II Russian-Spanish Congress

Particle and Nuclear Physics at all Scales and Cosmology

Saint-Petersburg, October 1-4, 2013

Saint Petersburg State University

http://hep.phys.spbu.ru/conf/esp-rus2013/

Universitat de Barcelona

MAIN TOPICS:

Strong interactions of hadrons at LHC
Relativistic Heavy Ion Physics on LHC and RHIC
Low and intermediate energy hadron physics
AdS/CFT and AdS/QCD correspondence
and Holographic models of Strong Interactions
Search for Physics beyond the Standard Model
Modern Cosmology and Dark Energy
Dark Matter in the Universe and Axion manifestation
Integrability in Quantum Mechanics and Quantum Field Theory

Search for SUSY: MSSM versus NMSSM (model dependence of the analysis)

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BLTP JINR (Dubna)/ITEP(Moscow)

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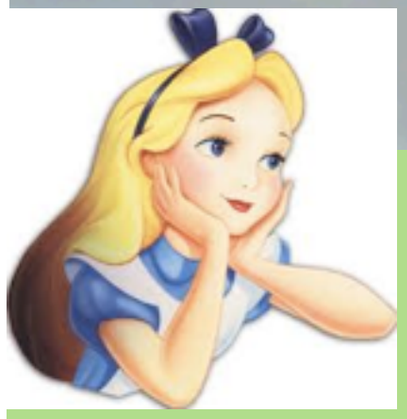

Search for SUSY: MSSM versus NMSSM (model dependence of the analysis)

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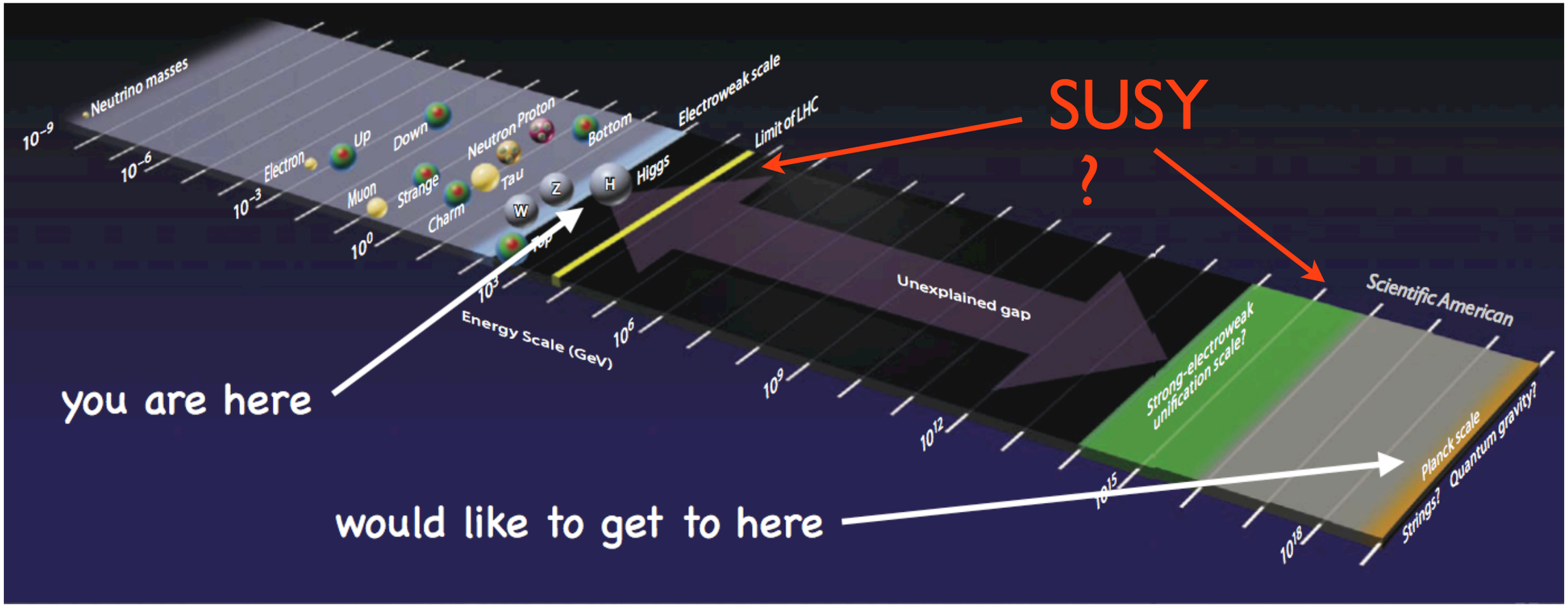
HEP Scale


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

SUSY Models

What SUSY?

SUSY Models

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

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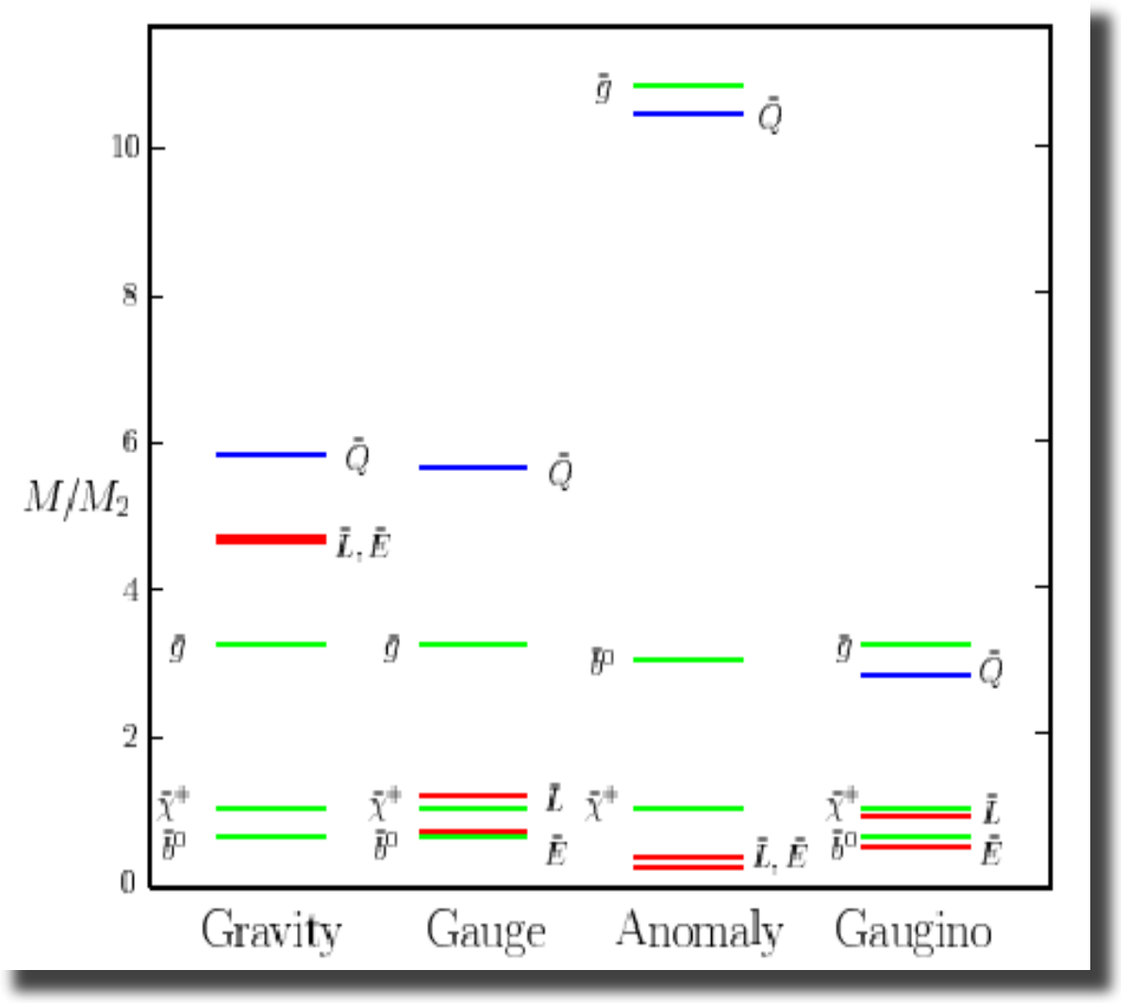
Sample superparticle spectrum



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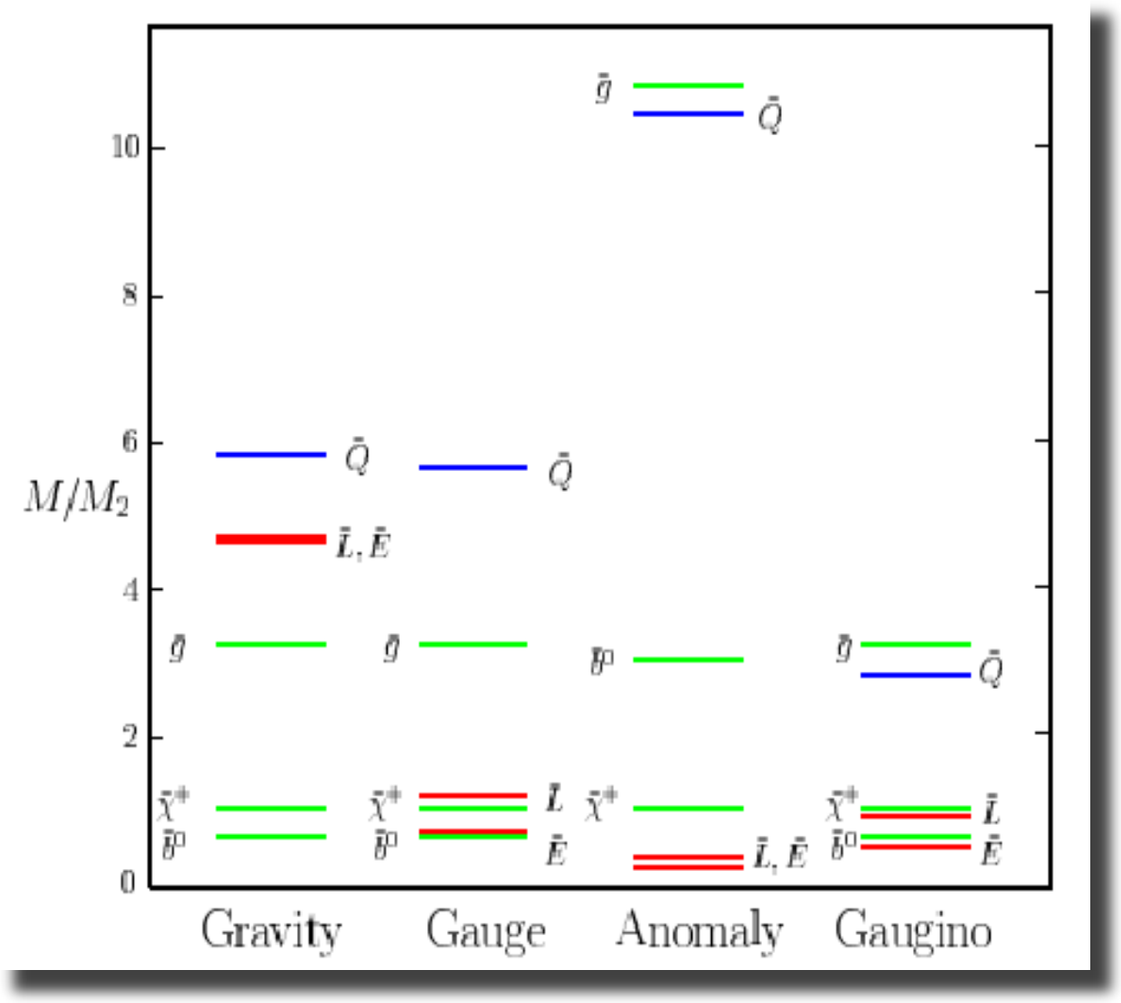

Despite supersymmetric rigidity of dimensionless couplings the arbitrariness of soft terms make predictions strongly model dependent !

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

Search for SUSY Manifestation

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Particle Phys

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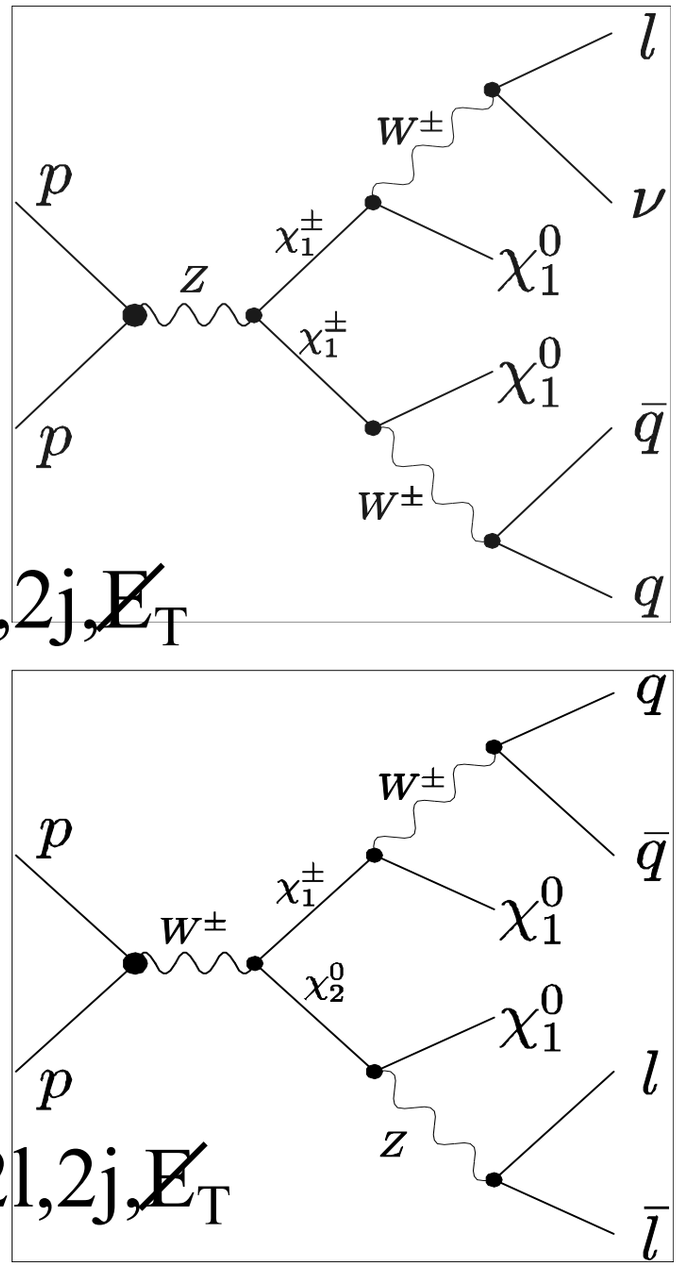
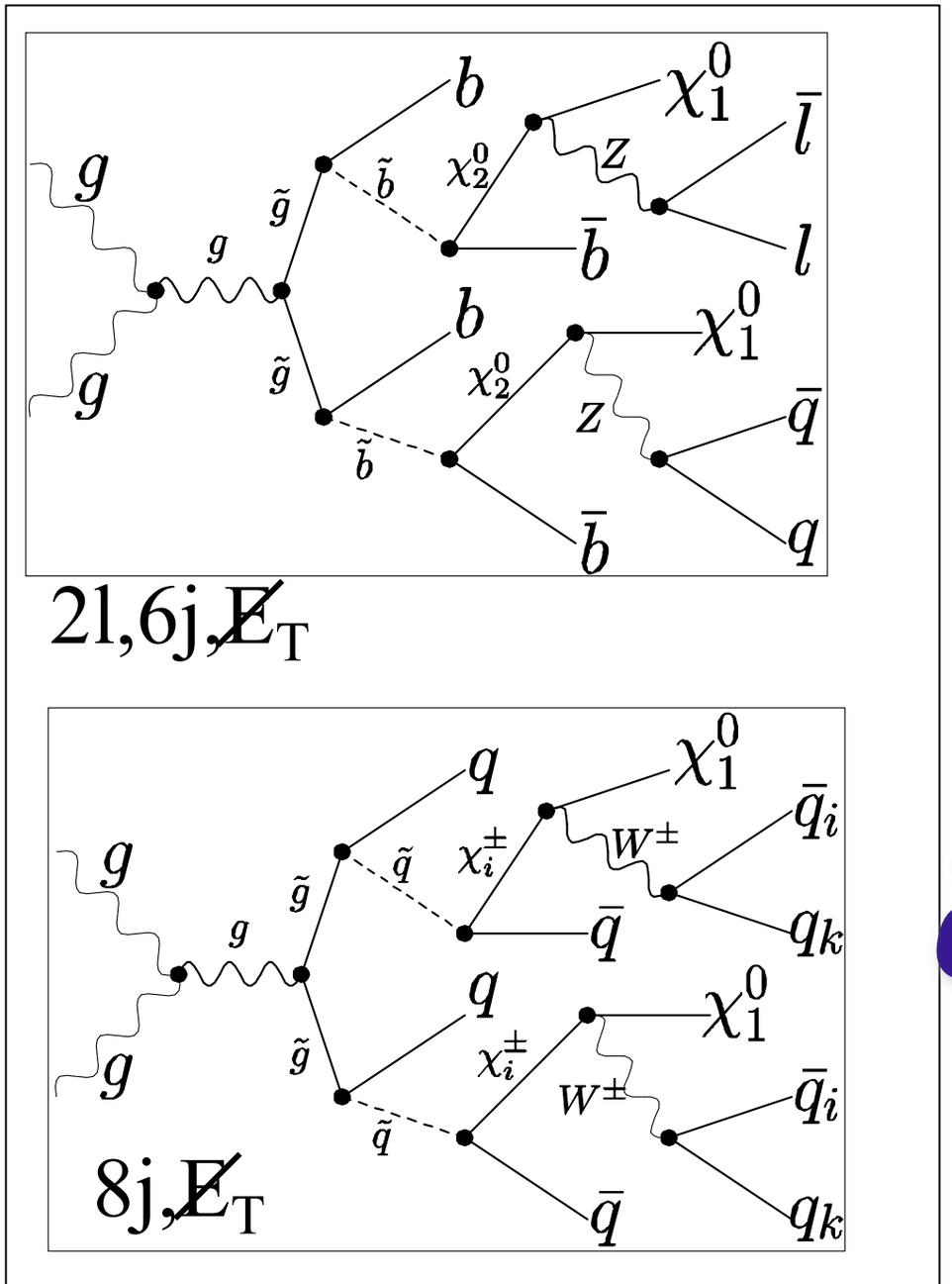
Nothing so far ...

Creation and Decay of Superpartners in Cascade Processes @ LHC

weak int's





Strong int's

Typical SUSY signature: Missing Energy and Transverse Momentum

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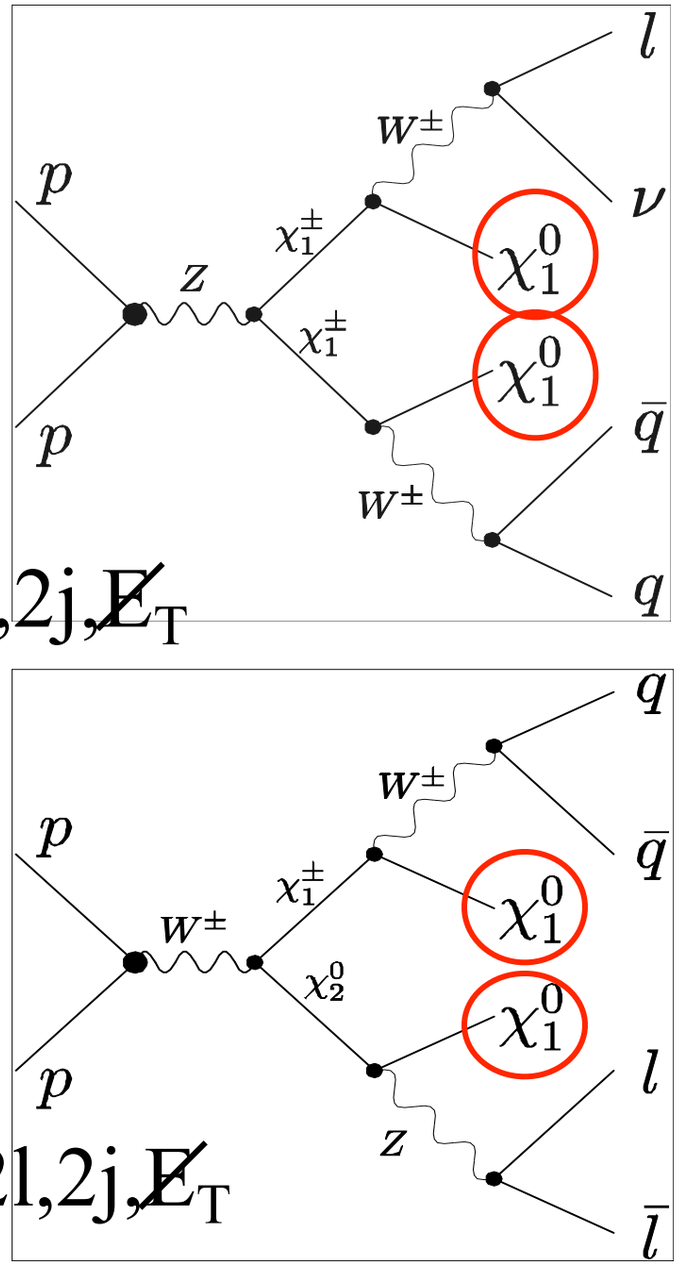

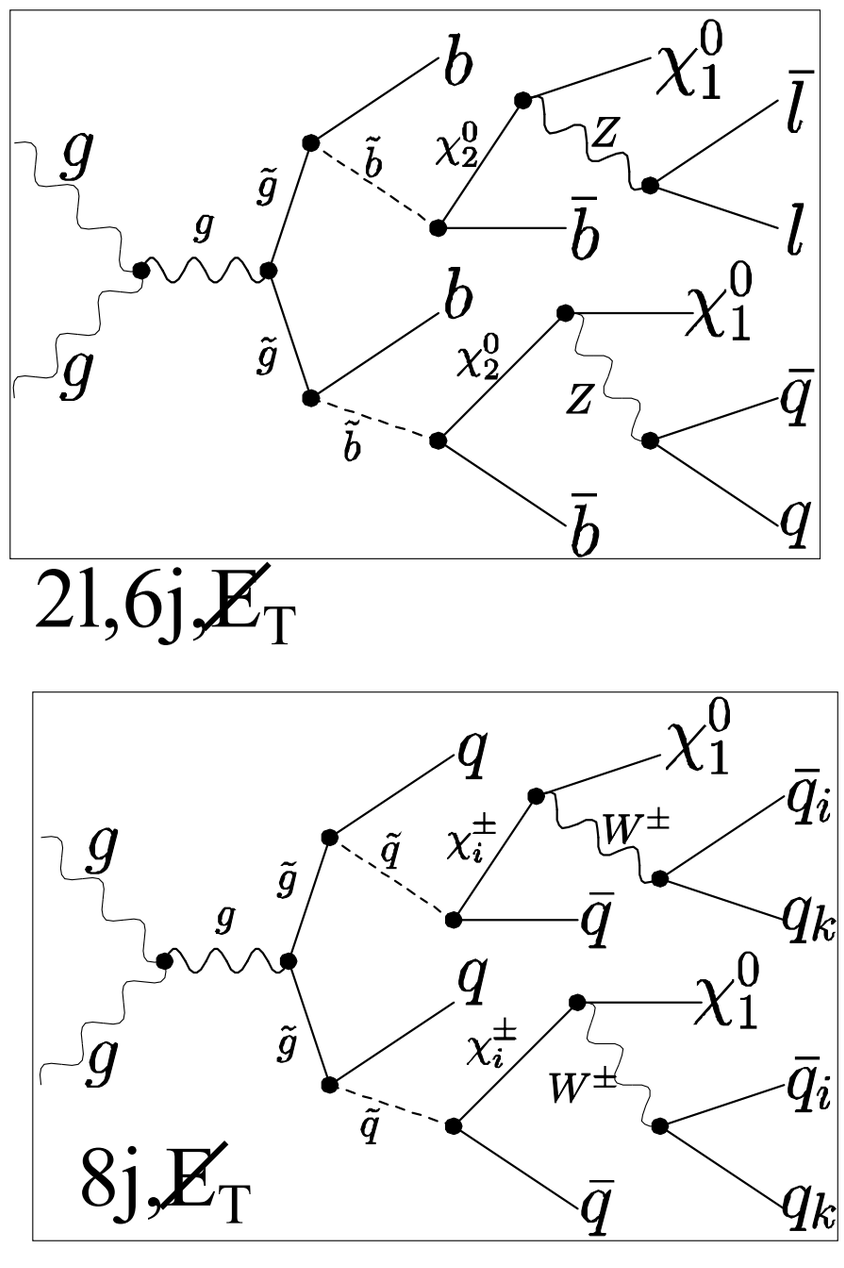

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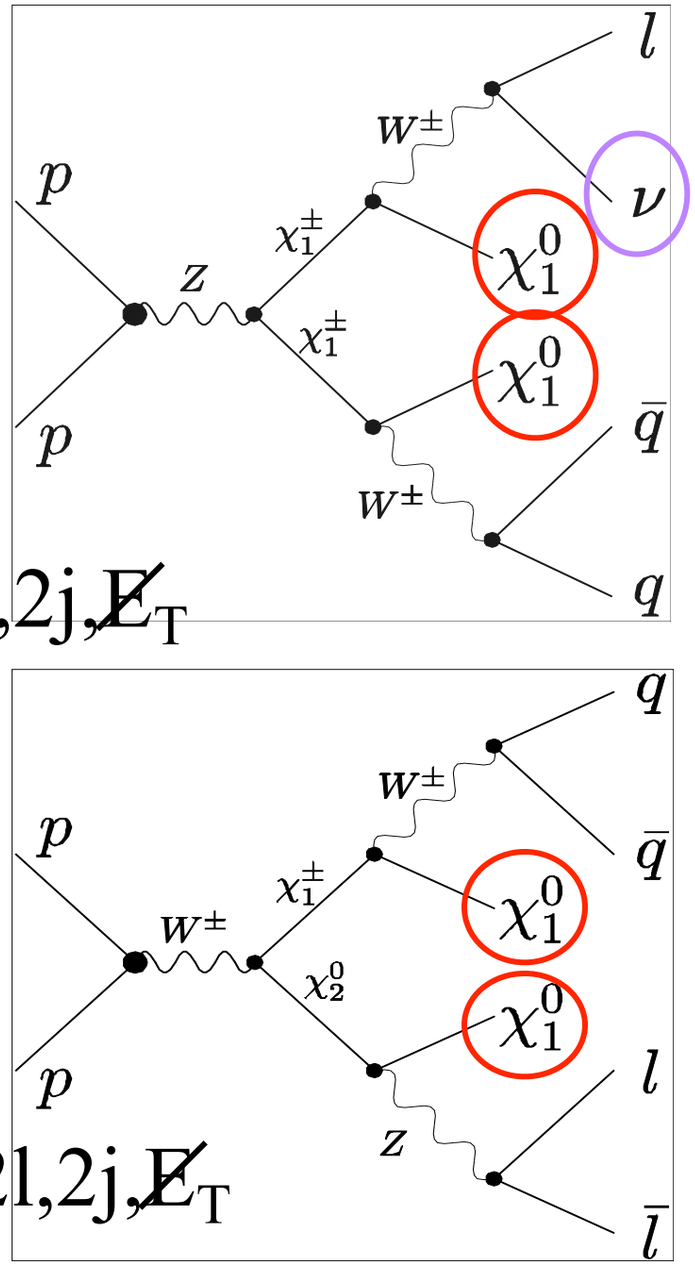

