



March 2nd - 9th, 2013
EW INTERACTIONS AND UNIFIED THEORIES

SUSY (Pheno) Today

Dmitry Kazakov

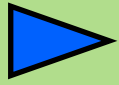
BLTP JINR (Dubna)

Why SUSY?

SUSY at TeV scale:

-  Provides the Unification of the gauge couplings
-  Solves the hierarchy problem
-  Explains the electroweak symmetry breaking
-  Provides the Dark matter candidate

SUSY:

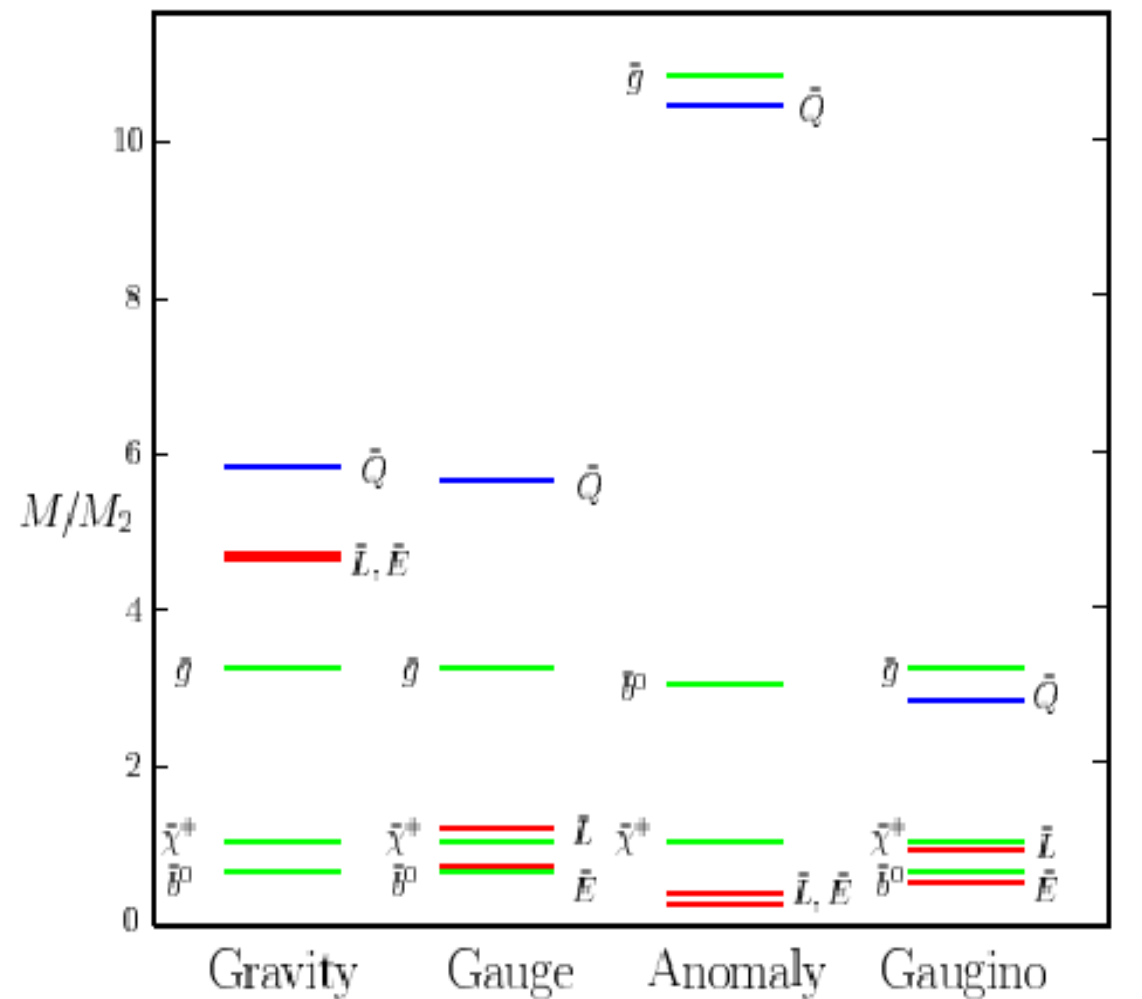
-  Provides Unification with gravity
-  Required for the String/Brane picture
-  Maximal SUSY theories might be integrable -
 a way to nonperturbative solutions and quantum gravity

SUSY Models

What
SUSY?

MSSM
CMSSM
mSUGRA
mGMSB
mAMSB
NUHM
NMSSM
No Scale
Split SUSY
...

Sample superparticle spectrum



Despite supersymmetric rigidity of dimensionless couplings the arbitrariness of soft terms make predictions strongly model dependent !

SUSY Particles

Particle Content of the MSSM

Superfield	Bosons		Fermions	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$	
Gauge							
G^a	gluon	g^a	gluino $\tilde{g}^a$	8	1	0	
V^k	Weak	$W^k(W^\pm, Z)$	wino, zino $\tilde{w}^k(\tilde{w}^\pm, \tilde{z})$	1	3	0	
V'	Hypercharge	$B(\gamma)$	binos $\tilde{b}(\tilde{\gamma})$	1	1	0	
Matter							
L_i	sleptons	$\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$ $\tilde{E}_i = \tilde{e}_R$	leptons	$L_i = (\nu, e)_L$ $E_i = e_R^c$	1	2	-1
E_i					1	1	2
Q_i	squarks	$\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$ $\tilde{U}_i = \tilde{u}_R$ $\tilde{D}_i = \tilde{d}_R$	quarks	$Q_i = (u, d)_L$ $U_i = u_R^c$ $D_i = d_R^c$	3	2	1 / 3
U_i					3^*	1	-4 / 3
D_i					3^*	1	2 / 3
Higgs							
H_1	Higgses	H_1 H_2	higgsinos	$\tilde{H}_1$ $\tilde{H}_2$	1	2	-1
H_2					1	2	1

Search for SUSY Manifestation

Particle Phys

- 📌 Direct production at colliders at high energies
- 📌 Indirect manifestation at low energies
 - Rare decays ($B_s \rightarrow s\gamma$, $B_s \rightarrow \mu^+\mu^-$, $B_s \rightarrow \tau\nu$)
 - g-2 of the muon
- 📌 Search for long-lived SUSY particles

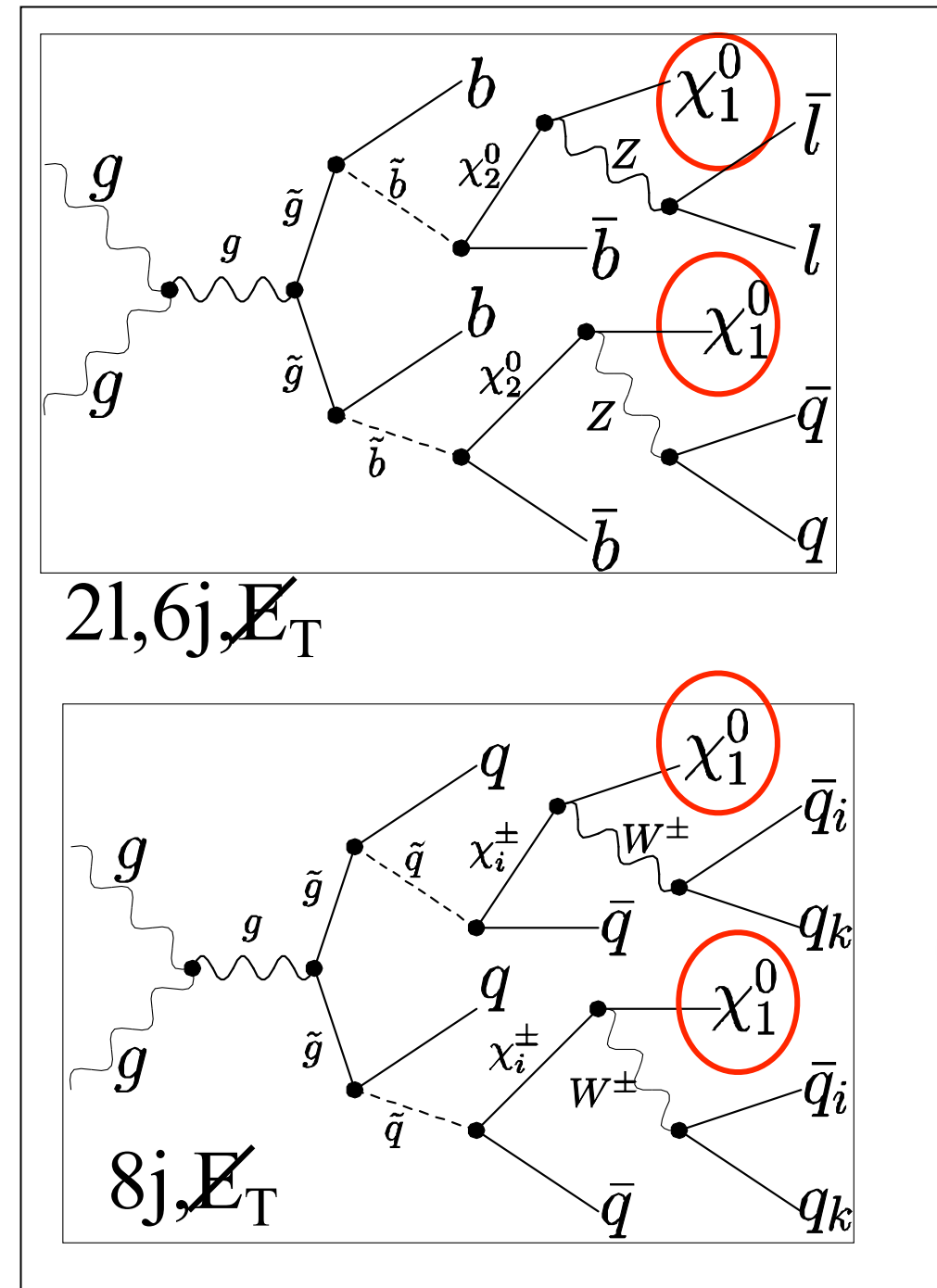
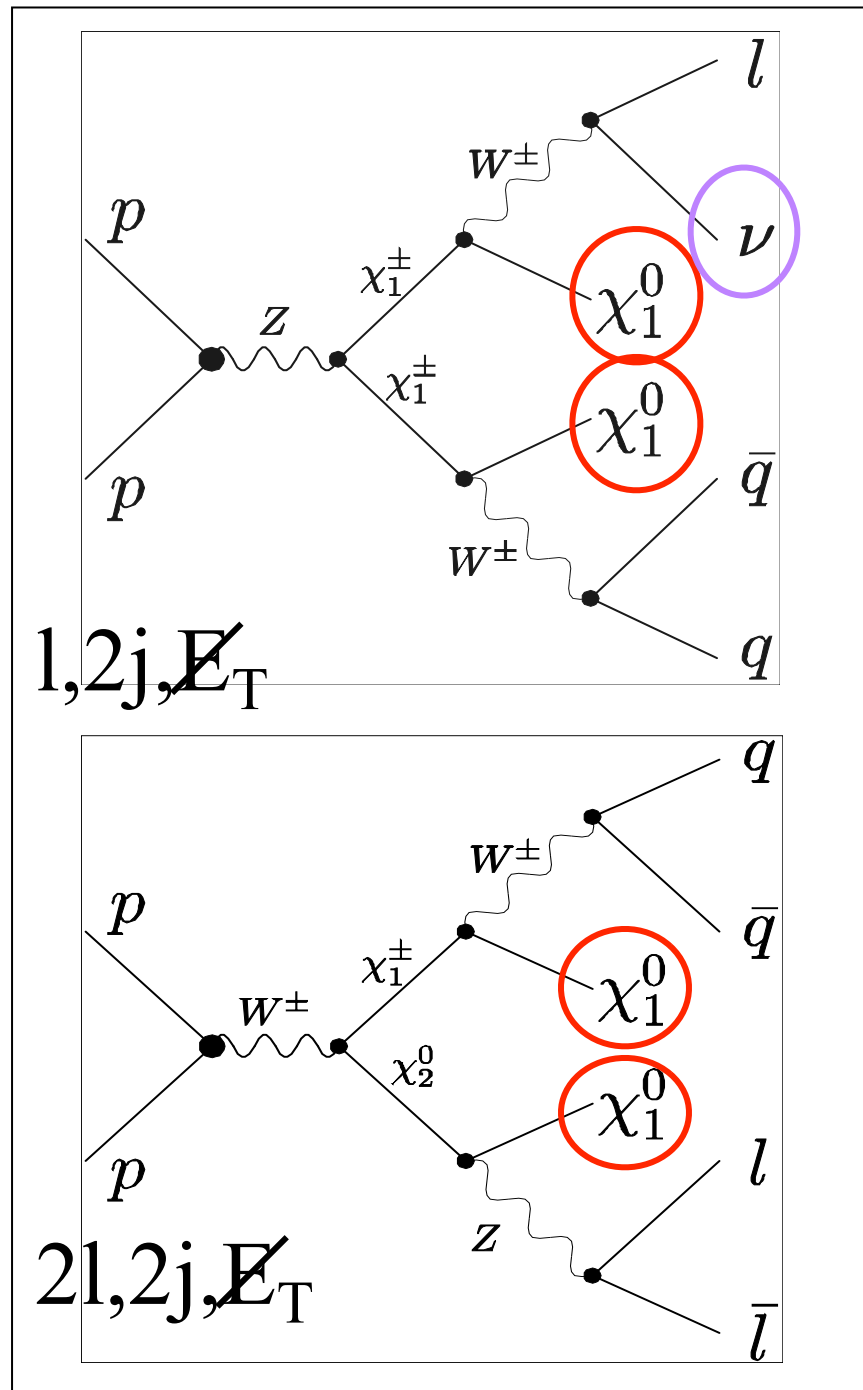
Astro Phys
(if SUSY DM)

