Theory of charged Higgs bosons in SUSY models

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outline

- Supersymmetry and the $H^{\pm}$
  - Supersymmetry
  - SUSY extensions of the SM
- $H^{\pm}$ in the MSSM
  - $H^{\pm}$ mass in the MSSM
  - $H^{\pm}$ interactions in the MSSM
- $H^{\pm}$ in SUSY models with an extra singlet
  - $H^{\pm}$ in the NMSSM
  - $H^{\pm}$ in the mnSSM
  - $H^{\pm}$ interactions compared
- $H^{\pm}$ in other SUSY models

• Supersymmetry and the $H^{\pm}$

– Supersymmetry. . .

. . . is *the* extension of the Poincaré-symmetry of space-time

. . . leads to a symmetry between Fermions & Bosons

gauge theory with minimal SUSY :

- same # of fermionic & bosonic d. o. f.
  $\longrightarrow$ a superpartner of different spin exists for each particle

- couplings are correlated
  $\longrightarrow$ e.g. scalar 4-point int. $\longleftrightarrow$ gauge couplings

- superpartners have the same mass
  $\longrightarrow$ SUSY must be broken at the electroweak scale

gauge theory with broken SUSY :

- superpartner masses enter as additional free parameters (essentially)

– SUSY extensions of the SM

- SM gauge group: $SU(3)_{\text{c(olour)}} \times SU(2)_{I\text{(isospin)}} \times U(1)_{Y\text{(hypercharge)}}$
- incorporate SM fields into $N = 1$ supermultiplets:
  - gauge fields V^{μ} into vector superfields $\left\{ \widehat{V} = \begin{pmatrix} \lambda^{\alpha}, & V^{\mu}, & D \\ S=\frac{1}{2}, & S=1, & S=0 \end{pmatrix} \right.$
  - fermion fields ψ^{α} into chiral superfields $\left\{ \widehat{\Phi} = \begin{pmatrix} A, & \psi^{\alpha}, & F \\ S=0, & S=\frac{1}{2}, & S=0 \end{pmatrix} \right.$
  - Higgs fields A into chiral superfields $\left\{ \widehat{\Phi} = \begin{pmatrix} A, & \psi^{\alpha}, & F \\ S=0, & S=\frac{1}{2}, & S=0 \end{pmatrix} \right.$

– SUSY extensions of the SM

- the Higgs sector needs two independent $SU(2)_I$-doublets:
  - the Higgsino partner of *only one* Higgs doublet upsets the cancellation of the chiral anomaly among the fermions.
    $\longrightarrow$ inconsistent quantum field theory
  - two oppositely hypercharged Higgsinos are needed in order to cancel all contributions to the chiral anomaly.

$\Rightarrow$ two Higgs doublets mandatory

$\Rightarrow$ two charged scalar d.o.f present

$\Rightarrow$ **SUSY extensions of the SM predict a physical $H^{\pm}$**

structure of the interaction Lagrangian:

- gauge self-interaction

$$\mathcal{L}_{\text{gauge self-int.}} = \frac{1}{4} Tr\{\widehat{\mathcal{W}}_n^\alpha \widehat{\mathcal{W}}_{n,\alpha}\}|_{\theta\theta} + \text{h.c.} \text{ with } \widehat{\mathcal{W}}_{n,\alpha} = \widehat{\mathcal{W}}_{n,\alpha}(\widehat{V}_n = T^{a_n}\widehat{V}_n^{a_n})$$

$$\rightarrow \text{contains } D\text{-terms : } \mathcal{L}_D = \frac{1}{2} D^{a_n} D^{a_n}$$

- Higgs and matter superfield gauge interaction

$$\mathcal{L}_{\text{gauge-matter}} = \widehat{\Phi}_i^\dagger e^{2g_n \widehat{V}_n} \widehat{\Phi}_i|_{\theta\theta\bar\theta\bar\theta}$$

$$= (D_\mu A_i)^\dagger (D^\mu A_i) + i\bar\psi_i \bar\sigma^\mu D_\mu \psi_i + i\sqrt{2} g_n (A_i^\dagger T^{a_n} \psi_i \lambda^{a_n} - \bar\lambda^{a_n} \bar\psi_i T^{a_n} A_i) + g_n D^{a_n} A_i^\dagger T^{a_n} A_i + F_i^\dagger F_i$$

- Super-Yukawa interaction

$$\mathcal{L}_{\text{superpotential}} = W(\{\widehat{\Phi}_i\})|_{\theta\theta} + \text{h.c.} = (m_{ij}\widehat{\Phi}_i\widehat{\Phi}_j + g_{ijk}\widehat{\Phi}_i\widehat{\Phi}_j\widehat{\Phi}_k)|_{\theta\theta} + \text{h.c.}$$

$$= m_{ij}(A_i F_j + A_i F_j - \psi_i \psi_j) + g_{ijk}(A_i A_j F_k - \psi_i \psi_j A_k + \text{cyclic}) + \text{h.c.}$$

- soft SUSY-breaking interactions

$$\mathcal{L}_{\text{soft}} = [\text{scalar mass terms}] + [\text{scalar 3-point interactions}] + [\text{gaugino mass terms}]$$

specific models : mandatory part

gauge group : $SU(3)_{\text{c(olour)}} \times SU(2)_{\text{I(isospin)}} \times U(1)_{\text{Y(hypercharge)}}$

particle content :

regular particles	spin	superfields	spin	superpartners
fermions				sfermions
quarks u, d, s, c, b, t	$\frac{1}{2}$	$\widehat{Q} = \begin{pmatrix} \widehat{u}_L \\ \widehat{d}_L \end{pmatrix}, \widehat{D} = \widehat{d}^c_R, \widehat{U}_R = \widehat{u}^c_R$	0	squarks $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}, \tilde{t}$
leptons $e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau$		$\widehat{L} = \begin{pmatrix} \widehat{\nu}_L \\ \widehat{e}_L \end{pmatrix}, \widehat{E} = \widehat{e}^c_R$		sleptons $\tilde{e}, \tilde{\nu}_e, \tilde{\mu}, \tilde{\nu}_\mu, \tilde{\tau}, \tilde{\nu}_\tau$
gauge bosons $G, W^{\pm}, Z, \gamma$	1	$\widehat{G}, \widehat{W}^{\pm}, \widehat{Z}, \widehat{\gamma}$	$\frac{1}{2}$	gauginos $\tilde{G}, \tilde{W}^{\pm}, \tilde{Z}, \tilde{\gamma}$

specific models: full model specification

gauge group : $SU(3)_{\text{c(olour)}} \times SU(2)_{\text{I(isospin)}} \times U(1)_{\text{Y(hypercharge)}} \left(\times \text{[xtra groups]} \right)$

particle content :

regular particles	spin	superfields	spin	superpartners
fermions				sfermions
quarks u, d, s, c, b, t	$\frac{1}{2}$	$\hat{Q} = \begin{pmatrix} \hat{u}_L \\ \hat{d}_L \end{pmatrix}, \widehat{D} = \hat{d}^c_R, \hat{U}_R = \hat{u}^c_R$	0	squarks $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}, \tilde{t}$
leptons $e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau$		$\hat{L} = \begin{pmatrix} \hat{\nu}_L \\ \hat{e}_L \end{pmatrix}, \hat{E} = \hat{e}^c_R$		sleptons $\tilde{e}, \tilde{\nu}_e, \tilde{\mu}, \tilde{\nu}_\mu, \tilde{\tau}, \tilde{\nu}_\tau$
gauge bosons $G, W^{\pm}, Z, \gamma$	1	$\hat{G}, \widehat{W}^{\pm}, \hat{Z}, \hat{\gamma}$	$\frac{1}{2}$	gauginos $\tilde{G}, \tilde{W}^{\pm}, \tilde{Z}, \tilde{\gamma}$

+ Higgs sector + Higgs-matter interaction (in $\mathcal{L}_{\text{Superpot.}}, \mathcal{L}_{\text{soft}}$)

