Lectures on Phenomenology

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Lecture 3:

- Limitations of the Standard Model
- Neutrino masses and mixing
- Supersymmetric extensions of the Standard Model
- Electroweak precision tests: SM vs. MSSM

The SM cannot be the ultimate theory

– doesn't contain gravity

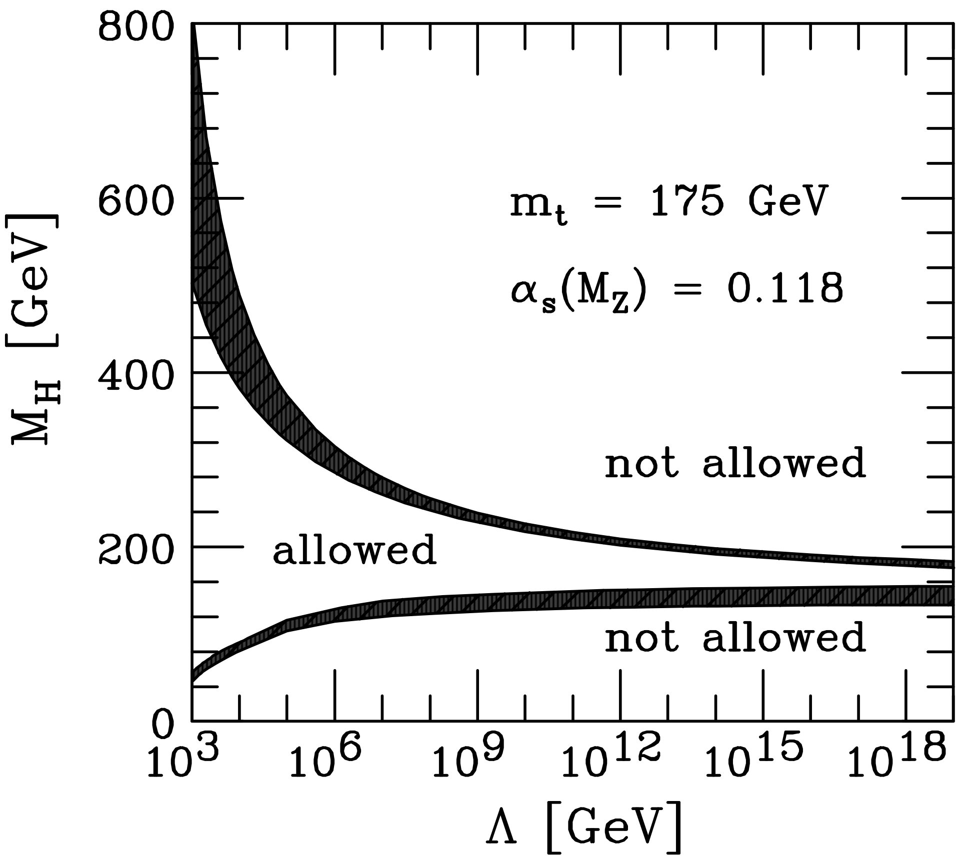
– further problems: "hierarchy problem", . . .

Up to which energy scale Λ can it be valid?

– $\Lambda < M_\mathrm{P} \approx 10^{19}$ GeV
(inclusion of gravity effects necessary)

– hierarchy problem: Higgs mass unstable w.r.t. large quantum corrections
$\Rightarrow \delta M_\mathrm{H}^2 \sim \Lambda^2$

– stability of Higgs potential:



[*T. Hambye, K. Riesselmann '97*]

Supersymmetry:

Symmetry between fermions and bosons

$$\begin{aligned} Q|\text{boson}\rangle &= |\text{fermion}\rangle \\ Q|\text{fermion}\rangle &= |\text{boson}\rangle \end{aligned}$$

$\Rightarrow$ solution of hierarchy problem:

large quantum corrections of fermions and bosons compensate each other

$\Rightarrow$ works if mass scale of SUSY partners

$$M_{\text{SUSY}} \lesssim 1\,\text{TeV}$$

$\Rightarrow$ low-energy SUSY provides attractive solution of hierarchy problem

Further properties of SUSY theories

- Gauge coupling unification:

  Running of gauge couplings: unify at high scale $M_{\text{GUT}} \approx 10^{16}$ GeV (for $M_{\text{SUSY}} = \mathcal{O}(1\text{ TeV})$)

  $\Leftrightarrow$ "Grand unified theories" (GUTs)

- Local SUSY $\Leftrightarrow$ gravity

- Radiative electroweak symmetry breaking:

  emerges naturally at scale $\sim 10^2$ GeV for $100\text{ GeV} \lesssim m_{\text{t}} \lesssim 200\text{ GeV}$

- Lightest SUSY particle (LSP):

  $\Rightarrow$ candidate for cold dark matter in the universe

- ...

Other recent proposals for solving hierarchy problem in models with extra spatial dimensions:

E.g.: Gravity in large extra dimensions
[*N. Arkani-Hamed, S. Dimopoulos, G. Dvali '98*]

Gravity propagates in δ large extra spatial dimensions

fundamental Planck scale in $4+\delta$-dimensional space, M_*, is of order 1 TeV

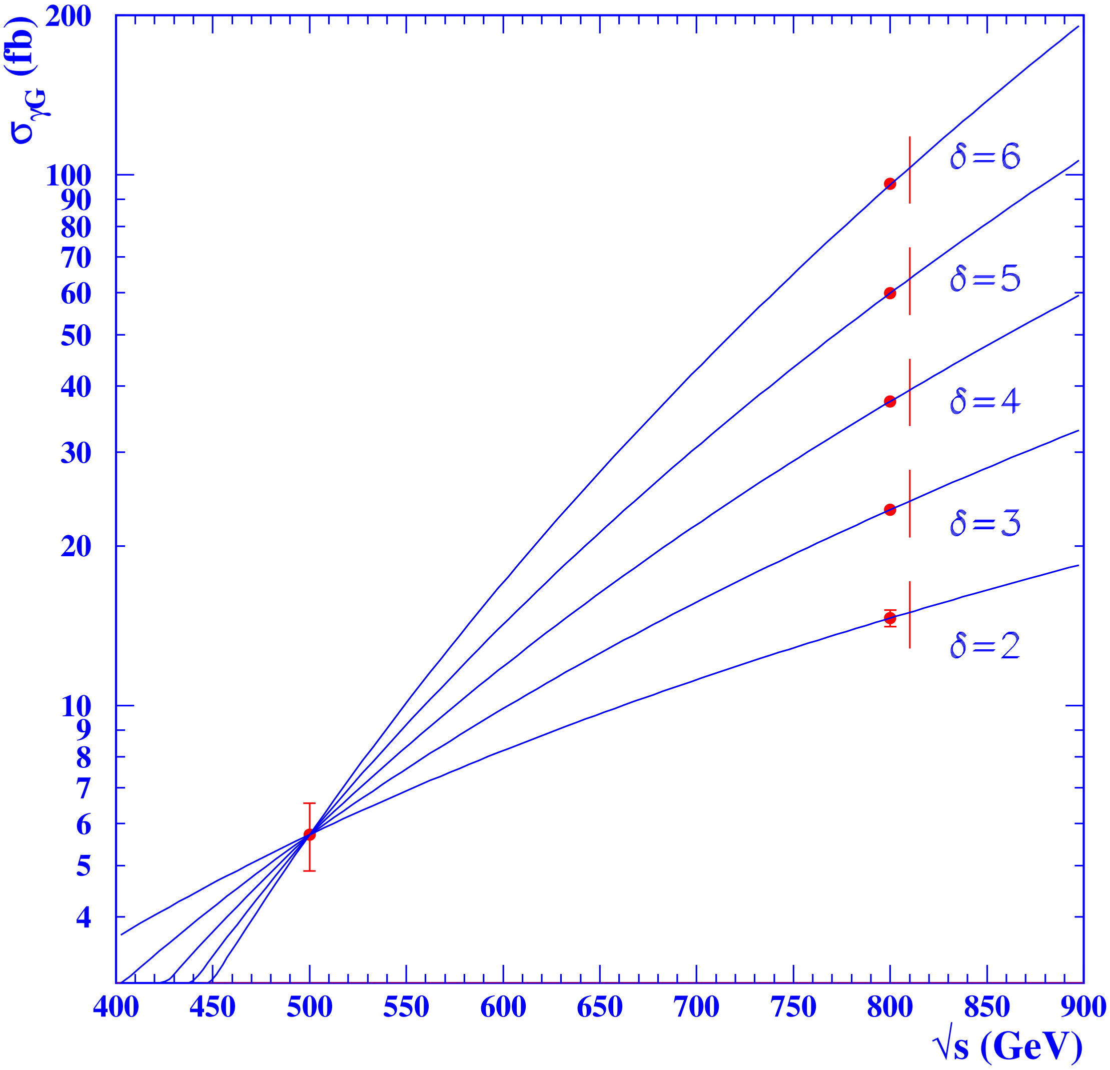
$$M_\mathrm{P}^2 = V_\delta \, M_*^{2+\delta}$$

