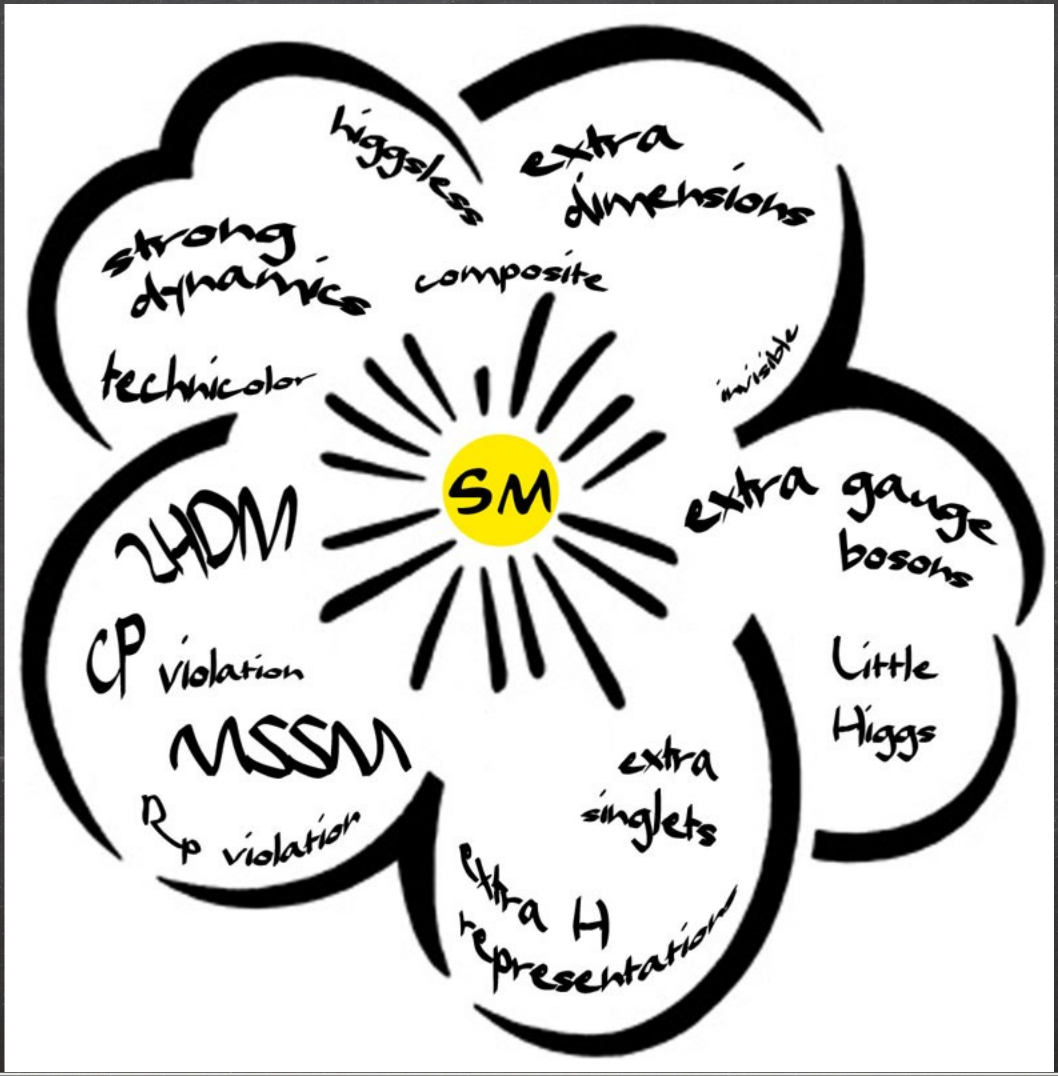
Lecture II: Effective Field Theory and Supersymmetry

Beyond the Higgs discovery

- Higgs properties are amazingly consistent with all main compelling underlying theories (except higgsless ones!) Some parameter space of BSM theories was eventually excluded.



CPNSH workshop
CERN 2006-009

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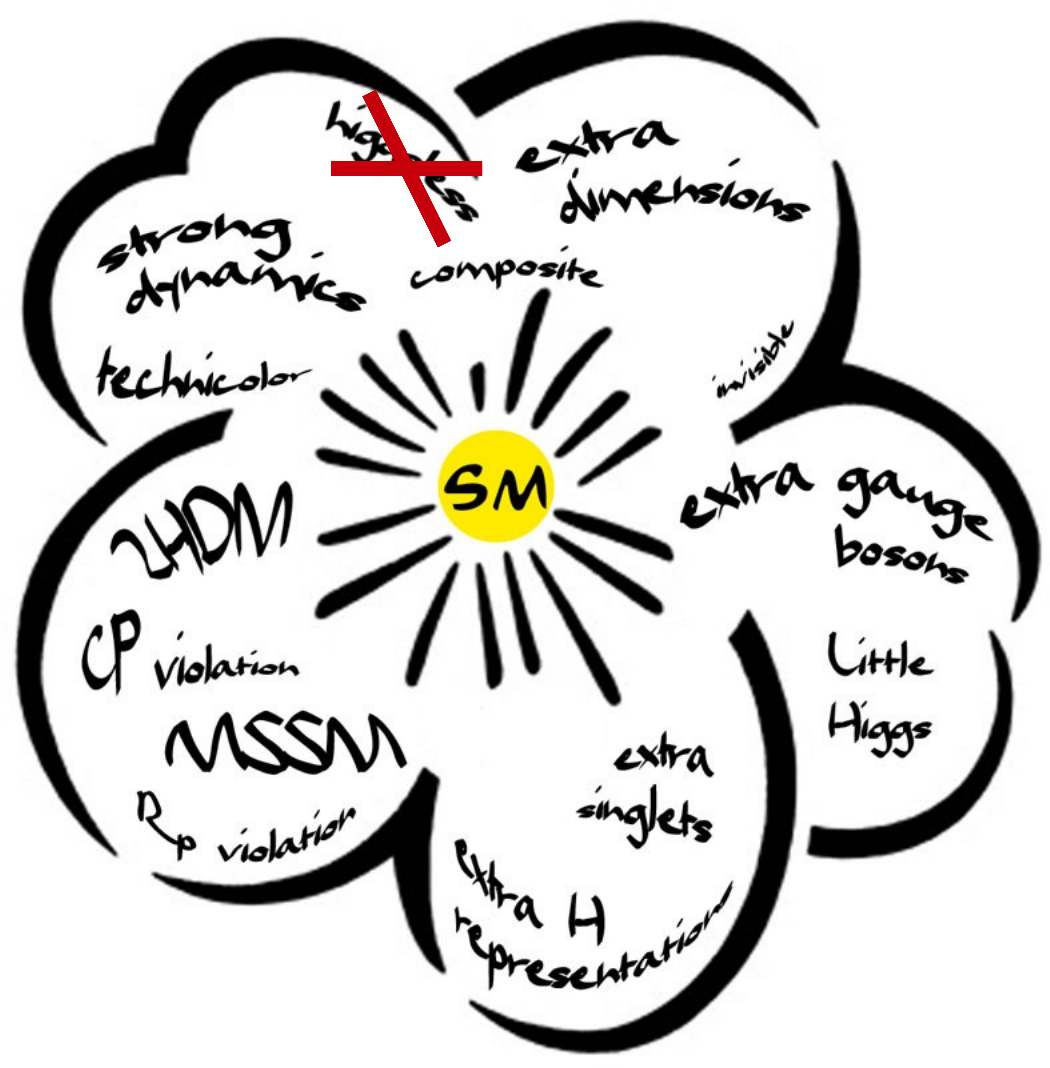

Present Status

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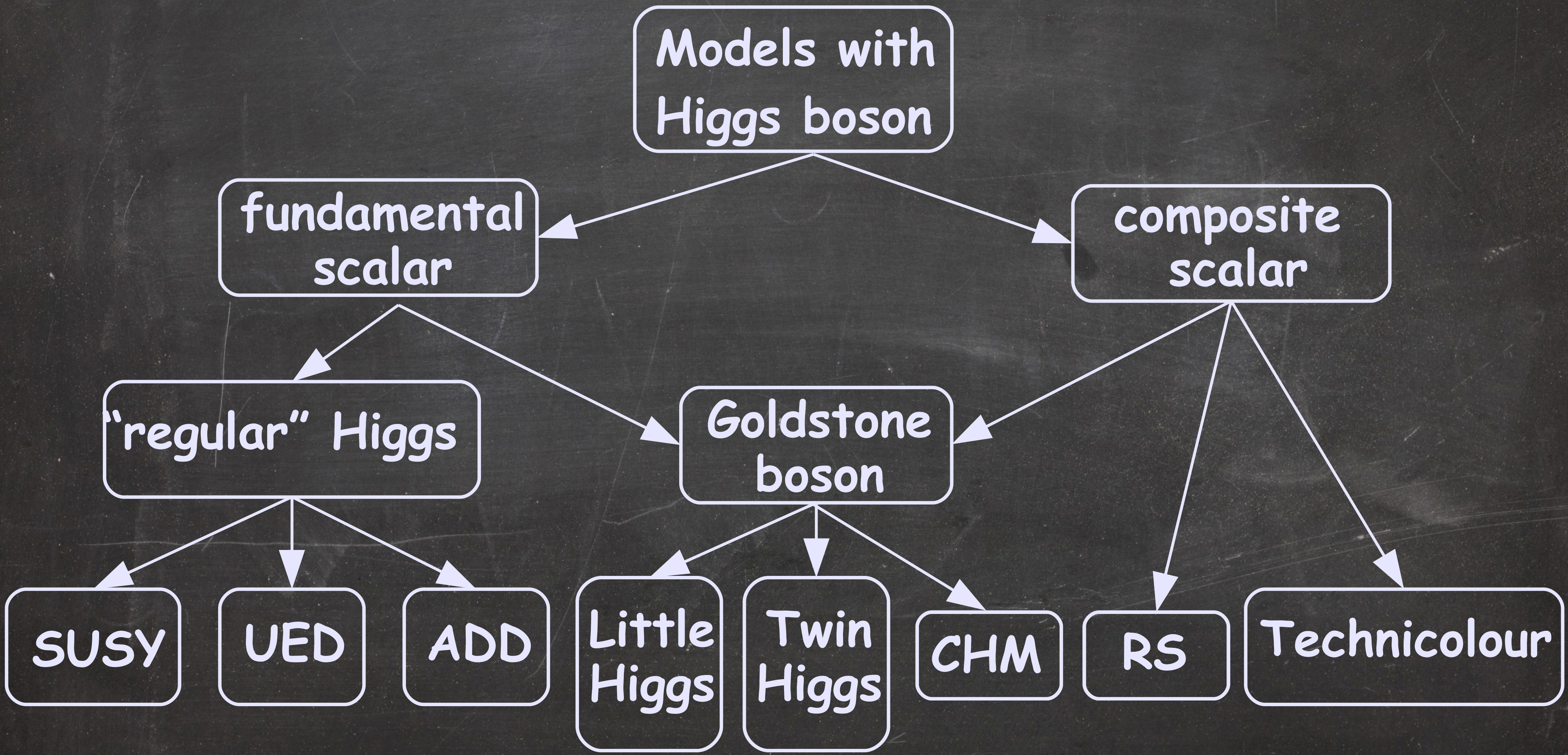

Remarks on the fine-tuning problem

- Actually the problem cannot be strictly formulated in the strict context of the Standard Model – the Higgs mass is not calculable
- However the this problem is related to yet unknown mechanism of underlying theory where Higgs mass is calculable! In this BSM theory Higgs mass should not have tremendous fine-tuing.
- There is no hint yet about such a mechanism – and this is the main source of our worries about fine-tuning

Effective Field Theory
useful reviews

- J. Polchinski “Effective field theory and the Fermi surface” hep-th/9210046
- A. V. Manohar “Effective field theories” hep-ph/9606222
- I. Z. Rothstein, “TASI lectures on effective field theories” hep-ph/0308266
- D. B. Kaplan “Five lectures on effective field theory” nucl-th/0510023
- B. Gripaios “Lectures on Effective Field Theory” arXiv:1506.05039

Effective Field Theory (EFT)

- Once we go BSM, it seems like an **infinity of possibilities** opens up - we could write down any Lagrangian we like. Fortunately, we have good starting point, since we know that **we must reproduce the SM in some limit!**

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- We start with the renormalizable SM, and consider only energies and momenta well below the weak scale ~ 100 GeV.
  - We can never produce W,Z or Higgs bosons on-shell and so we can simply do the path integral with respect to these fields (`integrate them out'). At tree-level, this just corresponds to replacing the fields using their classical equations of motion, and expanding and expanding

$$\frac{-1}{q^2 - m_W^2} = \frac{1}{m_W^2} + \frac{q^2}{m_W^4} + \dots$$

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  - Expansion breaks down for momenta ~ m_W and theory is naturally equipped with a cut-off scale.

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- So, let us imagine that the SM itself is really just an effective, low-energy description of some more complete BSM theory. Thus, the fields and the (gauge) symmetries of the theory are exactly the same as in the SM, but we no longer insist on renormalizability.

SM as an Effective Field Theory

- For operators up to dimension 4, we simply recover the SM. But at dimensions higher than 4, we obtain new operators, with new physical effects.
- As a striking example of these, we expect that the accidental baryon and lepton number symmetries of the SM will be violated at some order in the expansion, and protons will decay!
- We don't know what the BSM theory – need to write down all possible operators - infinitely many! Predictivity is lost?! (infinitely many measurements to fix all the coeff).
- No! Once we truncate the theory at a given order in the operator/momentum expansion – the number of coefficients is finite - can make predictions

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- **loop effects:** not obvious how to insert these operators into loops, and integrate over all loop momenta up to the cut-off Λ.
  - One can show, that expanded in powers of the external momenta they generate corrections to lower dimensional operators.
  - This suggests regularization scheme in which these corrections are already taken into account. The `right' scheme is turned to be DIM REG (Λ don't appear in the numerators of the loop amplitudes).

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- **If EFT make sense, why did we ever insist on renormalizability of SM?** Actually, it can now be thought of as a special case of a non-renormalizable theory, in which Λ to be very large.
  - **DIM>4** operators become completely negligible (**\`irrelevant'**)
  - **DIM=4** operators stay the same (**\`marginal'**)
  - **DIM <4** dominate (and are called **\`relevant'**) - actually has problem since m ~ Λ (from din analysis) – so theory needs dynamical mechanism or tuning

SM extension to EFT

D=0: the cosmological constant

- adds an arbitrary constant, to the Lagrangian; no dependence on any fields & derivatives, can be interpreted as the energy density of the vacuum

- the vacuum energy is measurable - is equivalent to including of Einstein's "cosmological constant" ρ_{cc} **~ $(10^{-3}$ev$)^4$** into the gravitational field equation
  - good news, on one hand - Universe is observed to accelerate
  - bad news, on the other hand - the size of this operator coefficient Λ^4:
    for Planck scale we need **$(10^{19}$ GeV/10^{-3}eV$)^4$ = $(10^{31})^4$=10^{124} tuning!**
    for SUSY scale we need **$(10^{3}$ GeV/10^{-3}eV$)^4$ = $(10^{15})^4$=10^{60} tuning!**
    many attempts - no satisfactory dynamical solution has been suggested
  - an alternative is to argue that we live in a multiverse in which the constant takes many different values in different corners, and we happen to live in one which is conducive to life (Weinberg, 1988)

SM extension to EFT

- **D=2: the Higgs mass parameter**
  the SM is the Higgs mass parameter, the natural size is Λ, while we measure v ~ 100 GeV -> two options: a) the natural cut-off of the SM is not far above the weak scale (LHC will tell) ; b) the cut-off is much larger, and the weak scale is tuned (anthropics etc)

- **D=4: marginal operators** – renormalisable SM – discussed at previous lecture

SM extension to EFT

- **D=5: neutrino masses and mixings**
  there is precisely one (**exercise**) operator $\frac{\lambda^{ll}}{\Lambda}(lH)^2$ where λ^{ll} is a dimensionless 3x3 matrix in flavour space
  - this operator violates the individual and total lepton numbers
  - it gives masses to neutrinos after EWSB, just as we observe
- given the observed $\Delta m^2 = 10^{-3}$ eV^2 for neutrinos, $\Lambda \sim 10^{14}$ GeV
  - one could argue that while neutrino masses are evidence for physics BSM
  - Alternatively one can add three ν^c, singlets under SU(3)x SU(2) xU(1) for each SM family replacing D=5 operator renormalizable Yukawa term

    $\lambda^\nu\ lH^c\ \nu^c$ (Dirac mass term after EWSB)

    and/or

    $m^\nu \nu^c \nu^c$ (Majorana mass term)

    (**exercise**: how λ^{ll} is related to λ^ν and m^ν ?)
  - neutrino mass eigenstates in this renormalizable model need not be heavy, but very weakly coupled to SM states!
    One can **redefine SM** to include these terms

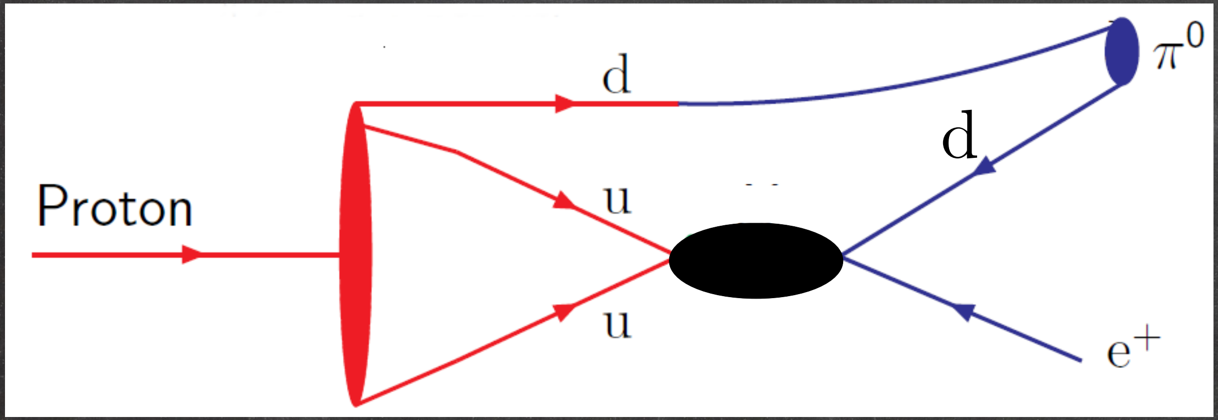
SM extension to EFT

- **D=6: mbaryon-number violation**
many operators appear, including baryon and lepton number violating ones

$$\frac{qq q\ell}{\Lambda^2} \quad \text{and} \quad \frac{u^c u^c d^c e^c}{\Lambda^2}$$

(**exercise:** check these are invariants)

- cause the proton decay $\mathrm{p} \to e^+ \pi^0$.
Λ > 10^{15} GeV comes the exp bounds on the proton lifetime, **τ^p > 10^{33} yr**:
- new physics either respects baryon or lepton number, or is a long way away



$$\Gamma(p \to \pi^0 e^+) \propto \frac{M_p^5}{\Lambda^4}$$

- Operators that give corrections to FCNC are highly suppressed in the SM
e.g. $(\mathrm{s}^c d)(d^c s)/\Lambda^2$ contributes to Kaon mixing, **Λ > 10^8 GeV**

Grand Unification

- The basic idea is that the Standard model gauge group SU(3)xSU(2)xU(1) is a subgroup of a larger gauge symmetry group
- The simplest is SU(5)
- Another example is SO(10): SU(5)xU(1) $\subset$ SO(10) comes with RH neutrinos!

