International Moscow Workshop on Phenomenology of Particle Physics devoted to the memory of Prof. Alexei Kaidalov

SUSY (Pheno) Today

Dmitry Kazakov

BLTP JINR (Dubna)/ITEP(Moscow)

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Why SUSY?

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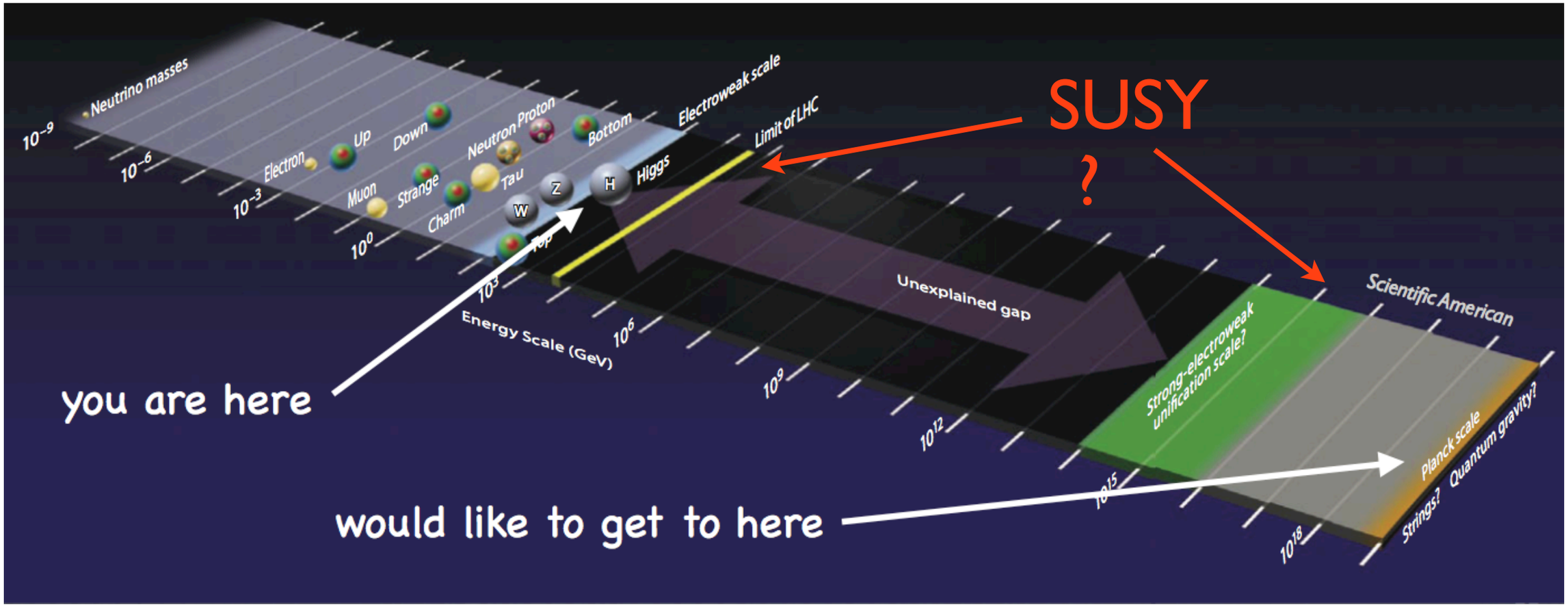
HEP Scale


Neutrino masses
Electron
Up
Down
Neutron
Proton
Muon
Strange
Tau
Charm
Bottom
Top
Z
W
H
Higgs
Electroweak scale
Limit of LHC
SUSY
?
Unexplained gap
Scientific American
Strong-electroweak unification scale?
Planck scale
Strings? Quantum gravity?
Energy Scale (GeV)
you are here
would like to get to here

SUSY Models

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What SUSY?

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- MSSM
- CMSSM
- mSUGRA
- mGMSB
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- NUHM
- NMSSM
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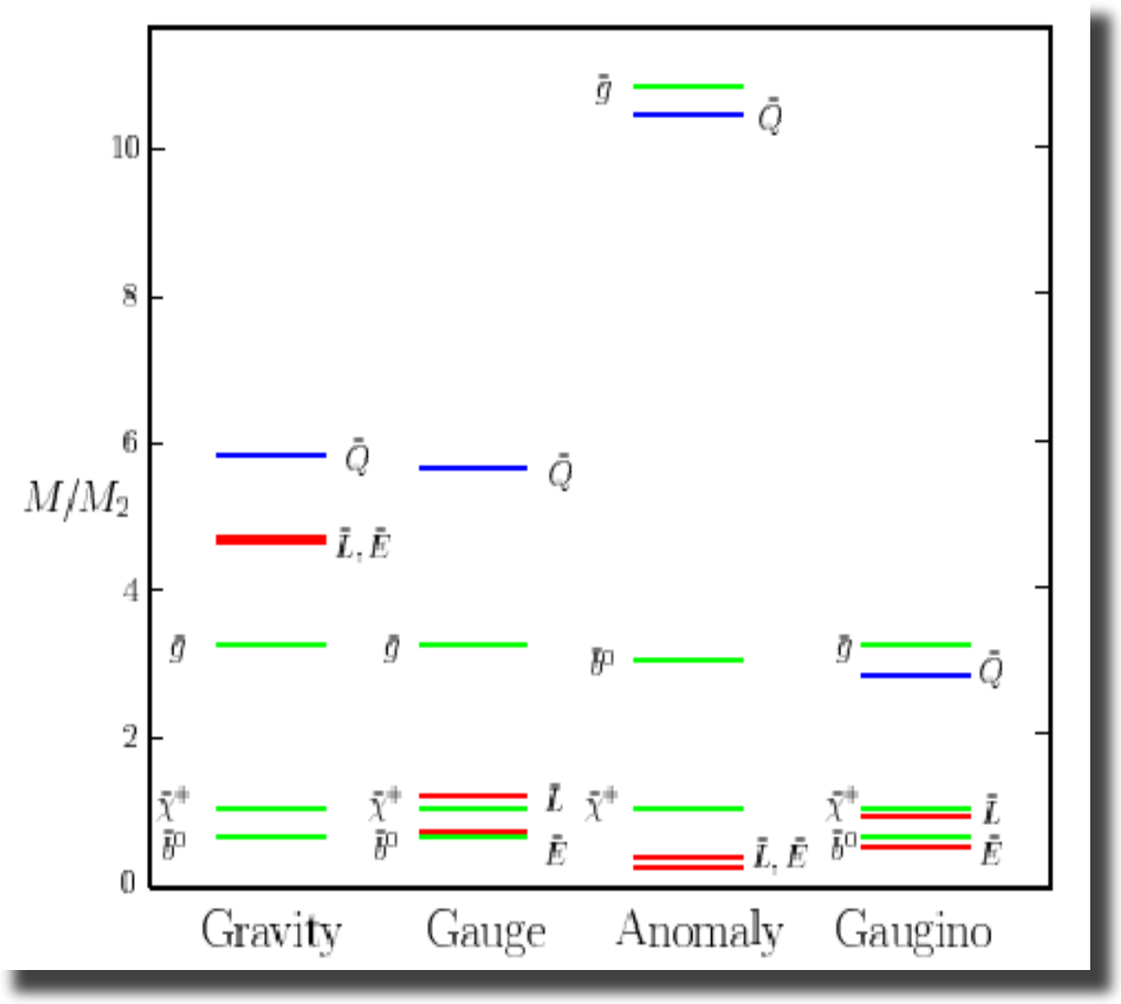
Sample superparticle spectrum



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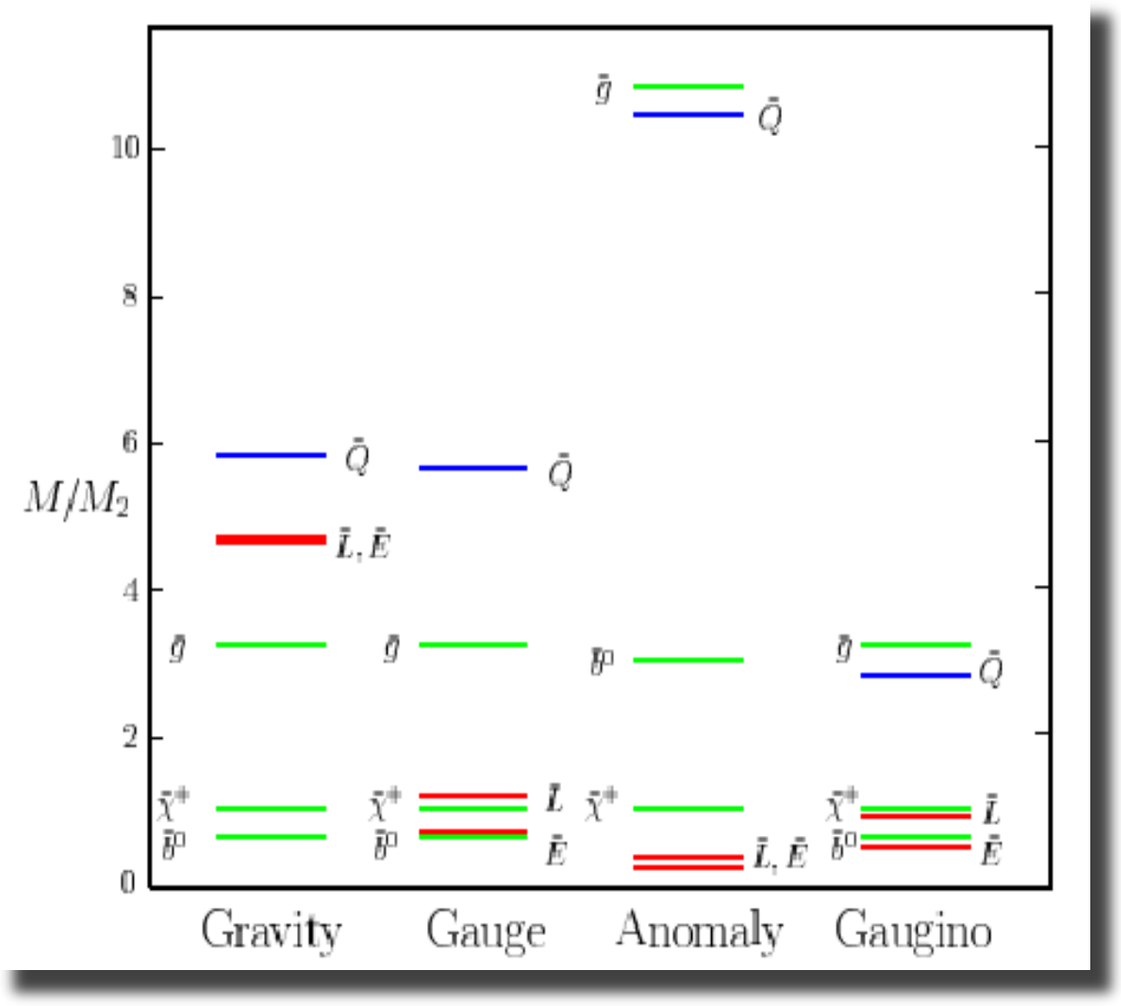

Despite supersymmetric rigidity of dimensionless couplings the arbitrariness of soft terms make predictions strongly model dependent !

SUSY Particles

Simplest (N=1) SUSY Multiplets

Bosons and Fermions come in pairs

$$(\varphi,\psi) \quad (\lambda, A_\mu) \quad (\tilde{g}, g)$$

Spin 0 Spin 1/2 Spin 1/2 Spin 1 Spin 3/2 Spin 2

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SUSY associates known bosons with new fermions
and known fermions with new bosons

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* $B(\gamma)$	*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	$\tilde{E}_i = \tilde{e}_R$	$E_i = e^c_R$	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	$\tilde{U}_i = \tilde{u}_R$	$U_i = u^c_R$	3^*	1	–4 / 3
D_i	$\tilde{D}_i = \tilde{d}_R$	$D_i = d^c_R$	3^*	1	2 / 3
Higgs					
H_1	Higgses H_1	higgsinos $\tilde{H}_1$	1	2	–1
H_2	H_2	$\tilde{H}_2$	1	2	1

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Particle Phys

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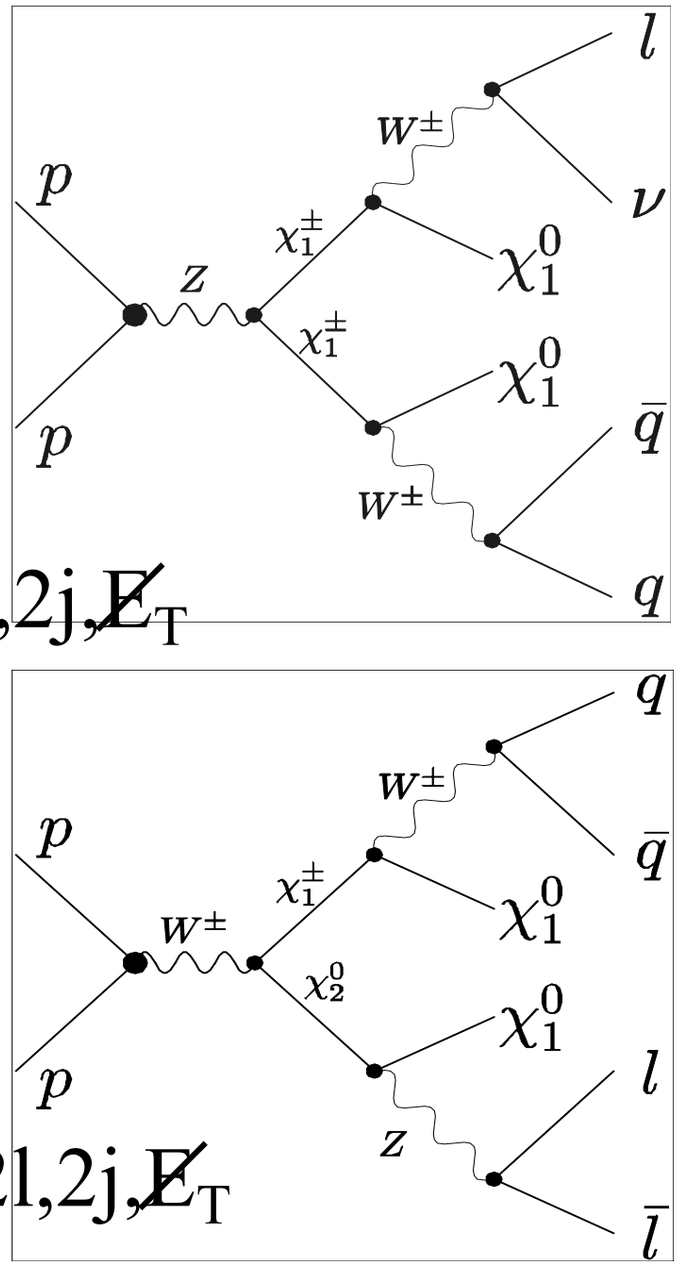
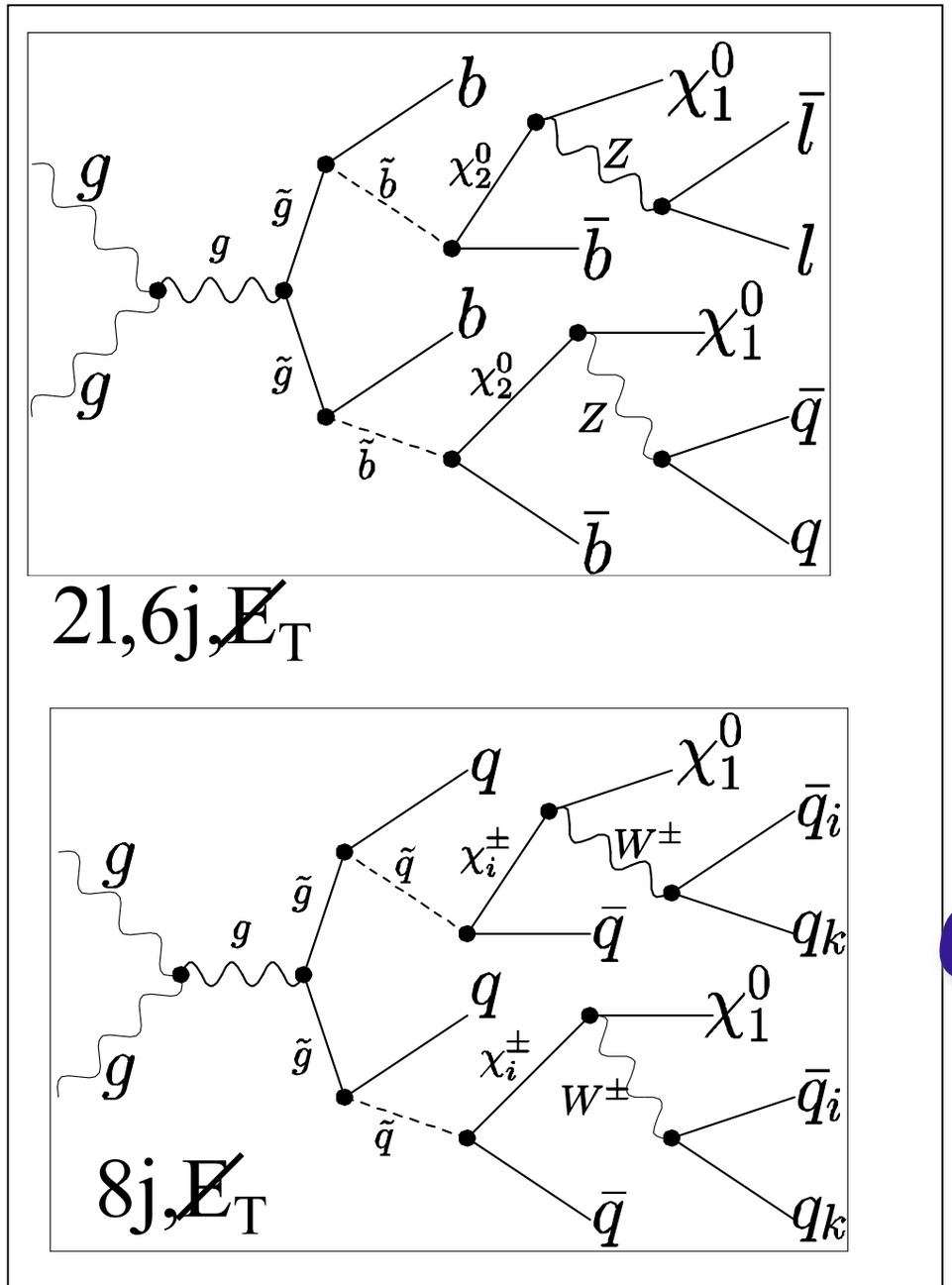
Nothing so far ...

Creation and Decay of Superpartners in Cascade Processes @ LHC

weak int's



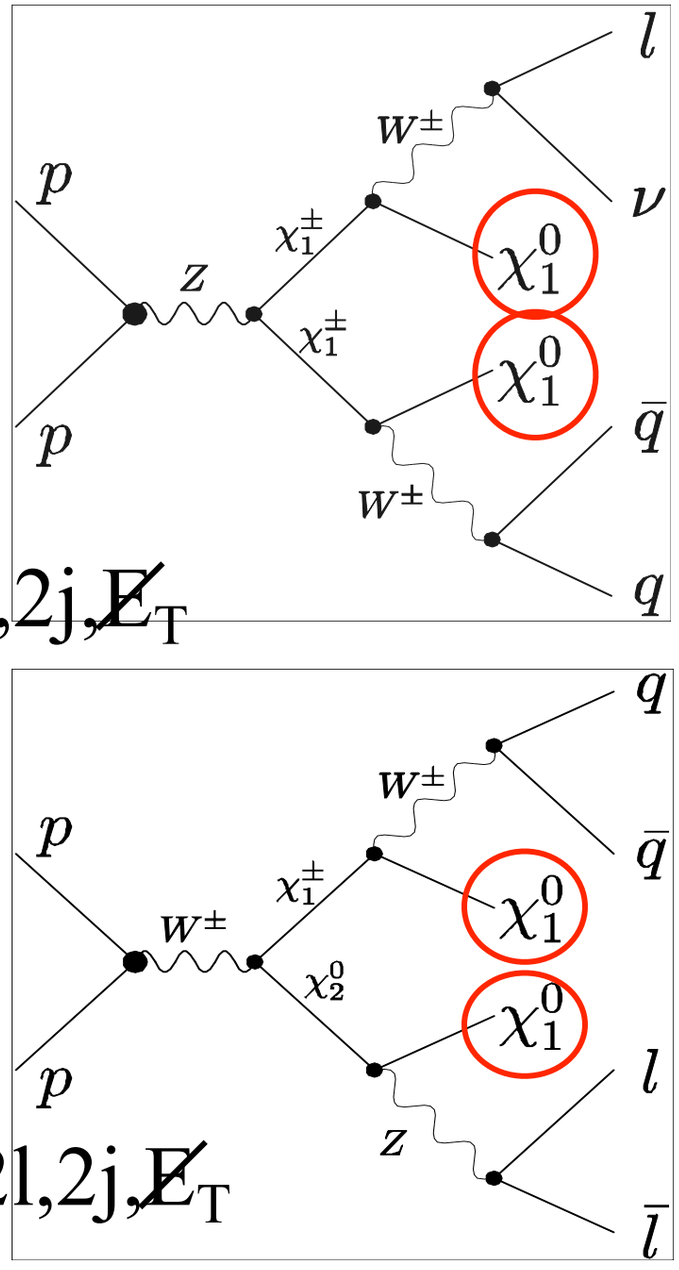


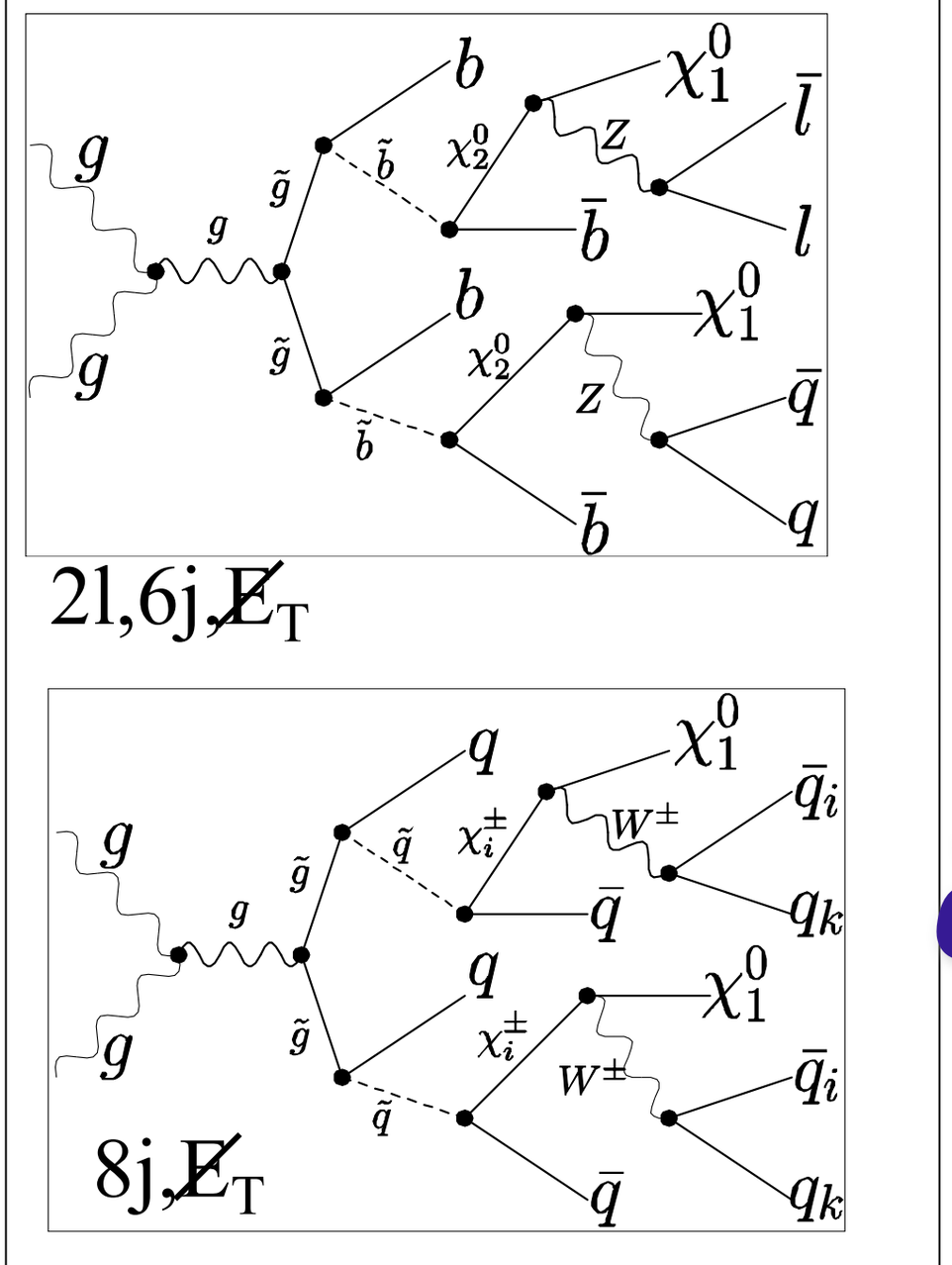
Strong int's

Typical SUSY signature: Missing Energy and Transverse Momentum

Creation and Decay of Superpartners in Cascade Processes @ LHC

weak int's





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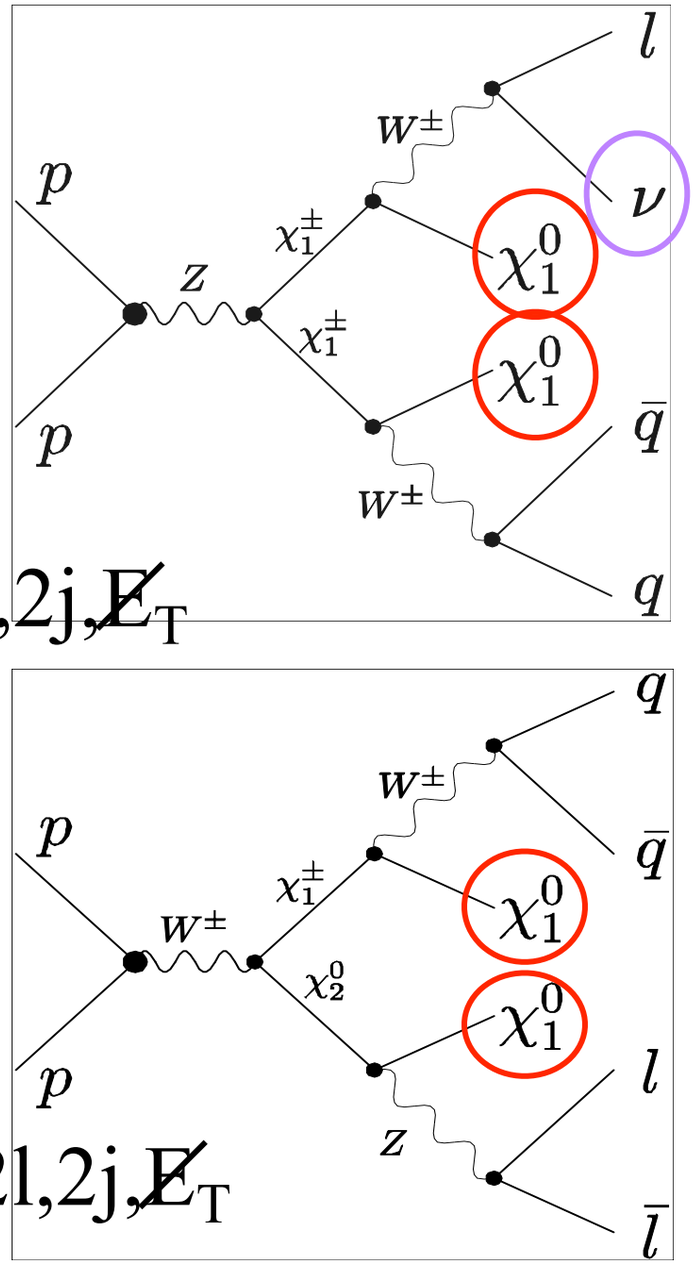