- 📌 Relic abundancy of Dark Matter in the Universe
- 📌 DM annihilation signal in cosmic rays
- 📌 Direct DM interaction with nucleons

Nothing so far ...

Creation and Decay of Superpartners in Cascade Processes @ LHC

weak int's

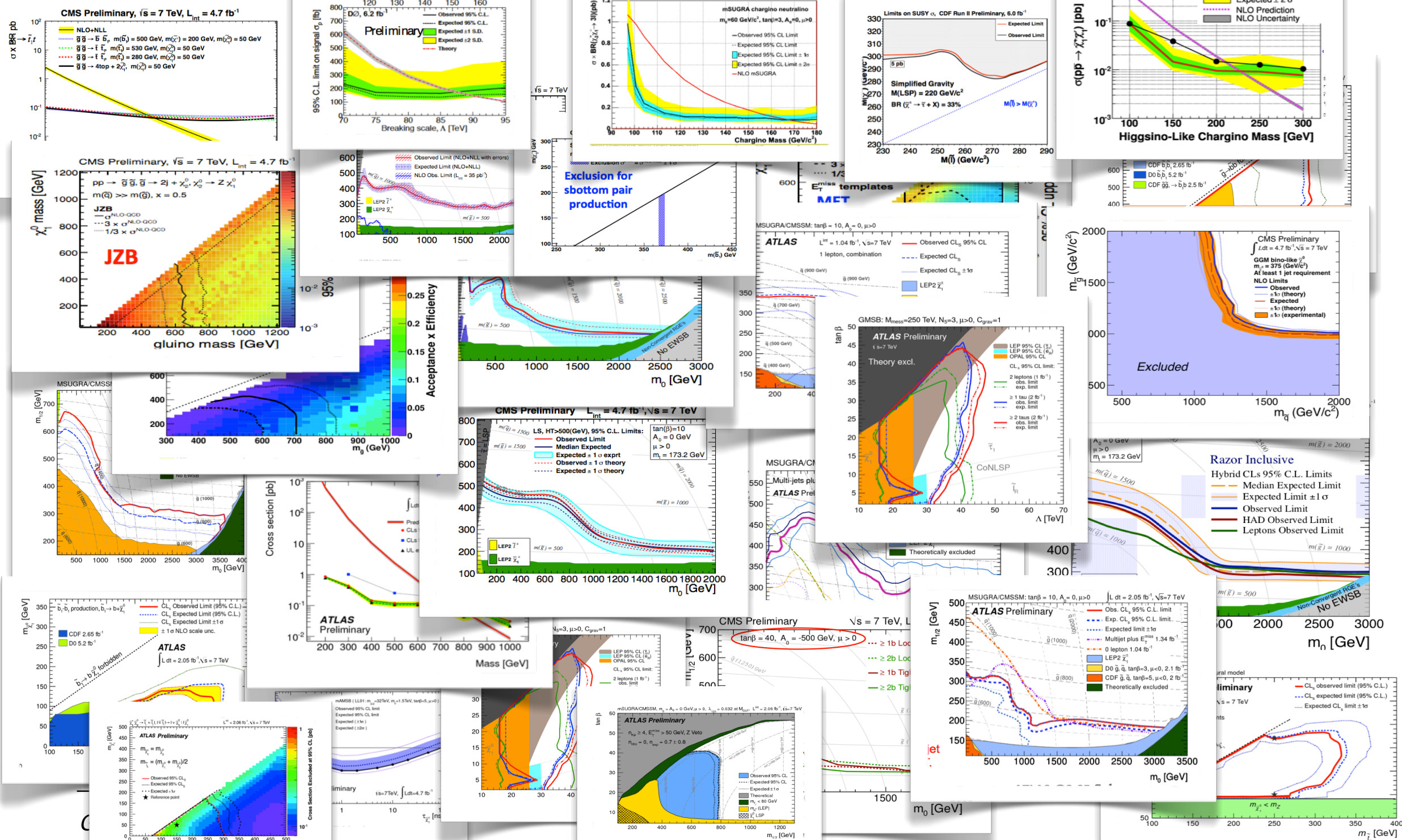


Strong int's

Typical SUSY signature: Missing Energy and Transverse Momentum



SUSY searches



Exp and Theor Framework

Two ways to present and analyse data:

1. High energy input:

introduce universal parameters at high energy scale (GUT)

Example $m_0, m_{1/2}, A_0, \tan \beta$ of MSSM

Advantage: small number of universal parameters for all masses

Disadvantage: strictly model dependent (MSSM, NMSSM, etc)

