LOW-ENERGY SUPERSYMMETRY: REVIEW AND CURRENT STATUS

july 20, 2016
IFIN-HH

Outline

1) Motivations for low-energy Supersymmetry
- The hierarchy problem
- Dark Matter
- Unification of gauge couplings
- Cosmology, Supergravity and String Theory

2) Supersymmetry breaking: scales and models

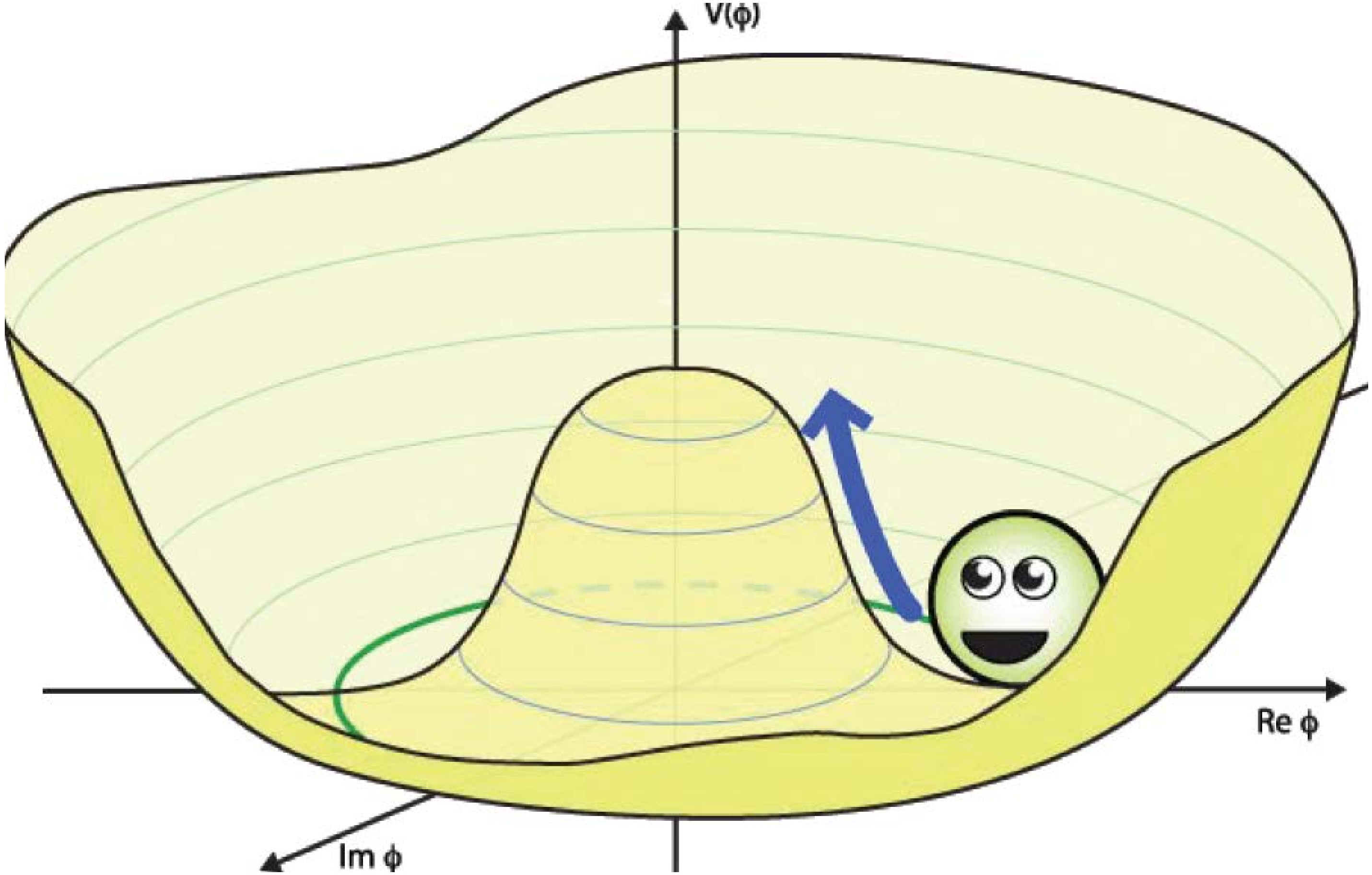
3) The supersymmetric flavor problem
- Flavor and inverted hierarchy/natural SUSY in MSSM

4) Expectations and experimental constraints
- SUSY constraints from LHC searches and Higgs mass

5) Perspectives

1) Motivations low-energy supersymmetry

- In july 2012, LHC discovered the last missing brick of the Standard Model, the Higgs boson.



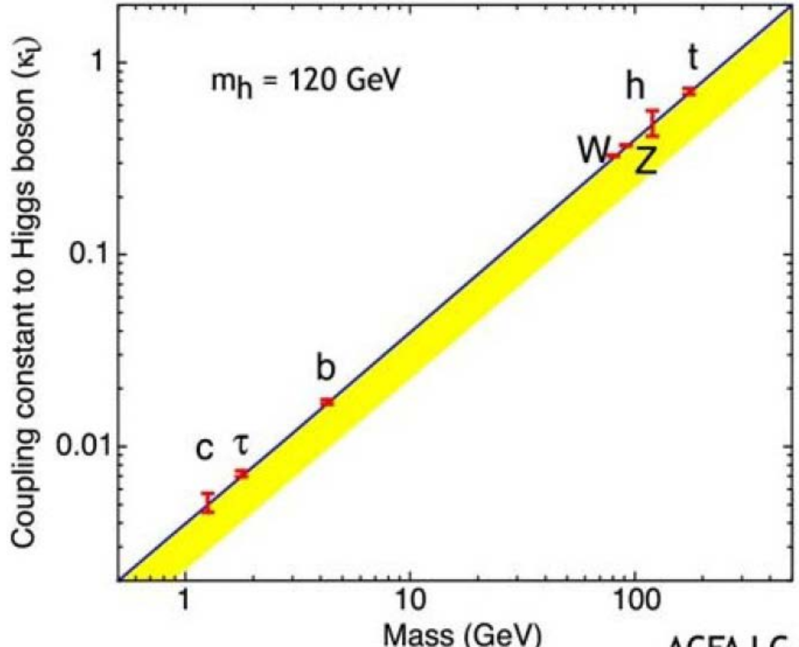
- It seems to be a scalar of mass close to 125 GeV.

There are many important questions:

- do the couplings to Standard Model (SM) particles exactly match that of the minimal SM one with a Higgs doublet ?

$$\mathcal{L}_{\rm ren} = -c_t\frac{m_t}{v}h\,t\,\bar{t} - c_c\frac{m_c}{v}h\,c\,\bar{c} - c_b\frac{m_b}{v}h\,b\,\bar{b} - c_\tau\frac{m_\tau}{v}h\,\tau\,\bar{\tau} + c_Z\frac{m_Z^2}{v}h\,Z^\mu\,Z_\mu + c_W\frac{2m_W^2}{v}h\,W^{+\mu}\,W_\mu^- \,.$$

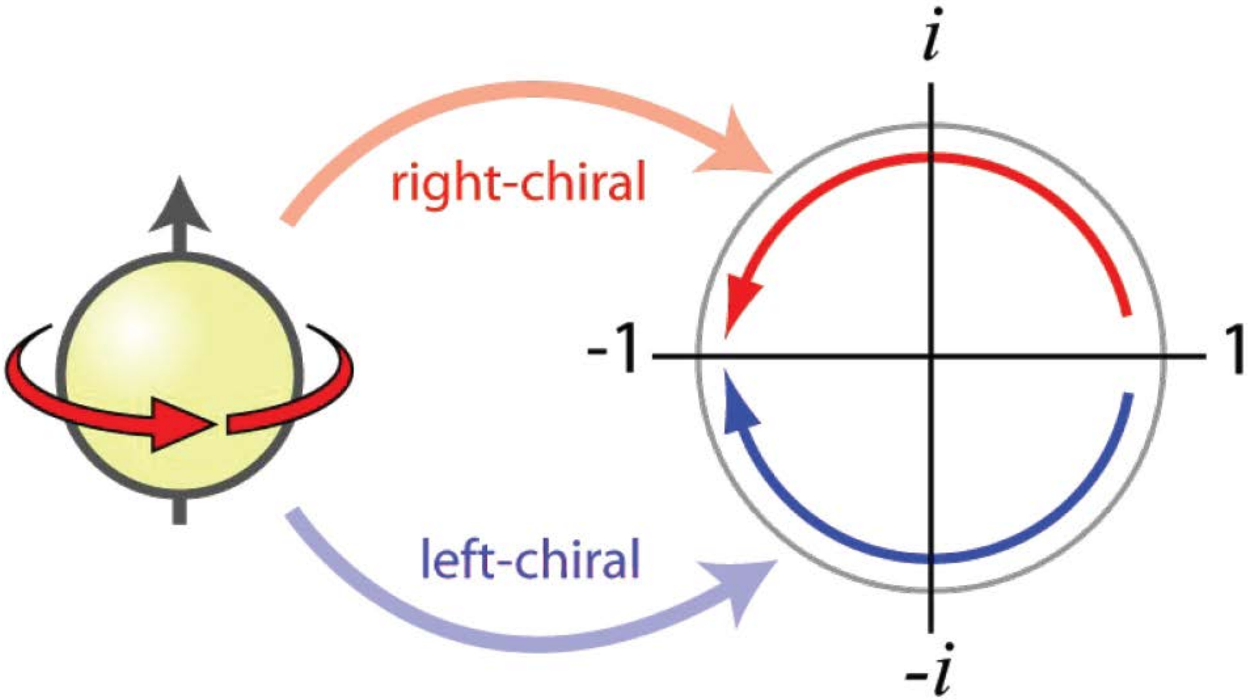
- c= 1 at tree-level in the SM



ACFA LC study

- There are light elementary fermions in nature, protected by chiral symmetries $\psi_R \to e^{i\alpha}\psi_R\ ,\ \psi_L \to e^{-i\alpha}\psi_L$

Ex: In QED $$\delta m_e = \frac{3\alpha}{4\pi} m_e \ln \frac{\Lambda^2}{m_e^2}$$



- Before Higgs boson discovery the only known light scalars were fermionic bound states (mesons).
- QUESTION : Is it the first fundamental scalar in nature ?

- Are fundamental scalars required by fundamental symmetries or principles ?