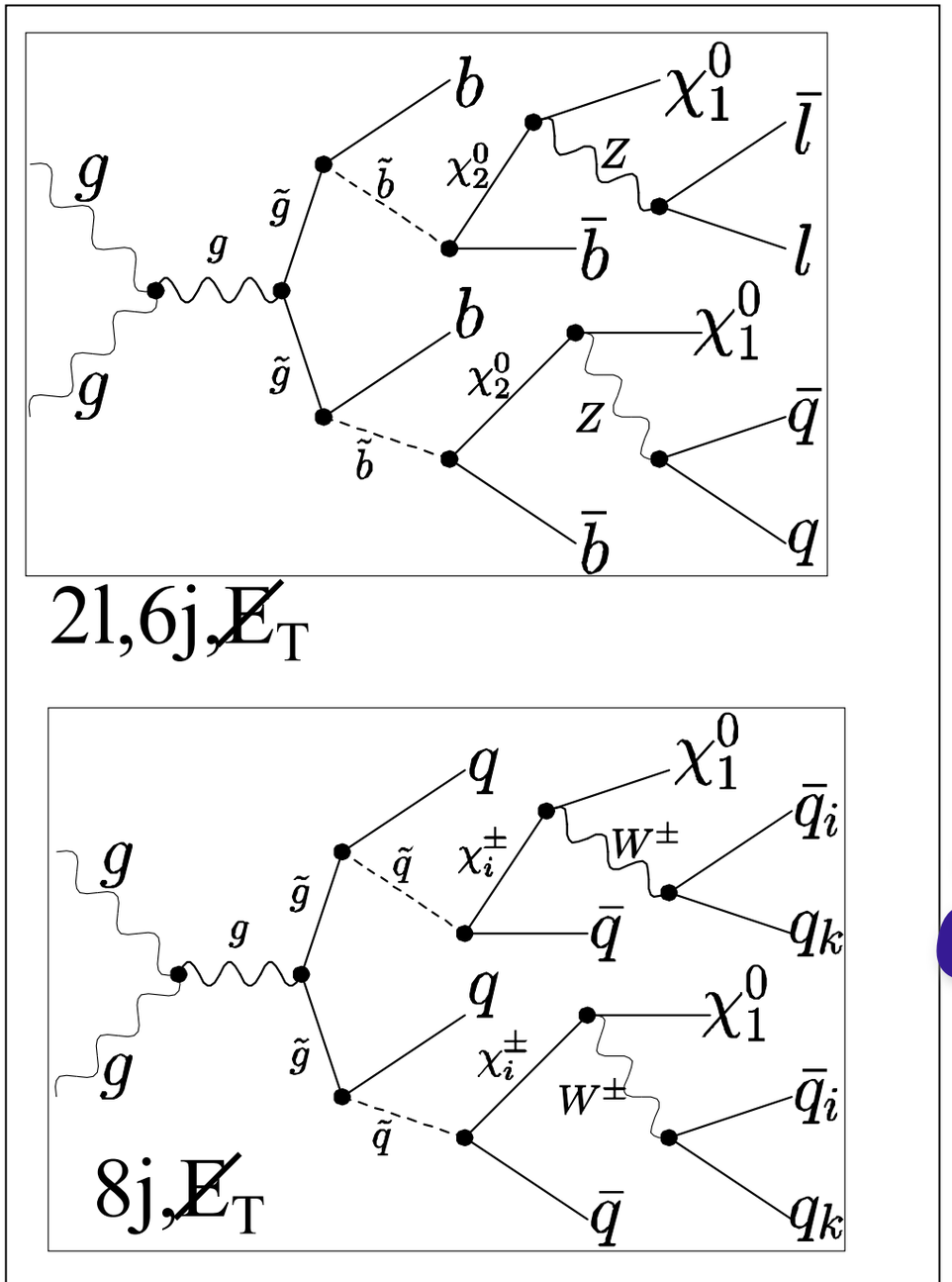

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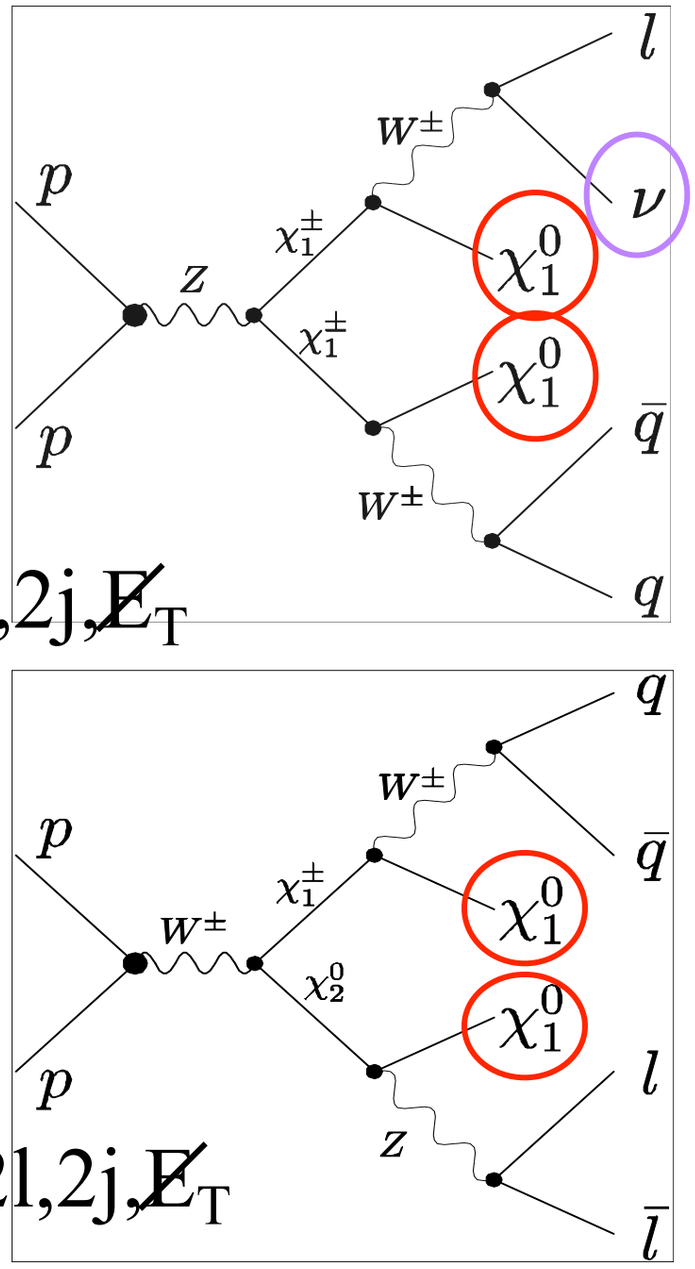

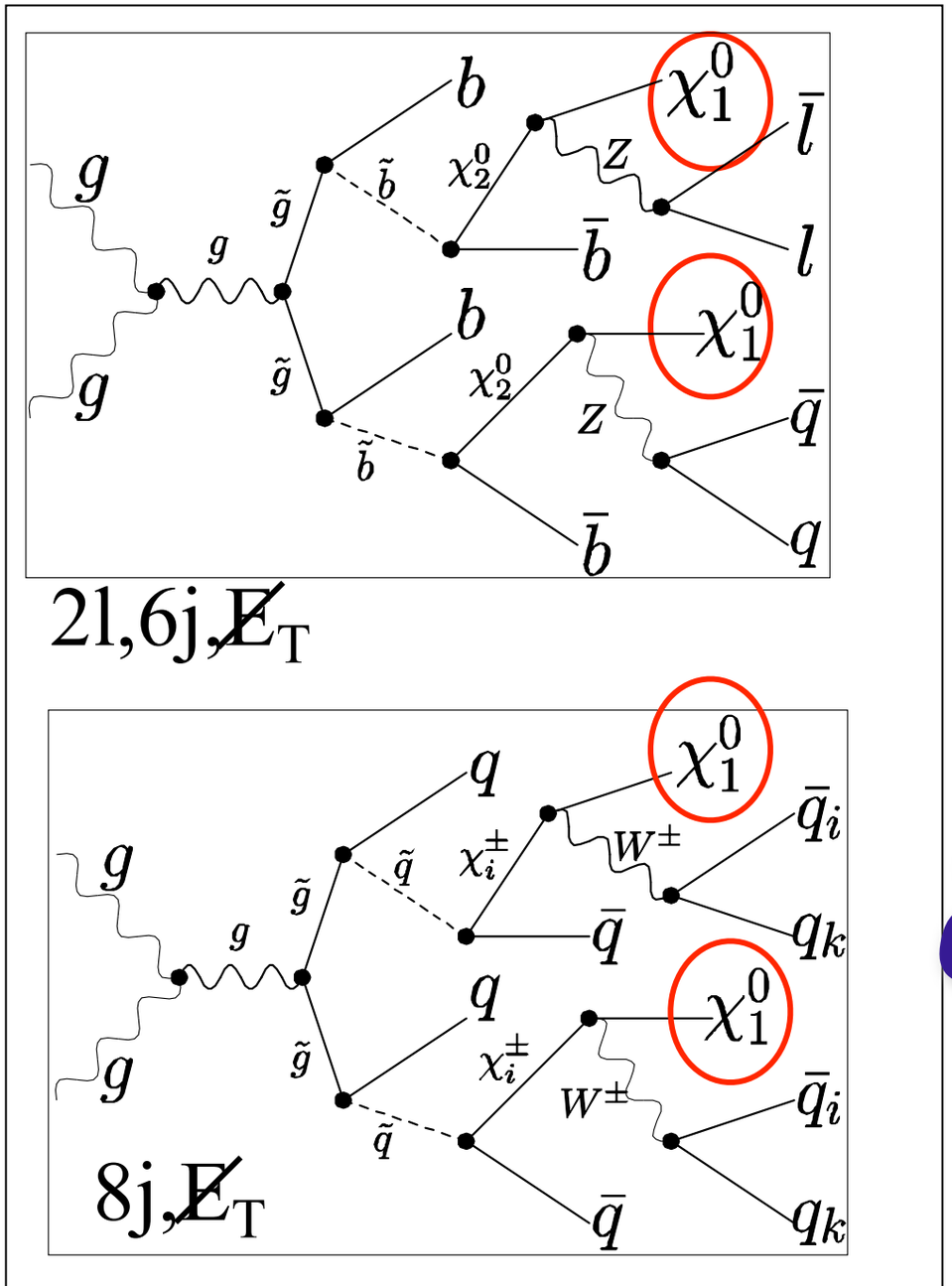

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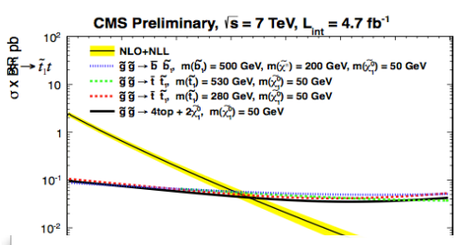
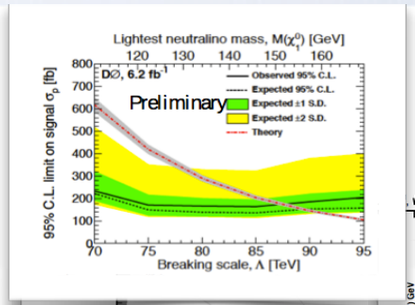
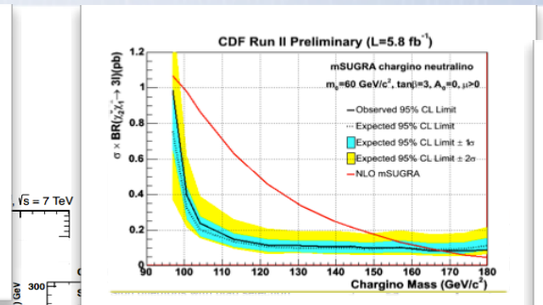
Both approaches are used