2. Low energy input:

use low energy parameters like masses of superpartners

Example $\tilde{m}_g, \tilde{m}_q, \tilde{m}_\chi$ or $m_A, \tan \beta$

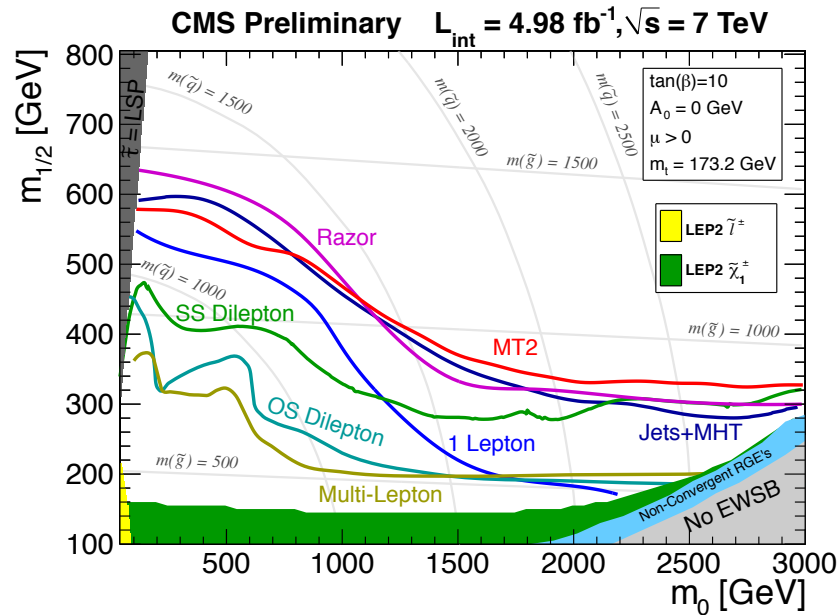
Advantage: less model dependent

Disadvantage: many parameters, process dependent

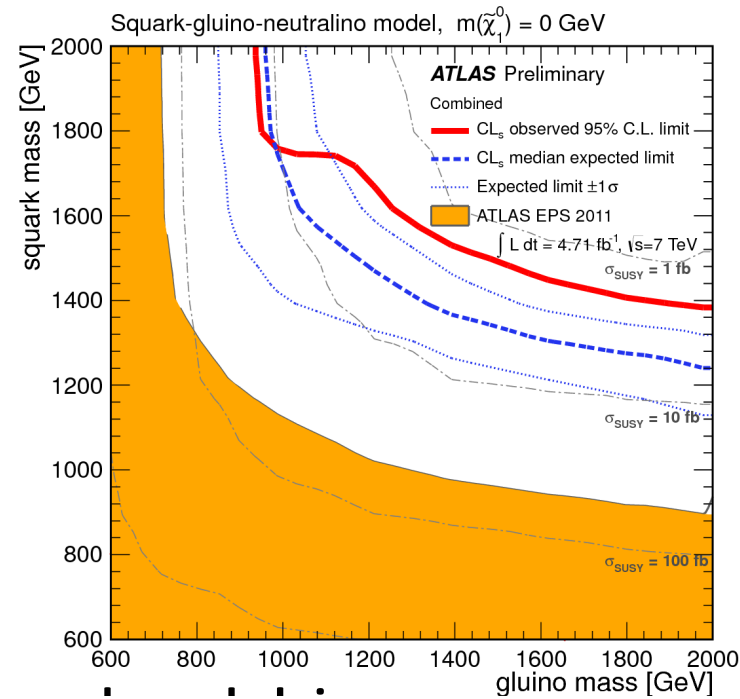
Both approaches are used

The Progress of LHC

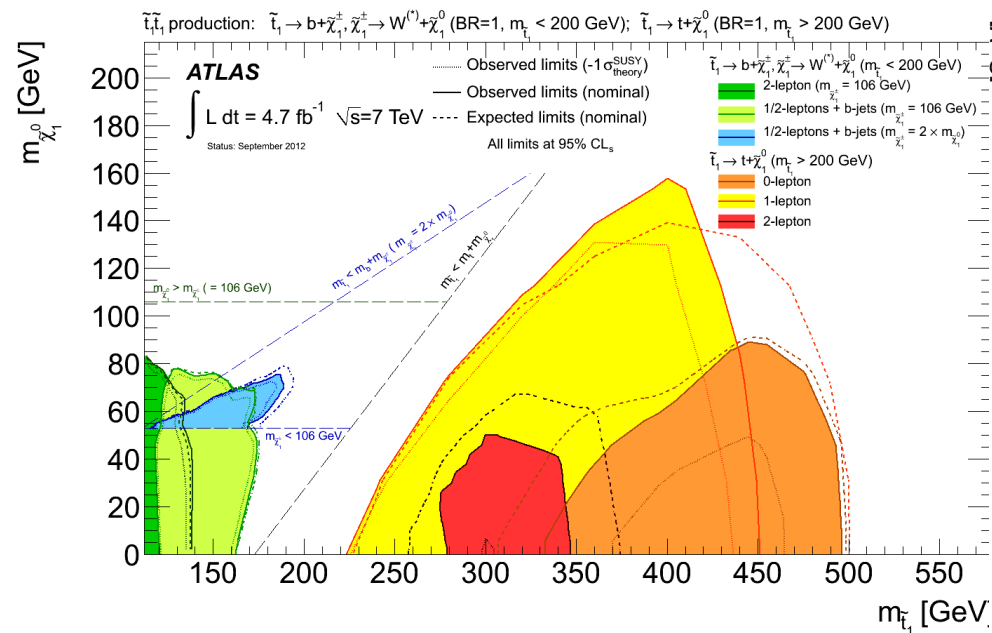
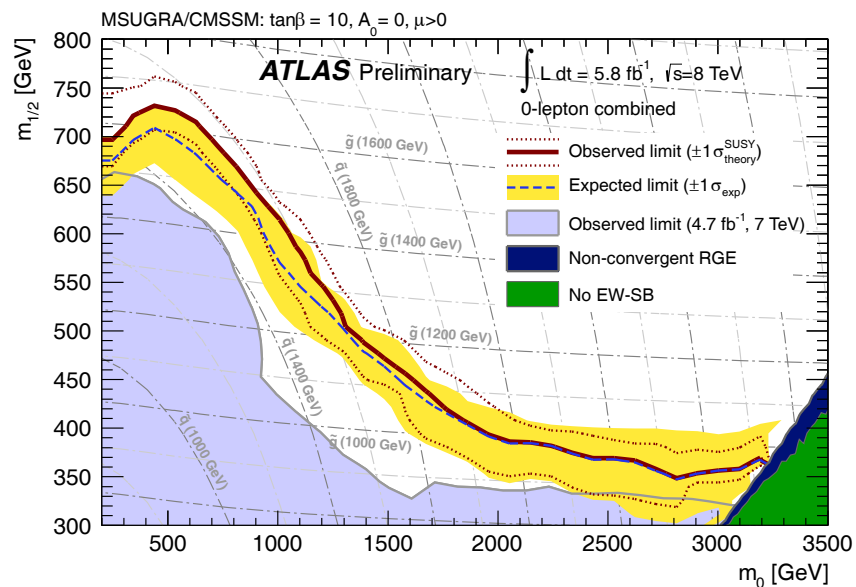
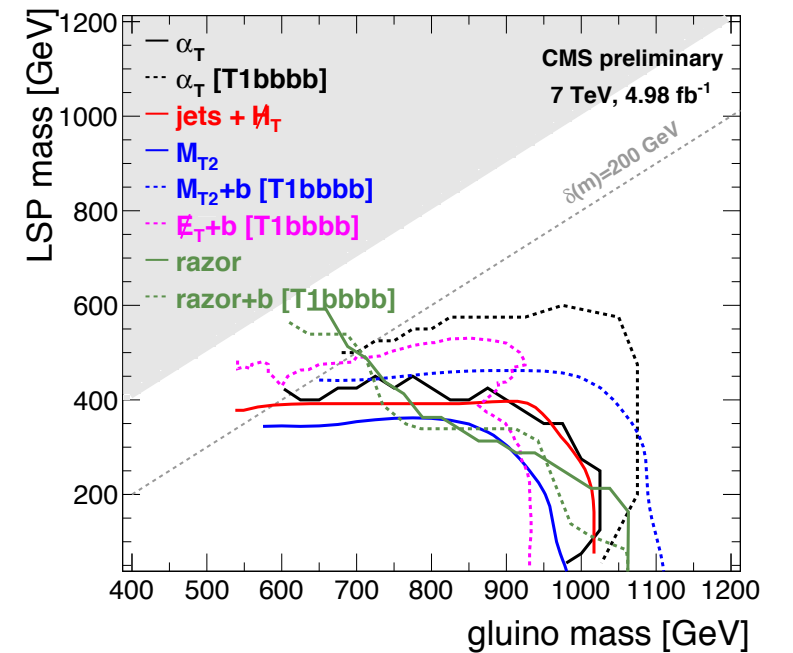
CMS CMSSM summary



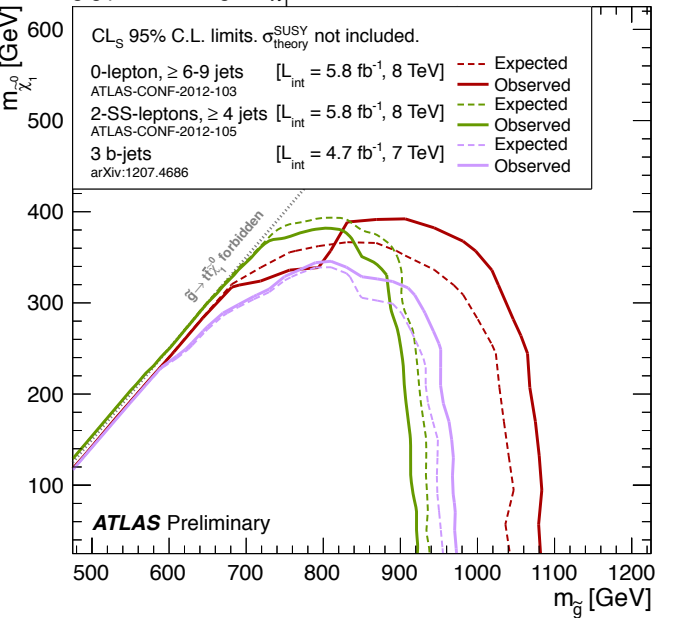
Look for squarks and gluinos with direct decays to SM+LSP



95% exclusion limits for $\tilde{g} \rightarrow q \bar{q} \tilde{\chi}_1^0$; $m(\tilde{q}) \gg m(\tilde{g})$



$\tilde{g}\tilde{g}$ production, $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$