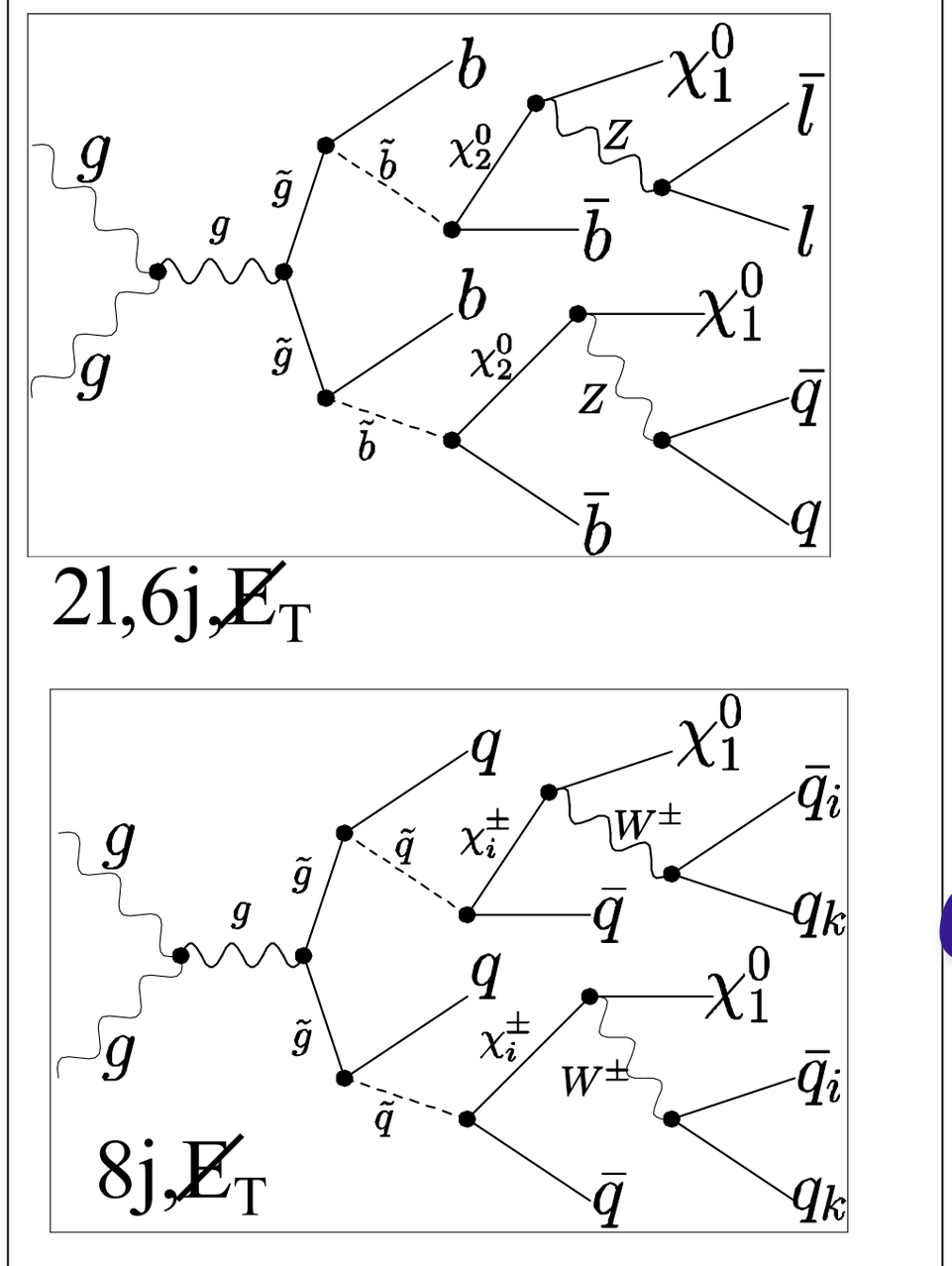

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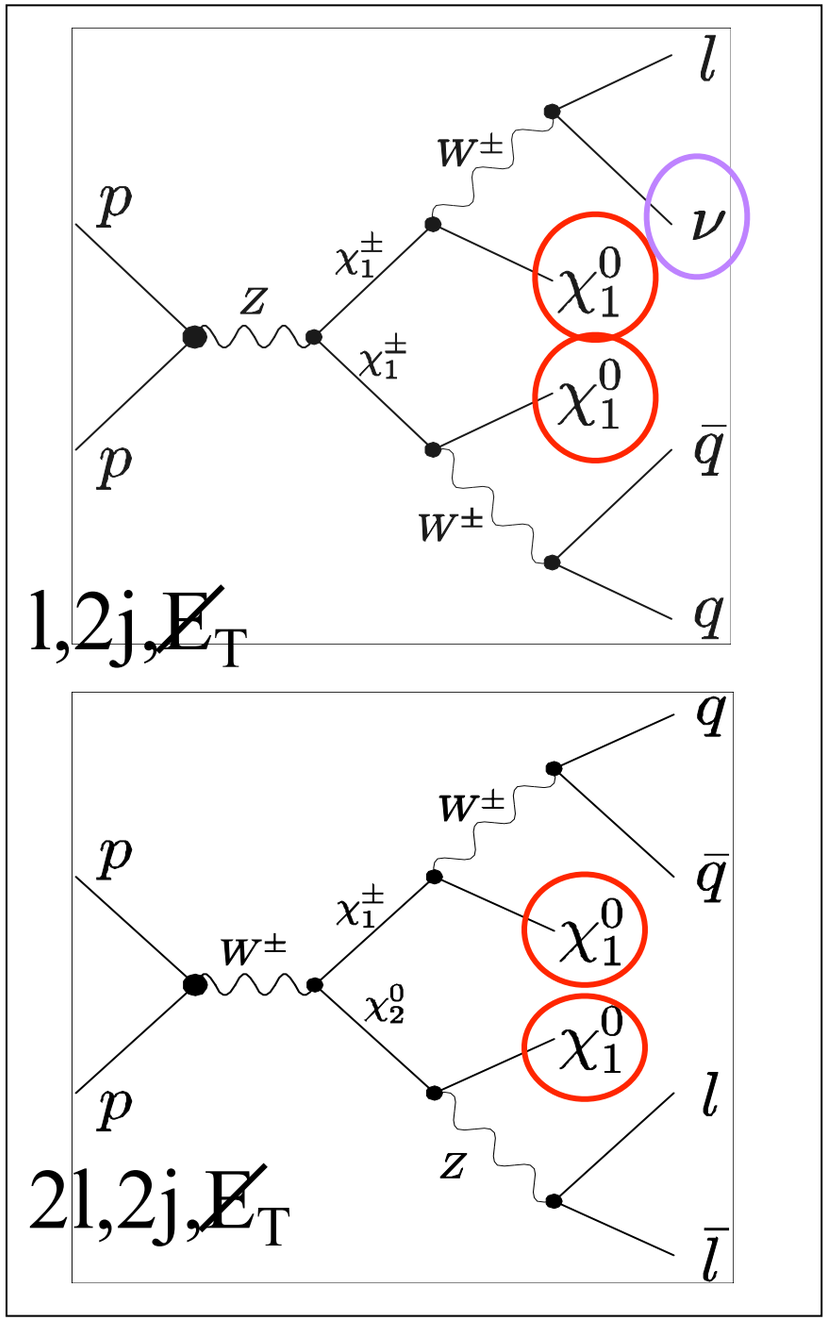

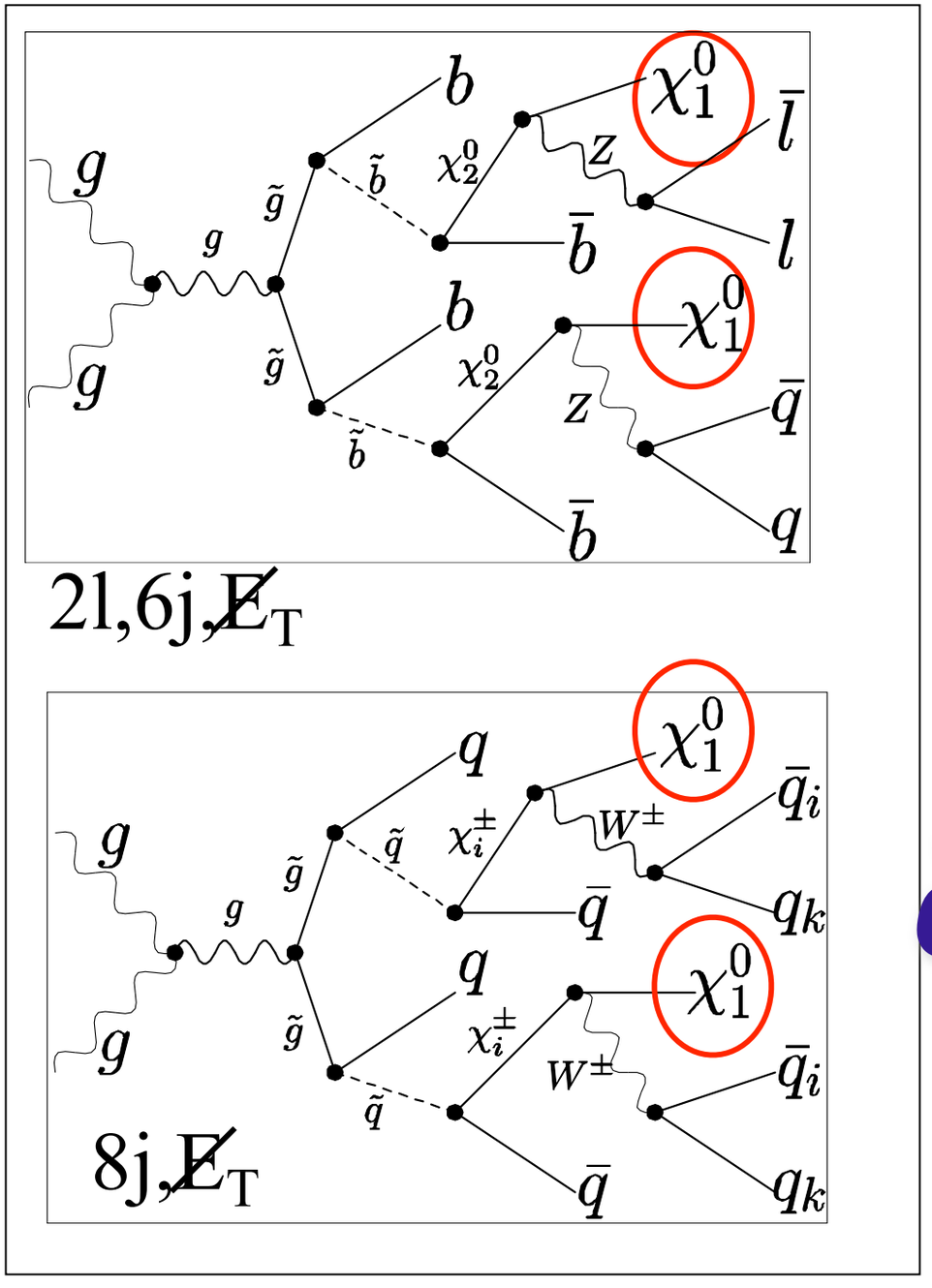

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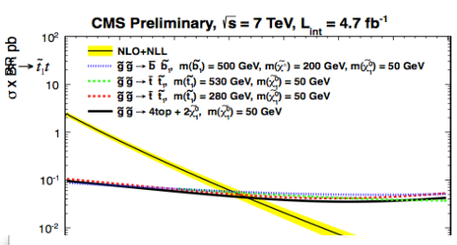
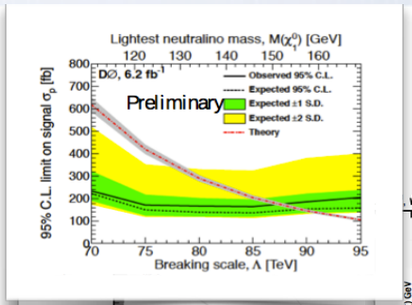
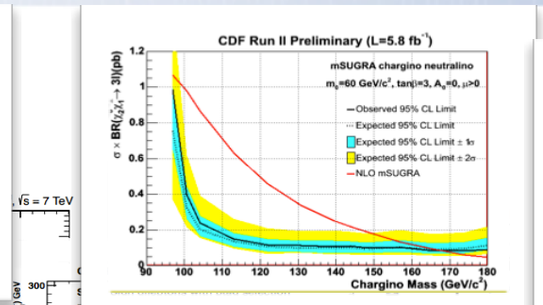
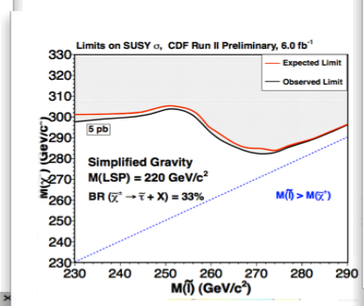
Guido Tonelli

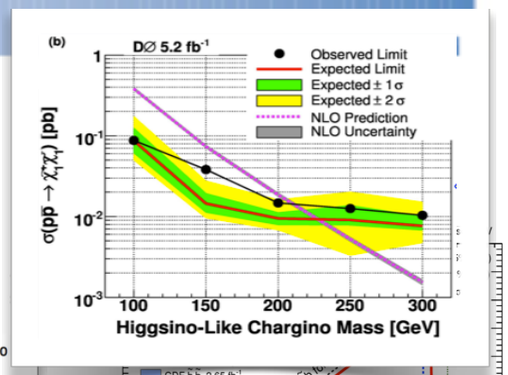
SUSY searches

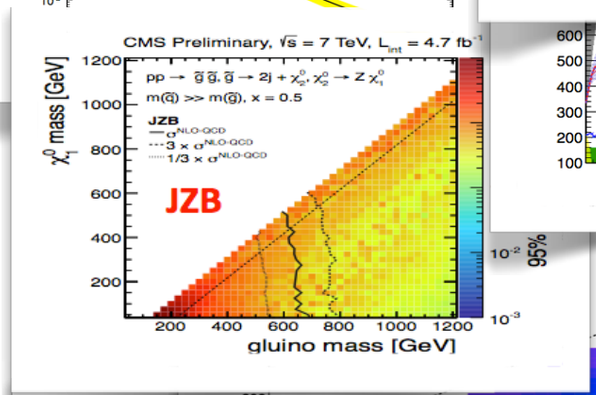


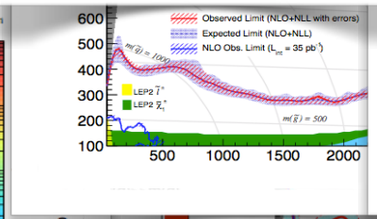


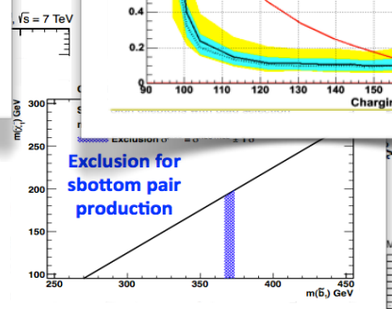


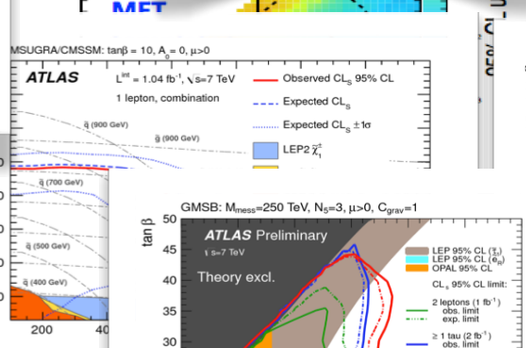


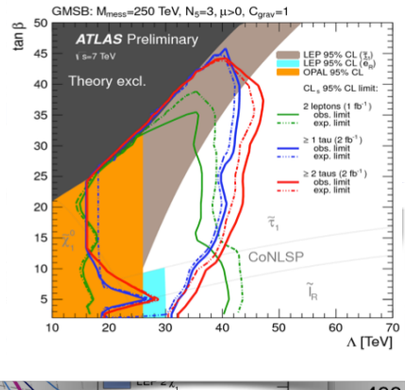


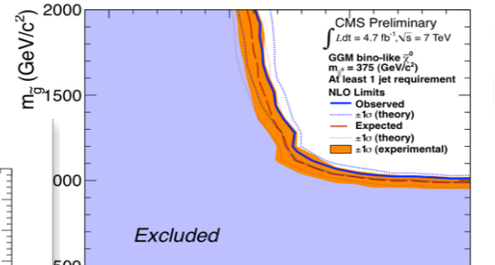


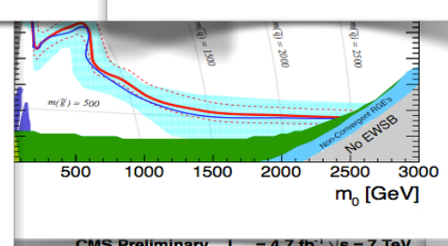


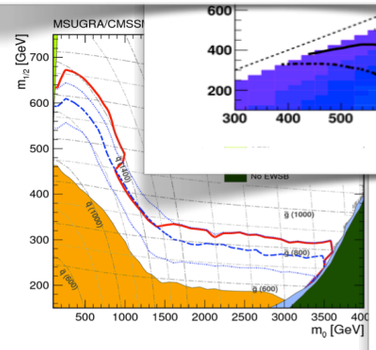


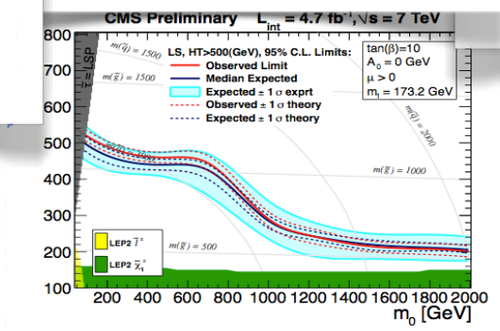


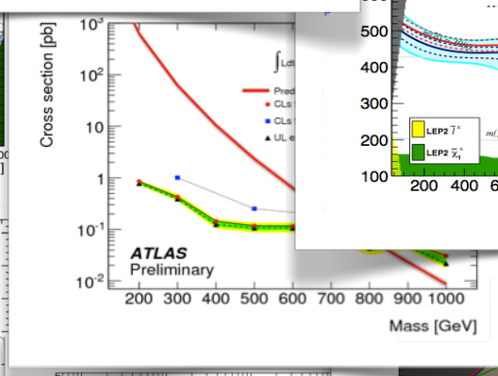


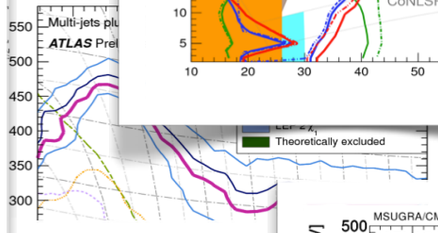


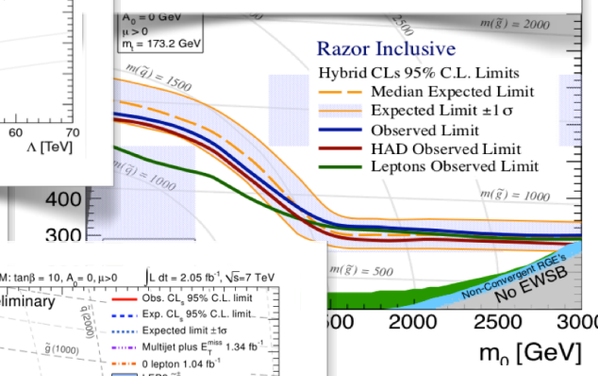


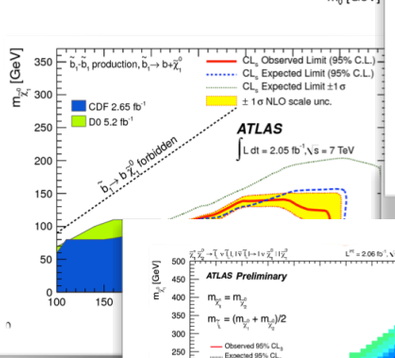


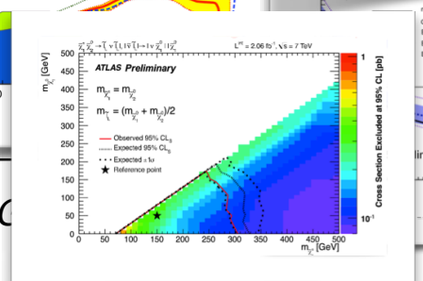


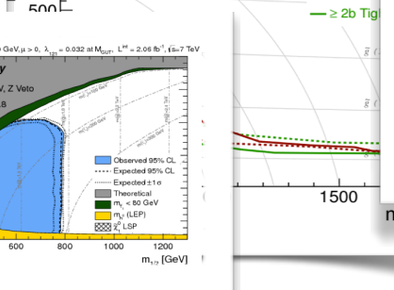


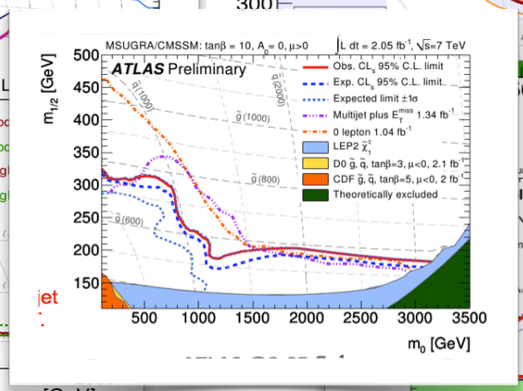


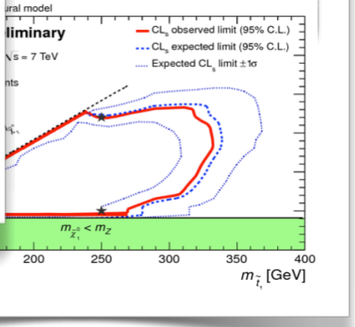












Exp and Theor Framework

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Two ways to present and analyse data:

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introduce universal parameters at high energy scale (GUT)
Example $m_0,\ m_{1/2},\ A_0,\ \tan\beta$ of MSSM

