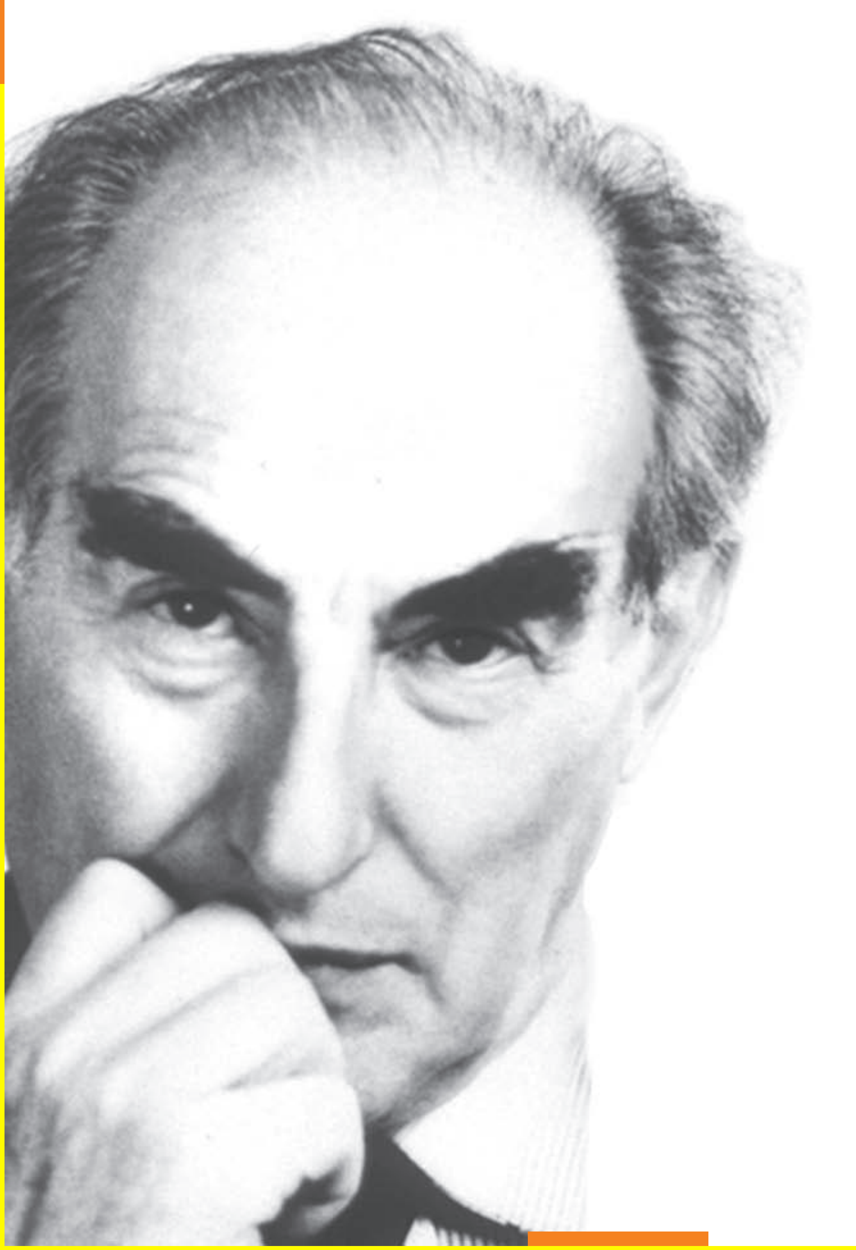
GINZBURG CONFERENCE on PHYSICS

May 28 - June 2, 2012
Lebedev Institute / Moscow



- Is the low-energy SUSY still alive?
- What is the current situation with SUSY searches?
- Is there a time/energy limit for such a game?

Constraints on Supersymmetry using 5 fb^{-1} LHC data

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KIT (Karlsruhe)

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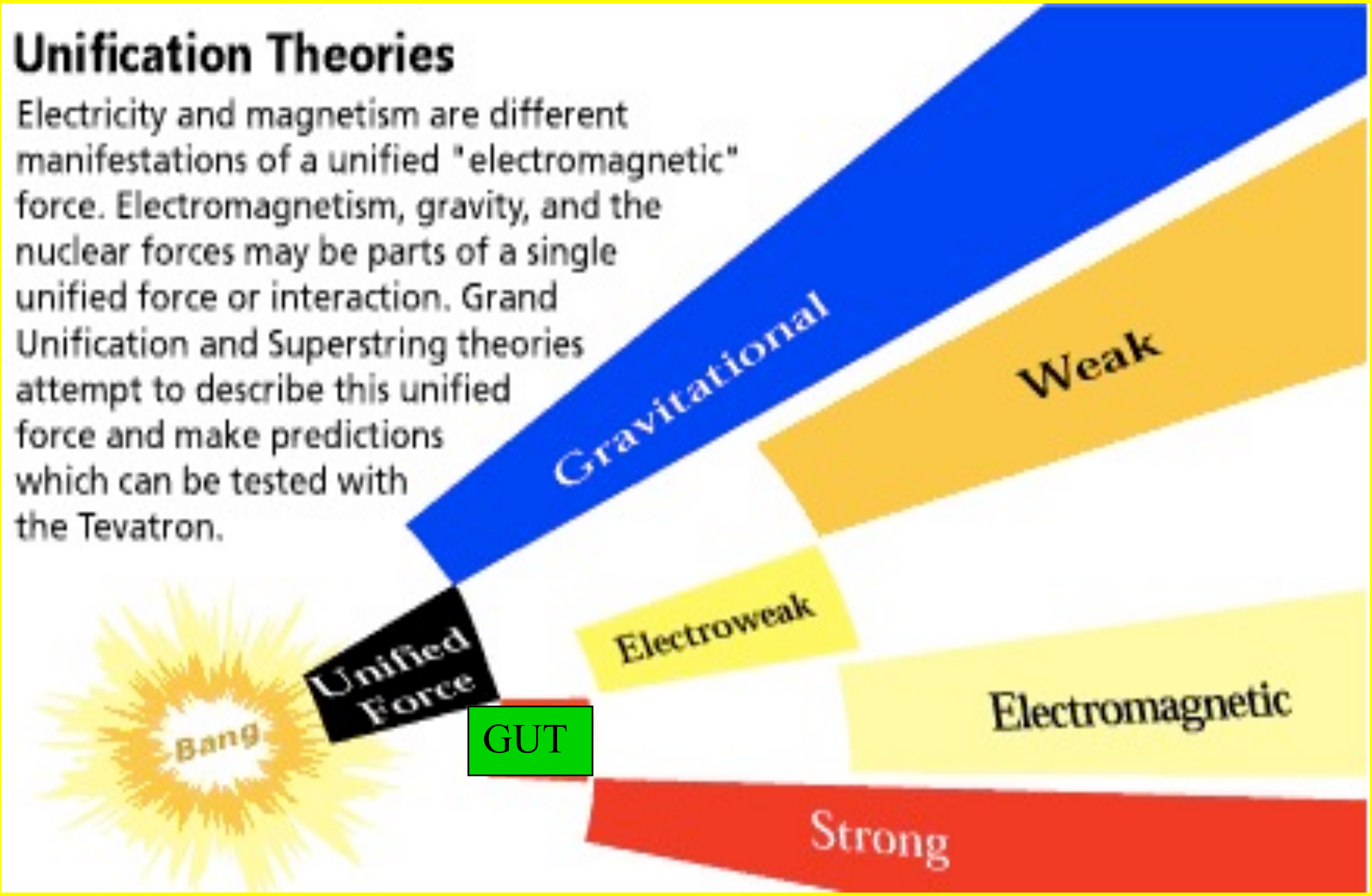
JHEP 05 (2012) 94 (arXiv: 1202.3366)

Why do we love SUSY?

✓ Unifying various spins SUSY opens the road toward unification with gravity
Local SUSY = Theory of (super)gravity



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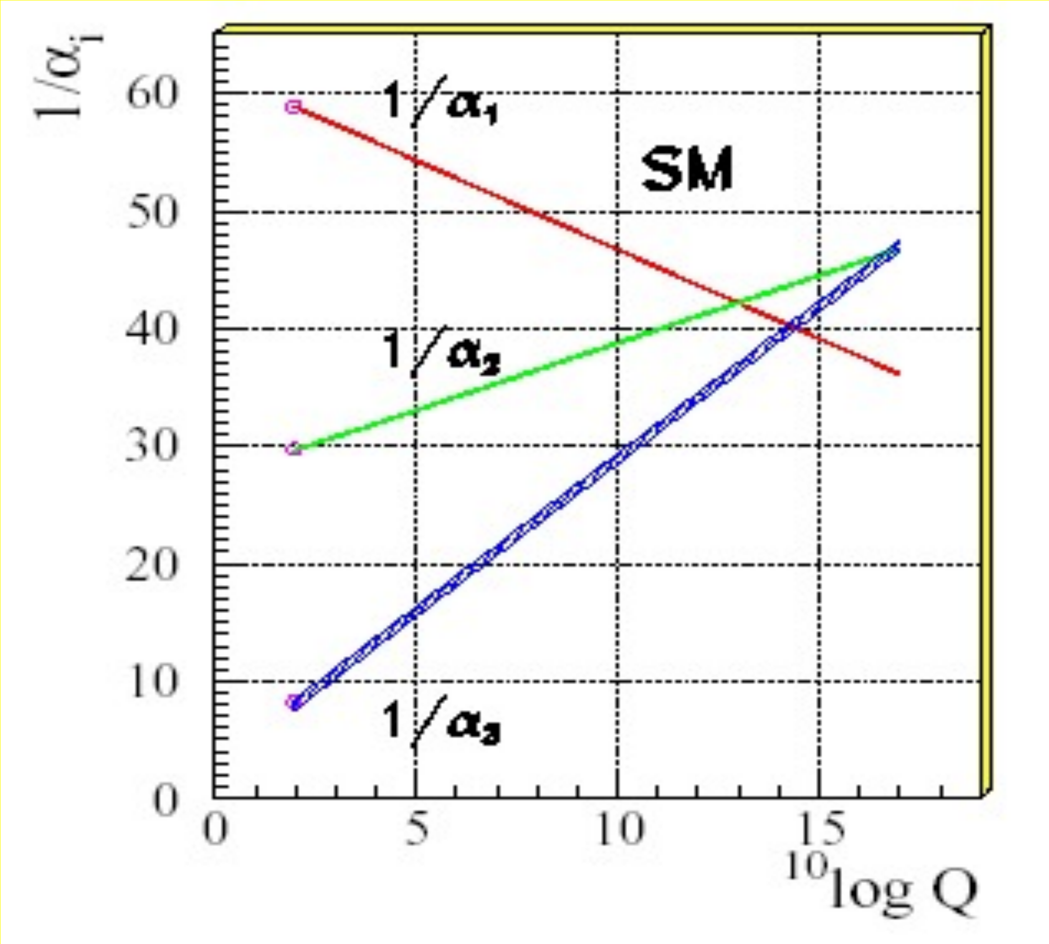

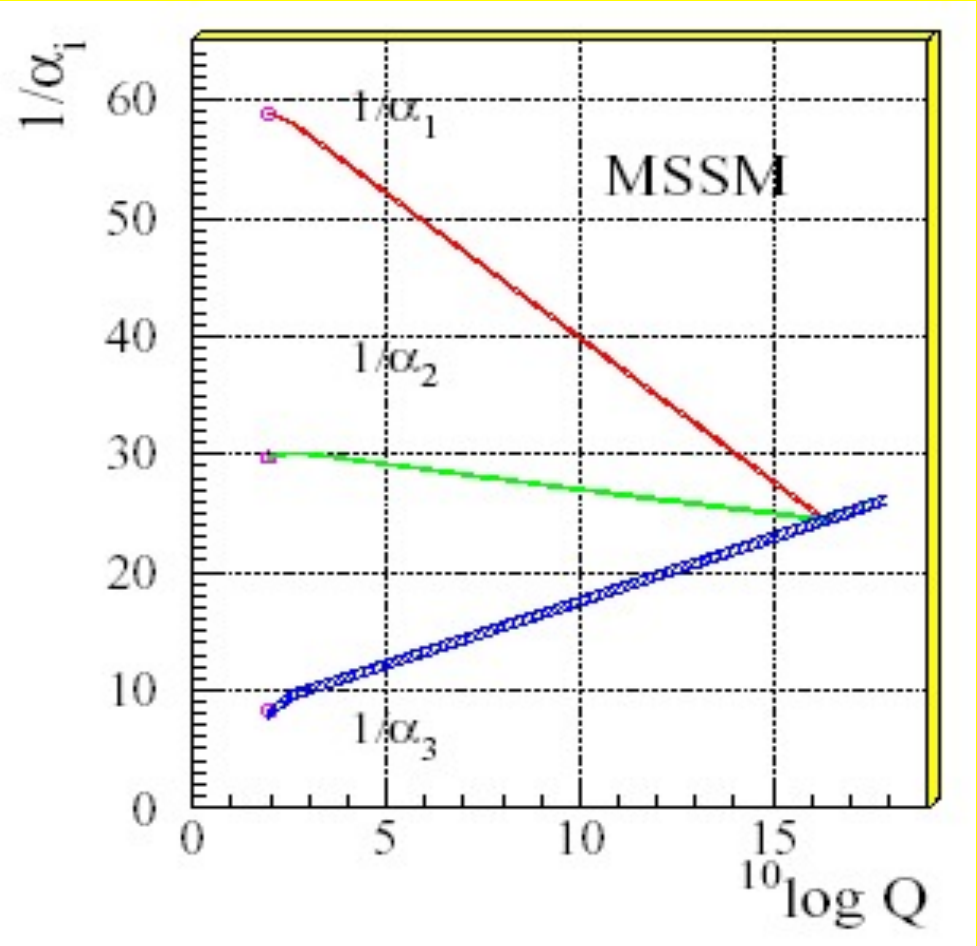

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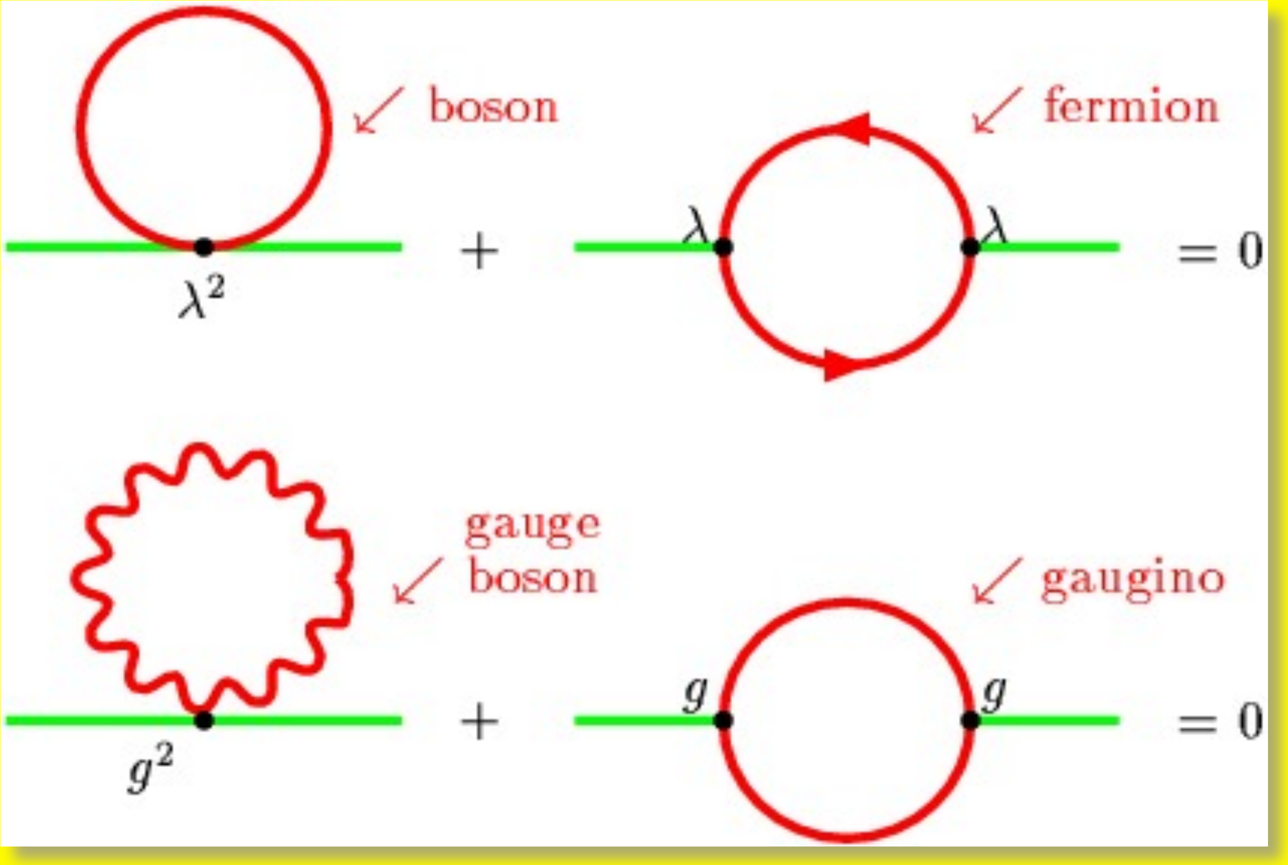
Cancellation of quadratic terms (divergences)

$$\delta m_H^2 \sim g^2 M_{SUSY}^2$$



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✓ Provides the Dark Matter particle (WIMP)

Dark Matter in the Universe:

→ **Hot DM (not favoured by galaxy formation)**

→ **Cold DM (rotation curves of Galaxies)** ← SUSY

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✓ Provides the first integrable 4-dim quantum theory (N=4 SYM)

N=4 maximally Supersymmetric Yang-Mills theory shows all the features and seems to provide the first integrable model in 4 space-time dimensions

