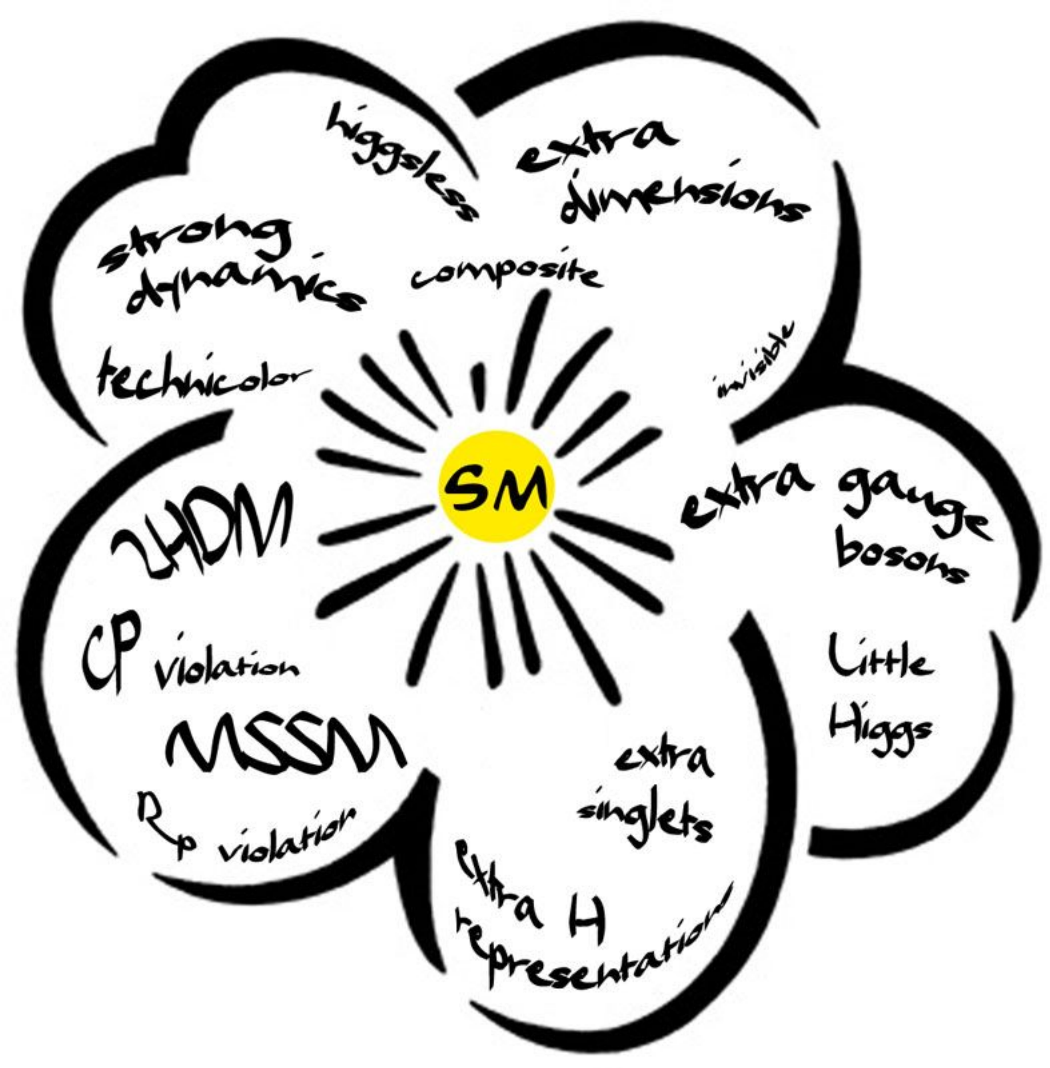
Lecture II:
Effective Field Theory and Supersymmetry

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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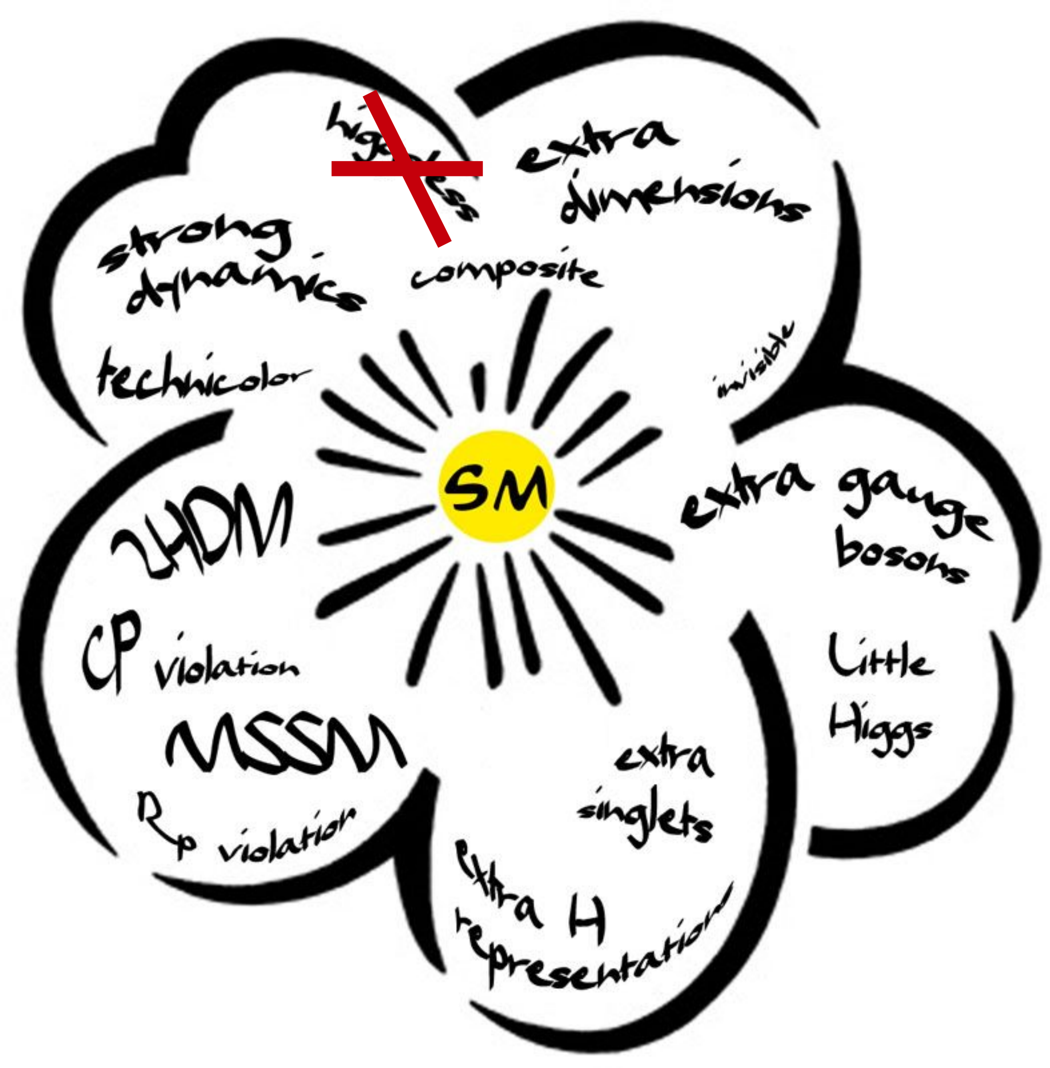

Present Status

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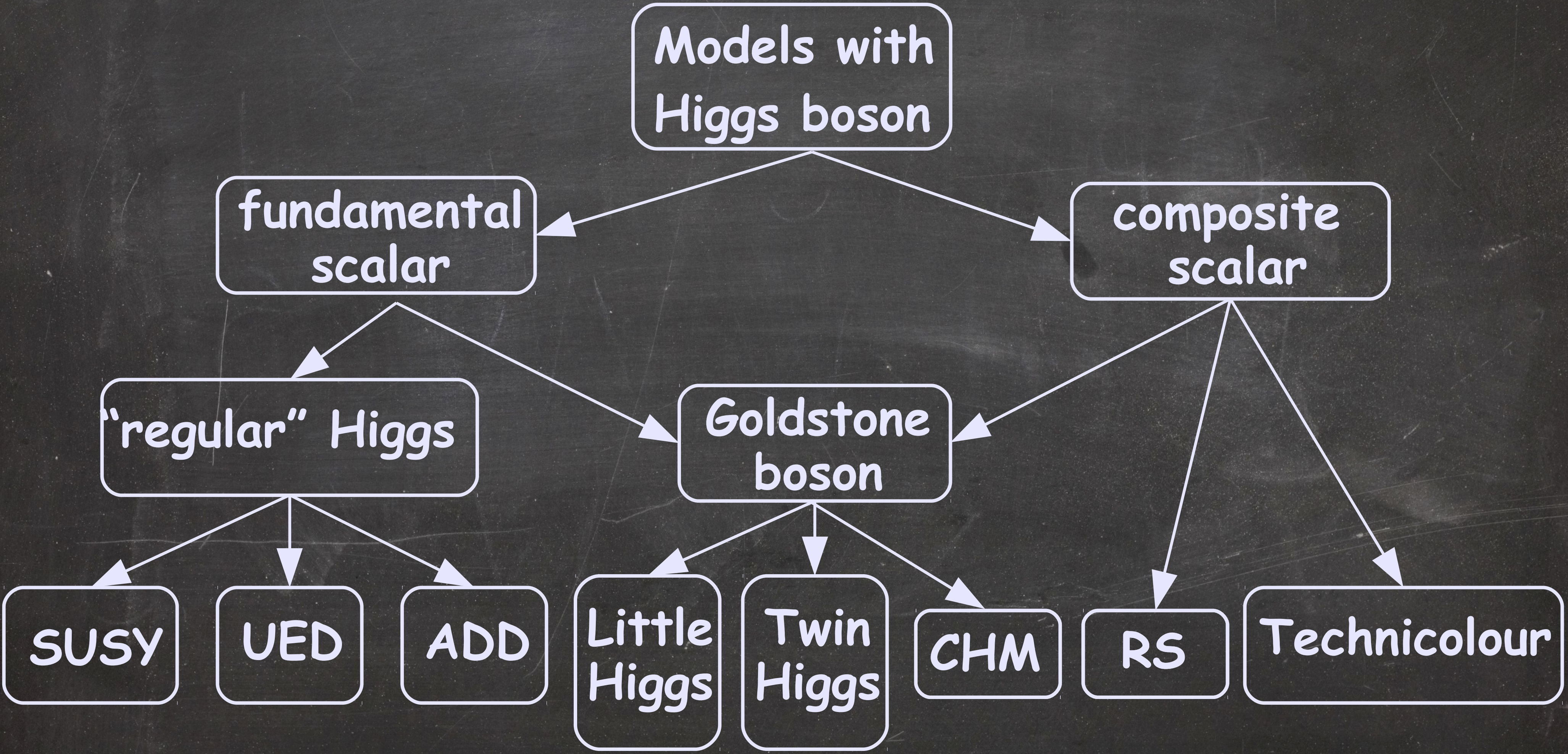
Models with Higgs boson

fundamental scalar

composite scalar

"regular" Higgs

Goldstone boson

SUSY

UED

ADD

Little Higgs

Twin Higgs

CHM

RS

Technicolour

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)

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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

    $$\lambda^{\nu}\, l H^c\, \nu^c \text{ (Dirac mass term after EWSB)}$$

    and/or

    $$m^{\nu}\nu^c\nu^c \text{ (Majorana mass term)}$$

    (**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 (recall yesterday remark from Dima Kazakov)

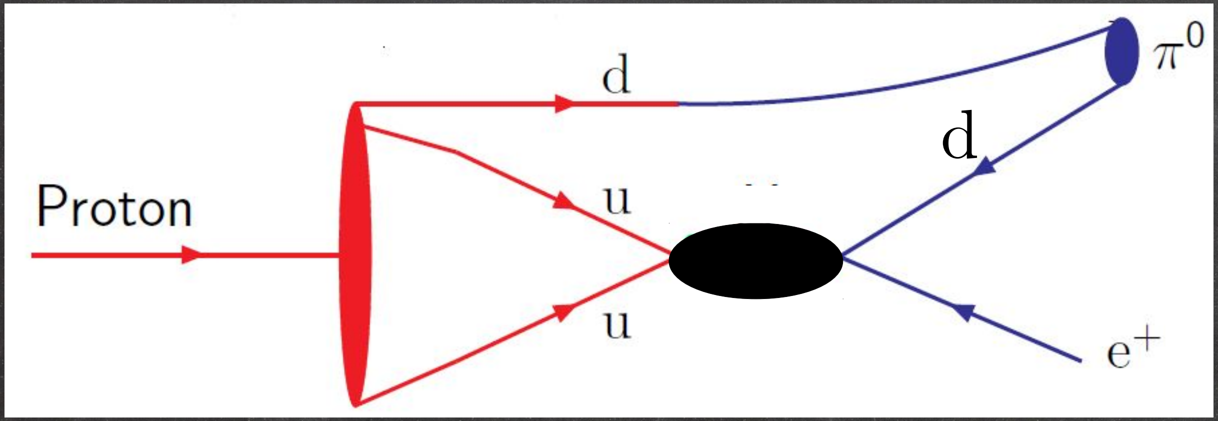
SM extension to EFT

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

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

(**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)

