Supersymmetry and Dark Matter post LHC2010 and XENON100

Why Supersymmetry?

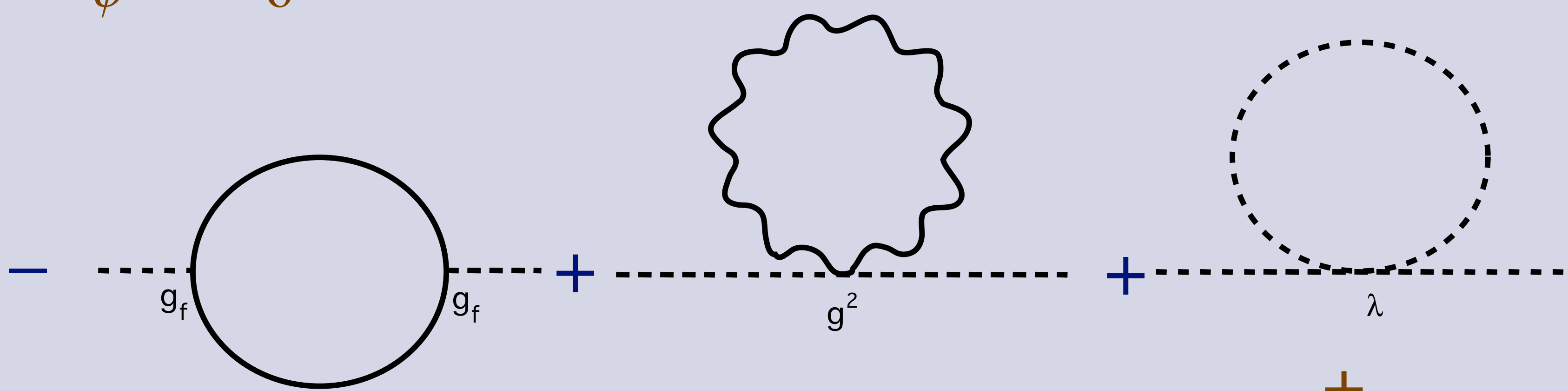
- Gauge Hierarchy Problem

Gauge Hierarchy Problem

$$\delta m_H^2 \simeq g_f^2, g^2, \lambda \int d^4k \frac{1}{k^2} \sim O(\frac{\alpha}{4\pi})\Lambda^2$$

Scalar masses corrected by loops

$m_\phi{}^2 = m_o{}^2\ +$



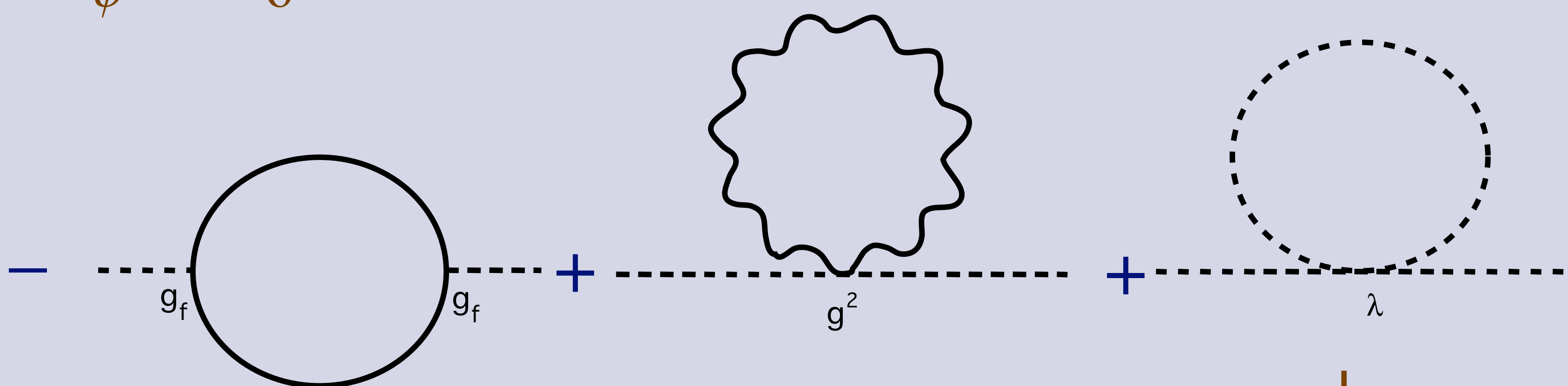
+ ....

Gauge Hierarchy Problem

$$\delta m_H^2 \simeq O(\frac{\alpha}{4\pi})(\Lambda^2 + m_B^2) - O(\frac{\alpha}{4\pi})(\Lambda^2 + m_F^2) = O(\frac{\alpha}{4\pi})(m_B^2 - m_F^2)$$

Scalar masses corrected by loops

$m_\phi{}^2 = m_o{}^2$ +



+ ....

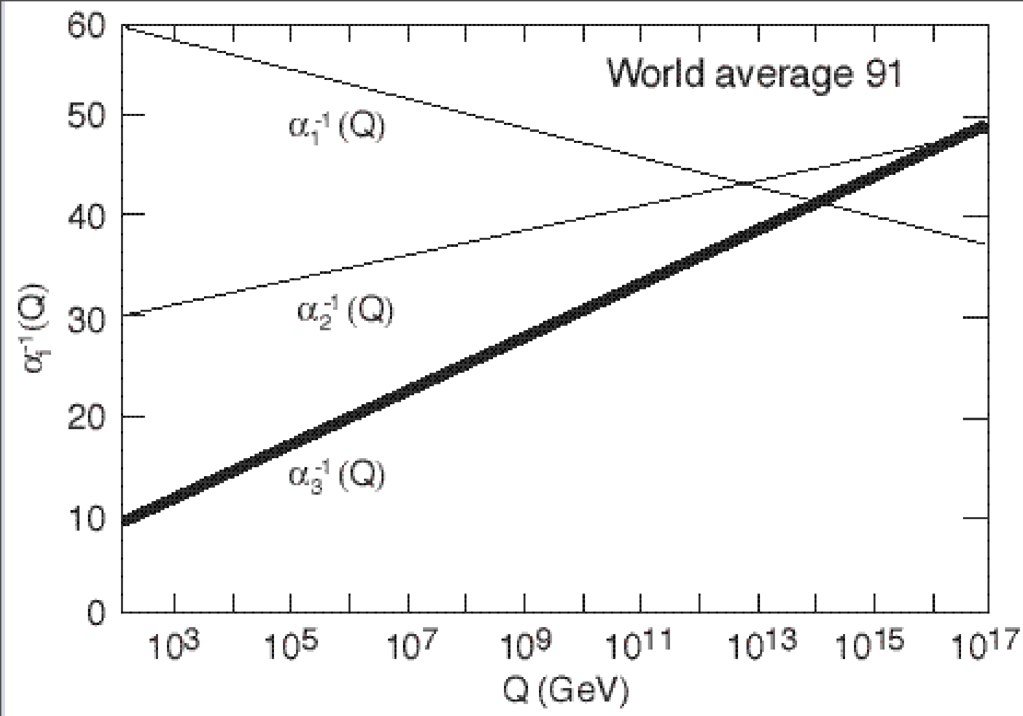
= $m_o{}^2$

Set it and Forget it!

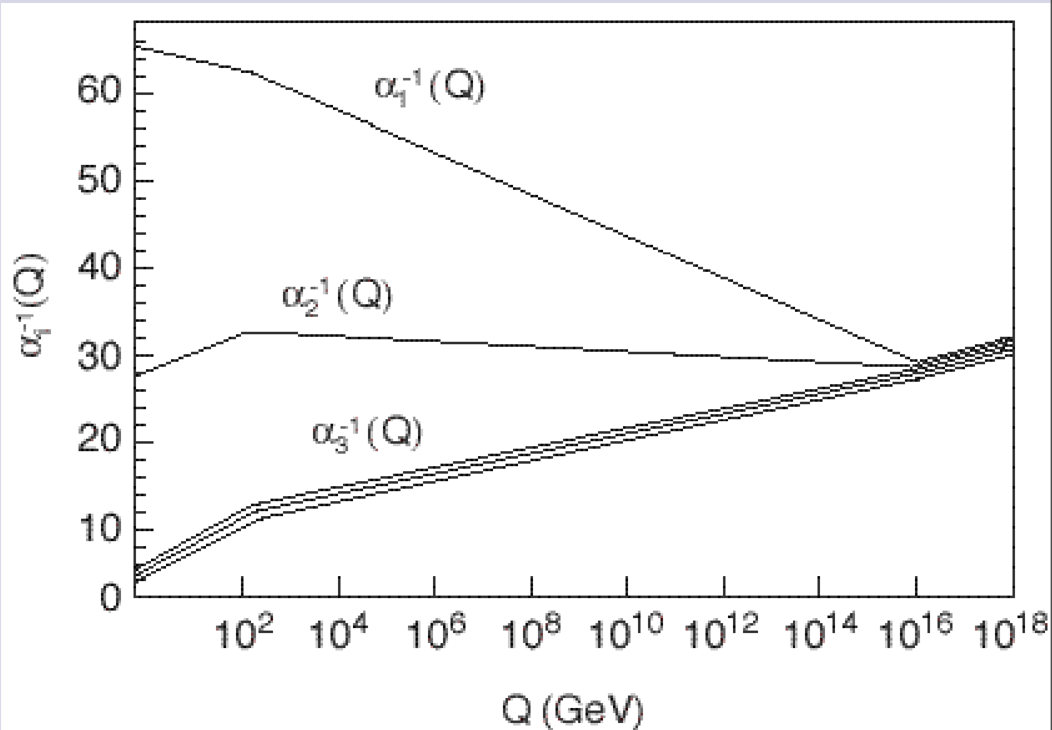
$$|m_B^2 - m_F^2| \lesssim 1 \text{ TeV}^2$$

Why Supersymmetry?

