March 2nd - 9th, 2013

EW INTERACTIONS AND UNIFIED THEORIES

SUSY (Pheno) Today

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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 -

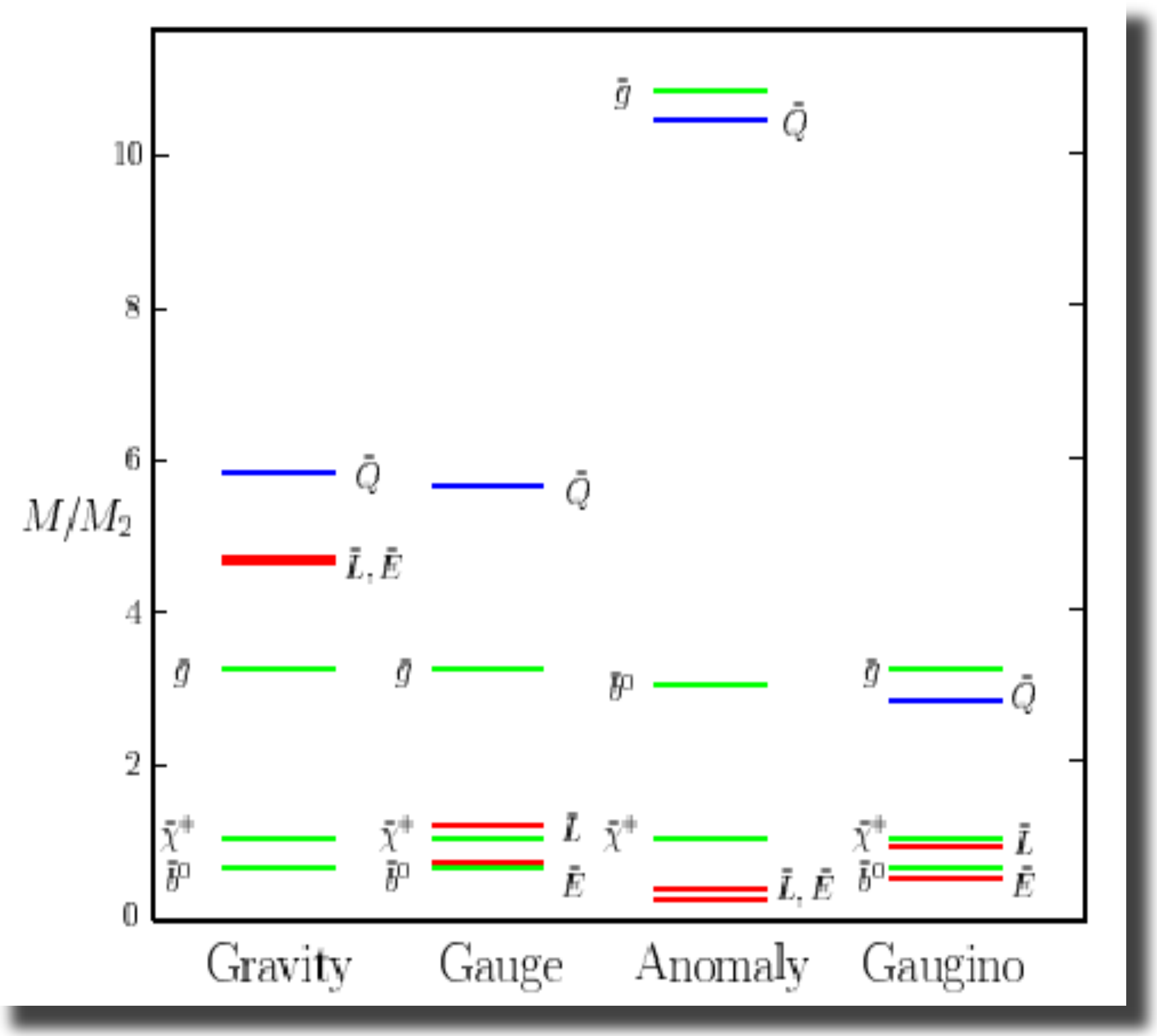
► a way to nonperturbative solutions and quantum gravity

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

Search for SUSY Manifestation

Particle Phys

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

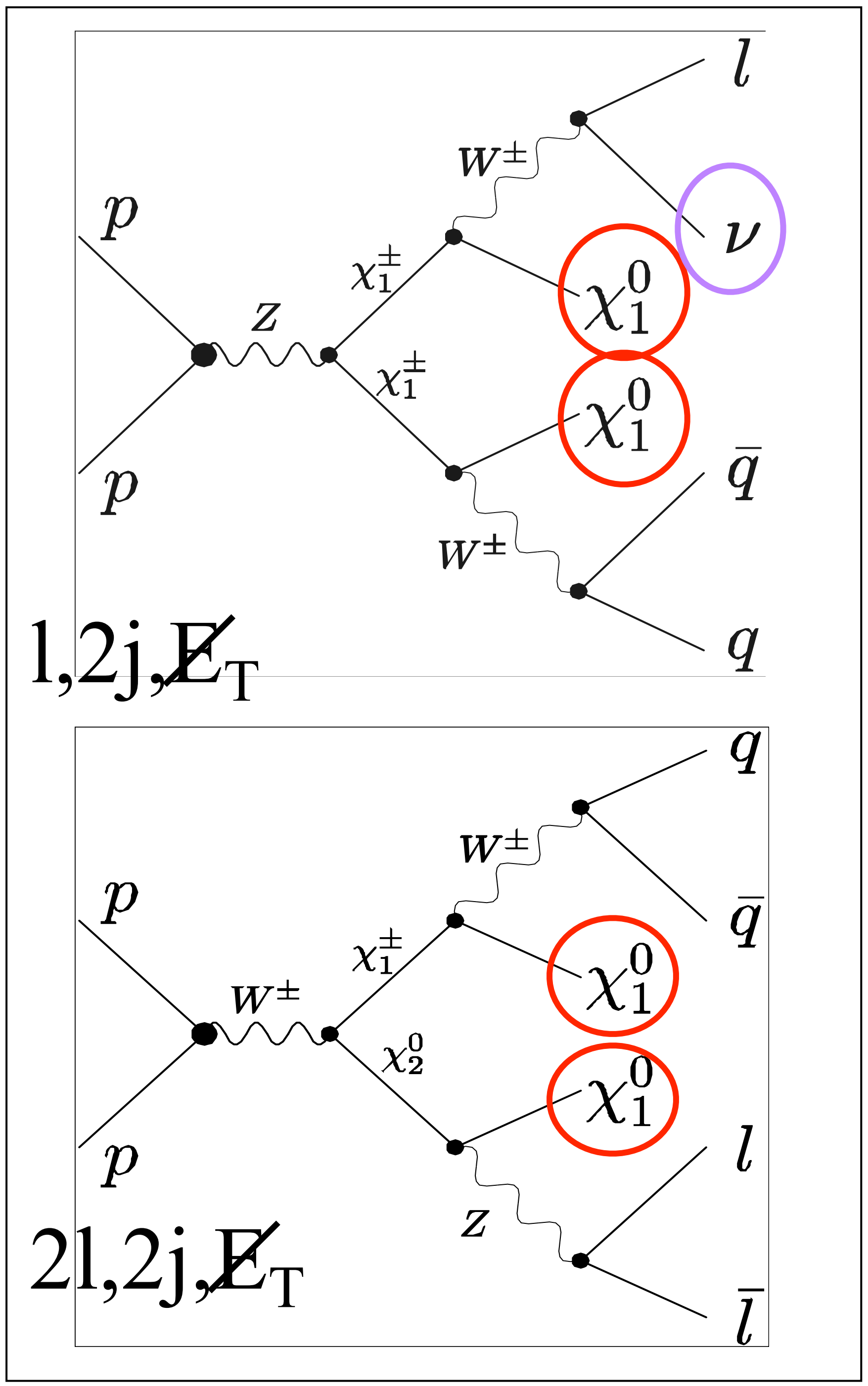
Astro Phys (if SUSY DM)