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Both approaches are used

The Progress of LHC

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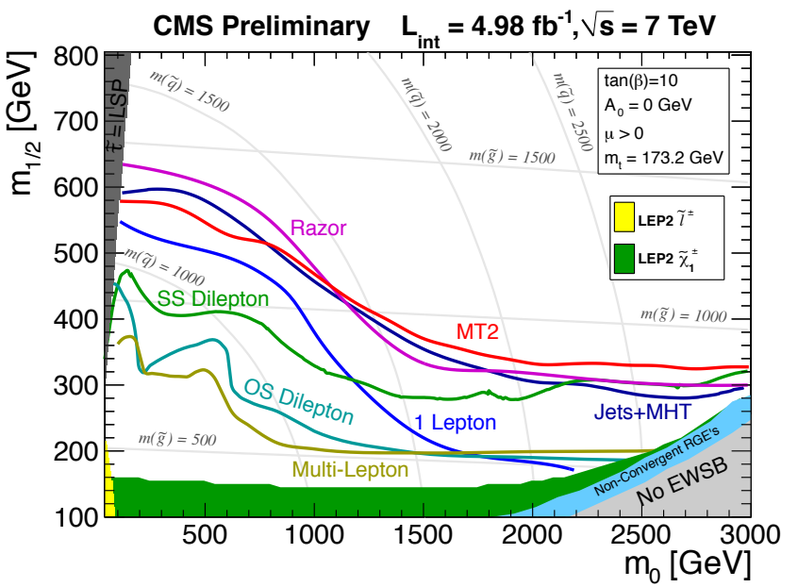
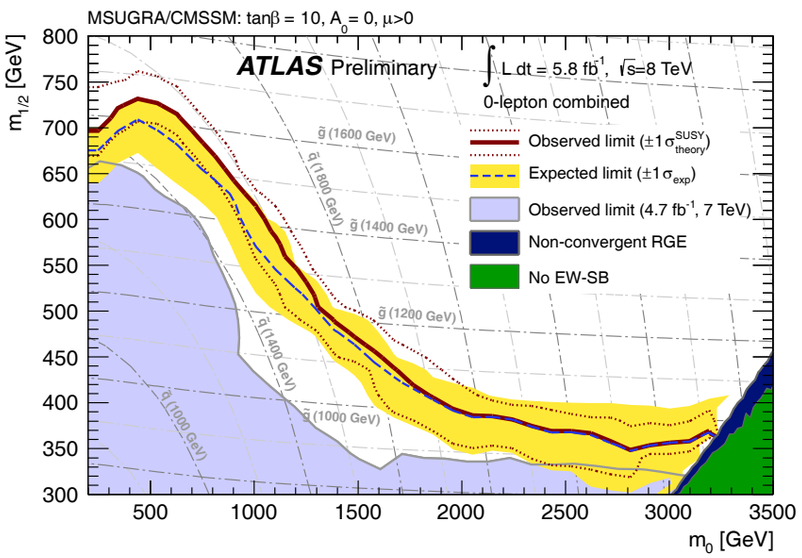
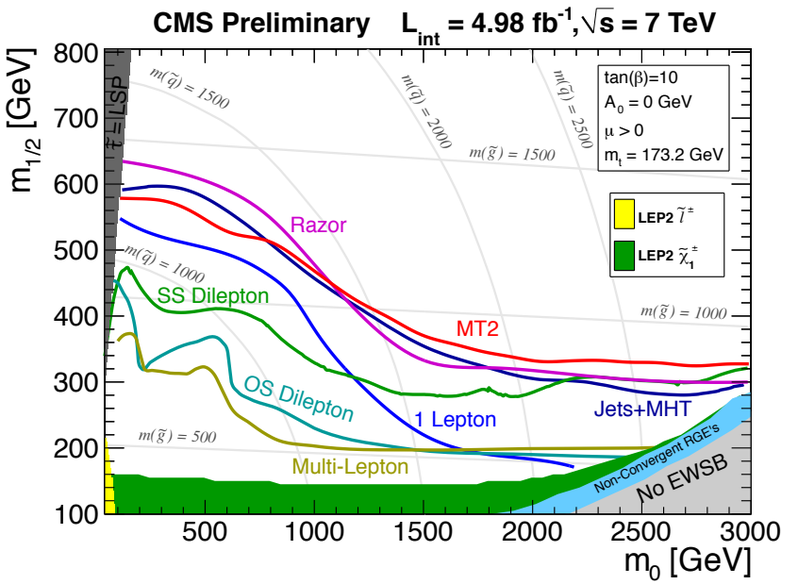
CMS CMSSSM summary



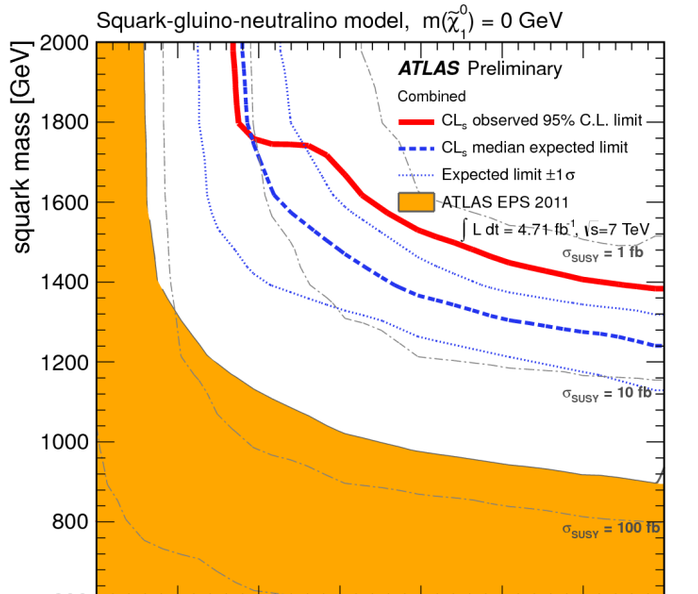


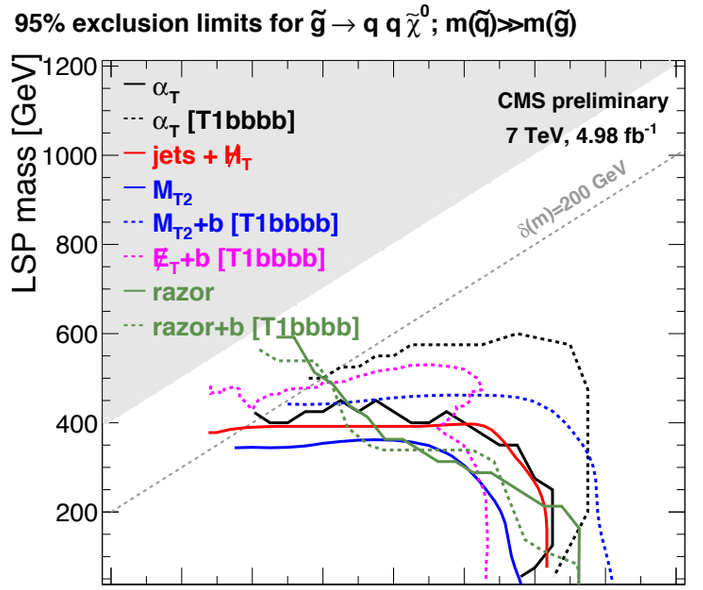
The Progress of LHC

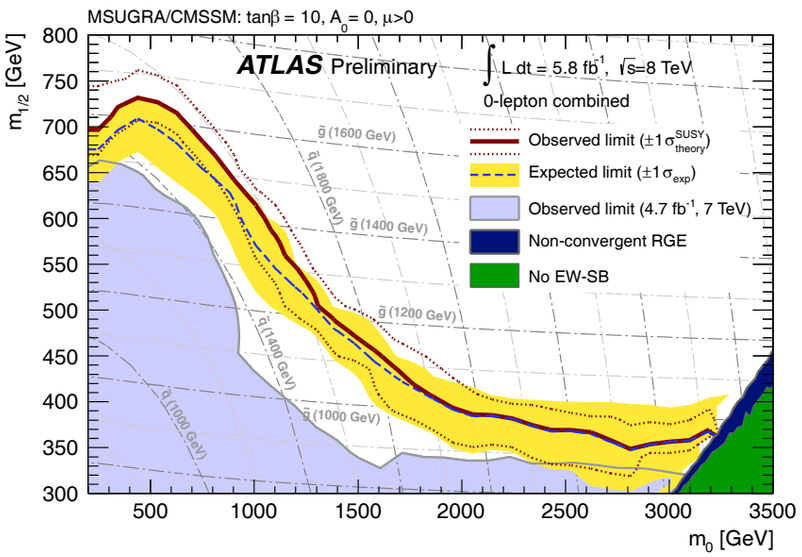
CMS CMSSSM summary

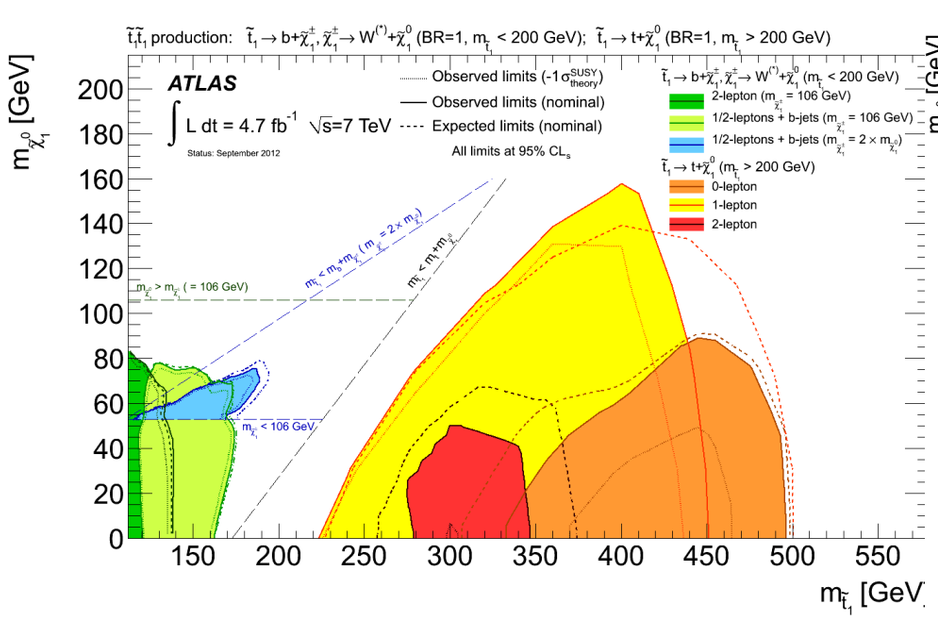


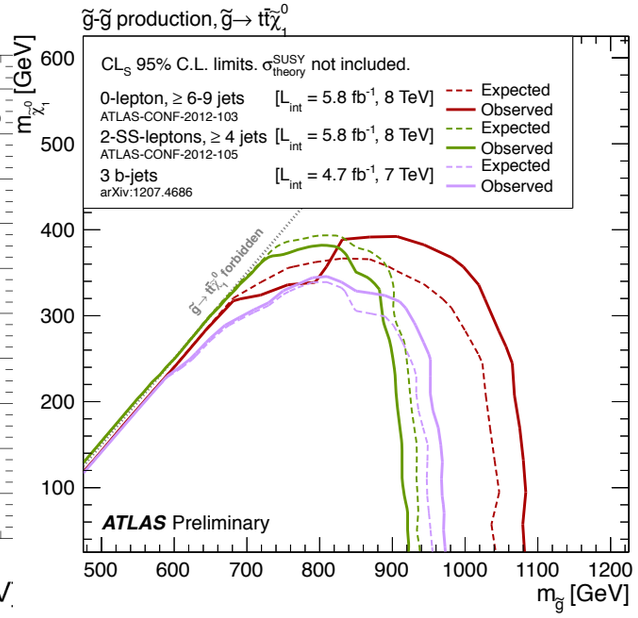
Look for squarks and gluinos with direct decays to SM+LSP





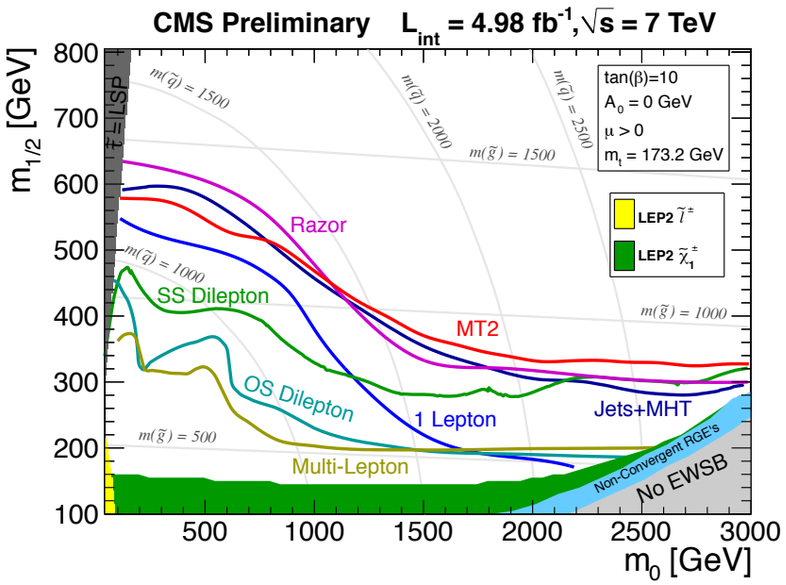






The Progress of LHC

CMS CMSSSM summary



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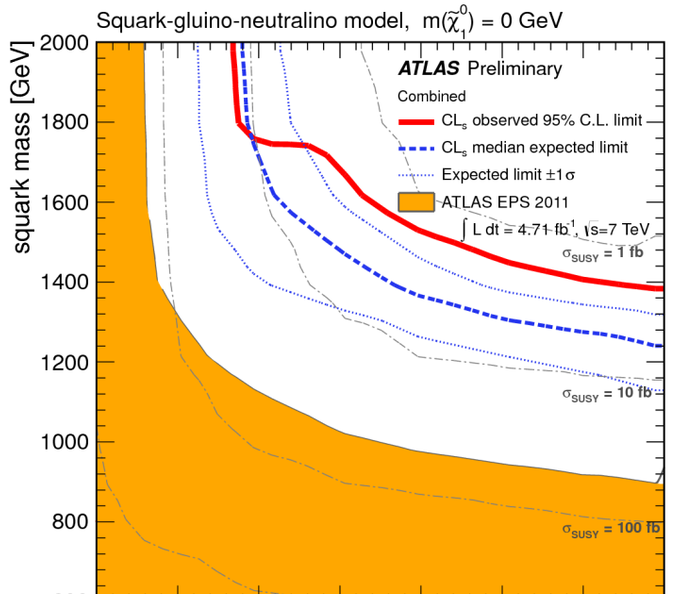
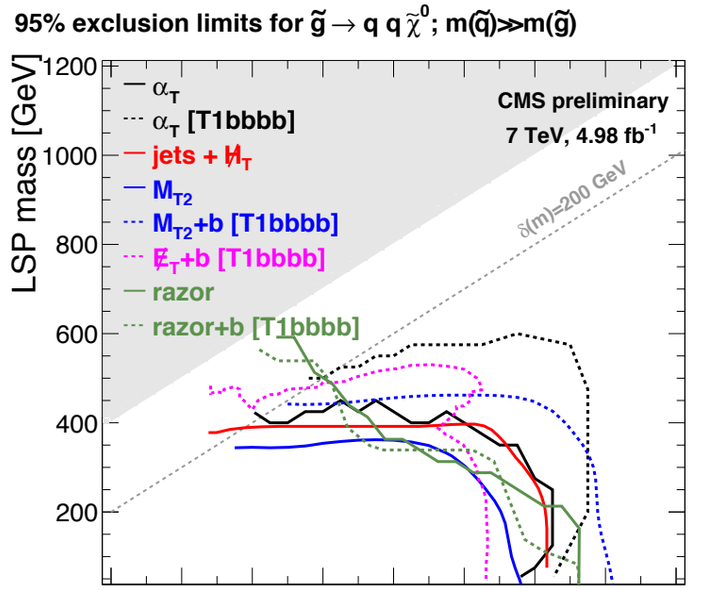
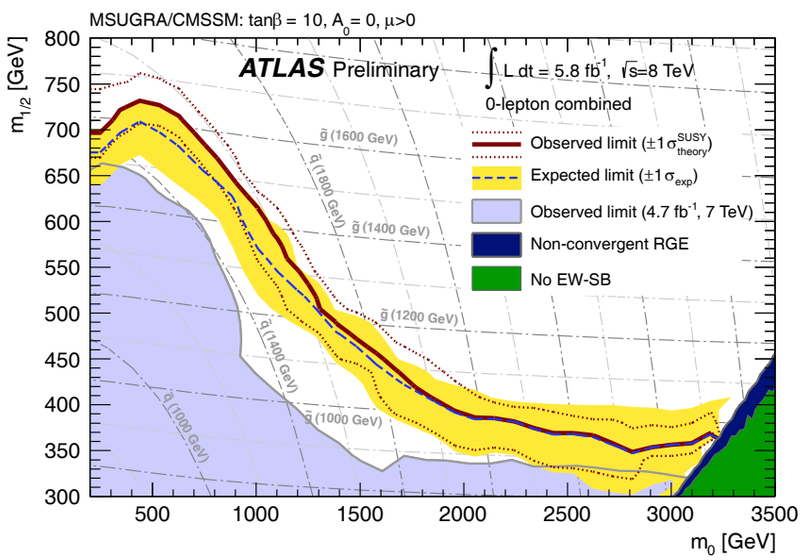
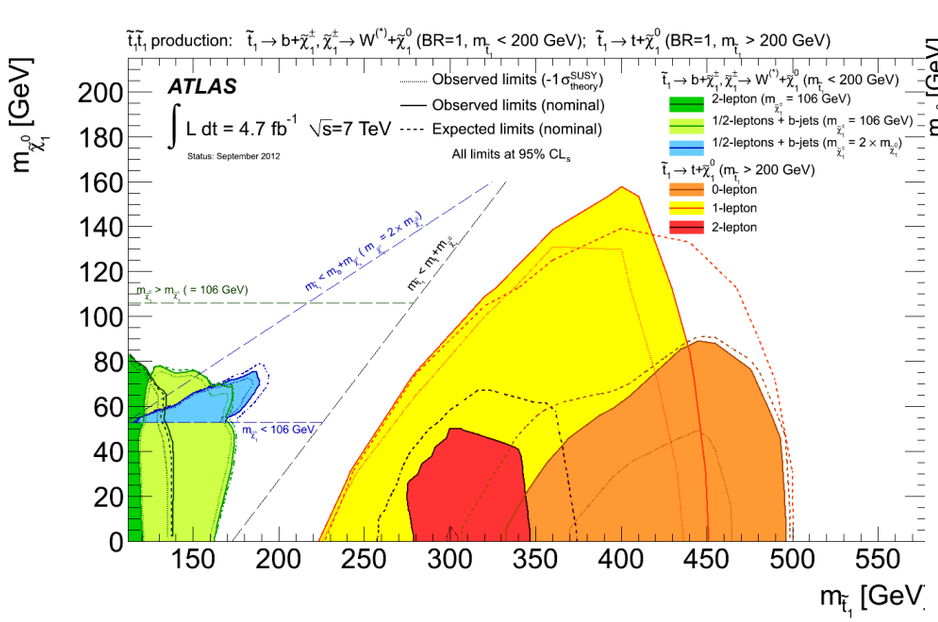
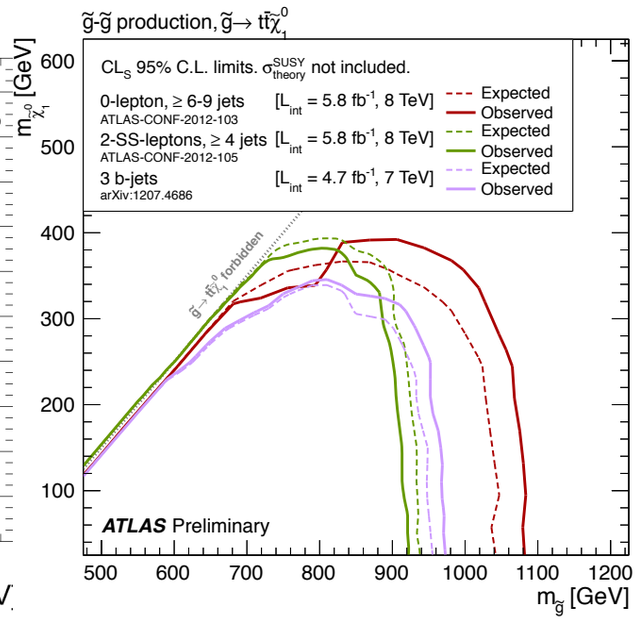






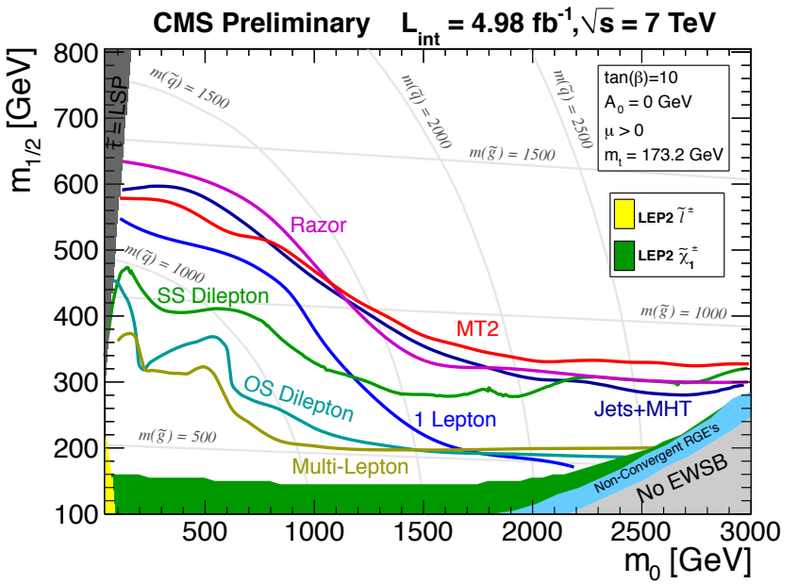




$$\tilde{m}_g > 1000\ GeV$$

The Progress of LHC

CMS CMSSM summary



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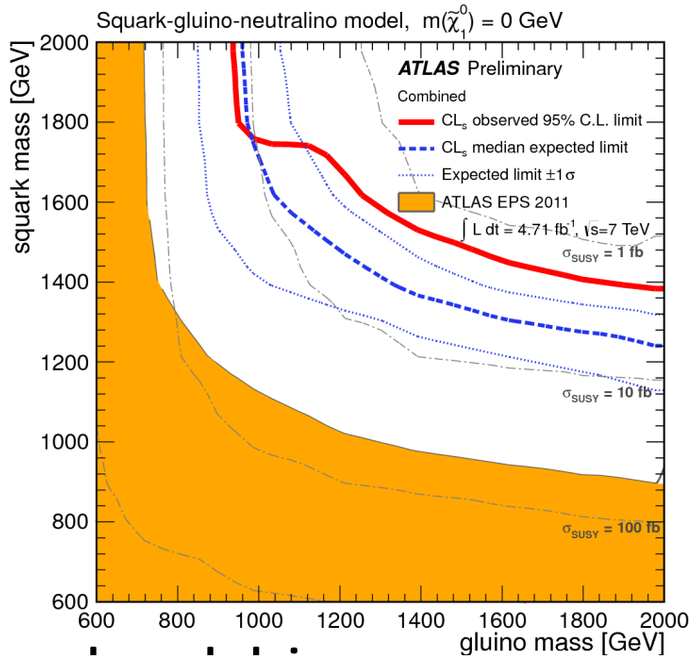
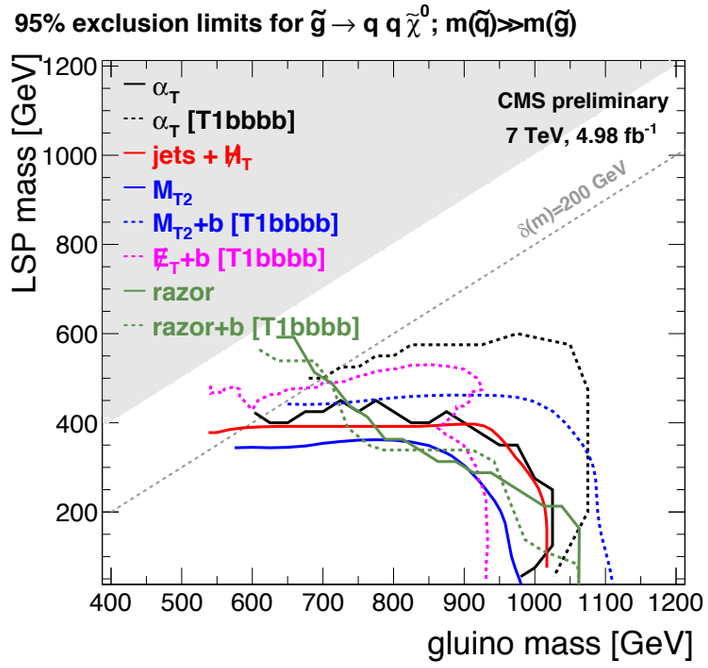
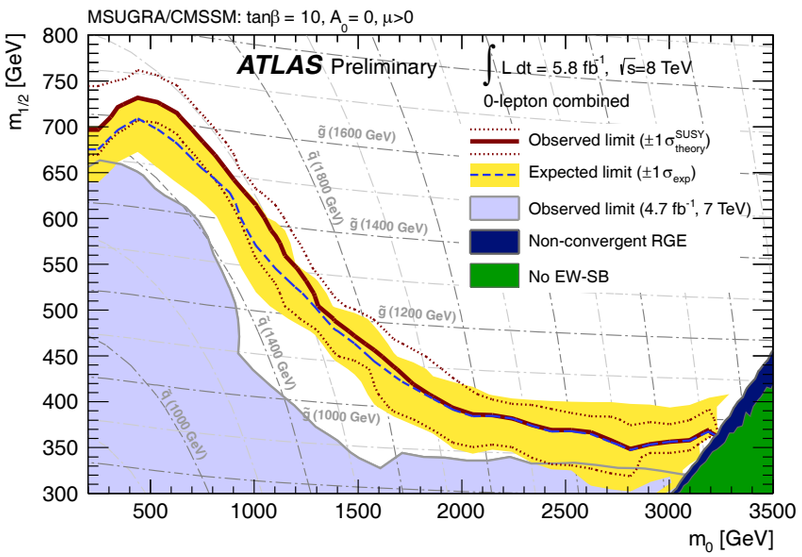
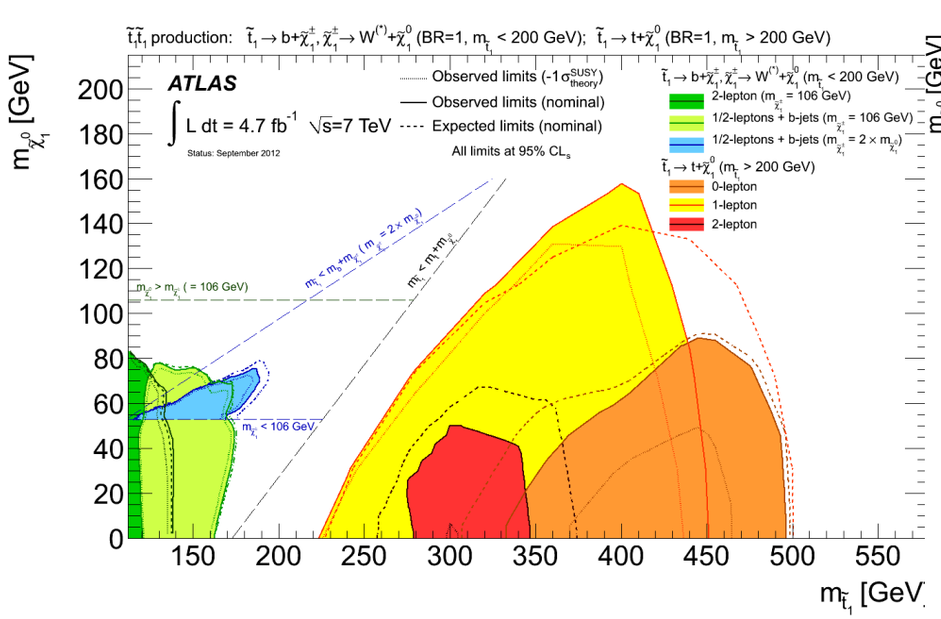
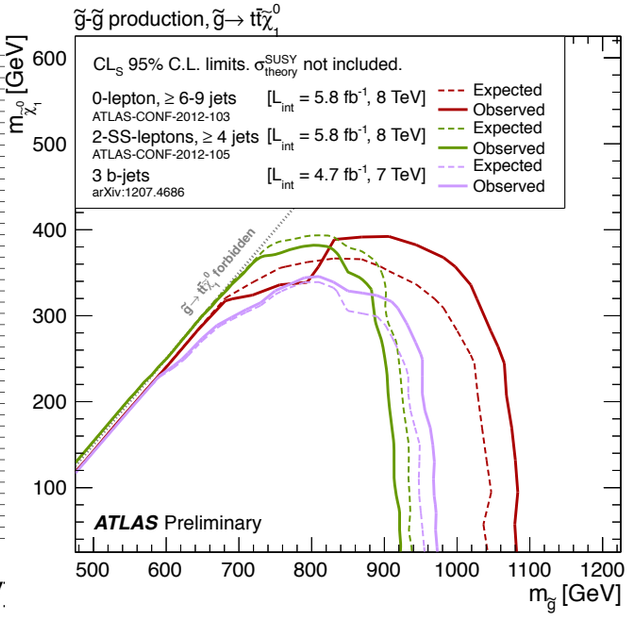








