BEYOND THE STANDARD MODEL

Sommersemester 2017, U. Wien

~~Wednesday~~ Thursday 11:00 – 13:00 with additional slots on some Wednesdays, 11:00 – 13:00

Rough plan of the lecture

- Motivation, deficiencies of the Standard Model
- SUSY as a standard paradigm (focus on MSSM and pheno)
- Composite Higgs Models
- Little Higgs Models / Twin Higgs Models
- Top Partners / Electroweak Precision Observables
- Higgs EFT (Effective Field Theory) and BSM
- Dibosons, Tribosons, Vector Boson Scattering
- Dark Matters at Colliders, axions and relaxions
- Kinematics, cascades and all that.

The SM in a nutshell

We first summarize a few details about the SM to elaborate on its deficiencies:

The SM is an $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge theories with the following particle content:

3 families of $Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} : (3, 2, \tfrac{1}{3})$, $u_R : (3, 1, -\tfrac{4}{3})$

$d_R : (3, 1, +\tfrac{2}{3})$, $L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} : (1, 2, -1)$, $e_R : (1, 1, -2)$

as well as the Higgs doublet: $H = \begin{pmatrix} h^+ \\ h^- \end{pmatrix} : (1, 2, 2)$

(1) 1998: Confirmation for explicit neutrino masses which makes introduction of right-handed neutrino fields necessary:

$\nu_R = (1,1,0)$ Field completely uncharged under SM gauge group.

Neutrino mass term may be written as standard Yukawa term:

$$Y_\nu \left(\bar{L}_L H \nu_R \right) + h.c.$$

Tiny neutrino masses might motivate mechanism like seesaw. (one eigenvalue of mass mixing matrix driven extremely small). [not part of this lecture]

(2) 1968: Sacharov conditions for the explanation of the generation of the matter – antimatter asymmetry:

$$\frac{N_B}{N_\gamma} \sim 10^{-9}$$

1 Deviation from thermal equilibrium.
2 Baryon number violation
3 C-, CP violation.

CP violation discovered in 1964 in Kaon decays, needs existence of a (physical) complex phase in the SM interactions. $\longrightarrow$ Necessity of 3 generations, because phase in 2x2 mixing matrix can be absorbed by field redefinitions (is not physical)

CKM phase: Cabibbo – Kobayashi – Maskawa. Rotation between electroweak interaction basis (cf. above) and mass basis parameterized by Euler angles and one complex phase.

$\boxed{\text{CP violation is not enough in the SM!}}$

Measured in Kaon- and B meson system.
$\Longrightarrow$ Precision measurements as constraints.

(3) Connected: possible phase in QCD Lagrangian connected to CP violation as well:

$$\mathcal{L}_{gluon} = -\frac{1}{4\pi g_s^2} G^a_{\mu\nu} G^{a\mu\nu} + \frac{i\theta}{4\pi g^{12}} G^a_{\mu\nu} \varepsilon^{\mu\nu\rho\sigma} G^a_{\rho\sigma}.$$

2nd term smaller than natural scales in QCD suggest by 9 orders of magnitudes, as measured by (absence of) electrical dipole moments of the neutrons and also heavier nuclei.

$\Longrightarrow$ Precision measurements as constraints.

$\Rightarrow$ Possible solution: existence of a certain (global) symmetry in the QCD Lagrangian, spontaneously broken and rendered small by small vacuum expectation value.

Corresponding Goldstone boson: a, axion.

Physics of axions will be later covered by Christophe G.

④ a) Astrophysical observations:

rotation curves of galaxies, micro lensing, cosmic microwave background:

⟹ existence of form of matter, that interacts only gravitationally and maybe also weakly $\boxed{\text{(DARK MATTER)}}$

Mass ranges from eV to 10^{16} GeV

Might be connected by the WIMP paradigm / miracle to the TeV / electroweak scale

WIMP: weakly interacting massive particles.

Triggered by (accidental)? coincidence of annihilation rates in the early universe with the size of cross sections with weak interactions strength of TeV-scale particles.

⟶ Many searches: direct + indirect searches,

collider searches ⟶ discussed in this lecture

④b) cosmic microwave background: ⟹

existence of a fast expansion / inflationary phase in the early universe.

Concise proof would be measurement of scalar-to-tensor ratio in CMB (inflaton vs. graviton fluctuations).

Simplest / standard models: inflation driven by potential of a scalar field: inflaton field.

Possibility to connect this to scalar field of the SM and simple extensions (Higgs inflation etc.).

↳ partially covered by Christophe G.

④c) supernovae data, CMB

⟹ acceleration of universe: cosmological constant, dark energy etc.

believed not to have a particle ~~physics origin~~.

⑤. Quantum gravity

Not part of the SM.

unclear where effects come in.

but most likely at $M_{Pl} \sim \frac{1}{\sqrt{G_N}} \sim 10^{19}$ GeV.

⇒ 6 $\boxed{\text{Hierarchy problem}}$ existence of the big difference of $m_H \sim V \sim \frac{1}{\sqrt{G_F}} \sim 10^2$ GeV. and

$M_{Pl} \sim \frac{1}{\sqrt{G_N}} \sim 10^{19}$ GeV.

Abundant in Nature: scale separation by strong interactions, large scale fluctuations.

⟶ seems to be ruled out by precision data.

(electroweak measurements)

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7. $\boxed{\text{Fine tuning problem:}}$

fundamental difference between dependence of fermions vs. bosons on new physics scale / heavy particles or thresholds: Fermion masses protected by chiral symmetries (global independent rotations of left- and right-handed fields) which leads to $\delta m_f^2 \sim m_f^2 \ln\left(\frac{M_{NP}^2}{m_f^2}\right)$ (logarithmic dependence)

for scalars this is $\delta m^2 \sim M_{NP}^2$ (quadratic dependence)

Quadratic divergencies in perturbative corrections are not seen obstacle.

↳ NP models developed to protect scalar masses by symmetries (SUSY, Little Higgs, Twin Higgs)

or by making scalars composite (Technicolor, Compositeness etc.)

or by changing hierarchies (higher dimensions effectively lower M_{Pl}.)

(gravity only tested at $(10^{-1}\,\text{mm})^{-1} \ll M_{Pl}$.

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(8) "Fundamentalism of the SM" (or New SM, incl. ν_R)

Standard model / theory (?) has 28 independent parameters:

– 12 masses of fermions	$(u, d, c, s, t, b, e, \mu, \tau, \nu_1, \nu_2, \nu_3)$	12
– 3 gauge couplings	$(\alpha, \alpha_s, \alpha_w)$	15
– QCD vacuum angle	θ_{QCD}	16
– 2 Higgs sector parameters	$(v, m_H$ or $v, \lambda)$	18
– 3 CKM + 3 PMNS mixing angles.		24
– ϕ_{CKM}, ϕ_{PMNS}	2 phases	26
– 2 Majorana phases in neutrino sector		28

aesthetic argument against. → Searching for embeddings in more unified theories. (GUTs etc.).

↳ not part of this lecture).

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(9) Flavor:

Why 3 generations? Pattern of masses and mixings? Derivable from some unified model of flavor?

Vast set of data from K-system (CLOE, DAPHNE, BES, etc)

D-system and B-system (BaBaR, BELLE, BELLE2, LHC).

↳ (not part of this lecture.)

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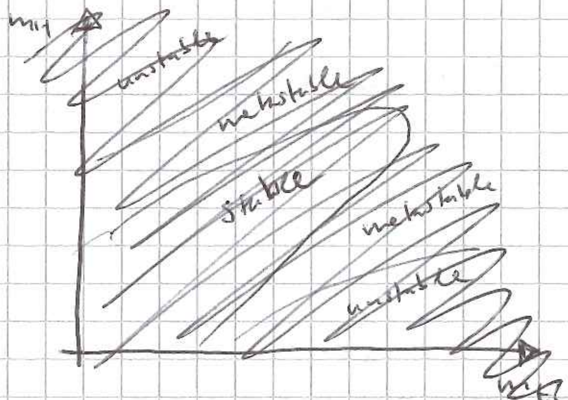
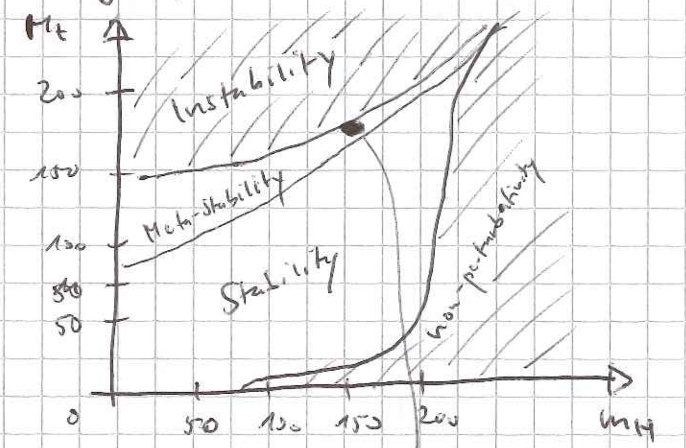
(10). Connected to (6), (7): stability of the electroweak vacuum





So, it seems that the canonical embedding of the SM into a quantum gravity theory at M_{Pl} doesn't work: one needs a UV completion, either some NP or yet unknown effects from quantum gravity.

(11) $\boxed{\text{Aestetic Arguments}}$ "arbitrary" pattern of masses, field content, 3 families, fractional charges, predictability vs. anthropic principle/landscape

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(12). $\boxed{\text{Electroweak Symmetry Breaking / Higgs sector}}$

Higgs-potential $V = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2$ seems ad hoc; ok, only renormalizable terms, but this is a mathematical concept

There is no microscopic explanation like e.g. the underlying electron spin dynamics ~~[illegible]~~ in Ginzburg-Landau theory which produces a similar potential for the magnetization.