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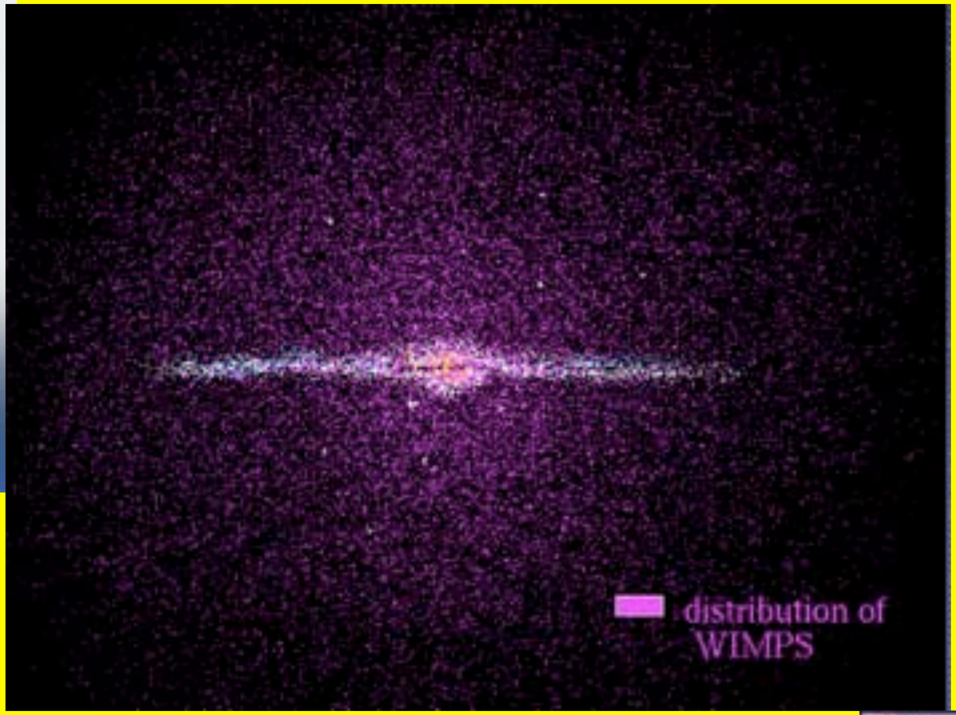
✓ Provides the dark Matter particle (WIMP)
✓ Provides the first integrable 4-dim quantum theory (N=4 SYM)
✓ Stabilizes the string as an origin of a unified superstring theory ⟶ No tachions

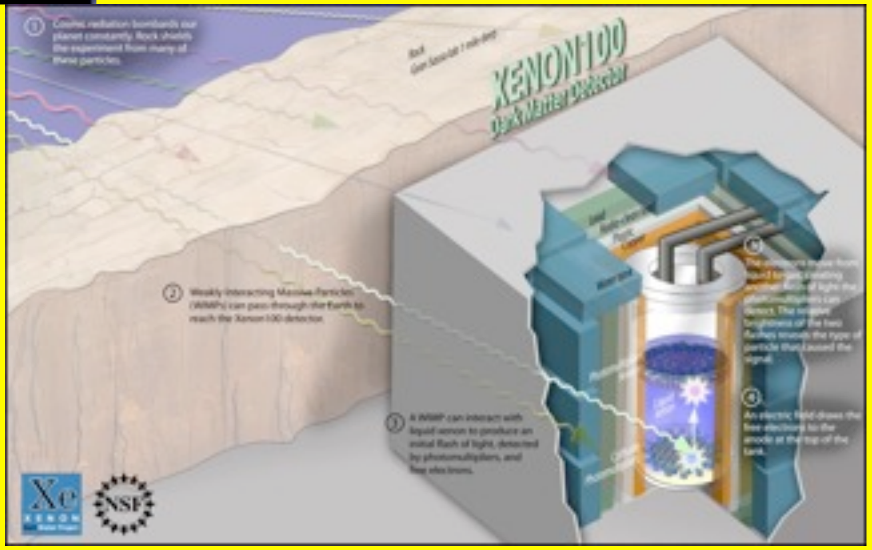
Where is SUSY?

Accelerators

Telescopes



Underground facilities



Exp Data & Th Frame

Exp data

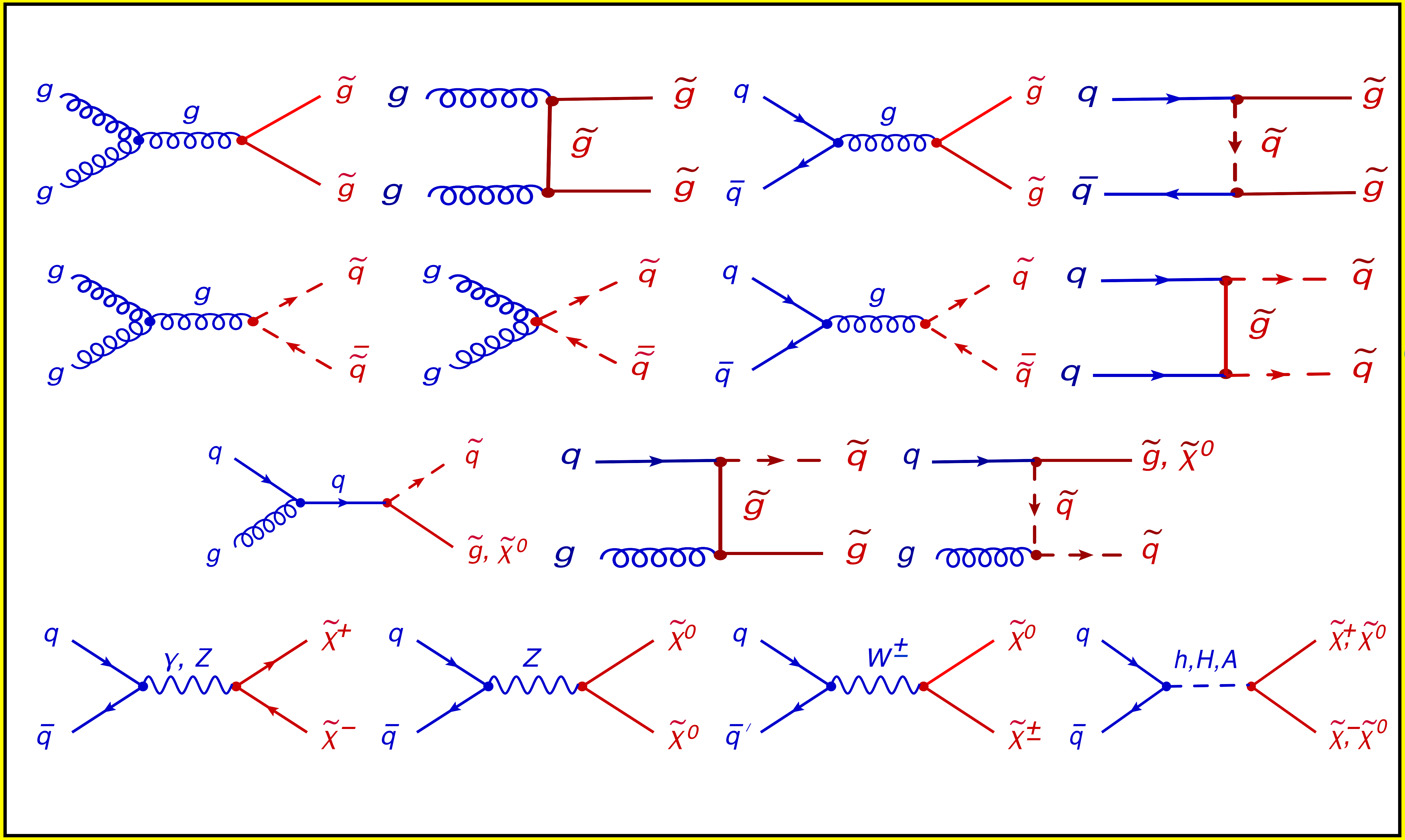
- ✓ LEP II & Tevatron limits on SUSY particle masses
- ✓ Direct SUSY search at LHC @ 5/fb
- ✓ Higgs boson(s) searches
- ✓ Rare decays ($B_s \to s\gamma,\ B_s \to \mu^+\mu^-, B_s \to \tau\nu$)
- ✓ Relic abundancy of Dark Matter in the Universe
- ✓ Direct search for the DM
- ✓ g-2 of the muon

