Minimal Supersymmetric Standard Model (MSSM)

HIGGS SECTOR AND DARK MATTER

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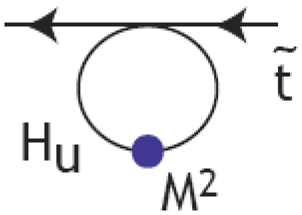
Radiative correction to Higgs mass

- Negative contribution

$$\mathcal{L} = -\left|y_t H_u \cdot \tilde{t}\right|^2$$



$$= -i y_t^2 \int \frac{d^4k}{(2\pi)^4} \frac{i}{k^2} (-i M_{H_u}^2) \frac{i}{k^2}$$

$$= y_t^2 M_{H_u}^2 \cdot \frac{i}{(4\pi)^2} \log \Lambda^2$$

Radiative electroweak symmetry breaking

$$\frac{dM_t^2}{d\log Q} = \frac{2}{(4\pi)^2}\cdot 1\cdot y_t^2[M_t^2 + M_{\bar{t}}^2 + M_{Hu}^2 + A_t^2] - \frac{8}{3\pi}\alpha_3 m_3^2 + \cdots$$

$$\frac{dM_{\bar{t}}^2}{d\log Q} = \frac{2}{(4\pi)^2}\cdot 2\cdot y_t^2[M_t^2 + M_{\bar{t}}^2 + M_{Hu}^2 + A_t^2] - \frac{8}{3\pi}\alpha_3 m_3^2 + \cdots$$

$$\frac{dM_{Hu}^2}{d\log Q} = \frac{2}{(4\pi)^2}\cdot 3\cdot y_t^2[M_t^2 + M_{\bar{t}}^2 + M_{Hu}^2 + A_t^2] + \cdots$$

Notice the sign

Notice the factor

H_u becomes negative

Higgs potential

$$V = \mu^2(H_u^{0*}H_u^0 + H_d^{0*}H_d^0) + M_{Hu}^2 H_u^{0*}H_u^0 + M_{Hd}^2 H_d^{0*}H_d^0$$
$$-(B\mu H_u^0 H_d^- + h.c.) + \frac{g^2+g'^2}{8}(H_u^{0*}H_u^0 - H_d^{0*}H_d^0)^2$$

Can you tell where each of the terms come from?

Minimizing the potential

$$\mu^2 + M_{Hu}^2 = B\mu \cot\beta + m_Z^2 \cos 2\beta/2$$
$$\mu^2 + M_{Hd}^2 = B\mu \tan\beta - m_Z^2 \cos 2\beta/2$$

$$\tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}$$

Maturalness and mu problem

$$\mu^2 = \frac{M_{Hd}^2 - \tan^2\beta\, M_{Hu}^2}{\tan^2\beta - 1} - \frac{1}{2} m_Z^2$$

or

$$m_Z^2 = 2\frac{M_{Hd}^2 - \tan^2\beta\, M_{Hu}^2}{\tan^2\beta - 1} - 2\mu^2$$

Mu-term cannot be much larger than SUSY breaking parameters.

SUSY scale cannot be very high

Charged Higges

- Charged Higges

$$H_u^+ = \cos\beta\, H^+ + \sin\beta\, G^+$$
$$H_d^- = \sin\beta\, H^- - \cos\beta\, G^-$$

Charged Goldstone boson eaten by $W^\pm$,

General Consideration about P and CP

Scalar versus pseudoscalar

$$\lambda \phi \bar{\psi}_L \psi_R + \mathrm{H.c.}$$

$$\lambda \phi \bar{\psi}_L \psi_R + \mathrm{H.c.} = \Re[\lambda\phi]\bar{\psi}\psi + \Im[\lambda\phi](i\bar{\psi}\gamma_5\psi)$$

$\bar{\psi}\psi \xrightarrow{\text{P and CP}} \bar{\psi}\psi$

$(i\bar{\psi}\gamma_5\psi) \xrightarrow{\text{P and CP}} -(i\bar{\psi}\gamma_5\psi)$

$$\phi = \frac{\phi_1 + i\phi_2}{\sqrt{2}}$$

Real λ : $\phi_1 \xrightarrow{\text{P and CP}} \phi_1$ $\phi_2 \xrightarrow{\text{P and CP}} -\phi_2$

Scalar   Pseudoscalar

Complex λ : P and CP are violated.