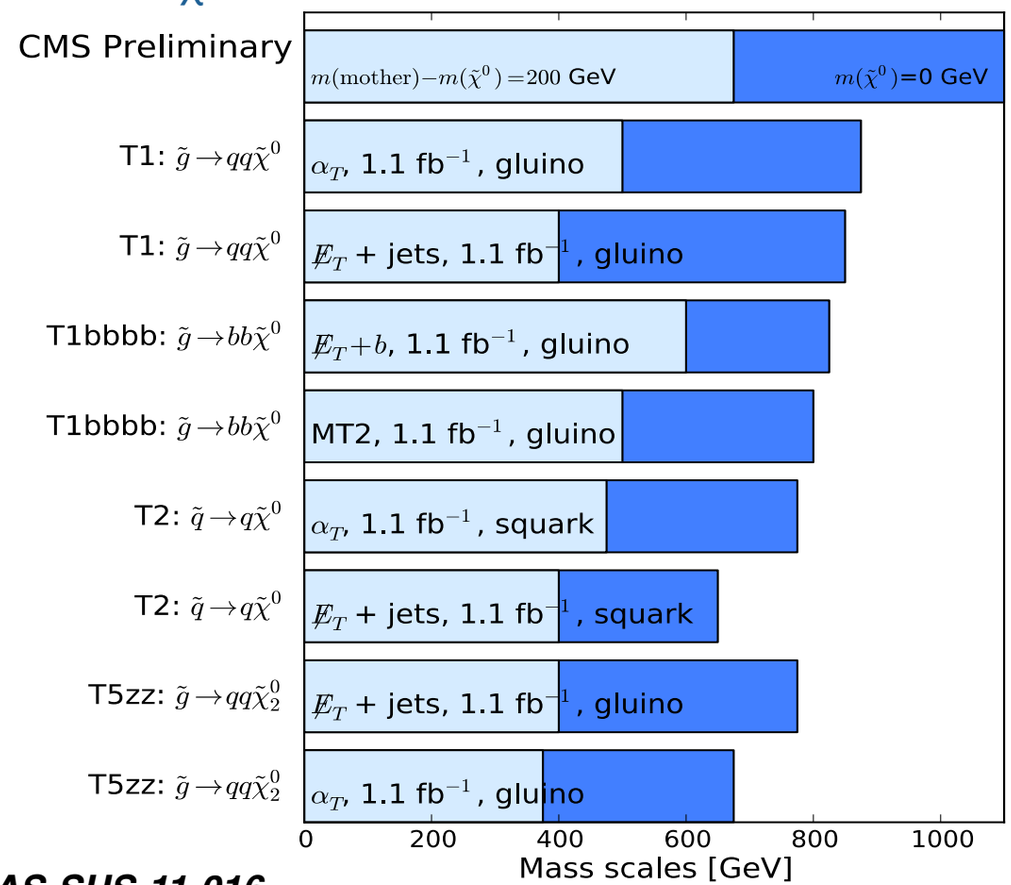


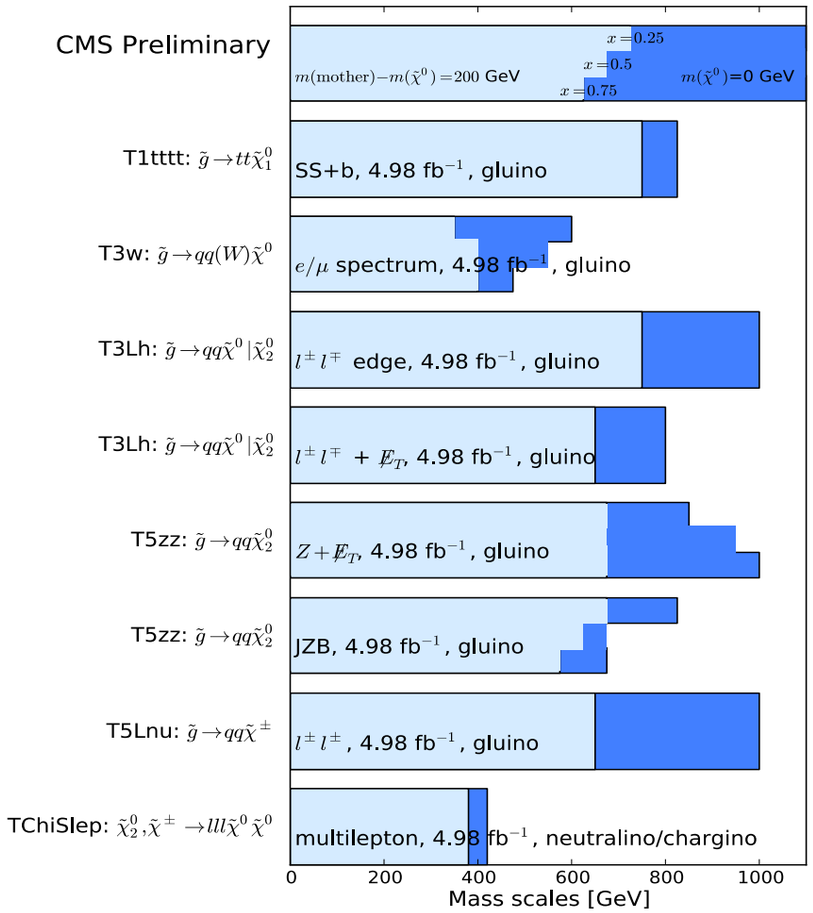
$\tilde{m}_g > 1000\ GeV$

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

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).



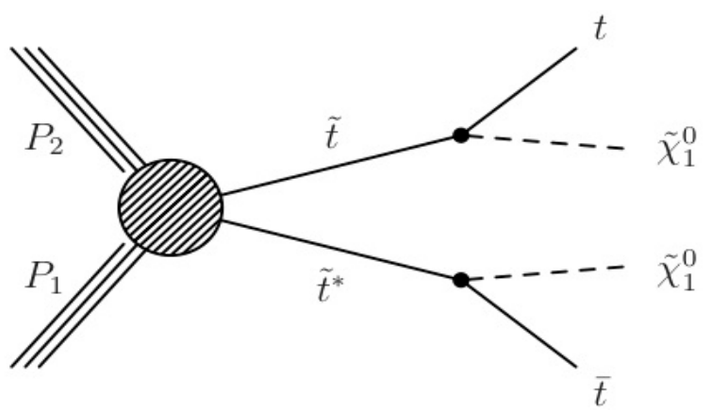


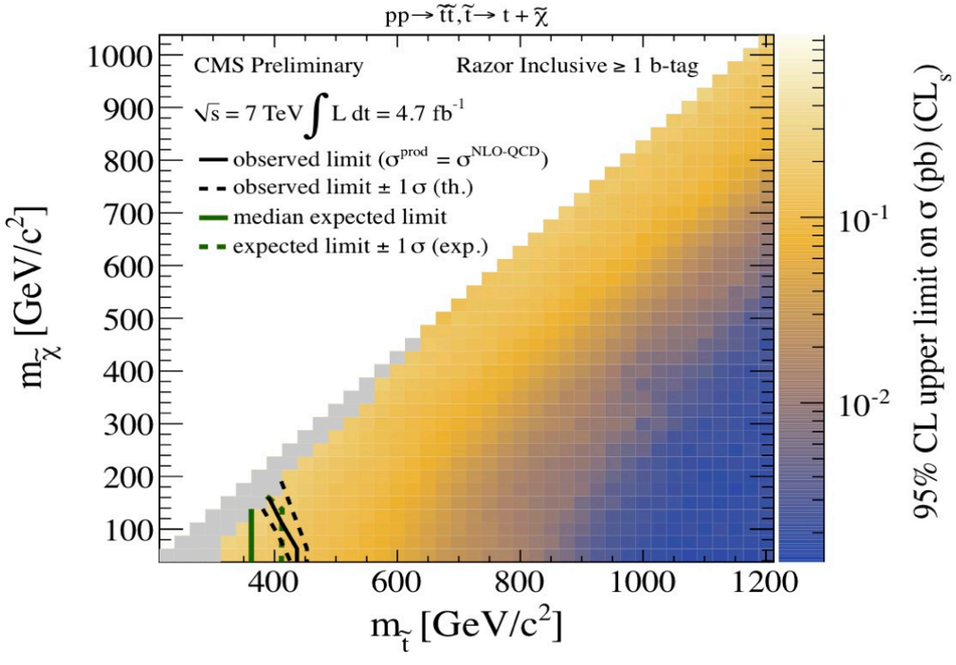
CMS-PAS-SUS-11-016

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.

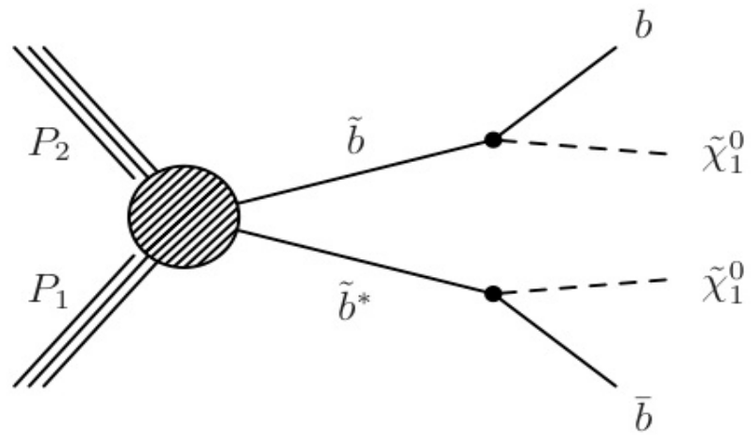
Stop and Sbottom Searches at LHC

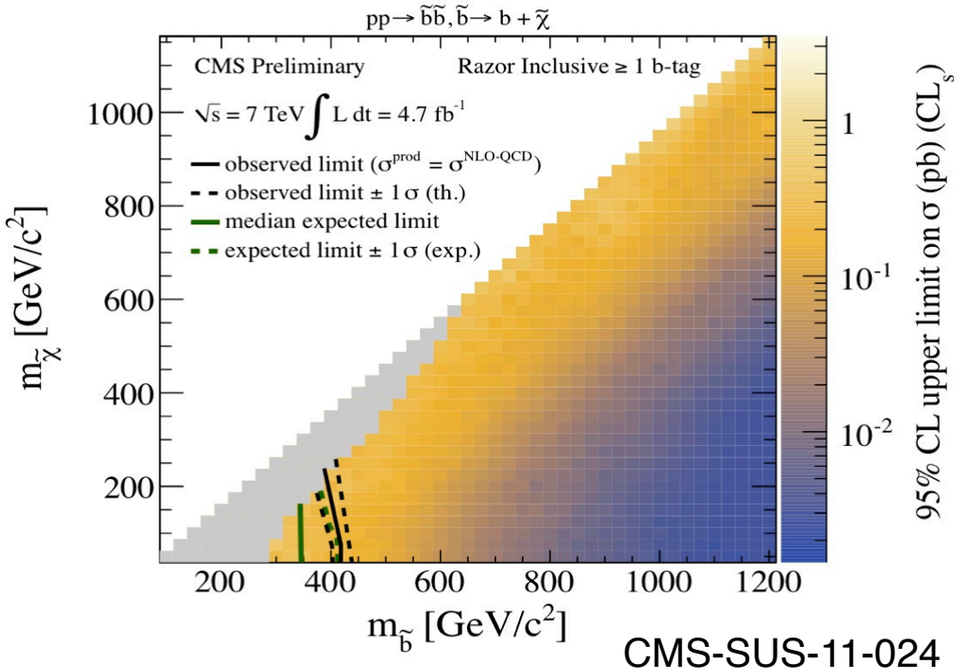
Di-stop production resulting in 2 top quarks +MET final states





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

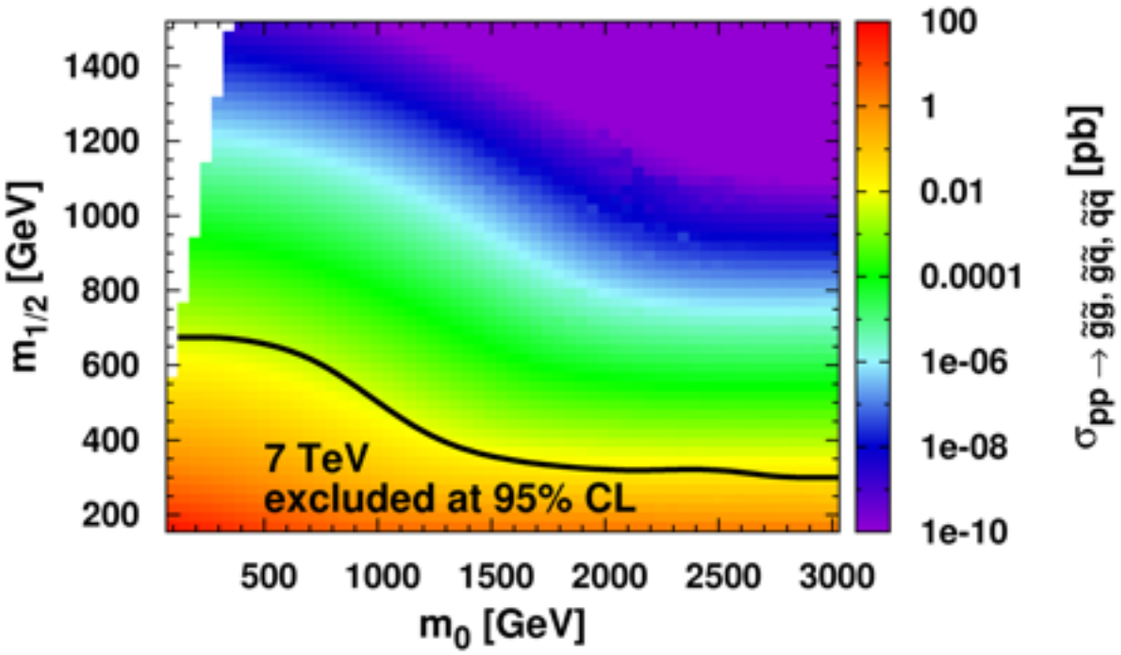




CMS-SUS-11-024

LHC Reach at 7 and 14 TeV

LHC Reach at 7 and 14 TeV



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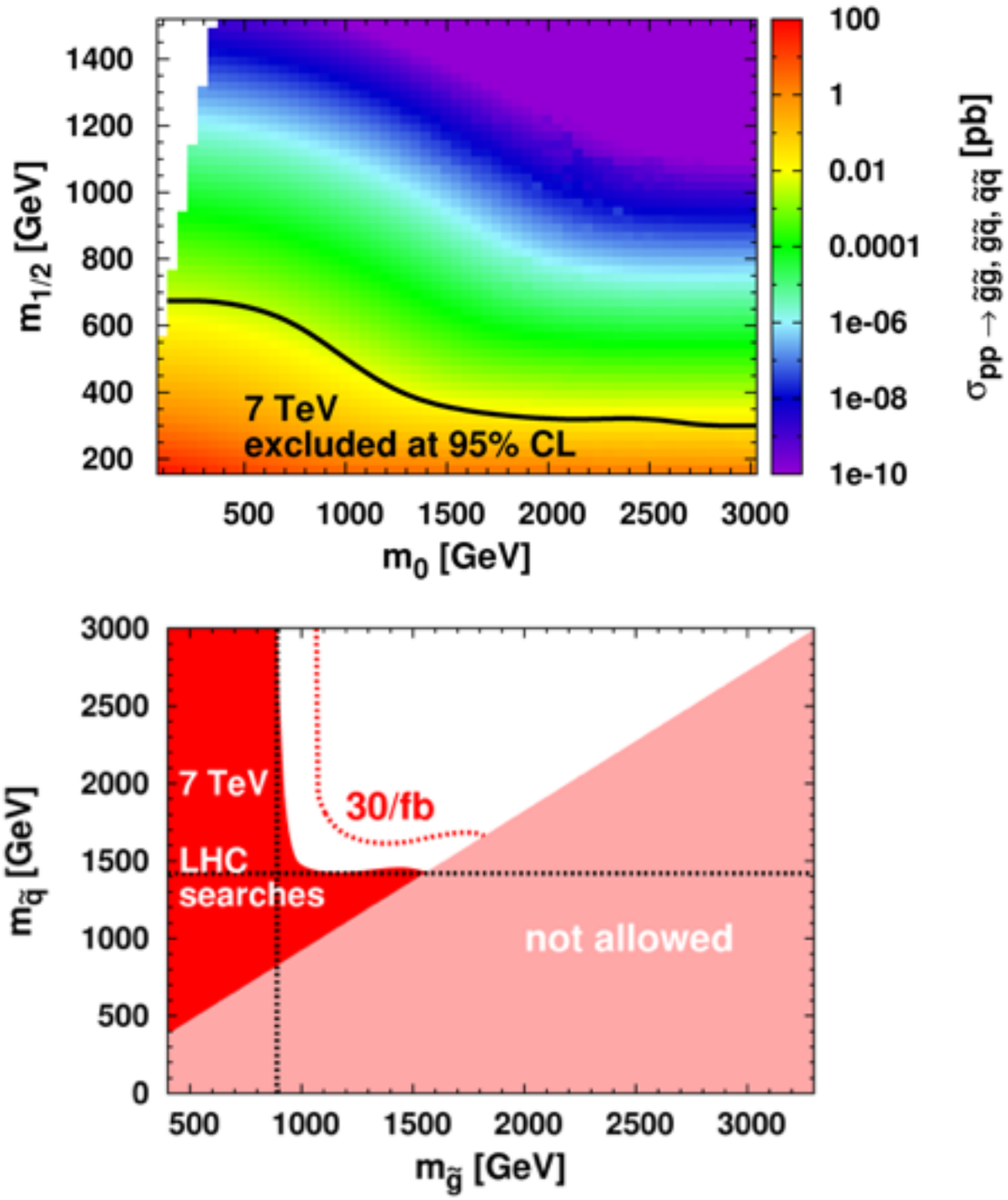

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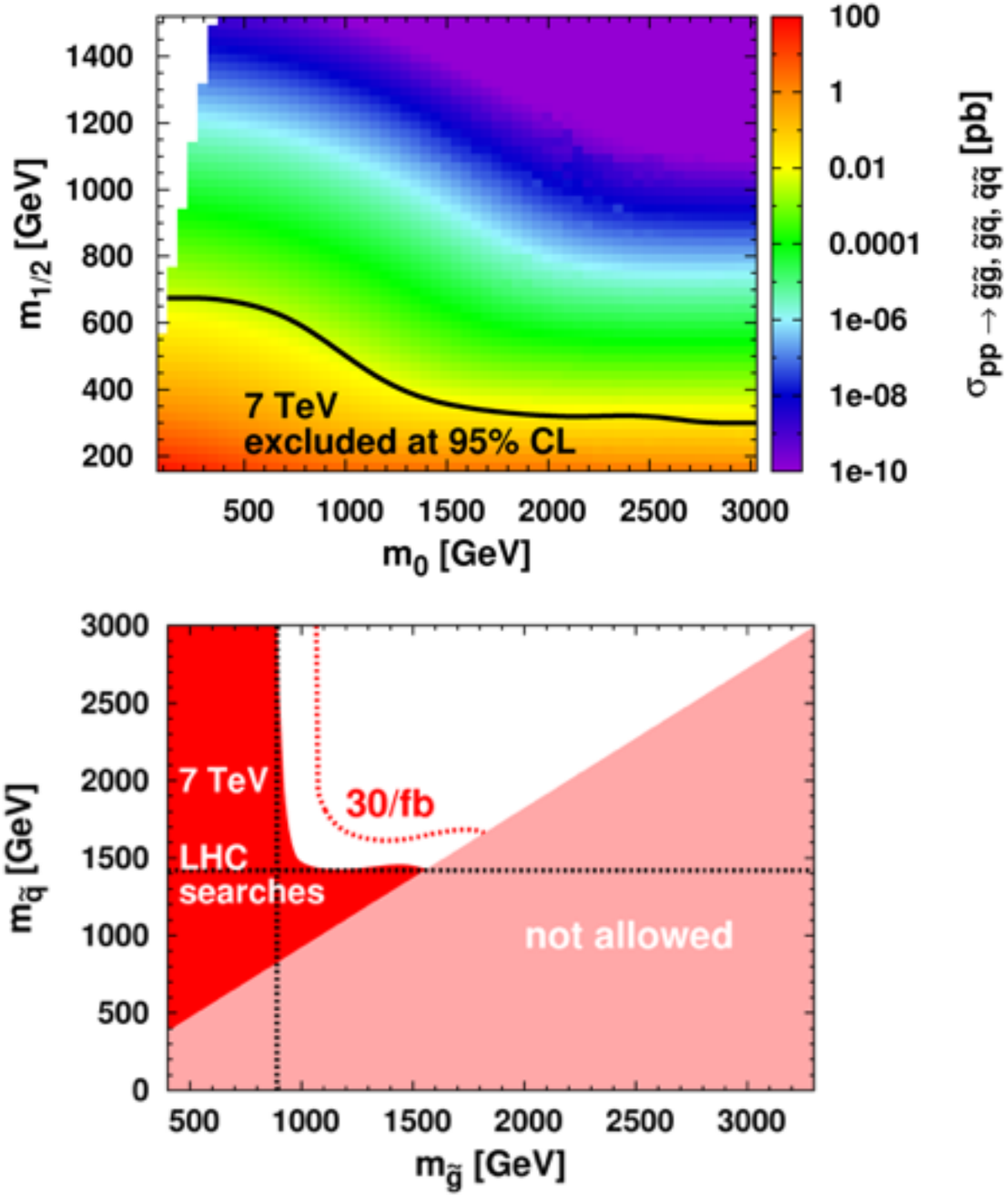