Theory Framework

MSSM with SUGRA SUSY breaking

Min parameter set: $m_0,\ m_{1/2},\ A_0,\ \tan\beta$

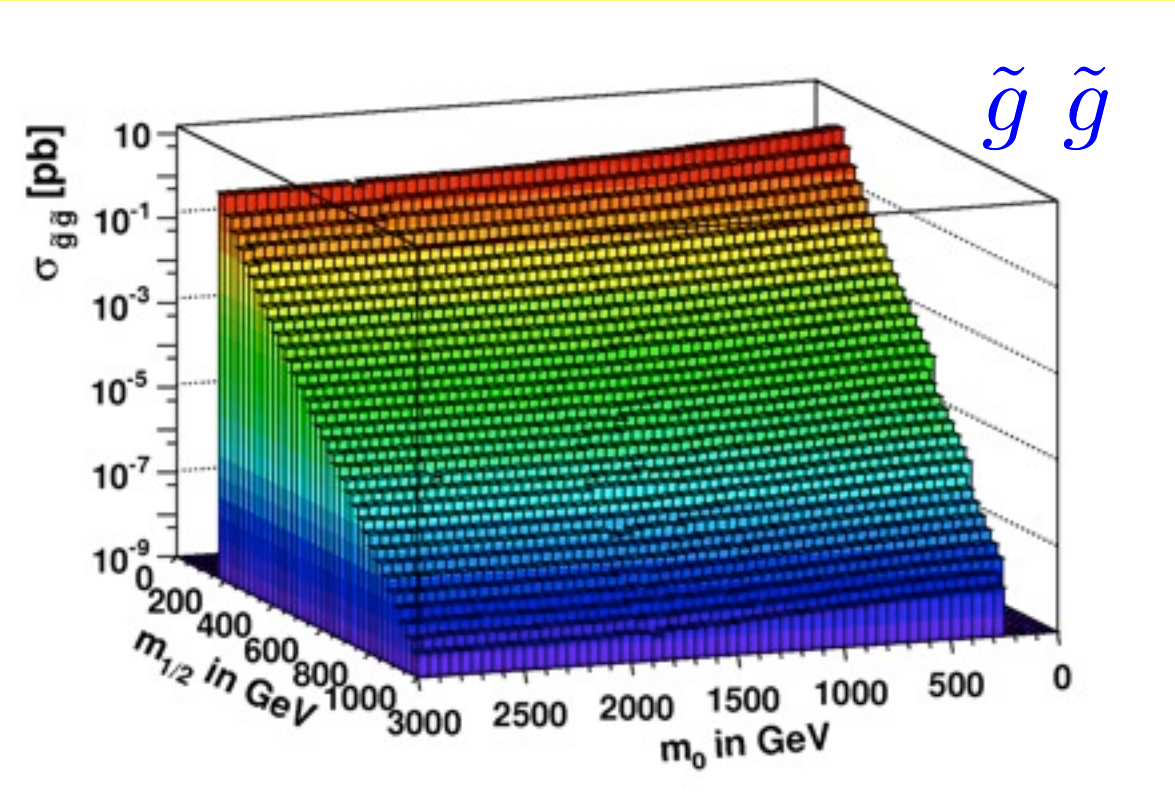
SUSY Production at the LHC

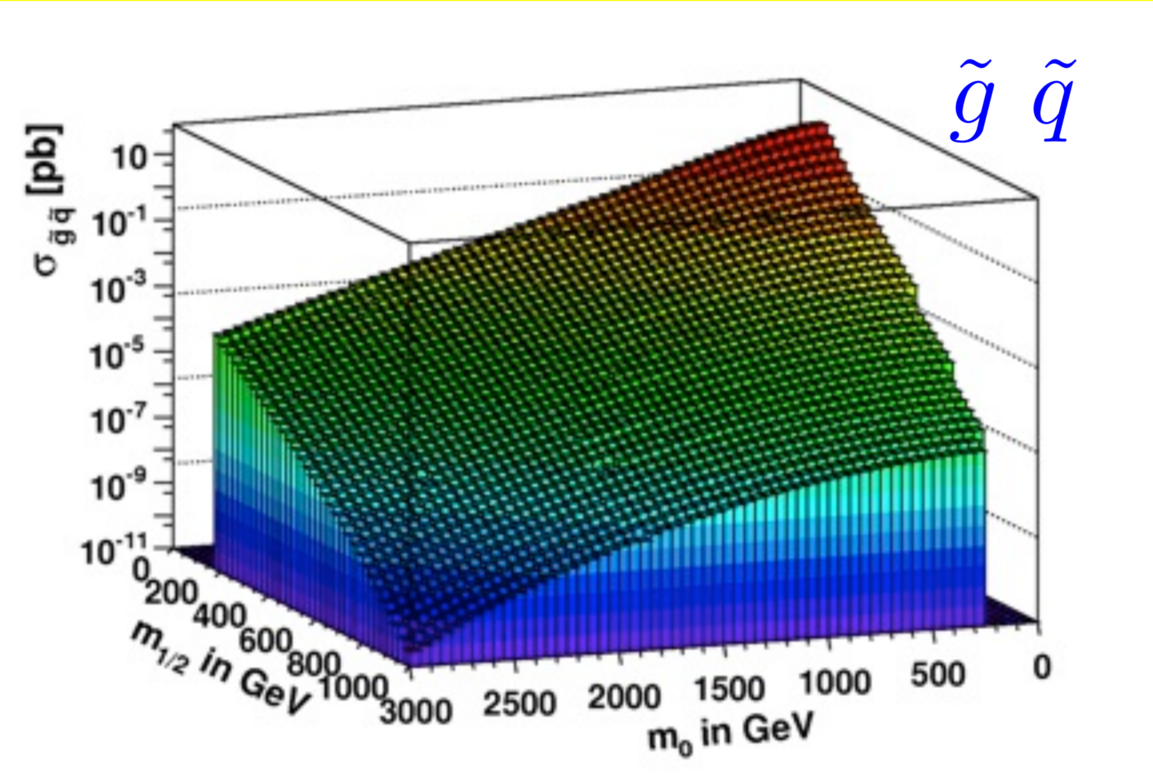


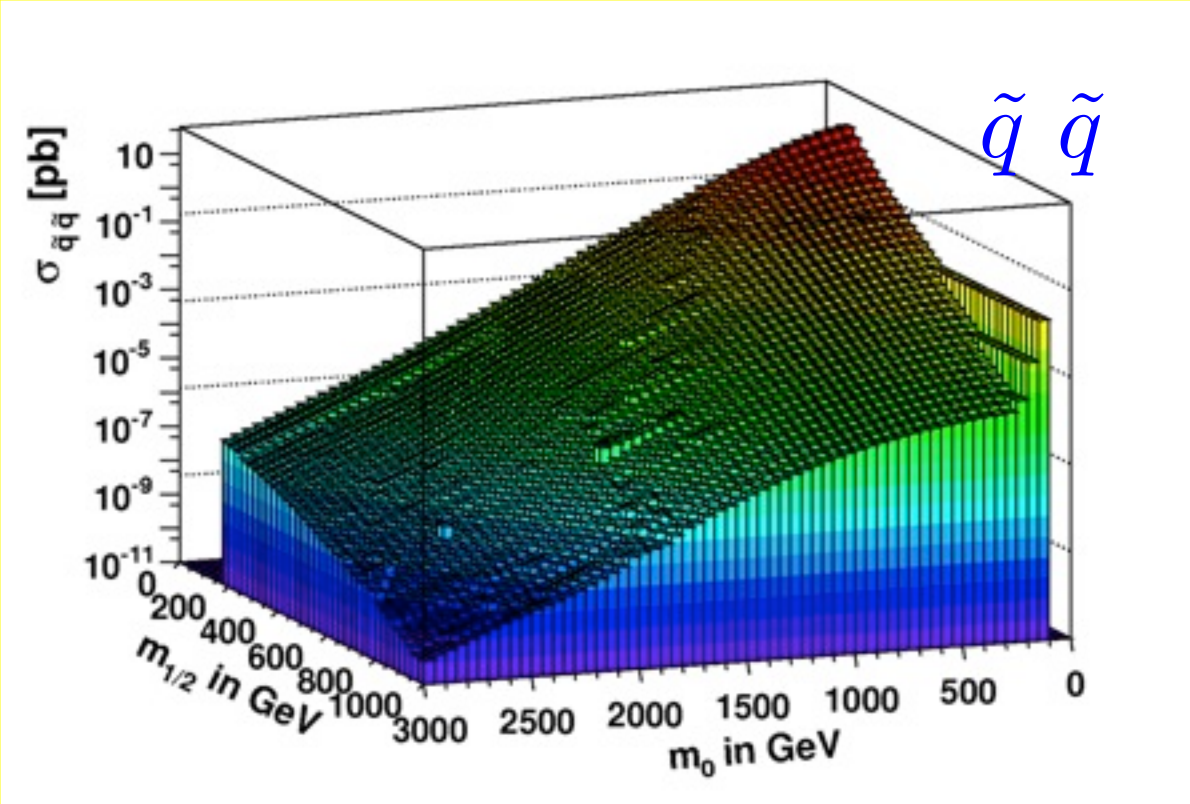
Strong Int's

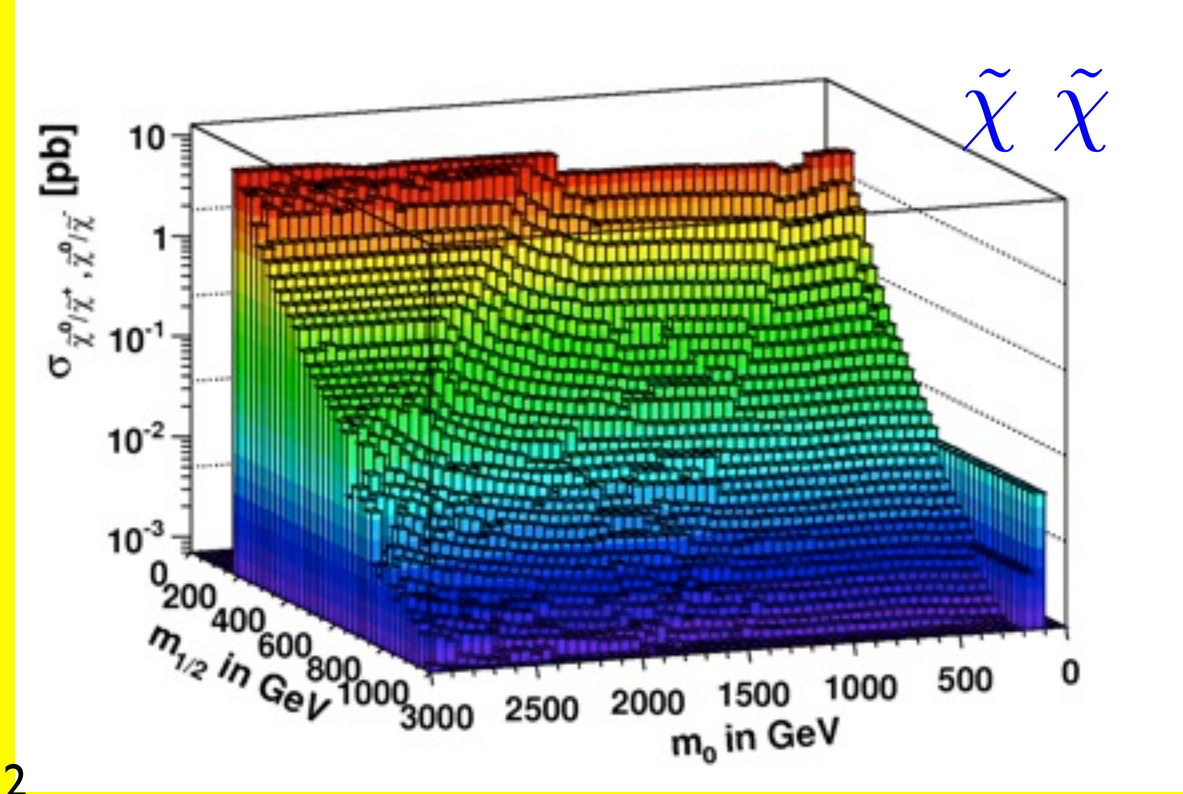
Weak Int's

SUSY x-sections at the LHC @ 7 TeV





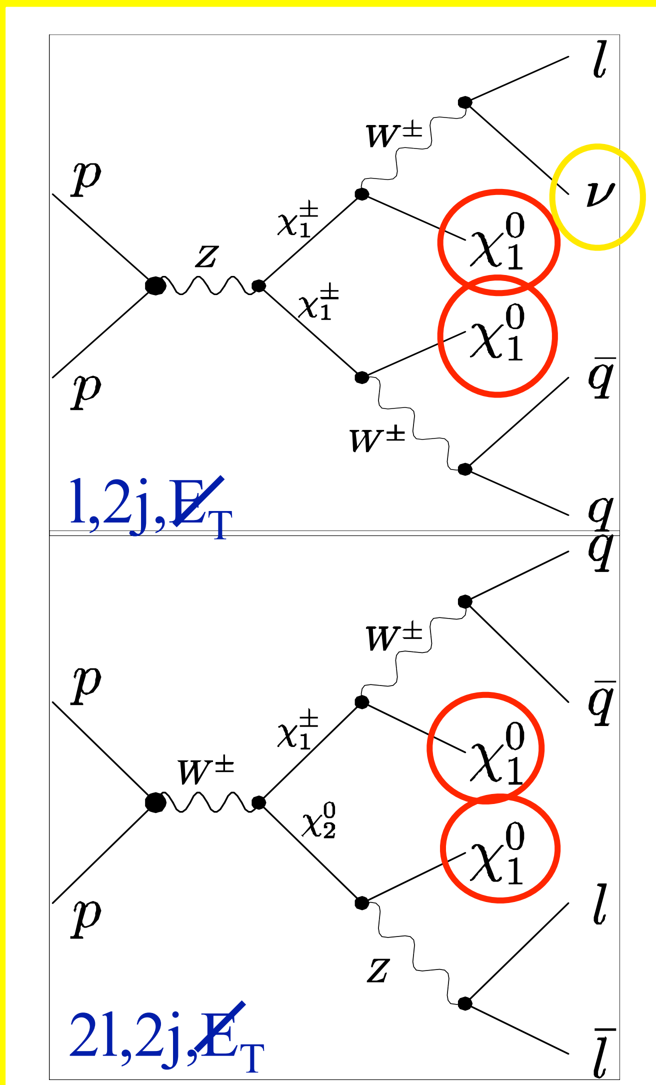


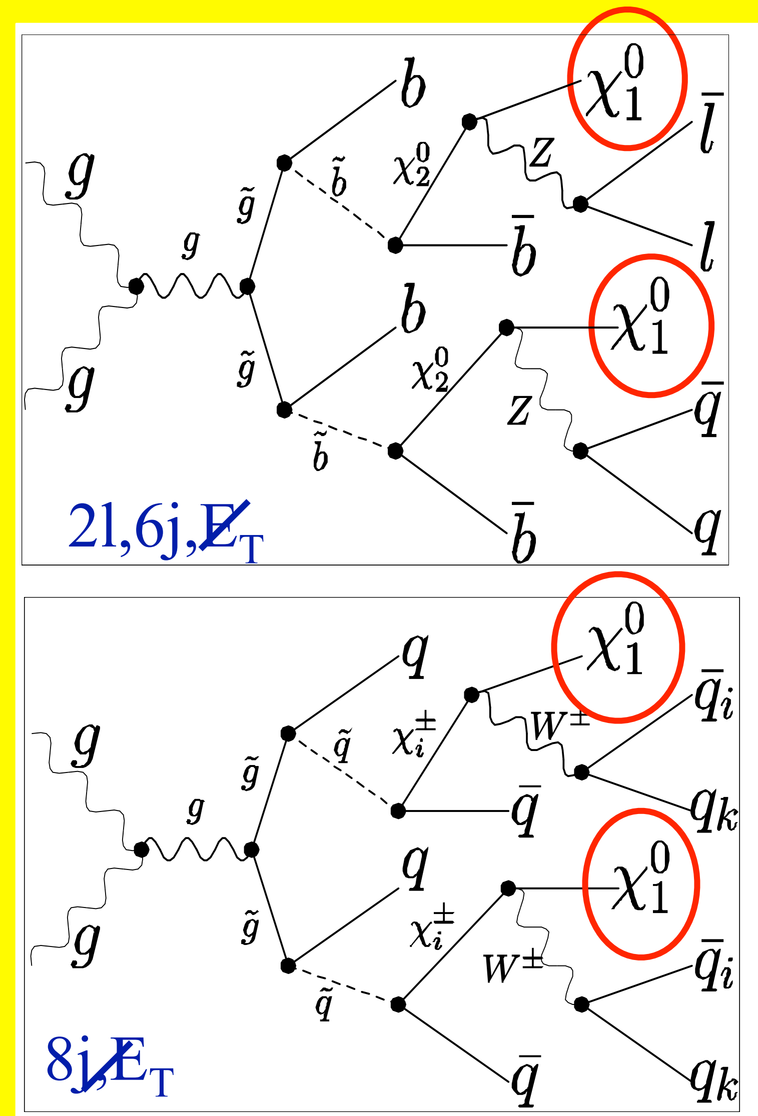


SUSY Signatures at the LHC

Search for superpartners within the MSSM

weak int's



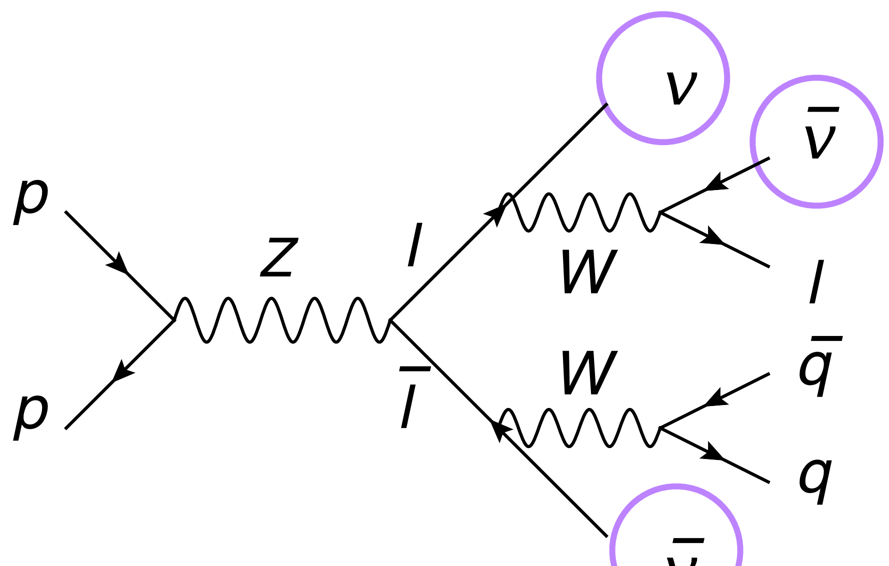


strong int's

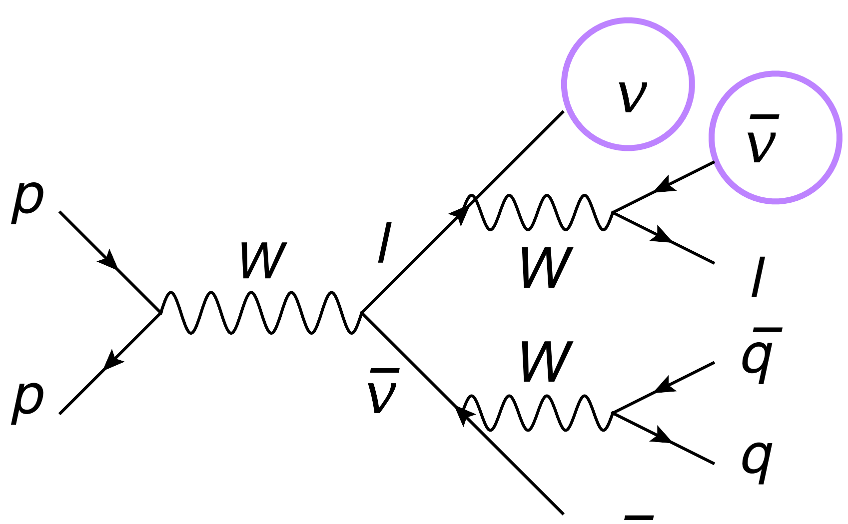
Typical SUSY signature: Missing Energy and Transverse Momentum