$\Rightarrow$ large value of M_P related to relatively large volume V_δ (10^{-3} m–10^{-15} m for $\delta = 2$–6) of extra dimensions

$\Rightarrow$ should have observable signatures in TeV-scale experiments

E.g.: graviton emission, $e^+e^- \to \gamma/Z + G_n$

determination of δ from LC measurements of single photon cross section at $\sqrt{s} = 500$ GeV and $\sqrt{s} = 800$ GeV with polarized e^- and e^+ beams: [*TESLA TDR '01*]



Neutrino masses and mixing

SM requires massless neutrinos

contains no right-handed neutrinos

We now have compelling experimental evidence that neutrinos have non-zero mass

$\Rightarrow$ **Experimental evidence for physics beyond the Standard Model**

Evidence both from

neutrinos emitted from the sun (solar neutrinos): verification of flavor conversion
$\nu_e \to \nu_\mu$ or ν_τ at $\approx 5\sigma$

atmospheric neutrinos:
disappearance of ν_μ at $> 15\ \sigma$, most likely to ν_τ

Most likely explanation: neutrino oscillations

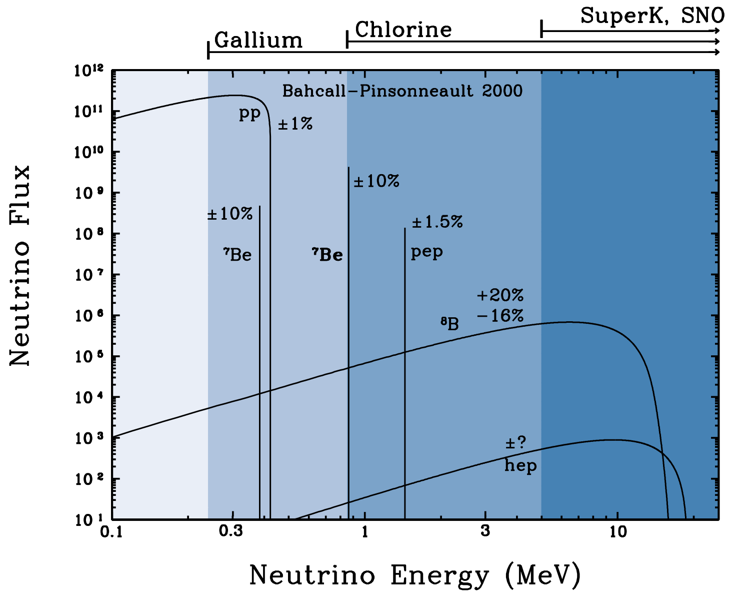
Will soon be tested with neutrino beams from reactors and accelerators

II. Global Fits

Solar Neutrinos

- The sun emits $\nu_e's$.

- Detected at

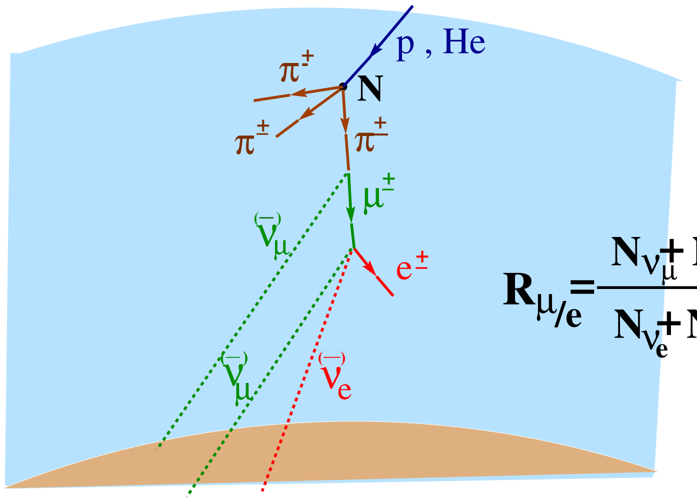


	Experiment	Detection	Flavour	$E_{\rm th}$ (MeV)	$\frac{\text{Data}}{\text{BP00}}$
radio-chemical	Homestake	$^{37}\mathrm{Cl}(\nu, e^-)^{37}\mathrm{Ar}$	ν_e	$E_\nu > 0.81$	0.35 ± 0.06
	Sage + Gallex+GNO	$^{71}\mathrm{Ga}(\nu, e^-)^{71}\mathrm{Ge}$	ν_e	$E_\nu > 0.23$	0.55 ± 0.05
real time	Kam $\Rightarrow$ SK	ES $\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$ $\left(\frac{\sigma_{\mu\tau}}{\sigma_e} \simeq \frac{1}{6}\right)$	$E_e > 5$	0.46 ± 0.09
	SNO	CC $\nu_e d \to p p e^-$	ν_e	$T_e > 5$	$0.35 \pm 0.07^*$
		NC $\nu_x d \to \nu_x d$	$\nu_e, \nu_{\mu/\tau}$	$T_\gamma > 5$	$1.01 \pm 0.23^*$
		ES $\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$	$T_e > 5$	$0.46 \pm 0.23^*$

(* For undistorted ^{8}B spectrum)

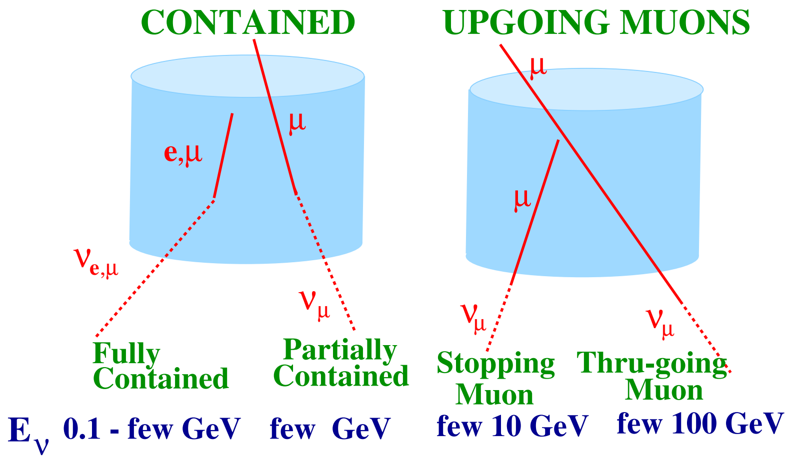
Atmospheric Neutrinos

$\nu_{e,\mu}$ are produced by interaction of cosmic rays (p, He . . .) with the atmosphere

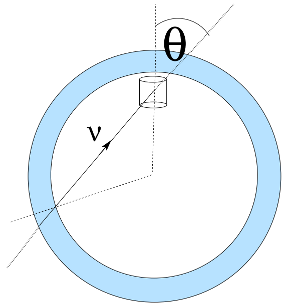


$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar{\nu}_\mu}}{N_{\nu_e} + N_{\bar{\nu}_e}} \sim 2$$

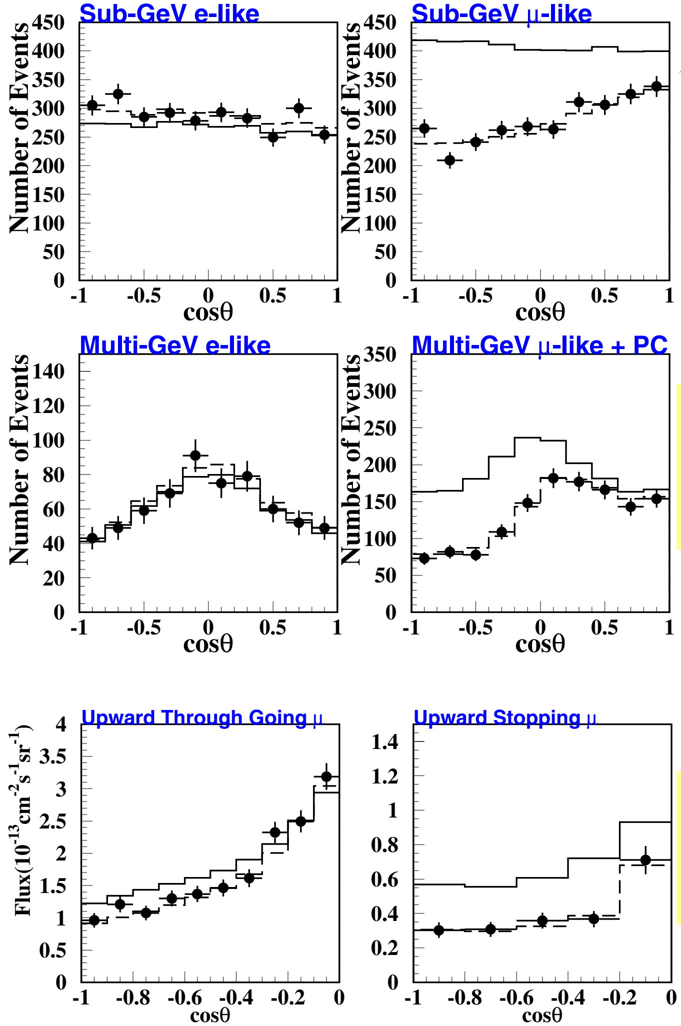
EVENT CLASSIFICATION



Angular Distribution at SK



ν_e in agreement with SM



→ Deficit grows with L

→ Decreases with E

If neutrinos have mass $\Rightarrow$ mixing as in quark sector

mixing matrix for three neutrino generations described by 3 mixing angles and 1 complex phase