MSSM (minimal supersymmetric standard model)

gauge group : $SU(3)_{\mathrm{c(olour)}} \times SU(2)_{\mathrm{I(isospin)}} \times U(1)_{\mathrm{Y(hypercharge)}}$

regular particles	spin	superfields	spin	superpartners
fermions quarks u, d, s, c, b, t leptons $e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau$	$\frac{1}{2}$	$\hat{Q} = \begin{pmatrix} \hat{u}_L \\ \hat{d}_L \end{pmatrix}, \widehat{D} = \hat{d}^c_R, \hat{U}_R = \hat{u}^c_R$ $\hat{L} = \begin{pmatrix} \hat{\nu}_L \\ \hat{e}_L \end{pmatrix}, \hat{E} = \hat{e}^c_R$	0	sfermions squarks $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}, \tilde{t}$ sleptons $\tilde{e}, \tilde{\nu}_e, \tilde{\mu}, \tilde{\nu}_\mu, \tilde{\tau}, \tilde{\nu}_\tau$
gauge bosons $G, W^{\pm}, Z, \gamma$	1	$\hat{G}, \widehat{W}^{\pm}, \hat{Z}, \hat{\gamma}$	$\frac{1}{2}$	gauginos $\tilde{G}, \tilde{W}^{\pm}, \tilde{Z}, \tilde{\gamma}$
Higgs bosons H_d, H_u	0	$\widehat{H}_d = \begin{pmatrix} \widehat{H}^0_d \\ \widehat{H}^-_d \end{pmatrix}, \widehat{H}_u = \begin{pmatrix} \widehat{H}^+_u \\ \widehat{H}^0_u \end{pmatrix}$	$\frac{1}{2}$	Higgsinos $\tilde{H}_d, \tilde{H}_u$

H_d, H_u lead to **5 physical Higgs bosons:** h^0, H^0, A^0, H^+, H^-

$\tilde{W}^{\pm}, \tilde{Z}, \tilde{\gamma}$ and $\tilde{H}_d, \tilde{H}_u$ mix to **2 charginos** $\chi^{\pm}_1, \chi^{\pm}_2$ and **4 neutralinos** $\chi^0_1, \ldots, \chi^0_4$

NMSSM (next-to-minimal ...) and **mnSSM** (minimal nonminimal ...)

gauge group : $SU(3)_{\text{c(olour)}} \times SU(2)_{\text{I(isospin)}} \times U(1)_{\text{Y(hypercharge)}}$

regular particles	spin	superfields	spin	superpartners
fermions quarks u, d, s, c, b, t leptons $e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau$	$\frac{1}{2}$	$\hat{Q} = \begin{pmatrix} \hat{u}_L \\ \hat{d}_L \end{pmatrix}, \widehat{D} = \hat{d}^c_R, \hat{U}_R = \hat{u}^c_R$ $\hat{L} = \begin{pmatrix} \hat{\nu}_L \\ \hat{e}_L \end{pmatrix}, \hat{E} = \hat{e}^c_R$	0	sfermions squarks $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}, \tilde{t}$ sleptons $\tilde{e}, \tilde{\nu}_e, \tilde{\mu}, \tilde{\nu}_\mu, \tilde{\tau}, \tilde{\nu}_\tau$
gauge bosons $G, W^{\pm}, Z, \gamma$	1	$\hat{G}, \widehat{W}^{\pm}, \hat{Z}, \hat{\gamma}$	$\frac{1}{2}$	gauginos $\tilde{G}, \tilde{W}^{\pm}, \tilde{Z}, \tilde{\gamma}$
Higgs bosons H_d, H_u, S	0	$\widehat{H}_d$, $\widehat{H}_u$, singlet $\hat{S}$	$\frac{1}{2}$	Higgsinos $\tilde{H}_d, \tilde{H}_u, \tilde{S}$

H_d, H_u, S lead to **7 physical Higgs bosons:** $H^0_1, H^0_2, H^0_3, A^0_1, A^0_2, H^+, H^-$

$\tilde{W}^{\pm}, \tilde{Z}, \tilde{\gamma}$ and $\tilde{H}_d, \tilde{H}_u, \tilde{S}$ mix to **2 charginos** $\chi^{\pm}_1, \chi^{\pm}_2$ and **5 neutralinos** $\chi^0_1, \ldots, \chi^0_5$

Superpotential :

MSSM

$$W_{\text{MSSM}} = \epsilon_{ij} h_e \widehat{H}_d^i \widehat{L}^j \widehat{E} + \epsilon_{ij} h_d \widehat{H}_d^i \widehat{Q}^j \widehat{D} - \epsilon_{ij} h_u \widehat{H}_u^i \widehat{Q}^j \widehat{U} + \epsilon_{ij} \mu \widehat{H}_d^i \widehat{H}_u^i$$

$$\mathcal{L}_{\text{soft}} = -m_{H_d}^2 |H_d|^2 - m_{H_u}^2 |H_u|^2 - (\mu B_\mu \epsilon_{ij} H_u^i H_d^j + \text{h.c.}) + [\text{sfermion} + \text{gaugino mass terms}]$$

NMSSM

$$W_{\text{NMSSM}} = \epsilon_{ij} h_e \widehat{H}_d^i \widehat{L}^j \widehat{E} + \epsilon_{ij} h_d \widehat{H}_d^i \widehat{Q}^j \widehat{D} - \epsilon_{ij} h_u \widehat{H}_u^i \widehat{Q}^j \widehat{U} + \epsilon_{ij} \lambda \widehat{S} \widehat{H}_d^i \widehat{H}_u^i + \frac{\kappa}{3} \widehat{S}^3$$

$$\mathcal{L}_{\text{soft}} = -m_{H_d}^2 |H_d|^2 - m_{H_u}^2 |H_u|^2 - m_S^2 |S|^2 - (\lambda A_\lambda \epsilon_{ij} S H_u^i H_d^j + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.}) + [\text{sfermion} + \text{gaugino mass terms}]$$

mnSSM [Panagiotakopoulos, Pilaftsis'00; Dedes et al. '00]

$$W_{\text{mnSSM}} = \epsilon_{ij} h_e \widehat{H}_d^i \widehat{L}^j \widehat{E} + \epsilon_{ij} h_d \widehat{H}_d^i \widehat{Q}^j \widehat{D} - \epsilon_{ij} h_u \widehat{H}_u^i \widehat{Q}^j \widehat{U} + \epsilon_{ij} \lambda \widehat{S} \widehat{H}_d^i \widehat{H}_u^i + t_F \widehat{S}$$

$$\mathcal{L}_{\text{soft}} = -m_{H_d}^2 |H_d|^2 - m_{H_u}^2 |H_u|^2 - m_S^2 |S|^2 + t_S S - (\lambda A_\lambda \epsilon_{ij} S H_u^i H_d^j + \text{h.c.}) + [\text{sfermion} + \text{gaugino mass terms}]$$

• $H^\pm$ in the MSSM

– $H^\pm$ mass in the MSSM

tree level mass relation:

$$m^2_{H^\pm} = m^2_W + m^2_A$$

radiative corrections: [Brignole et al.'91;Chankowski et al.'91;Haber, Diaz'92]

- large for $\tan\beta < 1$
- small for $\tan\beta \in [1, 50]$

  $\delta m_{H^\pm} = (m_{H^\pm})_{\text{1-loop}} - (m_{H^\pm})_{\text{tree}}$ at most $\approx 10\,\text{GeV}$

  $\rightarrow$ tree-level good qualitative description

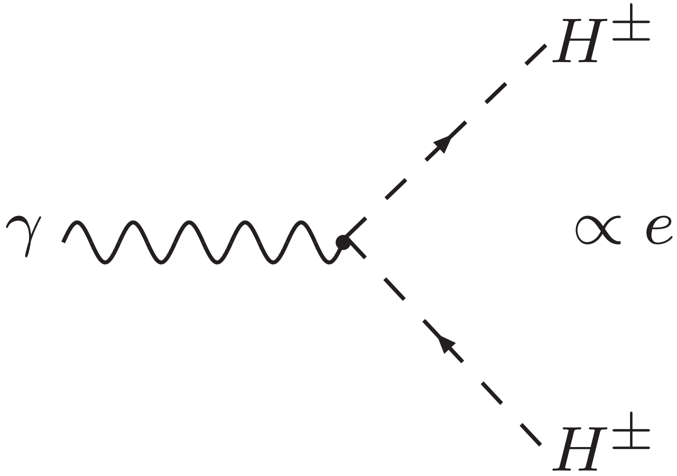
radiative corrections (contd)

- CP violating effects: [→ talk of A. Pilaftsis]
  - can give larger mass shifts $\delta m_{H^\pm}$ in both directions
    [Carena et al.'92; Pilaftsis,Wagner'99;Woo Han et al'01]
  - LEP bounds on $m_{H_1^0}$ much lower ($\approx 50\,\text{GeV}$) than for the CP conserving MSSM
    → much lighter $H^\pm$ still allowed [Ghosh,Godbole,Roy'05]

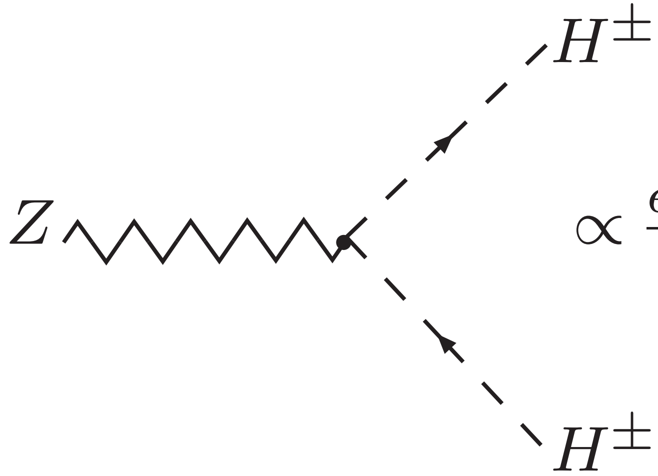
Even in the CP conserving MSSM: with an expected mass resolution of 1-2% @ LHC a mass measurement would be sensitive to the radiative corrections.