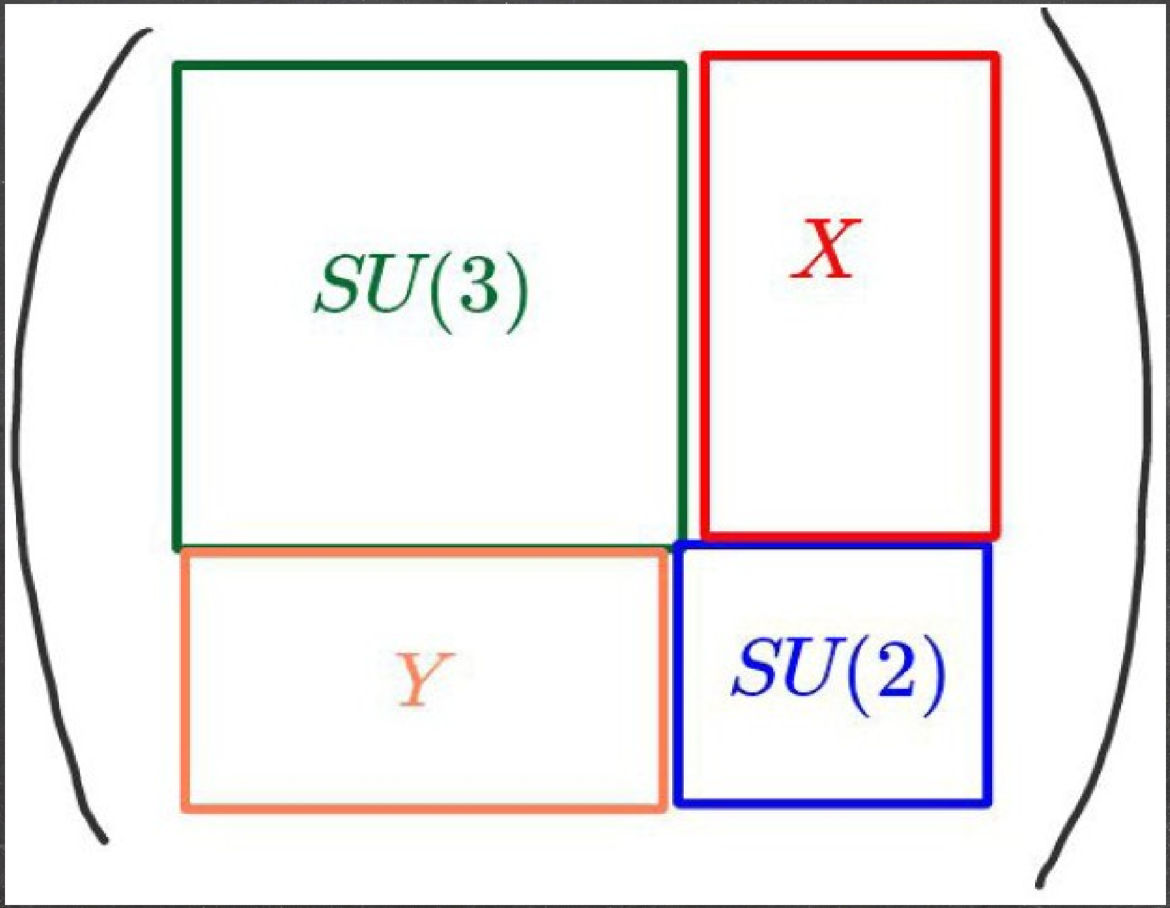
SU(5)

- SU(3) has 3^2-1=8 generators, they correspond to
  - the 8 gluons
  - The quarks are in the fundamental representation of SU(3)

- SU(5) has 5^2-1=24 generators, which means that
  - we have 24 gauge bosons
    - 8 gluons and 4 electroweak bosons
    - so we get 12 new gauge bosons

SU(5)

- Generators of SU(5)



SU(5)

- The right handed down type quarks and left-handed leptons form a 5 representation of SU(5)
- The rest forms a 10 representation

$$\begin{pmatrix} d \\ d \\ d \\ e^c \\ \bar{\nu}_e \end{pmatrix} \qquad \begin{pmatrix} 0 & u^c & -u^c & -u & -d \\ u^c & 0 & u^c & -u & -d \\ u^c & -u^c & 0 & -u & -d \\ u & u & u & 0 & -e^c \\ d & d & d & e^c & 0 \end{pmatrix}$$

Simplest rep:

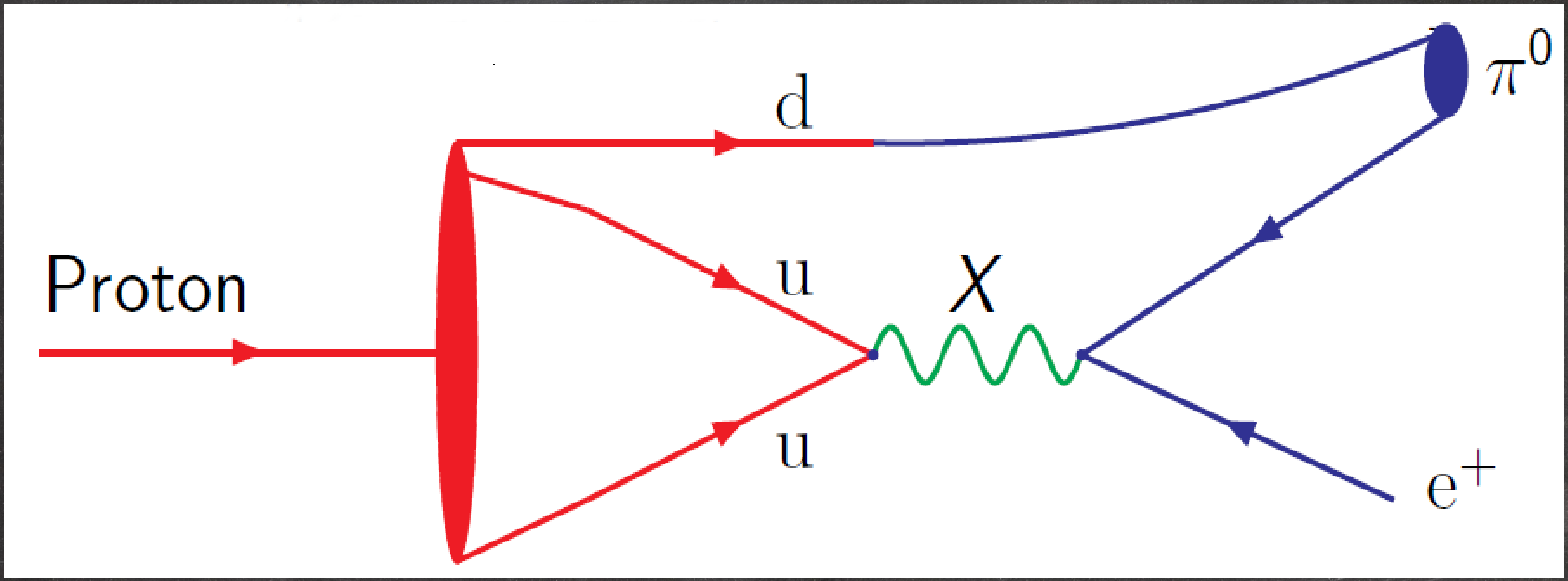
$$\overline{5} = (\overline{3}, 1)_{+2/3} \oplus (1, 2)_{-1} \qquad 10 = (\overline{3}, 1)_{-4/3} \oplus (3, 2)_{+1/3} \oplus (1, 1)_{+2}$$

Grand Unified Theories

- In this model there are two stages of symmetry breaking
- At the GUT scale the SU(5) symmetry is broken and the X and Y bosons get masses
- At the electroweak scale the SU(2)xU(1) symmetry is broken as before
- Problems with this theory
  - The couplings don't meet at the GUT scale
  - Proton decay

Proton Decay

- Since in Grand Unified theories we have the X/Y bosons which couple quarks and leptons, they predict the decay of the proton



- The expected rate would be $$\Gamma(p \to \pi^0 e^+) \propto \frac{M_p^5}{M_X^4}$$

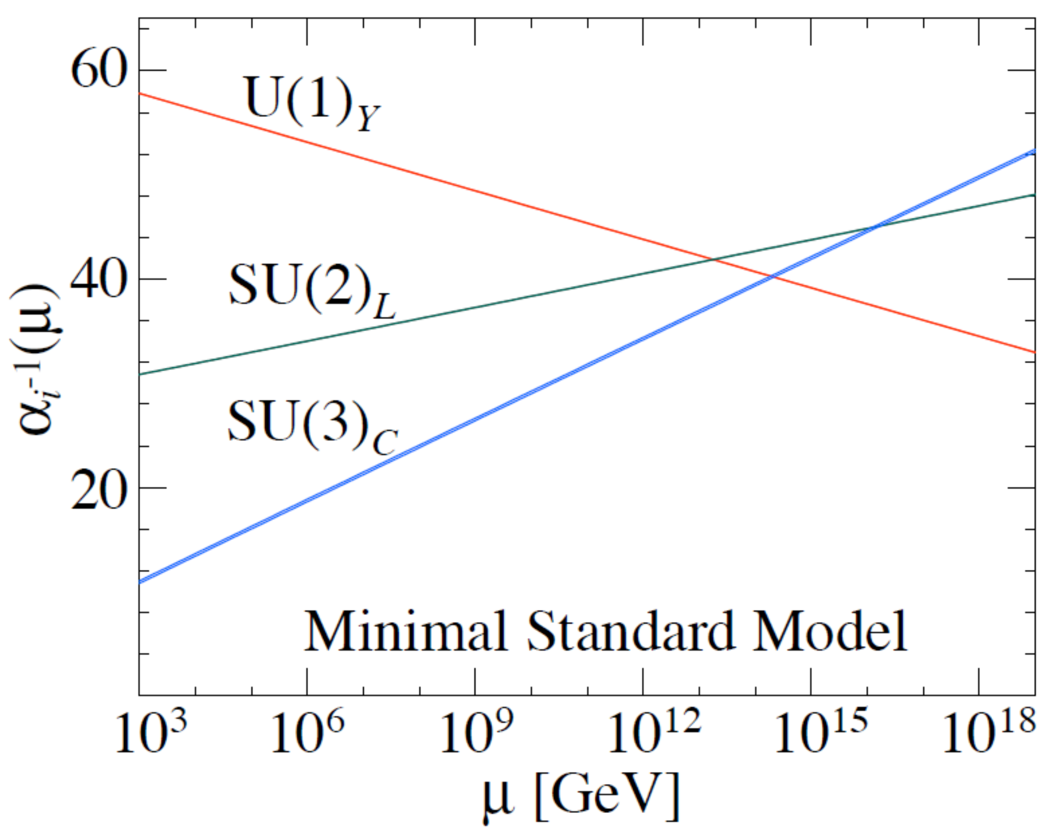
The hint about GUT scale and couplings unification

We ignore threshold corrections and assume desert! Then 1-loop RGEs for $SU(N)$:

$$\frac{1}{g_i^2(\mu)} = \frac{1}{g_i^2(Q)} + b_i \log\left(Q^2/\mu^2\right) \quad b_N = \frac{1}{(4\pi)^2}\left[-\frac{11}{3}N + \frac{4}{3}n_g\right]$$

$$b_1 = \frac{1}{4\pi^2} \quad b_2 = -\frac{5}{24\pi^2} \quad b_3 = -\frac{7}{16\pi^2}$$

The hint about GUT scale and couplings unification



- There is a clear hing about couplings unification
- Couplings do not unify exactly
- GUT scale can be roughly estimated to be in the 10^{14} -10^{17} GeV range

Hints on Supersymmetry

From Hitoshi Murayama, 2007

Once upon a time, there was a hierarchy problem...

- At the end of 19th century: a "crisis" about electron
  - Like charges repel: hard to keep electric charge in a small pack
  - Electron is point-like
  - At least smaller than 10^{-17}cm
- Need a lot of energy to keep it small!

$$\Delta m_e c^2 \sim \frac{e^2}{r_e} \sim \mathrm{GeV}\frac{10^{-17}\mathrm{cm}}{r_e}$$

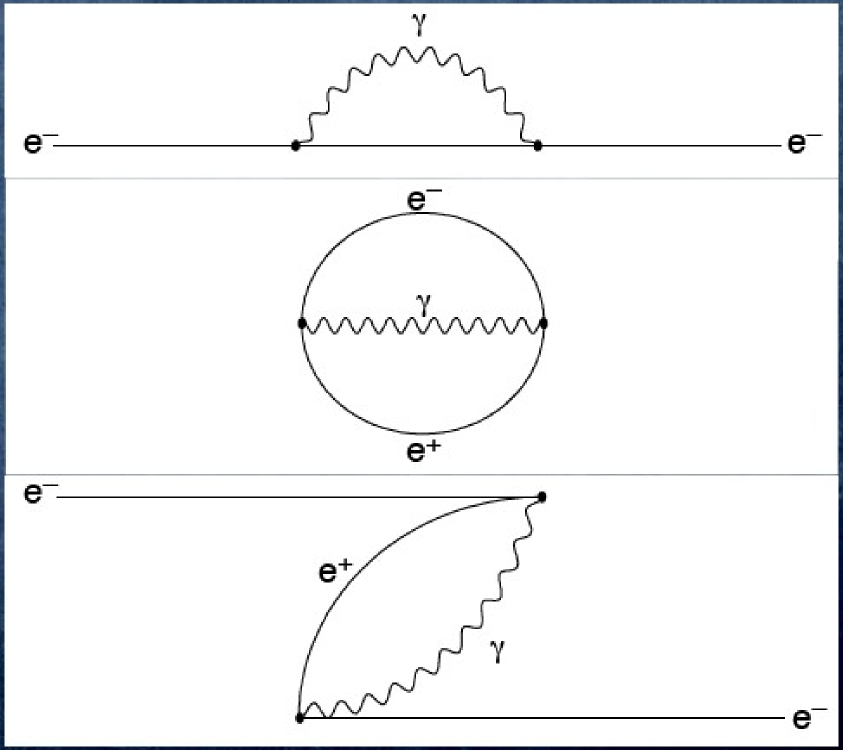
- Correction $\Delta m_e c^2 > m_e c^2$ for $r_e < 10^{-13}$cm
- Breakdown of theory of electromagnetism
  $\Rightarrow$ Can't discuss physics below 10^{-13}cm

From Hitoshi Murayama, 2007

Anti-Matter Comes to Rescue by Doubling of #Particles

- Electron creates a force to repel itself
- Vacuum bubble of matter anti-matter creation/annihilation
- Electron annihilates the positron in the bubble

$\Rightarrow$ only 10% of mass even for Planck-size r_e~10^{-33}cm



$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

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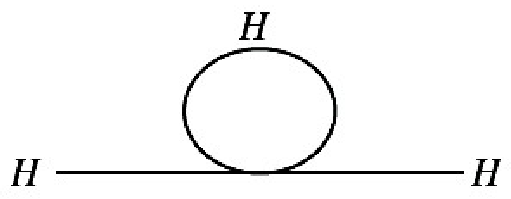
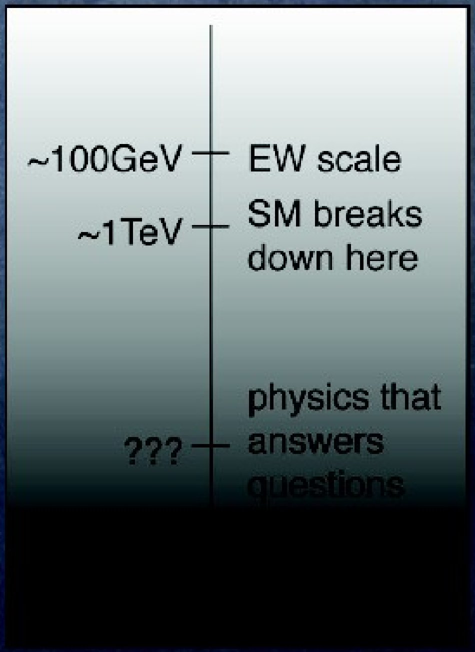
Higgs repels itself, too



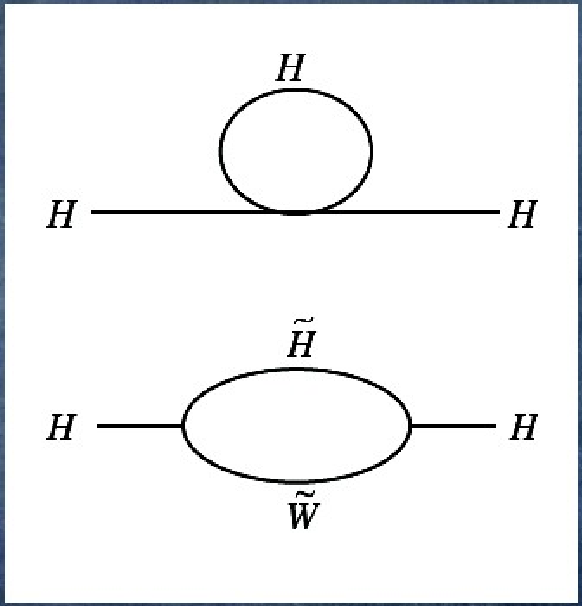
$$\Delta m_H^2 c^4 \sim \left(\frac{\hbar c}{r_H}\right)^2$$

- Just like electron repelling itself because of its charge, Higgs boson also repels itself
- Requires a lot of energy to contain itself in its point-like size!
- Breakdown of theory of weak force
- Can't get started!



History repeats itself?