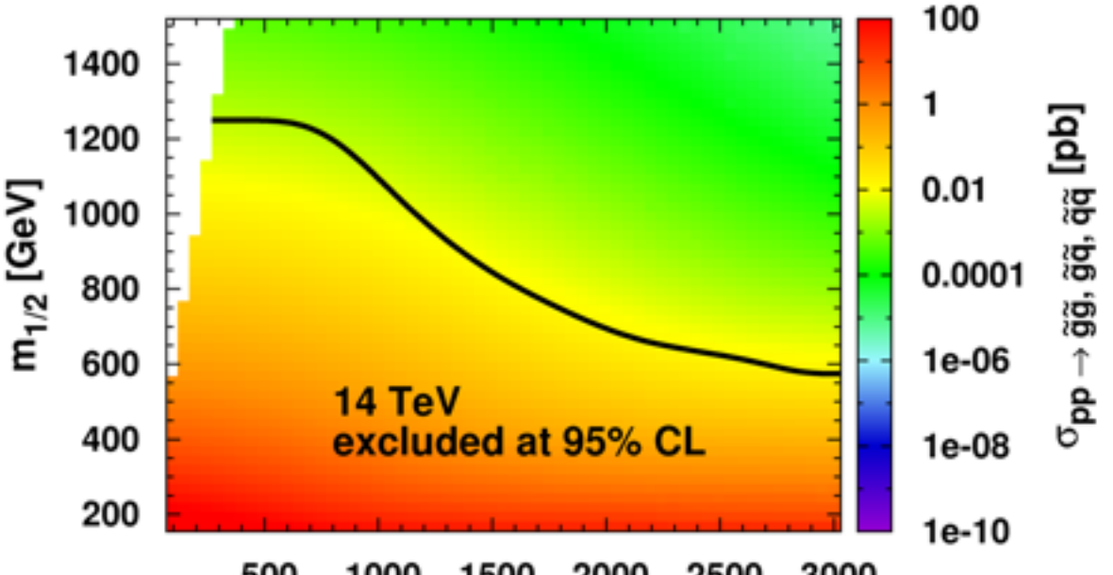

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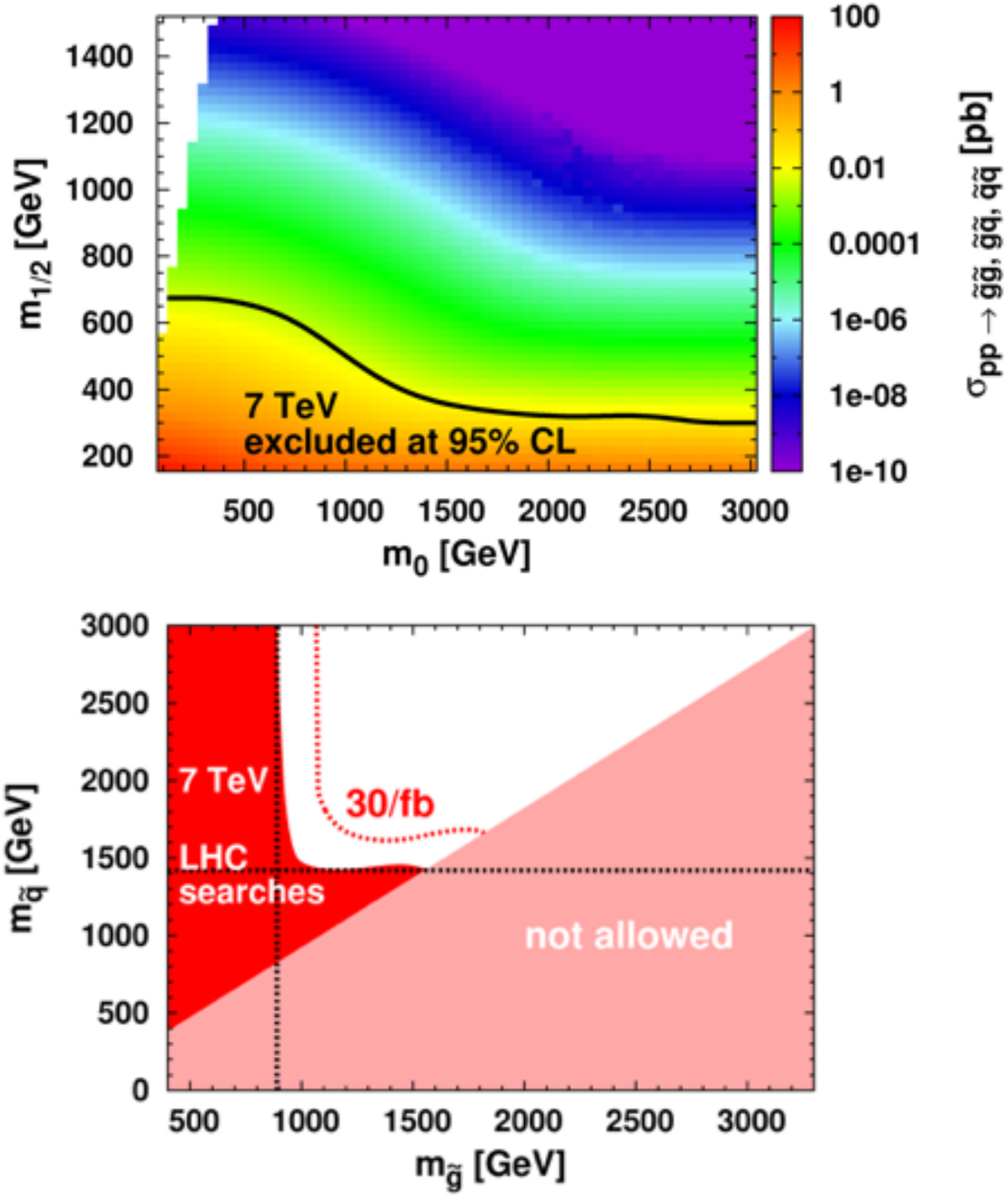

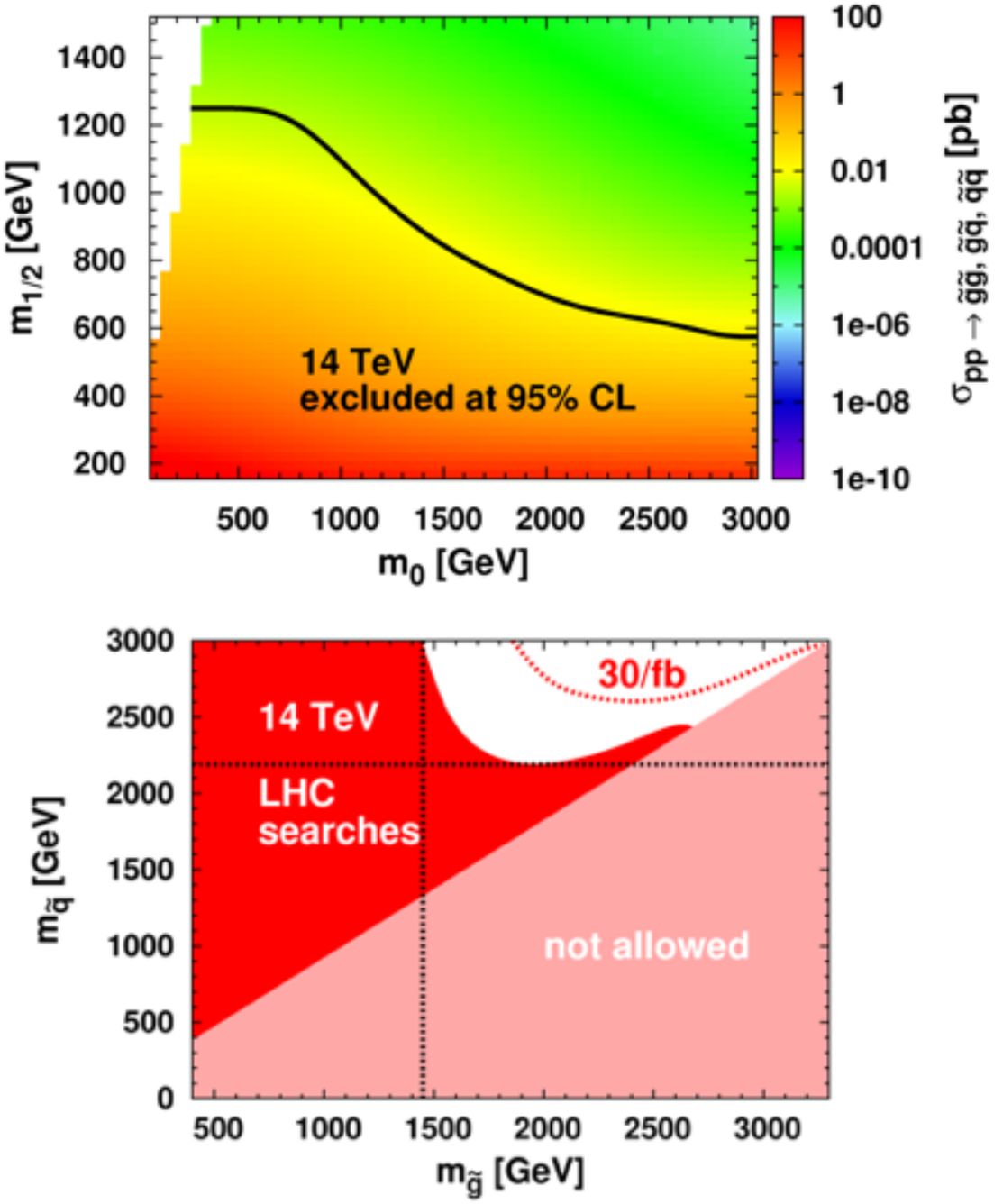

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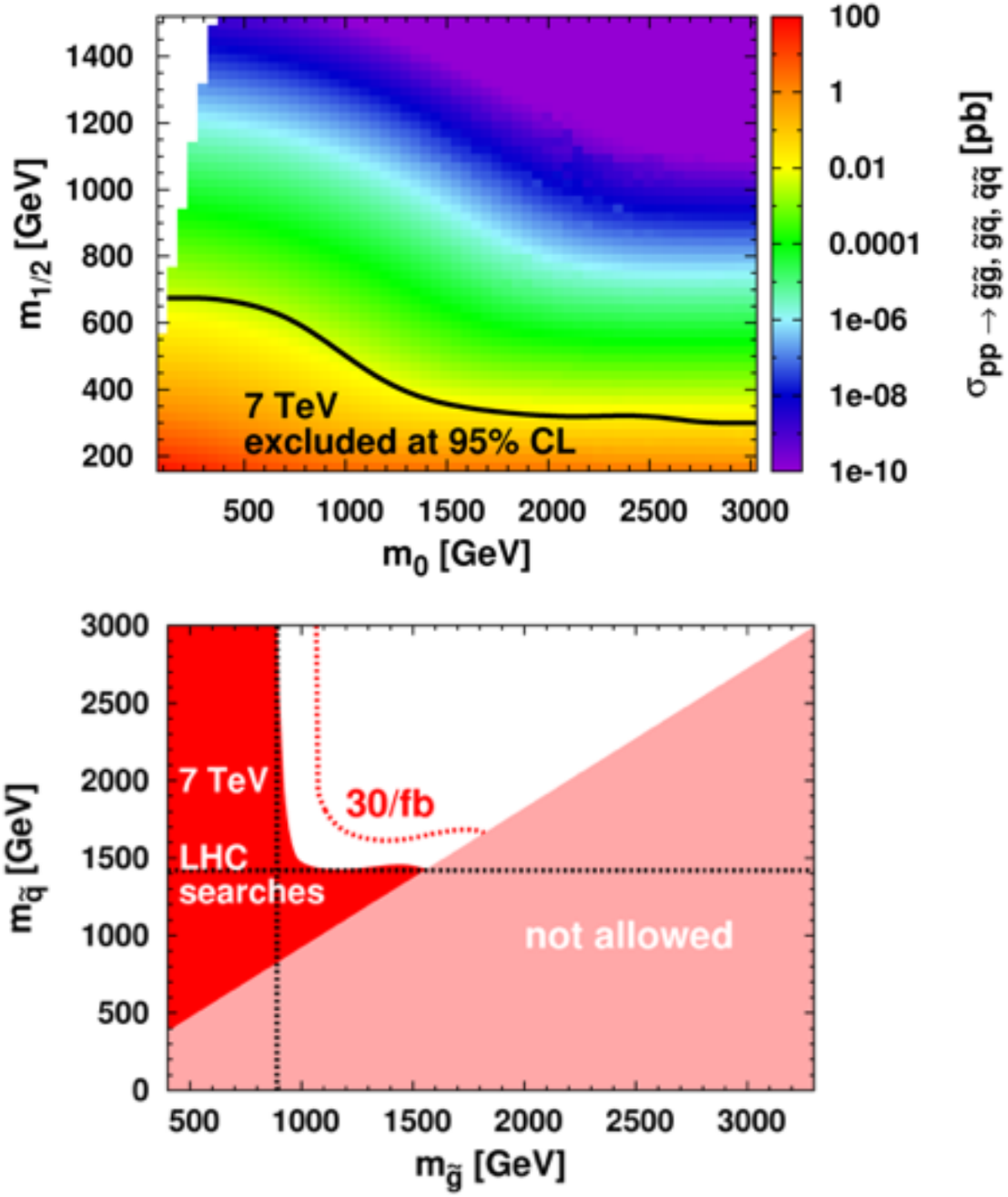
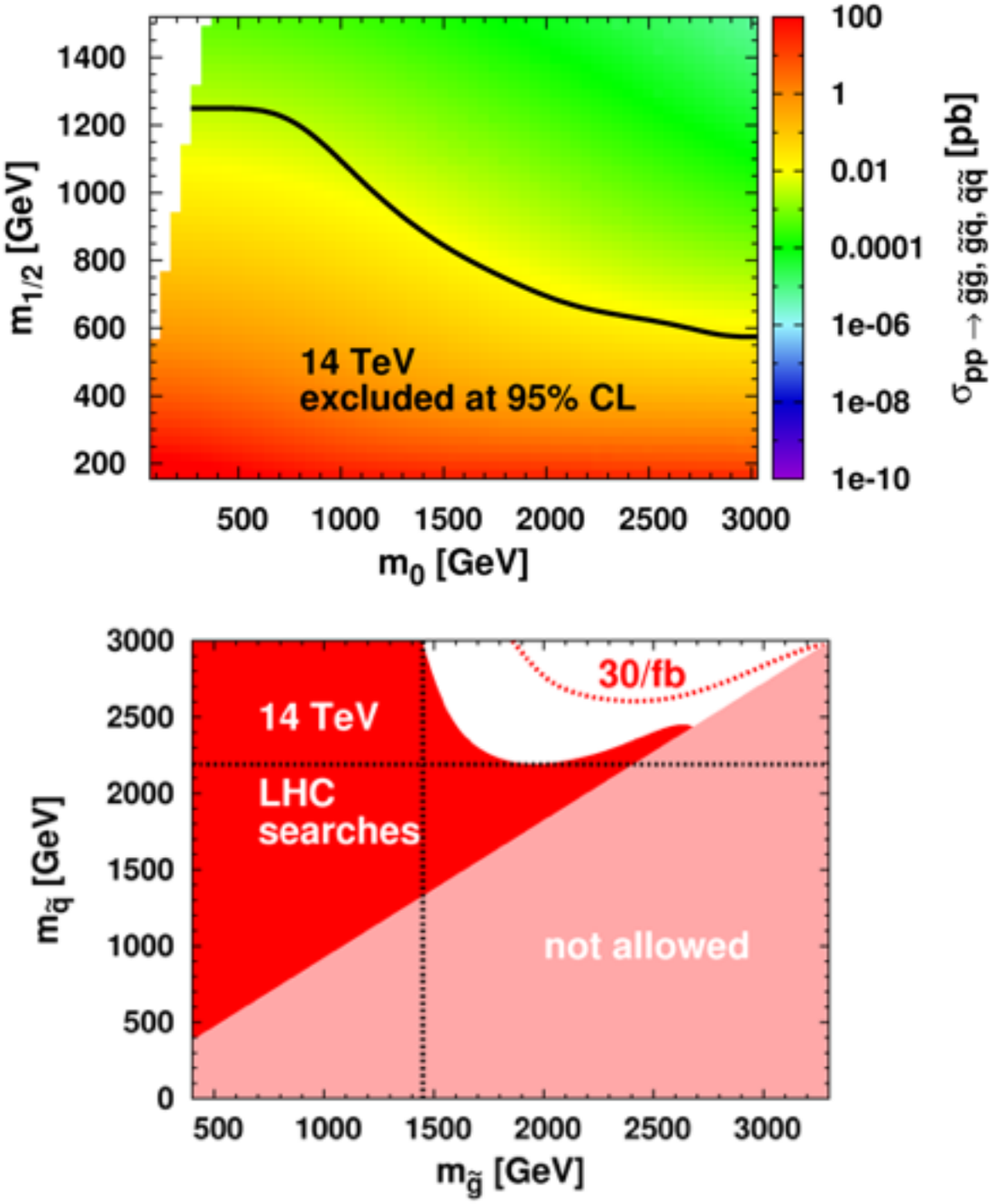




Energy is more important than luminosity

Indirect Search at LHC

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

$$B_s \to X_s \gamma$$

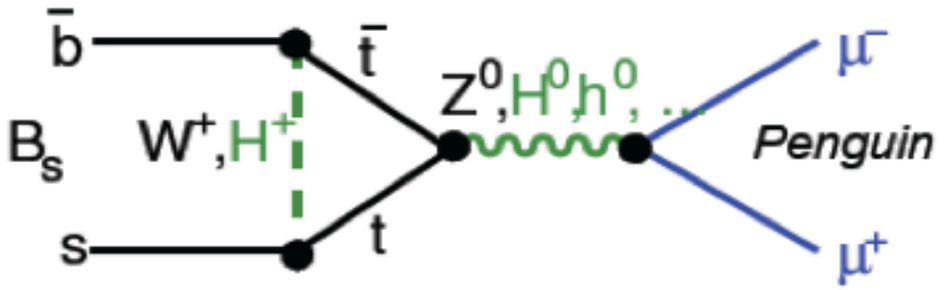
$$B_u \to \tau \nu$$

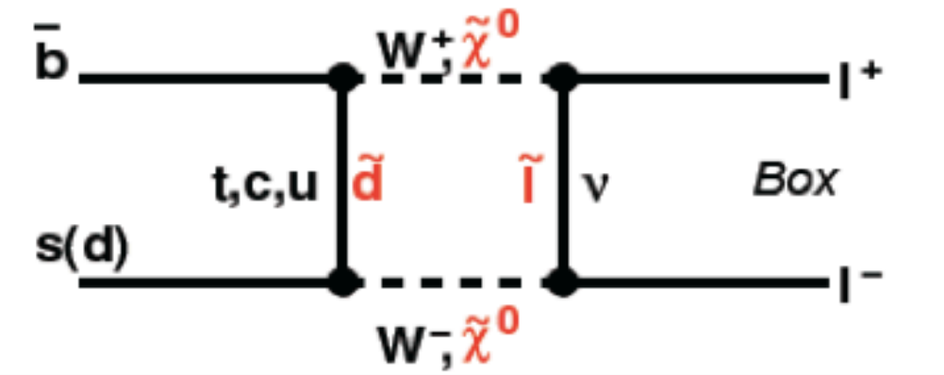
$$g - 2$$

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 $(m_\mu/m_B)^2$
- **Standard Model Predictions**
  - Bs→μμ = $(3.2\pm0.2)\ 10^{-9}$
  - Bd→μμ = $(1.0\pm0.1)\ 10^{-10}$
- **Sensitivity to New Physics**
  - BR in MSSM proportional to $\tan\beta^6$
- **LHCb measurement**

$$BR(B_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$





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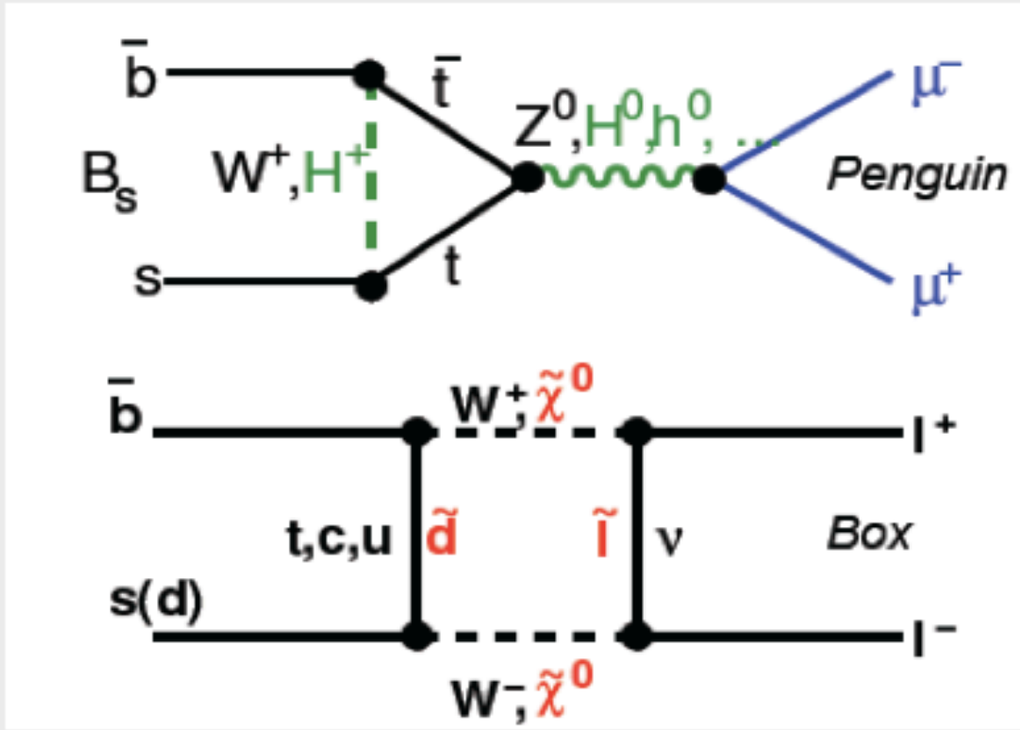

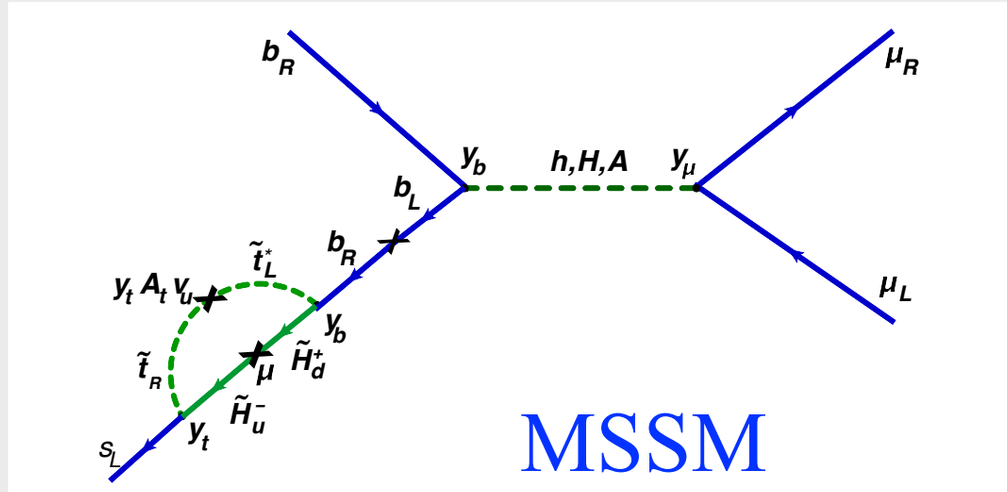

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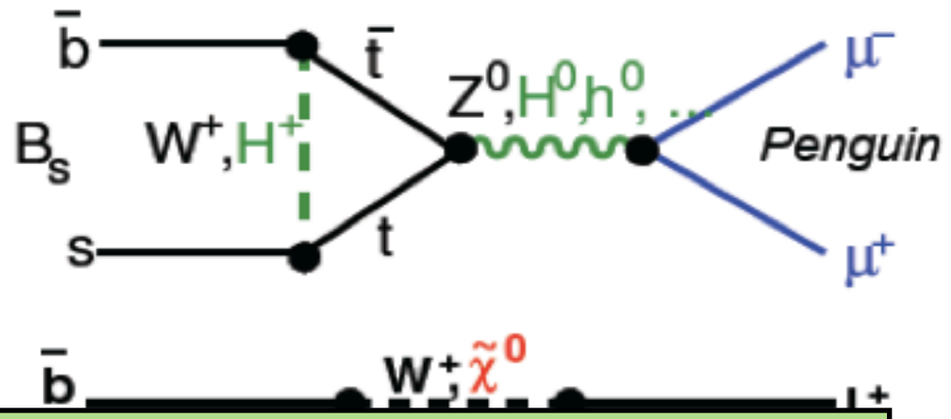


$$Br[B_s \to \mu\mu] = \frac{2\tau_B m_B^5}{64\pi} f_{B_s}^2 \sqrt{1-\frac{4m_l^2}{m_B^2}} \left[\left(1-\frac{4m_l^2}{m_B^2}\right) \left| \frac{(C_S - C_S')}{(m_b+m_s)} \right|^2 + \left| \frac{(C_P - C_P')}{(m_b+m_s)} + 2\frac{m_\mu}{m_{B_s}^2}(C_A - C_A') \right|^2 \right]$$