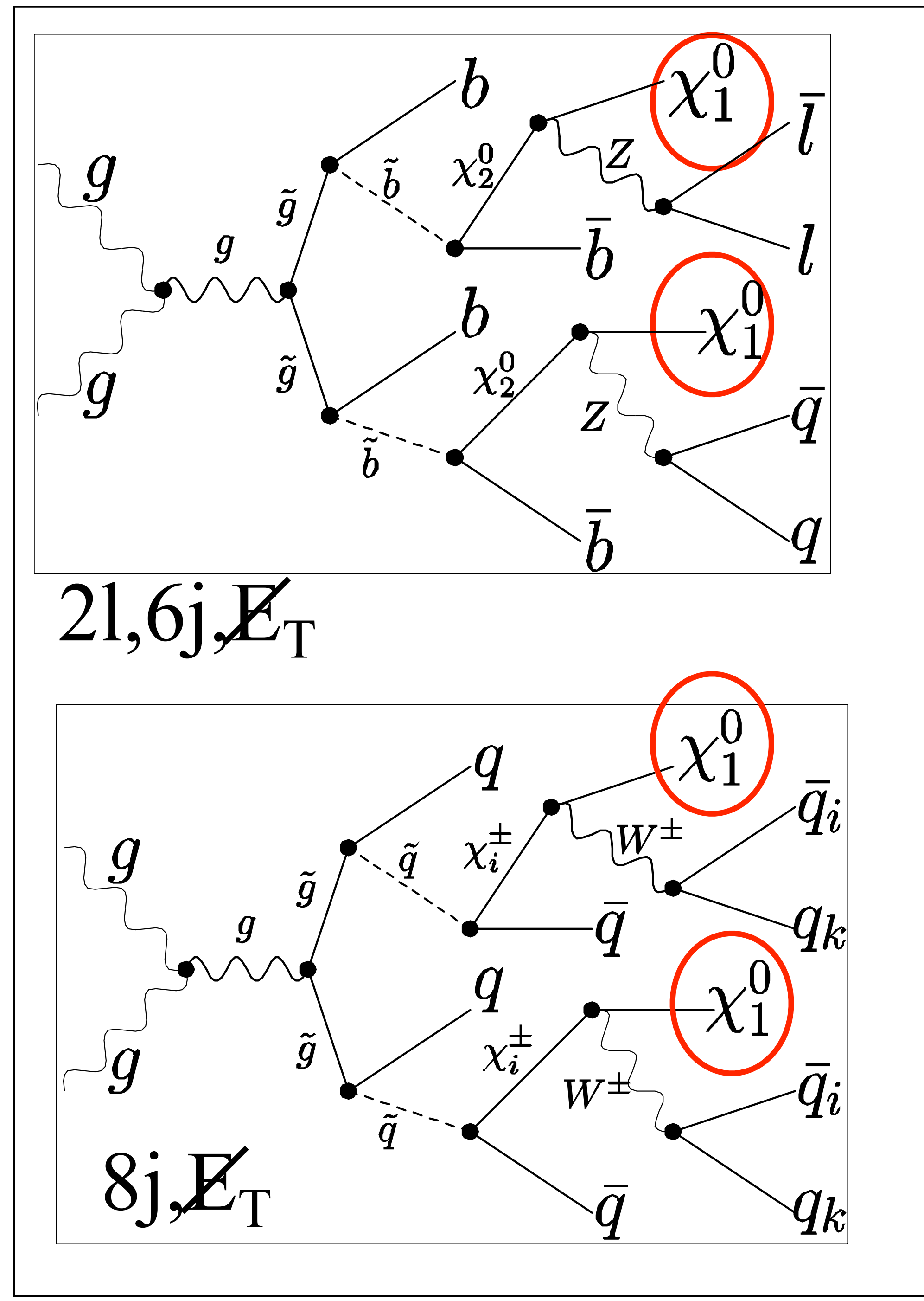
- Relic abundancy of Dark Matter in the Universe
- DM annihilation signal in cosmic rays
- Direct DM interaction with nucleons

Nothing so far ...

Creation and Decay of Superpartners in Cascade Processes @ LHC

weak int's



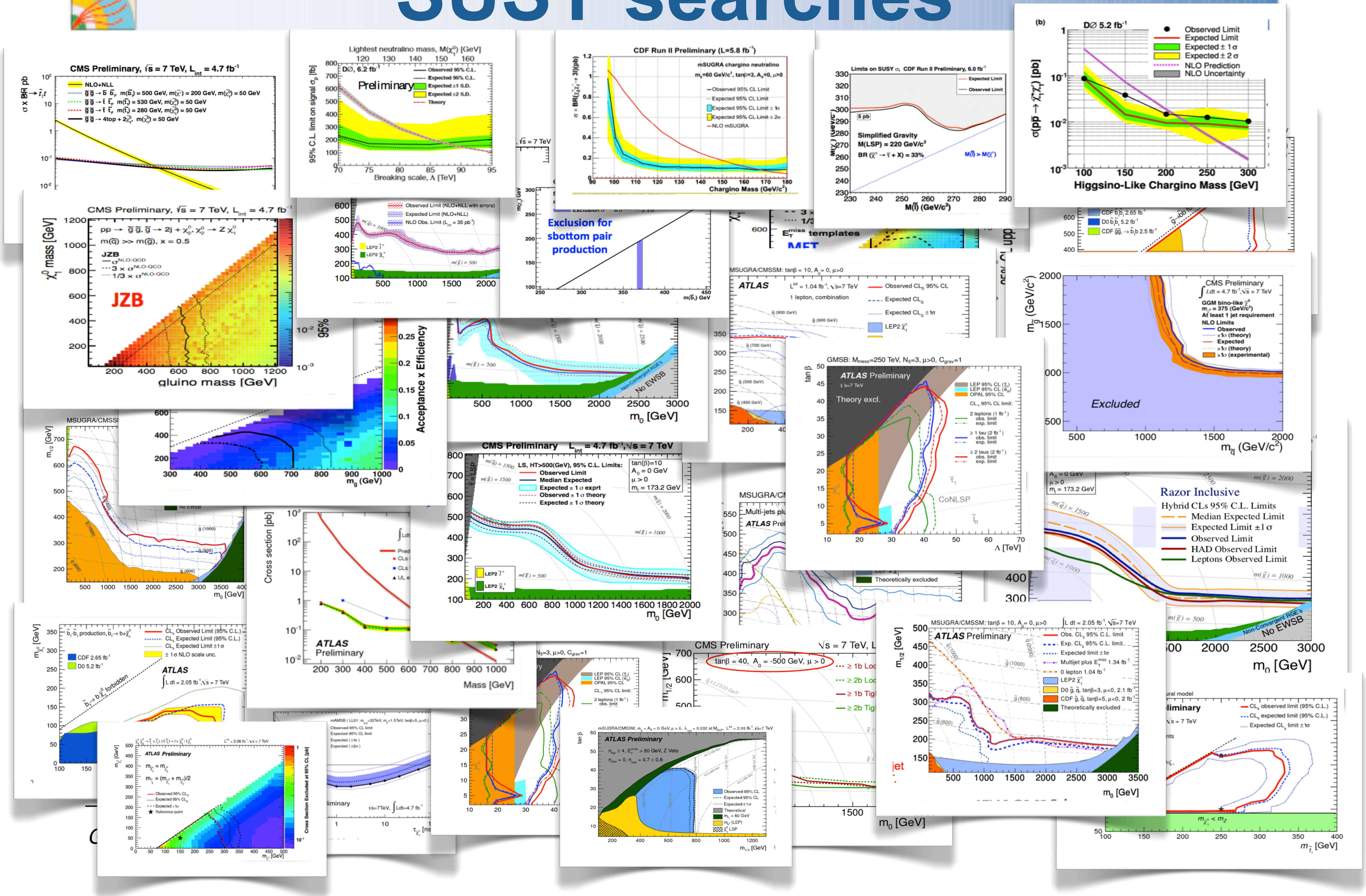


Strong int's

Typical SUSY signature: Missing Energy and Transverse Momentum

Guido Tonelli

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

Advandage: small number of universal parameters for all masses
Disadvantage: strictly model dependent (MSSM, NMSSM, etc)

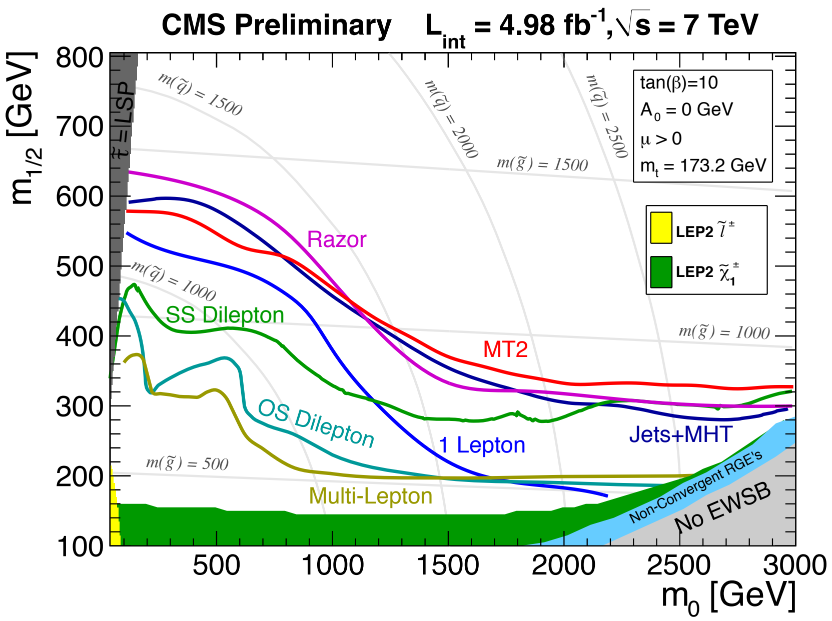
2. Low energy input:
use low energy parameters like masses of superpartners
Example $\tilde{m}_g, \ \tilde{m}_q, \ \tilde{m}_\chi$ or $m_A, \tan\beta$