- Gauge Hierarchy Problem
- Gauge Coupling Unification



Running of the Gauge couplings in the standard model

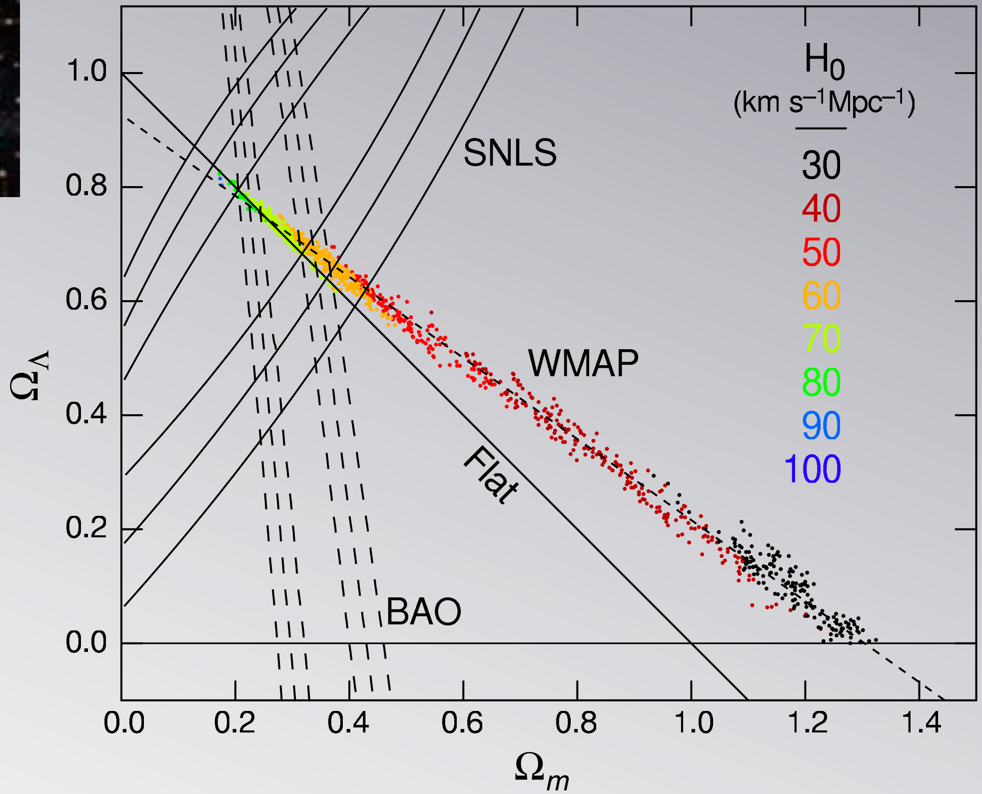


Running of the Gauge couplings in the supersymmetric standard model

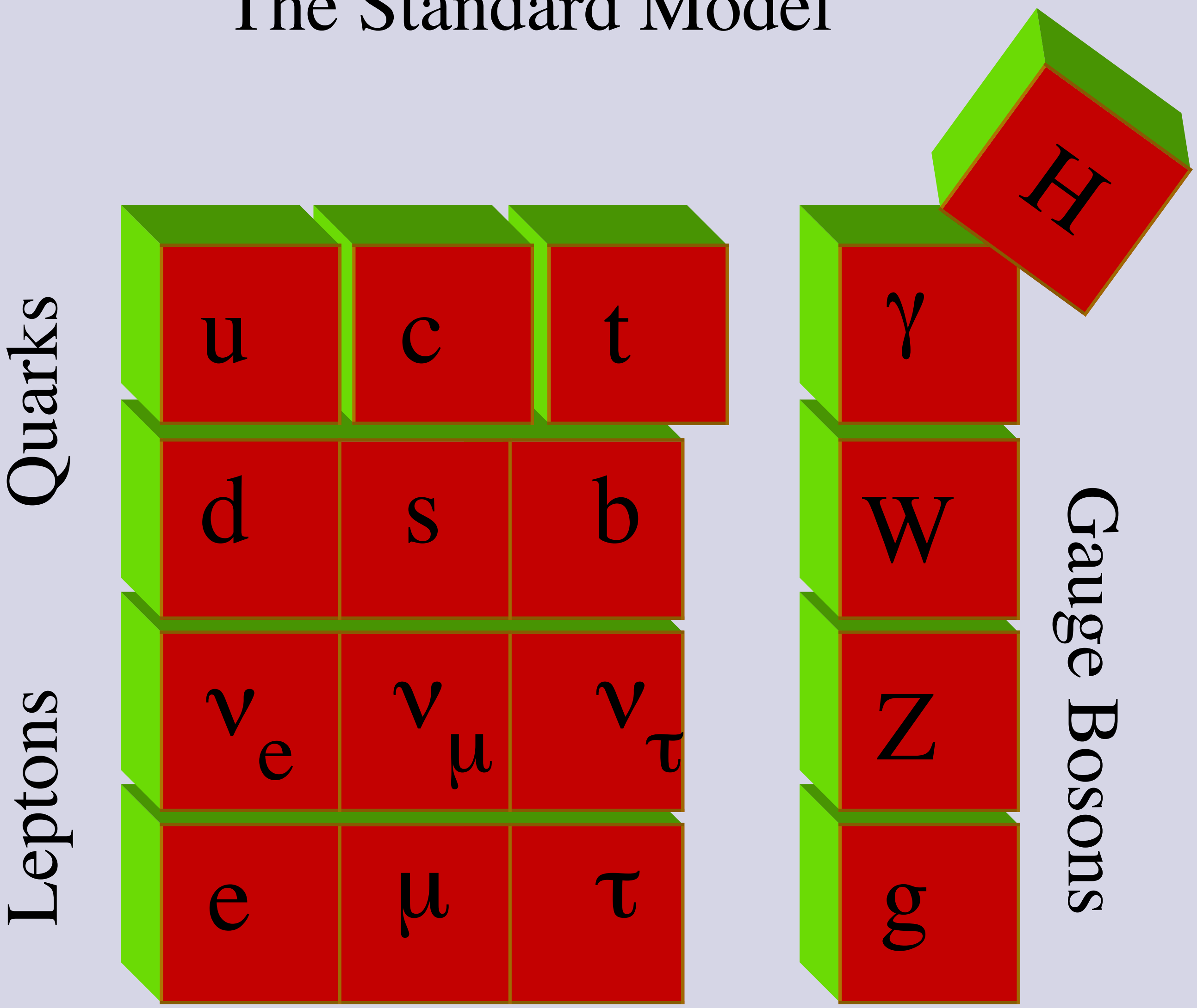
Why Supersymmetry?

- Gauge Hierarchy Problem
- Gauge Coupling Unification
- Dark Matter

(Supersymmetric) Dark Matter



The Standard Model



+ gravity

What is supersymmetry?

$$Q|Boson\rangle = |Fermion\rangle$$
$$Q|Fermion\rangle = |Boson\rangle$$

Chiral multiplet $\begin{pmatrix} \tilde{e} \\ e \end{pmatrix}$ $\begin{pmatrix} \text{scalar} - \text{spin } 0 \\ \text{fermion} - \text{spin } 1/2 \end{pmatrix}$

Vector multiplet $\begin{pmatrix} \tilde{\gamma} \\ \gamma \end{pmatrix}$ $\begin{pmatrix} \text{fermion} - \text{spin } 1/2 \\ \text{vector} - \text{spin } 1 \end{pmatrix}$

(also gravitational multiplet with
gravitino (spin 3/2) and graviton (spin 2).

SUSY Dark Matter

MSSM and R-Parity → Stable DM candidate

1) Neutralinos

$$\chi_i = \alpha_i \widetilde{B} + \beta_i \widetilde{W} + \gamma_i \widetilde{H}_1 + \delta_i \widetilde{H}_2$$

2) Sneutrino

Excluded (unless add L-violating terms)

3) Other:

Axinos, Gravitinos, etc

Why Supersymmetry?

- Gauge Hierarchy Problem
- Gauge Coupling Unification
- Dark Matter
- Improvement in low energy phenomenology

Which Supersymmetric Model?

- MSSM with R-Parity (still more than 100 parameters)

What is the MSSM

1) Add minimal number of new particles:

Partners for all SM particles + 1 extra Higgs EW doublet.

2) Add minimal number of new interactions:

Impose R-parity to eliminate many UNWANTED interactions.

$$R = (-1)^{3B+L+2S}$$

SUSY Superpotential + Soft terms

$$
\begin{aligned}
W &= h_u H_2 Q u^c + h_d H_1 Q d^c + h_e H_1 L e^c + \mu H_2 H_1 \\
\mathcal{L}_{\text{soft}} &= -\frac{1}{2} M_\alpha \lambda^\alpha \lambda^\alpha - m_{ij}^2 \phi^{i*} \phi^j \\
&\quad - A_u h_u H_2 Q u^c - A_d h_d H_1 Q d^c - A_e h_e H_1 L e^c - B\mu H_2 H_1 + h.c.
\end{aligned}
$$

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\end{aligned}
$$

$$
\langle H_1 \rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix} \qquad \langle H_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}
$$

$$
\tan\beta = \frac{v_2}{v_1}
$$

SUSY Superpotential + Soft terms

$$W = h_u H_2 Q u^c + h_d H_1 Q d^c + h_e H_1 L e^c + \mu H_2 H_1$$

$$\mathcal{L}_{\rm soft} = -\frac{1}{2} M_\alpha \lambda^\alpha \lambda^\alpha - m_{ij}^2 \phi^{i*} \phi^j$$
$$-A_u h_u H_2 Q u^c - A_d h_d H_1 Q d^c - A_e h_e H_1 L e^c - B\mu H_2 H_1 + h.c.$$

$$\langle H_1 \rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix} \qquad \langle H_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1}$$

R-parity conservation assumed

Which Supersymmetric Model?

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- Gaugino mass Unification
- A-term Unification

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- MSSM with R-Parity (still more than 100 parameters)
- Gaugino mass Unification
- A-term Unification
- Scalar mass unification
- $B_0 = A_0 - m_0$ (VCMSSM)
- $m_0 = m_{3/2}$ (mSUGRA)

The Constrained and Very Constrained MSSM

- CMSSM - as a 4+ parameter theory
- NUHM1 - as a 5+ parameter theory
- VCMSSM models - 3+ parameter theory (mSUGRA)
- No-Scale models - 1+ parameter theory

