High Energy Frontier - Recent Results from the LHC

University of Heidelberg WS 2012/13

Lecture 3

LHC-Searches II

Supersymmetry

Please Register!

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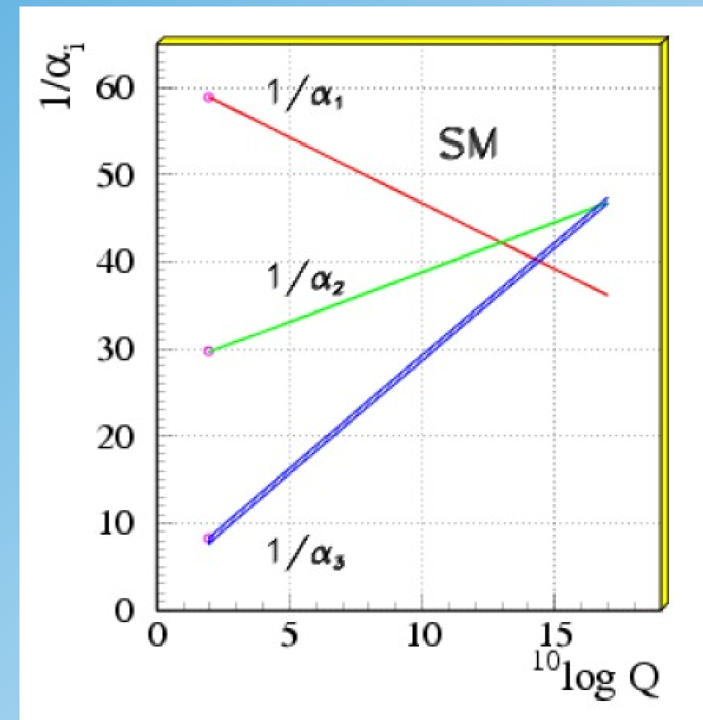
Searches for New Symmetries at LHC

- **Fourth generation quarks** (extension of the three generations)
- **Heavy** new vector **bosons** (W´, Z´) → Left-Right Symmetric Models
- Search for large **extra dimensions** (extension of 3D+1 space-time)
- Search for **supersymmetry**: → fermion-boson symmetry
- and many more models (symmetries) …
- and many variants ...

Theory Arguments for New Physics

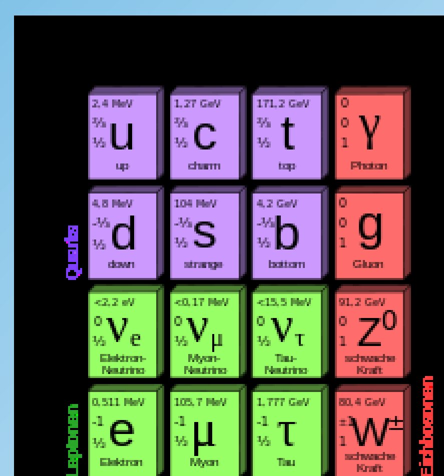
- (Too) many parameters (25)!
- Why three generations?
- Why so different masses (Yukawa couplings)
- Grand Unification (GUT) → couplings?
- Fine Tuning and Naturalness Problem of the Higgs Mass ($M_H < M_{planck}$)
- Ultraviolet catastrophe at high energies
- Unification with Gravitation?
- Mechanism of CP violation?



electromagnetic (γ) $\alpha_1 \sim 1/137$

weak IA (W, Z) $\alpha_2 \sim 1/29$

strong IA (gluon) $\alpha_3 \sim 1/10$



Overview

- Preface
  - Standard Model extensions
  - SU(5)
- Supersymmetry
  - Theory
  - Phenomenology
- Experimental Searches for Supersymmetry

Beyond the Standard Model

SM Gauge Group (unbroken):

$$SU(3)_{QCD} \times SU(2)_L \times U(1)_Y$$

Fermions have the following transformation properties:

$$U^a = \begin{pmatrix} u \\ d \end{pmatrix} = (3,\ 2,\ 1/6)$$

$$\bar{u} = (\bar{3},\ 1,\ -2/3)$$

$$\bar{d} = (\bar{3},\ 1,\ 1/3)$$

$$L^a = \begin{pmatrix} \nu_e \\ e \end{pmatrix} = (1,\ 2,\ -1/2)$$

$$\bar{e} = (\bar{1},\ 1,\ 1)$$

relation to electric charge: $Q = T_3 + Y$

Comments:

SM is a <u>real</u> gauge theory (renormalizable)

renormalizability requires:
- same number of quark and lepton families
- conservation of baryon and lepton number

Absence of gauge anomalies requires
- quantized hypercharges (electric charges)

Gauge couplings g_1, g_2 and g_3 are different!

Grand Unification

Idea: unify couplings

Complete fermion family fits into a SU(5) group representation

SU(5) with SU(3) x SU(2) embedding of left-handed (chiral) particles

$$\bar{\psi}_i = \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e^- \\ \nu \end{pmatrix}, \qquad \psi_{ij} = \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ & 0 & u_1^c & u_2 & d_2 \\ & & 0 & u_3 & d_3 \\ & & & 0 & e^+ \\ & & & & 0 \end{pmatrix}.$$

$\{\bar{5}\}$ $\{10\}$

Remark: anti-neutrino can be embedded in SO(10)

SU(5) Gauge Boson matrix

$$\begin{pmatrix} & & & X_1^{-4/3} & Y_1^{-1/3} \\ & \frac{1}{\sqrt{2}}\lambda\cdot\mathbf{V}_{(8)} + \sqrt{\frac{2}{15}}V_{24} & & X_2^{-4/3} & Y_2^{-1/3} \\ & & & X_1^{-4/3} & Y_3^{-1/3} \\ X_1^{4/3} & X_2^{4/3} & X_3^{4/3} & & \\ Y_1^{1/3} & Y_2^{1/3} & Y_3^{1/3} & \multicolumn{2}{c}{\frac{1}{\sqrt{2}}\tau\cdot\mathbf{W} - \sqrt{\frac{3}{10}}V_{24}} \end{pmatrix}$$

V_8 corresponds to the gluon fields

W corresponds to the W field

V_{24} corresponds to the hypercharge field

X,Y correspond to Leptoquarks: X,Y → l q and Diquarks: X → uu, Y→ du

SU(5) Fermion matrices

New X,Y bosons

$$\lambda_9 = \begin{pmatrix} & & & 1 & 0 \\ & 0 & & 0 & 0 \\ & & & 0 & 0 \\ 1 & 0 & 0 & & \\ 0 & 0 & 0 & & 0 \end{pmatrix}, \quad \lambda_{10} = \begin{pmatrix} & & & -i & 0 \\ & 0 & & 0 & 0 \\ & & & 0 & 0 \\ i & 0 & 0 & & \\ 0 & 0 & 0 & & 0 \end{pmatrix},$$

$$\lambda_{11} = \begin{pmatrix} & & & 0 & 1 \\ & 0 & & 0 & 0 \\ & & & 0 & 0 \\ 0 & 0 & 0 & & \\ 1 & 0 & 0 & & 0 \end{pmatrix}, \quad \lambda_{12} = \begin{pmatrix} & & & 0 & -i \\ & 0 & & 0 & 0 \\ & & & 0 & 0 \\ 0 & 0 & 0 & & \\ i & 0 & 0 & & 0 \end{pmatrix},$$

$$\lambda_{13} = \begin{pmatrix} & & & 0 & 0 \\ & 0 & & 1 & 0 \\ & & & 0 & 0 \\ 0 & 1 & 0 & & \\ 0 & 0 & 0 & & 0 \end{pmatrix}, \quad \lambda_{14} = \begin{pmatrix} & & & 0 & 0 \\ & 0 & & -i & 0 \\ & & & 0 & 0 \\ 0 & i & 0 & & \\ 0 & 0 & 0 & & 0 \end{pmatrix},$$

$$\lambda_{15} = \begin{pmatrix} & & & 0 & 0 \\ & 0 & & 0 & 1 \\ & & & 0 & 0 \\ 0 & 0 & 0 & & \\ 0 & 1 & 0 & & 0 \end{pmatrix}, \quad \lambda_{16} = \begin{pmatrix} & & & 0 & 0 \\ & 0 & & 0 & -i \\ & & & 0 & 0 \\ 0 & 0 & 0 & & \\ 0 & i & 0 & & 0 \end{pmatrix},$$

$$\lambda_{17} = \begin{pmatrix} & & & 0 & 0 \\ & 0 & & 0 & 0 \\ & & & 1 & 0 \\ 0 & 0 & 1 & & \\ 0 & 0 & 0 & & 0 \end{pmatrix}, \quad \lambda_{18} = \begin{pmatrix} & & & 0 & 0 \\ & 0 & & 0 & 0 \\ & & & -i & 0 \\ 0 & 0 & i & & \\ 0 & 0 & 0 & & 0 \end{pmatrix},$$

$$\lambda_{19} = \begin{pmatrix} & & & 0 & 0 \\ & 0 & & 0 & 0 \\ & & & 0 & 1 \\ 0 & 0 & 0 & & \\ 0 & 0 & 1 & & 0 \end{pmatrix}, \quad \lambda_{20} = \begin{pmatrix} & & & 0 & 0 \\ & 0 & & 0 & 0 \\ & & & 0 & -i \\ 0 & 0 & 0 & & \\ 0 & 0 & i & & 0 \end{pmatrix},$$

W+,W0, W-

$$\lambda_{20+j} = \begin{pmatrix} & & & 0 & 0 \\ & 0 & & 0 & 0 \\ & & & 0 & 0 \\ 0 & 0 & 0 & & \\ 0 & 0 & 0 & \tau_j & \end{pmatrix}, \quad j = 1, 2, 3,$$

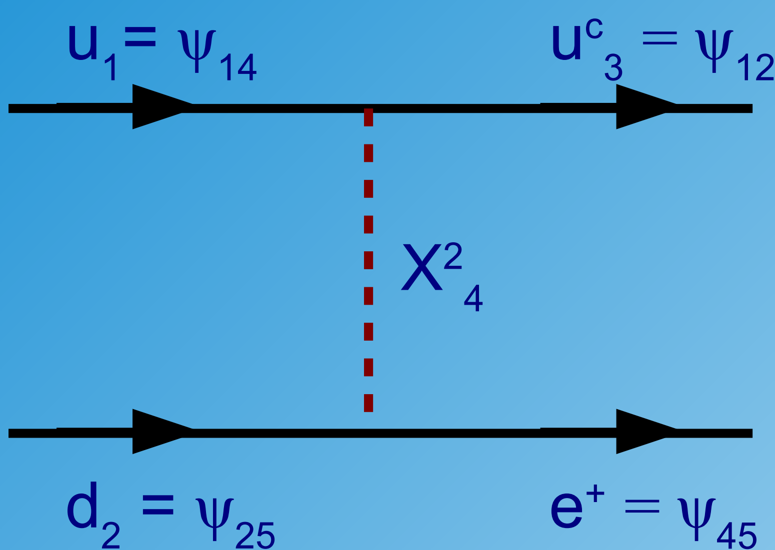
B-field

$$\lambda_{24} = \frac{2}{\sqrt{15}} \begin{pmatrix} 1 & & & & \\ & 1 & & & \\ & & 1 & & \\ & & & -3/2 & \\ & & & & -3/2 \end{pmatrix}.$$

gluons

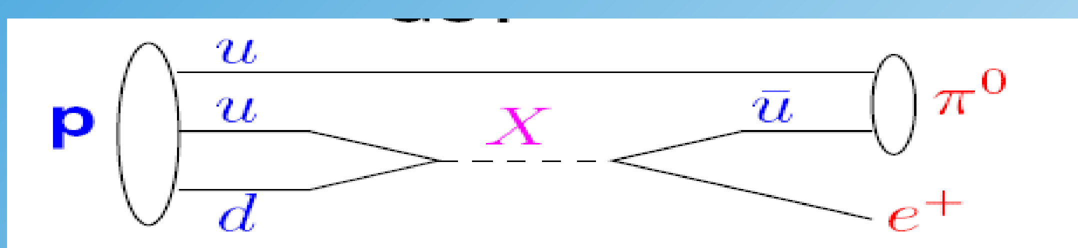
$$\lambda_i = \begin{pmatrix} & & & 0 & 0 \\ & \lambda_i & & 0 & 0 \\ & & & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}, \quad i = 1, \ldots, 8,$$

Baryon/Lepton Number Violation in SU(5)



$$\psi_{ij} = \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ & 0 & u_1^c & u_2 & d_2 \\ & & 0 & u_3 & d_3 \\ & & & 0 & e^+ \\ & & & & 0 \end{pmatrix}.$$

Proton Decay



Lifetime ~ $1/M_X^4$

Proton Lifetime >> 10^{30} years

$m_X > 10^{15}$ GeV

Running of Couplings:

Evolve couplings from renormalization group equations:

$$\frac{1}{\alpha_i(\mu)} = \frac{1}{\alpha_i(m)} + \frac{b_i}{2\pi}\log\left(\frac{m}{\mu}\right)$$

with $$b_i = -\frac{11}{3}C + \frac{4}{3}N_f l_f + \frac{1}{3}N_s l_s$$

N_f = number of fermions

N_s = number of scalars (Higgs)