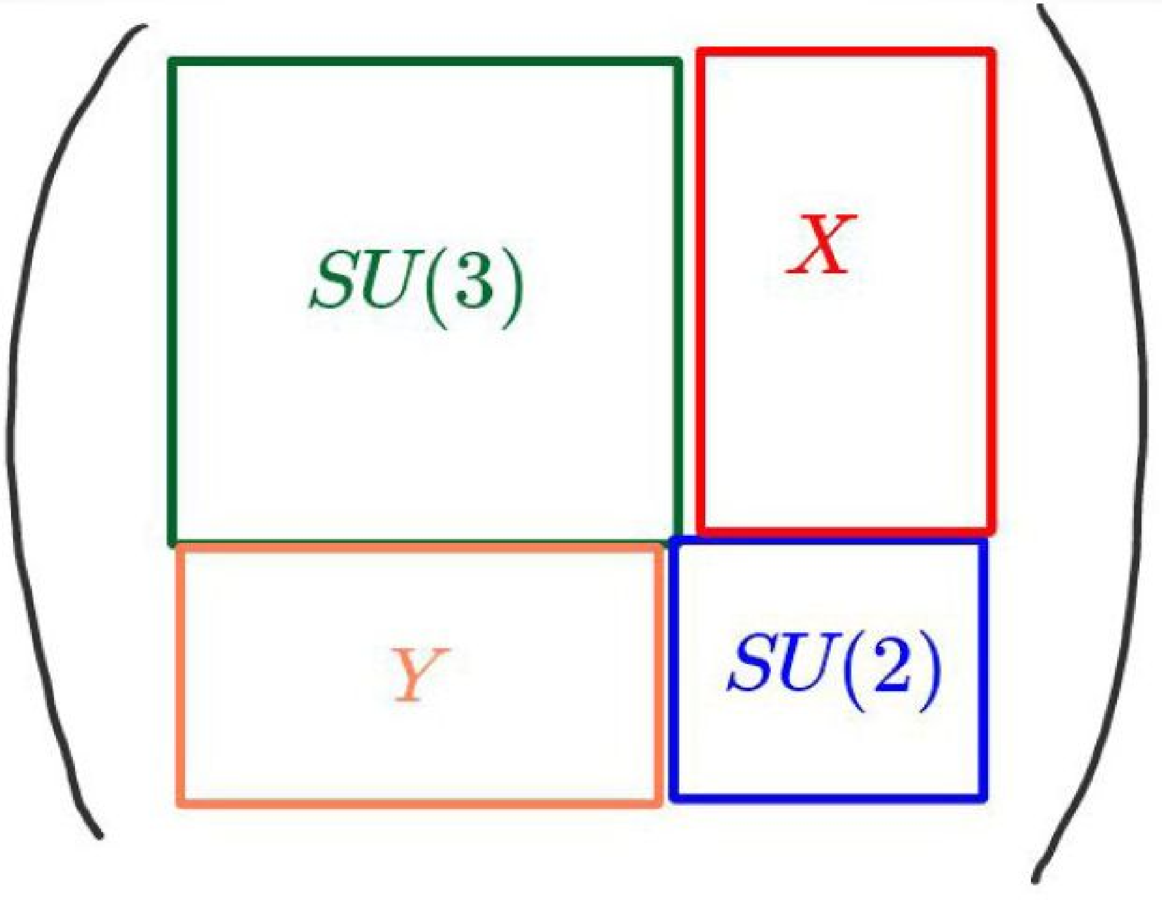
- SU(5) has $5^2-1=24$ generators, which means that
  - we have 24 gauge bosons

    – 8 gluons and 4 electroweak bosons

    – so we get 12 new gauge bosons

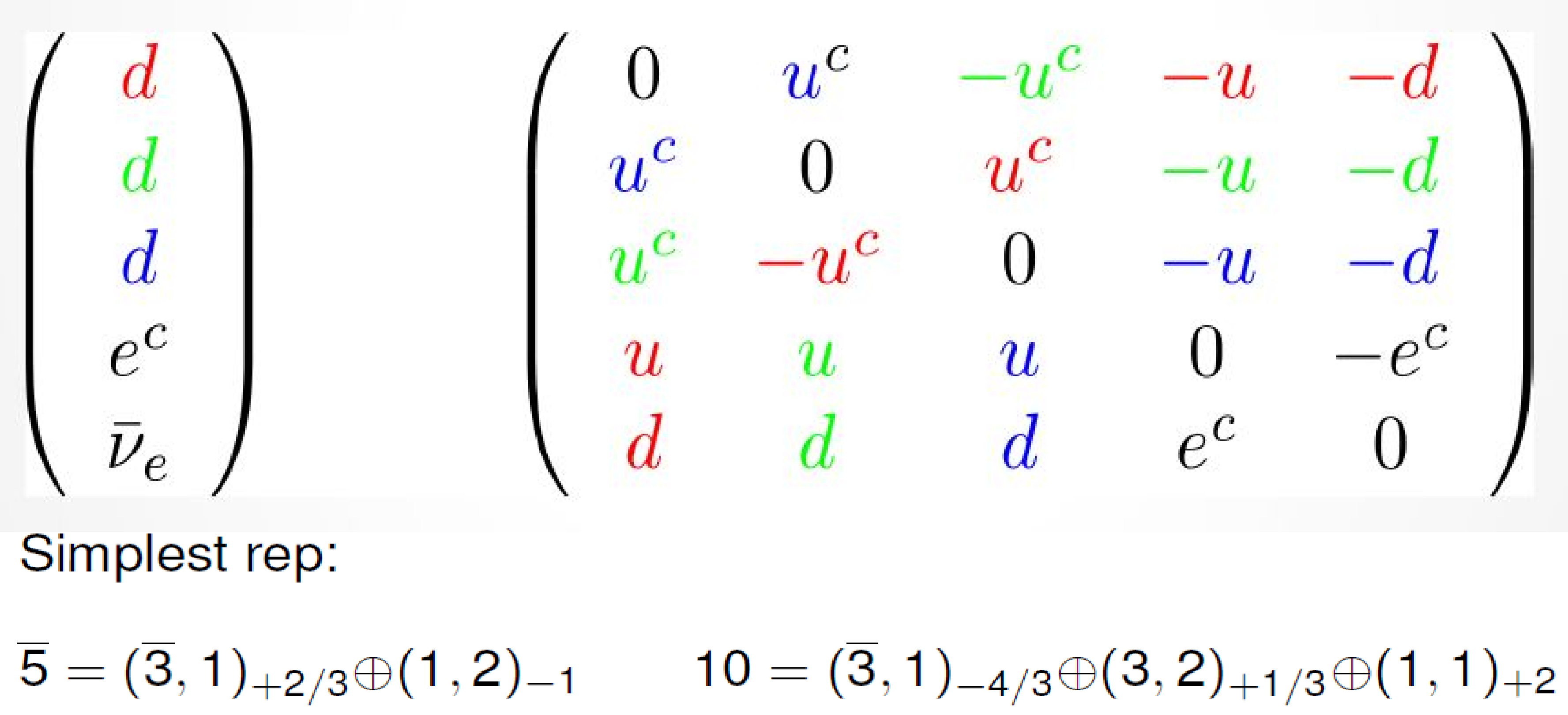
SU(5)

- 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:

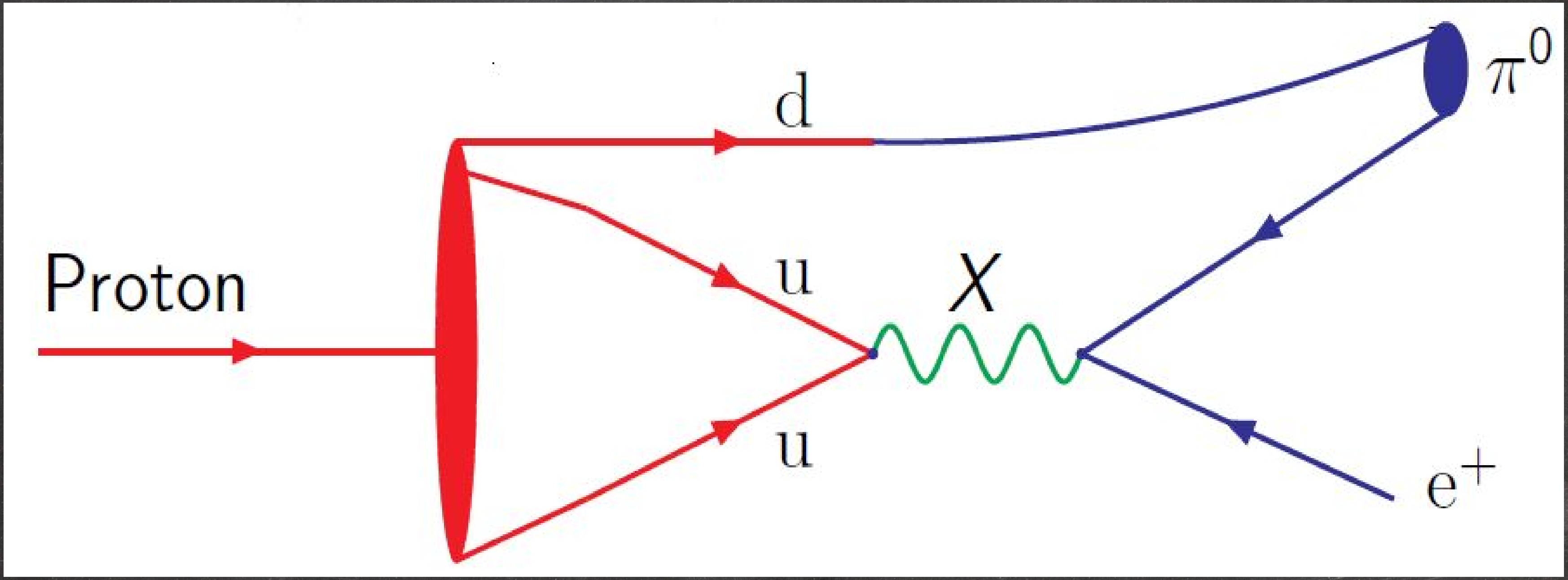
$\overline{5} = (\overline{3}, 1)_{+2/3} \oplus (1, 2)_{-1}$ $\qquad 10 = (\overline{3}, 1)_{-4/3} \oplus (3, 2)_{+1/3} \oplus (1, 1)_{+2}$

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

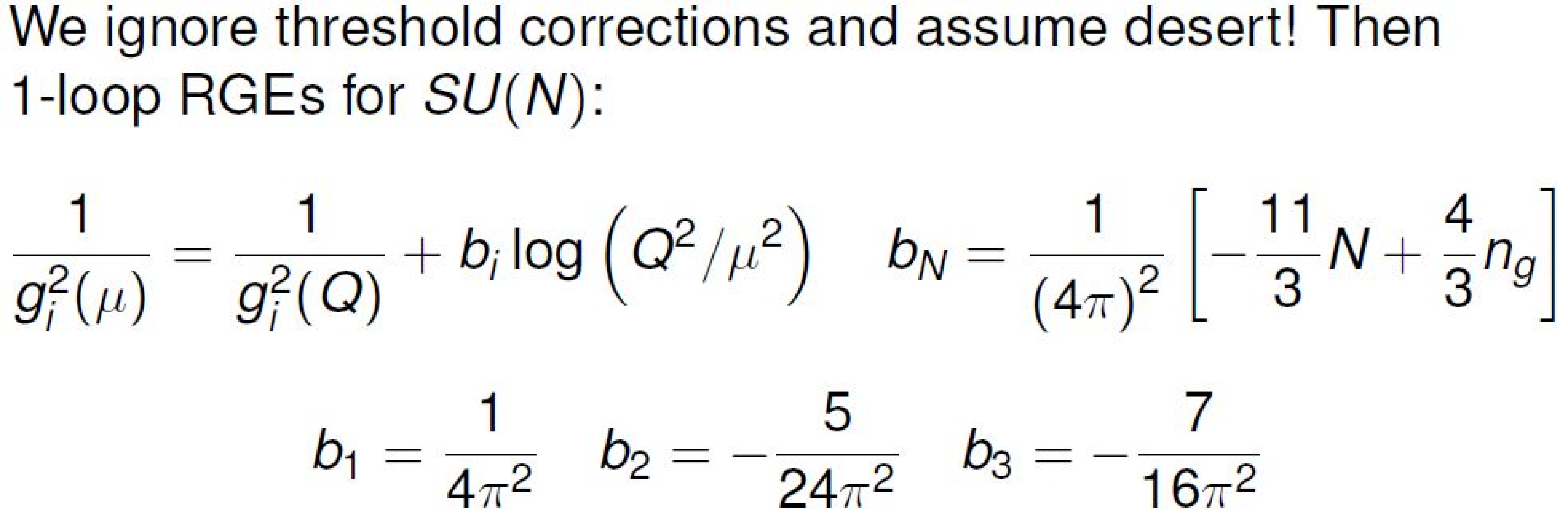
Proton Decay

- 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

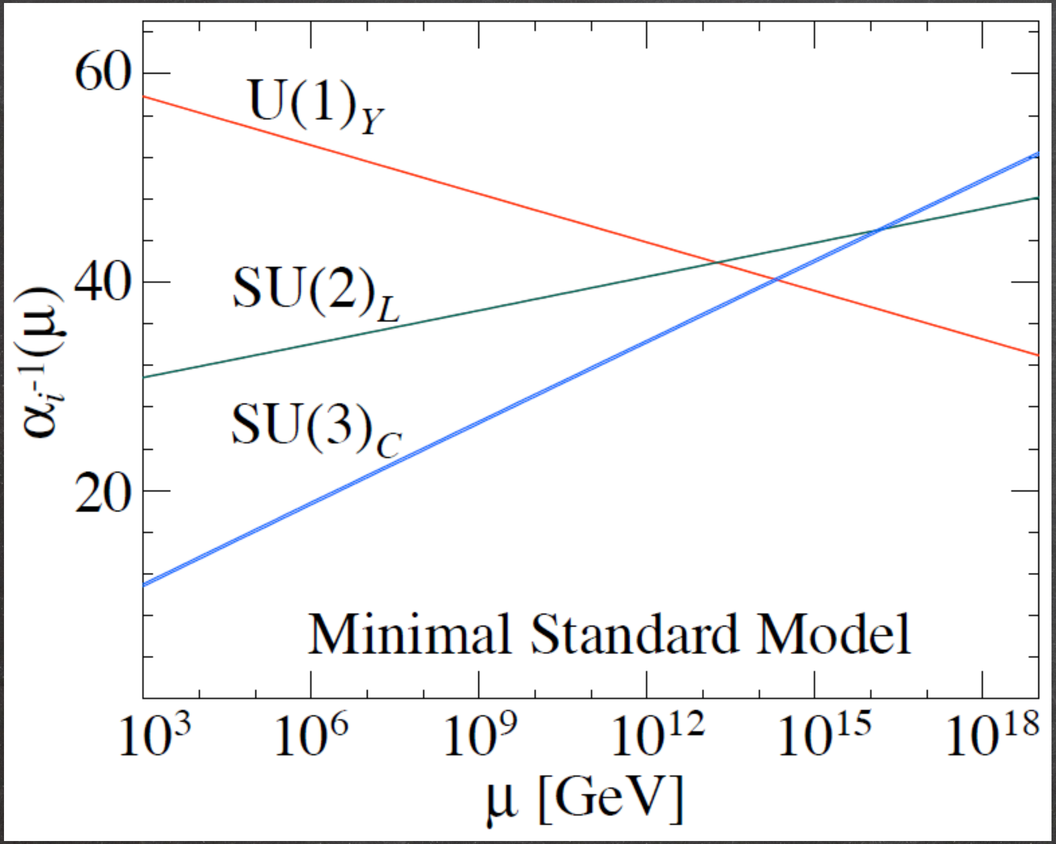


We ignore threshold corrections and assume desert! Then 1-loop RGEs for $SU(N)$:

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

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

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

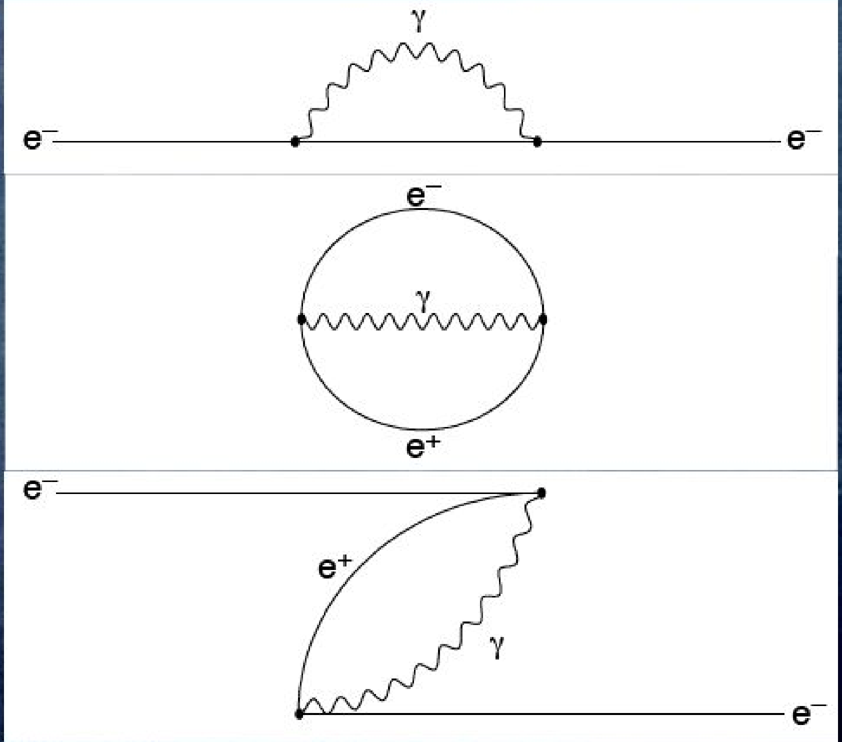
  $\Rightarrow$ Can't discuss physics below 10^{-13}cm

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

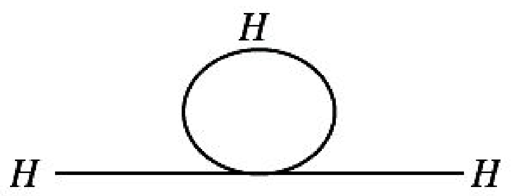
$\Rightarrow$ only 10% of mass even for Planck-size $r_e \sim 10^{-33}$cm



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

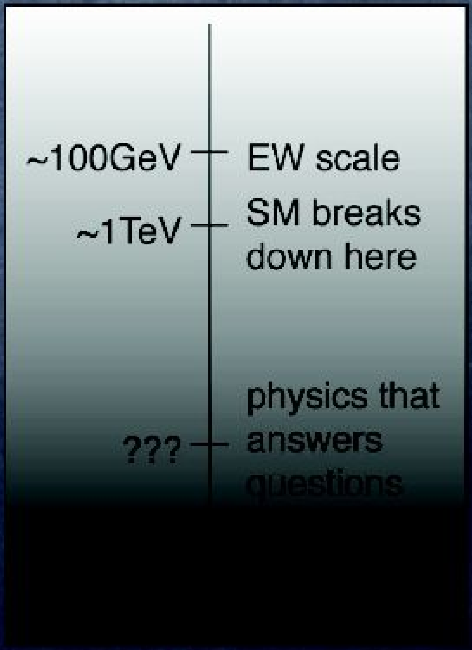
From Hitoshi Murayama, 2007

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!



~100GeV — EW scale

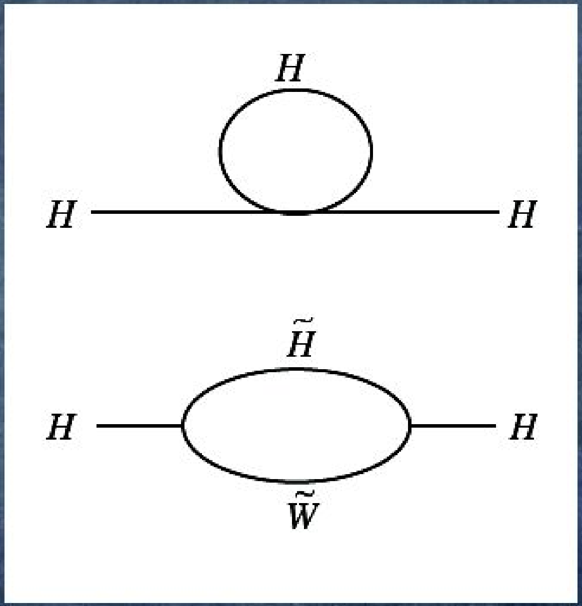
~1TeV — SM breaks down here

??? — physics that answers questions

From Hitoshi Murayama, 2007

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

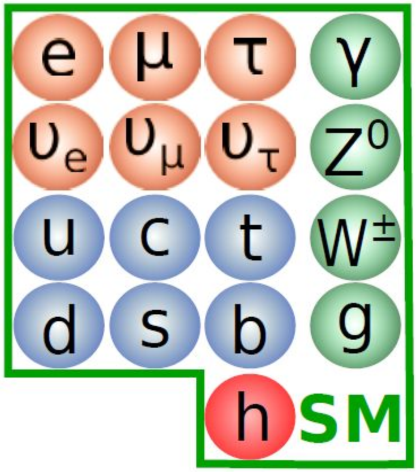
$$Q|\text{BOSON}\rangle = |\text{FERMION}\rangle, \quad Q|\text{FERMION}\rangle = |\text{BOSON}\rangle$$

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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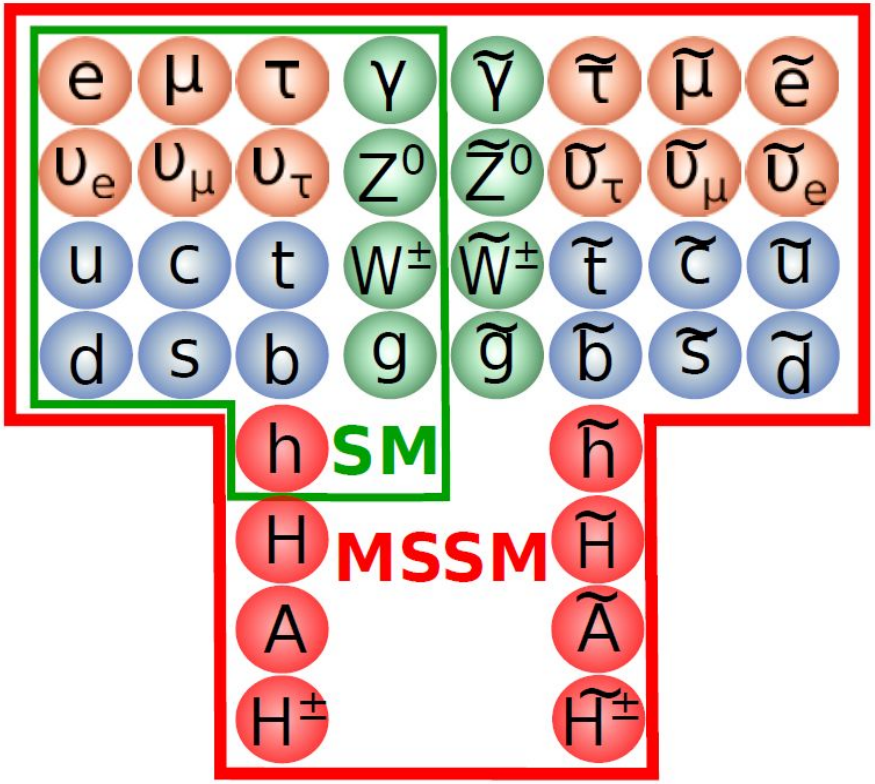

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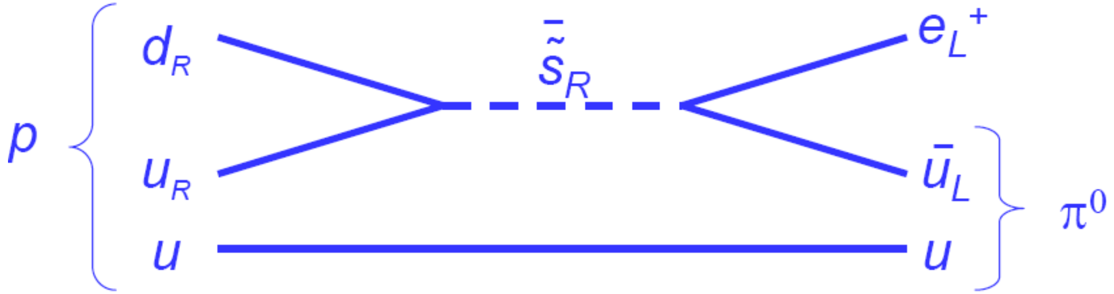
Particle	SUSY partner
e,ν,u,d *spin 1/2*	$\tilde{e}, \tilde{\nu}, \tilde{u}, \tilde{d}$ *spin 0*
γ,W,Z h,H,A,H± *spin 1 and 0*	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$ $\tilde{\chi}_1^0 \cdots \tilde{\chi}_4^0$ *spin 1/2*



could give rise the proton decay!

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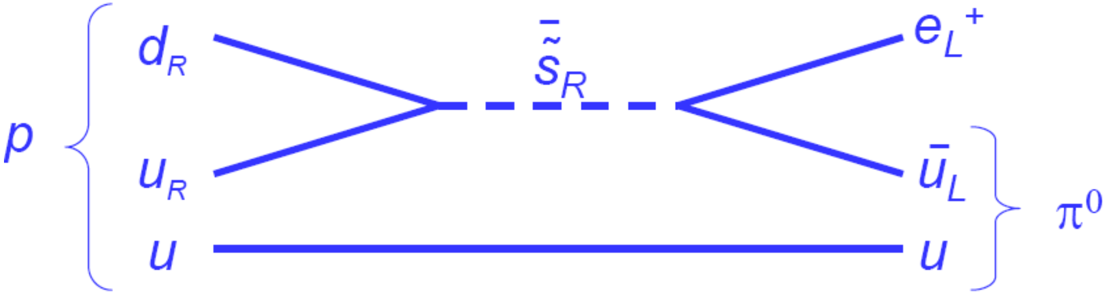
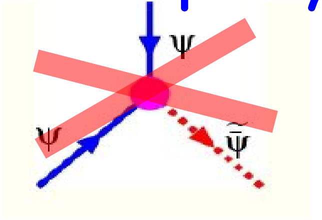
γ,W,Z h,H,A,H± *spin 1 and 0*	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^\pm$ $\boxed{\tilde{\chi}_1^0}\ldots\tilde{\chi}_4^0$ *spin 1/2*



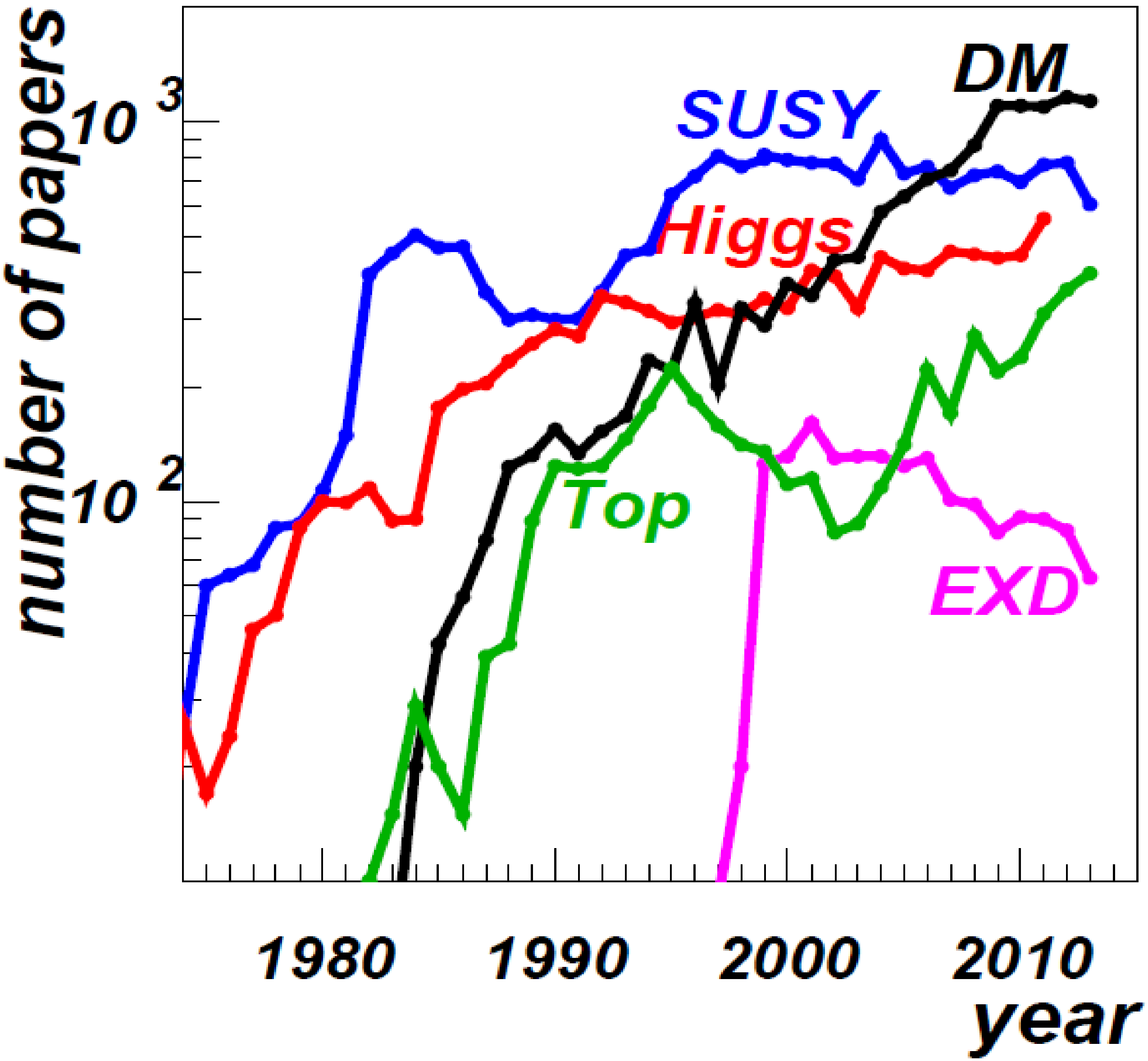
the absence of proton decay suggests R-parity