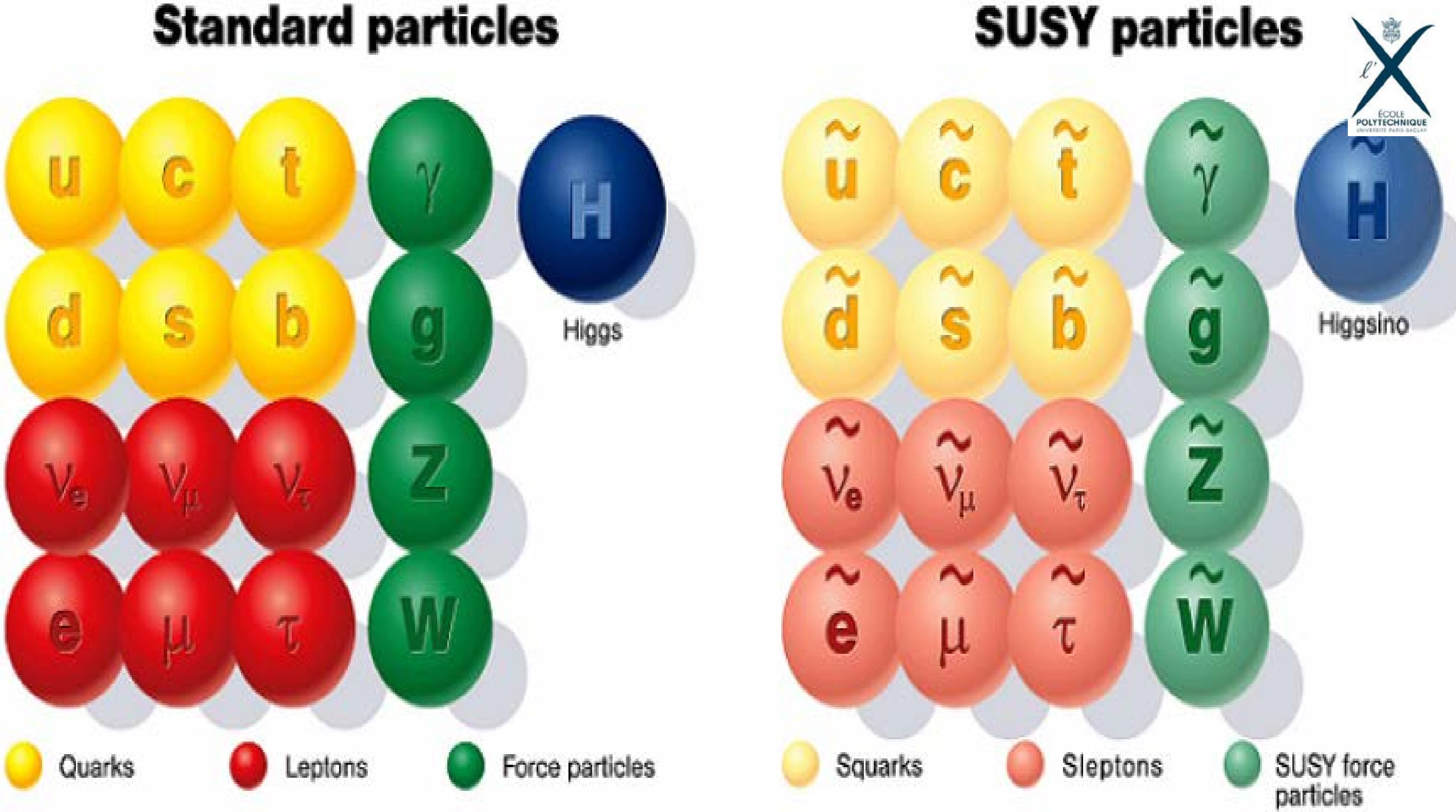
YES, SUPERSYMMETRY

Fermions ⟺ Bosons

Unbroken SUSY ⟹ $m_F = m_B$

Broken SUSY, TeV splittings = Low-energy SUSY

$$\mathcal{L} = \mathcal{L}_{SUSY} + \mathcal{L}_{soft}$$



'Soft' terms: scalar (squarks,sleptons,higgs masses) $m_0^2|\tilde{q}|^2$

gaugino (λ) masses $M_{1/2}\lambda\lambda$

A-terms $A_u\tilde{q}\tilde{u}h_2$

B-term Higgs sector $B_\mu h_1 h_2$

Standard Model | MSSM

Higgs doublet

$$h$$

v.e.v. $v = 246\ GeV$

$$V(h) = -\mu^2 |h^2| + \frac{\lambda}{2} |h|^4$$

Two Higgs doublets

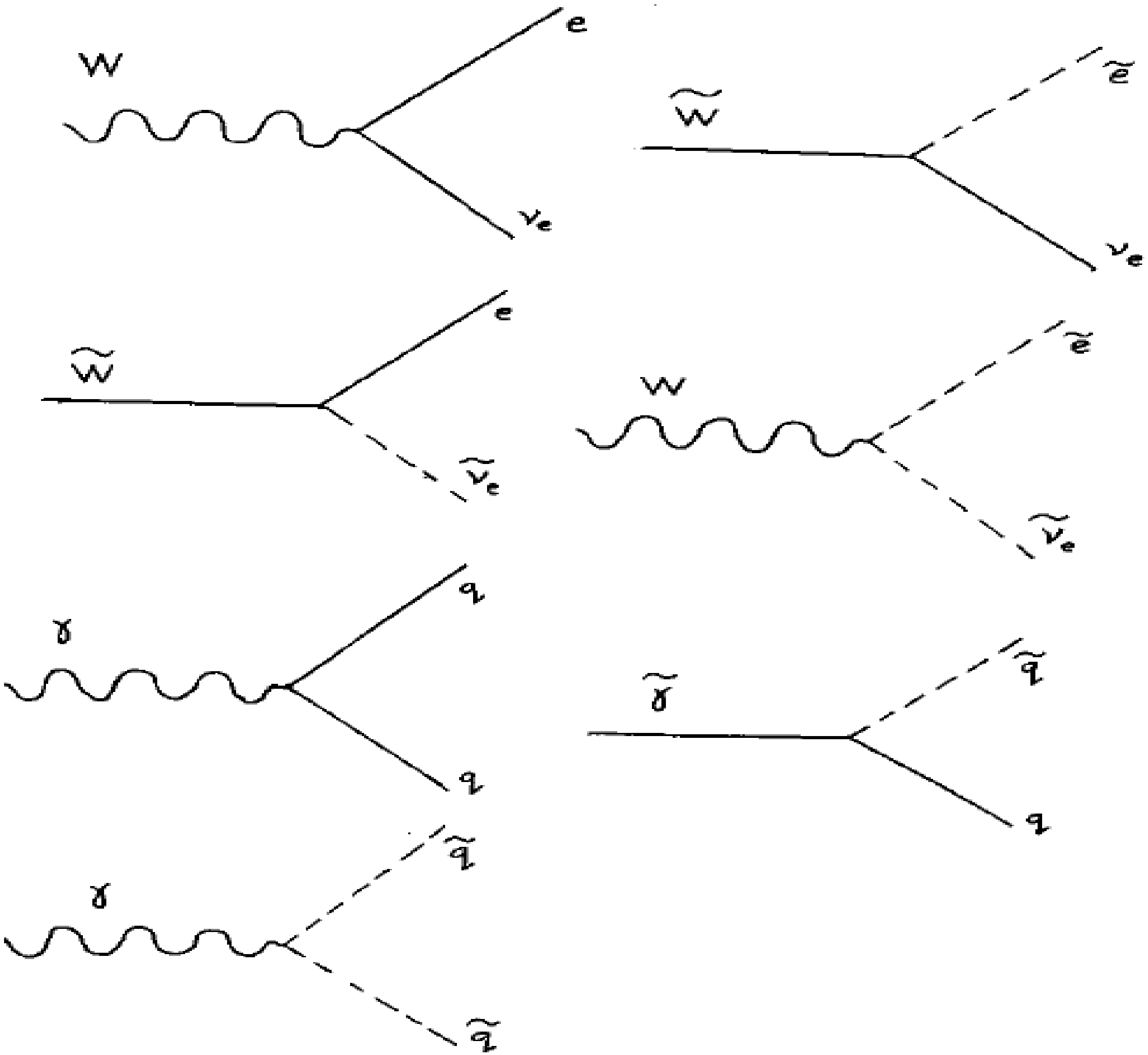
$$h_1, h_2$$

vev's v_1, v_2

$$v_1^2 + v_2^2 = v^2, \qquad \tan\beta = \frac{v_2}{v_1}$$

$$V(h_i) = V_{mass} + \frac{g_1^2 + g_2^2}{8} (|h_1|^2 - |h_2|^2)^2$$

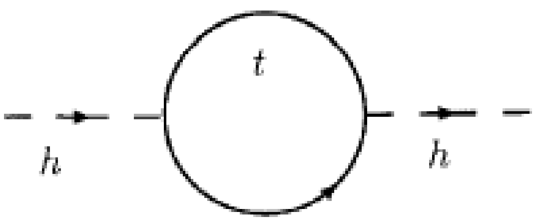
SUSY interactions



Low-energy Supersymmetry naturally adresses some of the mysteries of the SM:

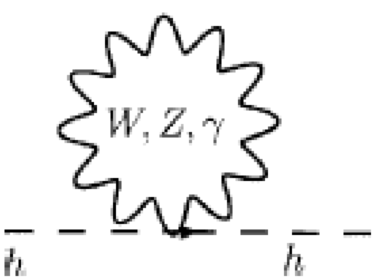
a) The **hierarchy problem** (mis?)guided BSM physics for the last 30 years. Quantum corrections to the Higgs mass in The SM are UV sensitive

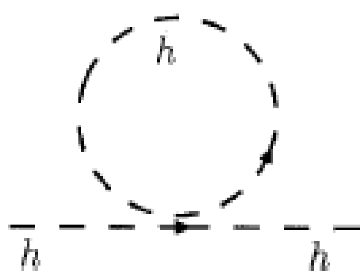
$$\delta m_h^2 \simeq \frac{3\Lambda^2}{8\pi^2 v^2}(4m_t^2 - 4M_W^2 - 2M_Z^2 - m_h^2)$$



$$\Lambda = 10^{16}\ GeV$$

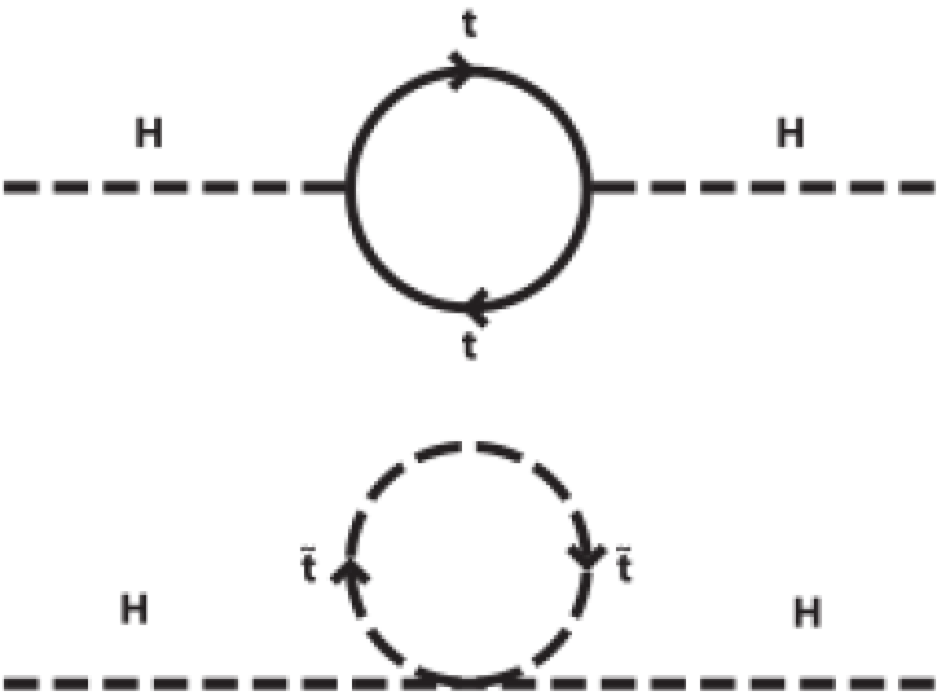
$$\delta m_h^2 \sim 10^{32} m_h^2$$





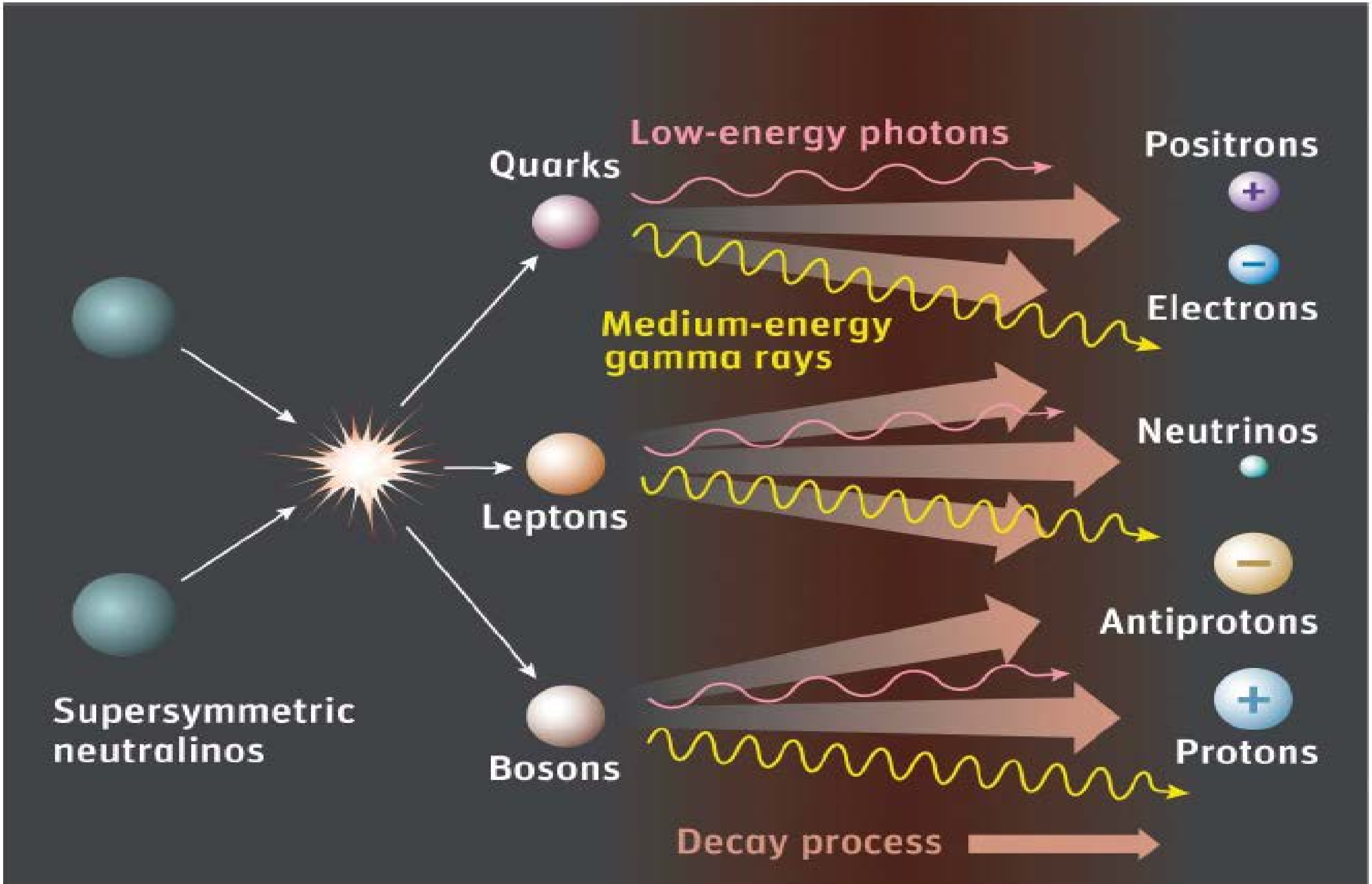
In SUSY models, cancelation between fermionic and bosonic loops removes the UV sensitivity

$$\text{SM} \ : \ \Delta M_h^2 \sim \frac{\Lambda^2}{16\pi^2} \ , \ \text{MSSM} \ : \ \Delta M_h^2 \sim \frac{m_t^2}{16\pi^2} \ \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