- Double #particles again ⇒ superpartners
- "Vacuum bubbles" of superpartners cancel the energy required to contain Higgs boson in itself
- Standard Model made consistent with whatever physics at shorter distances



$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

Supersymmetry

Supersymmetry (SUSY)

boson-fermion symmetry aimed to unify all forces in nature

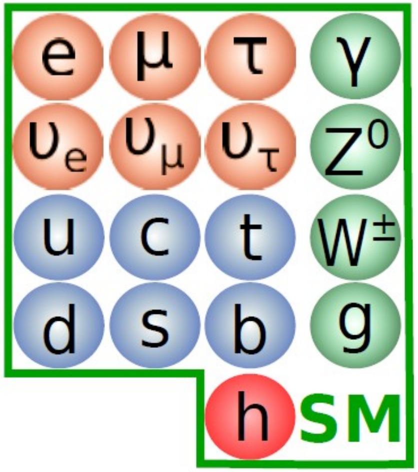
$$Q|\text{BOSON}\rangle = |\text{FERMION}\rangle, \quad Q|\text{FERMION}\rangle = |\text{BOSON}\rangle$$

extends Poincare algebra to Super-Poincare Algebra:

the most general set of space-time symmetries! (1971-74)

$$\{f,f\}=0, \quad [B,B]=0, \quad \{Q_\alpha,\bar{Q}_\beta\}=2\gamma^\mu_{\alpha\beta}P_\mu$$

Golfand and Likhtman'71; Ramond'71; Neveu,Schwarz'71; Volkov and Akulov'73; Wess and Zumino'74



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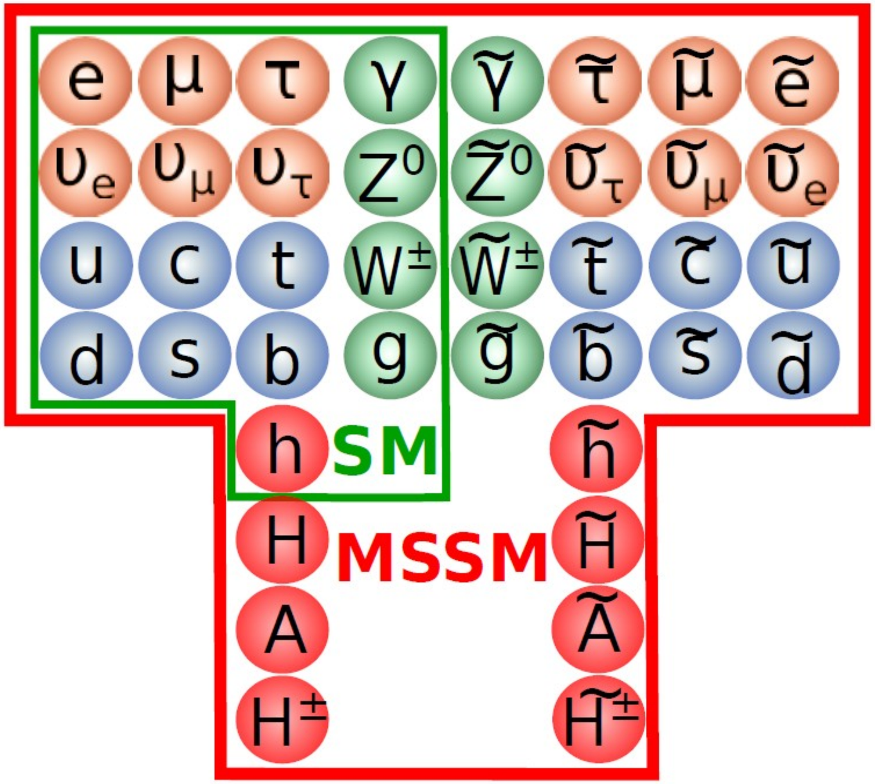

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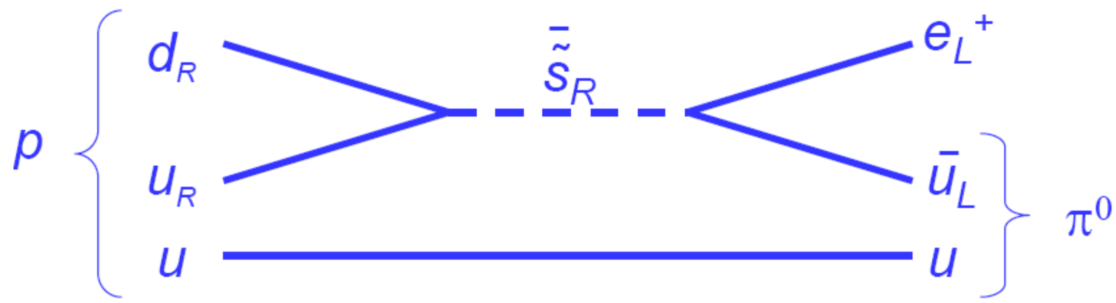
Particle	SUSY partner
e,ν,u,d *spin 1/2*	$\tilde{e},\tilde{\nu},\tilde{u},\tilde{d}$ *spin 0*
γ,W,Z h,H,A,H± *spin 1 and 0*	$\tilde{\chi}^\pm_1,\tilde{\chi}^\pm_2$ $\tilde{\chi}^0_1\cdots\tilde{\chi}^0_4$ *spin 1/2*



could give rise the proton decay!

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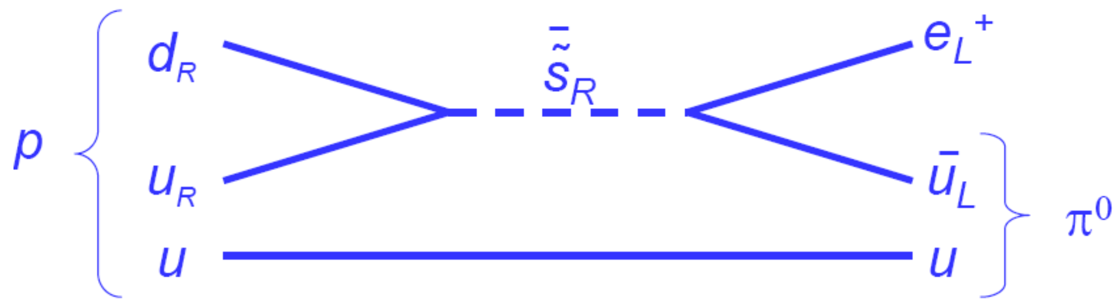
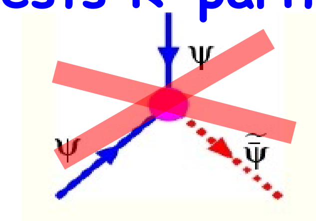


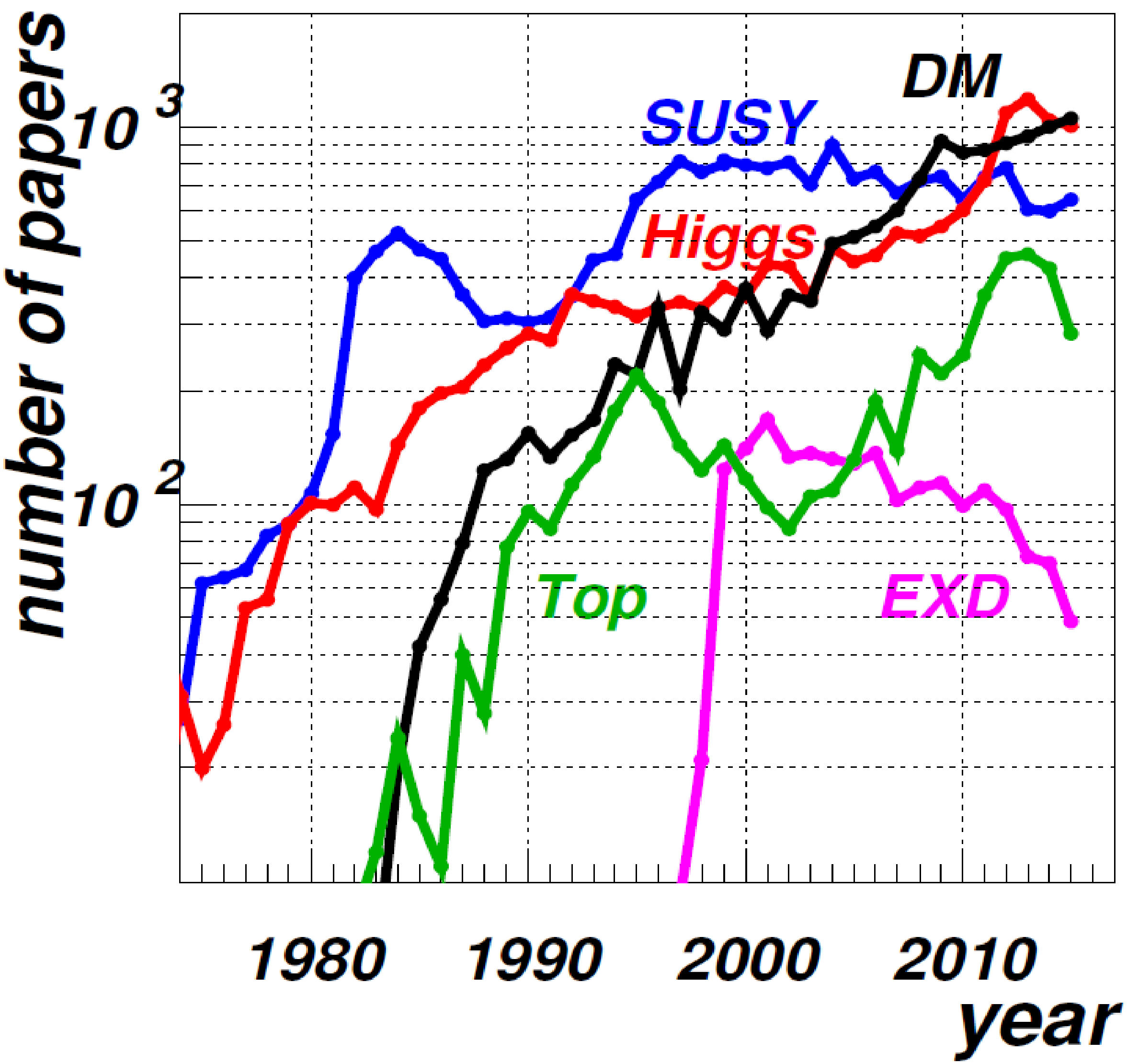
the absence of proton decay suggests R-parity

$$\boxed{R = (-1)^{3(B-L)+2S}}$$

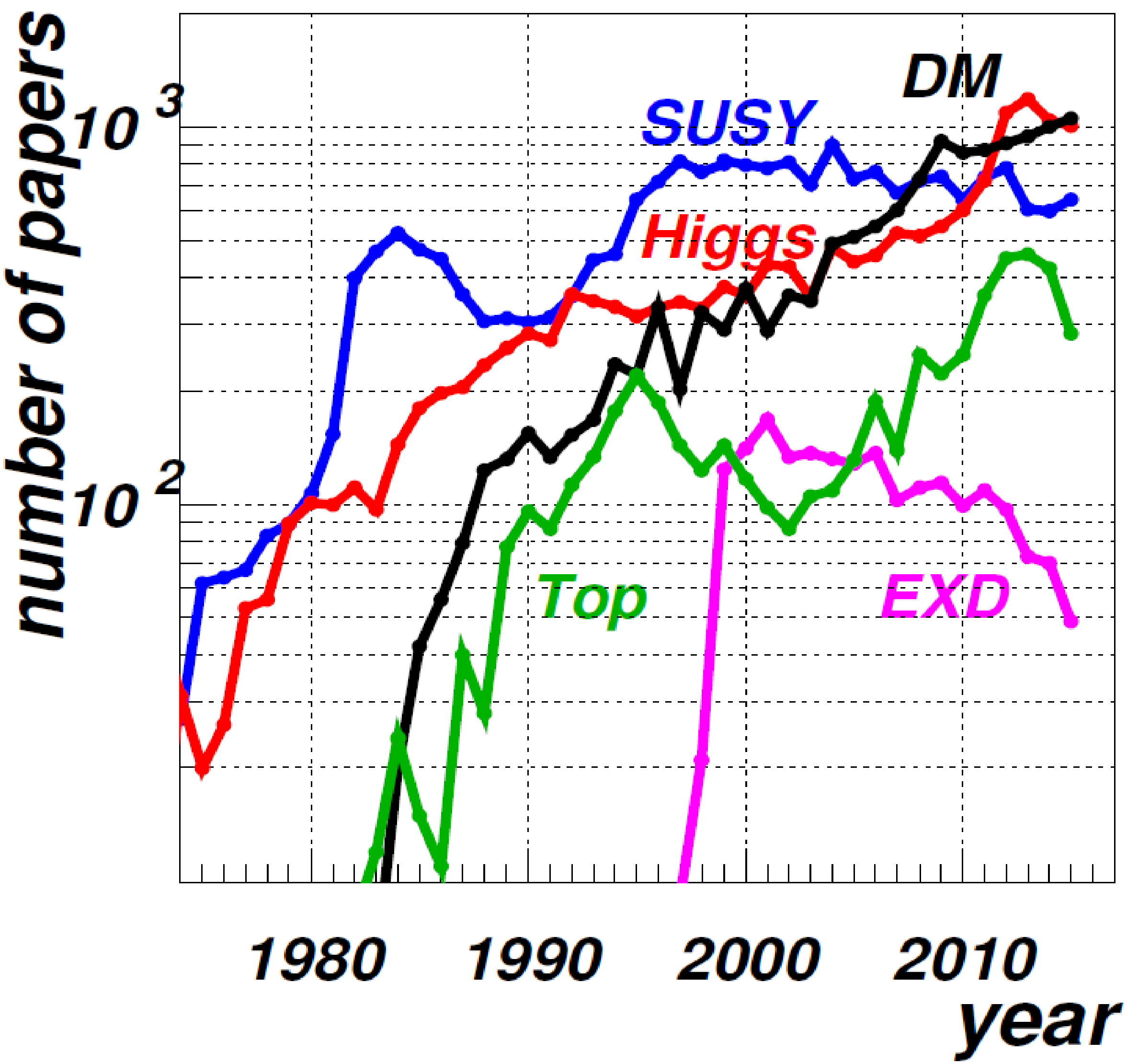


R-parity guarantees Lightest SUSY particle (LSP) is stable - DM candidate!

We are still inspired by this beauty ...

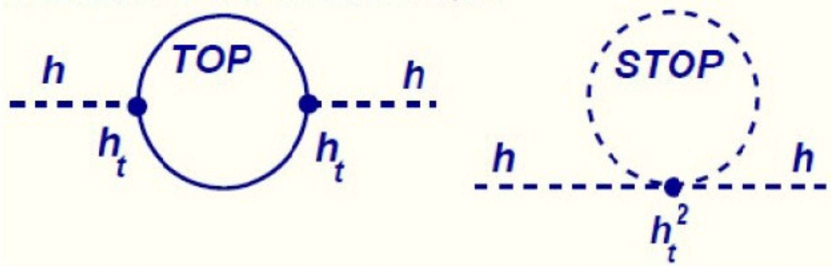


We are still inspired by this beauty ...
after more than 30 year unsuccessful searches ...

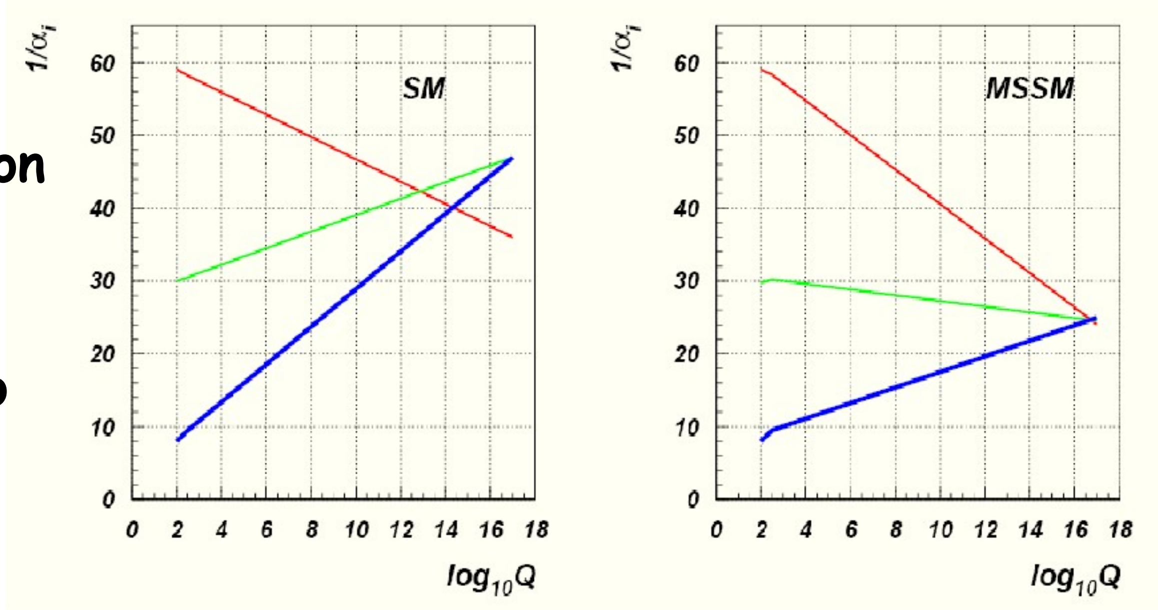


Beauty of SUSY

- Provides good DM candidate – LSP
- CP violation can be incorporated - baryogenesis via leptogenesis
- Radiative EWSB
- Solves fine-tuning problem
- Provides gauge coupling unification
- local supersymmetry requires spin 2 boson – graviton!
- allows to introduce fermions into string theories



$$\Delta M_H^2 \sim M_{SUSY}^2 \log(\Lambda/M_{SUSY})$$



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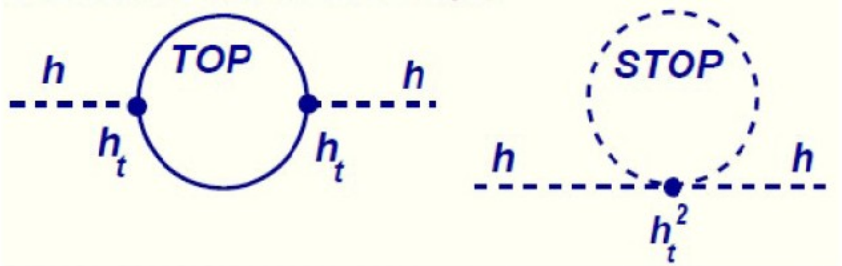
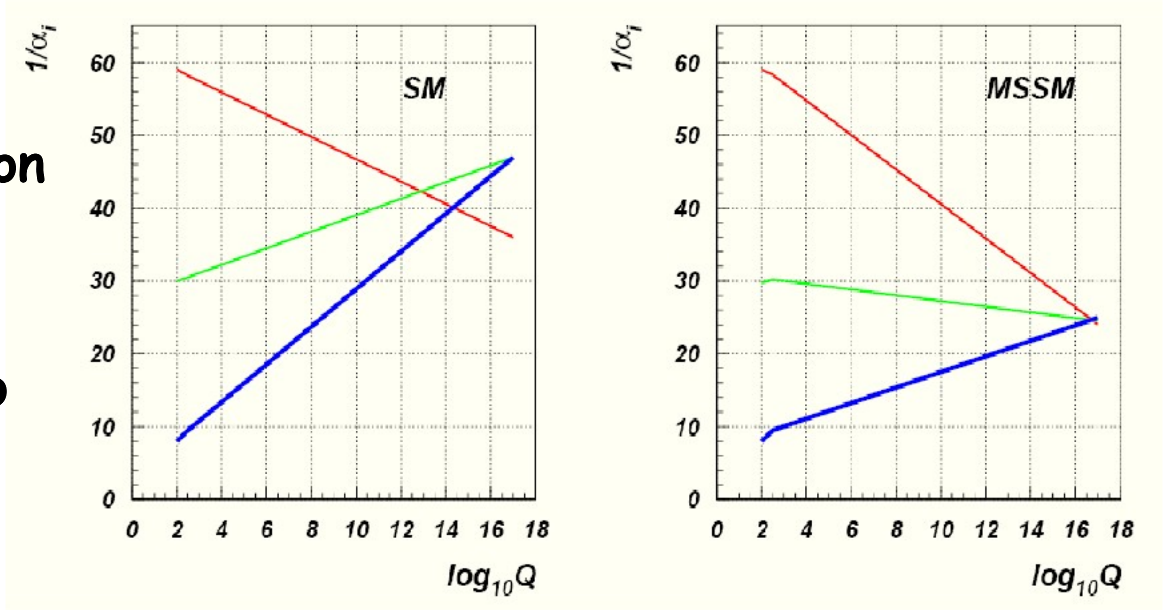
- local supersymmetry requires spin 2 boson – graviton!
- allows to introduce fermions into string theories



$$\Delta M_H^2 \sim M_{SUSY}^2 \log(\Lambda/M_{SUSY})$$

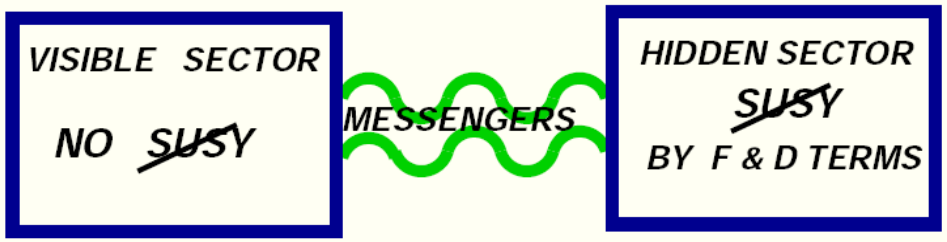


But the real beauty of SUSY is that

It was not deliberately designed to solve the SM problems!