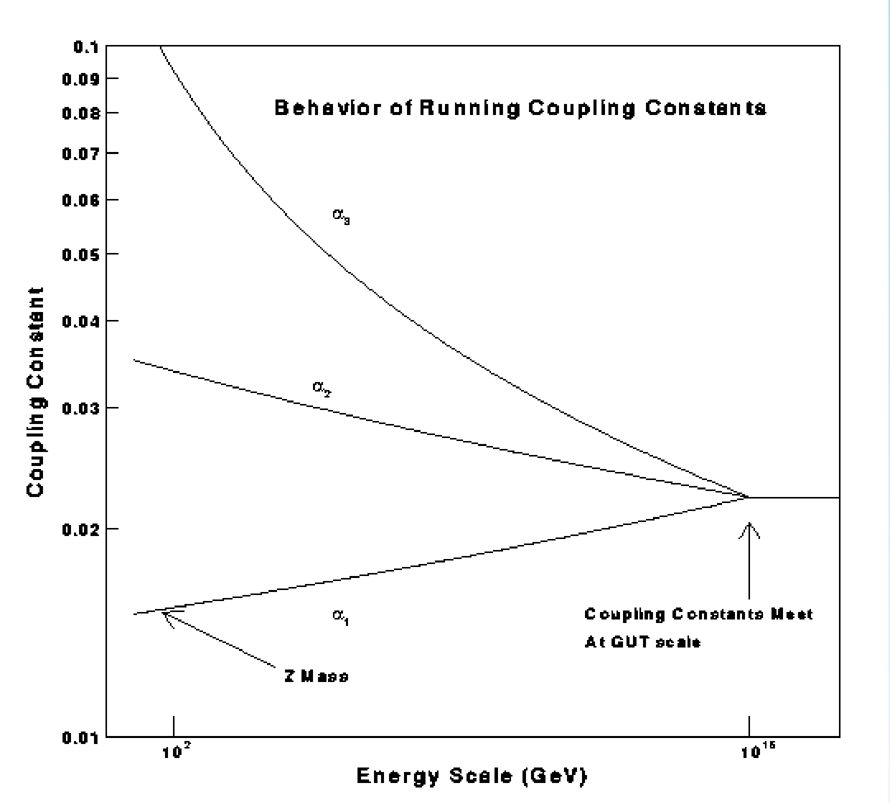
C, l_f, and l_s are quadratic Casimir element of representation

For SU(5) model

$$b_1 = -11 + \frac{4}{3}N_G$$ ← generations

$$b_2 = -22/3 + \frac{4}{3}N_G + \frac{1}{6}H$$ ← Higgs doublets

$$b_3 = \frac{4}{3}N_G + \frac{1}{10}H$$



unification scale below proton lifetime bound !

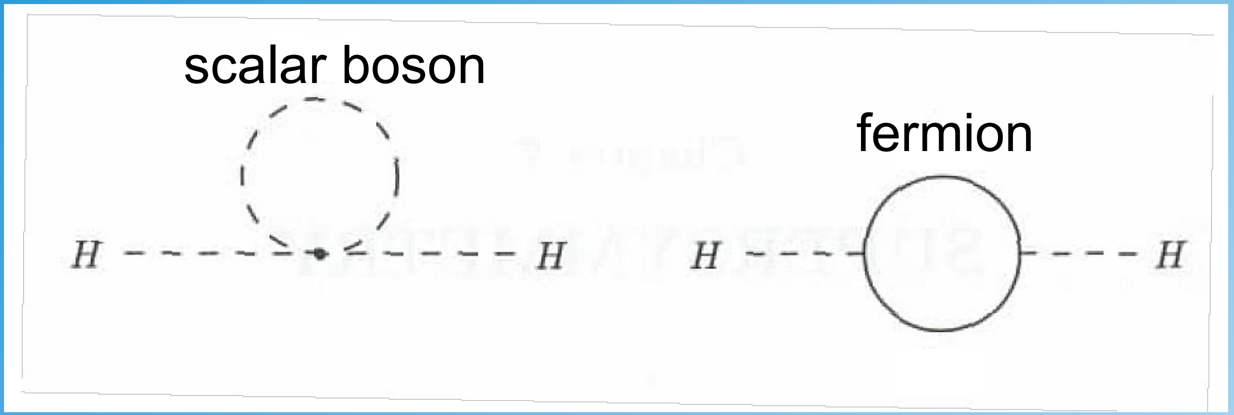
Lessons from SU(5)

- Unification of coupling possible if right amount of Higgs doublets
- Weinberg angle is more or less correctly predicted $\sin^2 \theta = 3/8$
  (at unification scale)
- New bosons are predicted with masses $M_X \sim 10^{15}$ GeV
- Proton is unstable due to new interactions X

The Hierarchy Problem in the SM

SM Fine Tuning Problem

The Higgs mass acquires large radiative corrections



$$\delta M^2_{Hs} = \frac{|\lambda_s^2|}{16\pi^2}\left[\Lambda^2 + 2m_s^2 \log \Lambda / m_s\right] \qquad \delta M^2_{Hf} = \frac{|g_f^2|}{16\pi^2}\left[-2\Lambda^2 + 6m_f^2 \log \Lambda / m_f\right]$$

note factor 2

In the SM divergences corresponding to physical objects are renormalized. However, the ratio of bare Higgs mass to the observed Higgs mass of $M_{Higgs} / M_{Planck} = 10^{-17}$ is considered to be unnatural → fine tuning problem

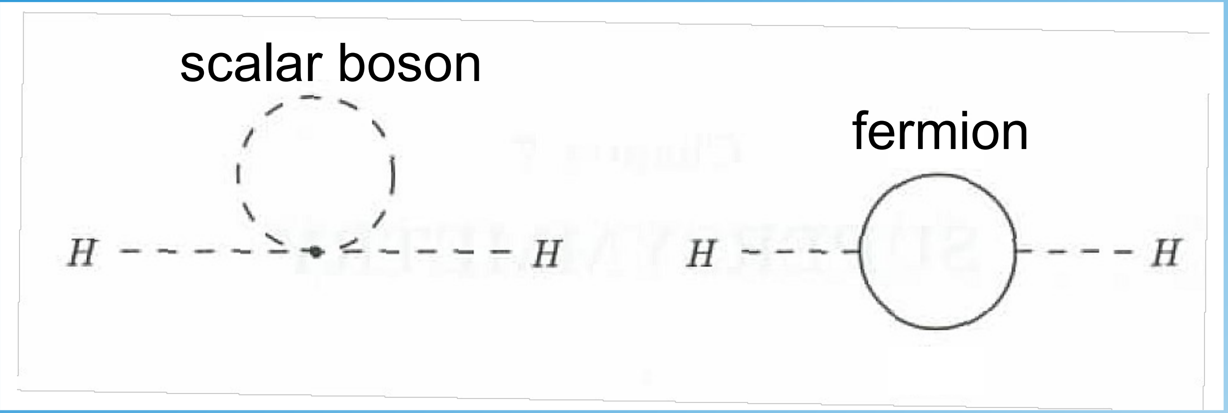
$$\delta M_H^2 = M^2_{H,bare} + \delta M_H^2$$

In SUSY the quadratic divergences from fermion loops are compensated by scalars. Only “usual” logarithmic divergences remain.

The Hierarchy Problem in the SM

SM Fine Tuning Problem

The Higgs mass acquires large radiative corrections



$$\delta M_{Hs}^2 = \frac{|\lambda_s^2|}{16\pi^2}\left[\Lambda^2 + 2m_s^2 \log \Lambda/m_s\right] \qquad \delta M_{Hf}^2 = \frac{|g_f^2|}{16\pi^2}\left[-2\Lambda^2 + 6m_f^2 \log \Lambda/m_f\right]$$

note factor 2

An exact cancellation happens if the number of scalars is twice the number of fermions

invent symmetry: **2 x # scalars $\leftrightarrow$ # fermions**

Superpartners

- Supersymmetry (SUSY) connects SM particles with SUSY partners

- SUSY partners are different from SM particles only in spin by -1/2. All other quantum numbers are identical

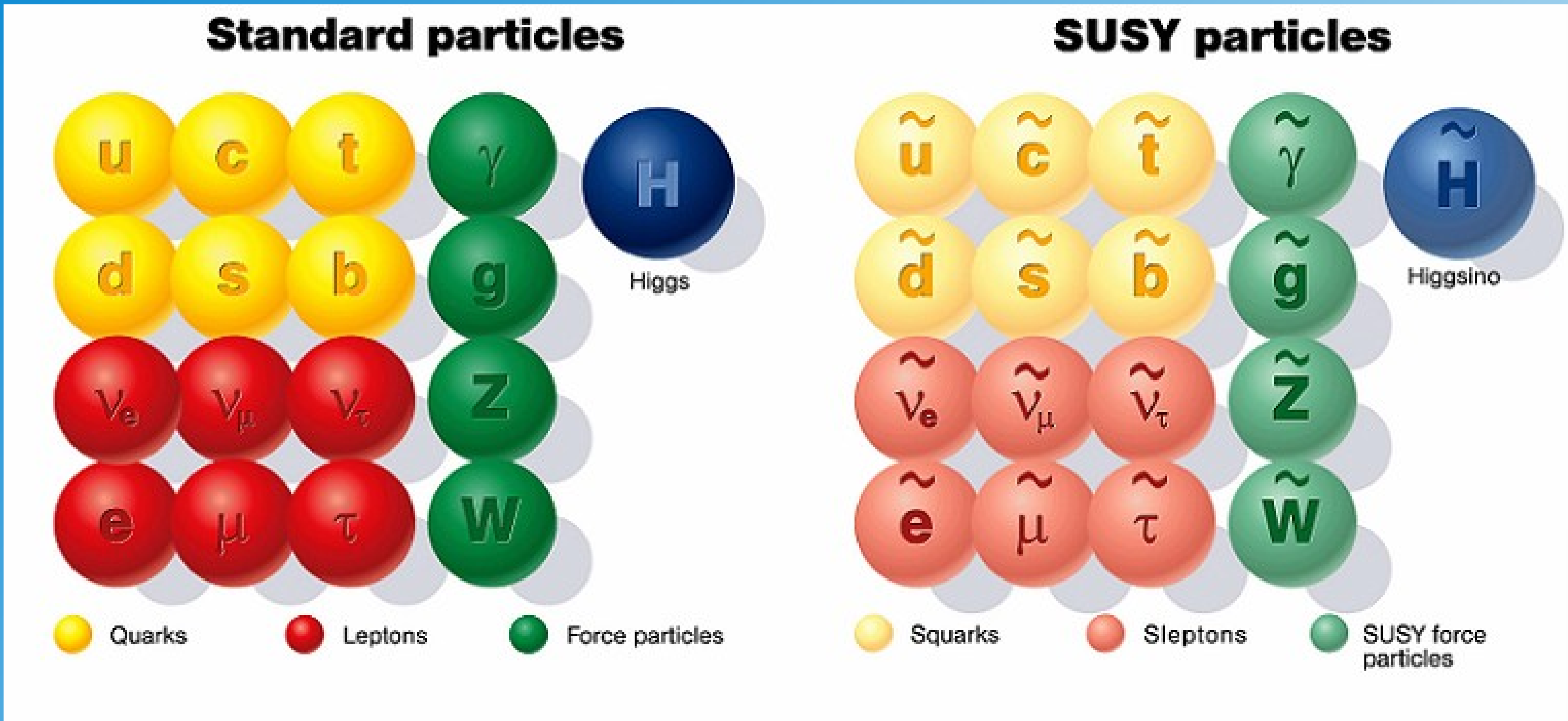
- SUSY is broken because we haven't seen SUSY particles yet (different mass of SM and SUSY particles)

- SUSY particles are SM partners with respect to the SM chiral particles and denoted in the following way:

$$e_L \rightarrow \tilde{e}_L$$
$$e_R \rightarrow \tilde{e}_R$$

- To each SM fermion correspond two SUSY particles!

Superpartners



actually, there are two Higgs doublets → 4 Higgs states!