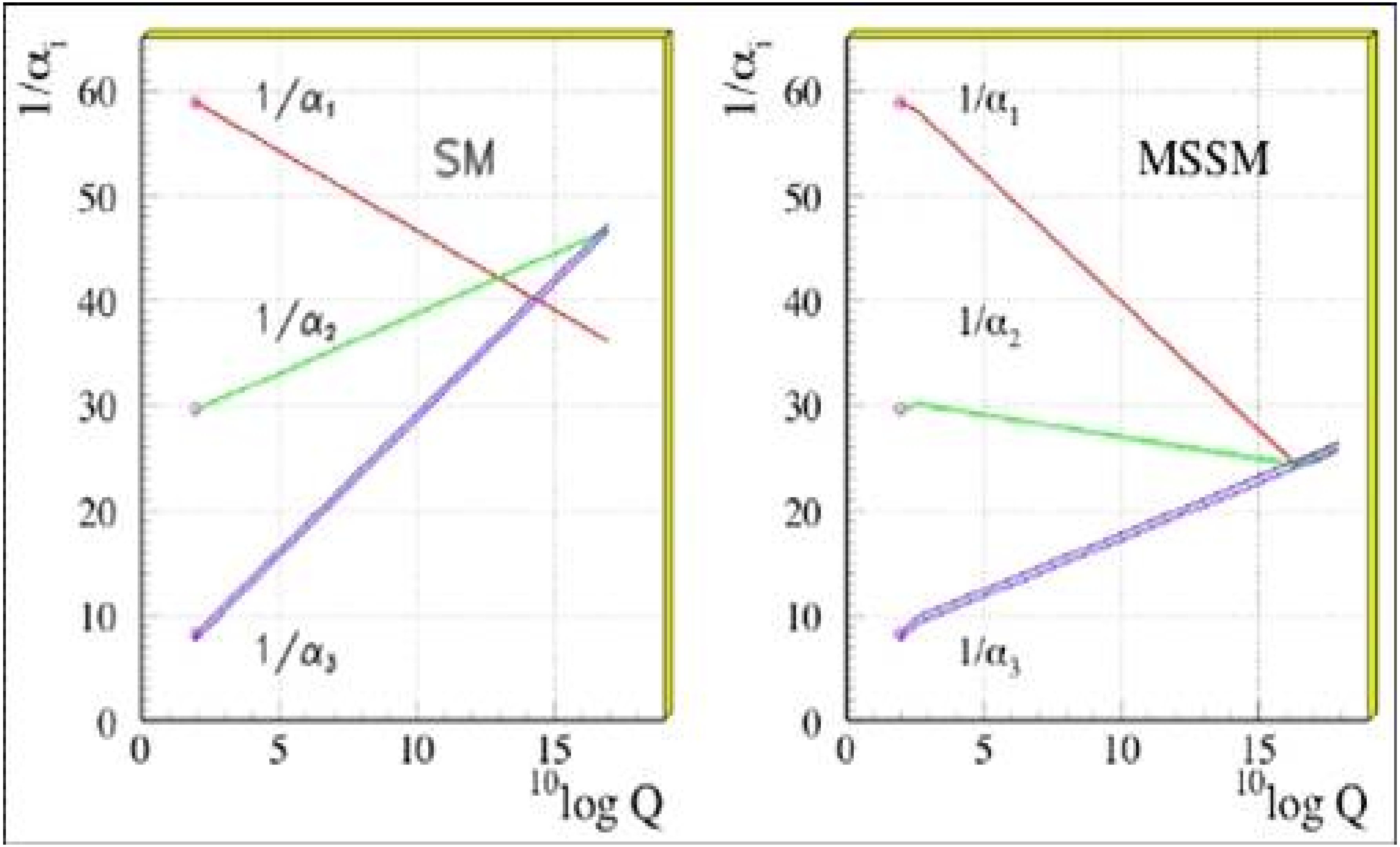


b) The missing Dark Matter Candidate: LSP (Ligthest Supersymmetric Particle=WIMP), protected by R-parity ?

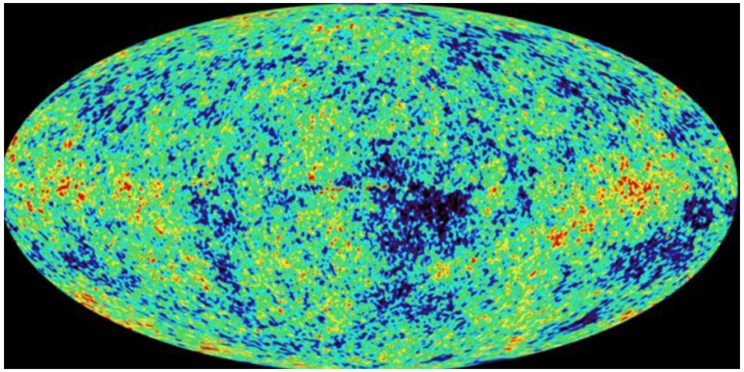
(Fayet), R=1 (SM particles), R = -1 (superpartners)



c) Gauge coupling unification (Dimopoulos,Raby,Wilczek) around $2 \times 10^{16}\ GeV$ very close to the energy scale during inflation. Coincidence ???



d) Cosmology, Supergravity and String Theory



- Local supersymmetry implies Einstein gravity

- Inflation with super-Planckian field variations need an UV description → String Theory

- Supersymmetry crucial ingredient in String Theory

- SUSY-GUTS seem a right framework for inflation.

I think that low-energy SUSY is the only known framework naturally incorporating a),b) , c) + d) simultaneously.

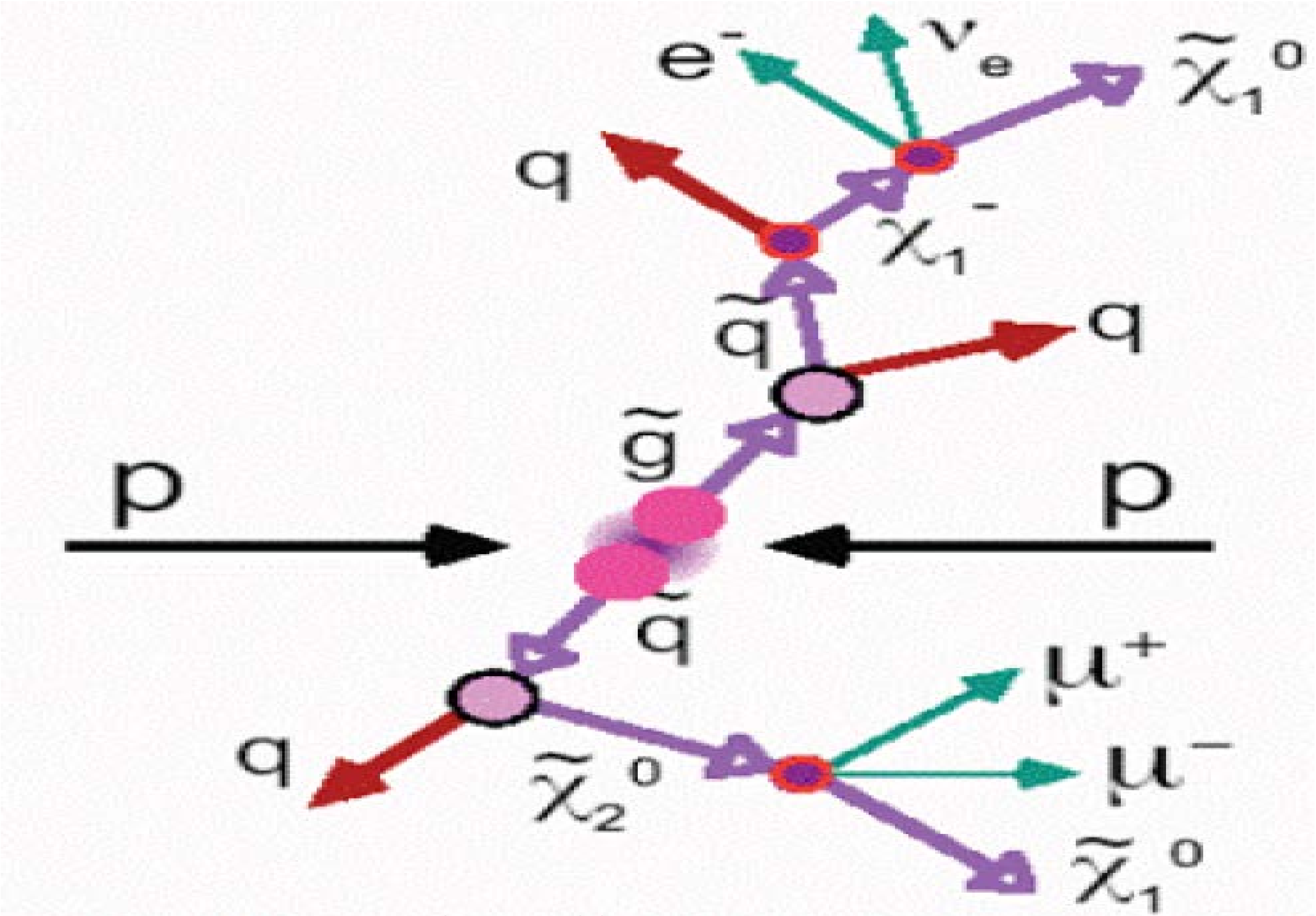
Typical low-energy SUSY (MSSM) predictions:

- Higgs mass < 130 GeV

- TeV-scale superpartners: squarks,sleptons,gluinos, higgsinos,neutralinos, 4 additional Higgs scalars.

However, at tree level $M_h < M_Z$ ⟹ need large radiative corrections : some superpartners may be heavy.

- Missing energy signatures (LPS's) from the LSP


e⁻
ν_e
$\tilde{\chi}_1{}^0$
q
$\chi_1{}^-$
$\tilde{q}$
q
$\tilde{g}$
p
p
$\tilde{q}$
μ^+
q
μ^-
$\tilde{\chi}_2{}^0$
$\tilde{\chi}_1{}^0$

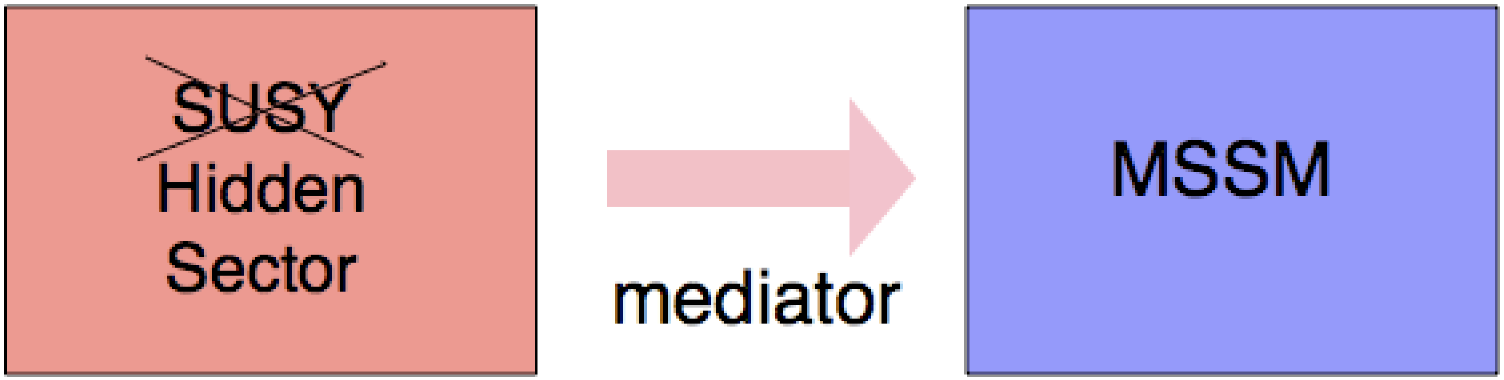
2) Transmission of supersymmetry breaking: mass scales and models

- Analogy

	electroweak symm. breaking	SUSY breaking
Order Parameter	M_W	$m_{3/2}$
Goldstone particles	$G^{\pm}, G^0$	G^{α} (goldstino)
Gauge fields	$W^{\pm}, Z$	Ψ_{μ}^{α} (gravitino)

Supersymmetry breaking is the key question:
its origin and transmission to Standard Model fields.