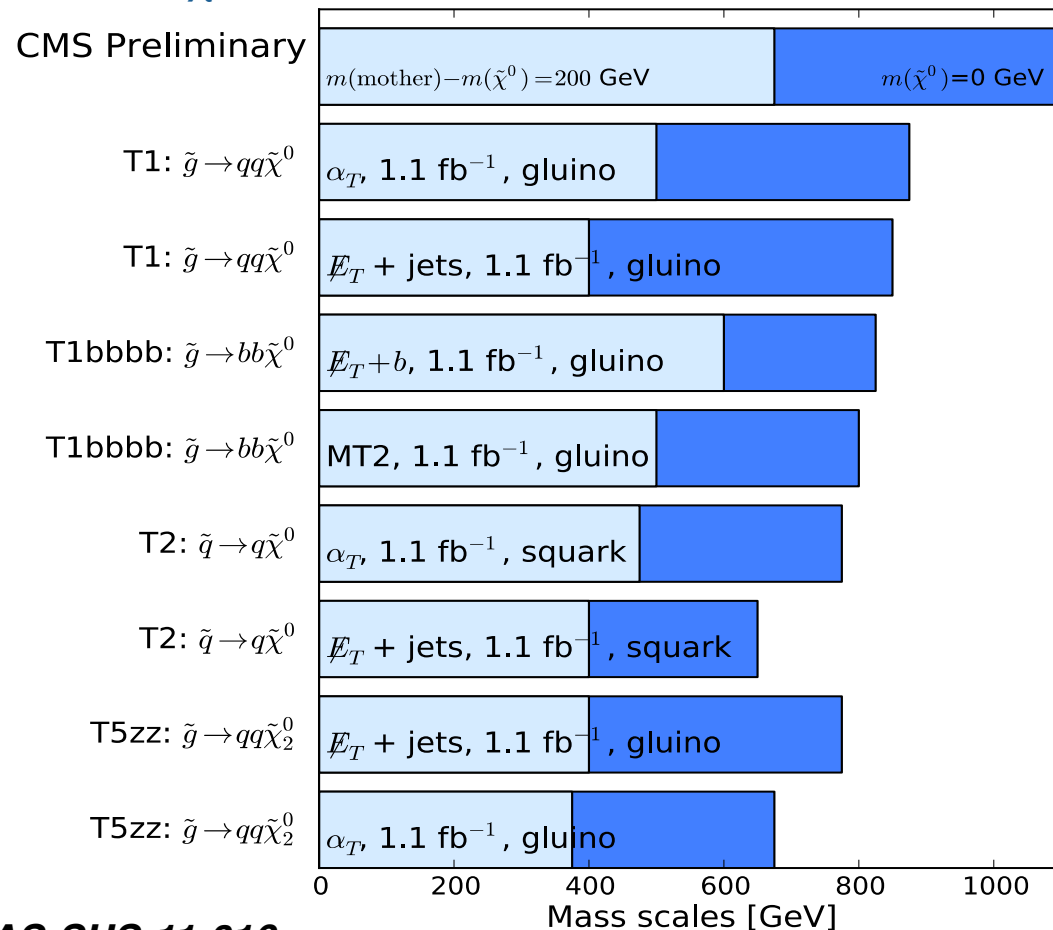
$$\tilde{m}_g > 1000 \text{ GeV}$$

$$\tilde{m}_q > 1400 \text{ GeV}$$

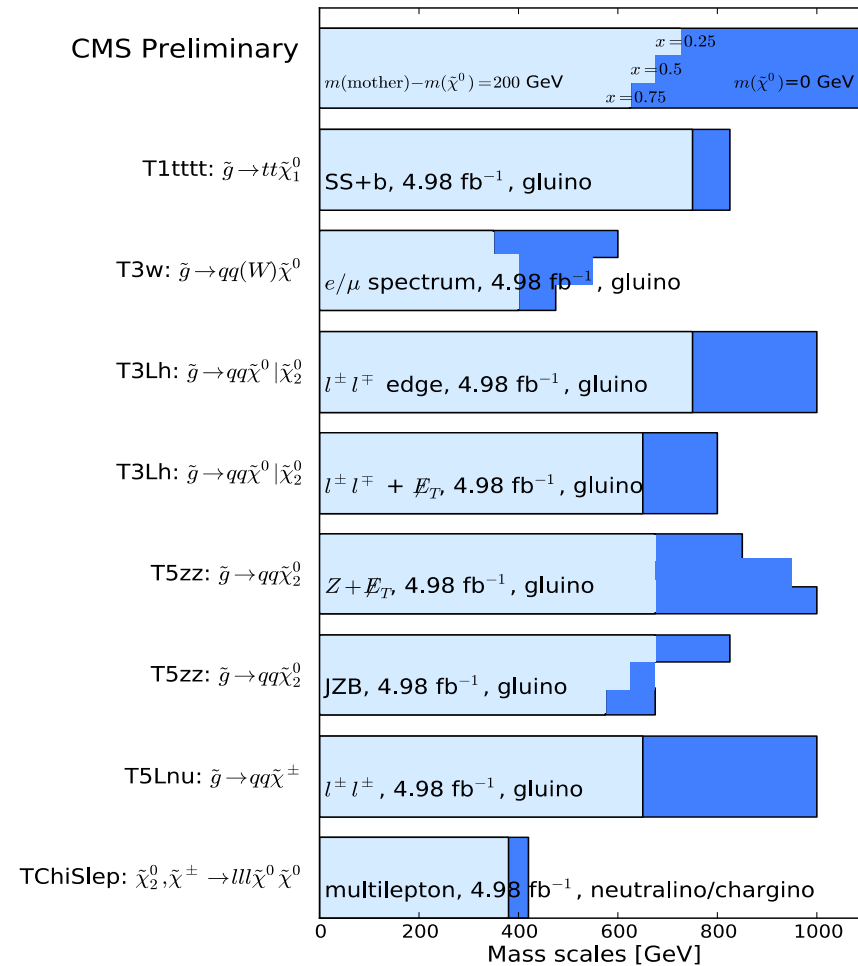


SUSY in simplified models

Hadronic (left) and leptonic (right) SUSY searches in simplified SUSY models. Exclusion limits for gluino and squark masses, for $m_{\tilde{\chi}^0} = 0$ GeV (dark blue) and $m_{\text{mother}} - m_{\tilde{\chi}^0} = 200$ GeV (light blue).



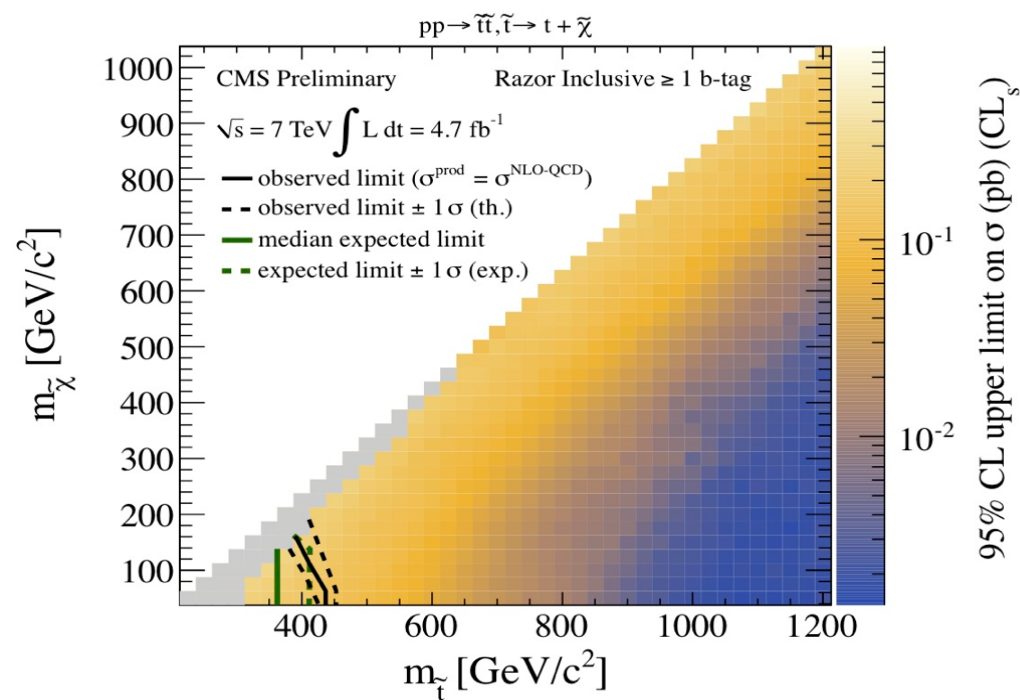
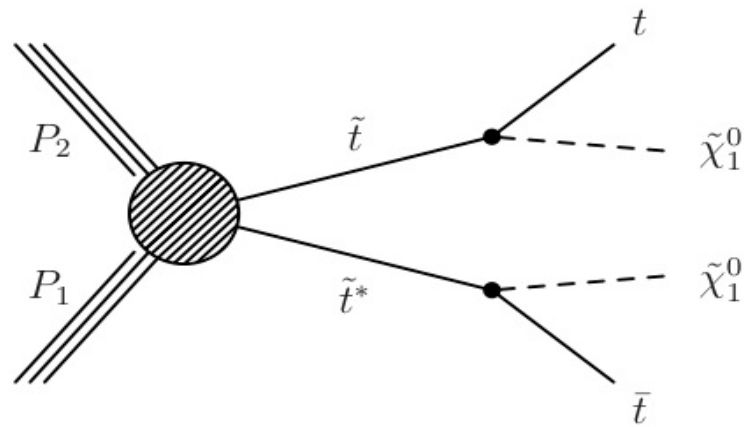
CMS-PAS-SUS-11-016



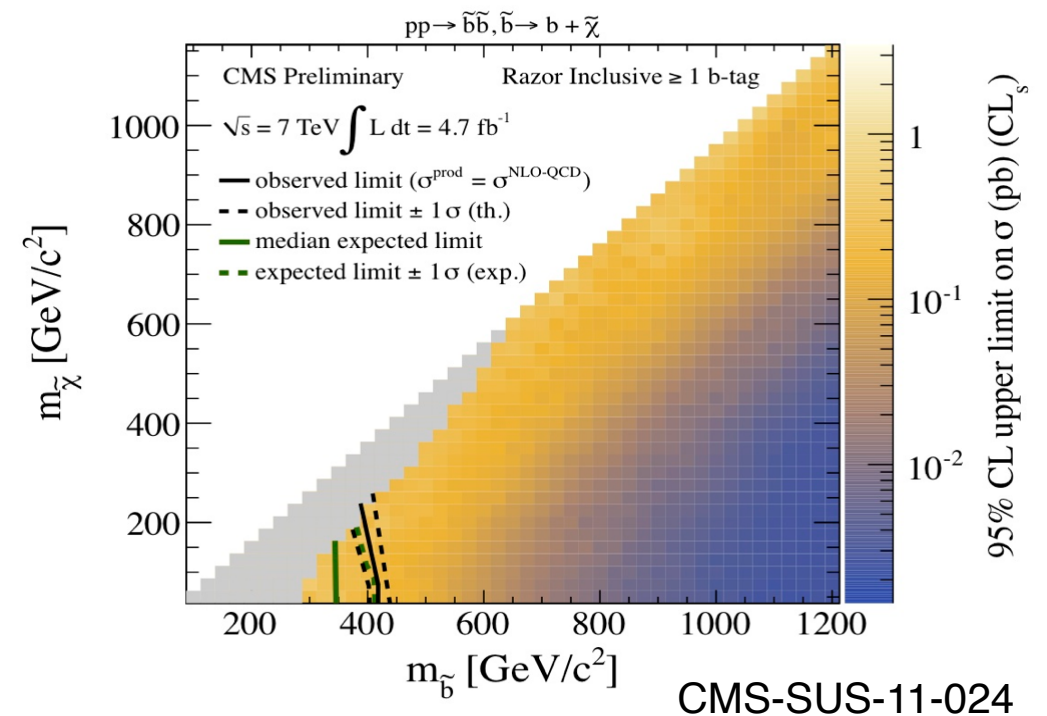
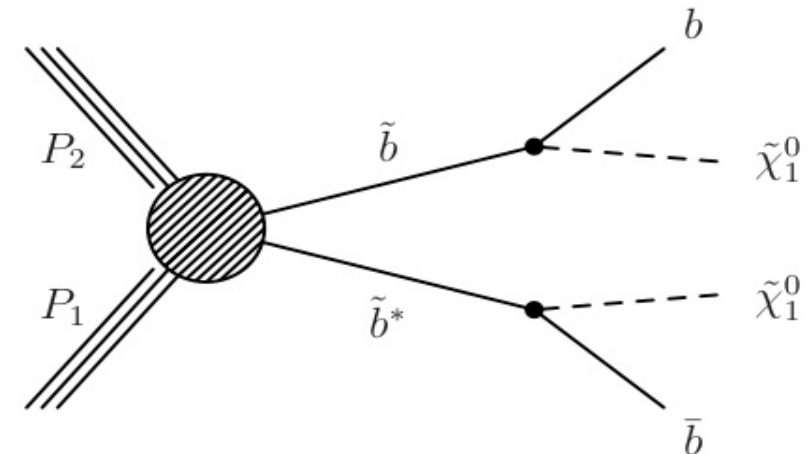
SUSY is not dead (yet). It might still hide in low MET/low HT events. More complicated models are under investigation → more challenging searches. For some it is hard to even get the data on tape.