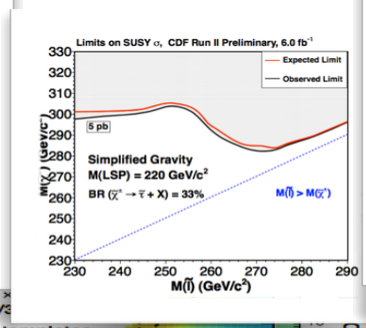
Guido Tonelli

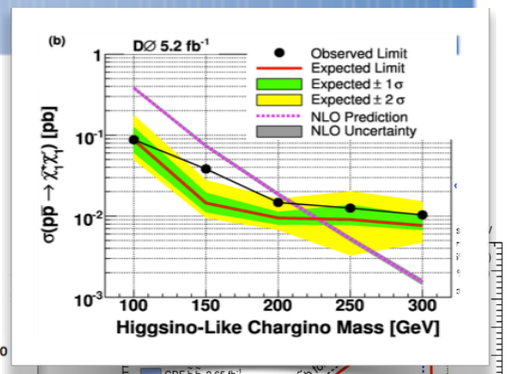
SUSY searches

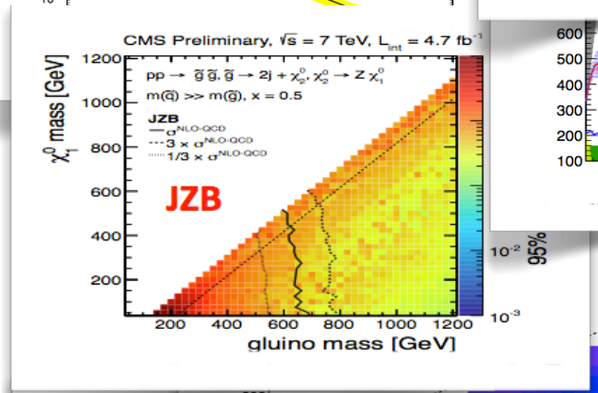


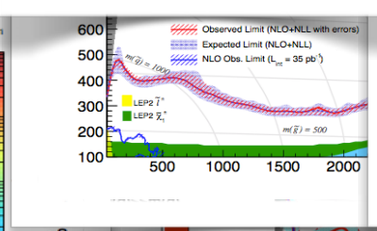


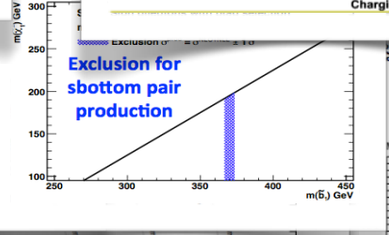


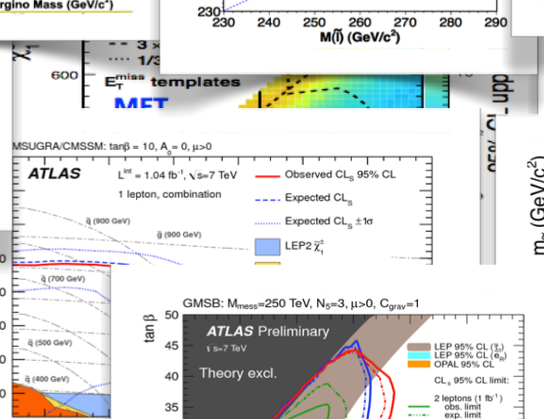


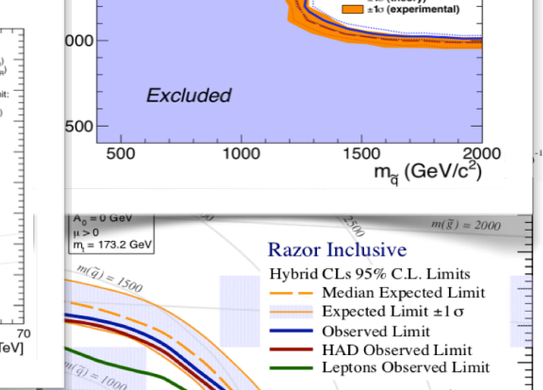


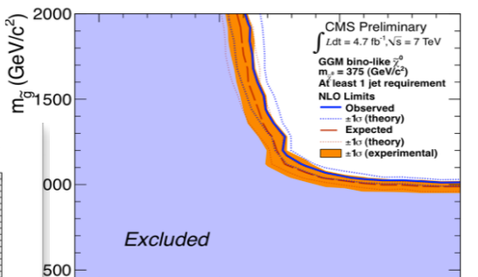


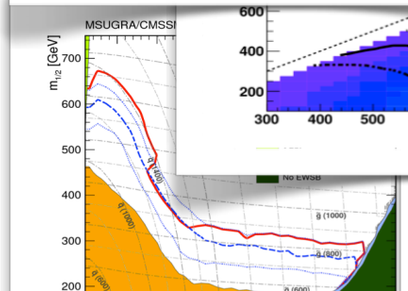


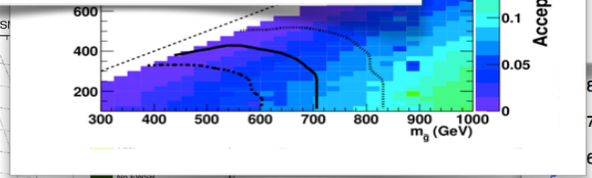


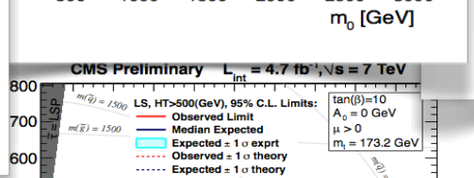


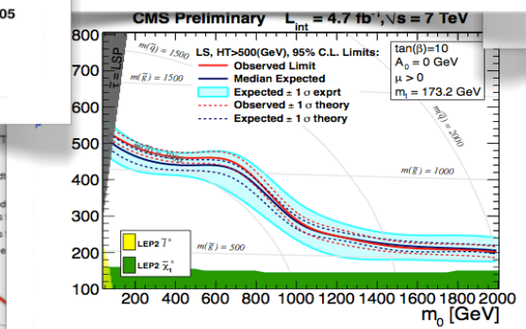


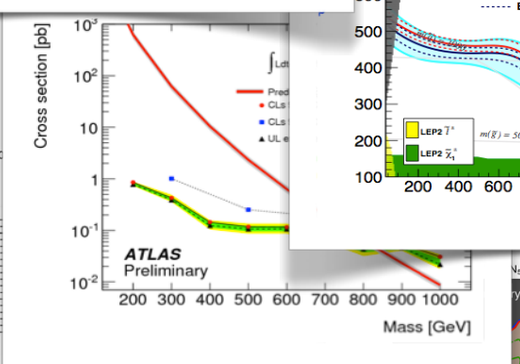


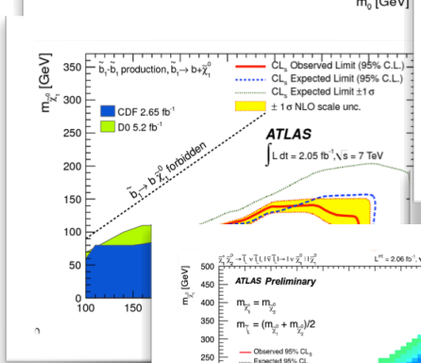


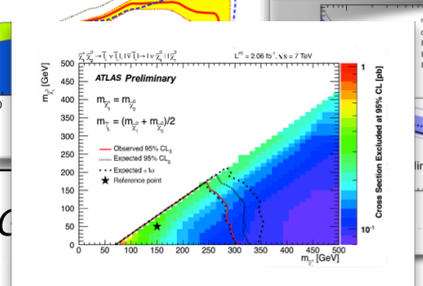


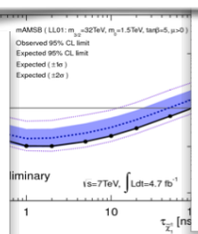


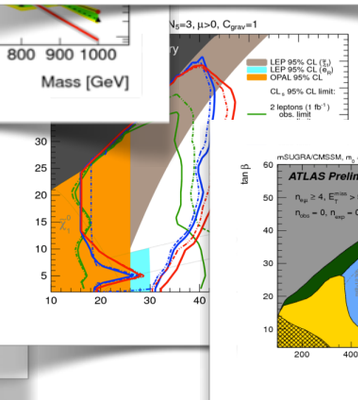


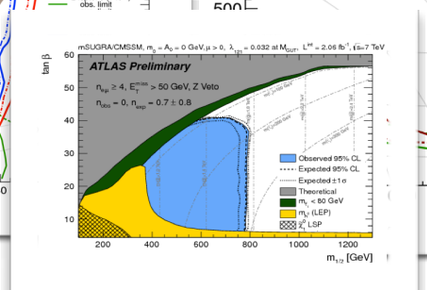


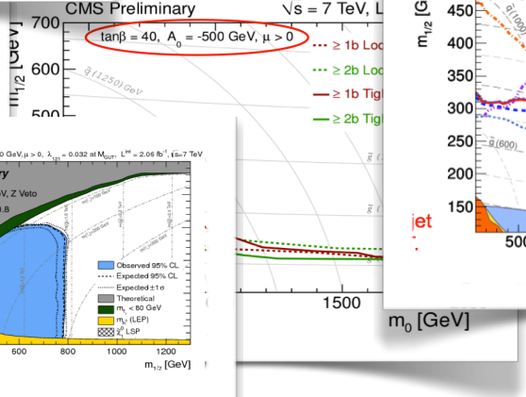


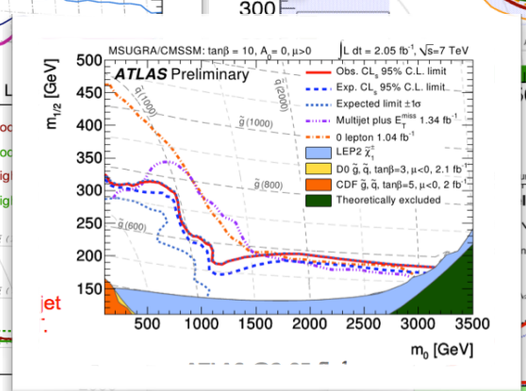


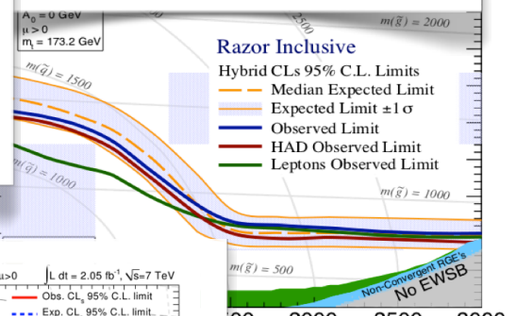


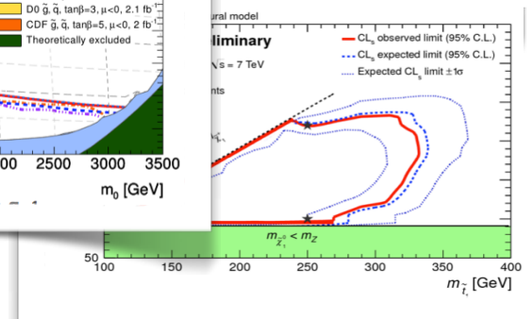








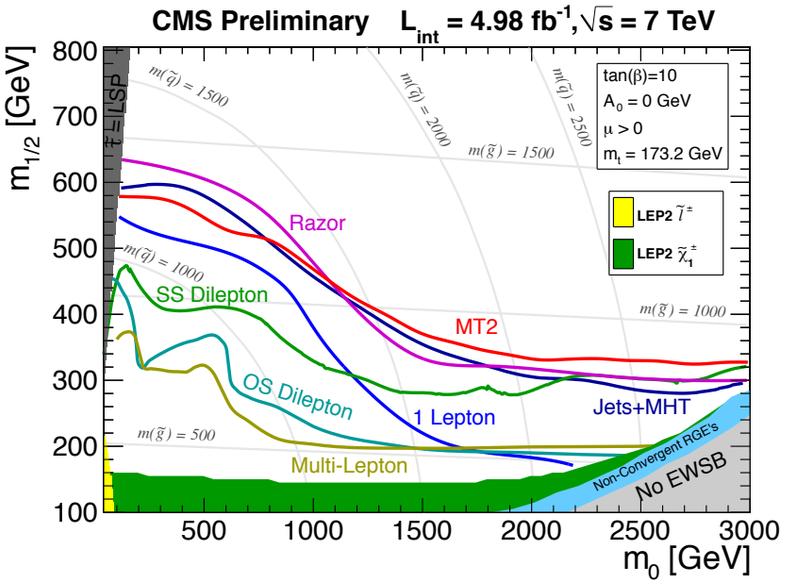


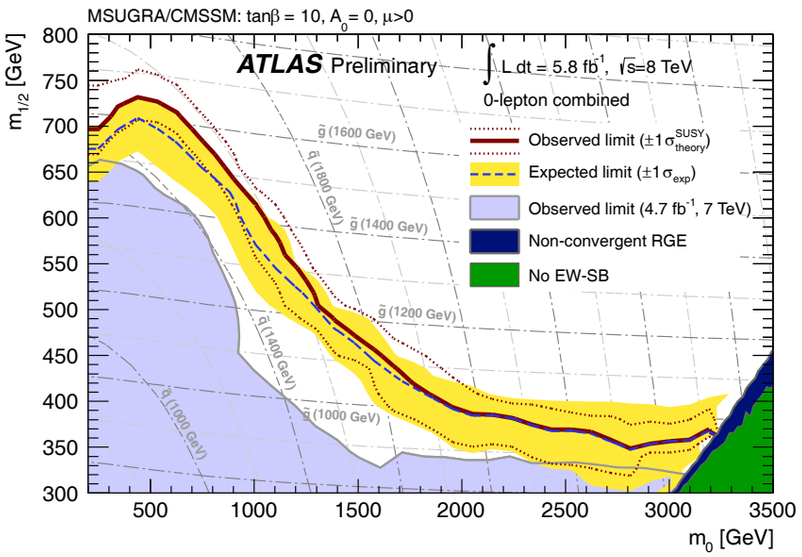


The Progress of LHC

The Progress of LHC

CMS CMSSSM summary





The Progress of LHC

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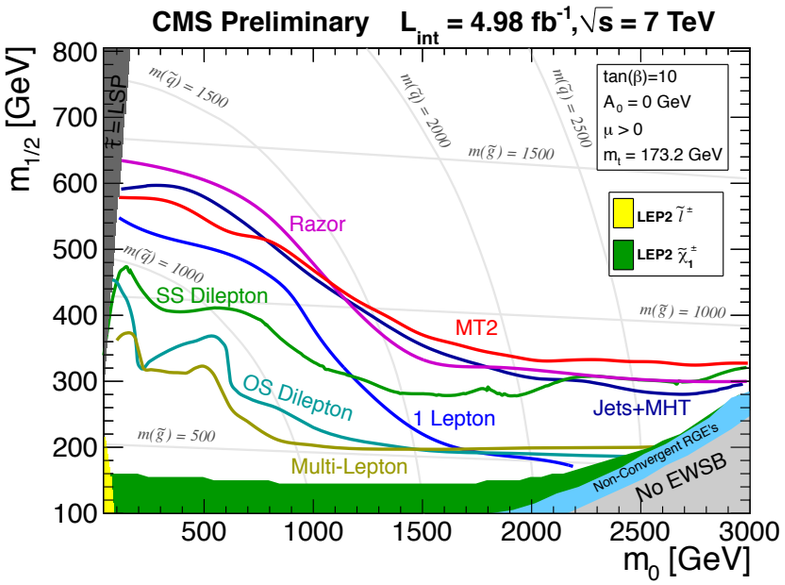
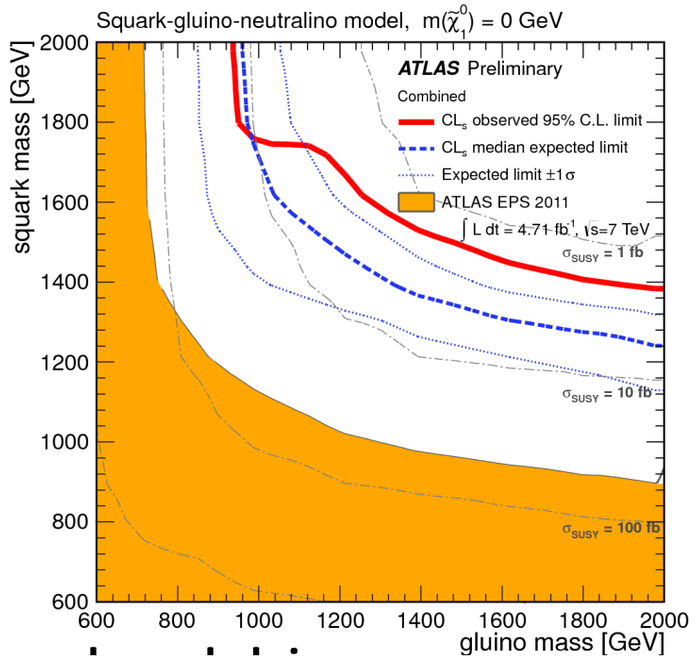
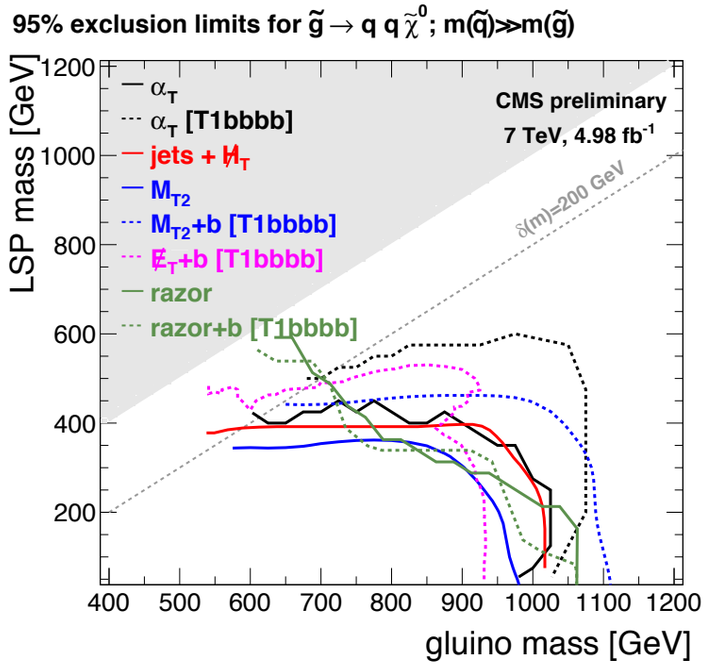
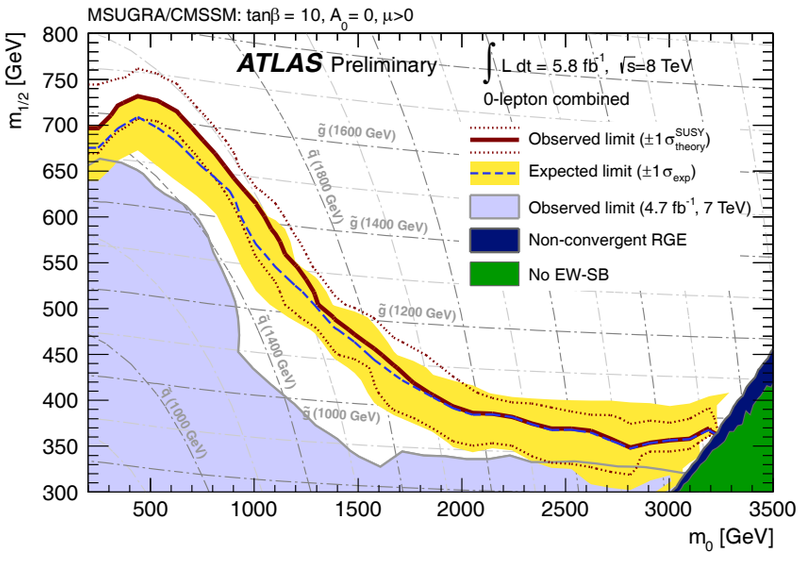
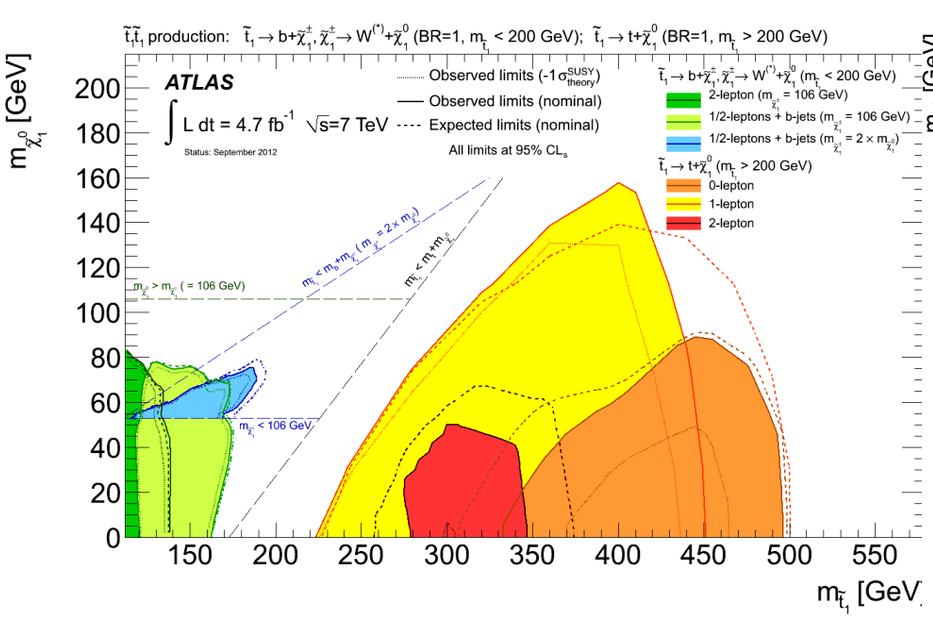


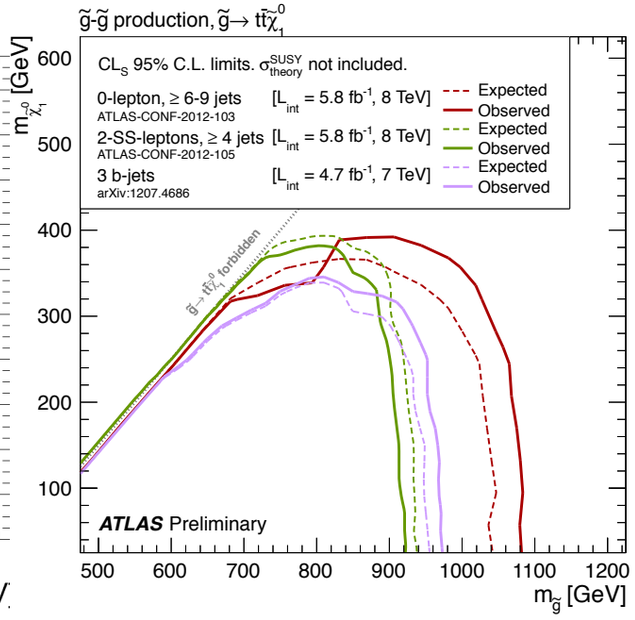
Look for squarks and gluinos with direct decays to SM+LSP





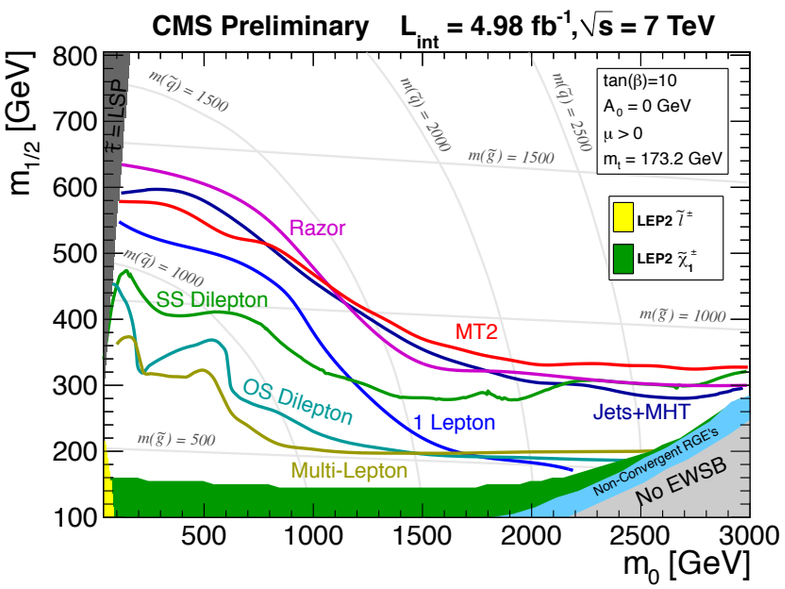






The Progress of LHC

CMS CMSSSM summary



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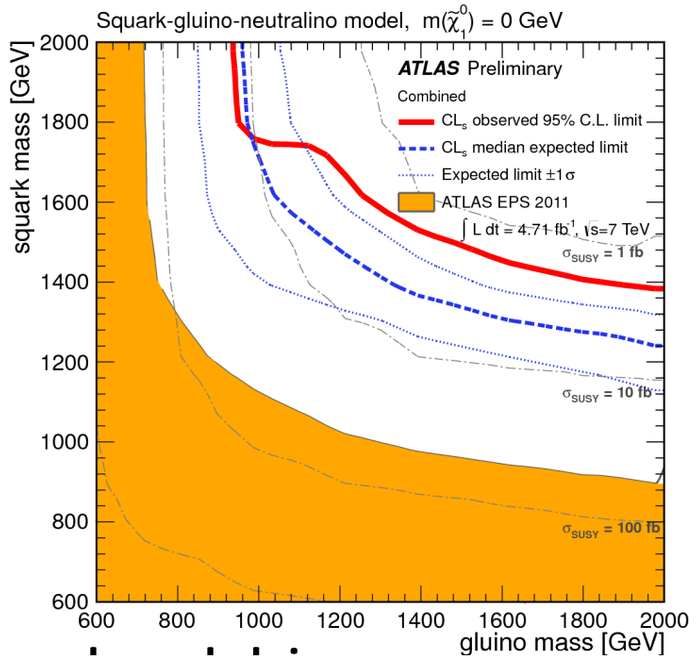
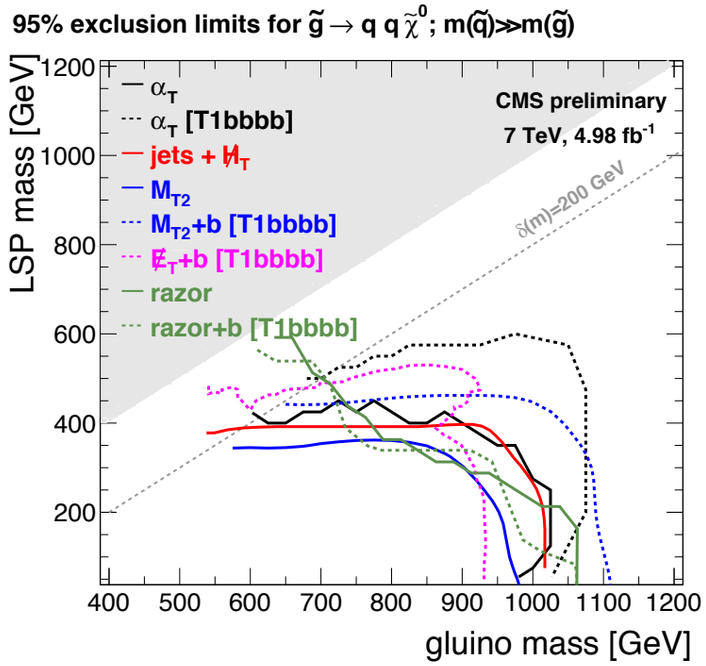
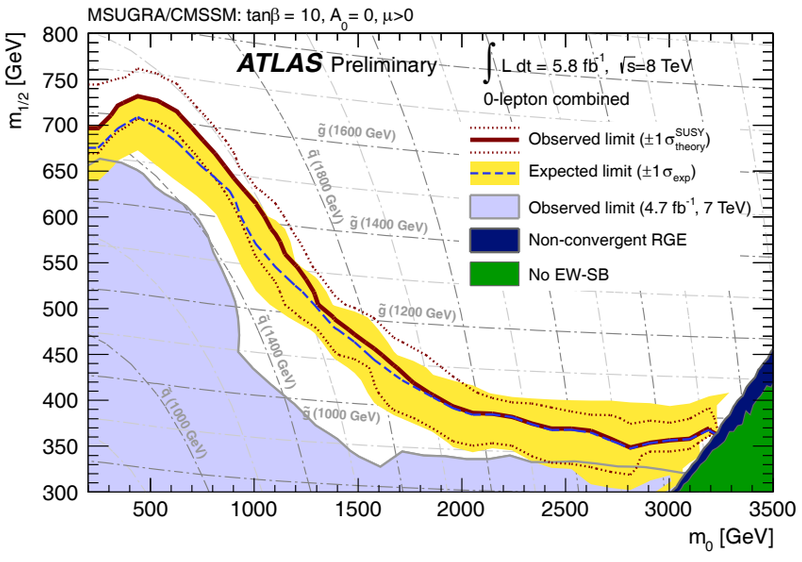
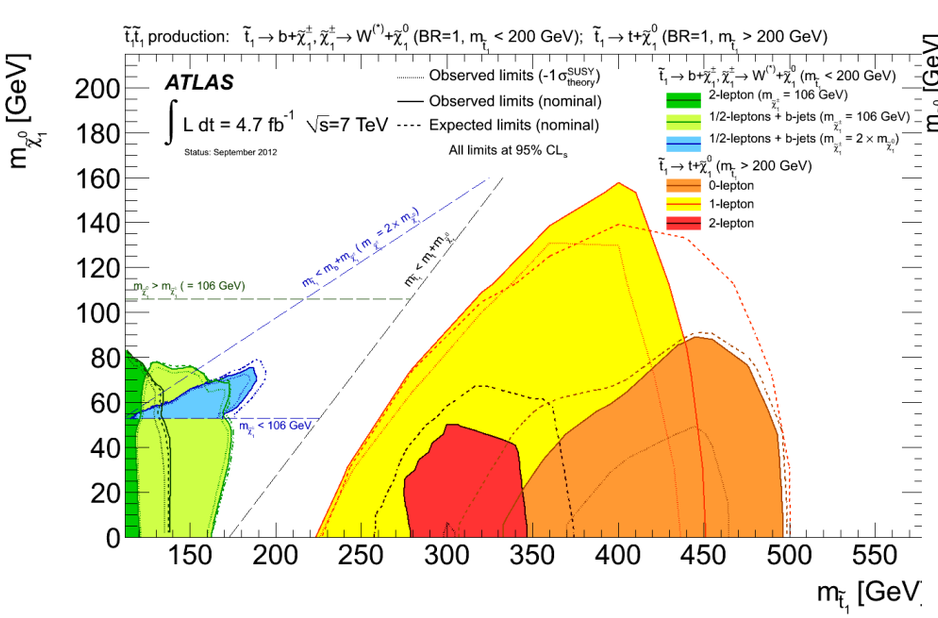
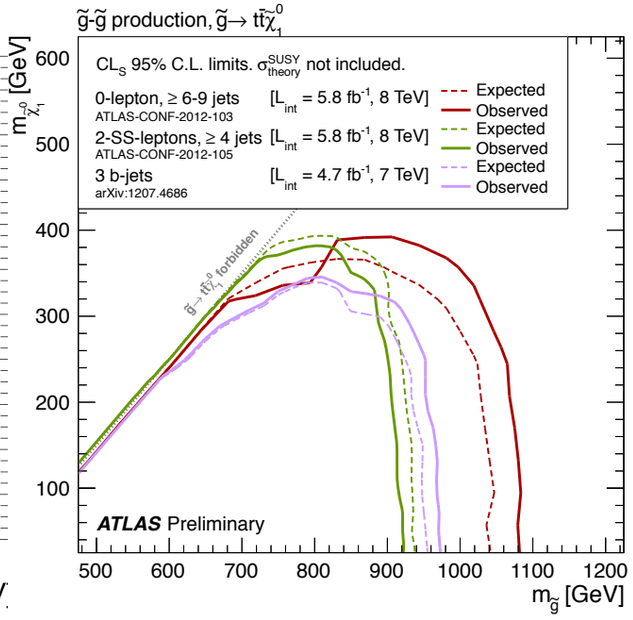