LEP results
$\Rightarrow$ number of light ($< M_Z/2$) active neutrinos $= 3$

Weak eigenstate $|\nu_\alpha\rangle$ produced in $l_\alpha + N \to \nu_\alpha + N'$ is linear combination of mass eigenstates $|\nu_i\rangle$:

$$|\nu_\alpha\rangle = \sum_{i=1}^{n} V_{\alpha i} |\nu_i\rangle$$

After distance L (time t):
mass eigenstates evolve with $e^{-iE_i t}$

$\Rightarrow$ can be detected with different flavor β with probability $|\langle \nu_\beta | \nu(t) \rangle|^2$

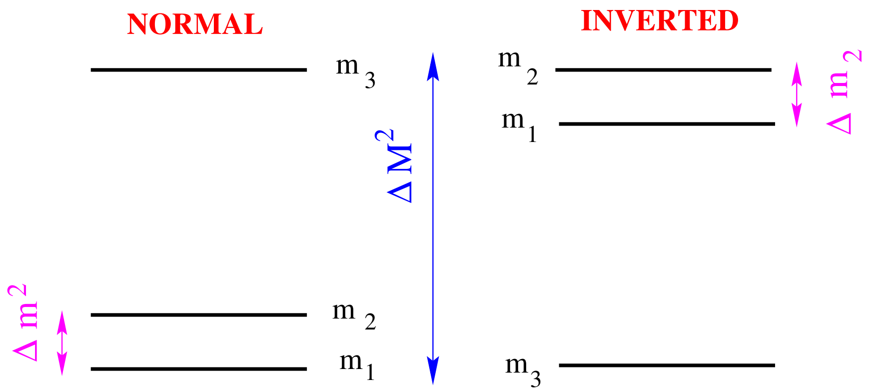
$\Rightarrow$ neutrino oscillations

Solar + Atmospheric 3ν Oscillations

U: 3 angles, 1 CP-phase
+ (2 Majorana phases)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Two mass schemes



2ν oscillation analysis $\Rightarrow \Delta m^2 = \Delta m^2_\odot \ll \Delta M^2 \simeq \pm\Delta m^2_{atm} \simeq \pm\Delta m^2_{32} \simeq \pm\Delta m^2_{31}$

$\Rightarrow$ Generic 3ν effects in ATM+SOLAR+CHOOZ oscillations :

	Potential Dependence							$\Delta m^2 \ll \Delta M^2$						
	θ_{12}	θ_{13}	θ_{23}	Δm^2	ΔM^2	δ	N/I	θ_{12}	θ_{13}	θ_{23}	Δm^2	ΔM^2	δ	N/I
Solar	X	X		X	X		X	X	X		X			
Atmos	X	X	X	X	X	X	X		X	X		X		X?
Chooz	X	X		X	X		X	X	X		X			

CP violation *Unobservable*
2 wavelengths *Unobservable*
N versus I *Below sensitivity*
θ_{13}?

Additional ingredient: neutrinos have no charge

Right-handed neutrino ν_R is electroweak singlet

$\Rightarrow$ can have Majorana mass term $M\,\overline{\nu^c_\mathrm{R}}\nu_\mathrm{R}$

Explicit mass term, not related to electroweak symmetry breaking

$\Rightarrow$ $M \gg$ electroweak scale naturally

$\Rightarrow$ “Seesaw mechanism”:

$$\begin{pmatrix} \nu_\mathrm{L} & \nu_\mathrm{R} \end{pmatrix} \begin{pmatrix} 0 & m \\ m^T & M \end{pmatrix} \begin{pmatrix} \nu_\mathrm{L} \\ \nu_\mathrm{R} \end{pmatrix}$$

$\Rightarrow$ yields for $m \ll M$:

$$\underbrace{m^T \frac{1}{M} m}_{\text{light}} \qquad\qquad \underbrace{M}_{\text{heavy}}$$

Works approximately if

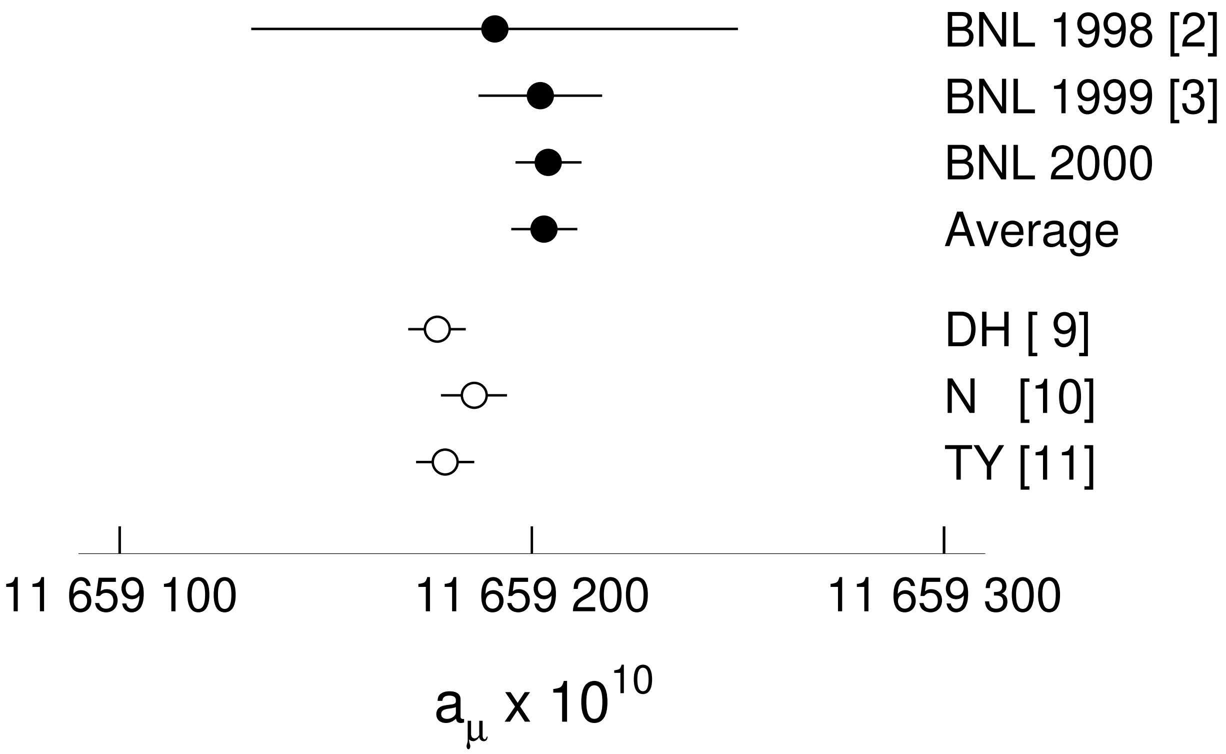
$m \approx$ electroweak scale: $\sim 10^2$ GeV

$M \approx$ GUT scale $\sim 10^{16}$

$\Rightarrow$ neutrino mass $\sim m^2/M \sim 10^{-3}$ eV

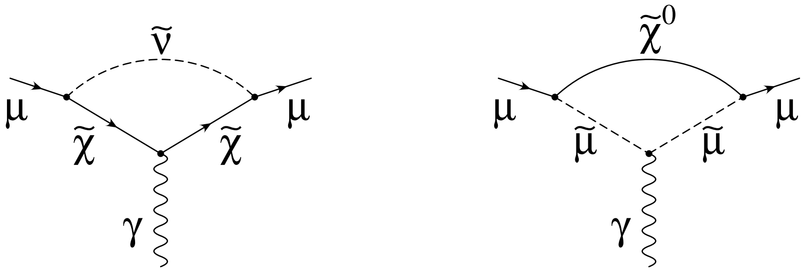
$\Rightarrow$ Further motivation for new physics close to GUT scale

Experimental result for anomalous magnetic moment of the muon vs. SM prediction:
[*Muon $(g-2)$ Collaboration '02*]



$\Rightarrow$ a_μ(exp) $-$ a_μ(SM): 1.6–2.6 σ deviation

Compatible with effect of SUSY contributions to a_μ



with $\tilde{m} \simeq$ (60 GeV)$\sqrt{\tan\beta}$

SUSY phenomenology:

The Minimal Supersymmetric Standard Model:

Superpartners for Standard Model particles:

$$\Big[u, d, c, s, t, b\Big]_{L,R} \quad \Big[e, \mu, \tau\Big]_{L,R} \quad \Big[\nu_{e,\mu,\tau}\Big]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$\Big[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\Big]_{L,R} \quad \Big[\tilde{e}, \tilde{\mu}, \tilde{\tau}\Big]_{L,R} \quad \Big[\tilde{\nu}_{e,\mu,\tau}\Big]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^{0}_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector:
Two Higgs doublets, physical states: $h^0, H^0, A^0, H^{\pm}$

Exact SUSY: $m_f = m_{\tilde{f}}, \; \ldots$

$\Rightarrow$ SUSY must be broken: $M_{\text{SUSY}} \lesssim 1$ TeV

SUSY breaking mechanism not well understood

Unconstrained MSSM:

no particular SUSY breaking mechanism assumed, parameterization of possible soft SUSY-breaking terms

$\Rightarrow$ relations between dimensionless couplings unchanged
no quadratic divergencies (hierarchy problem)

most general case:

$\Rightarrow$ 105 new parameters: masses, mixing angles, phases

Good phenomenological description for universal breaking terms (FCNC, . . .)

Specific models for soft-SUSY breaking:

"Hidden sector":	$\longrightarrow$	Visible sector:
SUSY breaking		MSSM

"Gravity-mediated": mSUGRA
"Gauge-mediated": GMSB
"Anomaly-mediated": AMSB
. . .

Determination of SUSY parameters

$\Rightarrow$ Patterns of SUSY breaking

R parity

minimal SUSY extension of the SM contains only terms in the Lagrangian with even number of SUSY particles

$\Rightarrow$ additional symmetry: "R parity"

$\Rightarrow$ all SM particles have even R parity, all SUSY particles have odd R parity

Phenomenological consequences of R parity conservation:

- SUSY particles can only be produced in pairs, e.g. $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$

- Decay of SUSY particles into SM particles + odd number of SUSY particles

  $\Rightarrow$ Lightest SUSY particle (LSP) is stable

- All SUSY particles will eventually decay into LSP

  $\Rightarrow$ Decay cascades of heavy SUSY particles

- LSP stable

  ⇒ some LSP must have survived from Big Bang

  ⇒ Weakly interacting massive particle ("WIMP")
  (otherwise ruled out from bounds on exotic isotopes etc.)

  ⇒ Candidate for cold dark matter in the Universe if $M_{\text{SUSY}} \lesssim 1$ TeV

- LSP neutral, uncolored

  ⇒ leaves no traces in collider detectors

  ⇒ Typical SUSY signatures: "missing energy"

Relations between SUSY parameters

Symmetry properties of MSSM Lagrangian (SUSY, gauge invariance) give rise to coupling and mass relations

Soft SUSY breaking does not affect SUSY relations between dimensionless couplings

E.g.: gauge boson–fermion coupling

=

gaugino–fermion–sfermion coupling

for U(1), SU(2), SU(3) gauge groups

In SM: all masses are free input parameters
(except M_W–M_Z interdependence)

MSSM:

- Upper bound on mass of lightest $\mathcal{CP}$-even Higgs boson

- Relations between neutralino and chargino masses

- Sfermion mass relations, e.g.

$$m^2_{\tilde{e}_L} = m^2_{\tilde{\nu}_L} - M^2_W \cos(2\beta)$$

All relations receive corrections from loop effects

$\Leftrightarrow$ effects of soft SUSY breaking, electroweak symmetry breaking

$\Rightarrow$ Experimental verification of parameter relations is a crucial test of SUSY!

The Higgs sector of the MSSM

Two Higgs doublets:

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1^0 + i\chi_1^0)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2^0 + i\chi_2^0)/\sqrt{2} \end{pmatrix}
\end{aligned}
$$

Higgs potential:

$$
\begin{aligned}
V &= m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2(\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
&\quad + \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2
\end{aligned}
$$

gauge couplings, in contrast to SM

Mixing of $\mathcal{CP}$-even, $\mathcal{CP}$-odd, charged fields:

$$
\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}
$$

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \end{pmatrix}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

$$\tan(2\alpha) = \tan(2\beta)\frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}$$

Three Goldstone bosons (as in SM): G^0, $G^\pm$

$\longrightarrow$ longitudinal components of $W^\pm$, Z

$\Rightarrow$ Five physical states: $h^0, H^0, A^0, H^\pm$

h, H: neutral, $\mathcal{CP}$-even

A^0: neutral, $\mathcal{CP}$-odd

$H^\pm$: charged

Gauge-boson masses:

$$M_W^2 = \frac{1}{2}g'^2(v_1^2 + v_2^2), \quad M_Z^2 = \frac{1}{2}(g^2 + g'^2)(v_1^2 + v_2^2),$$

$$M_\gamma = 0$$

Parameters in Higgs potential V (besides g, g'):

$$v_1,\ v_2,\ m_1,\ m_2,\ m_{12}$$

relation for M_W^2, M_Z^2
$\Rightarrow$ 1 condition

minimization of V w.r.t. neutral Higgs fields H_1^1, H_2^2
$\Rightarrow$ 2 conditions

$\Rightarrow$ only two free parameters remain in V
conventionally chosen as

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

$\Rightarrow$ m_h, m_H, mixing angle α, $m_{H^\pm}$:

no free parameters, can be predicted

In lowest order:

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

Predictions for m_{h}, m_{H} from diagonalization of tree-level mass matrix:

$\phi_1 - \phi_2$ basis:

$$M^{2,\text{tree}}_{\text{Higgs}} = \begin{pmatrix} m^2_{\phi_1} & m^2_{\phi_1\phi_2} \\ m^2_{\phi_1\phi_2} & m^2_{\phi_2} \end{pmatrix} =$$

$$\begin{pmatrix} M_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -(M_A^2 + M_Z^2)\sin\beta\cos\beta \\ -(M_A^2 + M_Z^2)\sin\beta\cos\beta & M_A^2\cos^2\beta + M_Z^2\sin^2\beta \end{pmatrix}$$

$$\Big\Downarrow \quad \leftarrow \quad \text{Diagonalization}, \alpha$$

$$\begin{pmatrix} m^{2,\text{tree}}_{H} & 0 \\ 0 & m^{2,\text{tree}}_{h} \end{pmatrix}$$

Tree-level result for m_{h}, m_{H}:

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

$\Rightarrow$ $m_{\mathsf{h}} \leq M_{\mathsf{Z}}$ at tree level

$\Rightarrow$ Light Higgs boson h required in SUSY

Higgs couplings, tree level:

$$g_{\rm hVV} = \sin(\beta - \alpha)\, g_{\rm HVV}^{\rm SM}, \qquad V = W^\pm, Z$$

$$g_{\rm HVV} = \cos(\beta - \alpha)\, g_{\rm HVV}^{\rm SM}$$

$$g_{\rm hAZ} = \cos(\beta - \alpha)\, \frac{g'}{2\cos\theta_{\rm W}}$$

$$g_{\rm hb\bar{b}}, g_{\rm h\tau^+\tau^-} = -\frac{\sin\alpha}{\cos\beta}\, g_{\rm Hb\bar{b}, H\tau^+\tau^-}^{\rm SM}$$

$$g_{\rm ht\bar{t}} = \frac{\cos\alpha}{\sin\beta}\, g_{\rm Ht\bar{t}}^{\rm SM}$$

$$g_{\rm Ab\bar{b}}, g_{\rm A\tau^+\tau^-} = \gamma_5 \tan\beta\, g_{\rm Ab\bar{b}}^{\rm SM}$$

$\Rightarrow$ $g_{\rm hVV} \leq g_{\rm HVV}^{\rm SM}$

$g_{\rm hVV}$, $g_{\rm HVV}$, $g_{\rm hAZ}$ cannot all be small

$g_{\rm hb\bar{b}}, g_{\rm h\tau^+\tau^-}$: significant suppression or enhancement w.r.t. SM coupling possible

Measurement of $m_{\rm h}$, Higgs couplings

$\Rightarrow$ test of the theory (more directly than in SM)

Specific SUSY-breaking scenarios:

Experimental constraints give guidance concerning possible "organizing principle" for soft breaking terms in MSSM:

Strong constraints on

– lepton number violation (e.g. $\mu \to e\gamma$)

– flavor changing neutral currents (FCNC, e.g. $b \to s\gamma$)

– electric dipole moments

...

$\Rightarrow$ Constraints on flavor off-diagonal terms, $\mathcal{CP}$-violating phases

$\Rightarrow$ Experimental constraints satisfied if SUSY-breaking is sufficiently "universal"

Can occur if SUSY breaking in "hidden sector" is communicated to visible sector by flavor-blind interactions

Gravity-mediated SUSY breaking:

communication via gravitational interactions

terms (non-renormalizable) in supergravity Lagrangian proportional to $1/M_\mathrm{P}$ and SUSY-breaking v.e.v.