– $H^\pm$ interactions in the MSSM

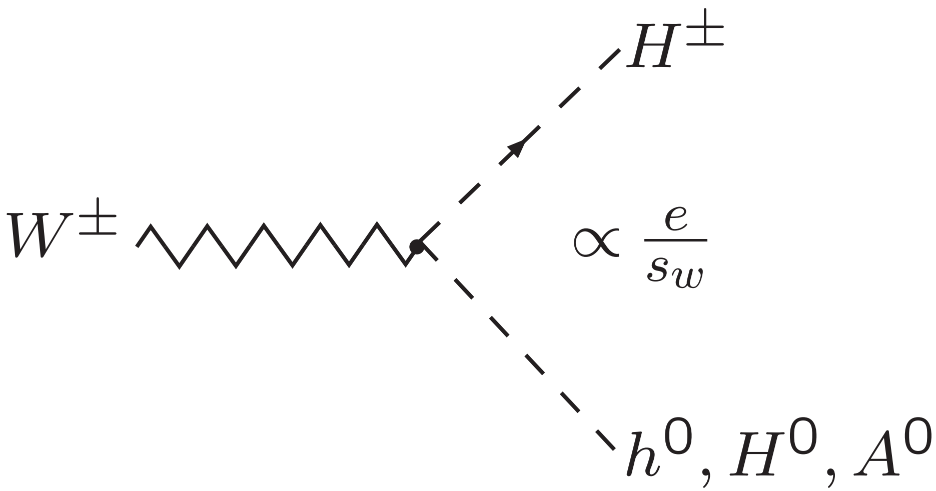
$H^\pm$ gauge interactions (3 point)



$\propto e$



$\propto \frac{e(c_w^2 - s_w^2)}{c_w s_w}$

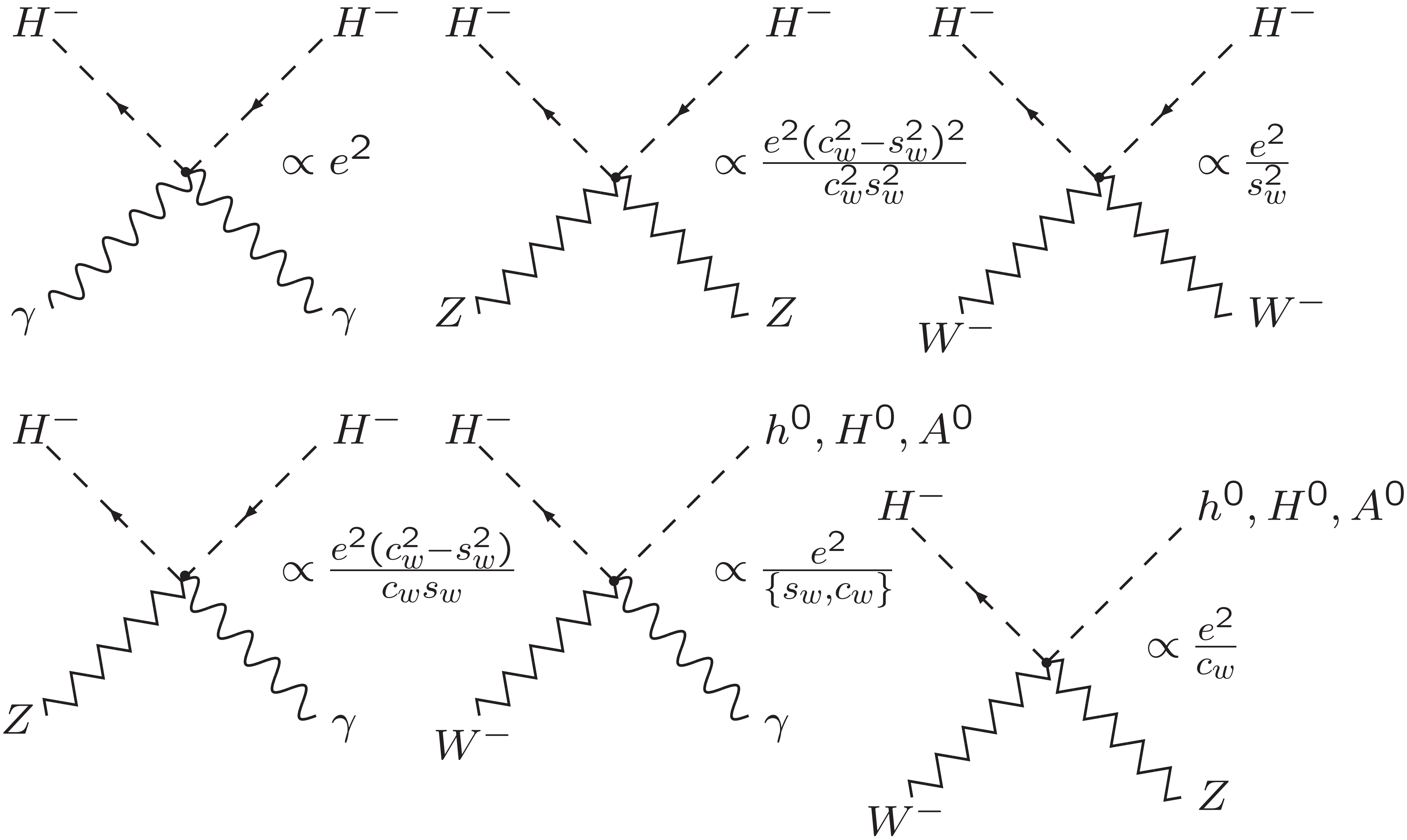


$\propto \frac{e}{s_w}$

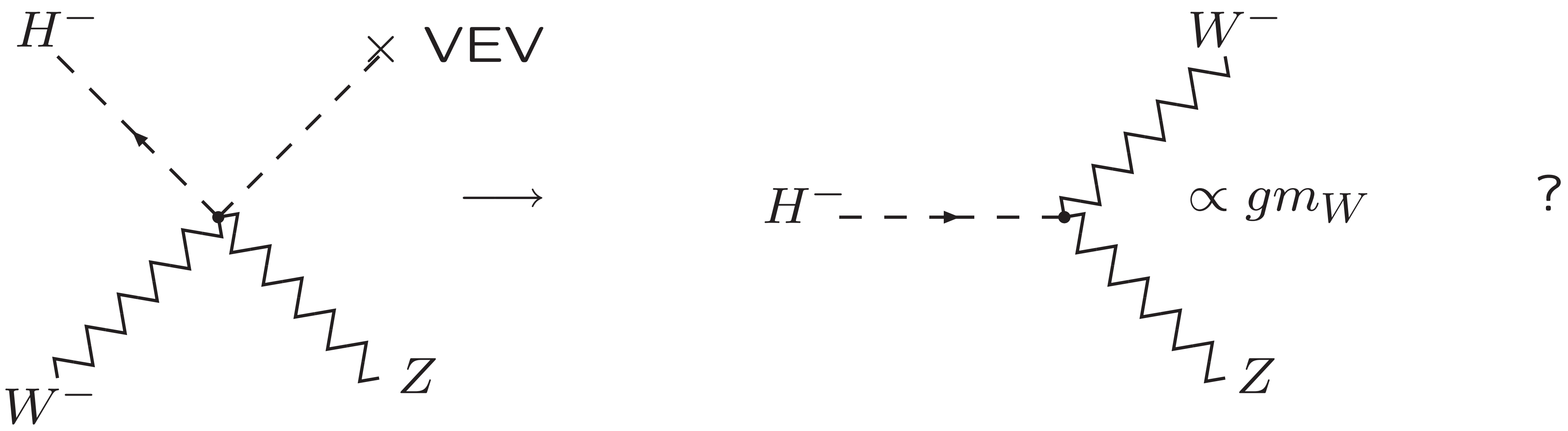
The $H^\pm$ is the only Higgs boson with at least one unsuppressed coupling to stable particles (photons)

note! dependence on Higgs mixing angles α, β (usually) not shown

$H^{\pm}$ gauge interactions (4 point)



Q: What about a $H^\pm W^\mp Z$ interaction ?



