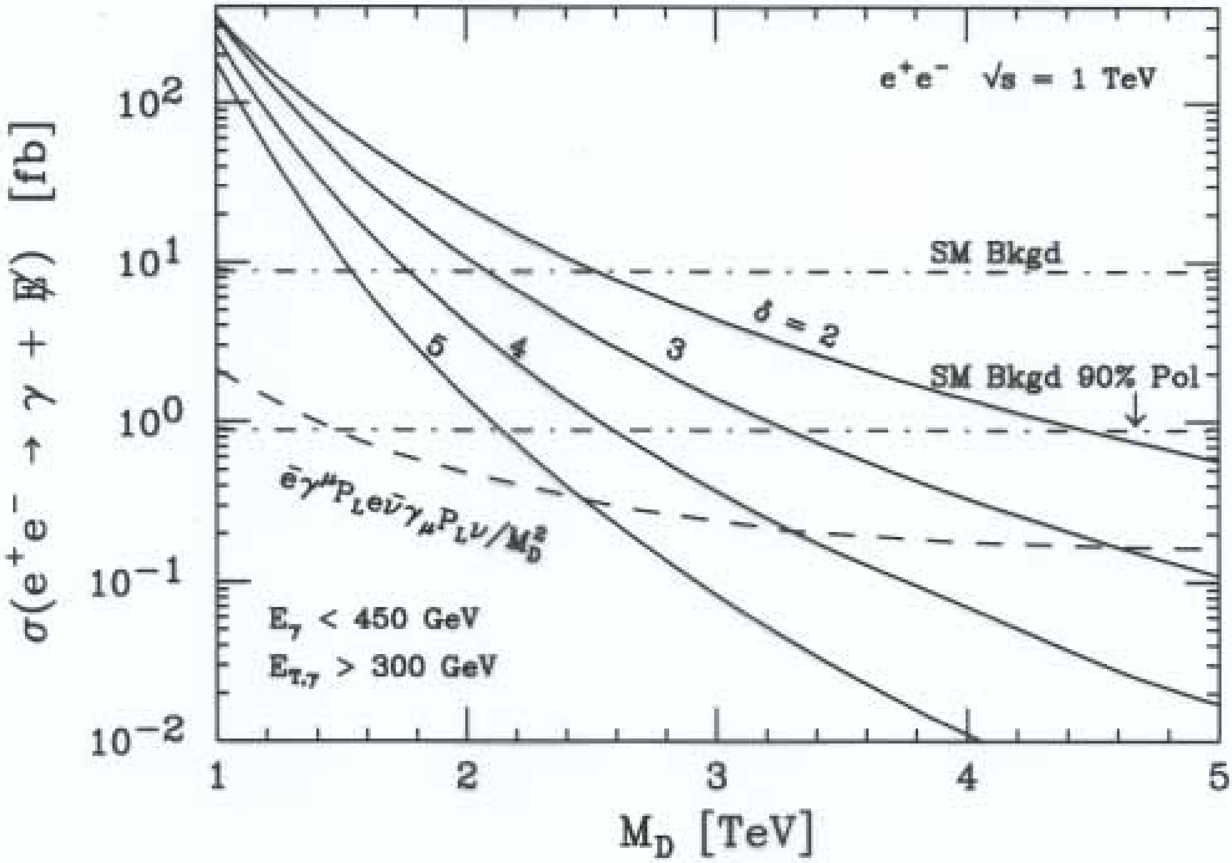


Figure 2: Total $e^+e^- \to \gamma +$ nothing cross-section at a 1 TeV centre-of-mass energy e^+e^- collider. The signal from graviton production is presented as solid lines for various numbers of extra dimension ($\delta = 2, 3, 4, 5$). The Standard Model background for unpolarized beams is given by the upper dash-dotted line, and the background with 90% polarization is given by the lower dash-dotted line. The signal and background are computed with the requirement $E_\gamma < 450\,\mathrm{GeV}$ in order to eliminate the $\gamma Z \to \gamma\bar{\nu}\nu$ contribution to the background. The dashed line is the Standard Model background subtracted signal from a representative dimension-6 operator.

