36th International Conference on High Energy Physics

4 – 11 July 2012
Melbourne Convention and Exhibition Centre
Melbourne, Australia

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

Dmitri Kazakov

JINR(Dubna) / ITEP (Moscow)

ICHEP2012 Melbourne

36th International Conference on High Energy Physics

4 – 11 July 2012

Melbourne Convention and Exhibition Centre

Melbourne, Australia

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

Dmitri Kazakov

JINR(Dubna) / ITEP (Moscow)

in collaboration with W. de Boer, C. Beskidt and F. Ratnikov, KIT (Karlsruhe)

Phys.Lett. B705 (2011) 393 (arXiv: 1109.6775)

JHEP 05 (2012) 94 (arXiv: 1202.3366)

Where is SUSY?

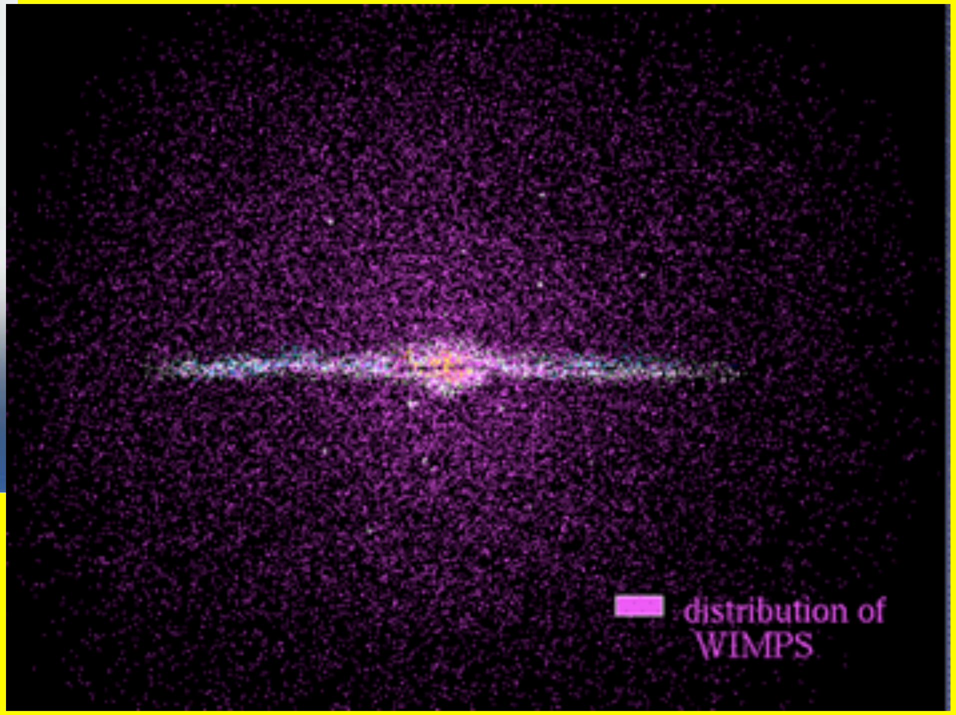
Where is SUSY?

Accelerators

Where is SUSY?

Accelerators

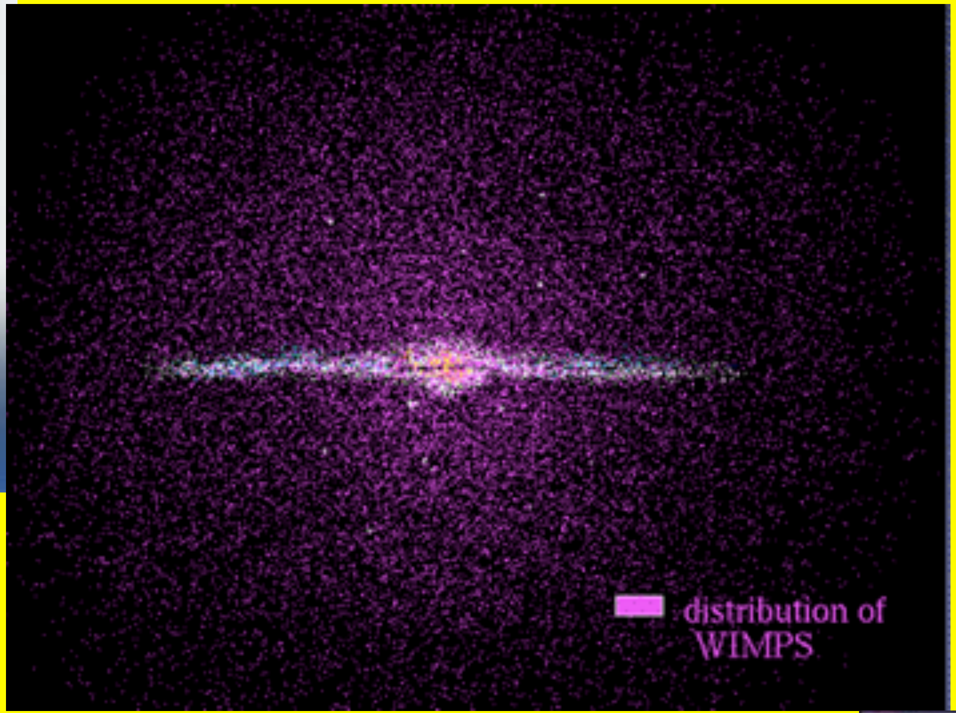
Telescopes



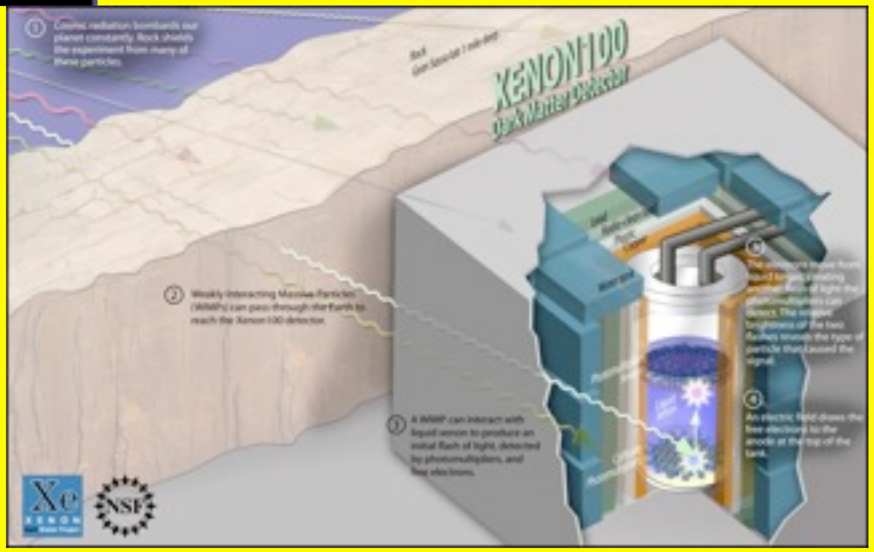
Where is SUSY?

Accelerators

Telescopes



Underground
facilities



Exp Data & Th Frame

Exp Data & Th Frame

Exp data

Exp Data & Th Frame

Exp data

✓ LEP II & Tevatron limits on SUSY particle masses

Exp Data & Th Frame

Exp data

✓ LEP II & Tevatron limits on SUSY particle masses

✓ Direct SUSY search at LHC @ 5/fb

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

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

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

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

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

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

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

Exp Data & Th Frame

Exp data

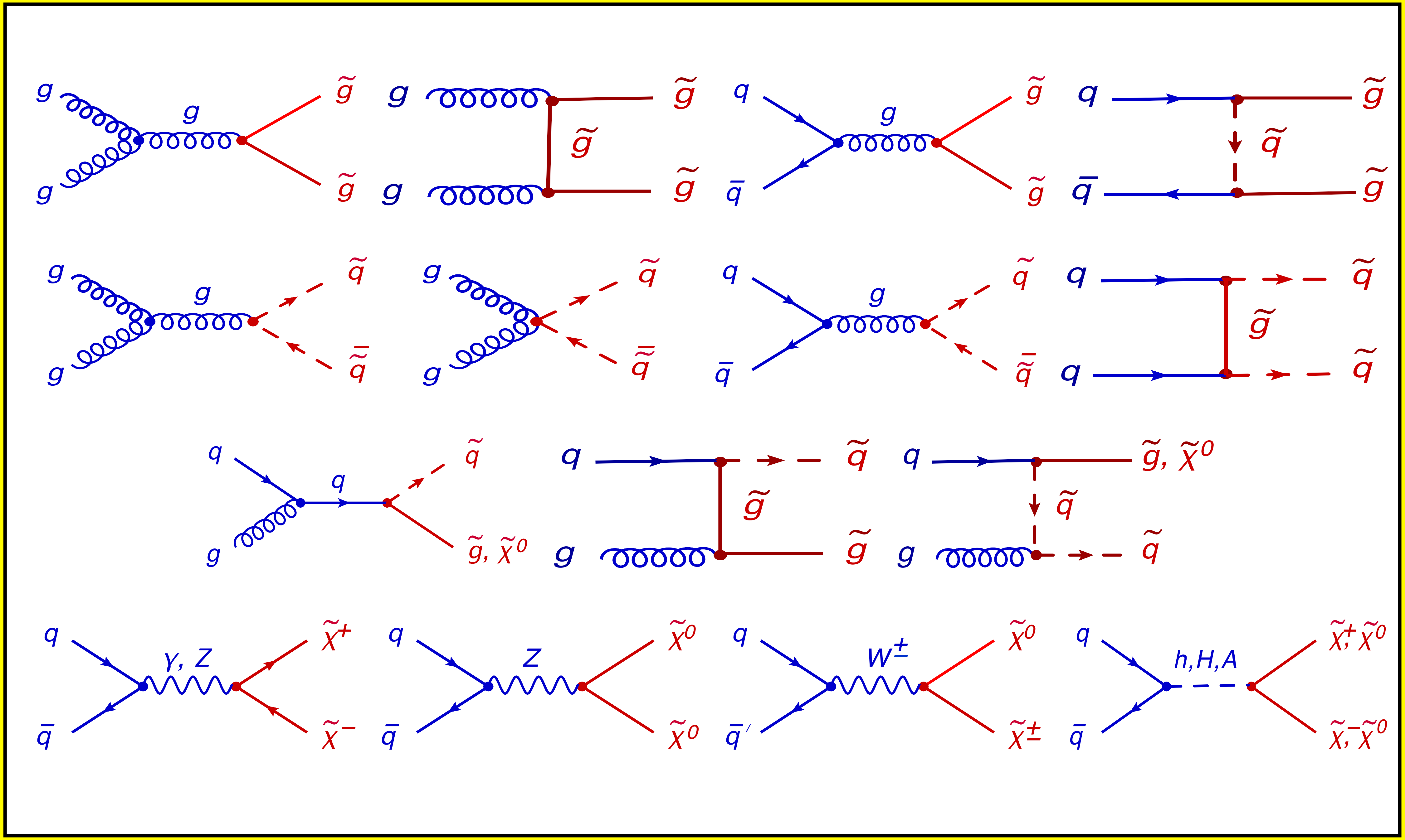
✓ LEP II & Tevatron limits on SUSY particle masses
✓ Direct SUSY search at LHC @ 5/fb
✓ Higgs boson(s) searches
✓ Rare decays ($B_s \to s\gamma,\ B_s \to \mu^+\mu^-, B_s \to \tau\nu$)
✓ Relic abundancy of Dark Matter in the Universe
✓ Direct search for the DM
✓ g-2 of the muon