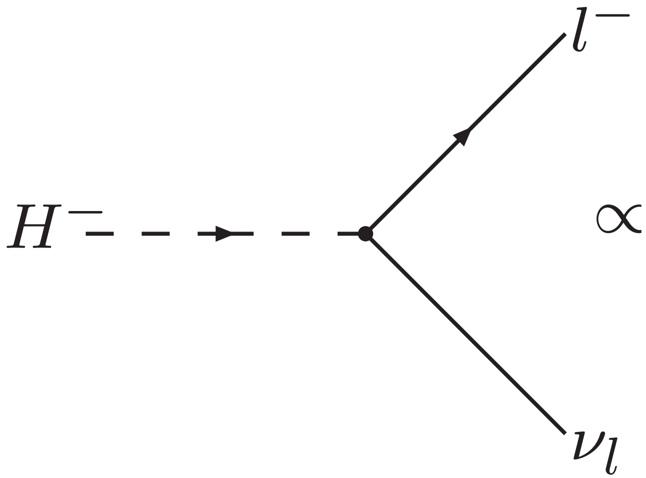
A: **There is no $H^\pm W^\mp Z$ interaction !** [Grifols, Mendez '80]

- For a number of isospin multiplets of the *same* SU(2)-representation, all containing an $H^\pm$ d.o.f and a neutral VEV, *only one linear combination couples to* $W^\mp Z$

  $\rightarrow$ That's the Goldstone $G^\pm$ in our case (two Higgs doublets).

- In order to have $H_i^\pm W^\mp Z$ couplings of physical $H_i^\pm$ one would need at least *two* Higgs multiplets belonging to *different* SU(2)-representations.
  Such models exist (e.g. models with an extra Higgs triplet).
  But, usually very restricted by ρ-parameter constraint.

$H^\pm$ Yukawa interactions

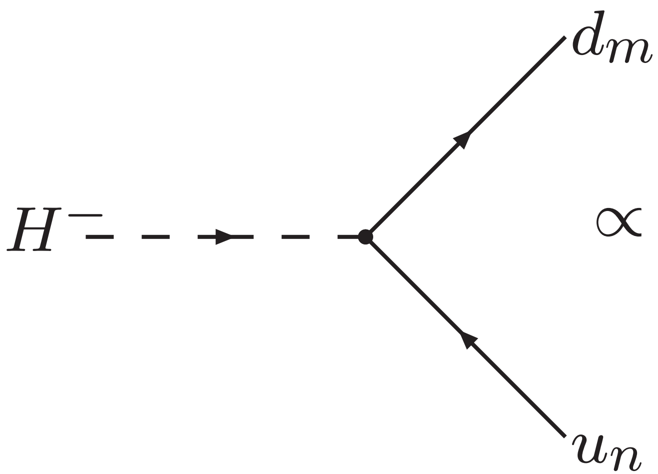


$$\propto \frac{e}{\sqrt{2} s_w m_W} m_l \tan\beta \, P_L$$

large $\tan\beta$: large m_d, m_l-terms, small m_u-terms

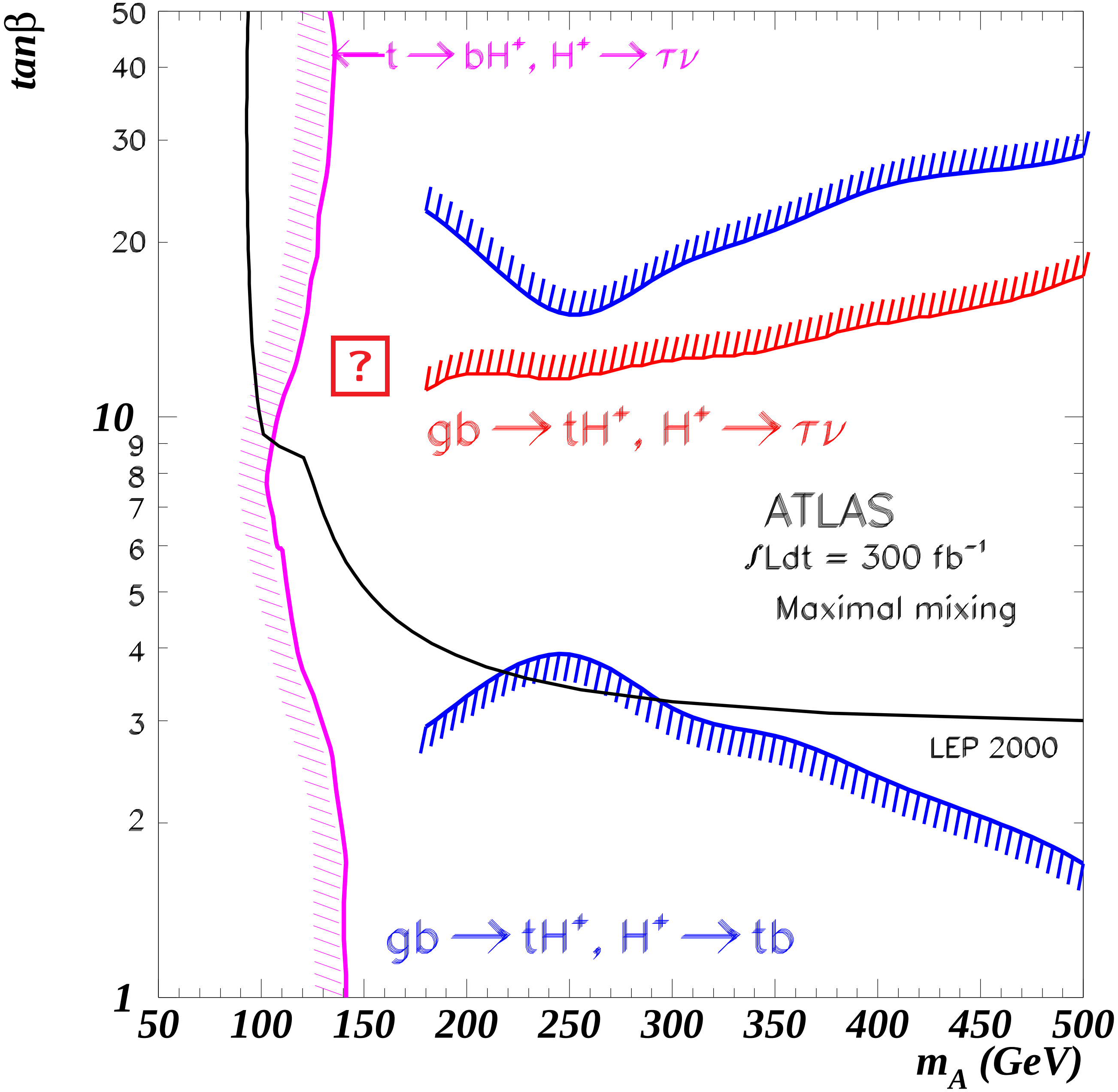
small $\tan\beta$: small m_d, m_l-terms, large m_u-terms

→ "in-between" $\tan\beta$ region ("wedge-region") where $H^\pm$ detection is difficult at the LHC



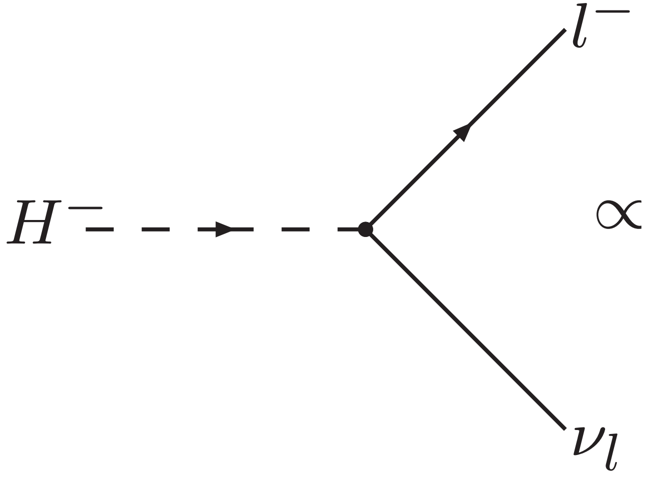
$$\propto \frac{e V_{nm}^{\text{CKM},\star}}{\sqrt{2} s_w m_W} \left\{ m_{d_m} \tan\beta \, P_L + \frac{m_{u_n}}{\tan\beta} P_R \right\}$$

the wedge-region (nightmare for $H^{\pm}$ searchers)



situation
in threshold region ?
clarified by
[Assamagan, Guchait, Moretti'04]