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



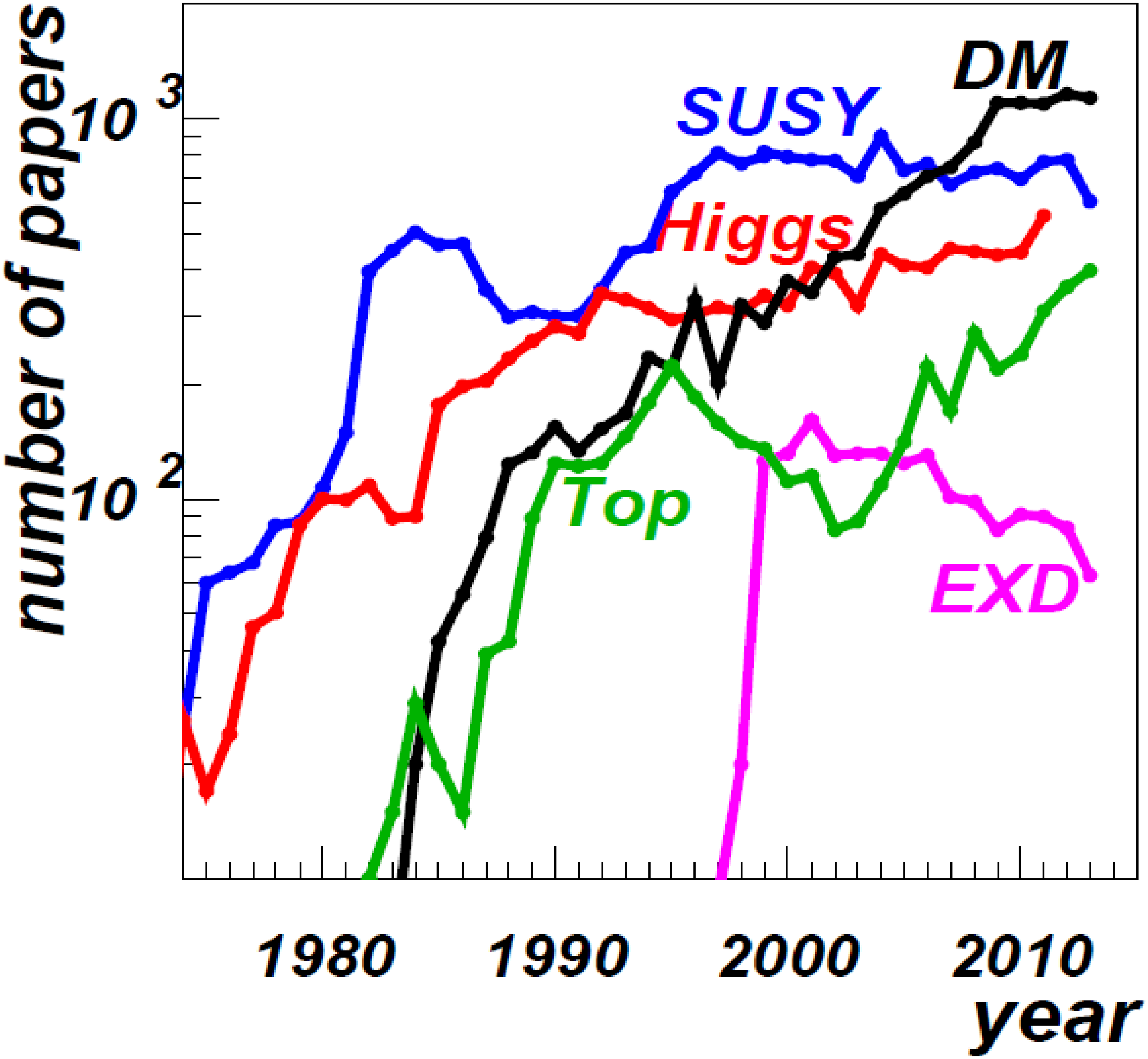
R-parity guarantees Lightest SUSY particle (LSP) is stable - DM candidate!

We are still inspired by this beauty ...



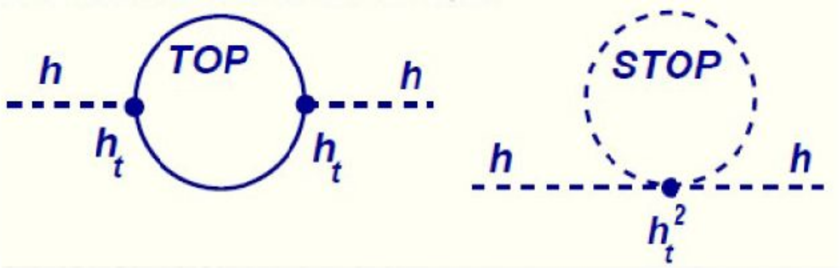
We are still inspired by this beauty ...

after more than 30 year unsuccessful searches ...

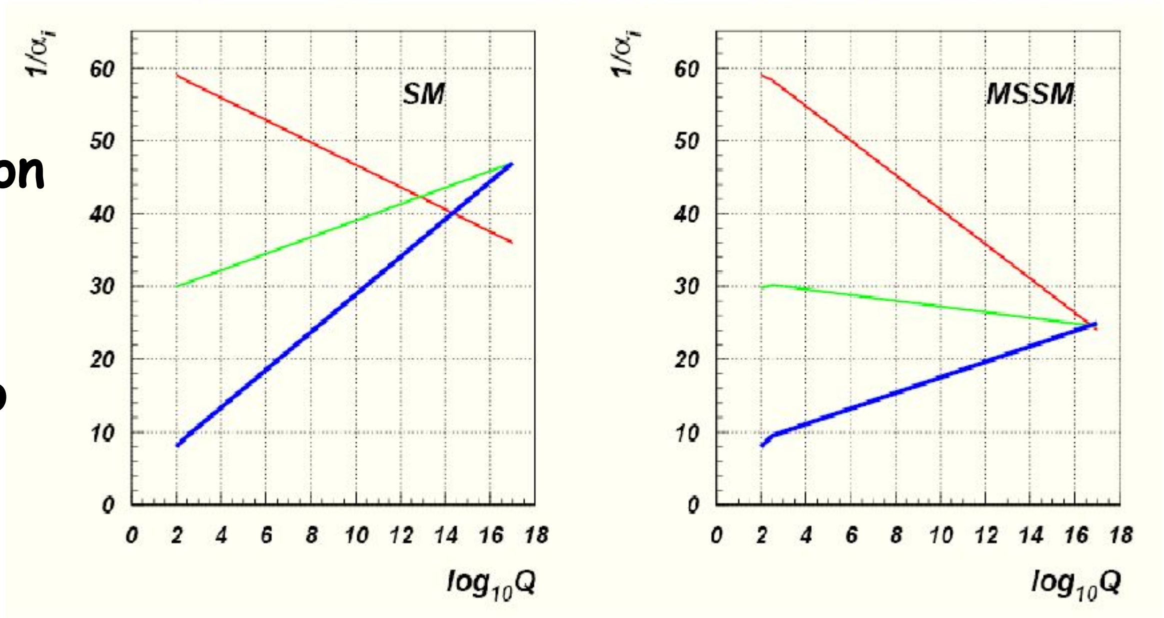


Beauty of SUSY

- 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

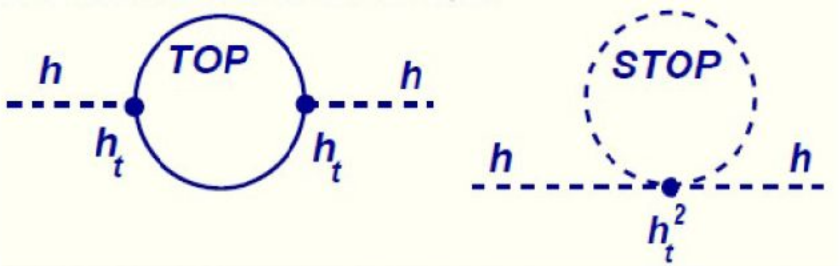


$$\Delta M_H^2 \sim M_{SUSY}^2 \log(\Lambda/M_{SUSY})$$



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



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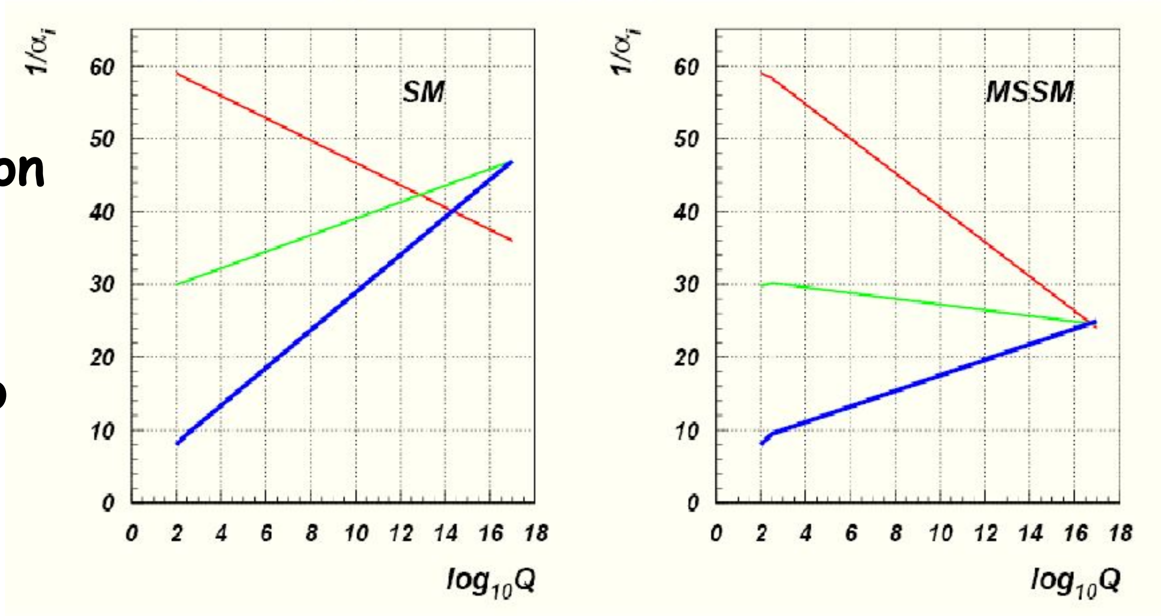
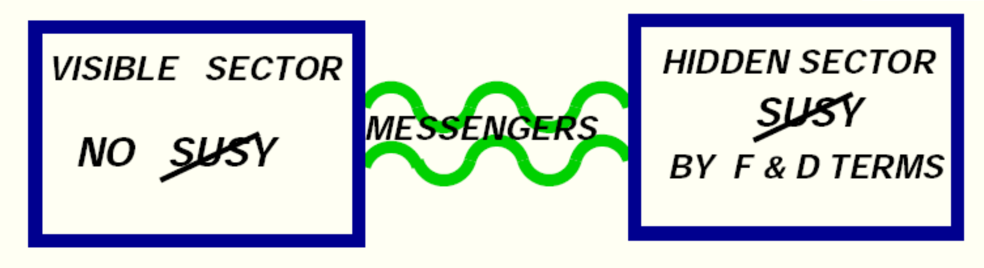


But the real beauty of SUSY is that

It was not deliberately designed to solve the SM problems!

SUSY breaking and mSUGRA scenario

- *SUSY is not observed ⇒ must be broken*



VISIBLE SECTOR

NO ~~SUSY~~

MESSENGERS

HIDDEN SECTOR

~~SUSY~~

BY F & D TERMS

Gravity mediation
Gauge mediation
Anomaly mediation
Gaugino mediation

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

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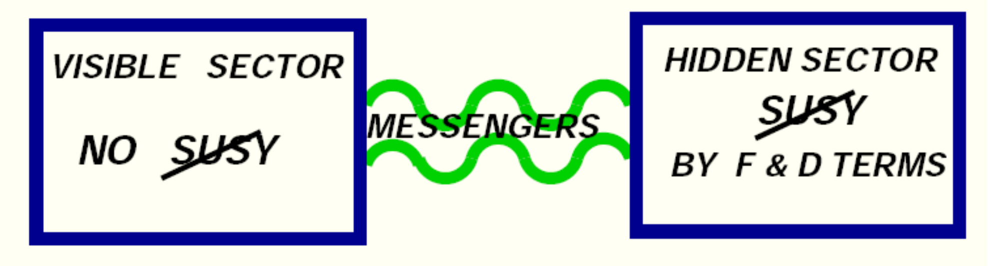

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- **SUGRA:** *the hidden sector communicates with visible one via gravity*

  – all soft terms are non-zero in general($\sim m_{3/2}$ -gravitino mass)

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

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

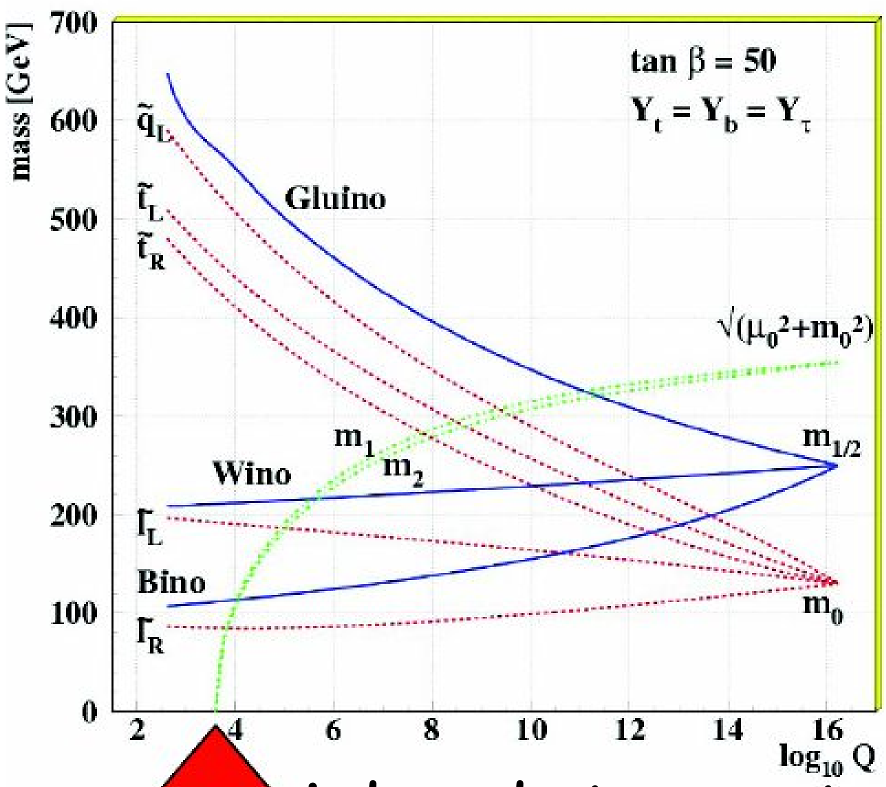
  flat Kähler metric takes care of constraining of Flavor violating processes