- Gravity mediation: Planck-suppressed interactions between the hidden and the observable sector generate soft terms of order $m_{3/2} \sim TeV$. Here $M_{SUSY} \sim 10^{11} GeV$



Simplest scenario: minimal Supergravity (mSUGRA) :

- all scalar masses equal $m_{\tilde{q}} = m_{\tilde{l}} = \cdots = m_0$
- all gaugino masses equal $m_{\lambda_3} = m_{\lambda_2} = m_{\lambda_1} = M_{1/2}$
- All trilinear terms equal A_0

- Potential flavor (FCNC) problems

- Gauge mediation

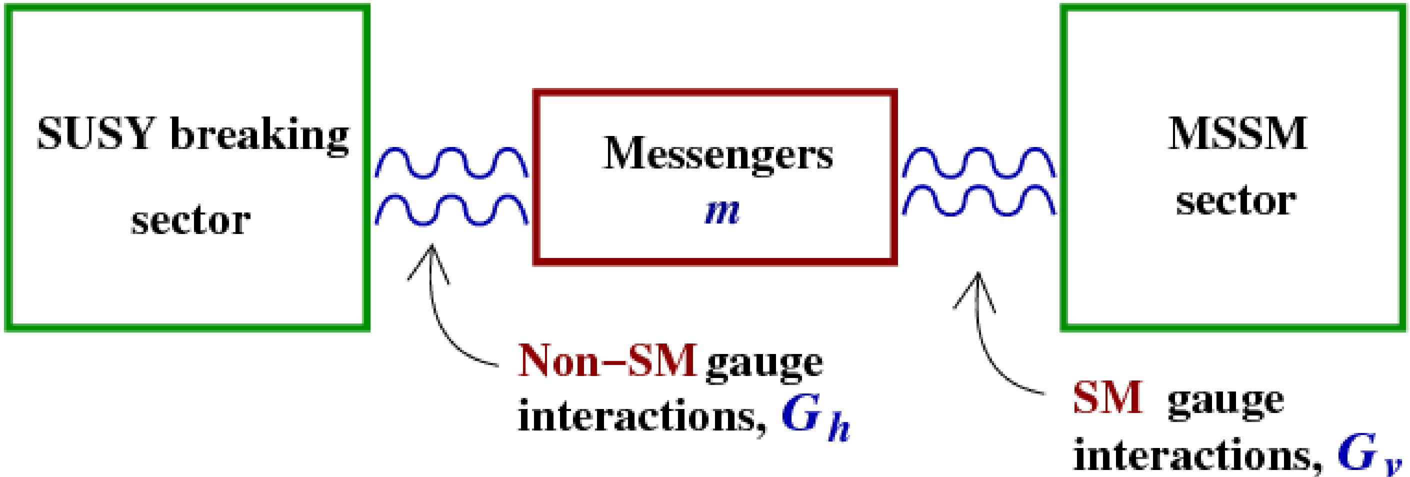
Transmission of SUSY breaking through SM gauge loops

= gauge mediation

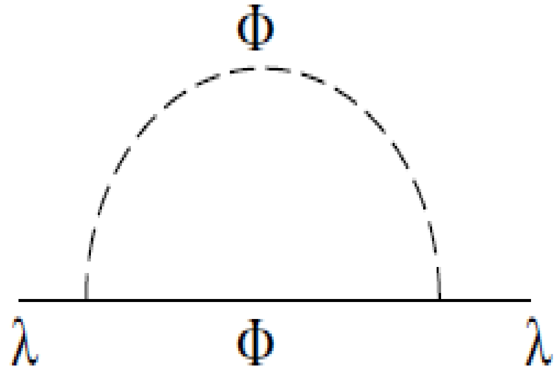
SUSY breaking sector $\leftrightarrow$ Messenger sector $\leftrightarrow$ MSSM

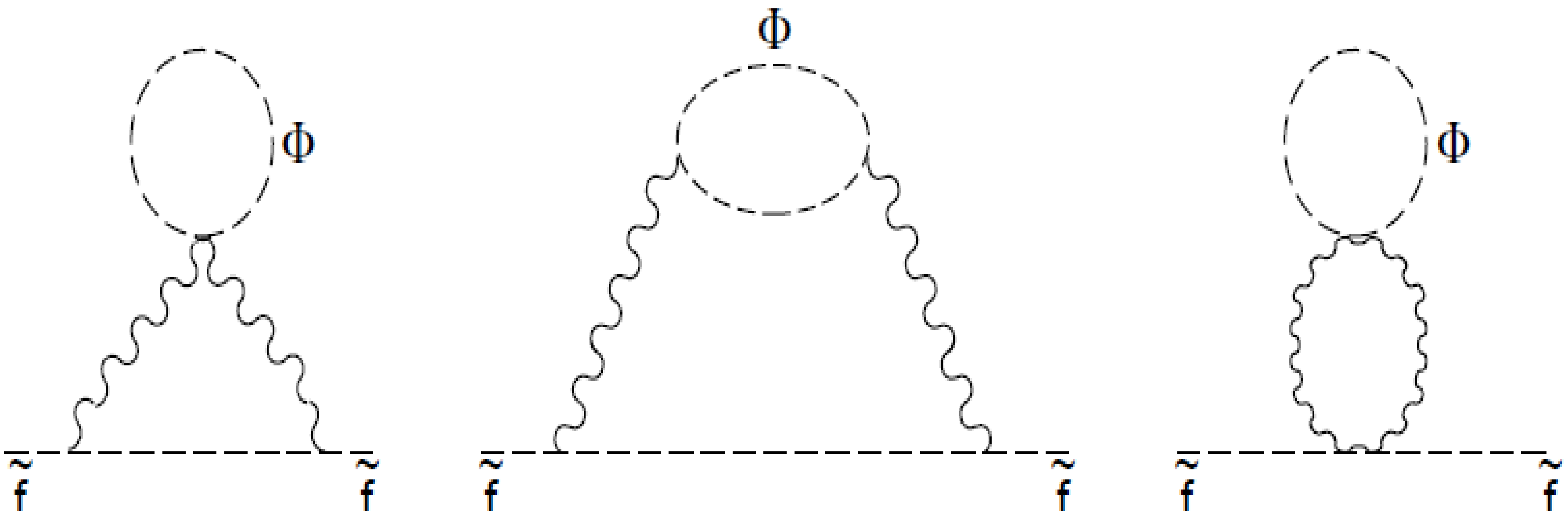
$$X = \langle X \rangle + \theta^2 F_X \quad \rightarrow \quad X \Phi \tilde{\Phi} \quad \rightarrow \quad \text{soft terms}$$

Here $M_{SUSY} > 100\ TeV \quad , \ 1\ eV < m_{3/2} < 10\ GeV$



Gaugino and scalar soft masses in gauge mediation





- Low-scale dynamics

There are no perturbative models with $M_{SUSY} < 50\ TeV$
It is however possible to use strong dynamics (holographic models) such that $M_{SUSY} \equiv f \sim 5 - 10\ TeV$

In this case, insisting on (non-linear) supersymmetry instead of explicit breaking (soft-breaking terms) leads to additional dynamics (Antoniadis,ED,Ghilencea,Tziveloglou,2010).

Ex: Higgs potential is modified, Higgs mass can be increased

$$V = V_{MSSM} + \frac{1}{f^2} |m_1^2 |h_1|^2 + m_2^2 |h_2|^2 + B_\mu h_1 h_2|^2$$

- Split, mini-split and high-scale SUSY

- Split SUSY $m_{\text{scalars}} >> m_{\text{fermions}} \sim TeV$

This is realized for high-scale SUSY breaking and approximate R-symmetries (Arkani-Hamed,Dimopoulos, 2004)
- Long-lived gluinos, displaced vertices.

Mini-split SUSY models

- Most « economic » versions of split-SUSY with:
- scalar masses at 100-1000 TeV , of the order the gravitino mass $m_0 \sim m_{3/2}$

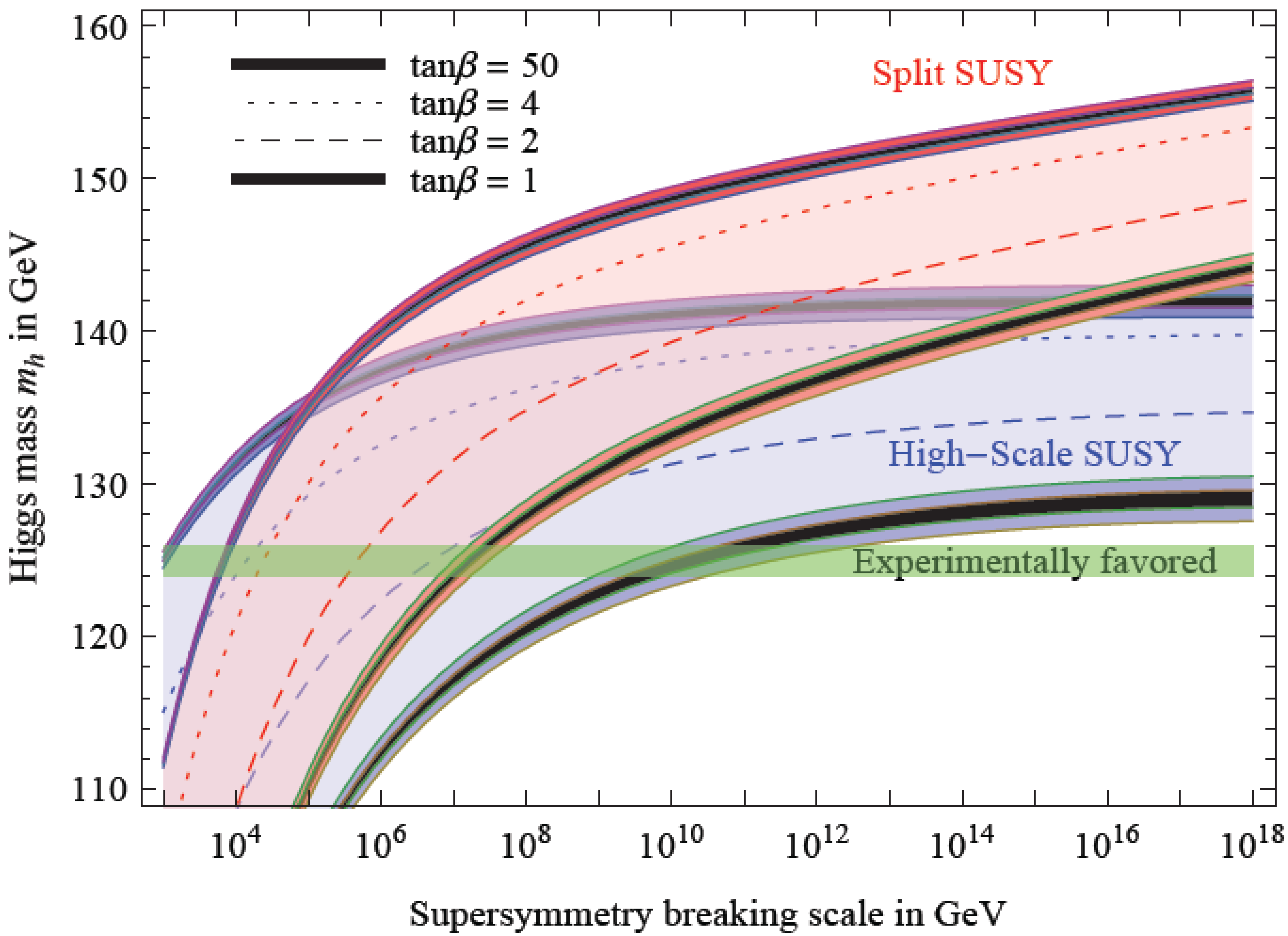
- gaugino masses in the TeV range (loop suppressed , anomaly mediation)

$$M^a_{1/2} = \frac{b_a g_a^2}{16\pi^2} m_{3/2}$$

LHC is pushing SUSY bounds. Perhaps soon time to abandon low-energy supersymmetry and contemplate fine-tuned theories ?