$H^{\pm}$ Yukawa interactions



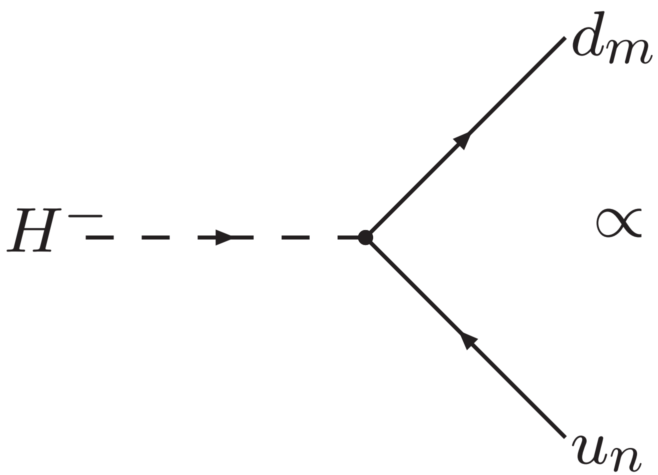
$$\propto \frac{e}{\sqrt{2} s_w m_W} h_l v_1 \tan\beta \, P_L$$

large $\tan\beta$ region:
large radiative corrections $\Delta_b \tan\beta$
to b-quark Yukawa-coupling $h_b = m_b / v_1$
need to be resummed for reliable predictions:

$\rightarrow$ i.e. use $h_b^{\text{resummed}} = \frac{m_b}{v_1(1+\Delta_b \tan\beta)}$

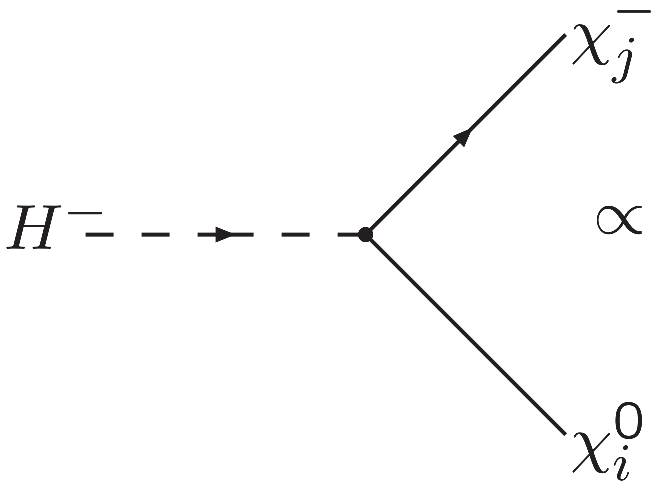
instead of $h_b^{\text{1-loop}} = \frac{m_b}{v_1}(1 - \Delta_b \tan\beta)$

[→ talks of J. Guasch, S. Peñaranda]



$$\propto \frac{e \, V_{nm}^{\text{CKM},\star}}{\sqrt{2} s_w m_W} \left\{ h_{d_m} v_1 \tan\beta \, P_L + \frac{h_{u_n} v_2}{\tan\beta} P_R \right\}$$

$H^\pm$-Chargino-Neutralino interaction



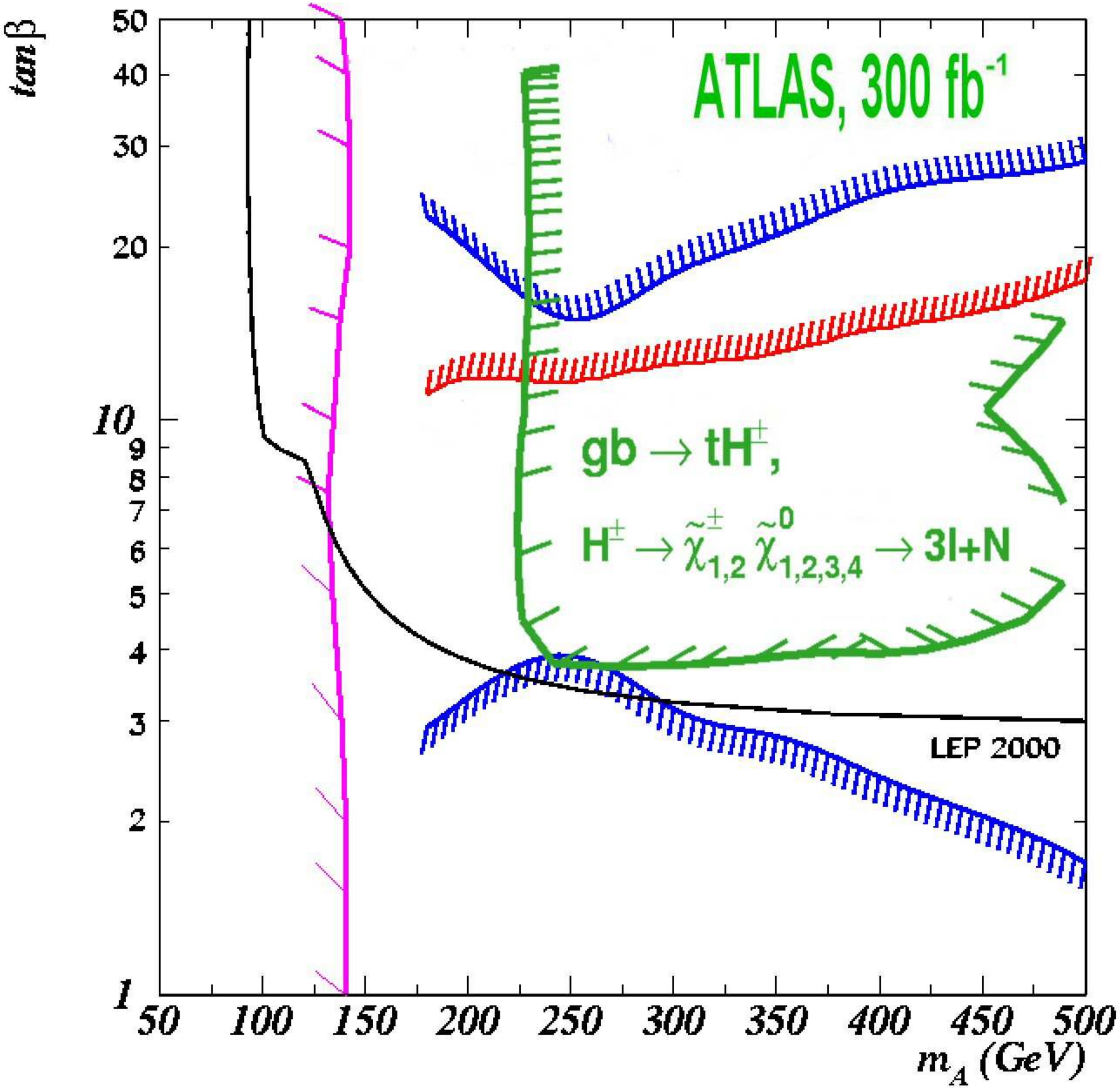
$\propto \frac{e}{\{s_w, c_w\}} \times$ [Higgs-, χ^+-, χ^0-mixing matrices]

- electroweak gauge coupling strength
- interesting new $H^\pm$ decay mode if $m_{H^\pm} > m_{\chi_1^0} + m_{\chi_1^+}$

  $\rightarrow$ may improve situation in the wedge-region for LHC

  [ATLAS study: Hansen, Gollub, Assamagan, Ekelöf ’05]