The CMSSM

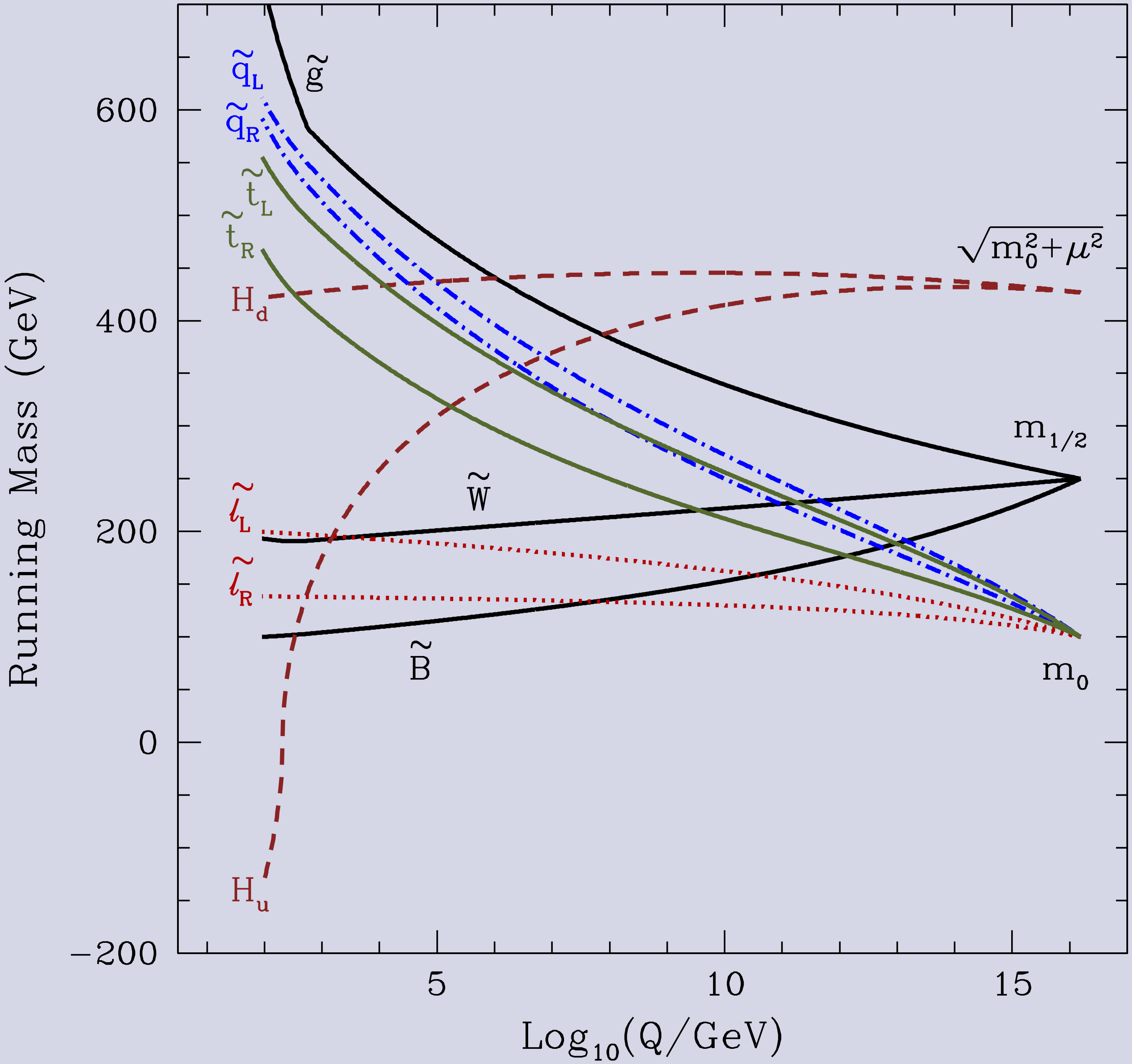
Parameters: $m_{1/2}$, m_0, A_0, tan β, sgn(μ)

Electroweak Symmetry Breaking conditions:

$$\mu^2 = \frac{m_1^2 - m_2^2 \tan^2\beta + \frac{1}{2}M_Z^2(1-\tan^2\beta) + \Delta_\mu^{(1)}}{\tan^2\beta - 1 + \Delta_\mu^{(2)}}$$

$$B\mu = -\frac{1}{2}(m_1^2 + m_2^2 + 2\mu^2)\sin 2\beta + \Delta_B$$

CMSSM Spectra



Falk

Unification to rich spectrum + EWSB

The Relic Density

At high temperatures $T \gg m_\chi$;

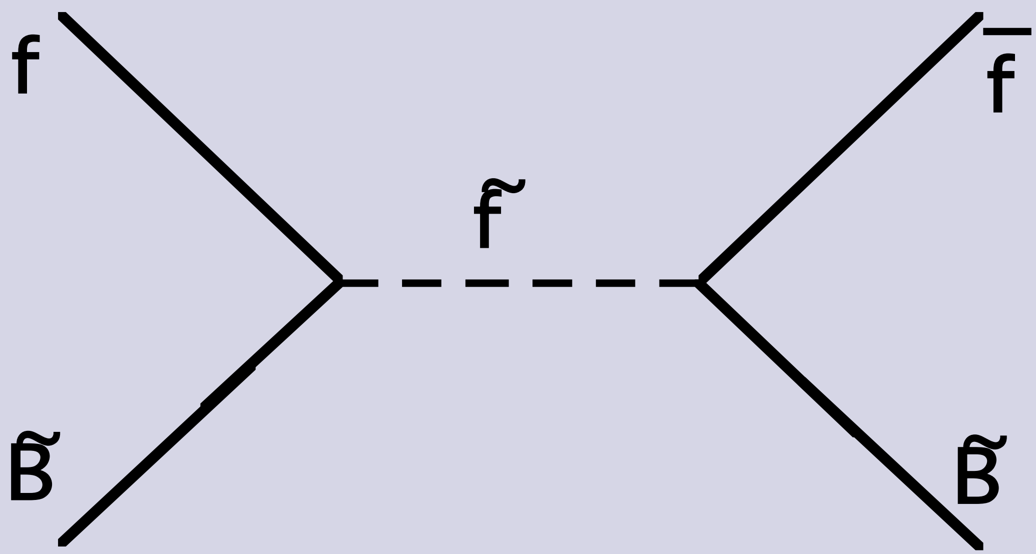
χ's in equilibrium $\Gamma > H$ $n_\chi \sim n_\gamma$

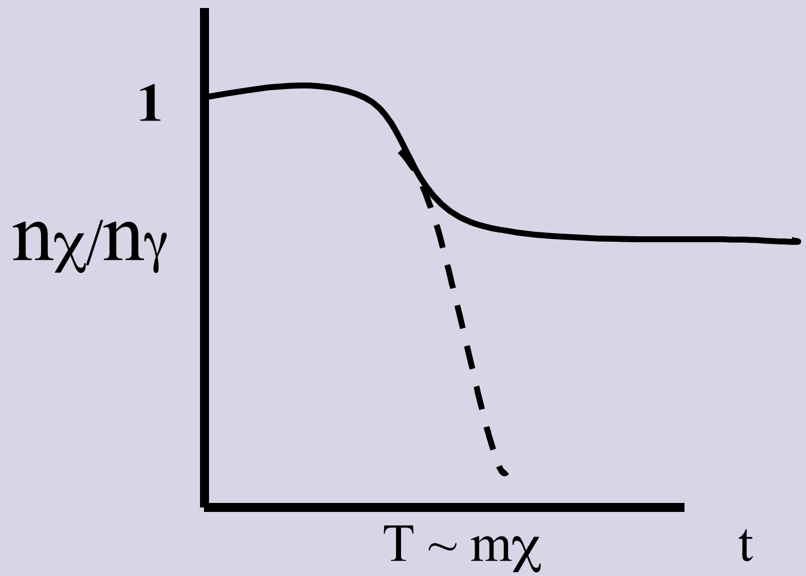
$\Gamma \sim n\sigma v \sim T^3\sigma v$; $HM_p \sim \sqrt{\rho} \sim T^2$

As $T < m_\chi$; annihilations drop n_χ

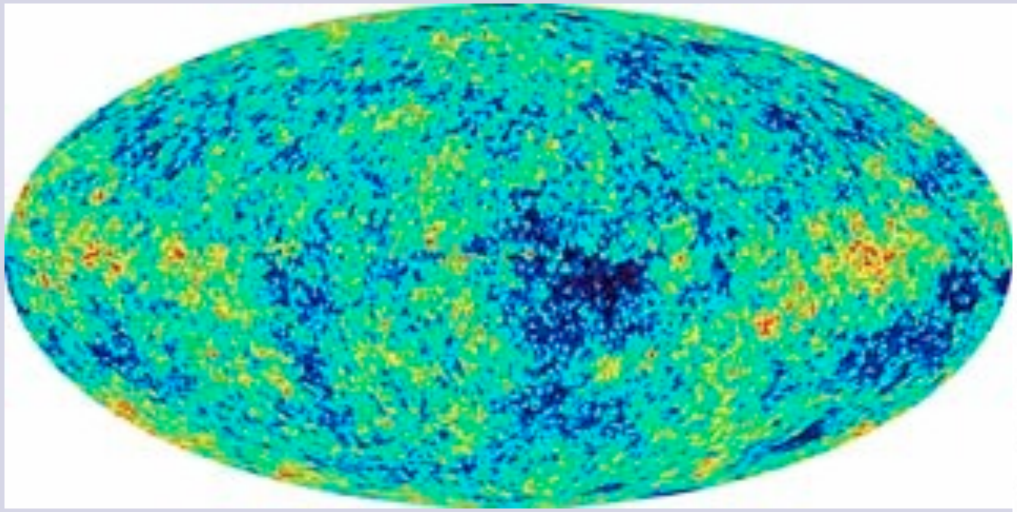
$n_\chi \sim e^{-m_\chi/T}\, n_\gamma$

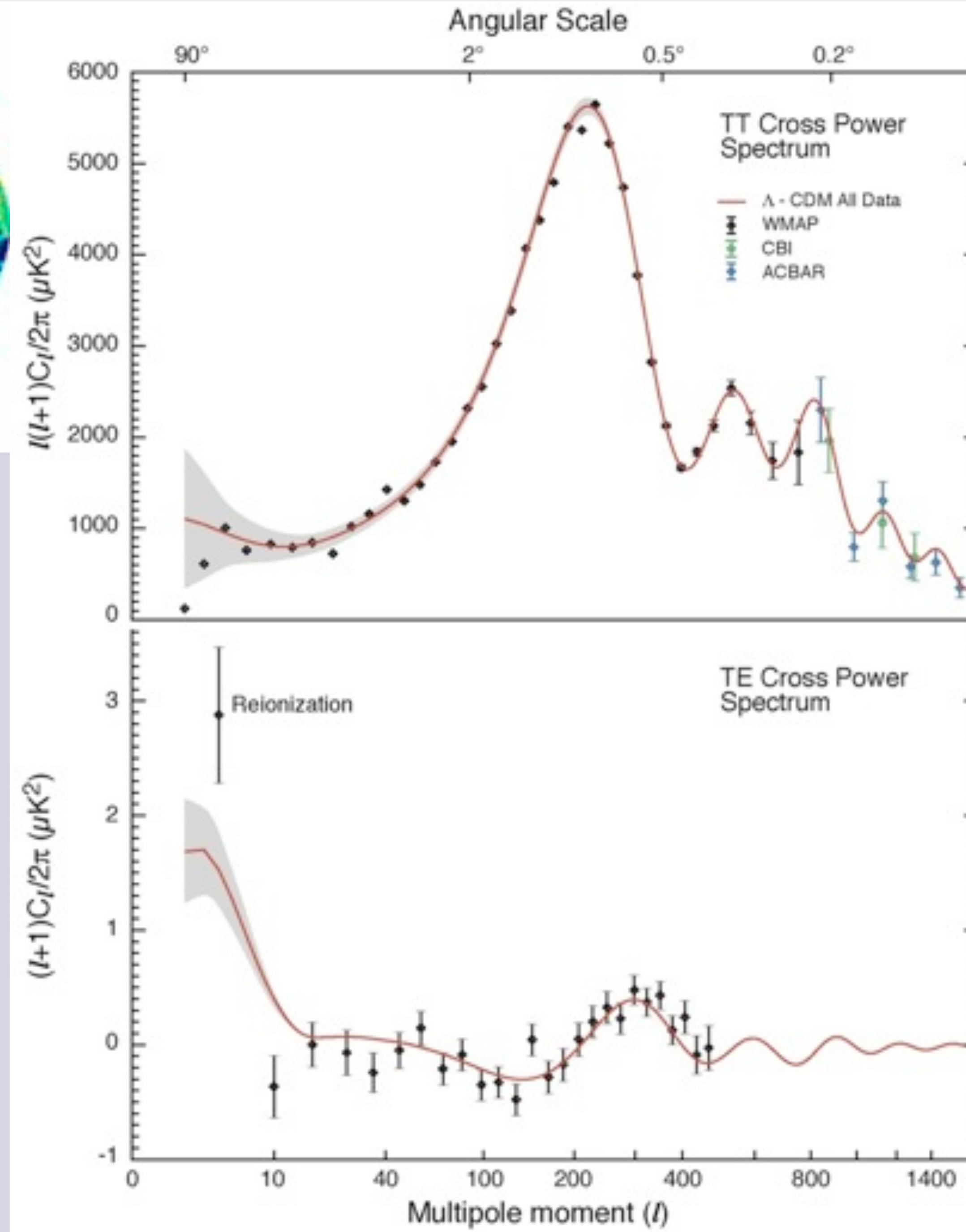
Until freeze-out, $\Gamma < H$ $n_\chi/n_\gamma \sim$ constant