Or: in the potential / fundamental field picture: no explanation for the negative sign of the quadratic term $\longrightarrow$ radiative symmetry breaking doesn't work in the SM.

Part I: $\boxed{\text{SUPERSYMMETRY}}$

Literature:

- M. Drees & R. Godbole / P. Roy: Theory + Pheno of SUSY, World Scientific, 2004
- H. Baer / X. Tata: Weak Scale SUSY, Cambridge U. Pr., 2006
- S. Weinberg: The Quantum Theory of Fields III, Cambridge U. Pr., 1998
- S. Martin: SUSY Primer. arXiv.org/abs/hep-ph/9709356
- Kalka / Soff: Supersymmetrie, Teubner, 1997
- J. Wess / J. Bagger: SUSY and SUGRA, Princeton U. Press, 1991.
- J. Terning: Modern SUSY, Oxford U. Press, 2006

SUSY is symmetry between bosons and fermions:

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

$\longrightarrow$ Couple properties of bosons and fermions, use chiral protection of fermion masses also for boson masses.

Historically: No-Go-Theorem (Coleman / Mandula, 1967)

Every Lie Group containing Poincaré group and an internal symmetry group must be a direct product.

Way out: Use anticommutators, i.e. graded Lie algebras or super Lie algebras, the generators must then be ~~fermionic~~ spinors under the Lorentz algebra.

Super-Poincaré algebra

$$[J^{\mu\nu}, J^{\rho\sigma}] = -i\left(g^{\mu\rho}J^{\nu\sigma} + g^{\nu\sigma}J^{\mu\rho} - g^{\mu\sigma}g^{\nu\rho} - g^{\nu\rho}J^{\mu\sigma}\right)$$

$$[P^\mu, P^\nu] = 0, \qquad [P^\mu, J^{\rho\sigma}] = i(g^{\mu\rho}P^\sigma - g^{\mu\sigma}P^\rho)$$

(P^μ is spin 1)

$$\{Q_r, \bar{Q}_s\} = 2\delta_{rs}\,\sigma^\mu P_\mu, \qquad \{Q_r, Q_s\} = Z_{rs} \text{ (central charges)}$$

$$[P_\mu, Q_r] = [P_\mu, \bar{Q}_s] = 0$$

$$[Q_r, M^{\mu\nu}] = i(\sigma^{\mu\nu}Q_r), \qquad [\bar{Q}, M^{\mu\nu}] = i(\bar{\sigma}\,\bar{Q}_s)$$

Classification of these algebras: theorem of Haag / Lopuszanski / Sohnius, NPB 88 (1975), 257

Z: central charges, not for $N=1$ SUSY (i.e. only one pair of $Q, \bar{Q}$ spinors).

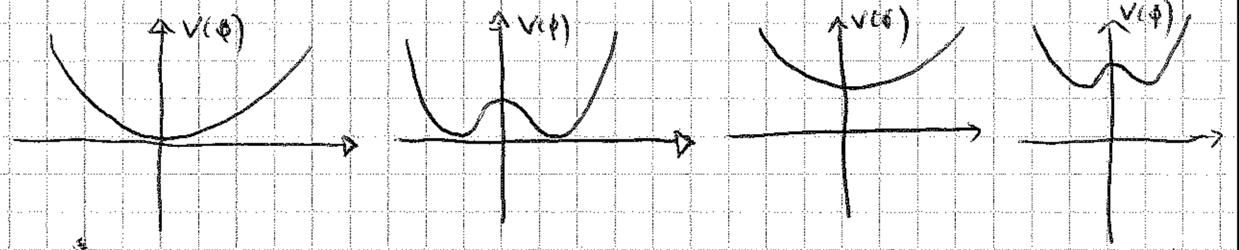
Irreducible representations of SUSY algebra contain equal # of boson + fermion states.

$$H \sim \sum QQ^\dagger \quad \text{is positive semidefinite} \Longrightarrow$$

$$\langle 0|H|0\rangle = 0 \iff Q|0\rangle = \bar{Q}|0\rangle = 0$$

or $\langle 0|H|0\rangle \neq 0 \iff Q|0\rangle \neq 0$ SUSY broken.

4 scenarios: for scalar potentials



SUSY ✓	SUSY ✓	SUSY ↯	SUSY ↯
int. symm. ✓	int. symm. ↯	int. symm. ✓	int. symm. ↯

Building blocks → irreducible representations → superfields (lin. representation of SUSY).

chiral superfields: $\Psi_L(x)$, $\phi_L(x)$ $[F(x)]$ $F(x)$: auxiliary field.

vector superfields: (Wess-Zumino gauge) $A_\mu(x)$, $\lambda(x)$ $[D(x)]$ $D(x)$: auxiliary field.

Two building blocks for supersymmetric theories:

1) SUSY generalizations of kinetic / gauge-kinetic terms
2) superpotential terms.

Minimal supersymmetric extension of the SM ⟶ MSSM.

all ~~write~~ all SM fields to superfields.

Observations: 1) no SM fermion can be superpartner of a gauge boson (chirality + adjoint gauge representation)

2) Higgs cannot be superpartner of lepton doublet because of lepton number constraints (though identical quantum numbers)

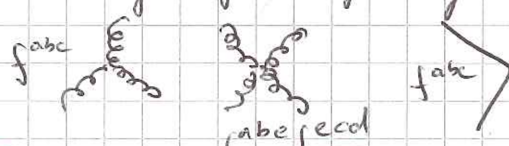
3) Anomalies (quantum level violations of classical symmetries) demand two Higgs doublets with their fermionic superpartners. Also SUSY would forbid using the same Higgs superfield for up-type and down-type Yukawa mass terms.

Superfield		Spin 0	Spin 1/2	Spin 1	Quantum numbers	
Squarks, Quarks	$\hat{Q}$	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	—	$(3,2)_{+1/3}$	3 families
"	$\hat{u}^c$	$\tilde{u}_R^*$	u_R^c	—	$(\bar{3},1)_{-4/3}$	
"	$\hat{d}^c$	$\tilde{d}_R^*$	d_R^c	—	$(\bar{3},1)_{2/3}$	
Sleptons/Sneutrinos Leptons/Neutrinos	$\hat{L}$	$(\tilde{\nu}_{L}, \tilde{e}_L)$	(ν, e_L)	—	$(1,2)_{-1}$	
	$\hat{e}^c$	$\tilde{e}_R^*$	e_R^c	—	$(1,1)_{+2}$	
	$[\hat{\nu}^c]$	$(\tilde{\nu}_R^*)$	(ν_R^c)	—	$(1,1)_0$	
Higgs/Higgsinos	$\hat{H}_u$	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	—	$(1,2)_{+1}$	
	$\hat{H}_d$	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	—	$(1,2)_{-1}$	
Gluino, Gluon	$\hat{V}_G$	—	$\tilde{g}$	g	$(8,1)_0$	
Wino, W-Boson	$\hat{V}_W$	—	$\tilde{W}^{\pm}, \tilde{W}^0$	$W^{\pm}, W^0$	$(1,3)_0$	
Bino, B-Boson	$\hat{V}_B$	—	$\tilde{B}$	B	$(1,1)_0$.	

Kinetic terms for superfields:

$$\boxed{\mathcal{L}_{kin,VSF} = -\frac{1}{4} \underbrace{F^a_{\mu\nu} F^{\mu\nu,a}}_{\text{gluon field strength}} + \frac{i}{2} \underbrace{\bar{\lambda}^a (\not{D}\lambda)^a}_{\text{gluino kinetic term}} + \frac{1}{2} D^a D^a}$$

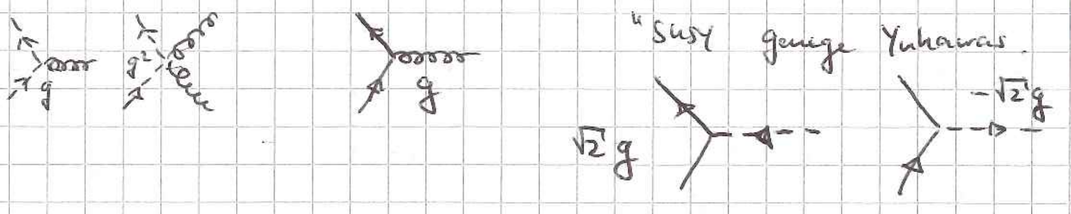
"D-term auxiliary fields"



SUSY generalization of kinetic terms

$$\mathcal{L}_{kin,XSF} = |D_\mu \phi|^2 + \bar{\Psi} \not{D} \Psi - \sqrt{2}\, i g \left[(\bar{\Psi}\lambda)\phi + h.c. \right]$$

"SUSY gauge Yukawas"



$$+ \underbrace{g D |\phi|^2}_{\text{D auxiliary term}} + \underbrace{|F|^2}_{\text{F auxiliary term}}$$

Non-gauge interactions in supersymmetry

only way to write this down is by means of the so-called superpotential which must be a holomorphic functions of its arguments, i.e. a function of only left-chiral superfields (and then the Hermitian adjoint). Otherwise, the SUSY trafo wouldn't map this in a total derivative (action invariant); or it could be undone by a simple field redefinition.

Renormalizable superpotentials just have linear, quadratic and cubic terms:

$$\boxed{W(\hat{\Phi}) = \sum_i \lambda_i^{(1)} \hat{\Phi}_i + \sum_{i,j} \lambda_{ij}^{(2)} \hat{\Phi}_i \hat{\Phi}_j + \sum_{i,j,k} \lambda_{i,j,k}^{(3)} \hat{\Phi}_i \hat{\Phi}_j \hat{\Phi}_k}$$

only allowed, if $\hat{\Phi}_i$ is a complete singlet.

no vector superfields allowed in the superpotential.