$H^\pm$-Chargino-Neutralino interaction: application

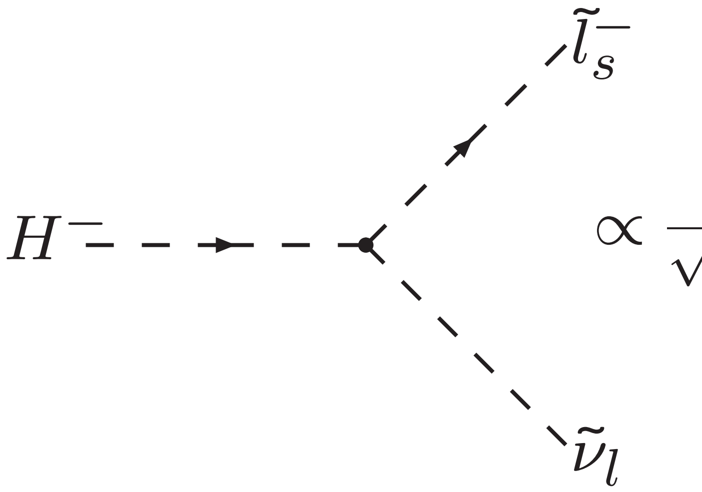


great improvement of the ATLAS $H^\pm$ discovery reach in the wedge-region

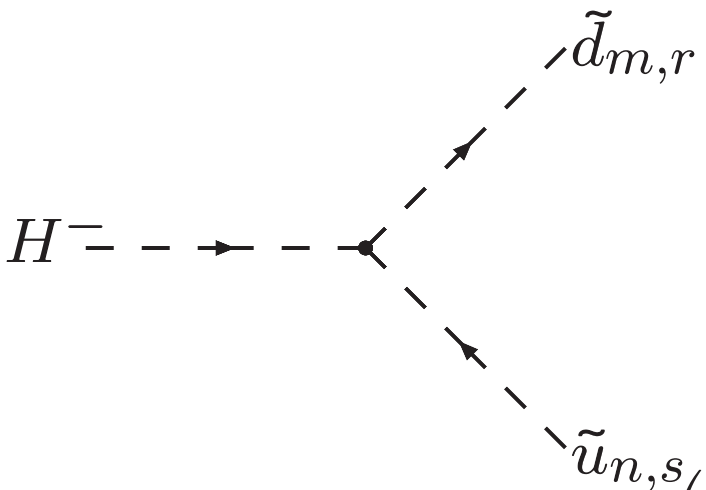
if $m_{H^\pm} > m_{\chi_1^0} + m_{\chi_1^+}$

[Hansen et al.'05]

$H^\pm$ sfermion interactions (3 point)



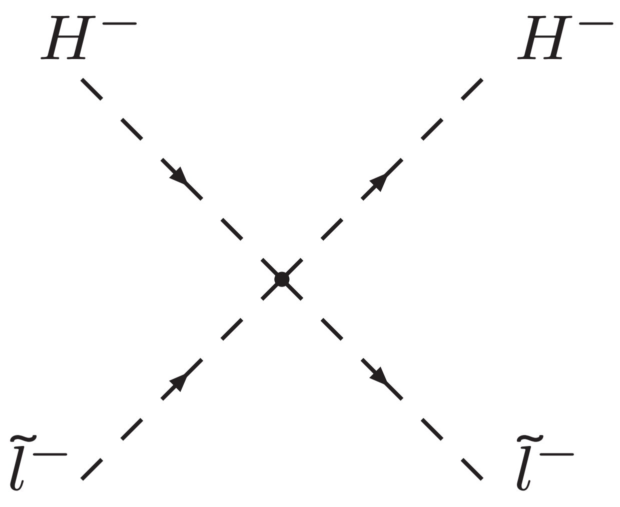
$$\propto \frac{e}{\sqrt{2} s_w m_W} (U^l_{s,1}, U^l_{s,2}) \begin{pmatrix} m_W^2 \sin 2\beta - m_l^2 \tan\beta \\ -m_l(\mu^\star + A^l_n \tan\beta) \end{pmatrix}$$

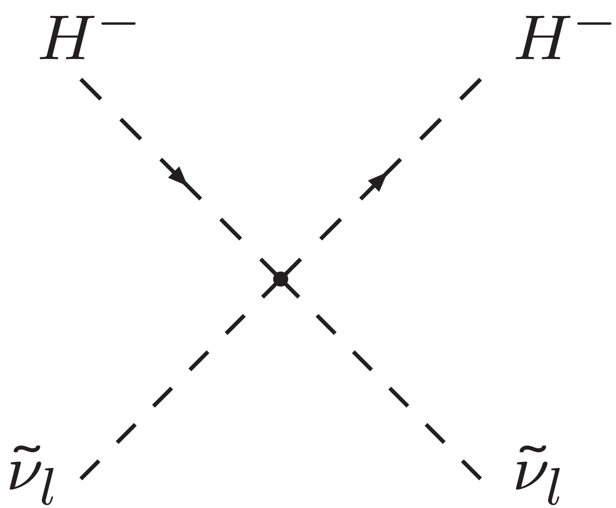


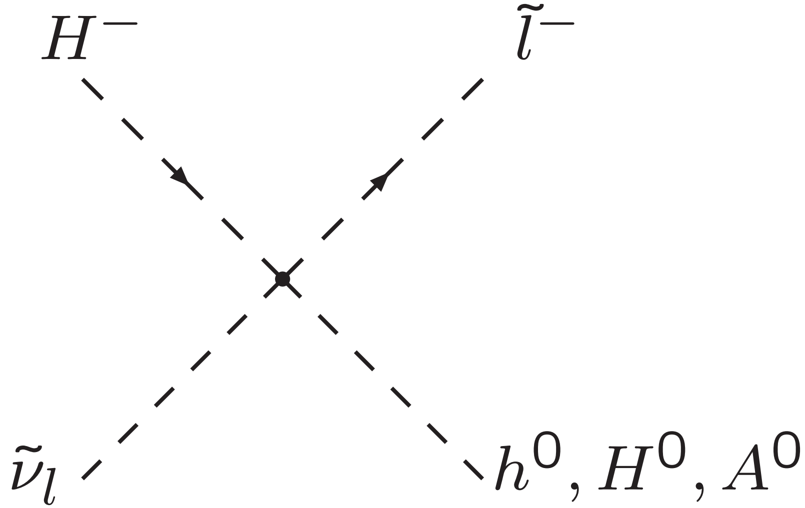
- depends critically on
  SUSY breaking parameters A^l_n, A^d_m, A^u_n (n=1,2,3),
  sfermion mixing $U^l_{r,s}, U^{dm}_{r,s}, U^{un}_{r,s}$,
  μ and $\tan\beta$
- A^l_n, A^d_m, A^u_n, μ in general complex quantities
  → possibility of large CP violating effects
  [→ talk of A. Pilaftsis]

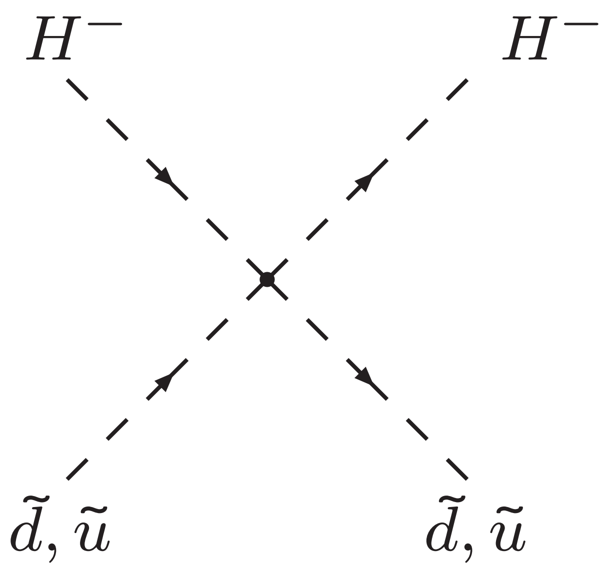
$$\propto \frac{e V_{nm}^{\mathrm{CKM},\star}}{\sqrt{2} s_w m_W} (U^{dn}_{r,1}, U^{dn}_{r,2}) \begin{pmatrix} m_W^2 s_{2\beta} - m_{dm}^2 t_\beta - \frac{m_{un}^2}{t_\beta}, & -m_{dm}(\mu^\star + A^d_m t_\beta) \\ -m_{un}(\mu + \frac{A_n^{u,\star}}{t_\beta}), & m_{un} m_{dm}(t_\beta + \frac{1}{t_\beta}) \end{pmatrix} \begin{pmatrix} U^{um,\star}_{s,1} \\ U^{um,\star}_{s,2} \end{pmatrix}$$