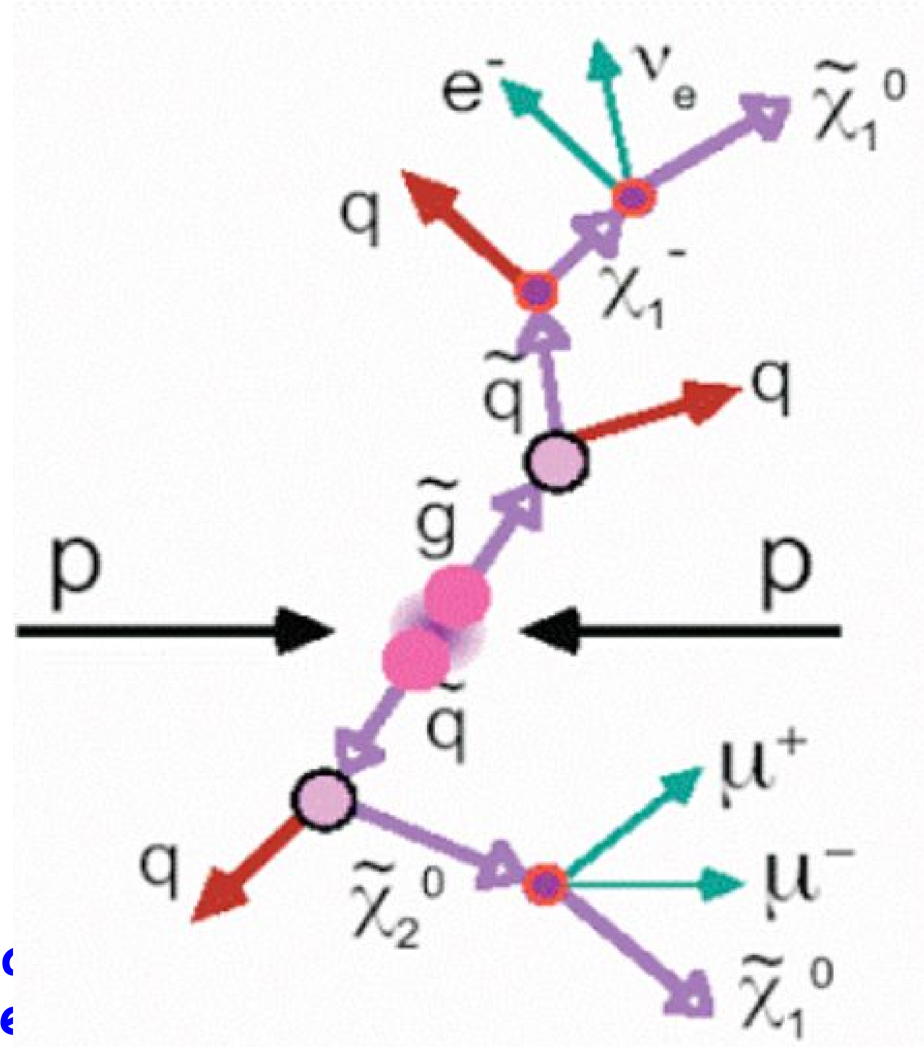
- $sign(\mu)$, μ^2 *value is fixed by the minim condition for Higgs potential*

- 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

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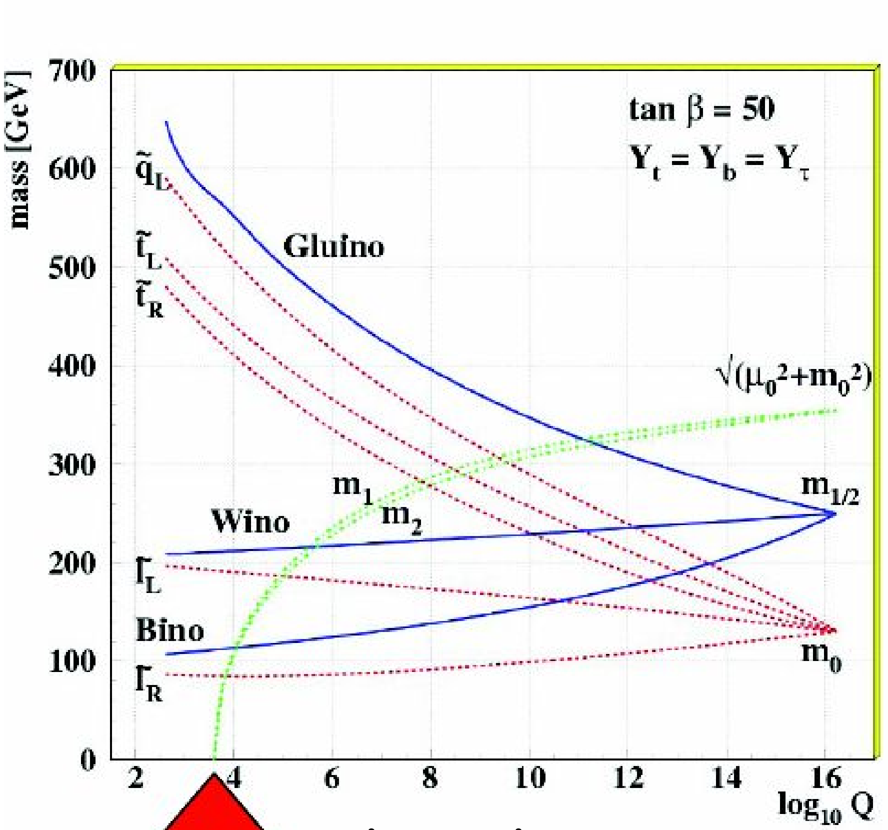

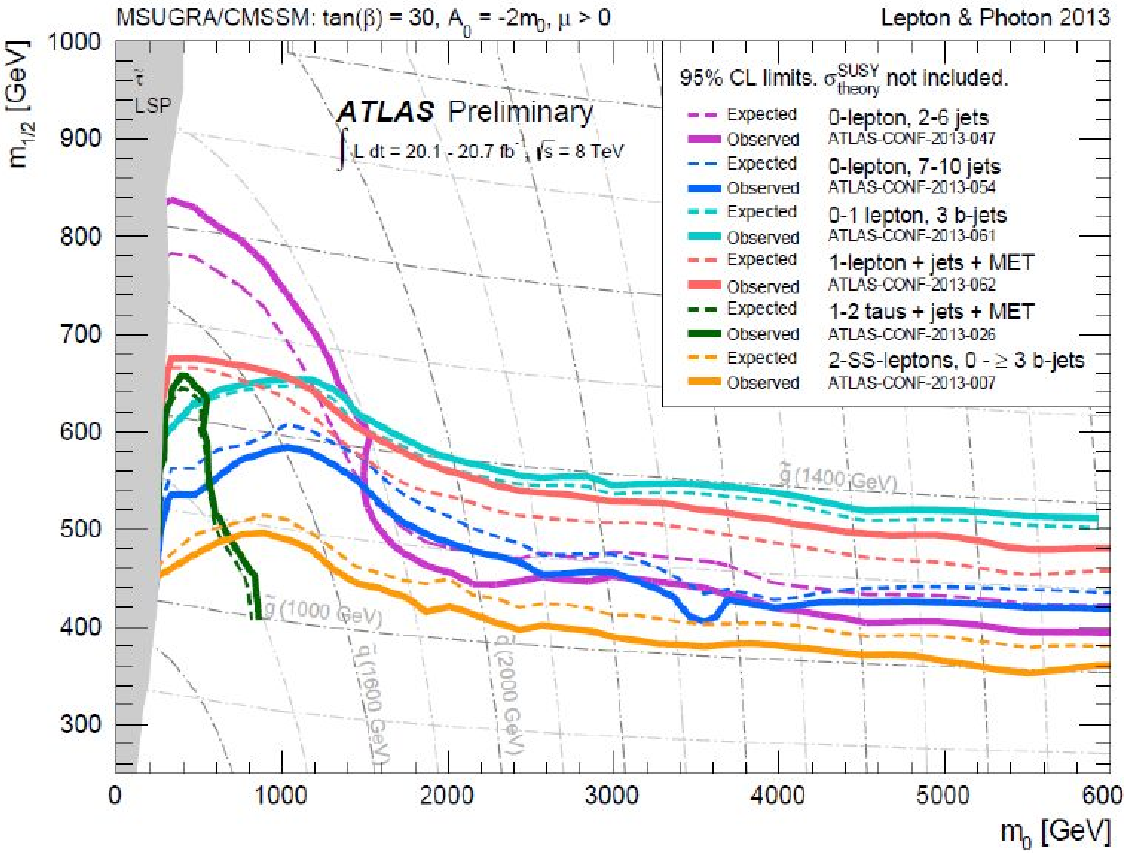

independent parameter

m0 – universal scalar mass

m1/2 – universal gaugino masses

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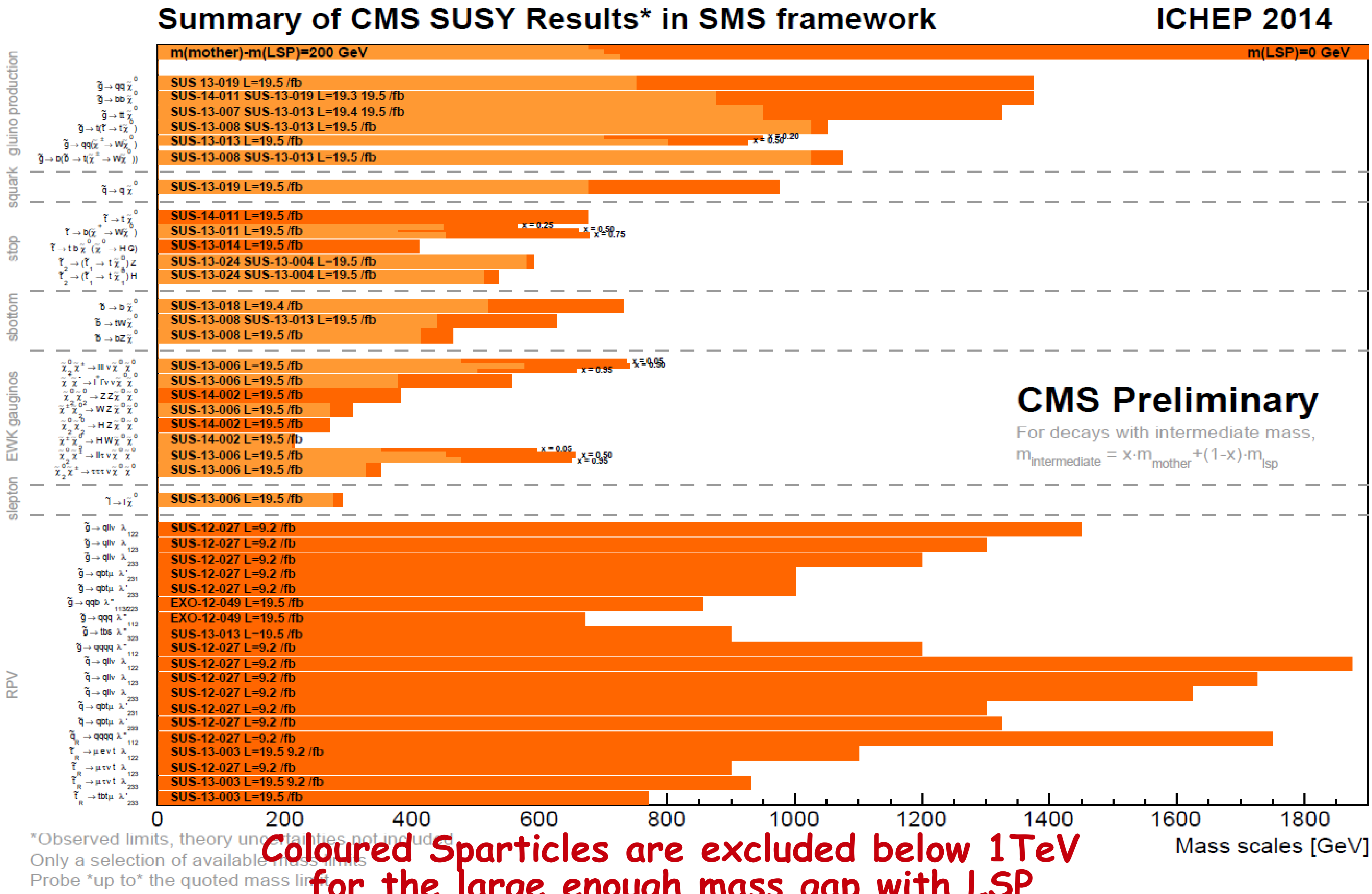
tan(beta) - v1/v2

jets + missing transverse momentum signature

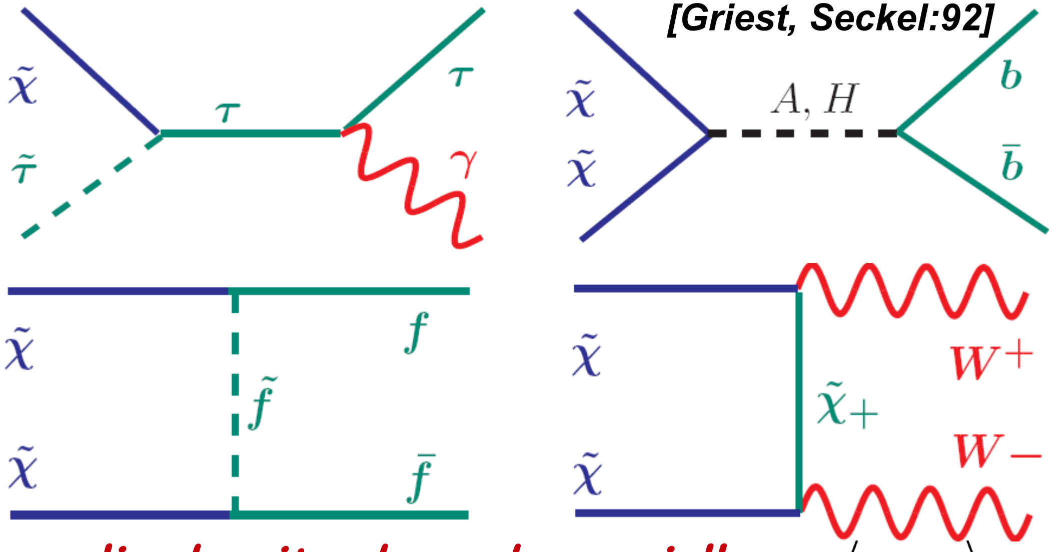
SUSY, where are you?!