- SUSY partners not seen (heavy) → SUSY is broken
- SUSY Breaking Scale should be ~ 1 TeV otherwise hierarchy problem reappears

Superpartners

Table 8.1 *Chiral supermultiplet fields in the MSSM.*

Names		spin 0	spin 1/2	$SU(3)_c, SU(2)_L, U(1)_y$
squarks, quarks (× 3 families)	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L) or (χ_u, χ_d)	**3**, **2**, 1/3
	$\bar{u}$	$\tilde{\bar{u}}_L = \tilde{u}_R^\dagger$	$\bar{u}_L = (u_R)^c$ or $\chi_{\bar{u}} = \psi_u^c$	$\bar{\mathbf{3}}$, **1**, −4/3
	$\bar{d}$	$\tilde{\bar{d}}_L = \tilde{d}_R^\dagger$	$\bar{d}_L = (d_R)^c$ or $\chi_{\bar{d}} = \psi_d^c$	$\bar{\mathbf{3}}$, **1**, 2/3
sleptons, leptons (× 3 families)	L	$(\tilde{\nu}_{eL}, \tilde{e}_L)$	(ν_{eL}, e_L) or (χ_{ν_e}, χ_e)	**1**, **2**, −1
	$\bar{e}$	$\tilde{\bar{e}}_L = \tilde{e}_R^\dagger$	$\bar{e}_L = (e_R)^c$ or $\chi_{\bar{e}} = \psi_e^c$	**1**, **1**, 2
Higgs, Higgsinos	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	**1**, **2**, 1
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	**1**, **2**, −1

Table 8.2 *Gauge supermultiplet fields in the MSSM.*

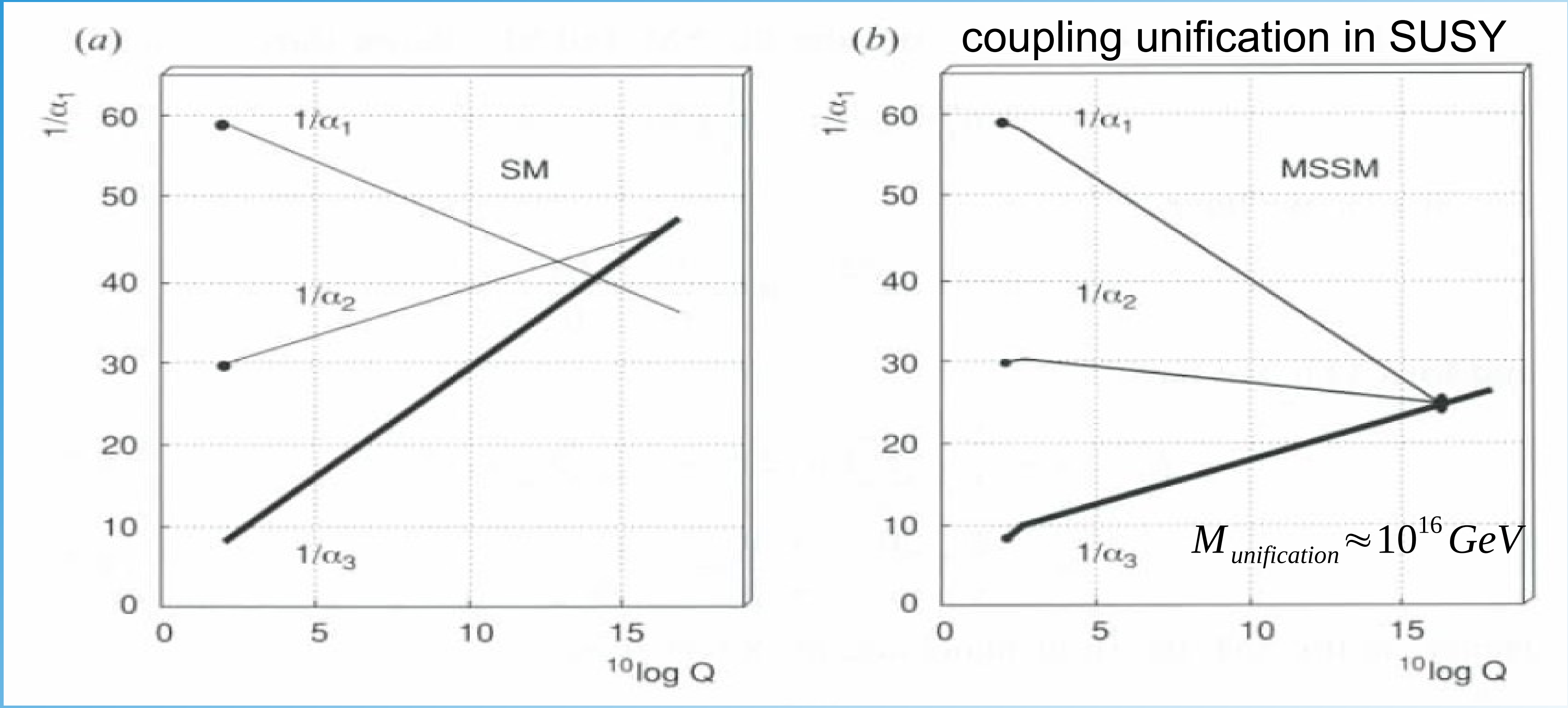
Names	spin 1/2	spin 1	$SU(3)_c, SU(2)_L, U(1)_y$
gluinos, gluons	$\tilde{g}$	g	**8**, **1**, 0
winos, W bosons	$\tilde{W}^\pm, \tilde{W}^0$	$W^\pm, W^0$	**1**, **3**, 0
bino, B boson	$\tilde{B}$	B	**1**, **1**, 0

SUSY Gauge Coupling Unification

logarithmic slopes:

SM: $\vec{b}^{SM} = (41/10, -19/6, -7)$

SUSY: $\vec{b}^{SM} = (33/5, 1, -3)$



Problems solved by SUSY?

- **(Too) many parameters (25)!**
- **Why three generations?**
- **Why so different masses (Yukawa couplings)**
- **Grand Unification (GUT) → couplings?**
- **Fine Tuning and Naturalness Problem of the Higgs Mass ($M_H < M_{planck}$)**
- **Ultraviolet catastrophe at high energies**
- **Unification with Gravitation?**
- **Mechanism of CP violation?**

What breaks SUSY?

Different models developed:

- SuperGravity SUSY-Breaking (SUGRA)
- Gauge Mediated SUSY-Breaking (GMSB)
- Anamolous Mediated Gravity SUSY-Breaking (AMSB)
- ….

How man Parameters in SUSY?

too many!

- 124 parameters in Minimal SUSY Model (MSSM)

Simplified models often used:

- constrained MSSM
- Supergravity models (mSUGRA)
- ...

SUSY breaking and the large number of parameters are concerns!

MSSM Parameters

- Coulings: g_s, g, g' corresponding to the SU(3) x SU(2) x U(1) gauge groups
- Higgsino mass parameter μ
- Higgs-Fermion Yukawa coupling y_u, y_d, y_e (fermion-Higgs, sfermion-Higgsino)

<u>SUSY breaking parameters:</u>

Masses:

- gaugino masses M_3 , M_2 , M_1 associated to SU(3) x SU(2) x U(1)
- scalar squared mass parameters

  $M^2_{\tilde{Q}}$, $M^2_{\tilde{U}}$, $M^2_{\tilde{D}}$, $M^2_{\tilde{L}}$, $M^2_{\tilde{E}}$ corresponding to $(u,d)_L$, u^c_L , d^c_L , $(\nu, e^-)_L$, e^c_L

- trilinear Higgs-sfermion-sfermion couplings: A_u, A_d, A_e
- scalar Higgs mass parameters: $m_1^2+\mu^2$, $m_2^2+\mu^2$, $m_{12}^2=B\mu$

  can also be re-expressed by: $\tan\beta=v_u/v_d$ $\quad v_u^2+v_d^2=(246\,GeV)^2$

In total 124 parameters in MSSM

SUSY Phenomenology

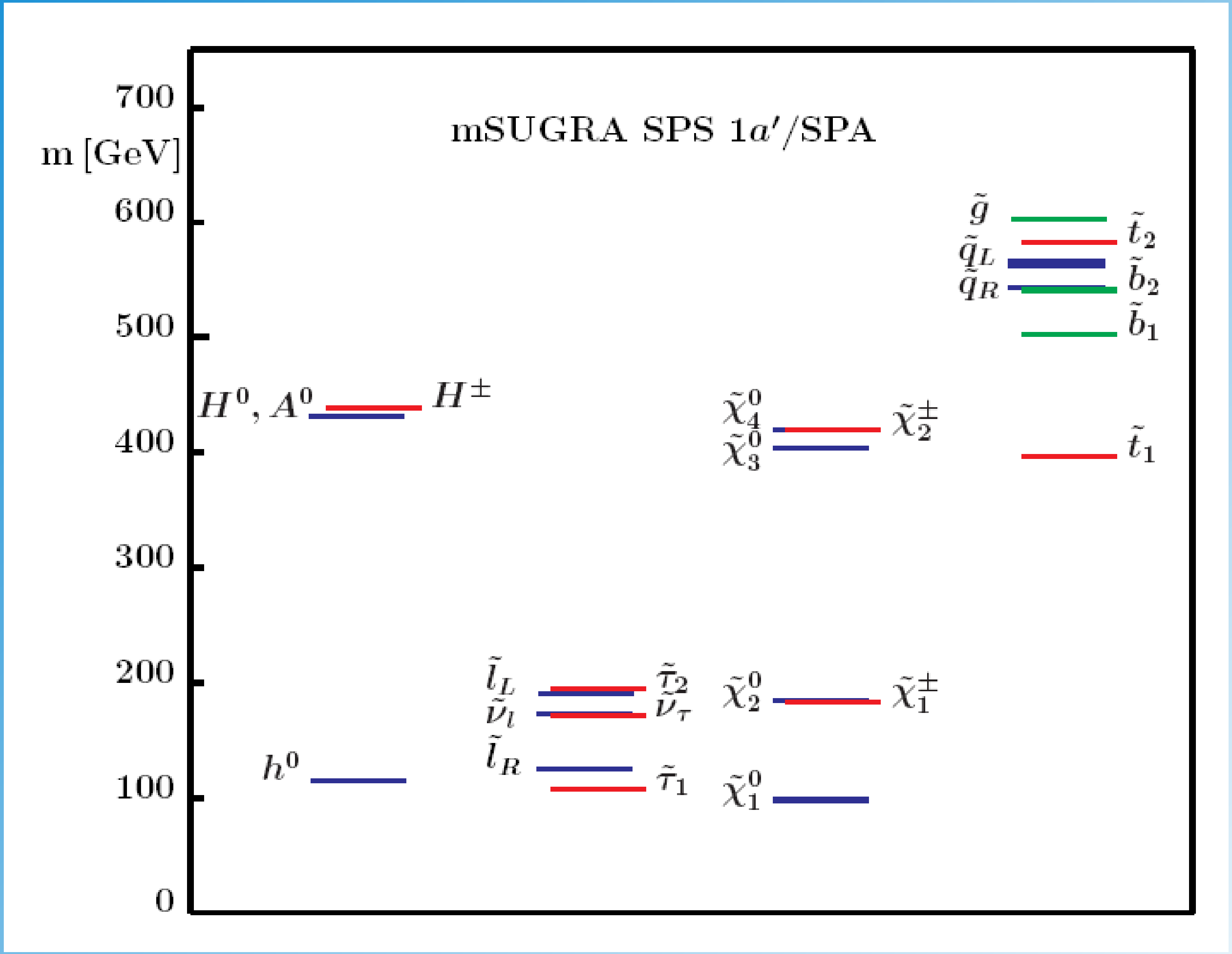
- particle spectrum is rich and complicated
- several particles can mix!

$$\tilde{B}, \tilde{W}^0, \tilde{H}, \tilde{h} \rightarrow \chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0$$ neutralinos