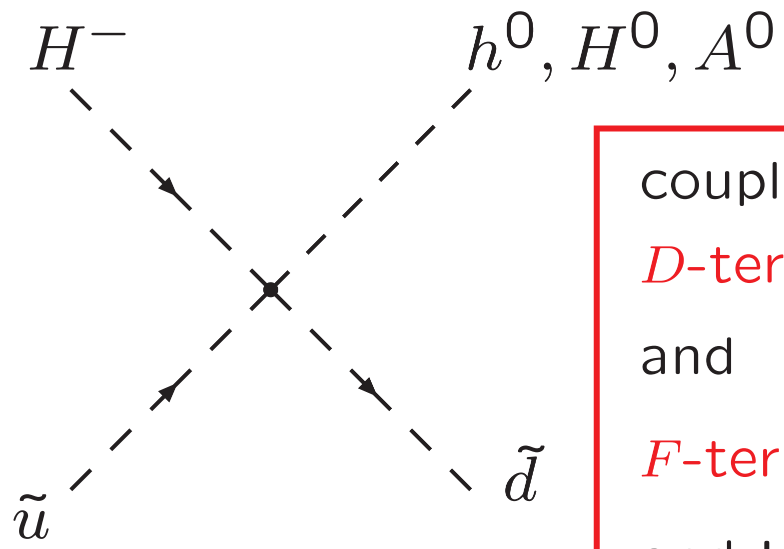
$H^{\pm}$ sfermion interactions (4 point)











couplings: mixture of

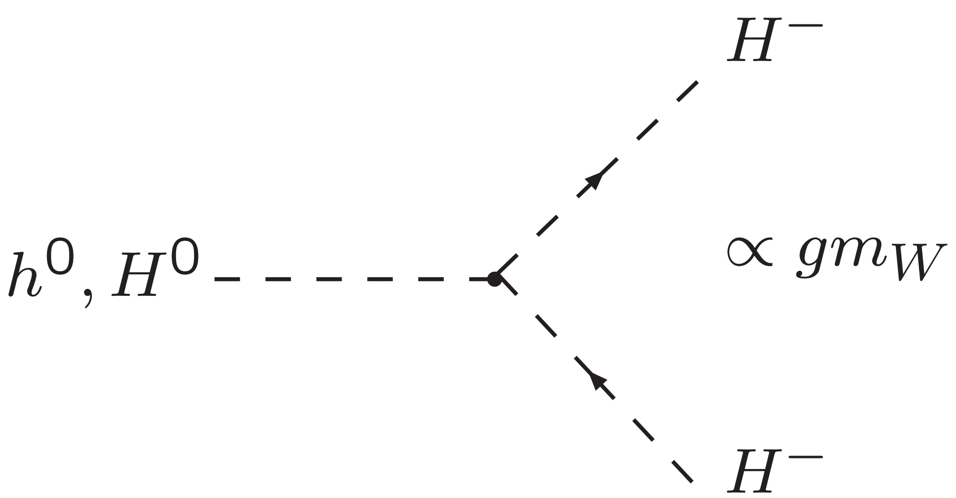
D-term contributions $\propto \frac{e^2}{s_w^2}$

and

F-term contributions $\propto \frac{e^2}{s_w^2}\frac{m_f^2}{m_W^2}$

and Higgs and sfermion mixing matrices [no μ or A_n^f]

$H^{\pm}$-Higgs self interactions (3 point)



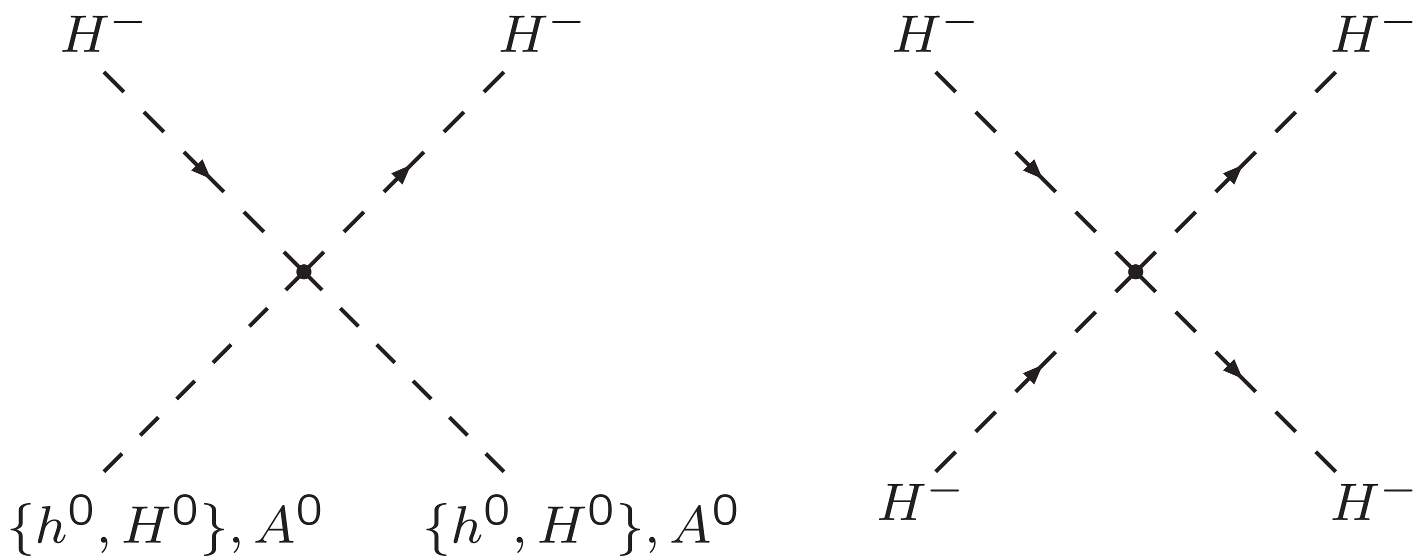
– coupling *completely* from D-terms: $\phi^4 \to \text{(VEV)} \times \phi^3$

– gives interesting contribution to H^+H^- pair production

– analogous coupling in the THDM totally different: $\propto \left(\frac{g\, m^2_{H^\pm}}{m_W}, \{\frac{g\, m^2_{h^0}}{m_W}, \frac{g\, m^2_{H^0}}{m_W}\}, \ldots \right)$
$\to$ sensitivity to Higgs self couplings

– no $A^0H^+H^-$ coupling due to CP conservation in the Higgs sector

$H^{\pm}$-Higgs self interactions (4 point)



– all couplings $\propto g^2$ (come from D-terms)

• $H^\pm$ in SUSY models with an extra singlet

– $H^\pm$ in the NMSSM

$$W_{\text{NMSSM}} = \epsilon_{ij} h_e \widehat{H}_d^i \widehat{L}^j \widehat{E} + \epsilon_{ij} h_d \widehat{H}_d^i \widehat{Q}^j \widehat{D} - \epsilon_{ij} h_u \widehat{H}_u^i \widehat{Q}^j \widehat{U} + \epsilon_{ij} \lambda \widehat{S} \widehat{H}_d^i \widehat{H}_u^i + \frac{\kappa}{3} \widehat{S}^3$$

$$\mathcal{L}_{\text{soft}} = -m_{H_d}^2 |H_d|^2 - m_{H_u}^2 |H_u|^2 - m_S^2 |S|^2 - (\lambda A_\lambda \epsilon_{ij} S H_u^i H_d^j + \\ + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.}) + [\text{sfermion and gaugino mass terms}]$$

changes compared to MSSM:

– in the minimum of the scalar potential H_u, H_d, S acquire VEVs

→ MSSM μ-term generated dynamically $\mu_{\text{eff}} = \lambda \langle S \rangle$

→ μ_{eff} is naturally $\mathcal{O}$(SUSY breaking scale)

– tree-level mass relation of charged Higgs to m_W changed:

$$m_{H^\pm}^2 = m_W^2 + \frac{2\mu_{\text{eff}}}{\sin 2\beta} \left(A_\lambda + \frac{\kappa \mu_{\text{eff}}}{\lambda} \right) - \frac{1}{2} \lambda^2 v^2 ,$$