Leads to the following Lagrangian:

(using $\lambda_{ij}^{(2)} \equiv m_{ij}$, $\lambda_{ijk}^{(3)} \equiv g_{ijk}$

$$\mathcal{L}_{\text{Sup Pot.}} = m_{ij}\left(\phi_i F_j - \frac{1}{2}\overline{\Psi^c_{L_i}}\Psi_{L_j}\right) + g_{ijk}\left(\phi_i \phi_j F_k - \overline{\Psi_{L_i}}\Psi_{L_j}\phi_k\right) + \lambda_i F_i + \text{h.c.}$$

$$\mathcal{L}_{\text{kin}} \longrightarrow F_i^* F_i$$

Equation of motion (E.O.M.) for ancillary fields:

$$\boxed{\frac{\partial \mathcal{L}}{\partial F_k^*} = F_k + \lambda_k^* + m_{ik}^* \phi_k^* + g_{ijk}^* \phi_i^* \phi_j^* = 0}$$

(and conjugate equation)

General structure of SUSY theories:

$$\mathcal{L} = \mathcal{L}_{\text{kin}} - \sum_k |F_k|^2 - \sum_i |D_i|^2 \qquad \text{(after insertion of e.o.m.)}$$

$$\mathcal{L}_{\text{sup pot.}} + \sum_k |F_k|^2 = \underbrace{-\frac{1}{2} m_{ik}\overline{\Psi^c_{i_L}}\Psi_{k_L} - \frac{1}{2} m_{ik}^* \overline{\Psi^c_{R_R}}\Psi_{k_R}}_{\text{no vector-like mass terms allowed for SM superfields!}}$$

$$\underbrace{-g_{ijk}\overline{\Psi^c_{i_L}}\Psi_{j_L}\phi_k - g_{ijk}^*\overline{\Psi^c_{i_R}}\Psi_{j_R}\phi_k^*}_{\text{Yukawa terms}} \underbrace{- \sum_k \left|\lambda_k + m_{ki}\phi_i + g\,\phi_k^2\right|^2}_{\text{Scalar potential,}}$$

does contain only quartic terms.

As λ_k and m_{ki} is 0 for the MSSM (except for the Higgs superfield mass term $\mu \hat{H}_u \hat{H}_d$) this is in principle only a quartic scalar term.

SUSY breaking

again: (spontaneous) SUSY breaking $Q|0\rangle \neq 0 \Rightarrow \langle 0|H|0\rangle = E_{vac.} \neq 0$.

$\langle H\rangle = 0$ SUSY vs. $\langle H\rangle \neq 0$ ~~SUSY~~

SUSY multiplets contain bosons and fermions of identical masses, not seen in nature $\Rightarrow$ SUSY must be broken

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Scalar potential from kinetic terms and superpotential:

$$V = \frac{1}{2}|D|^2 + \frac{1}{2}|F|^2 \overset{!}{\geq} 0 \Rightarrow \begin{array}{l}\text{SUSY broken if } \langle V\rangle \neq 0 \\ \text{SUSY intact for } \langle V\rangle = 0.\end{array}$$

either $\langle D\rangle \neq 0 \Rightarrow$ D-term breaking: Fayet/Iliopoulos 1974

$\langle F\rangle \neq 0 \Rightarrow$ F-term breaking: O'Raifeartaigh (Lochlainn) 1975

Spontaneously broken (global) SUSY leads to a massless fermion, the Goldstino (analogue of Goldstone boson).

In general: $\boxed{\tilde{G} = \frac{\langle D^a\rangle}{\sqrt{2}}\lambda^a + \langle F_i\rangle \psi_i}$

Goldstino has gaugino and matter fermion components if $\langle D^a\rangle$ and $\langle F\rangle$ terms are both present.

By simple construction one can show that for any spontaneously broken SUSY theory one has:

$$\boxed{\mathrm{STr}\left[\underline{\underline{m}}^2\right] := \sum (-1)^j (2j+1)\, \mathrm{tr}\left(\underline{\underline{m}}_j^2\right) = 0}$$

"supertrace"

(Ferrara/Girardello, Palumbo, Fayet, 1979)

$m_d^2 + m_s^2 + m_b^2 \simeq (5\text{ GeV})^2 \Longrightarrow$ no squark could have a mass larger than 7 GeV.

$\hookrightarrow$ Even more: from the only allowed D-terms (QCD and EM) in the MSSM, there must either be a up-squark of $Q = +2/3$ lighter than the u-quark, or a down squark of $Q = -1/3$ lighter than the d-quark

(Mass-splitting rules).

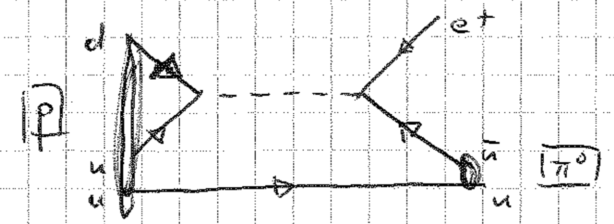
MSSM Superpotential:

$$W = (\underline{u}^c \underline{\underline{Y}}_u \underline{Q}_j)\epsilon H_u - (\underline{d}^c \underline{\underline{Y}}_d \underline{Q})\epsilon H_d - (\underline{e}^c \underline{\underline{Y}}_e \underline{L})\epsilon H_d + \mu H_u \epsilon H_d$$

$$\underbrace{+ \frac{1}{2}\lambda^{ijk} L_i d_j e_k^c + \lambda'^{ijk}(L_i \epsilon Q_j) d_k^c + \mu'^i (L_i \epsilon H_u)}_{\Delta L = 1,\ \text{lepton-number violating}} + \underbrace{\frac{1}{2}\lambda''^{ijk} u_i^c d_j^c d_k^c}_{\Delta B = 1\ \text{baryon-number violating.}}$$

1st line: SUSY-generalization of Yukawa couplings; SUSY Higgs mass term.

2nd line:



Tree-level contribution to proton decay $p \to e^+ \pi^0$; experimental bounds $\tau_p \gtrsim 10^{33}$ yrs.

$$\Gamma_{\mu \to e\nu\nu} \sim g^4 \frac{m_\mu^5}{M_W^4} \sim G_F^2 m_\mu^5 \xrightarrow{\text{analogy}} \Gamma_{p \to e^+\pi^0} \sim \lambda'^2 \lambda''^2 \frac{m_p^5}{m_{\tilde{d}}^4}$$

$\Rightarrow$ either both $\lambda', \lambda'' \lesssim 10^{-7}, 10^{-8}$ or $m_{\tilde{d}}$ very, very large.
(SUSY proton decay problem)

Solve this by introducing R parity / matter parity

$$\boxed{P_M = (-1)^{3(B-L)}}$$

multiplicative quantum number

Q, L, e^c, u^c, d^c have $P_M = -1$
H_u, H_d have $P_M = +1$
V_G, V_W, V_B have $P_M = +1$.

$\hookrightarrow$ kinetic terms and W_{MSSM}, W_{RPV} forbidden.

Rewrite this as an additive quantum number: $\boxed{P_R = (-1)^{3(B-L)+2s}}$

$\to$ SM particles: $P_R = +1$ $u_L, d_L, u_R, d_R, e_L, e_R, e_R, \nu, H_u, H_d, g, W^\pm, W^0, B$

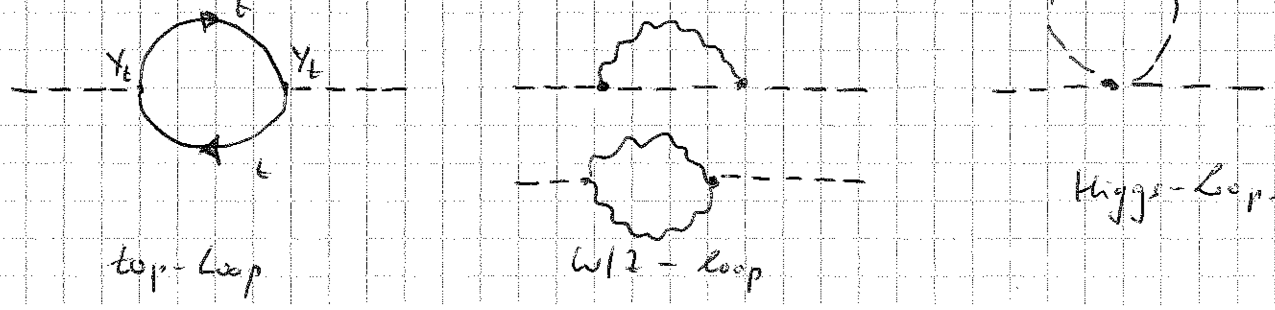
SUSY particles: $P_R = -1$ $\tilde{u}_L, \tilde{d}_L, \tilde{u}_R, \tilde{d}_R, \tilde{e}_L, \tilde{e}_R, \tilde{\nu}, \tilde{H}_u, \tilde{H}_d, \tilde{g}, \tilde{W}^\pm, \tilde{W}^0, \tilde{B}$

$\hookrightarrow$ Two main consequences:

* SUSY partners can be produced only pair-wise (+ phase-space penalty)
* Lightest R-odd / SUSY particle is stable $\to$ DM candidate (LSP).