SUSY breaking and mSUGRA scenario

- SUSY is not observed $\Rightarrow$ must be broken



Gravity mediation
Gauge mediation
Anomaly mediation
Gaugino mediation

$$\mathcal{L}^{MSSM}_{soft} = \underbrace{\sum_{i,j} B_{ij}\mu_{ij} S_i S_j}_{\text{bilinear terms}} + \underbrace{\sum_{ij} m^2_{ij} S_i S^\dagger_j}_{\text{scalar mass terms}} + \underbrace{\sum_{i,j,k} A_{ijk} f_{ijk} S_i S_j S_k}_{\text{trilinear scalar interactions}} + \underbrace{\sum_{A,\alpha} M_{A\alpha} \bar{\lambda}_{A\alpha} \lambda_{A\alpha}}_{\text{gaugino mass terms}}$$

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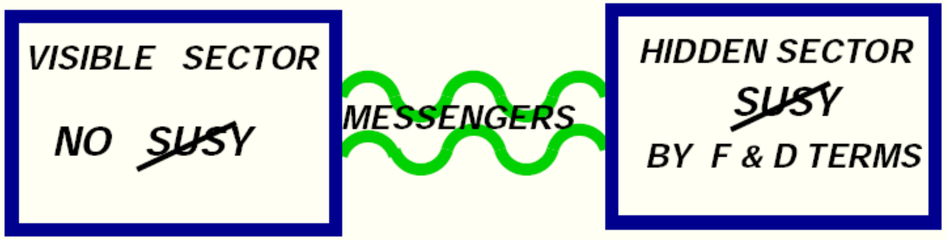

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- SUGRA: the hidden sector communicates with visible one via gravity
  – all soft terms are non-zero in general($\sim m_{3/2}$ -gravitino mass)

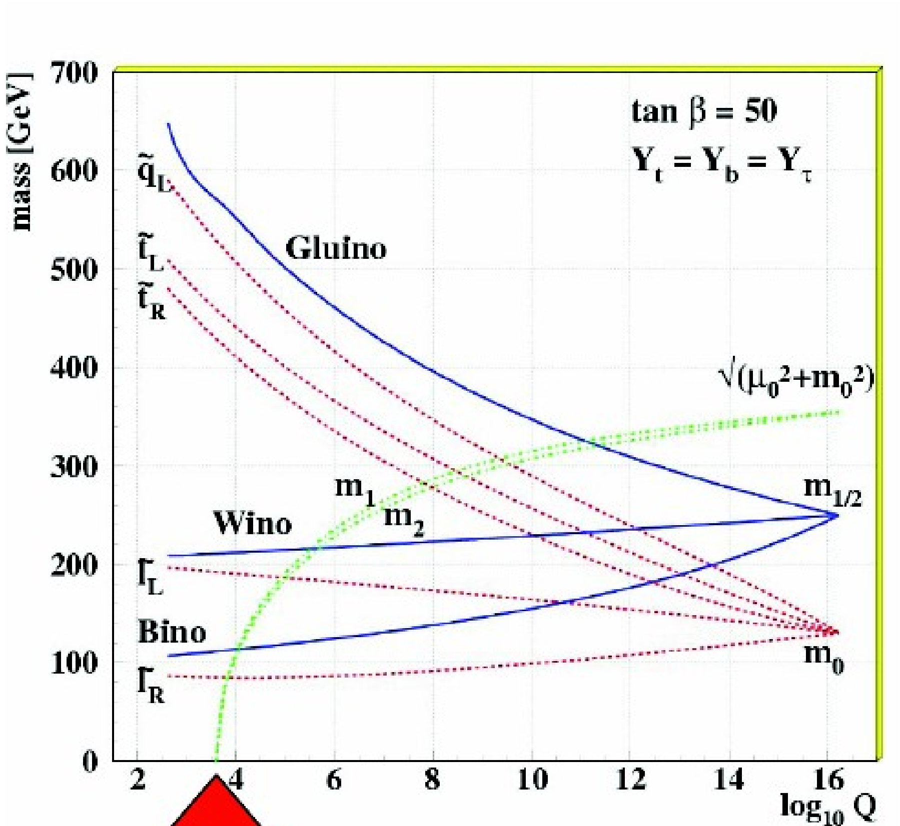
  SUGRA: $M_a = f_a \frac{\langle F \rangle}{M_P}$ $\quad m^2_{ij} = k_{ij}\frac{|\langle F \rangle|^2}{M^2_P}$ $\quad A_{ijk} = y_{ijk}\frac{\langle F \rangle}{M_P}$

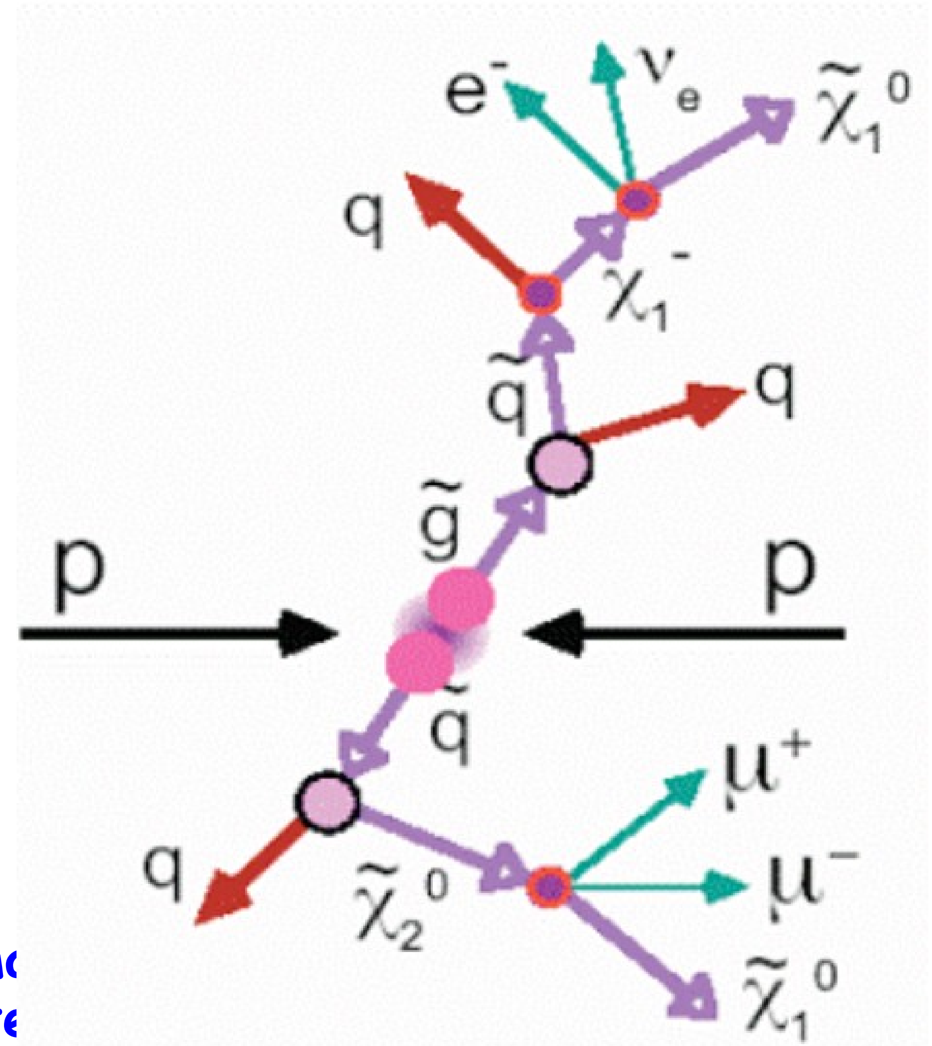
  mSUGRA: $\Longrightarrow m_{1/2}$ $\quad \Longrightarrow m^2_0$ $\quad \Longrightarrow A_0$

  flat Kähler metric takes care of constraining of Flavor violating processes

- $sign(\mu)$, μ^2 value is fixed by the minim condition for Higgs potential
- B - parameter – usually expressed via $\tan\beta$
- $\Rightarrow$ mSUGRA parameters: $m_0, m_{1/2}, A_0, \tan\beta, sign(\mu)$

Limits from LHC for mSUGRA scenario





independent parameters:

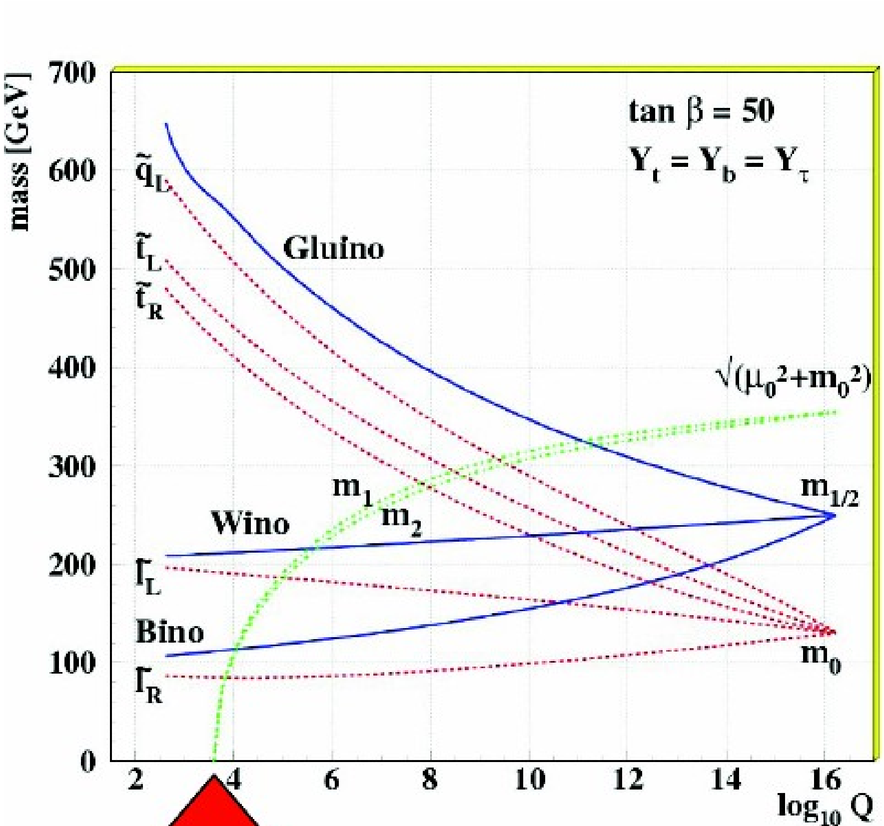
m0 – universal scalar mass

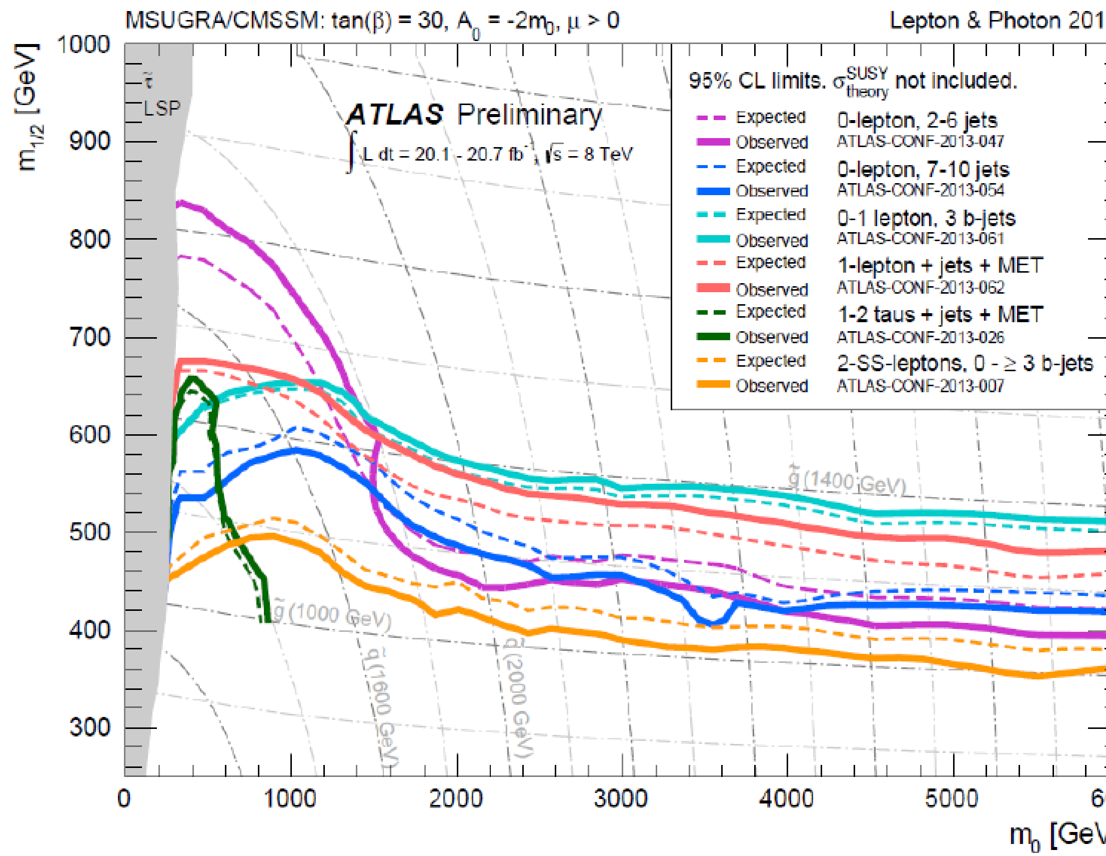
m1/2 – universal gaugino m

A – trilinear soft paramete

tan(beta) – v1/v2

Limits from LHC for mSUGRA scenario





independent parameter

m0 – universal scalar mass

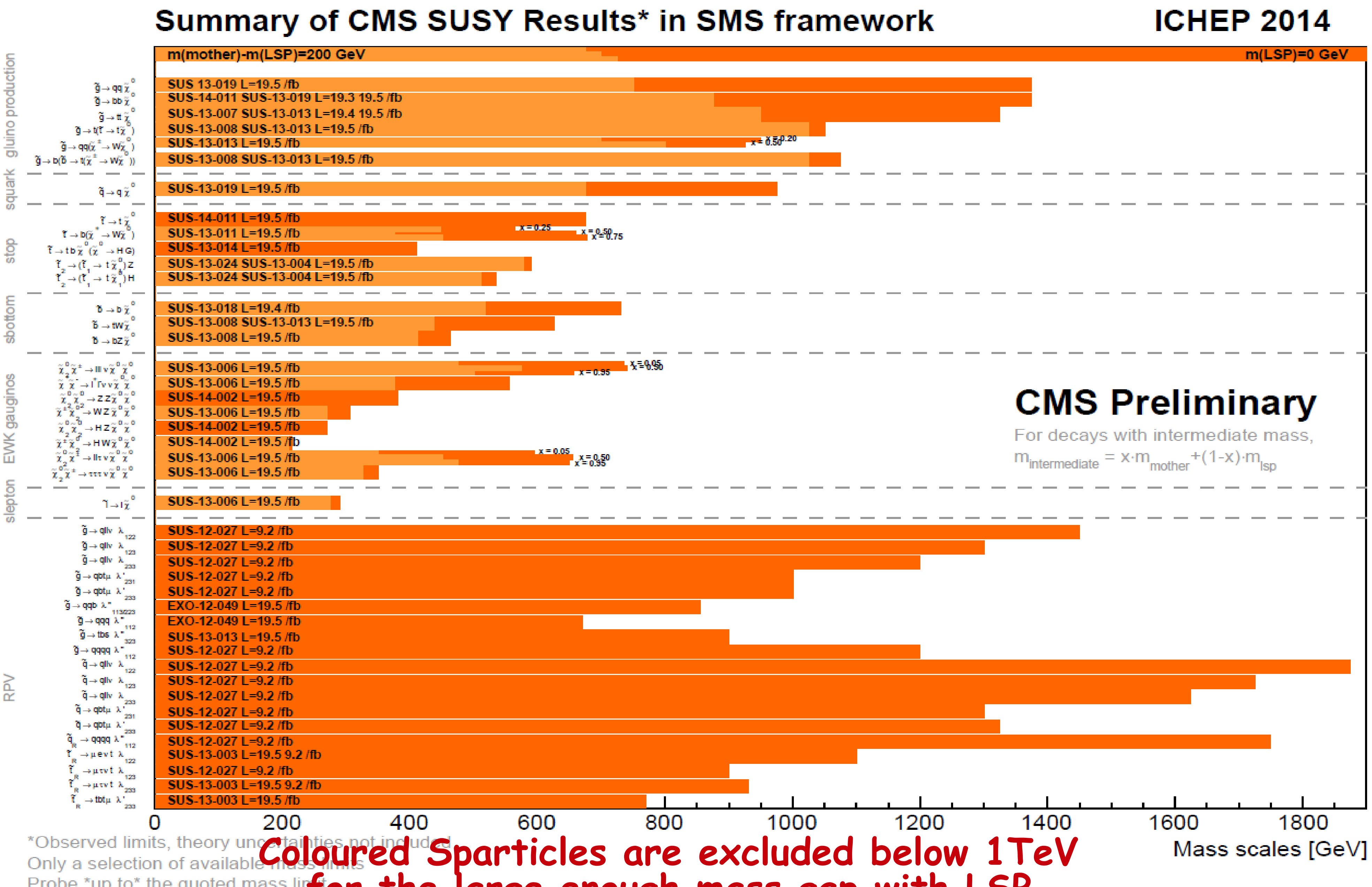
m1/2 – universal gaugino masses

A – trilinear soft parameter

tan(beta) – v1/v2

jets + missing transverse momentum signature

SUSY, where are you?!