Theory Framework

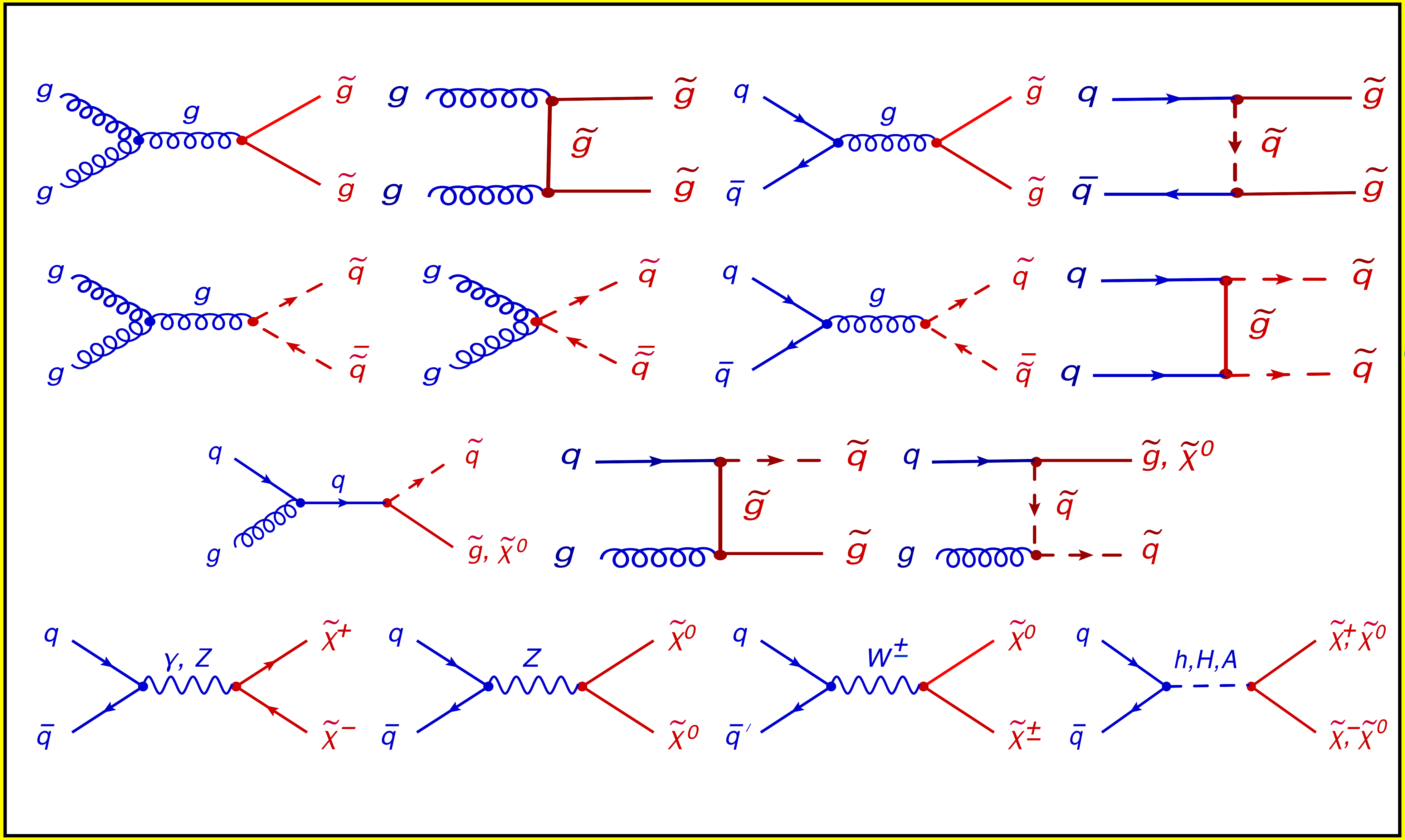
MSSM with SUGRA SUSY breaking

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

SUSY Production at the LHC

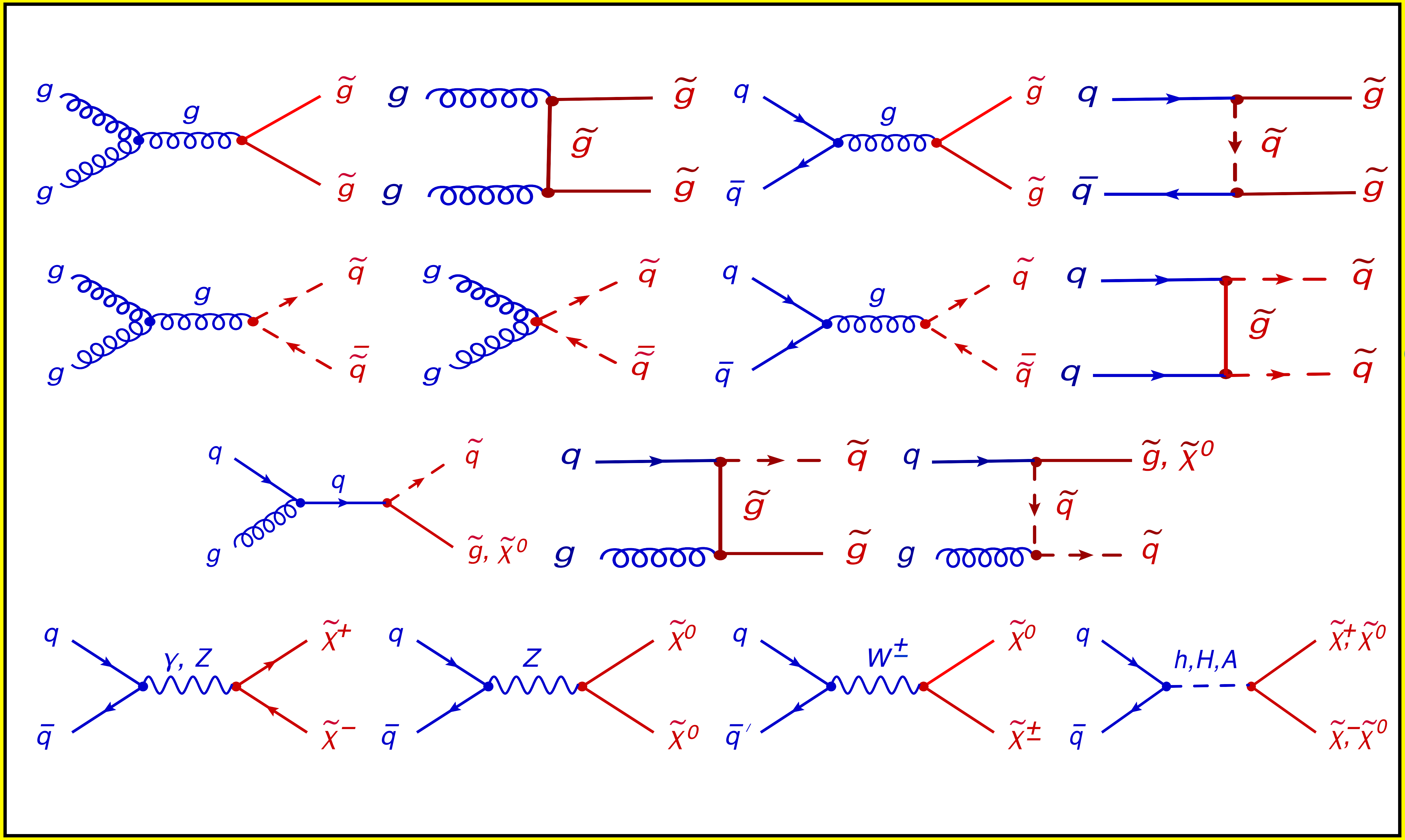


SUSY Production at the LHC



Strong Int's

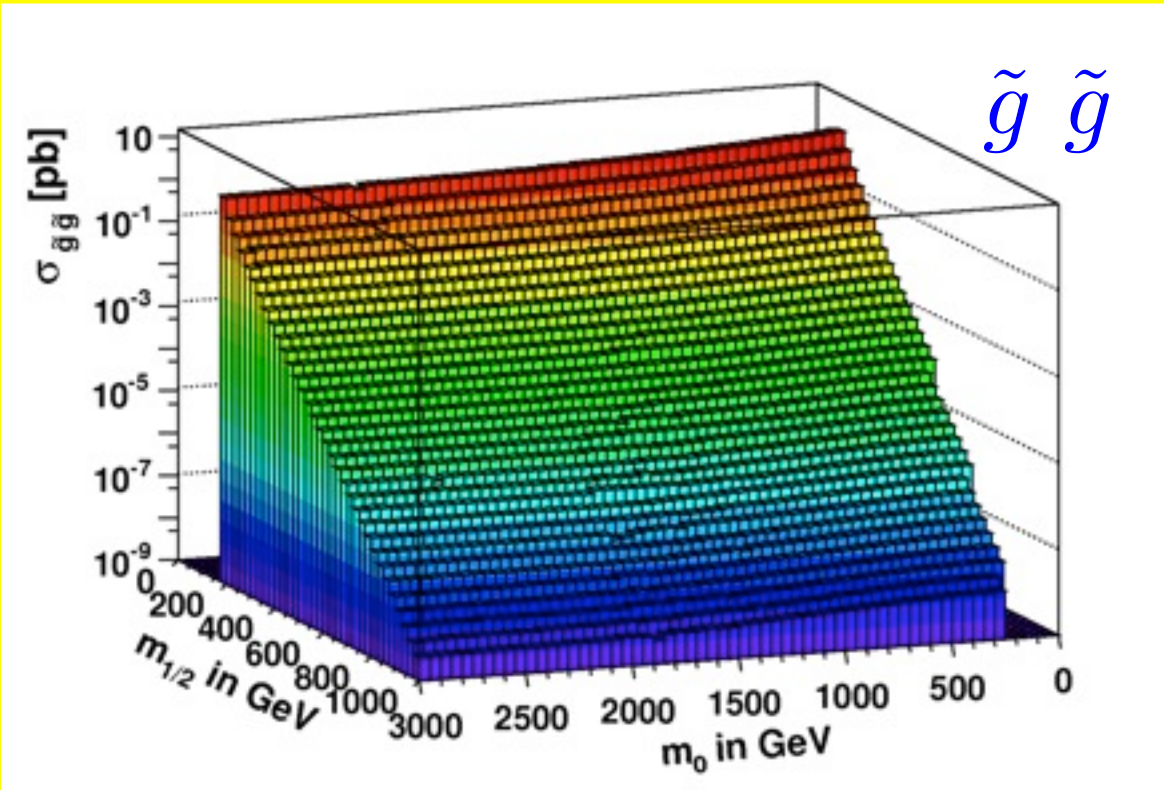
SUSY Production at the LHC

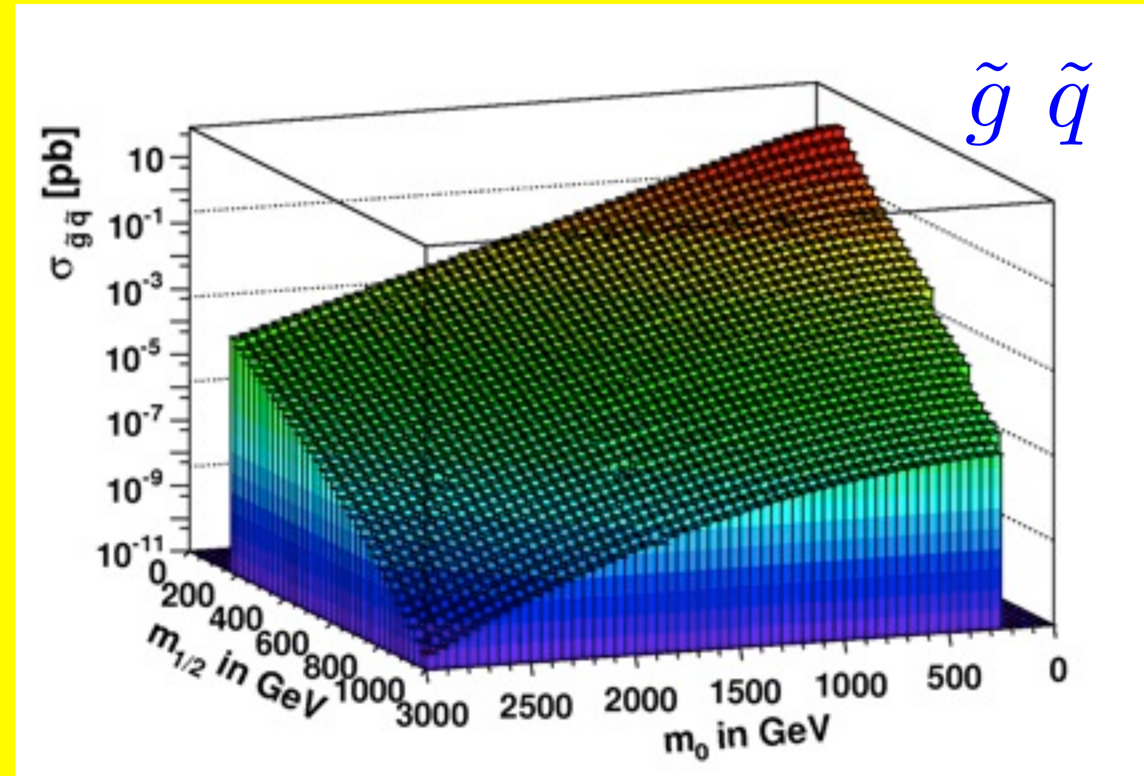


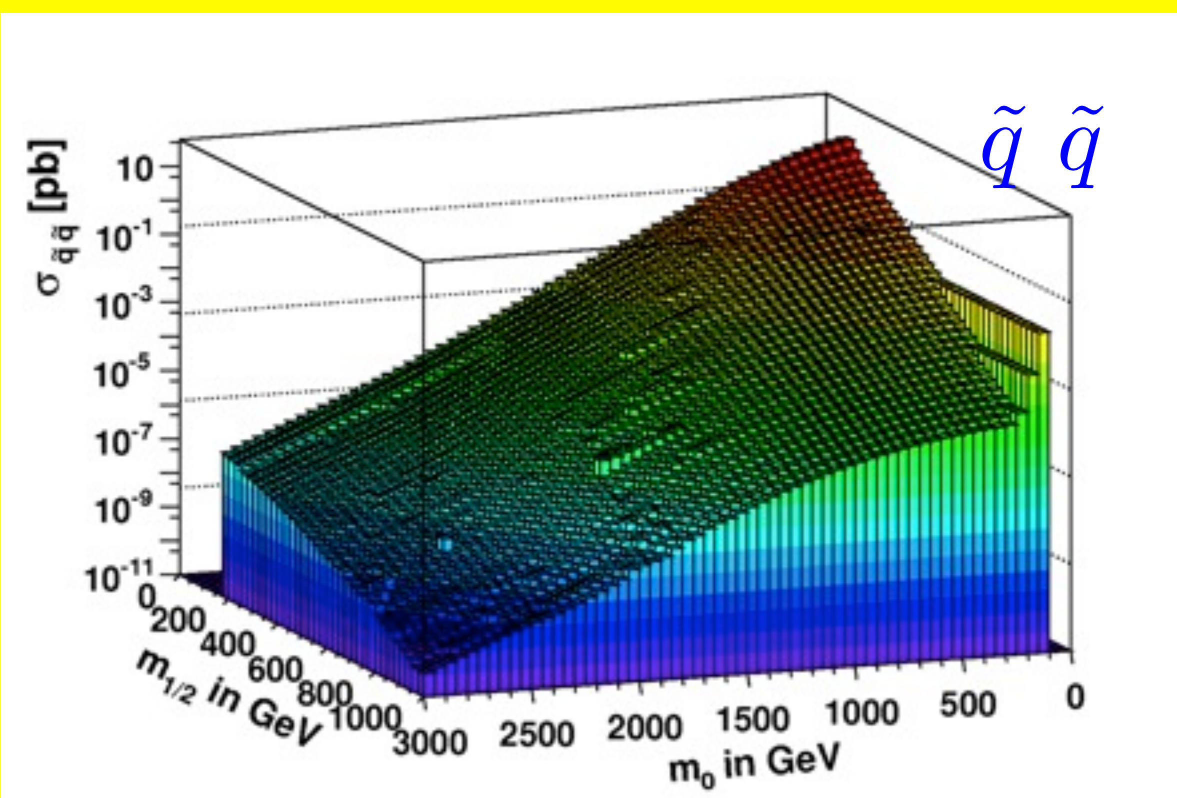
Strong Int's

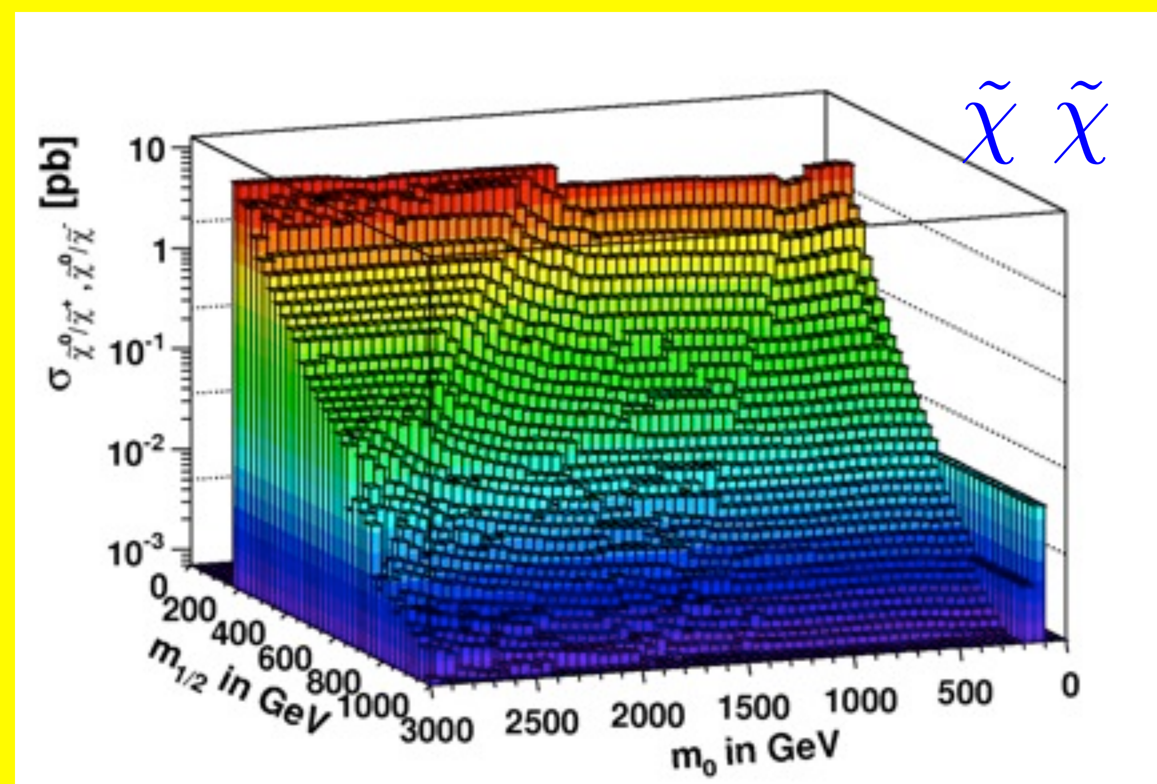
Weak Int's

SUSY x-sections at the LHC @ 7 TeV





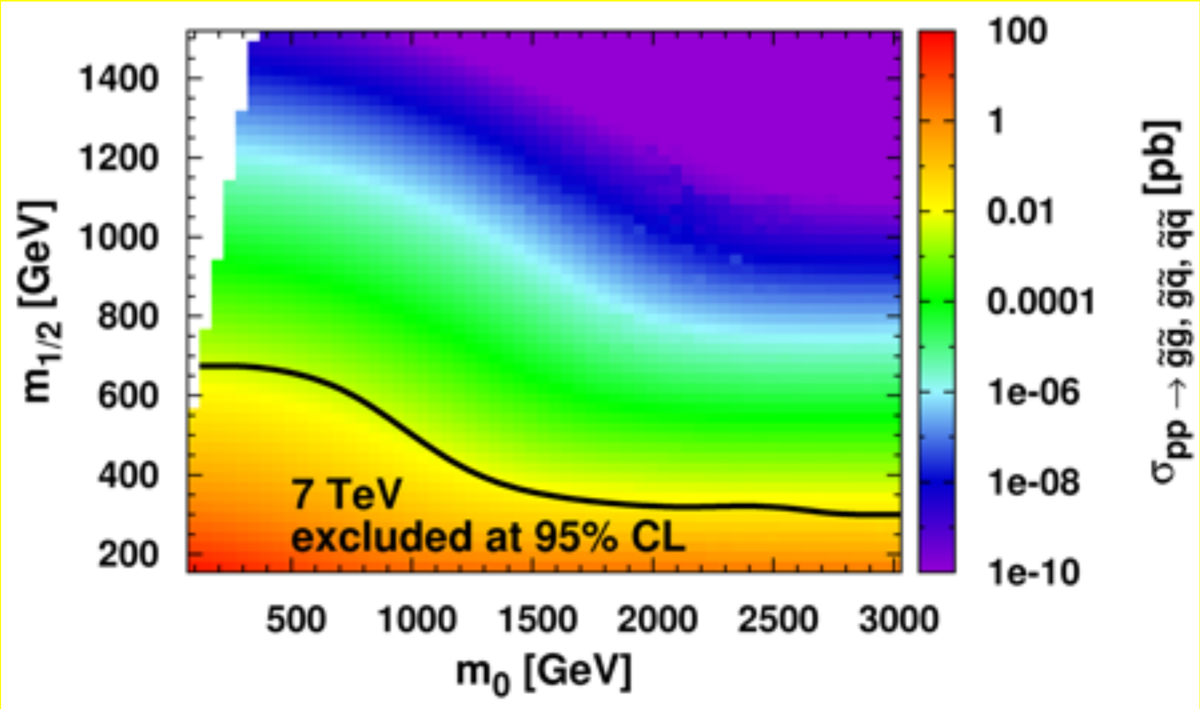




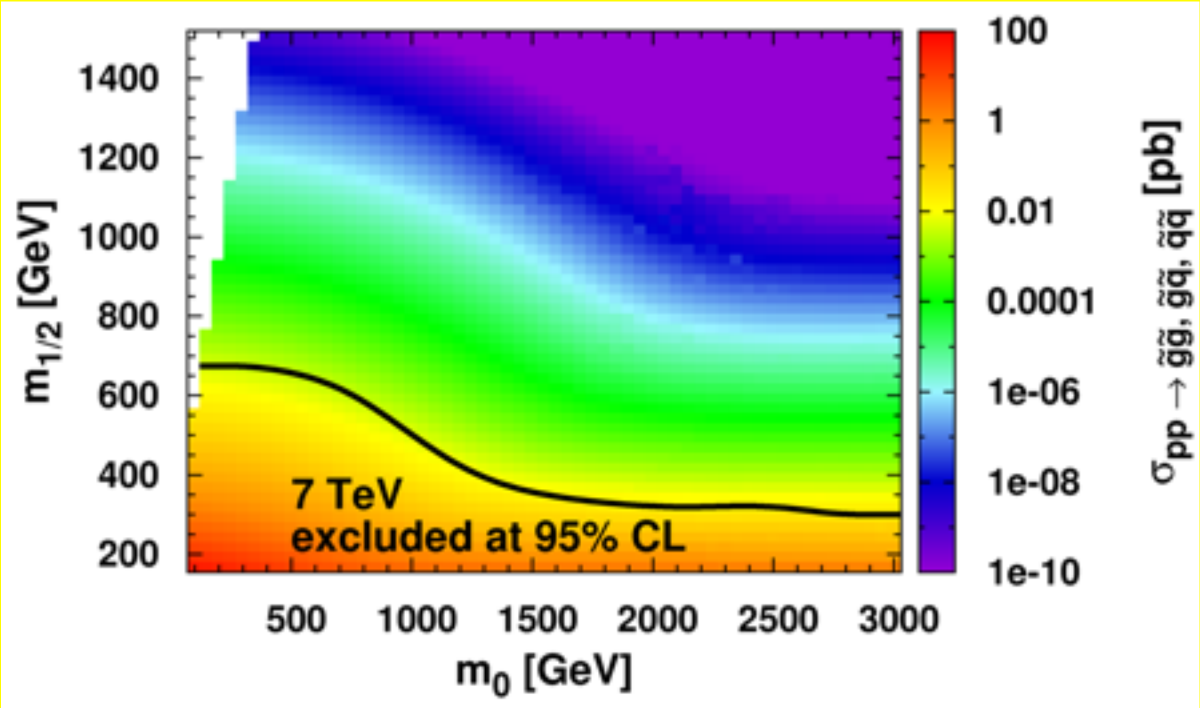
5

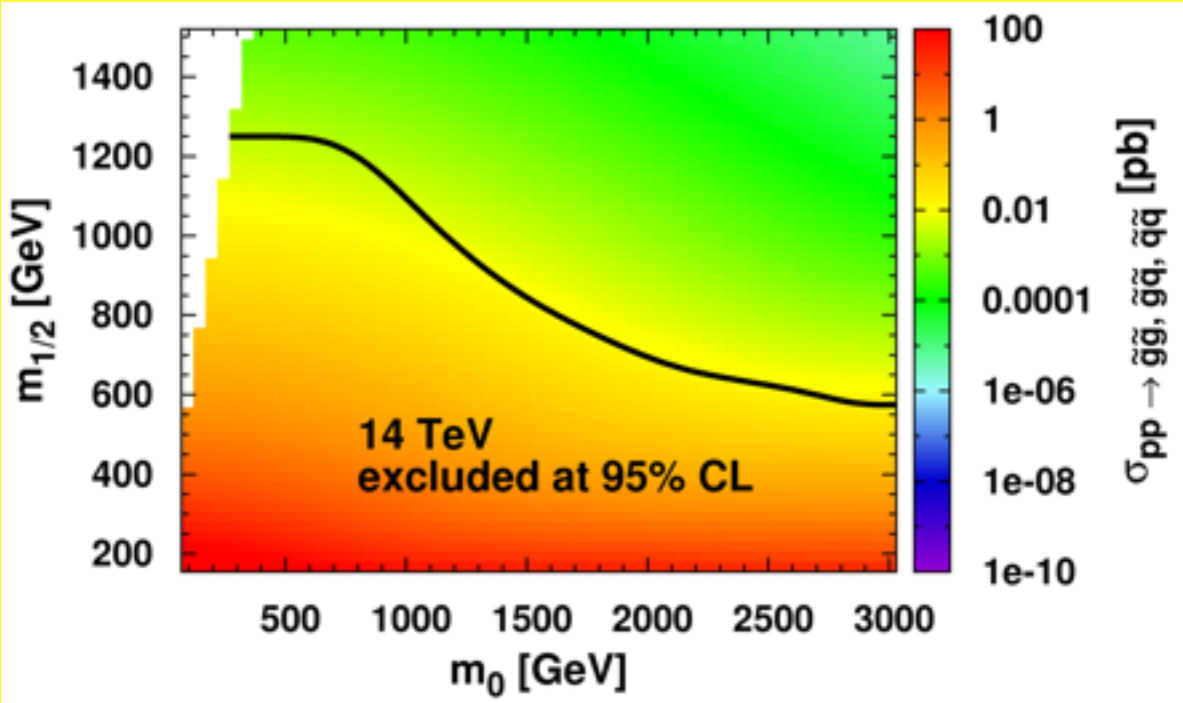
LHC Reach at 7 and 14 TeV

LHC Reach at 7 and 14 TeV

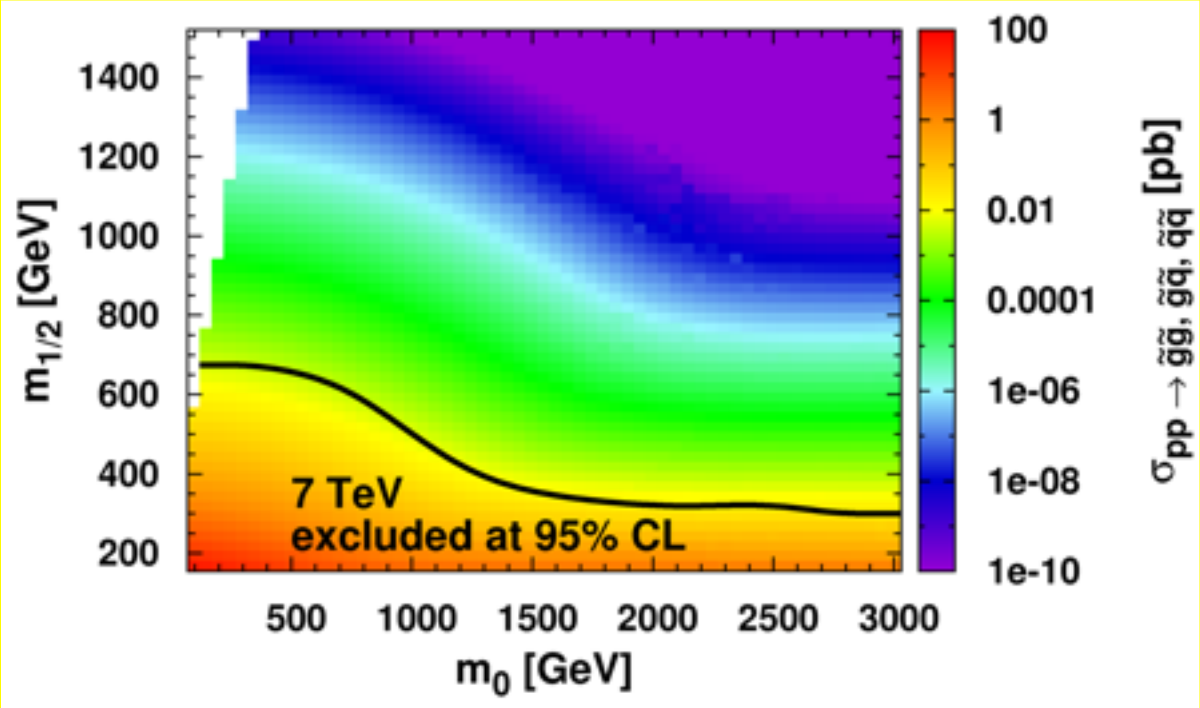


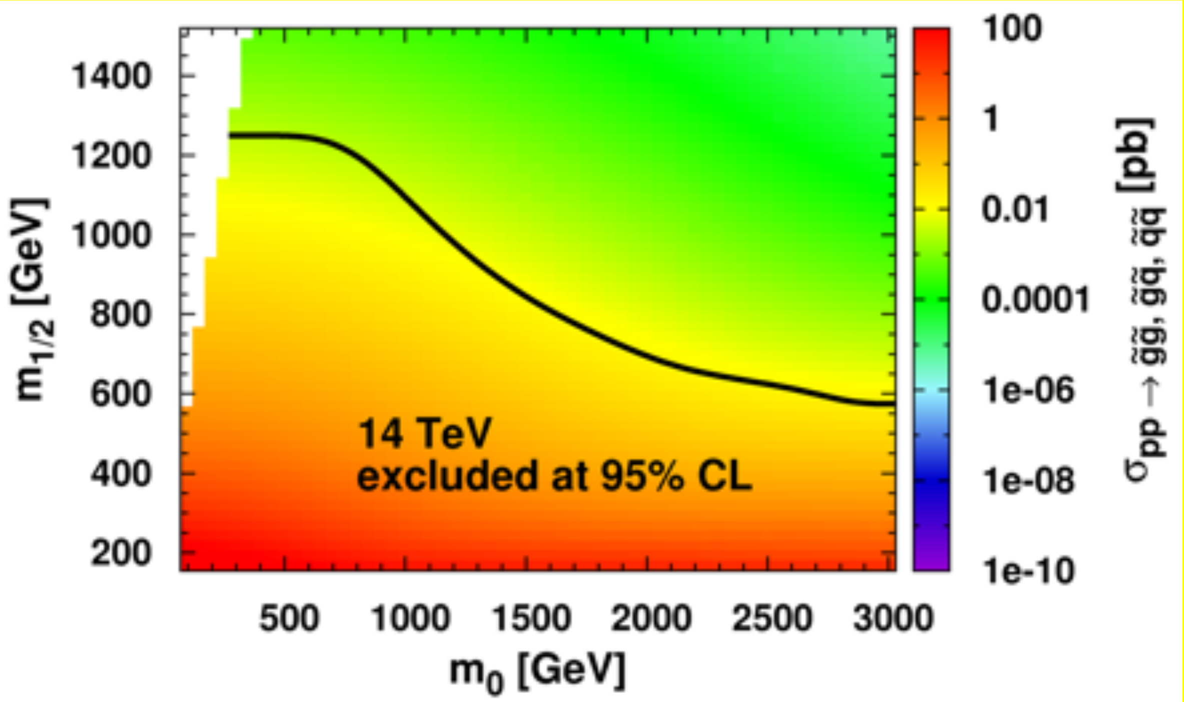
LHC Reach at 7 and 14 TeV

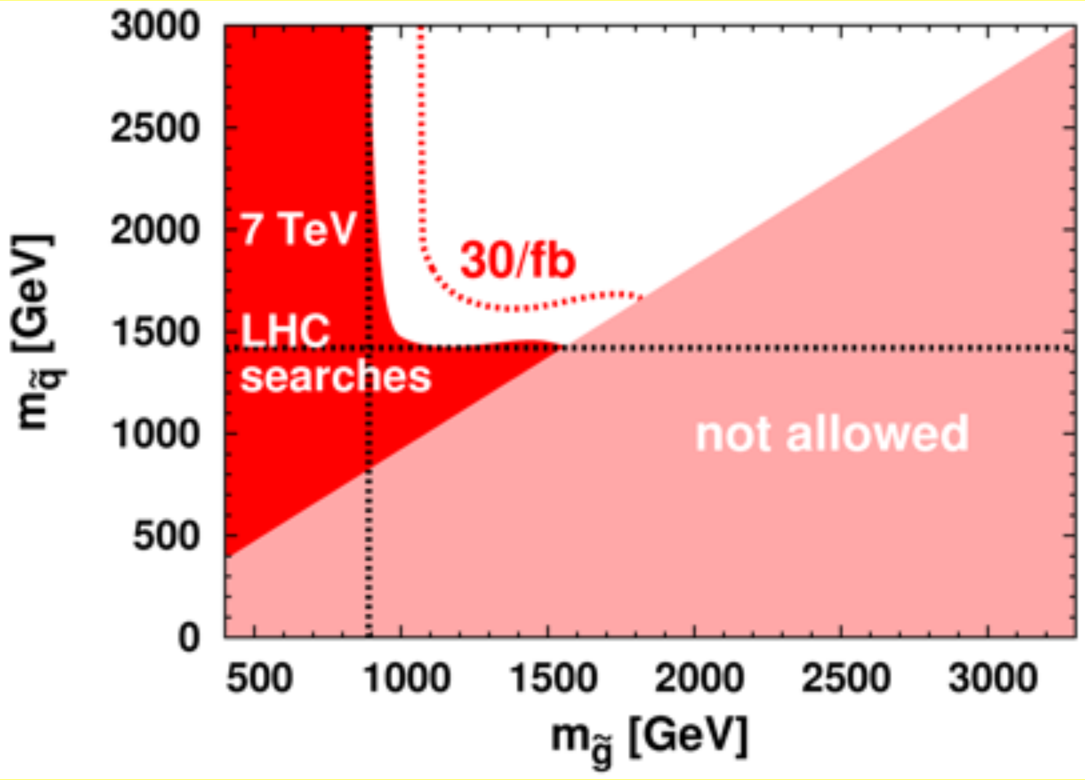




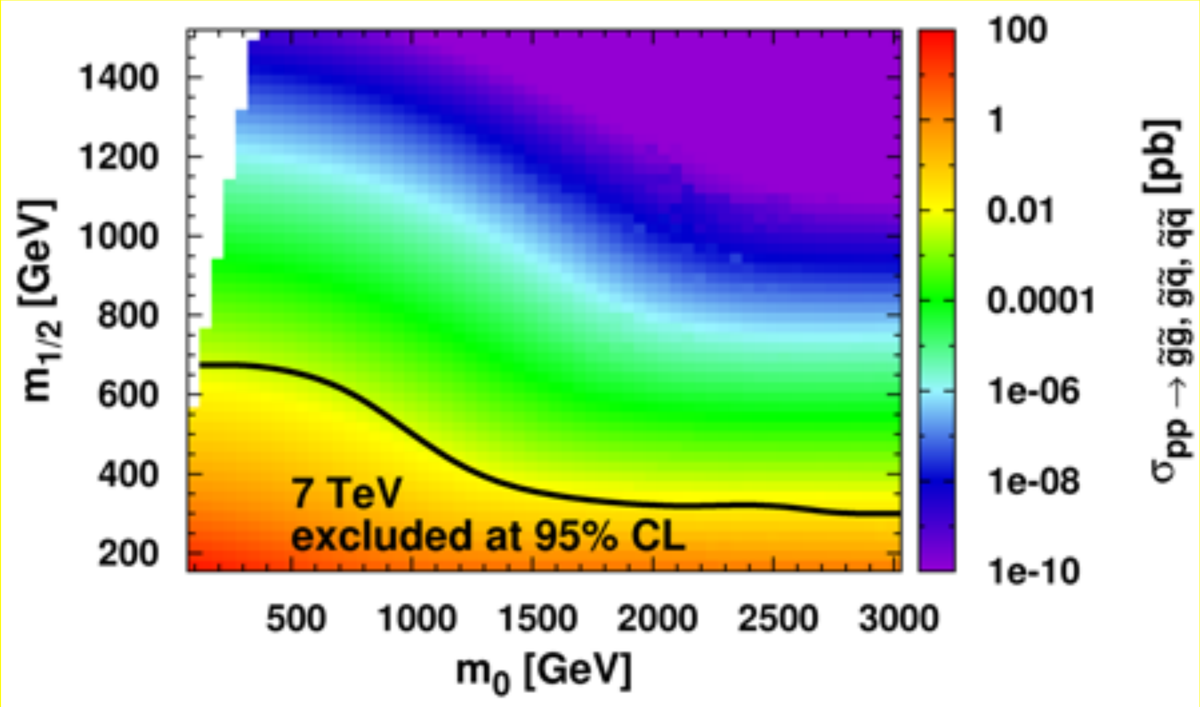
LHC Reach at 7 and 14 TeV

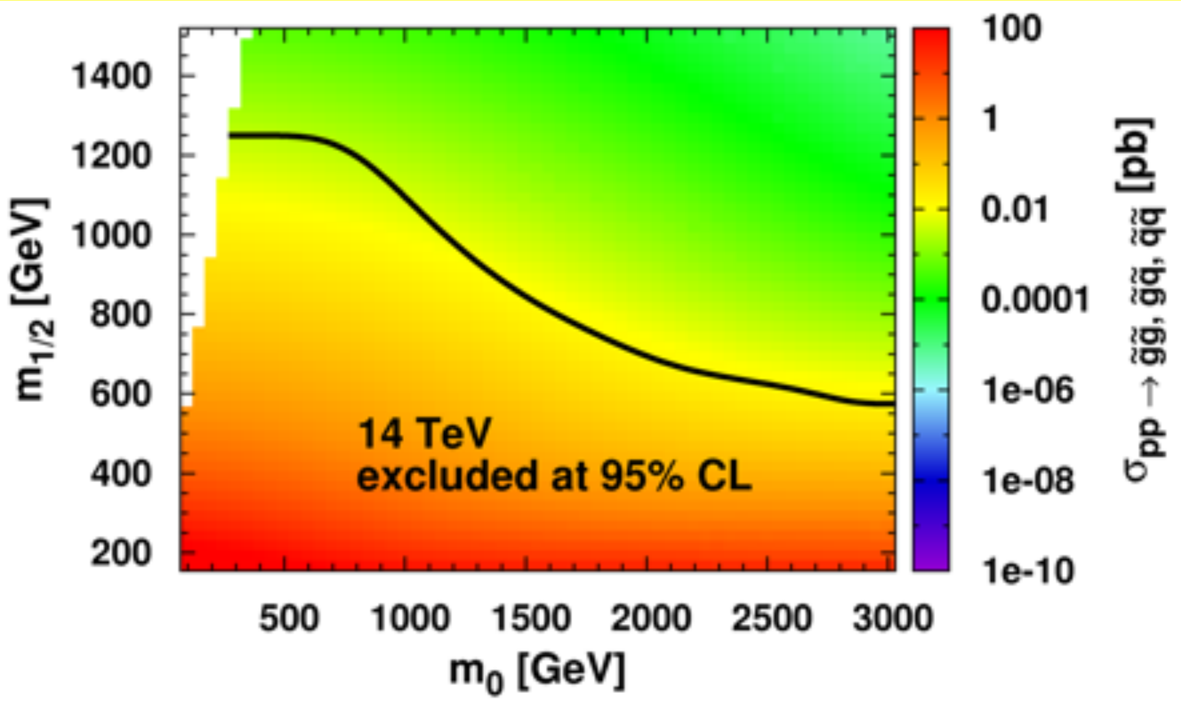


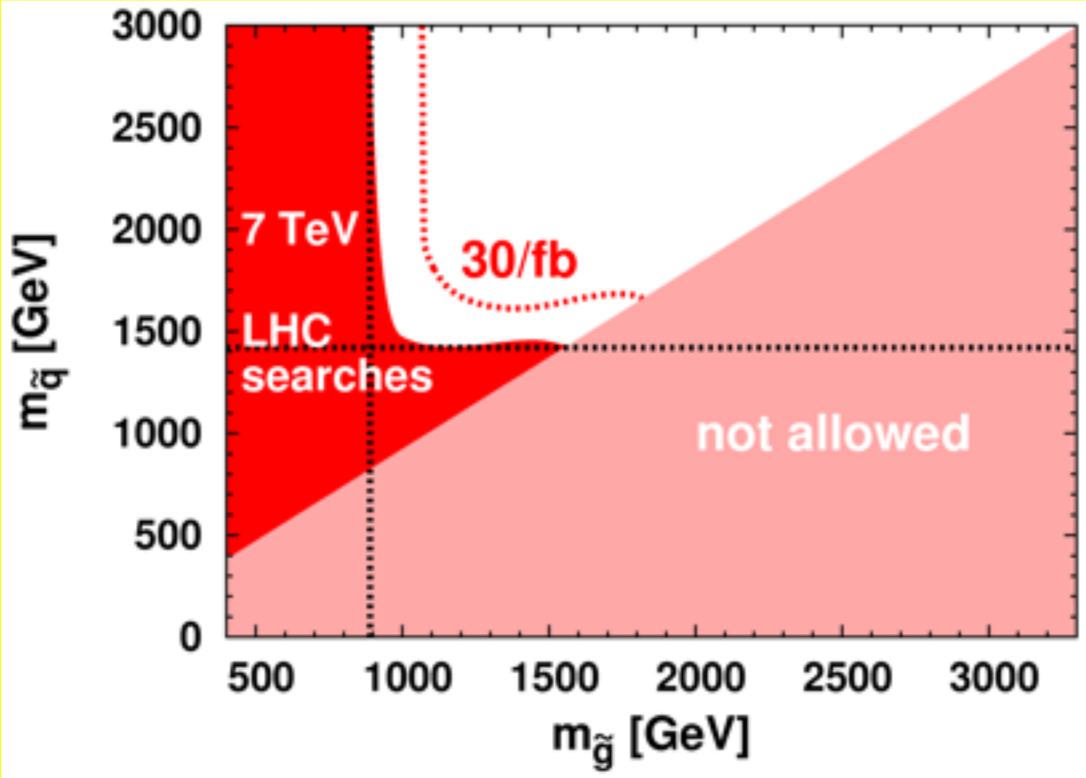


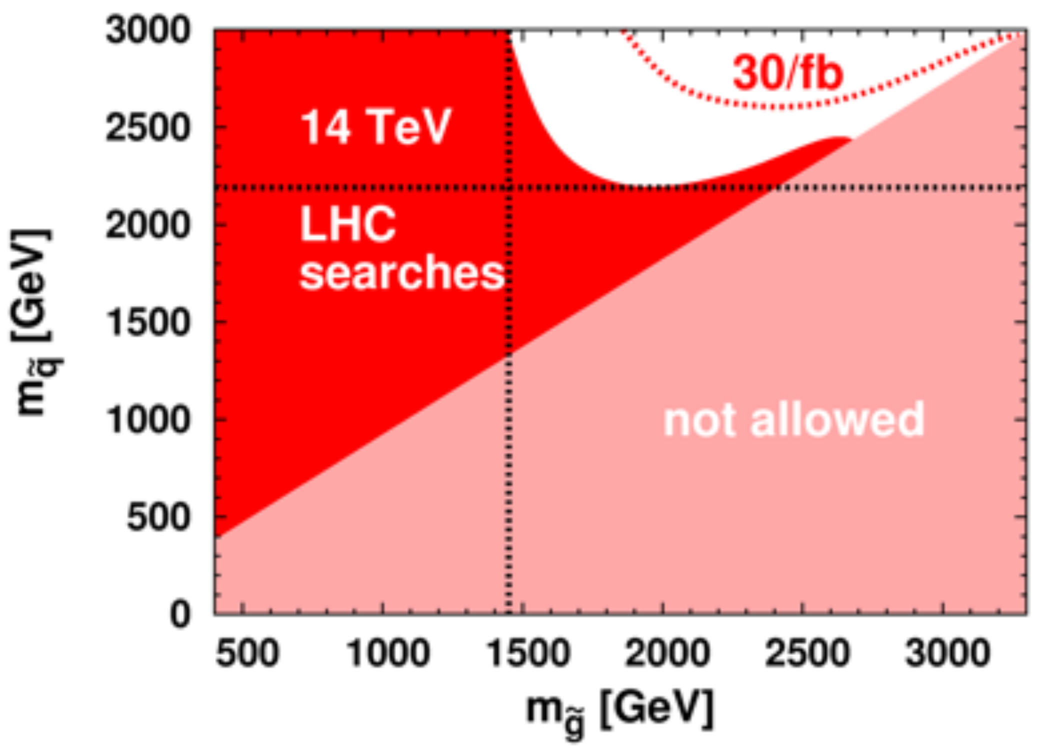


LHC Reach at 7 and 14 TeV

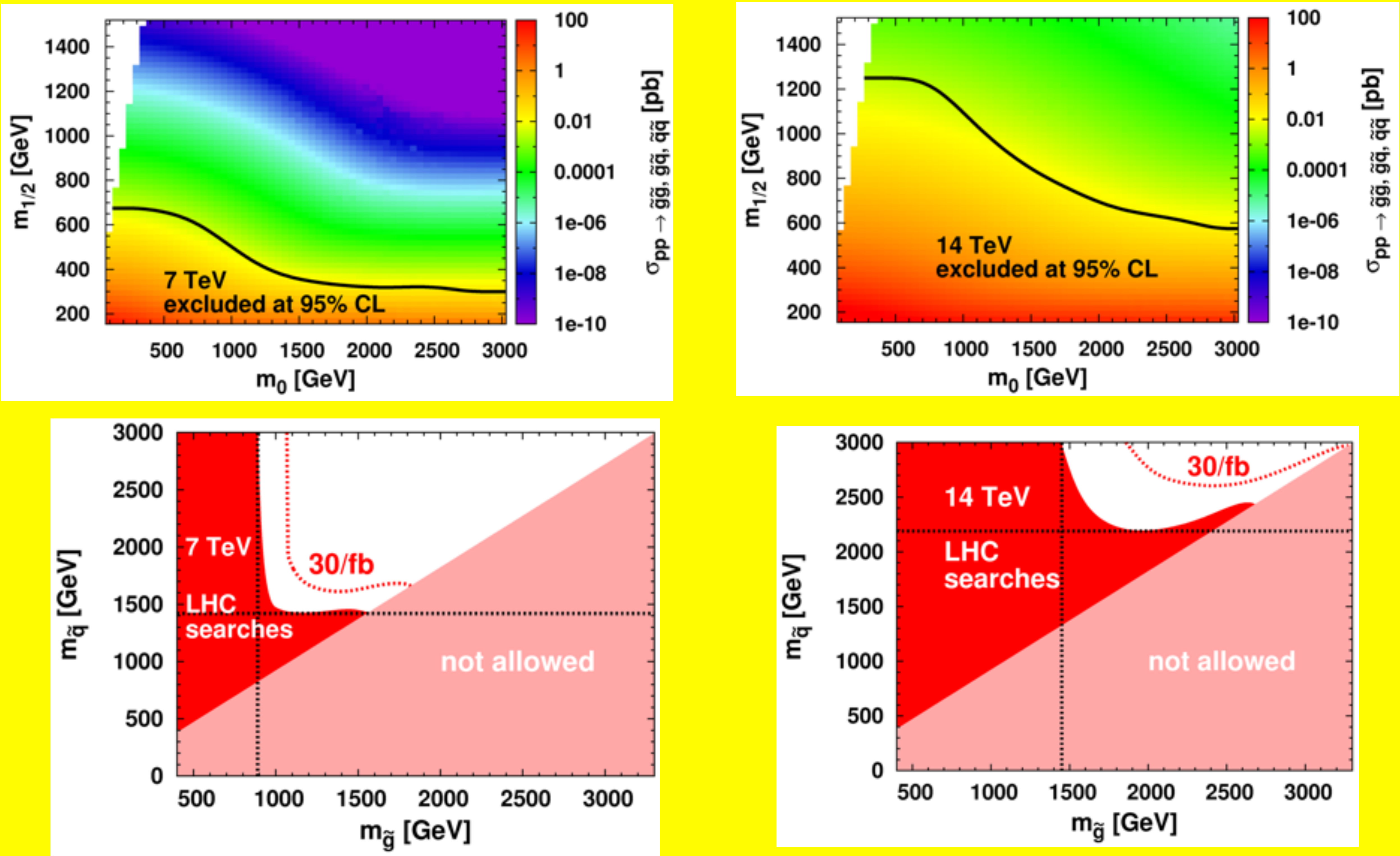








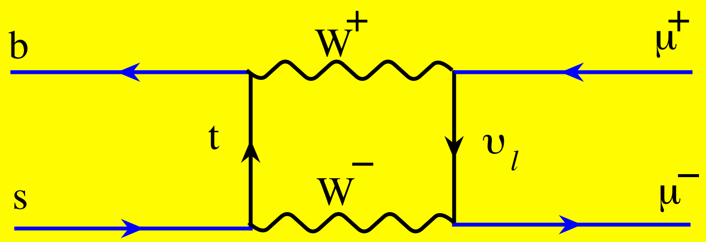
LHC Reach at 7 and 14 TeV

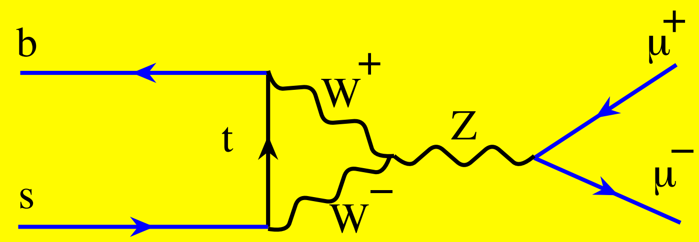


Energy is more important than luminosity

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

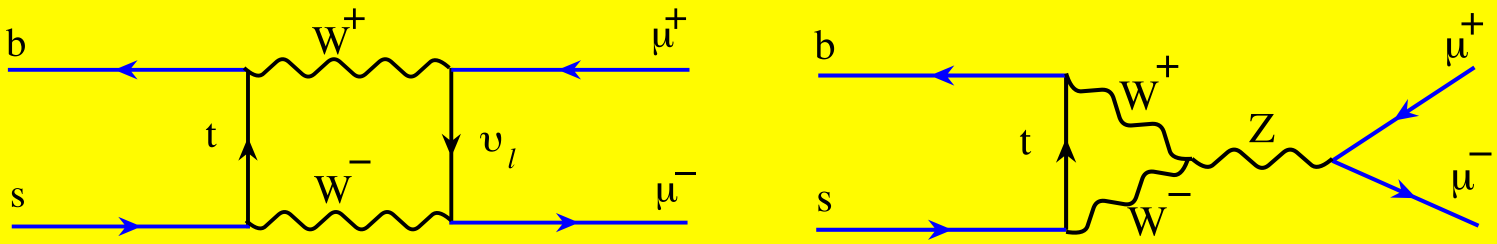
Rare Decays: $Br[B_s \to \mu^+\mu^-]$



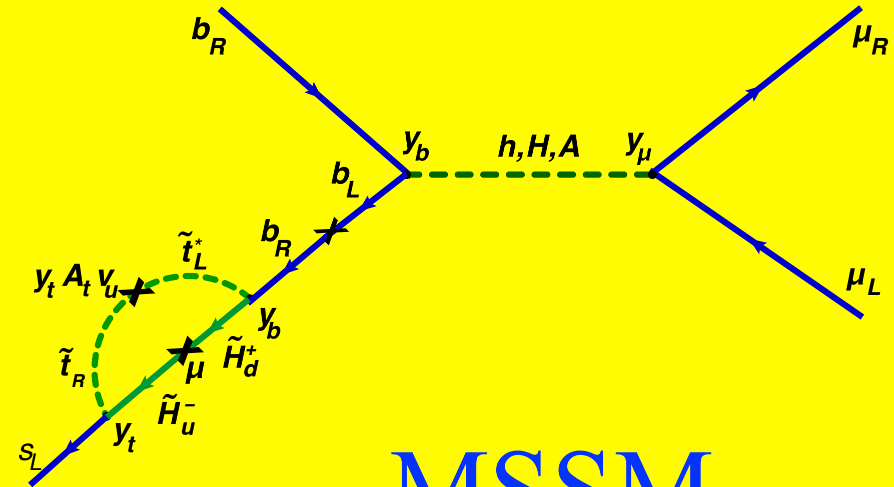


SM

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

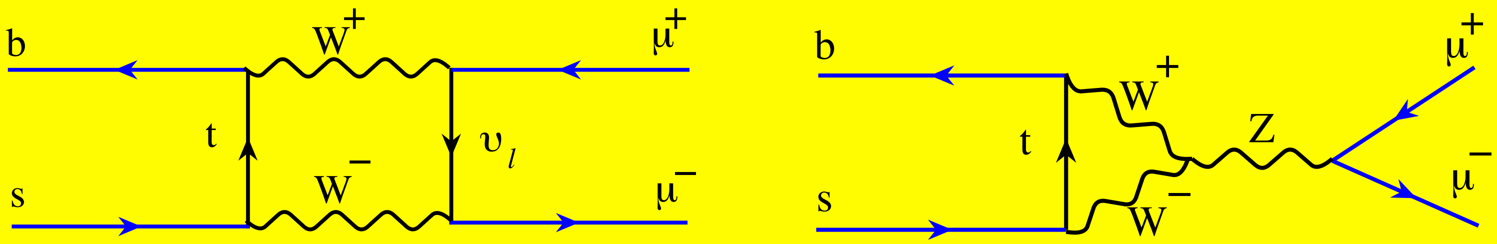


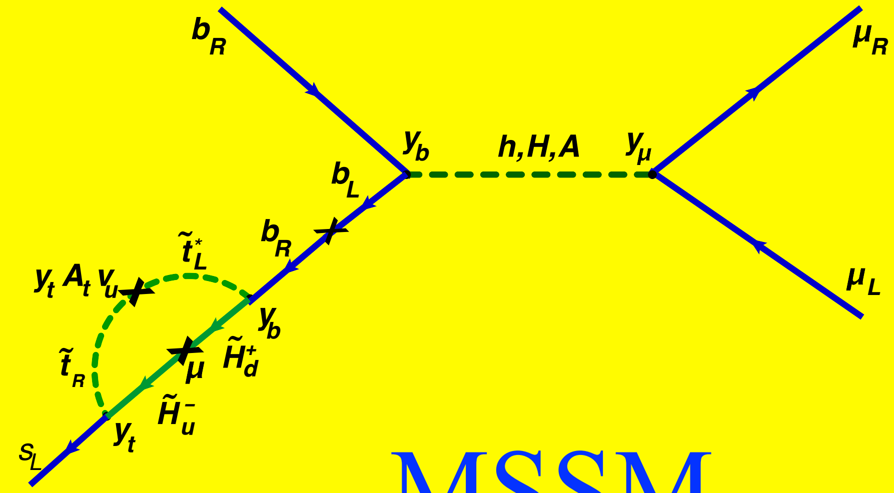
SM



MSSM

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





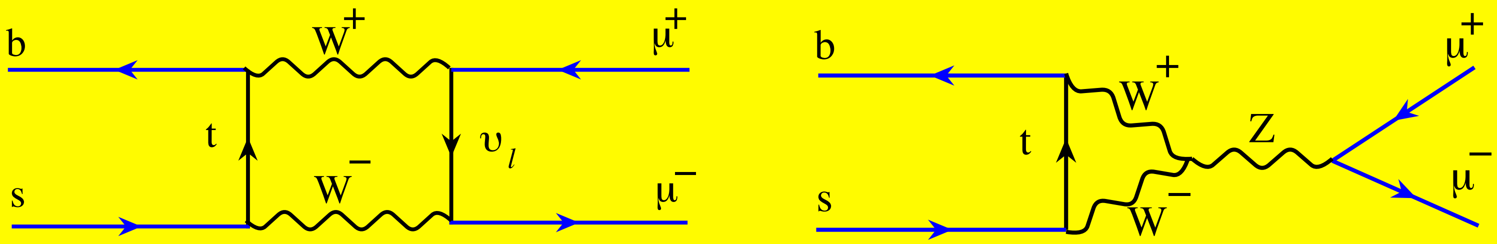
SM: Br=3.5 · 10^{-9}

Ex: <4.5 · 10^{-9}

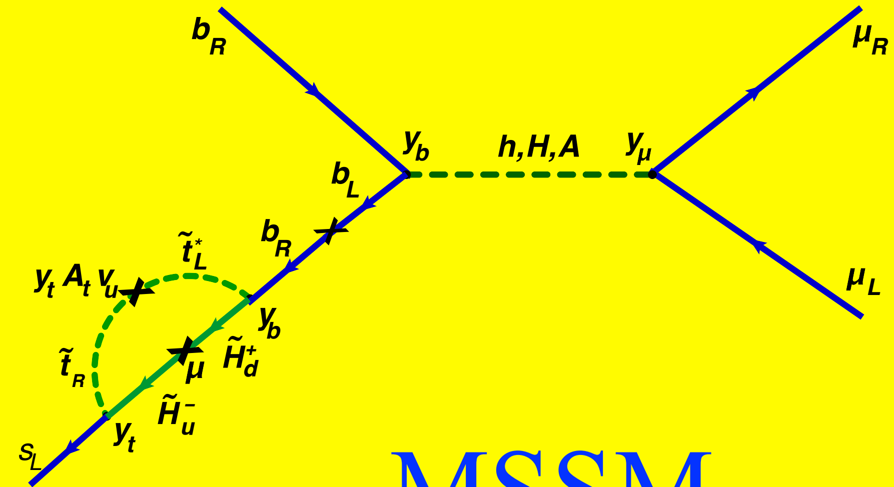
SM

MSSM

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



SM



MSSM

SM: Br=3.5·10^{-9}

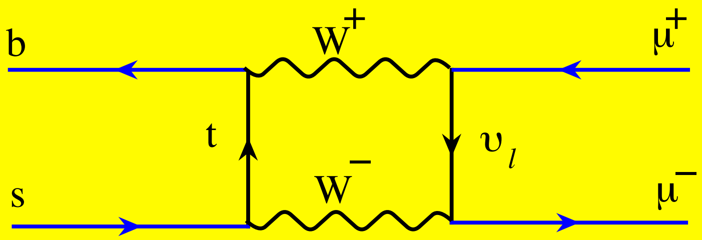
Ex: <4.5· 10^{-9}

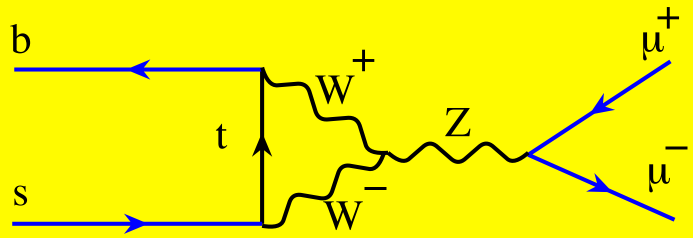
$$Br[B_s \to \mu\mu] = \frac{2\tau_B m_B^5}{64\pi} f_{B_s}^2 \sqrt{1 - \frac{4m_l^2}{m_B^2}}$$