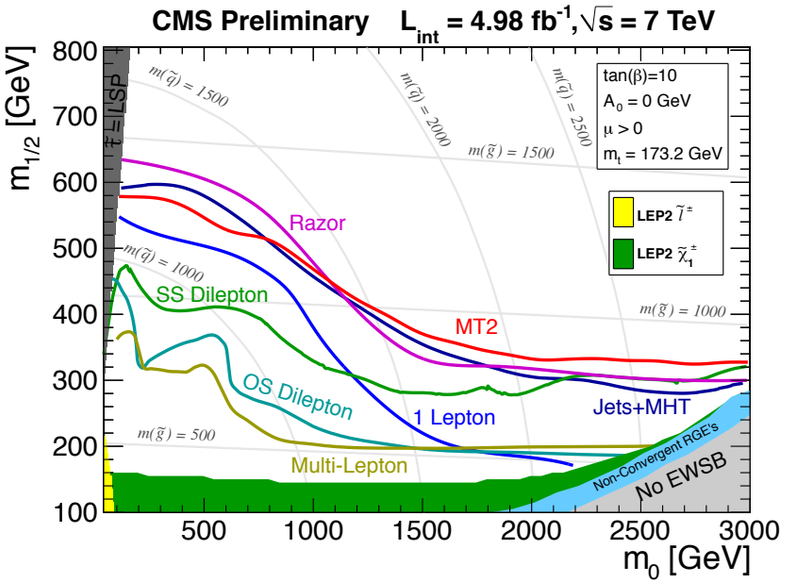




$$\tilde{m}_g > 1000\ GeV$$

The Progress of LHC

CMS CMSSM summary



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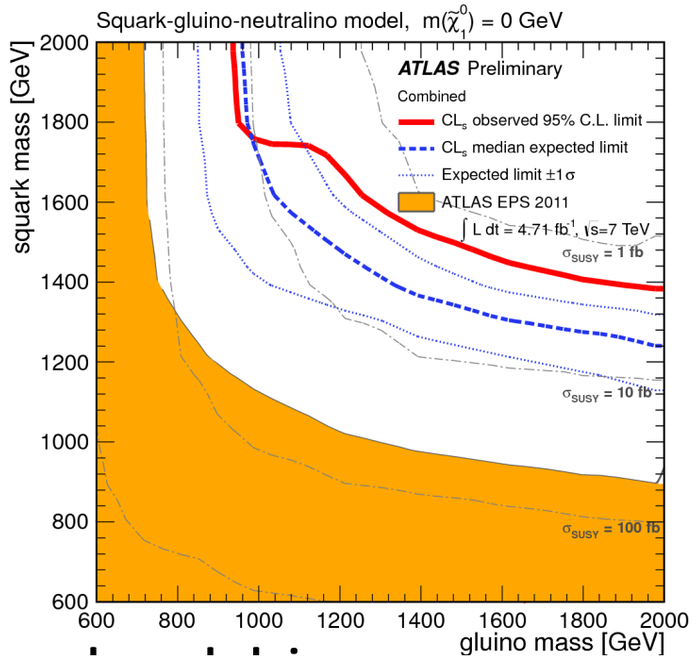
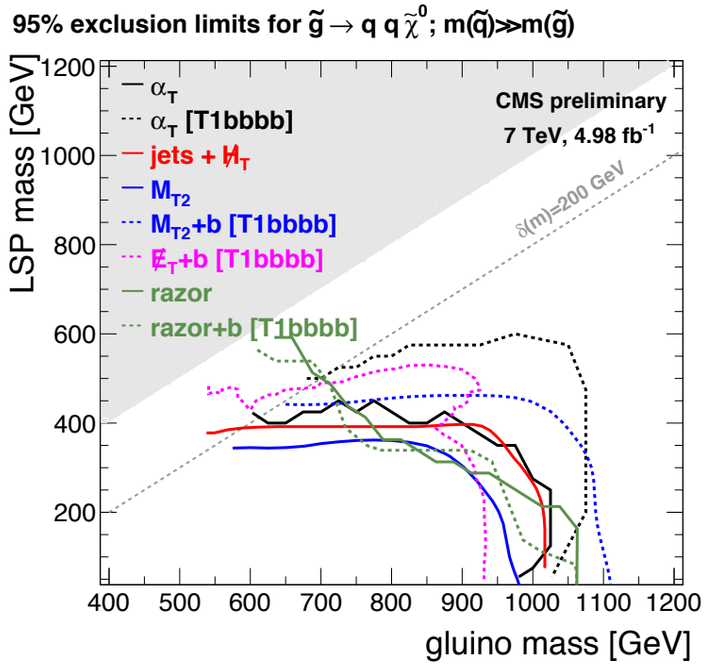
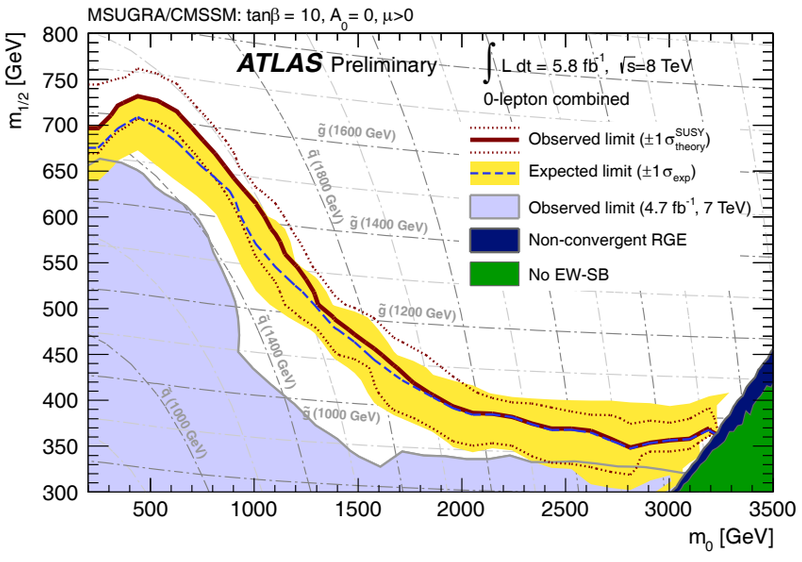
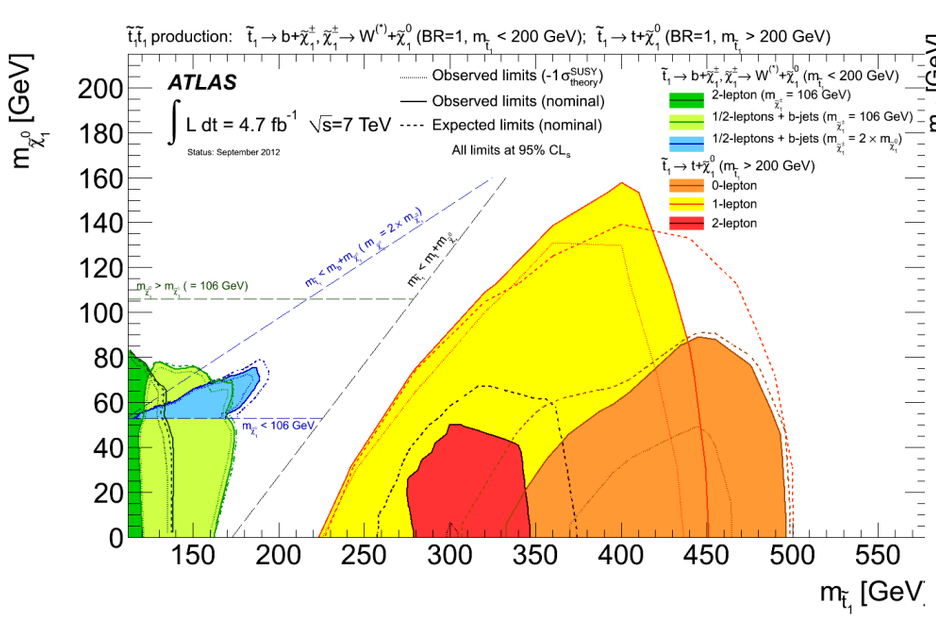
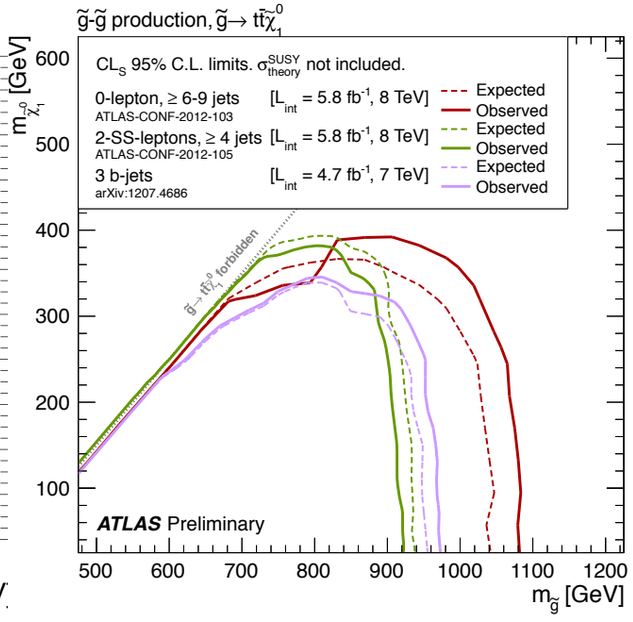








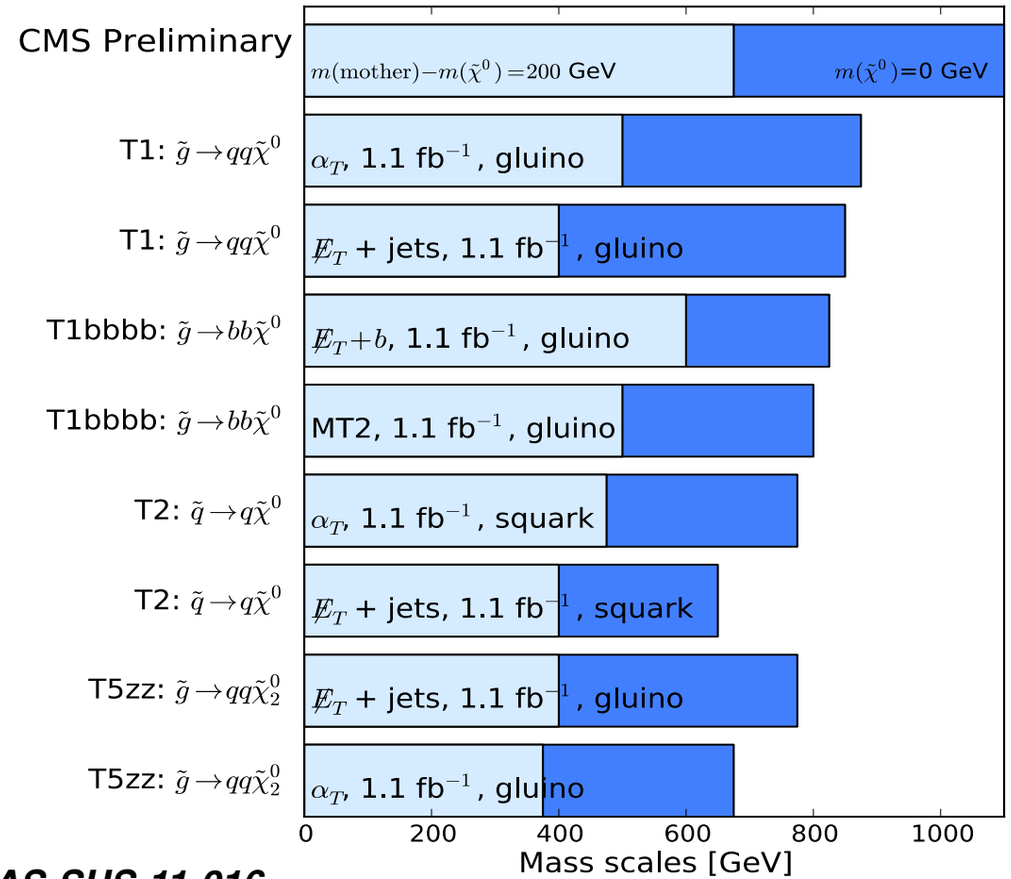


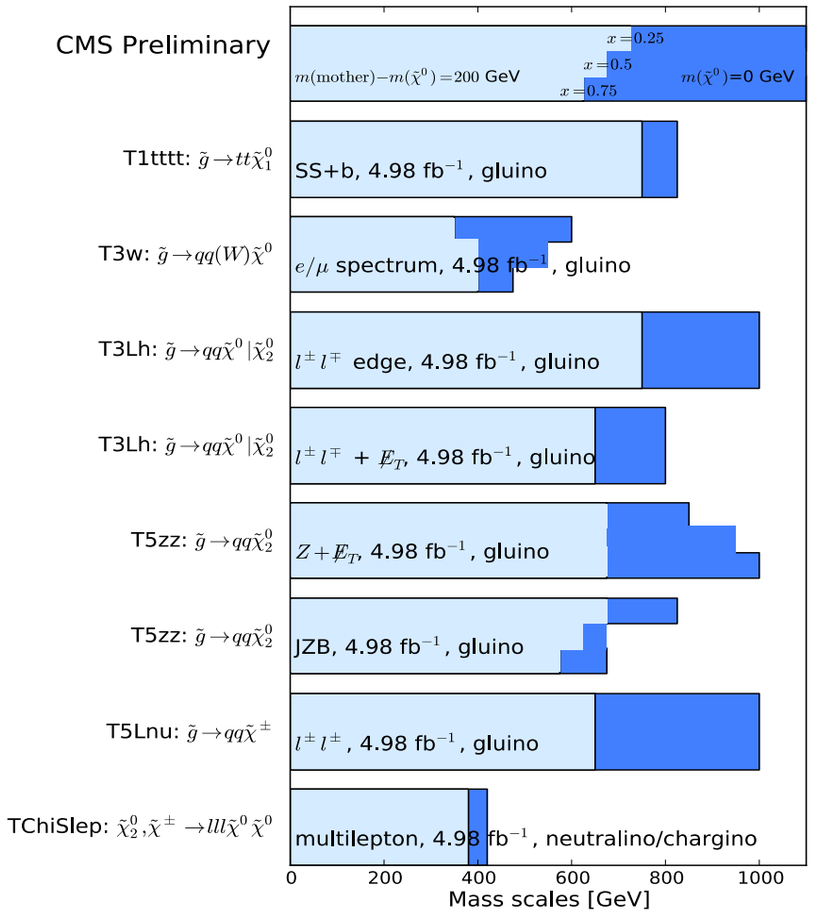
$\tilde{m}_g > 1000\ GeV$

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

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).



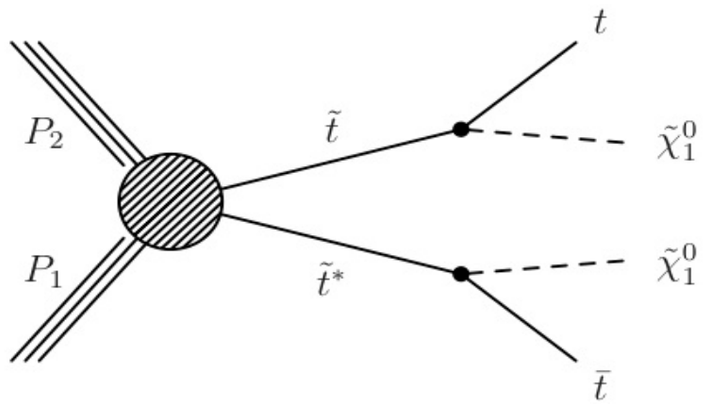


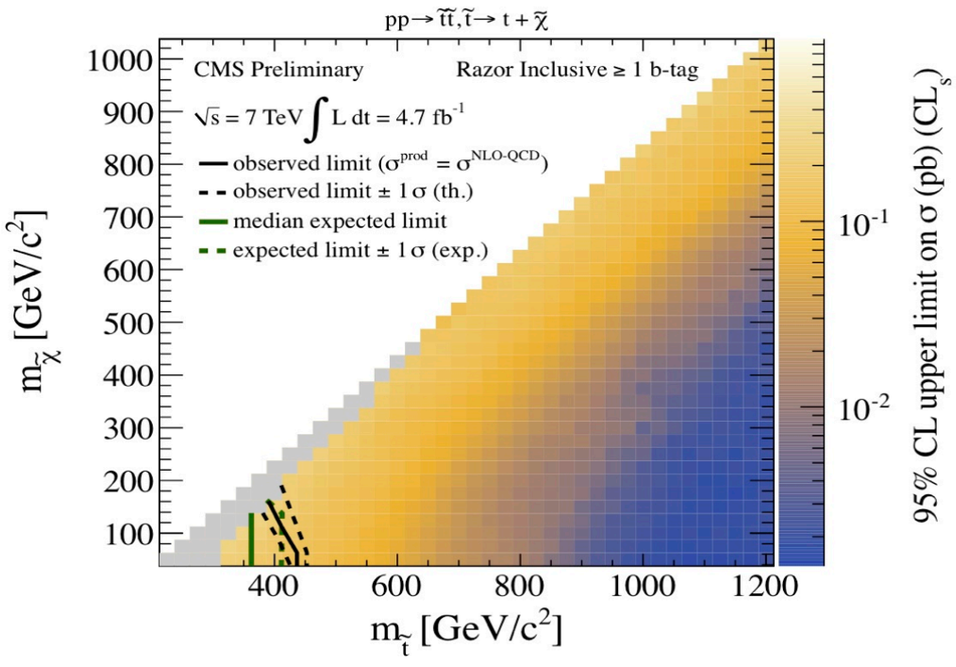
CMS-PAS-SUS-11-016

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.

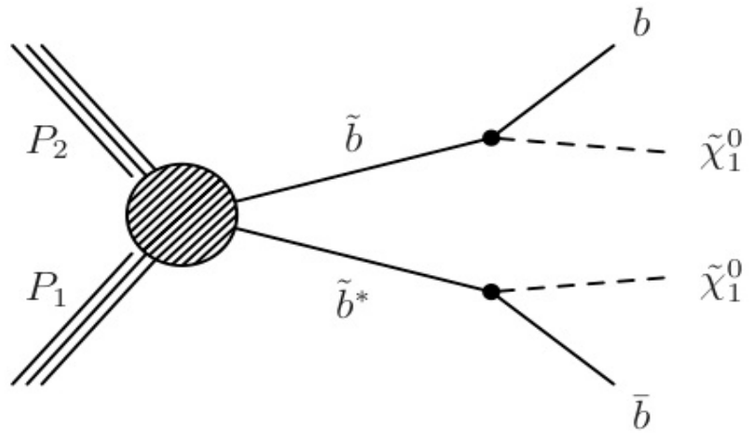
Stop and Sbottom Searches at LHC

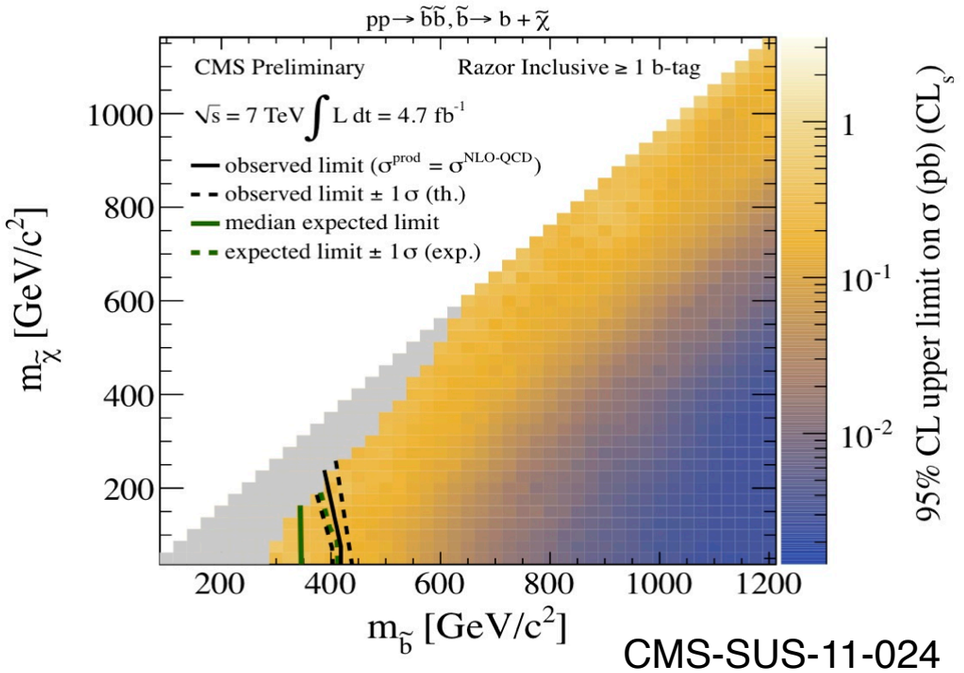
Di-stop production resulting in 2 top quarks +MET final states