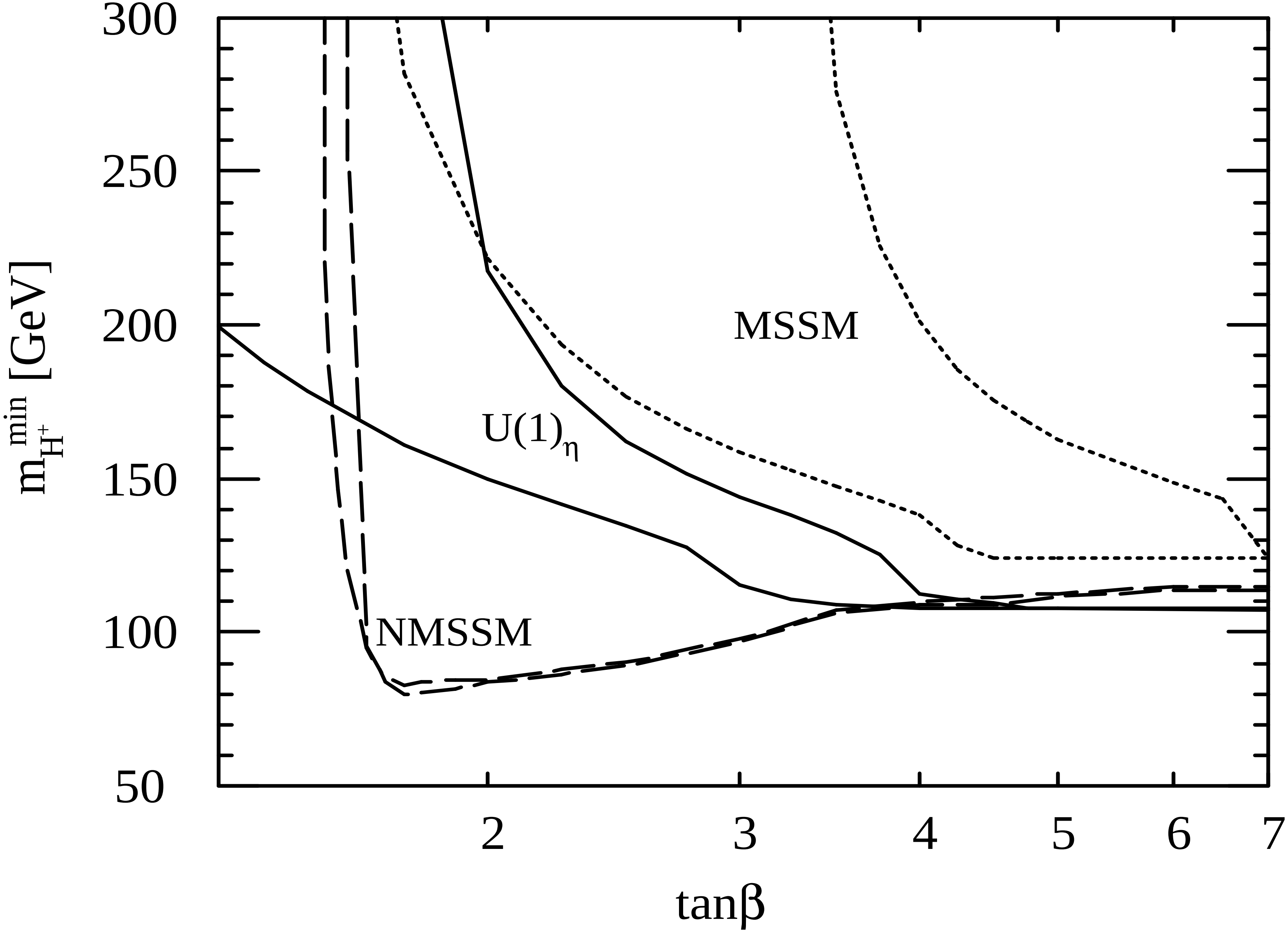
where one of the 2 CP-odd Higgs bosons has the mass

$$m_{A_1}^2 \approx \frac{2\mu_{\text{eff}}}{\sin 2\beta} \left(A_\lambda + \frac{\kappa \mu_{\text{eff}}}{\lambda} \right) \left(1 + \frac{\lambda^2 v^2}{8 \mu_{\text{eff}}^2} \sin^2 2\beta \right)$$

consequences of the changed mass relation

LEP bounds on m_{A_2} weaker than on m_A^{MSSM} + negative λ^2-term:
→ indirect $m_{H^{\pm}}$-bounds are weakened

[Drees et al.'98; Godbole, Roy '06]



– $H^\pm$ in the mnSSM

$$W_{\text{mnSSM}} = \epsilon_{ij} h_e \widehat{H}_d^i \widehat{L}^j \widehat{E} + \epsilon_{ij} h_d \widehat{H}_d^i \widehat{Q}^j \widehat{D} - \epsilon_{ij} h_u \widehat{H}_u^i \widehat{Q}^j \widehat{U} + \epsilon_{ij} \lambda \widehat{S} \widehat{H}_d^i \widehat{H}_u^i + t_F \widehat{S}$$

$$\mathcal{L}_{\text{soft}} = -m_{H_d}^2 |H_d|^2 - m_{H_u}^2 |H_u|^2 - m_S^2 |S|^2 + t_S S - (\lambda A_\lambda \epsilon_{ij} S H_u^i H_d^j + \text{h.c.}) + [\text{sfermion + gaugino mass terms}]$$

changes compared to NMSSM:

– S acquires a VEV because of the tadpole term t_S

– no $\widehat{S}^3, S^3$ terms present → neutral Higgs(ino) interactions changed

– tree-level mass sum rule holds:

$$m_{H_1}^2 + m_{H_2}^2 + m_{H_3}^2 = m_Z^2 + m_{A_1}^2 + m_{A_2}^2$$

→ similar to MSSM: $m_h^2 + m_H^2 = m_Z^2 + m_A^2$

→ no such sum rule in the NMSSM

changes compared to NMSSM (contd)

– tree-level mass relation of charged Higgs to m_W changed:

$$m_{H^\pm}^2 = m_W^2 + \frac{2\mu_{\rm eff}}{\sin 2\beta}\left(A_\lambda - \frac{\lambda t_S}{\mu_{\rm eff}}\right) - \frac{1}{2}\lambda^2 v^2$$

but similar to the NMSSM, for typical values of t_S ($1 \ldots 10\,\text{TeV}^3$), it holds

$$m_{H^\pm}^2 \approx m_W^2 + m_{A_1}^2 - \frac{1}{2}\lambda^2 v^2$$

– $H^\pm$ interactions compared

In both models (like in the MSSM):

$$\begin{pmatrix} H_d^+ \\ H_u^+ \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} G^+ \\ H^+ \end{pmatrix} \quad \text{with } \tan\beta = \frac{v_2}{v_1}$$

- all $H^\pm$ interactions without neutral Higgs bosons and Higgsinos are the same as in the MSSM
- changed/new $H^\pm$ interactions involving the 5 neutral Higgs bosons $(H_1, H_2, H_3, A_1, A_2)$
- changed/new $H^\pm$ interactions with the 5 neutralinos and the 2 charginos

In both models (like in the MSSM): $m_{H^\pm}$ can be chosen as input parameter

→ The major $H^\pm$ production and decay cross sections have the same tree-level prediction in all three models.
Differences start at loop-level, where neutral Higgs bosons are involved.

→ The real difference is in the neutral Higgs sector.
Thus, testing mass relations among Higgs particles may be crucial in order to decide which model fits the data.

• $H^{\pm}$ in other SUSY models

– SUSY Higgs triplet models

$$W_{\text{OHT-MSSM}} = \epsilon_{ij} h_e \widehat{H}_d^i \widehat{L}^j \widehat{E} + \epsilon_{ij} h_d \widehat{H}_d^i \widehat{Q}^j \widehat{D} - \epsilon_{ij} h_u \widehat{H}_u^i \widehat{Q}^j \widehat{U} + \epsilon_{ij} \mu_D \widehat{H}_d^i \widehat{H}_u^i + \epsilon_{ij} \lambda \widehat{H}_d^i (\widehat{\Sigma} \widehat{H}_u)^j + \mu_T Tr\{\widehat{\Sigma}^2\}$$

$$\mathcal{L}_{\text{soft}} = -m_{H_d}^2 |H_d|^2 - m_{H_u}^2 |H_u|^2 - m_{\Sigma}^2 Tr\{\Sigma^\dagger \Sigma\} - (\lambda A \epsilon_{ij} H_d^i (\Sigma H_u)^j + B_D \mu_D \epsilon_{ij} H_u^i H_d^j + B_T \mu_T Tr\{\Sigma^2\} + \text{h.c.}) + [\text{sfermion and gaugino mass terms}]$$

with Higgs triplet superfield $\widehat{\Sigma}$

[→ talk of J.L. Diaz Cruz]

– ... (and many more models)

summary

- SUSY extensions of the Standard Model predict the existence of a charged Higgs boson.

- The major $H^{\pm}$ production processes in MSSM, NMSSN and mnSSM are not terribly different.

  The real distinction is in the neutral Higgs (and Higgsino) sector.

- More exiting SUSY extensions exist, the $H^{\pm}$ phenomenology of which need to be examined (e.g. SUSY Higgs triplet models, Twin SUSY, etc.)