Background Processes of the SM for creation of Superpartners

weak int's

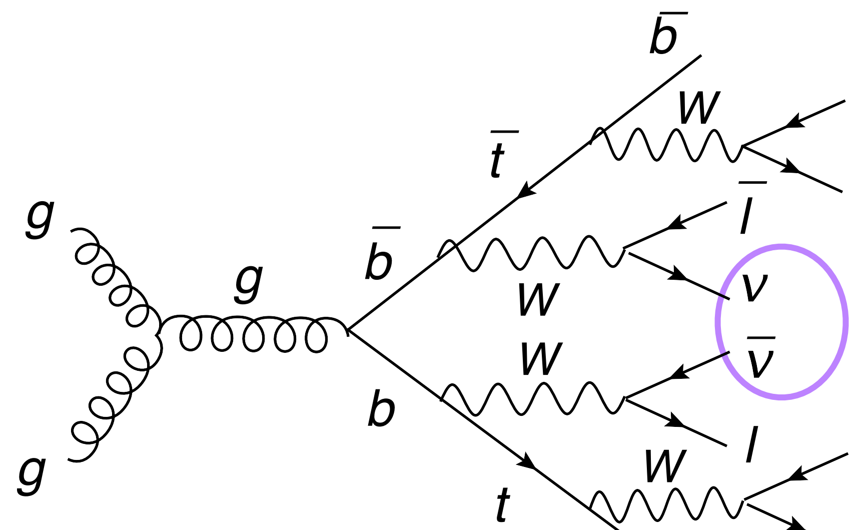


$l, 2j, \not{E}_T$

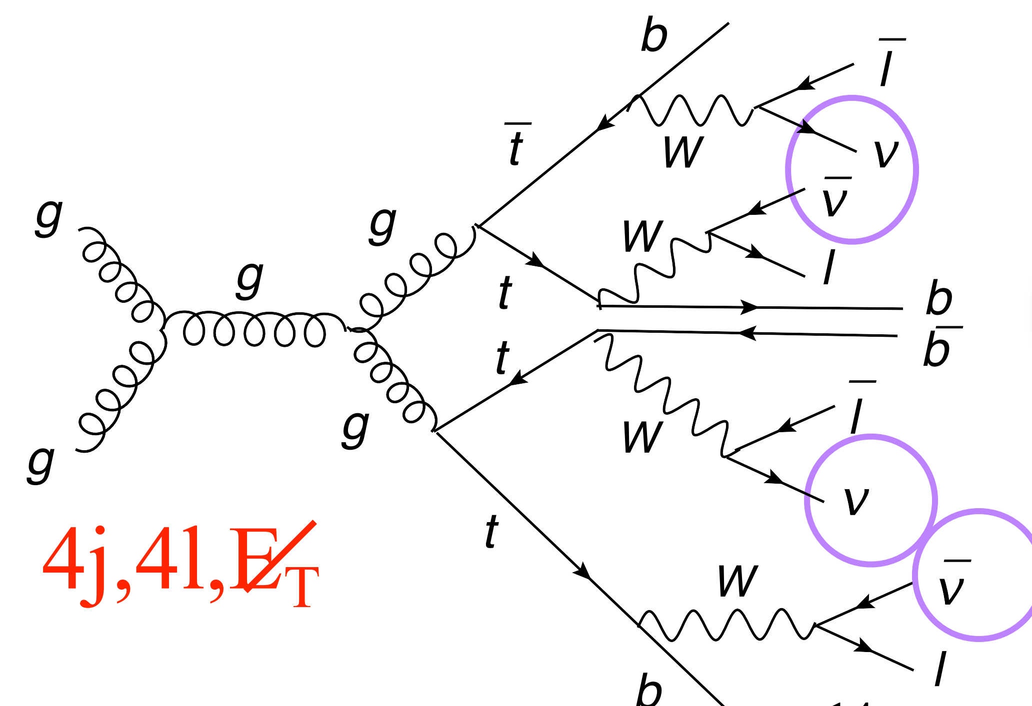


$2l, 2j, \not{E}_T$

Strong int's



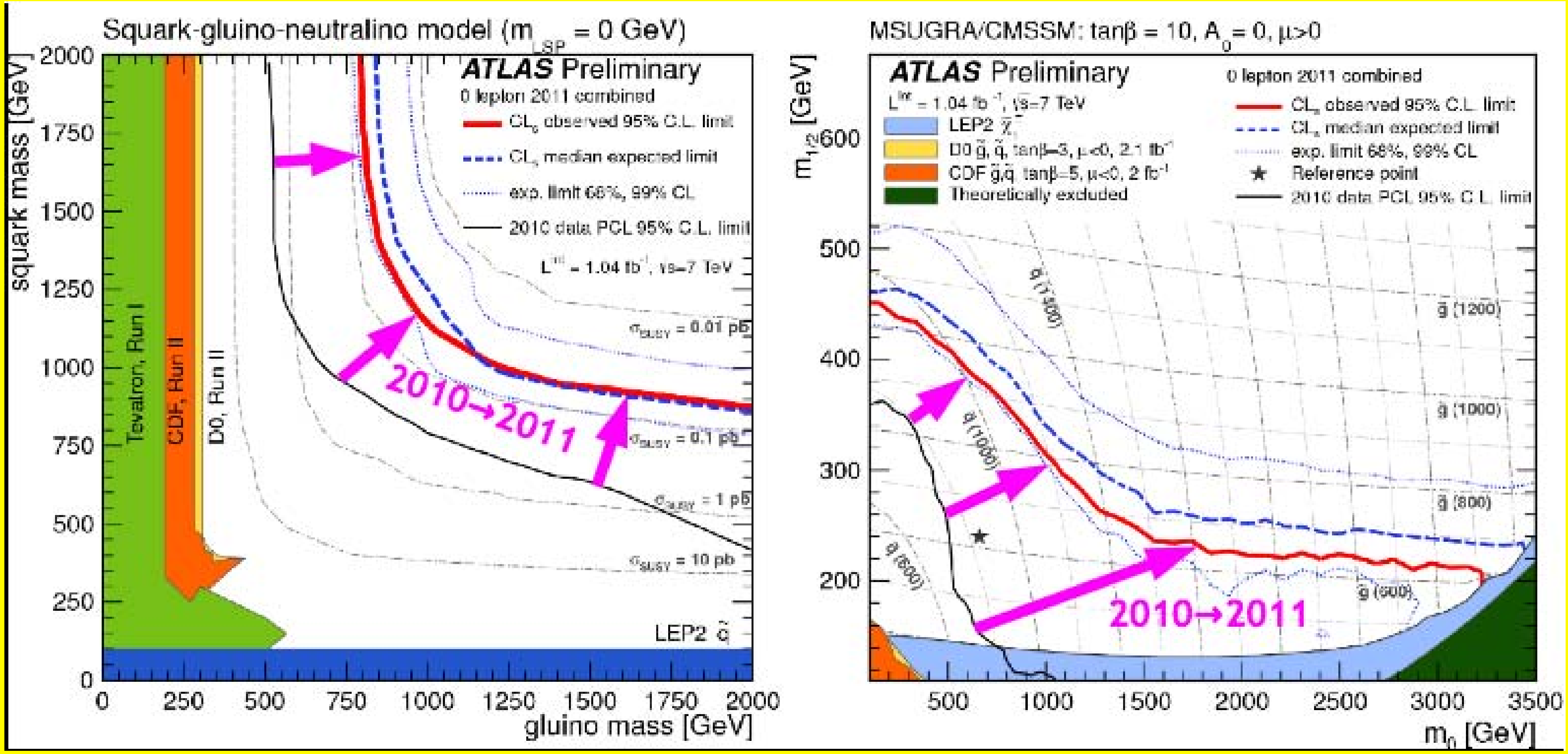
$2l, 6j, \not{E}_T$



$4j, 4l, \not{E}_T$

First SUSY results @ LHC

SUSY in 0-lepton channel

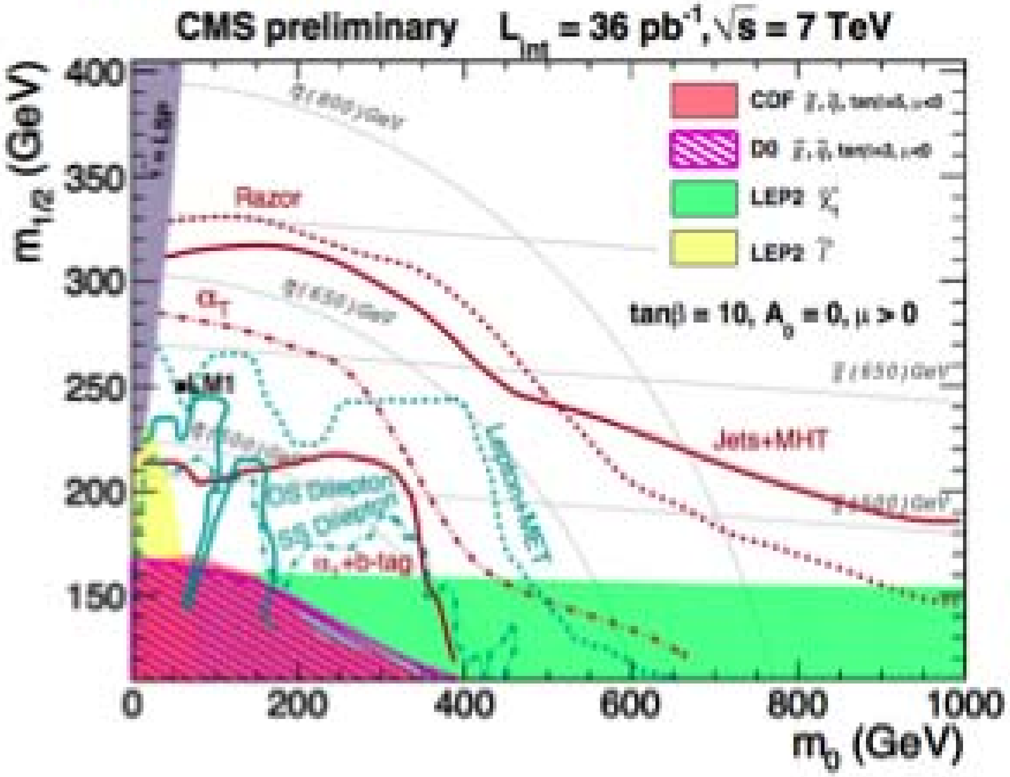


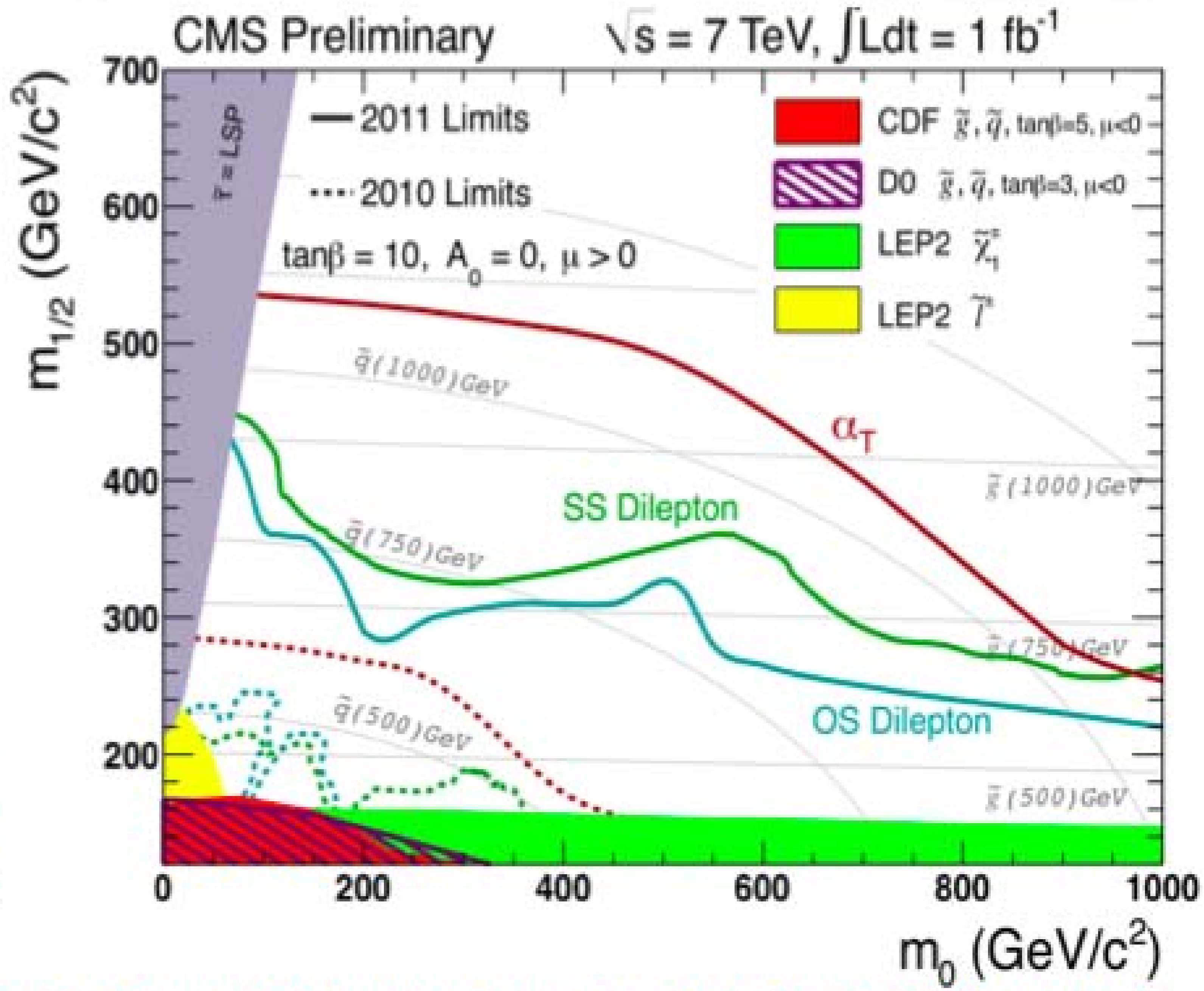
Simplified model with two q generations, m(χ 0)~01mg>800 GeV mq>850 GeV
Equal mass case: mg=mq>1.075 TeV

MSUGRA/CMSSM: tanβ=10, A0=0, μ>0 Equal mass case: mq=mg > 980 GeV

Progress on SUSY Searches

Results of the first three SUSY analyses completed on 2011 data (α_T , Same Sign and Opposite Sign dileptons).





Within the constrained SSM models we are crossing the border of excluding gluinos and squarks up to 1TeV and beyond. The air is getting thin for constrained SUSY. More conclusive results after summer.

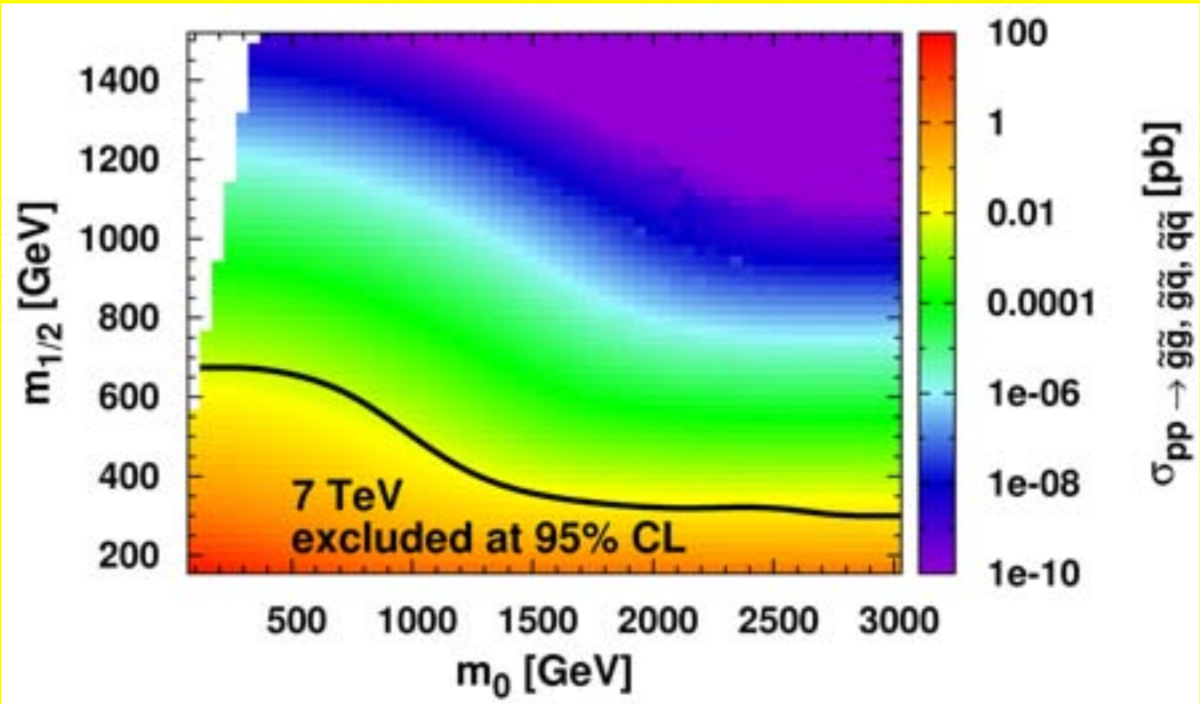
Ximo Poveda (University of Wisconsin-Madison)
on behalf of the ATLAS Collaboration

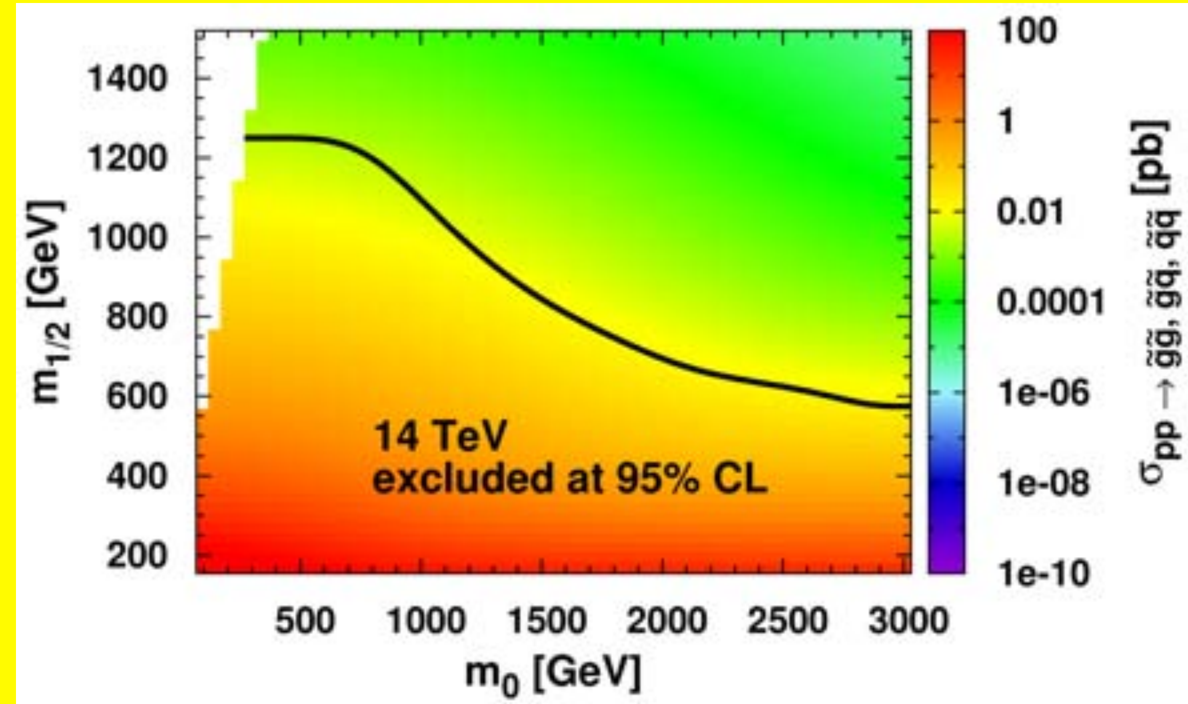
Summary

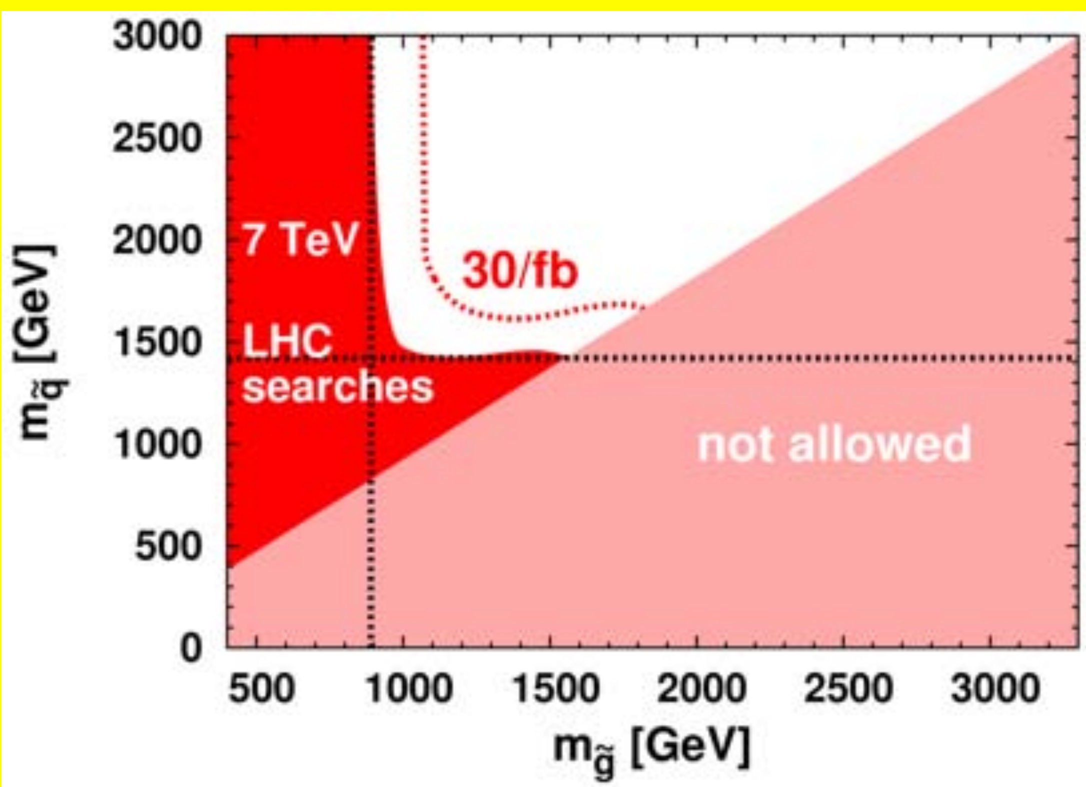
- Variety of searches for SUSY events with third generation squarks and sleptons
- Exploring signatures with heavy quarks or tau leptons using 2 fb^{-1} of data:
  - 1 or 2 τ leptons: gluino or squark mediated $\tilde{\tau}_1$ production
  - 2 b-jets + lepton veto: direct $\tilde{b}_1\tilde{b}_1^*$ production
  - 0 lepton + b-jets: gluino mediated $\tilde{b}_1$ production
  - 1 lepton + b-jets: direct $\tilde{t}_1\tilde{t}_1^*$ and gluino mediated $\tilde{t}_1$ production
  - 2 SS leptons: gluino mediated $\tilde{t}_1$ production
- No significant excess observed over SM expectations → Limits on the masses of the sparticles in a various SUSY scenarios

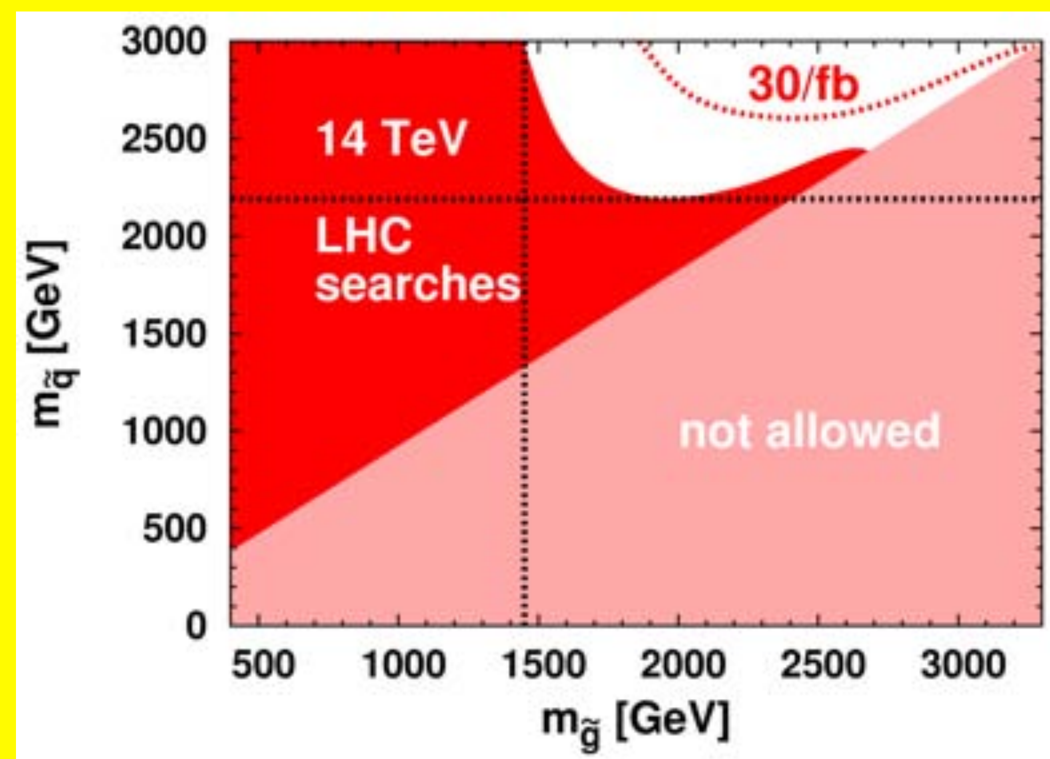
$\tilde{b}_1\tilde{b}_1^*$ (MSSM)	$\tilde{b}_1 \to b\tilde{\chi}_1^0$	$m_{\tilde{b}_1} = 390$ GeV ($m_{\tilde{\chi}_1^0} = 0$)	2 b-jets
$\tilde{b}_1\tilde{b}_1^*$ (MSSM)	$\tilde{b}_1 \to b\tilde{\chi}_1^0$	$m_{\tilde{b}_1} = 350$ GeV ($m_{\tilde{\chi}_1^0} = 120$ GeV)	2 b-jets
$\tilde{g}\tilde{g}$, $\tilde{b}_1\tilde{b}_1^*$ (MSSM)	$\tilde{g} \to \tilde{b}_1 b$, $\tilde{b}_1 \to b\tilde{\chi}_1^0$	$m_{\tilde{g}} = 920$ GeV ($m_{\tilde{b}_1} < 800$ GeV)	0ℓ + b-jets
$\tilde{g}\tilde{g}$ (simpl. model)	$\tilde{g} \to \bar{b}\tilde{\chi}_1^0$	$m_{\tilde{g}} = 900$ GeV ($m_{\tilde{\chi}_1^0} < 300$ GeV)	0ℓ + b-jets
$\tilde{g}\tilde{g}$, $\tilde{t}_1\tilde{t}_1^*$ (MSSM)	$\tilde{g} \to \tilde{t}_1 t$, $\tilde{t}_1 \to t\tilde{\chi}_1^0$	$m_{\tilde{g}} = 620$ GeV ($m_{\tilde{t}_1} < 440$ GeV)	1ℓ + b-jets
$\tilde{g}\tilde{g}$, $\tilde{t}_1\tilde{t}_1^*$ (MSSM)	$\tilde{g} \to \tilde{t}_1 t$, $\tilde{t}_1 \to t\tilde{\chi}_1^0$	$m_{\tilde{g}} = 650$ GeV ($m_{\tilde{t}_1} < 450$ GeV)	2ℓSS
$\tilde{g}\tilde{g}$ (simpl. model)	$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$	$m_{\tilde{g}} = 700$ GeV ($m_{\tilde{\chi}_1^0} < 100$ GeV)	1ℓ + b-jets
$\tilde{g}\tilde{g}$ (simpl. model)	$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$	$m_{\tilde{g}} = 650$ GeV ($m_{\tilde{\chi}_1^0} < 215$ GeV)	2ℓSS
$\tilde{g}\tilde{g}$ (simpl. model)	$\tilde{g} \to tb + \tilde{\chi}_1^0$	$m_{\tilde{g}} = 710$ GeV ($m_{\tilde{\chi}_1^0} < 100$ GeV)	1ℓ + b-jets