Coloured Sparticles are excluded below 1TeV for the large enough mass gap with LSP

The MSSM Higgs Sector

Comparison with SM case:

$$\mathcal{L}_{\text{SM}} = \underbrace{m_d \bar{Q}_L \Phi d_R}_{\text{d-quark mass}} + \underbrace{m_u \bar{Q}_L \Phi_c u_R}_{\text{u-quark mass}}$$

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \Phi_c = i\sigma_2 \Phi^*, \quad \Phi \to \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \Phi_c \to \begin{pmatrix} v \\ 0 \end{pmatrix}$$

In SUSY: term $\bar{Q}_L \Phi^*$ not allowed

Superpotential is holomorphic function of chiral superfields, i.e. depends only on φ_i, not on φ_i^*

No soft SUSY-breaking terms allowed for chiral fermions

$\Rightarrow$ $H_d (\equiv H_1)$ and $H_u (\equiv H_2)$ needed to give masses to down- and up-type fermions

Furthermore: two doublets also needed for cancellation of anomalies, quadratic divergences

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2(\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}} (H_1\bar{H}_1 - H_2\bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

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

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

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

Rotation to physical basis:

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} \qquad \tan(2\alpha) = \tan(2\beta)\frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}$$

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \end{pmatrix}, \qquad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

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:

$$M_W^2 = \frac{1}{2}g'^2(v_1^2 + v_2^2), \quad M_Z^2 = \frac{1}{2}(g^2 + g'^2)(v_1^2 + v_2^2), \quad M_\gamma = 0$$

Parameters in MSSM 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, $m_{\mathrm{H}^\pm}$: no free parameters, can be predicted

In lowest order:

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

Predictions for m_h, m_H from diagonalization of tree-level mass matrix:

$\phi_1 - \phi_2$ basis:

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

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

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

$$\begin{pmatrix} m_H^{2,\text{tree}} & 0 \\ 0 & m_h^{2,\text{tree}} \end{pmatrix}$$

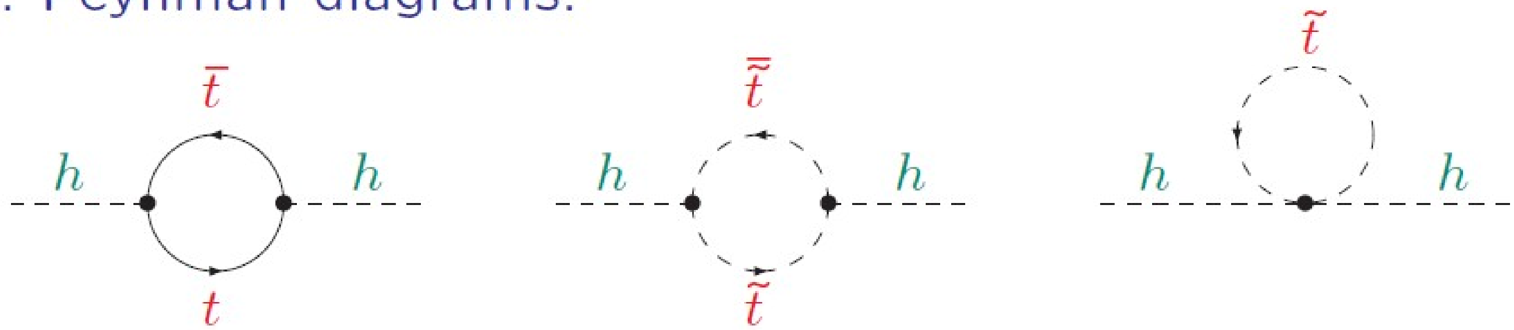
Tree-level result for m_h, m_H:

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

$\Rightarrow m_h \leq M_Z$ at tree level

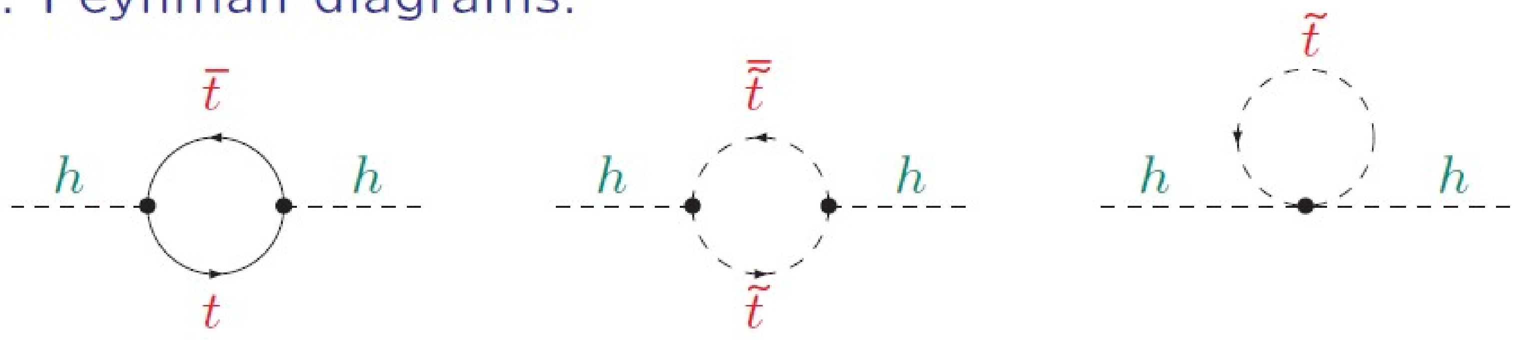
$\Rightarrow$ Light Higgs boson h required in SUSY

1-Loop: Feynman diagrams:



Dominant 1-loop corrections: $\Delta m_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

1-Loop: Feynman diagrams:

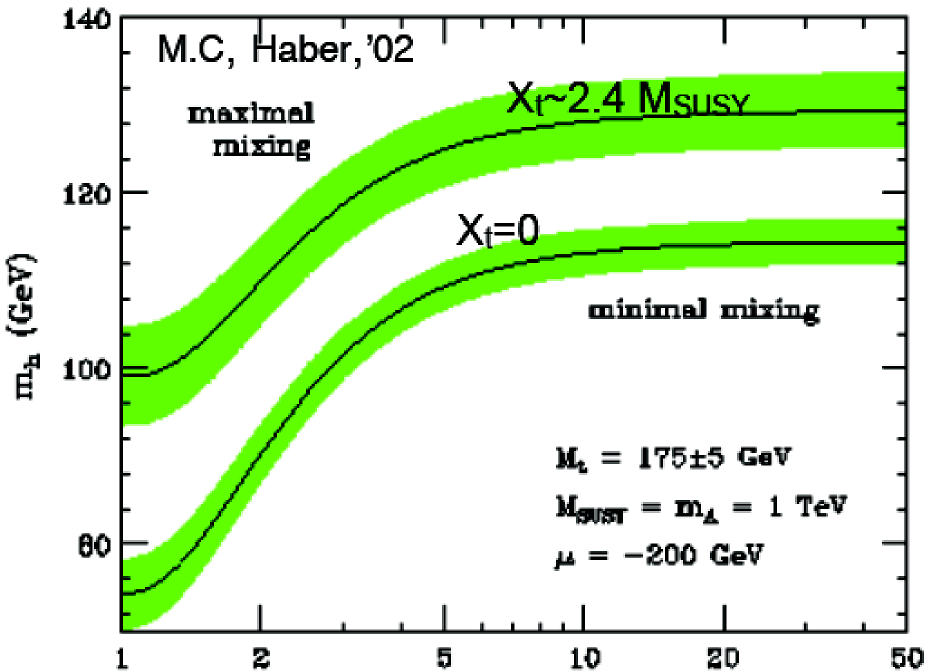


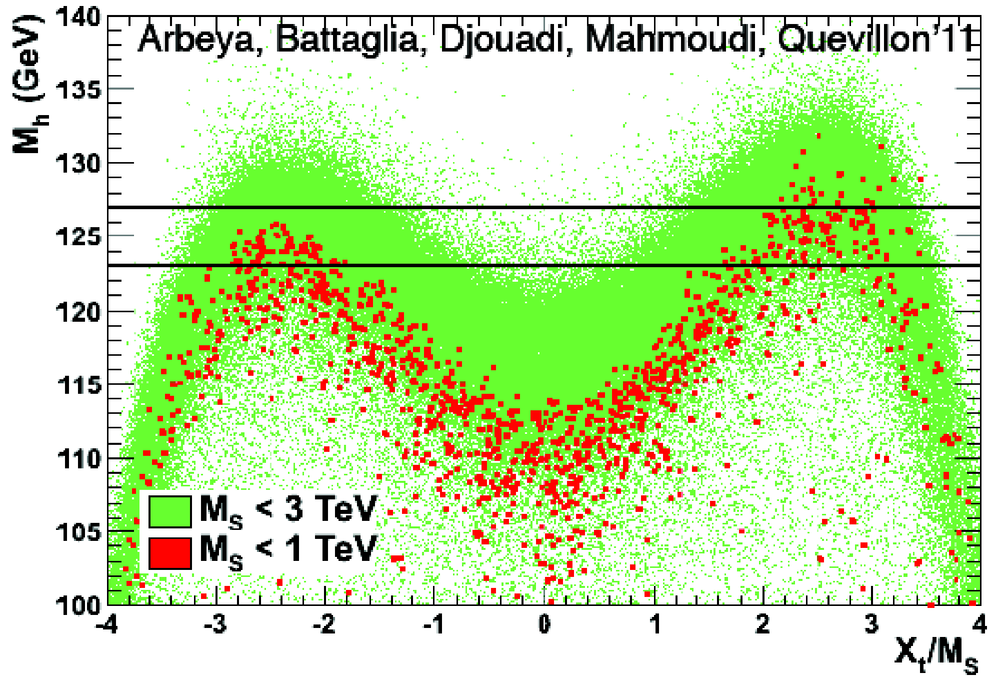
Dominant 1-loop corrections: $\Delta m_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

Stop, sbottom mass matrices ($X_t = A_t - \mu/\tan\beta$, $X_b = A_b - \mu\tan\beta$):

$$\mathcal{M}_{\tilde{t}}^2 = \begin{pmatrix} M_{\tilde{t}_L}^2 + m_t^2 + DT_{t_1} & m_t X_t \\ m_t X_t & M_{\tilde{t}_R}^2 + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m_{\tilde{t}_1}^2 & 0 \\ 0 & m_{\tilde{t}_2}^2 \end{pmatrix}$$

$$\mathcal{M}_{\tilde{b}}^2 = \begin{pmatrix} M_{\tilde{b}_L}^2 + m_b^2 + DT_{b_1} & m_b X_b \\ m_b X_b & M_{\tilde{b}_R}^2 + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m_{\tilde{b}_1}^2 & 0 \\ 0 & m_{\tilde{b}_2}^2 \end{pmatrix}$$





For moderate to large values of tan beta and large non-standard Scalar boson masses

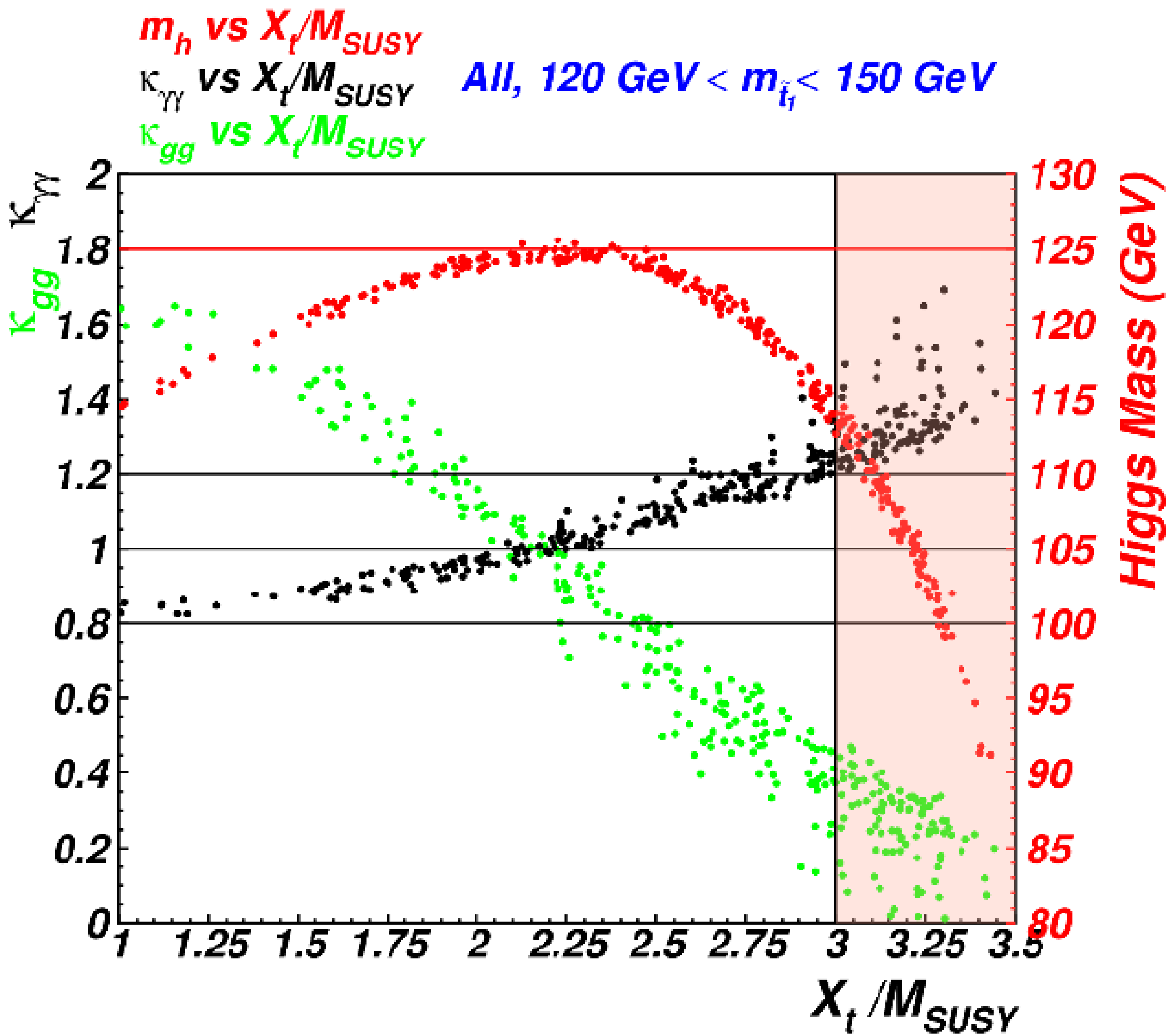
$$\boxed{m_h^2 \cong M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]}$$

$$t = \log(M_{SUSY}^2 / m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12M_{SUSY}^2}\right)$$

$X_t = A_t - \mu/\tan\beta$ →LR stop mixing

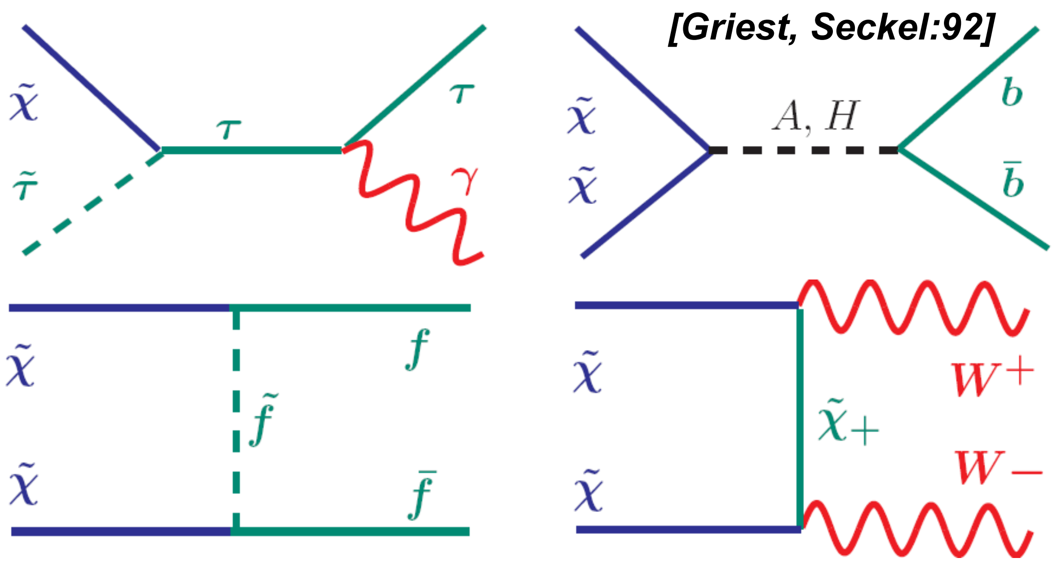
$\boxed{m_h \leq 130 \text{ GeV}}$ (for sparticles of ~ 1 TeV)

Effects from the light Stops



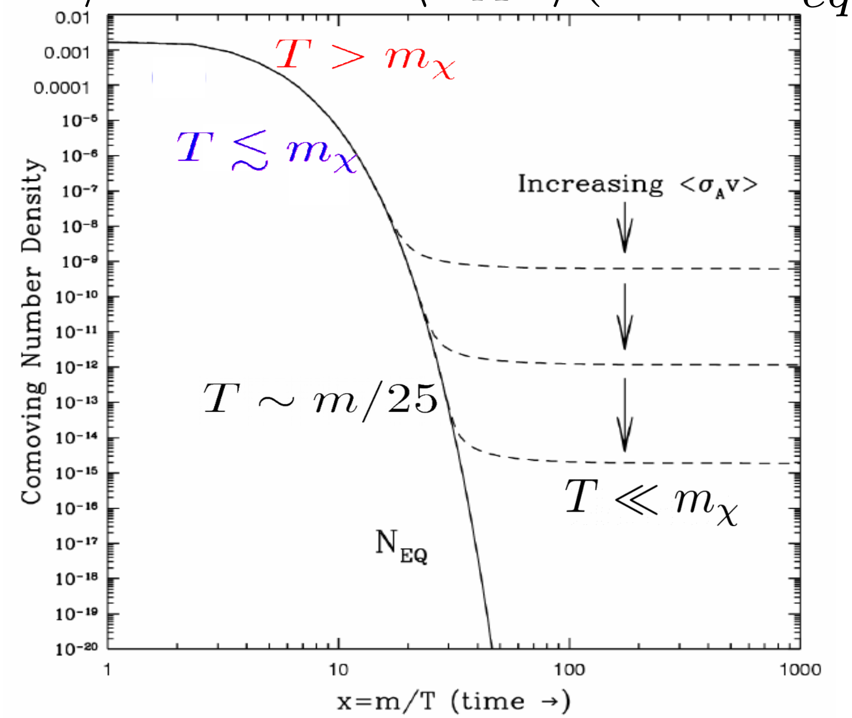
Evolution of neutralino relic density

Challenge is to evaluate thousands annihilation/co-annihilation diagrams



time evolution of number density is given by Boltzmann equation

$$\mathrm{dn/dt}\text{=-3Hn-}\langle\sigma_A v\rangle(n^2 - n_{eq}^2)$$



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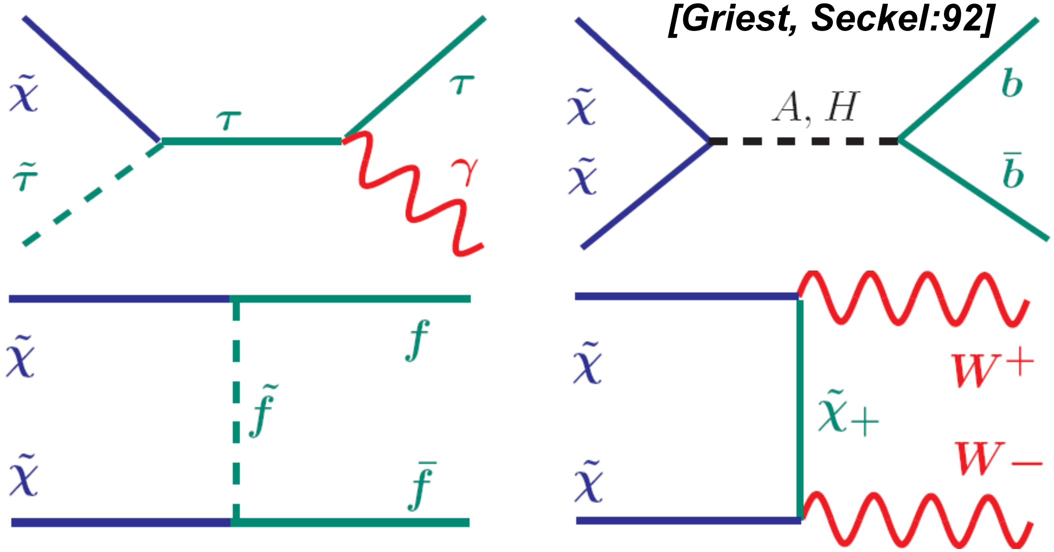
[Griest, Seckel:92]