$\sigma_S > 5\sqrt{\sigma_B/L} \sim 1\,\mathrm{fb}$

Givdice, Rottazzi, Wells

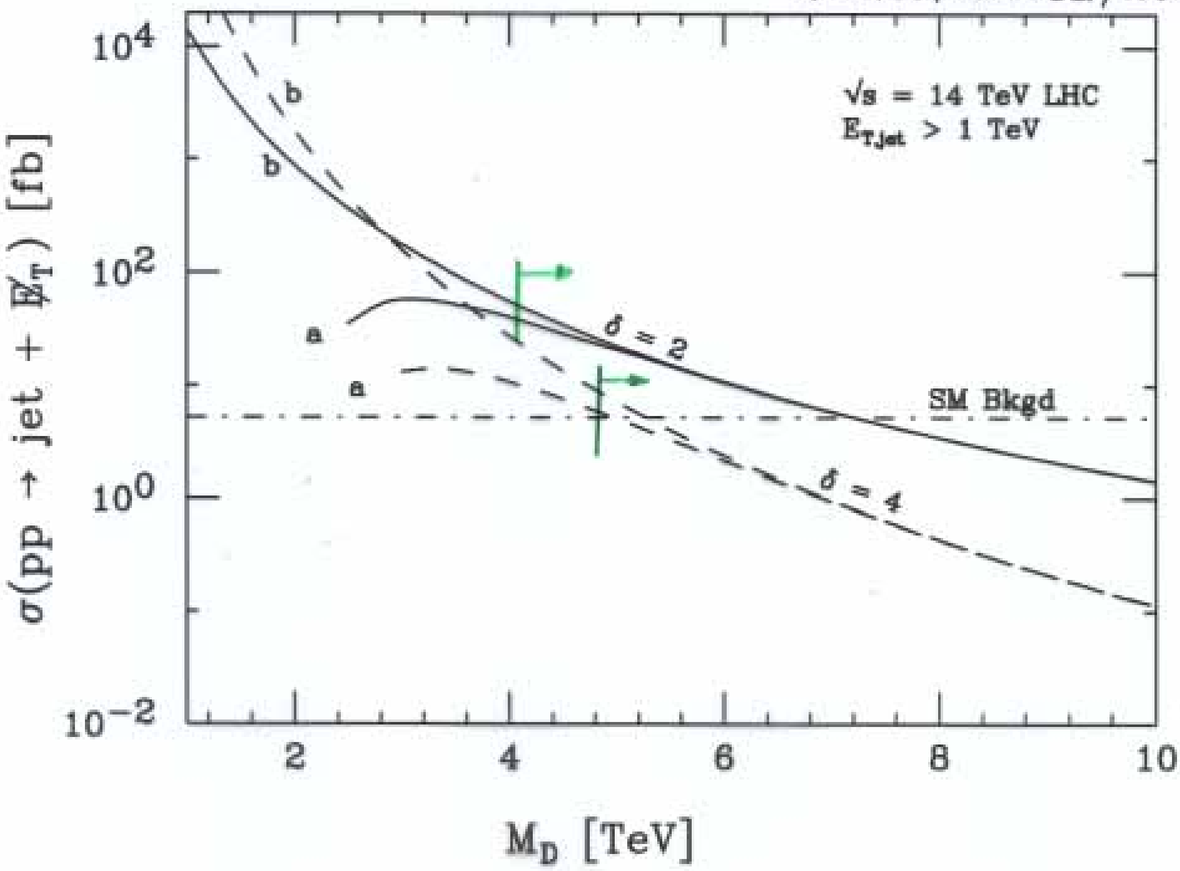


Figure 4: The total jet + nothing cross-section versus M_D at the LHC integrated for all $E_{T,jet} > 1$ TeV with the requirement that $|\eta_{jet}| < 3.0$. The Standard Model background is the dash-dotted line, and the signal is plotted as solid and dashed lines for $\delta = 2$ and 4 extra dimensions. The **a** (**b**) lines are constructed by integrating the cross-section over $\hat{s} < M_D^2$ (all $\hat{s}$).

$M_D \equiv M_{pl}^{fund}$

Current & future sensitivities to large extra dimensions

Mirabelli, Perelstein, Peskin

R [cm], M [GeV]   95% C.L. limits

Collider		R / M ($n = 2$)	R / M ($n = 4$)	R / M ($n = 6$)
Present:	LEP 2	4.8×10^{-2} / 1200	1.9×10^{-9} / 730	6.9×10^{-12} / 520
	Tevatron	11.0×10^{-2} / 750	2.4×10^{-9} / 610	5.8×10^{-12} / 610
Future:	Tevatron	3.9×10^{-2} / 1300	1.4×10^{-9} / 900	4.0×10^{-12} / 810
	LC	1.2×10^{-3} / 7700	1.2×10^{-10} / 4500	6.5×10^{-13} / 3100
	LHC	3.4×10^{-3} / 4500	1.9×10^{-10} / 3400	6.1×10^{-13} / 3300

LEP $\rightarrow \sqrt{s} = 183$ GeV
LC $\rightarrow \sqrt{s} = 1$ TeV
Tevatron $\sqrt{s} = 1.8$ TeV, 2 TeV
LHC $\rightarrow \sqrt{s} = 14$ TeV

Overview

What is interesting in Physics BSM, today?