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

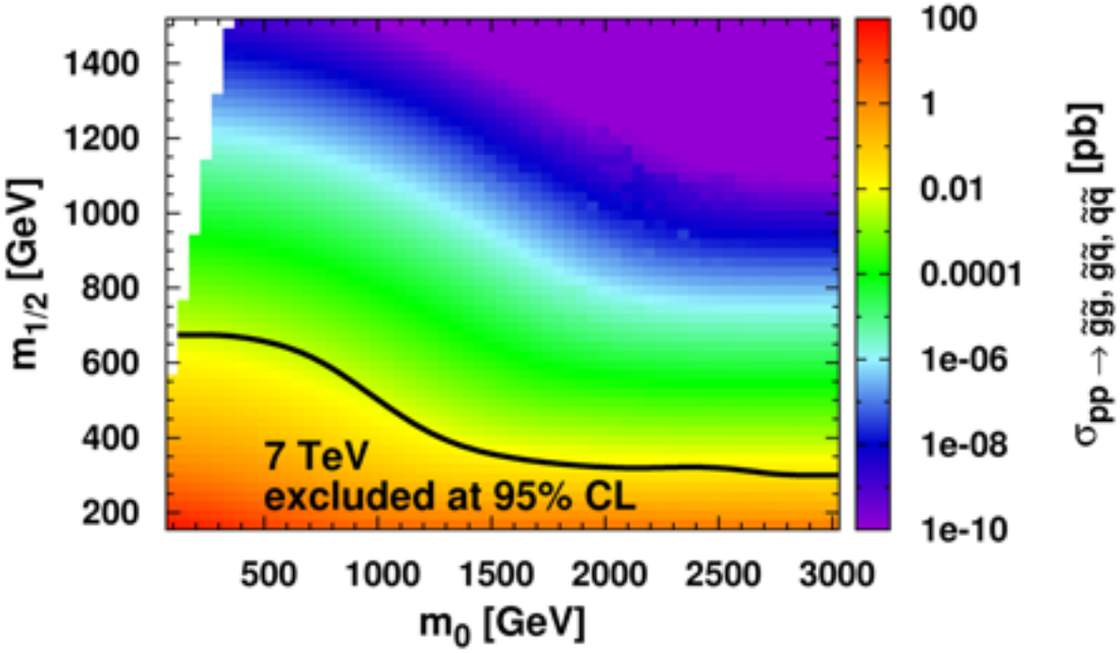




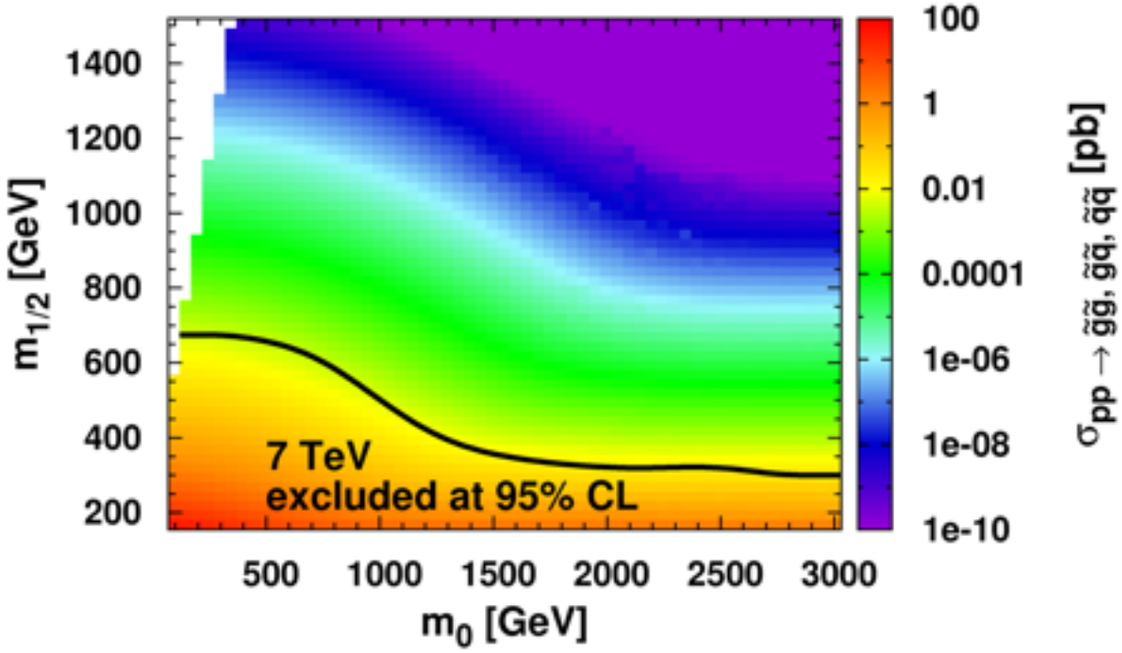
CMS-SUS-11-024

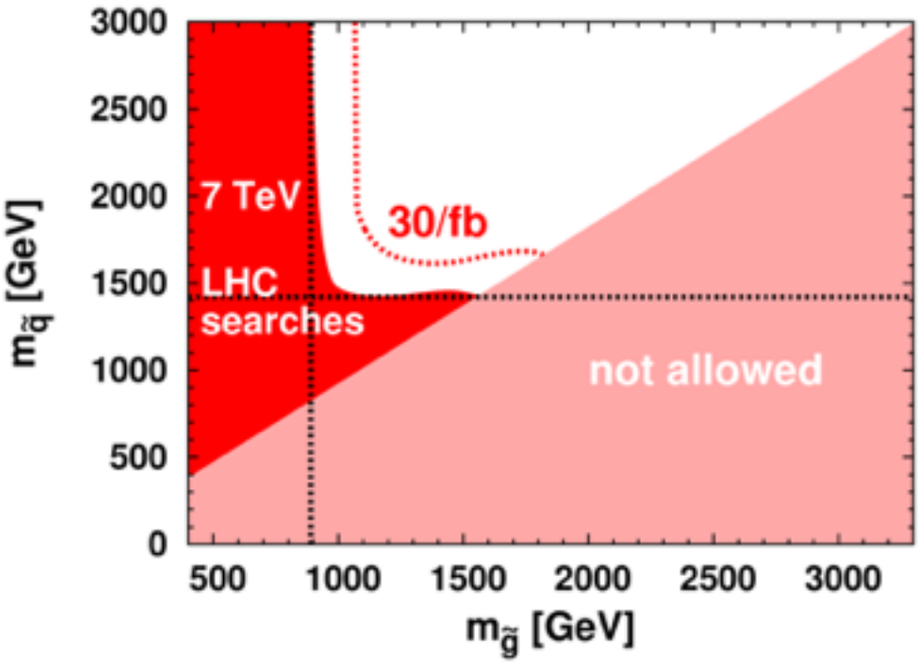
LHC Reach at 7 and 14 TeV

LHC Reach at 7 and 14 TeV

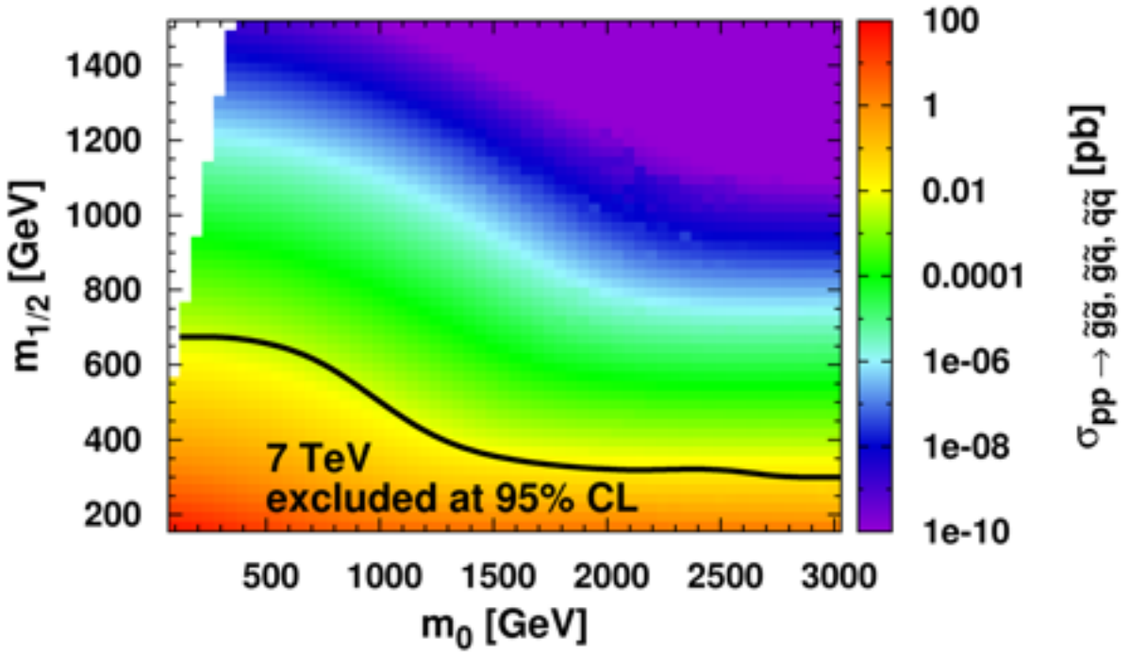


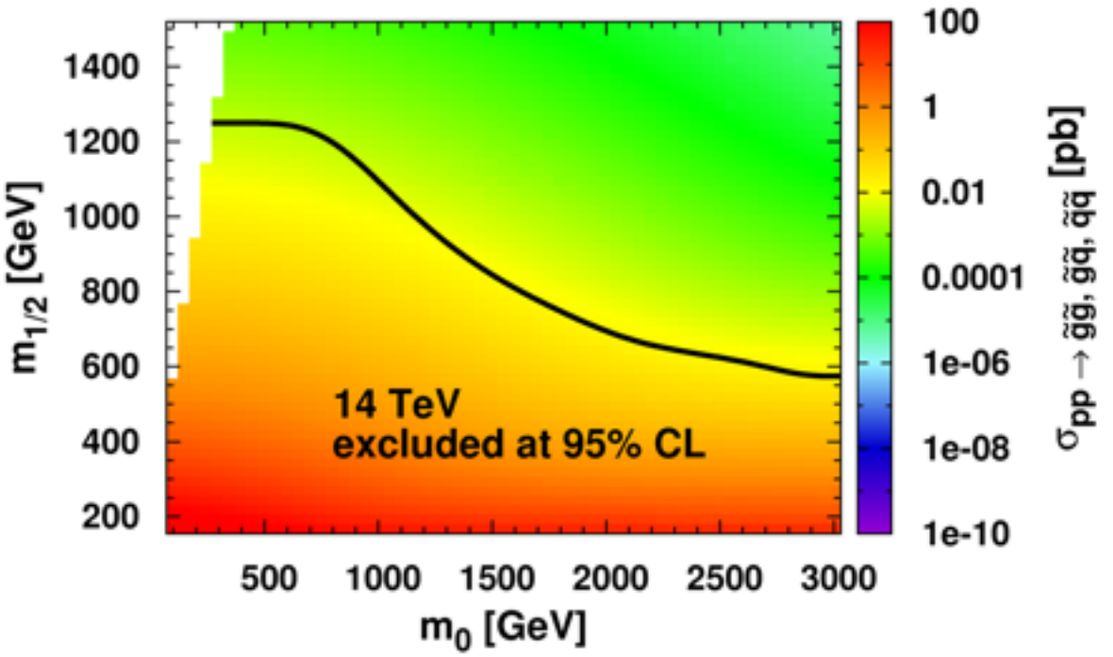
LHC Reach at 7 and 14 TeV

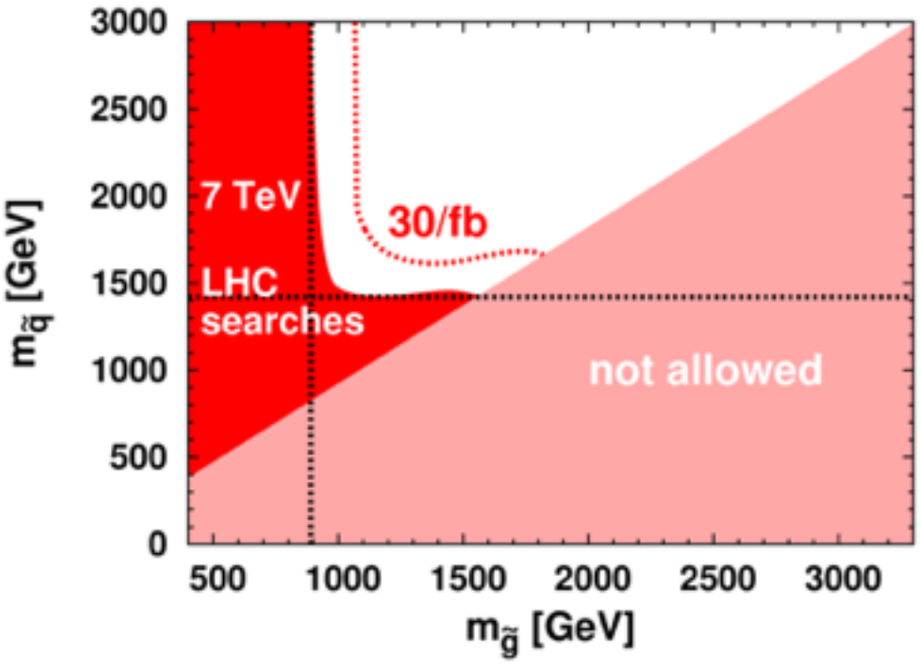




LHC Reach at 7 and 14 TeV







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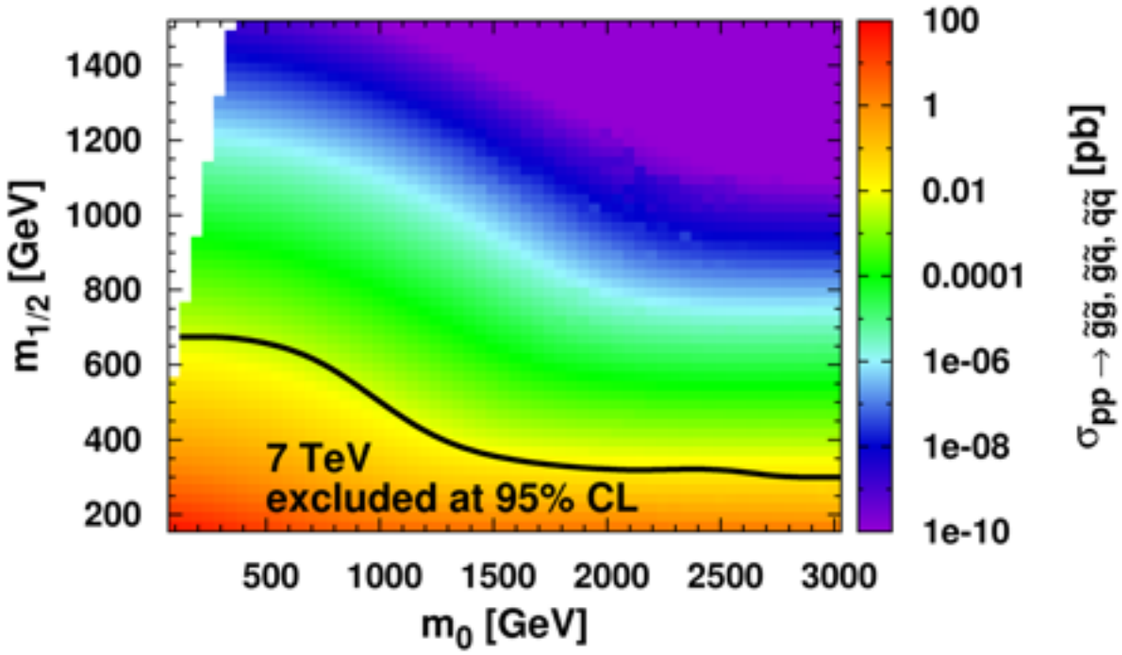

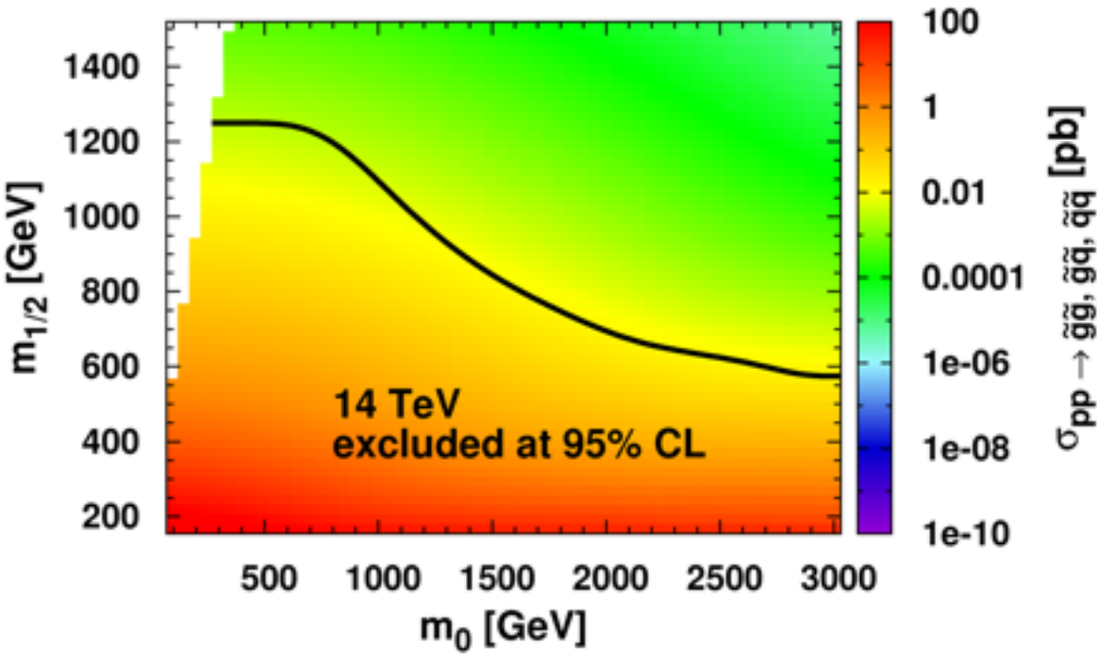

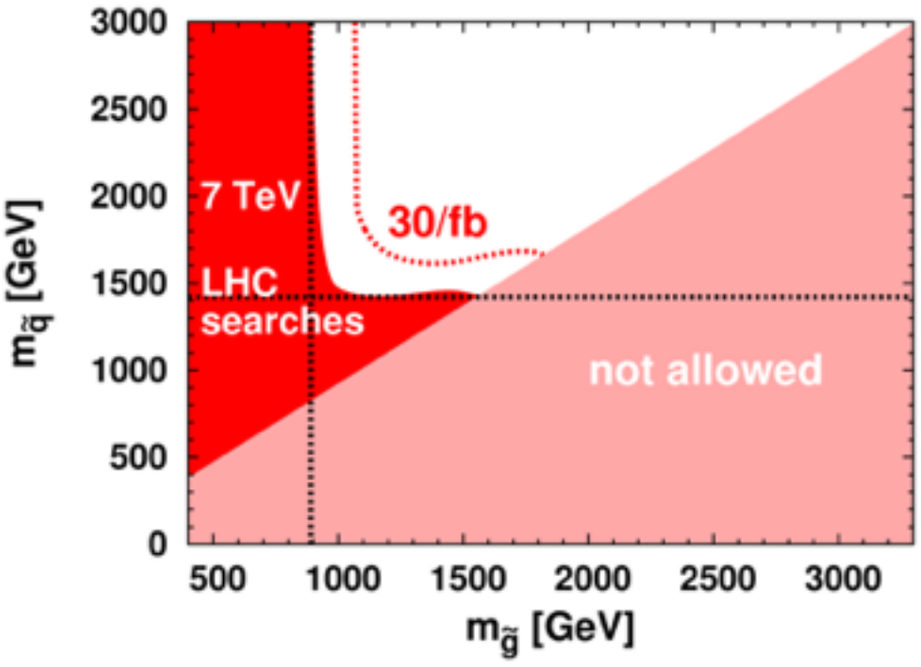

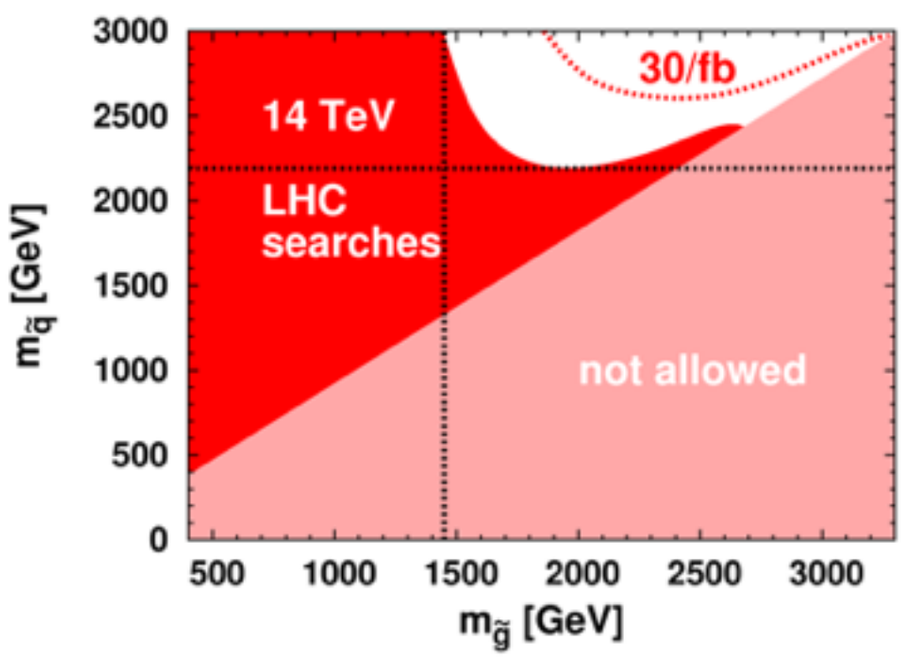

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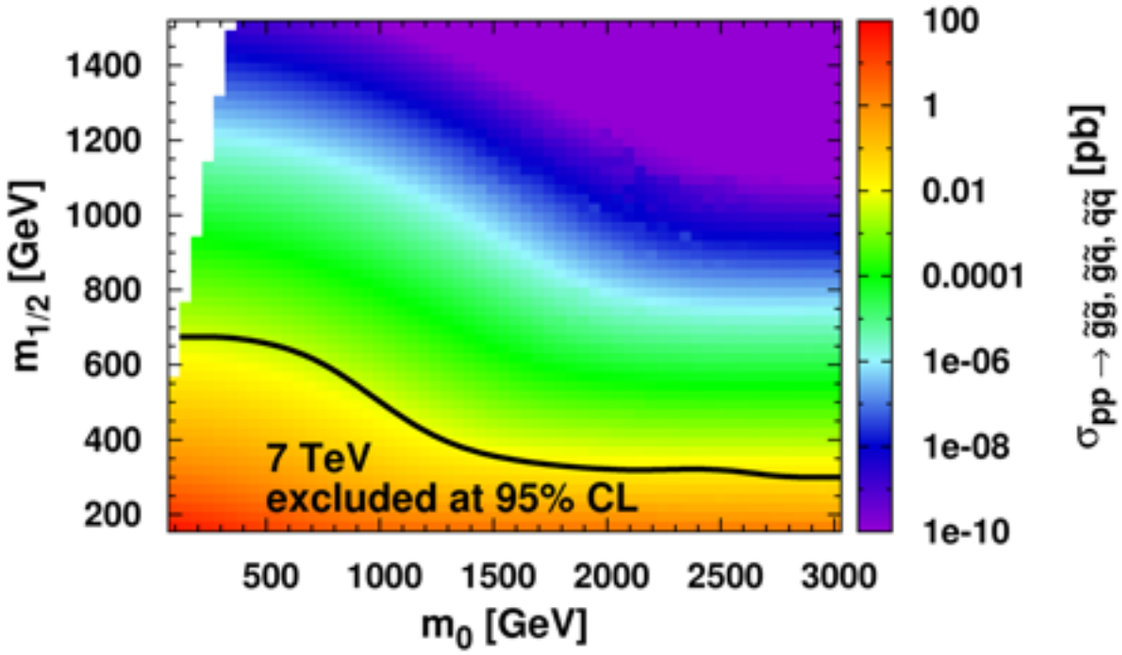
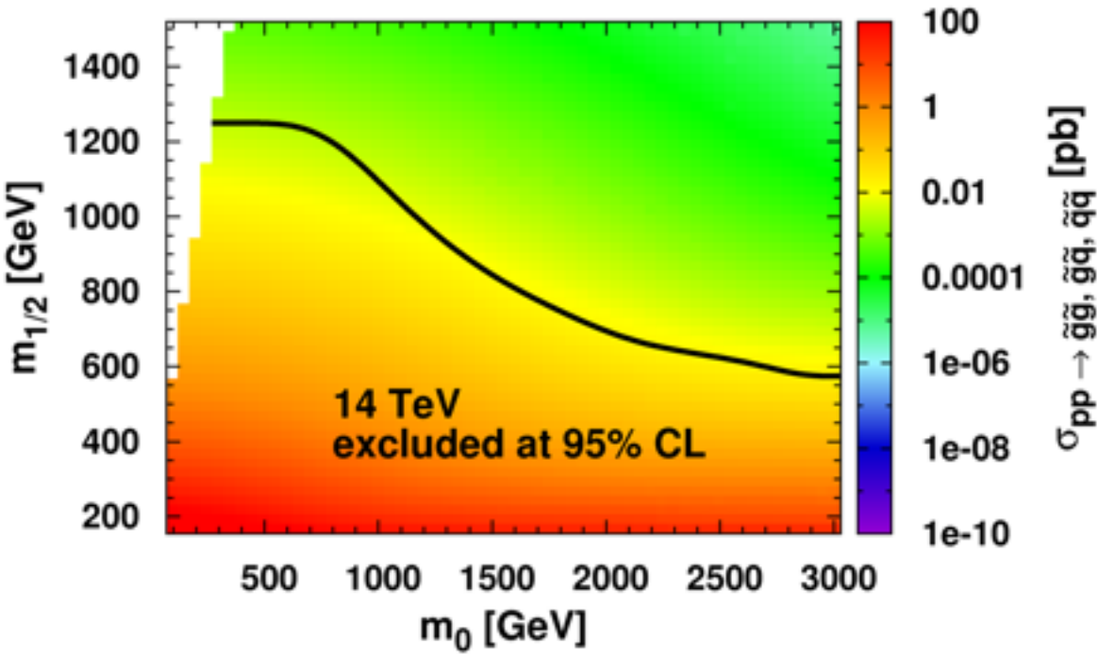
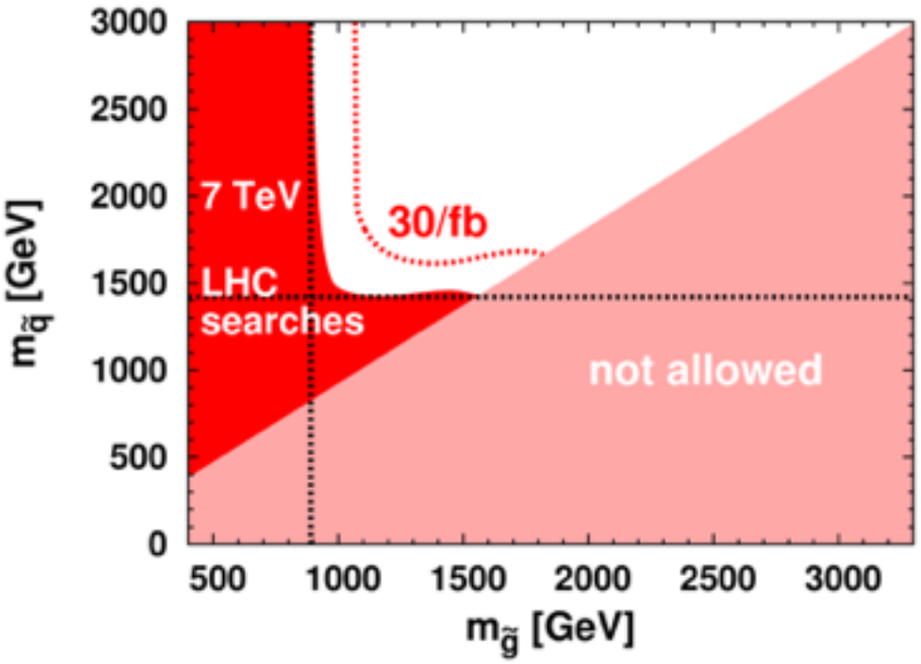
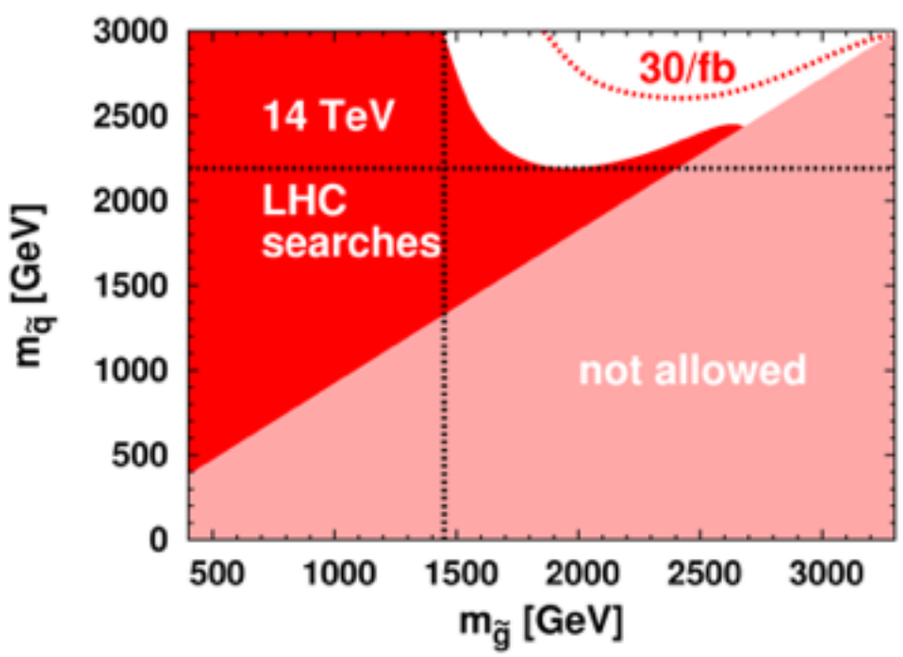








Energy is more important than luminosity

Indirect Search at LHC

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

$$B_s \to X_s \gamma$$

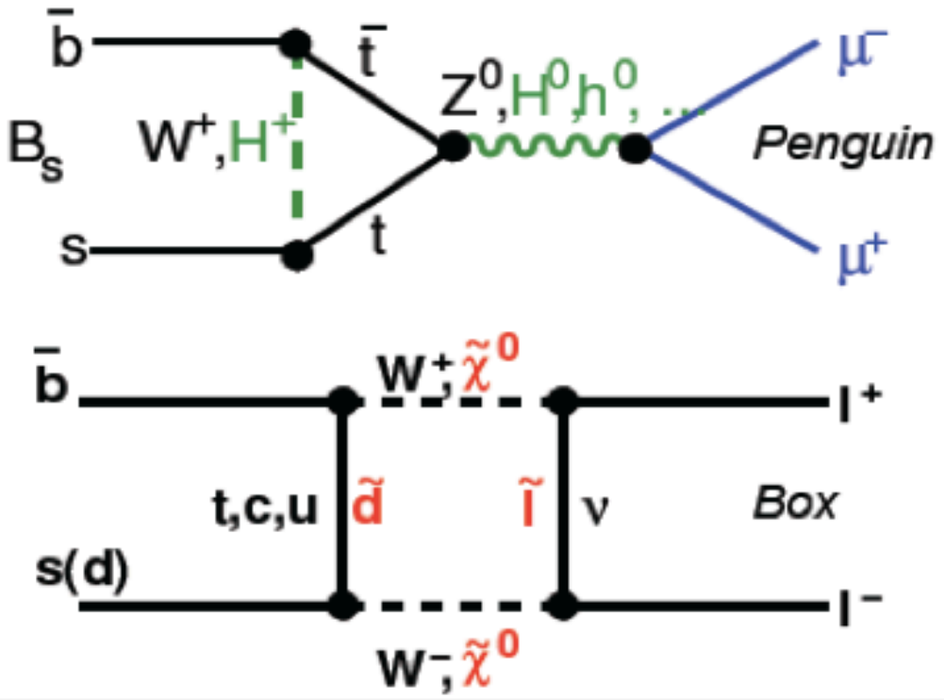
$$B_u \to \tau \nu$$

$$g - 2$$

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

- **Decays highly suppressed in SM**
  - Forbidden at tree level
  - $b \to s(d)$ FCNC transition only through penguin and box diagrams
  - Helicity suppressed by factors of $(m_\mu / m_B)^2$
- **Standard Model Predictions**
  - $Bs \to \mu\mu = (3.2 \pm 0.2)\ 10^{-9}$
  - $Bd \to \mu\mu = (1.0 \pm 0.1)\ 10^{-10}$
- **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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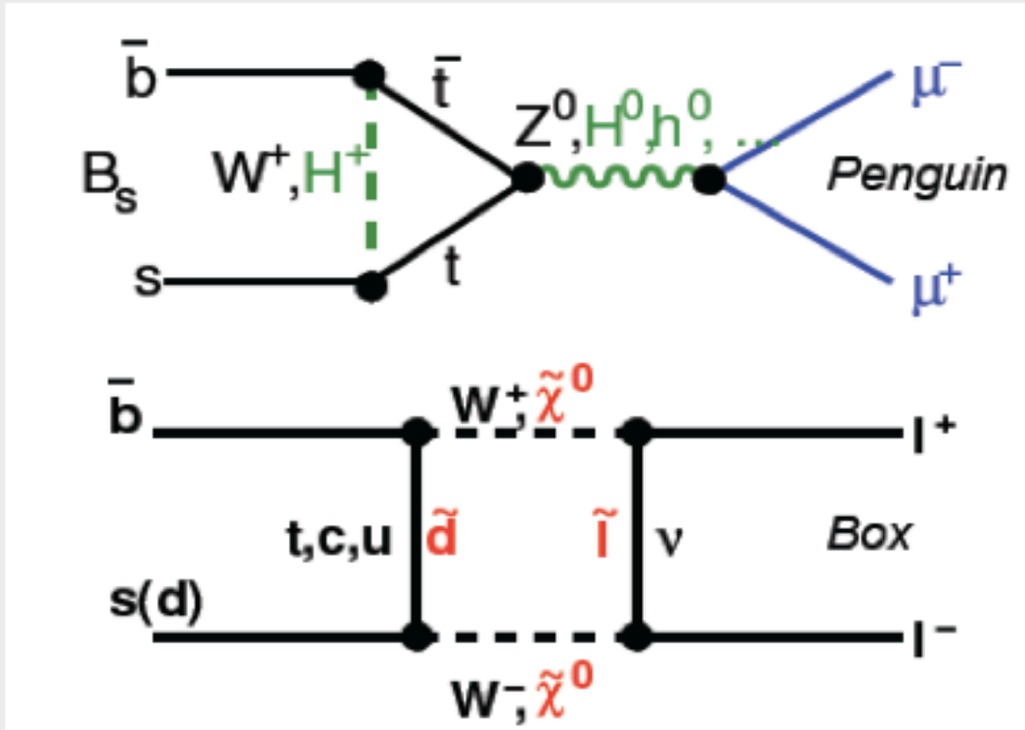