Stop and Sbottom Searches at LHC

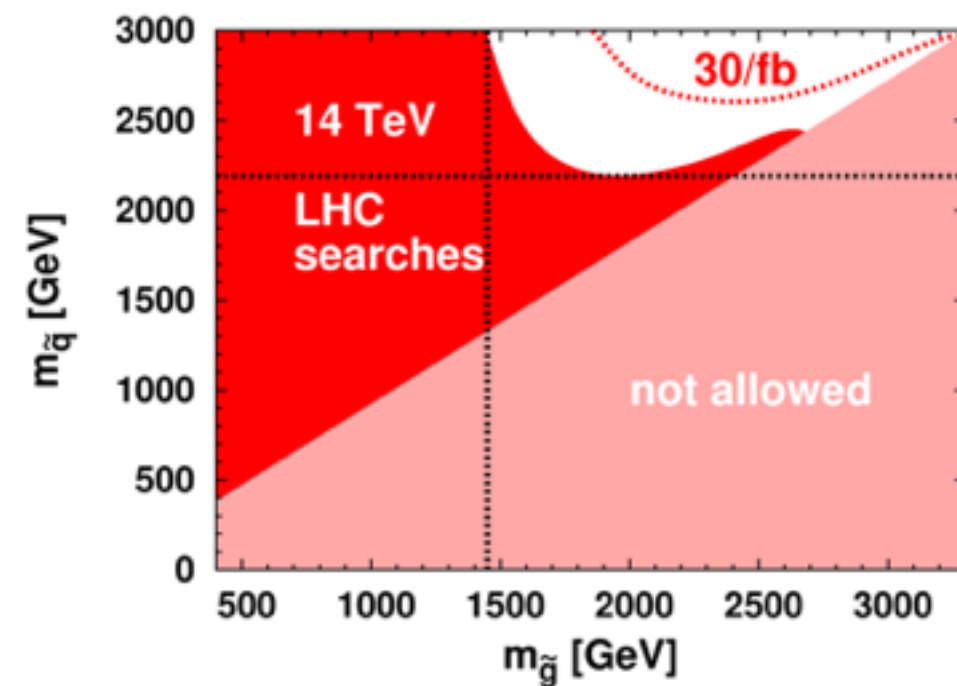
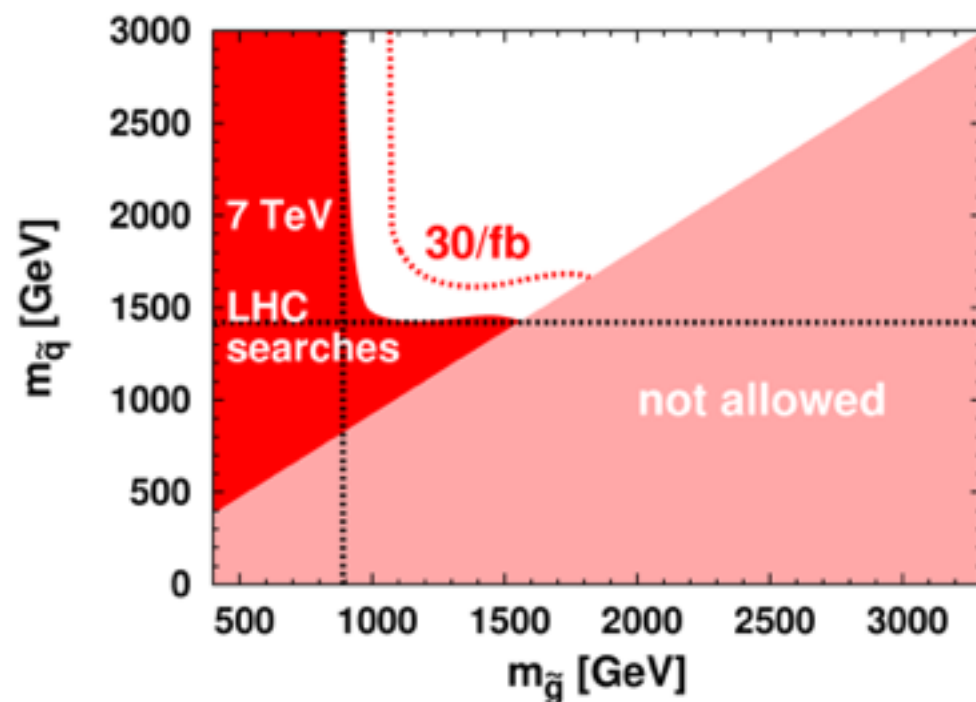
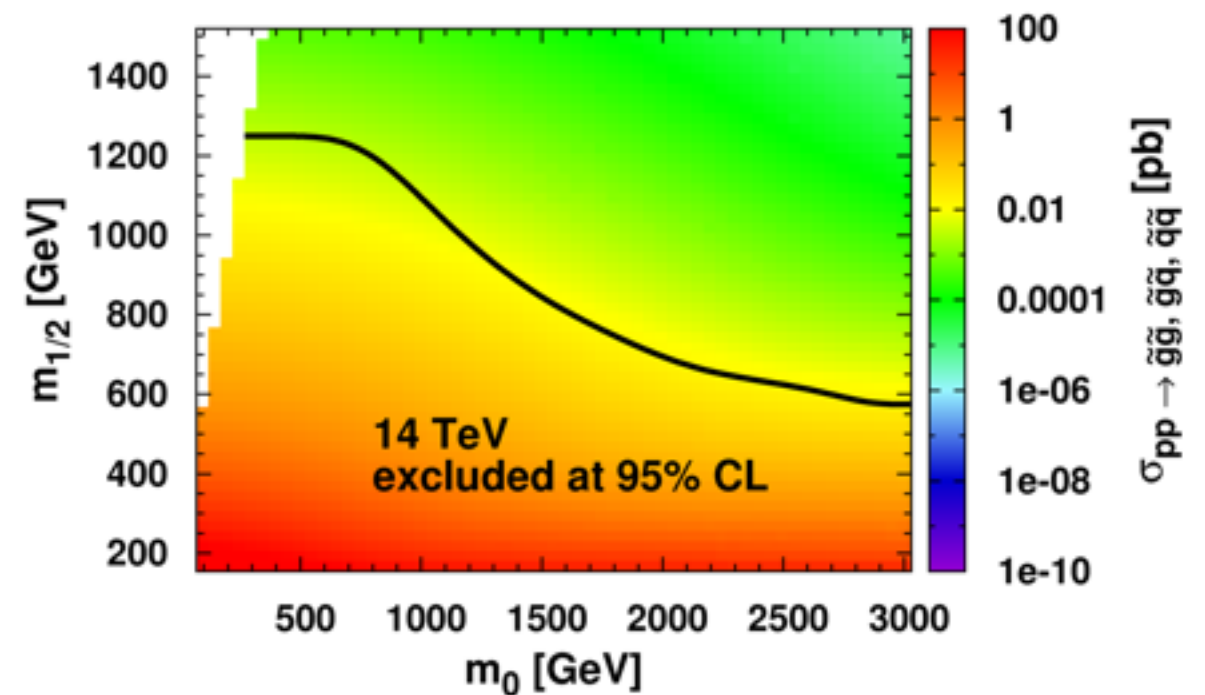
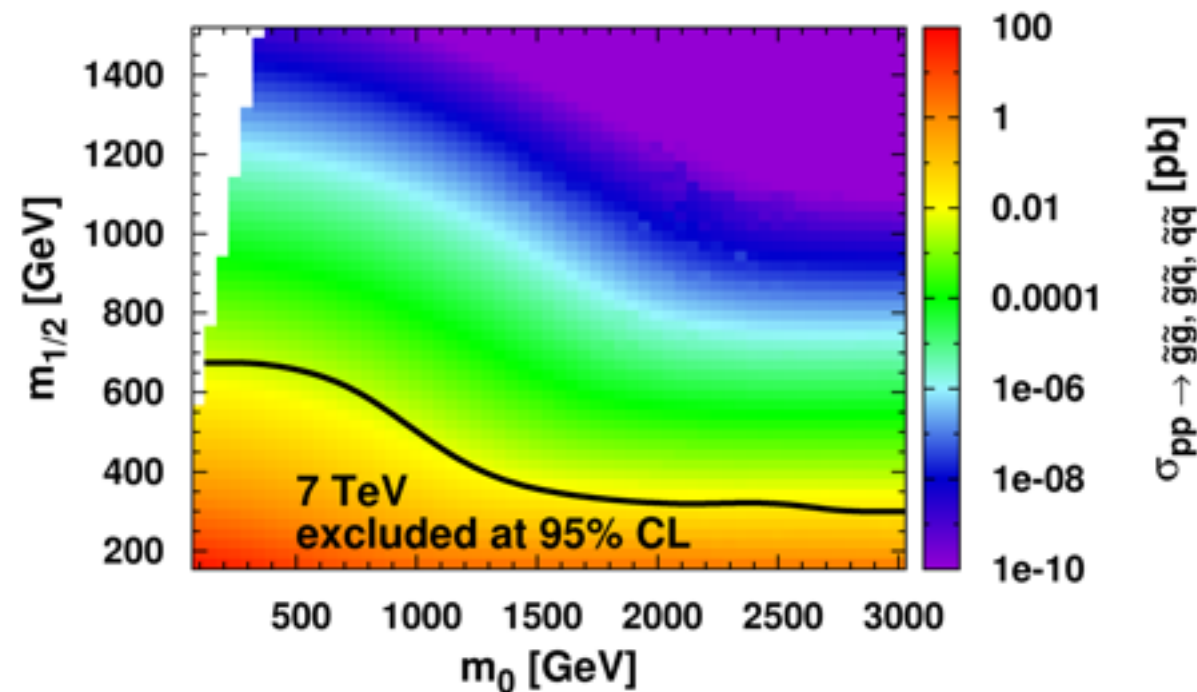
Di-stop production resulting in 2 top quarks +MET final states