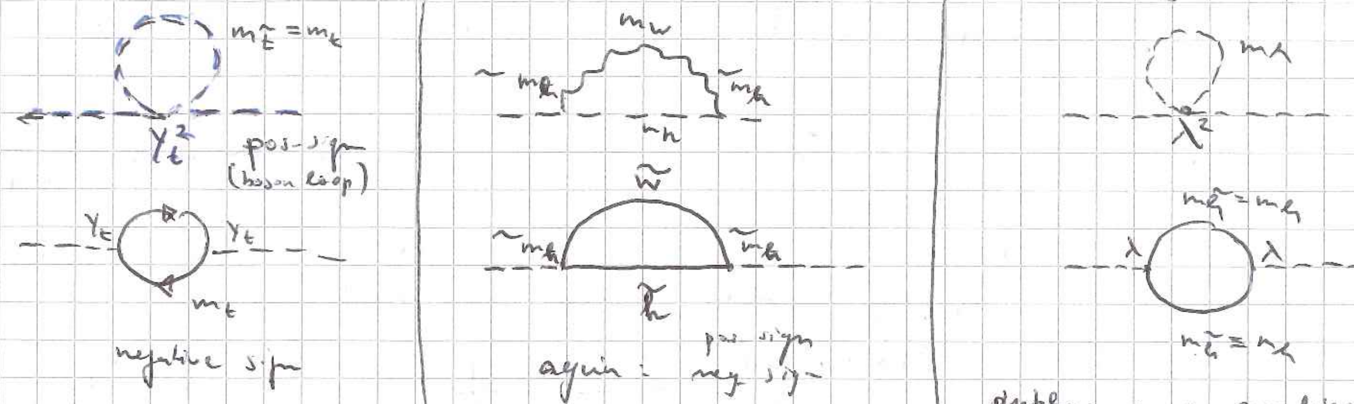
What about SUSY breaking now?

Insertion: SUSY solution to hierarchy / fine-tuning problem:
quadratic divergences / quadratic sensitivity to New Physics



gives contributions to Higgs potential and Higgs mass term proportional to m_t^2, m_W^2, m_h^2, top-loop negative, the others positive.

In a supersymmetric theory, these contributions are exactly cancelled:



negative sign

(fermion loop)

again: neg. sign

sketchy: more complicated due to 2HDM in SUSY

$\Longrightarrow$ exact cancellation for exact SUSY

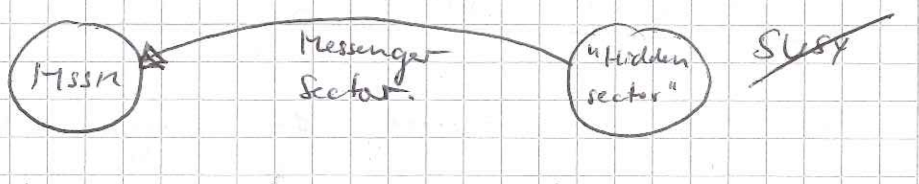
It can be shown (by the holomorphy of the superpotential), that to all orders in perturbation theory (!) the superpotential does not get any corrections $\Longrightarrow$ $\boxed{W_{\text{eff-all orders}} = W_{\text{tree}}}$

[SUSY non-renormalization theorems, N. Seiberg, 1993/94; + earlier work]

Remark: There is wave-function renormalization, as the kinetic terms are not holomorphic, hence couplings of canonically normalized fields run.

However, SUSY gauge couplings only get 1-loop corrections plus non-perturbative (instanton) corrections.

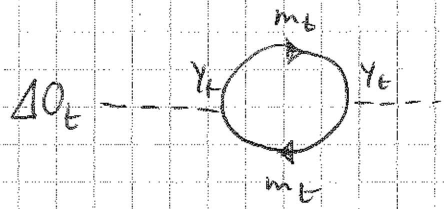
SUSY breaking necessary, and because of STr formula not possible in the MSSM field sector. Hence, hide/shadow SUSY breaking into a different sector of fields:

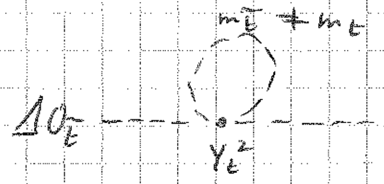


$\Longrightarrow$ MSSM is an effective field theory with explicit SUSY breaking

introduce this breaking as <u>soft breaking</u>, i.e. only by dimensionful coupling constants in operators in order not to spoil non-renormalization theorems (or alternatively: cancellation of quadratic divergencies).

$\hookrightarrow$ e.g.





$$\Longrightarrow \Delta O_t + \Delta O_{\tilde t} \sim (m_{\tilde t}^2 - m_t^2) \cdot \log\left(\frac{m_{\tilde t}^2 - m_t^2}{\Lambda^2_{SUSY}}\right)$$

but not $\sim \Lambda^2_{SUSY}$!

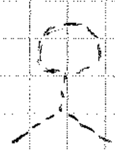
<u>Classification of soft-breaking terms</u> Girardello / Grisaru, NPB 194 (1982), 65

- scalar mass terms $m_\phi^2 |\phi|^2$ dim $m_\phi^2 = 2$
- trilinear scalar terms $A_{ijk}\phi_i\phi_j\phi_k + h.c.$ dim $A = 1$
- gaugino masses $\frac{1}{2} m(\lambda\lambda + \bar\lambda\bar\lambda) = \frac{1}{2} m \bar\chi\chi$ dim $m = 1$
- bilinear terms $B_{ij}\phi_i\phi_j + h.c.$ dim $B = 2$
- linear terms $C_i\phi_i + h.c.$ dim $C = 3$

not possible in the MSSM because of gauge symmetries.

⊗ [– mixed trilinear terms $C_{ijk}\phi_i^*\phi_j\phi_k + h.c.$ dim $C = 1$]

With those and only those soft terms, the Lagrangian remains free of quadratic divergencies to all orders in perturbation theory.



could introduce quadratic divergencies, if ϕ_i gauge singlet

doesn't appear in MSSM, nor in any model of SUSY breaking.

Summary of all possible soft terms.

$$\boxed{\begin{aligned}\mathcal{L}^{soft}_{MSSM} = &-\tfrac{1}{2}\left(M_3\tilde g\tilde g + M_2 \tilde W\tilde W + M_1 \tilde B\tilde B + h.c.\right) - m^2_{H_u}|H_u|^2 - m^2_{H_d}|H_d|^2 \\ &-(b H_u \epsilon H_d + h.c.) - \tilde Q^\dagger \underline{\underline{m}}_Q^2 \tilde Q - \tilde L^\dagger \underline{\underline{m}}_L^2 \tilde L - \tilde u^* \underline{\underline{m}}_u^2 \tilde u \\ &- \tilde d^* \underline{\underline{m}}_d^2 \tilde d - \tilde e^* \underline{\underline{m}}_e^2 \tilde e - \left(\tilde u^* \underline{\underline{A}}_u \tilde Q \epsilon H_u - \tilde d^* \underline{\underline{A}}_d \tilde Q \epsilon H_d - \tilde e^* \underline{\underline{A}}_e \tilde L \epsilon H_d + h.c.\right)\end{aligned}}$$

There are different breaking scenarios: mSUGRA (by higher-dim. op. at M_{Pl}, most likely by gravitational interactions), GMSB (gauge-mediated SUSY breaking, normal QCD + EW interactions are mediators), AMSB (anomaly-mediated), etc. gaugino mediation, mirage mediation

Sfermionen.

Potential terms for sfermions:

soft masses: $m_{\tilde f_L}^2 |\tilde f_L|^2 + m_{\tilde f_R}^2 |\tilde f_R|^2$

F-terms from superpotential: $Y_f |H_{u,d} \tilde f_L|^2 + Y_f^2 |H_{u,d} \tilde f_R|^2 + |\mu|^2 (H_{u,d} \tilde f_L \tilde f_R^* + h.c.)$

soft A terms: $A_f H_{u,d} \tilde f_L \tilde f_R^* + h.c.$

D-terms: $g^2 |\tilde f_L|^2 |H_{u,d}|^2 + g'^2 |\tilde f_{L/R}|^2 |H_{u,d}|^2$

$$X_{f\uparrow} = A_{f\uparrow} - \mu \cot\beta .$$

Discuss the Higgs sector first

1) Use an $SU(2)$ gauge trafo to rotate away VEV of H_u^+, so $\langle H_u^+ \rangle = 0$.

2) $\frac{\partial V}{\partial H_u^+} \overset{!}{=} 0$

$$V_{Higgs} = \underbrace{\frac{g^2}{2} |H_u^+ H_d|^2 + \frac{g^2+g'^2}{8} \left[(H_u^\dagger H_u) - (H_d^\dagger H_d) \right]^2}_{D\ terms}$$
$$+ (m_1^2 + |\mu|^2)(H_1^\dagger H_1) + (m_2^2 + |\mu|^2)(H_2^\dagger H_2)$$
$$- (B\mu) \, Re\left[H_u^0 H_d^0 - H_u^- H_d^+ \right]$$

soft terms

F terms

$$\Rightarrow \quad \langle H_u^- \rangle \left((B\mu) + \frac{g^2}{2} \langle H_u^{0*} \rangle \langle H_d^{0*} \rangle \right) \overset{!}{=} 0$$

Now, use $U(1)_Y$ trafo, to choose $\langle H_u^- \rangle = 0$, and to choose $\langle H_u^0 \rangle, \langle H_d^0 \rangle, (B\mu)$ real and positive

by: only $(B\mu)$ depends on the phases $\Rightarrow$ phase trafo of H_u and H_d $\Rightarrow \mathbb{R} \ni (B\mu) > 0 \Rightarrow \mathbb{R} \ni H_u^0 H_d^0 > 0 \Rightarrow H_u, H_d$ have opposite phases $\Rightarrow U(1)_Y$ trafo: $\mathbb{R} \ni \langle H_d^0 \rangle, \langle H_u^0 \rangle > 0$

(using CP eigen states).