$$W^{\pm}, H^{\pm} \rightarrow \chi_1^{\pm}, \chi_2^{\pm}$$ charginos

Masses of states depend on SUSY-breaking scheme and parameters

SUSY Mass Phenomenology



SUSY Mass Phenomenology

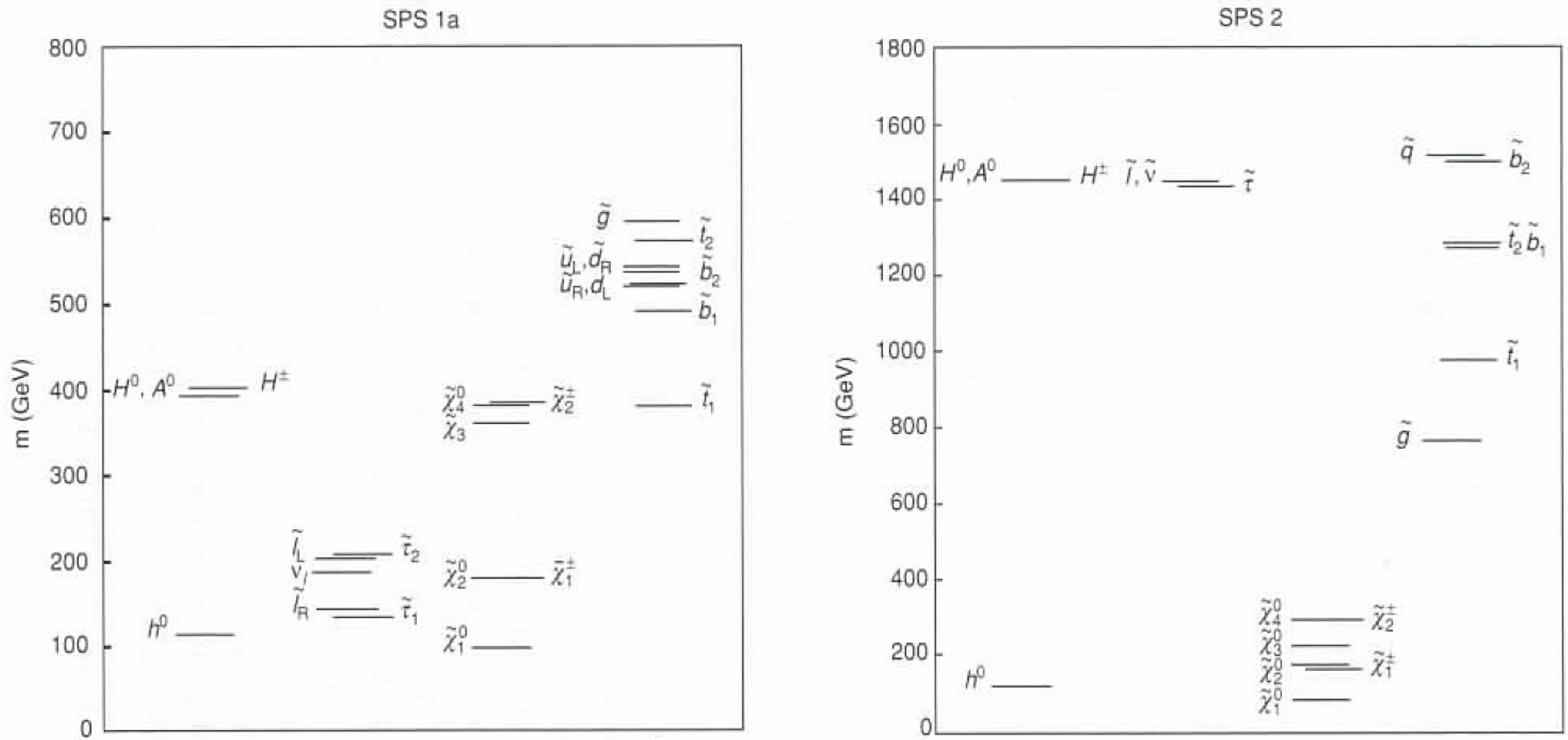


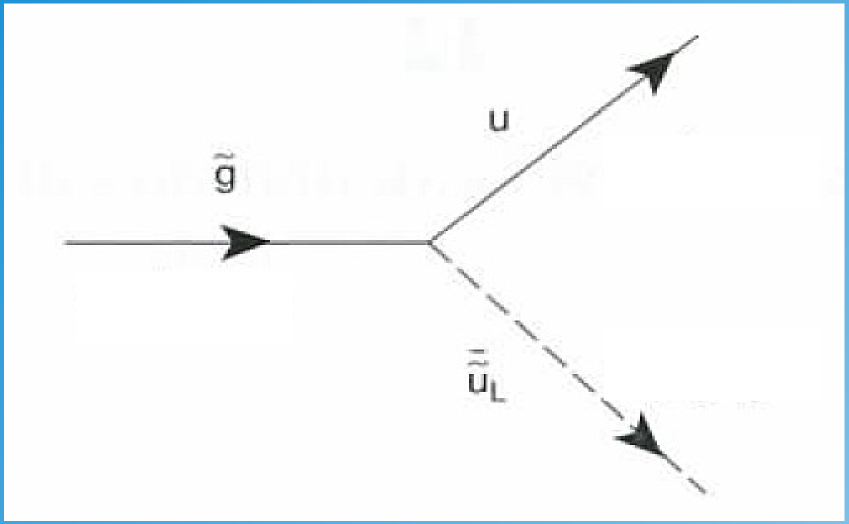
Figure 12.10 The SUSY particle spectra for the benchmark points corresponding to the parameter values SPS 1a (equation (12.155)) and SPS 2 (equation (12.156)). [From B. C. Allanach, *et al.*, *Eur. Phys. J.* **C25** Figure 1, p. 118 (2002), reprinted with the permission of Springer Science and Business Media.]

comparison of two different parameters sets (“Snowmass Points”)

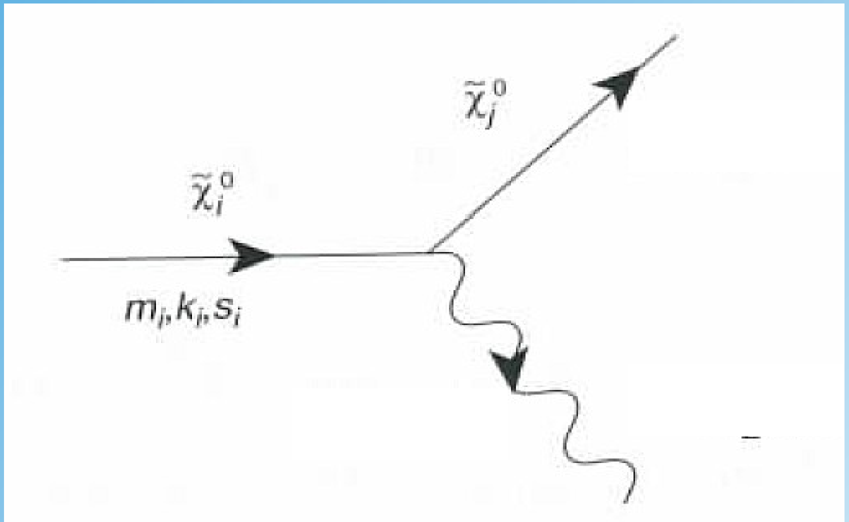
both are excluded in the meantime...

SUSY R_P-Conserving Couplings

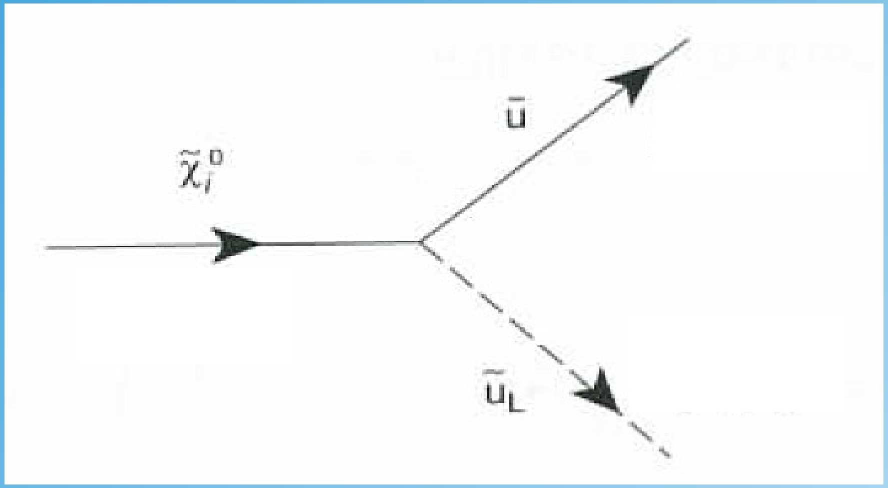
Gluino-squark-quark:



Neutralino-Neutralino-Z-boson:



Neutralino-squark-quark:



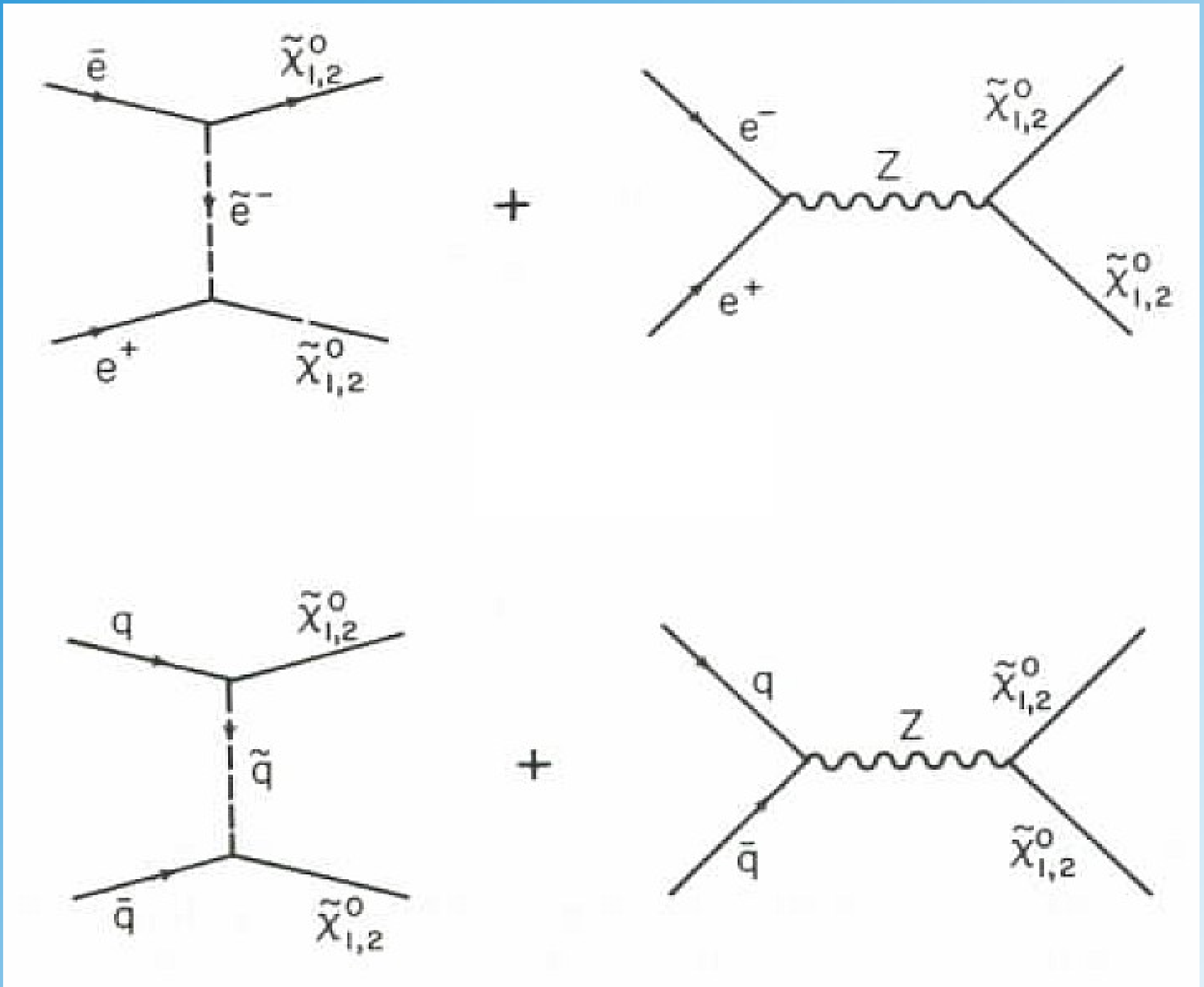
$$R|SM\rangle = 1 \quad R|SUSY\rangle = -1$$

- R_P is a multiplicative quantum number
- if conserved SUSY particles can only produced in pairs and “SUSYness” is conserved in decays

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

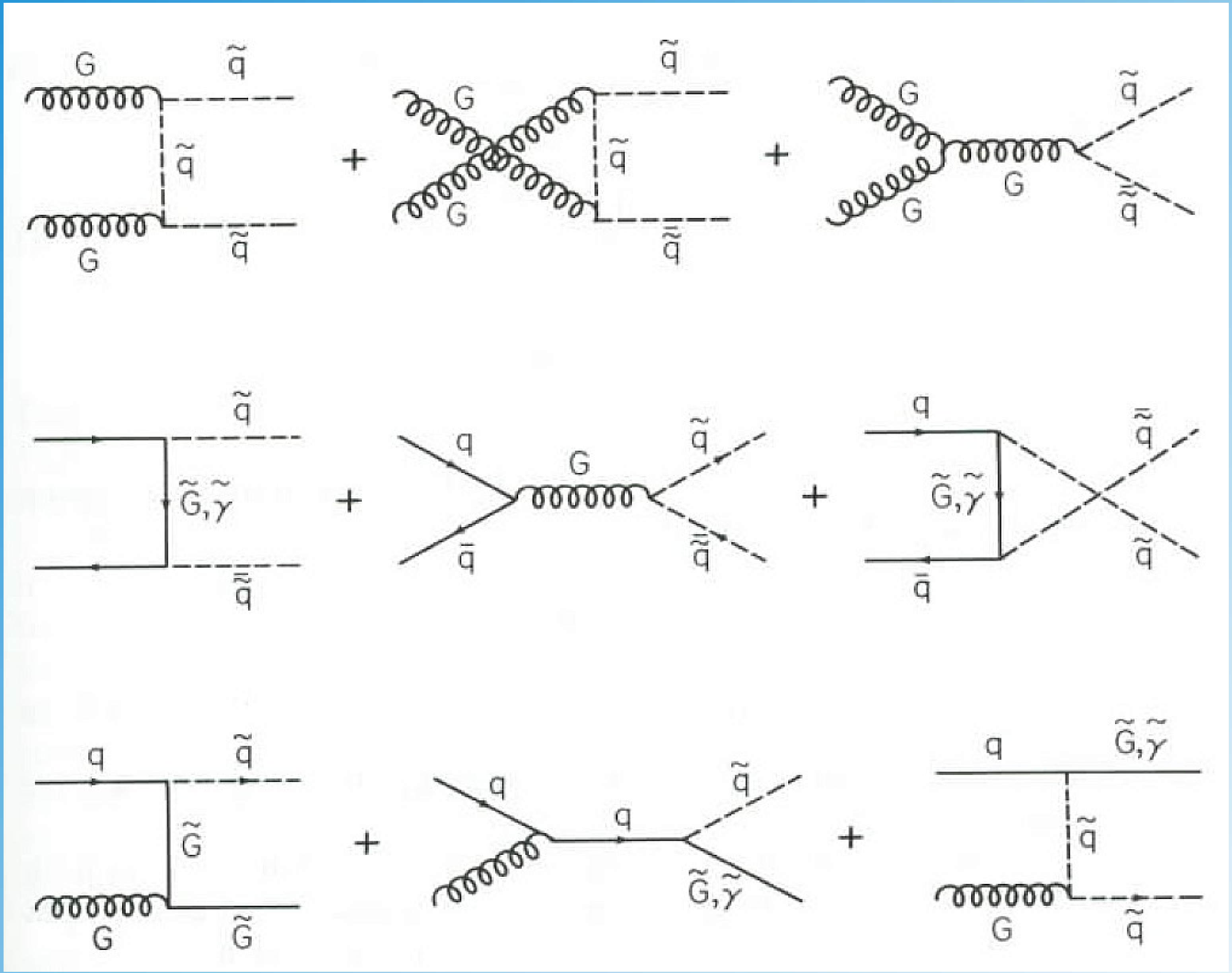
SUSY Feynman Graphs

Neutralino Pair-Production:



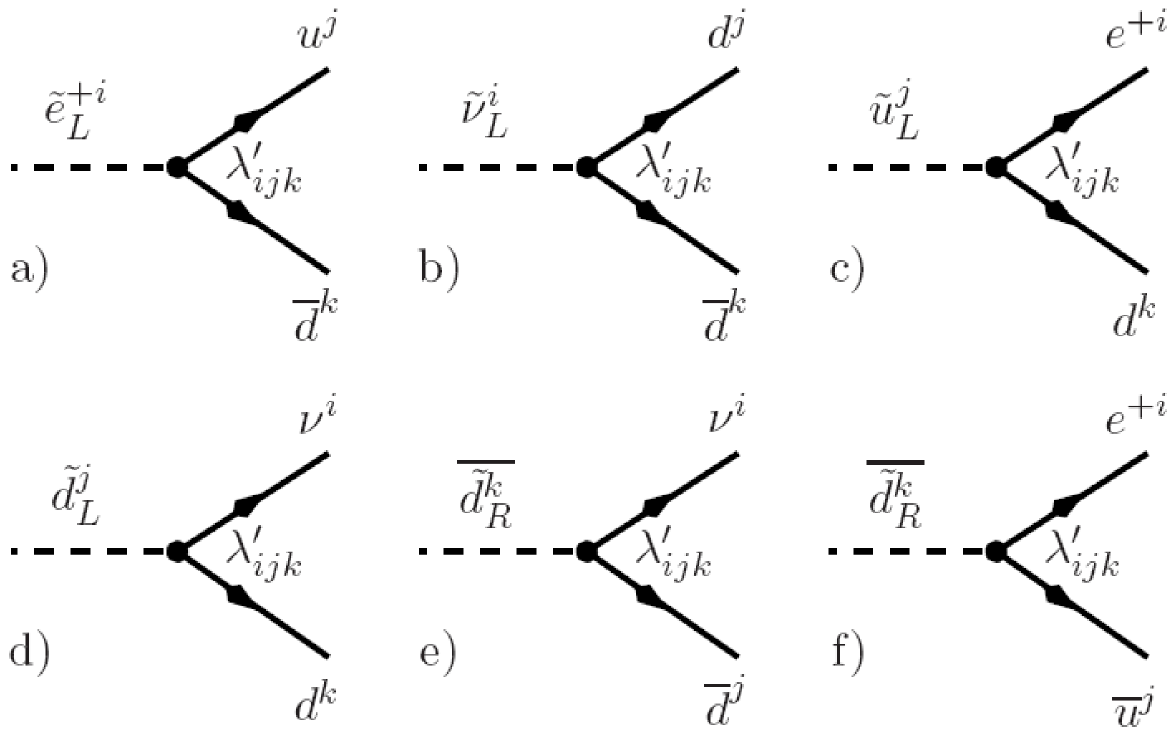
SUSY Feynman Graphs

SUSY production in hadron interactions (e.g. LHC)



R-Parity Violating Coulings

Trilinear RPV-Yukawa Couplings:



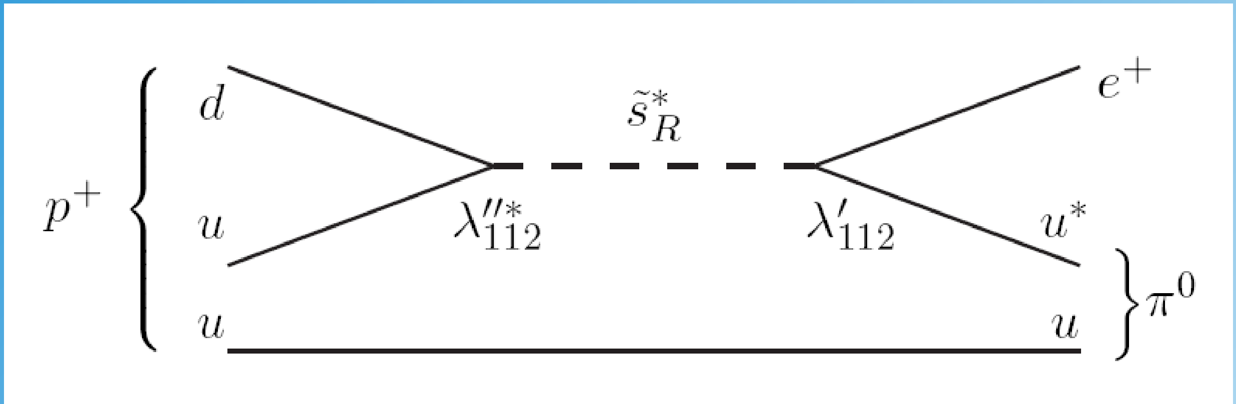
$$\mathcal{L}_{L_i Q_j \overline{D}_k} = \lambda'_{ijk} \Big[-\tilde{e}^i_L u^j_L \bar{d}^k_R - e^i_L \tilde{u}^j_L \bar{d}^k_R - (\bar{e}^i_L)^c u^j_L \tilde{d}^{k*}_R + \tilde{\nu}^i_L d^j_L \bar{d}^k_R + \nu_L \tilde{d}^j_L \bar{d}^k_R + (\bar{\nu}^i_L)^c d^j_L \tilde{d}^{k*}_R \Big] + \text{c.c.}.$$

lightest SUSY particle (dark matter candidate!) not stable

RPV sparticles decay: $\Gamma_{RPV} = \frac{1}{16\pi} \lambda^2_{ijk} M_{\tilde{q}}$ (but could be long-lived)

L,B Number Violation and R-Parity

if R-parity is violated with first generation couplings ΔL=1 and ΔB=1, the proton would undergo a catastrophic decay:



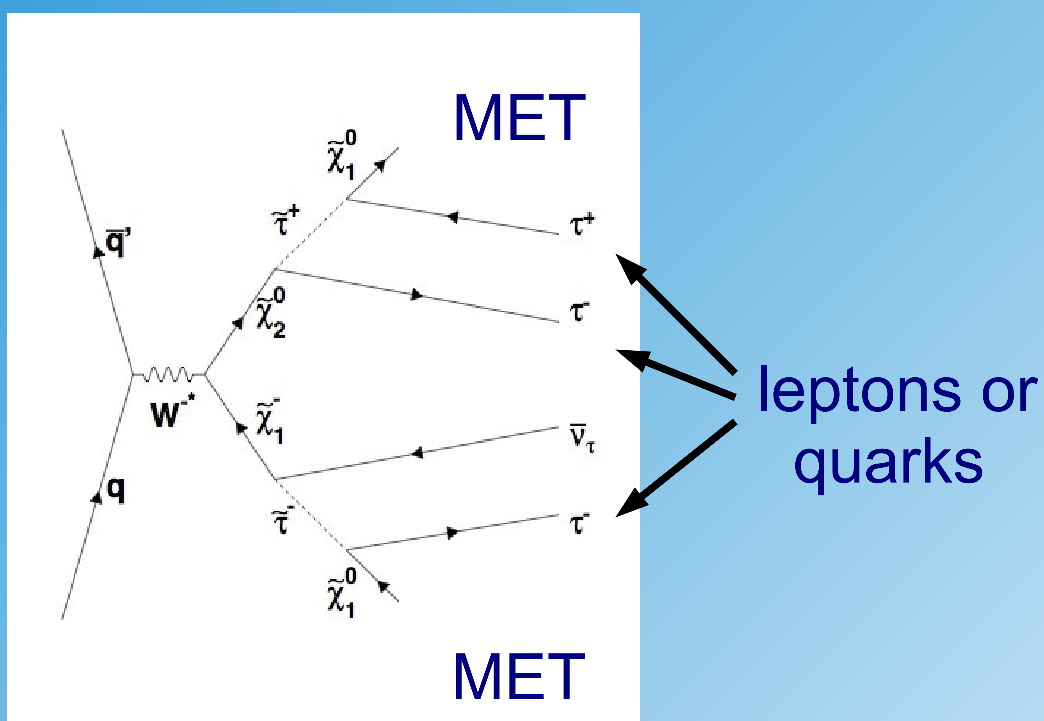
$$L_{\Delta L=1} = \frac{1}{2}\lambda^{ijk} L_i L_j \bar{e}_k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \mu^i L_i H_u$$

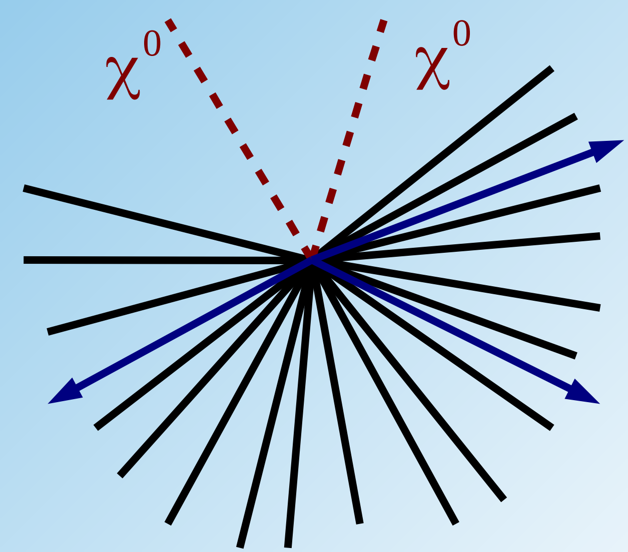
$$L_{\Delta B=1} = \frac{1}{2}\lambda''^{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

RP-Violating couplings are not excluded in general
but many combinations of non-zero terms are constrained!

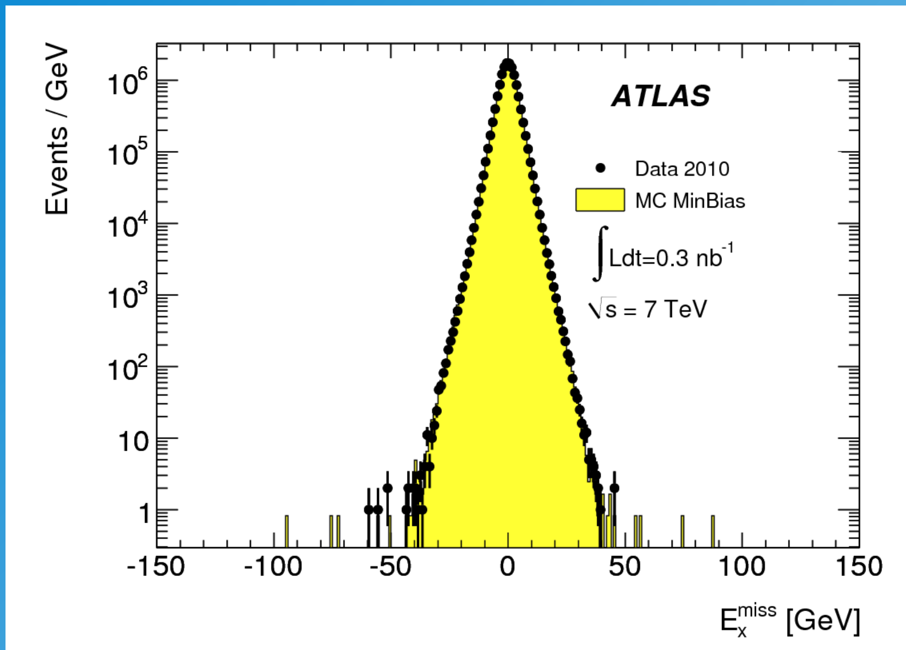
Experimental Search Strategy at LHC

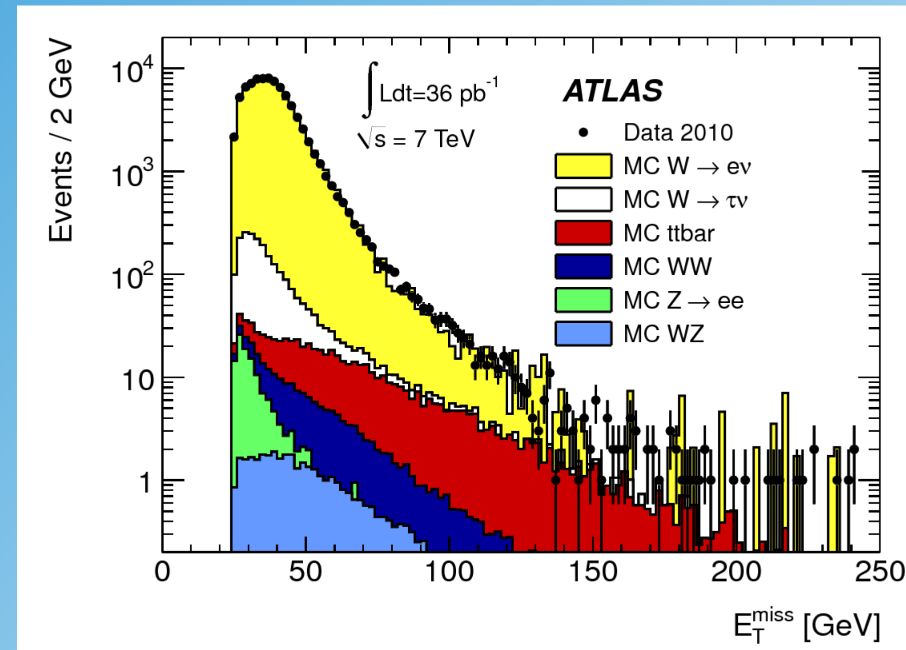
- Assumption: R_P is conserved
- SUSY particles produced in pairs will decay in cascades
- In many models the neutralino is the lightest SUSY particle and stable
- The neutralino escapes detection and leads to missing energy in the detector