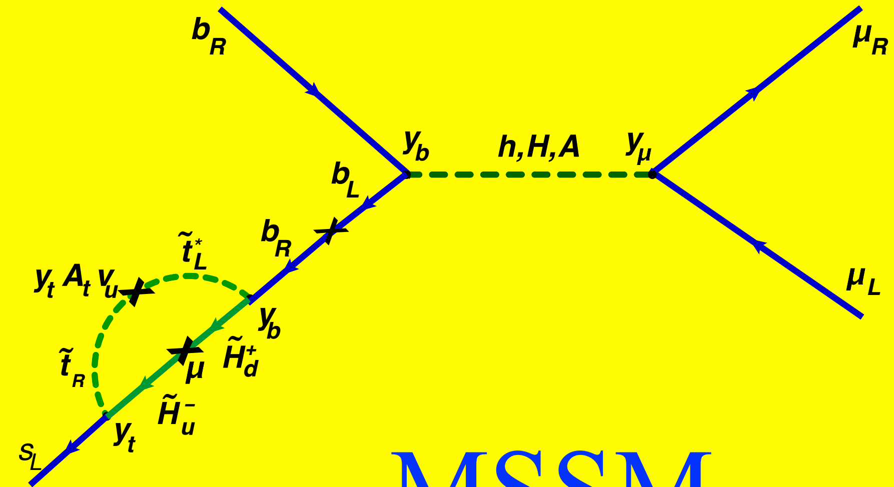
$$\left[\left(1 - \frac{4m_l^2}{m_B^2}\right)\left|\frac{(C_S - C'_S)}{(m_b + m_s)}\right|^2 + \left|\frac{(C_P - C'_P)}{(m_b + m_s)} + 2\frac{m_\mu}{m_{B_s}^2}(C_A - C'_A)\right|^2\right]$$

ICHEP2012 Melbourne

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







SM: Br=3.5·10^{-9}

Ex: <4.5· 10^{-9}

SM

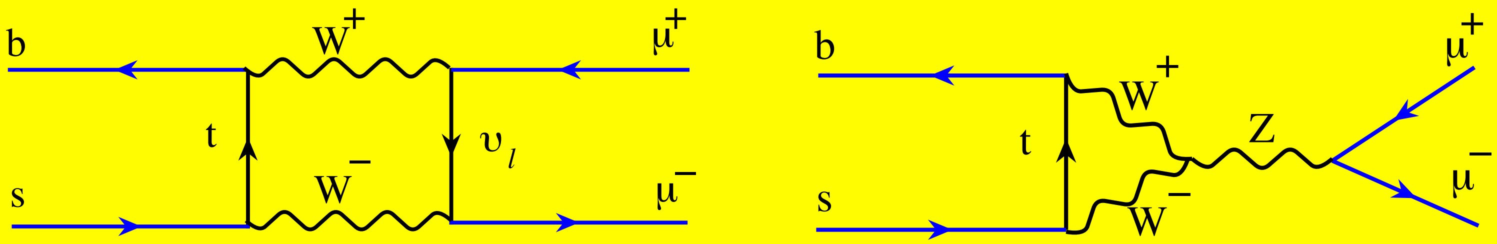
MSSM

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

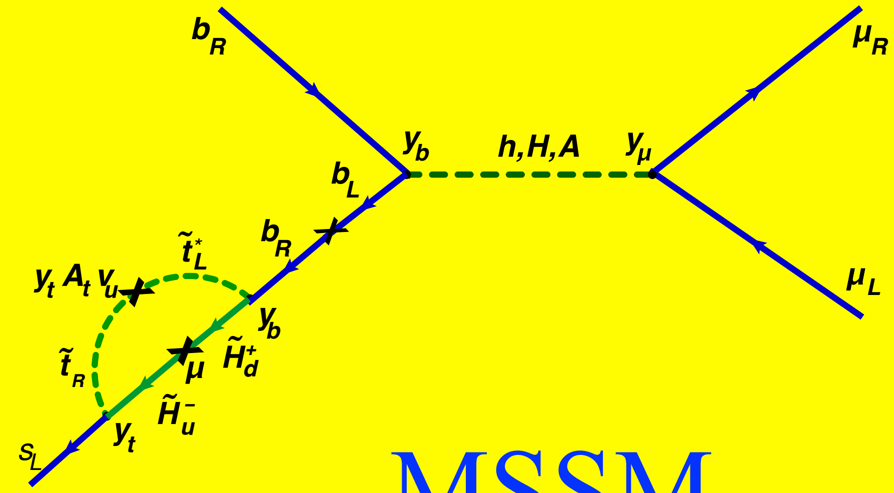
$$\left[\left(1 - \frac{4m_l^2}{m_B^2}\right)\left|\frac{(C_S - C_S')}{(m_b + m_s)}\right|^2 + \left|\frac{(C_P - C_P')}{(m_b + m_s)} + 2\frac{m_\mu}{m_{B_s}^2}(C_A - C_A')\right|^2\right]$$

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

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



SM



MSSM

SM: Br=3.5·10^-9

Ex: <4.5· 10^-9

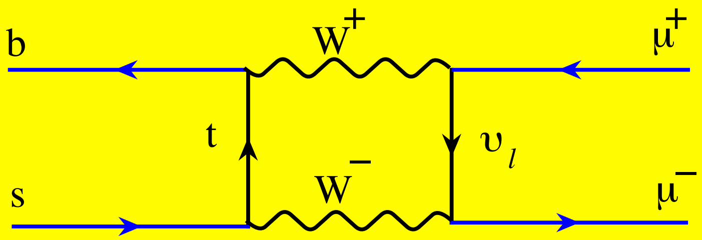
$$Br[B_s \to \mu\mu] = \frac{2\tau_B m_B^5}{64\pi} f_{B_s}^2 \sqrt{1-\frac{4m_l^2}{m_B^2}}$$

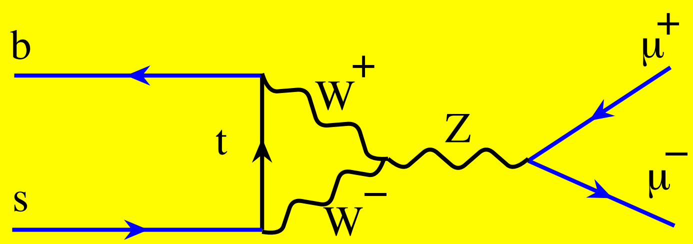
$$\left[\left(1-\frac{4m_l^2}{m_B^2}\right)\left|\frac{(C_S-C'_S)}{(m_b+m_s)}\right|^2 + \left|\frac{(C_P-C'_P)}{(m_b+m_s)} + 2\frac{m_\mu}{m_{B_s}^2}(C_A-C'_A)\right|^2\right]$$

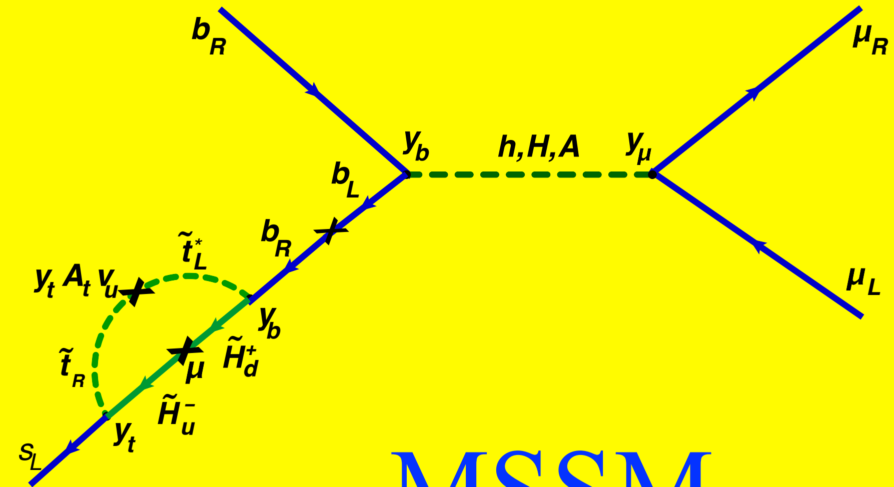
$$C_S \simeq \frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^* \left(\frac{\tan^3\beta}{4\sin^2\theta_W}\right)\left(\frac{m_b m_\mu m_t \mu}{M_W^2 M_A^2}\right)\frac{\sin 2\theta_{\tilde{t}}}{2}\left(\frac{m_{\tilde{t}_1}^2 \log\left[\frac{m_{\tilde{t}_1}^2}{\mu^2}\right]}{\mu^2-m_{\tilde{t}_1}^2} - \frac{m_{\tilde{t}_2}^2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

Enhancement

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







SM: Br=3.5·10^{-9}

Ex: <4.5· 10^{-9}

SM

MSSM

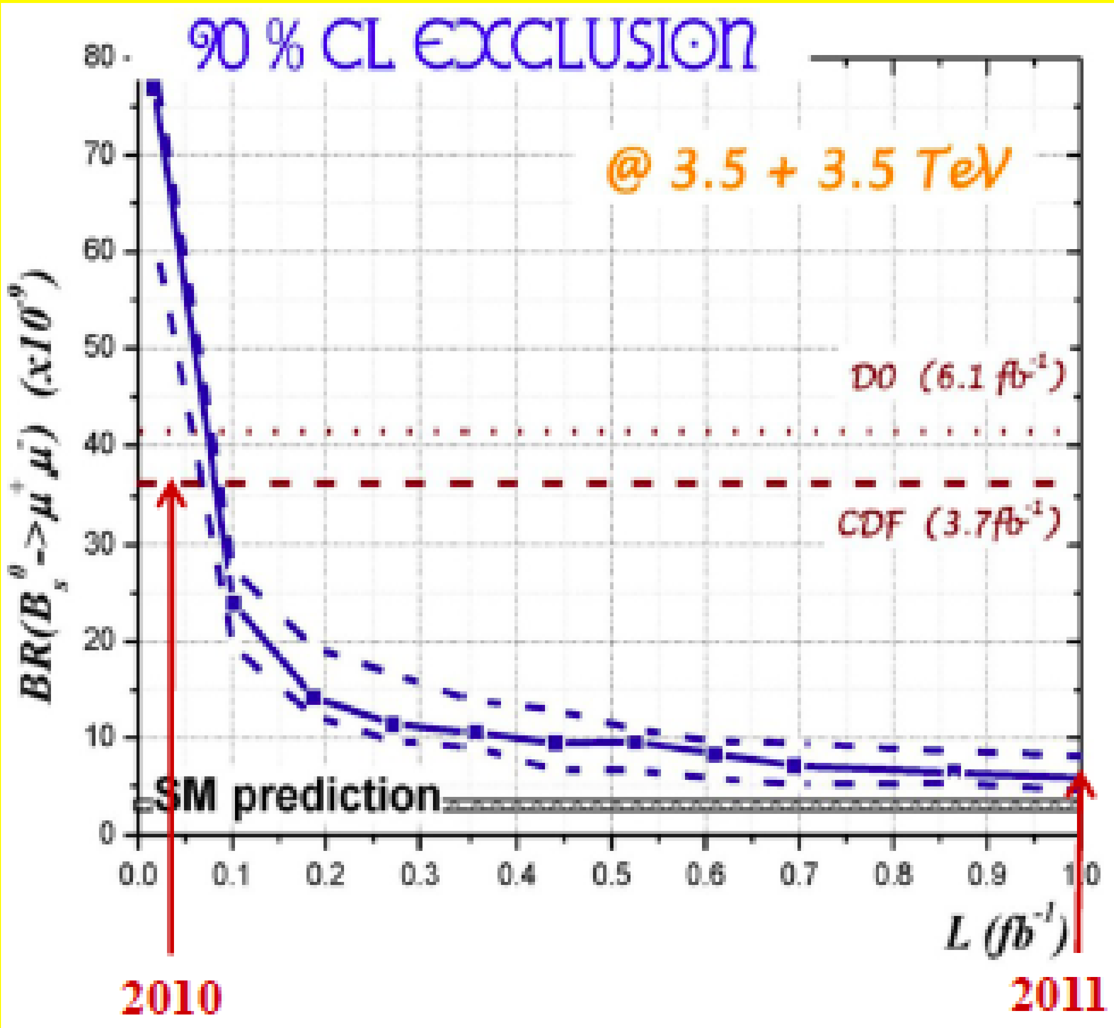
$$Br[B_s \to \mu\mu] = \frac{2\tau_B m_B^5}{64\pi} f_{B_s}^2 \sqrt{1-\frac{4m_l^2}{m_B^2}} \left[\left(1-\frac{4m_l^2}{m_B^2}\right)\left|\frac{(C_S-C_S')}{(m_b+m_s)}\right|^2 + \left|\frac{(C_P-C_P')}{(m_b+m_s)} + 2\frac{m_\mu}{m_{B_s}^2}(C_A-C_A')\right|^2\right]$$