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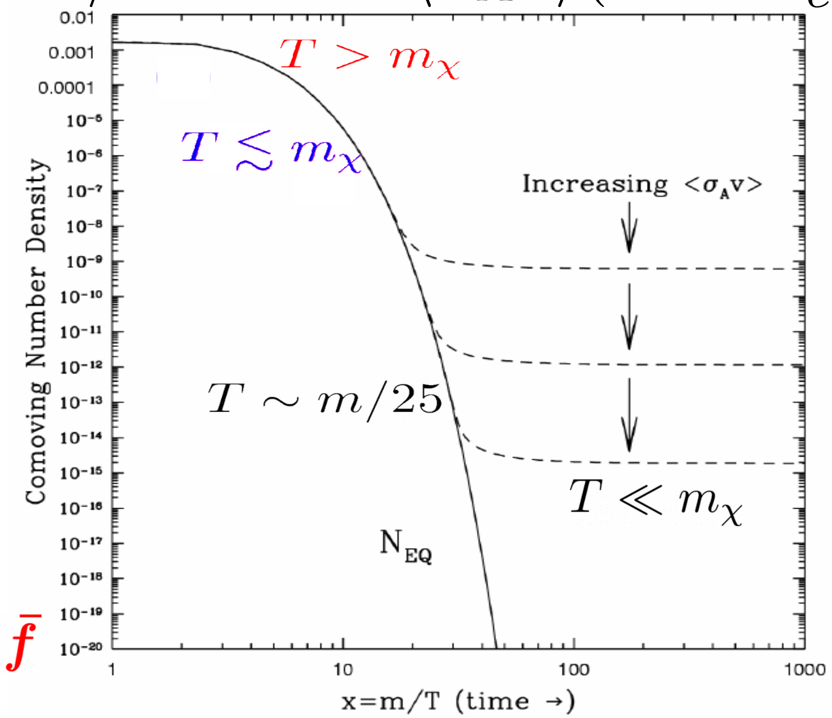

relic density depends crucially on $\langle\boldsymbol{\sigma_A v}\rangle$

thermal equilibrium stage: $T > m_\chi, \quad \chi\chi \leftrightarrow f\bar{f}$

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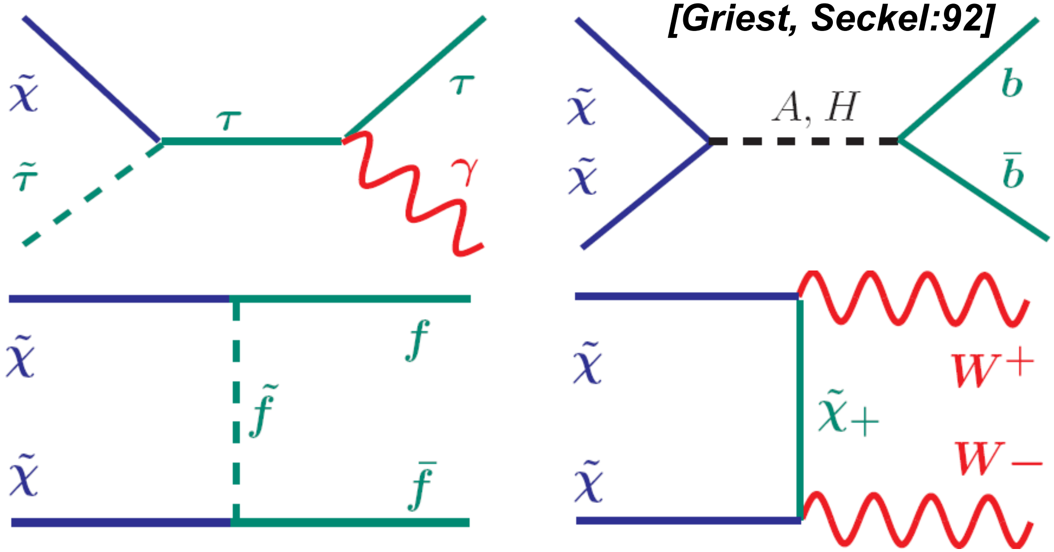

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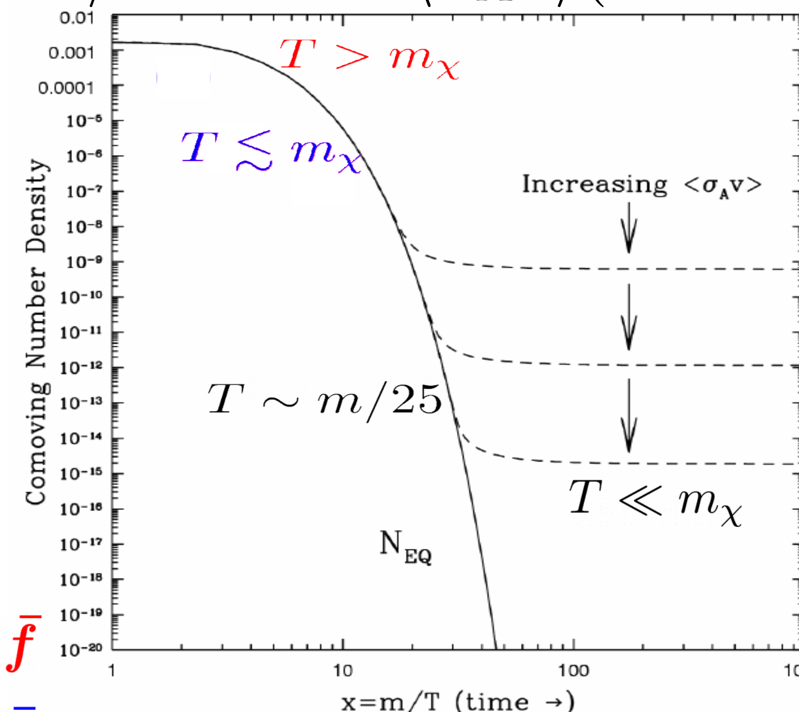

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n = $n_{eq} \sim e^{-m/T}$

Evolution of neutralino relic density

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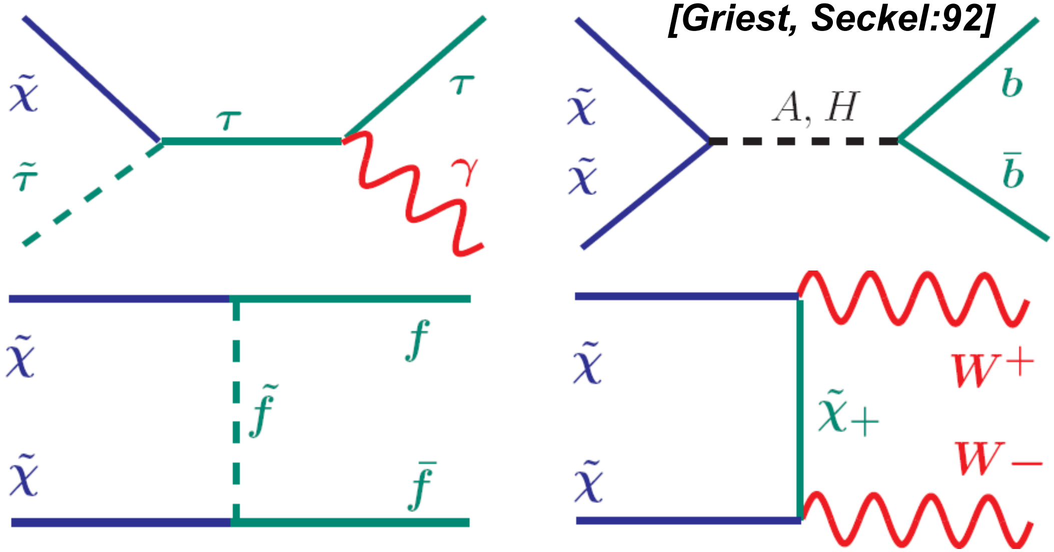

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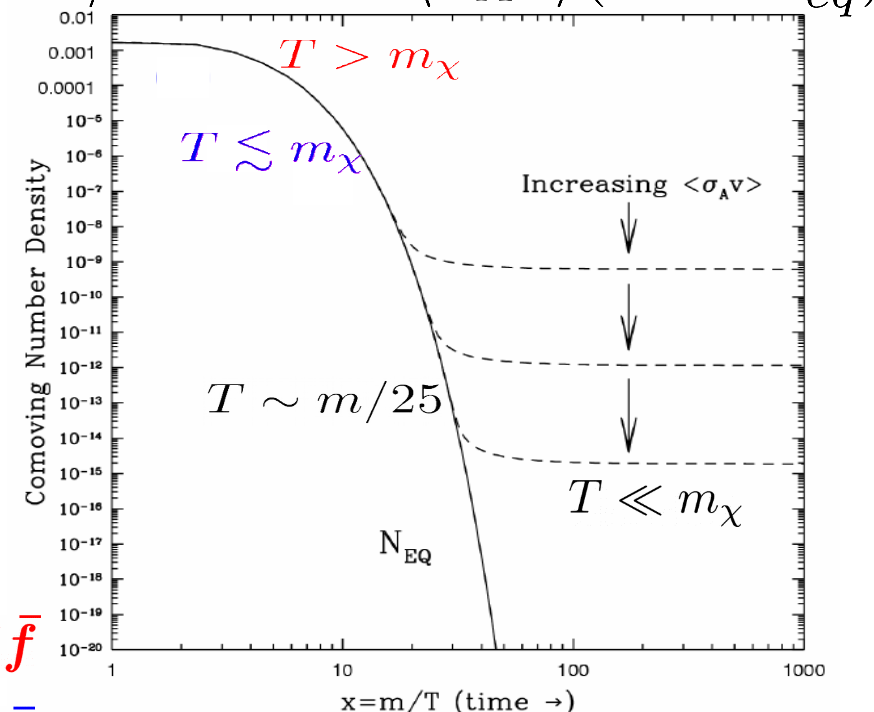

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neutralinos "freeze-out" at $T_F \sim m/25$

Packages:
MicrOMEGAs (Pukhov et al), DarkSusy, ISARED

Evolution of neutralino relic density

Challenge is to evaluate thousands annihilation/co-annihilation diagrams

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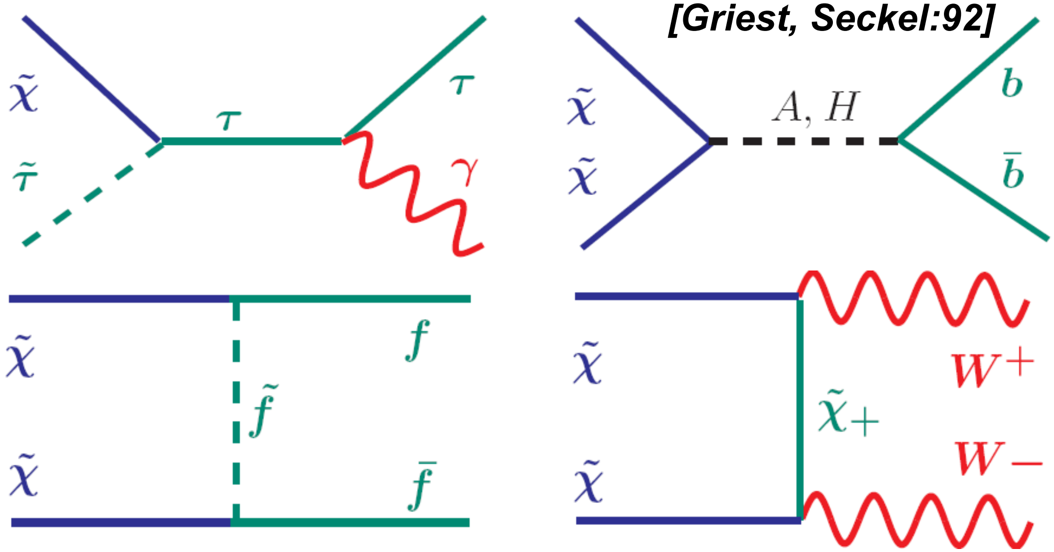

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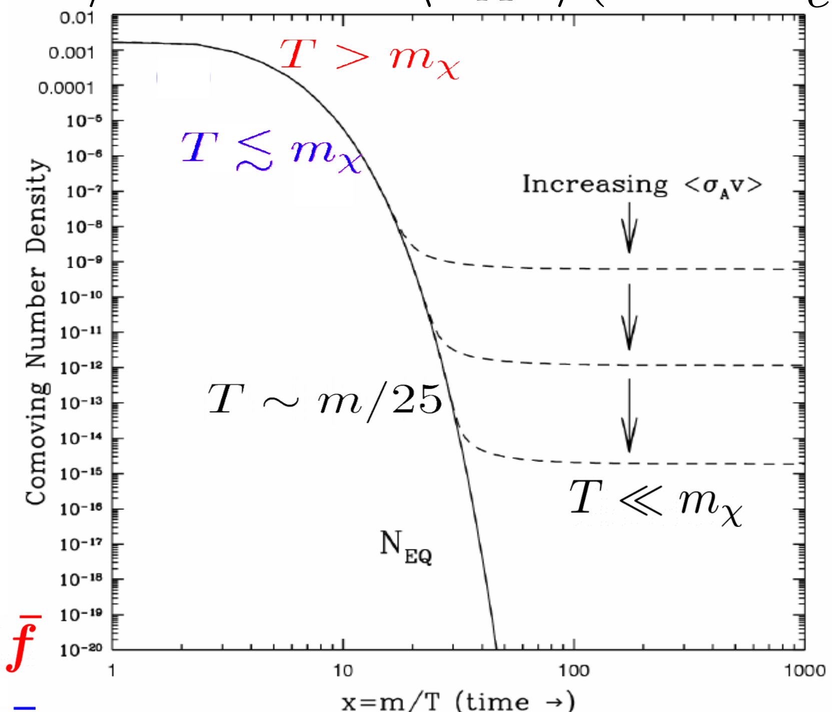

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$$\Omega_\chi = \frac{10^{-10}\mathrm{GeV}^{-2}}{\langle\sigma_A v\rangle}$$

$$\Omega_\chi = 0.112 \rightarrow \langle\sigma_A v\rangle = 1\mathrm{pb}$$

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

$$m = 100\mathrm{GeV}$$

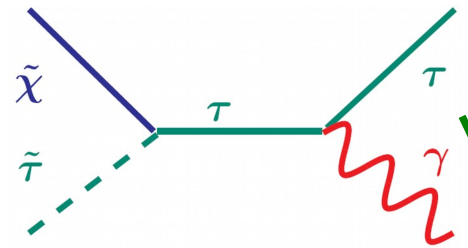
mass of the mediator

Packages:
MicrOMEGAs (Pukhov et al), DarkSusy, ISARED

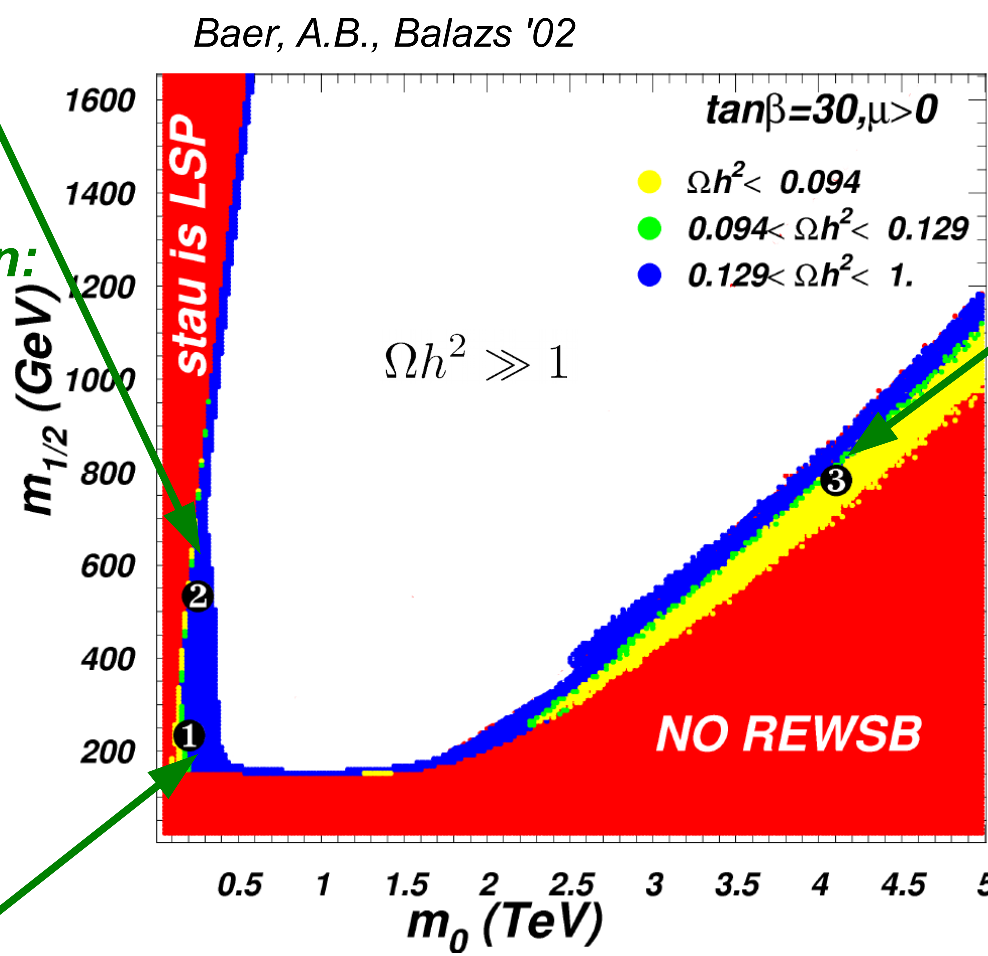
Neutralino relic density in mSUGRA

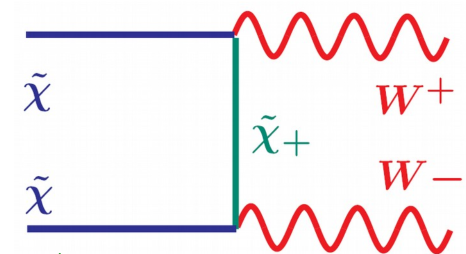
most of the parameter space is ruled out! $\Omega h^2 \gg 1$

special regions with high σ_A are required to get $0.094 < \Omega h^2 < 0.129$



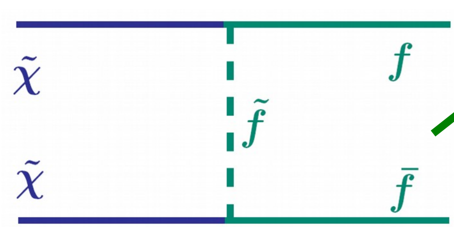
2. stau coannihilation:
degenerate χ and stau