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

Evolution of neutralino relic density

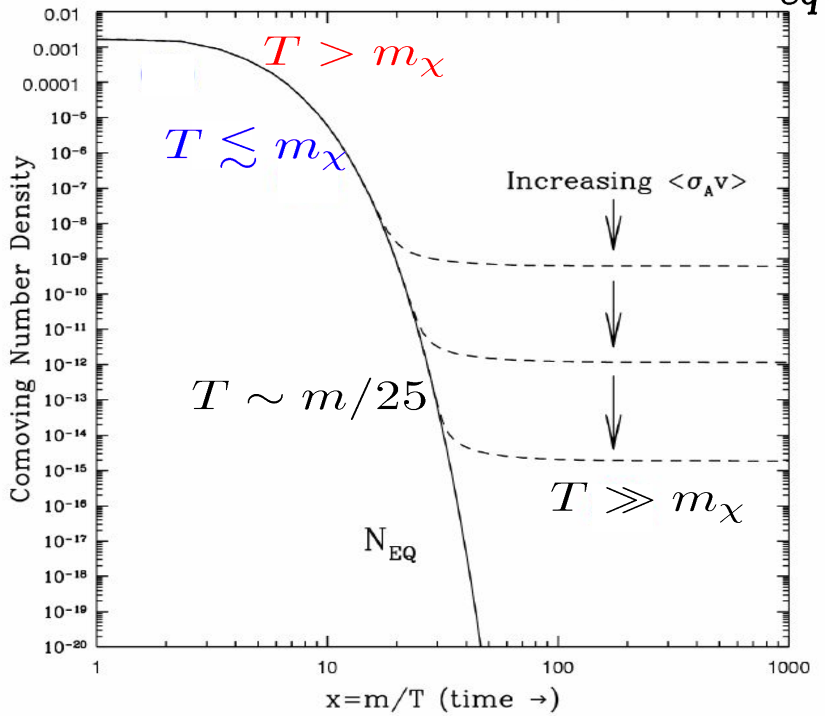
- ***Challenge is to evaluate thousands annihilation/co-annihilation diagrams***



[Griest, Seckel:92]

time evolution of number density is given by Boltzmann equation

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



- ***relic density depends crucially on*** $\langle\sigma_A v\rangle$
- ***thermal equilibrium stage:*** $T > m_\chi, \quad \chi\chi \leftrightarrow f\bar f$
- ***universe cools:***

  $n = n_{eq} \sim e^{-m/T}$ $\qquad T \lesssim m_\chi, \quad \chi\chi \not\leftrightarrow f\bar f$
- ***neutralinos "freeze-out" at*** $T_F \sim m/25$

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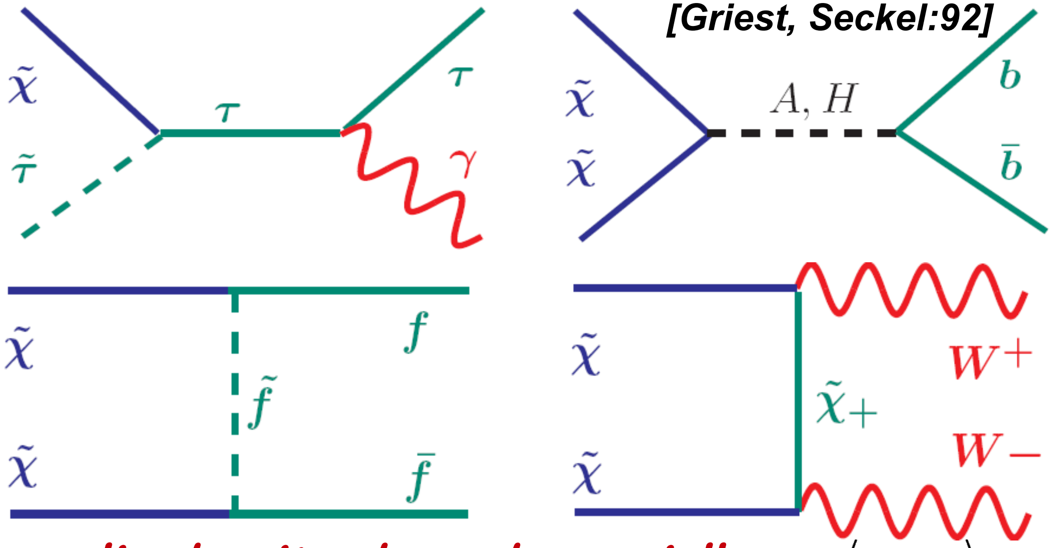

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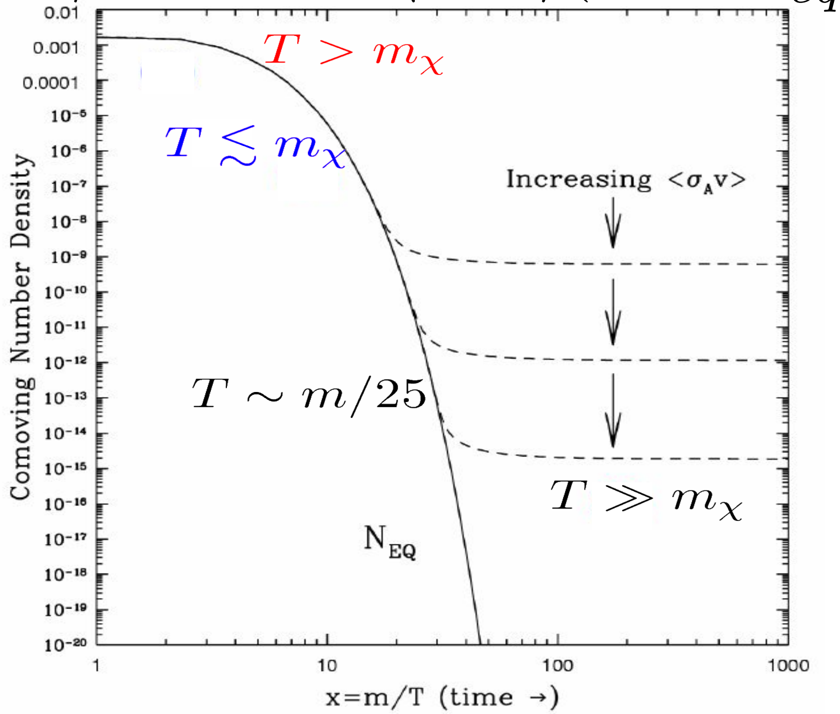

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  n = n

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

$$\langle\sigma_A v\rangle = 1\mathrm{pb}$$

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

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

mass of the mediator

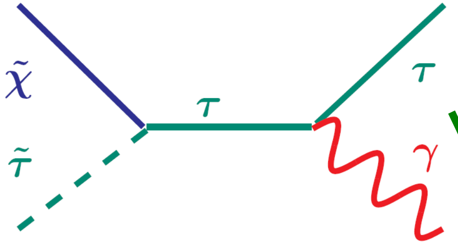
Packages:
MicrOMEGAs(Pukhov et al), DarkSusy, ISARED

Neutralino relic density in mSUGRA

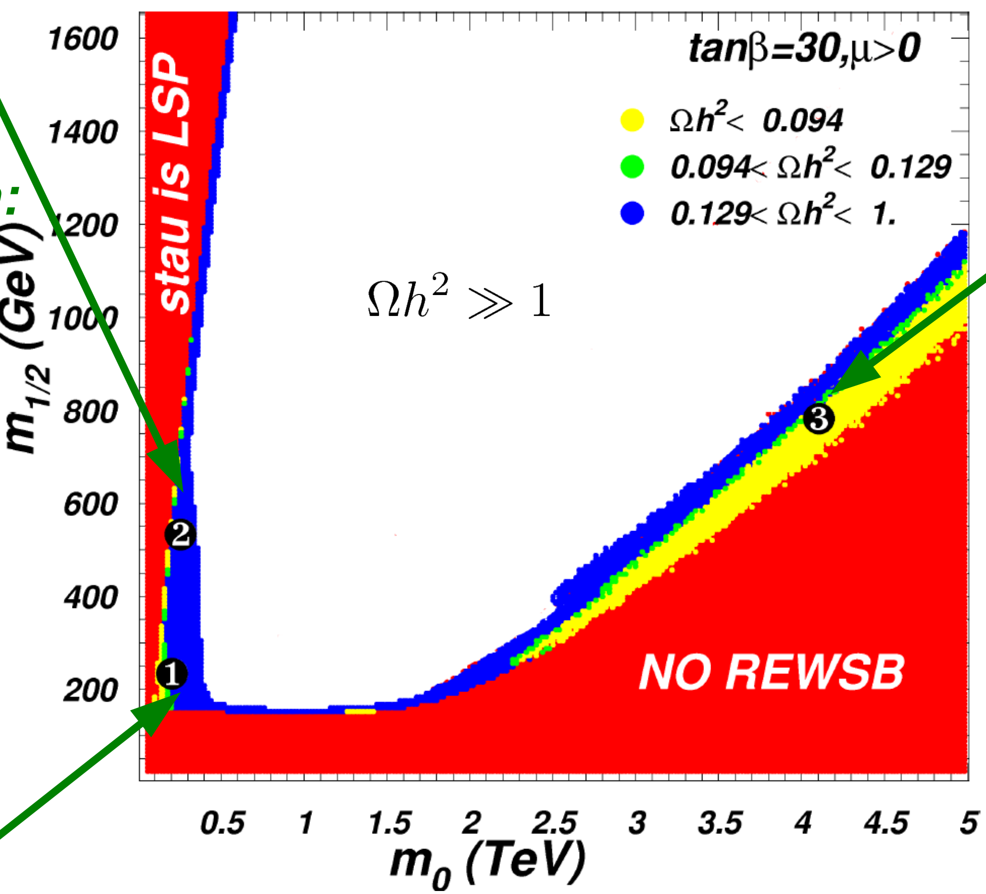
most of the parameter space is ruled out! $\Omega h^2 \gg 1$

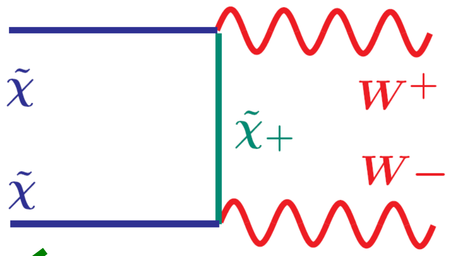
special regions with high σ_A are required to get $0.094 < \Omega h^2 < 0.129$

Baer, A.B., Balazs '02



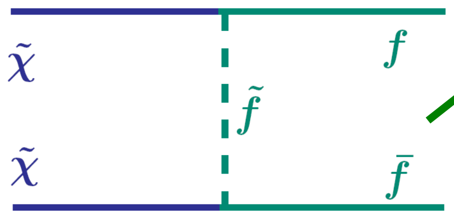
2. stau coannihilation:
degenerate χ and stau





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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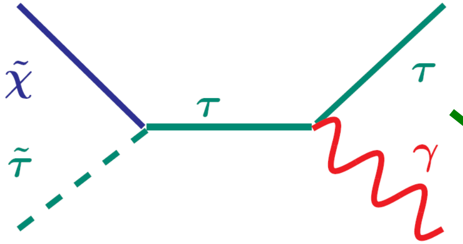

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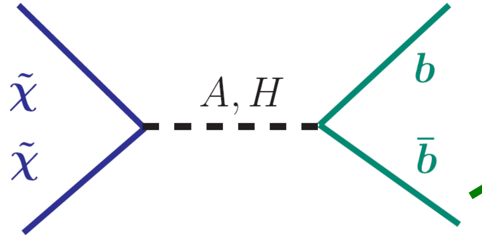
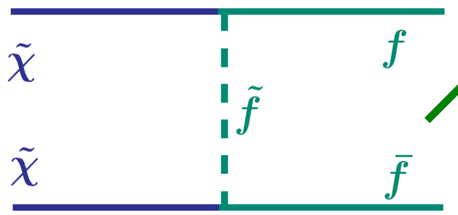
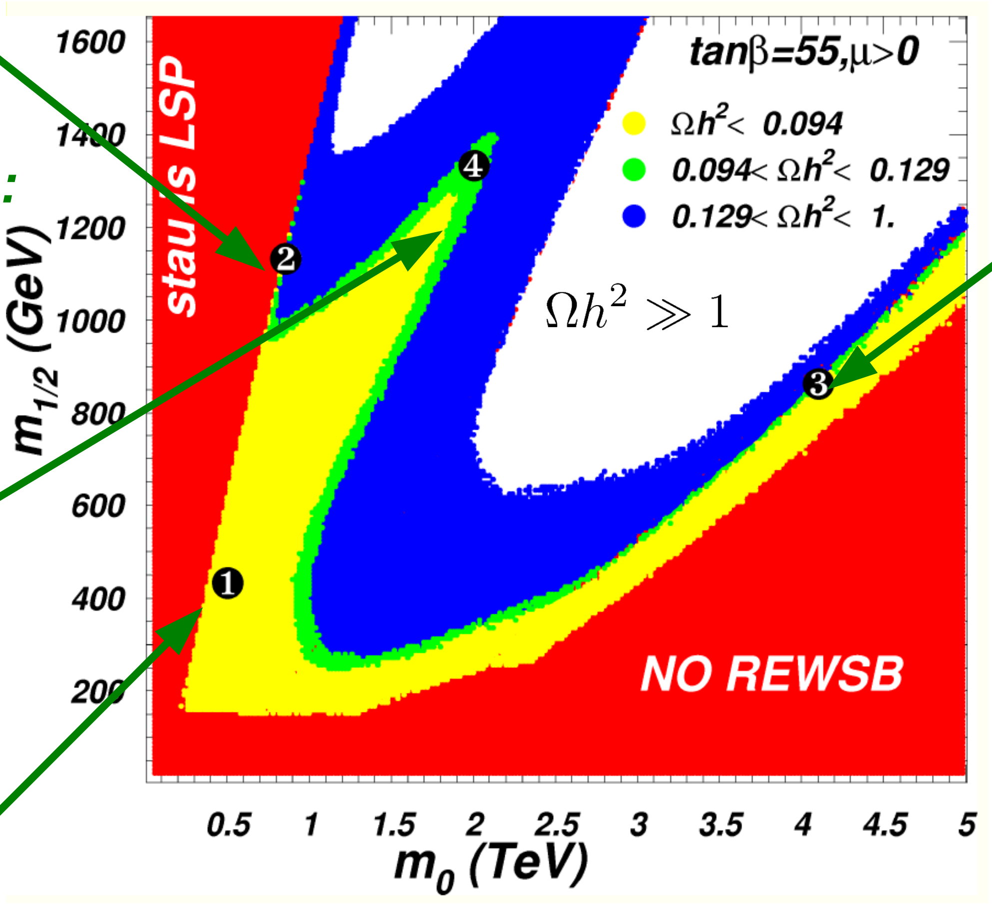


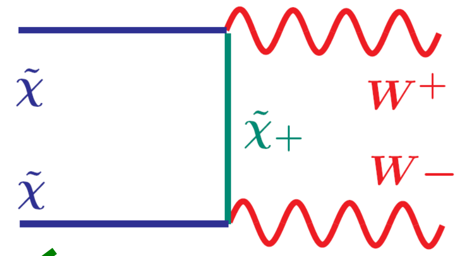
4. funnel: *(large tanβ)*
annihilation via A, H



Baer, A.B., Balazs '02



1. bulk region: **light sfermions**



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additional regions:
Z/h annihilation
stop coannihilation

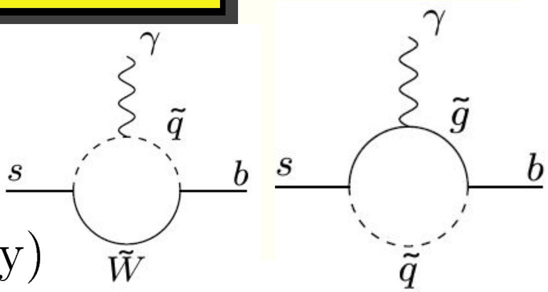
$b \to s\gamma$, $(g-2)_\mu/2$, $B_S \to \mu^+\mu^-$ constraints

- ◆ $b \to s\gamma$: $BF(b \to s\gamma) = (3.55 \pm 0.26) \times 10^{-4}$ *[BELLE,CLEO and ALEPH]*