$\Rightarrow$ soft SUSY-breaking terms of MSSM

minimal version (universality assumptions): mSUGRA

Gauge-mediated SUSY breaking:

"Messenger fields" couple to SUSY-breaking v.e.v. in hidden sector

interact with MSSM fields via ordinary electroweak and QCD gauge interactions

Anomaly-mediated SUSY breaking:

SUSY-breaking happens on separate brane

communicated to visible sector via super-Weyl anomaly

mSUGRA

parameters: $m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sign}(\mu)$

m_0: universal scalar mass parameter

$m_{1/2}$: universal gaugino mass parameter

A_0: universal trilinear coupling

$\tan\beta$: ratio of Higgs vacuum expectation values

$\mathrm{sign}(\mu)$: sign of supersymmetric Higgs parameter

m_0, $m_{1/2}$, A_0: GUT scale parameters

$\Rightarrow$ particle spectra from renormalization group running to weak scale

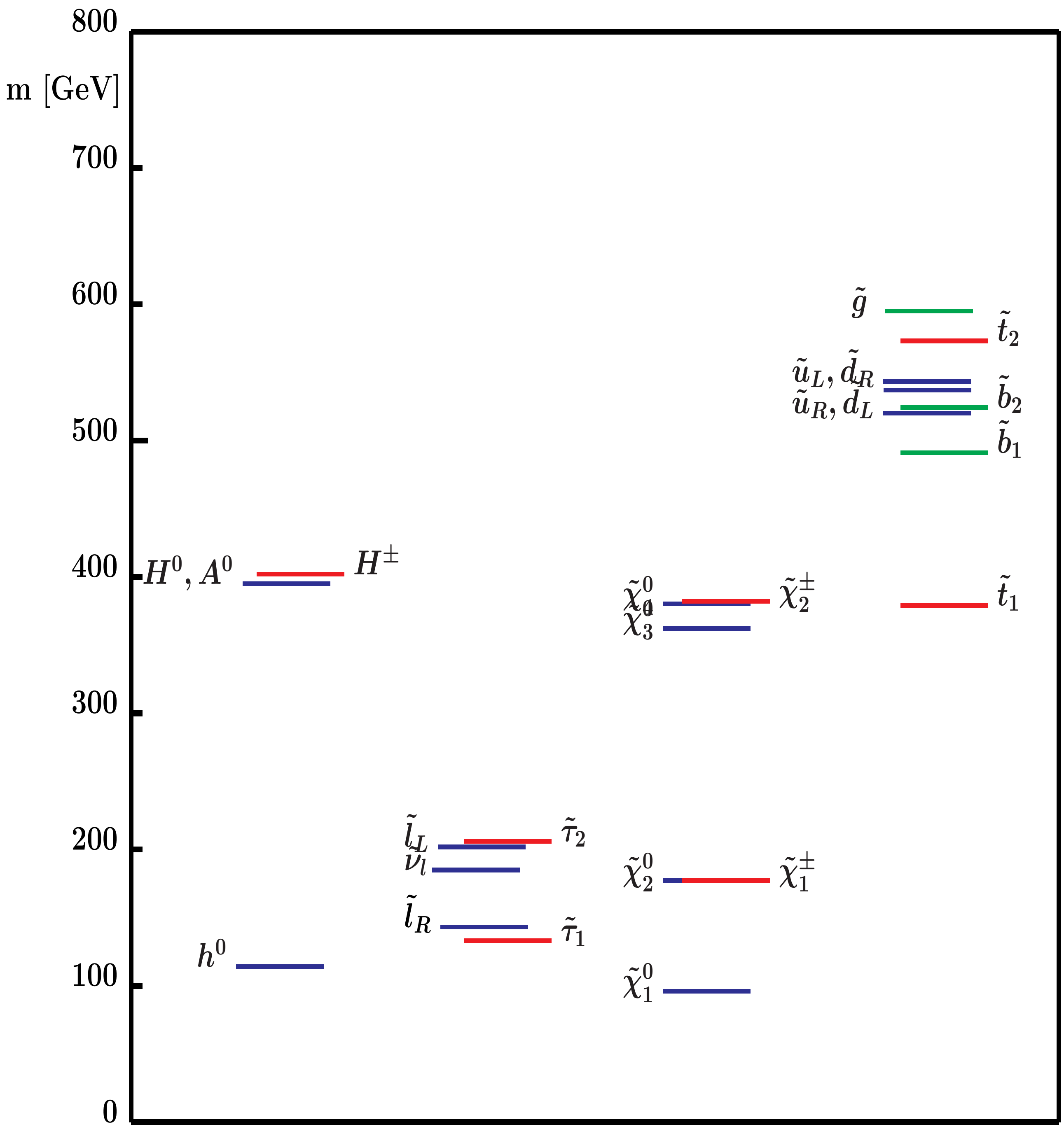
LSP is usually lightest neutralino

gaugino masses run in same way as gauge couplings
$\Rightarrow$ gluino heavier than charginos, neutralinos

The "Snowmass Points and Slopes" (SPS): benchmarks for SUSY searches

www.ippp.dur.ac.uk/∼georg/sps

SPS 1a: "typical" mSUGRA scenario



GMSB

parameters: $M_{\text{mes}}, N_{\text{mes}}, \Lambda, \tan\beta, \text{sign}(\mu)$

M_{mes}: messenger mass scale

N_{mes}: messenger index (number of messenger multiplets)

Λ: universal soft SUSY breaking mass scale felt by low-energy sector

LSP is always the gravitino, $m_{\frac{3}{2}} \approx 10^{-9}$ GeV

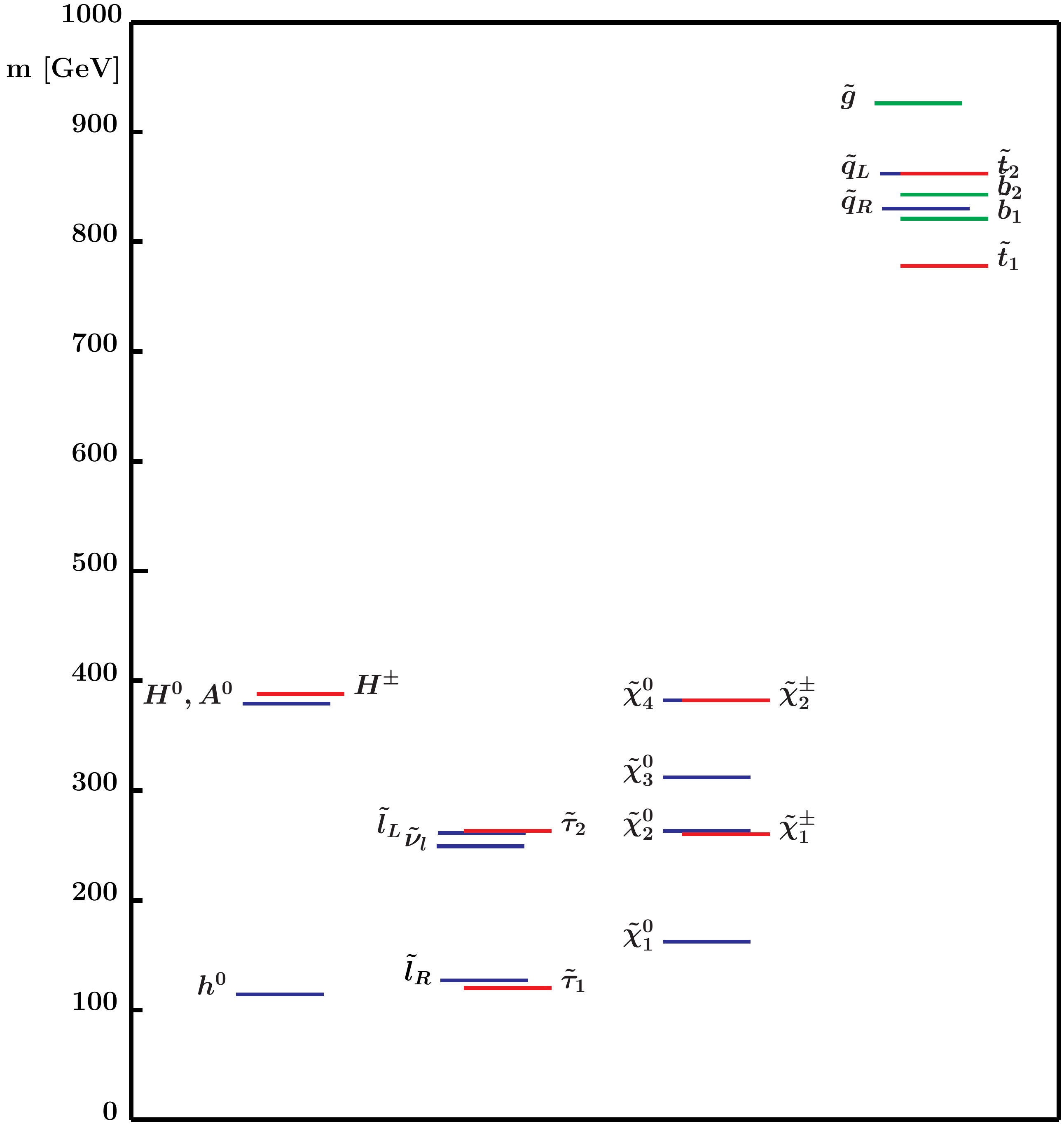
Next-to-lightest SUSY particle (NLSP): $\tilde{\chi}_1^0$ or $\tilde{\tau}_1$

can decay into LSP inside or outside the detector

masses of SUSY particles from loop diagrams involving messenger fields, couple to MSSM fields via ordinary gauge interactions