LHC Reach at 7 and 14 TeV



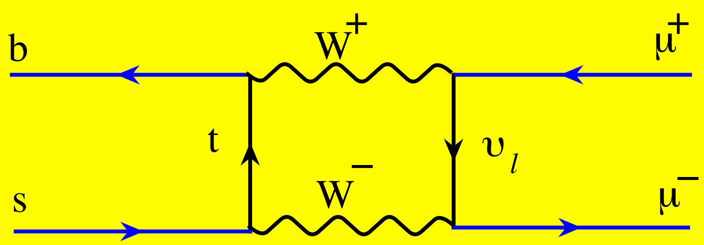


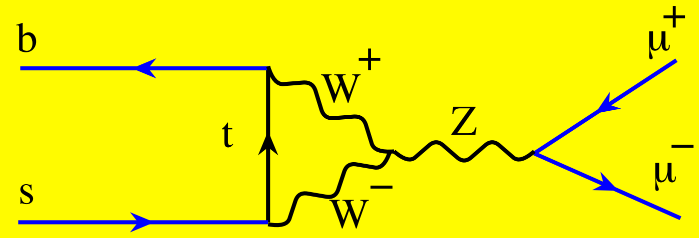


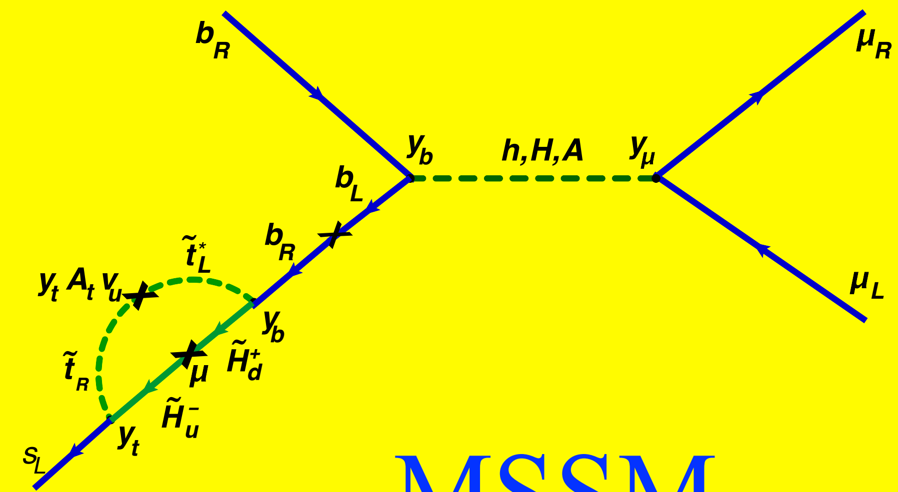


Energy is more important than luminosity

Rare Decays: $Br[B_s \to \mu^+ \mu^-]$







SM: Br=3.5·10^-9

Ex: <4.5· 10^-9

SM

MSSM

$$Br[B_s \to \mu\mu] \; = \; \frac{2\tau_B m_B^5}{64\pi} f_{B_s}^2 \sqrt{1 - \frac{4m_l^2}{m_B^2}}$$

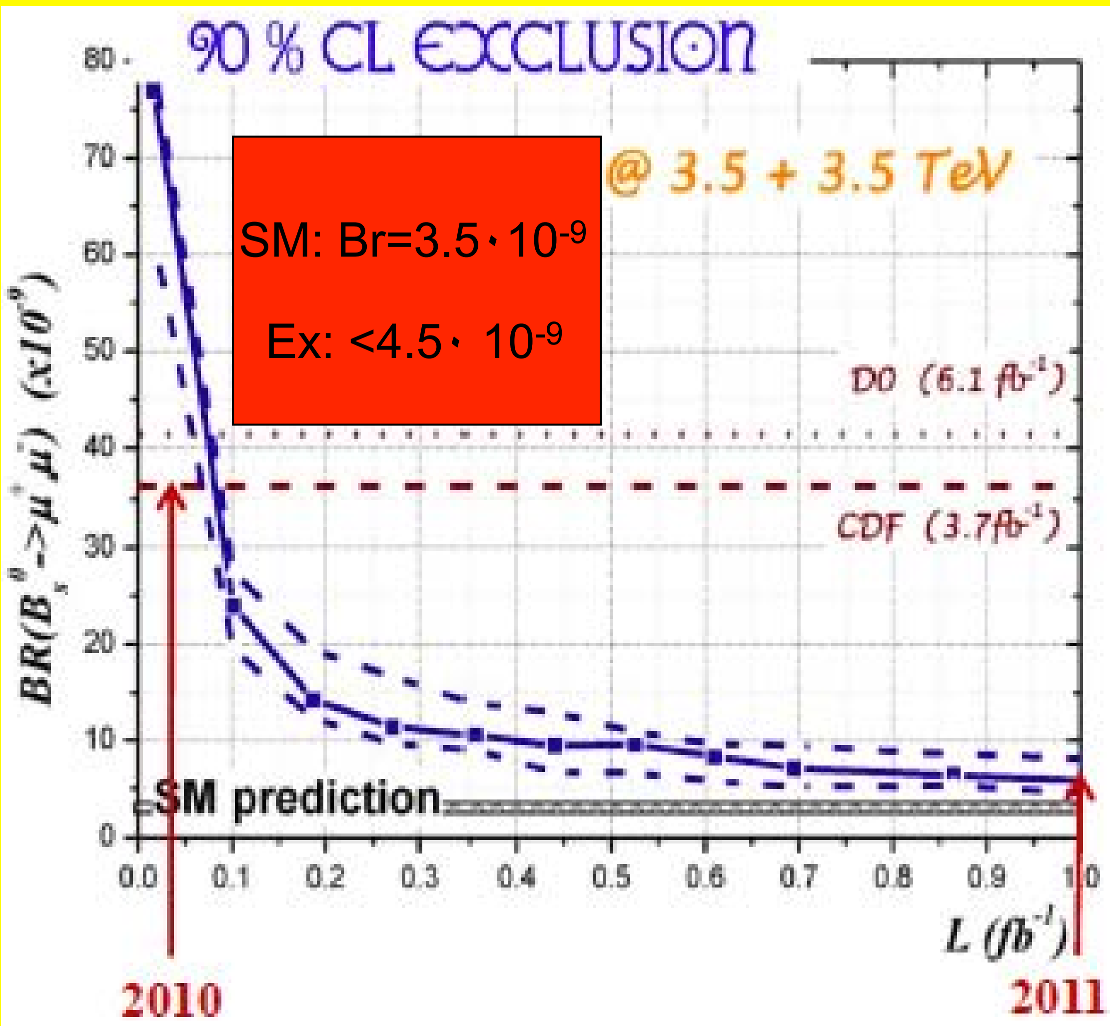
$$\left[\left(1 - \frac{4m_l^2}{m_B^2}\right) \left| \frac{(C_S - C_S')}{(m_b + m_s)} \right|^2 + \left| \frac{(C_P - C_P')}{(m_b + m_s)} + 2\frac{m_\mu}{m_{B_s}^2}(C_A - C_A') \right|^2 \right]$$

$$C_S \simeq \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left(\frac{\tan^3\beta}{4\sin^2\theta_W}\right) \left(\frac{m_b m_\mu m_t \mu}{M_W^2 M_A^2}\right) \frac{\sin 2\theta_{\tilde{t}}}{2} \left(\frac{m_{\tilde{t}_1}^2 \log\left[\frac{m_{\tilde{t}_1}^2}{\mu^2}\right]}{\mu^2 - m_{\tilde{t}_1}^2} - \frac{m_{\tilde{t}_2}^2 \log\left[\frac{m_{\tilde{t}_2}^2}{\mu^2}\right]}{\mu^2 - m_{\tilde{t}_2}^2} \right)$$

Enhancement

Suppression

Rare Decays: $Br[B_s \to \mu^+\mu^-]$ Constraint

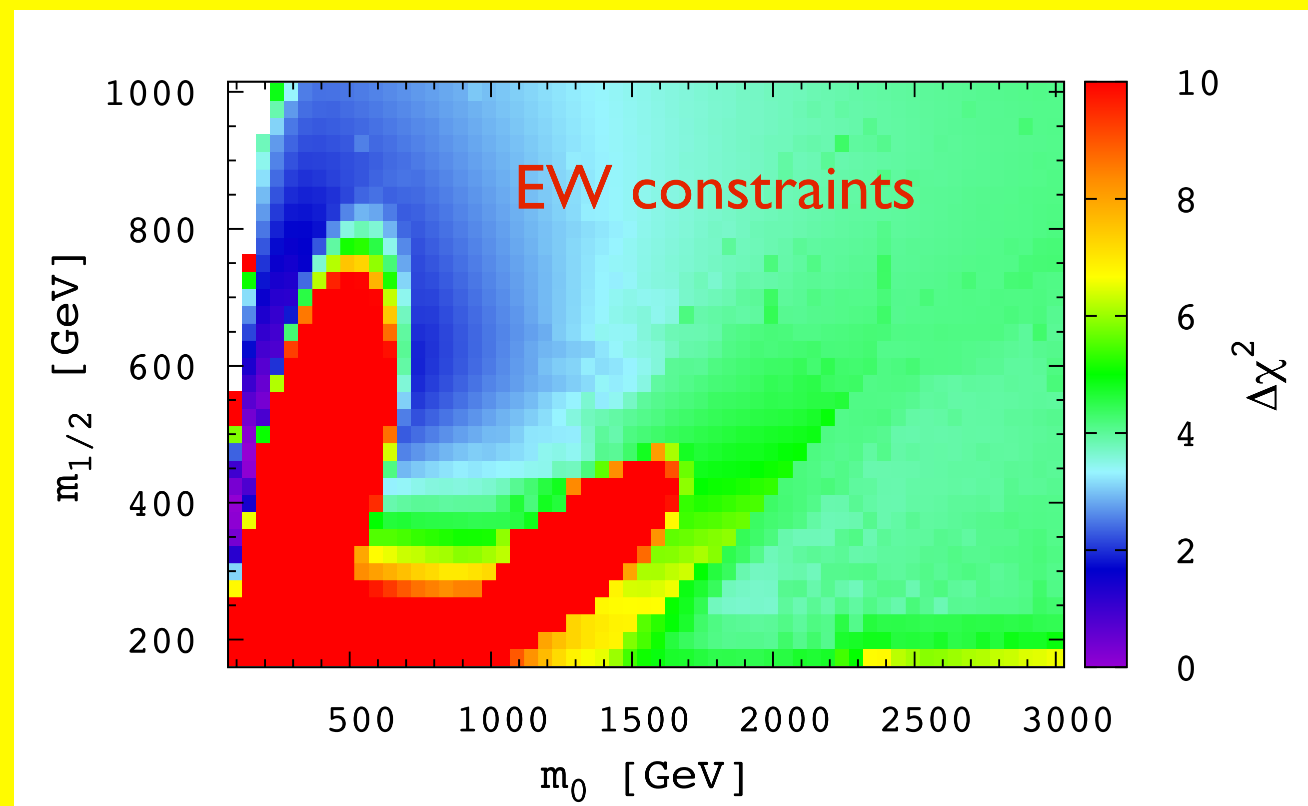


95% C.L. Excluded regions for

$$Br[B_s \to \mu^+\mu^-] < 4.5 \cdot 10^{-9}$$

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

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



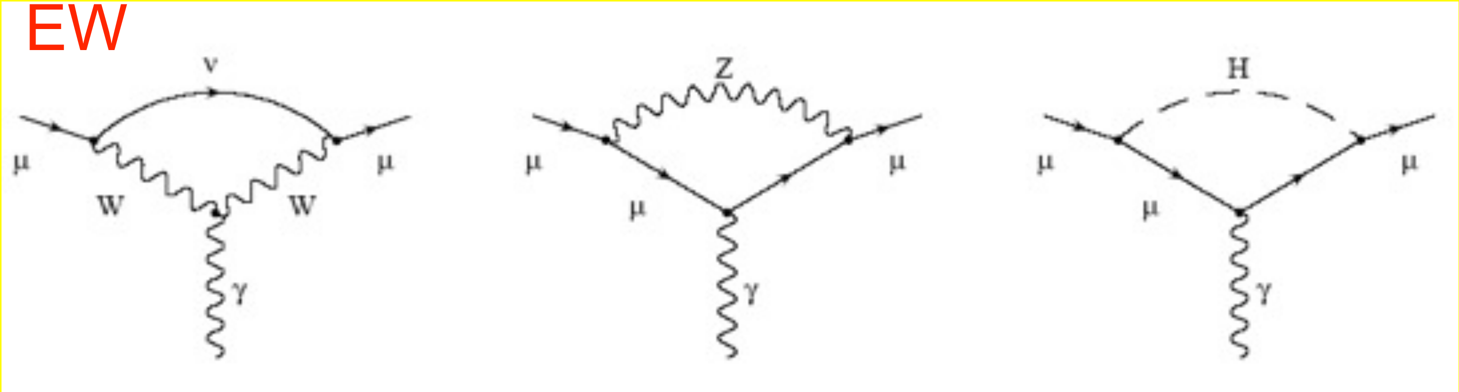
Negative interference is possible

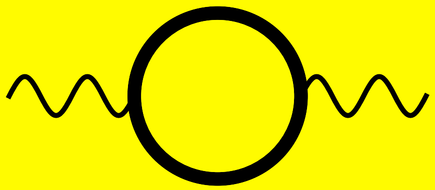
Anomalous magnetic moment

$$a_\mu^{exp} = 11\,659\,202\,(14)(6) \cdot 10^{-10}$$
$$a_\mu^{SM} = 11\,659\,159.6\,(6.7) \cdot 10^{-10}$$