Di-sbottom production resulting in 2 b quarks +MET final states



LHC Reach at 7 and 14 TeV



Energy is more important than luminosity

Indirect Search at LHC

$$B_{s,d} \rightarrow \mu^+ \mu^-$$

$$B_s \rightarrow X_s \gamma$$

$$B_u \rightarrow \tau \nu$$

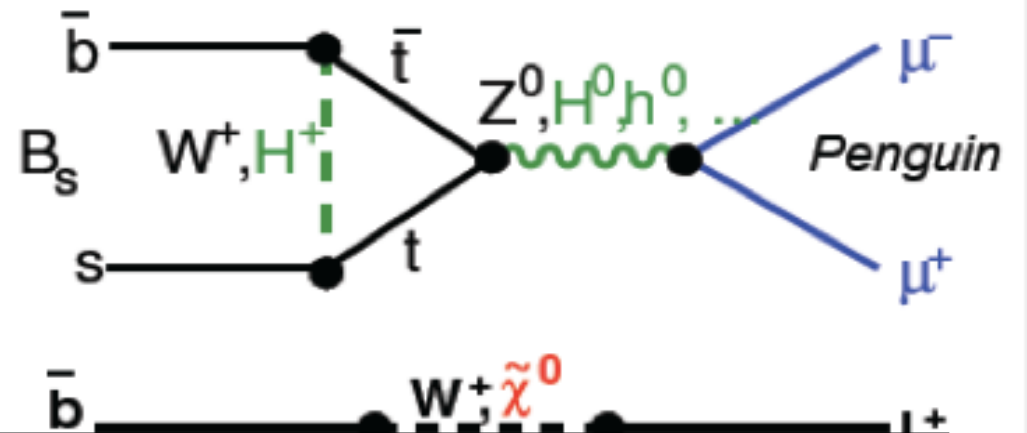
$$g - 2$$

Probing SUSY with

$$B_{s,d} \rightarrow \mu^+ \mu^-$$

• Decays highly suppressed in SM

- Forbidden at tree level
- $b \rightarrow s(d)$ FCNC transition only through penguin and box diagrams
- Helicity suppressed by factors of $(m_\mu/$



$$Br[B_s \rightarrow \mu\mu] = \frac{2\tau_B m_B^5}{64\pi} f_{B_s}^2 \sqrt{1 - \frac{4m_l^2}{m_B^2}} \left[\left(1 - \frac{4m_l^2}{m_B^2}\right) \left| \frac{(C_S - C'_S)}{(m_b + m_s)} \right|^2 + \left| \frac{(C_P - C'_P)}{(m_b + m_s)} + 2 \frac{m_\mu}{m_{B_s}^2} (C_A - C'_A) \right|^2 \right]$$

$$C_S \simeq \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left(\frac{\tan^3 \beta}{\sin^2 \theta_W} \right) \left(\frac{m_b m_\mu m_t \mu}{M_W^2 M_A^2} \right) \frac{\sin 2\theta_{\tilde{t}}}{2} \left(\frac{m_{\tilde{t}_1}^2 \log \left[\frac{m_{\tilde{t}_1}^2}{\mu^2} \right]}{\mu^2 - m_{\tilde{t}_1}^2} - \frac{m_{\tilde{t}_2}^2 \log \left[\frac{m_{\tilde{t}_2}^2}{\mu^2} \right]}{\mu^2 - m_{\tilde{t}_2}^2} \right)$$

Enhancement

Suppression

Indirect: MSSM v NMSSM

95% CL exclusion

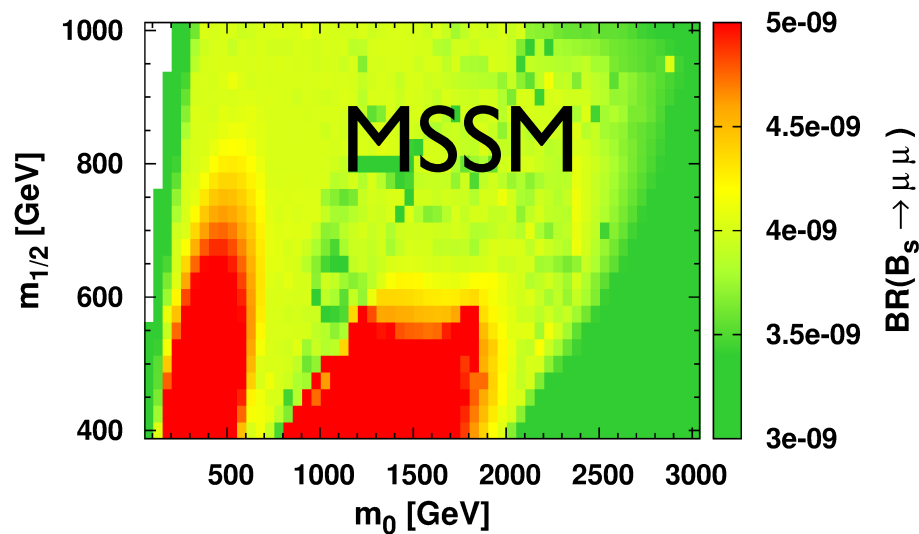
W.de Boer, C.Beskidt, D.K.'11'12

MicrOMEGAs 2.4.1

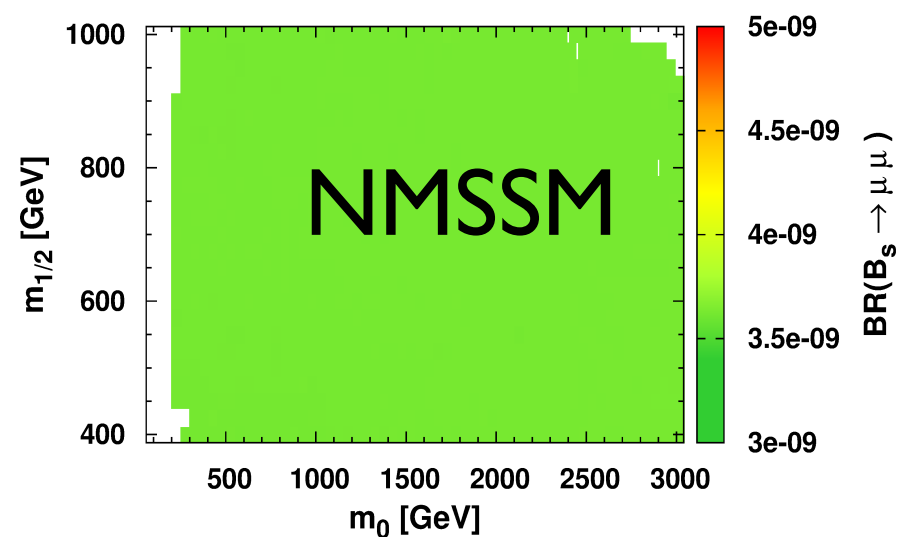
G. Bélanger et al

NMSSM calculations made with NMSSMTools

U.Ellwanger et al



$B_s \rightarrow s\gamma, B_s \rightarrow \mu^+\mu^-, B_s \rightarrow \tau\nu$

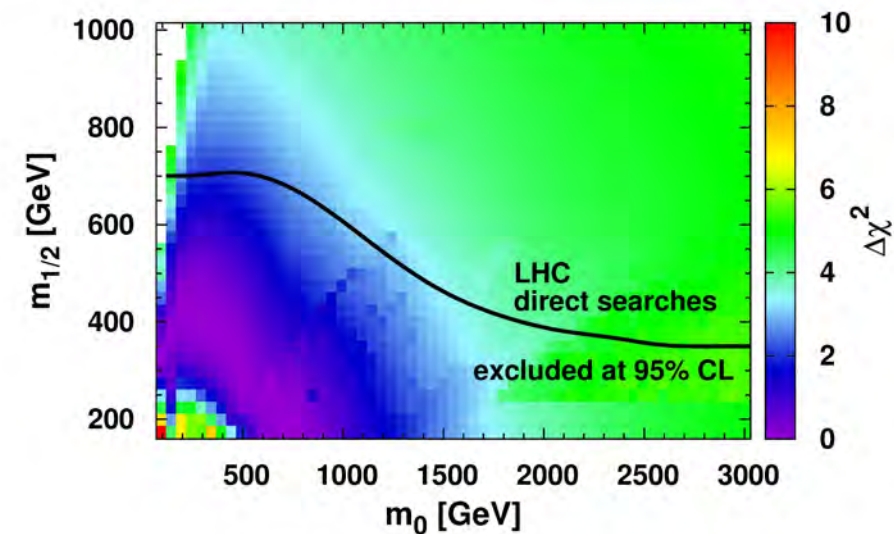


$$Br[B_s \rightarrow X_s \gamma] = (3.55 \pm 0.24) \cdot 10^{-4}$$

$$Br[B_u \rightarrow \tau \nu] = (1.68 \pm 0.31) \cdot 10^{-4}$$

$$Br[B_s \rightarrow \mu^+ \mu^-] = 3.2 \cdot 10^{-9}$$

$$\Delta a_\mu = (302 \pm 63(exp)) \pm 61(theo) \cdot 10^{-11}$$



muon $g-2$

AstroPhys Search

- DM abundance
- DM annihilation
- DM-nucleon interaction

Relic Abundance

Boltzman Equation

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle (n_\chi^2 - n_{\chi,eq}^2), \quad H = \dot{R} / R \quad \leftarrow \text{Hubble constant}$$

Relic Abundance

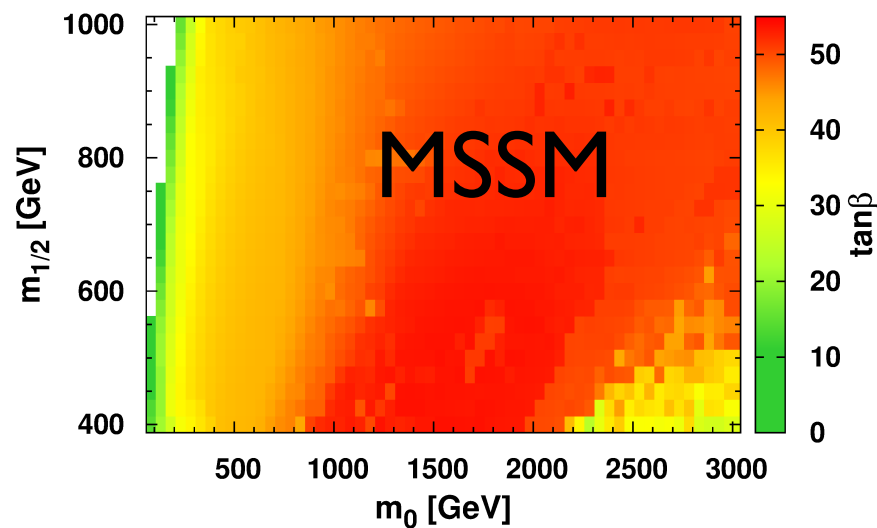
$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \approx \frac{3 \cdot 10^{-27} \text{ cm}^3 \text{ sec}^{-1}}{\langle \sigma v \rangle}$$