$\Rightarrow$ colored particles usually heavier than weakly interacting particles

SPS 7: GMSB scenario with $\tilde{\tau}$ NLSP



AMSB

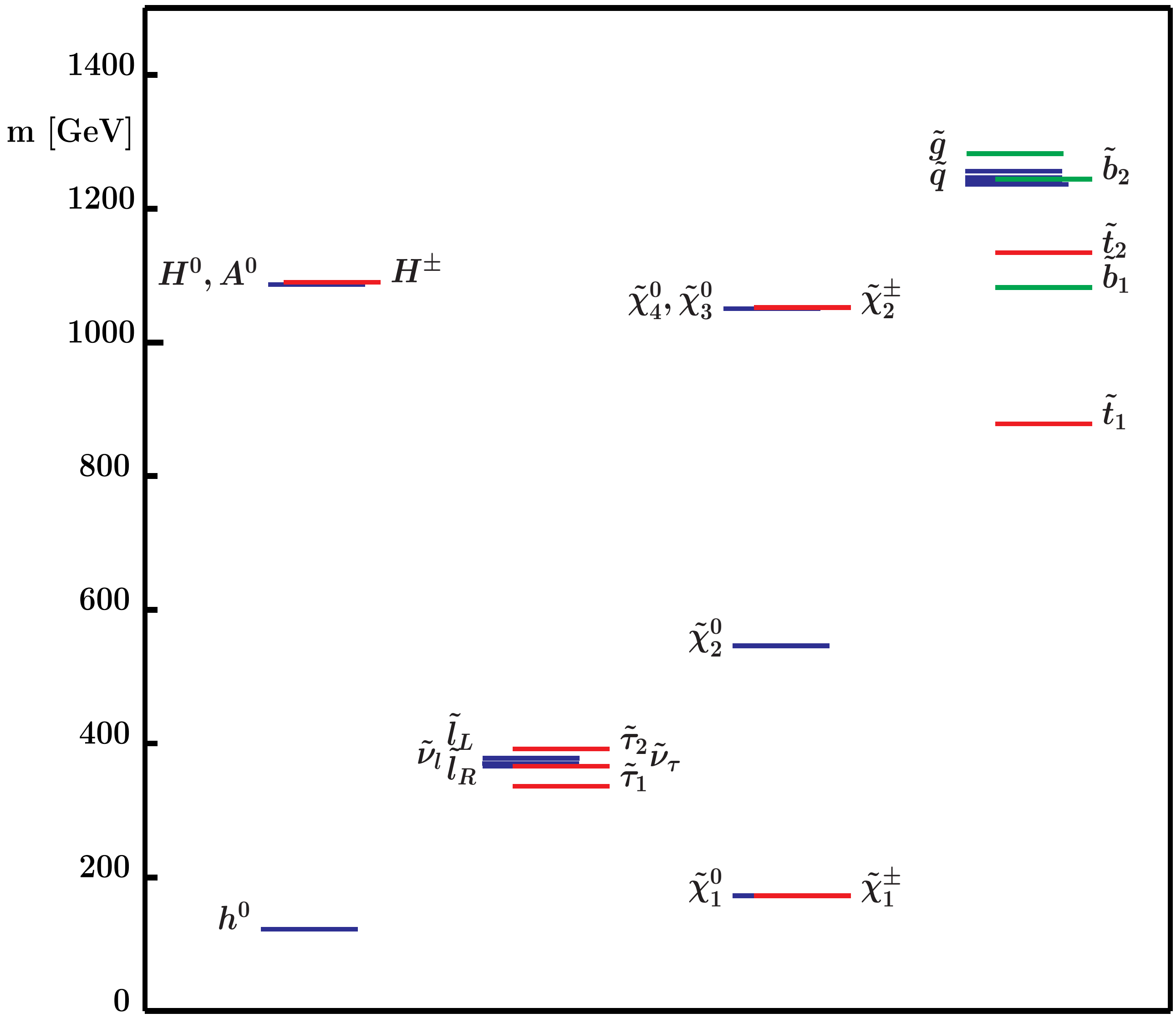
parameters: $m_{\mathsf{aux}}, m_0, \tan\beta, \mathrm{sign}(\mu)$

m_{aux}: overall scale of SUSY particle masses

m_0: phenomenological parameter: universal scalar mass term

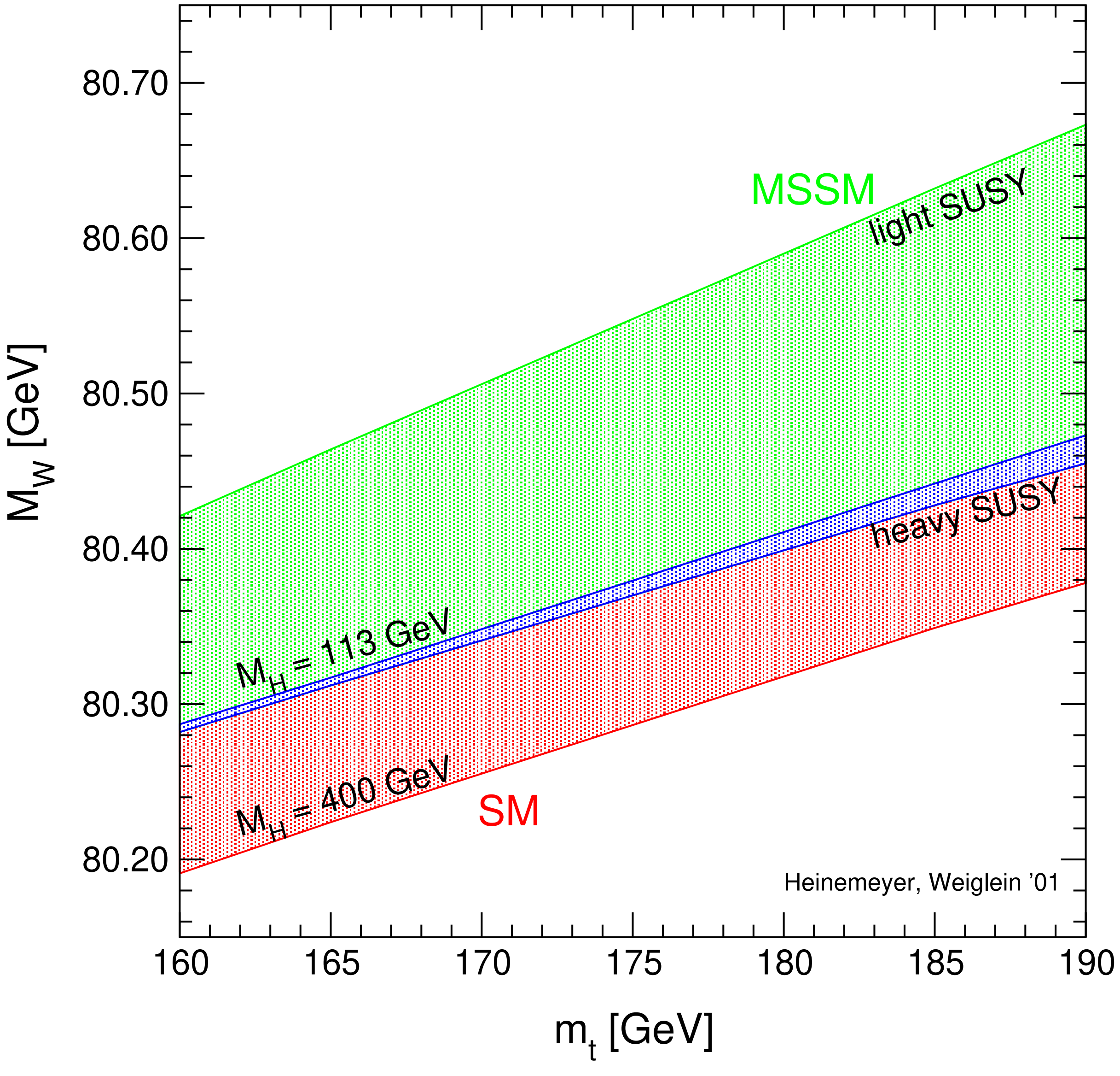
typical feature: very small neutralino–chargino mass difference