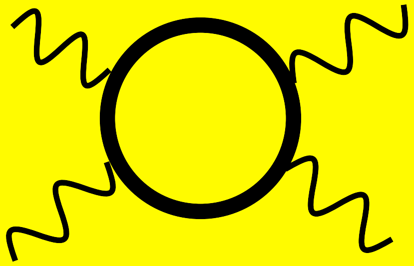
$$a_\mu^{exp} - a_\mu^{SM} = (27 \pm 10) \cdot 10^{-10}$$

$$\begin{aligned} a_\mu^{QED} &= 11\,658\,470.56\,(0.29) \cdot 10^{-10} \\ a_\mu^{weak} &= 15.1\,(0.4) \cdot 10^{-10} \\ a_\mu^{hadr} &= 673.9\,(6.7) \cdot 10^{-10} \end{aligned}$$





vacuum pol

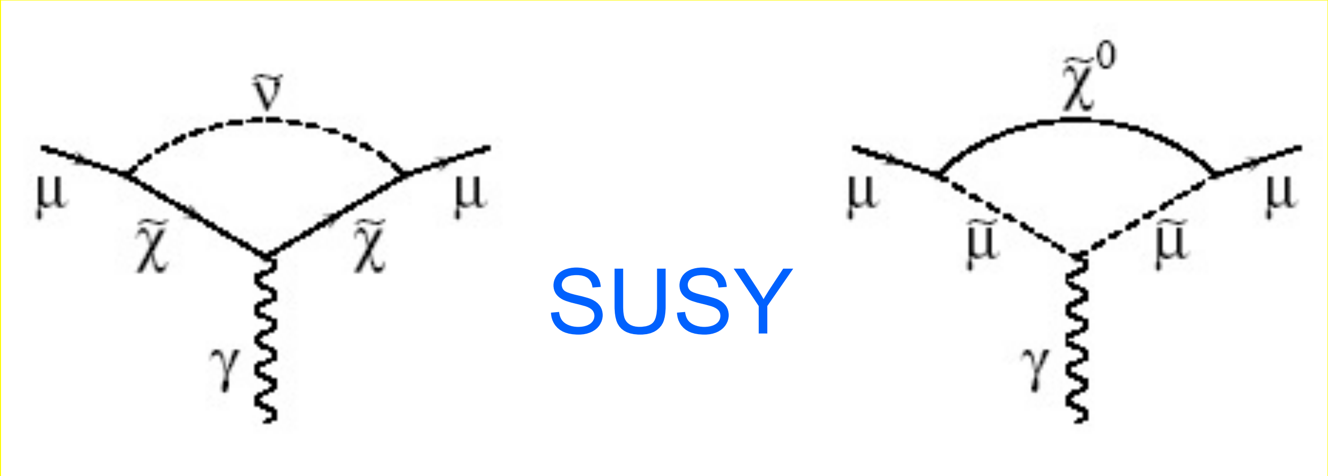


light-light scat

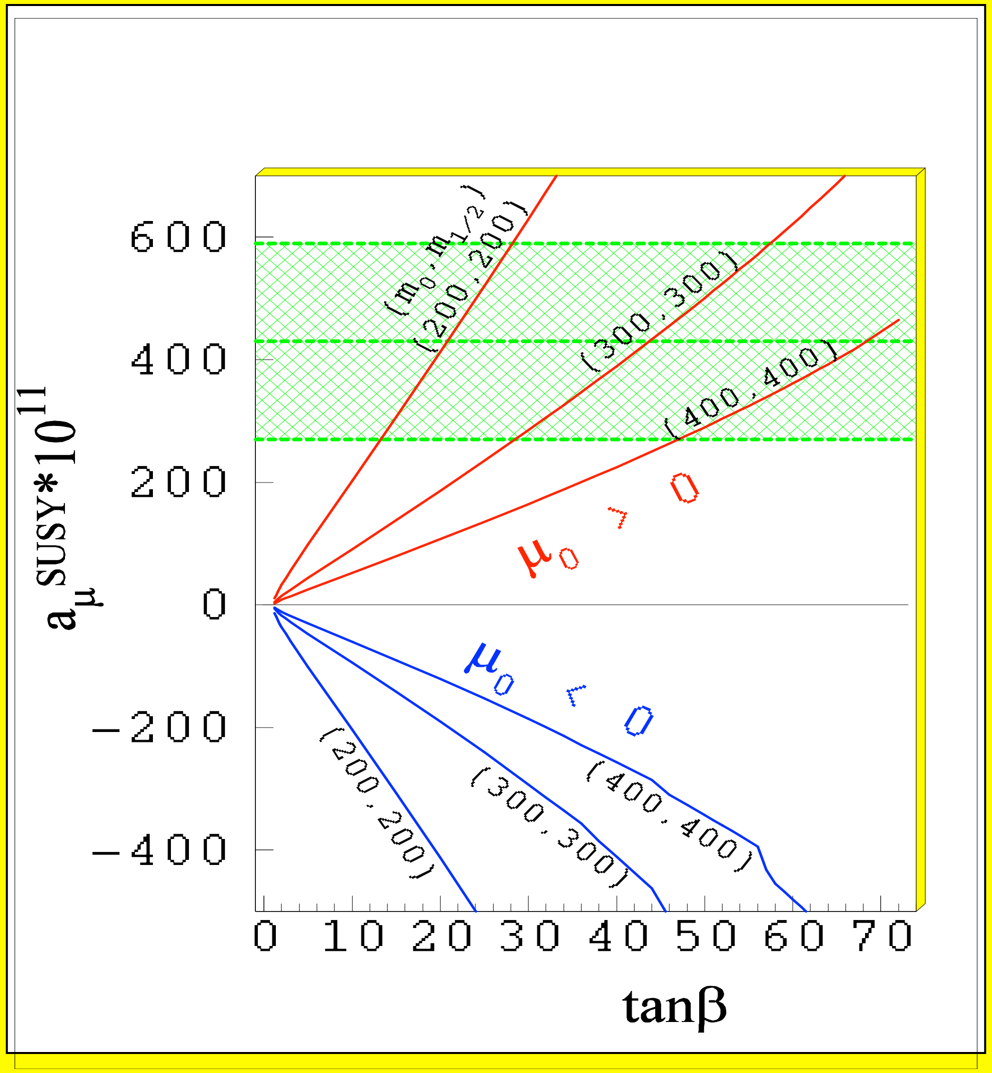
$$|a_\mu^{SUSY}| \simeq \frac{\alpha(M_Z)}{8\pi\, Sin^2\theta_W} \frac{m_\mu^2}{M_{SUSY}^2} tan\beta \left(1 - \frac{4\alpha}{\pi} log \frac{M_{SUSY}}{m_\mu}\right) \simeq 140 \cdot 10^{-11} \left(\frac{100\ \text{GeV}}{M_{SUSY}}\right)^2 tan\beta$$

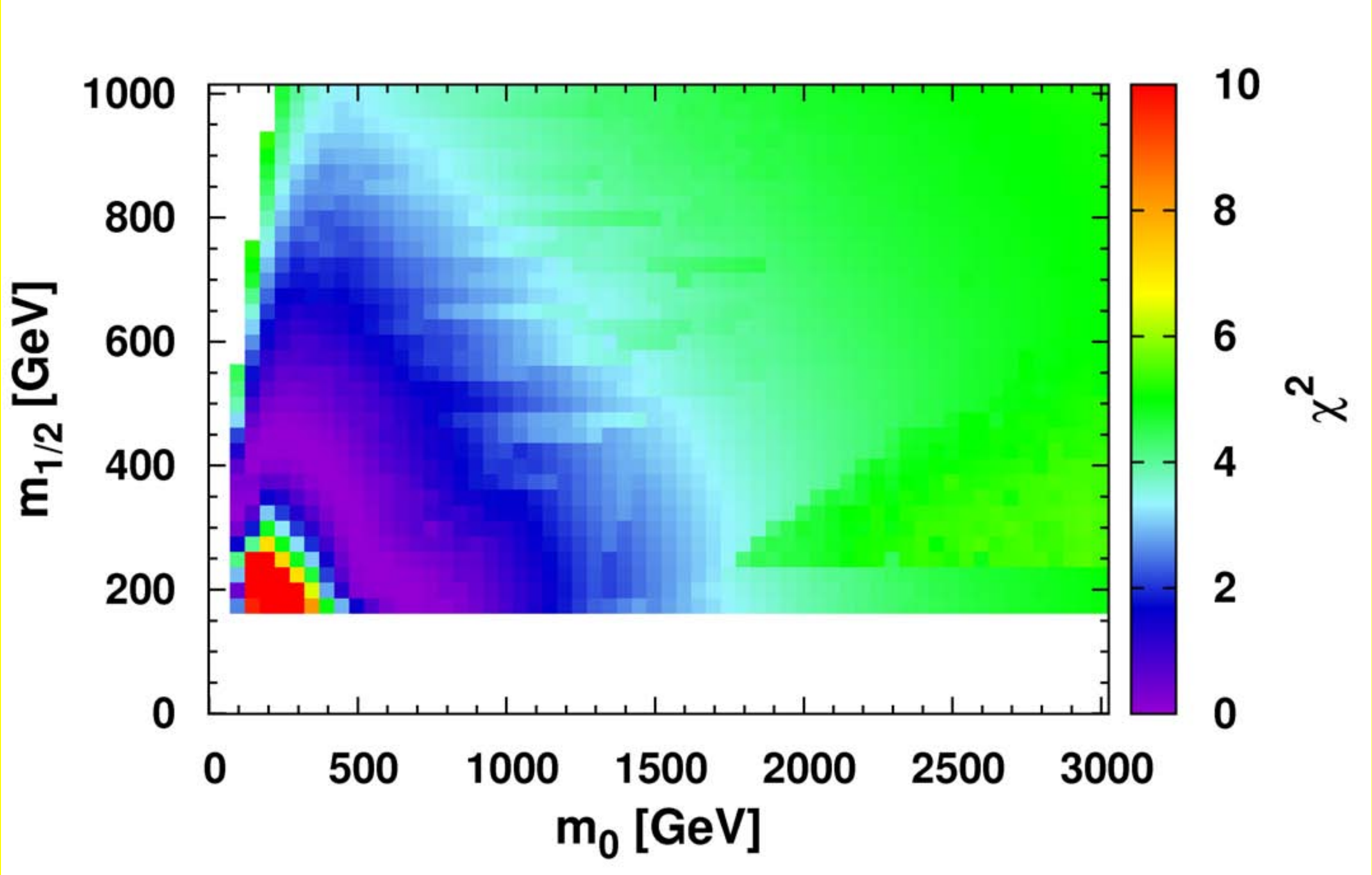
Suppression

Enhancement



g-2 Constraint on Parameter space





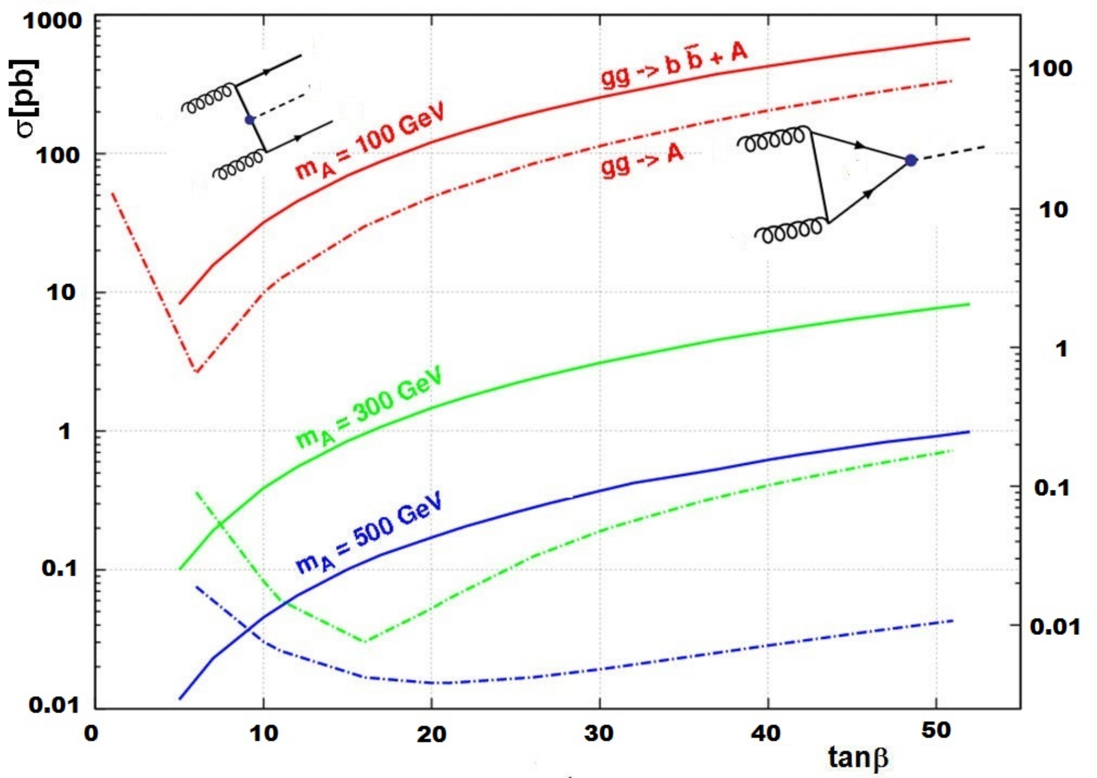
Fixes the sign of μ

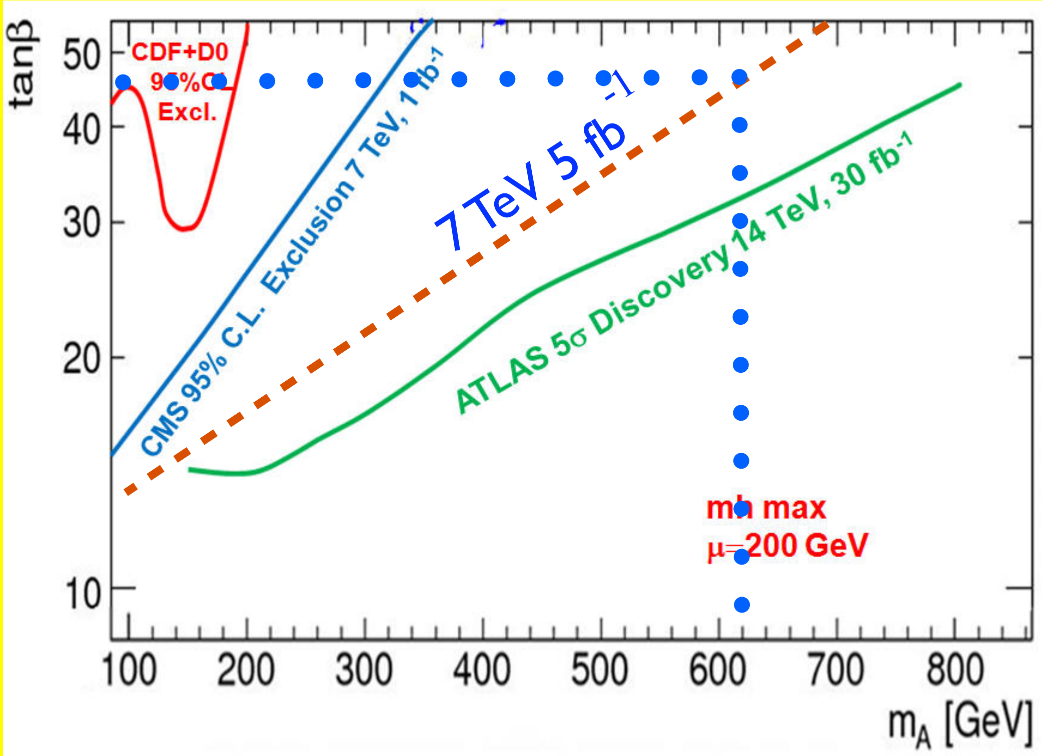
The only requirement that limits the SUSY masses from above

Almost excluded by rare decay

$$Br[B_s \to \mu^+\mu^-]$$

Heavy Higgs Production at the LHC





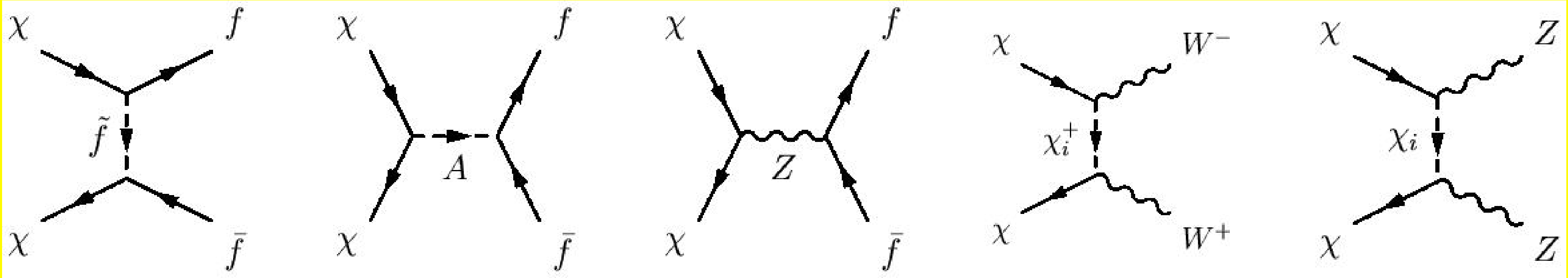
$$\sigma_{Higgs} = \frac{1}{32}\int_0^1 dx_1 dx_2\ g[x_1]\ g[x_2]\ |\mathcal{M}_{Higgs}|^2 \frac{2\pi}{m^2_{Higgs}} \delta(E^2 x_1 x_2 - m^2_{Higgs})$$

$$\mathcal{M}_h = \frac{\alpha_s}{4\pi}\frac{m_h^2}{2\sqrt{2}v}\left(\frac{\cos\alpha}{\sin\beta}F^h_{1/2}[\frac{4m_t^2}{m_h^2}] - \frac{\sin\alpha}{\cos\beta}F^h_{1/2}[\frac{4m_b^2}{m_h^2}]\right),$$

$$\mathcal{M}_H = \frac{\alpha_s}{4\pi}\frac{m_H^2}{2\sqrt{2}v}\left(\frac{\sin\alpha}{\sin\beta}F^H_{1/2}[\frac{4m_t^2}{m_H^2}] + \frac{\cos\alpha}{\cos\beta}F^H_{1/2}[\frac{4m_b^2}{m_H^2}]\right),$$

$$\mathcal{M}_A = \frac{\alpha_s}{4\pi}\frac{m_A^2}{2\sqrt{2}v}\left(\frac{\cos\beta}{\sin\beta}F^A_{1/2}[\frac{4m_t^2}{m_A^2}] + \frac{\sin\beta}{\cos\beta}F^A_{1/2}[\frac{4m_b^2}{m_A^2}]\right)$$

Relic Abundace of the Dark Matter



$\propto \frac{\mathbf{m_\chi \cdot m_f}}{\mathbf{m_{\tilde{f}}^2}}$ $\quad$ $\propto \frac{\tan\beta \cdot \mathbf{m_{f_d}}}{\mathbf{m_W}} \mathbf{N_1 N_{3(4)}}$, $\tan\beta \cdot \mathbf{m_{f_d}} \leftrightarrow \frac{\mathbf{m_{f_u}}}{\tan\beta}$ $\quad$ $\propto \frac{\mathbf{m_f \cdot m_\chi}}{\mathbf{m_Z^2}} \mathbf{N^2_{3(4)}}$ $\quad$ $\propto \frac{\mathbf{1}}{\mathbf{1+(m_{\chi_i^+}/m_\chi)^2-(m_W/m_\chi)^2}}$, $(\mathbf{m_{\chi_i^+}, m_W}) \leftrightarrow (\mathbf{m_{\chi_i}, m_Z})$