3. focus point:
mixed neutralino, low μ, importance of higgsino-wino component

$$\mu^2 + M_Z^2/2 \approx -\varepsilon m_0^2 + 2m_{1/2}^2$$



1. bulk region: ***light sfermions***

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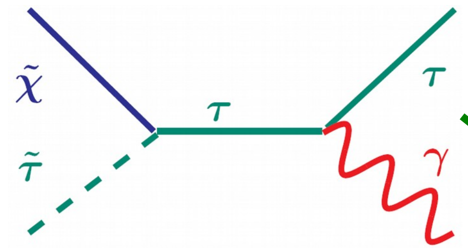

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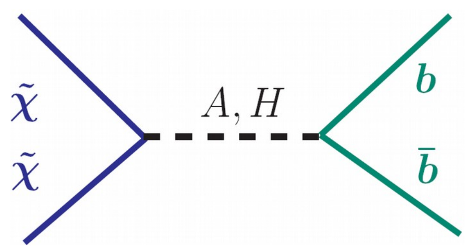
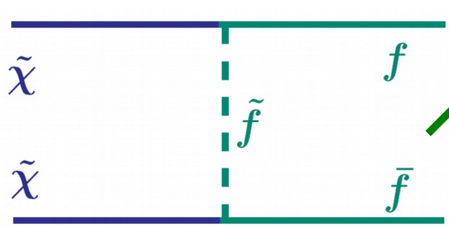
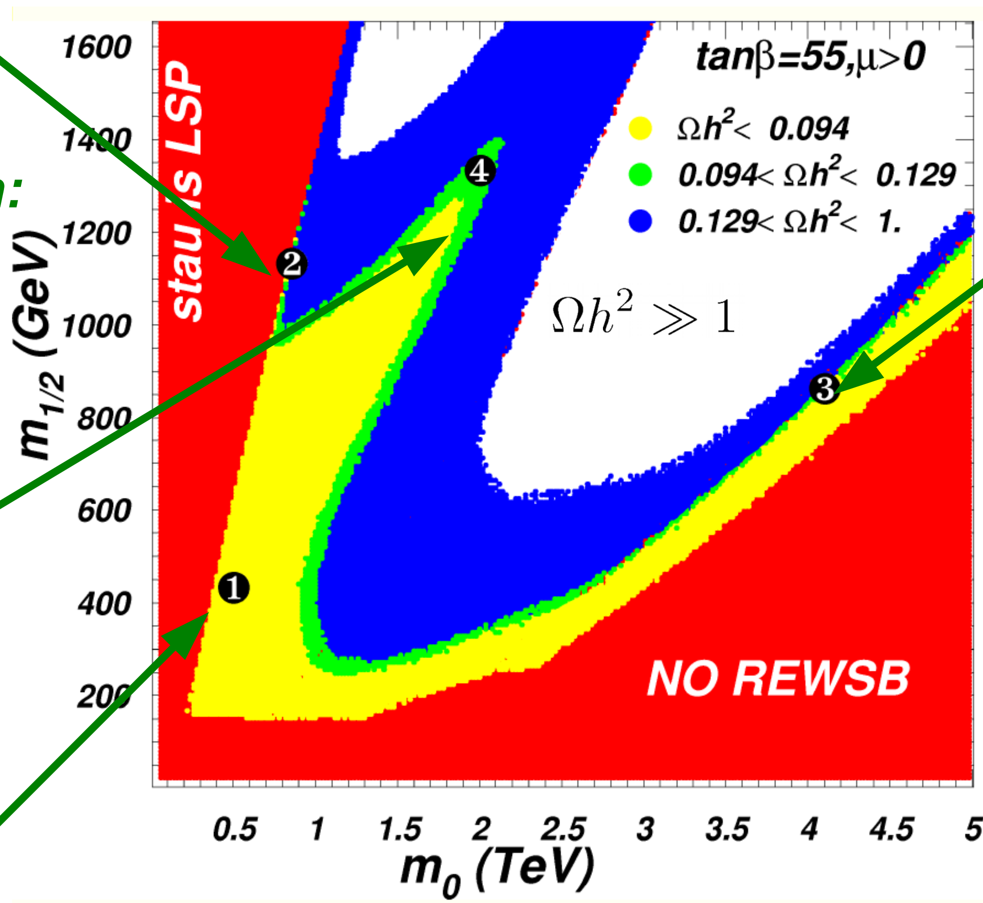


4. funnel: ***(large tanβ) annihilation via A, H***



Baer, A.B., Balazs '02



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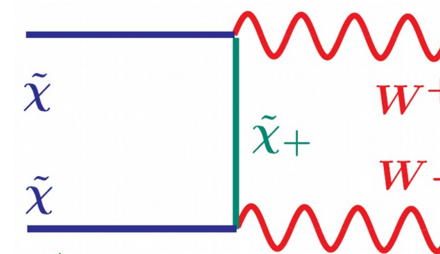

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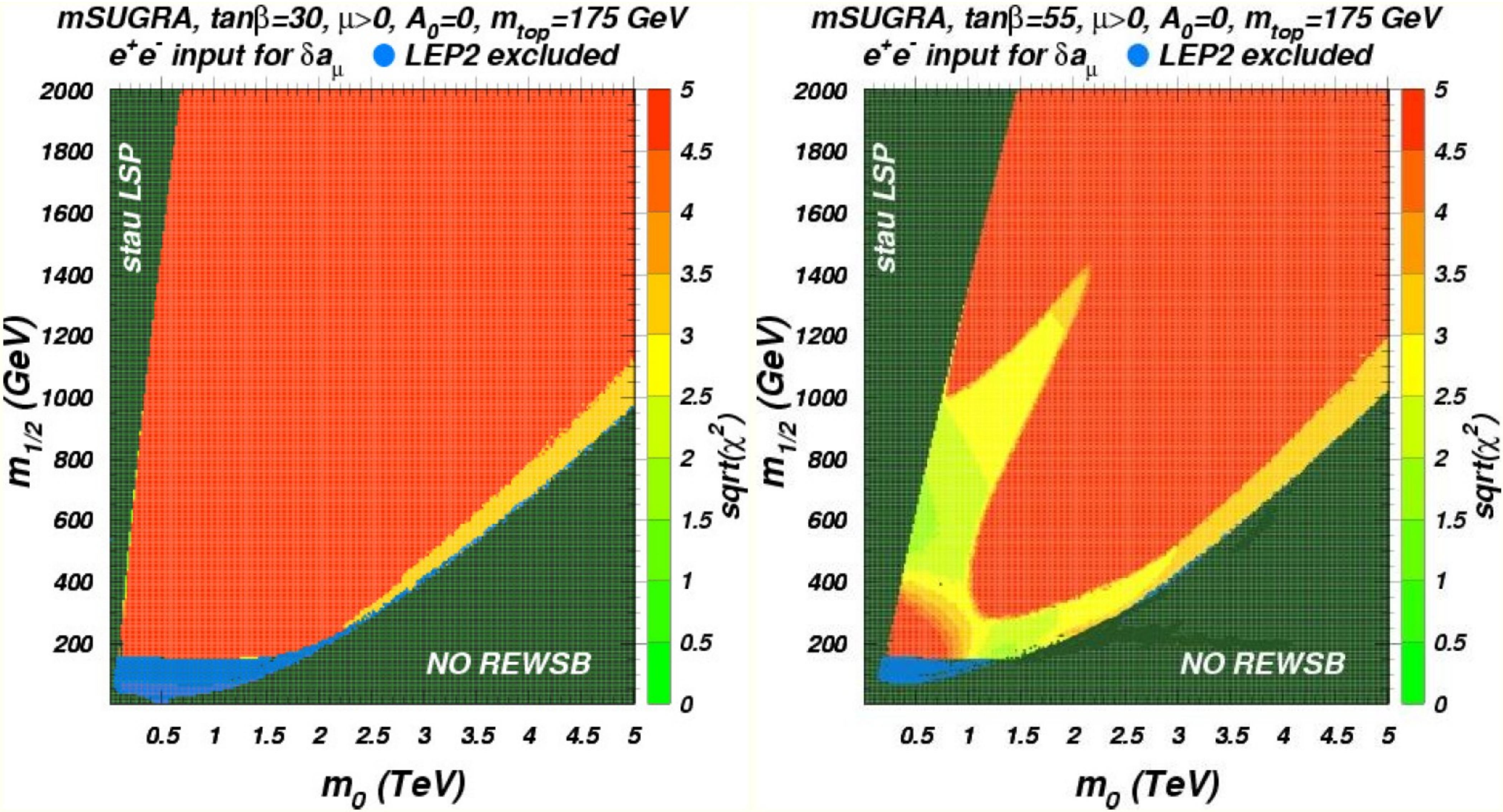
mixed neutralino, low μ, importance of higgsino-wino component

$$\mu^2 + M_Z^2/2 \approx -\varepsilon m_0^2 + 2m_{1/2}^2$$

additional regions:
Z/h annihilation
stop coannihilation

Pre LHC mSUGRA $\chi^2 = \chi^2_{\delta a_\mu} + \chi^2_{\Omega h^2} + \chi^2_{b\to s\gamma}$ analysis

- Δa_μ favors light second generation sleptons, while $BF(b \to s\gamma)$ prefers heavy third generation: hard to realize in mSUGRA model.

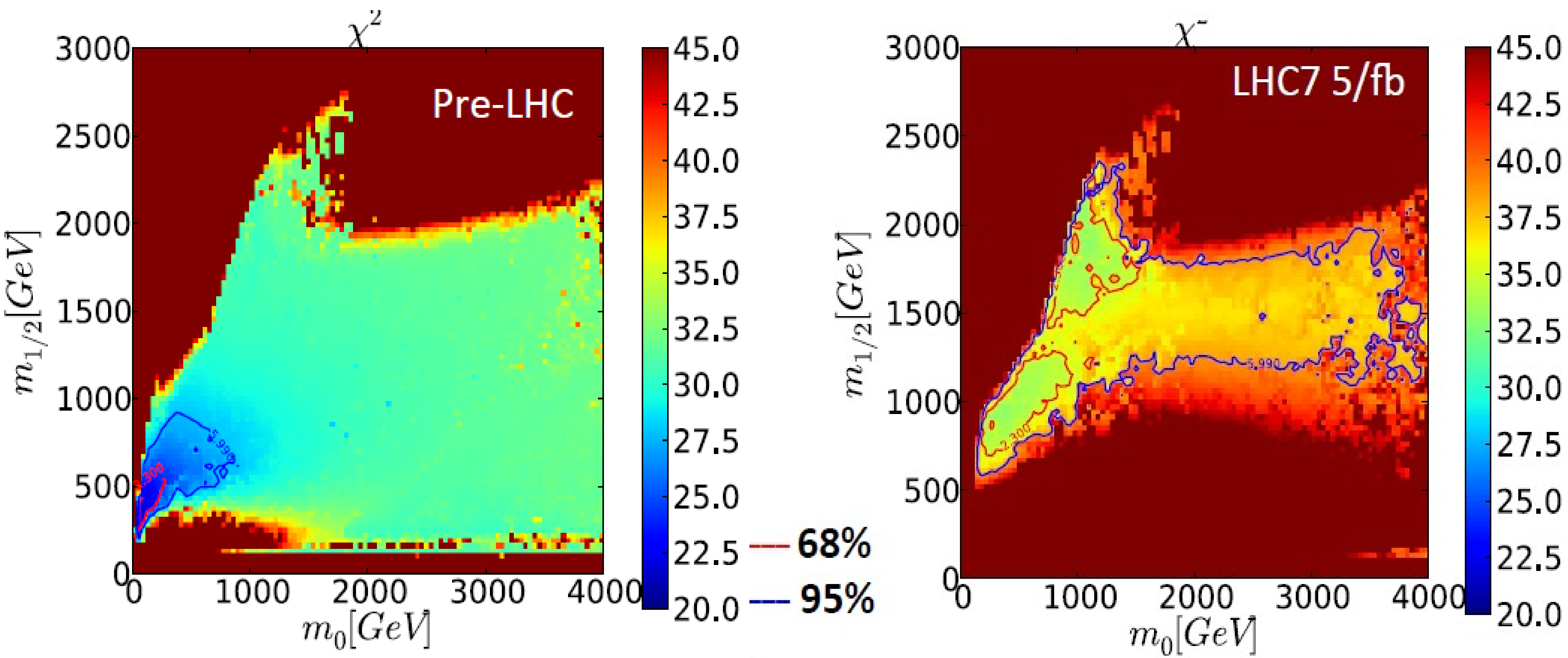


Baer, A.B., Krupovnickas, Mustafayev hep-ph/0403214

Implications of LHC search for SUSY fits

Buchmueller, Cavanaugh, De Roeck, Dolan, Ellis, Flaecher, Heinemeyer, Isidori, Marrouche, Martınez, Santos, Olive, Rogerson, Ronga, de Vries, Weiglein,

Global frequentist fits to the CMSSM using the MasterCode framework



The EW measure of Fine Tuning

$$\mathcal{L}_{\text{MSSM}} = \mu \tilde{H}_u \tilde{H}_d + \text{h.c.} + (m_{H_u}^2 + |\mu|^2)\ |H_u|^2 + (m_{H_d}^2 + |\mu|^2)\ |H_d|^2 + \ldots$$

The EW measure requires that there be no large/unnatural cancellations in deriving m_Z from the weak scale scalar potential:

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2 \simeq -m_{H_u}^2 - \mu^2$$

using fine-tuning definition which became standard

Ellis, Enqvist, Nanopoulos, Zwirner '86; Barbieri, Giudice '88

$$\Delta_{FT} = max[c_i], \qquad c_i = \left|\frac{\partial \ln m_Z^2}{\partial \ln p_i}\right| = \left|\frac{p_i}{m_Z^2}\frac{\partial m_Z^2}{\partial p_i}\right|$$

one finds $\Delta_{FT} \simeq \Delta_{EW}$ **which requires as well as**

$$\boxed{\begin{aligned} |\mu^2| &\simeq M_Z^2 \\ |m_{H_u}^2| &\simeq M_Z^2 \end{aligned}}$$

The last one is GUT model-dependent, so we consider the value $|\mu^2|$ as a measure of the minimal fine-tuning

"Compressed Higgsino" Scenario (CHS)

chargino-neutralino mass matrices

in $(\tilde{W}^-, \tilde{H}^-)$ basis

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

charginos

in $(\tilde{B}^0, \tilde{W}^0, \tilde{H}^0_1, \tilde{H}^0_2)$ basis

$$\begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_w & m_Z s_\beta s_w \\ 0 & M_2 & m_Z c_\beta c_w & -m_Z s_\beta c_w \\ -m_Z c_\beta s_w & m_Z c_\beta c_w & 0 & -\mu \\ m_Z s_\beta s_w & -m_Z s_\beta c_w & -\mu & 0 \end{pmatrix}$$

neutralinos

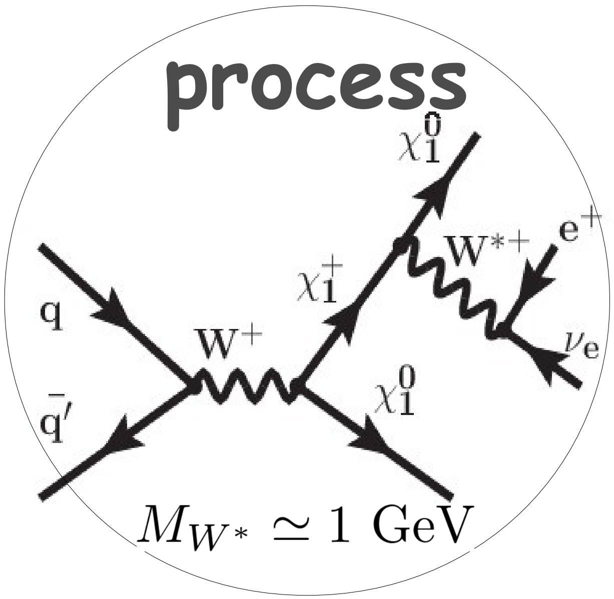
M_2 real, $\quad M_1 = |M_1| e^{-\Phi_1}, \quad \mu = |\mu| e^{i\Phi_\mu}$

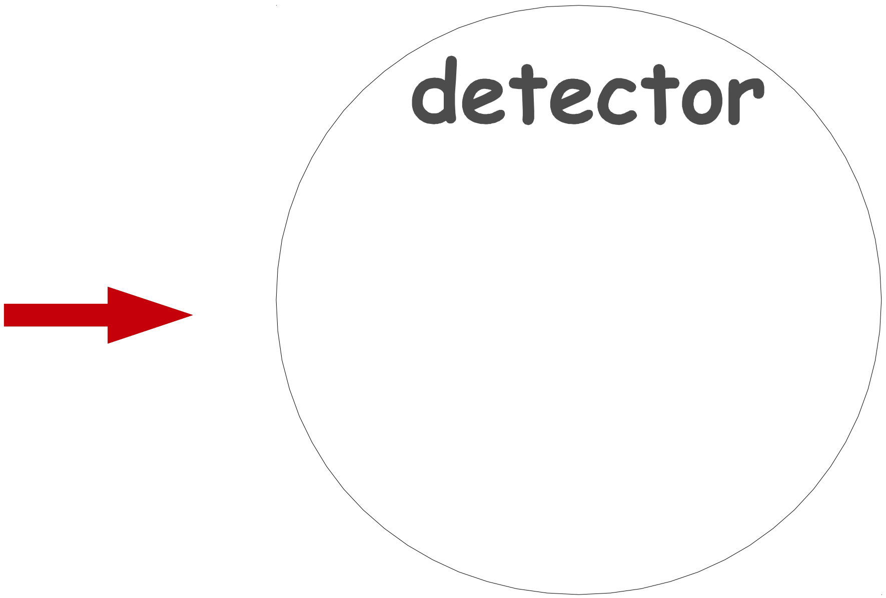
- Case of μ << M1, M2: $\chi^0_{1,2}$ and $\chi^\pm$ become quasi-degenerate and acquire large higgsino component. This provides a naturally low DM relic density via gaugino annihilation and co-annihilation processes into SM V's and H
- This is the case of relatively light higgsinos-electroweakinos compared to the other SUSY particles.
- This scenario is not just motivated by its simplicity, but also by the lack of evidence for SUSY to date

CHS Mass Spectrum and Challenge for the LHC

- The most challenging case takes place when only $\chi^0_{1,2}$ and $\chi^\pm$ are accessible at the LHC, and the mass gap between them is not enough for any leptonic signature