Advandage: less model dependent
Disadvantage: many parameters, process dependent

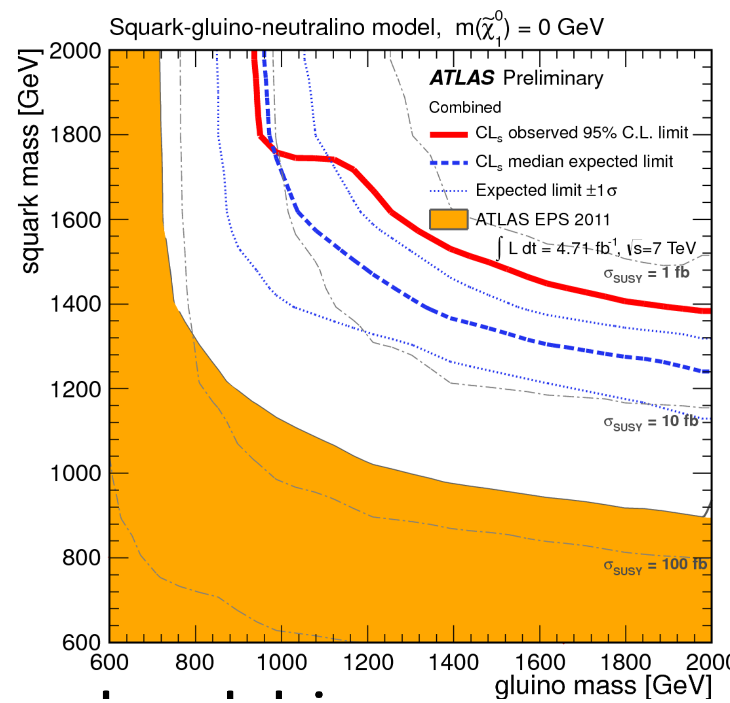
Both approaches are used

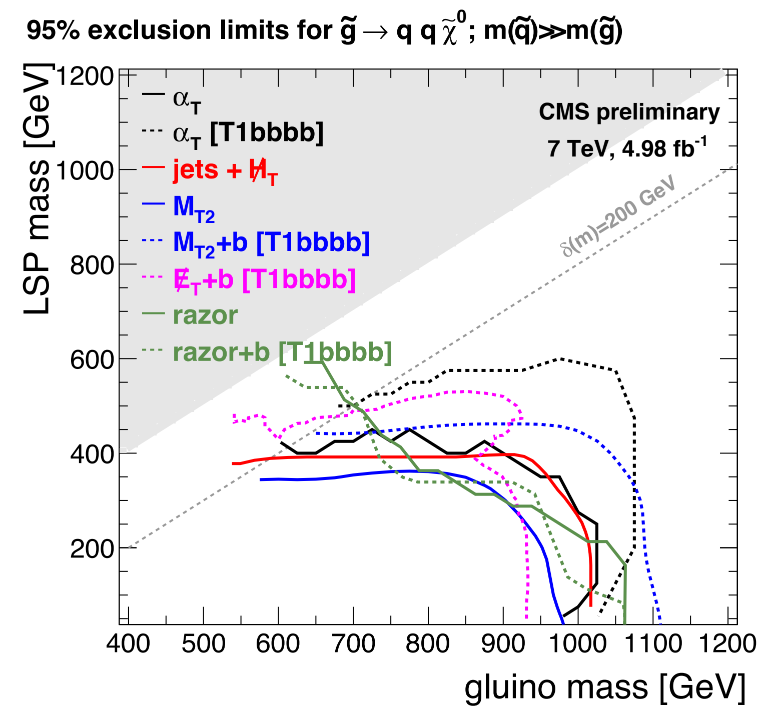
The Progress of LHC

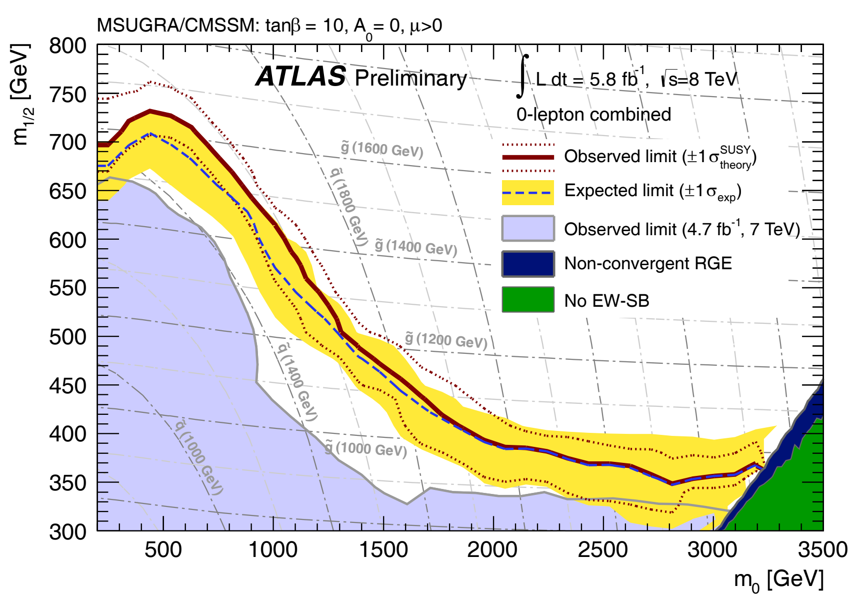
CMS CMSSM summary

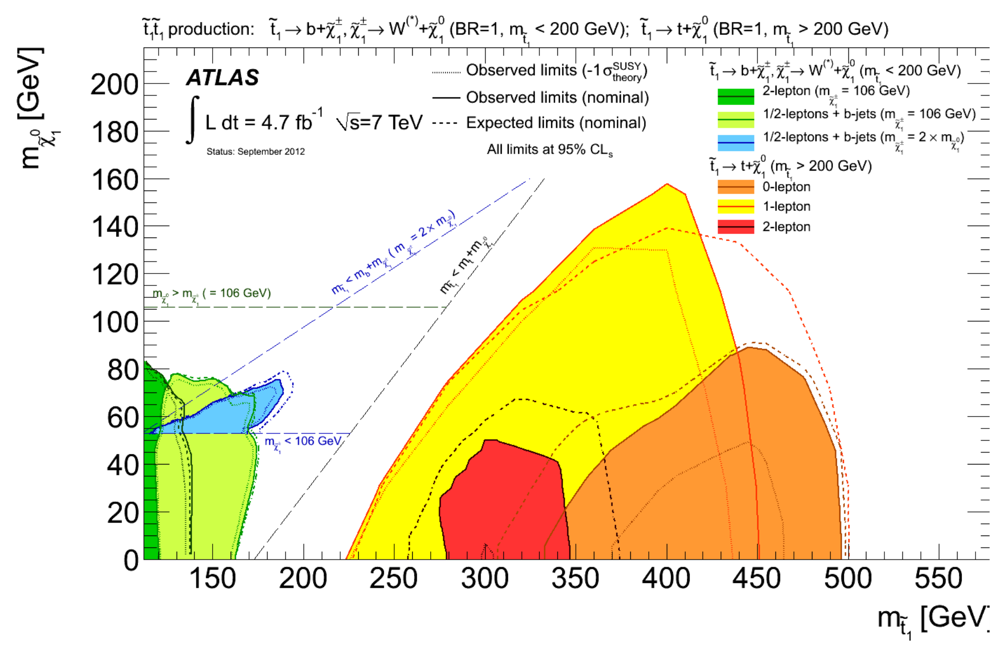


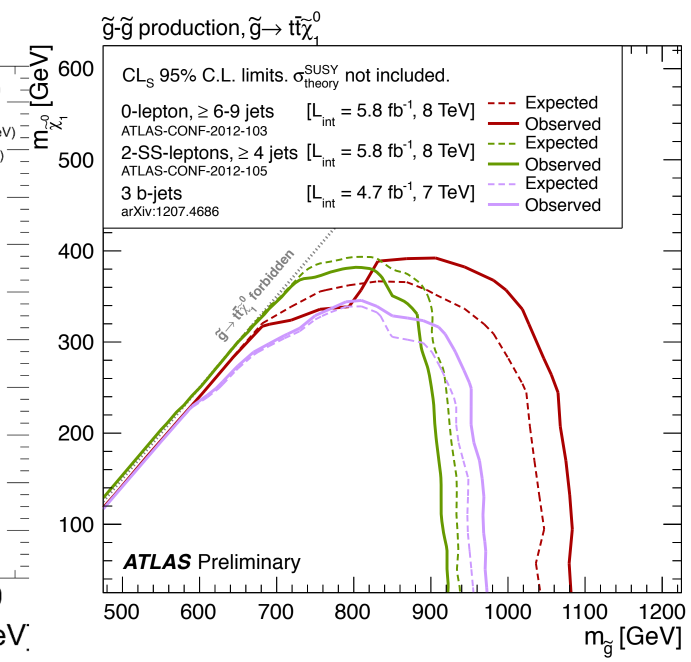
Look for squarks and gluinos with direct decays to SM+LSP