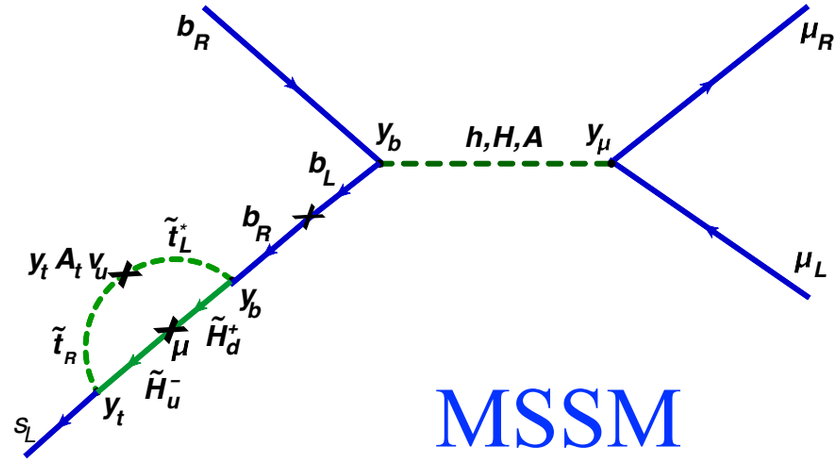

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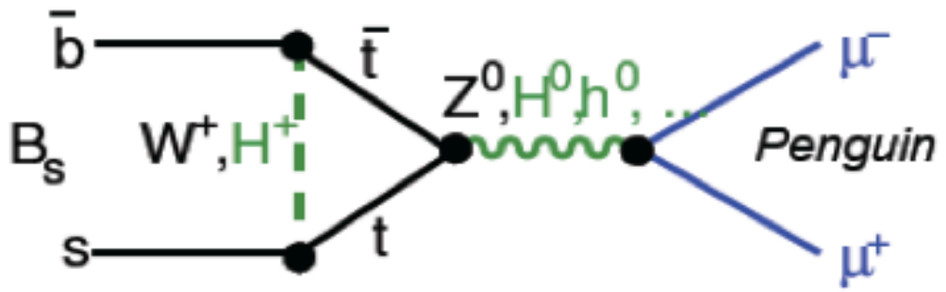


$$Br[B_s \to \mu\mu] = \frac{2\tau_B m_B^5}{64\pi} f_{B_s}^2 \sqrt{1-\frac{4m_l^2}{m_B^2}} \left[\left(1-\frac{4m_l^2}{m_B^2}\right)\left|\frac{(C_S-C_S')}{(m_b+m_s)}\right|^2 + \left|\frac{(C_P-C_P')}{(m_b+m_s)} + 2\frac{m_\mu}{m_{B_s}^2}(C_A-C_A')\right|^2\right]$$

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

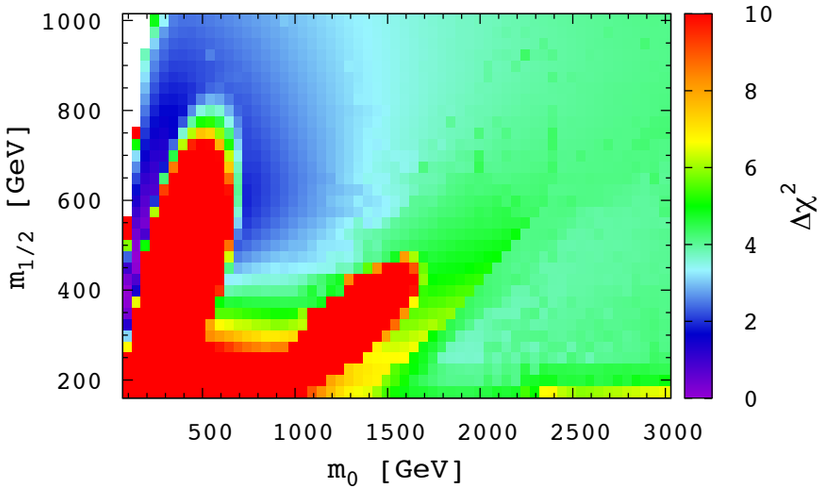
Enhancement

Suppression

Electroweak, g-2, and Dark Matter constraints

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

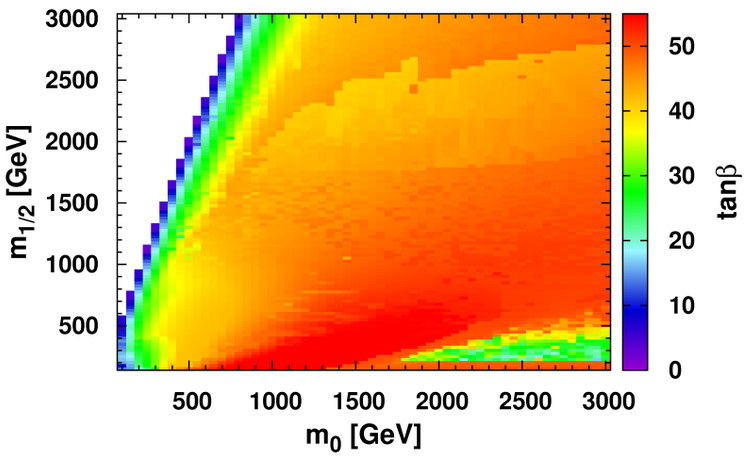
95% CL exclusion



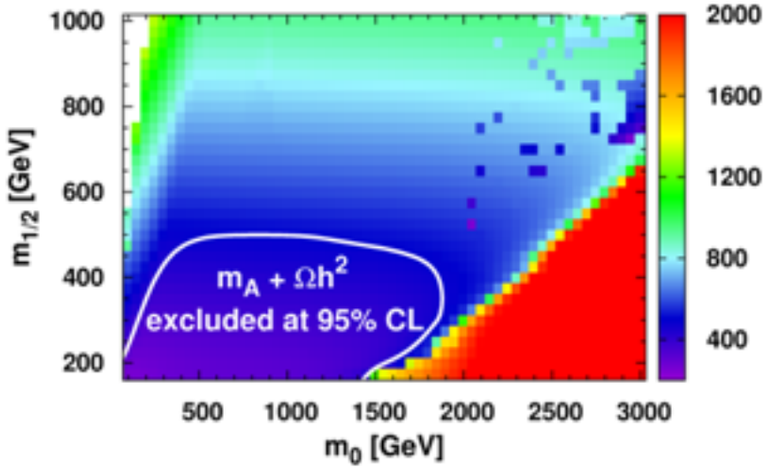
$B_s \to s\gamma,\ B_s \to \mu^+\mu^-,\ B_s \to \tau\nu$

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	$\sigma_{\chi N} < 8 \cdot 10^{-45} - 2 \cdot 10^{-44} cm^2$

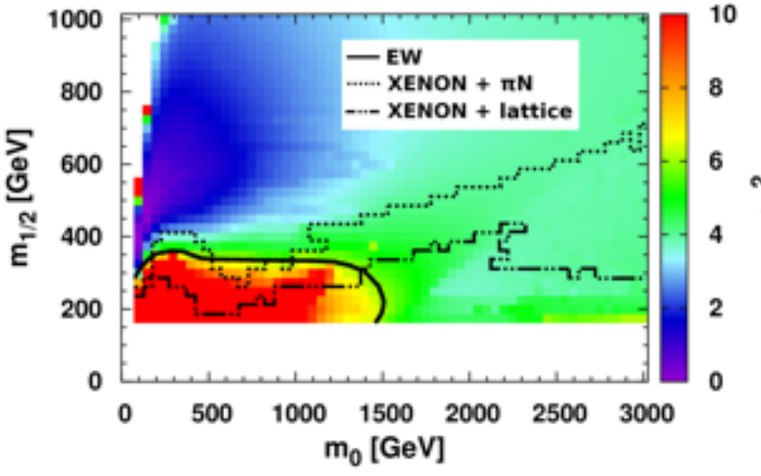
muon $g-2$



$\tan\beta$ fit of DM abundance



Dark matter abundance



Direct DM search

Electroweak, g-2, and Dark Matter constraints

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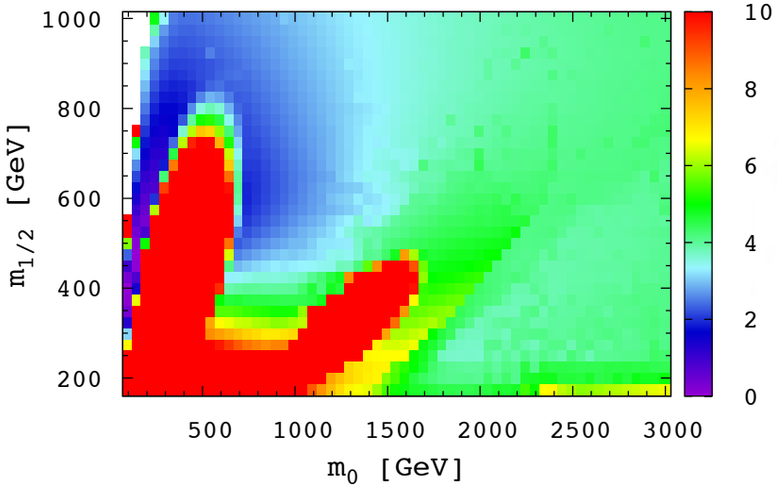
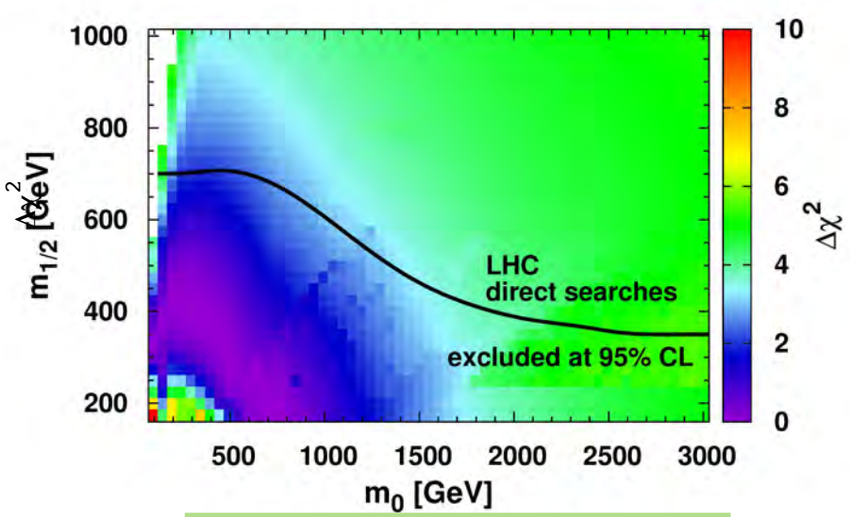
95% CL exclusion



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



muon $g-2$

Constraint	Data
Ωh^2	0.113 ± 0.004
$b \to X_s\gamma$	$(3.55 \pm 0.24) \cdot 10^{-4}$
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Δa_μ	$(302 \pm 63(exp) \pm 61(theo)) \cdot 10^{-11}$
$B_s^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^- < 4.5 \cdot 10^{-9}$
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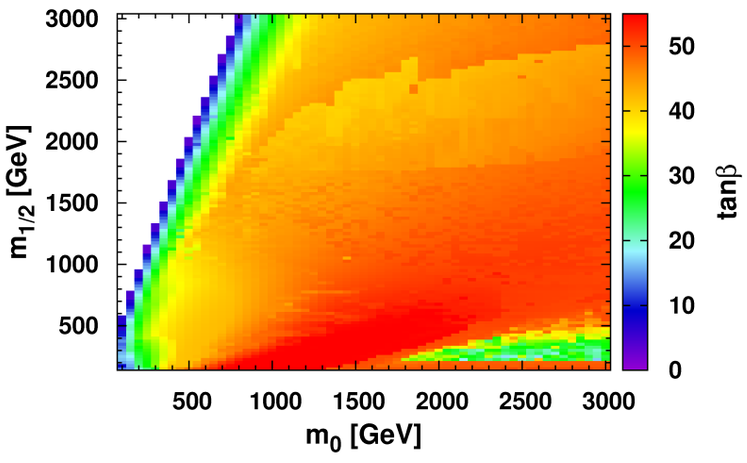

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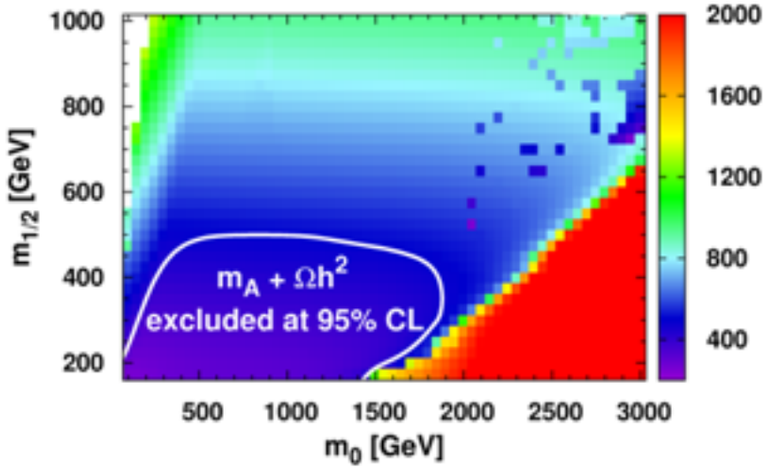
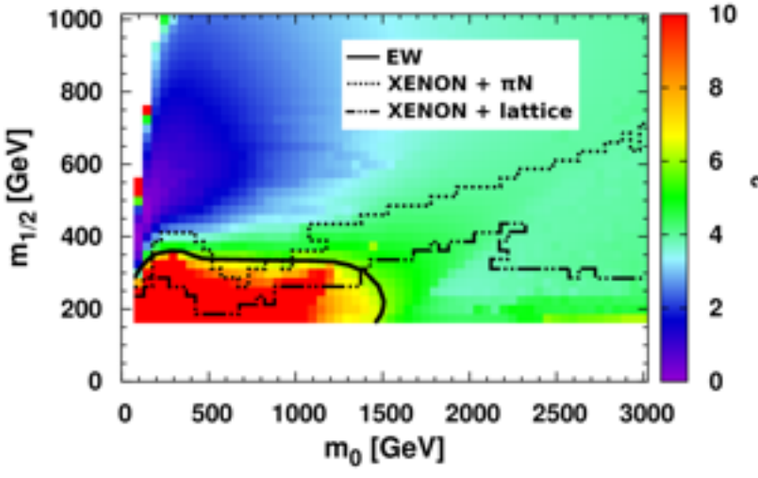


Dark matter abundance



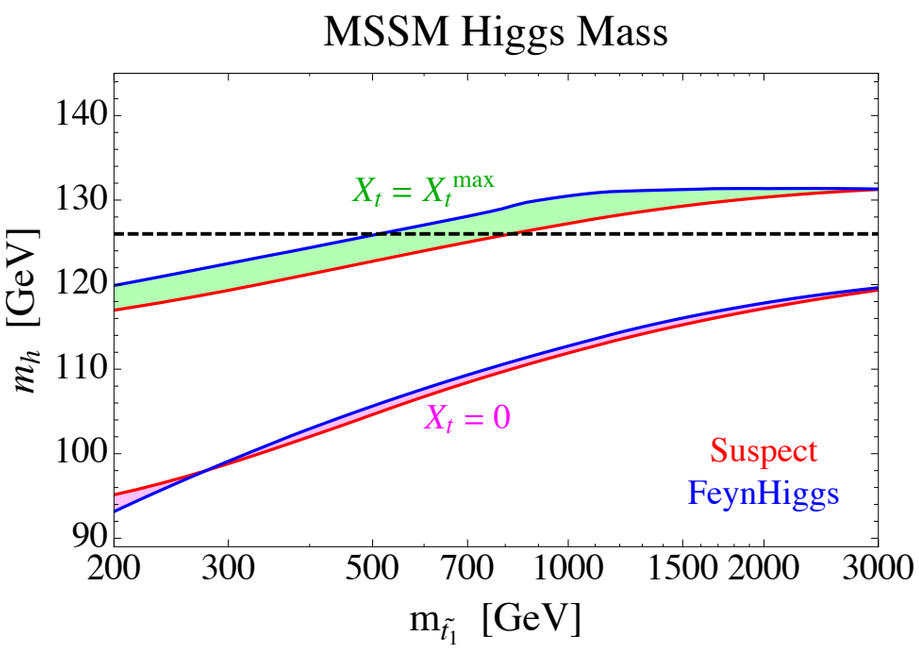
Direct DM search

Higgs v SUSY

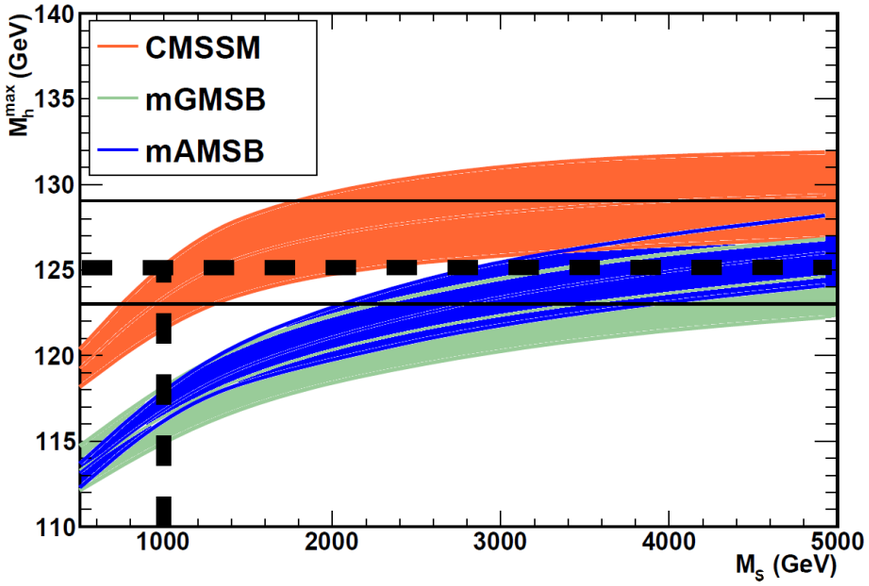
$$m^2_{Higgs} = M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2 \sin^2 \beta}\left[\log\frac{M_s^4}{m_t^4} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{6M_S^2}\right)\right] + 2-loop$$

$$M_S^2 = \tilde{m}_{t_1}\tilde{m}_{t_2} \qquad X_t = A_t - \mu\cot\beta$$

from JHEP 1204 (2012) 131



from arXiv:1207.1348



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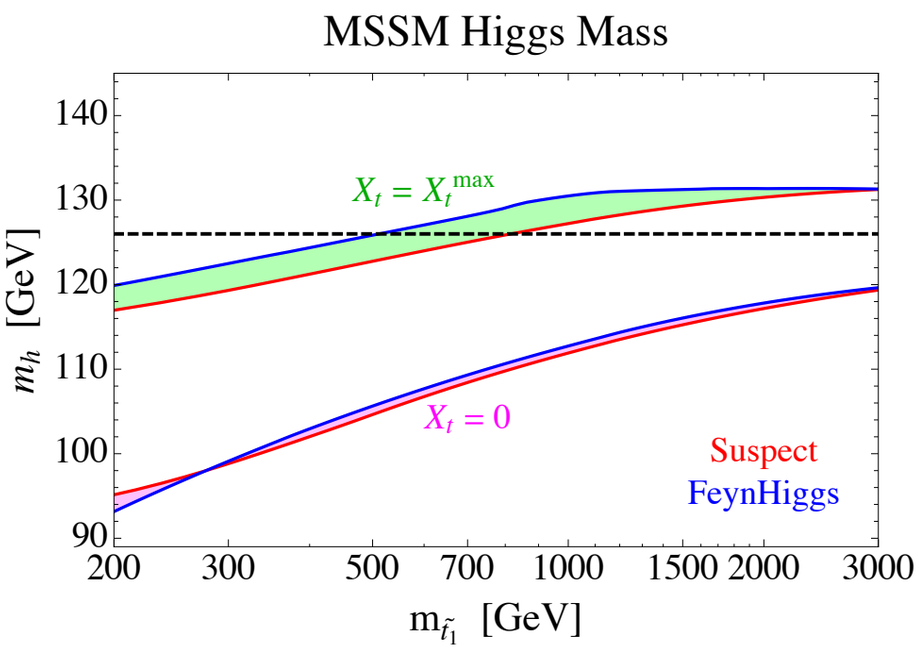
from JHEP 1204 (2012) 131



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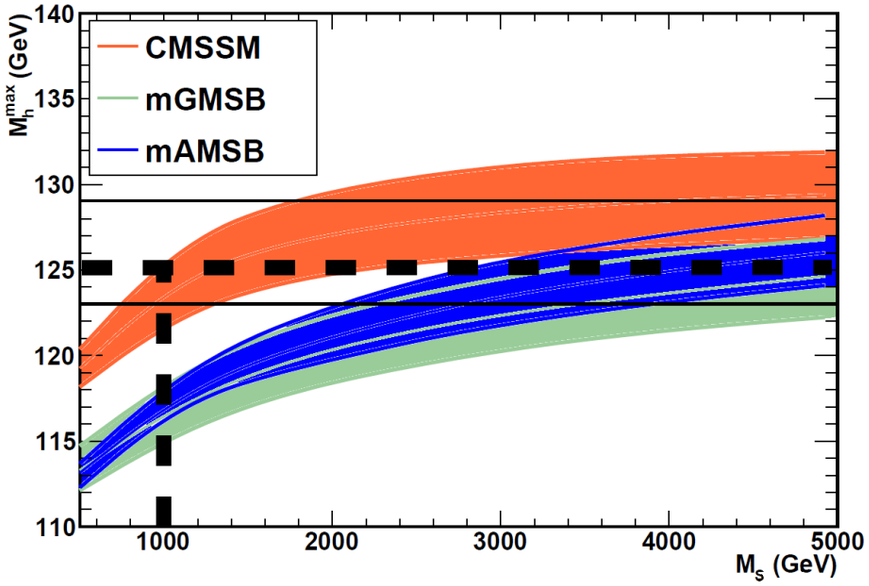
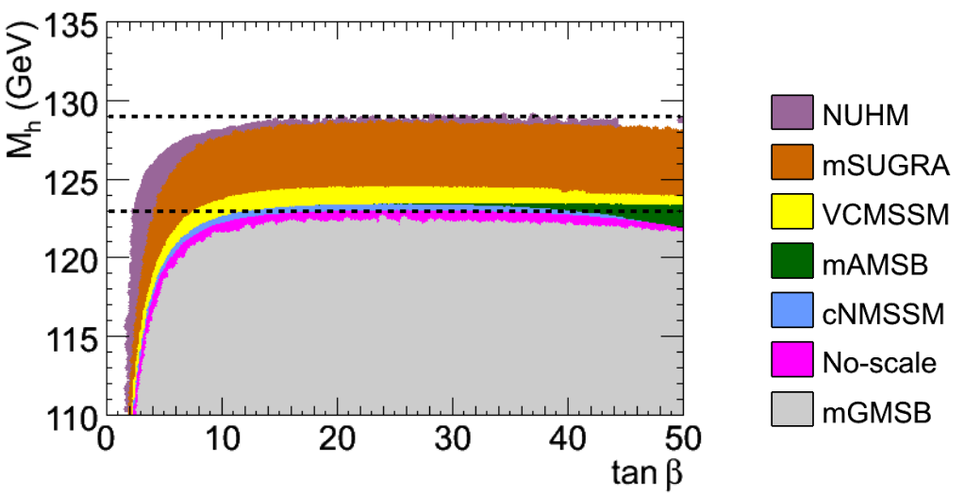