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

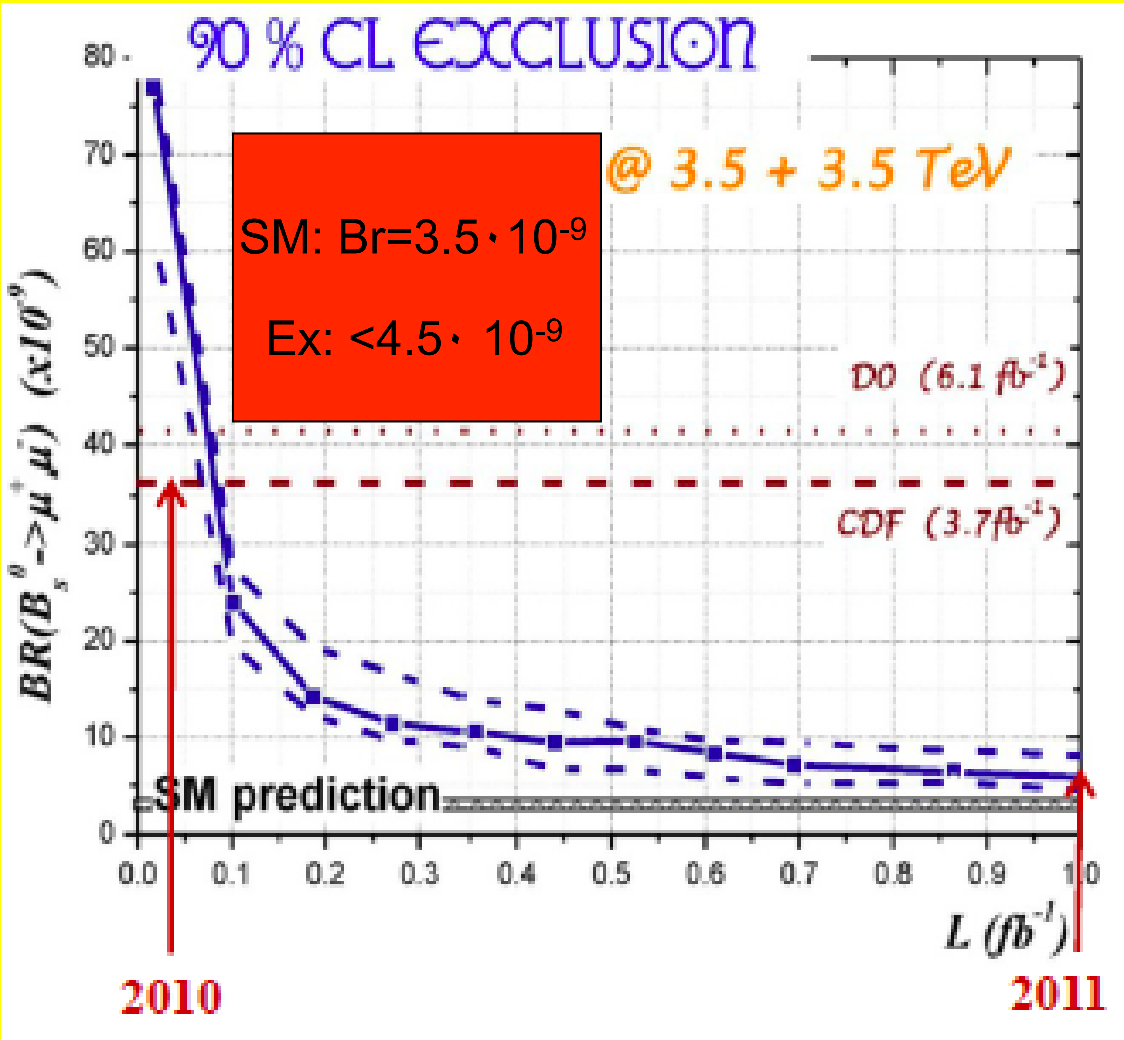
Enhancement

Suppression

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

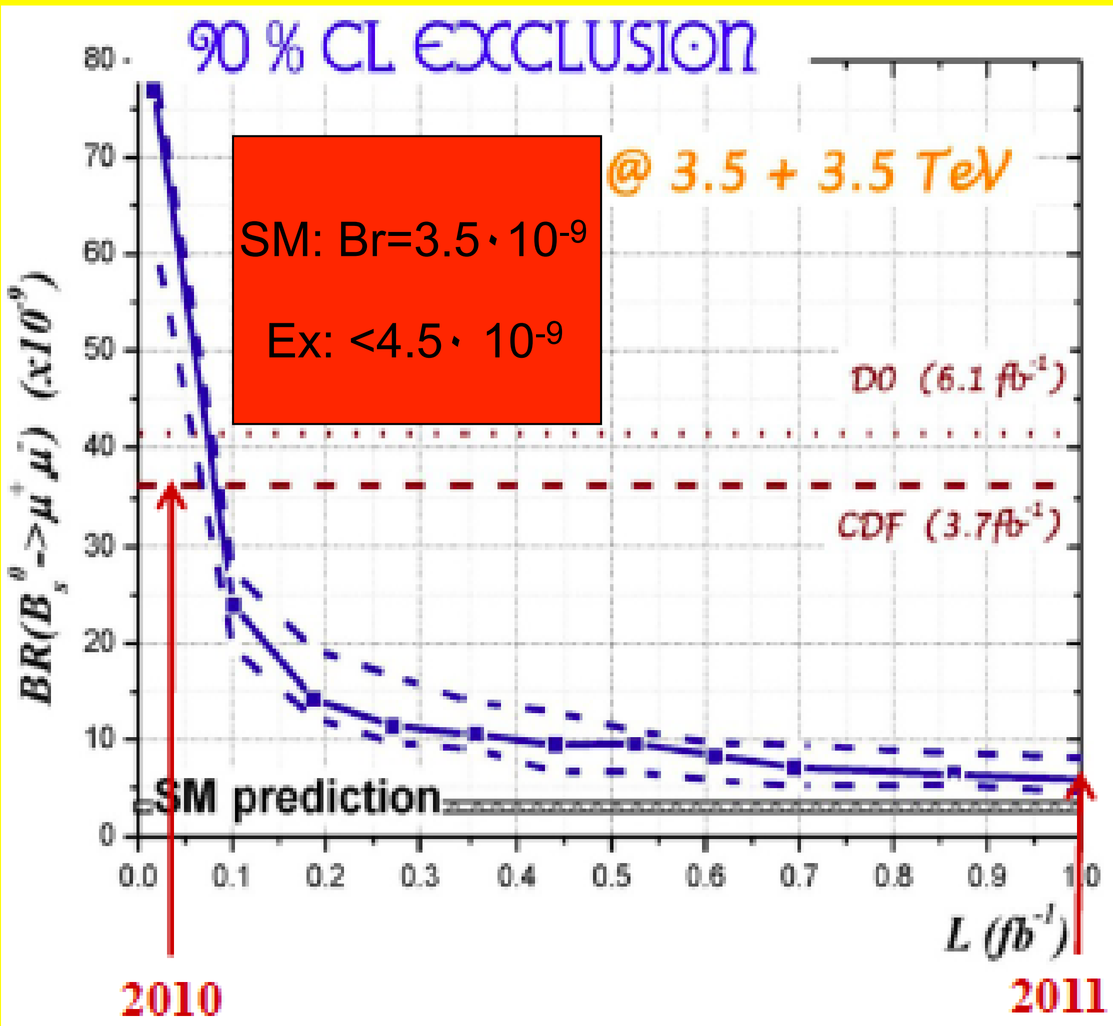


Rare Decays: $Br[B_s \to \mu^+\mu^-]$ Constraint



ICHEP2012 Melbourne

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



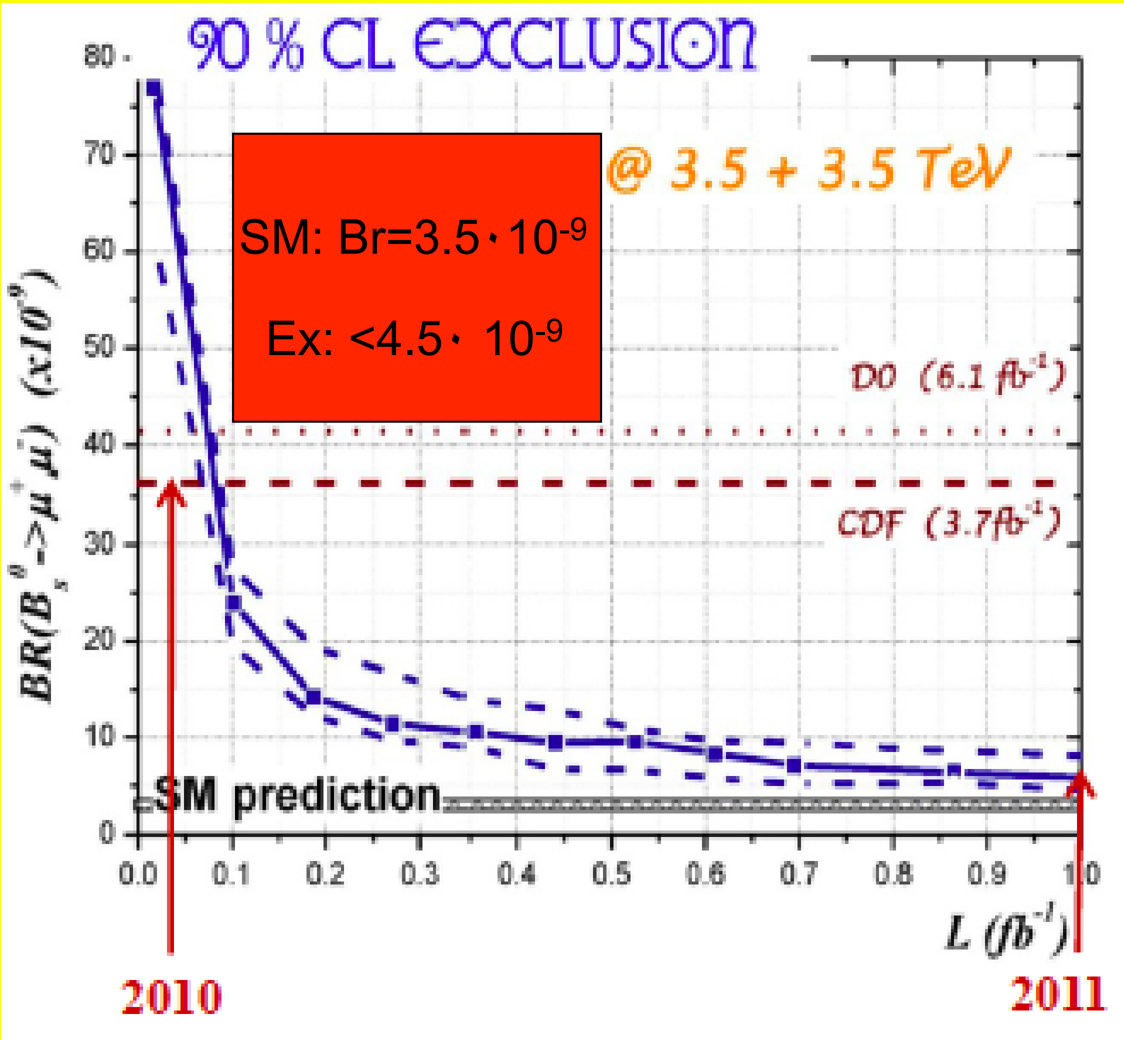
95% C.L. Excluded regions for

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

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

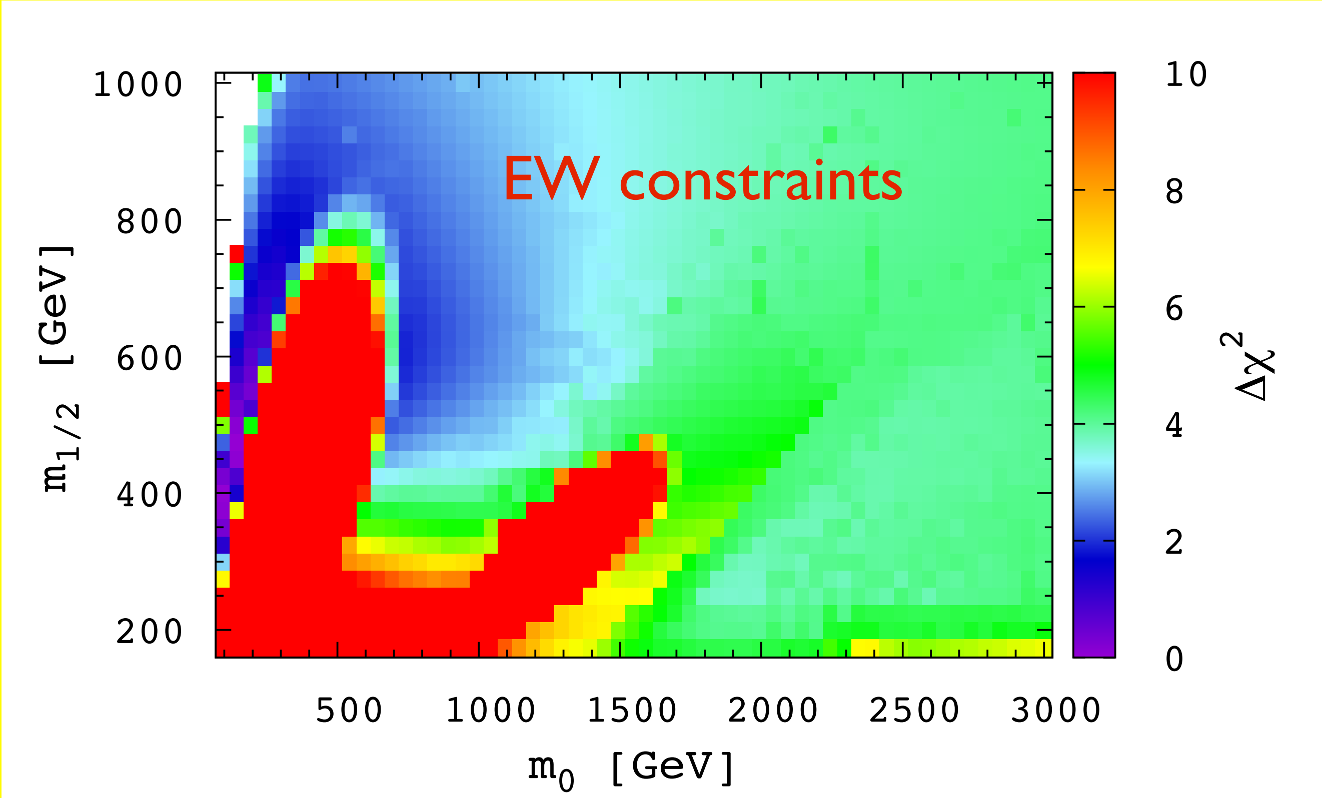
$$Br[B_u \to \tau\nu] = (1.68 \pm 0.31) \cdot 10^{-4}$$

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

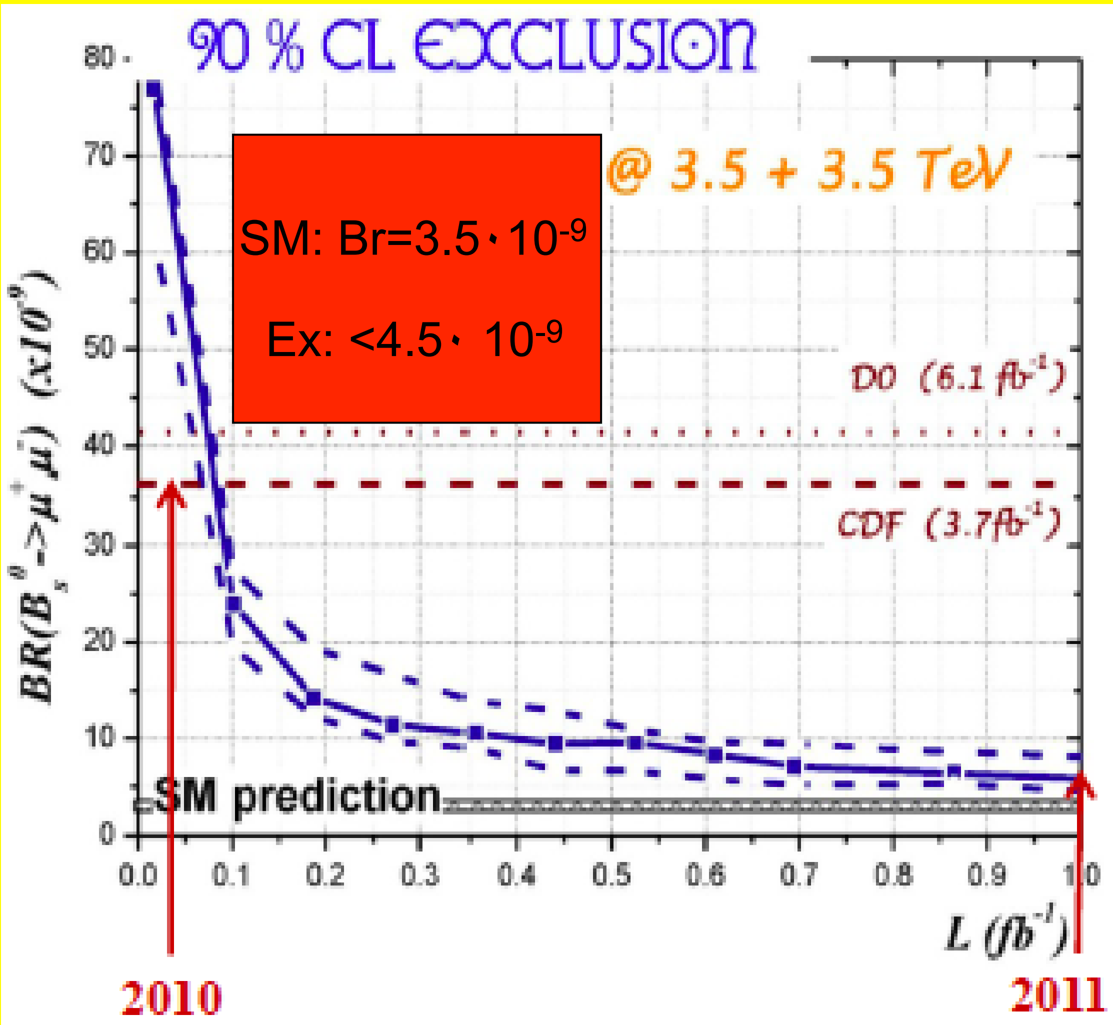


95% C.L. Excluded regions for

$$Br[B_s \to \mu^+\mu^-] < 4.5 \cdot 10^{-9}$$
$$Br[B_s \to X_s\gamma] = (3.55 \pm 0.24) \cdot 10^{-4}$$
$$Br[B_u \to \tau\nu] = (1.68 \pm 0.31) \cdot 10^{-4}$$



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

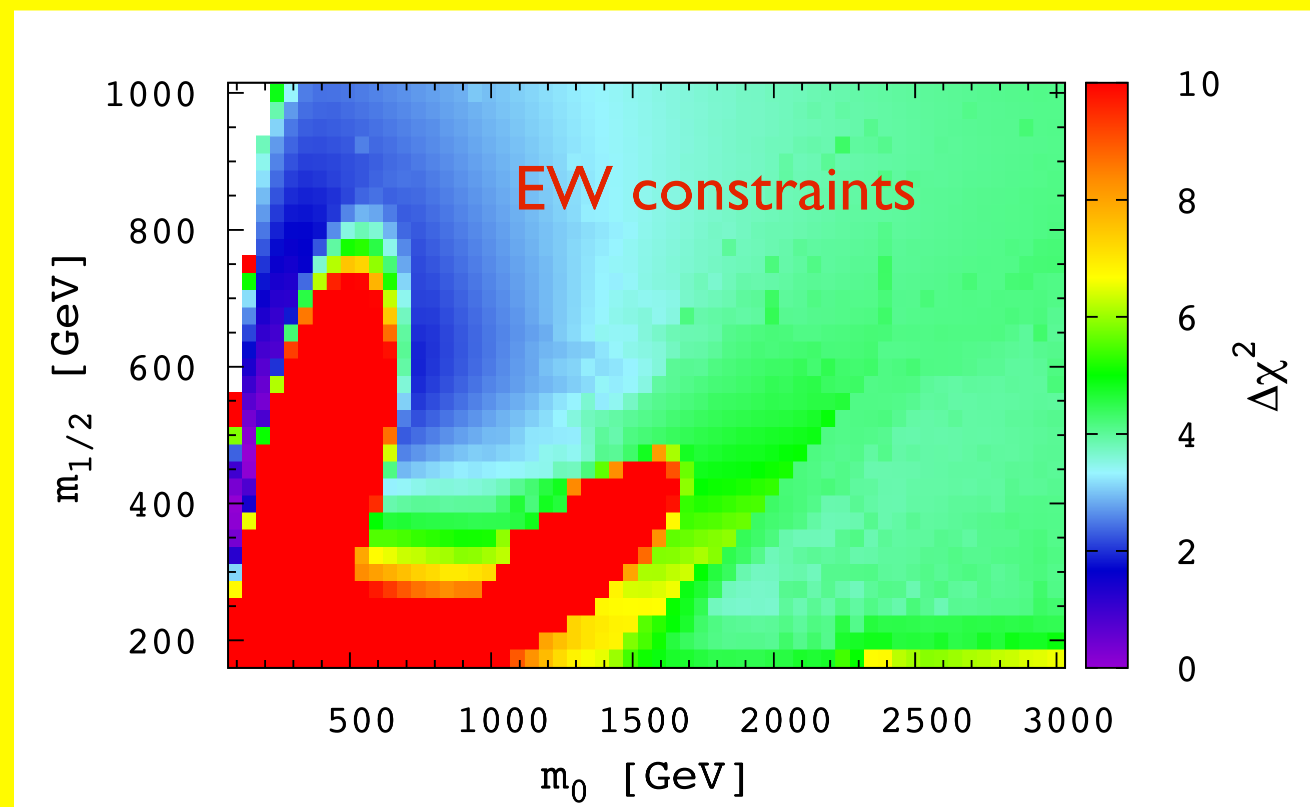


95% C.L. Excluded regions for

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

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

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



Negative interference is possible

Anomalous magnetic moment

9

Anomalous magnetic moment

$$a_\mu^{exp} = 11\ 659\ 2089(63) \cdot 10^{-11}$$

$$a_\mu^{SM} = 11\ 659\ 1834(49) \cdot 10^{-11}$$

9

Anomalous magnetic moment

$$a_\mu^{exp} = 11\ 659\ 2089(63) \cdot 10^{-11}$$

$$a_\mu^{SM} = 11\ 659\ 1834(49) \cdot 10^{-11}$$

$$\boxed{a_\mu^{exp} - a_\mu^{SM} = 255 \pm 80 \cdot 10^{-11}}$$

Anomalous magnetic moment

$$a_\mu^{exp} = 11\ 659\ 2089(63) \cdot 10^{-11}$$

$$a_\mu^{SM} = 11\ 659\ 1834(49) \cdot 10^{-11}$$

$$\boxed{a_\mu^{exp} - a_\mu^{SM} = 255 \pm 80 \cdot 10^{-11}}$$

$$a_\mu^{QED} = 11\ 658\ 4705.6(2.9) \cdot 10^{-11}$$

$$a_\mu^{weak} = 151(4) \cdot 10^{-11}$$

$$a_\mu^{hadr} = 6877.2(46.3) \cdot 10^{-11}$$

Anomalous magnetic moment

$$a_\mu^{exp} = 11\ 659\ 2089(63) \cdot 10^{-11}$$

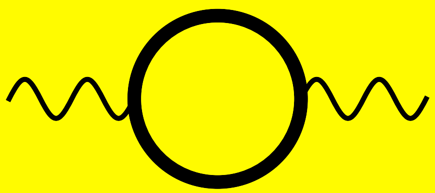
$$a_\mu^{SM} = 11\ 659\ 1834(49) \cdot 10^{-11}$$

$$\boxed{a_\mu^{exp} - a_\mu^{SM} = 255 \pm 80 \cdot 10^{-11}}$$

$$a_\mu^{QED} = 11\ 658\ 4705.6(2.9) \cdot 10^{-11}$$

$$a_\mu^{weak} = 151(4) \cdot 10^{-11}$$

$$a_\mu^{hadr} = 6877.2(46.3) \cdot 10^{-11}$$

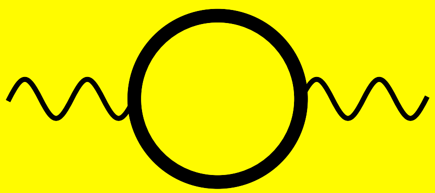


vacuum pol

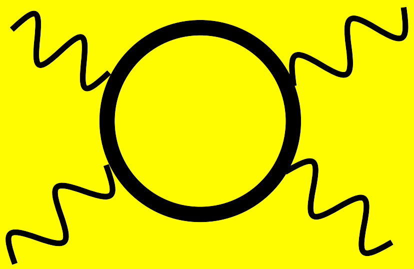
Anomalous magnetic moment

$$a_\mu^{exp} = 11\ 659\ 2089(63) \cdot 10^{-11}$$
$$a_\mu^{SM} = 11\ 659\ 1834(49) \cdot 10^{-11}$$
$$\boxed{a_\mu^{exp} - a_\mu^{SM} = 255 \pm 80 \cdot 10^{-11}}$$

$$a_\mu^{QED} = 11\ 658\ 4705.6(2.9) \cdot 10^{-11}$$
$$a_\mu^{weak} = 151(4) \cdot 10^{-11}$$
$$a_\mu^{hadr} = 6877.2(46.3) \cdot 10^{-11}$$



vacuum pol

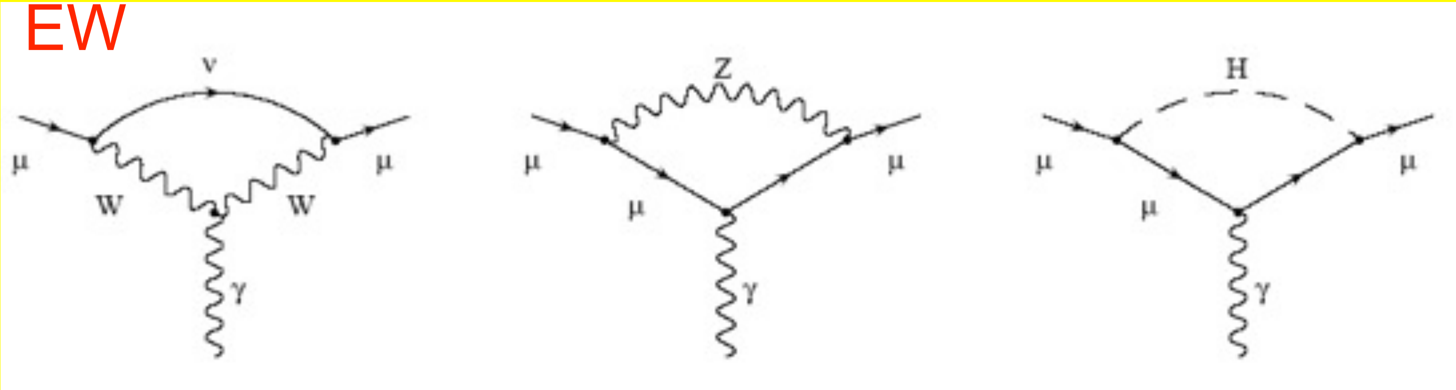


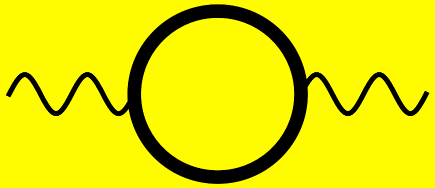
light-light scat

Anomalous magnetic moment

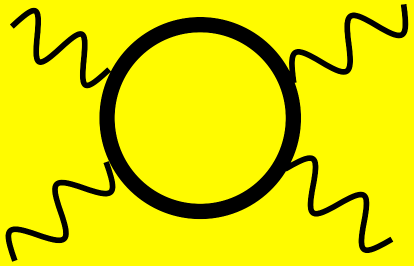
$$a_\mu^{exp} = 11\ 659\ 2089(63)\cdot 10^{-11}$$
$$a_\mu^{SM} = 11\ 659\ 1834(49)\cdot 10^{-11}$$
$$\boxed{a_\mu^{exp} - a_\mu^{SM} = 255 \pm 80 \cdot 10^{-11}}$$

$$a_\mu^{QED} = 11\ 658\ 4705.6(2.9)\cdot 10^{-11}$$
$$a_\mu^{weak} = 151(4)\cdot 10^{-11}$$
$$a_\mu^{hadr} = 6877.2(46.3)\cdot 10^{-11}$$





vacuum pol

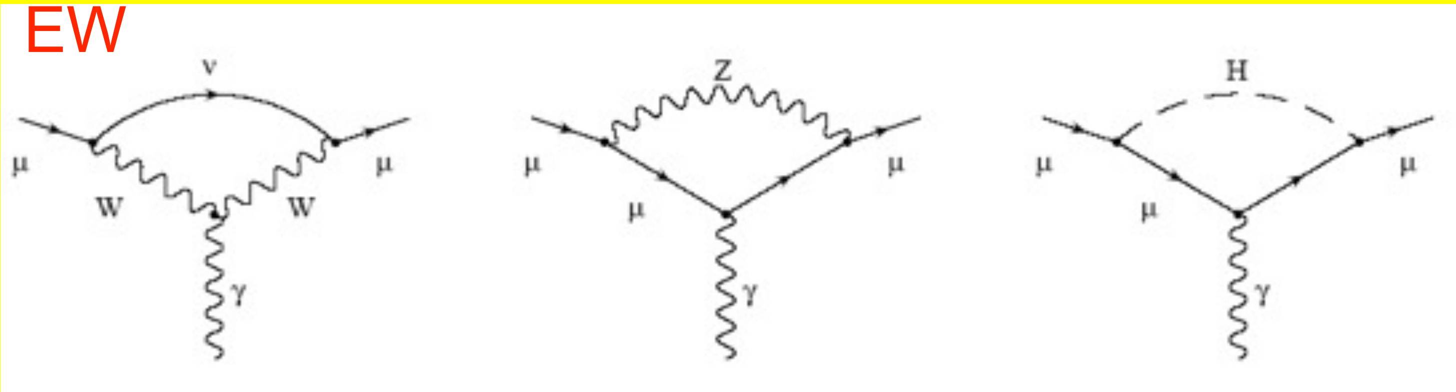


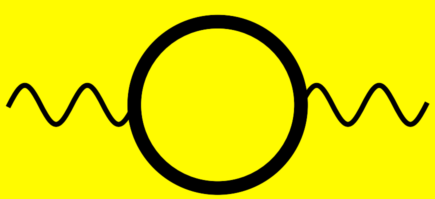
light-light scat

Anomalous magnetic moment

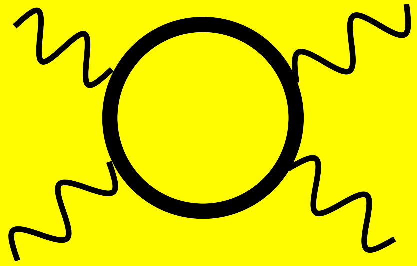
$$a_\mu^{exp} = 11\ 659\ 2089(63)\cdot 10^{-11}$$
$$a_\mu^{SM} = 11\ 659\ 1834(49)\cdot 10^{-11}$$
$$\boxed{a_\mu^{exp} - a_\mu^{SM} = 255 \pm 80 \cdot 10^{-11}}$$

$$a_\mu^{QED} = 11\ 658\ 4705.6(2.9)\cdot 10^{-11}$$
$$a_\mu^{weak} = 151(4)\cdot 10^{-11}$$
$$a_\mu^{hadr} = 6877.2(46.3)\cdot 10^{-11}$$