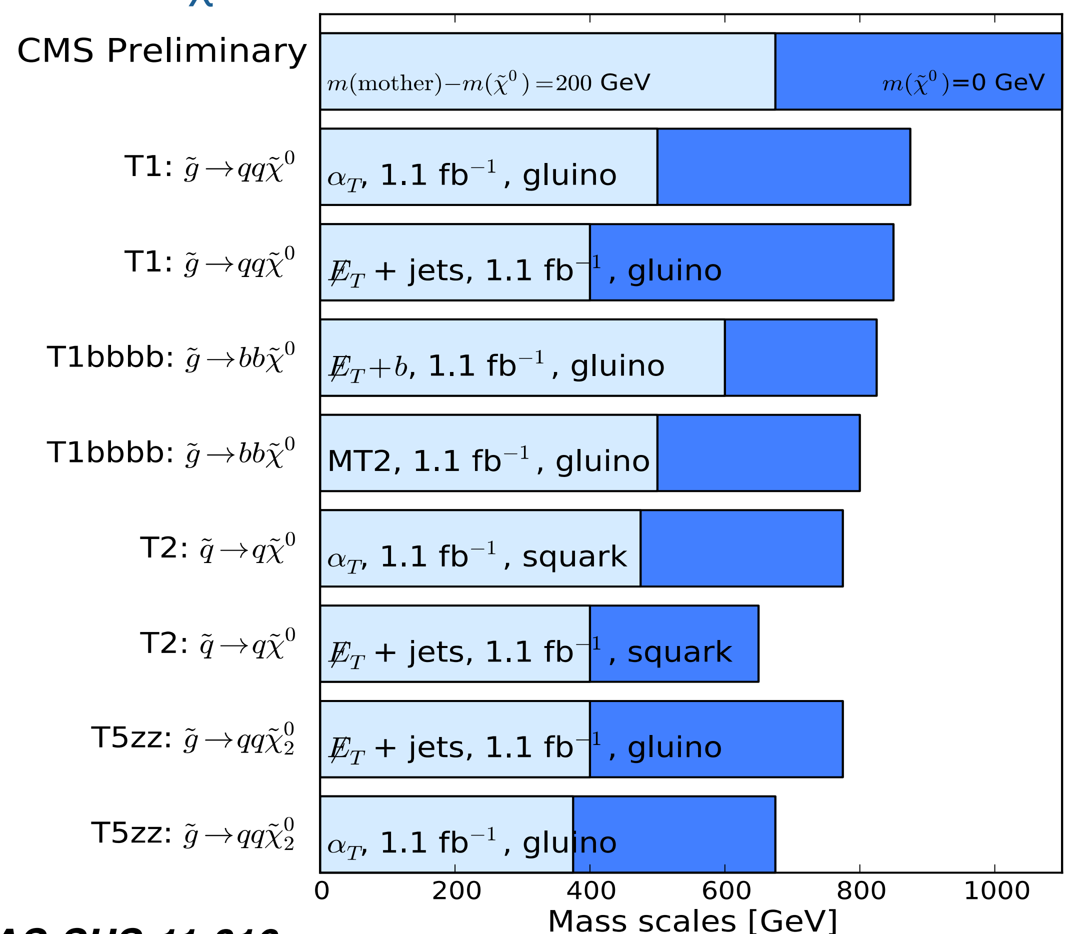


$\tilde{m}_g > 1000\ GeV$

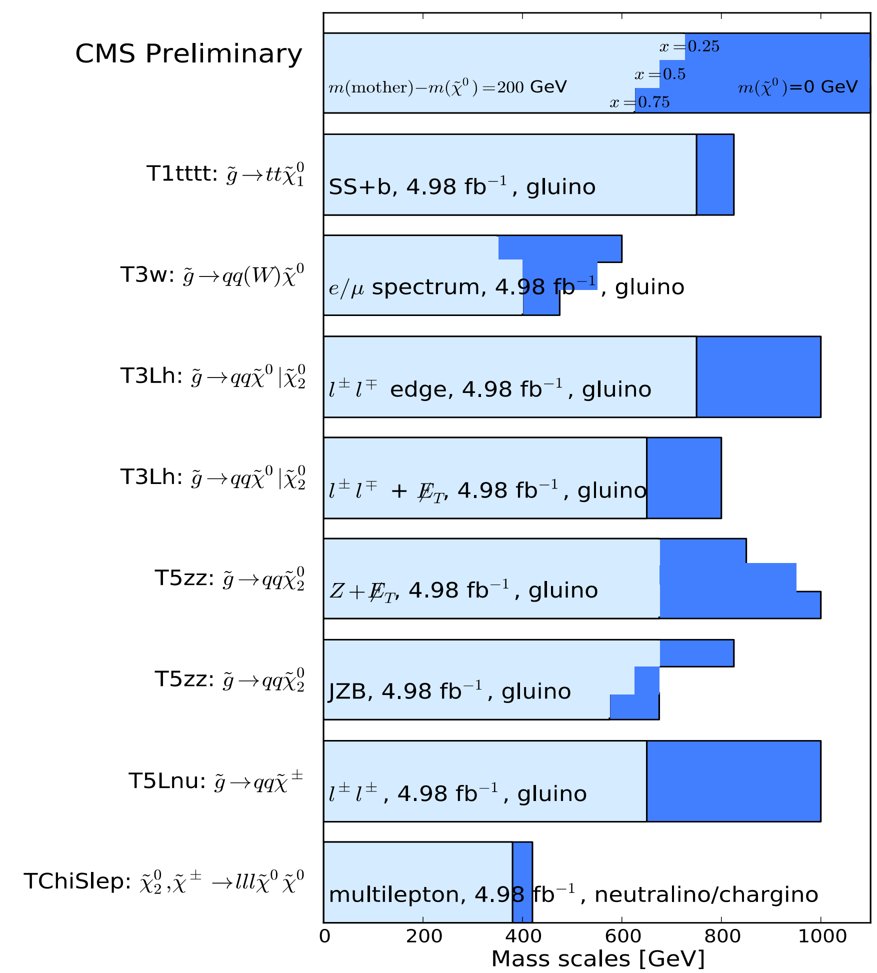
$\tilde{m}_q > 1400\ GeV$

SUSY in simplified models

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



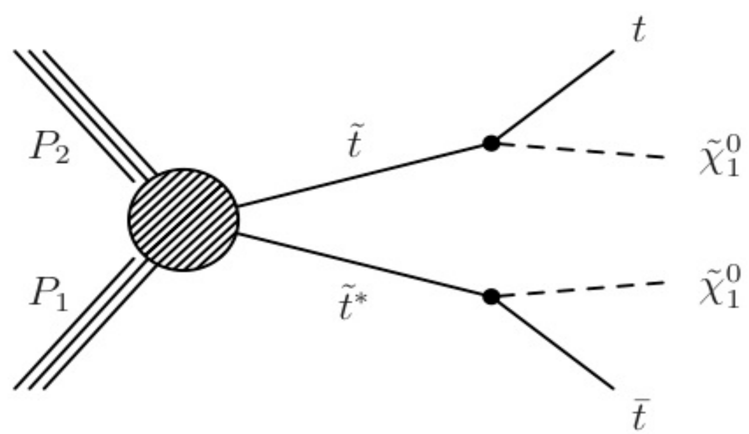
CMS-PAS-SUS-11-016

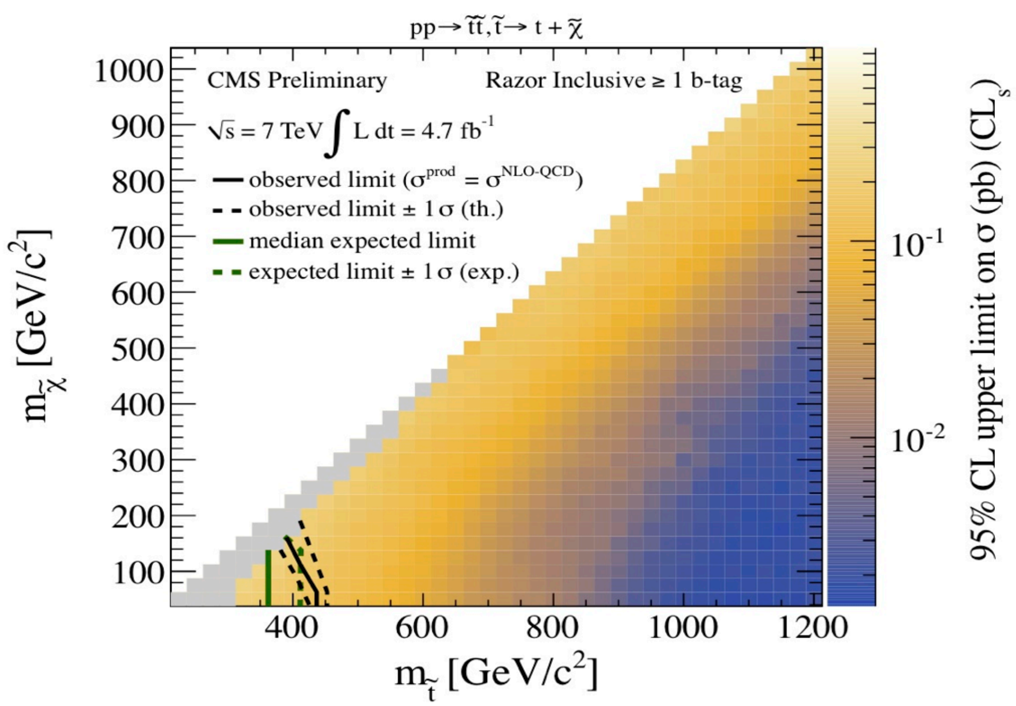


SUSY is not dead (yet). It might still hide in low MET/low HT events. More complicated models are under investigation→ more challenging searches. For some it is hard to even get the data on tape.