A. Arbey et al'12



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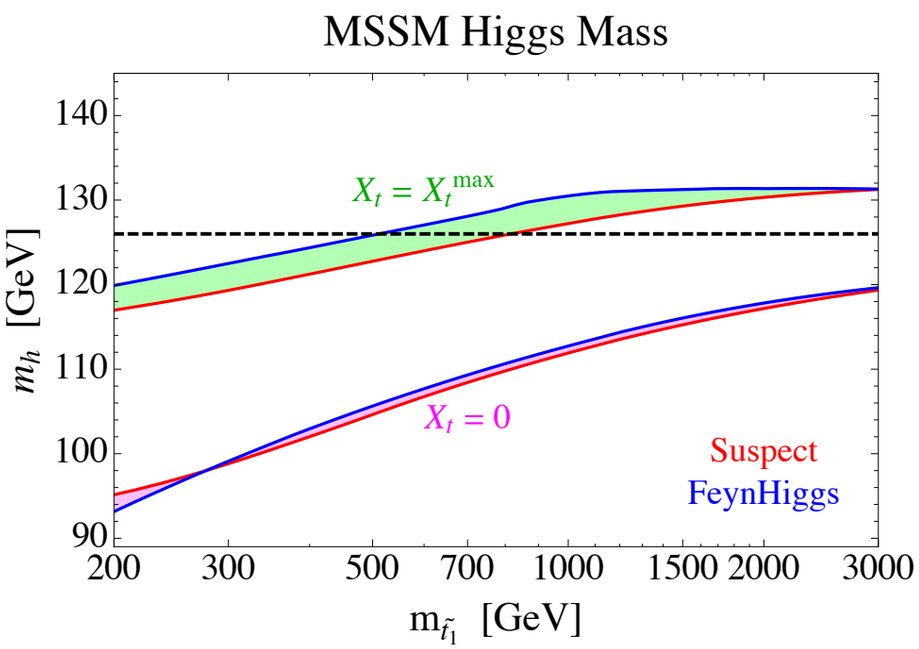

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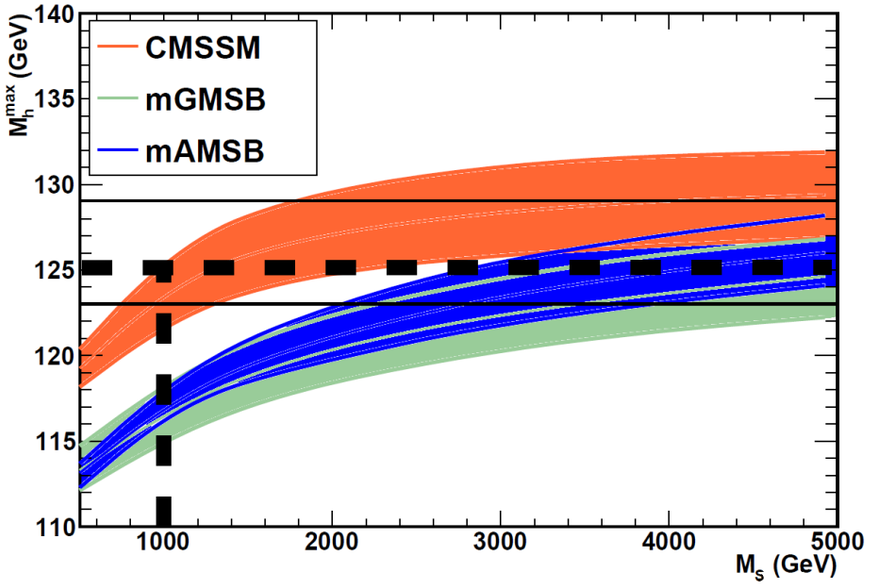

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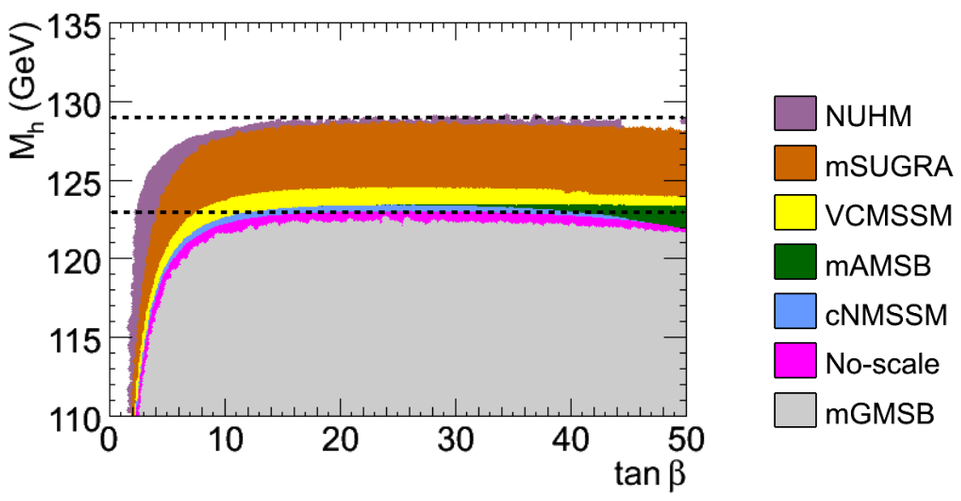
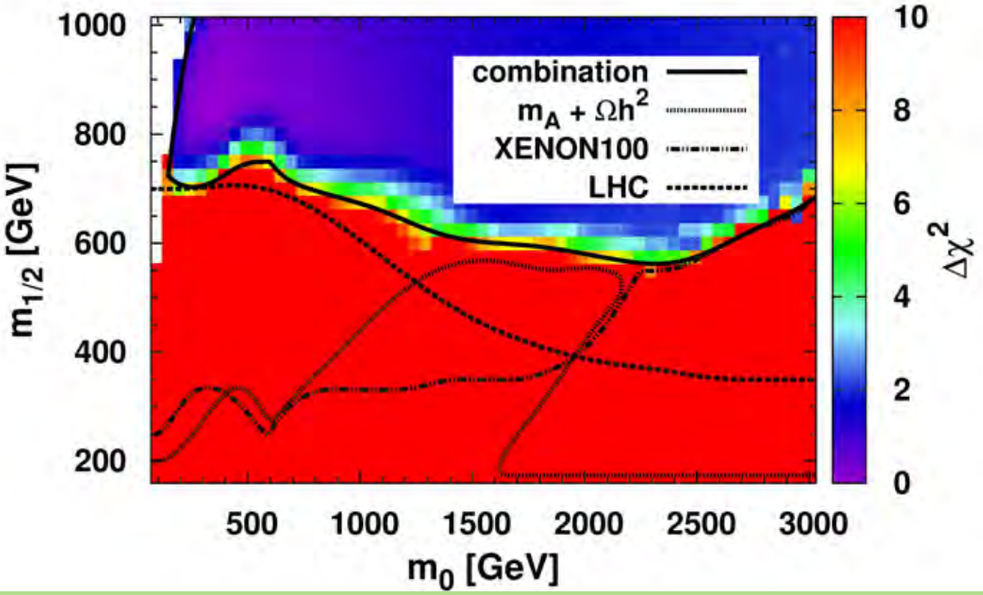


Resume

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

Combined Fit to all Data



without 125 GeV Scalar

Constraint	Data
Ωh^2	0.113 ± 0.004
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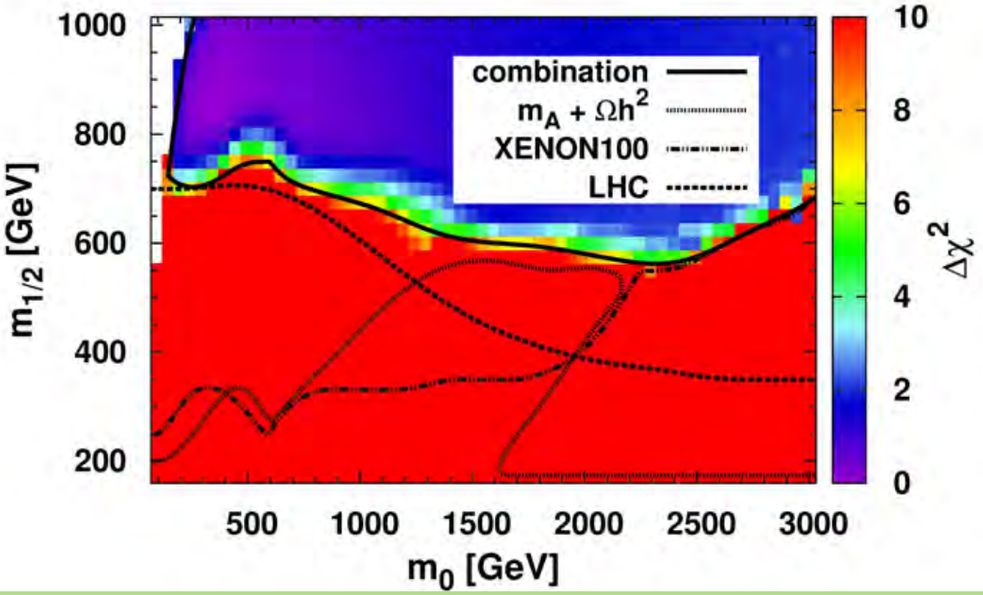
The values of $\tan\beta$ and A_0 are adjusted

Combined Fit to all Data

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

MSSM



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

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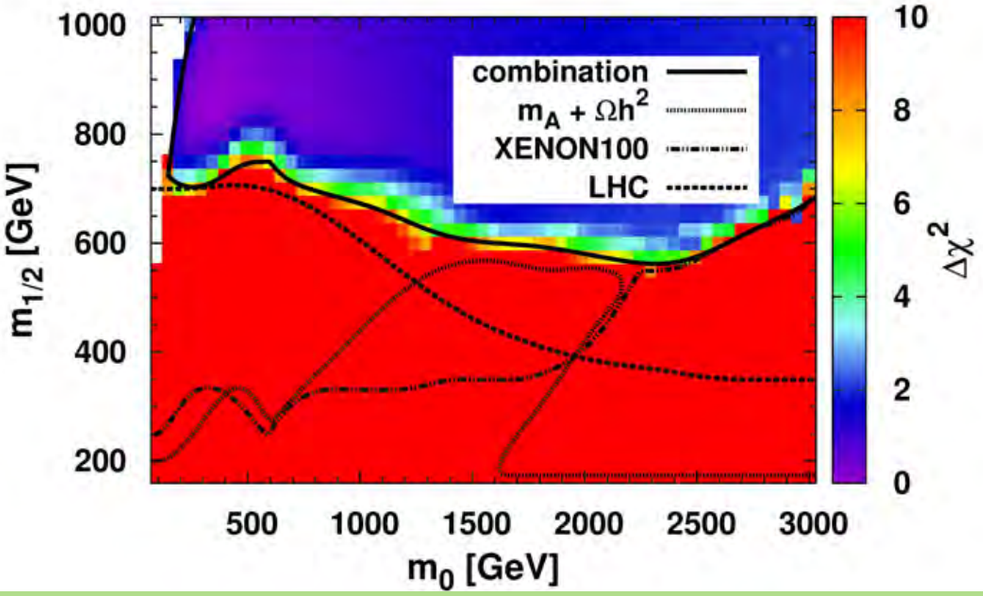

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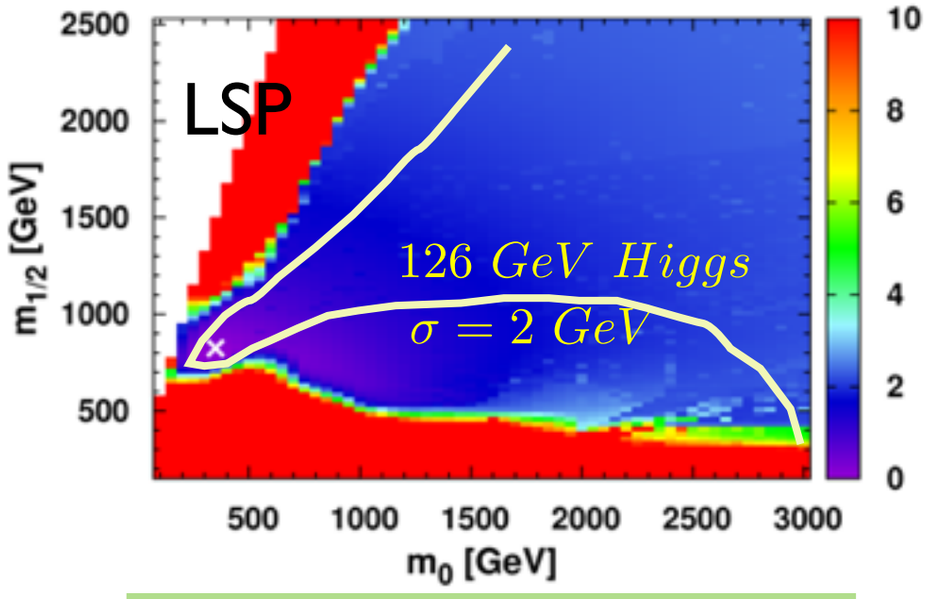


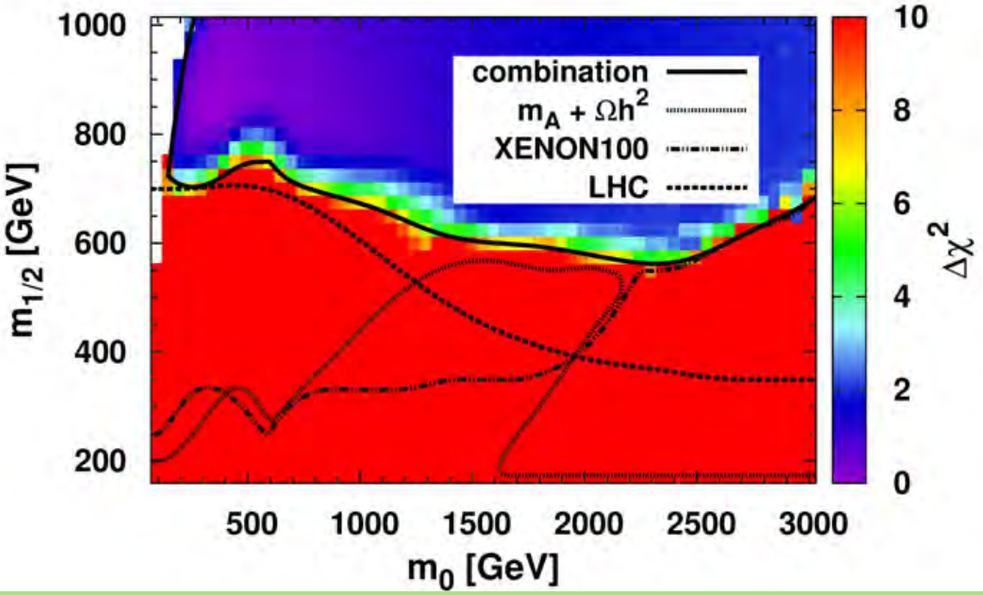
with 125 GeV Scalar

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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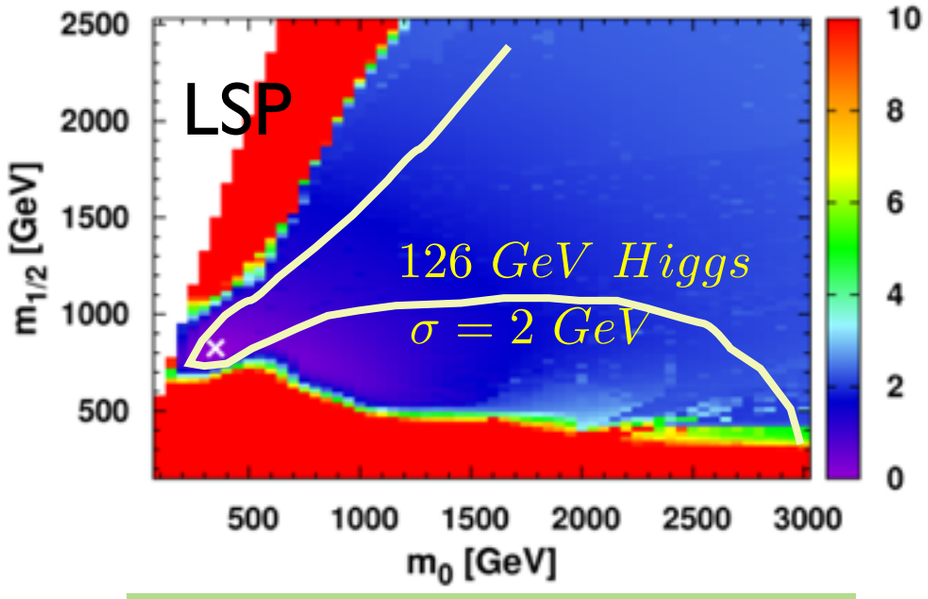


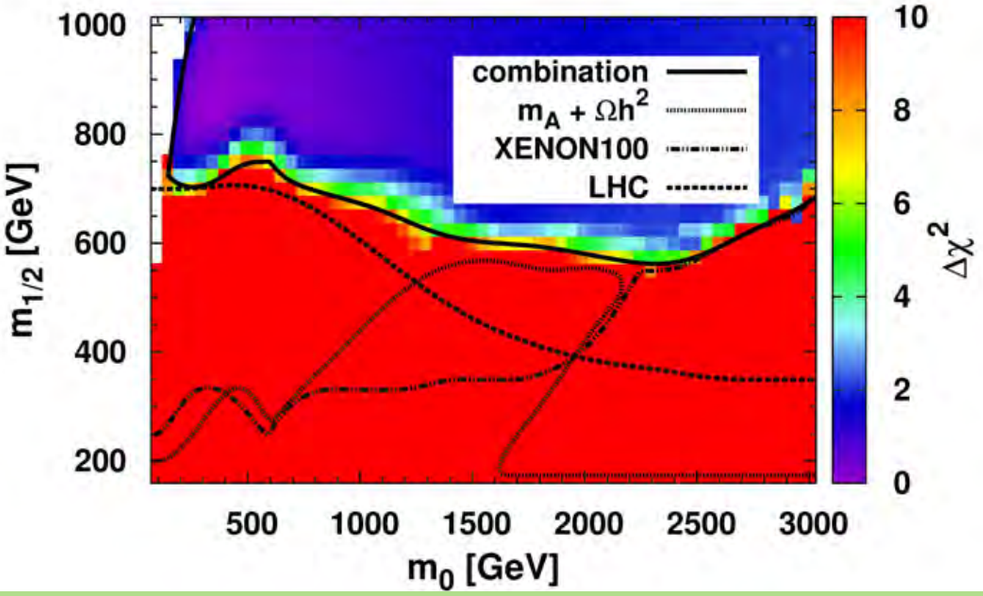
with 125 GeV Scalar

Larger scale for $m_{1/2}$

Combined Fit to all Data

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

MSSM



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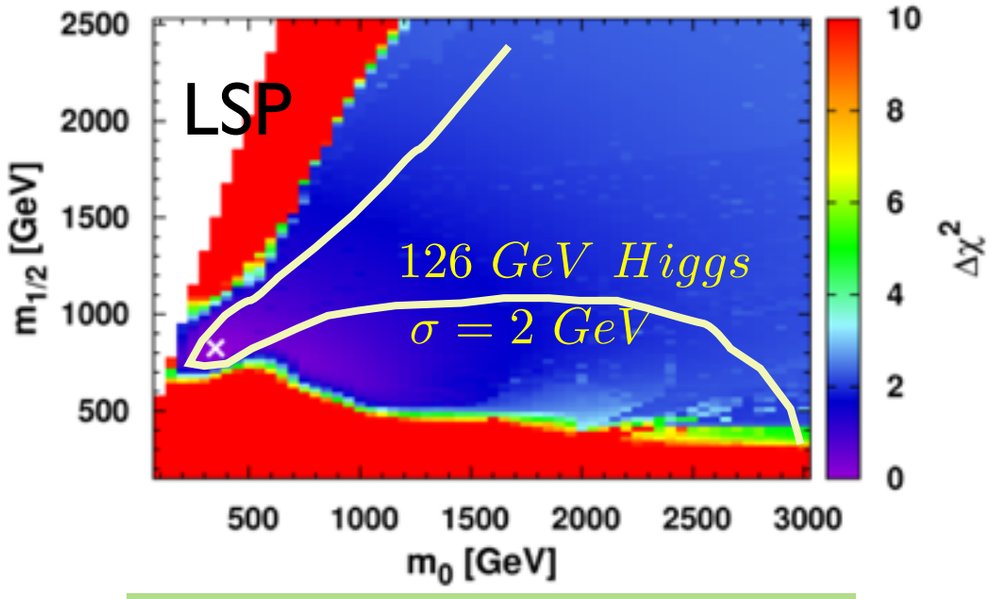


with 125 GeV Scalar

In MSSM 126 GeV Higgs mass constraint excludes $m_{1/2}$ below 1000 GeV thus leading to stops above 2.5 TeV

Larger scale for $m_{1/2}$

Alternatives to the SM Higgs

1. Two Higgs doublet model -> MSSM
2. + One singlet -> NMSSM

MSSM

$$H_d = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_u = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

Physical states

$CP\ even$	$neutral$	h, H
$CP\ odd$	$neutral$	A
$CP\ even$	$charged$	$H^\pm$

Mass hierarchy

$$h - light,\ \ H, A, H^\pm - heavy$$
$$m_H \approx m_A, m_{H^\pm} \geq m_A$$

NMSSM

extra S^0

Physical states

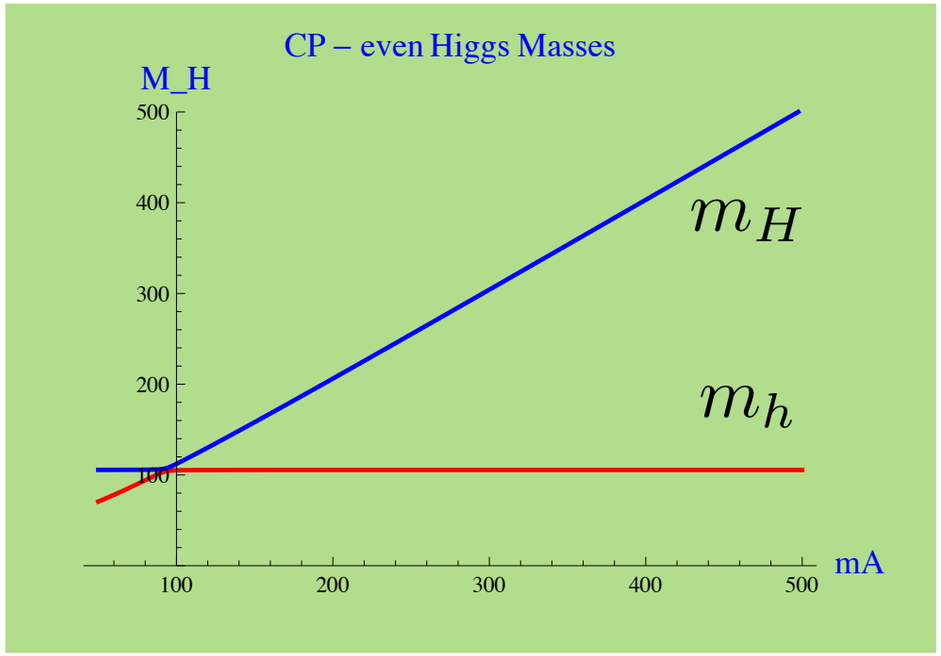
$CP\ even$	$neutral$	H_1, H_2, H_3
$CP\ odd$	$neutral$	A_1, A_2
$CP\ even$	$charged$	$H^\pm$

Mass hierarchy

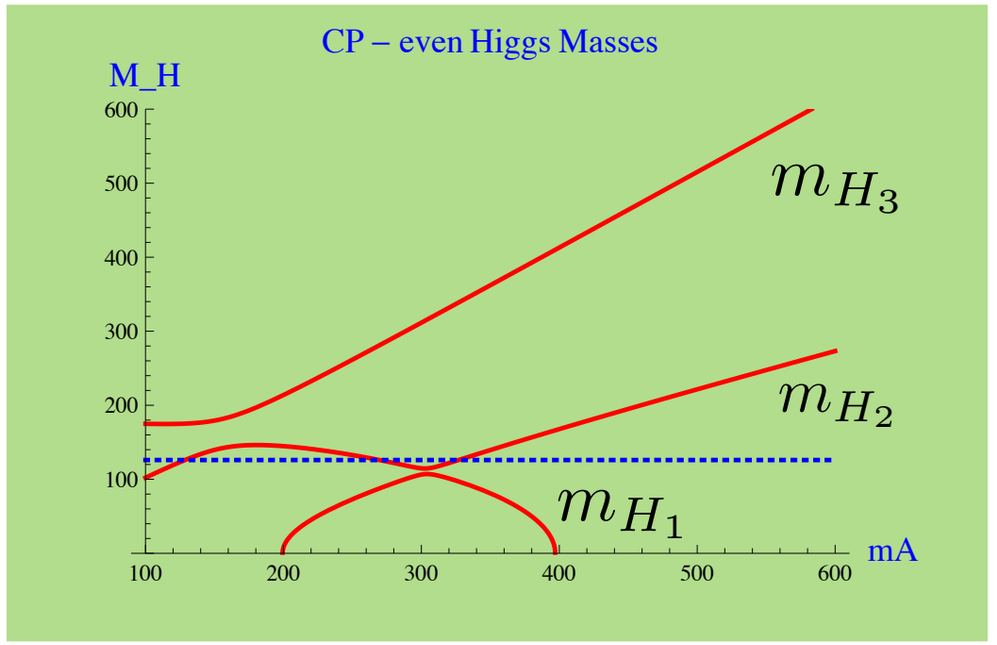
$$H_1, H_2, A_1 - light,\ \ H_3, A_2, H^\pm - heavy$$
$$m_{H_3} \approx m_{A_2}, m_{H^\pm} \geq m_{A_2}$$