Back to MSSM

Neutral Higgs

$$H_u^0 = (v\sin\beta + \sin\alpha\, H^0 + \cos\alpha\, h^0 + i\cos\beta\, A^0 + i\sin\beta\, G^0)/\sqrt{2}$$
$$H_d^0 = (v\cos\beta + \cos\alpha\, H^0 - \sin\alpha\, h^0 + i\sin\beta\, A^0 - i\cos\beta\, G^0)/\sqrt{2}$$

CP-even (H^0, h^0) CP-odd (A^0) Goldstone boson (G^0)

$$m_{H+}^2 = m_A^2 + m_W^2$$

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

At tree level: $m_h^2 \leq m_Z^2\cos^2 2\beta \leq m_Z^2$

Radiative correction

$$\delta m_h^2 \approx \frac{3}{\pi}\frac{m_t^4}{m_W^2}\sin^4\beta\,\log\frac{m_{\tilde t}m_{\tilde{\bar t}}}{m_t^2}$$

Pushes the Higgs mass to 130 GeV

- Adding singlet (singlino!!) MSSM → NMSSM
- Pushes the Higgs mass to 150 GeV

To obtain m_h > 200 GeV extra gauge boson

$$m_{A^0}^2 = 2b/\sin(2\beta) = 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2$$

$$m_{h^0,H^0}^2 = \frac{1}{2}\left(m_{A^0}^2 + m_Z^2 \mp \sqrt{(m_{A^0}^2 - m_Z^2)^2 + 4m_Z^2 m_{A^0}^2 \sin^2(2\beta)}\right),$$

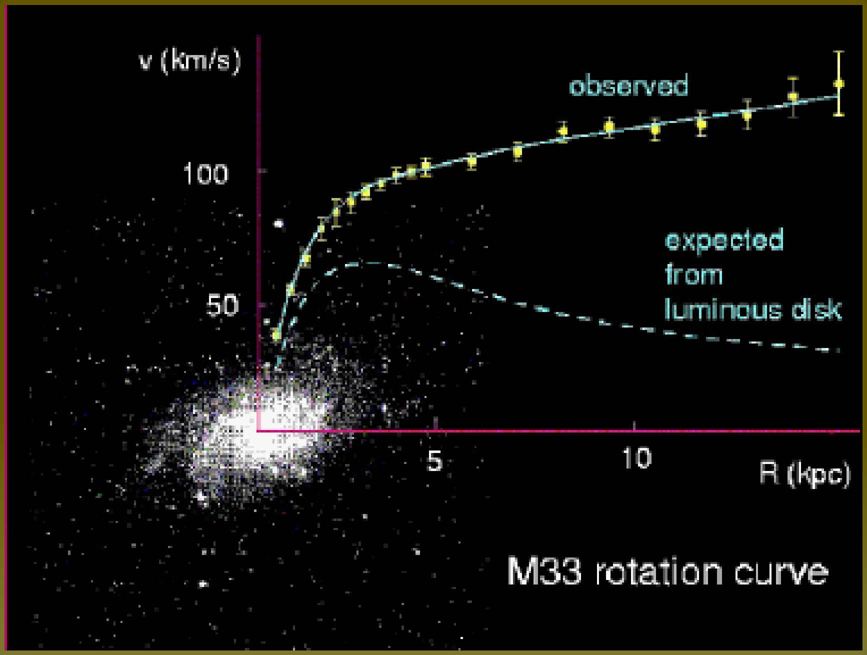
$$m_{H^\pm}^2 = m_{A^0}^2 + m_W^2.$$

SM-like Higgs

$$m_{A^0} \gg m_{h^0} \qquad m_{H^0} \simeq m_{A^0} \simeq m_{H^+} \gg m_{h^0}$$

$$h^0 \simeq H_u^0$$

Dark matter


v (km/s)
100
50
observed
expected
from
luminous disk
5
10
R (kpc)
M33 rotation curve

Dark Matter

$$\Omega_b = 0.043 \quad \Omega_N = 0.21 \quad \Omega_\Lambda = 0.75$$

Can SUSY solve Dark energy?

- How about DM?
- DM candidate can have any mass between keV to ....