1) Search for the Higgs (SM or SUSY)

may help us to understand EW symmetry mechanism $\longleftrightarrow$ origin of masses

may give hints of the scale of NEW Physics:

$\longrightarrow \Lambda \sim 10^3 - 10^{19}$ GeV?

2) Supersymmetry: if it is there, some answers to SM puzzles

but $\longrightarrow$ need to understand ~~SUSY~~ mechanism

- construct scenarios theoretically viable
- search for distinctive signatures to probe them

3) Neutrino Physics $\Longrightarrow$ demands physics BSM

- Exp. evidence of ν osc. ($m_\nu \neq 0$ & mixing)

$\Downarrow$

provides surprising amount of info about ν mass hierarchy & mixing pattern

⟨reconstruction of ν mass matrix on the horizon!⟩

- more data $\rightarrow$ to differentiate solar sol. $\rightarrow$ is coming!
- Unified Models (b-τ Unif ✓)

$\downarrow$ many possibilities   RG evol. & scales m_ν, M_N CRUCIAL!

4) Extra Dimensions:

Amazing possibility not ruled out by experiments!!

- Gravity only or also matter in E.D. $\Rightarrow$ Plethora of NEW ptles

Neutrino Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_L = V_{MNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Maki, Nakagawa, Sakata '62

$$V_{MNS} = \begin{pmatrix} c_1 c_3 & c_1 s_3 & s_1 e^{-i\delta} \\ -c_2 s_3 - s_1 s_2 c_3 e^{i\delta} & c_2 c_3 - s_1 s_2 s_3 e^{i\delta} & c_1 s_2 \\ s_2 s_3 - s_1 c_2 c_3 e^{i\delta} & -s_2 c_3 - s_1 c_2 s_3 e^{i\delta} & c_1 c_2 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i(\phi_3+\delta)} \end{pmatrix}$$

$c_i \equiv \cos\theta_i$; $s_i = \sin\theta_i$

extra Majorana phases, irrel. for osc.

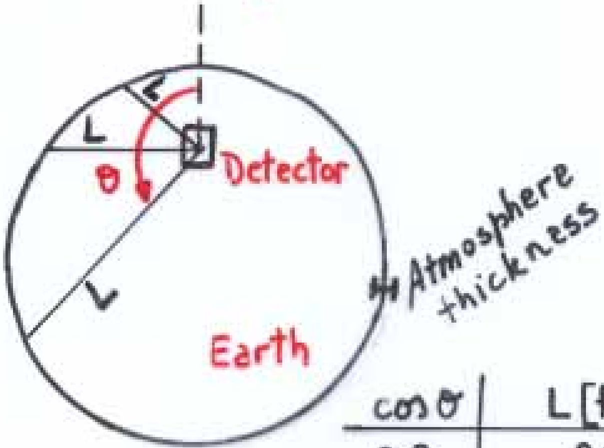
- *experimental indications of ν masses & mixings*

I) Atmospheric Neutrino oscillations

- Super-Kamiokande → zenith angle dependent deficit in ν_μ flux

SuperK Collab.

$P_{\nu_\mu \nu_\mu} < 1$; $P_{\nu_e \nu_e} \simeq 1$



$\cos\theta$	L [km]
0.8	25
0	500
-0.8	10.000

- if leading oscillation

$$P(\nu_\alpha \to \nu_\beta) = A_{\alpha\beta} \sin^2 \Delta m_{ATM}$$

with

$$A_{\mu\tau} = \cos^2\theta_1 \sin^2 2\theta_2$$

$$A_{\mu e} = \sin^2\theta_2 \sin^2 2\theta_1$$

$$A_{e\tau} = \cos^2\theta_2 \sin^2 2\theta_1$$

same for $\bar{\nu}$, no CP in lead. osc.

Barger, Pakvasa, Weiler ('80)

$$\Delta m_{ATM} = 1.27\, \delta m^2_{ATM} [eV^2]\, L[km] / E[GeV]$$