WMAP

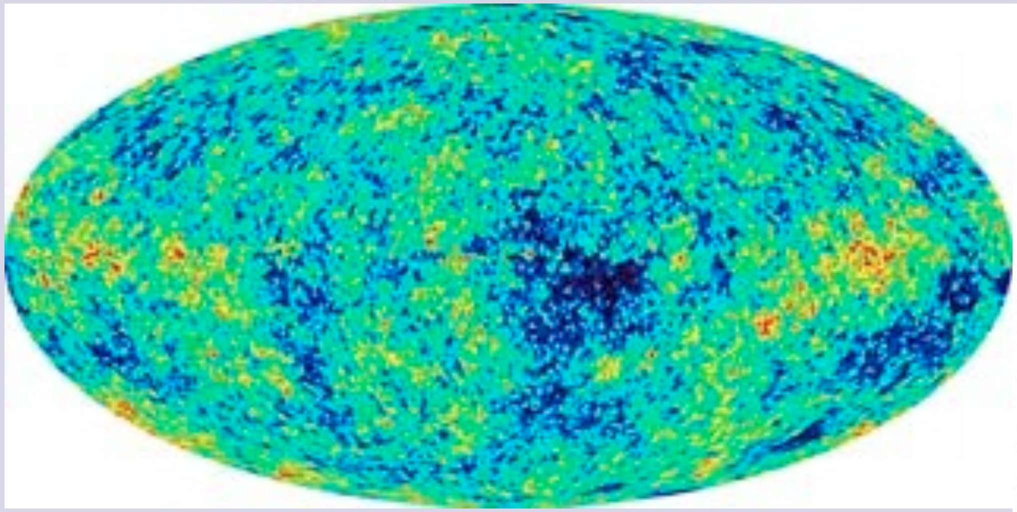


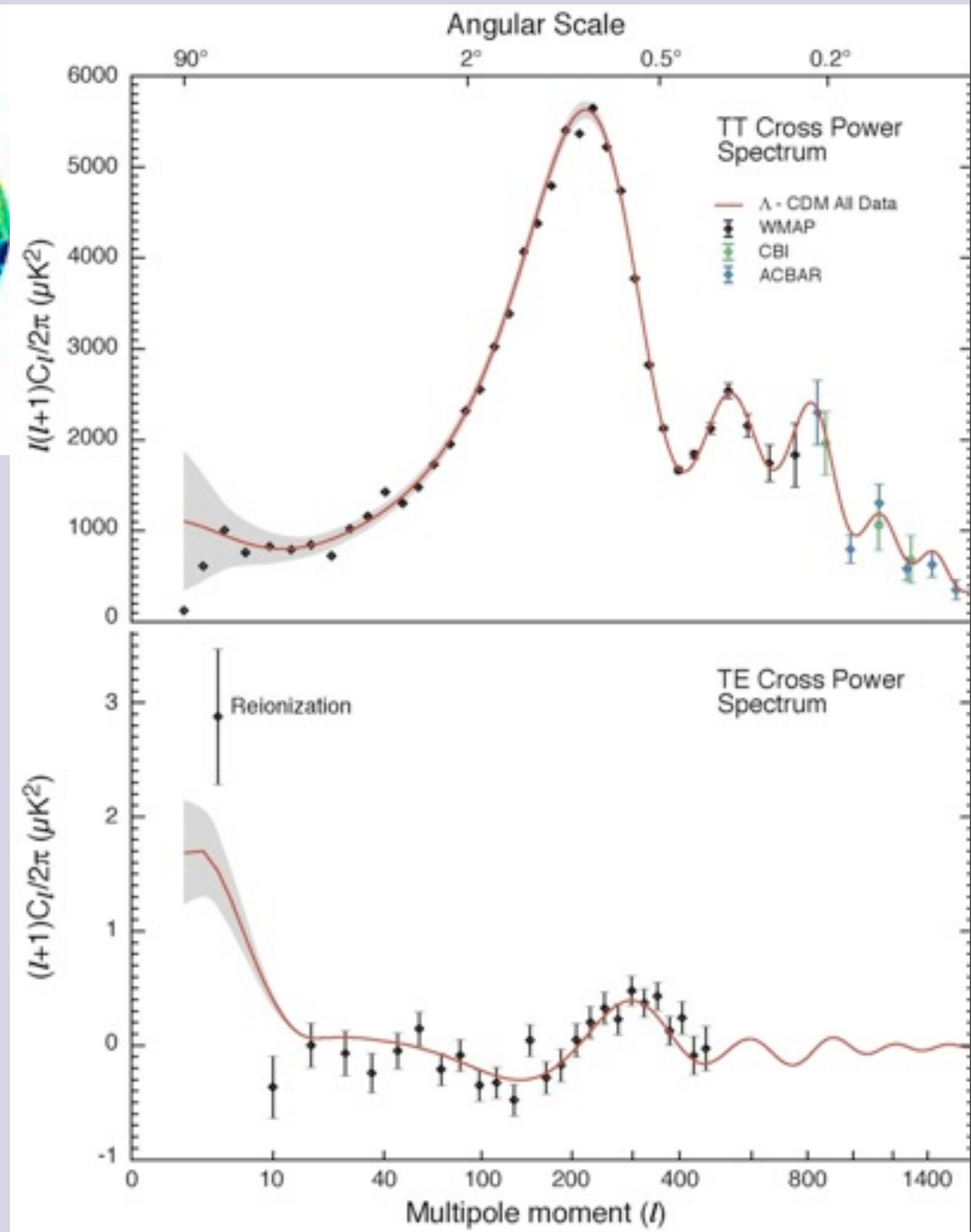


Position of 1st peak

$\Rightarrow \quad \Omega = 1$

WMAP





Position of 1st peak

$\Rightarrow \quad \Omega = 1$

$\Omega_m h^2 = 0.1334 \pm 0.0056$

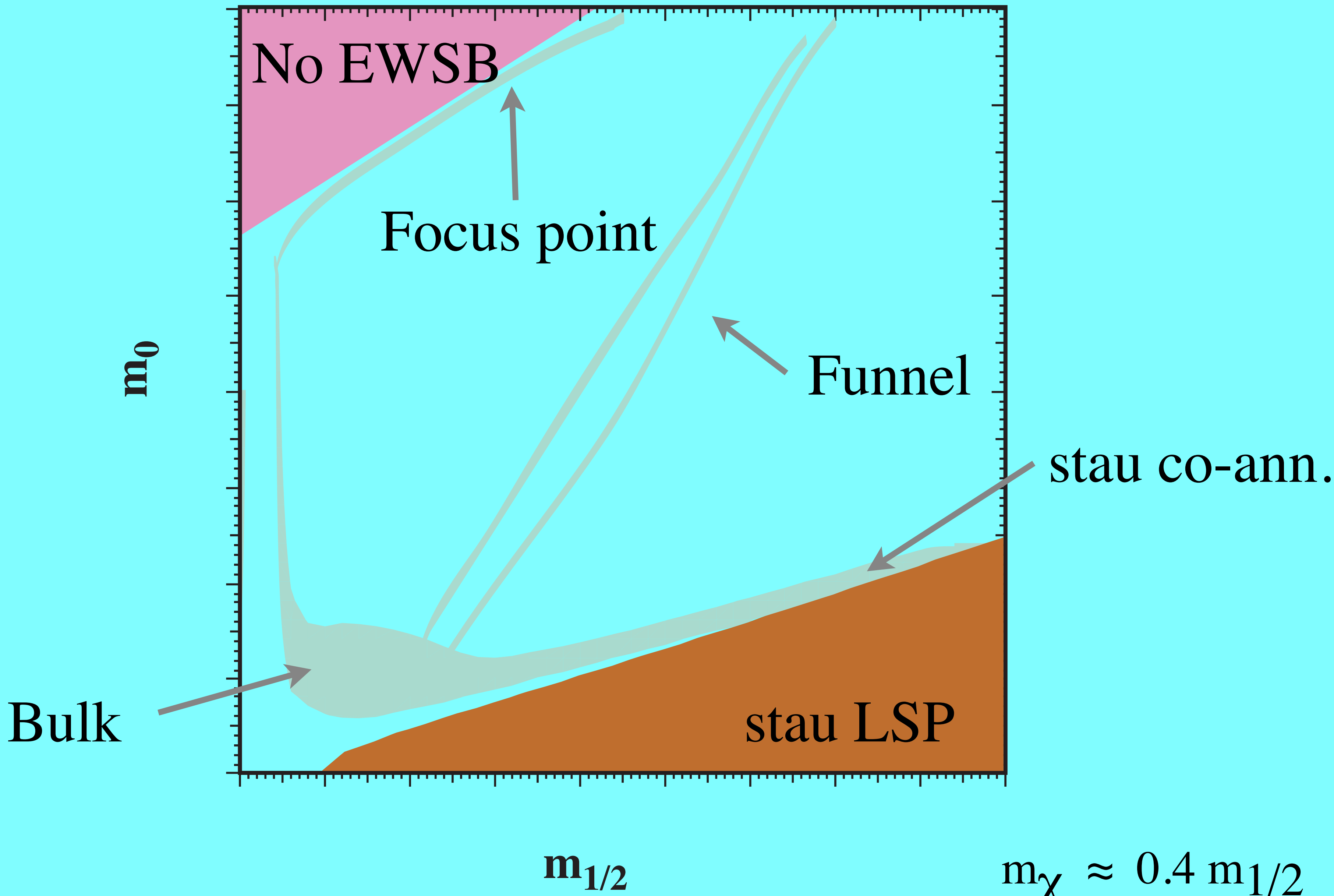
$\Omega_b h^2 = 0.0226 \pm 0.0006$

$\Omega_{cdm} h^2 = 0.1109 \pm 0.0056$

or

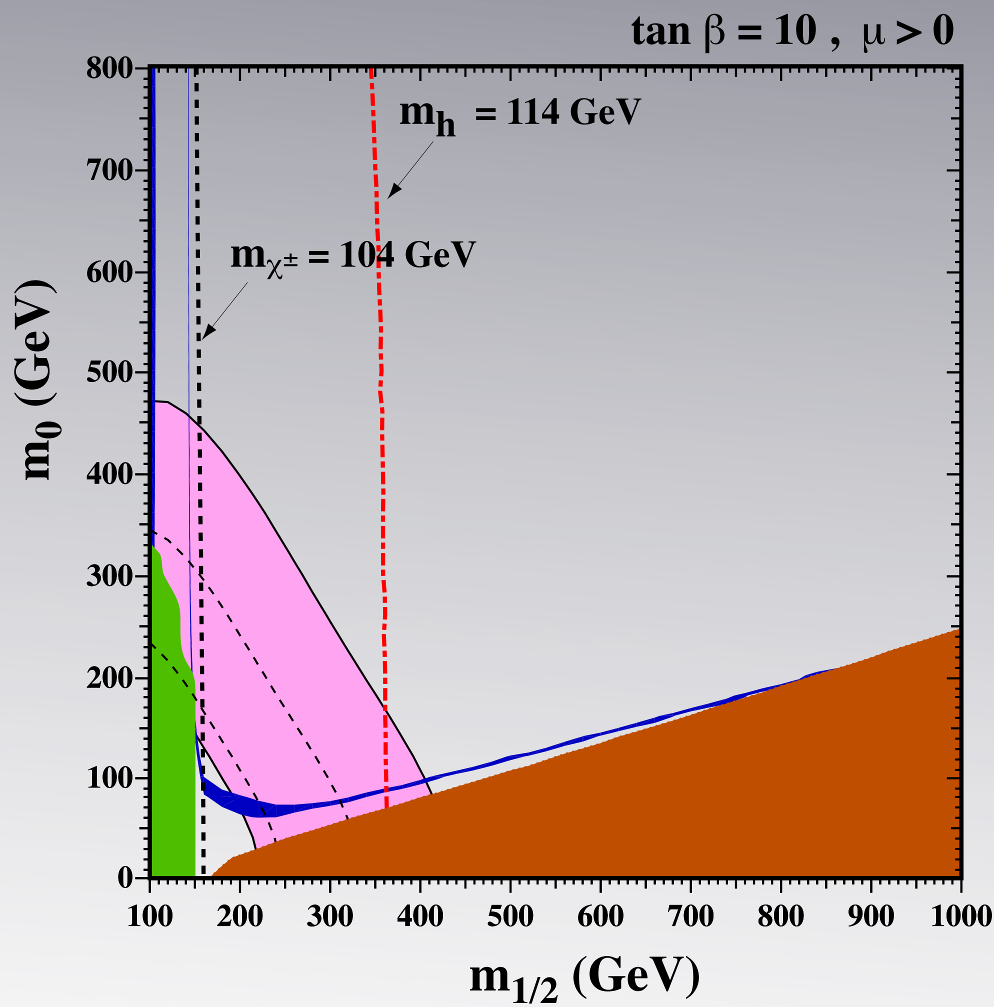
$\Omega_{cdm}\, h^2 = 0.0997 - 0.1221 \;\; (2\,\sigma)$