- High-scale SUSY $m_{\text{scalars}}, m_{\text{fermions}} >> TeV$

Maybe a hint towards a (more) perturbative SUSY breaking in string theory



Higgs scalar mass versus scalar masses in split and high-scale SUSY models (from Giudice-Strumia (2011))

3) The SUSY Flavor Problem

Flavor transitions (FCNC) in the Standard Model are protected by the GIM mechanism ⇨

FCNC transitions $K^0 - \bar{K}^0$, $\mu \to e\gamma$, $b \to s\gamma$, etc
are very weak, protected by the :

- Unitarity of CKM matrix, GIM mechanism
- Hierarchical structure of $V_{\rm CKM}$
- Smallness of neutrino masses

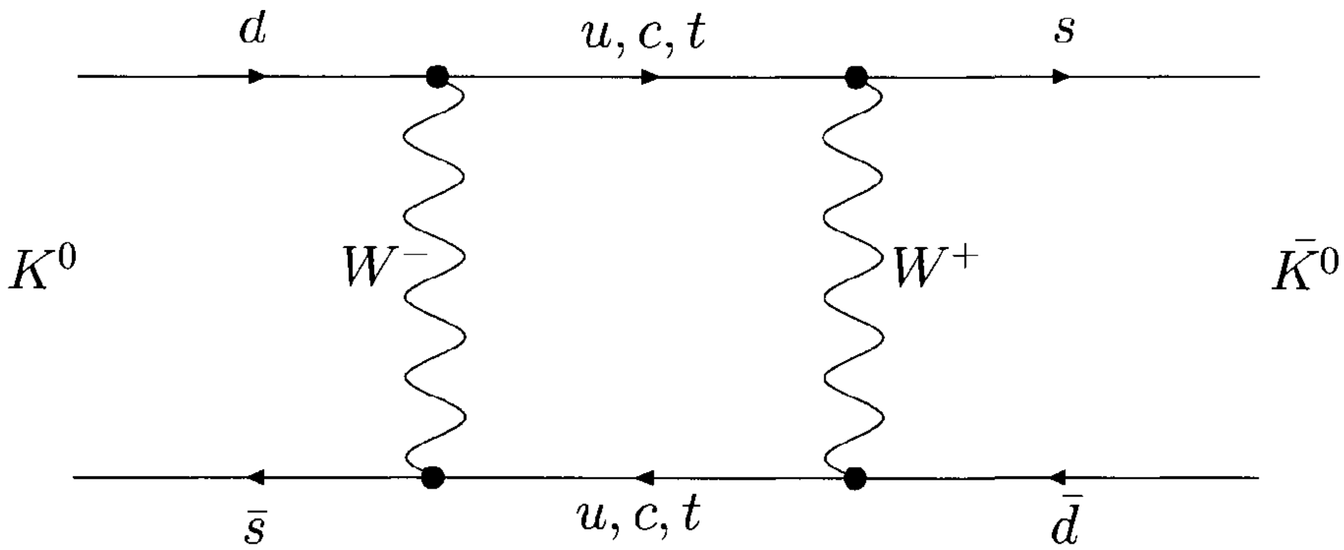
This protection is lost in most of extensions of the SM. In SUSY models, FCNC are suppressed if:

i) The three generations of squarks/sleptons are very degenerate

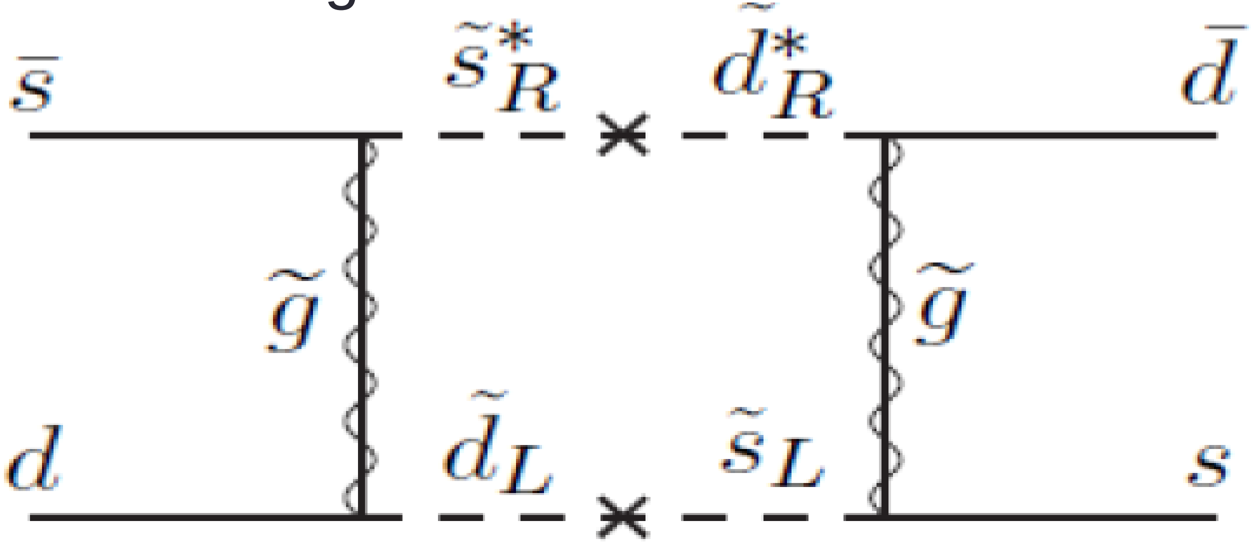
or

ii) Some squarks/sleptons are very heavy (> 10^4 TeV)

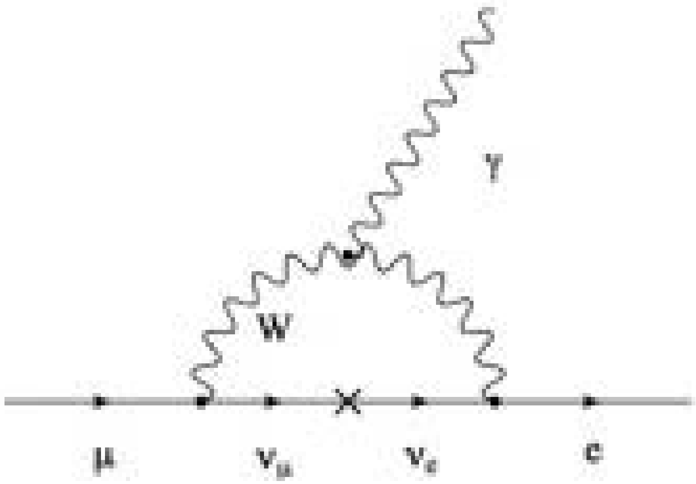
- $K^0 - K^0$ mixing in the SM

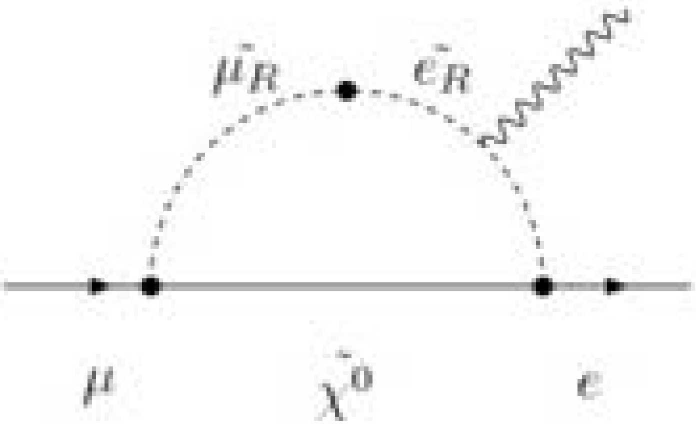


- In the MSSM: strong constraints from Δm_K and ϵ_K



$\mu \to e\gamma$ in the SM and MSSM





Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

TABLE I: Bounds on representative dimension-six $\Delta F = 2$ operators. Bounds on Λ are quoted assuming an effective coupling $1/\Lambda^2$, or, alternatively, the bounds on the respective c_{ij}'s assuming $\Lambda = 1$ TeV. Observables related to CPV are separated from the CP conserving ones with semicolons. In the B_s system we only quote a bound on the modulo of the NP amplitude derived from Δm_{B_s} (see text). For the definition of the CPV observables in the D system see Ref. [15].

- Naturalness, natural SUSY spectra

Corrections to Higgs mass in SUSY

$$\delta m_h^2 \approx \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{\rm SUSY}^2}\right)\right]$$

where and M_{SUSY} (A_t) denotes the average stop mass

(mass mixing in the stop sector).

Electroweak scale natural for light higgsinos,gluinos,stops and L-handed sbottom:

$$m_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + \ldots$$

$$\delta m_{H_u}^2 \approx -\frac{3y_t^2 m_{\tilde t}^2}{4\pi^2}(1 + a^2/2)\log\frac{\Lambda}{m_{\tilde t}}$$

$$\delta m_{\tilde t}^2 = \frac{8\alpha_s}{3\pi} M_3^2 \log\frac{\Lambda}{M_3}$$

- Inverted hierarchy/Natural SUSY

Old scenario, became popular because of LHC constraints:
- third generations squarks (light stops)
- First two generation scalars much heavier (10-15 TeV).

They affect little the tuning of the electroweak scale.

This is natural in flavor models and holographic constructions.
Simplest constructions:

1) U(1) gauged, spontaneously broken flavor symmetry (Froggatt-Nielsen,79). Yukawa matrices given by

$$\mathcal{L}_{\rm Yuk} = (\frac{\phi}{M})^{q_i+u_j+h_2} q_i u_j h_2 + \cdots$$

⇒ Yukawa couplings

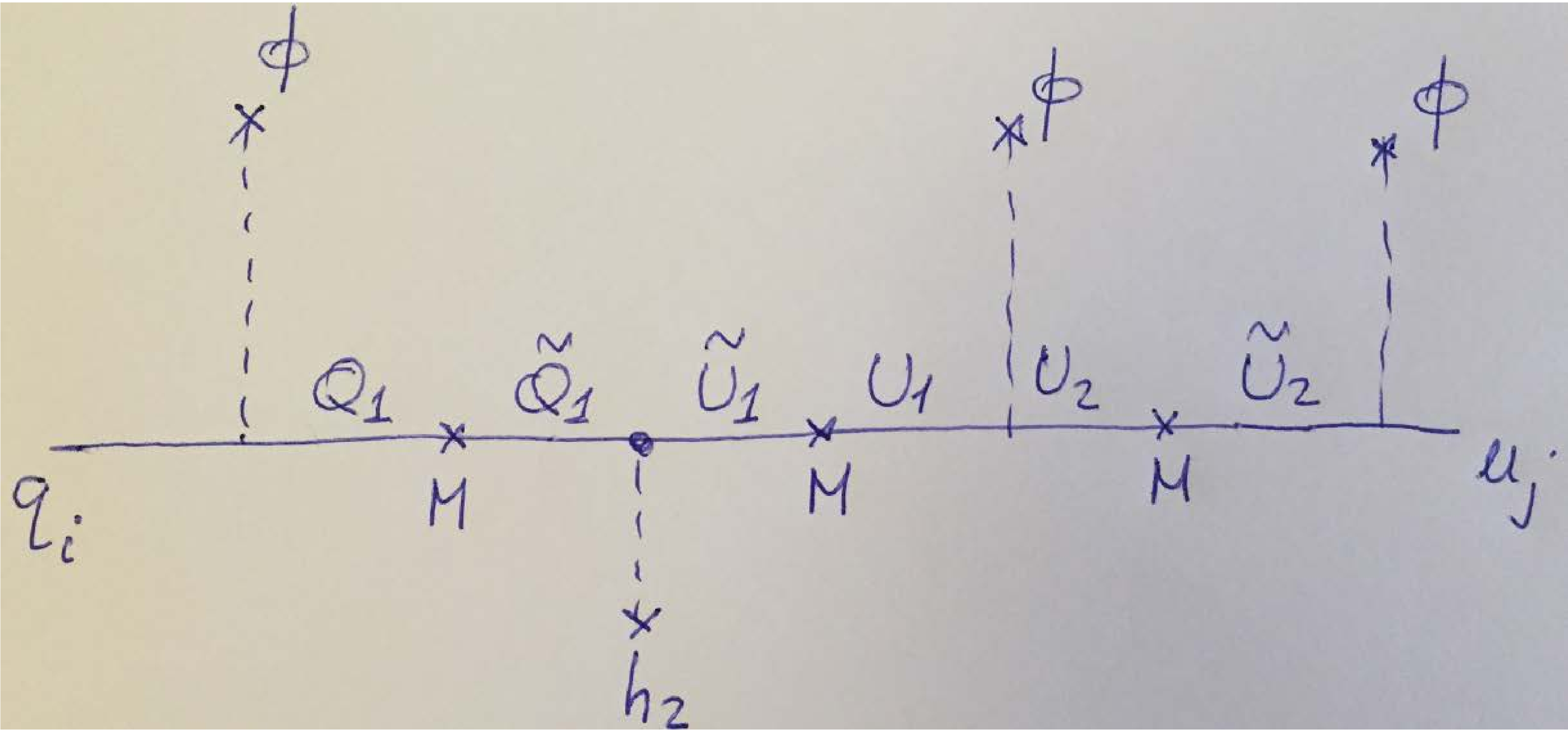
$$h_{ij}^U \sim \epsilon^{q_i+u_j+h_u} \quad , \quad h_{ij}^D \sim \epsilon^{q_i+d_j+h_d} \ ,$$

where $\epsilon = \frac{\langle \Phi \rangle}{M} \sim \lambda = 0.22$

and q_i are charges of left-handed quarks, etc.