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

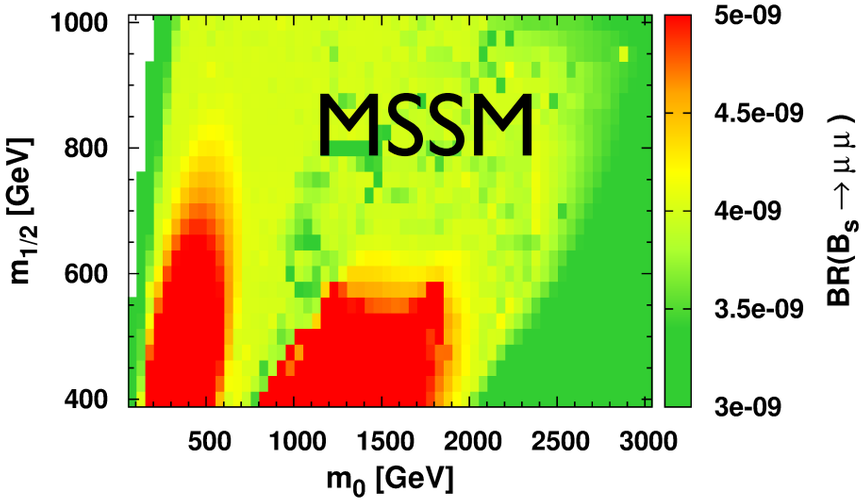
Enhancement

Suppression

Indirect: MSSM v NMSSM

95% CL exclusion

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



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

NMSSM calculations made with NMSSMTools

MicrOMEGAs 2.4.1

G. Bélanger et al

U.Ellwanger et al

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

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

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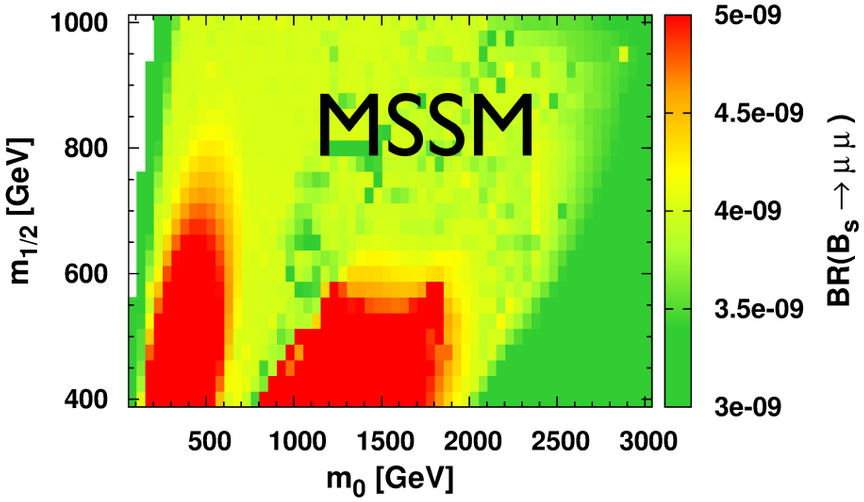

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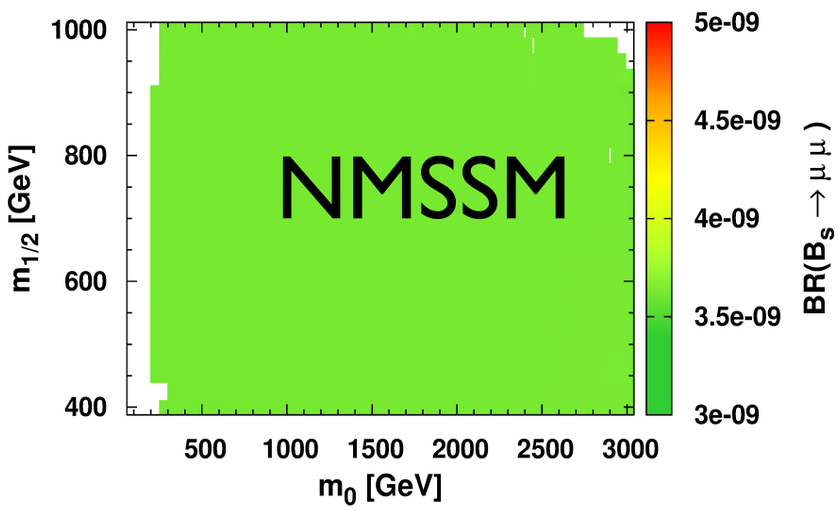

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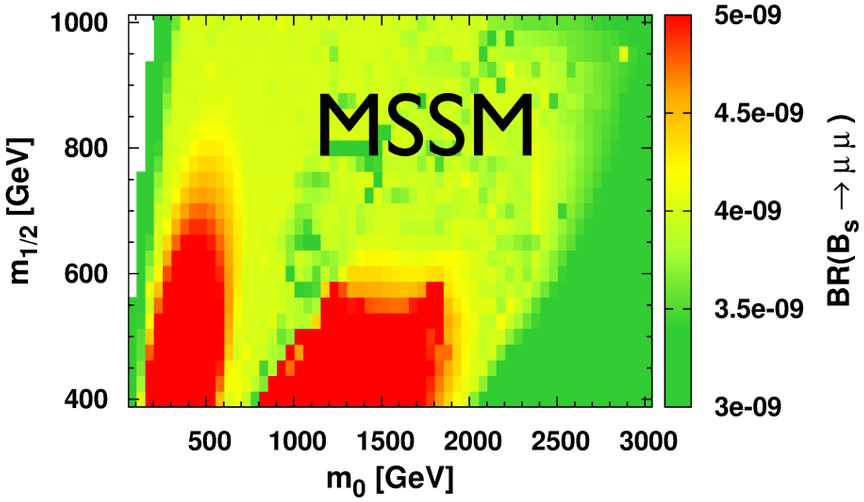

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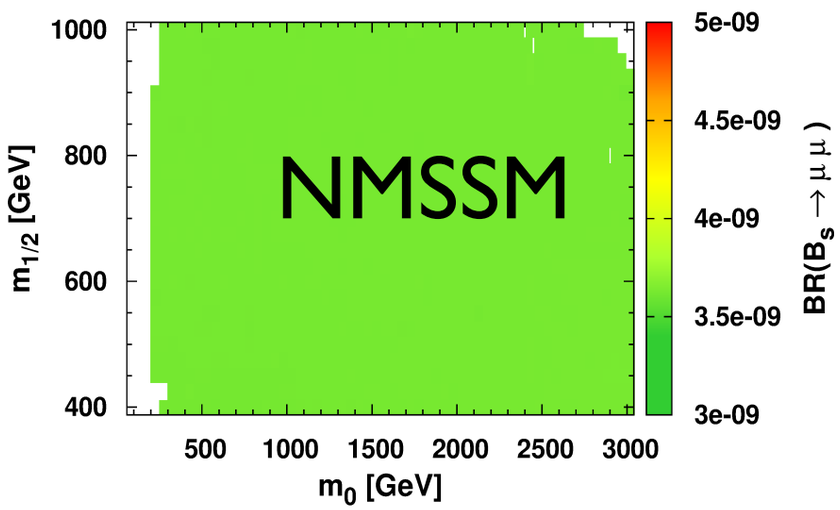

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95% CL exclusion

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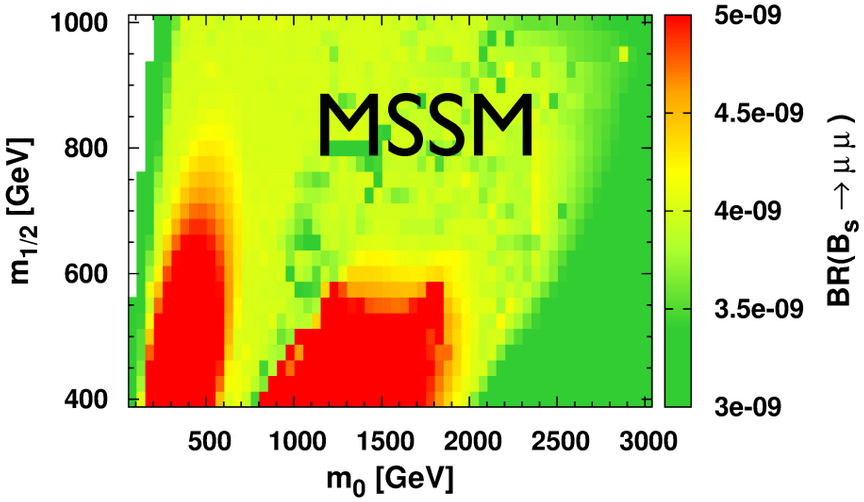

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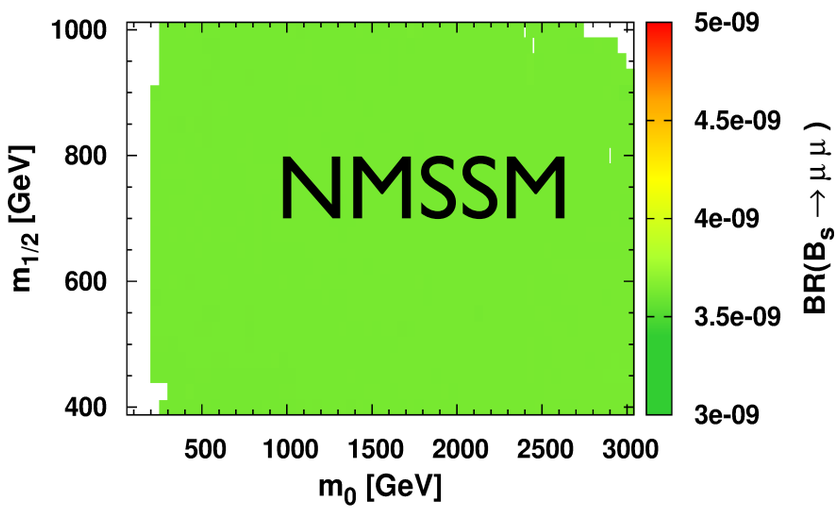
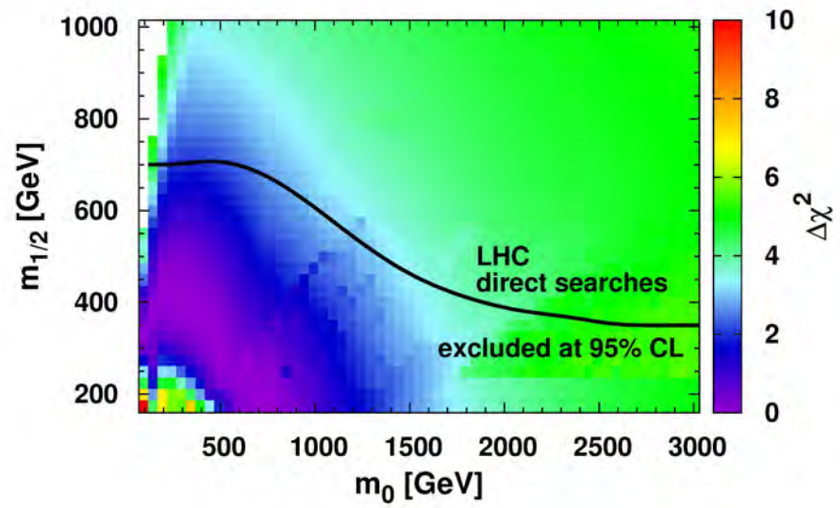
$B_s \to s\gamma,\ B_s \to \mu^+\mu^-,\ B_s \to \tau\nu$





muon $g-2$

Higgs v SUSY

$$m^2_{Higgs} = M^2_Z \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_s^4}{m_t^4} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{6M_S^2}\right)\right] + 2 - loop$$

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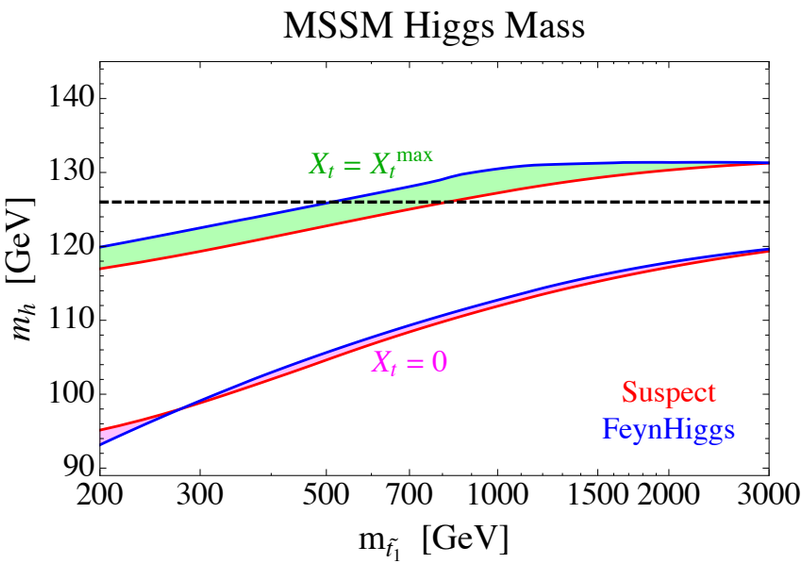
from JHEP 1204 (2012) 131



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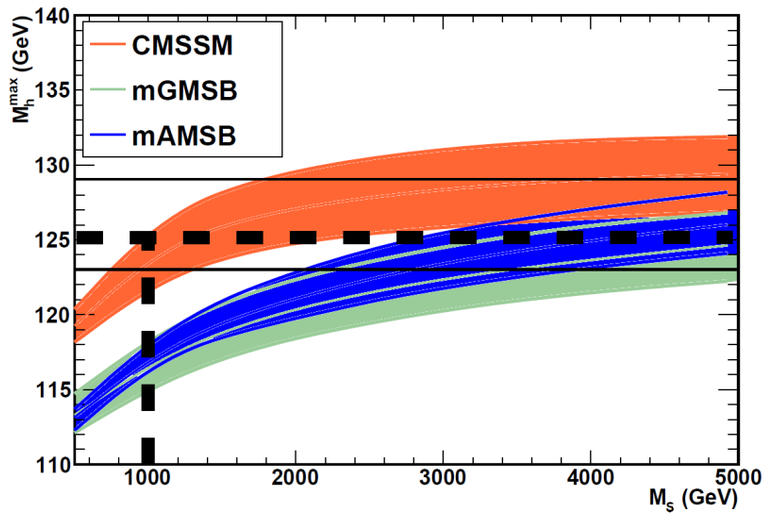

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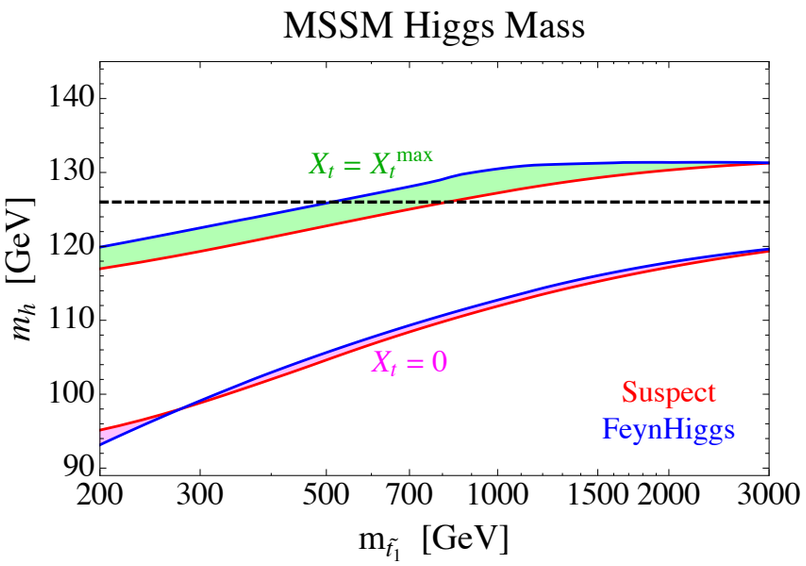

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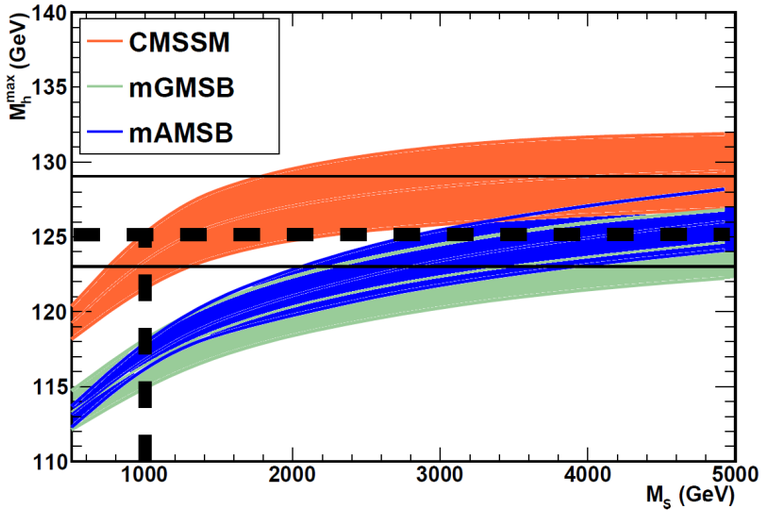

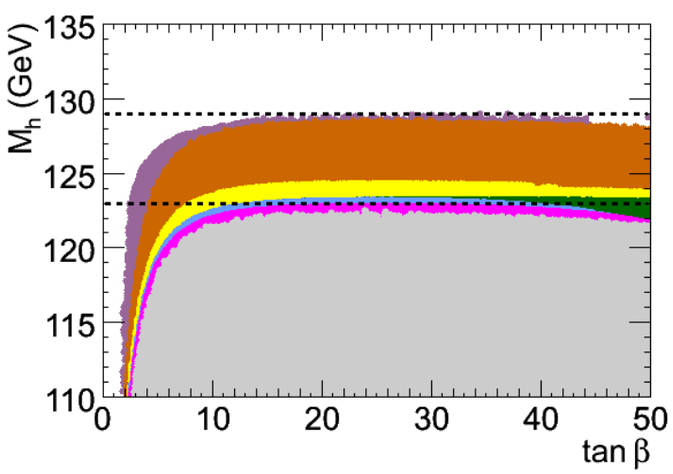

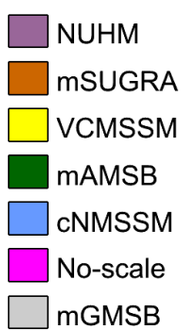

A. Arbey et al'12

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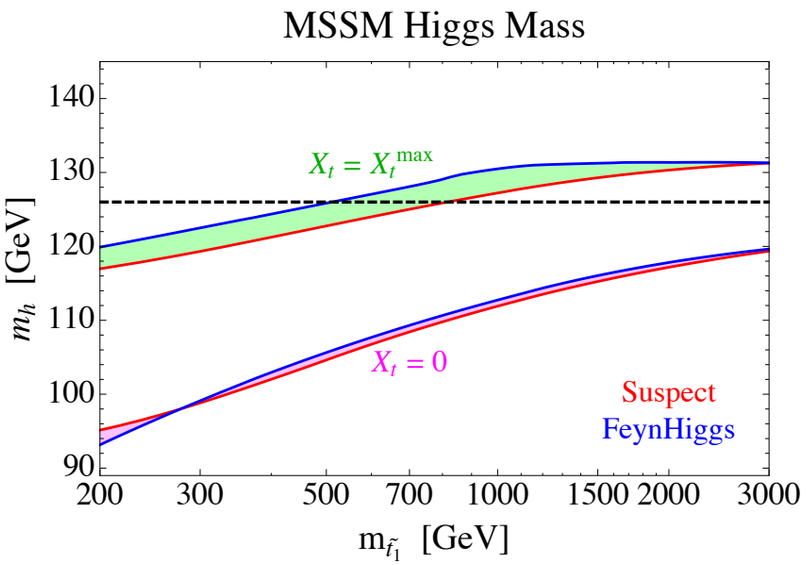

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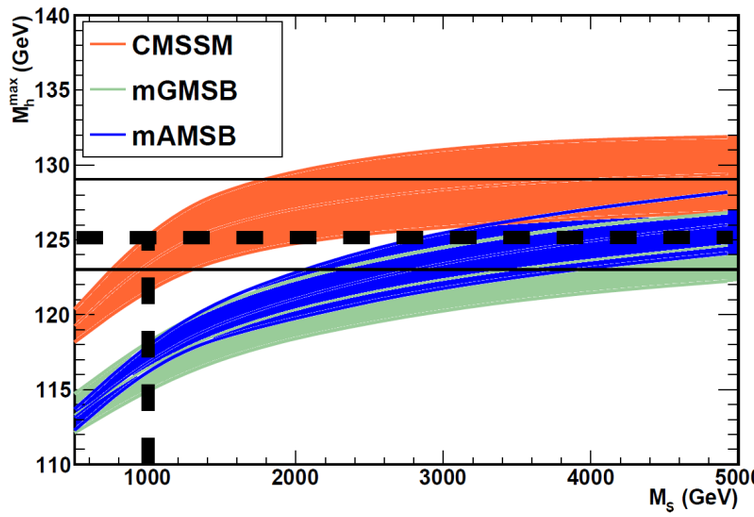

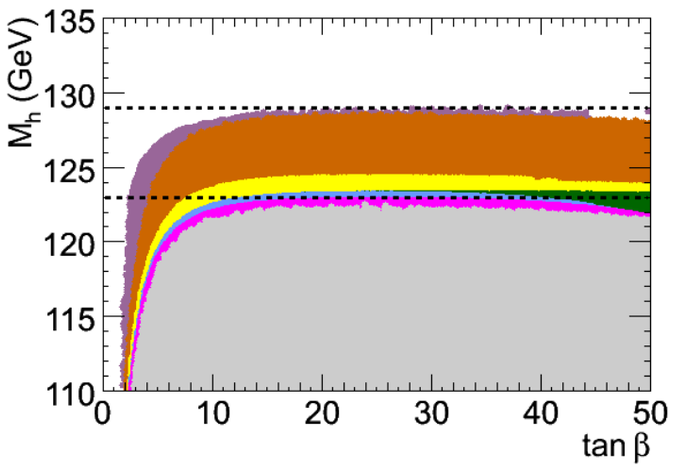

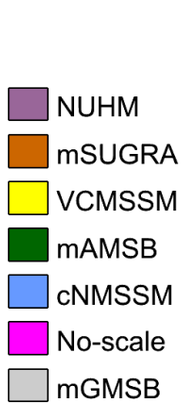

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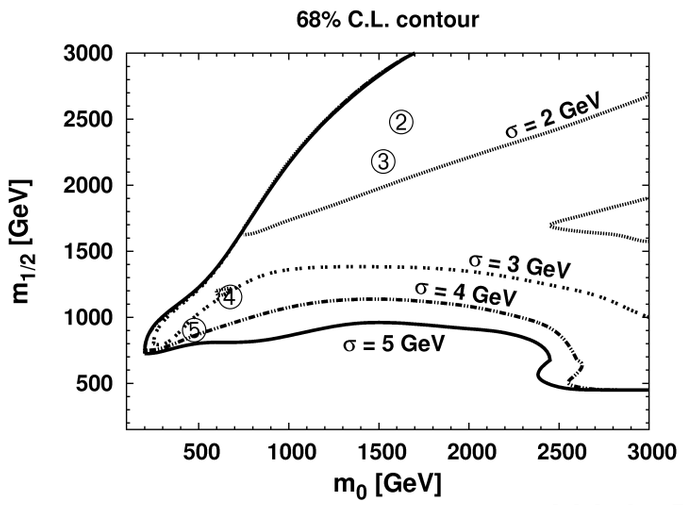

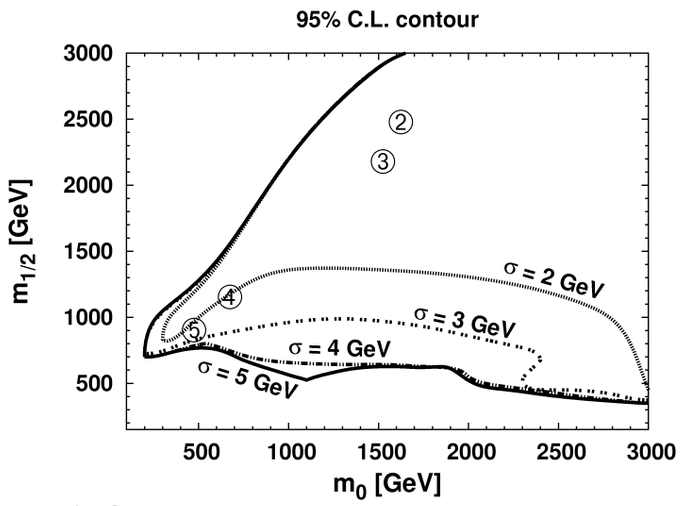

W. de Boer et al'12

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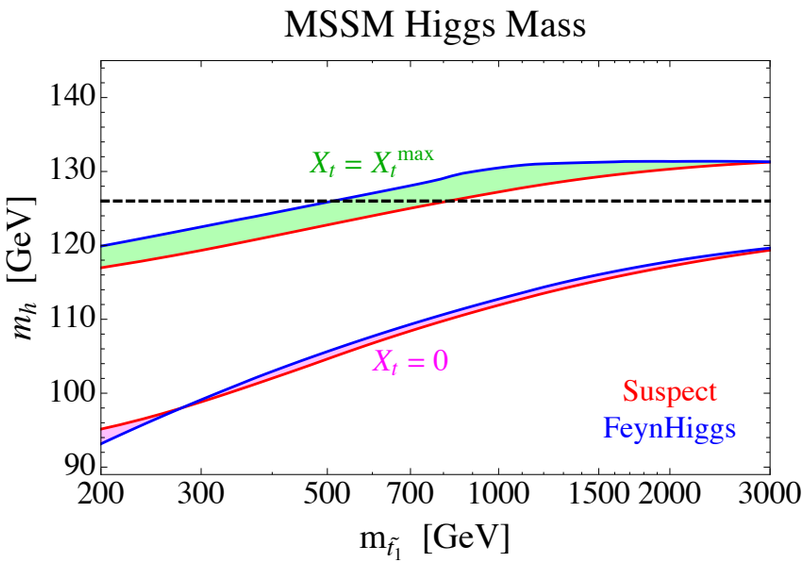