The Dark Matter Annihilation

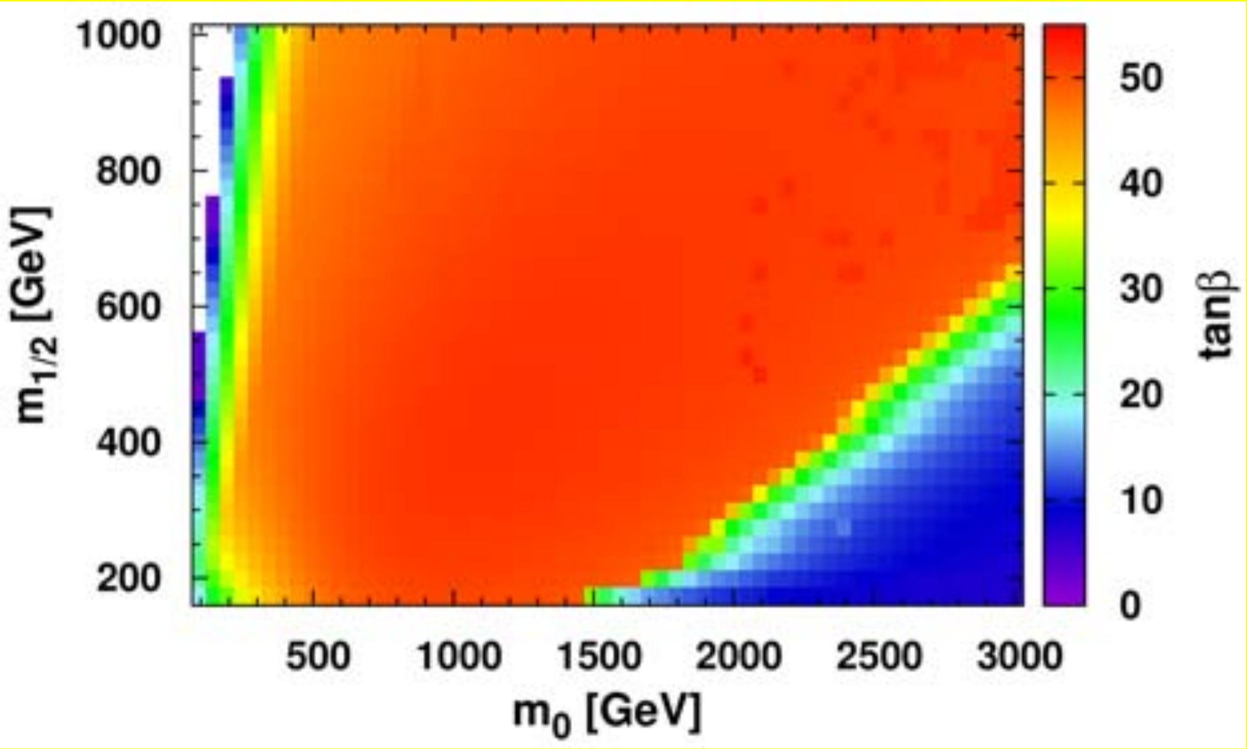
WMAP: $\Omega_{DM} h^2 = 0.1131 \pm 0.0034$ $\quad$ $\Omega h^2 = \frac{3 \cdot 10^{-27}}{< \sigma v >}$

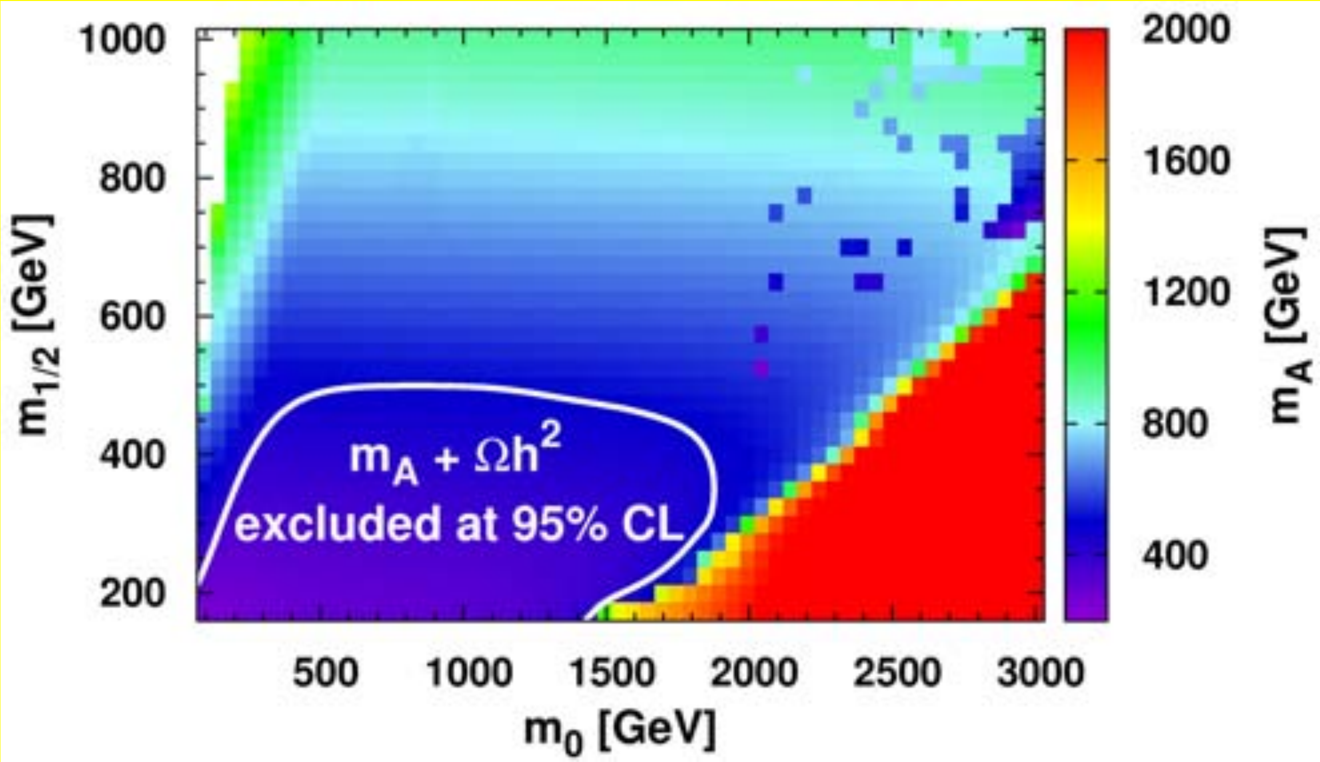
$h \approx 0.71$ $\quad$ $< \sigma v > = 2 \cdot 10^{-26} cm^3/s$

$$< \sigma v > \sim \frac{M_\chi^4 m_b^2 \tan^2\beta}{\sin^4 2\theta_W \, M_Z^2} \frac{(N_{31}\sin\beta - N_{41}\cos\beta)^2 (N_{21}\cos\theta_W - N_{11}\sin\theta_W)^2}{\left(4M_\chi^2 - M_A^2\right)^2 + M_A^2 \Gamma_A^2}$$

$$|\tilde{\chi}_1^0\rangle = N_{11}|B_0\rangle + N_{21}|W_0^3\rangle + N_{31}|H_1\rangle + N_{41}|H_2\rangle$$

Relic Abundace of the DM Constraint





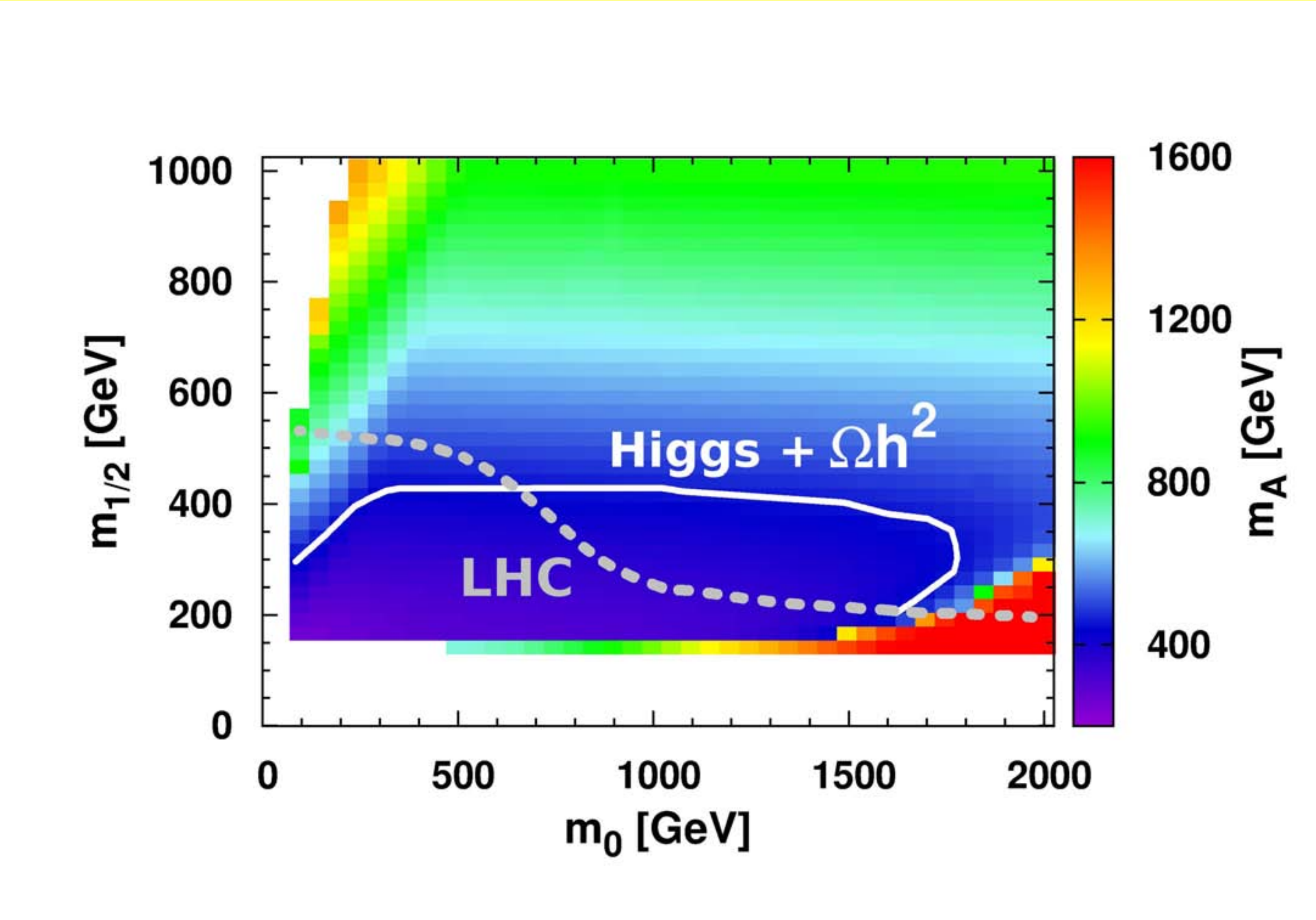
The value of $\tan\beta$

$\tan\beta \approx 50$ almost everywhere except for the coannihilation regions

The value of m_A

m_A may be as low as 500 GeV except for the coannihilation regions

SUSY Limits without Direct DM Search

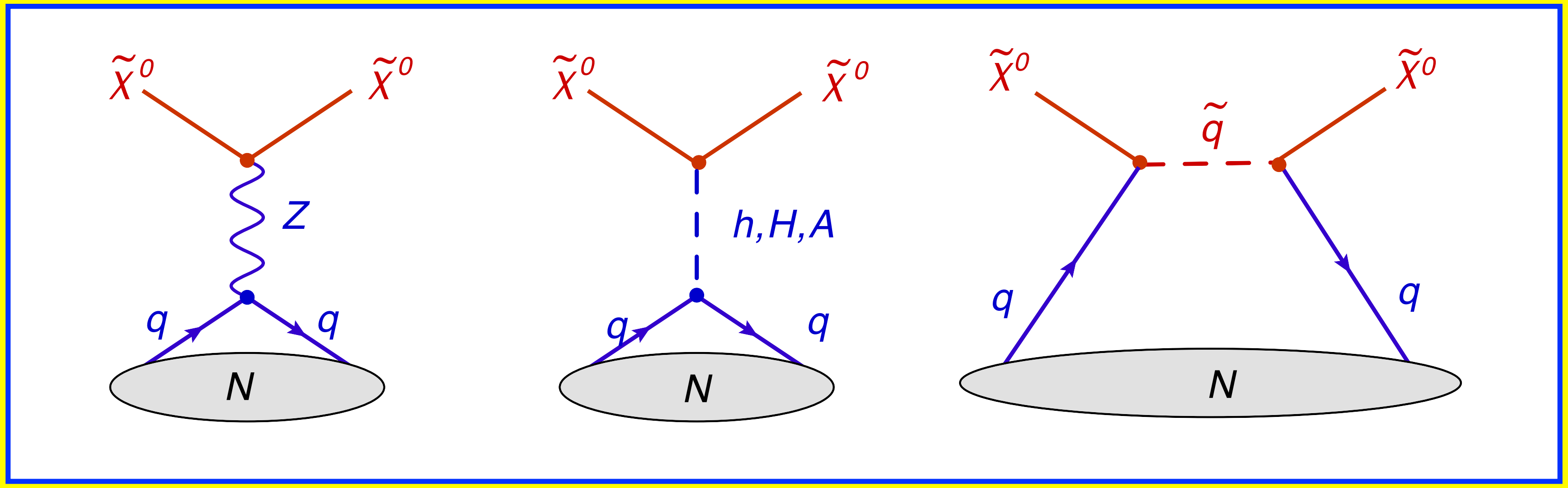


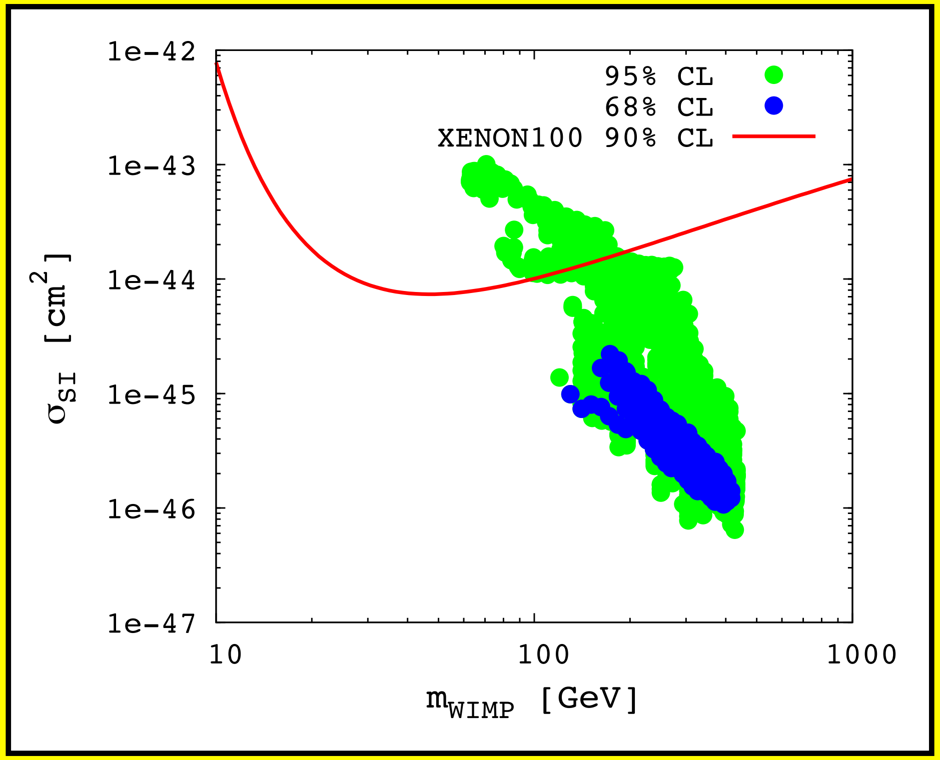
The values of A_0 and $\tan\beta$ are ajusted

This includes:

- the Higgs searches
- the relic abundancy
- and collider limits

Direct DM Searches



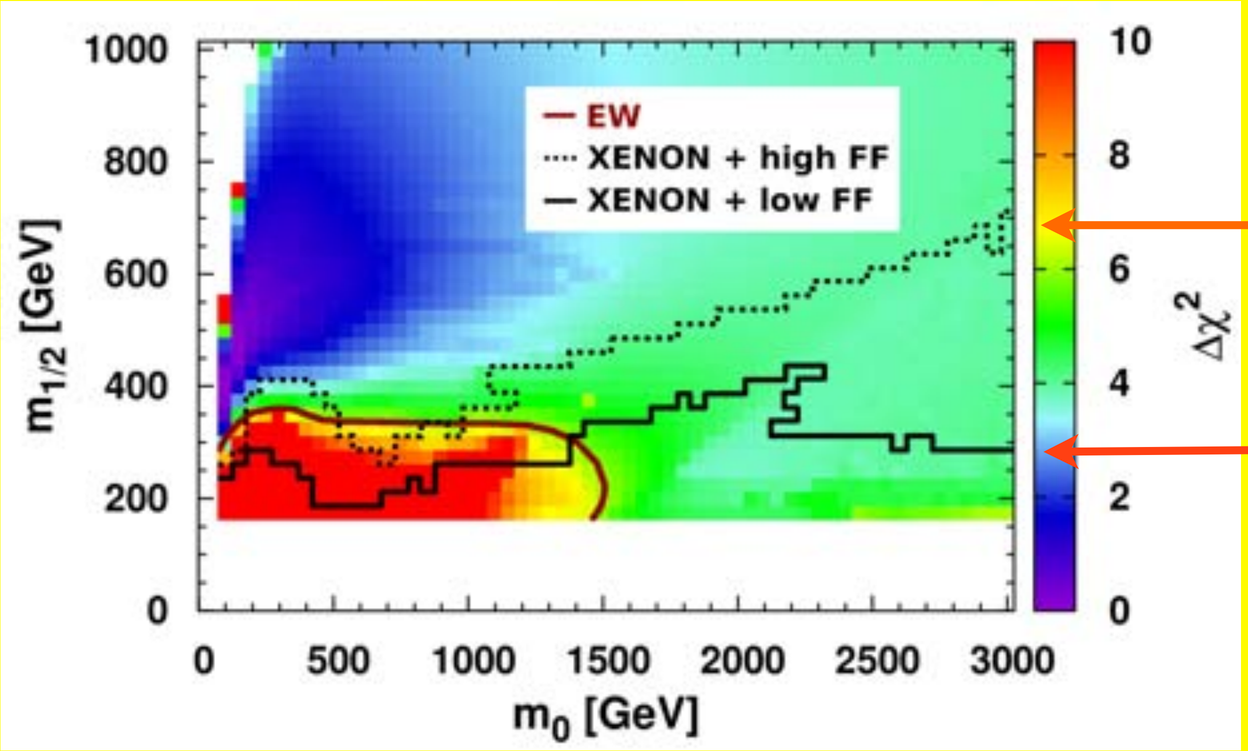


$$\sigma = \frac{4}{\pi}\frac{m_{\rm DM}^2 m_N^2}{(m_{\rm DM}+m_N)^2}\left(Zf_p+(A-Z)f_n\right)^2$$

$$f_{p,n} = \sum_{q=u,d,s} G_q f_{Tq}^{(p,n)}\frac{m_{p,n}}{m_q} + \frac{2}{27} f_{TG}^{(p,n)} \sum_{q=c,b,t} G_q \frac{m_{p,n}}{m_q} \qquad m_p f_{Tq}^{(p)} \equiv \langle p | m_q \bar{q} q | p \rangle$$

$$\begin{aligned}
G_q(A) &= 0, \\
G_u(h) &= \frac{-e^2 m_u}{2\sin^2 2\theta_W M_Z}(N_{21}\cos\theta_W - N_{11}\sin\theta_W)\frac{\cos\alpha}{\sin\beta}\frac{(N_{41}\cos\alpha + N_{31}\sin\alpha)}{M_h^2}, \\
G_d(h) &= \frac{e^2 m_d}{2\sin^2 2\theta_W M_Z}(N_{21}\cos\theta_W - N_{11}\sin\theta_W)\frac{\sin\alpha}{\cos\beta}\frac{(N_{41}\cos\alpha + N_{31}\sin\alpha)}{M_h^2}, \\
G_u(H) &= \frac{-e^2 m_u}{2\sin^2 2\theta_W M_Z}(N_{21}\cos\theta_W - N_{11}\sin\theta_W)\frac{\sin\alpha}{\sin\beta}\frac{(N_{41}\sin\alpha - N_{31}\cos\alpha)}{M_H^2}. \\
G_d(H) &= \frac{-e^2 m_d}{2\sin^2 2\theta_W M_Z}(N_{21}\cos\theta_W - N_{11}\sin\theta_W)\frac{\cos\alpha}{\cos\beta}\frac{(N_{41}\sin\alpha - N_{31}\cos\alpha)}{M_H^2}
\end{aligned}$$