Theory: $(3.15 \pm 0.23) \times 10^{-4}$ ***Misiak,Steinhauser '06***

$$2.85 \times 10^{-4} \leq Br(b \to s\gamma) \leq 4.24 \times 10^{-4} \text{ (95\% CL incl 10\% theory)}$$

no significant deviation from SM $\Longrightarrow$ $m_{\tilde{t}_{1,2}}, m_{\tilde{W}_{1,2}}, m_{H^+}$ *should be heavy!*



$\mathcal{BR}(b \to s\gamma)|_{\chi^\pm} \propto \mu A_t \tan\beta$

- ◆ $(g-2)_\mu/2$ *results*

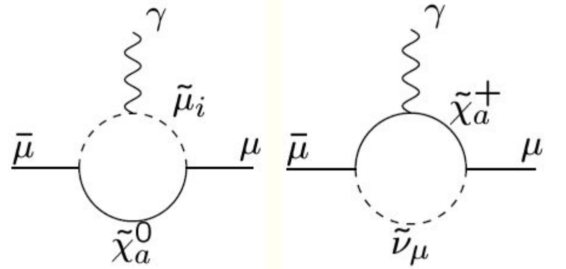
$(g-2)_\mu/2 =$ *11659 208(6) [g-2 collaboration]* **experiment**

$\Delta a_\mu = (27.1 \pm 9.4) \times 10^{-10}$ (Davier *et al.*)

$\Delta a_\mu = (31.7 \pm 9.5) \times 10^{-10}$ (Hagiwara *et al.*)

Theory based on e⁺e⁻ data

(τ decay data $\Delta a_\mu = (12.4 \pm 8.3) \times 10^{-10}$ (Davier et al.))



$$\approx \frac{\alpha}{\pi\, 8 s_W^2} \tan\beta \,\mathrm{sign}(\mu) \frac{m_\mu^2}{M_{\rm SUSY}^2}$$

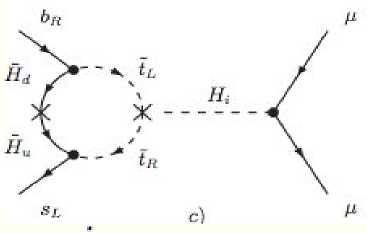
There are growing consensus that e^+e^- data are more to be trusted since they offer a direct determination of the hadronic vacuum polarization

$\sim 3\sigma \Longrightarrow$ *second generation of slepton are relatively light!*

- ◆ $BF(B_s \to \mu^+\mu^-) < 1.0 \times 10^{-7}$ *(CDF), (SM: 3.4×10^{-9})*

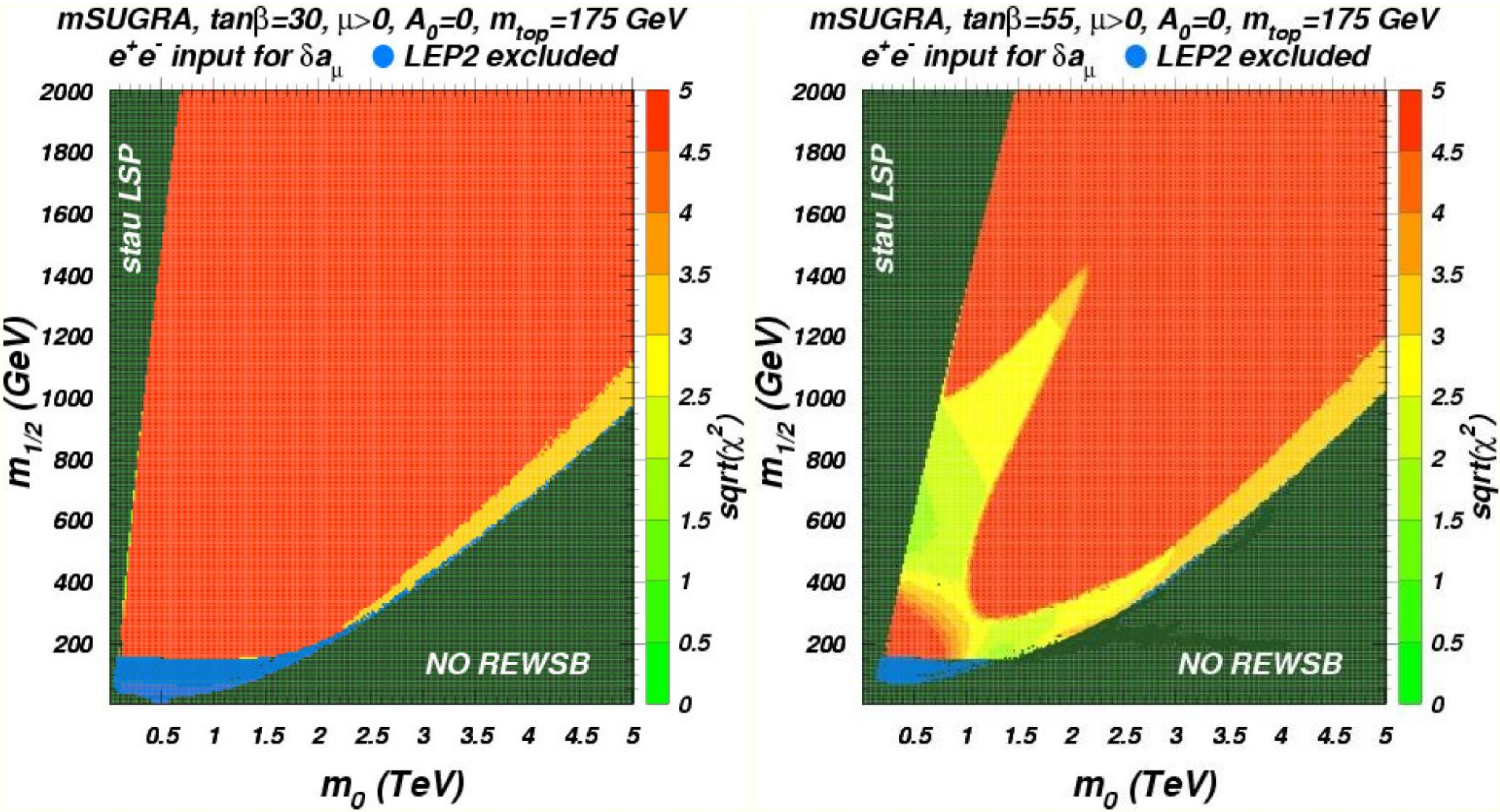
amplitude for H-mediated decay grows as $\tan\beta^3$ (!) $\Rightarrow$ relevant to high $\tan\beta$ scenario

[Babu,Kolda; Dedes,Dreiner,Nierste; Arnowitt,Dutta,Tanaka; Mizukoshi,Tata,Wang]



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.

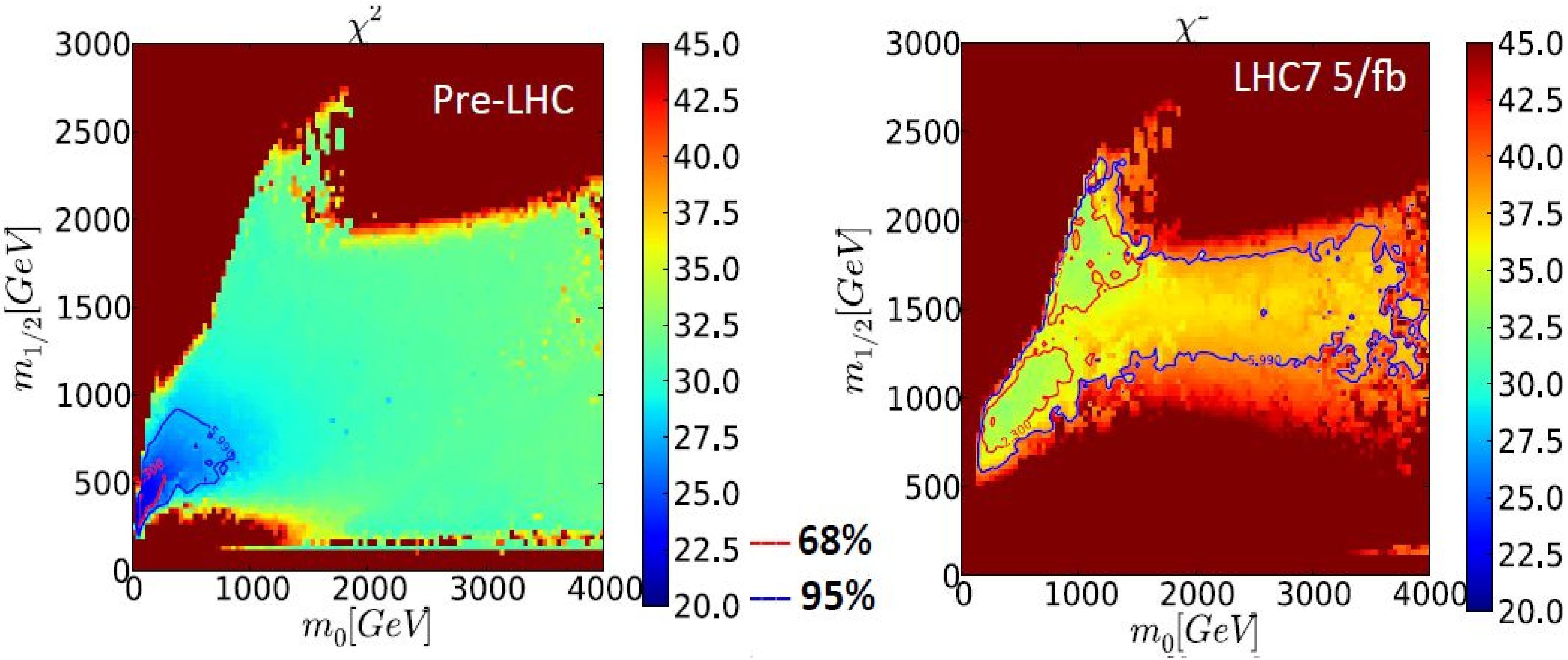


Baer, A.B., Krupovnickas, Mustafayev hep-ph/0403214

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

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

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

$$\frac{m_Z^2}{2} = \frac{(m^2_{H_d} + \Sigma^d_d) - (m^2_{H_u} + \Sigma^u_u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2 \simeq -m^2_{H_u} - \mu^2$$

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

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

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

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

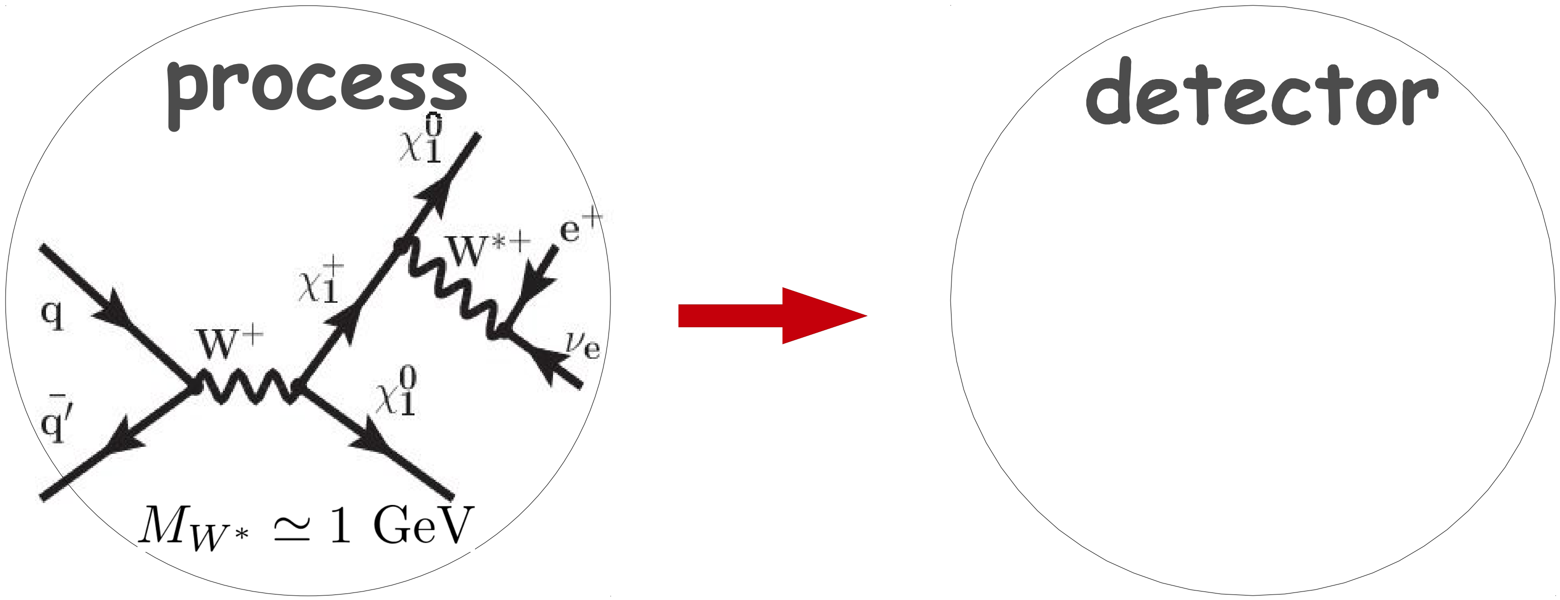
neutralinos

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

- 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, indicating that a weak scale SUSY spectrum is likely non-universal