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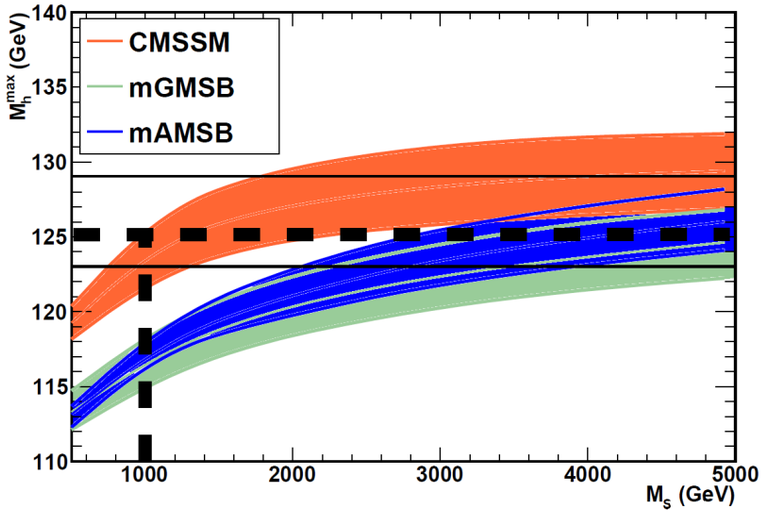
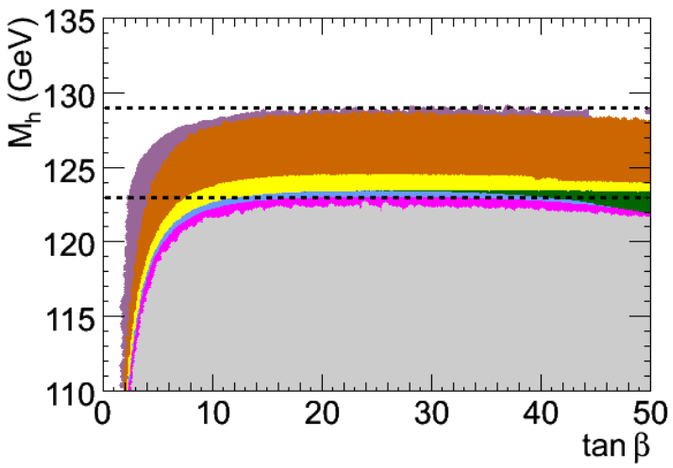
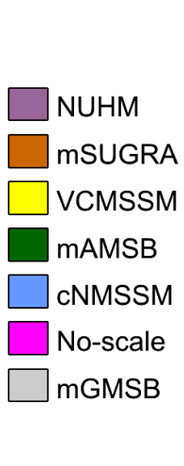


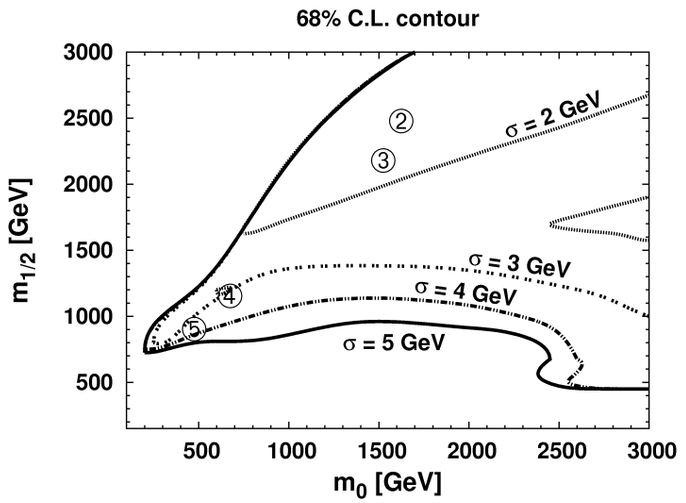
Resume

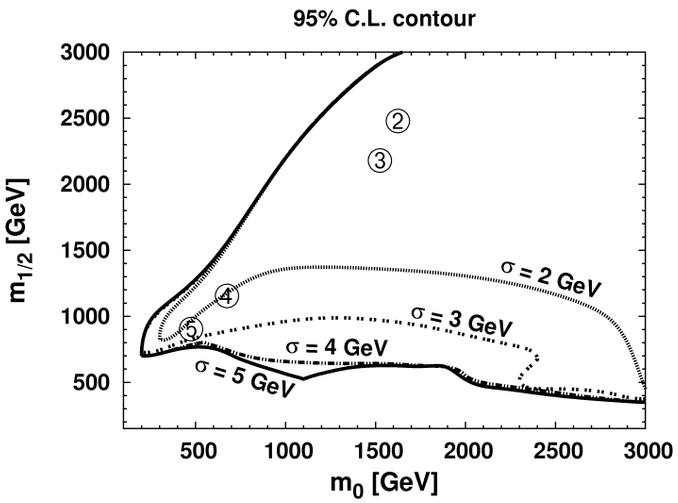
1. MSSM has already troubles to accomodate 126 GeV Higgs
2. Needs M_S ~ 1TeV
3. Large part of the parameter space is closed





A. Arbey et al'12





W. de Boer et al'12

AstroPhys Search

- DM abundance
- DM annihilation
- DM-nucleon interaction

Relic Abundance

Boltzman Equation

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

Hubble constant

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

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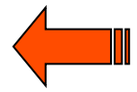

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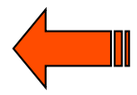

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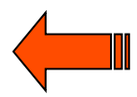

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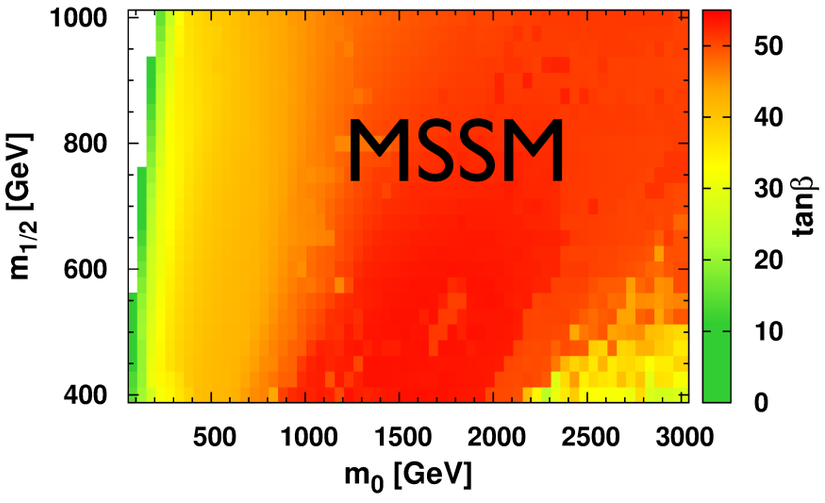

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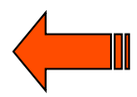

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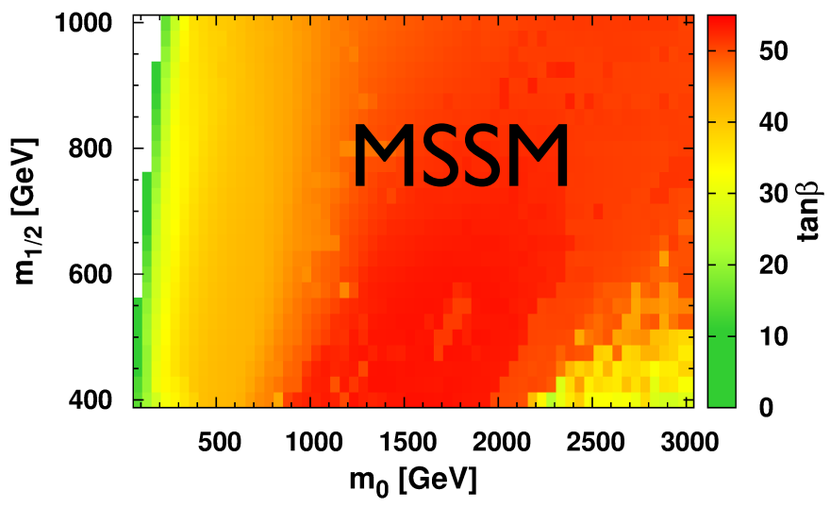

High $\tan\beta \sim 50$

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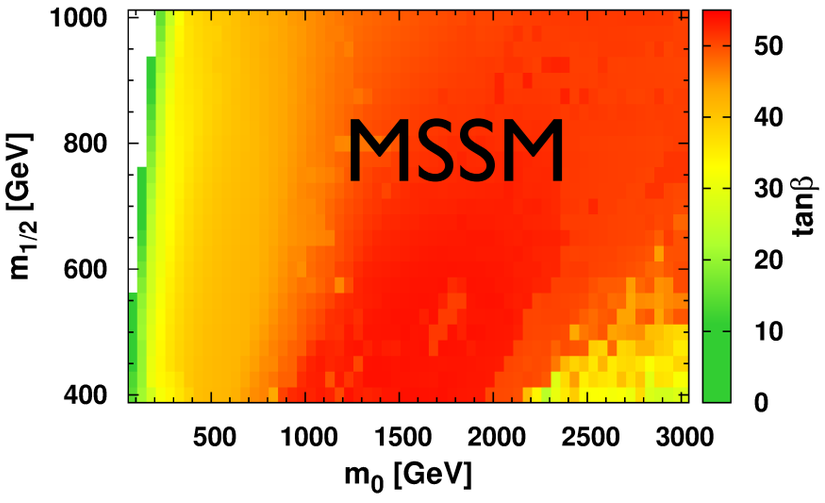

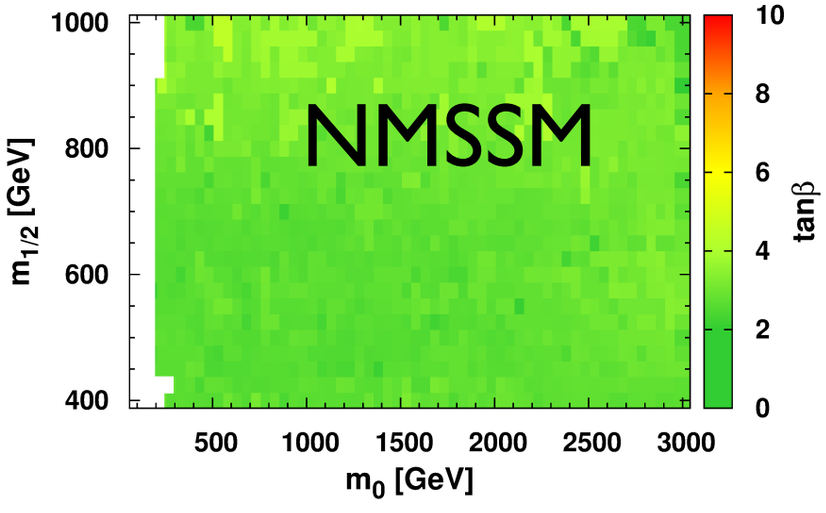

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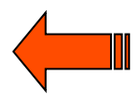

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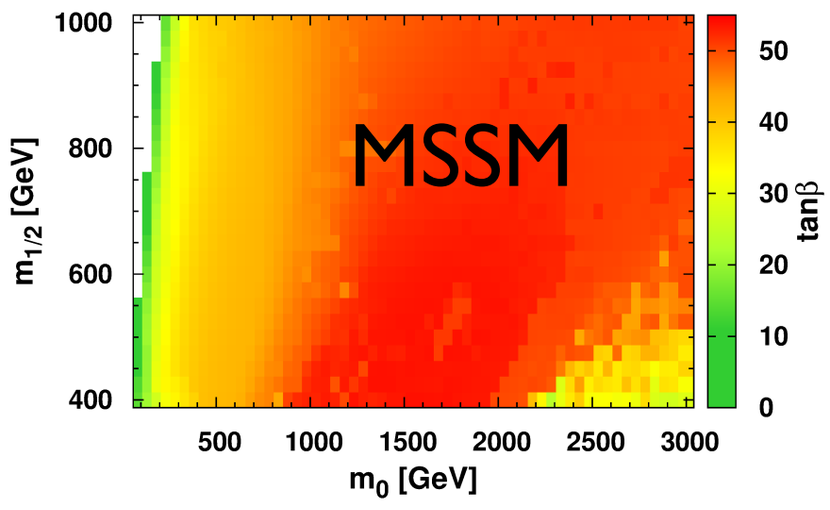

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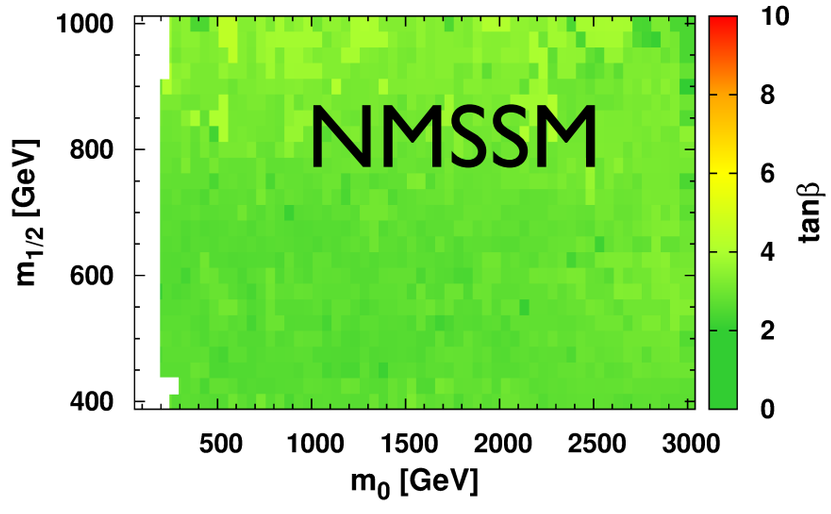
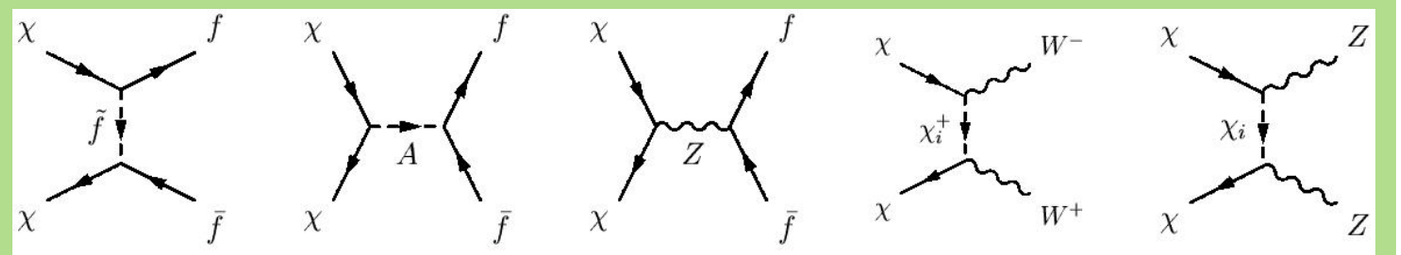


Low $\tan\beta \sim 3$

DM annihilation



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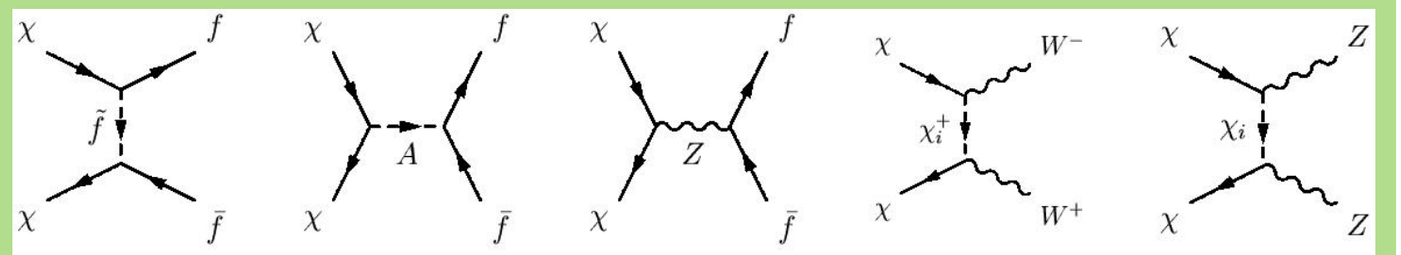

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$\propto \frac{\tan\beta \cdot m_{f_d}}{m_W} N_1 N_{3(4)}$

$\tan\beta \cdot m_{f_d} \leftrightarrow \frac{m_{f_u}}{\tan\beta}$

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

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

$(m_{\chi_i^+}, m_W) \leftrightarrow (m_{\chi_i}, m_Z)$

- Diffuse Gamma Rays

EGRET -> GLAST(FERM-LAT)

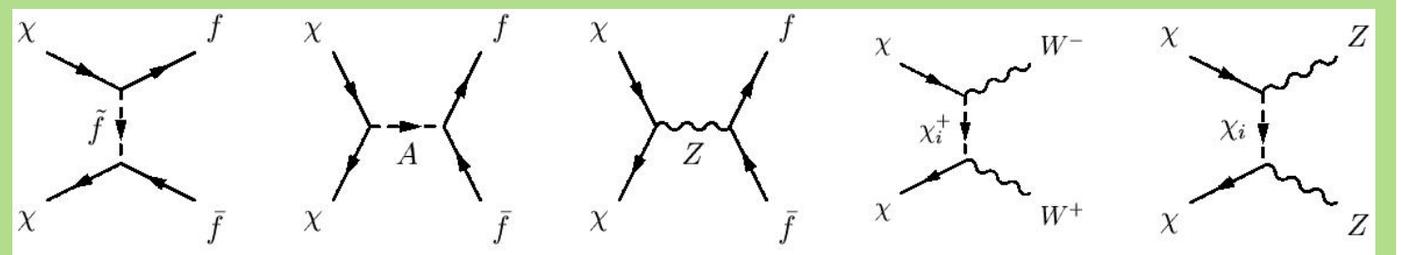
- Positrons in Cosmic Rays

HEAT, AMS01 -> PAMELA, FERMI

- Antiprotons in Cosmic Rays

BESS -> AMS02

DM annihilation



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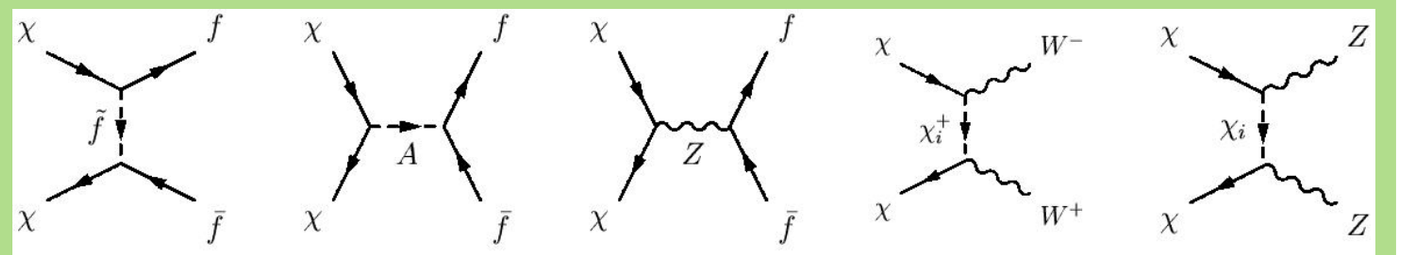
No significant excess

DM annihilation



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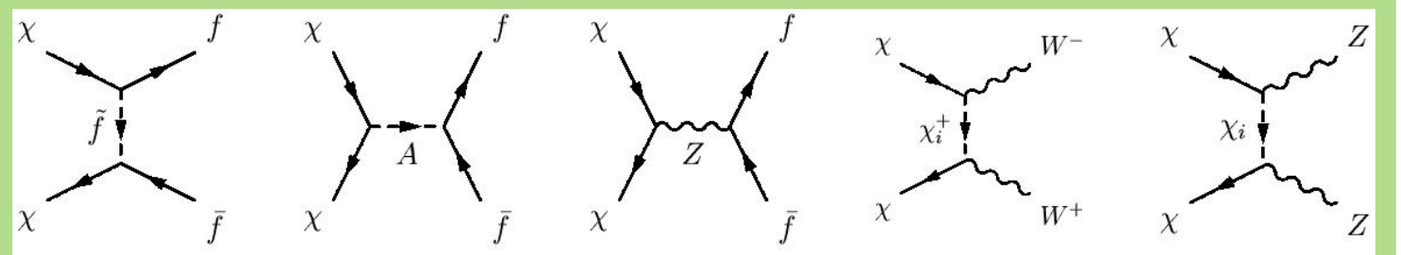
Contradictory interpretation

DM annihilation



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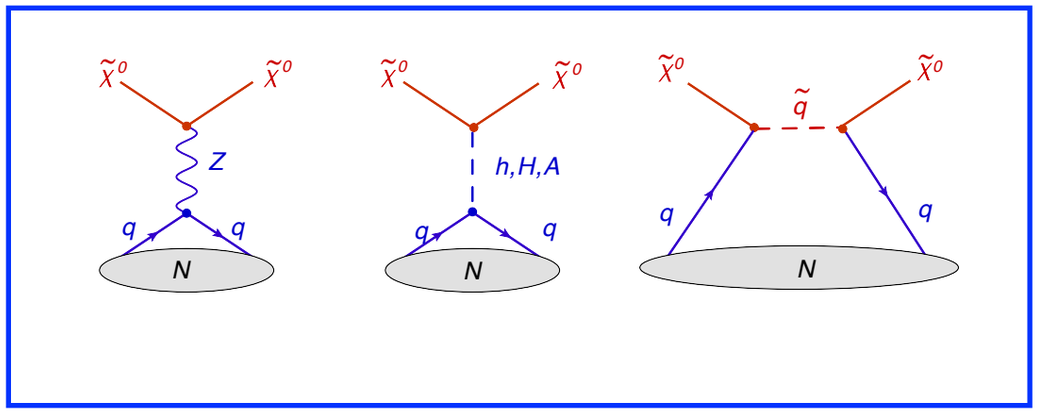
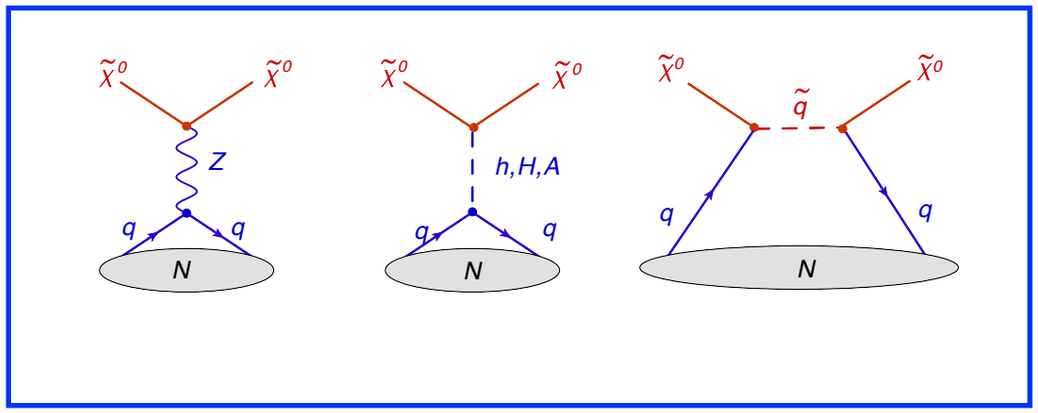
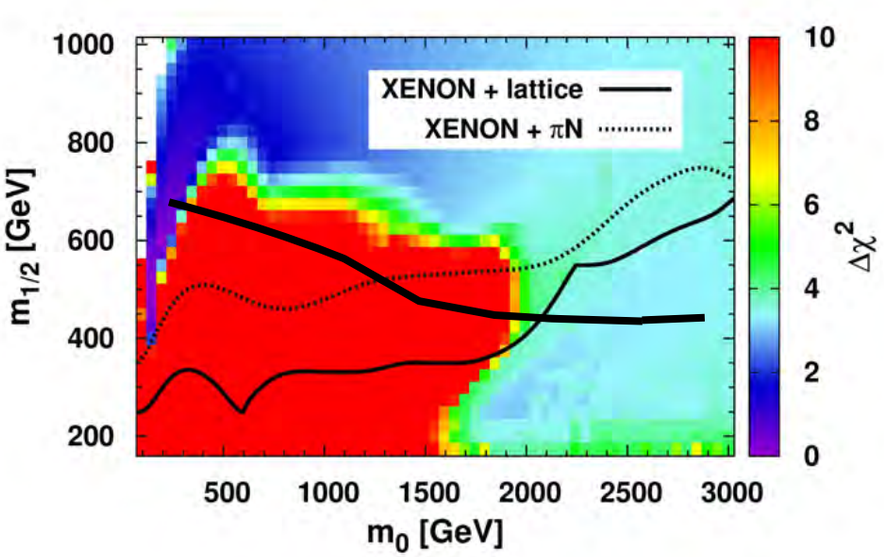
135 GeV $\gamma\gamma$ line?