Dark matter abundance in thermal scenario

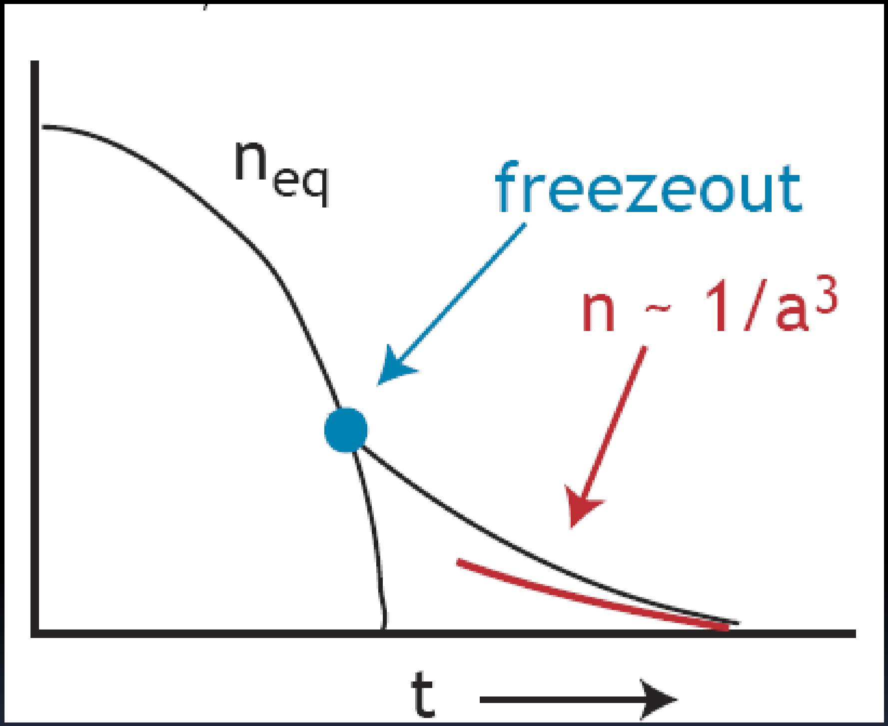
$$n_{eq} = \frac{g}{(2\pi)^{3/2}}(mT)^{3/2}e^{-m/T}$$

- Boltzmann Equation

$$\frac{dn}{dt} = -3Hn - \langle\sigma v\rangle\left(n^2 - n_{eq}^2\right)$$

$$H \sim T^2/m_{\rm Pl} \sim 10^{-18}T$$

Freeze-out



$$e^{-m/T_F} \sim \frac{1}{m_{\rm Pl} m \langle \sigma v \rangle} \quad \text{or} \quad \xi_F = \frac{T_F}{m} \sim \frac{1}{25}$$

Final density

$$\Omega_N = \frac{nm}{\rho_c} = \frac{s_0}{\rho_c}\sqrt{\frac{45}{\pi}}\frac{1}{g_*^{1/2} m_{\rm Pl}\xi_F}\frac{1}{\langle\sigma v\rangle}$$

$\Omega_N = 0.21$ implies $\langle\sigma v\rangle = 1$ pb

$$\langle\sigma v\rangle = \frac{\pi\alpha^2}{8m^2}$$

→ $m = 100$ GeV

WOW!!

Collider signature

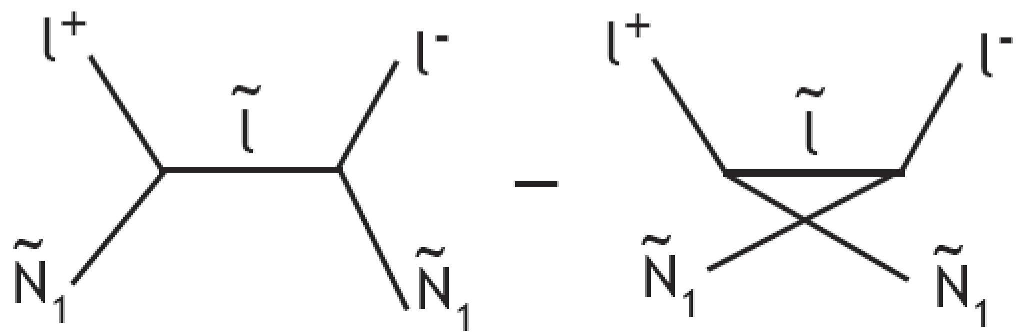
- Dark matter at LHC

Missing energy

Dark matter candidate

- Sneutrino ??? → (beyond MSSM with right-handed neutrino)
- Gravitino
- Neutralino Most popular DM candidate