The origin of such higher-dimensional operators can be :

- Mixing with heavy fermions:



- Operators present in String Theory

Quarks masses and mixings are given by ($q_{13} = q_1 - q_3$,etc)

$$\frac{m_u}{m_t} \sim \epsilon^{q_{13}+u_{13}} \ , \ \frac{m_c}{m_t} \sim \epsilon^{q_{23}+u_{23}} \ , \ \frac{m_d}{m_b} \sim \epsilon^{q_{13}+d_{13}} \ , \ \frac{m_s}{m_b} \sim \epsilon^{q_{23}+d_{23}}$$

$$\sin\theta_{12} \sim \epsilon^{q_{12}} \ , \ \sin\theta_{13} \sim \epsilon^{q_{13}} \ , \ \sin\theta_{23} \sim \epsilon^{q_{23}} \ .$$

Good fit to to data ⇨ larger charges for the lighter generations

$$q_1 > q_2 > q_3 \ , \ u_1 > u_2 > u_3 \ , \ d_1 > d_2 > d_3$$

$$m_t \sim 1 \qquad m_c \sim \epsilon^4 \qquad m_u \sim \epsilon^8$$

$$m_b \sim \epsilon^3 \qquad m_s \sim \epsilon^{5\div 6} \qquad m_d \sim \epsilon^{7\div 8}$$

$$m_\tau \sim \epsilon^3 \qquad m_\mu \sim \epsilon^5 \qquad m_e \sim \epsilon^9$$

$$V_{us} \sim \epsilon \qquad V_{ub} \sim \epsilon^3 \qquad V_{cb} \sim \epsilon^2$$

Gauge anomalies ⇒ constraints on the charges

$$K \sim \frac{X^\dagger X}{\Lambda_S^2} \left(\frac{\phi}{\Lambda_F} \right)^{|q_i - q_j|} Q_i^\dagger Q_j$$

⇒ F-term contributions to scalar masses.

Also D-term contributions; so scalar masses are of the form

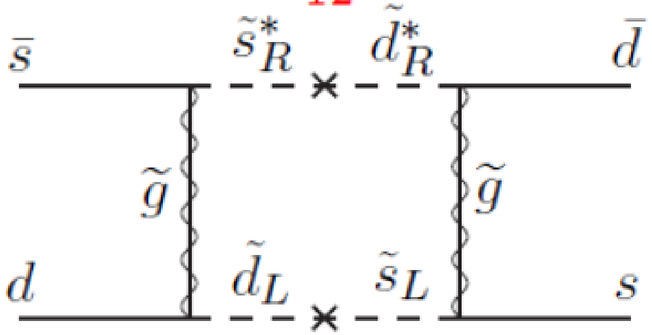
$$m_{ij}^2 = X_i \delta_{ij} \langle D \rangle + c_{ij} \epsilon^{|q_i - q_j|} (\tilde{m}_F)^2$$

If D-term dominates, then an inverted hierarchy is generated.

This can be realized in explicit models
(E.D.,Pokorski,Savoy; Binetruy,E.D.; Dvali,Pomarol,94-96)

Obs: 1-2 generations cannot be too heavy, otherwise tachyonic stops (Pomarol,Tommasini;Arkani-Hamed,Murayama)

FCNC constrain seriously these models :
need degeneracy between first two generations of squarks/sleptons



$$\sim \frac{1}{m^2} \quad \delta_{12}^{D,LL} \, \delta_{12}^{D,RR}$$

where $\delta_{12}^{D,LL} = \frac{m^2_{\tilde{d}_L \tilde{s}_L}}{m^2_{av}}$

In such flavor models $\delta_{12}^{D,LL} \delta_{12}^{D,RR} \sim \frac{m_d}{m_s}$ very large !

One can avoid this if D-term contributions are large and equal for 1,2 generations ⇨ $q_1 = q_2 \ , q_3 = 0$

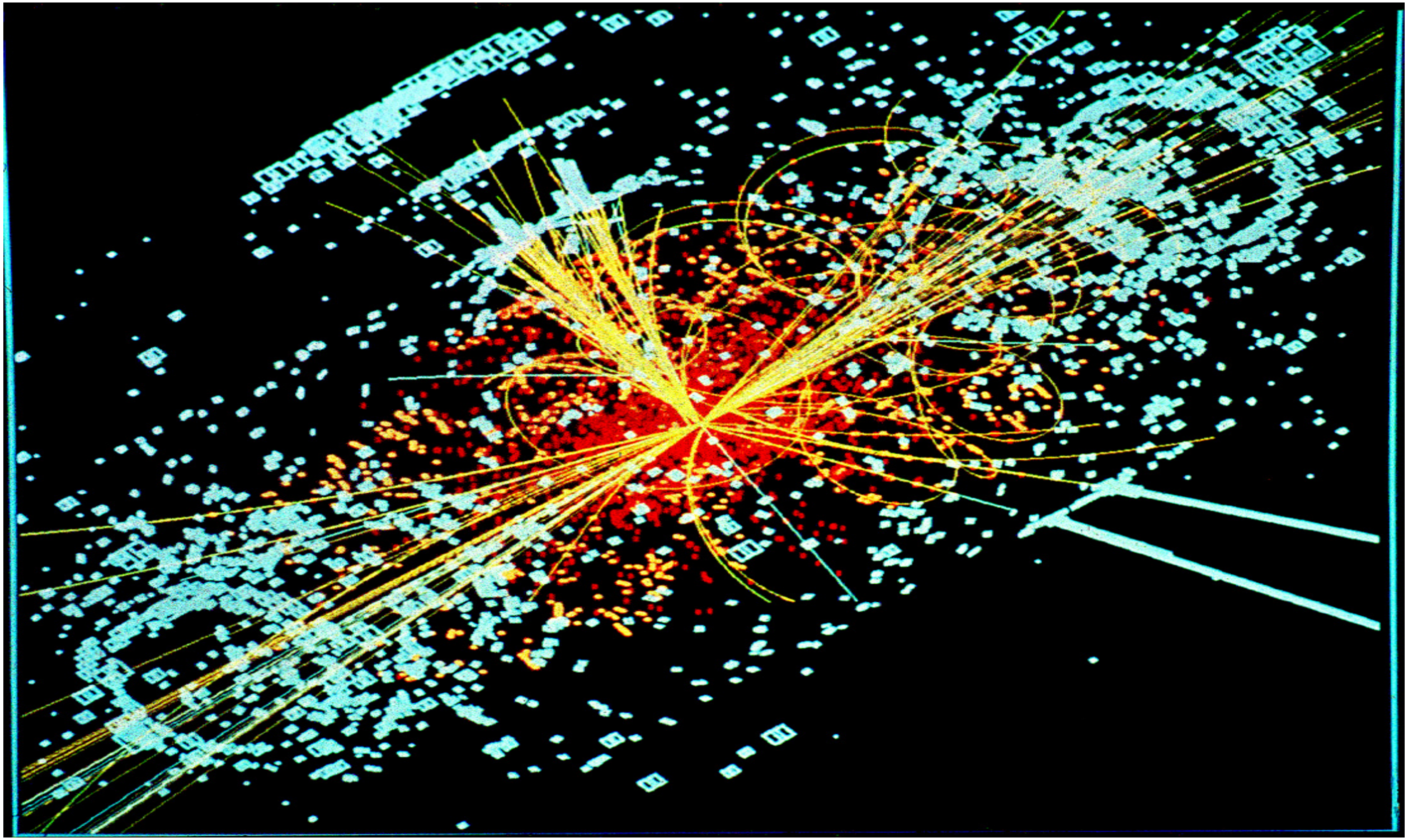
But then m^2_{12} squark mass not protected by the U(1) symmetry

→

There is a challenge to explain simultaneously fermion masses and FCNC within one flavour theory !

Without flavor symmetries one needs
m > 1000 – 100.000 TeV !