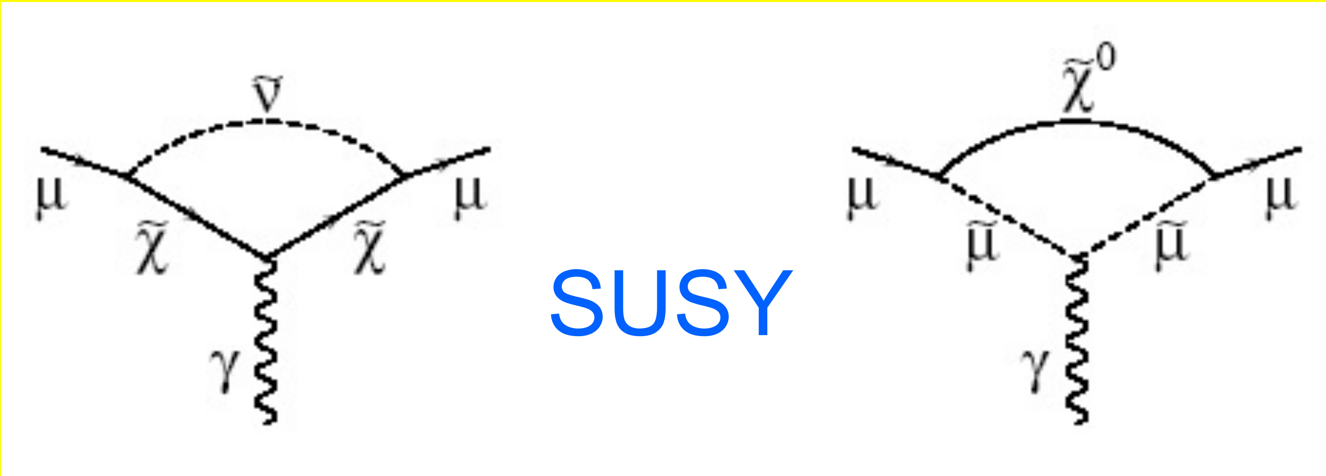




vacuum pol



light-light scat



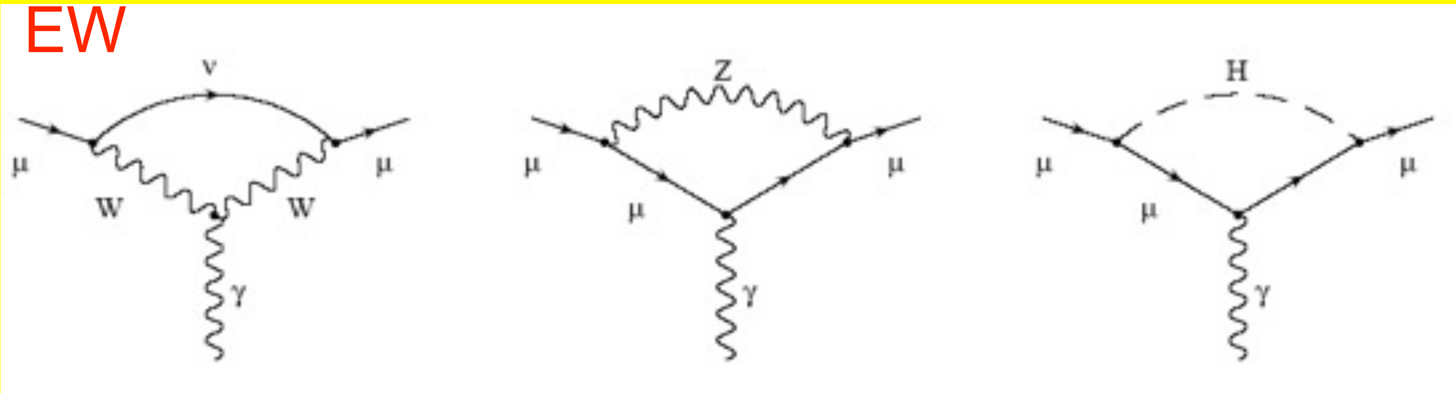
9

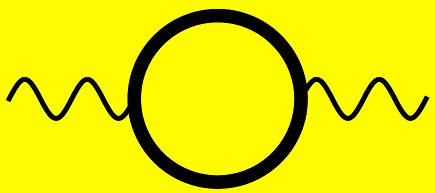
Anomalous magnetic moment

$$a_\mu^{exp} = 11\,659\,2089(63)\cdot 10^{-11} \qquad a_\mu^{QED} = 11\,658\,4705.6(2.9)\cdot 10^{-11}$$

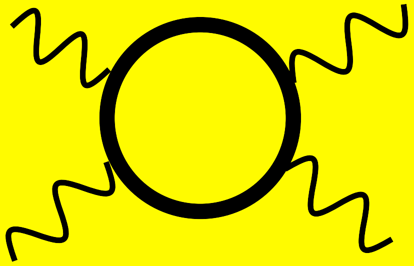
$$a_\mu^{SM} = 11\,659\,1834(49)\cdot 10^{-11} \qquad a_\mu^{weak} = 151(4)\cdot 10^{-11}$$

$$\boxed{a_\mu^{exp} - a_\mu^{SM} = 255 \pm 80 \cdot 10^{-11}} \qquad a_\mu^{hadr} = 6877.2(46.3)\cdot 10^{-11}$$



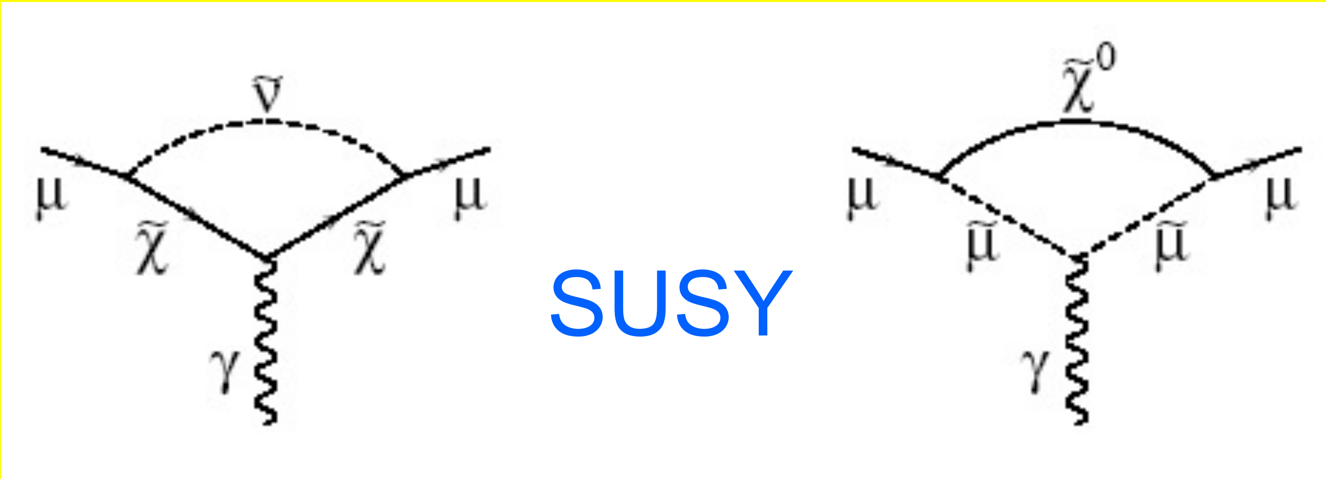


vacuum pol



light-light scat

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

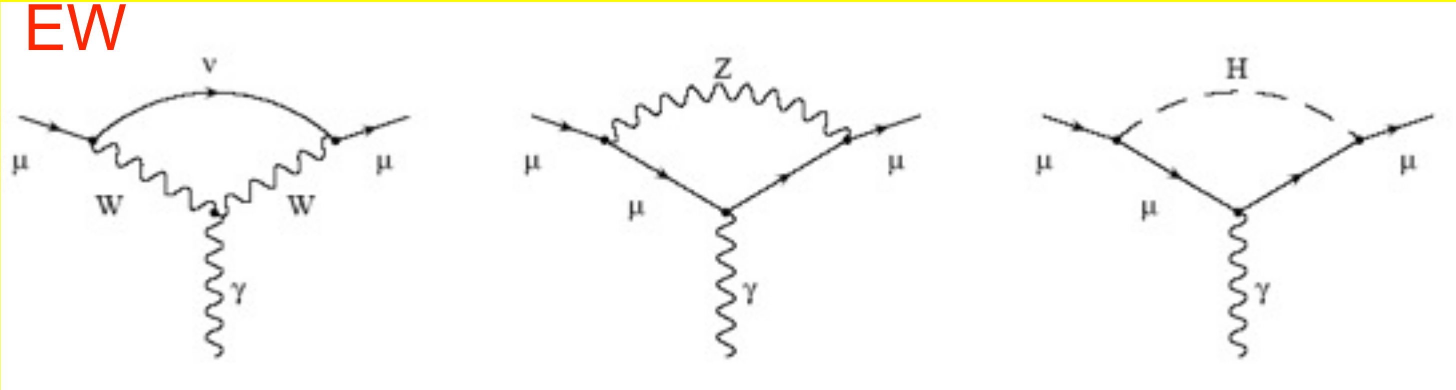


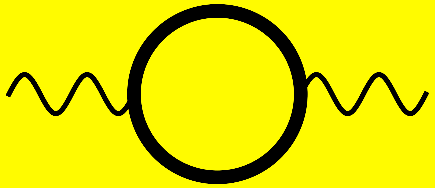
Anomalous magnetic moment

$$a_\mu^{exp} = 11\,659\,2089(63)\cdot 10^{-11} \qquad a_\mu^{QED} = 11\,658\,4705.6(2.9)\cdot 10^{-11}$$

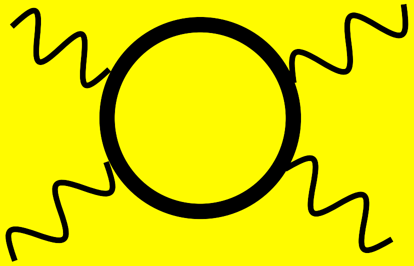
$$a_\mu^{SM} = 11\,659\,1834(49)\cdot 10^{-11} \qquad a_\mu^{weak} = 151(4)\cdot 10^{-11}$$

$$\boxed{a_\mu^{exp} - a_\mu^{SM} = 255 \pm 80\cdot 10^{-11}} \qquad a_\mu^{hadr} = 6877.2(46.3)\cdot 10^{-11}$$



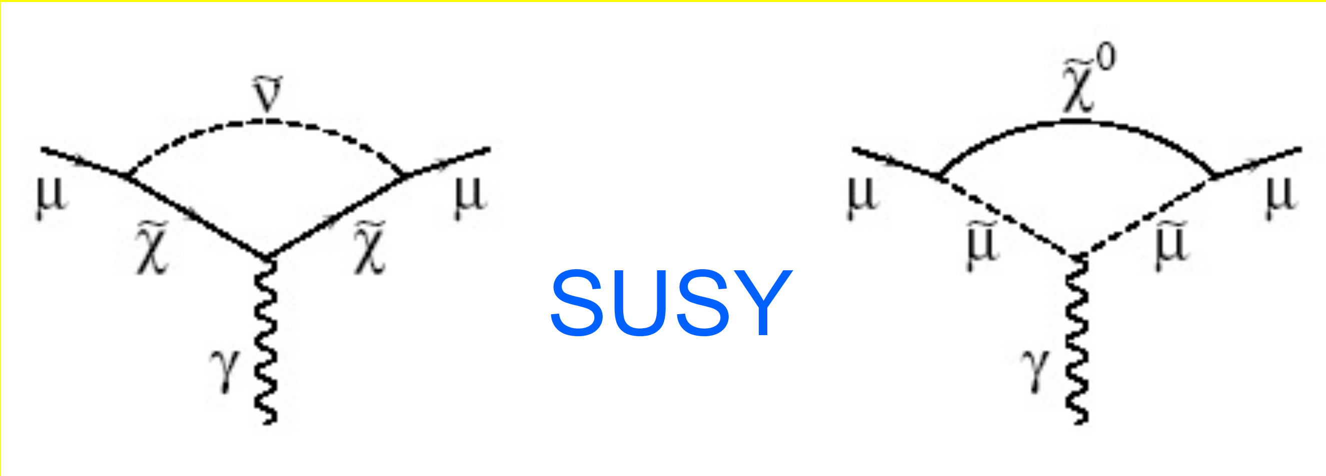


vacuum pol



light-light scat

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



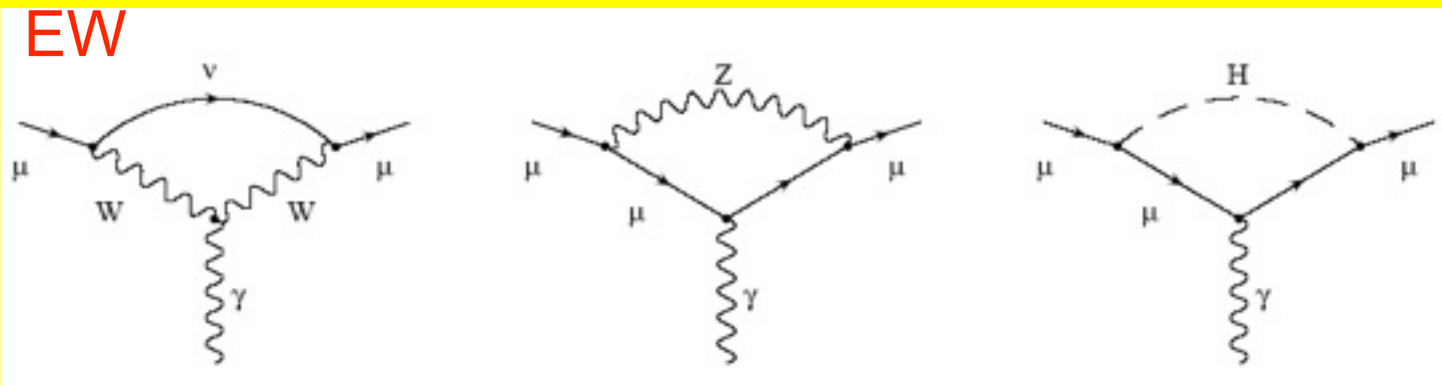
Enhancement

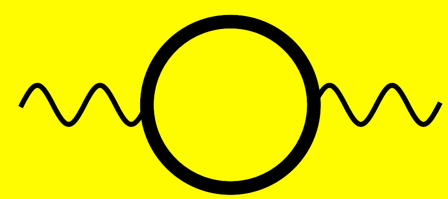
Anomalous magnetic moment

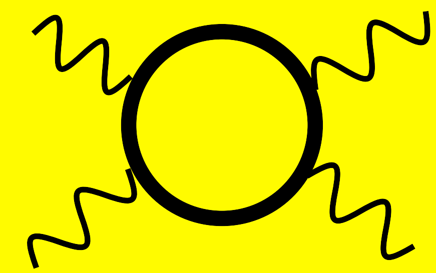
$$a_\mu^{exp} = 11\ 659\ 2089(63)\cdot 10^{-11} \qquad a_\mu^{QED} = 11\ 658\ 4705.6(2.9)\cdot 10^{-11}$$

$$a_\mu^{SM} = 11\ 659\ 1834(49)\cdot 10^{-11} \qquad a_\mu^{weak} = 151(4)\cdot 10^{-11}$$

$$\boxed{a_\mu^{exp} - a_\mu^{SM} = 255 \pm 80\cdot 10^{-11}} \qquad a_\mu^{hadr} = 6877.2(46.3)\cdot 10^{-11}$$



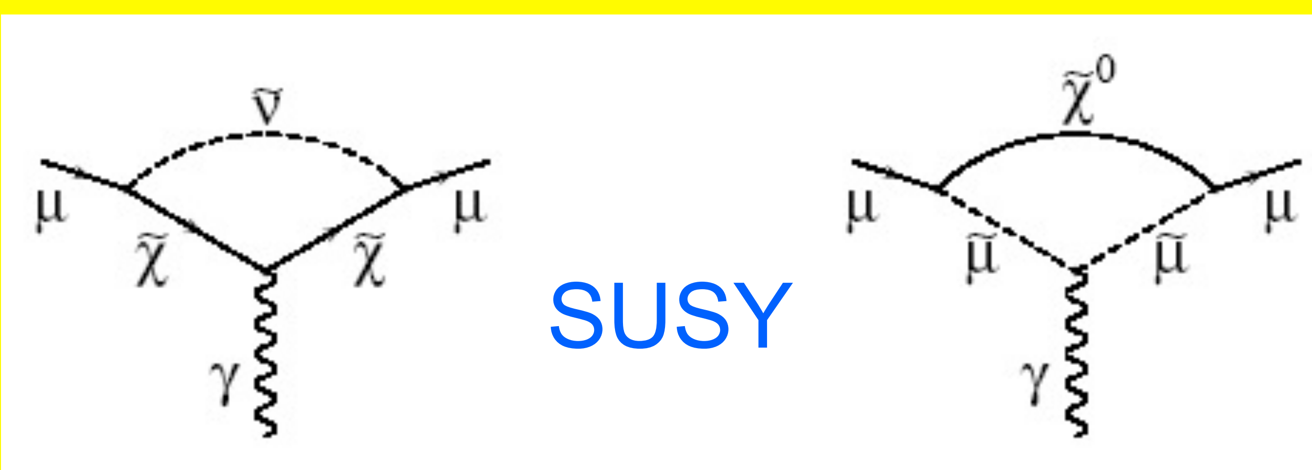




vacuum pol

light-light scat

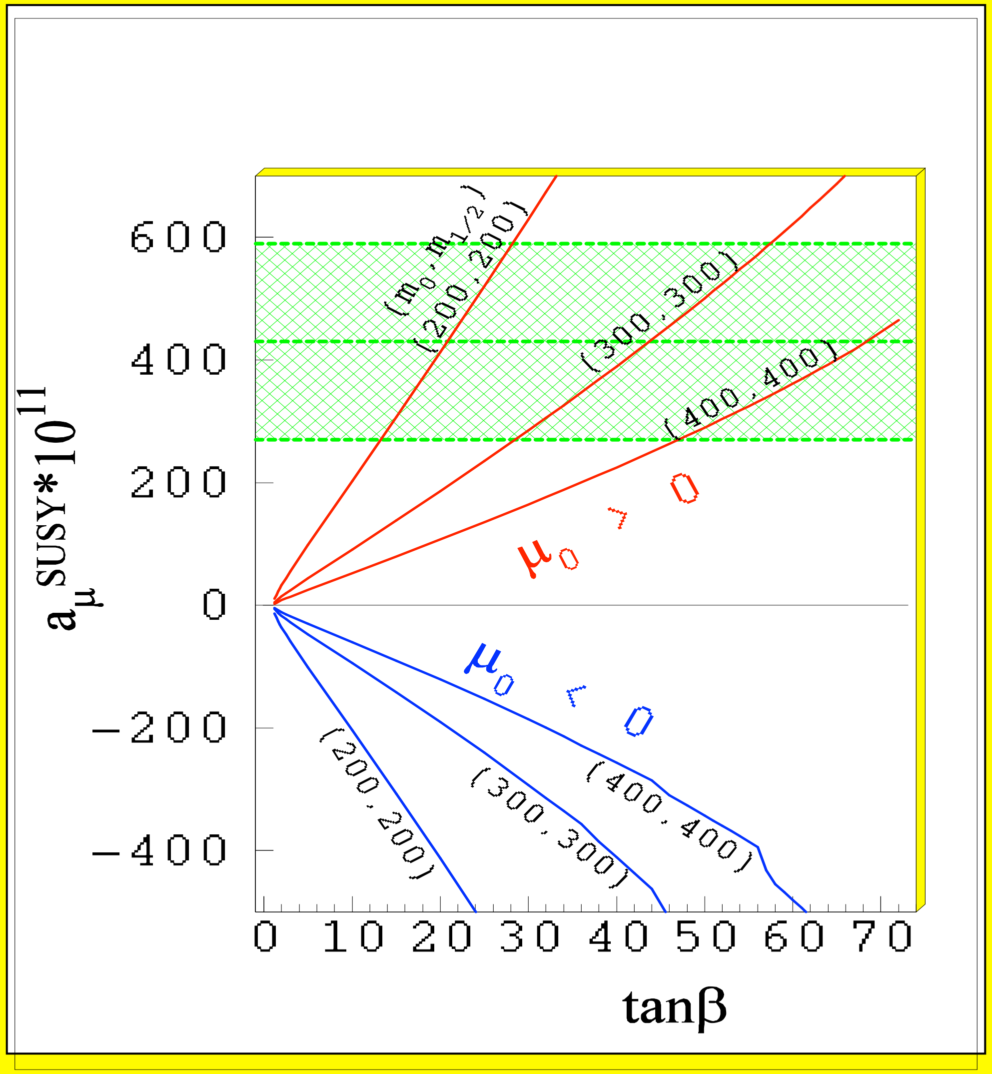
$$|a_\mu^{SUSY}| \simeq \frac{\alpha(M_Z)}{8\pi \, Sin^2\theta_W}\frac{m_\mu^2}{M_{SUSY}^2} tan\beta\left(1-\frac{4\alpha}{\pi}log\frac{M_{SUSY}}{m_\mu}\right) \simeq 140\cdot 10^{-11}\left(\frac{100\ \text{GeV}}{M_{SUSY}}\right)^2 tan\beta$$