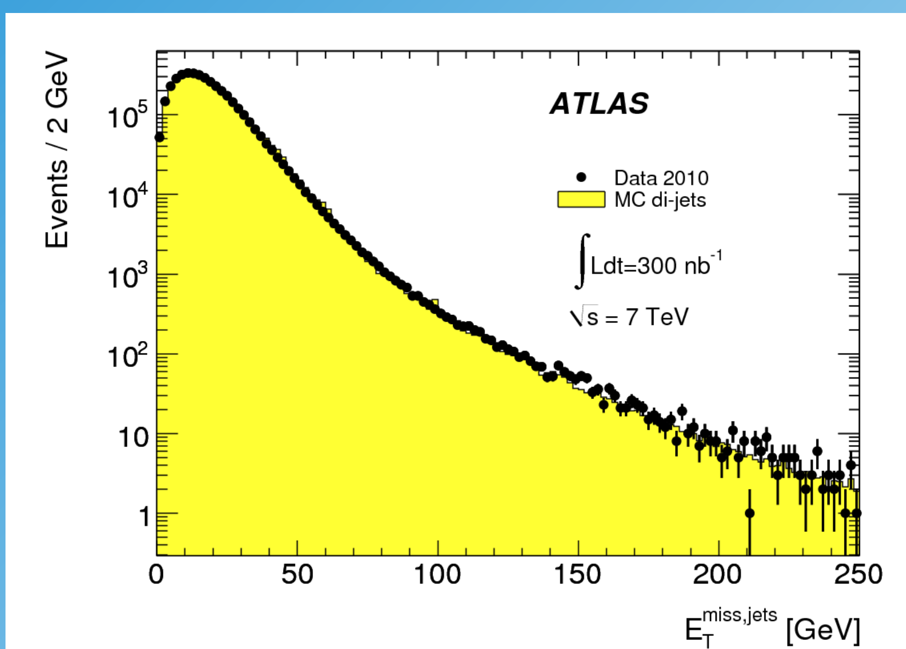


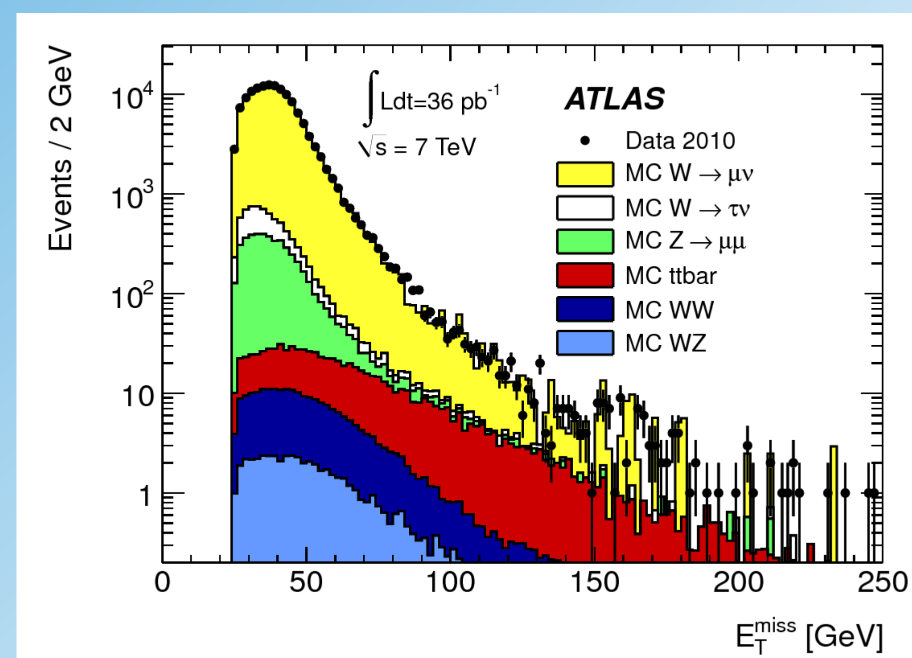


E_T^{miss} Performance

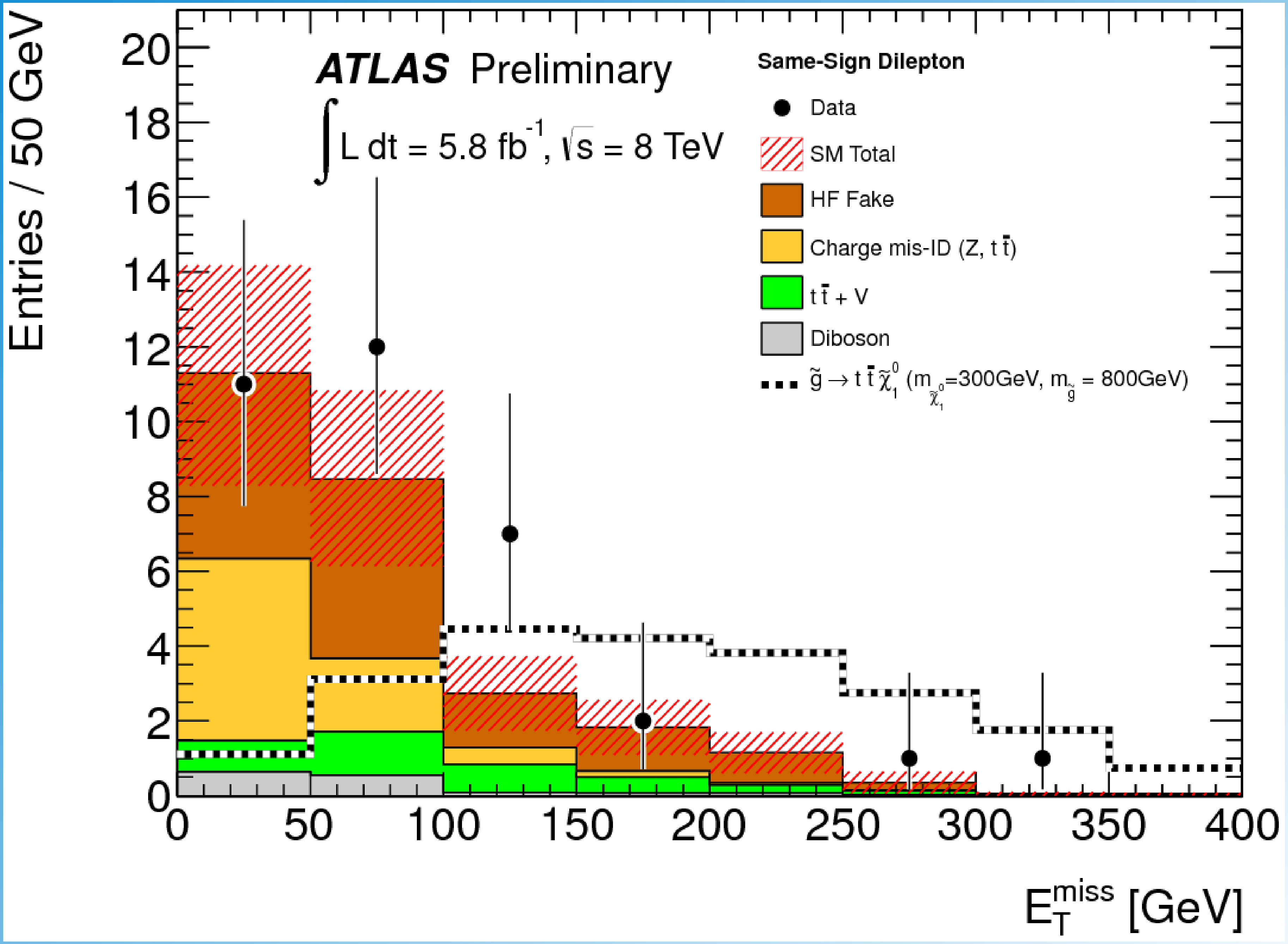




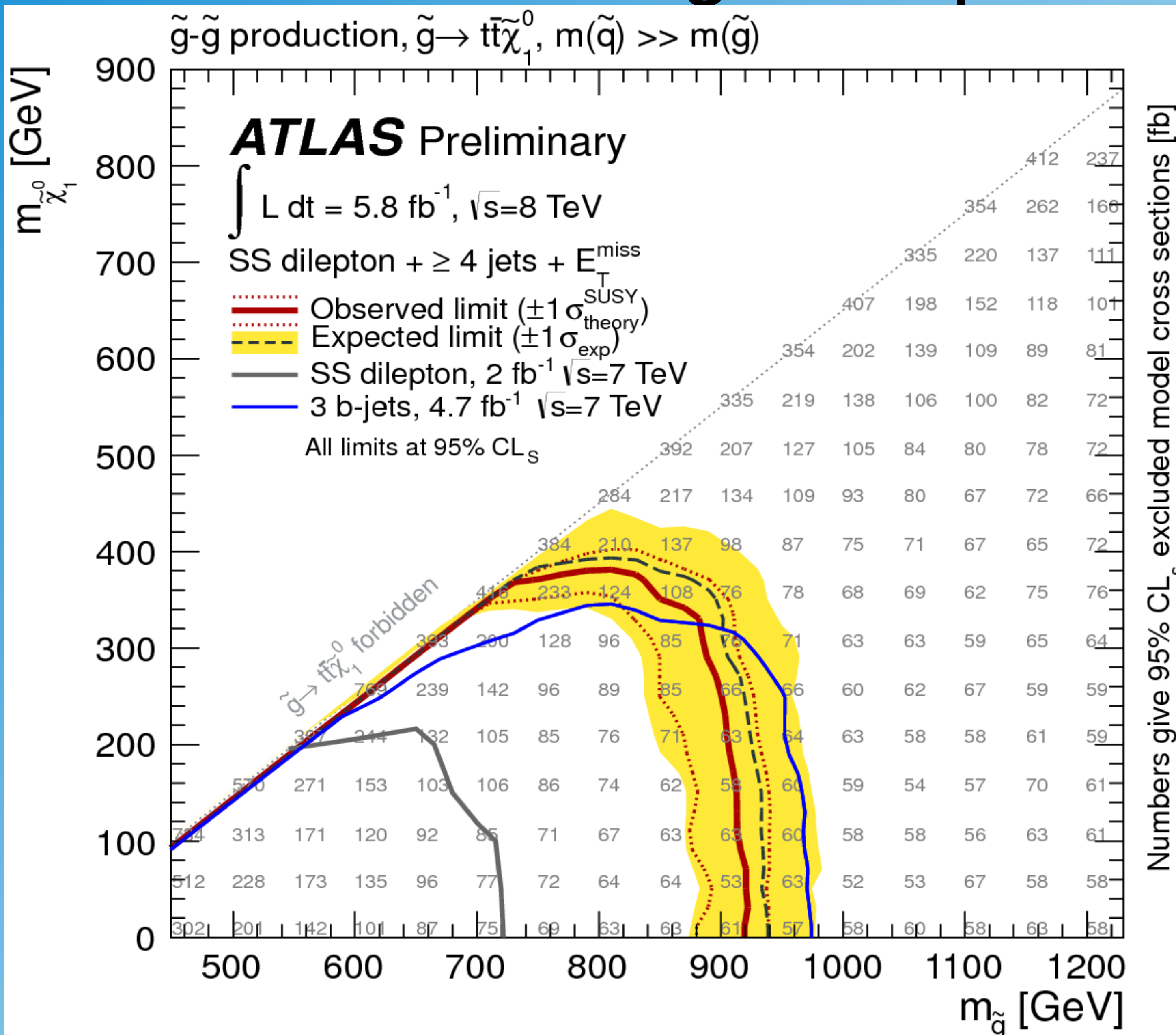




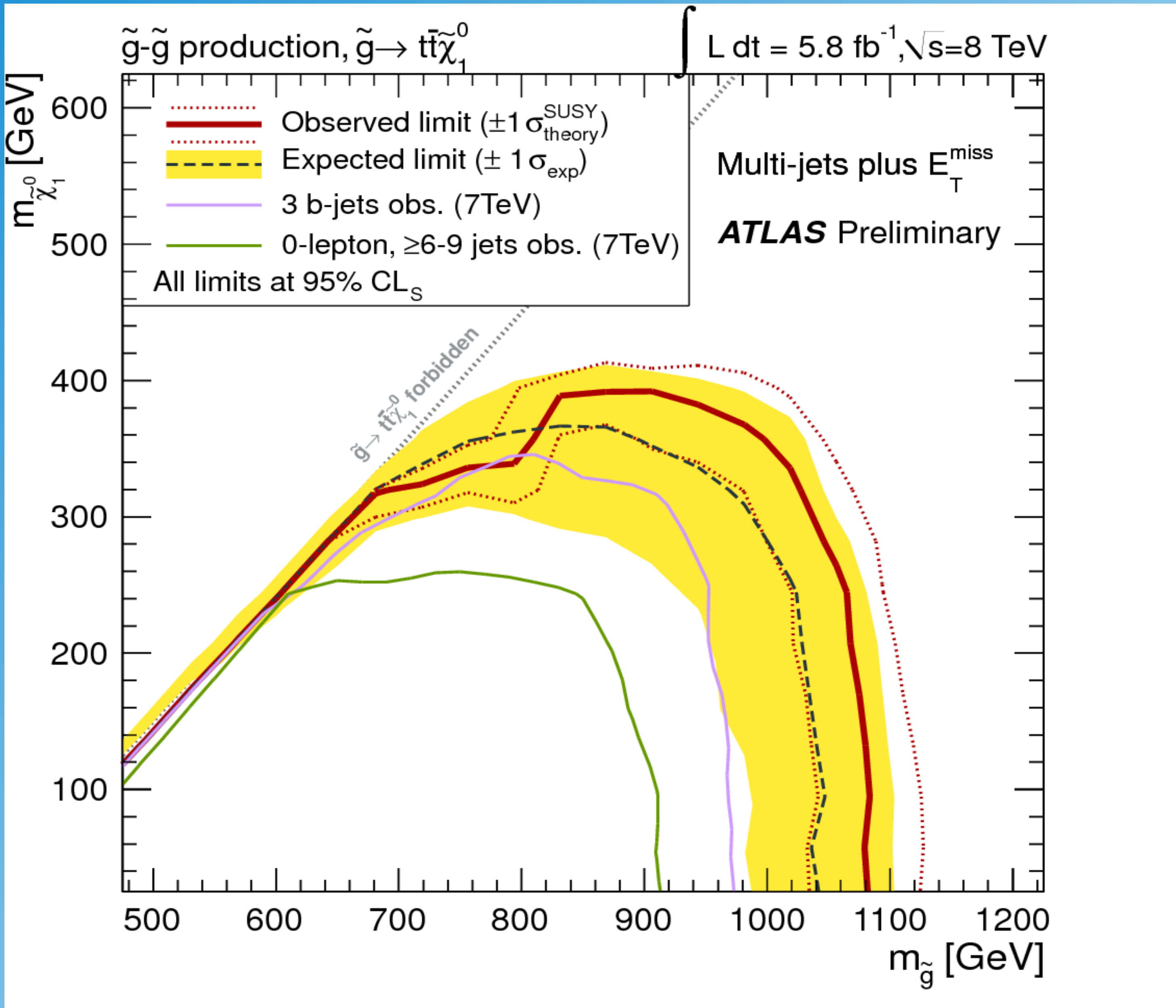
Same Charge Dilepton Sample



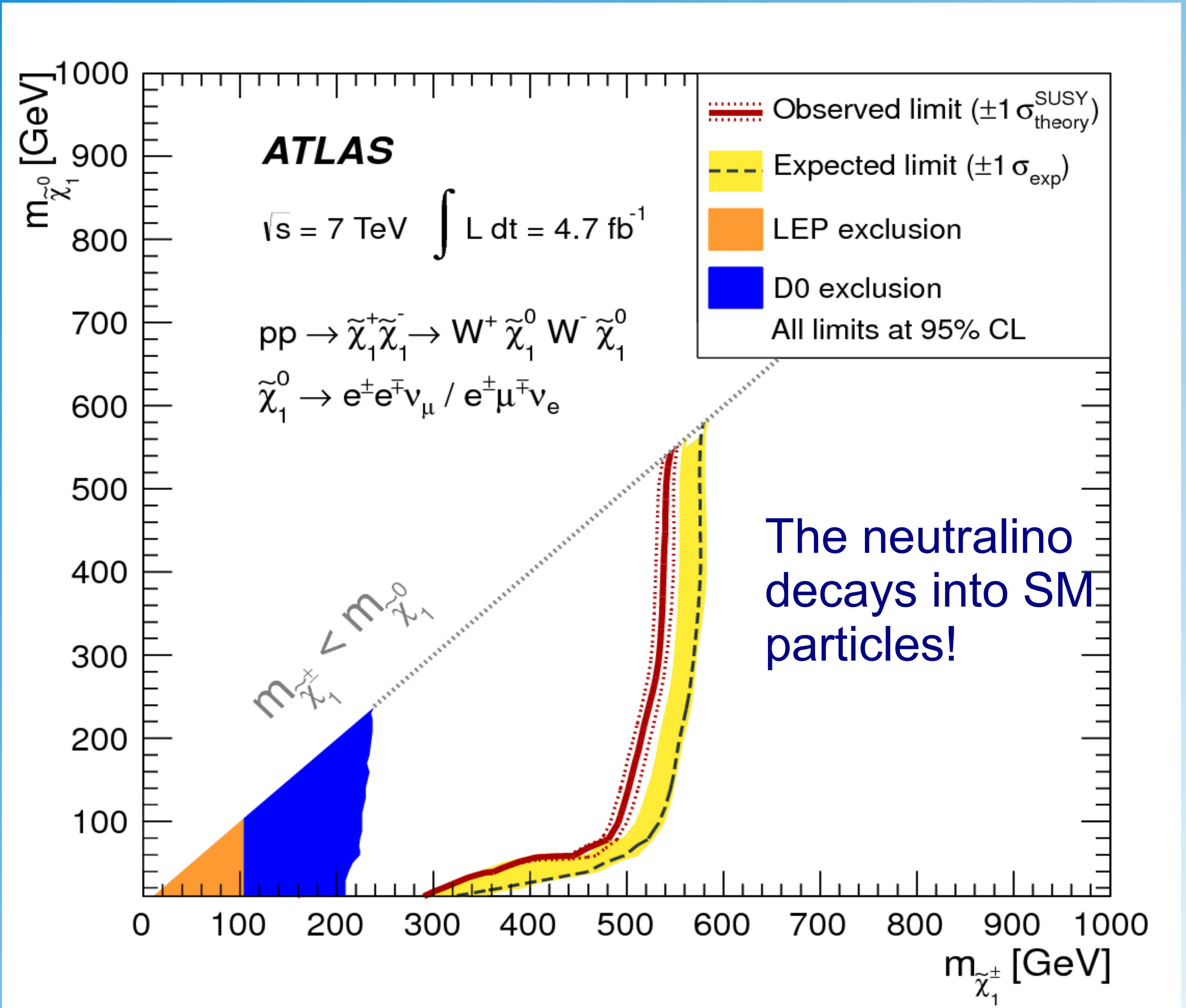
Search for SUSY in Top-Quark Final States with same charge Dileptons