Potential for the neutral Higgs:

$$\boxed{V_{\phi^0} = (|\mu|^2 + m_{H_u}^2) |H_u^0|^2 + (|\mu| + m_{H_d}^2) |H_d^0|^2 - \overset{b}{\overset{\shortparallel}{(B\mu)}} (H_u^0 H_d^0 + h.c.) + \frac{g^2+g'^2}{8} \left(|H_u^0|^2 - |H_d^0|^2 \right)^2}$$

Conditions for extrema:

$$\left. \frac{\partial V_{\phi^0}}{\partial H_u^0} \right|_{H_u^0 = 0} = \left. \frac{\partial V_{\phi^0}}{\partial H_d^0} \right|_{H_d^0 = 0} = 0 .$$

Define $\langle H_u \rangle = v_u \equiv v_2$, $\langle H_d \rangle = v_d \equiv v_1$. $\tan\beta = \frac{v_2}{v_1}$

One gets:
$$\boxed{\begin{aligned} m_{H_u}^2 + |\mu|^2 - b\cot\beta - \frac{m_Z^2}{2}\cos(2\beta) &= 0 \\ m_{H_d}^2 + |\mu|^2 - b\tan\beta + \frac{m_Z^2}{2}\cos(2\beta) &= 0 \end{aligned}}$$

inserting: $m_Z^2 = \frac{1}{4}(g^2+g'^2)(v_1^2+v_2^2)$ $\qquad m_A^2 = 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2$

(mass of the pseudoscalar Higgs)

$$\boxed{b = \frac{m_A^2}{2}\sin(2\beta)}$$

$$m_{H_d}^2 + |\mu|^2 = \frac{1}{2}m_A^2 - \frac{1}{2}(m_A^2+m_Z^2)\cos(2\beta)$$
$$m_{H_u}^2 + |\mu|^2 = \frac{1}{2}m_A^2 + \frac{1}{2}(m_A^2+m_Z^2)\cos(2\beta)$$

Mass matrix of neutral pseudoscalars:

$$(\mathcal{M}^2)_{Im} = \begin{pmatrix} \frac{1}{2}m_A^2(1-\cos(2\beta)) & \frac{1}{2}m_A^2\sin(2\beta) \\ \frac{1}{2}m_A^2\sin(2\beta) & \frac{1}{2}m_A^2(1+\cos(2\beta)) \end{pmatrix}$$
$$= \frac{1}{2}m_A^2\begin{pmatrix} 1-\cos(2\beta) & \sin(2\beta) \\ \sin(2\beta) & 1+\cos(2\beta) \end{pmatrix} \Longrightarrow$$

$$\boxed{m_{\phi_1^0}^2 = 0} \qquad \boxed{m_{\phi_2^0}^2 = m_A^2}$$

↳ Goldstone boson connected to the W^0 (or Z boson).

$$(\mathcal{M}^2)_{Re} = \begin{pmatrix} \frac{m_A^2}{2}(1-\cos(2\beta)) + \frac{m_Z^2}{2}(1+\cos(2\beta)) & -\frac{1}{2}(m_A^2+m_Z^2)\sin(2\beta) \\ -\frac{1}{2}(m_A^2+m_Z^2)\sin(2\beta) & \frac{m_A^2}{2}(1+\cos(2\beta)) + \frac{m_Z^2}{2}(1-\cos(2\beta)) \end{pmatrix}$$

(*)
$$\boxed{\begin{aligned} m_H^2 &= \frac{1}{2}\left[m_A^2+m_Z^2+\sqrt{(m_A^2+m_Z^2)^2-4m_A^2m_Z^2\cos^2(2\beta)}\right] \\ m_h^2 &= \frac{1}{2}\left[m_A^2+m_Z^2-\sqrt{(m_A^2+m_Z^2)^2-4m_A^2m_Z^2\cos^2(2\beta)}\right] \end{aligned}}$$

Relations: $\tan(2\alpha) = \tan(2\beta)\frac{m_A^2+m_Z^2}{m_A^2-m_Z^2} = \tan(2\beta)\frac{m_h^2+m_H^2}{m_A^2-m_Z^2}$

$$\cos(2\alpha) = -\cos(2\beta)\frac{m_A^2-m_Z^2}{m_H^2-m_h^2}, \qquad \sin(2\alpha) = -\sin(2\beta)\frac{m_A^2+m_Z^2}{m_H^2-m_h^2}$$

(*) m_H is always larger than the larger of $\{m_Z, m_A\}$, while m_h is always smaller than the smaller of $\{m_Z, m_A\}$.

Rotate the mass matrix for the real parts by $\begin{pmatrix}\cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha\end{pmatrix}$

As $m_A^2 > 0 \Longrightarrow 0 \leq \beta < \frac{\pi}{2}$.

Using $m_W^2 = \frac{1}{4}g^2(v_1^2+v_2^2)$, $\frac{m_W^2}{m_Z^2} = \frac{g^2}{g^2+g'^2} = \cos^2\theta_W$

The mass matrix for the charged states is:

$$\frac{1}{2}(m_W^2+m_A^2)\begin{pmatrix} 1-\cos(2\beta) & \pm\sin(2\beta) \\ \pm\sin(2\beta) & 1+\cos(2\beta) \end{pmatrix}$$

upper sign for real parts, lower sign for imaginary parts.

There is a massless mode, the Goldstone boson $G^\pm$ to $W^\pm$, while the massive mode is a charged Higgs:

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

The two Higgs doublets are now:

$$H_d = \begin{pmatrix} \frac{1}{\sqrt{2}}\left(v_1 + H^0\cos\alpha - h^0\sin\alpha + iA^0\sin\beta + iG^0\cos\beta\right) \\ H^-\sin\beta + G^-\cos\beta \end{pmatrix}$$

$$H_u = \begin{pmatrix} H^+\cos\beta - G^+\sin\beta \\ \frac{1}{\sqrt{2}}\left(v_2 + H^0\sin\alpha + h^0\cos\alpha + iA^0\cos\beta - iG^0\sin\beta\right) \end{pmatrix}$$

Modifications compared to SM couplings.

$$g_{hVV} = \sin(\beta-\alpha)\, g_{hVV}^{SM}, \quad VV = WW, ZZ$$

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

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

$$g_{hb b,\tau\tau} \equiv g_{hbb},\, g_{h\tau\tau},\, g_{h\mu\mu},\, g_{hss} = -\frac{\sin\alpha}{\cos\beta}\, g^{SM}_{Hbb,\, H\tau\tau,\, H\mu\mu,\, Hss}$$

$$g_{htt},\, g_{hcc} = \frac{\cos\alpha}{\sin\beta}\, g^{SM}_{Htt,\, hcc}$$

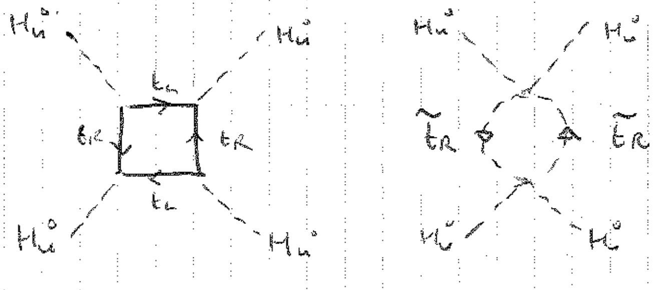
$$g_{Abb},\, g_{A\tau\tau} = \gamma_5 \tan\beta\, g^{SM}_{hbb}.$$

$\boxed{\text{Behavior of masses, "decoupling limit".}}$

cf. next page.

Conundrum with $m_h \lesssim m_Z$ is solved by radiative corrections:

$$m_h < |\cos(2\beta)|\, M_Z.$$



etc.

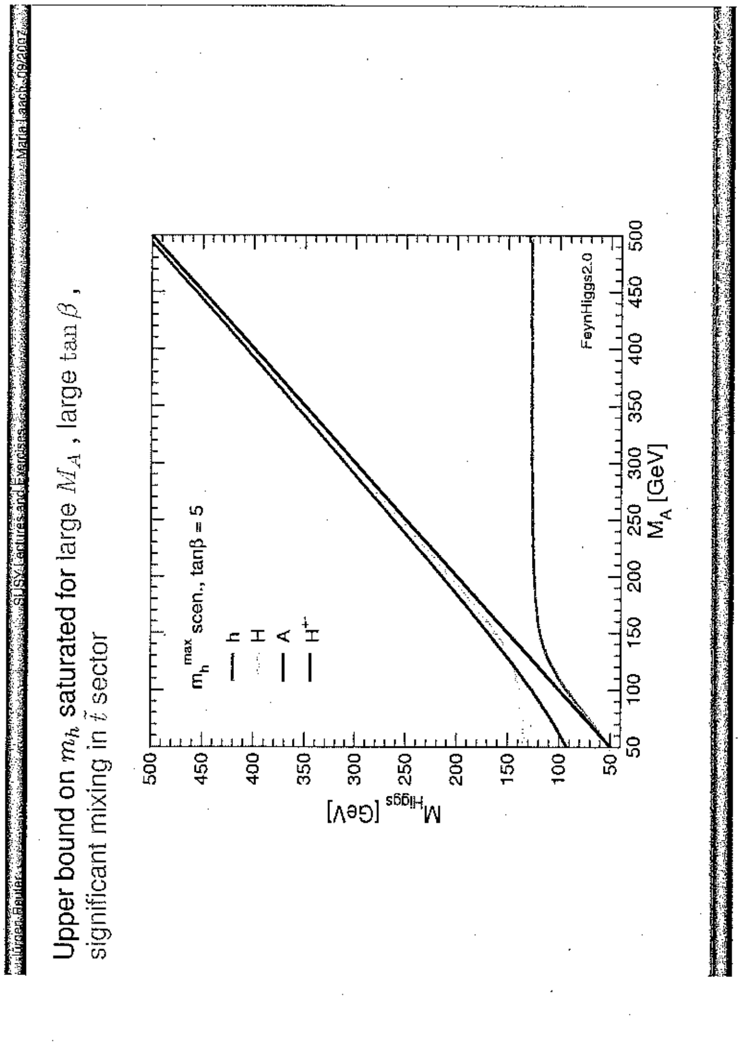
This leads to an upper bound of $m_{h^0} \leq 130$ GeV.