$$\langle \sigma v \rangle = 2 \cdot 10^{-26} \text{ cm}^3 / \text{s}$$

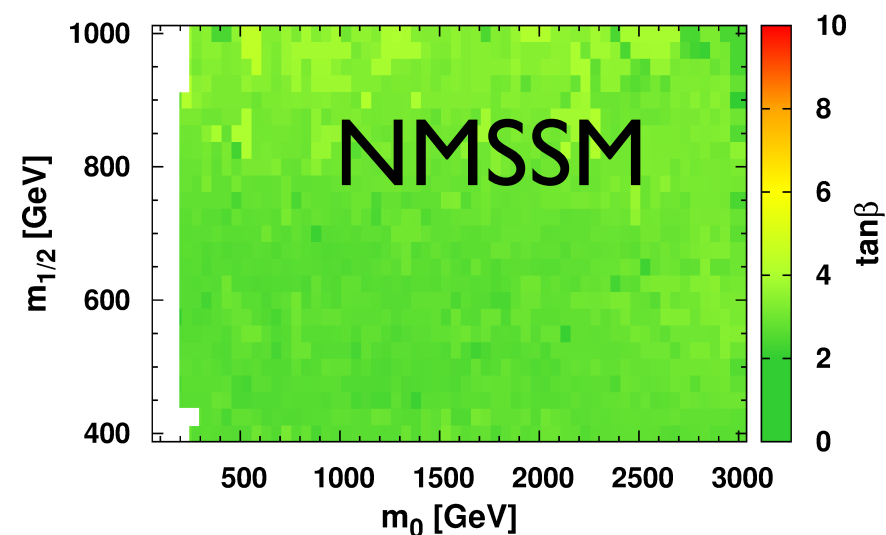
$$\Omega_\chi h^2 \sim 0.113 \pm 0.009,$$

$$v \sim 300 \text{ km / sec}$$

$$\sigma \sim 10^{-34} \text{ cm}^2 = 100 \text{ pb}$$

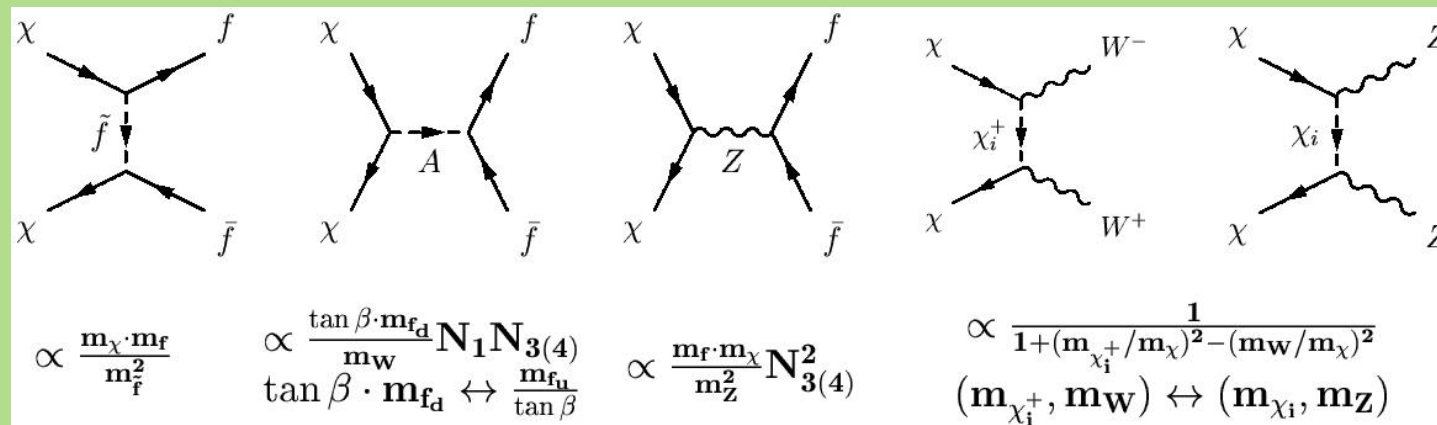


High $\tan \beta \sim 50$



Low $\tan \beta \sim 3$

DM annihilation



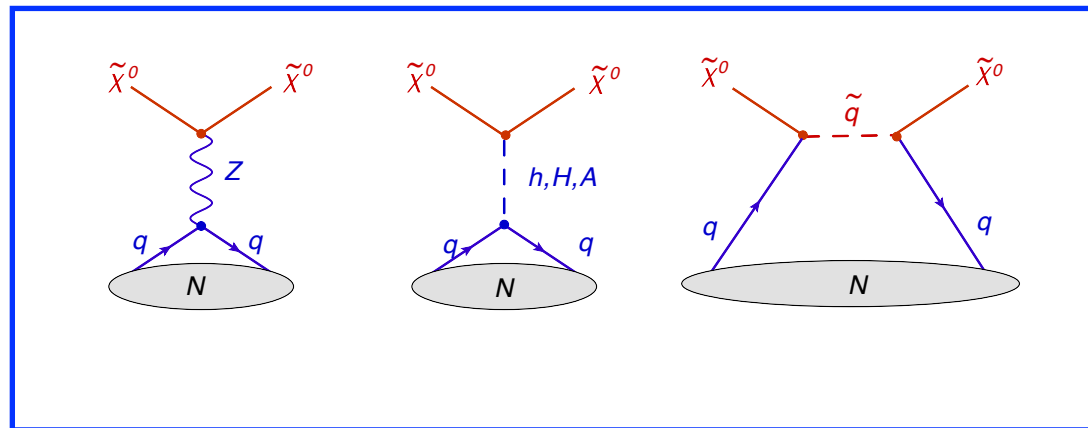
- Diffuse Gamma Rays
EGRET -> GLAST(FERM-LAT)
- Positrons in Cosmic Rays
HEAT, AMS01 -> PAMELA, FERMI
- Antiprotons in Cosmic Rays
BESS -> AMS02