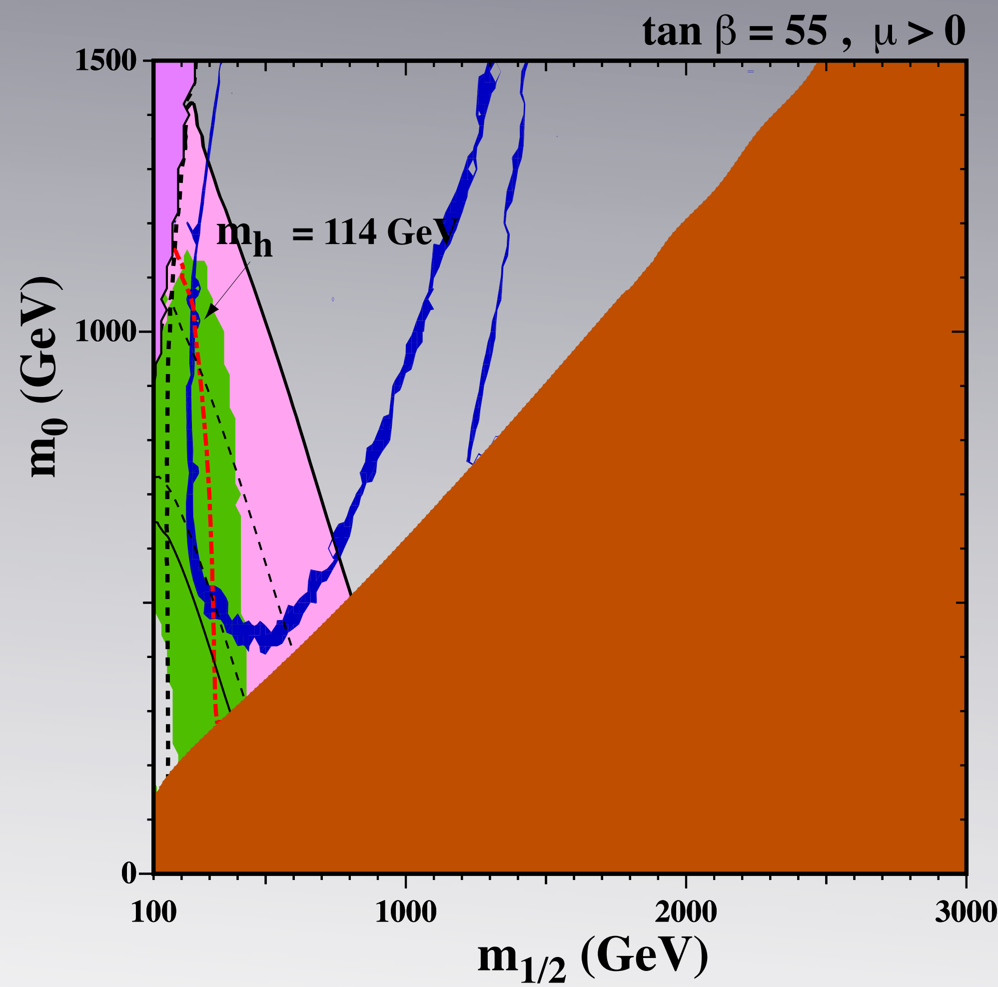
Typical Regions



$m_\chi \approx 0.4\, m_{1/2}$

$m_{1/2}$ - m_0 planes

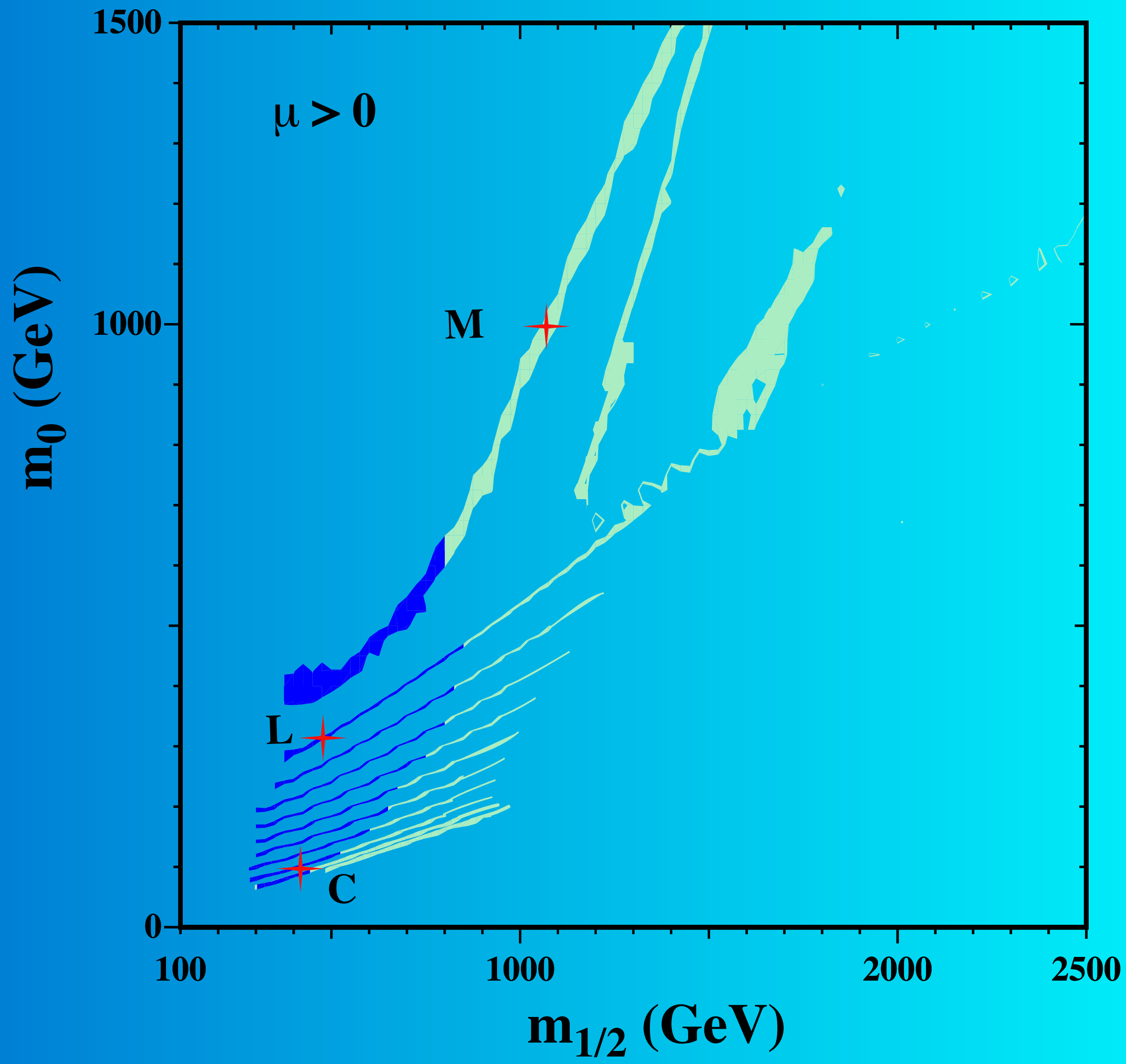




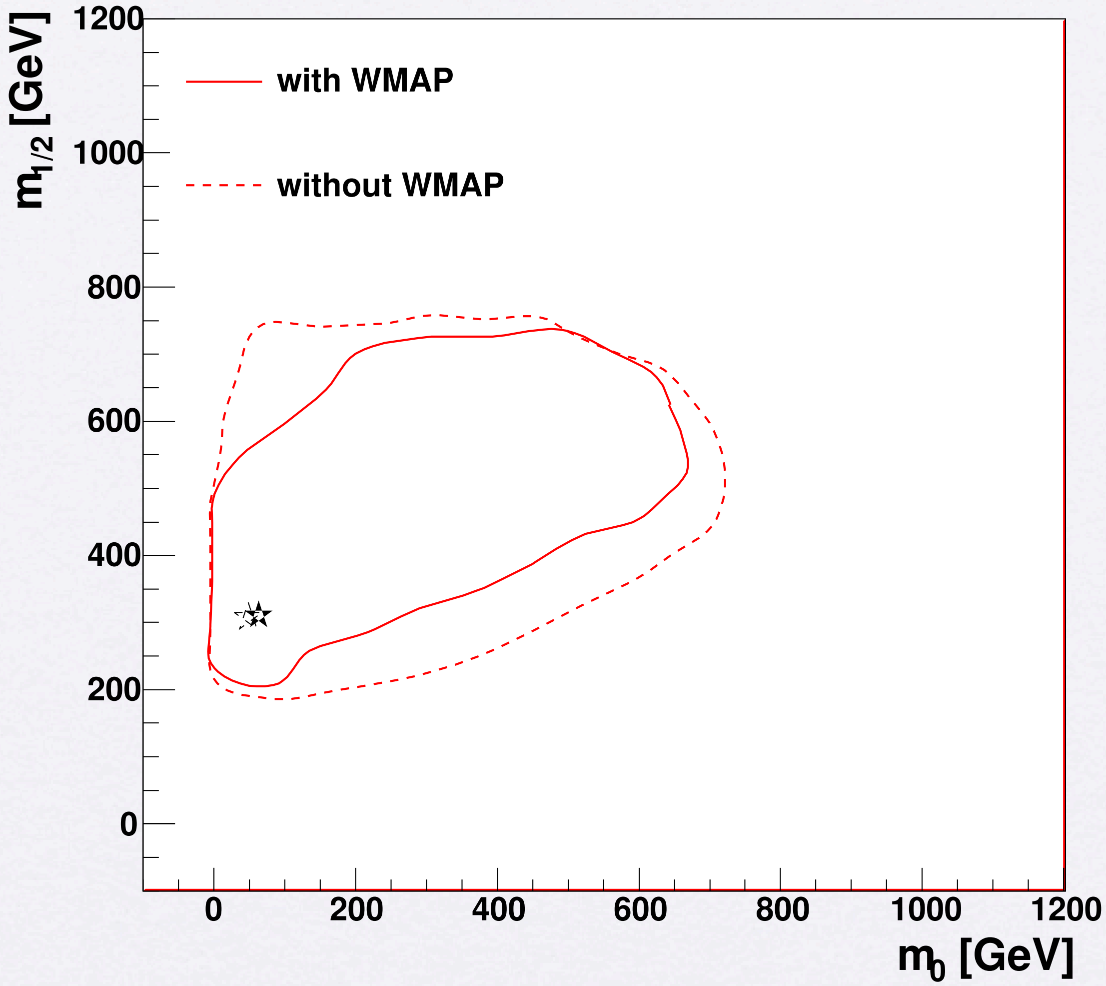
- CMSSM

Ellis, Olive, Santoso, Spanos

Foliation in tan β



Impact of CDM



Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Paradisi, Ronga, Weiglein

Effective four-fermion Lagrangian

$$\mathcal{L} = \bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}_i\gamma_\mu(\alpha_{1i} + \alpha_{2i}\gamma^5)q_i + \alpha_{3i}\bar{\chi}\chi\bar{q}_i q_i$$