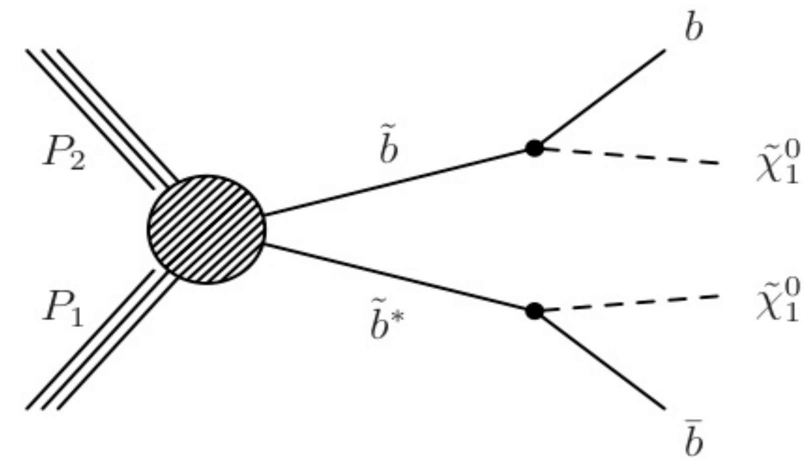
Stop and Sbottom Searches at LHC

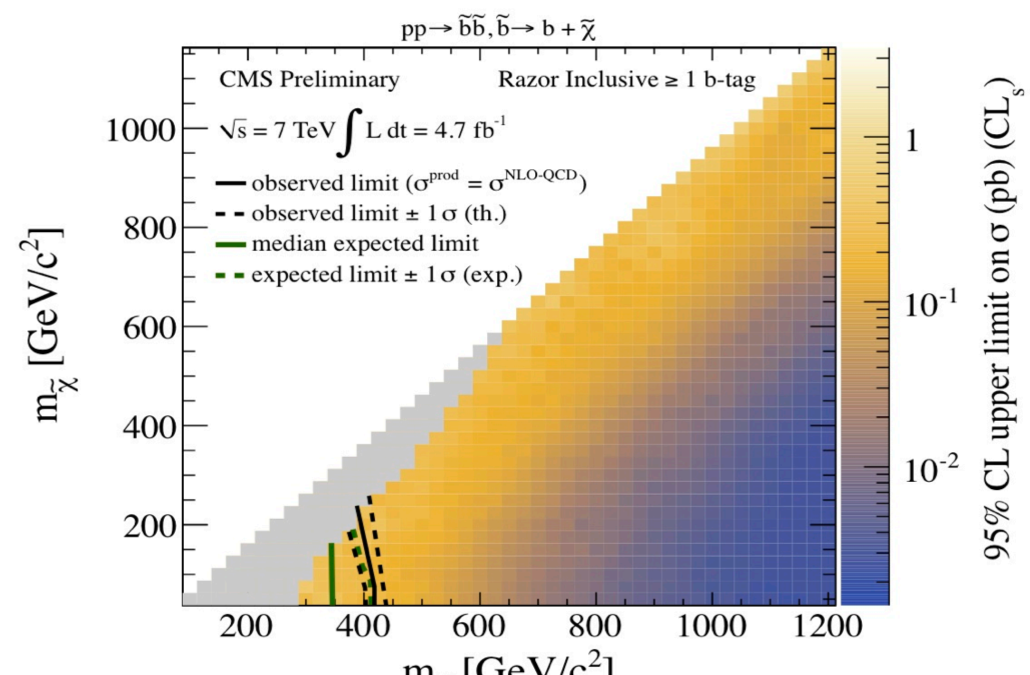
Di-stop production resulting in 2 top quarks +MET final states





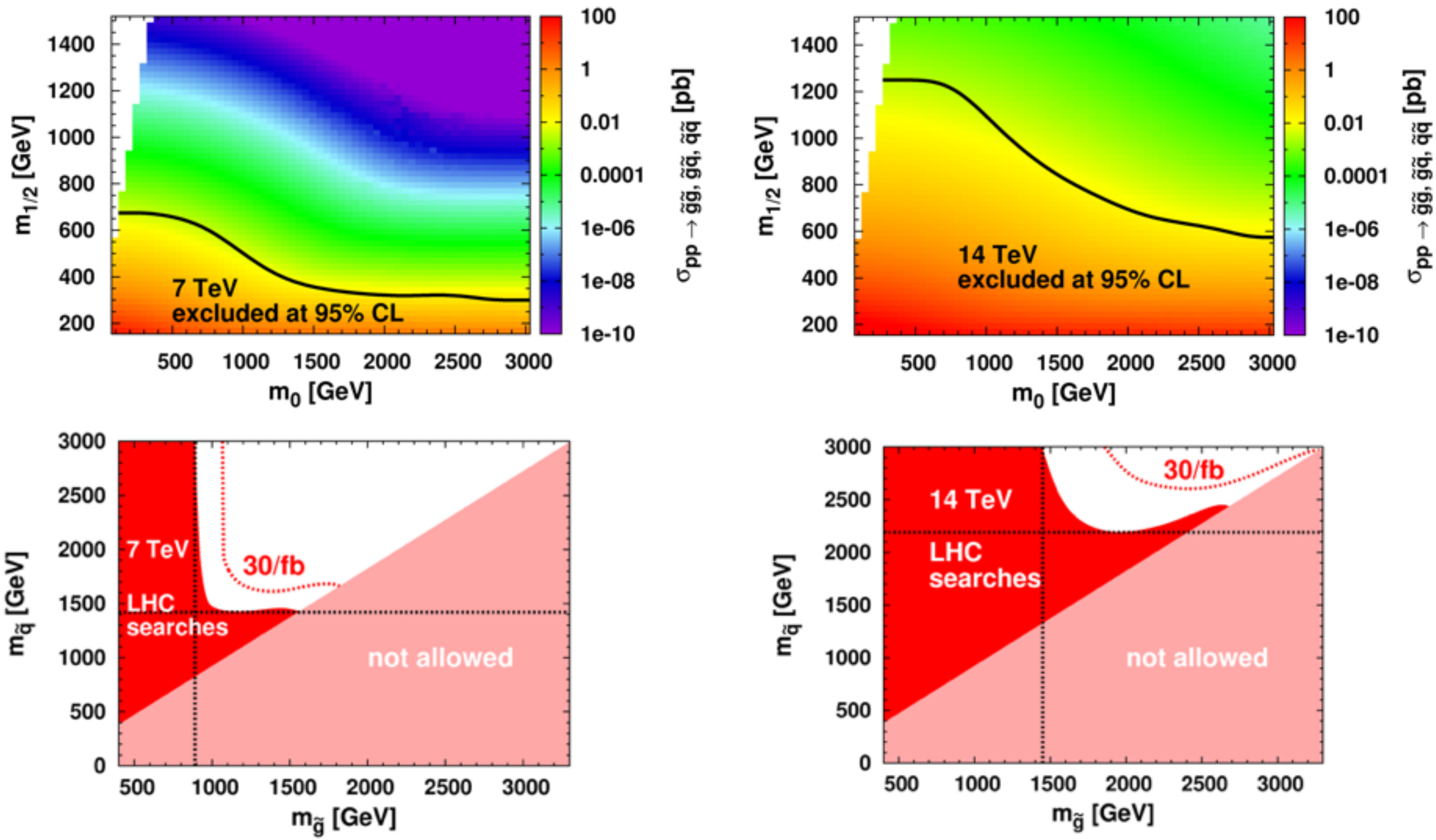
Di-sbottom production resulting in 2 b quarks +MET final states





CMS-SUS-11-024

LHC Reach at 7 and 14 TeV



Energy is more important than luminosity

Indirect Search at LHC

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

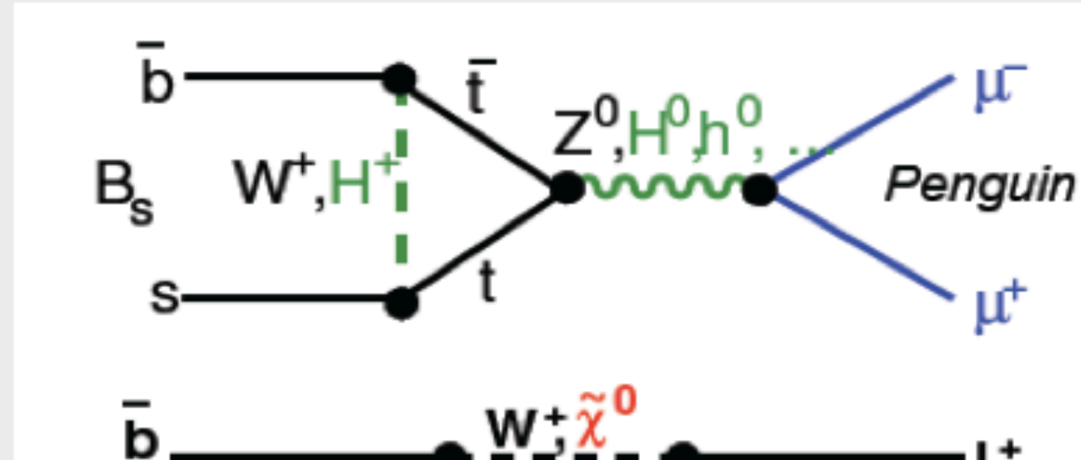
$$B_s \to X_s\gamma$$

$$B_u \to \tau\nu$$

$$g-2$$

Probing SUSY with $B_{s,d} \to \mu^+\mu^-$

- **Decays highly suppressed in SM**
  - Forbidden at tree level
  - b→s(d) FCNC transition only through penguin and box diagrams
  - Helicity suppressed by factors of (m_μ/