SPS 9: AMSB scenario



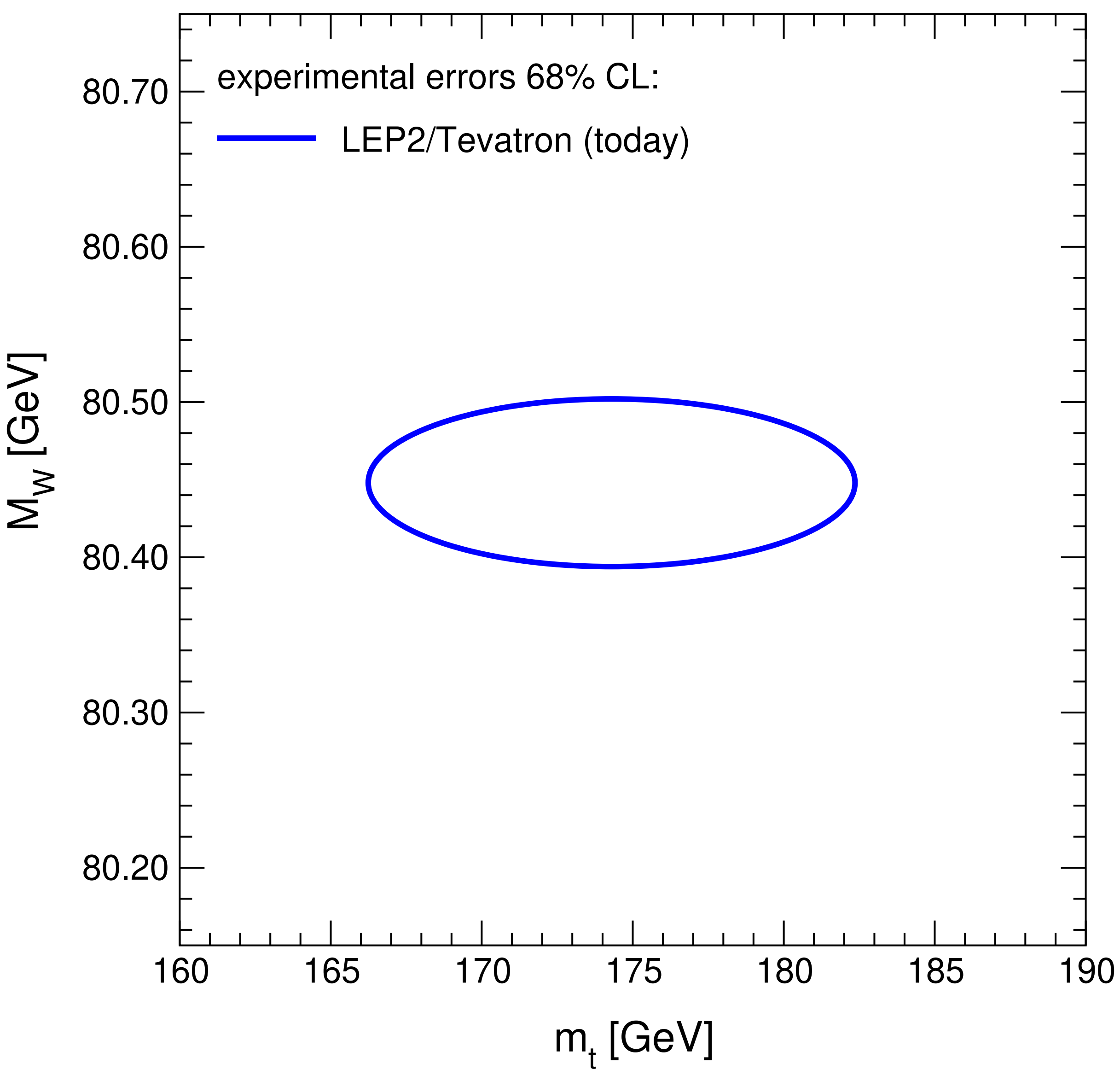
Electroweak precision tests: SM vs. MSSM

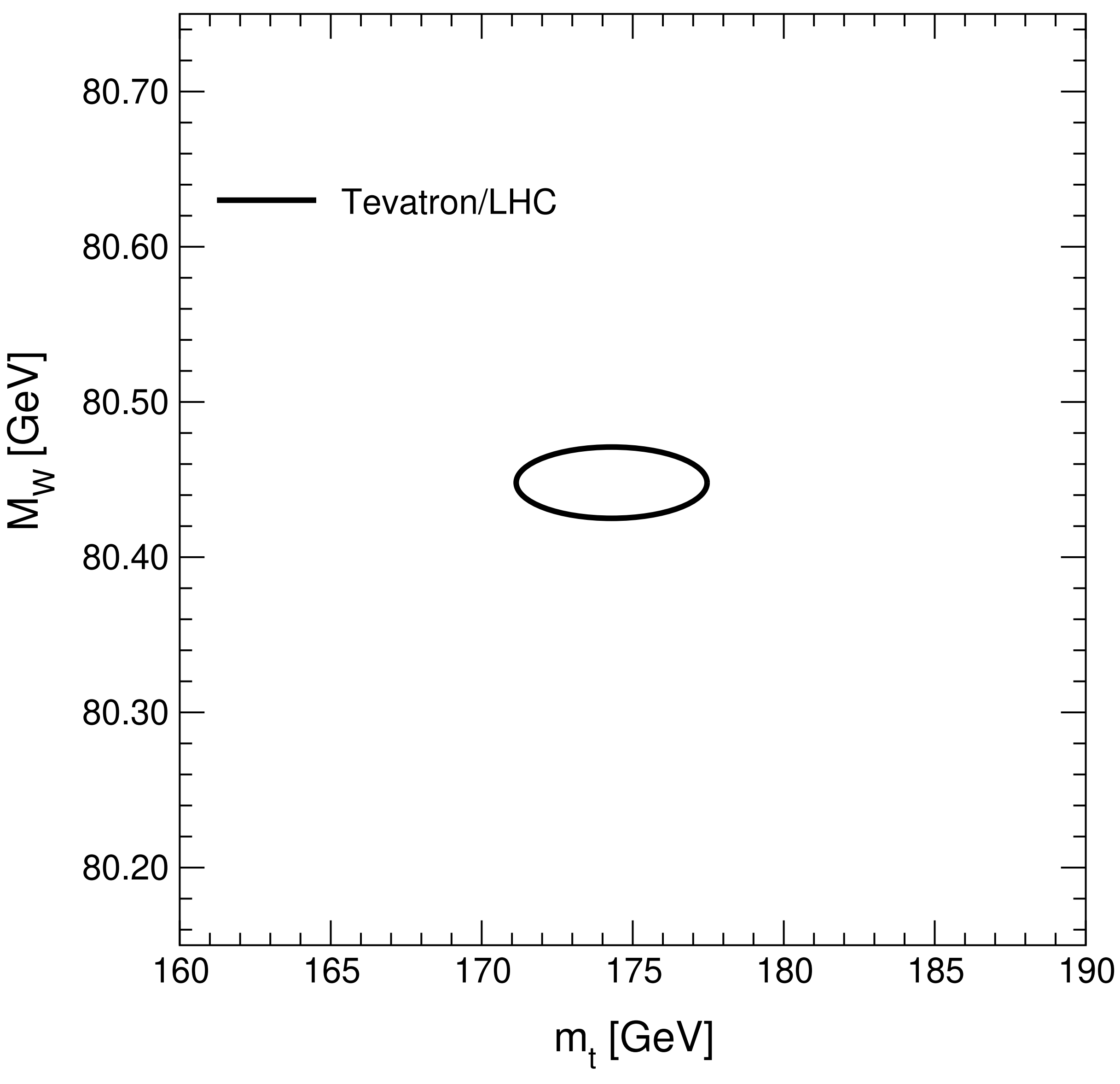
Prediction for M_W in the SM and the MSSM:
[*A. Djouadi, P. Gambino, S. Heinemeyer, W. Hollik, C. Jünger, G. W. '97*]
[*S. Heinemeyer, W. Hollik, G. W. '98*]