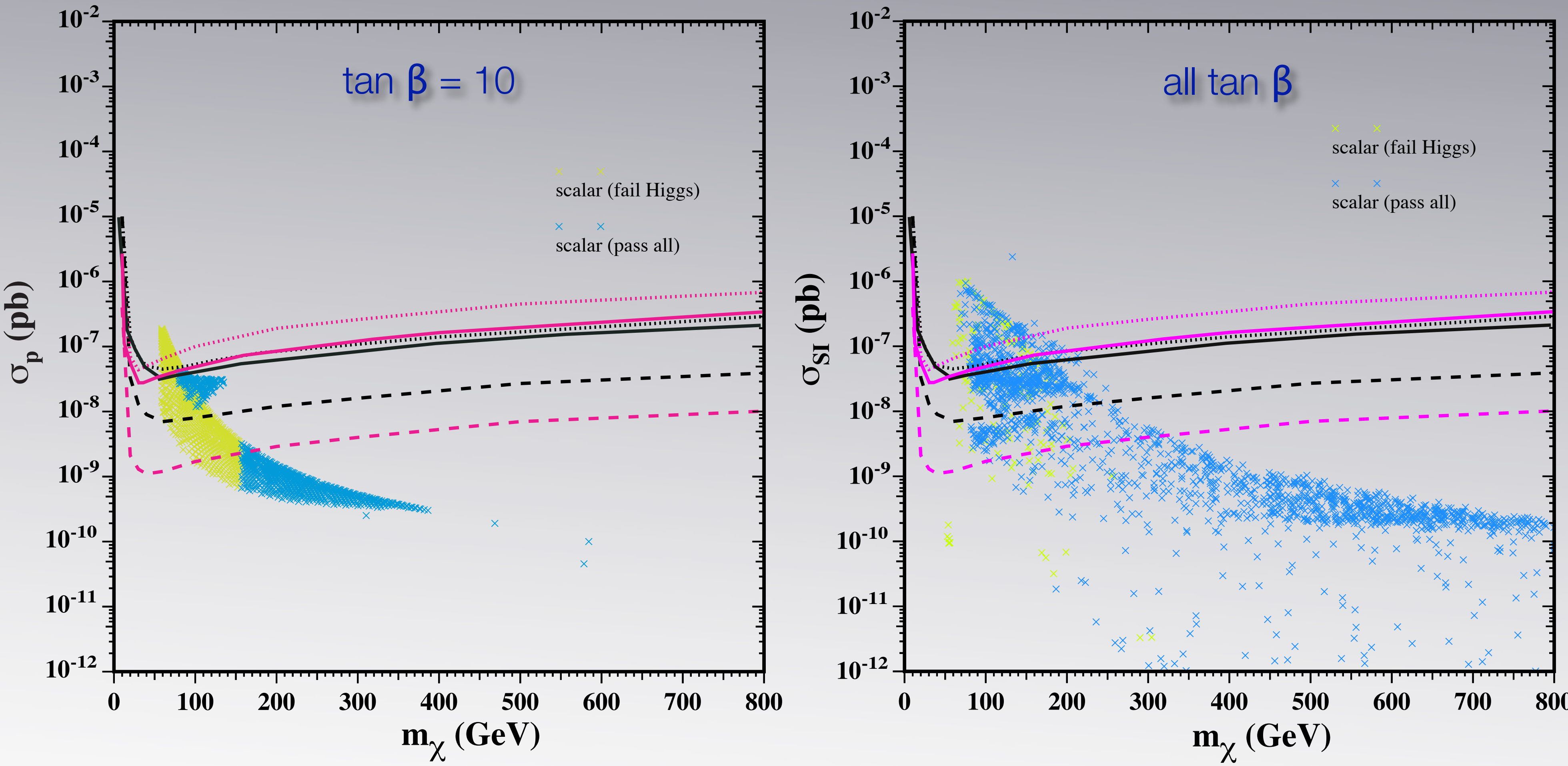
$$+ \alpha_{4i}\bar{\chi}\gamma^5\chi\bar{q}_i\gamma^5 q_i + \alpha_{5i}\bar{\chi}\chi\bar{q}_i\gamma^5 q_i + \alpha_{6i}\bar{\chi}\gamma^5\chi\bar{q}_i q_i$$

The terms proportional to α_1, α_4, α_5, α_6,
lead to velocity-dependent cross sections

Remaining terms:

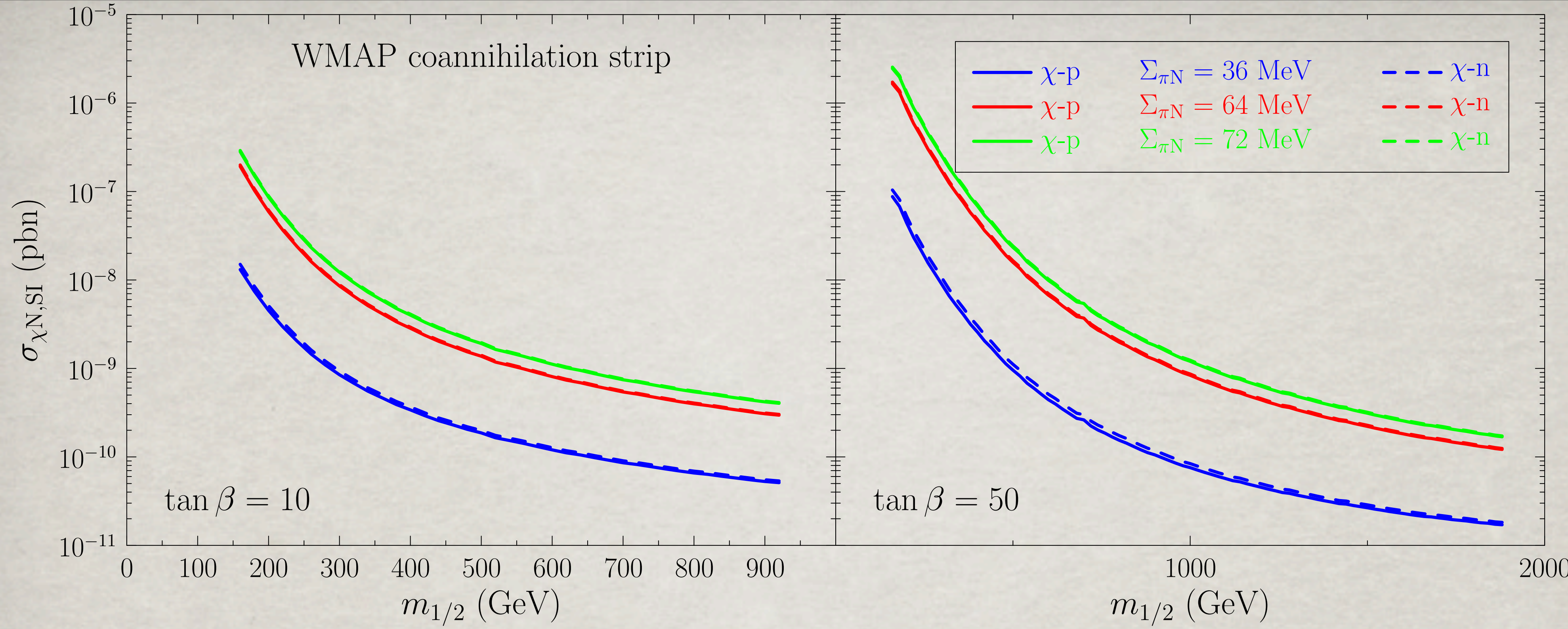
α_2: Spin-dependent cross section
α_3: Spin-independent cross section