- The only way to probe CHS is a mono-jet signature
  ["Where the Sidewalk Ends? ..." Alves, Izaguirre,Wacker '11] ,
  which has been used in studies on compressed SUSY spectra, *e.g.*
  Dreiner,Kramer,Tattersall '12; Han,Kobakhidze,Liu,Saavedra,Wu'13; Han,Kribs,Martin,Menon '14





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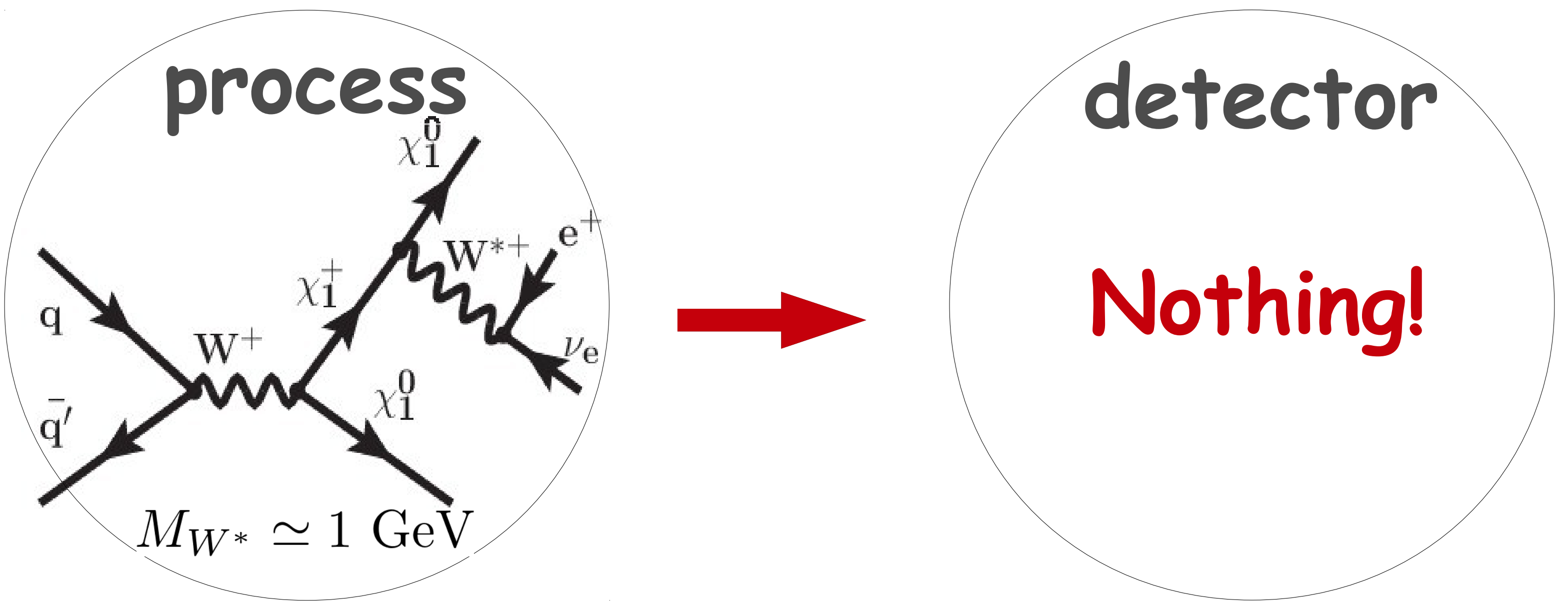

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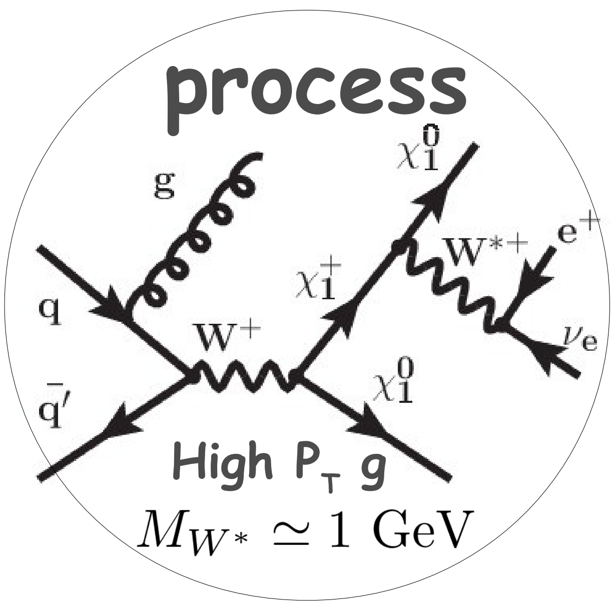

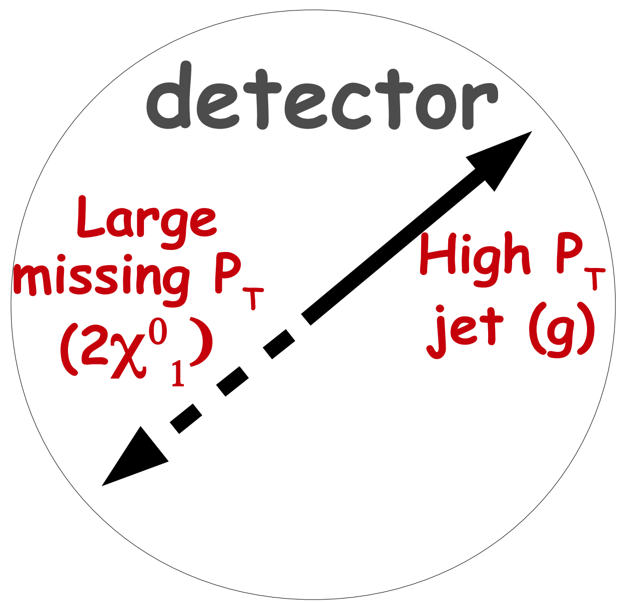

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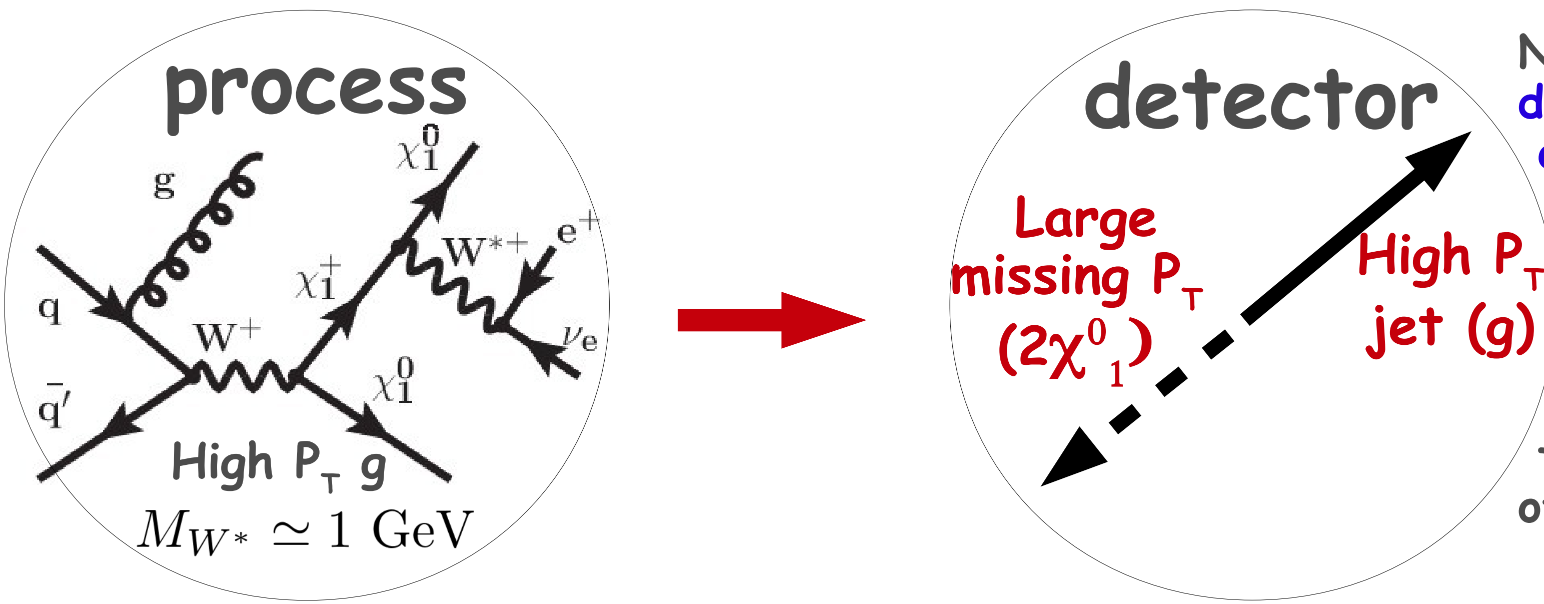
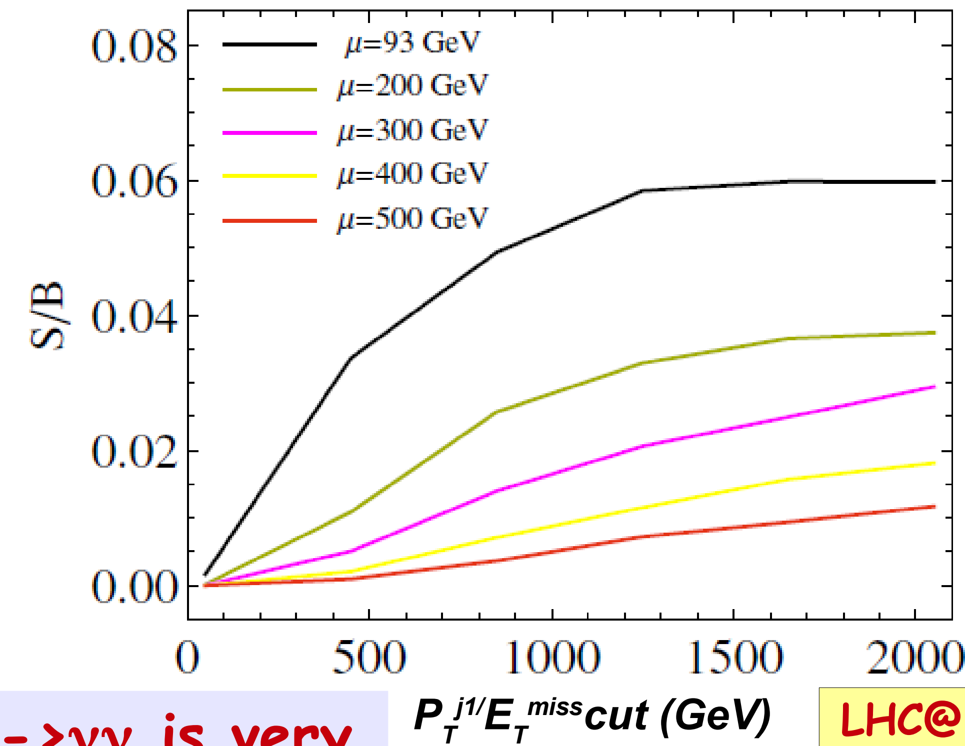
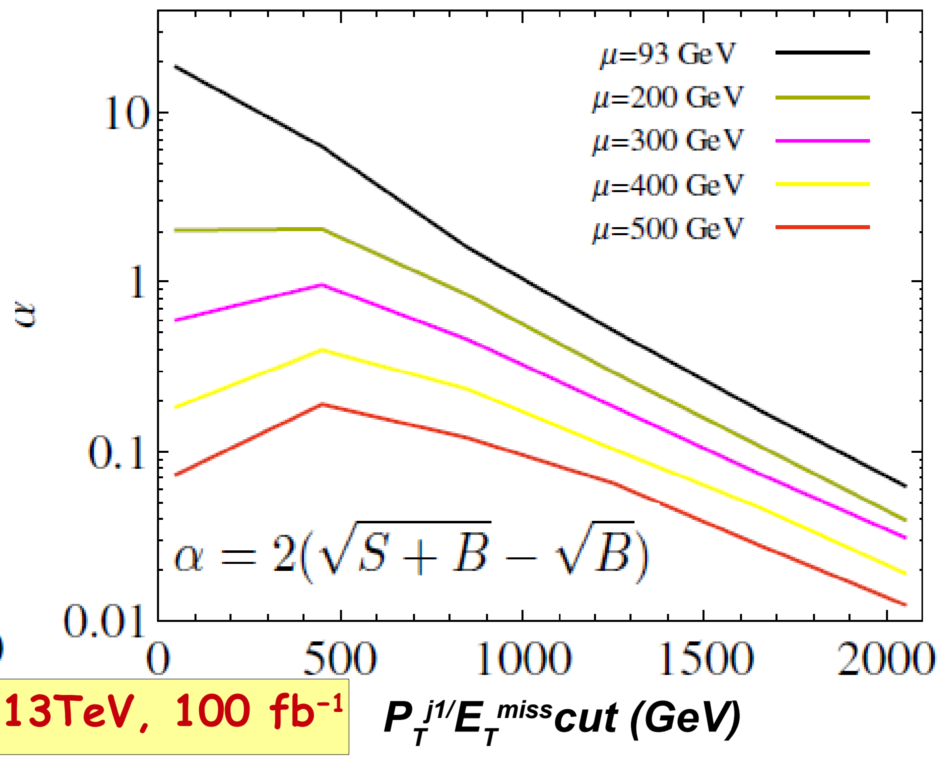


Note that W* decay products do not get large boost – it is proportional to the mass of W* which is much smaller than the mass of the LSP

S/B vs Signal significance





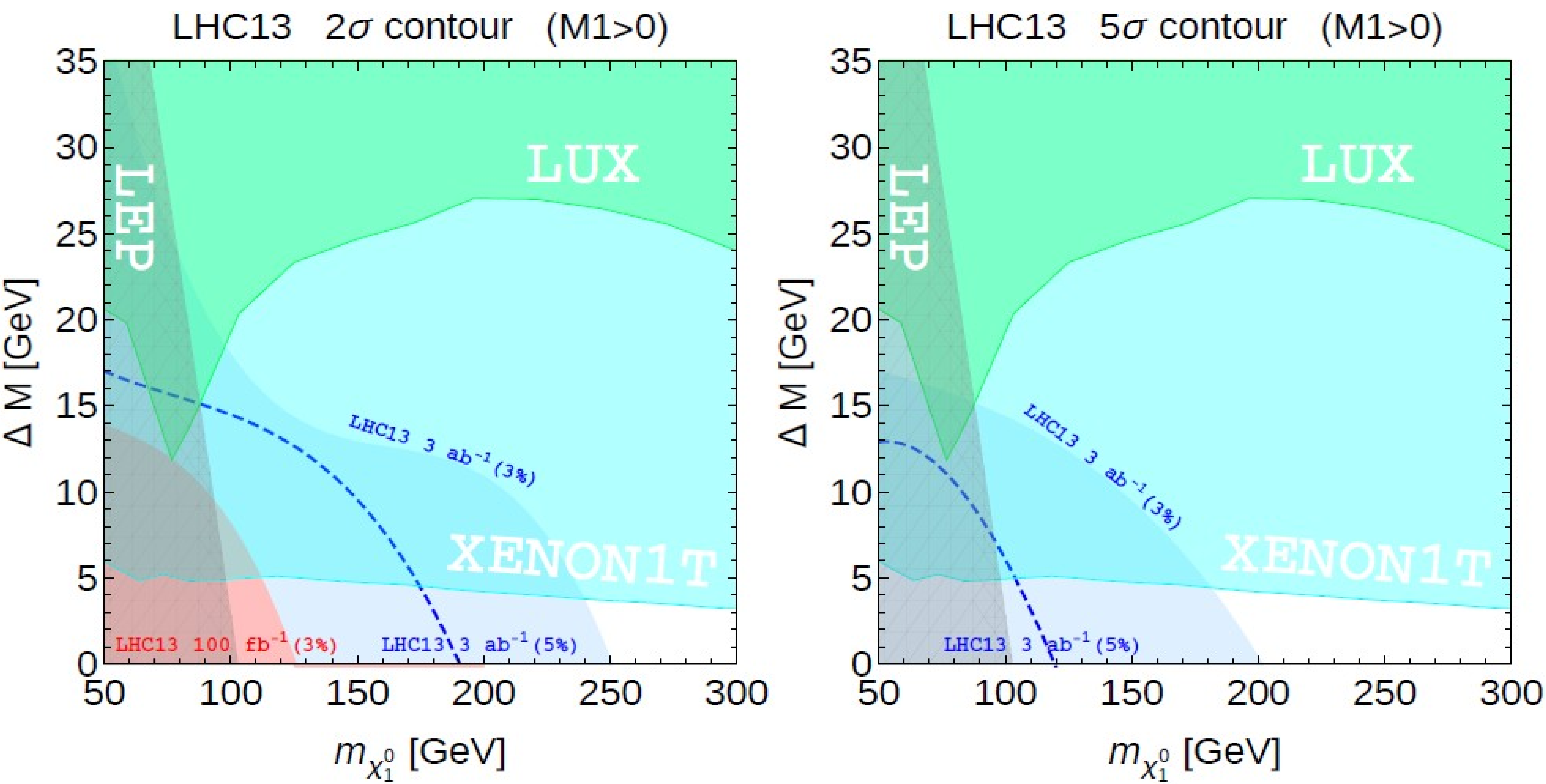
LHC@13TeV, 100 fb^{-1}

Z->νν is very problematic background!

	$Z(\nu\bar{\nu})j$	$W(\ell\nu)j$	$\mu = 93$ GeV	$\mu = 500$ GeV
$p^T_{jet} > 50$ GeV, $\lvert\eta_{jet}\rvert < 5$	6.4 E+7	2.9 E+8	2.6 E+5	948
Veto $p^T_{e^\pm,\mu^\pm/\tau^\pm}$ >10/20 GeV	6.2 E+7	1.2 E+8	2.5 E+5	921
p^T_j >500 GeV	2.5 E+4	2.0 E+4	1051	32
$p^T_j = \not{E}_T$ >500 GeV	1.5 E+4	4.1 E+3	747	27
$p^T_j = \not{E}_T$ >1000 GeV	315 (375)	65 (32)	21 (31)	2 (2)
$p^T_j = \not{E}_T$ >1500 GeV	18 (20)	2 (1)	1 (2)	0 (0)
$p^T_j = \not{E}_T$ >2000 GeV	1 (1)	0 (0)	0 (1)	0 (0)

- There is an important tension between S/B and signal significance
- S/B pushes E_t^{miss} cut up towards an acceptable systematic
- significance requires comparatively low (below 500 GeV) E_t^{miss} cut

LHC/DM direct detection sensitivity to CHS



"Uncovering Natural Supersymmetry via the interplay between the LHC and Direct Dark Matter Detection", Barducci,AB,Bharucha,Porod,Sanz, arXiv:1504.02472 (JHEP)

- **SUSY, at least DM, can be around the corner (100 GeV), it is just very hard to detect it!**

Question:

“Can experimentally rule out SUSY in general and e.g. cMSSM in particular?”

Question:

"Can experimentally rule out SUSY in general and e.g. cMSSM in particular?"

Answer:

NO!

SUSY can be either discovered or abandoned!

Original statement from Leszek Roszkowski: "Low energy SUSY cannot be experimentally ruled out. It can only be discovered. Or else abandoned."