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

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

Enhancement

Suppression

Indirect: MSSM v NMSSM

95% CL exclusion

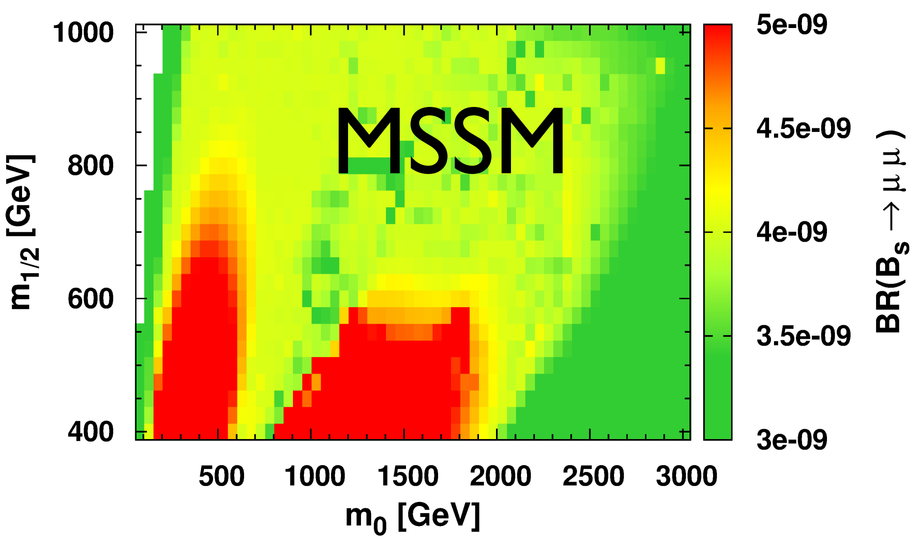
W.de Boer, C.Beskidt, D.K.‘11’12

NMSSM calculations made with NMSSMTools

MicrOMEGAs 2.4.1

G. Bélanger et al

U.Ellwanger et al



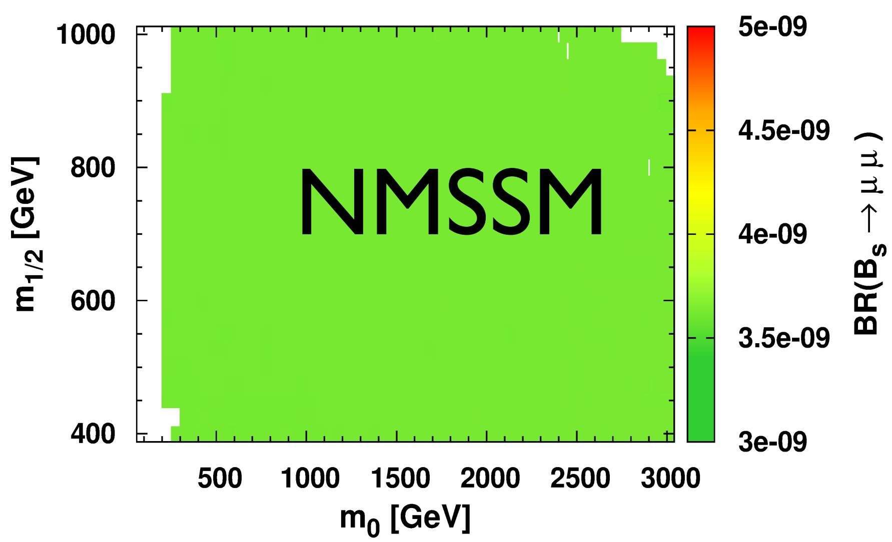
$$Br[B_s \to X_s\gamma] = (3.55 \pm 0.24) \cdot 10^{-4}$$

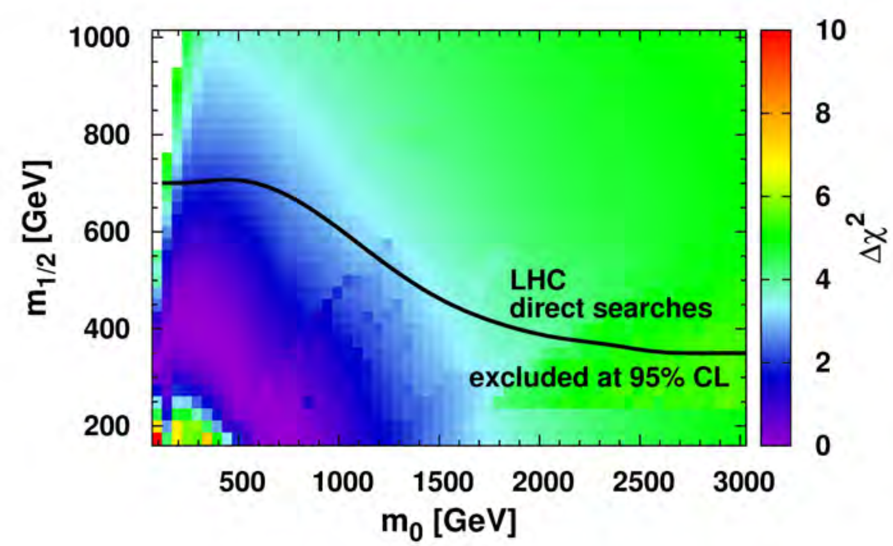
$$Br[B_u \to \tau\nu] = (1.68 \pm 0.31) \cdot 10^{-4}$$

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

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

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





muon $g-2$

AstroPhys Search

- DM abundance
- DM annihilation
- DM-nucleon interaction

Relic Abundance

Boltzman Equation

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -<\sigma \mathrm{v}>(n_\chi^2 - n_{\chi,eq}^2), \qquad H = \dot{R}/R$$

← Hubble constant

Relic Abundance

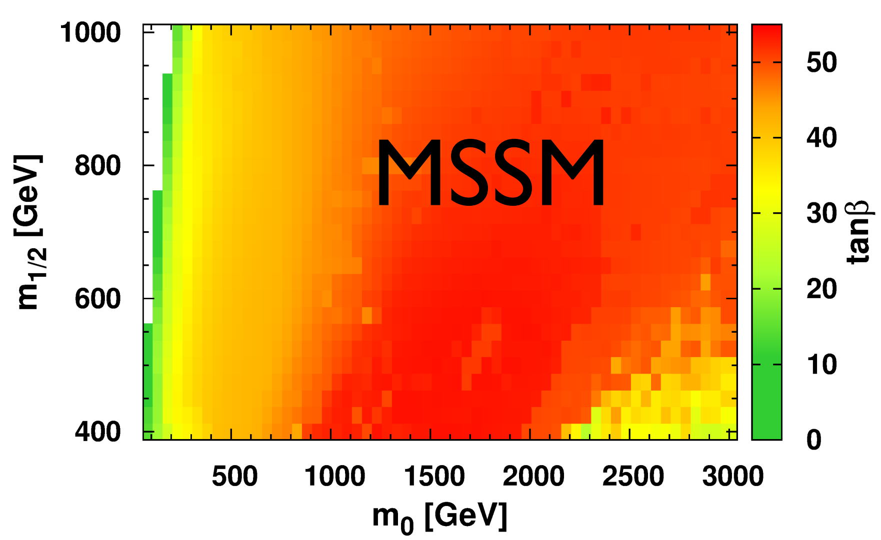
$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \approx \frac{3\cdot 10^{-27}\, cm^3 \sec^{-1}}{<\sigma \mathrm{v}>}$$