SUSY constraints from LHC searches and the Higgs mass

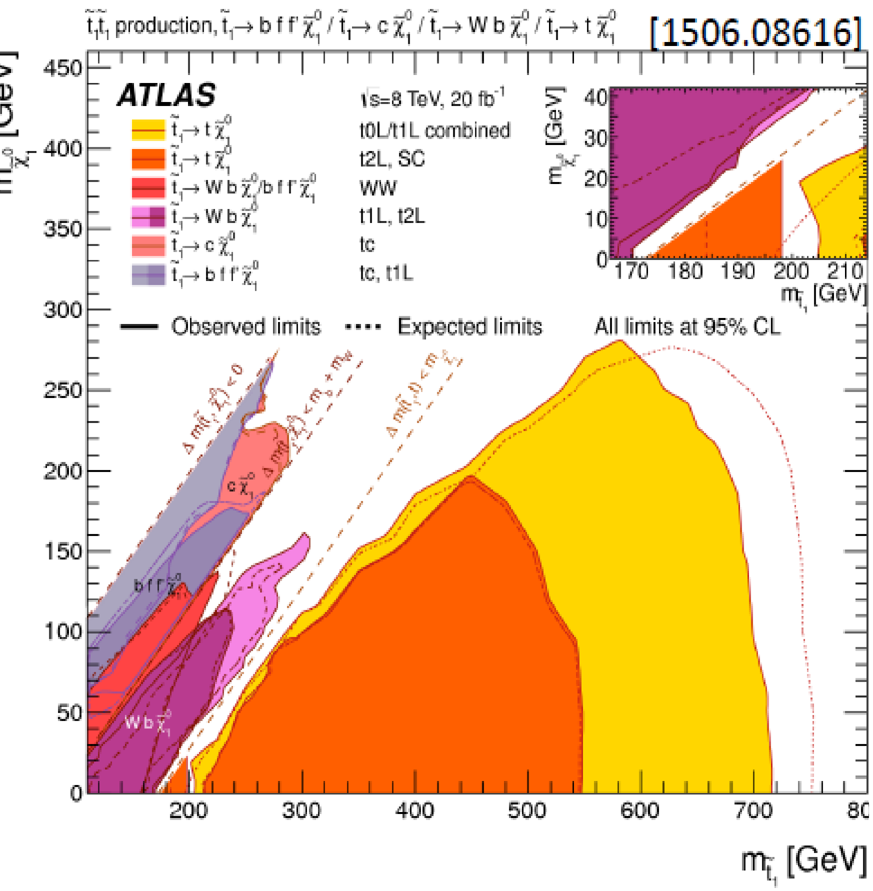


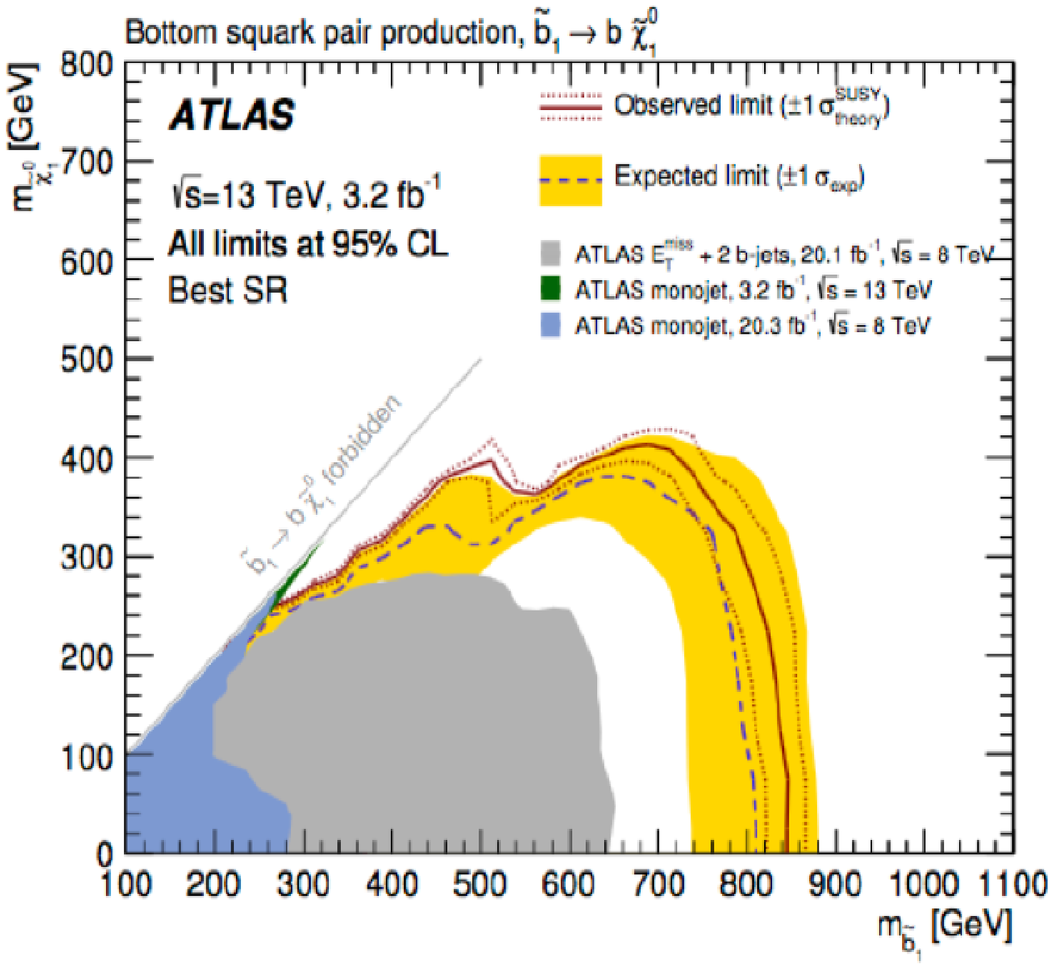
- LHC direct SUSY searches and Higgs mass set new limits on superpartner masses for simple (simplified) SUSY models

$$m_{gluinos}, m_{squarks} \geq 1.6 - 1.8\ TeV$$

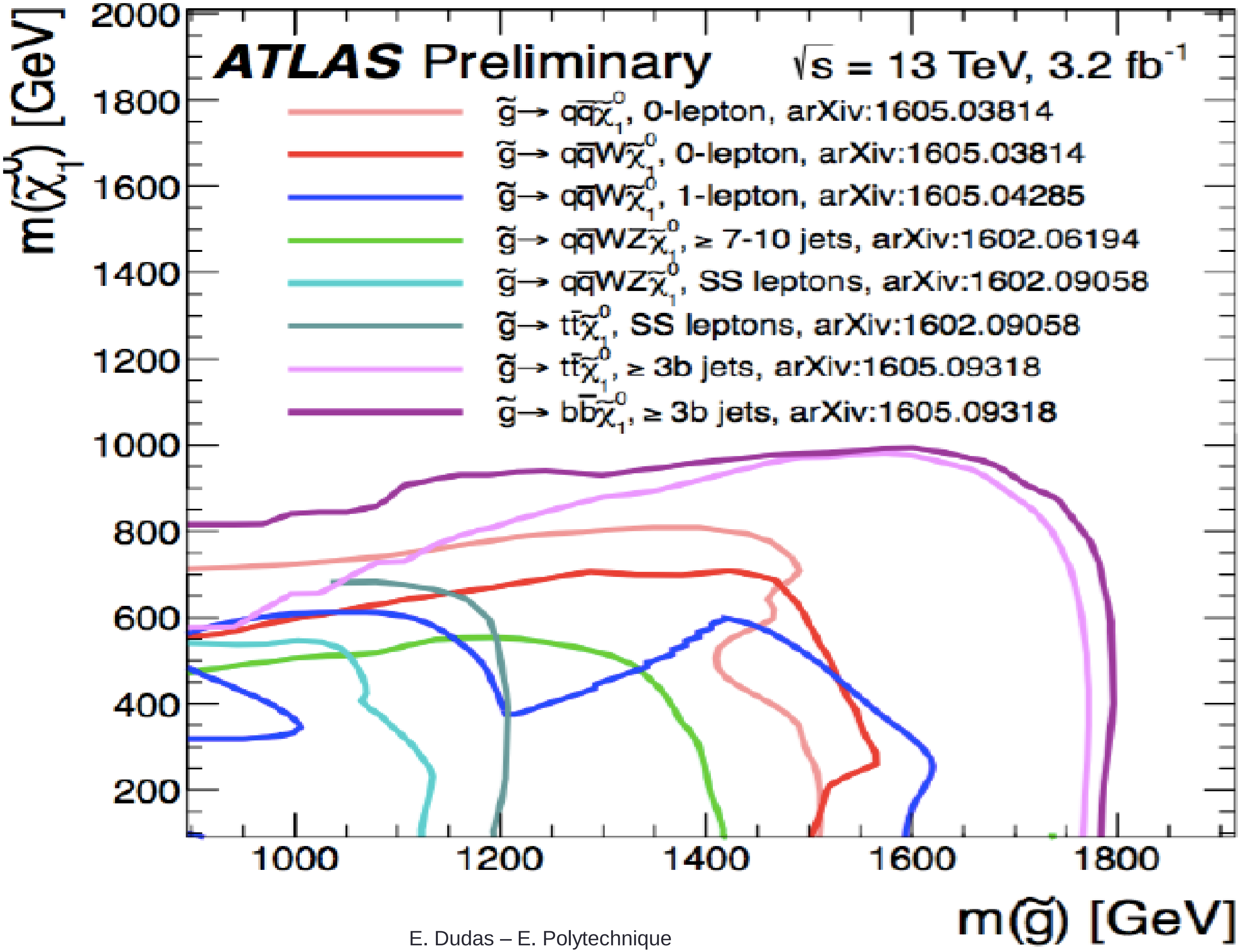
Bounds on « Natural SUSY » models

Example: $\tilde{t}_1$ pair production $m(\tilde{\chi}_1^0)$ vs $m(\tilde{t}_1)$
with various model assumptions





Direct gluino production



Popular models: CMSSM, minimal gauge mediation have more difficulties in accomodating the data :

$$m_{gluinos}, m_{squarks} \geq 1.8 - 2\ TeV$$

It is important to theoretically analyze and experimentally search for non-minimal SUSY models.

Signatures and constraints can change significantly if :

- Missing energy signatures difficult if NSLP close in mass to its superpartner or the LSP
- R-parity violation models
- colored particles production suppressed in Dirac gaugino extensions of MSSM (G.Kribbs,A.Martin)

Perspectives

- SUSY still the best option nature has to address misteries of the Standard Model. Alternatives (Xtra dims/strong dynamics) are more constrained by data.

- Popular SUSY models are more tuned; stringent limits from LHC searches and flavor physics. But no reason to reduce low-energy SUSY to MSSM; even less to its simplest incarnations (CMSSM, mGMSB).

- Theories of fermion masses generate flavor-dependent soft terms. Inverted hierarchy/natural SUSY arises naturally in flavor models . Signatures in flavour physics ? (B,D mesons mixings and decays)

- There are alternatives (Dirac gaugino models) that can suppress coloured particle production and FCNC.

- If no sign of SUSY at LHC14, maybe nature did chose other options, with fine-tuning :

- (mini)split SUSY, with very heavy scalars.
- high-scale SUSY or just SM until 10^{12} GeV or M_P , as suggested by the (meta)stability of the Higgs potential in SM.

THANK YOU

Backup slides

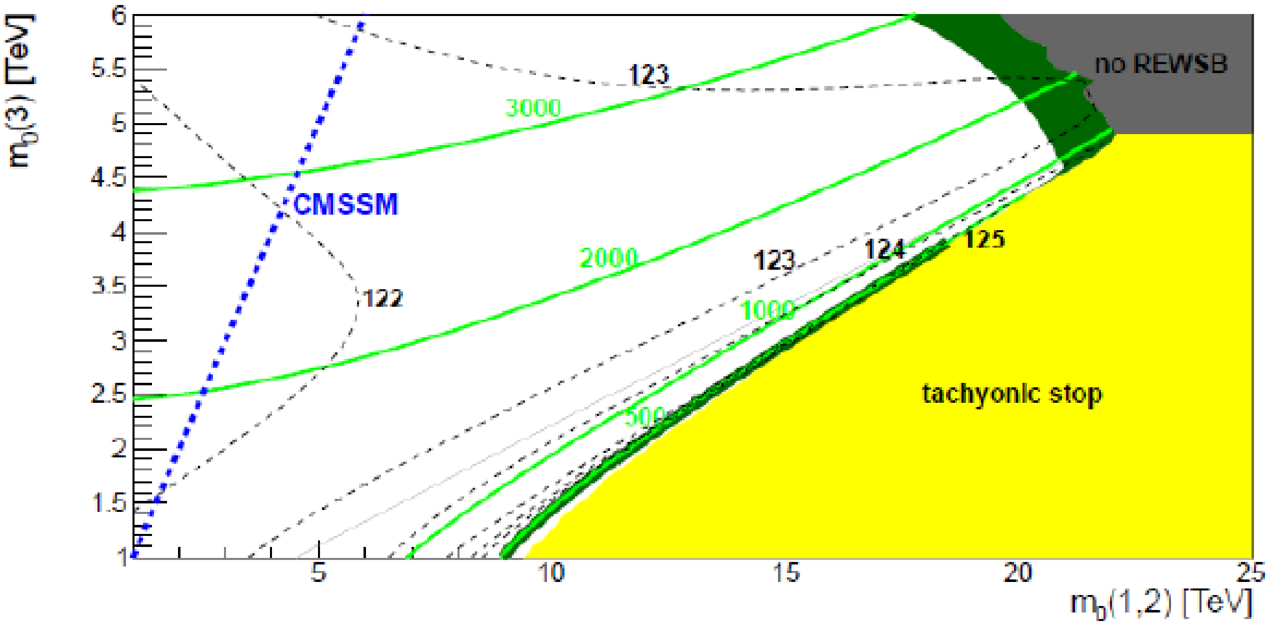
(More) Natural SUSY models:

- Natural SUSY/inverted hierarchy/split families :
light stops,gluinos,higgsinos (TeV)
heavier 1,2 generations (10-15 TeV)
- Extended scalar and/gauge sector (ex: NMSSM)
- RPV models (ex. baryonic RPV, operators UDD)
- Dirac gauginos
- Spectrum more degenerate/decays stealthy…

(Less) Natural SUSY theories :

- Mini-split/Spread SUSY models
- Split SUSY models: $m_{\text{scalars}} >> m_{\text{fermions}}$
- High-scale SUSY

Large stop mixing can be generated from RG running (M. Badziak et al, 2012; Brummer et al, 2012.)



Inverted hierarchy example. Higgs mass (black dashed), stop mass (solid green) for $\mu > 0, \tan\beta = 10, M_{1/2} = 1, A_0 = -2$ (TeV). Yellow "tachyonic stop" and grey "no REWSB" ($\mu^2 < 0$) regions are excluded. Dark green region: $\Omega_{DM} h^2 < 0.1288$.