No significant excess

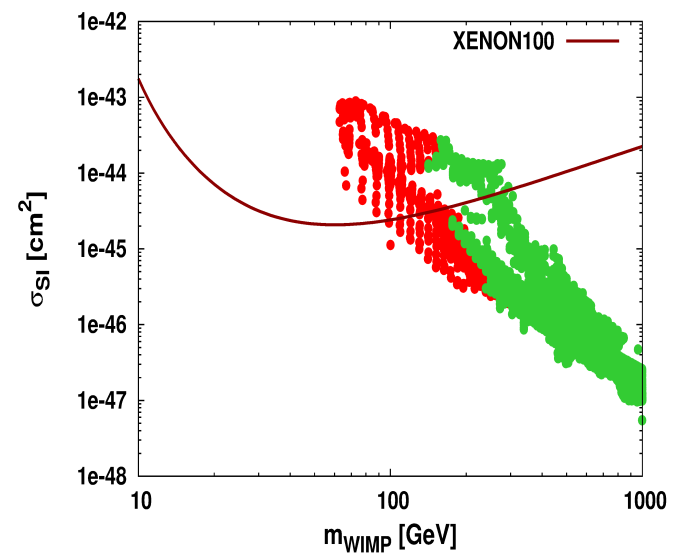
Contradictory interpretation

135 GeV $\gamma\gamma$ line?

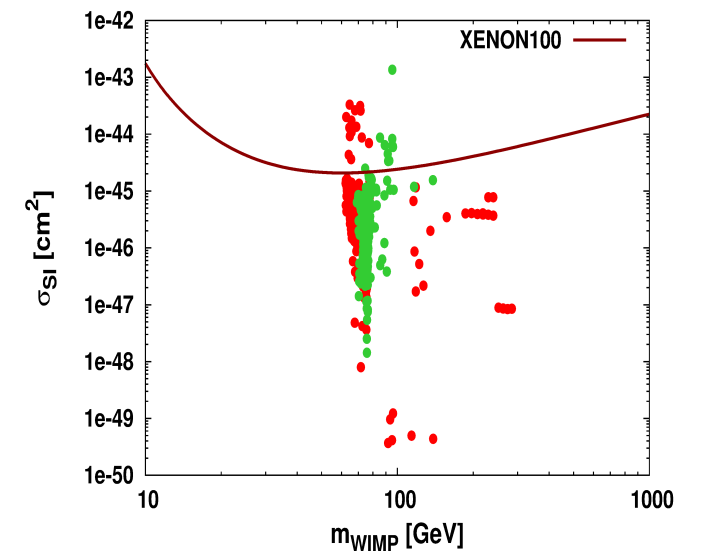
DM Nucleons Interaction



MSSM

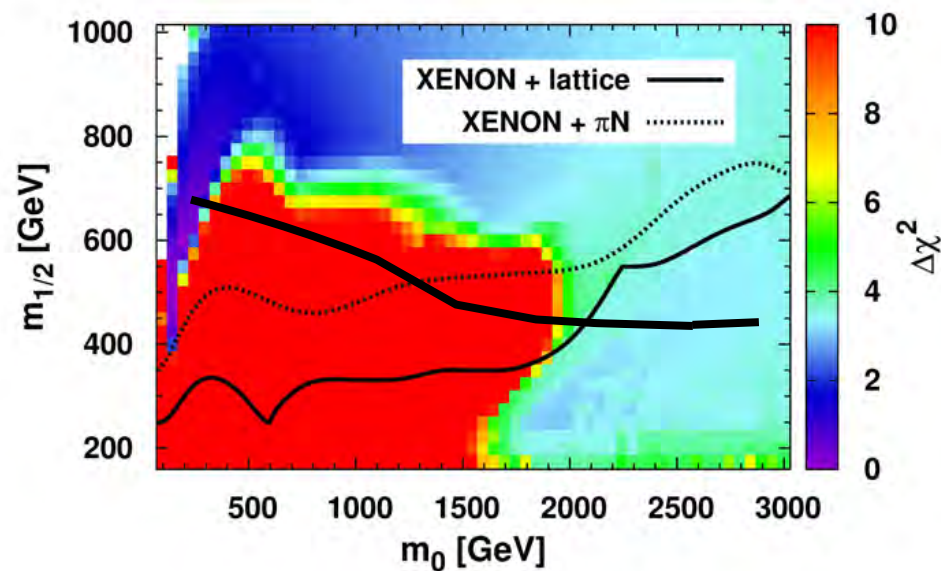


NMSSM



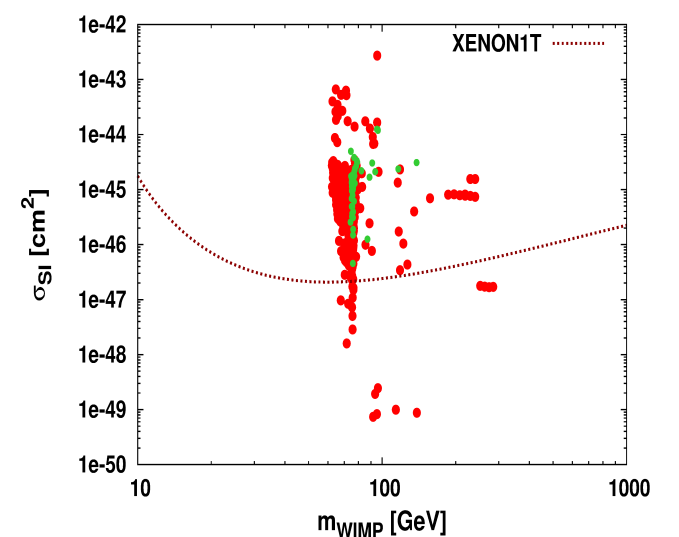
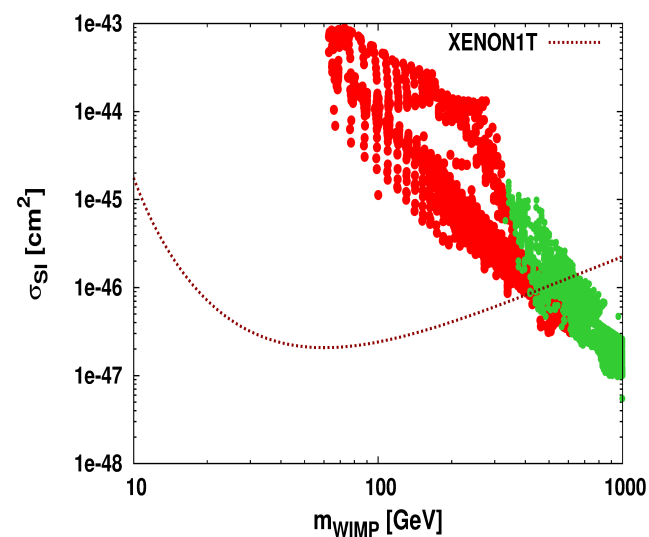
Red points - excluded by LHC

XENON100+LHC 8



MSSM

Direct DM search

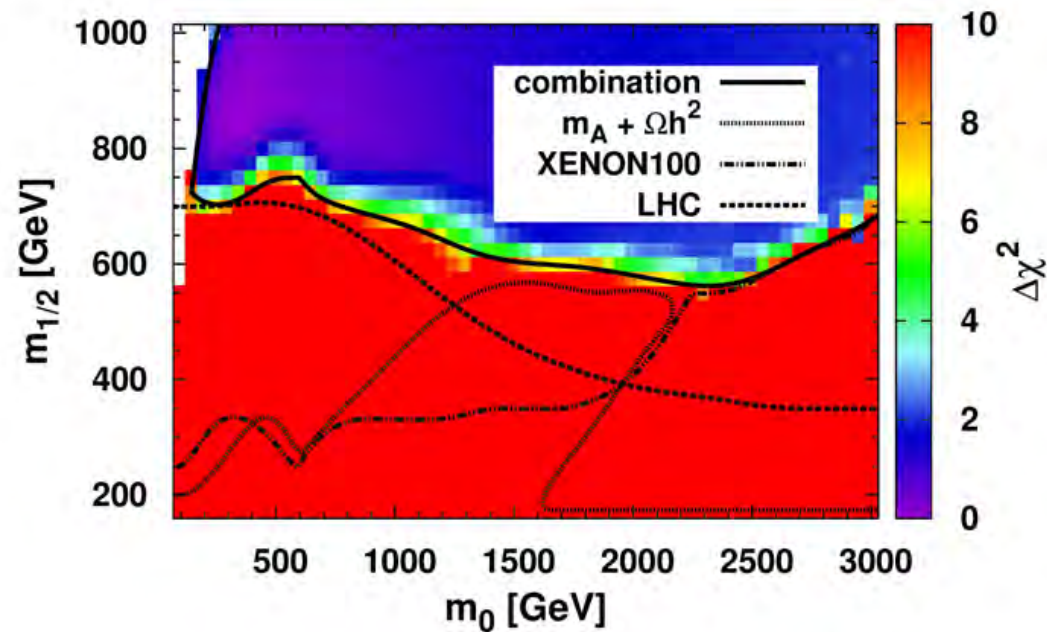


XENON1T+LHC 14

Combined Fit to all Data

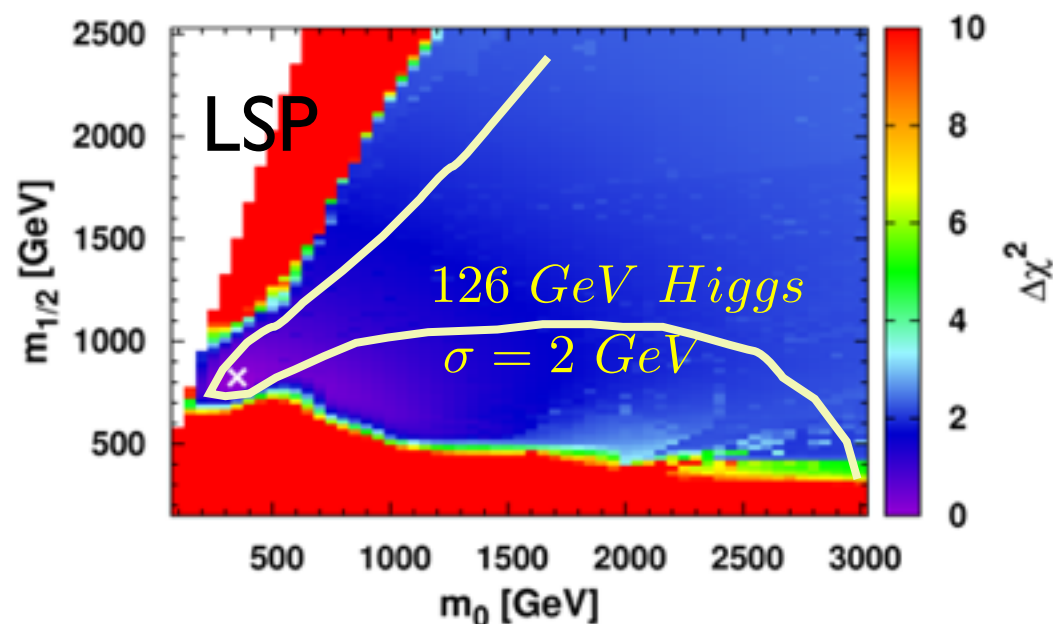
W.de Boer, C.Beskidt, D.K.'11'12

MSSM



without
125 GeV
Scalar

The values of $\tan\beta$ and A_0 are adjusted

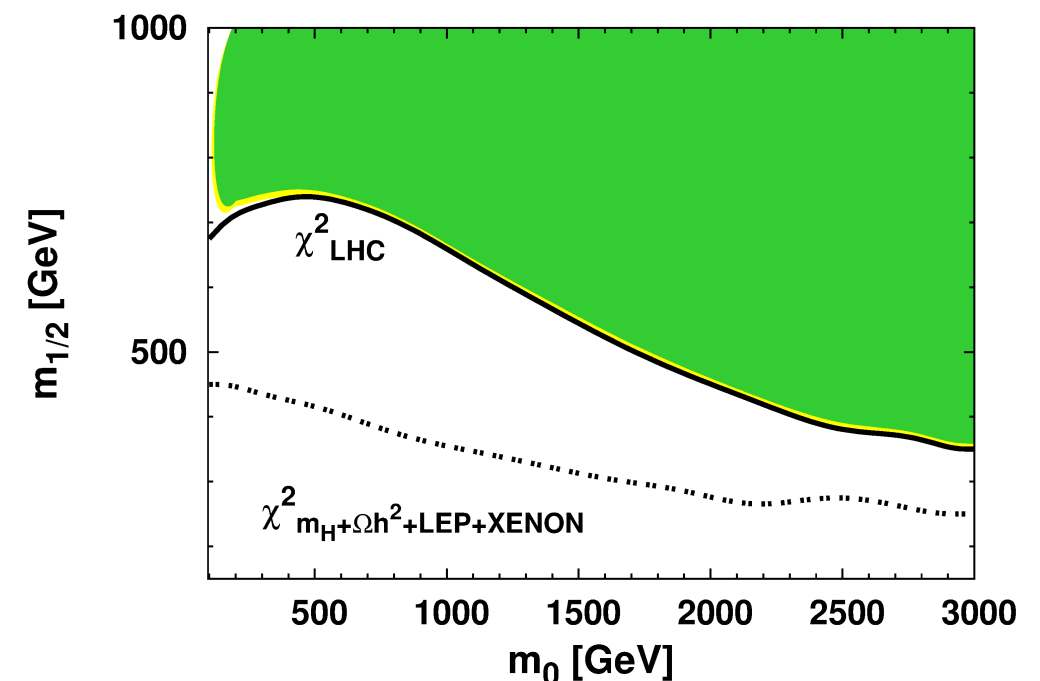


with 125
GeV
Scalar

Larger scale for $m_{1/2}$

Constraint	Data
Ωh^2	0.113 ± 0.004
$b \rightarrow X_s \gamma$	$(3.55 \pm 0.24) \cdot 10^{-4}$
$B_u \rightarrow \tau \nu$	$(1.68 \pm 0.31) \cdot 10^{-4}$
Δa_μ	$(302 \pm 63(exp) \pm 61(theo)) \cdot 10^{-11}$
$B_s^0 \rightarrow \mu^+ \mu^-$	$B_s^0 \rightarrow \mu^+ \mu^- < 4.5 \cdot 10^{-9}$
m_h	$m_h > 114.4$ GeV
m_A	$m_A > 480$ GeV for $\tan\beta \approx 50$
ATLAS	$\sigma_{had}^{SUSY} < 0.003 - 0.03$ pb
CMS	$\sigma_{had}^{SUSY} < 0.005 - 0.03$ pb
XENON100	$\sigma_{\chi N} < 8 \cdot 10^{-45} - 2 \cdot 10^{-44} cm^2$

NMSSM



Is SUSY dead?

- Under attack from all sides, but not dead yet.
- The searches leave little room for SUSY inside the reach of the existing data.
- But interpretations within SUSY models rely on many simplifying assumptions, and so care must be taken when making use of the limit plots
- Plausible “natural” scenarios still not ruled out: stop and/or RPV scenarios have few constraints.
- There is no reason to give up hope of finding SUSY at the LHC.

Concluding Remarks



SUSY today:

- No signal so far, but do not give up
- There is still plenty of room for SUSY
- Interpretations of searches are model dependent
- LHC run at 14 TeV might be crucial for low energy SUSY



- Give me something better and I will stick to it