Search for SUSY in Top-Quark Final States without Leptons

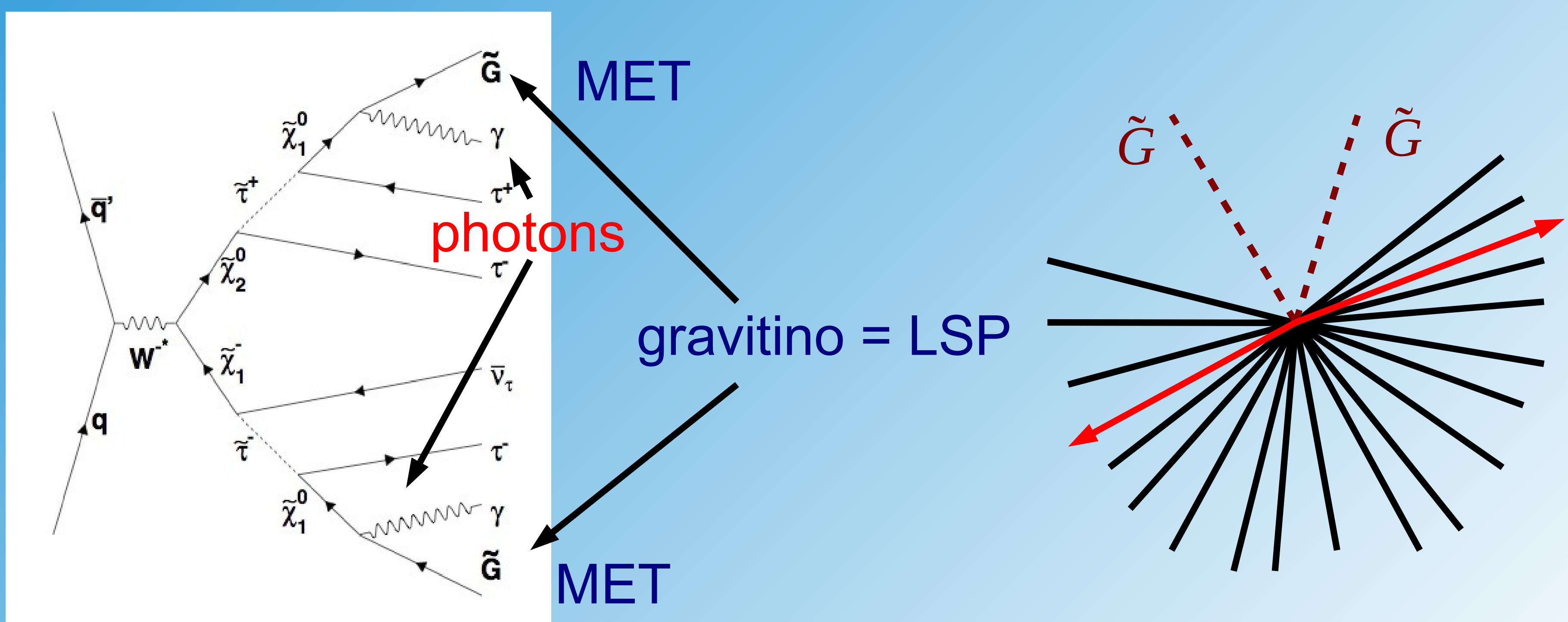


R_P Violation (RPV) Searches

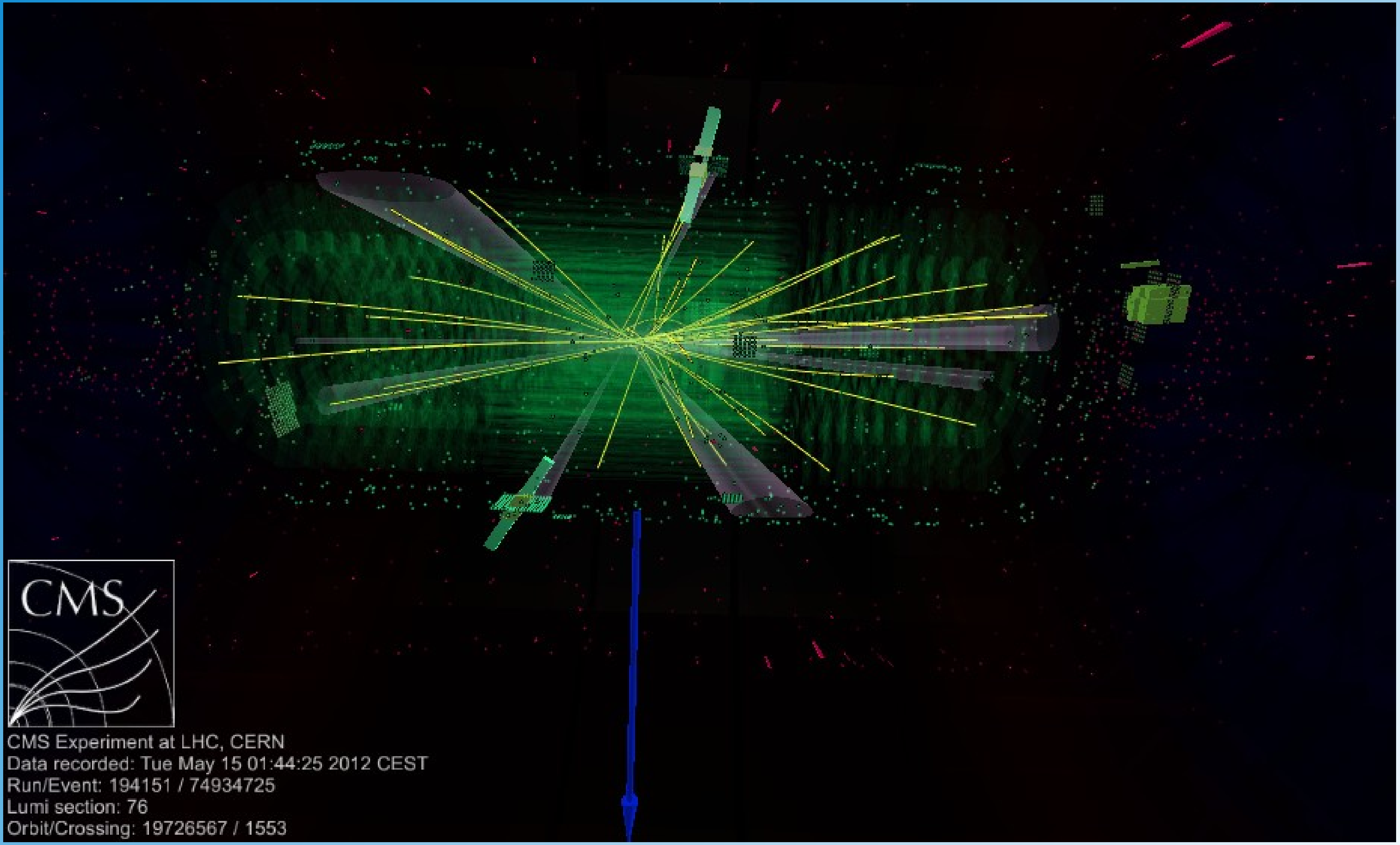


Search for GMSB-SUSY at LHC

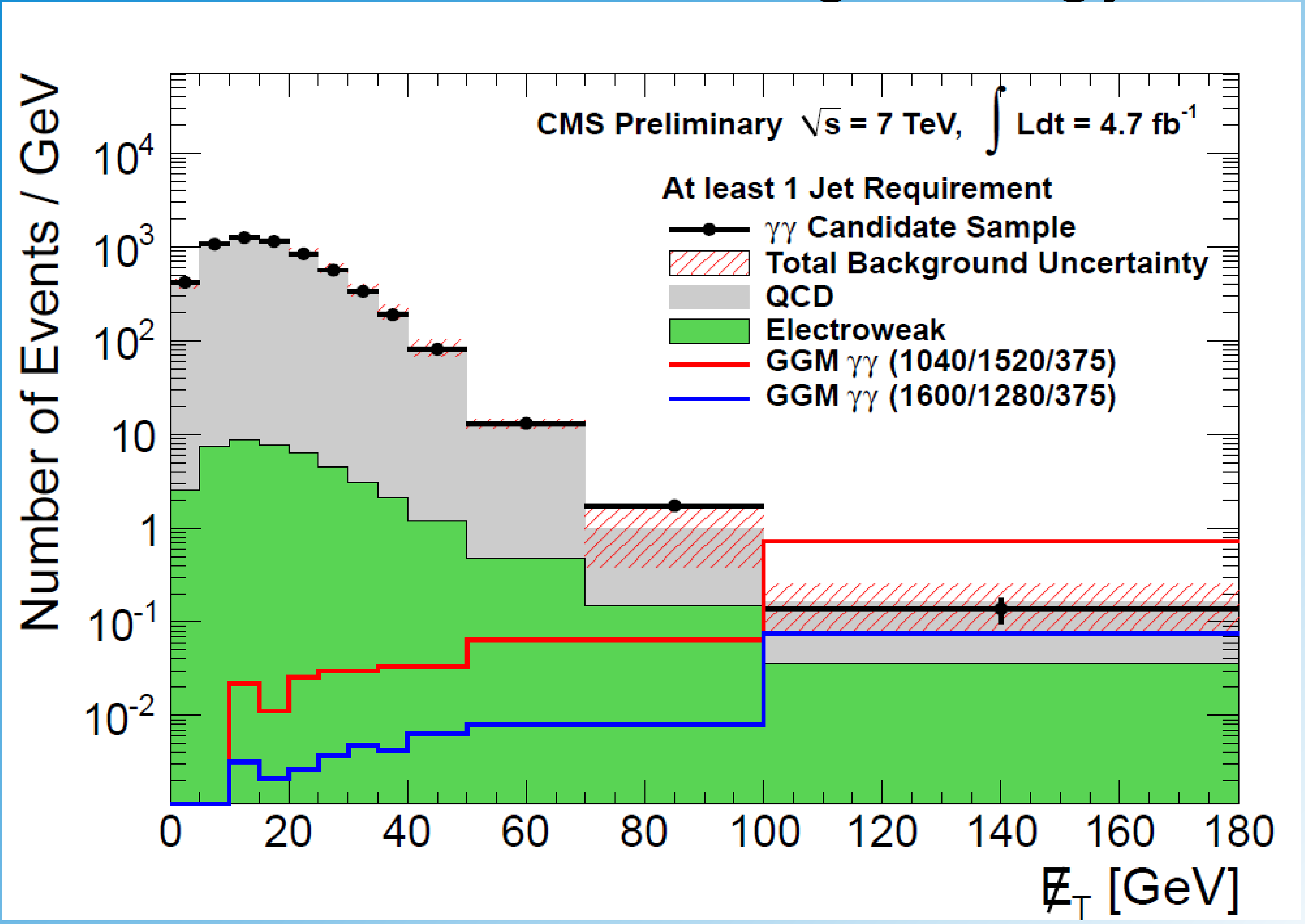
- Assumption: R_P is conserved
- In GMSB models the gravitino is the LSP (can be very light!)
- The neutralino is the NLSP and decays to photon and gravitino
- Search Topology: MET + photons



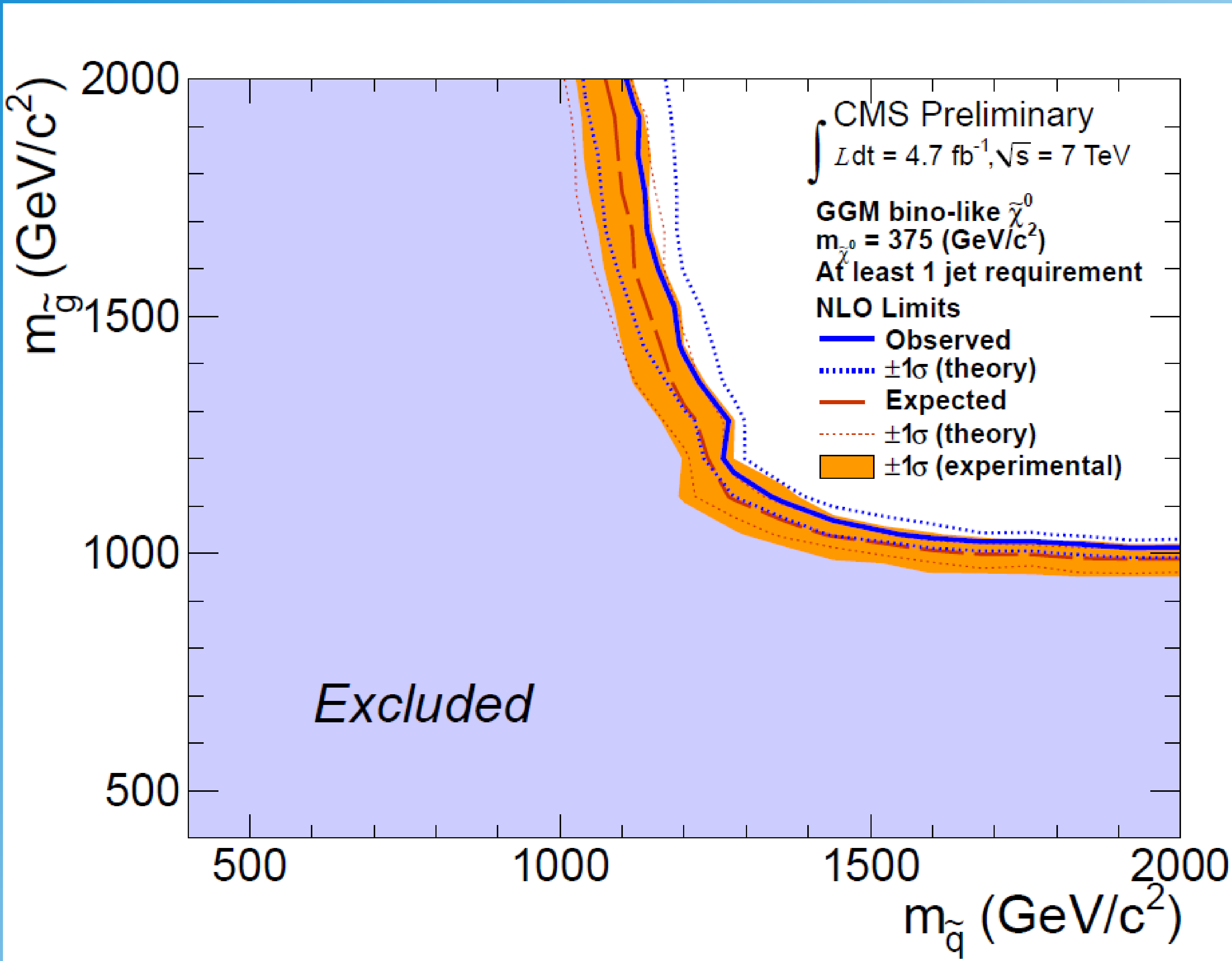
CMS Two Photon Event



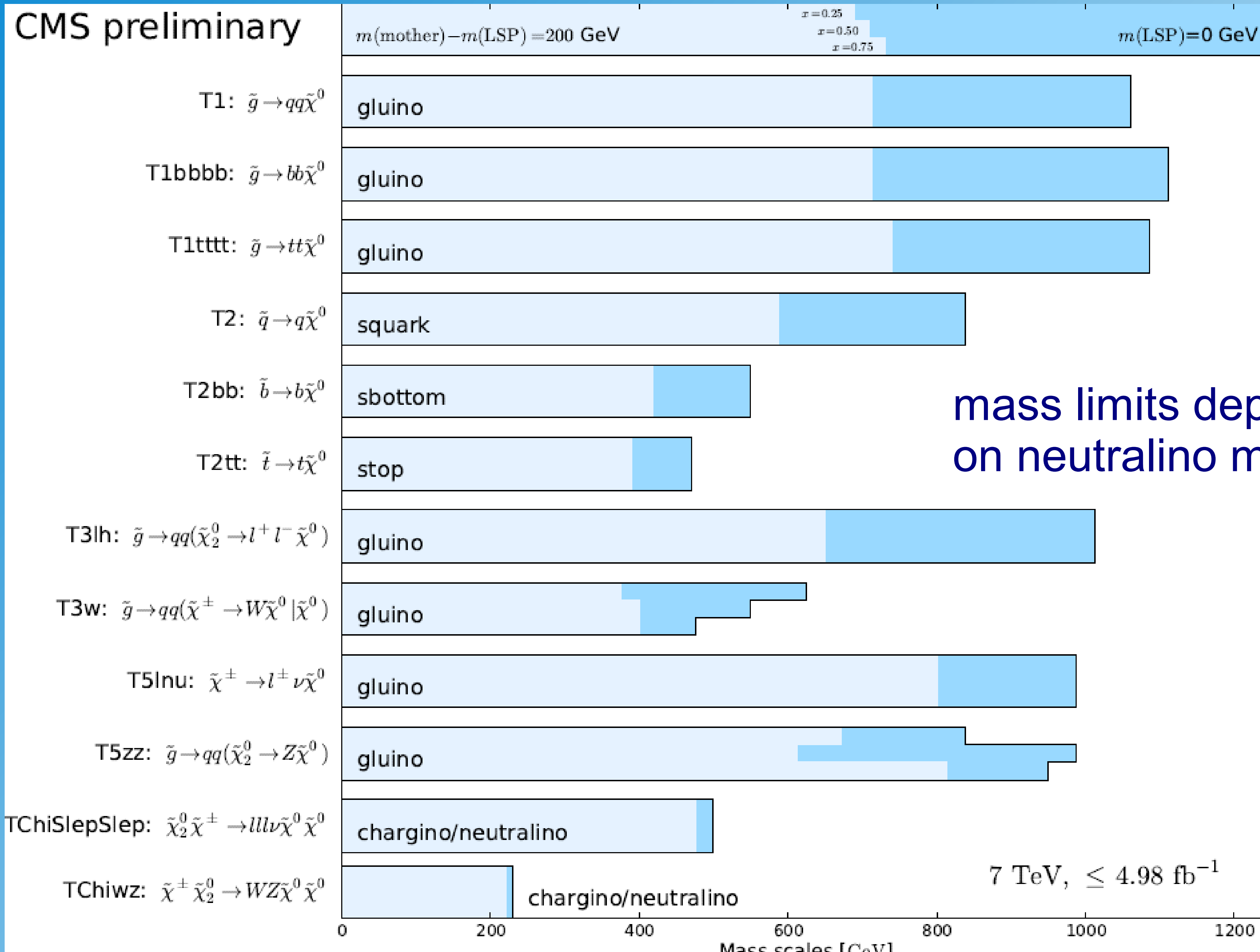
Di-Photon Missing Energy



CMS Results (GMSB)



Overview CMS Results (MSSM)



mass limits depending on neutralino mass

Other SUSY Searches

Discussed:

- MSSM SUSY searches with neutralino in final state (missing E_T)
- Searches with photons and gravitinos in final state (missing E_T)
- Searches with same-charge leptons and missing E_T
- Searches with R-parity violation

Not Discussed:

- Many more (complex) topologies exist and studied
- SUSY particles could be long-lived and massive (highly ionizing)
- SUSY particles could decay half way in the detector (kinks)
- SUSY particles could form R-hadrons (SUSY-hadrons) which interact in the detector
- and, and, and ….

Summary

- **Despite the fact that the cross section for the production of light SUSY particles is large at LHC, no sign of SUSY seen yet (in most simple models and analysis)**

- **Searches will continue with larger datasets and at higher beam energies ($s^{1/2}$=14 TeV). More complex models will be studied. Main problem is that the mechanism of SUSY breaking is unknown.**

- **SUSY cannot experimentally ruled at at LHC if the SUSY mass scale is large. However, than it would not solve the fine tuning problem.**