$<\sigma v>= 2\cdot 10^{-26} cm^3/s$

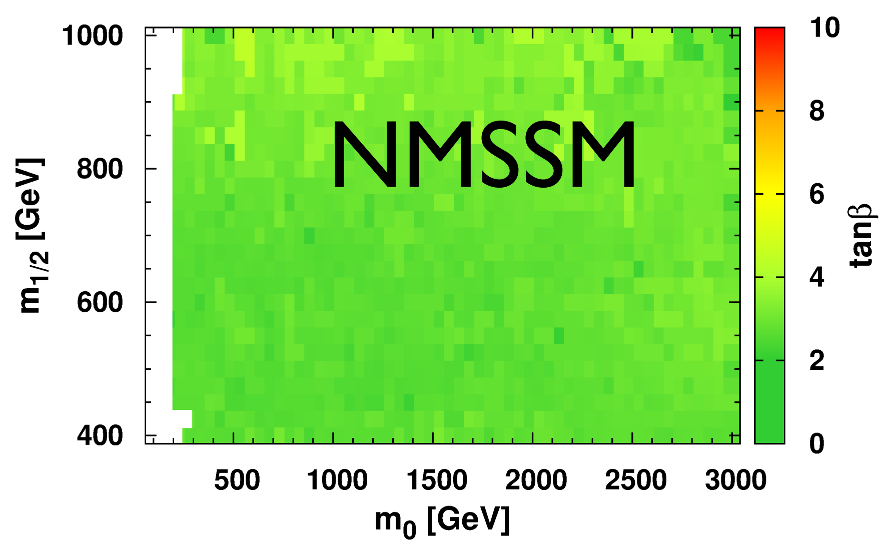
$\Omega_\chi h^2 \sim 0.113 \pm 0.009,$

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

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

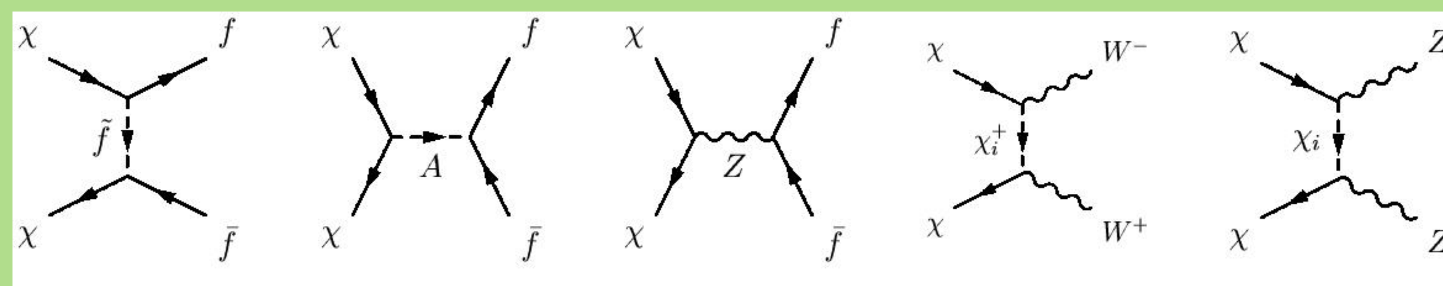


High $\tan\beta \sim 50$



Low $\tan\beta \sim 3$

DM annihilation



$\propto \frac{m_\chi \cdot m_f}{m_f^2}$

$\propto \frac{\tan\beta \cdot m_{f_d}}{m_W} N_1 N_{3(4)}$
$\tan\beta \cdot m_{f_d} \leftrightarrow \frac{m_{f_u}}{\tan\beta}$

$\propto \frac{m_f \cdot m_\chi}{m_Z^2} N_{3(4)}^2$

$\propto \frac{1}{1+(m_{\chi_i^+}/m_\chi)^2-(m_W/m_\chi)^2}$
$(m_{\chi_i^+}, m_W) \leftrightarrow (m_{\chi_i}, m_Z)$

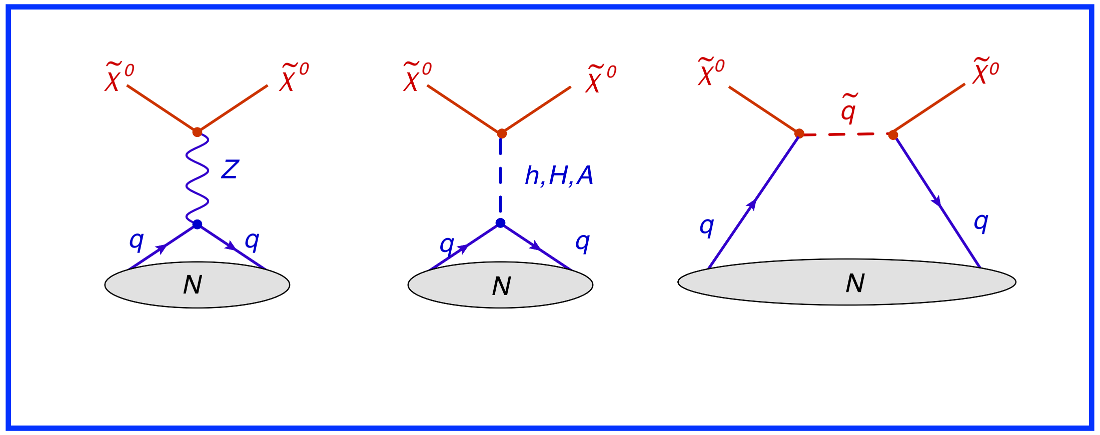
- Diffuse Gamma Rays
  EGRET -> GLAST(FERM-LAT)
- Positrons in Cosmic Rays
  HEAT, AMS01 -> PAMELA, FERMI
- Antiprotons in Cosmic Rays
  BESS -> AMS02

No significant excess

Contradictory interpretation

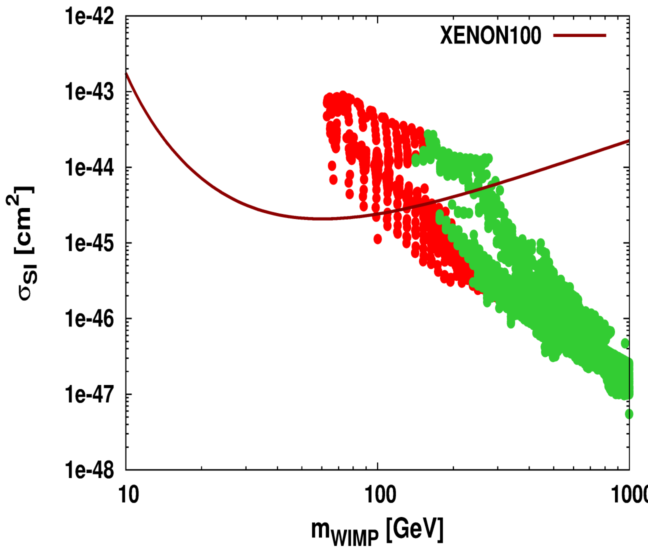
135 GeV $\gamma\gamma$ line?