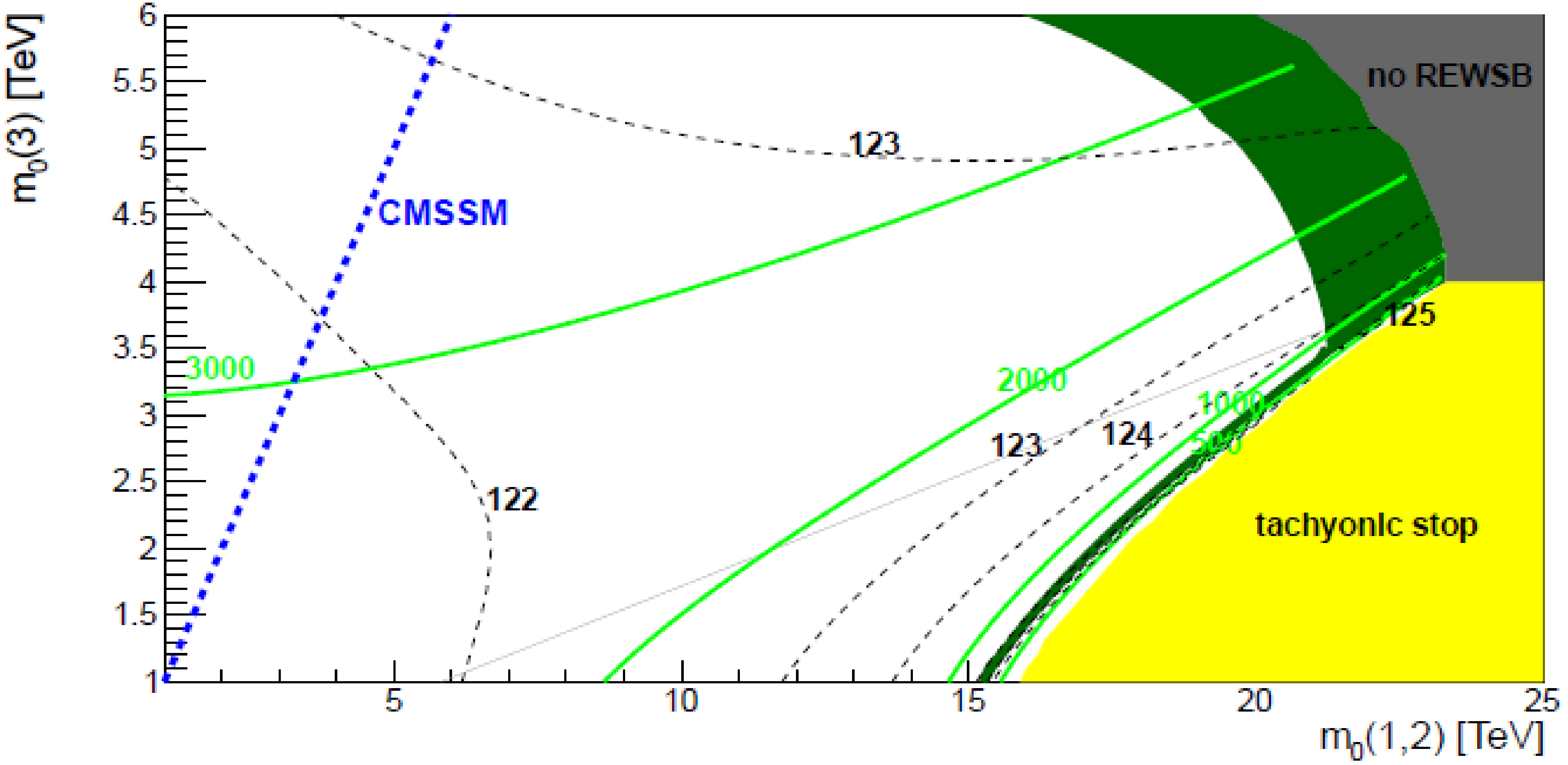


Figure 5: The same as in Figure 3 but for $M_{1/2} = 1.5$ TeV and $A_0 = 0$.

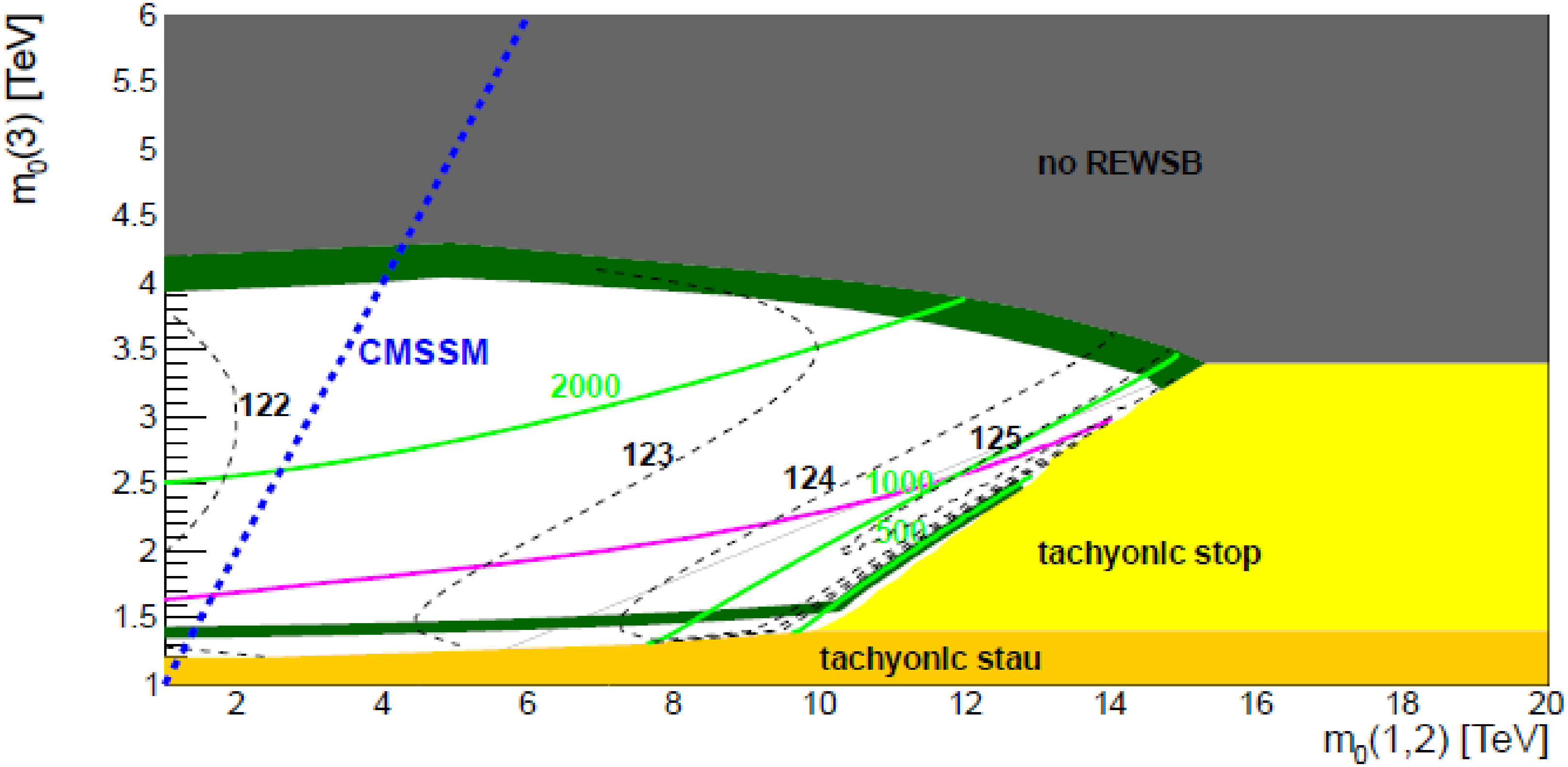


Figure 7: The same as in Figure 3 but for $\tan\beta = 50$ and $m_{H_d} = 1.6 m_0(3)$. The region below the purple line is excluded by $\mathrm{BR}(B_s \to \mu^+\mu^-)$ at 95% C.L. The orange region is excluded because it predicts a tachyonic stau.

Some string comments:

- Natural SUSY/Inverted hierarchy in string theory
- Anomalous U(1)'s in all string theories and F-theory, flavor dependent + additional discrete symmetries
- Different localization of the third generation versus the first two ones: twisted/untwisted fields, varying fluxes
- Some recent attempts to compute flavor structure of soft terms (Blumenhagen,Deser,Lust; Camara,E.D.,Palti; Camara,Ibanez,Valuenzuela).
- Dirac gauginos are natural in intersecting brane models (Antoniadis,Benakli,Delgado,Quiros and Tuckmantel)

Inverted hierarchy can also be realized in field theory:
- SUSY(SUGRA) RS 5d warped models
- flavored (higgsed) gauge mediation.

Some simple flavor models we are considering:

- One U(1) models with alignment; ex. charges

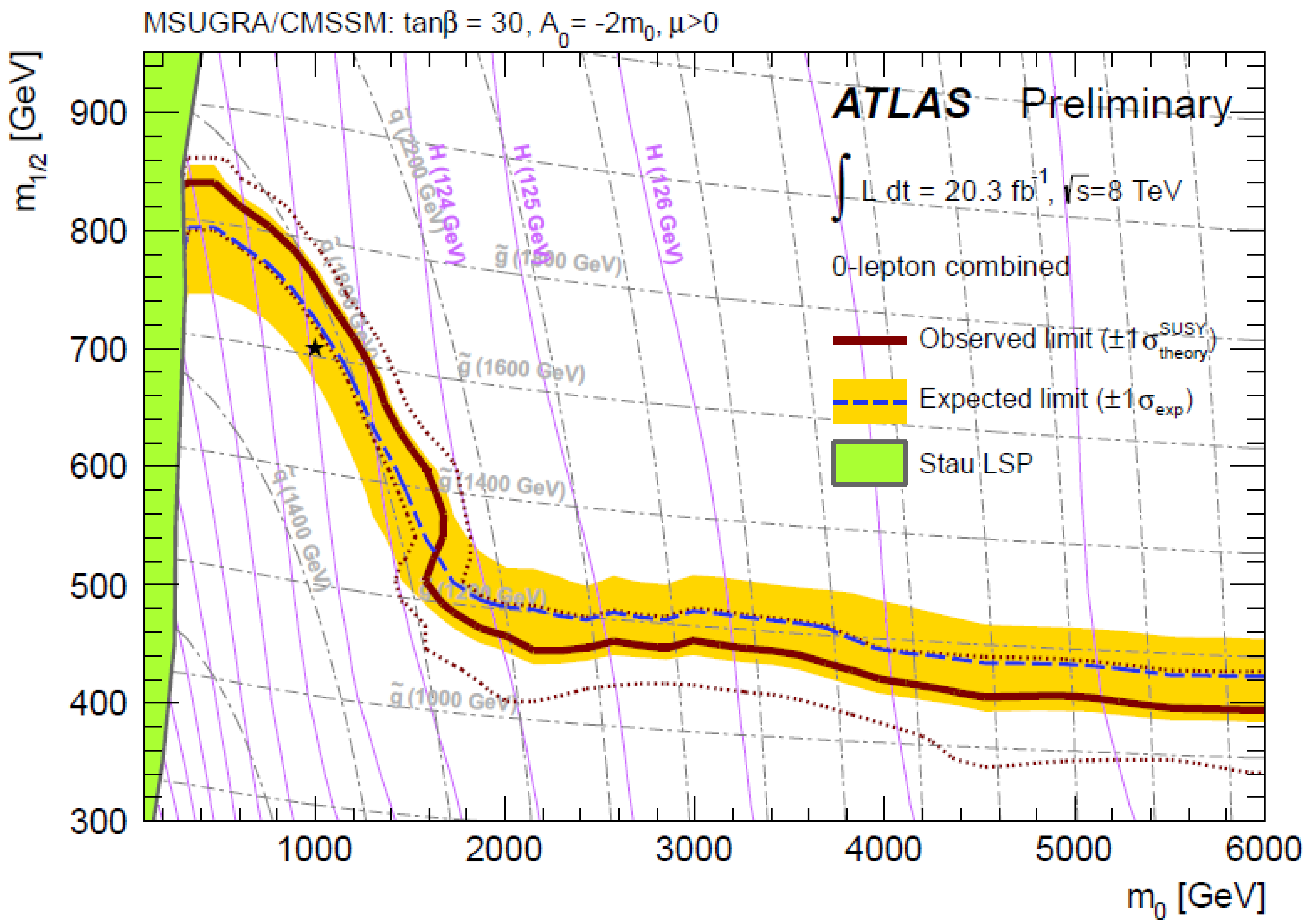
$$Q = (3,2,0) \qquad u = (3,1,0) \qquad d = (3,2,2)$$

Squark mass matrices are

$$\mathcal{M}^2_{d_L} \sim M_F^2 \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}, \qquad \mathcal{M}^2_{d_R} \sim M_F^2 \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}$$

and quark rotations are

$$U_L^d \sim \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^3 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}, \qquad U_R^d \sim \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}$$


MSUGRA/CMSSM: tanβ = 30, A0 = -2m0, μ>0
ATLAS Preliminary
∫L dt = 20.3 fb-1, √s=8 TeV
0-lepton combined
Observed limit (±1 σ SUSY theory)
Expected limit (±1 σexp)
Stau LSP
H (124 GeV)
H (125 GeV)
H (126 GeV)
g̃ (1800 GeV)
g̃ (1600 GeV)
g̃ (1400 GeV)
g̃ (1200 GeV)
g̃ (1000 GeV)
m1/2 [GeV]
m0 [GeV]
300
400
500
600
700
800
900
1000
2000
3000
4000
5000
6000

- MSSM soft terms, minimal gauge mediation:

- gaugino masses $\rightarrow$ 1-loop

$$M_{1/2} \sim N_m \frac{g^2}{16\pi^2} \left(\frac{F_X}{\langle X \rangle} \right) \sim N_m M_{GMSB}$$

- scalar (squarks,sleptons) masses : two-loops

$$m_0^2 \sim N_m \left(\frac{g^2}{16\pi^2} \right)^2 \left(\frac{F_X}{\langle X \rangle} \right)^2 \sim N_m M_{GMSB}^2$$

Typically $M_{GMSB} \gg m_{3/2}$, gravitino very light (LSP)