Elastic cross section for direct detection

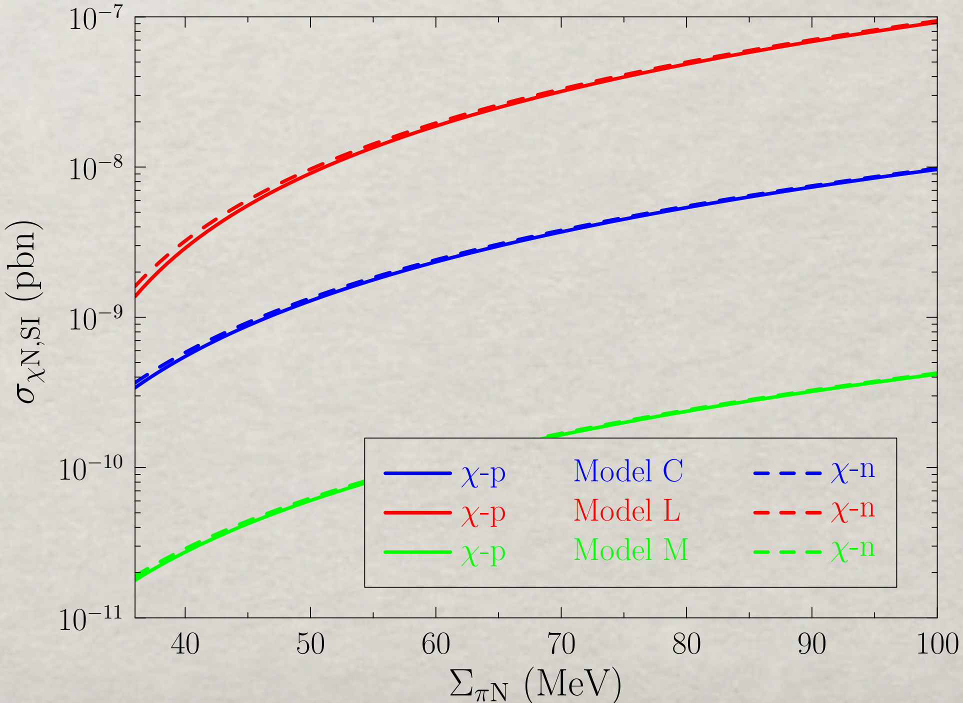


- CMSSM

Ellis, Olive, Sandick



Sensitivity to $\Sigma_{\pi N}$



Ellis, Olive, Savage

Mastercode - MCMC

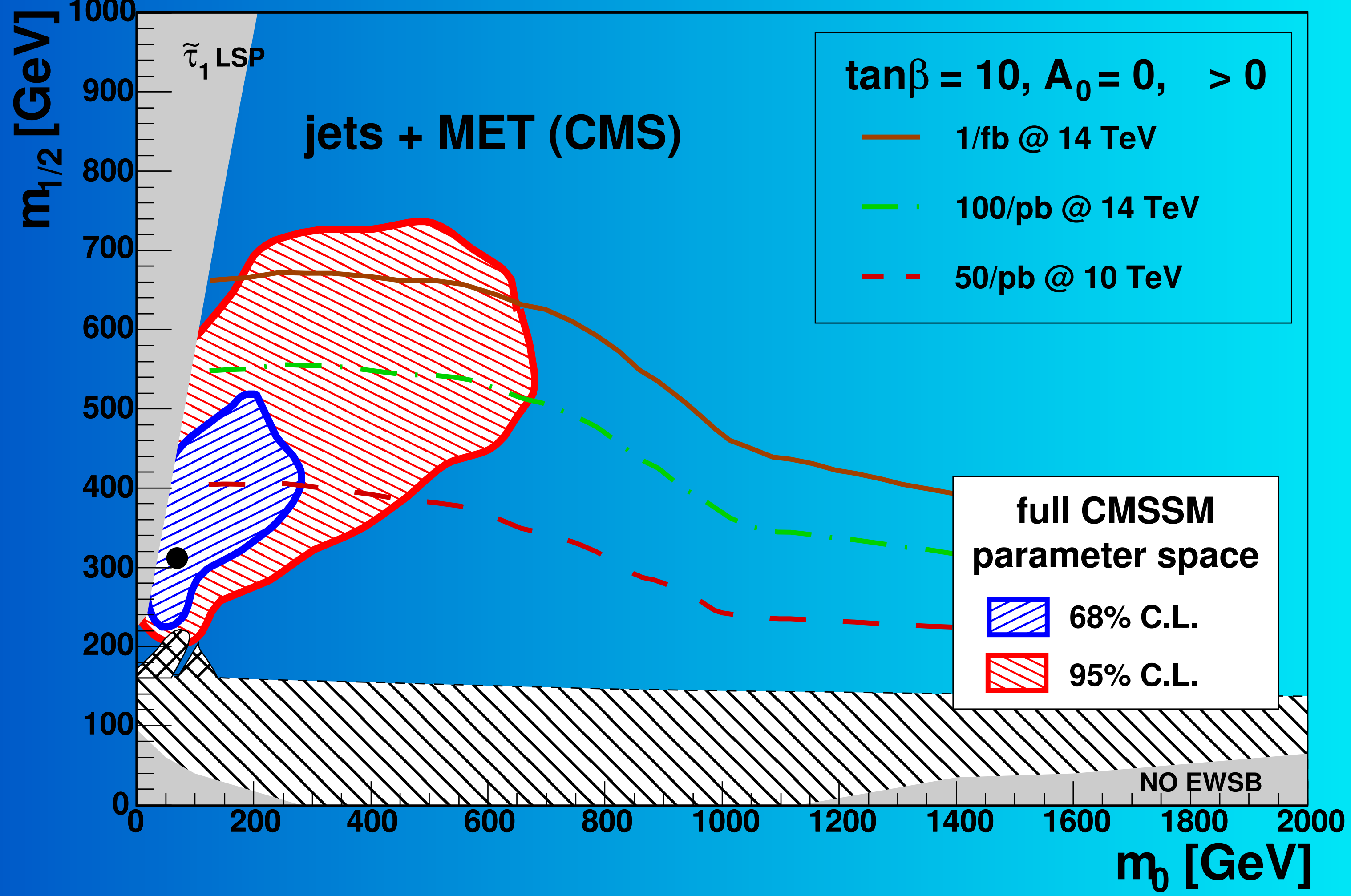
Long list of observables to constrain CMSSM parameter space

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2}$$
$$+ \chi^2(M_h) + \chi^2(\mathrm{BR}(B_s \to \mu\mu))$$
$$+ \chi^2(\text{SUSY search limits})$$
$$+ \sum_i^M \frac{(f^{\mathrm{obs}}_{\mathrm{SM}_i} - f^{\mathrm{fit}}_{\mathrm{SM}_i})^2}{\sigma(f_{\mathrm{SM}_i})^2}$$

- MCMC technique to sample efficiently the SUSY parameter space, and thereby construct the χ^2 probability function
- Combines SoftSusy, FeynHiggs, SuperFla, SuperIso, MicrOmegas, and Dark SUSY
- Purely frequentist approach (no priors) and relies only on the value of χ^2 at the point sampled and not on the distribution of sampled points.
- 25 million points sampled (CMSSM)

Buchmueller, Cavanaugh, Colling, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Olive, Rogerson, Ronga, Weiglein

LHC REACH VS CMSSM



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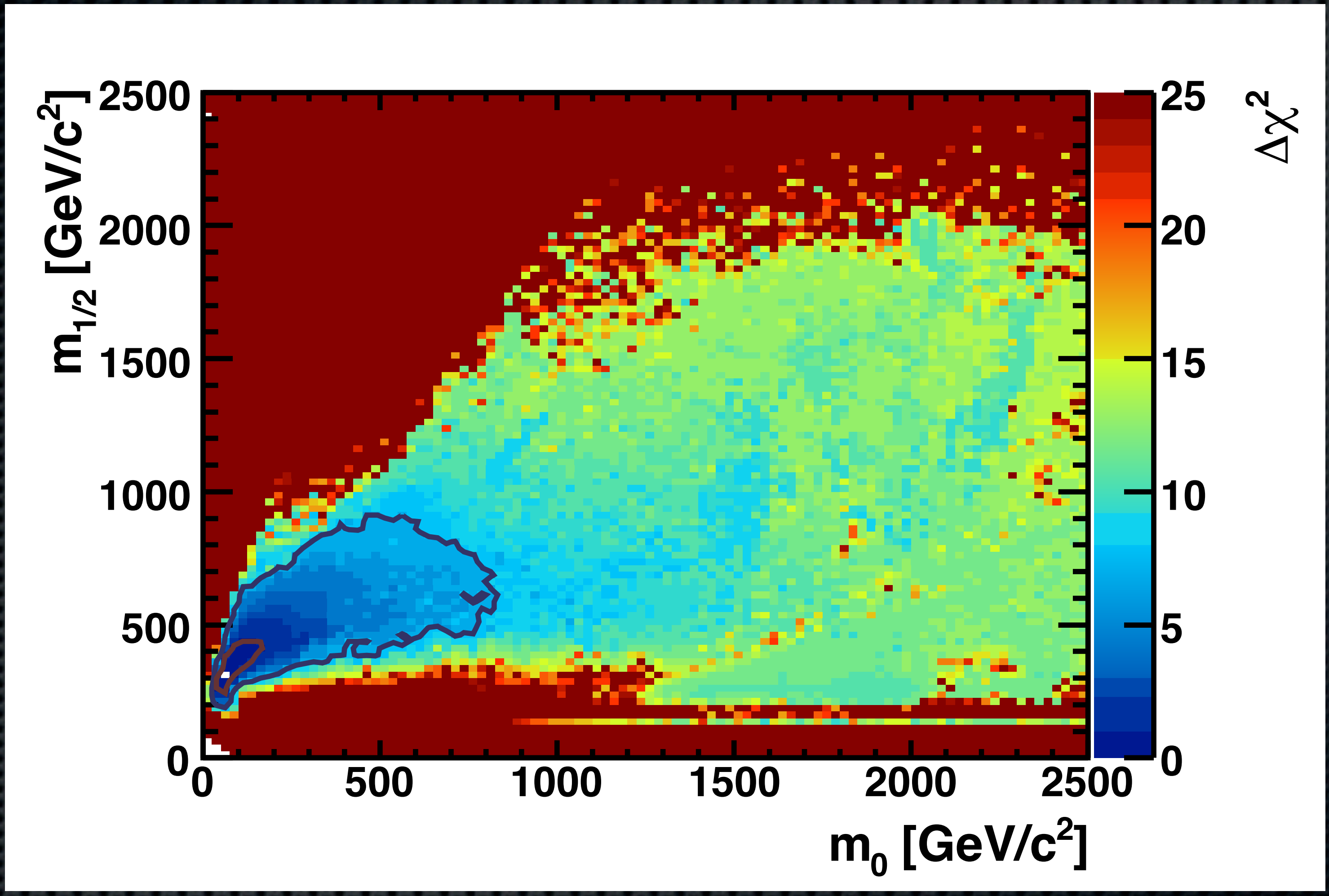
$\Delta\chi^2$ map of m_0 - $m_{1/2}$ plane