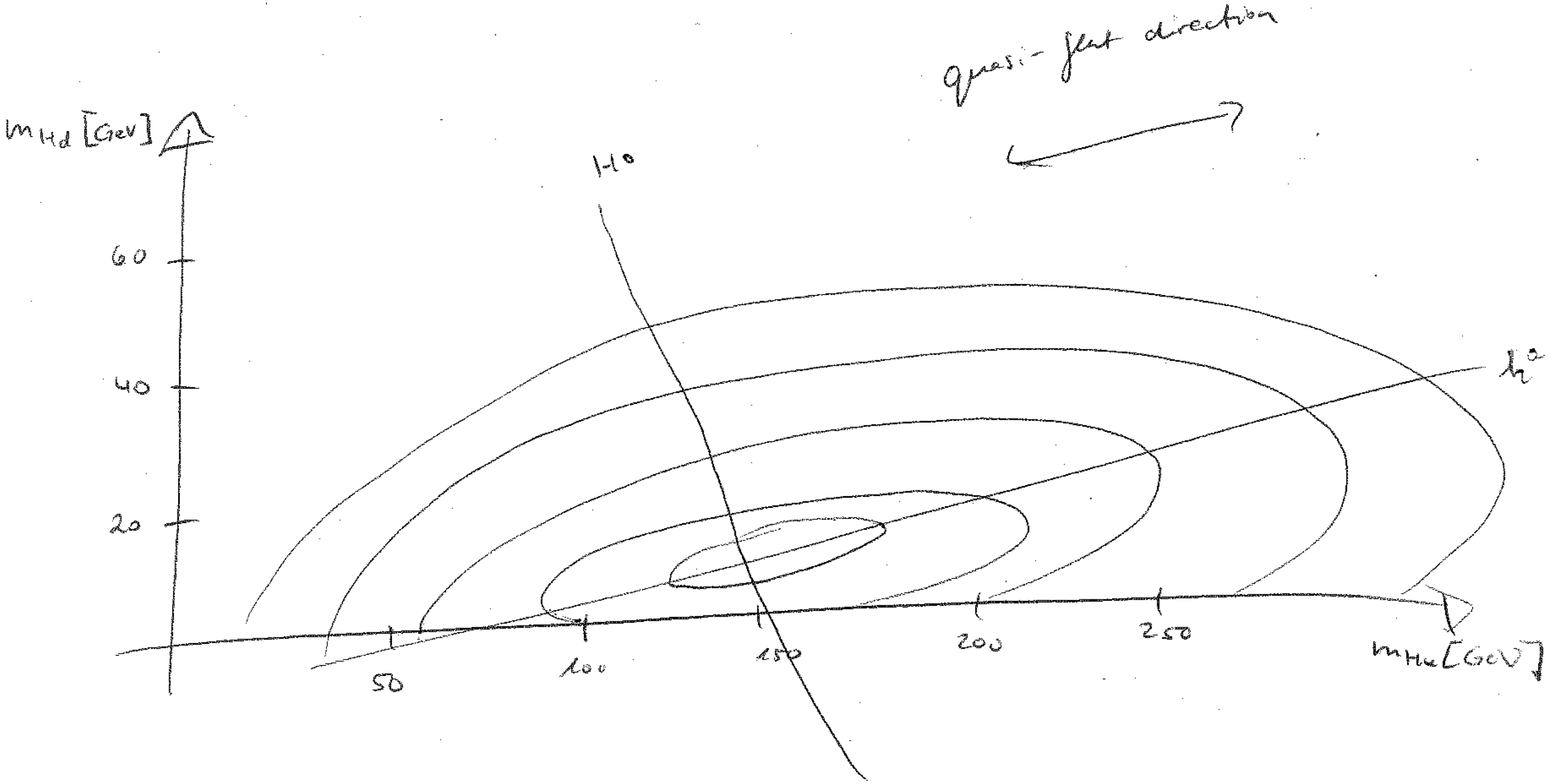
$$\Rightarrow m_{h^0}^2 \to m_{h^0}^2 + \Delta m_{h^0}^2$$

$$\Delta m_{h^0}^2 = \frac{3}{4\pi^2} v^2 y_t^4 \sin^2\beta \ln\left(\frac{\sqrt{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}}{m_t^2}\right) \approx \frac{(90\ \text{GeV})^2}{\sin^2\beta}$$

Behavior of MSSM

Higgs masses





MSSM has a rather special 2HDM, where the quartic terms are given by gauge interactions

Sfermions

Potential terms for sfermions

soft masses: $M^2_{\tilde f_L}|\tilde f_L|^2 + M^2_{\tilde f_R}|\tilde f_R|^2$

F-terms from the superpotential: $Y_f^2|H_{u,d}\tilde f_L|^2 + Y_f^2|H_{u,d}\tilde f_R|^2 + Y_f\mu\,(H_{u,d}\tilde f_L\tilde f_R^* + h.c.)$

soft A-terms: $A_f H_{u,d}\tilde f_L \tilde f_R^* + h.c.$

D-terms: $g^2|\tilde f_L|^2|H_{u,d}|^2 + g'^2|\tilde f|^2|H_{u,d}|^2$

Define: $X_{f\uparrow} \equiv A_{f\uparrow} - \mu\cot\beta\,,\quad X_{f\downarrow} \equiv A_{f\downarrow} - \mu\tan\beta$

$$M^2_{\tilde f\uparrow} = \left(\begin{array}{c|c} M^2_{\tilde f_L} + m^2_{f\uparrow} + \Delta D_{\tilde f\uparrow,L} & m_{f\uparrow}X_{f\uparrow} \\ \hline m_{f\uparrow}X_{f\uparrow} & M^2_{\tilde f_R\uparrow} + m^2_{f\uparrow} + \Delta D_{\tilde f\uparrow,R}\end{array}\right) \xrightarrow{\theta_{\tilde f\uparrow}} \begin{pmatrix} m^2_{\tilde f\uparrow,1} & 0 \\ 0 & m^2_{\tilde f\uparrow,2}\end{pmatrix}$$

$$\boxed{M^2_{\tilde f\downarrow} = \left(\begin{array}{c|c} M^2_{\tilde f_L} + m^2_{f\downarrow} + \Delta D_{\tilde f\downarrow,L} & m_{f\downarrow}X_{f\downarrow} \\ \hline m_{f\downarrow}X_{f\downarrow} & M^2_{\tilde f_R\downarrow} + m^2_{f\downarrow} + \Delta D_{\tilde f\downarrow,R}\end{array}\right) \xrightarrow{\theta_{\tilde f\downarrow}} \begin{pmatrix} m^2_{\tilde f\downarrow,1} & 0 \\ 0 & m^2_{\tilde f\downarrow,2}\end{pmatrix}}$$

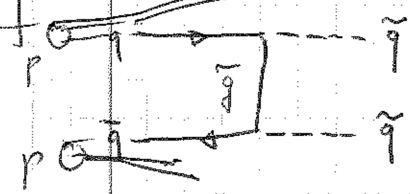
with the definition:

$$\Delta D_{\tilde f} = (T_{3,f} - Q_f\sin^2\theta_W)\cos(2\beta)\,m_Z^2.\quad \text{(for EWSB)}$$

Mixing often only considered for $\tilde\tau, \tilde b, \tilde t$ as it is proportional to m_f in the SM.

In general, the $\tilde\tau_1$ is the lightest slepton, very often the NLSP (next-to-lightest SUSY particle), $\tilde t_1$ the lightest squark.

1. + 2. generation squarks would be most copiously be produced at the LHC, e.g. from; $\tilde t$ and $\tilde b$ have smaller cross sections due to the lack of bottom (partially) and top content in the proton.



Sleptons are usually lighter than squarks as the soft mass terms, $M^2_{\tilde l}$ are smaller than there squark counterparts, $M^2_{\tilde q}$, due the large QCD radiative corrections compared to purely weak ones.

Charginos and Neutralinos (Electroweakinos)

These are the fermionic superfields components of the Higgs superfields, the Higgsinos, whose neutral components can be combined to a Majorana spinor

$$\tilde H_d = \begin{pmatrix}\psi^1_{H_d} \\ \bar\psi^1_{H_d}\end{pmatrix},\quad \tilde H_u = \begin{pmatrix}\psi^2_{H_u} \\ \bar\psi^2_{H_u}\end{pmatrix}.$$

The charged ones can be combined to a Dirac spinor.

$$\tilde{H}^+ = \begin{pmatrix} \Psi^1_{H_u} \\ \bar{\Psi}^2_{H_d} \end{pmatrix}, \quad \tilde{H}^- = \begin{pmatrix} \Psi^2_{H_d} \\ \bar{\Psi}^1_{H_u} \end{pmatrix}$$

For the fermionic partners of the gauge bosons, also introduce Majorana and Dirac 4-spinors, respectively.
Usually, an inclusion of a complex unit 'i' is used:

$$\tilde{W}^\pm = \begin{pmatrix} -i\lambda^\pm \\ i\bar{\lambda}^\mp \end{pmatrix}, \quad \tilde{A} = \begin{pmatrix} -i\lambda_A \\ i\bar{\lambda}_A \end{pmatrix}, \quad \tilde{Z} = \begin{pmatrix} -i\lambda_Z \\ i\bar{\lambda}_Z \end{pmatrix},$$

$\tilde{\lambda}_A$ and $\tilde{\lambda}_Z$ have been obtained after a weak-mixing angle rotation.

$$\lambda_A = \cos\theta_W \lambda_B + \sin\theta_W \lambda_{W^3}$$
$$\lambda_Z = -\sin\theta_W \lambda_B + \cos\theta_W \lambda_{W^3}$$

Names: Bino, Wino, (or: "photino", "zino")

The Gluino as a color-octet neutral fermion cannot mix with anything else.