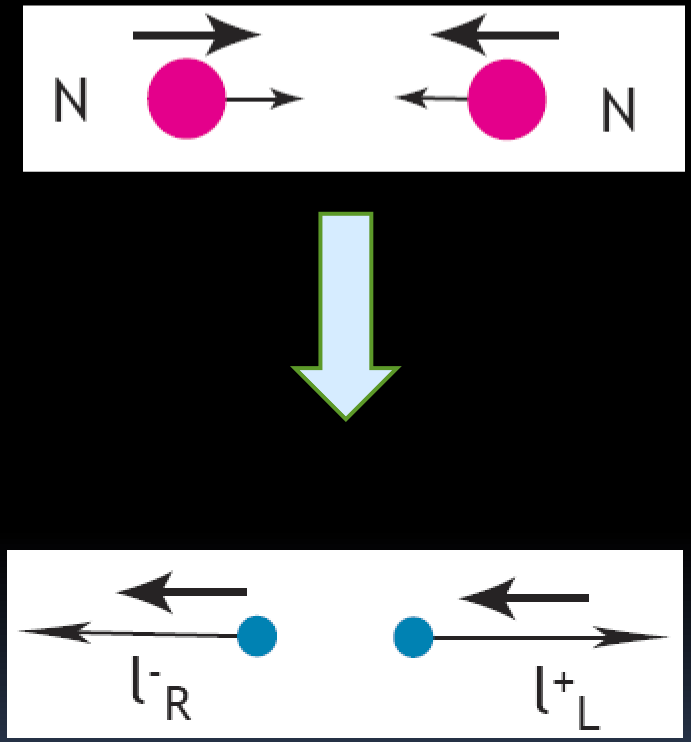
Bulk solution



$$v\frac{d\sigma}{d\cos\theta_{CM}} = \frac{\pi\alpha^2}{8m^2}\left|\frac{V_{011}}{c_w}\right|^2 \left|\frac{m_N^2}{|t|+m_{\tilde{l}}^2} - \frac{m_N^2}{|u|+m_{\tilde{l}}^2}\right|^2$$

Suppression

S-wave versus P-wave



Remedies

- Bulk solution requires too light sleptons

Other possibilities:

Resonant solution (funnel point) (1

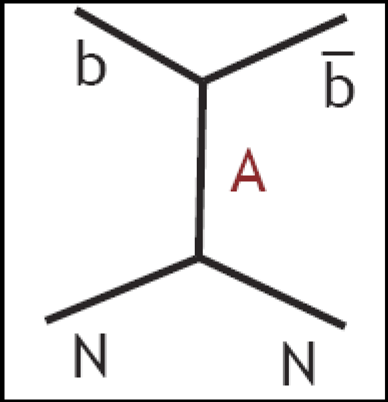
Annihilation to W pair (focus point) (2

Co-annihilation (3

Resonance annihilation

Funnel point

$$\langle \sigma v \rangle \sim \left(\frac{\pi \alpha^2}{8 m_N^2} \right) \cdot |\eta|^2 \cdot \left(\frac{m_b \tan\beta}{m_W s_w} \right)^2 \cdot \left| \frac{4 m_N^2}{(4 m_N^2 - m_A^2) + i m_A \Gamma_A} \right|^2$$