DM Nucleons Interaction



DM Nucleons Interaction

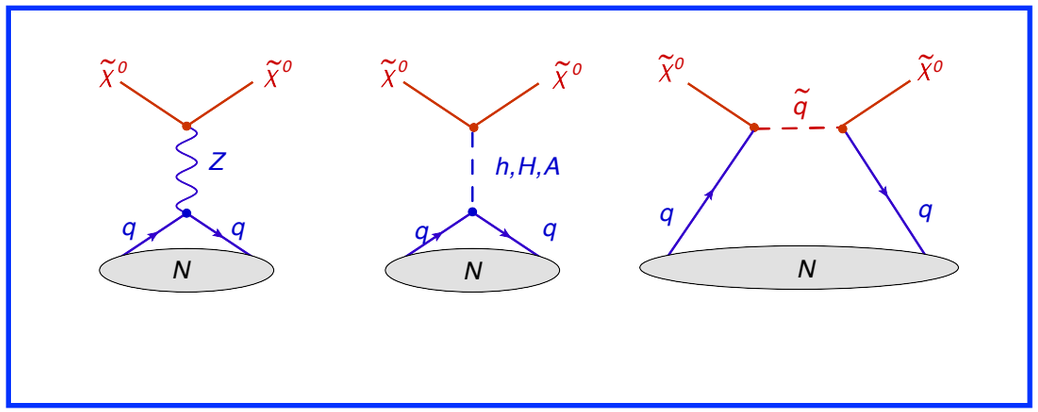




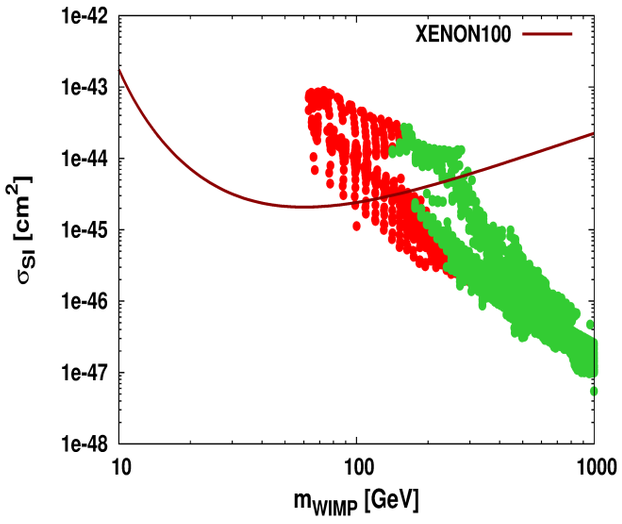
MSSM

Direct DM search

DM Nucleons Interaction

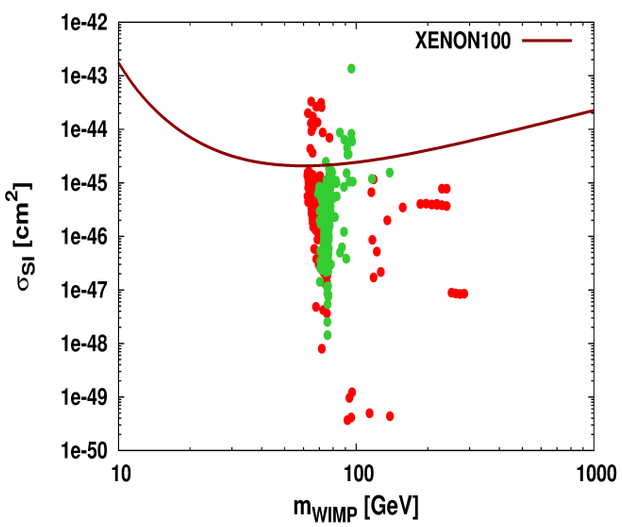


MSSM

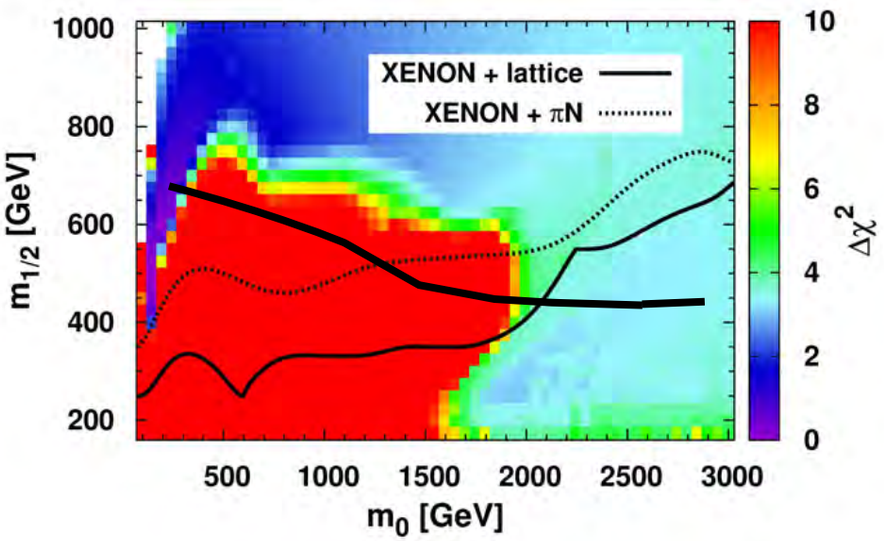


Red points - excluded by LHC

NMSSM



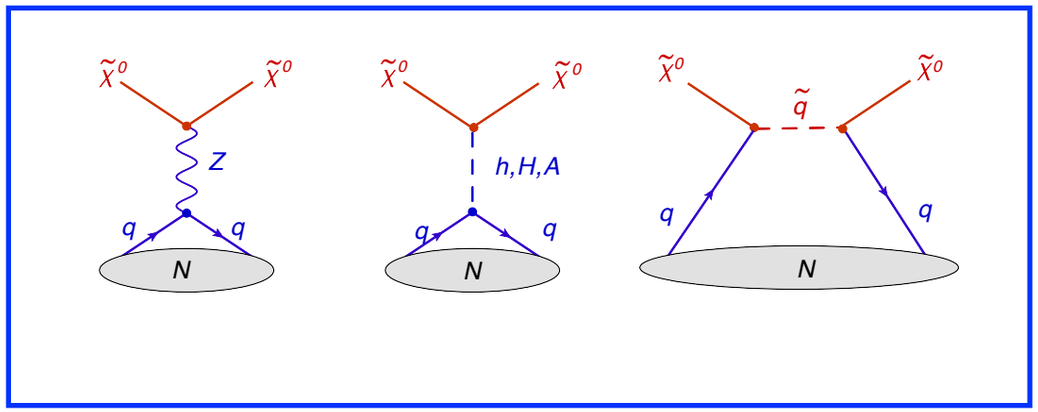
XENON100+LHC 8

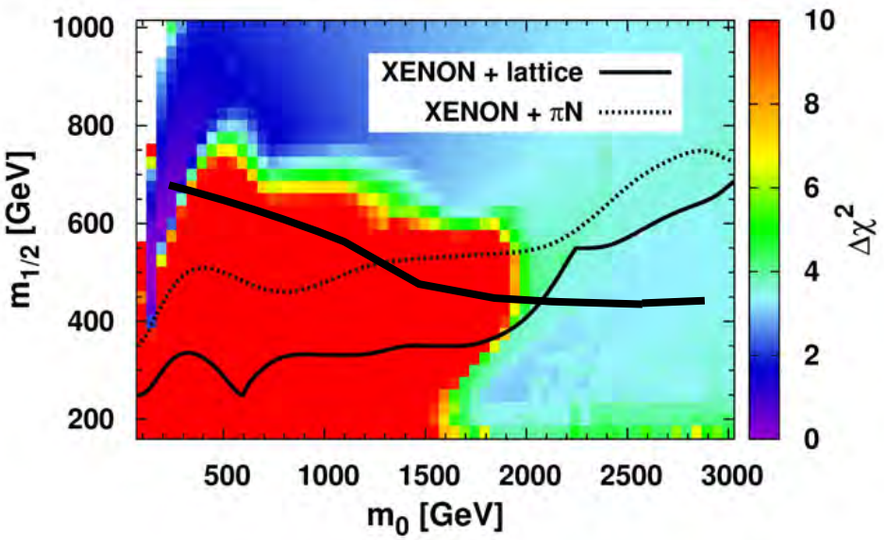


MSSM

Direct DM search

DM Nucleons Interaction

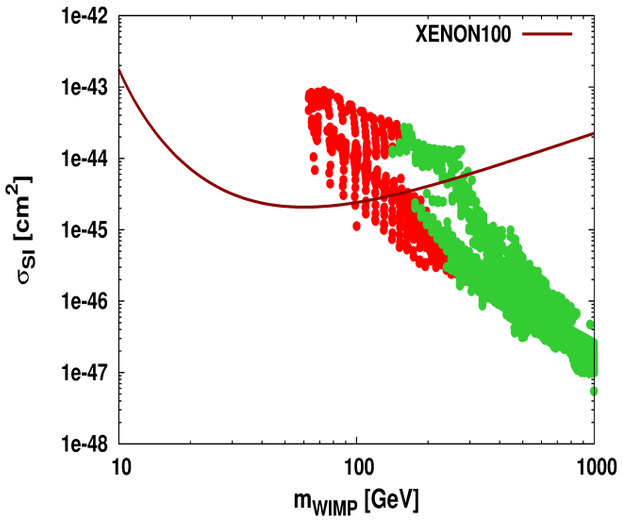




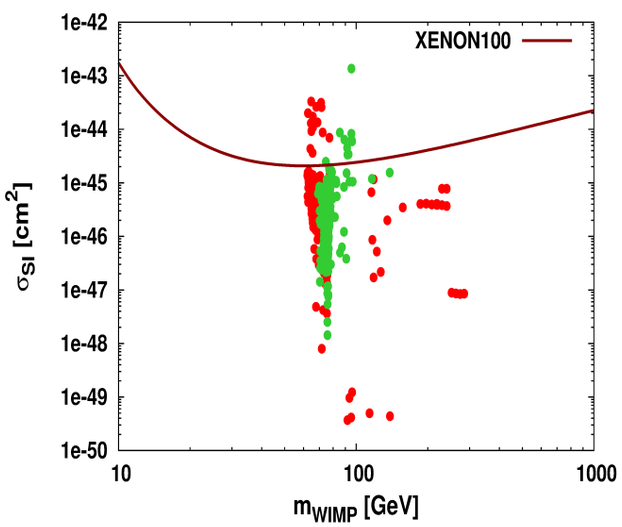
MSSM

Direct DM search

MSSM



NMSSM



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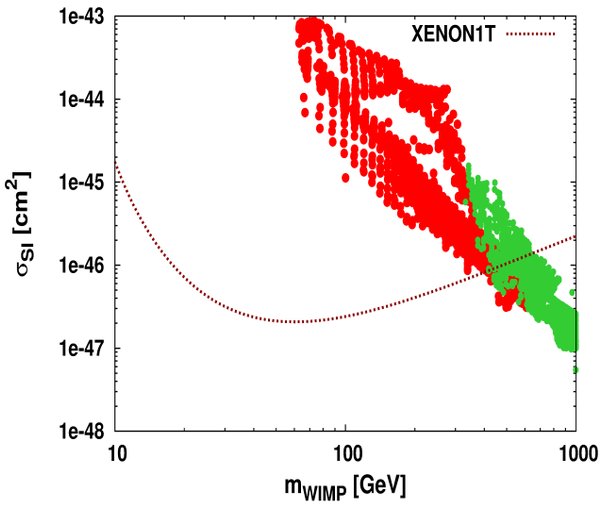
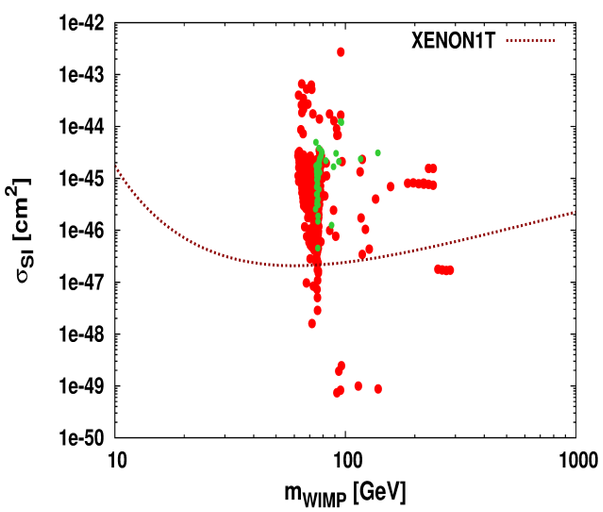
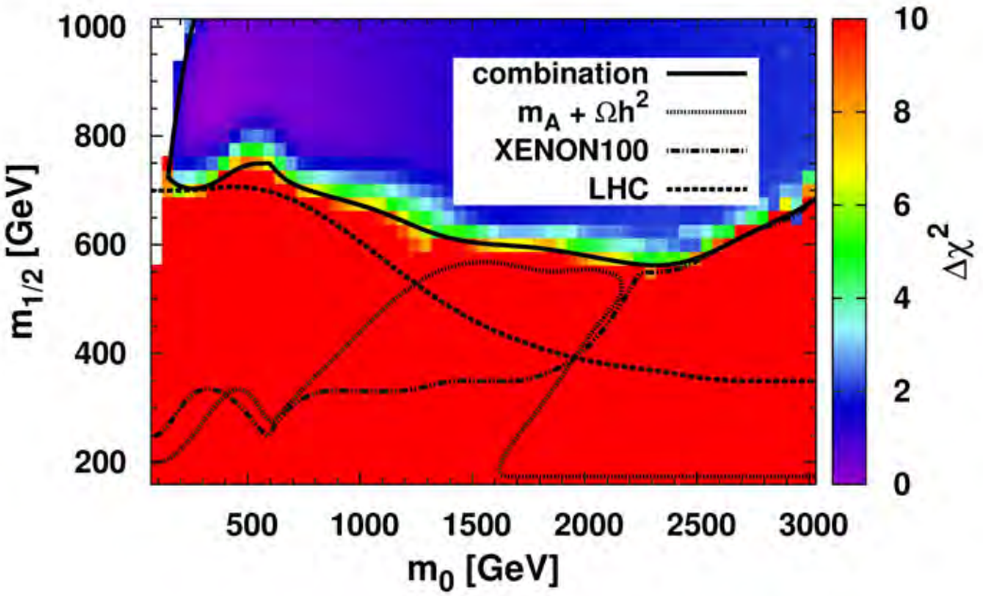
XENON100+LHC 8





XENON1T+LHC 14

Combined Fit to all Data

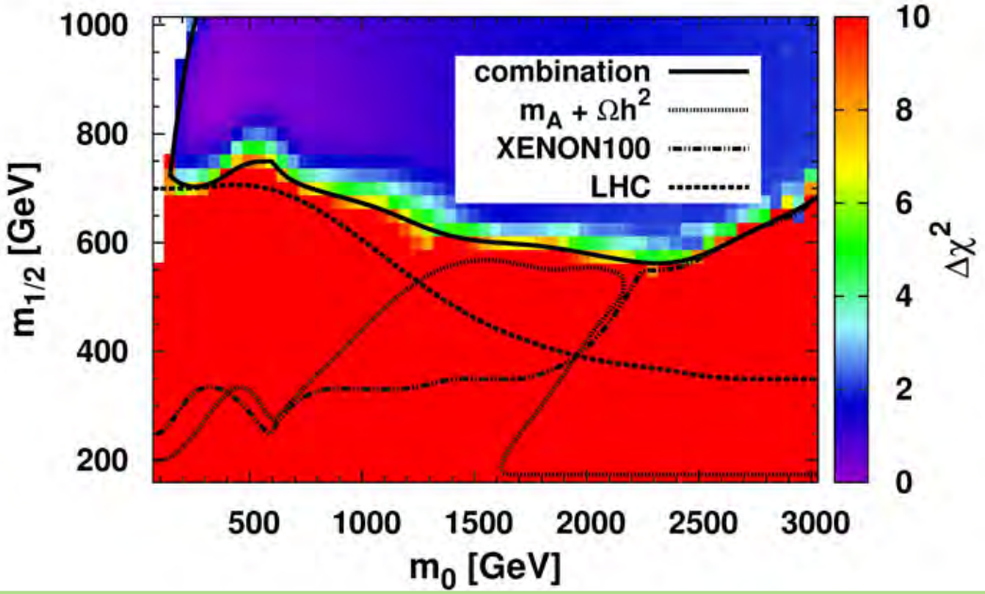


Constraint	Data
Ωh^2	0.113 ± 0.004
$b \to X_s\gamma$	$(3.55 \pm 0.24) \cdot 10^{-4}$
$B_u \to \tau\nu$	$(1.68 \pm 0.31) \cdot 10^{-4}$
Δa_μ	$(302 \pm 63(exp) \pm 61(theo)) \cdot 10^{-11}$
$B_s^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^- < 4.5 \cdot 10^{-9}$
m_h	$m_h > 114.4$ GeV
m_A	$m_A > 480$ GeV for $\tan\beta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

Combined Fit to all Data

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

MSSM



without 125 GeV Scalar

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

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

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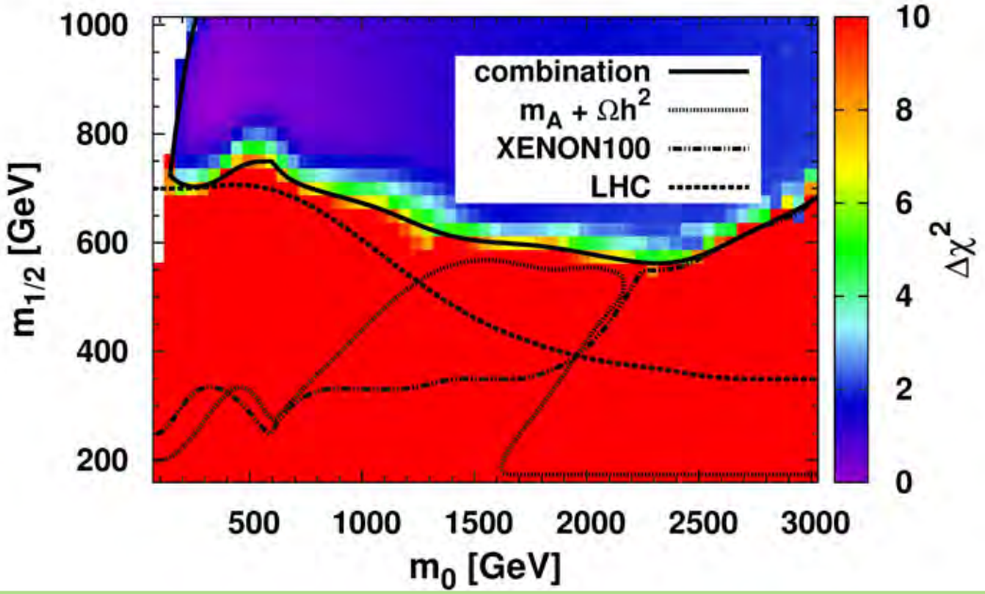

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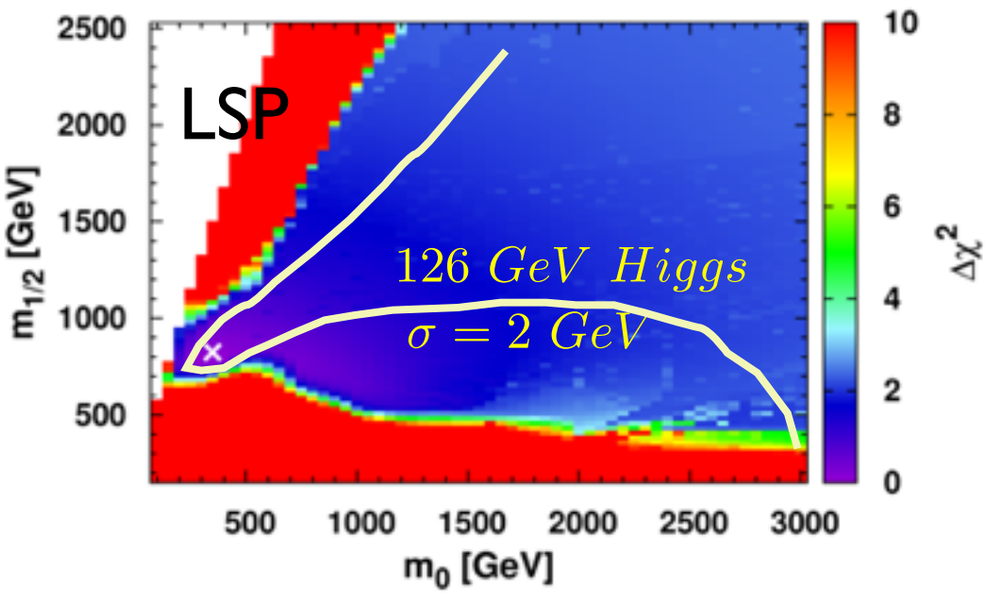


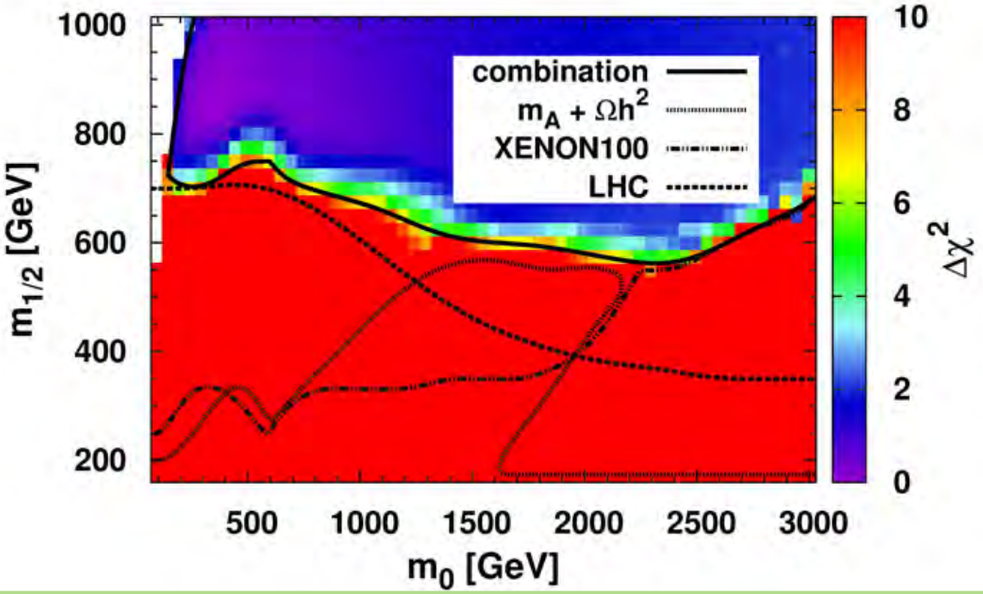
with 125 GeV Scalar

Larger scale for $m_{1/2}$

Combined Fit to all Data

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

MSSM



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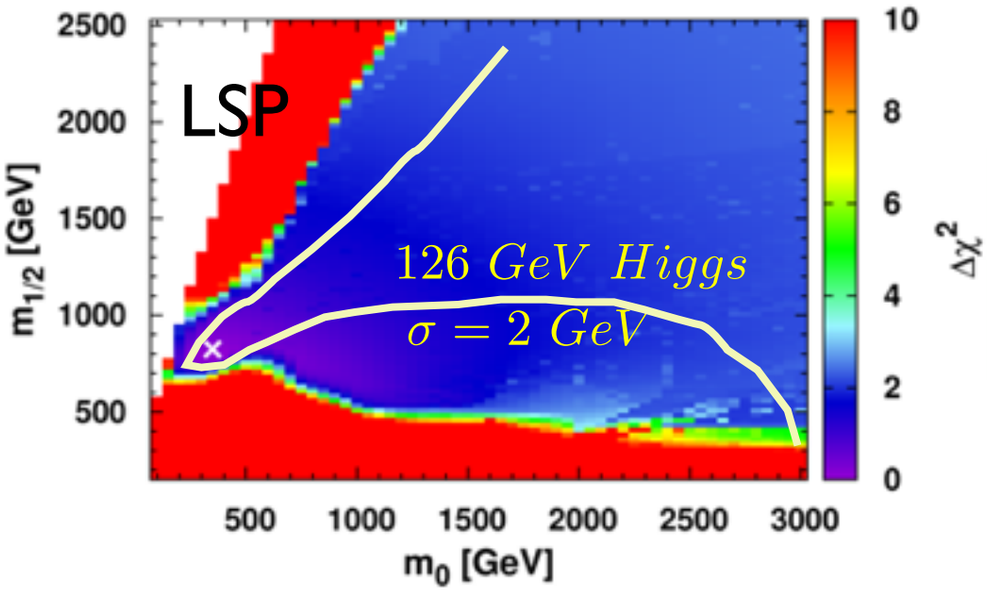
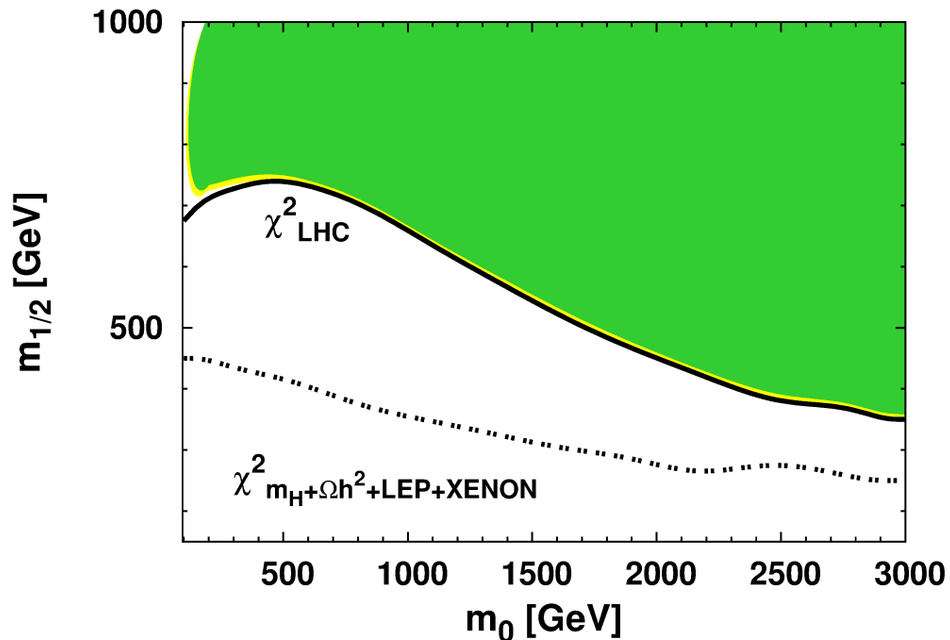


with 125 GeV Scalar

Larger scale for $m_{1/2}$

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

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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
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- Give me something better and I will stick to it