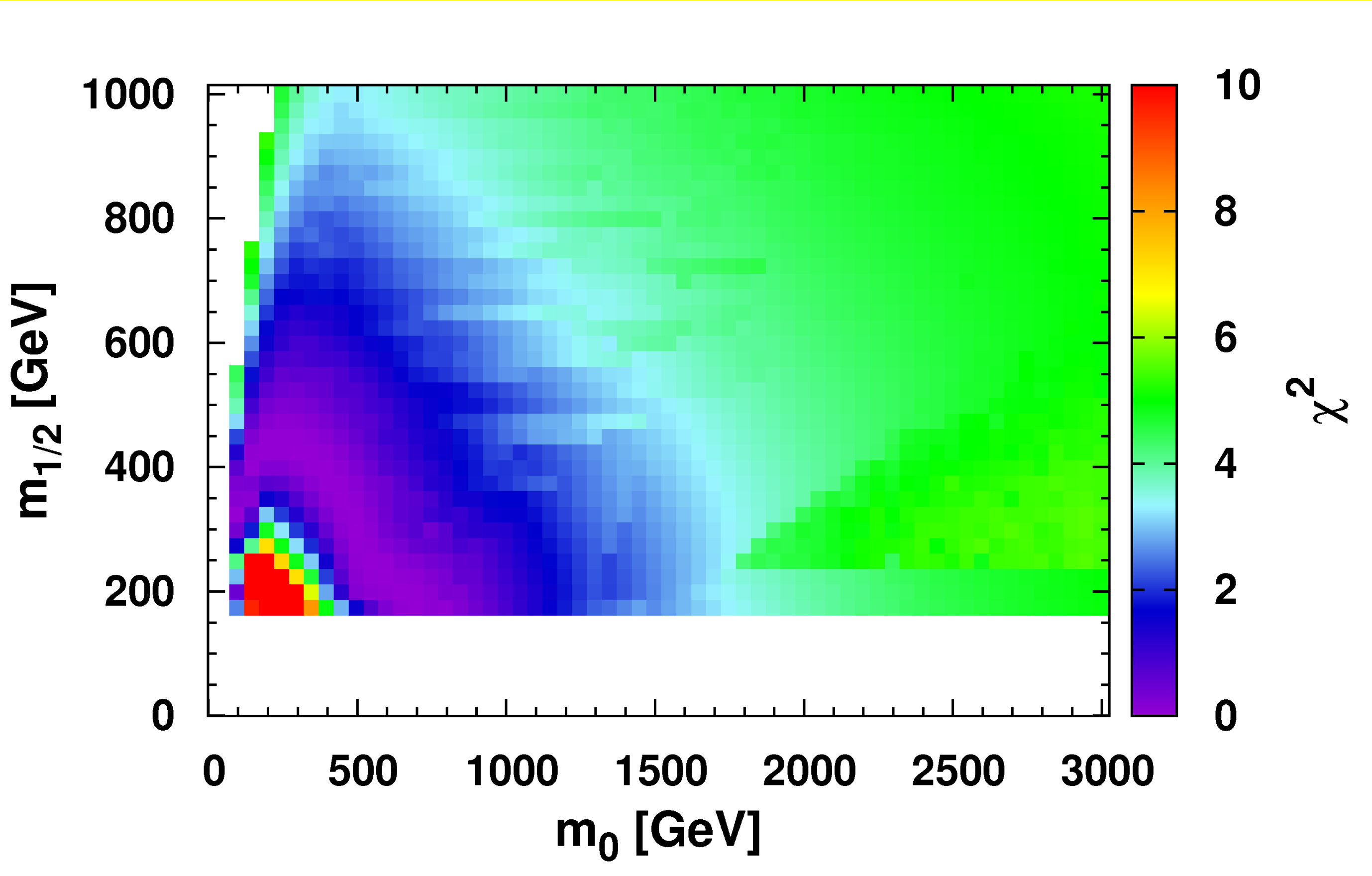
Suppression

Enhancement

g-2 Constraint on Parameter space

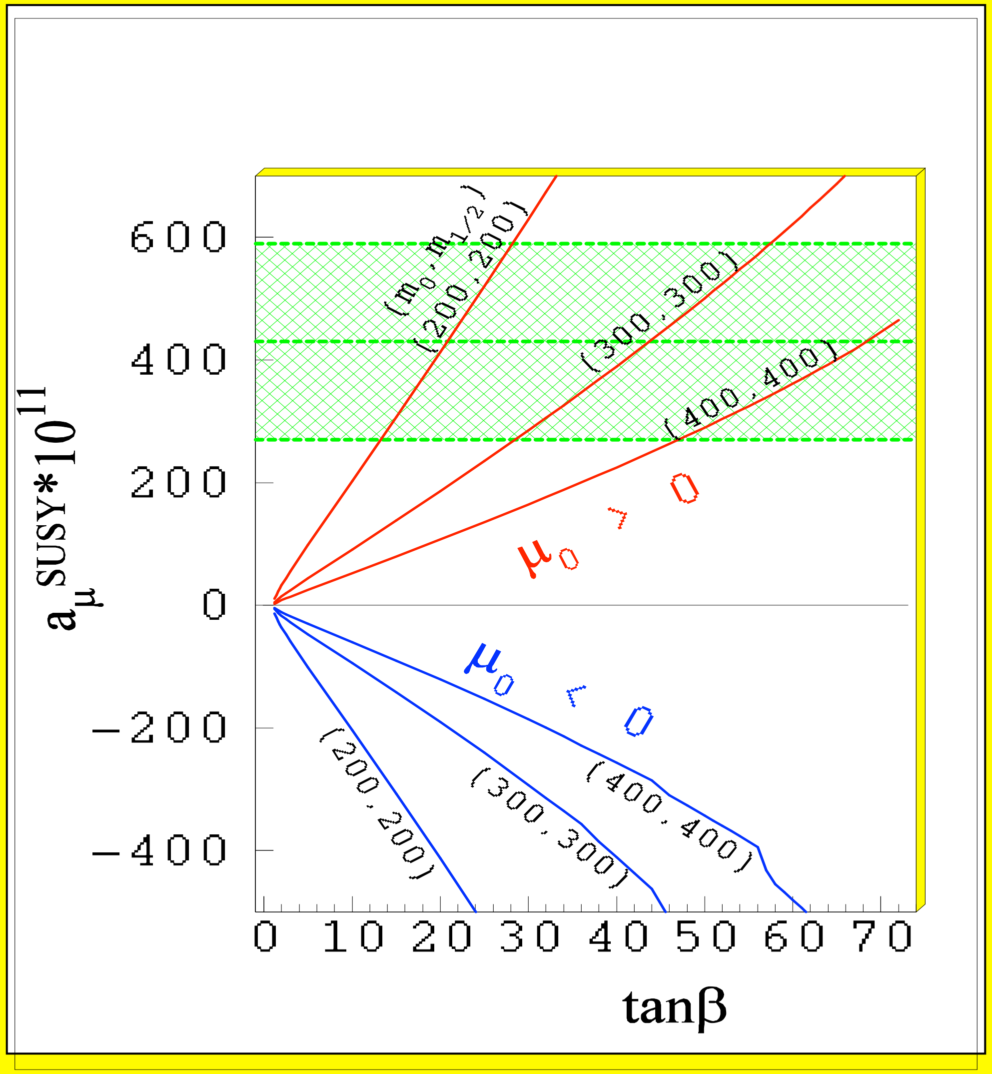


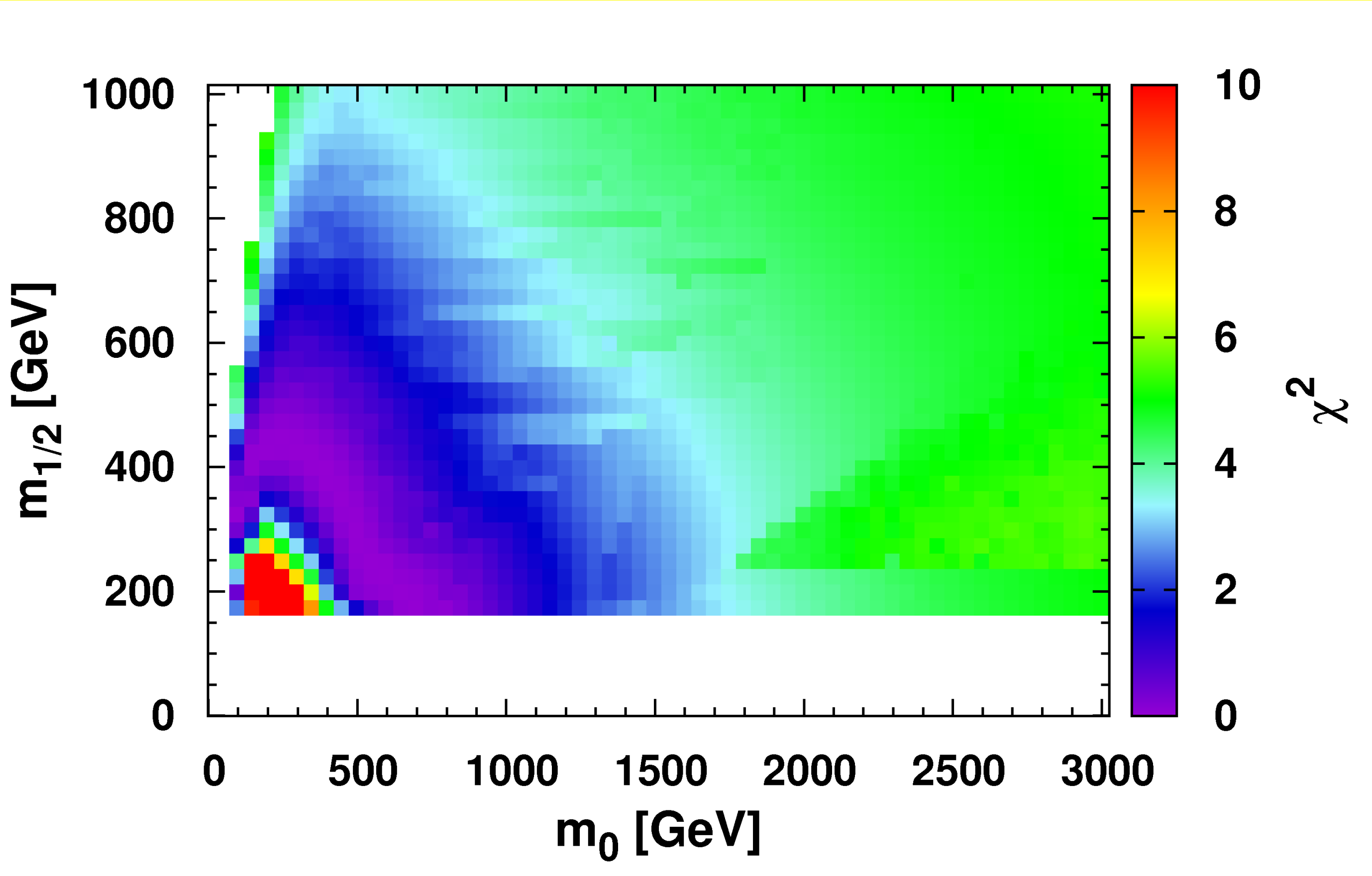
Fixes the sign of μ



The only requirement that limits the SUSY masses from above

g-2 Constraint on Parameter space





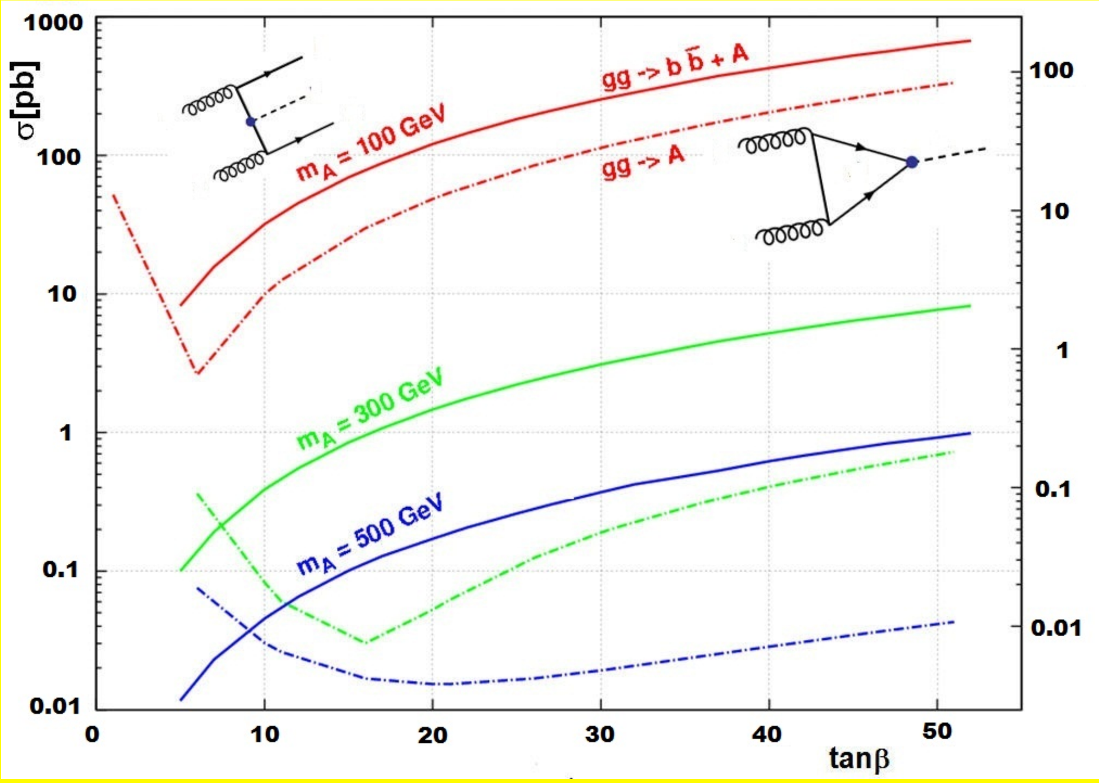
Fixes the sign of μ

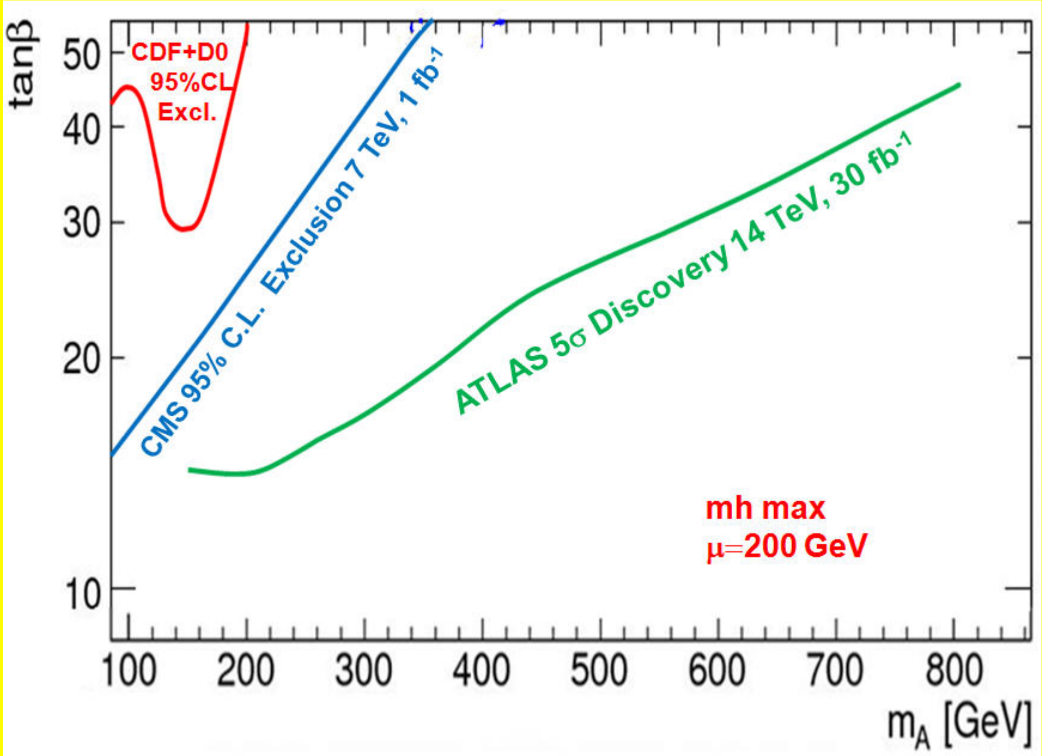
The only requirement that limits the SUSY masses from above

Almost excluded by rare decay

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

Heavy Higgs Production at the LHC

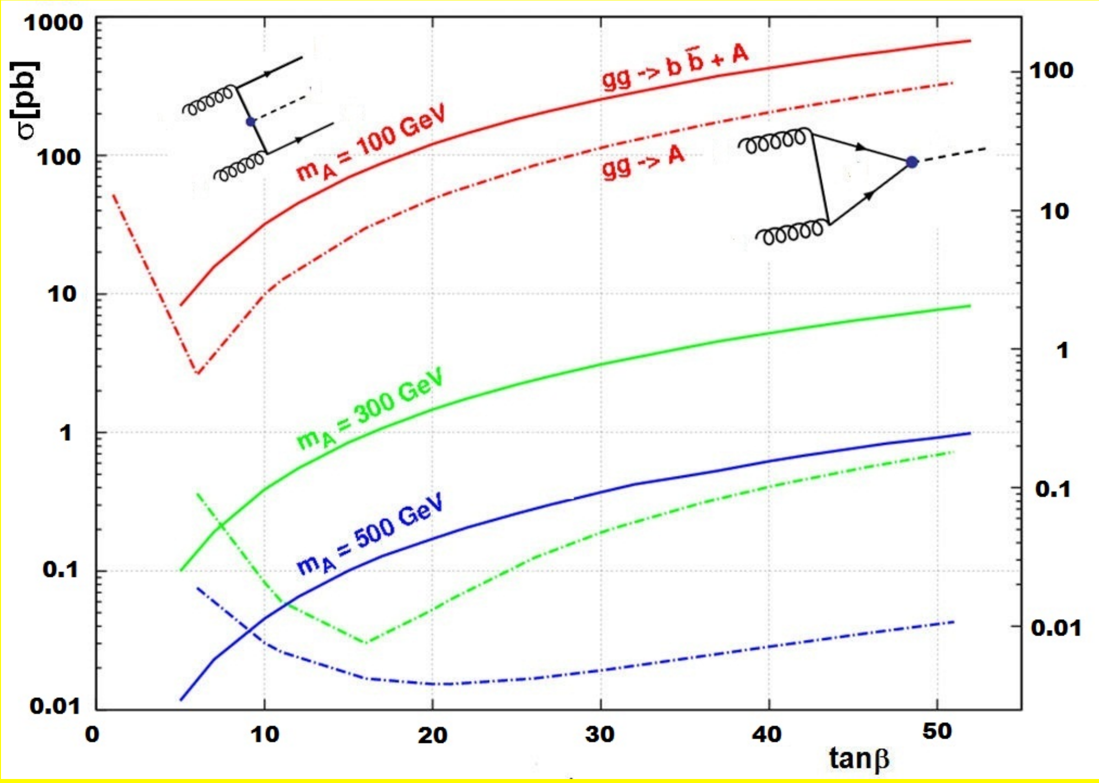


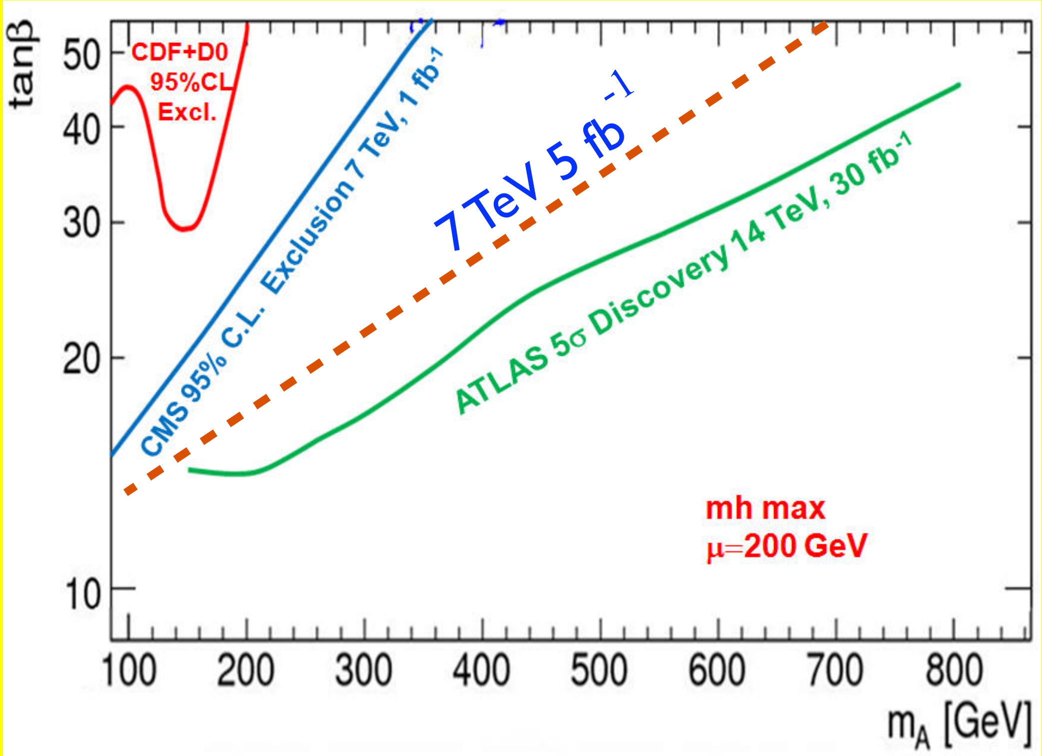


$$\sigma_{Higgs} = \frac{1}{32}\int_0^1 dx_1 dx_2\ g[x_1]\ g[x_2]\ |\mathcal{M}_{Higgs}|^2 \frac{2\pi}{m_{Higgs}^2}\delta(E^2 x_1 x_2 - m_{Higgs}^2)$$

$$\begin{aligned}
\mathcal{M}_h &= \frac{\alpha_s}{4\pi}\frac{m_h^2}{2\sqrt{2}v}\left(\frac{\cos\alpha}{\sin\beta}F_{1/2}^h[\frac{4m_t^2}{m_h^2}] - \frac{\sin\alpha}{\cos\beta}F_{1/2}^h[\frac{4m_b^2}{m_h^2}]\right), \\
\mathcal{M}_H &= \frac{\alpha_s}{4\pi}\frac{m_H^2}{2\sqrt{2}v}\left(\frac{\sin\alpha}{\sin\beta}F_{1/2}^H[\frac{4m_t^2}{m_H^2}] + \frac{\cos\alpha}{\cos\beta}F_{1/2}^H[\frac{4m_b^2}{m_H^2}]\right), \\
\mathcal{M}_A &= \frac{\alpha_s}{4\pi}\frac{m_A^2}{2\sqrt{2}v}\left(\frac{\cos\beta}{\sin\beta}F_{1/2}^A[\frac{4m_t^2}{m_A^2}] + \frac{\sin\beta}{\cos\beta}F_{1/2}^A[\frac{4m_b^2}{m_A^2}]\right)
\end{aligned}$$

Heavy Higgs Production at the LHC





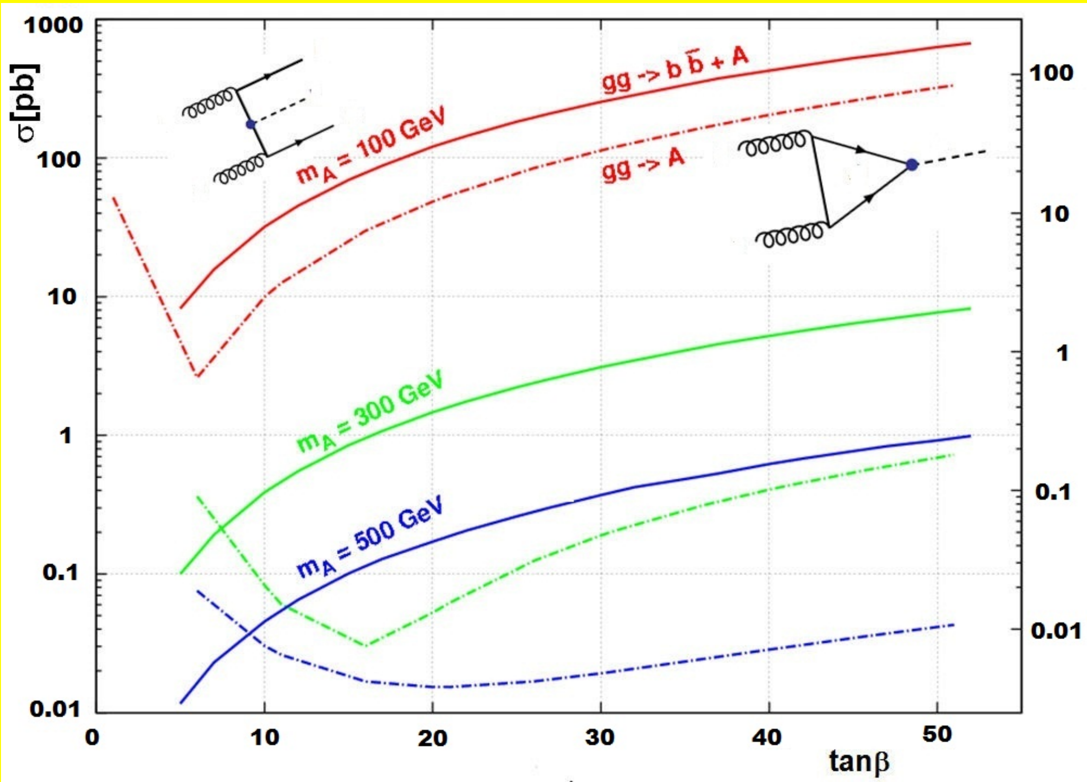
$$\sigma_{Higgs} = \frac{1}{32}\int_0^1 dx_1 dx_2\; g[x_1]\; g[x_2]\; |\mathcal{M}_{Higgs}|^2 \frac{2\pi}{m^2_{Higgs}} \delta(E^2 x_1 x_2 - m^2_{Higgs})$$

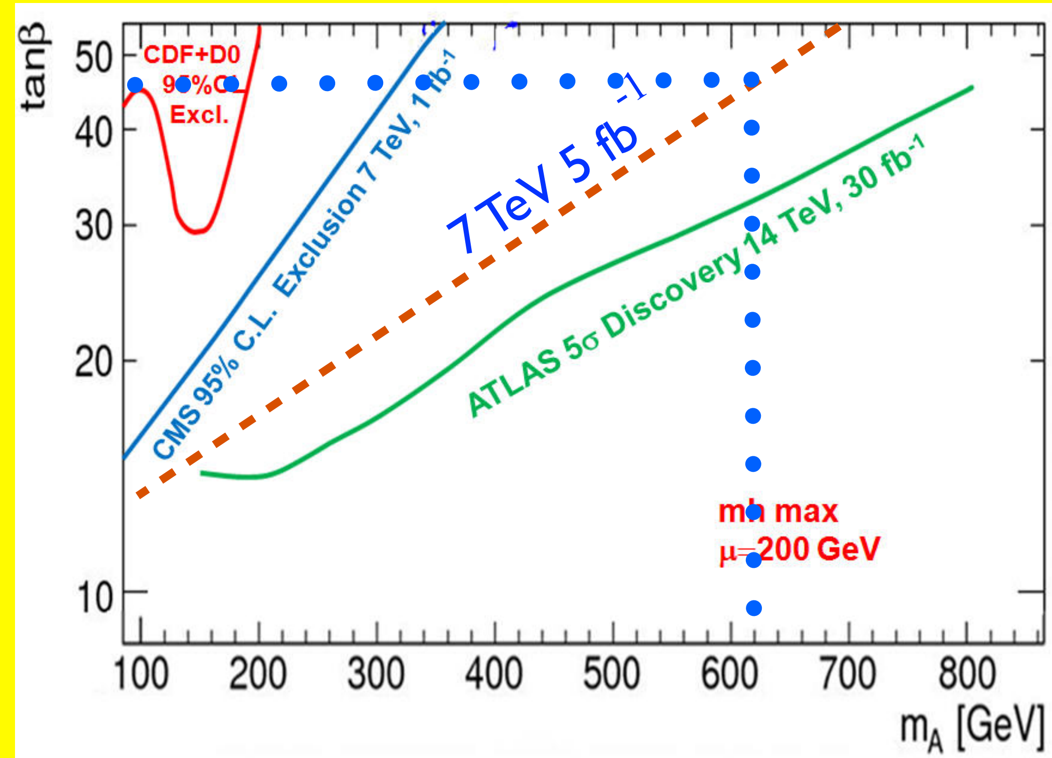
$$\mathcal{M}_h = \frac{\alpha_s}{4\pi}\frac{m_h^2}{2\sqrt{2}v}\left(\frac{\cos\alpha}{\sin\beta}F^h_{1/2}[\frac{4m_t^2}{m_h^2}] - \frac{\sin\alpha}{\cos\beta}F^h_{1/2}[\frac{4m_b^2}{m_h^2}]\right),$$

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

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

Heavy Higgs Production at the LHC

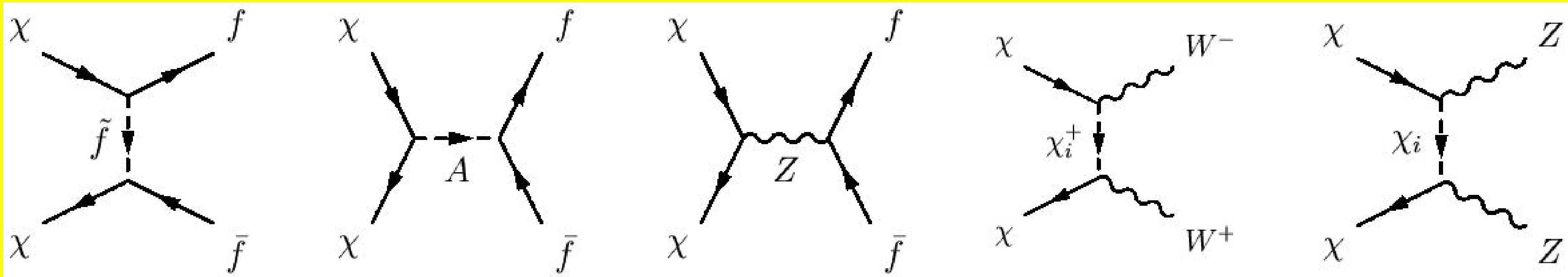




$$\sigma_{Higgs} = \frac{1}{32}\int_0^1 dx_1 dx_2\ g[x_1]\ g[x_2]\ |\mathcal{M}_{Higgs}|^2 \frac{2\pi}{m_{Higgs}^2}\delta(E^2 x_1 x_2 - m_{Higgs}^2)$$

$$\begin{aligned}
\mathcal{M}_h &= \frac{\alpha_s}{4\pi}\frac{m_h^2}{2\sqrt{2}v}\left(\frac{\cos\alpha}{\sin\beta}F_{1/2}^h[\frac{4m_t^2}{m_h^2}] - \frac{\sin\alpha}{\cos\beta}F_{1/2}^h[\frac{4m_b^2}{m_h^2}]\right), \\
\mathcal{M}_H &= \frac{\alpha_s}{4\pi}\frac{m_H^2}{2\sqrt{2}v}\left(\frac{\sin\alpha}{\sin\beta}F_{1/2}^H[\frac{4m_t^2}{m_H^2}] + \frac{\cos\alpha}{\cos\beta}F_{1/2}^H[\frac{4m_b^2}{m_H^2}]\right), \\
\mathcal{M}_A &= \frac{\alpha_s}{4\pi}\frac{m_A^2}{2\sqrt{2}v}\left(\frac{\cos\beta}{\sin\beta}F_{1/2}^A[\frac{4m_t^2}{m_A^2}] + \frac{\sin\beta}{\cos\beta}F_{1/2}^A[\frac{4m_b^2}{m_A^2}]\right)
\end{aligned}$$

Relic Abundance of the Dark Matter



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

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

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

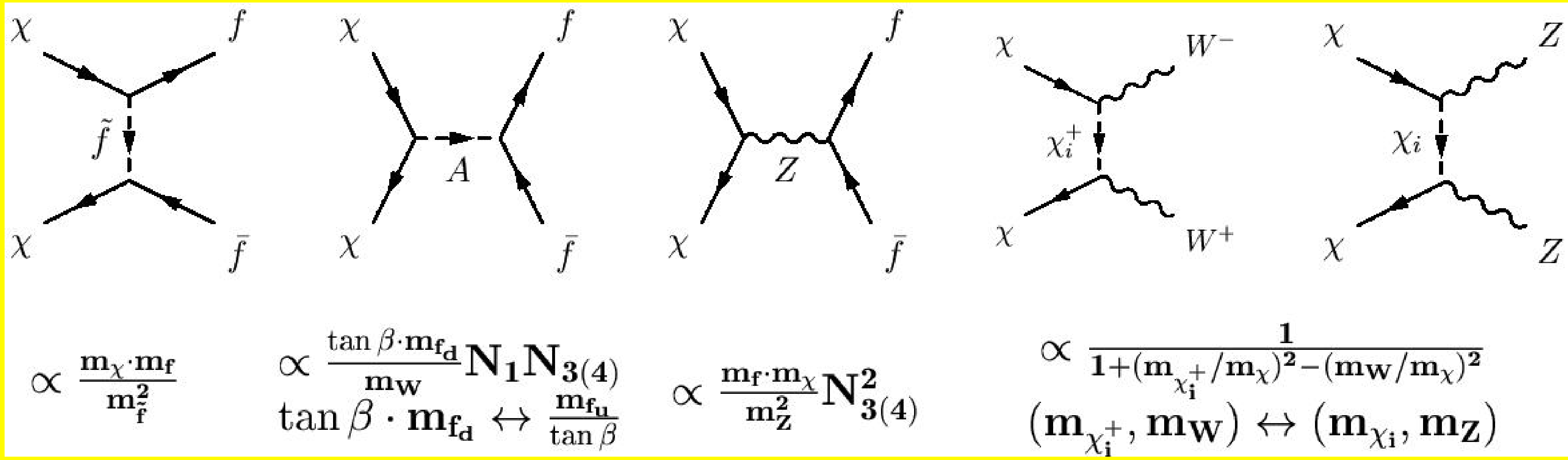
$\propto \frac{\mathbf{m_f \cdot m_\chi}}{\mathbf{m_Z^2}} \mathbf{N_{3(4)}^2}$