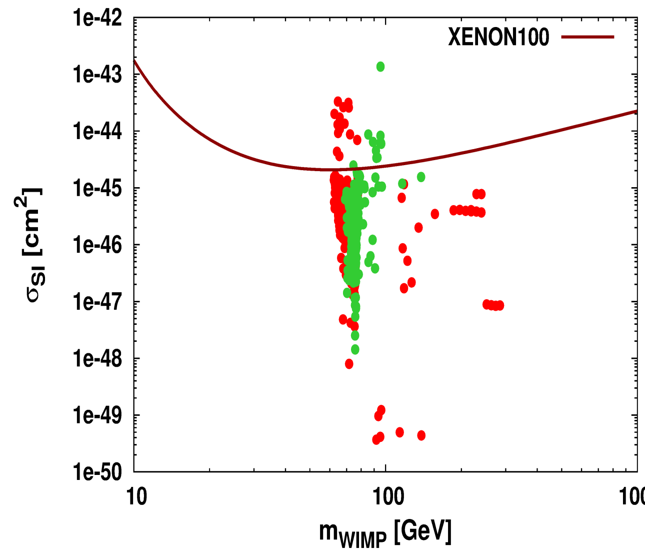
DM Nucleons Interaction



MSSM

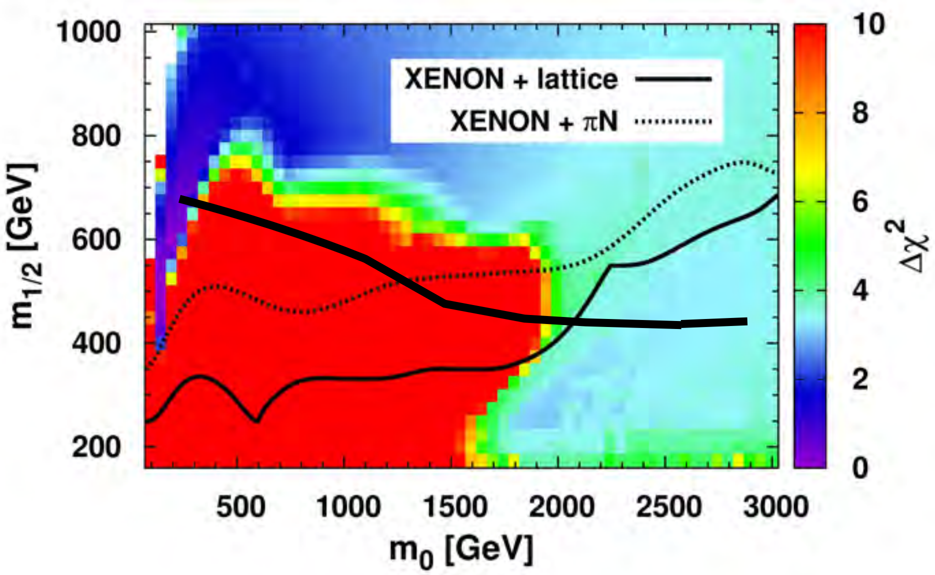
NMSSM





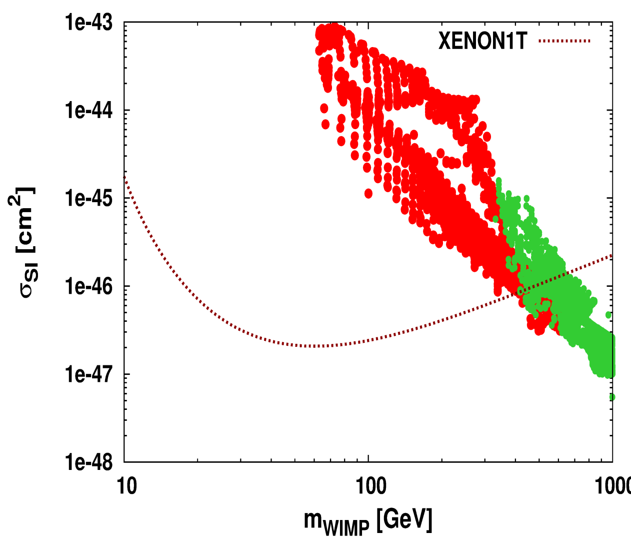
Red points - excluded by LHC

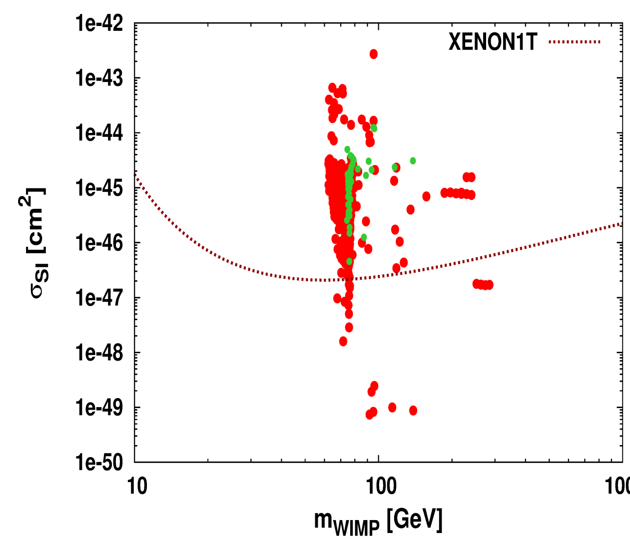
XENON100+LHC 8



MSSM

Direct DM search



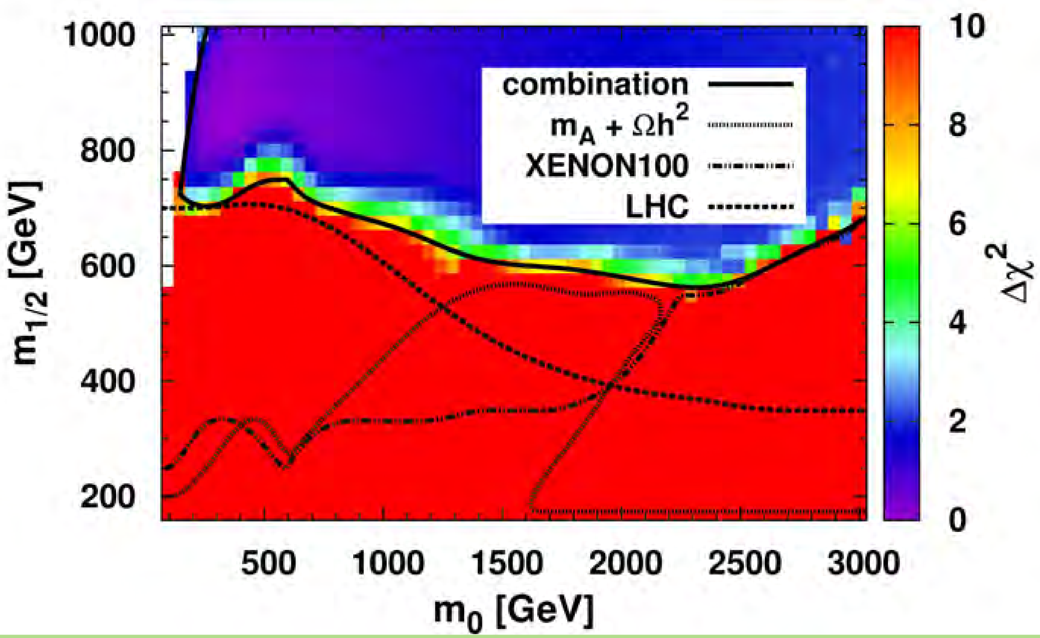


XENON1T+LHC 14

Combined Fit to all Data

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

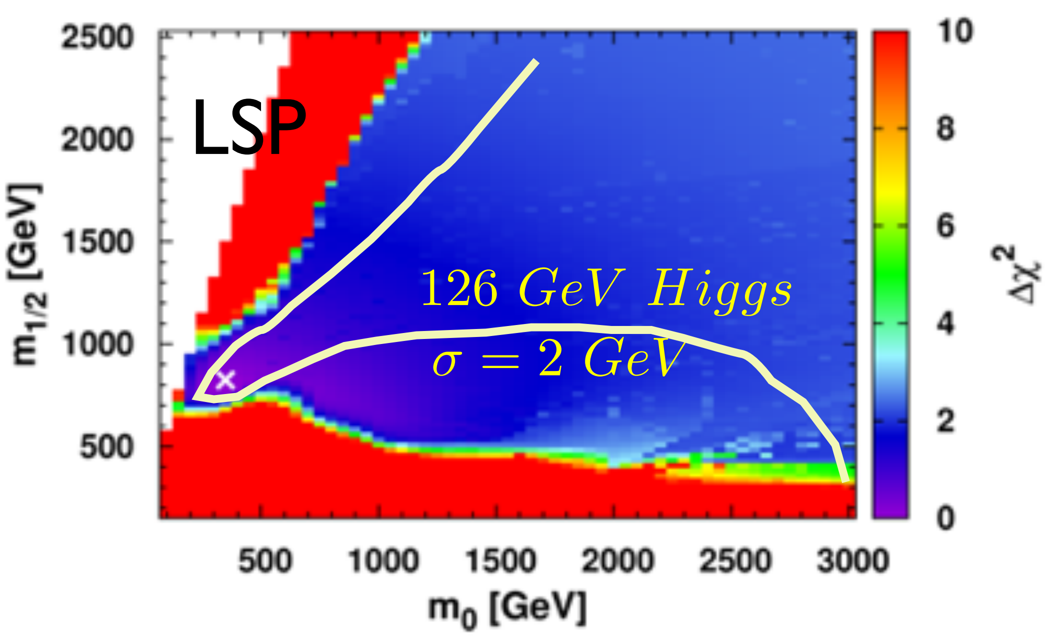
MSSM



without 125 GeV Scalar

Constraint	Data
Ωh^2	0.113 ± 0.004
$b \to X_s \gamma$	$(3.55 \pm 0.24) \cdot 10^{-4}$
$B_u \to \tau\nu$	$(1.68 \pm 0.31) \cdot 10^{-4}$
Δa_μ	$(302 \pm 63(exp) \pm 61(theo)) \cdot 10^{-11}$
$B_s^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^- < 4.5 \cdot 10^{-9}$
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	$\sigma_{\chi N} < 8 \cdot 10^{-45} - 2 \cdot 10^{-44} cm^2$

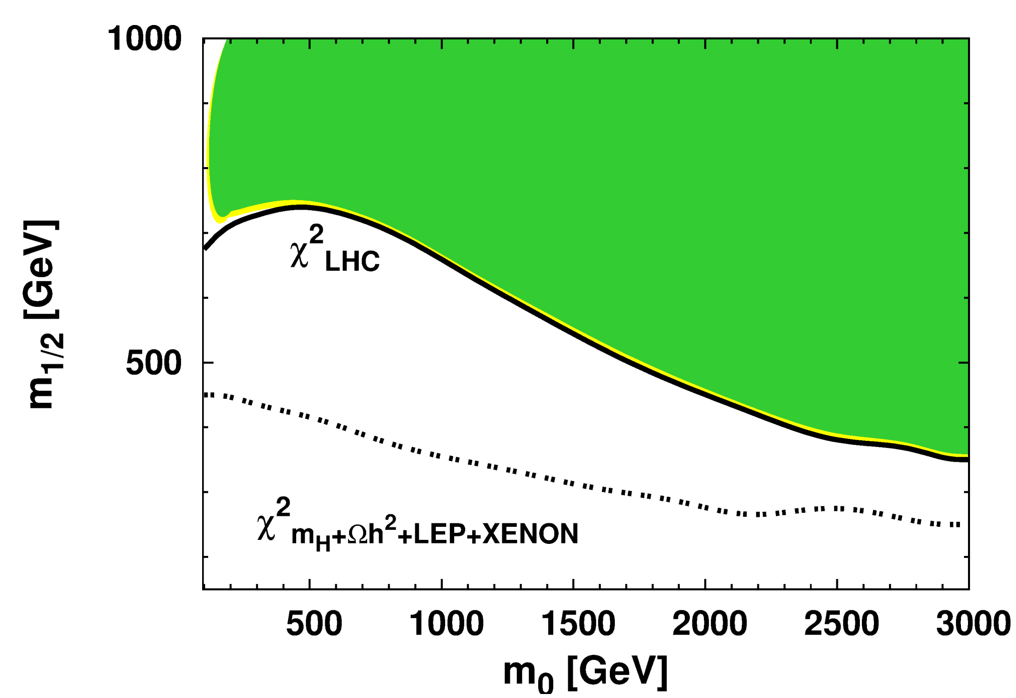
The values of $\tan\beta$ and A_0 are adjusted



with 125 GeV Scalar

Larger scale for $m_{1/2}$

NMSSM



четверг, 7 марта 13 г.

A.Parker
ICHEP'12

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