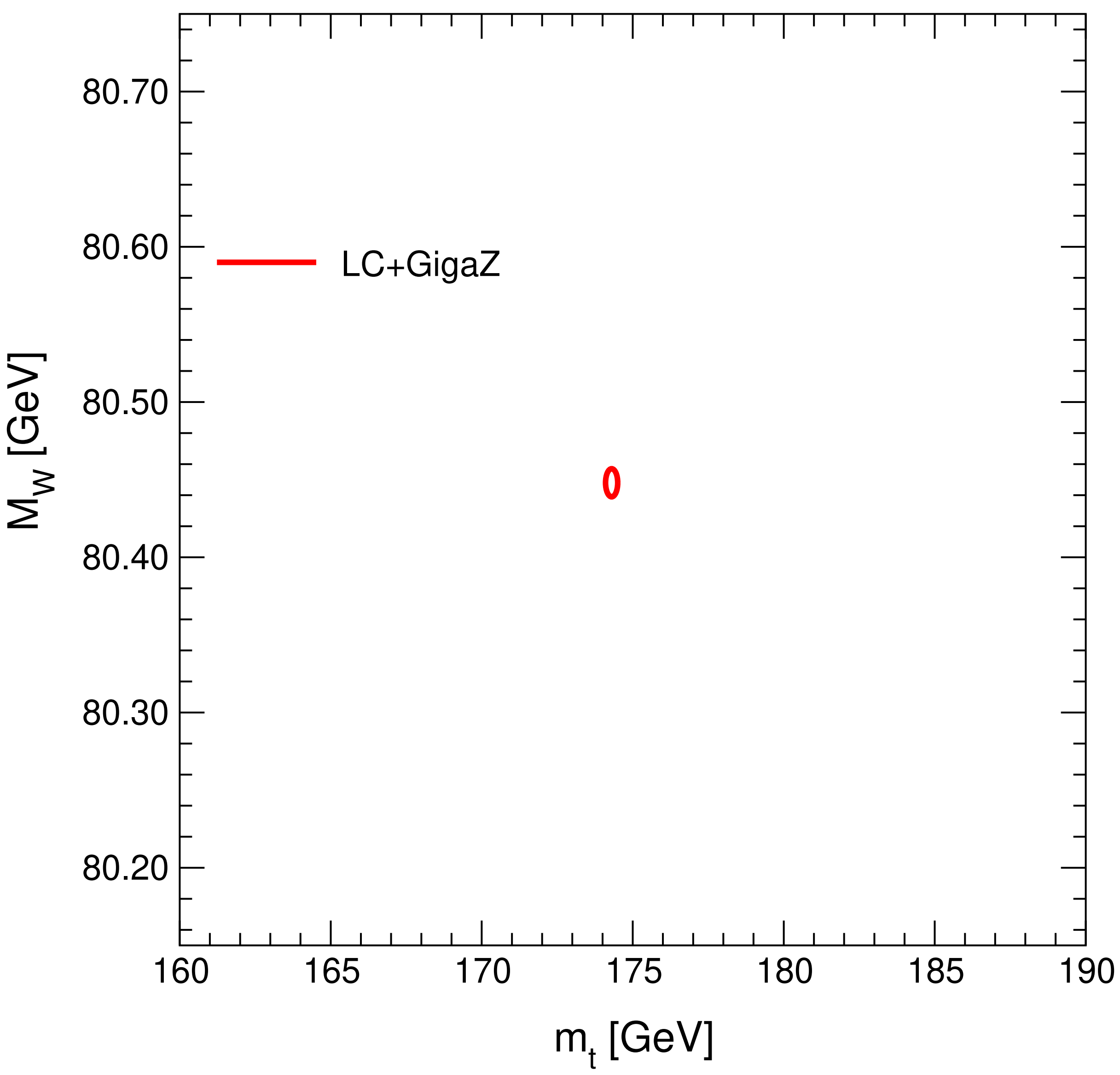
SM: M_H varied

MSSM: SUSY parameters varied


experimental errors 68% CL:
LEP2/Tevatron (today)
80.70
80.60
80.50
80.40
80.30
80.20
M_W [GeV]
160
165
170
175
180
185
190
m_t [GeV]

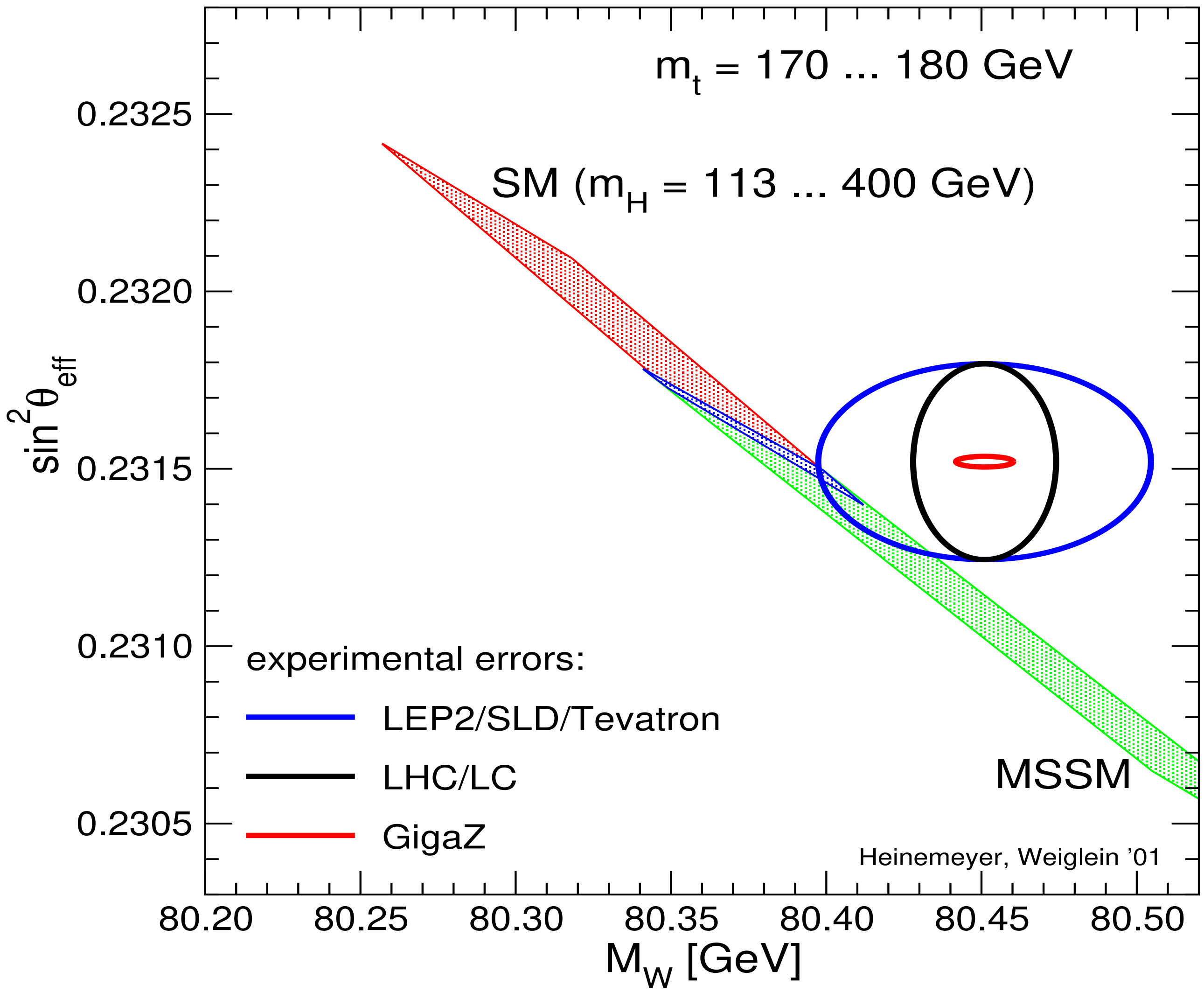


Tevatron/LHC
80.70
80.60
80.50
80.40
80.30
80.20
160
165
170
175
180
185
190
M_W [GeV]
m_t [GeV]



80.70
80.60
80.50
80.40
80.30
80.20
LC+GigaZ
M_W [GeV]
160
165
170
175
180
185
190
m_t [GeV]

Prediction for M_W, $\sin^2\theta_\mathrm{eff}$ in SM and MSSM:



$\Rightarrow$ Large improvement in experimental accuracy LEP/TevI $\to$ TevII/LHC/LC $\to$ GigaZ:

$\Rightarrow$ Very sensitive test of theory

Summary of Lecture 3:

- Standard Model cannot be the ultimate theory

  Hierarchy problem, . . .

  $\Rightarrow$ strong motivation for low-energy SUSY

- Neutrino masses and mixing:

  Experimental evidence for physics beyond the Standard Model

- SUSY theories:

  superpartners for SM particles required

  MSSM, most general parameterization:
  more than 100 new parameters

  Experimental constraints
  $\Rightarrow$ universal patterns of SUSY breaking preferred

  Specific SUSY-breaking scenarios (mSUGRA, GMSB, AMSB, . . .): 4–5 new parameters

- Electroweak precision tests:

  MSSM yields equally complete description as SM

  Comparison SM/MSSM prediction for M_{W}:

  Preference for non-zero SUSY contribution