SUSY Limits from Direct DM Search

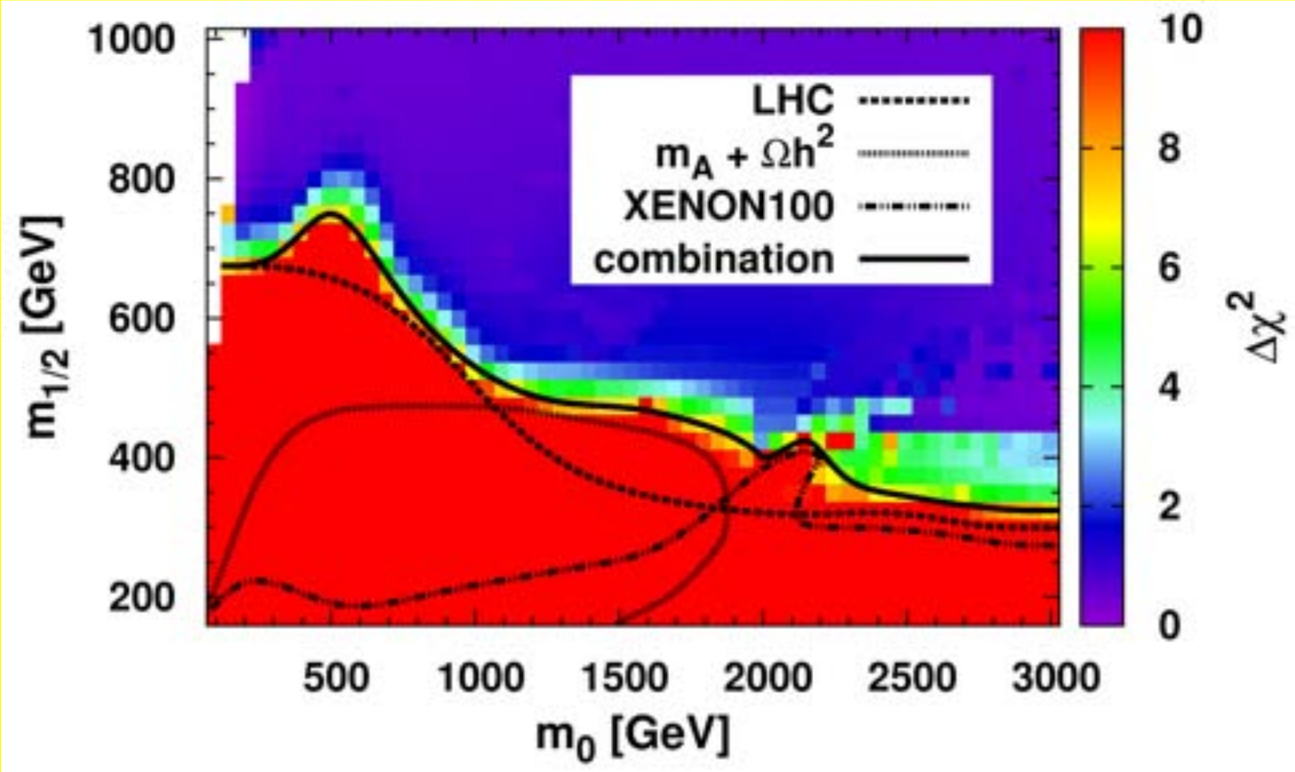


Low Energy Form Factors

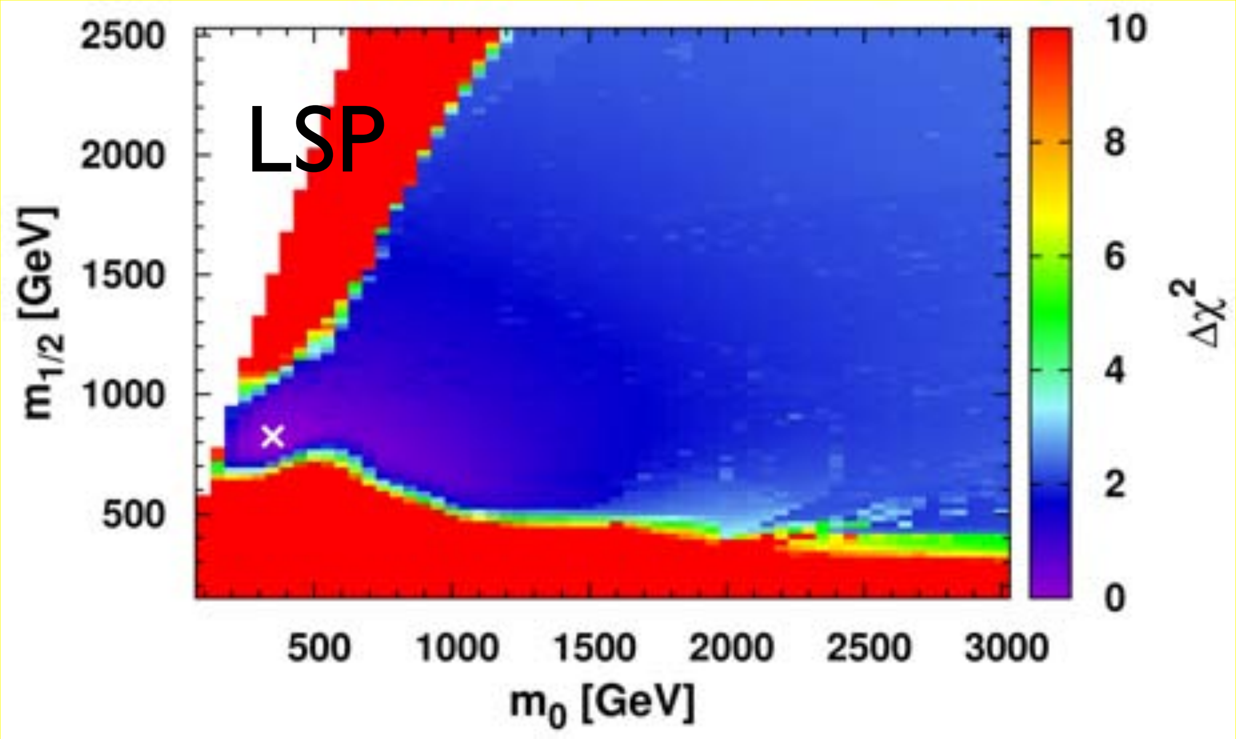
Lattice Form Factors

- LHC constraints are rather insensitive to large values of m_0
- They can be supplemented by direct DM searches

SUSY Limits from Combined Fit to all Data with 5/fb

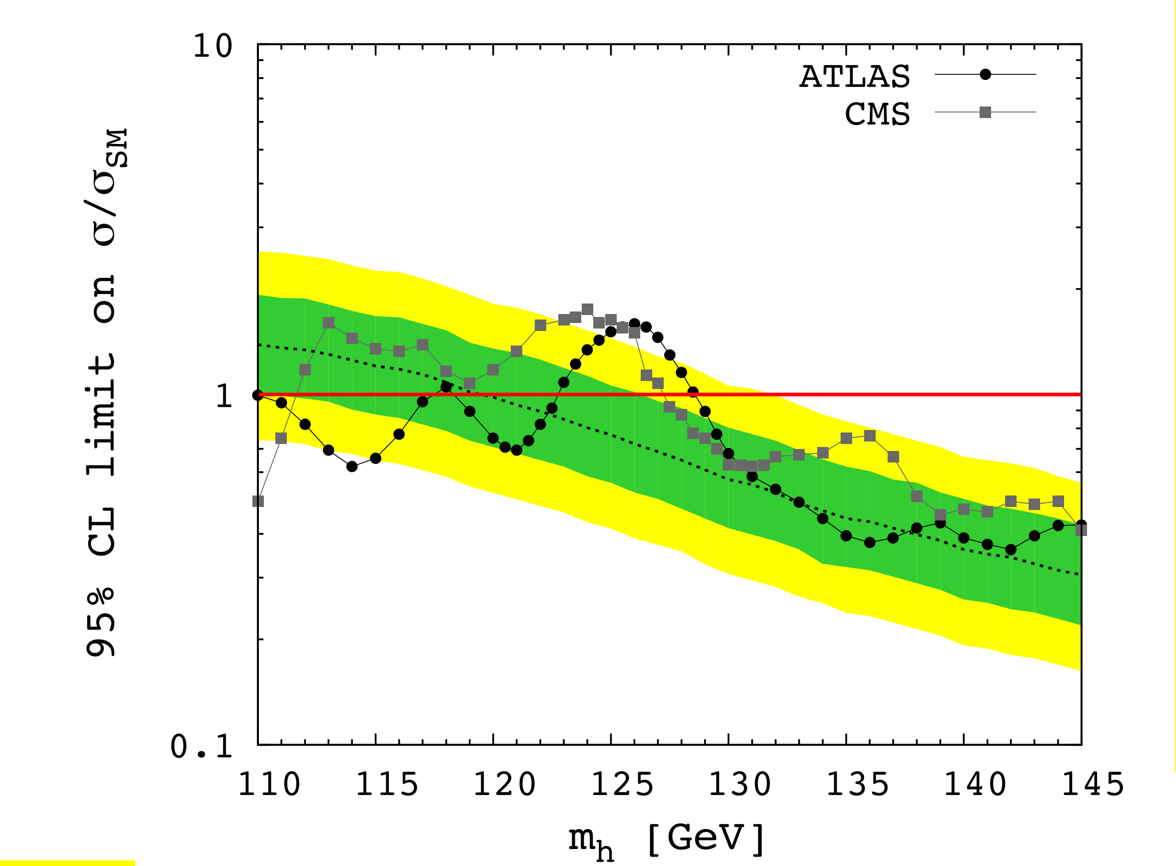


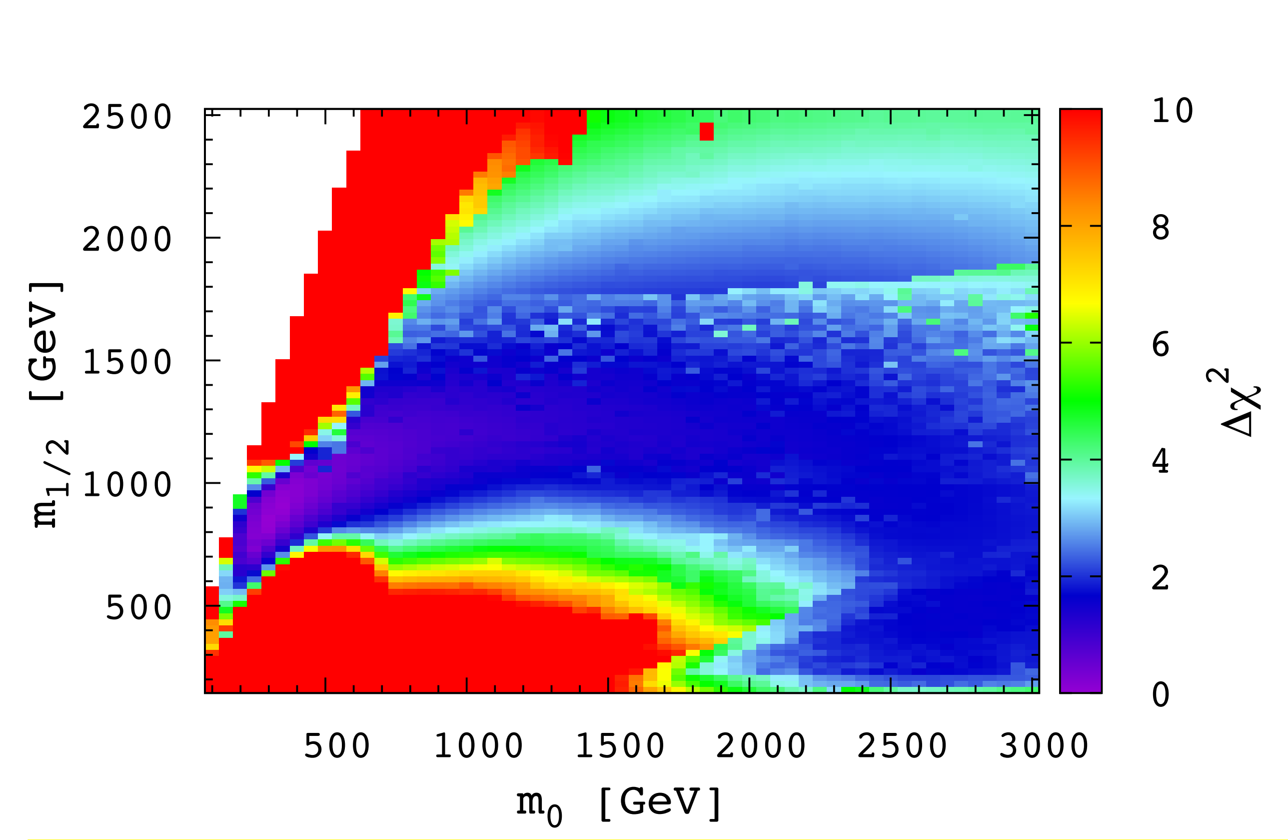
Larger scale for $m_{1/2}$



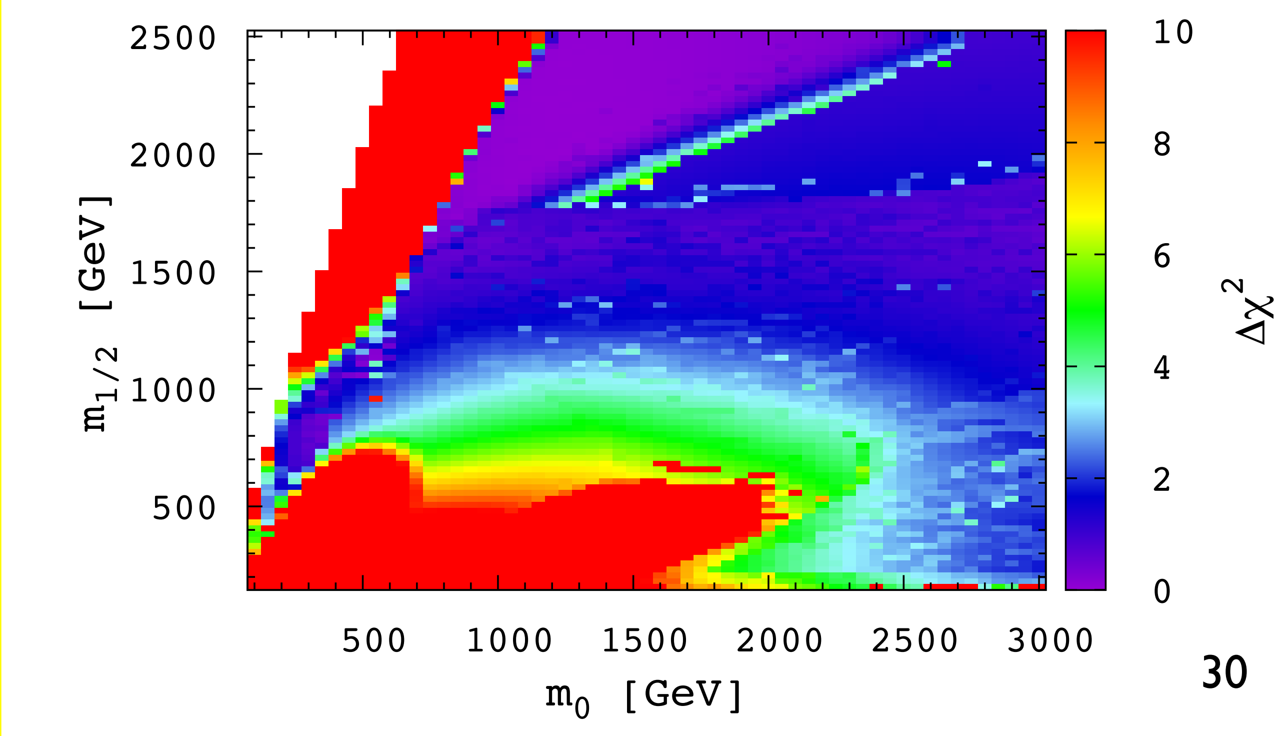
The values of $\tan\beta$ and A_0 are adjusted

Constraints from the lightest Higgs of 125 GeV





$$M_{Higgs} = 119 \pm 1.8\ GeV$$



$$M_{Higgs} = 125 \pm 3.6\ GeV$$

Conclusions

- LHC is on the way of covering the parameter space of the MSSM

- Modern combined limit on $m_{1/2}$ is about 500 GeV for $m_0 < 1000\ GeV$

- This implies the lower limit on the WIMP mass of 210 GeV and gluino of 1190 GeV

- For larger values of m_0 the values of $m_{1/2}$ drop below 350 GeV which gives LSP mass of 130 GeV and gluino mass of 970 GeV

- Today's lower limit on squark masses (except $\tilde{t}$) is 1400 GeV and gluino mass is 900 GeV

Let 2012 be the year of Higgs discovery and SUSY evidence!