But EWSB introduces, again, mixing between states with the same color and electromagnetic quantum numbers.

Use the basis: $\psi^0 \equiv (\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$; then we have

$$-\frac{1}{2}\overline{\psi^0} M_N \psi^0 \text{ with } M_N = \left(\begin{array}{cc|cc} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ \hline -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{array}\right)$$

Neglecting off-diagonal entries (assuming $m_Z \ll M_1, M_2, \mu$) leads to

$$\tilde{\chi}_1^0 = \tilde{B}, \quad \tilde{\chi}_2^0 = \tilde{W}_3^0, \quad \tilde{\chi}_{3,4}^0 = \frac{1}{\sqrt{2}}(\tilde{H}_u^0 \pm \tilde{H}_d^0)$$

<u>Slang:</u> Neutralinos are "bino-like", "wino-like", "higgsino-like"

After the mixing, neutralinos are assumed to be mass-ordered:

$$\underbrace{N^* M_N N^{-1}}_{\text{neutralino mixing matrix}} = \begin{pmatrix} m_{\chi_1} & & & 0 \\ & m_{\chi_2} & & \\ & & m_{\chi_3} & \\ 0 & & & m_{\chi_4} \end{pmatrix} \quad \text{with } m_{\chi_1} \leq m_{\chi_2} \leq m_{\chi_3} \leq m_{\chi_4}$$

There are many different conventions concerning signs of the masses and phases etc.

<u>Charginos:</u> using the 2-component spinor basis

$$\psi^\pm \equiv (\tilde{W}^+, \tilde{H}_u^+, \tilde{W}^-, \tilde{H}_d^-)$$

$$M_{\chi^\pm} = \begin{pmatrix} 0 & \underline{X}^T \\ \underline{X} & 0 \end{pmatrix} \quad \text{with} \quad \underline{X} = \begin{pmatrix} M_2 & g v_u \\ g v_d & \mu \end{pmatrix}$$

$$= \begin{pmatrix} M_2 & \sqrt{2} s_\beta m_W \\ \sqrt{2} c_\beta m_W & \mu \end{pmatrix}$$

This will be diagonalized in the following way:

$$\begin{pmatrix} \tilde{\chi}_1^+ \\ \tilde{\chi}_2^+ \end{pmatrix} = V \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \end{pmatrix}, \quad \begin{pmatrix} \tilde{\chi}_1^- \\ \tilde{\chi}_2^- \end{pmatrix} = U \begin{pmatrix} \tilde{W}^- \\ \tilde{H}_d^- \end{pmatrix} \quad \text{as}$$

$$U^* X V^{-1} = \begin{pmatrix} m_{\tilde{\chi}_1^\pm} & 0 \\ 0 & m_{\tilde{\chi}_2^\pm} \end{pmatrix}$$

In general, the lightest neutralino, $\tilde{\chi}_1^0$, is very bino like, while the second neutralino, $\tilde{\chi}_2^0$ is very wino-like and hence quite mass-degenerate with the $\tilde{\chi}_1^\pm$. $\tilde{\chi}_{3,4}^0$ and $\tilde{\chi}_2^\pm$ are rather Higgsino-like.

EWinos are hard to produce at the LHC, and are mainly expected as decay products from gluino and squark production.

Gluinos are Majorana particles, so have identical BRs to opposite sign-states:

$$\tilde{g} \to \tilde{q}^* q \longrightarrow \tilde{\ell}^+ \tilde{\chi}_1^0 q \longrightarrow \ell^+ q\, \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

$$\tilde{g} \to \tilde{q}\bar{q} \to \tilde{\ell}^- \tilde{\chi}_1^0 \bar{q} \longrightarrow \ell^- \bar{q}\, \tilde{\chi}_1^0 \tilde{\chi}_1^0. \qquad \text{etc. etc.}$$

Counting of parameters in the MSSM. (without right-handed neutrinos).

(1) Gauge sector

g, g', g_s or $\alpha_1, \alpha, \alpha_s$ 3 real gauge couplings.

θ_{QCD}: QCD vacuum angle.

$m_{\tilde{w}}, m_{\tilde{B}}, m_{\tilde{g}}$: 3 complex gaugino mass parameters.

---

(2). Higgs sector:

m_1^2, m_2^2 or $m_{H_u}^2, m_{H_d}^2$ 2 real mass squares

$(B\mu), \mu$ 2 complex mass parameters.

---

(3). For the limit $m_{\tilde{w}} \equiv m_{\tilde{B}} \equiv m_{\tilde{g}} \equiv \mu \equiv (B\mu) \equiv A^D \equiv A^U \equiv A^E \equiv 0$

$\Rightarrow$ 2 flavor-conserving symmetries: $U(1)_R$, $U(1)_{PQ}$ $\Longrightarrow$

$U(1)_R$-rotation to achieve $\mathbb{R} \ni m_{\tilde{g}} > 0$.

$U(1)_{PQ}$-rotation to achieve $(B\mu) \in \mathbb{R}$. $\Rightarrow$

Higgs sector is CP-conserving, (at tree- and 1-loop level)

2-loop-level brings in phases from sfermion-/fermion sector.

There are 7 real parameters in the Higgs-/Higgsino-/ Gaugino sector!

④ Flavor sector

h_E, h_u, h_D or Y_E, Y_u, Y_D like in the SM 27 real parameters + 27 phases

A_E, A_u, A_D additional 27 + 27 parameters.

$M_{\tilde{Q}}^2, M_{\tilde{u}}^2, M_{\tilde{D}}^2, M_{\tilde{L}}^2, M_{\tilde{E}}^2$ Hermitian 3×3 matrices of sparticles mass squares 30 + 15 d.o.f.

Global $U(3)^5$ rotations of the superfields (due to gaugino interactions with matter)

⟹ Elimination of unphysical d.o.f. Difference to the SM (without neutrino mixing)

due to arbitrary sneutrino masses, the separate lepton numbers L_e, L_μ, L_τ are not conserved, only the global lepton number L.

⟹ elimination of 15 real parameters and 28 phases. (*)

$U(3)$ has 3 real parameters (Euler angles) and 6 phases.

3×3 complex matrix has $2\cdot 9 = 18$ real parameters $U^+U = 1$ ⟶

orthonormality of $\binom{3}{2} = 3$ colums eliminates 3 real + 3 phases

normalization of colums to 1 eliminates 3 real parameters ⟹ 3 reals + 6 phases.

⟹ Flavor sector has

$$27 + 27 + 30 - 15 = 69 \text{ real parameters.}$$

(6 quark masses, 3 lepton masses, 3 CKM angles, 12 squark masses, 9 slepton masses, 36 new real mixing angles.

$$27 + 27 + 15 - 28 = 41 \text{ phases}$$ (CKM phase + 40 new phases)

in general 105 new parameters!

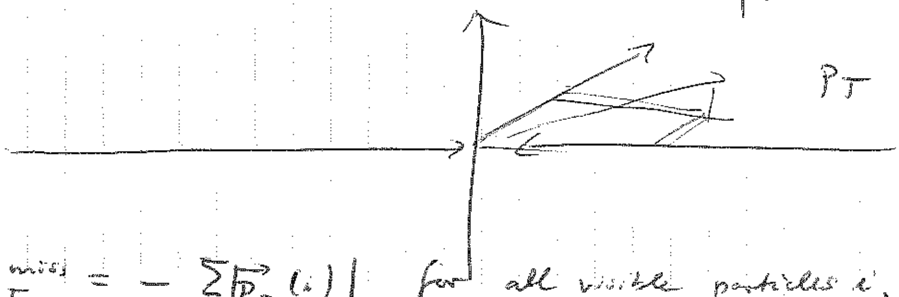
(*) normally B, L_e, L_μ, L_τ have to be accounted for as active / intact symmetries and to be subtracted from the elimination.

Search for supersymmetry:

in general signatures are jets + "MET", jets + leptons + MET, monojets + MET.

MET: "Missing E_T" = Missing transverse energy

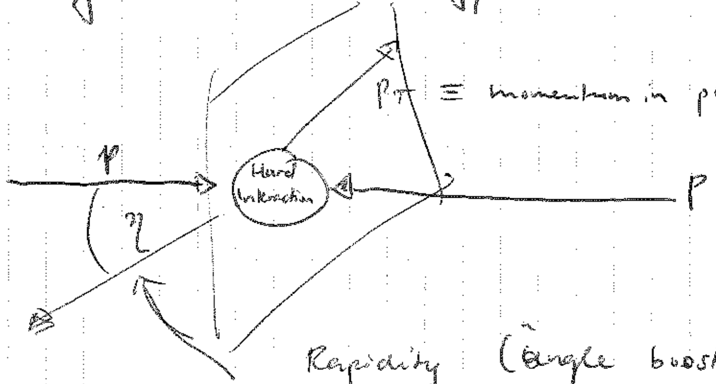
$E_T = \sqrt{m^2 + p_T^2}$ for an object of mass m and transverse momentum p_T.



$E_T^{miss} = -\sum_i |\vec{p}_T(i)|$ for all visible particles i.