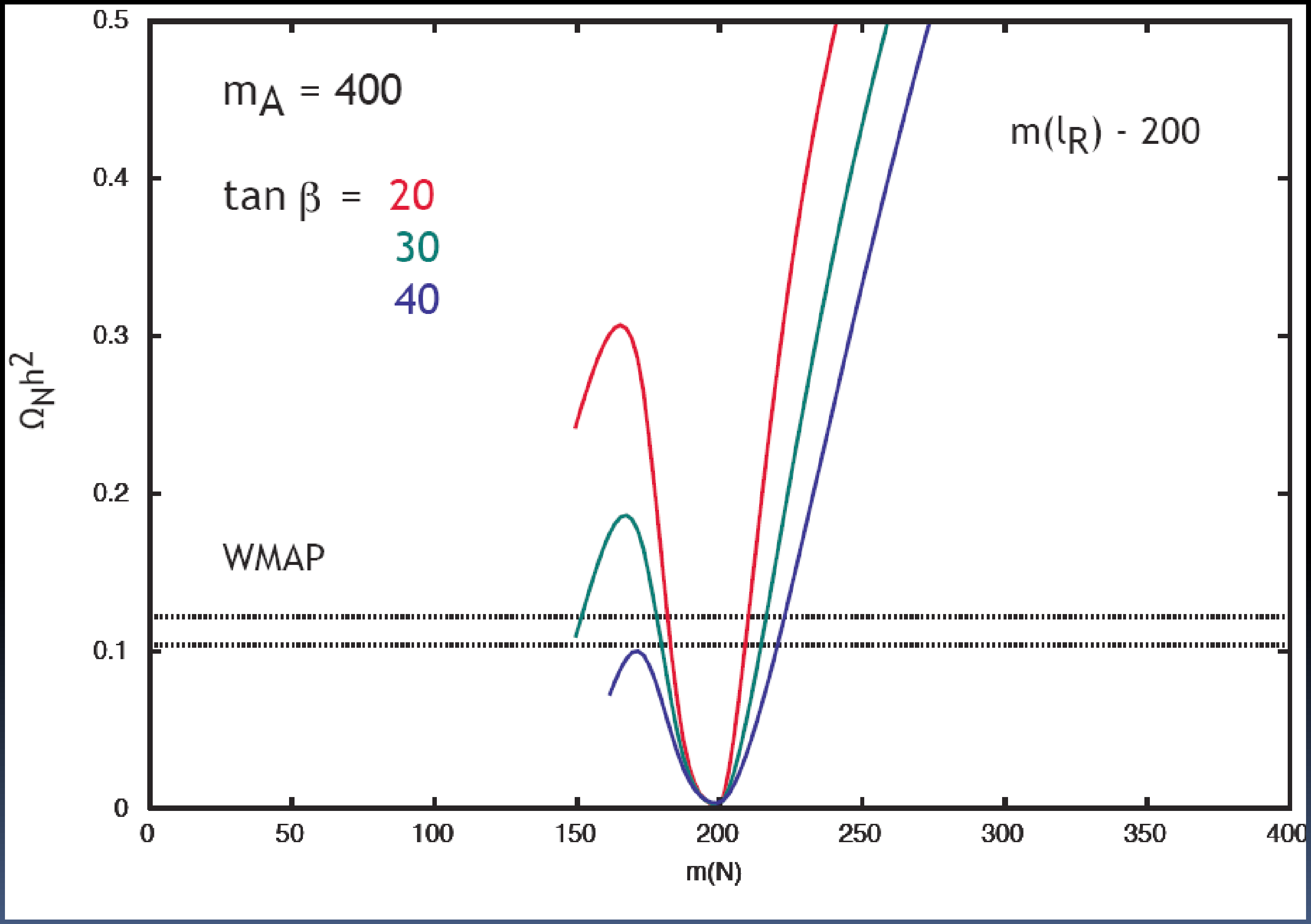


η = Higgsino fraction in N
$m_b \tan\beta / m_W s_w \sim 1$ for $\tan\beta \sim 10$
$\Gamma_A / m_A \sim 1 - 2\%$

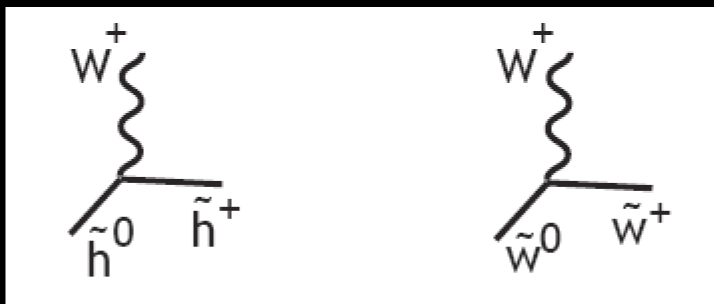
Why b?

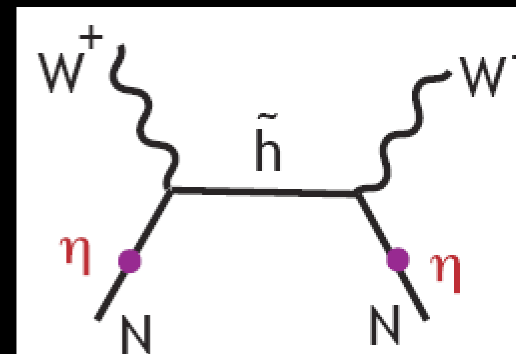
Why A and not h or H?

Funnel point



Focus point





- Neutralino should not be Bino-like!
- Neutralino should not be Higgsino-like!
- Just right amount of mixing is required

Coannihilation

- In the early universe plasma

$$N + \ell^- \leftrightarrow \widetilde{\ell}^- + \gamma$$

$$m_{\widetilde{\ell}} - m_N \sim T_f$$

$$\frac{m_{\widetilde{\ell}} - m_N}{m_N} \sim \xi \sim 4\%$$

$$\tilde{l} + \tilde{N} \to l + \gamma, Z$$

Signature at colliders

- Funnel point

$$m(A) \sim 2m(N)$$

- Coannihilation

$$m(N) \sim m(\widetilde{l})$$