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

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

The Dark Matter Annihilation

Relic Abundance of the Dark Matter

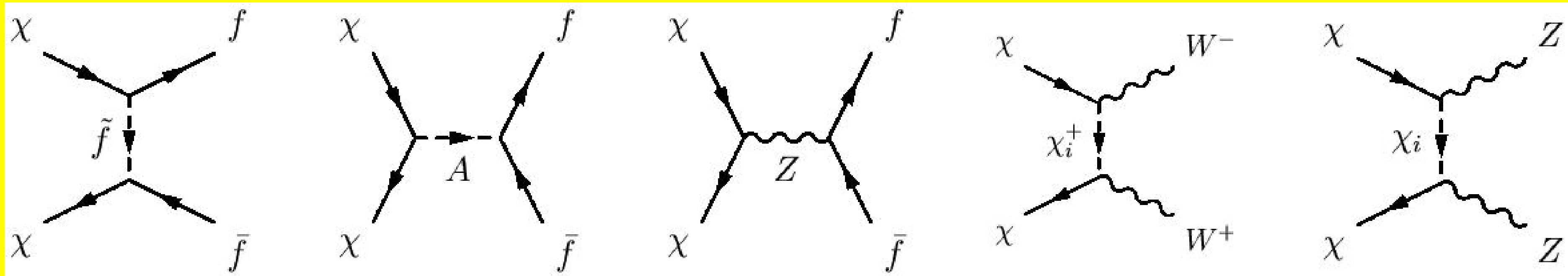


The Dark Matter Annihilation

WMAP: $\Omega_{DM} h^2 = 0.1131 \pm 0.0034$

$h \approx 0.71$

Relic Abundance of the Dark Matter



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

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

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

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

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

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

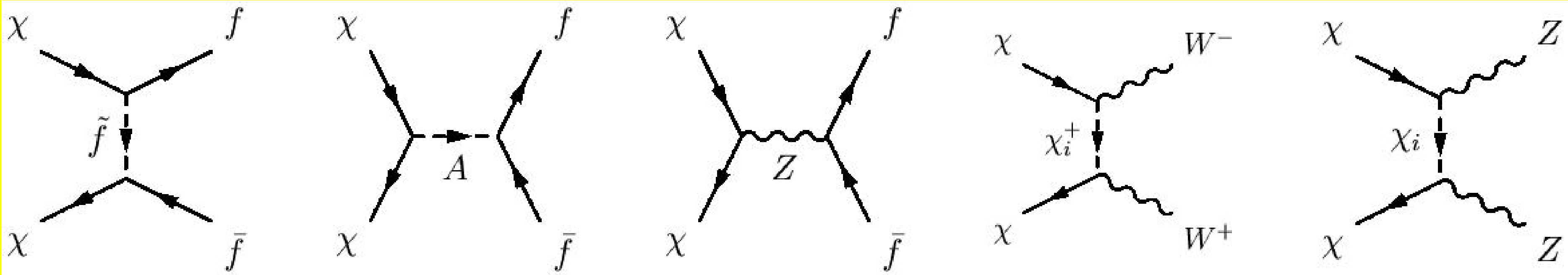
The Dark Matter Annihilation

WMAP: $\Omega_{DM} h^2 = 0.1131 \pm 0.0034$

$$\Omega h^2 = \frac{3 \cdot 10^{-27}}{< \sigma v >}$$

$h \approx 0.71$

Relic Abundance of the Dark Matter



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

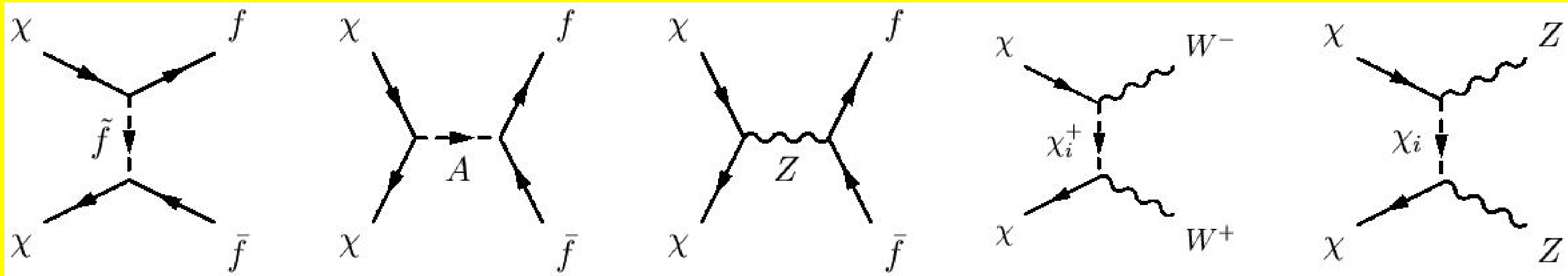
$\tan\beta \cdot \mathbf{m}_{\mathbf{f_d}} \leftrightarrow \frac{\mathbf{m}_{\mathbf{f_u}}}{\tan\beta}$ $\quad (\mathbf{m}_{\chi_i^+}, \mathbf{m_W}) \leftrightarrow (\mathbf{m}_{\chi_i}, \mathbf{m_Z})$

The Dark Matter Annihilation

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

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

Relic Abundance of the Dark Matter



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

The Dark Matter Annihilation

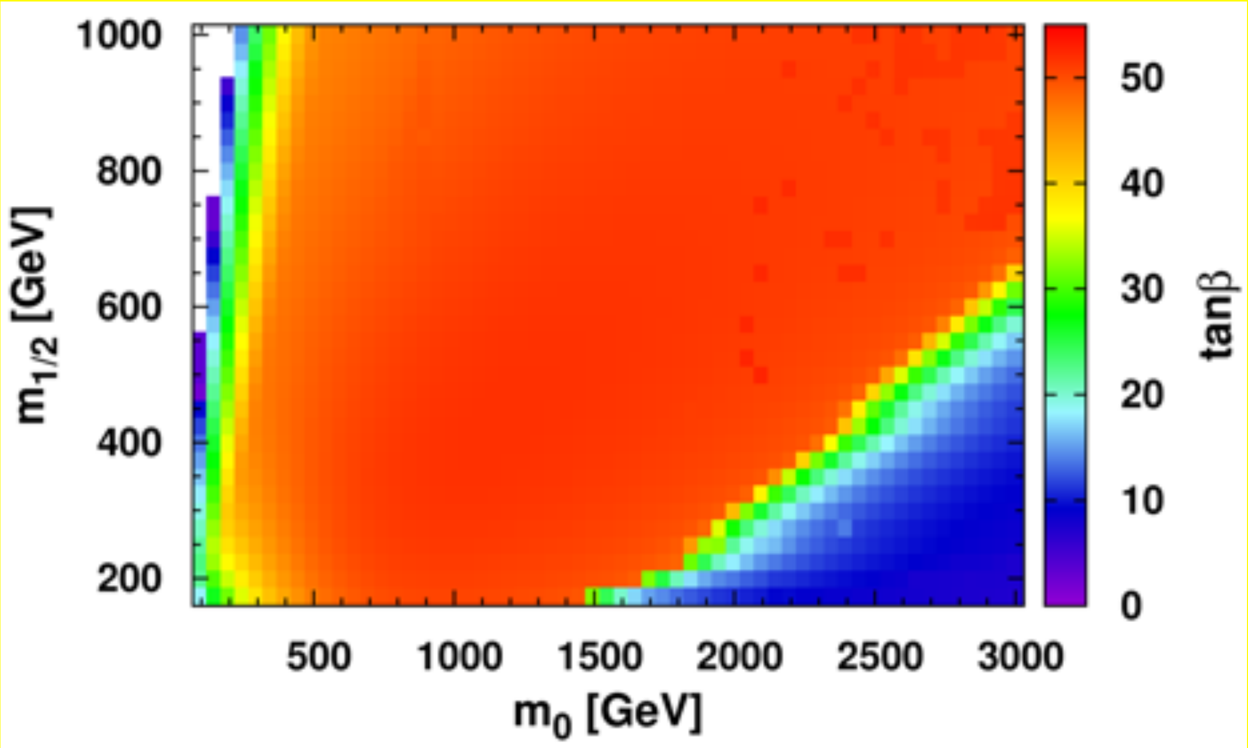
WMAP: $\Omega_{DM} h^2 = 0.1131 \pm 0.0034$ $\qquad \Omega h^2 = \frac{3 \cdot 10^{-27}}{< \sigma v >}$

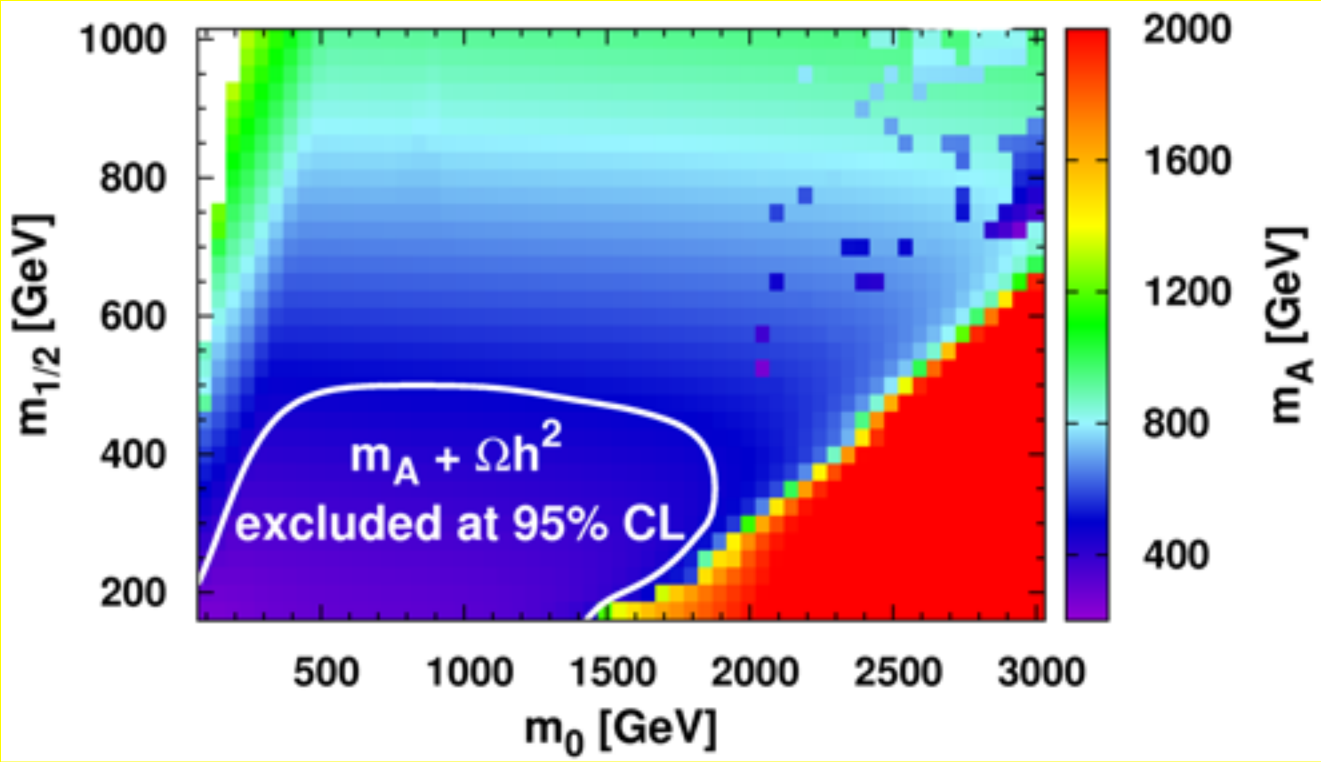
$h \approx 0.71$ $\qquad \boxed{< \sigma v >= 2 \cdot 10^{-26} cm^3/s}$

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

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

Relic Abundance of the DM Constraint





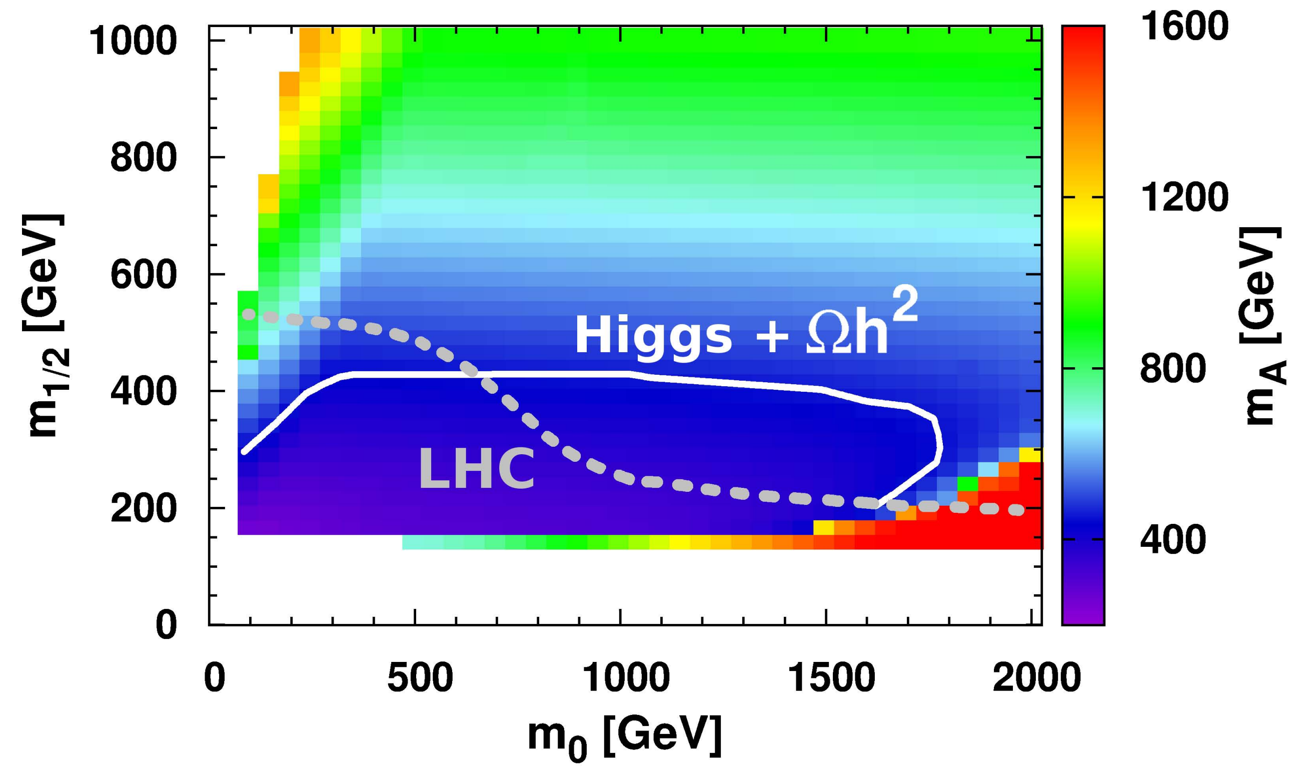
The value of $\tan\beta$

$\tan\beta \approx 50$ 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

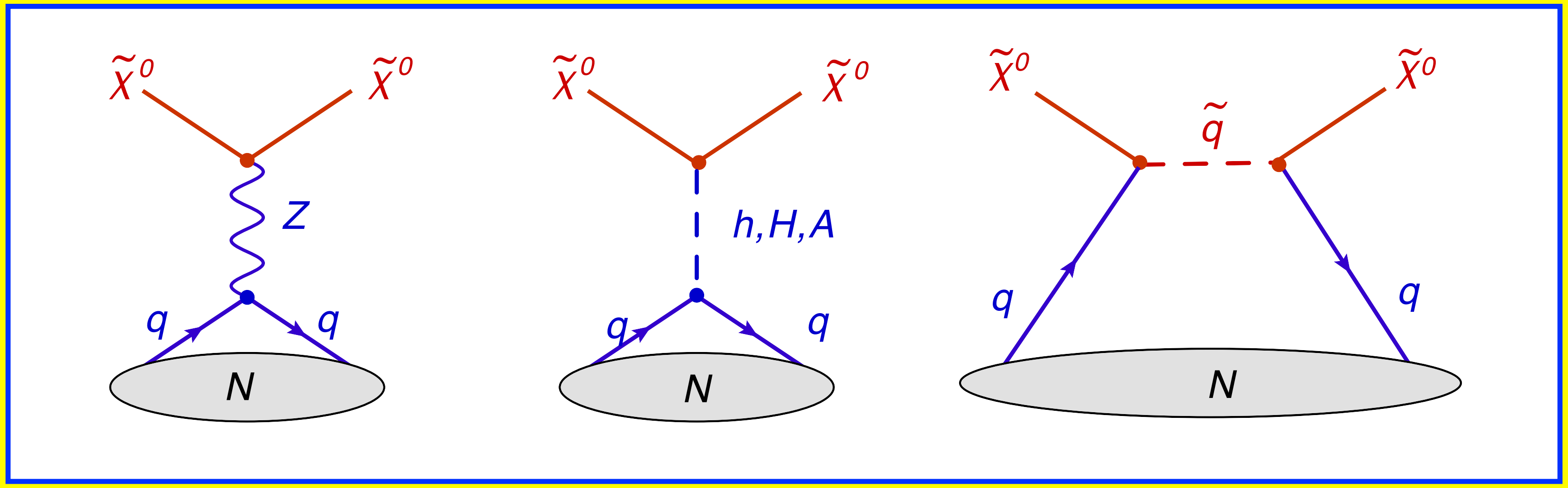


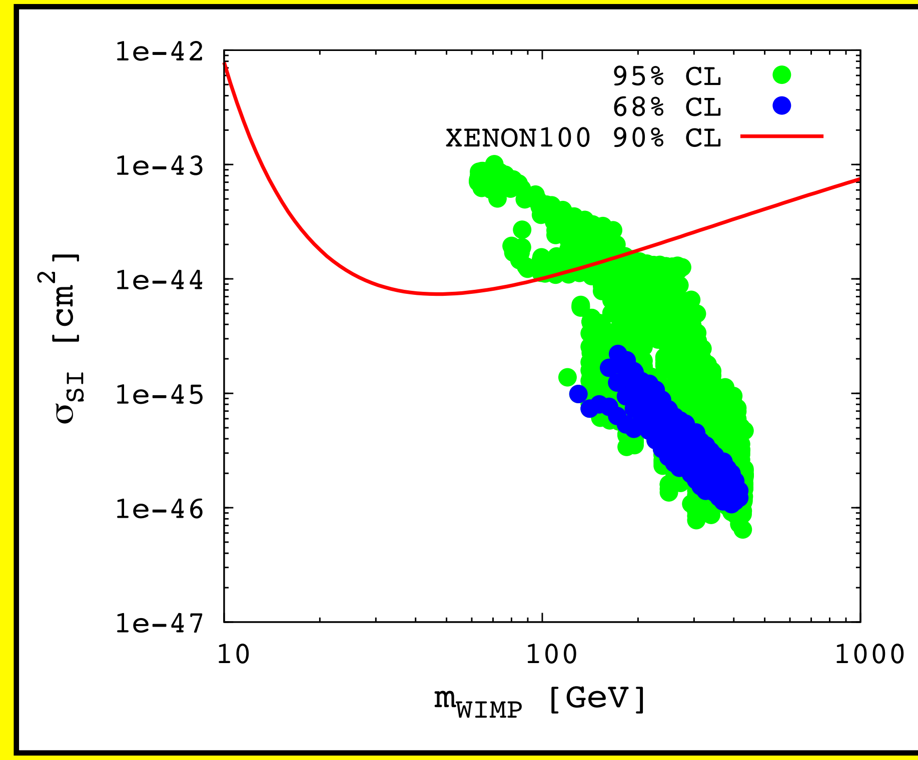
The values of A_0 and $\tan\beta$ are ajusted

This includes:

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

Direct DM Searches



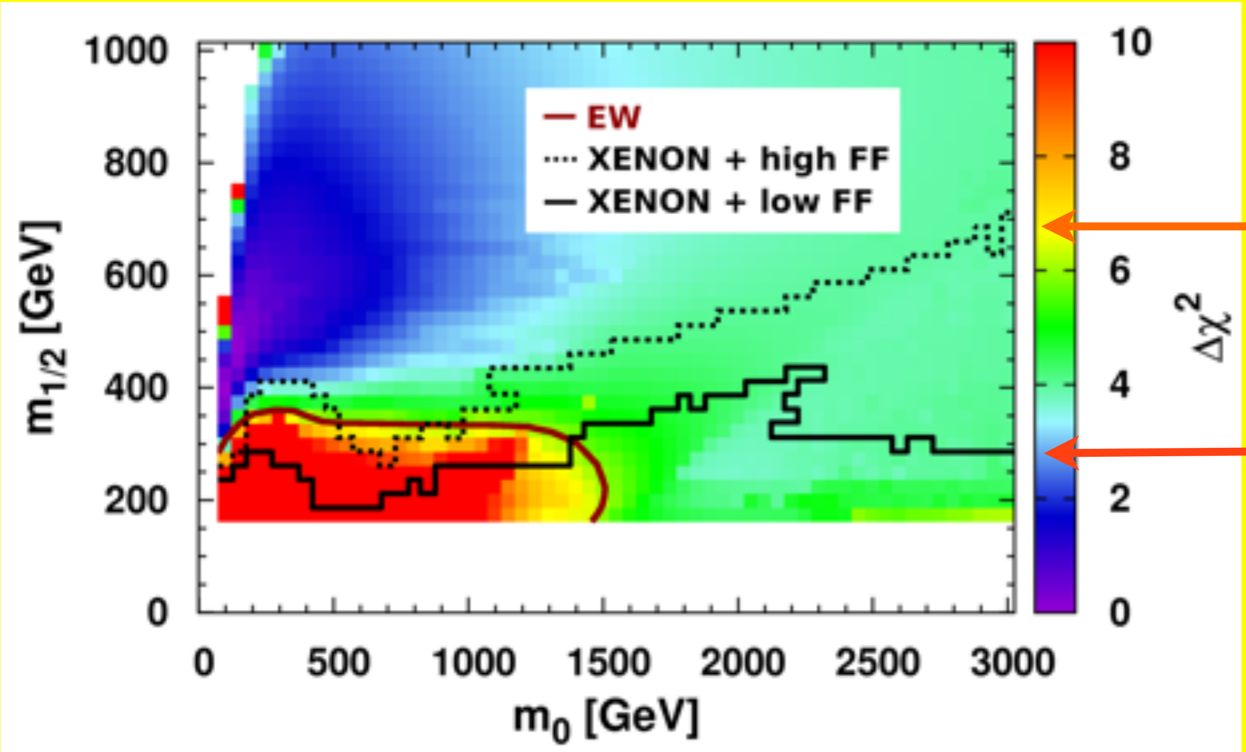


$$\sigma = \frac{4}{\pi}\frac{m_{\rm DM}^2 m_N^2}{(m_{\rm DM}+m_N)^2}\left(Zf_p+(A-Z)f_n\right)^2$$