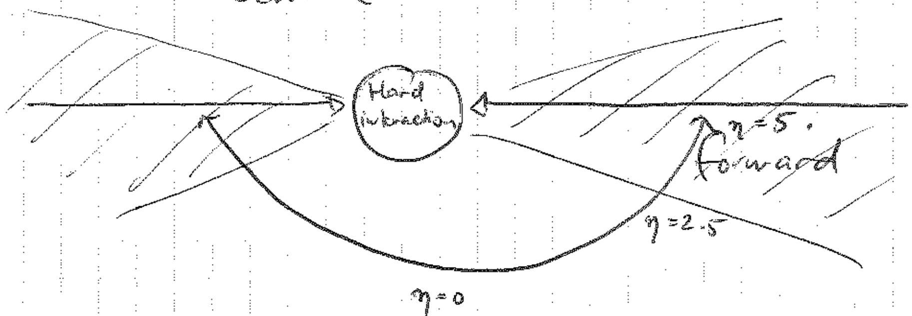
Missing transverse energy because of the escaping LSP.

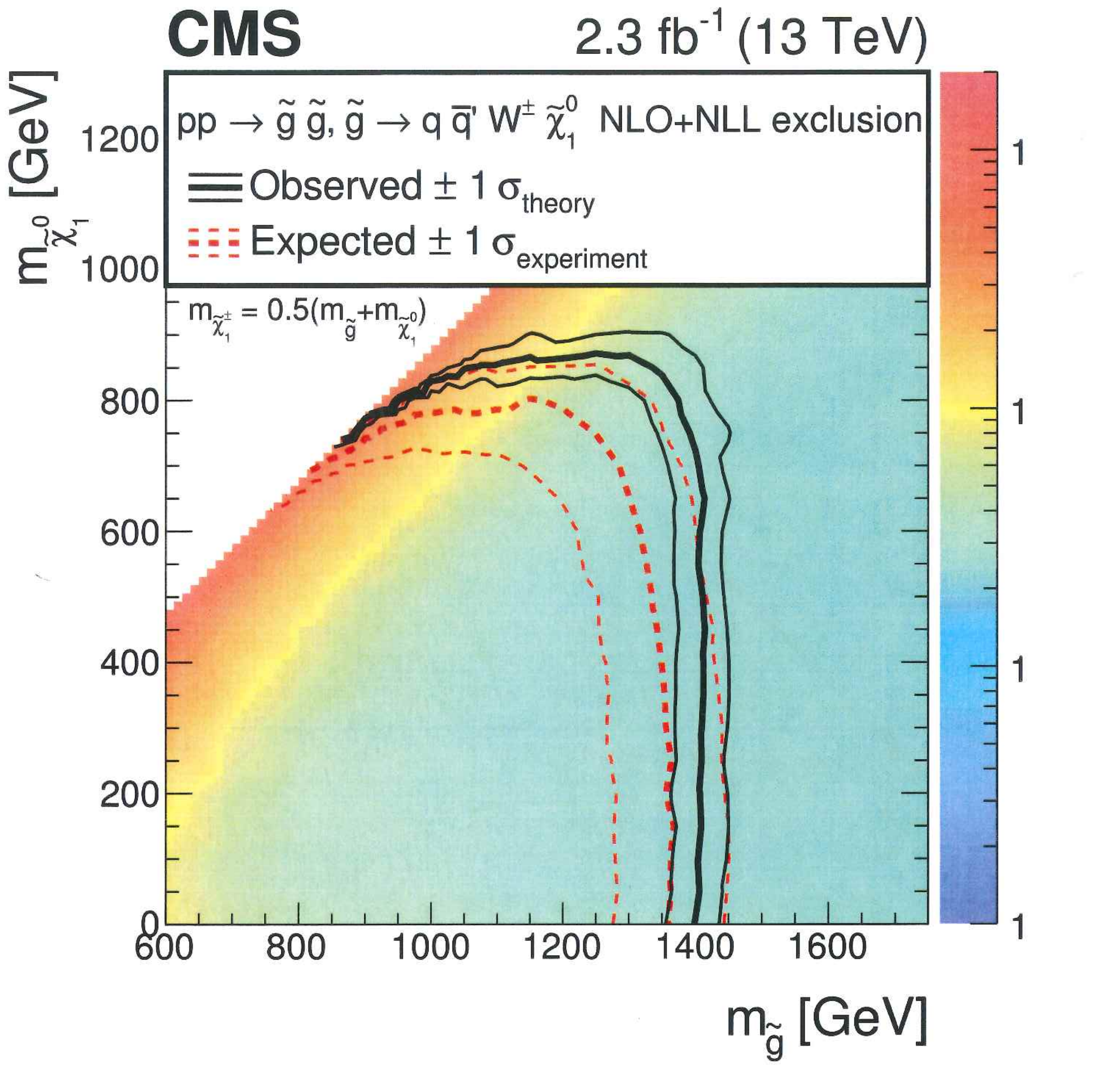
$p_T \equiv$ momentum in plane transverse to beams.



Rapidity ("angle boost-invariant along the beam axis").

Central



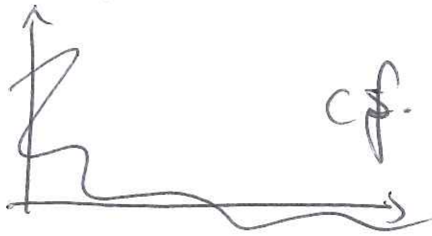


Note that there are always some assumptions in LHC search / exclusion plots, like e.g. here

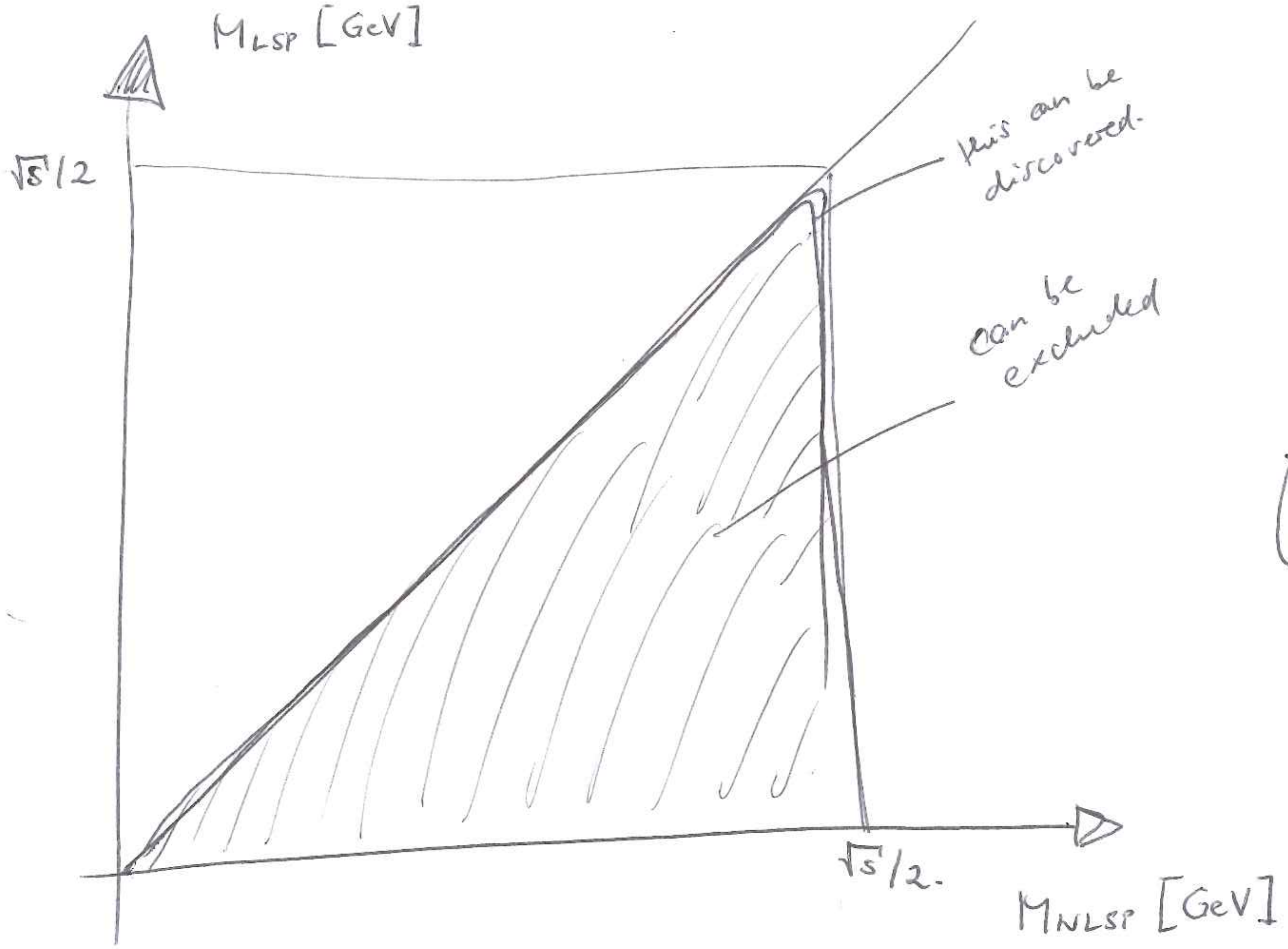
$\tilde g \to q\bar q' W^\pm \tilde\chi_1^0$ at 100% BR, $m_{\tilde\chi_1^\pm} = \frac{1}{2}(m_{\tilde g}+m_{\tilde\chi_1^0})$

etc.

On the other, an e^+e^- machine can search until (almost) the kinematical limit:



cf. backside



From Mikael Berggren