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 as happen in FFP scenario.
- The only way to probe FFP 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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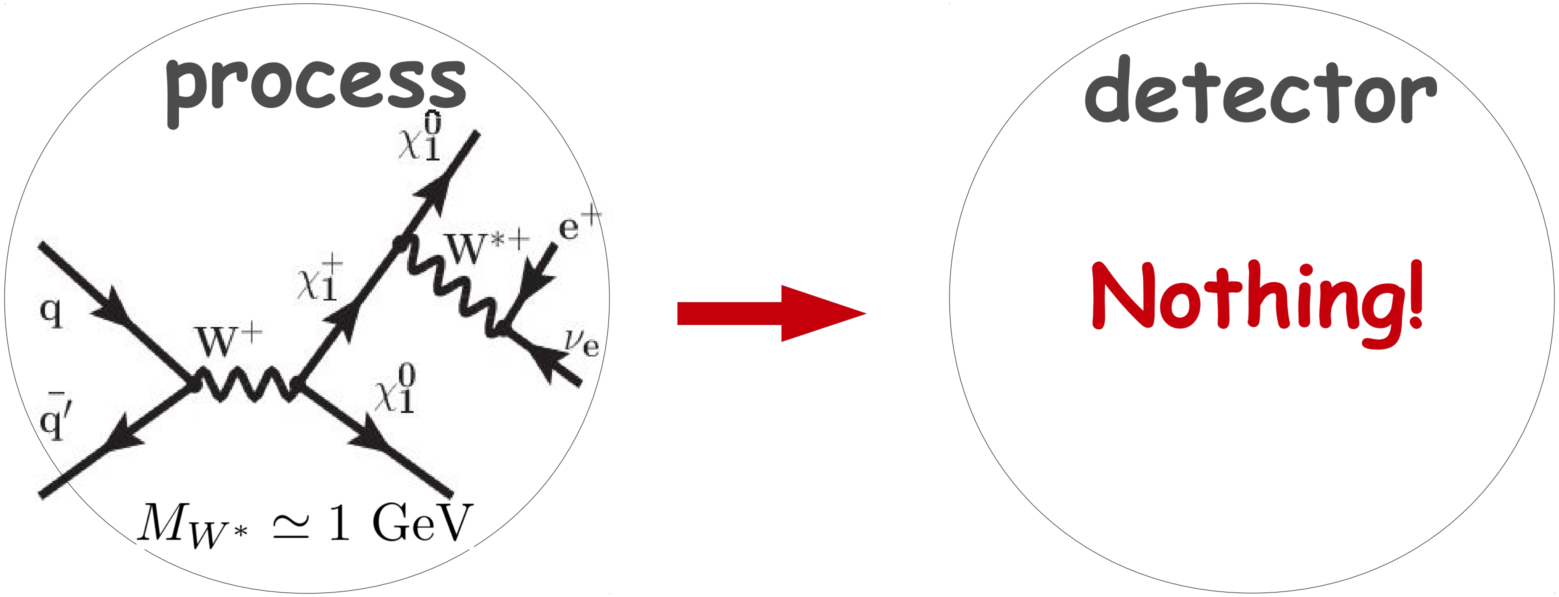

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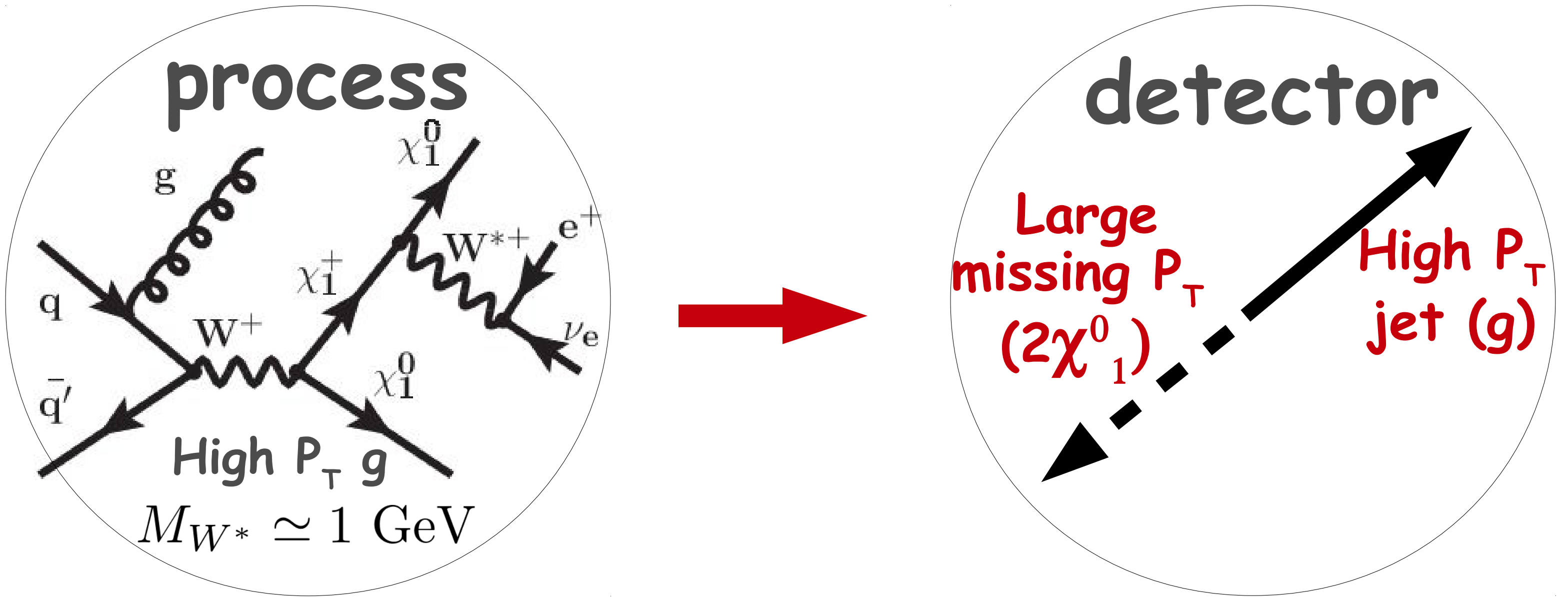

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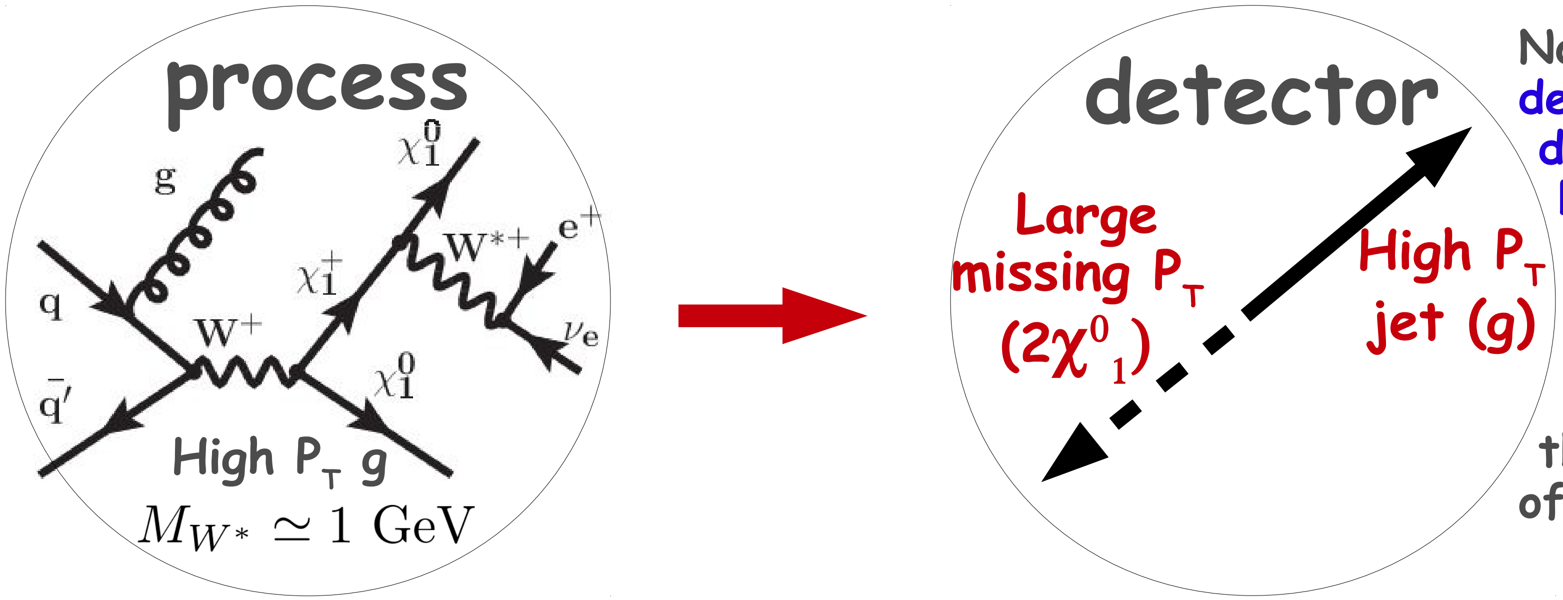


process

High P_T g

$M_{W^*} \simeq 1$ GeV

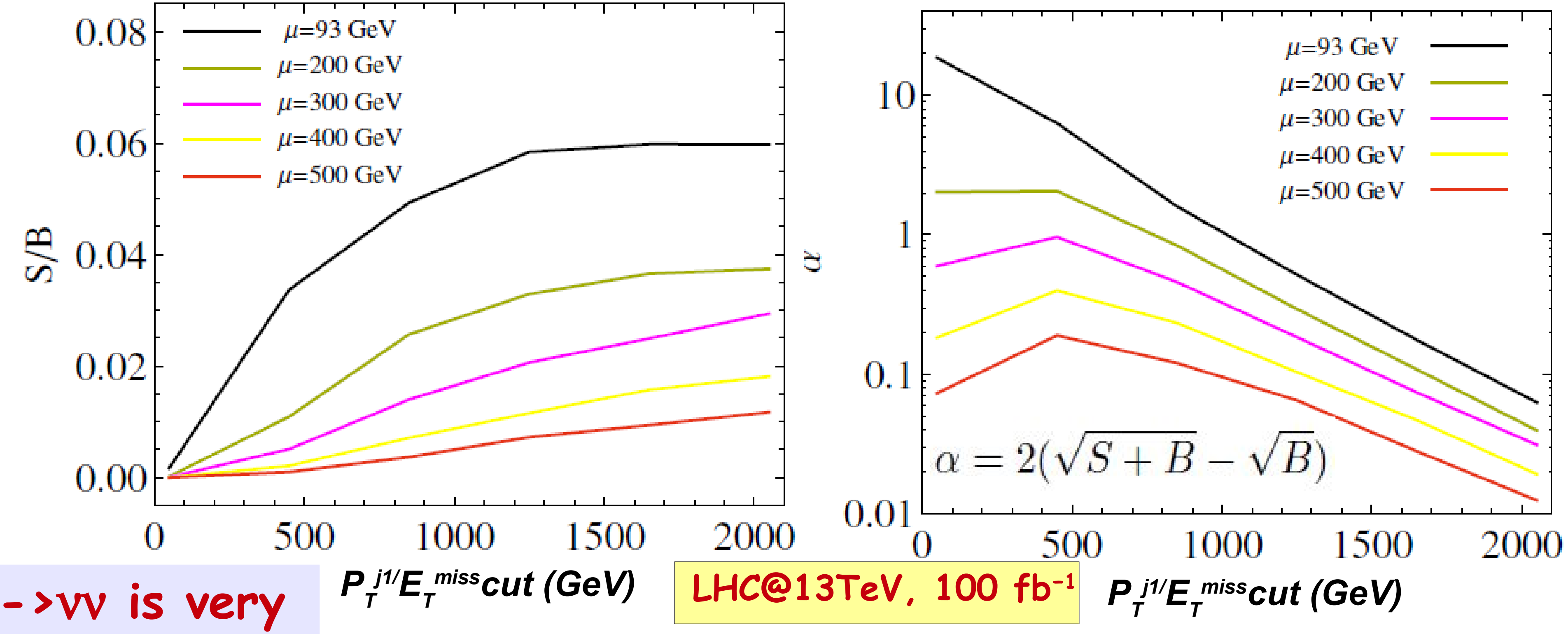
detector

Large missing P_T $(2\chi^0_1)$

High P_T jet (g)

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



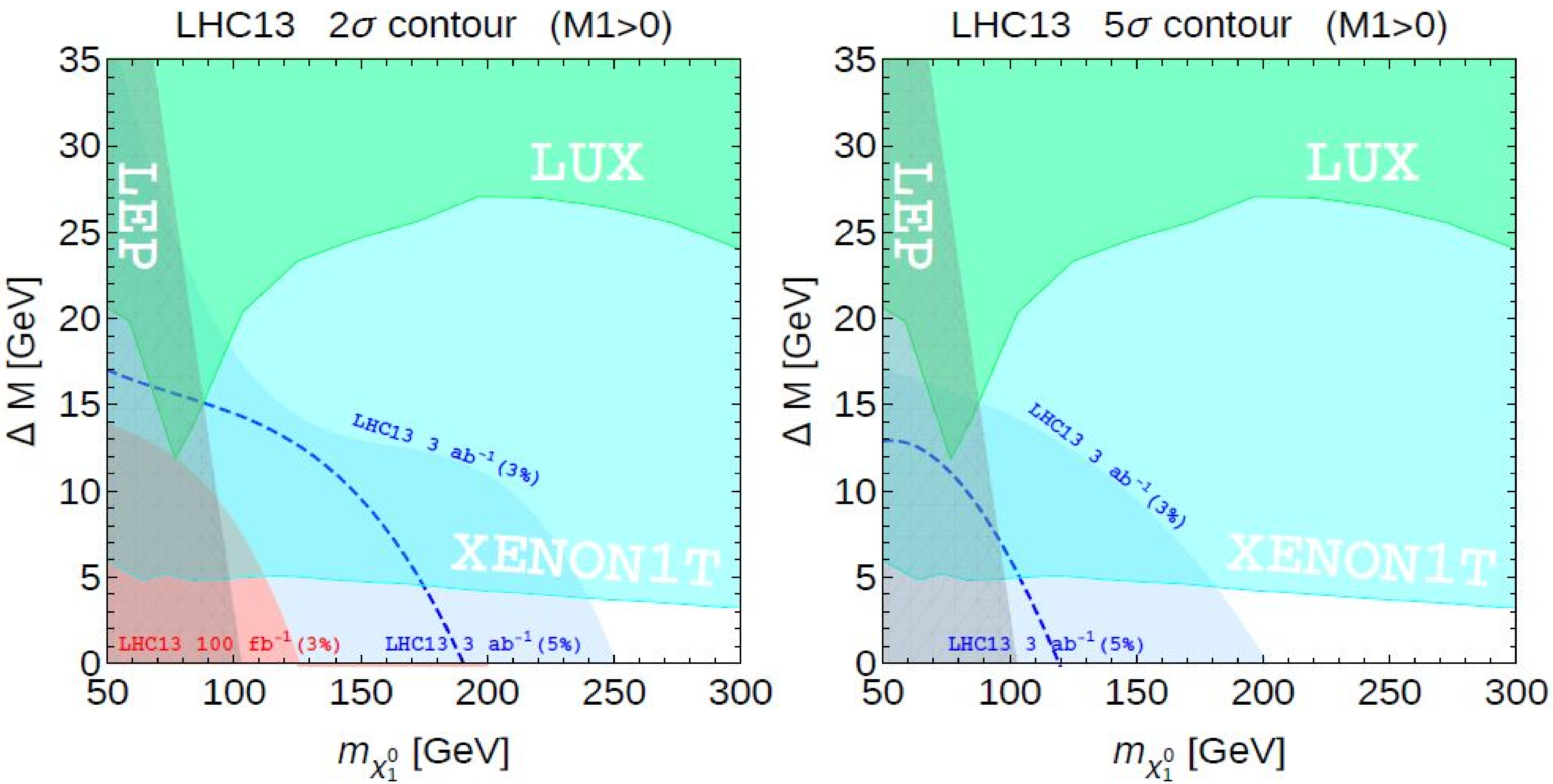
LHC@13TeV, 100 fb^{-1}

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!**

Your question:

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

Your question:

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

The Answer is:

NO!

SUSY can be either discovered or abandoned!