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

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

SUSY Limits from Direct DM Search

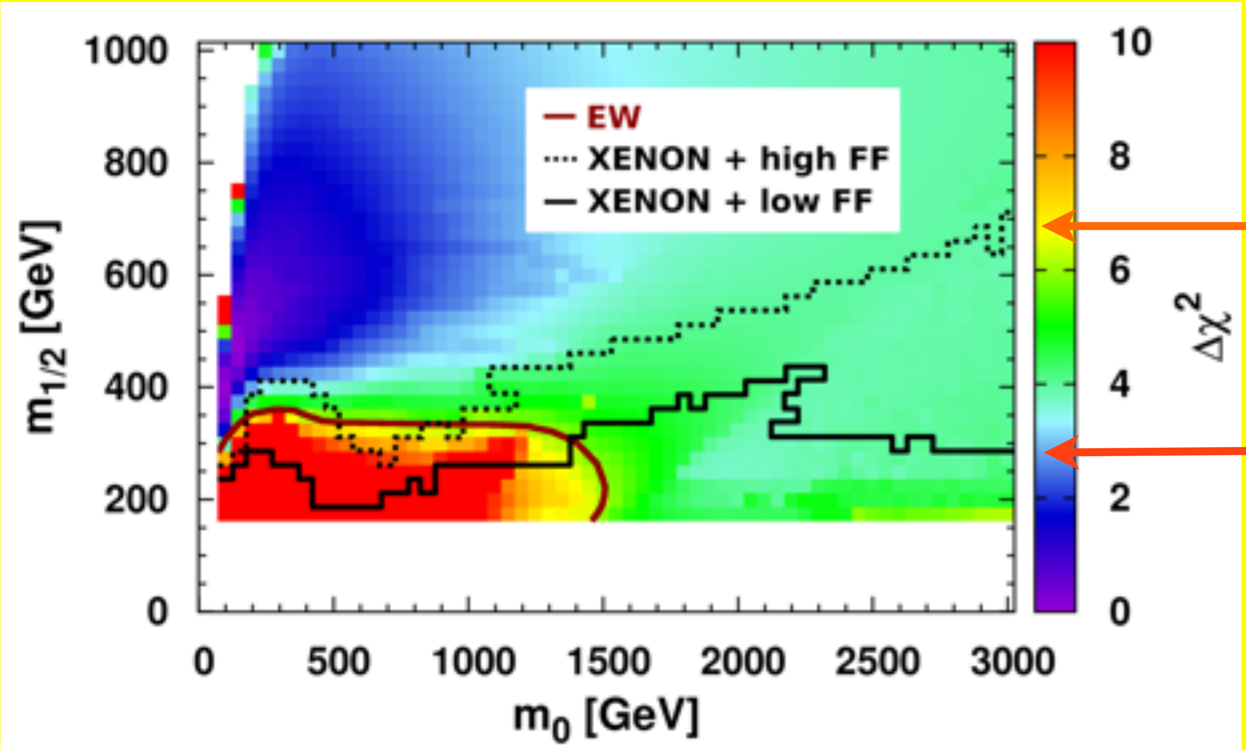


Low Energy Form Factors

Lattice Form Factors

ICHEP2012
Melbourne

SUSY Limits from Direct DM Search

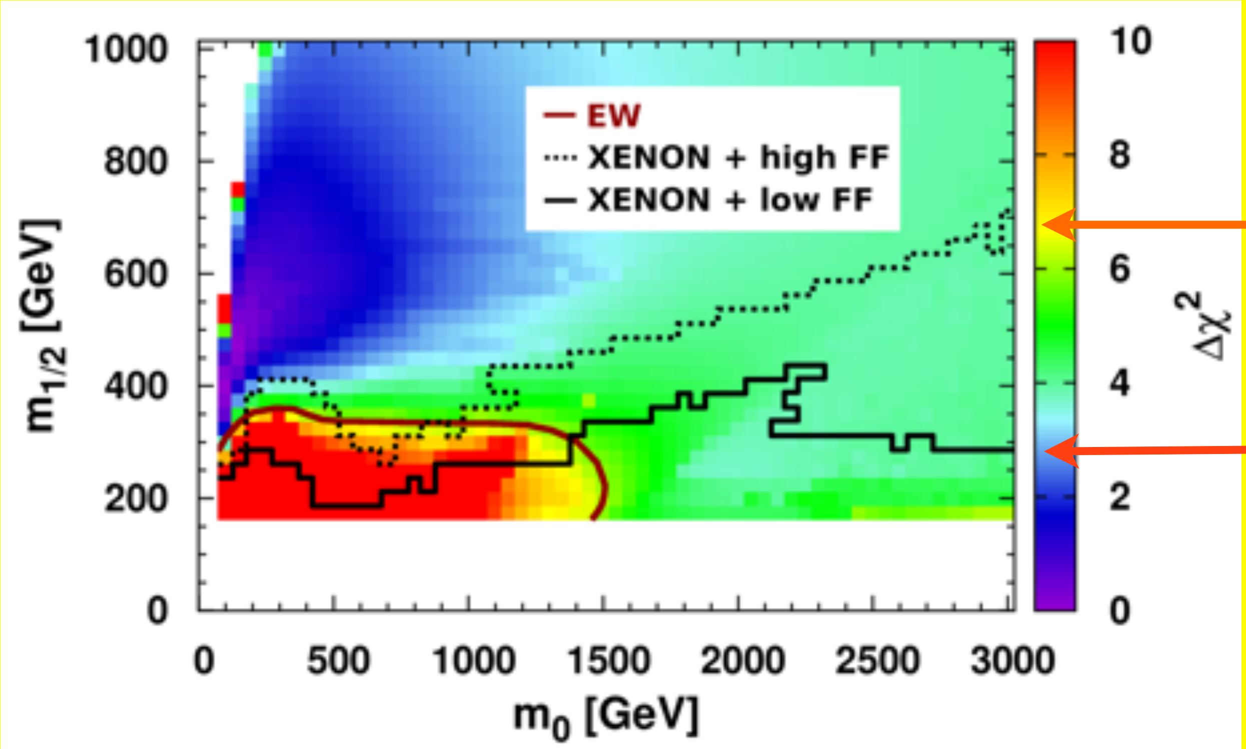


Low Energy Form Factors

Lattice Form Factors

- LHC constraints are rather insensitive to large values of m_0

SUSY Limits from Direct DM Search

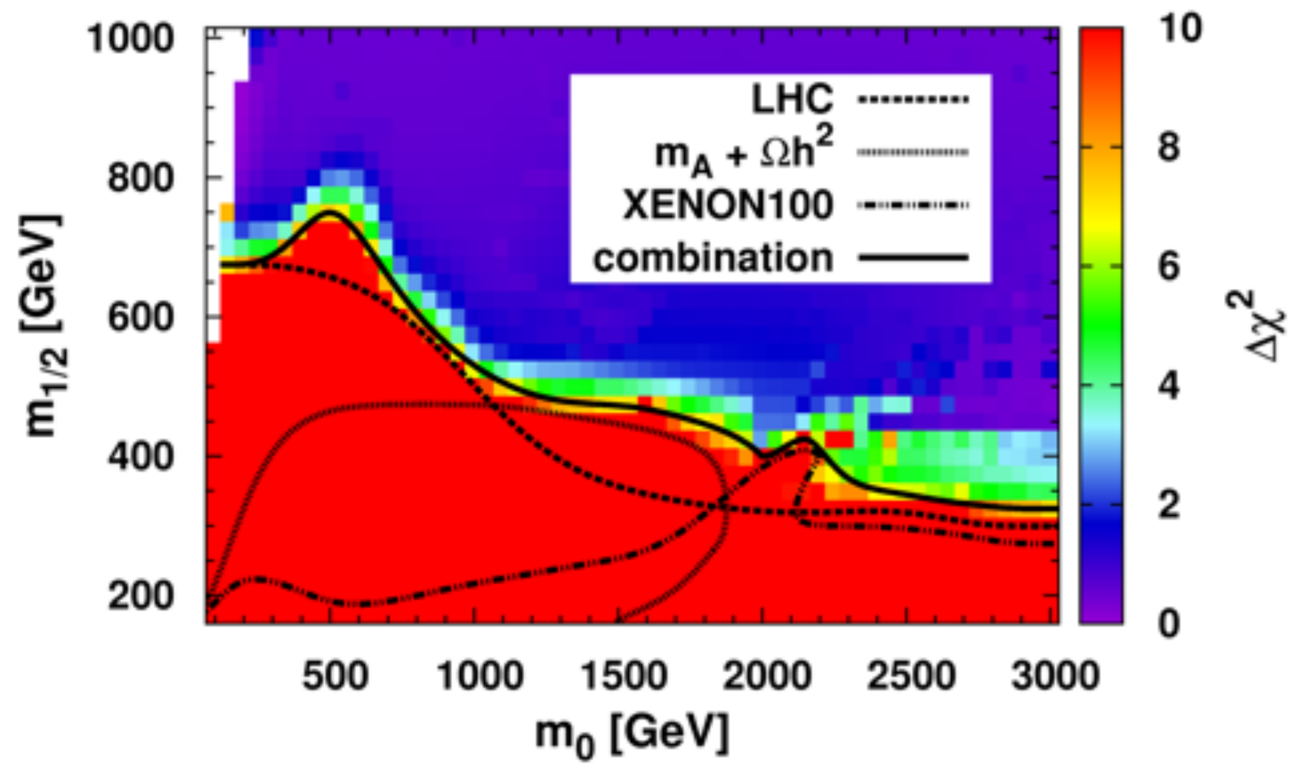


Low Energy Form Factors

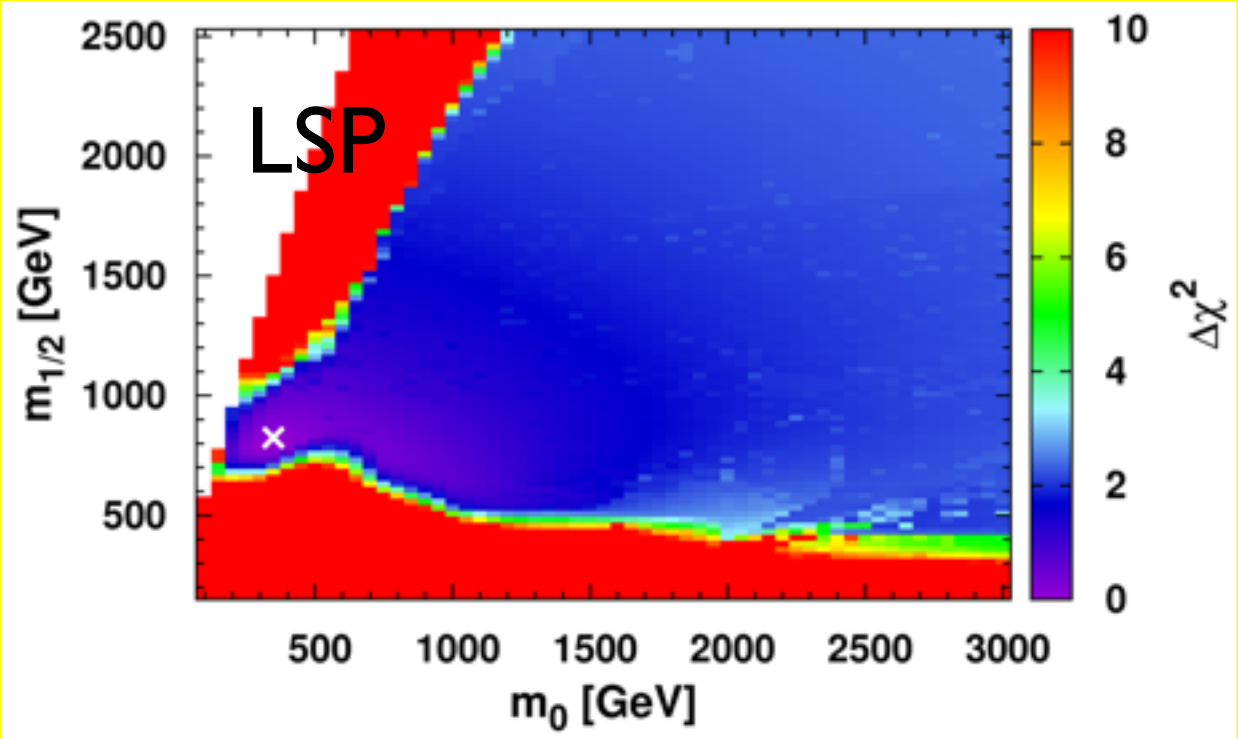
Lattice Form Factors

- 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

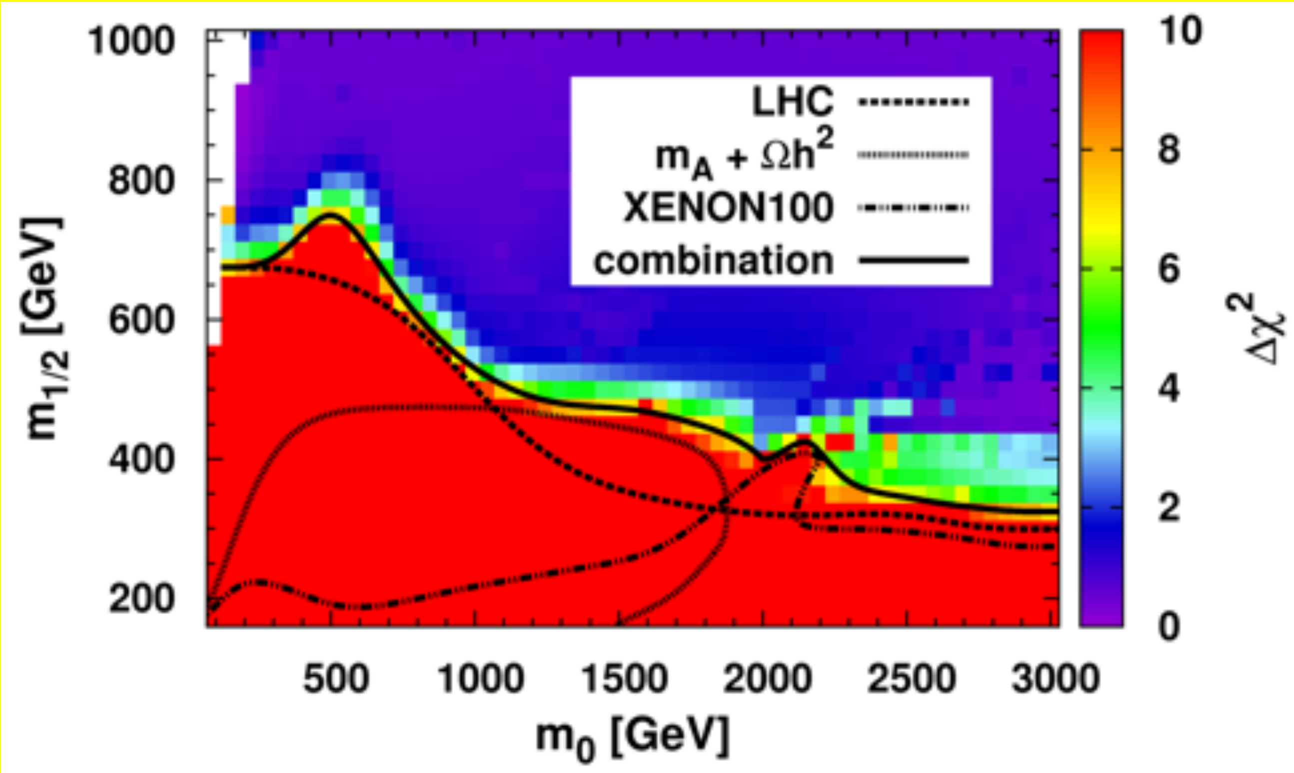


Larger scale for

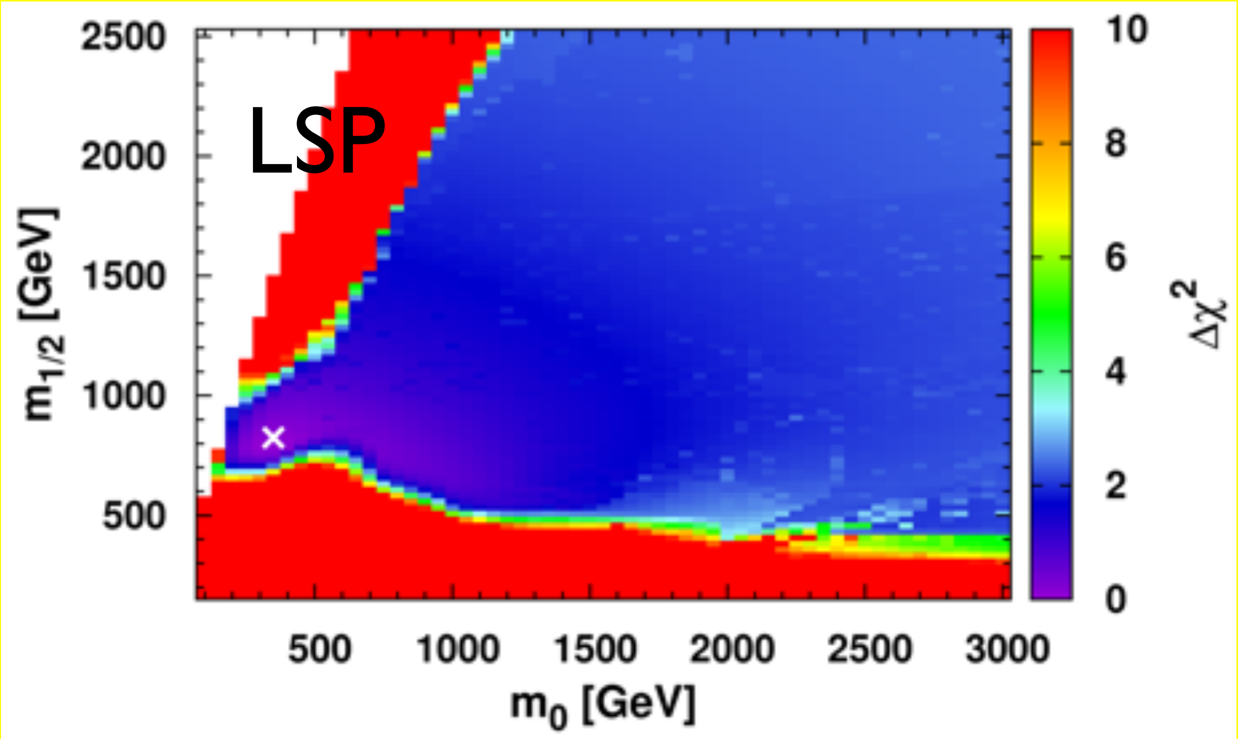


The values of $\tan\beta$ and A_0 are adjusted

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

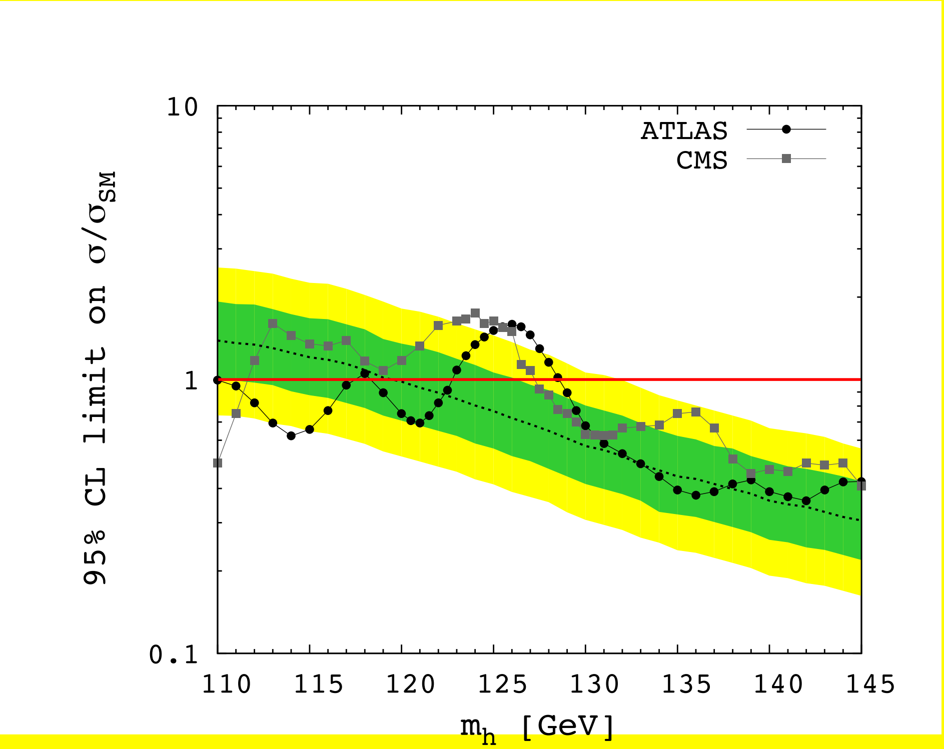


Larger scale for $m_{1/2}$



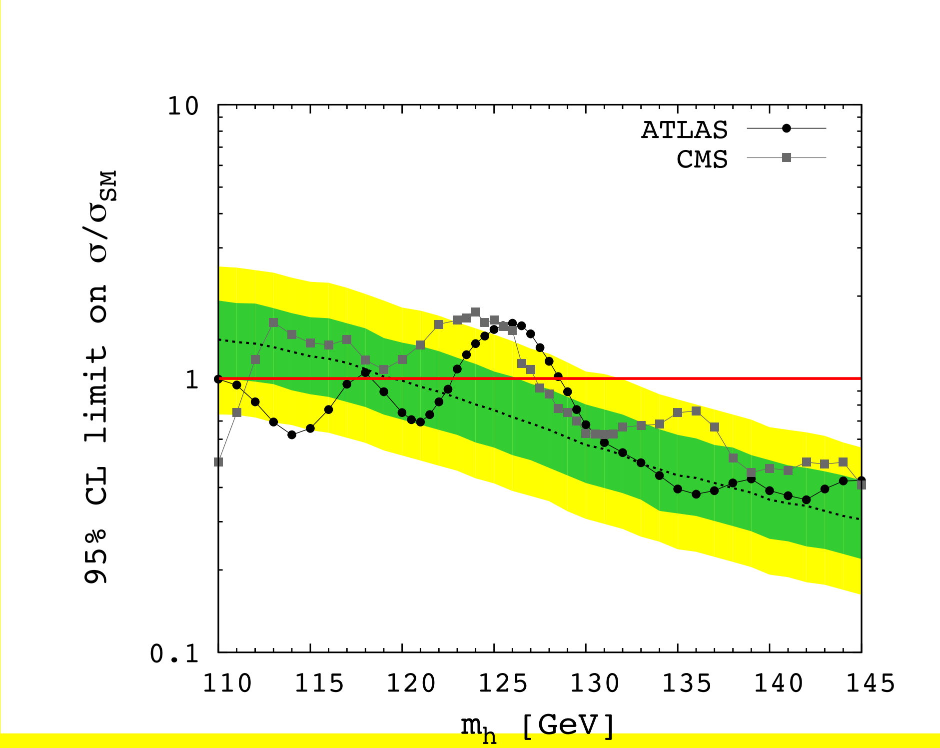
The values of $\tan\beta$ and A_0 are adjusted

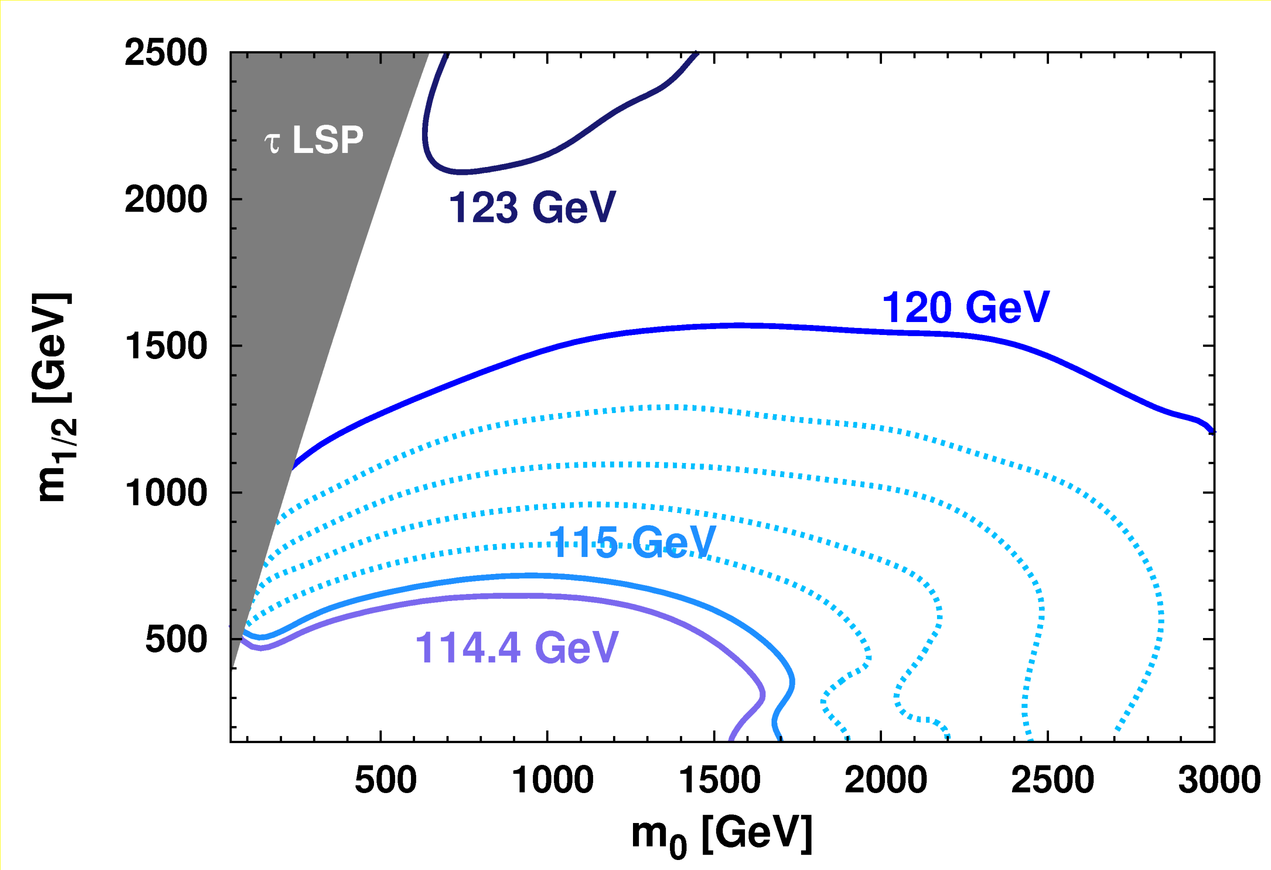
Constraints from the lightest Higgs of 125 GeV



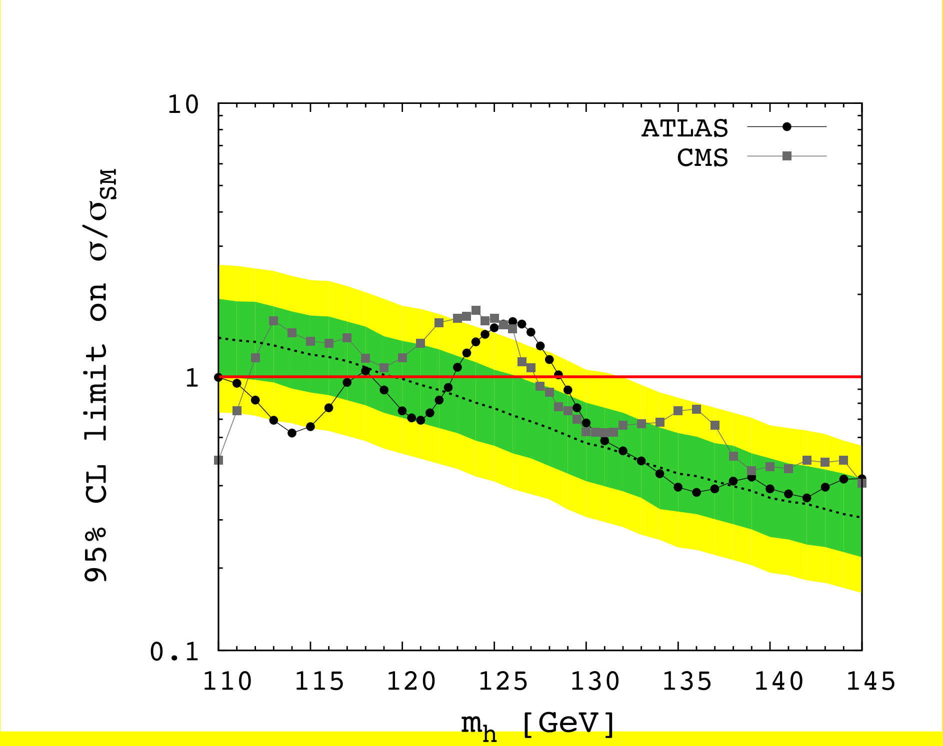
18

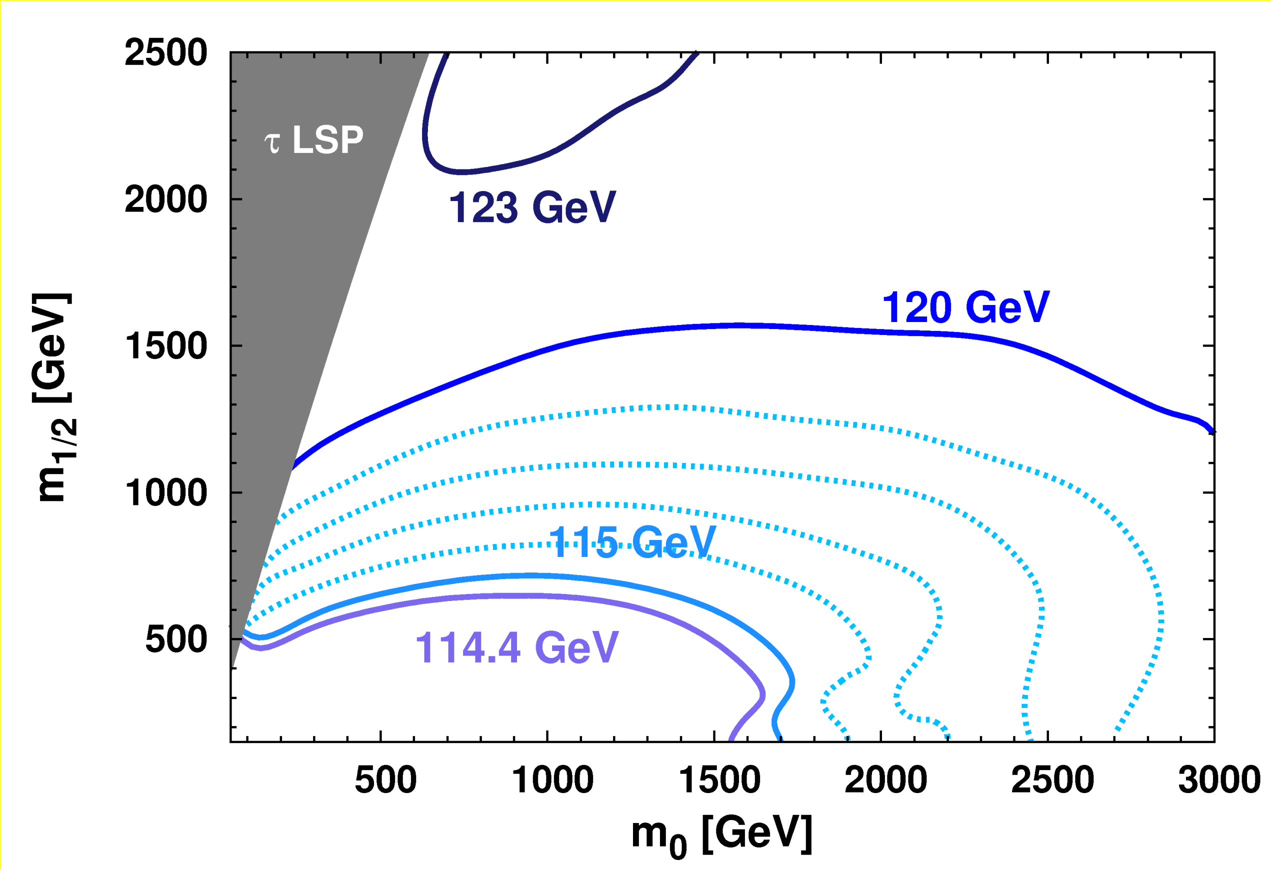
Constraints from the lightest Higgs of 125 GeV

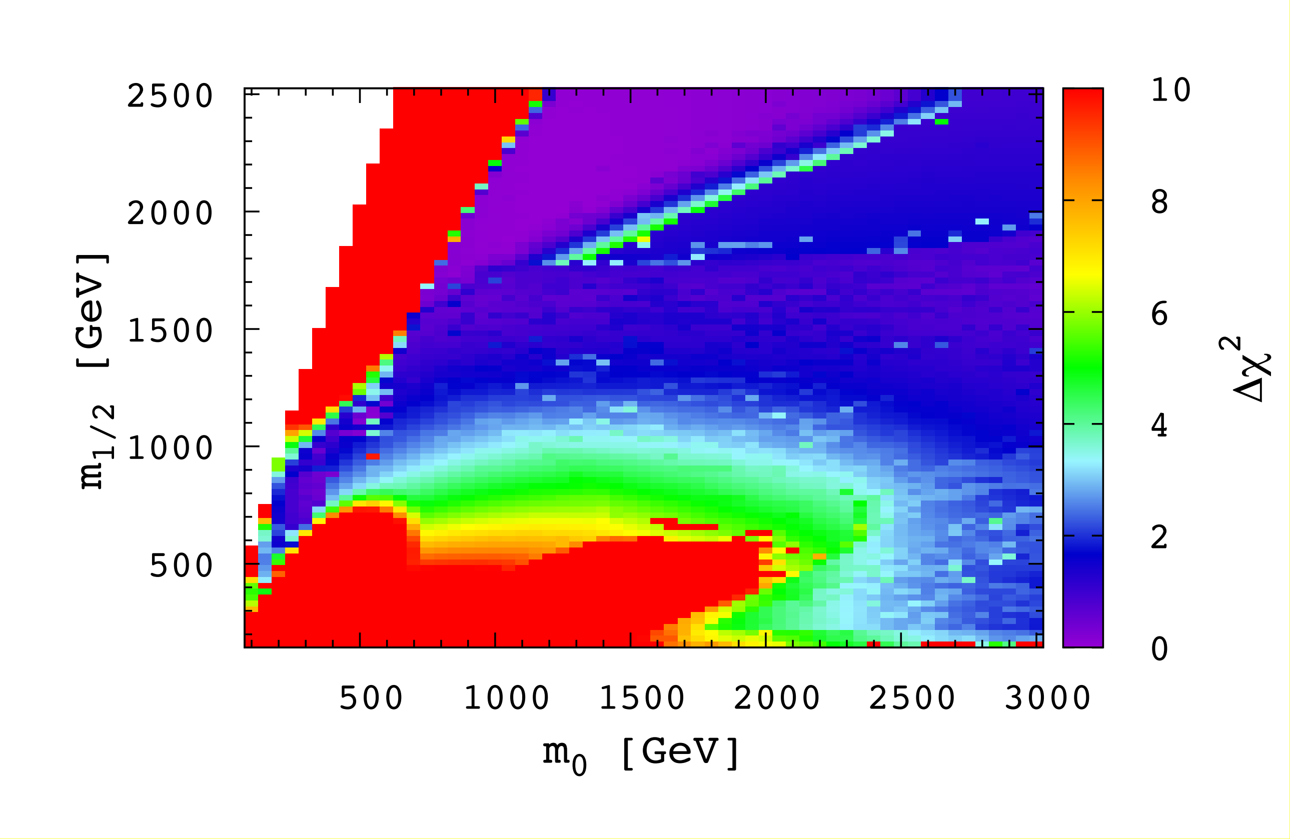




Constraints from the lightest Higgs of 125 GeV







combined experimental
and theoretical error

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

Conclusions

Conclusions

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

Conclusions

ICHEP2012 Melbourne

- 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 $m_0 < 1000\ GeV$

19

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

Conclusions

ICHEP2012 Melbourne

- 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

Conclusions

ICHEP2012 Melbourne

- 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

Conclusions

ICHEP2012 Melbourne

- 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!