Higgs Masses in MSSM and NMSSM

MSSM



NMSSM

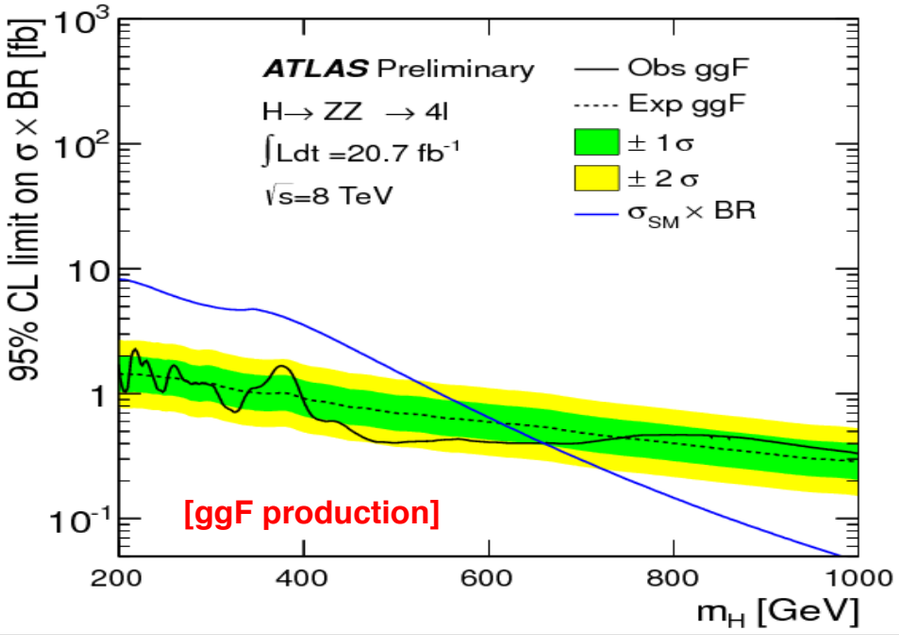


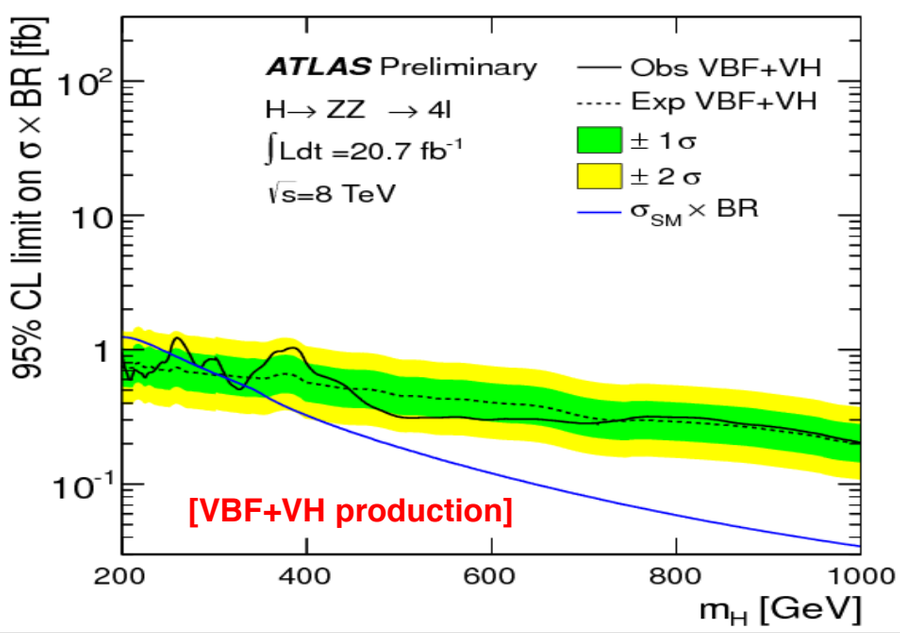
Couplings:

- h has coulings like the SM Higgs
  H has couplings diferent from the SM ($\tan\beta$ dept)
- H_1 or H_2 has coulings like the SM Higgs
  H_3 has couplings diferent from the SM ($\tan\beta$ dept)

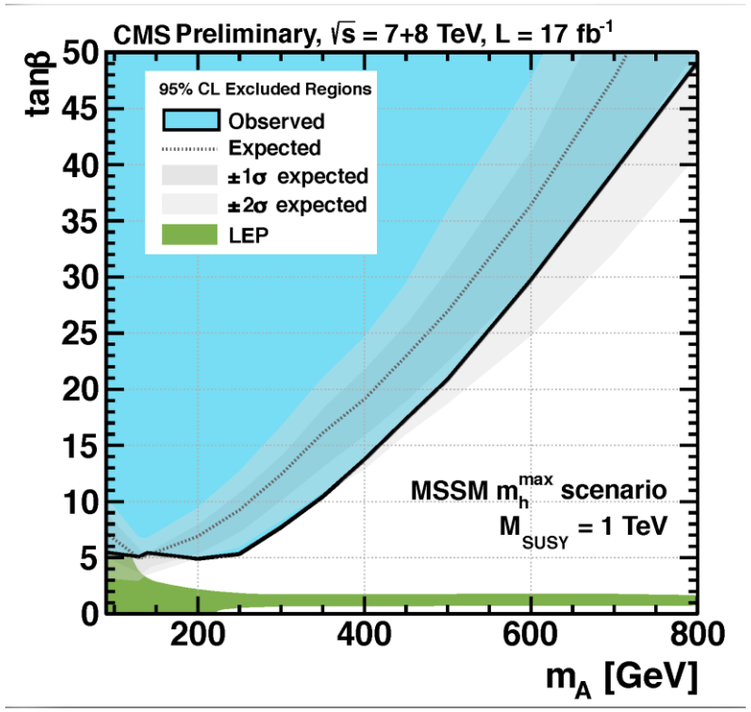
Search for the Heavy Higgs

➔ **Upper limits on production cross section × branching ratio**

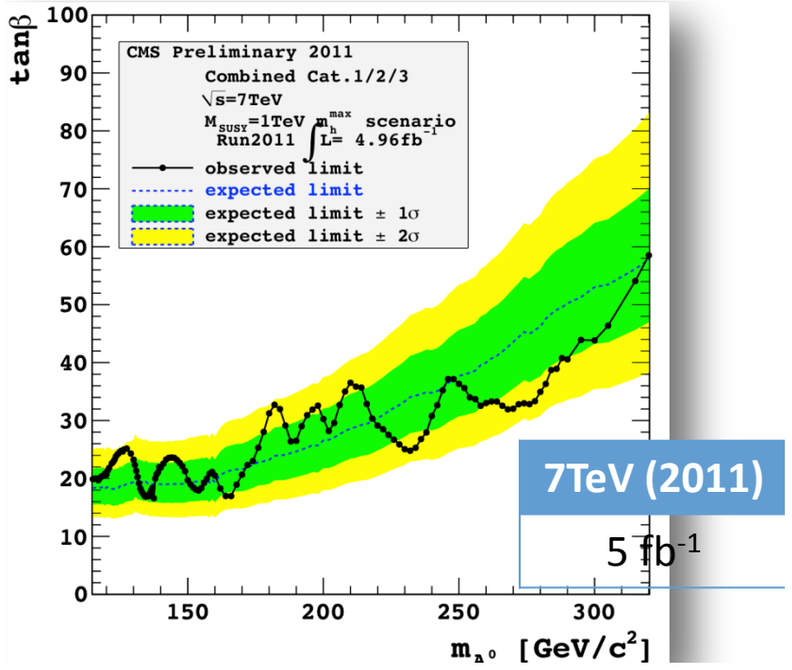




Φ→ττ



Φ→μμ



Next-to Minimal SUSY Model

$$W_{\rm NMSSM} = W_F + \lambda \hat{H}_u \cdot \hat{H}_d \hat{S} + \frac{1}{3}\kappa \hat{S}^3,$$

Potential

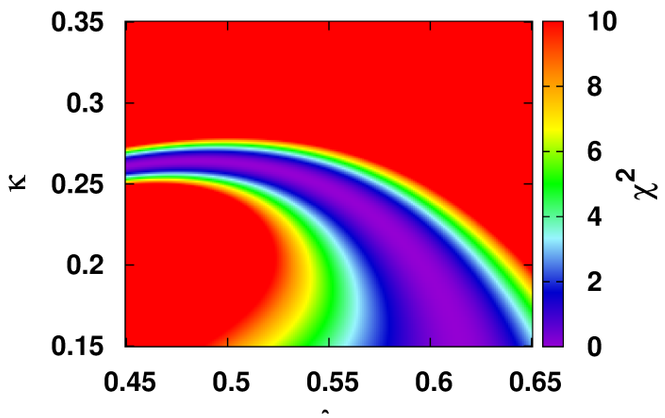
$$V_{\rm soft}^{\rm NMSSM} = \tilde{m}_u^2 |H_u|^2 + \tilde{m}_d^2 |H_d|^2 + \tilde{m}_S^2 |S|^2 + (A_\lambda \lambda S H_u \cdot H_d + \frac{A_\kappa}{3}\kappa S^3).$$

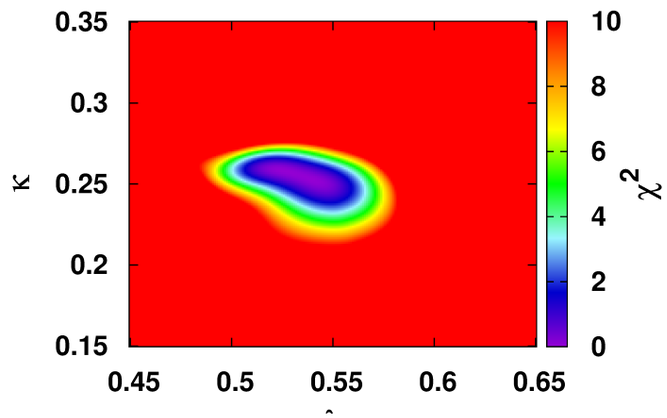
Parameters

$$m_0,\ m_{1/2},\ \tan\beta,\ A_0,\ \lambda,\ \kappa,\ A_\lambda,\ A_\kappa,\ \mu_{eff} \equiv \lambda s$$

Fixing parameters

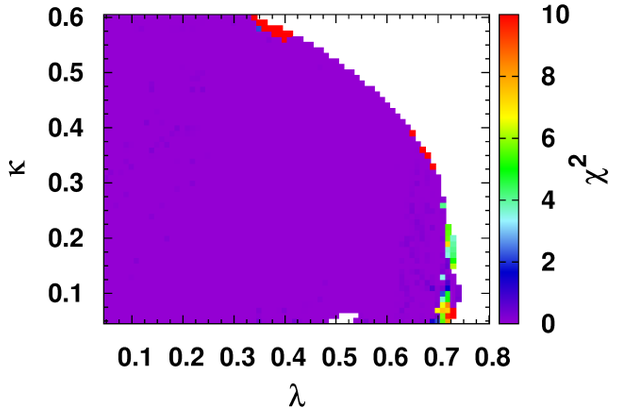
Higgs mass constraint (fixed A, tanb)

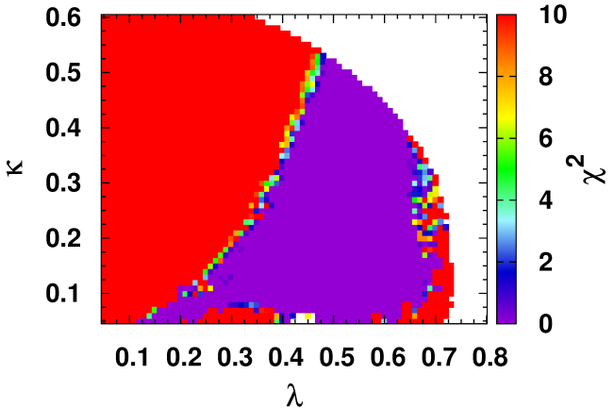




+ relic density constraint (fixed A, tanb)

Higgs mass constraint (free A, tanb)





+ relic density constraint (free A, tanb)

Constraints

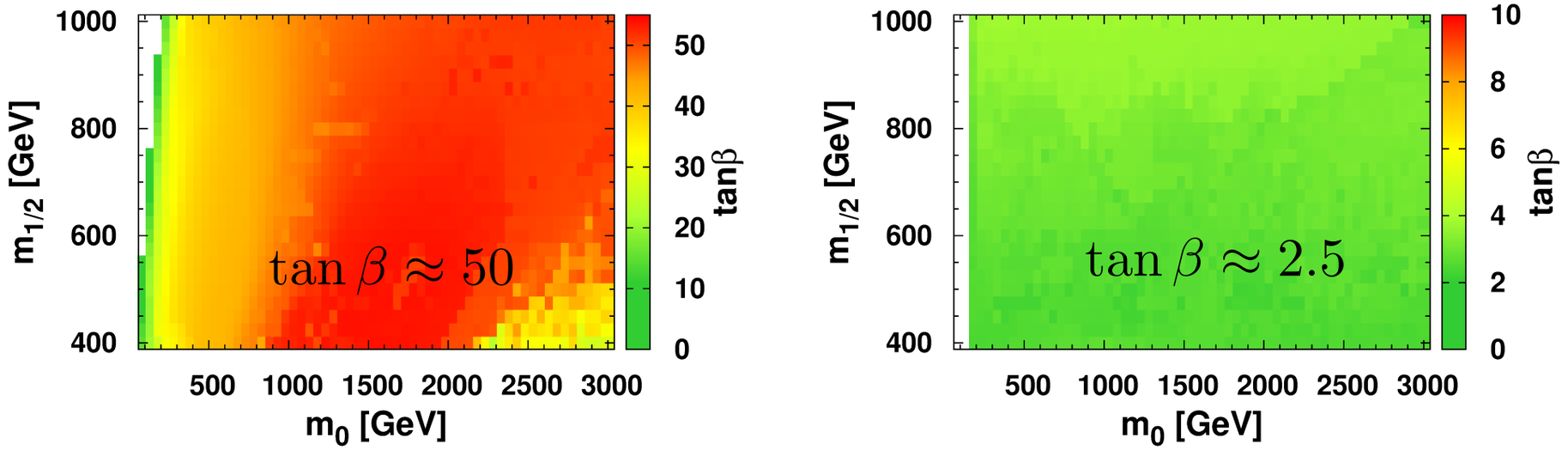
NMSSM calculations made with NMSSMTools

U.Ellwanger et al

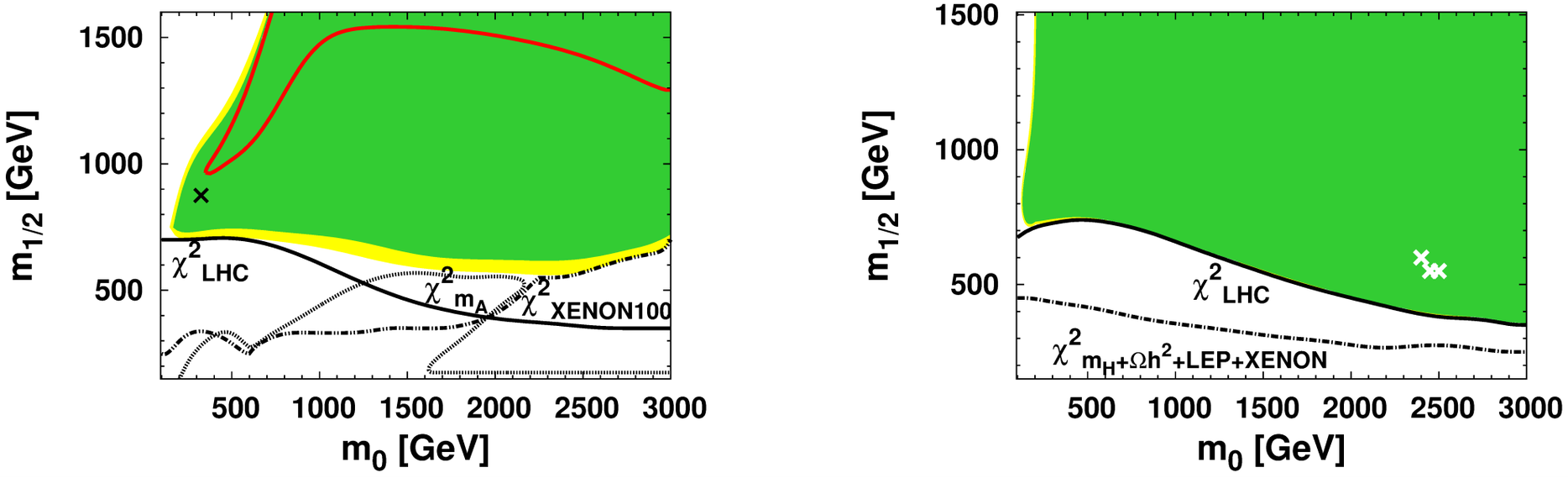
MicrOMEGAs 2.4.1

G. Bélanger et al

Optimisation of $\tan\beta$



Combination of all constraints



W. de Boer et al'
ArXiv: 1308.1333

Constraints

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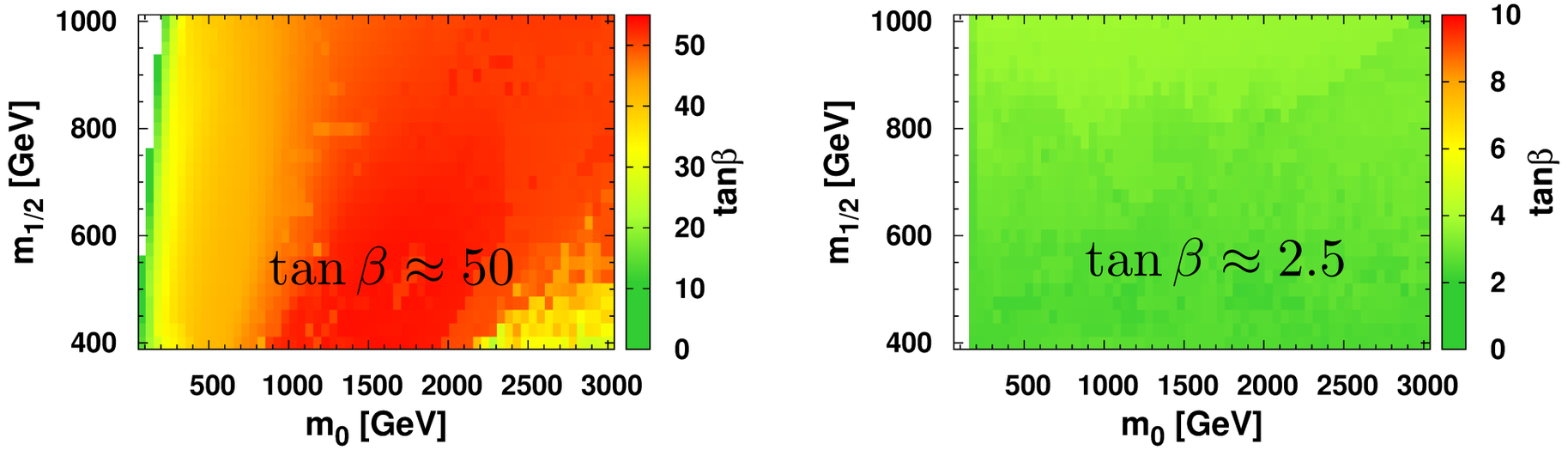
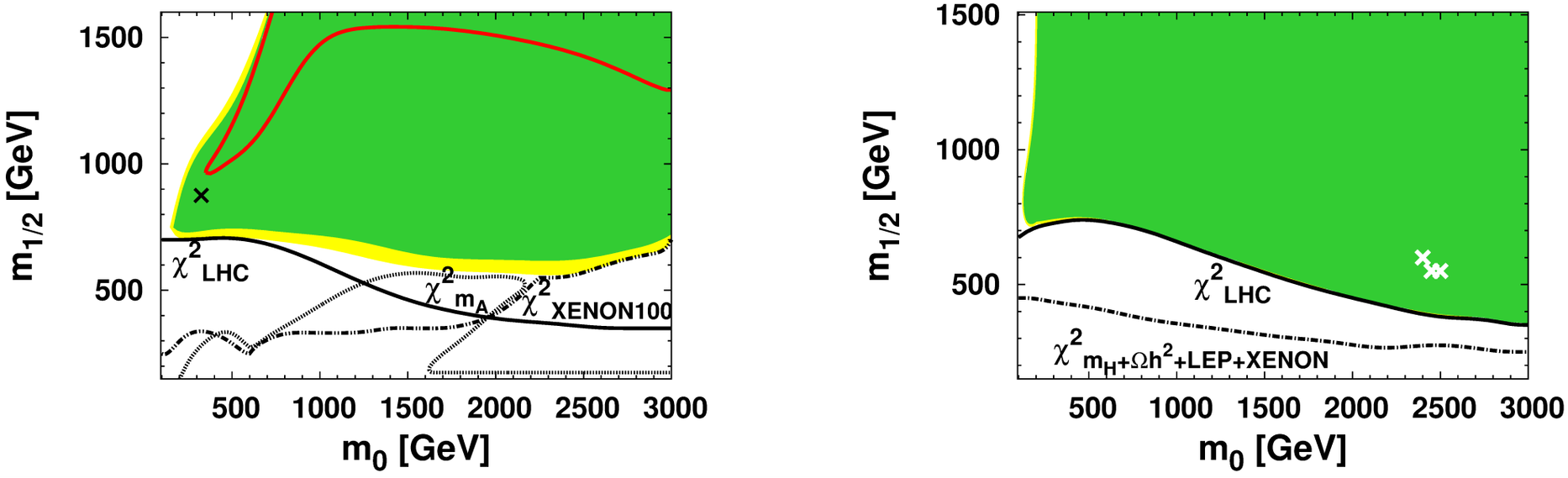
NMSSM

Optimisation of $\tan\beta$



Combination of all constraints



MSSM versus NMSSM

	χ_1^0	χ_2^0	χ_3^0	χ_4^0	χ_5^0	$\chi_1^\pm$	$\chi_2^\pm$	$\tilde{t}_1$	$\tilde{t}_2$	$\tilde{b}_1$	$\tilde{b}_2$
MSSM	1075	1993	3332	3334	-	1993	3334	3263	3908	3902	4014
BMP I	76	160	197	248	477	109	477	992	1925	1918	2552
BMP II	80	212	266	271	484	217	484	983	1957	1947	2596
BMP III	119	232	293	297	527	249	526	960	1952	1942	2588

Branching Ratios [%]

	MSSM			NMSSM (BMP I)				
	h	H	A	H_1	H_2	H_3	A_1	A_2
Mass [GeV]	126	2256	2256	86	126	336	214	325
$b\bar{b}$	67.6	85.2	85.2	90.6	63.6	3.0	0.2	1.9
W^+W^-	17.7	1.7e-5	-	6.5e-7	19.6	0.2	-	-
$\tau\tau$	5.0	14.6	14.6	8.8	6.5	0.4	0.02	0.2
hh	-	8.9e-5	-	-	-	-	-	-
H_1H_2	-	-	-	-	-	41.9	-	-
A_1H_1	-	-	-	-	-	-	-	4.0
Zh	-	-	1.7e-5	-	-	-	-	-
ZH_1	-	-	-	-	-	-	0.3	26.8
$\chi_1^0\chi_1^0$	-	4.7e-5	5.3e-4	-	-	5.7	99.5	38.1
$\chi_1^0\chi_3^0$	-	-	-	-	-	20.8	-	4.2
$\chi_1^+\chi_1^-$	-	-	-	-	-	20.7	-	18.4
σ_{prod} [pb]	19.3	1.3e-5	1.3e-5	2.57	19.1	0.57	1.6e-2	0.41

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Branching Ratios [%]

	NMSSM (BMP II)					NMSSM (BMP III)				
	H_1	H_2	H_3	A_1	A_2	H_1	H_2	H_3	A_1	A_2
Mass [GeV]	103	126	1001	91	1001	126	129	870	118	869
$b\bar{b}$	90.5	61.9	0.9	90.9	0.9	61.7	88.6	0.7	90.4	0.6
$t\bar{t}$	0.0	0.0	9.6	0.0	10.4	0.0	0.0	22.1	0.0	23.5
$\tau\tau$	9.1	6.4	0.1	8.8	0.1	6.3	9.3	0.1	9.3	0.1
W^+W^-	1.2e-4	20.6	1.7e-4	-	-	20.6	1.7	7.9e-3	-	-
$\chi_1^0\chi_1^0$	-	-	10.7	-	11.8	-	-	9.0	-	9.6
$\chi_1^0\chi_3^0$	-	-	5.1	-	6.3	-	-	5.5	-	8.9
$\chi_1^+\chi_1^-$	-	-	3.2	-	5.9	-	-	2.4	-	6.3
H_1H_2	-	-	14.8	-	-	-	-	13.6	-	-
A_1H_2	-	-	-	-	13.5	-	-	-	-	0.2
ZA_1	-	-	12.3	-	-	-	-	10.6	-	-
ZH_1	-	-	-	-	13.6	-	-	-	-	0.04
A_1H_1	-	-	-	-	0.3	-	-	-	-	11.7
ZH_2	-	-	-	-	8.1e-4	-	-	-	-	11.9
σ_{prod} [pb]	0.33	19.3	1.6e-3	0.13	1.9e-3	19.5	3.9e-2	7.1e-3	1.7e-2	7.6e-3

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- Give me something better and I will stick to it