Mastercode



- CMSSM

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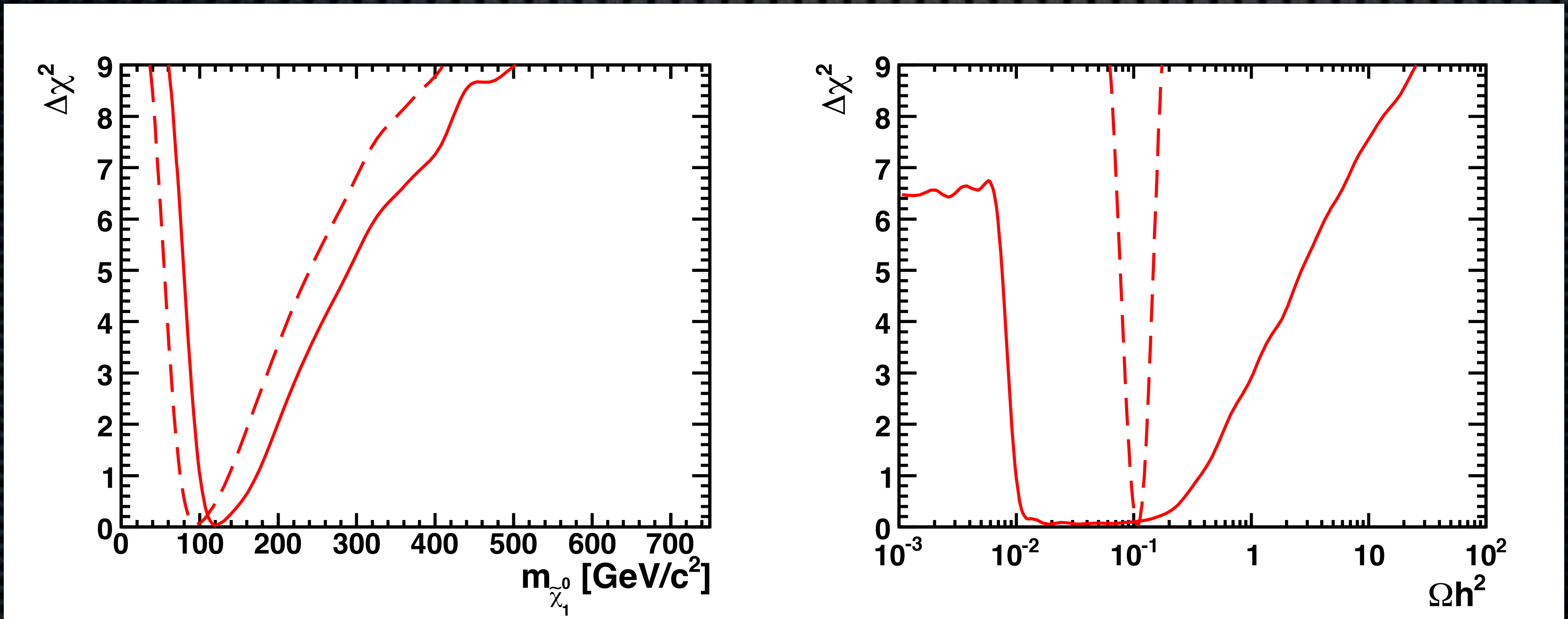
Isidori, Olive, Ronga, Weiglein

Neutralino mass and Relic Density from MCMC analysis

Mastercode



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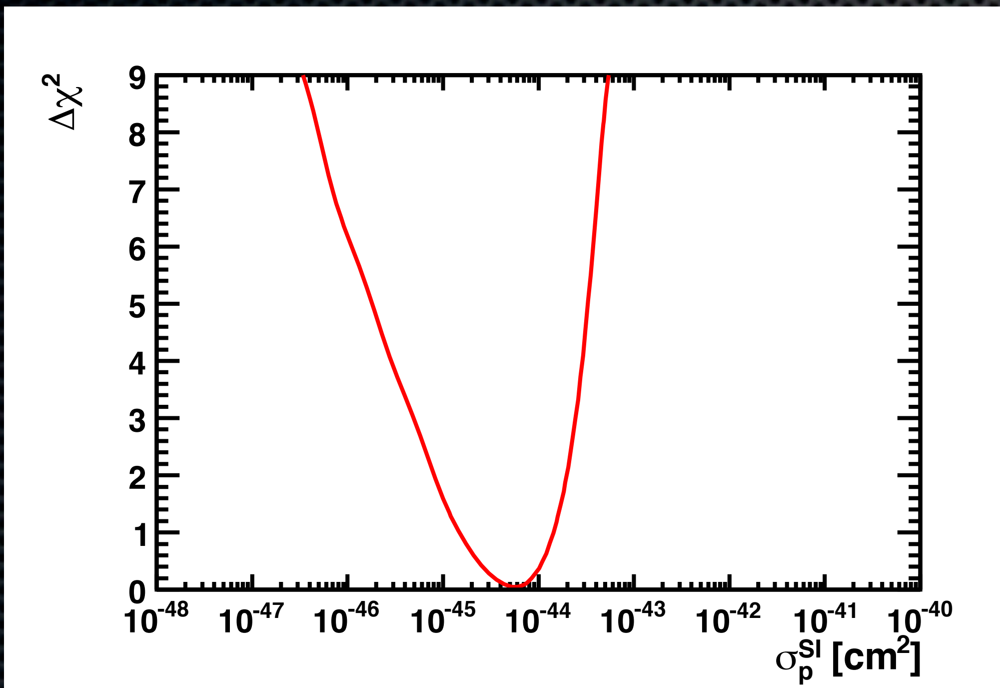
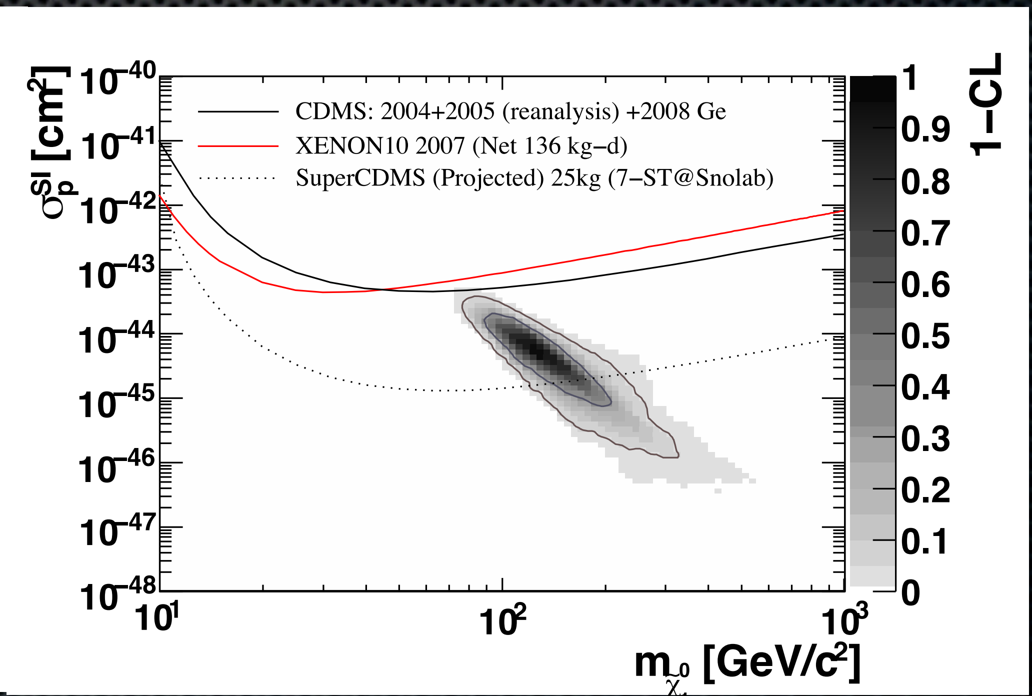
Elastic cross section from MCMC analysis

Mastercode





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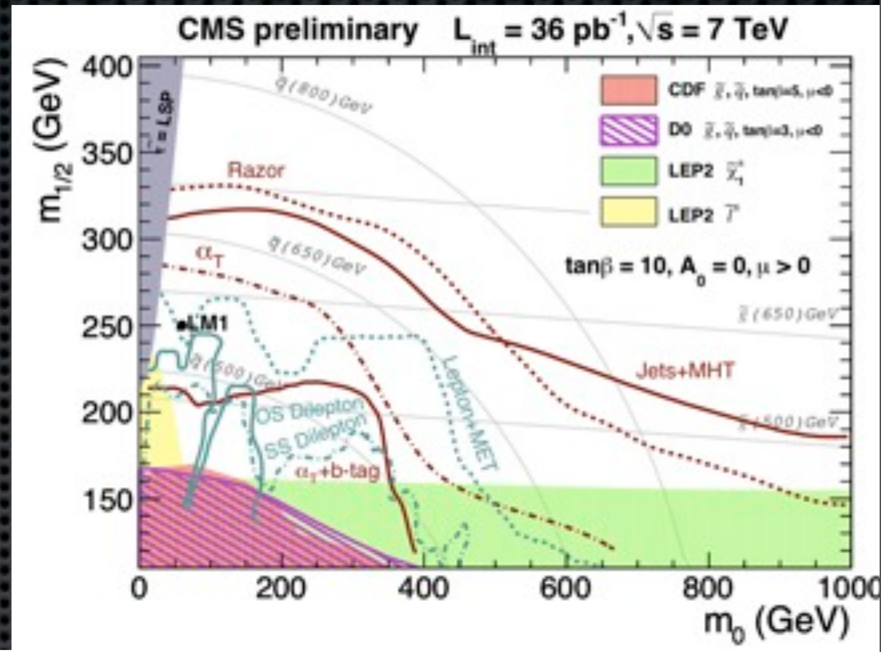
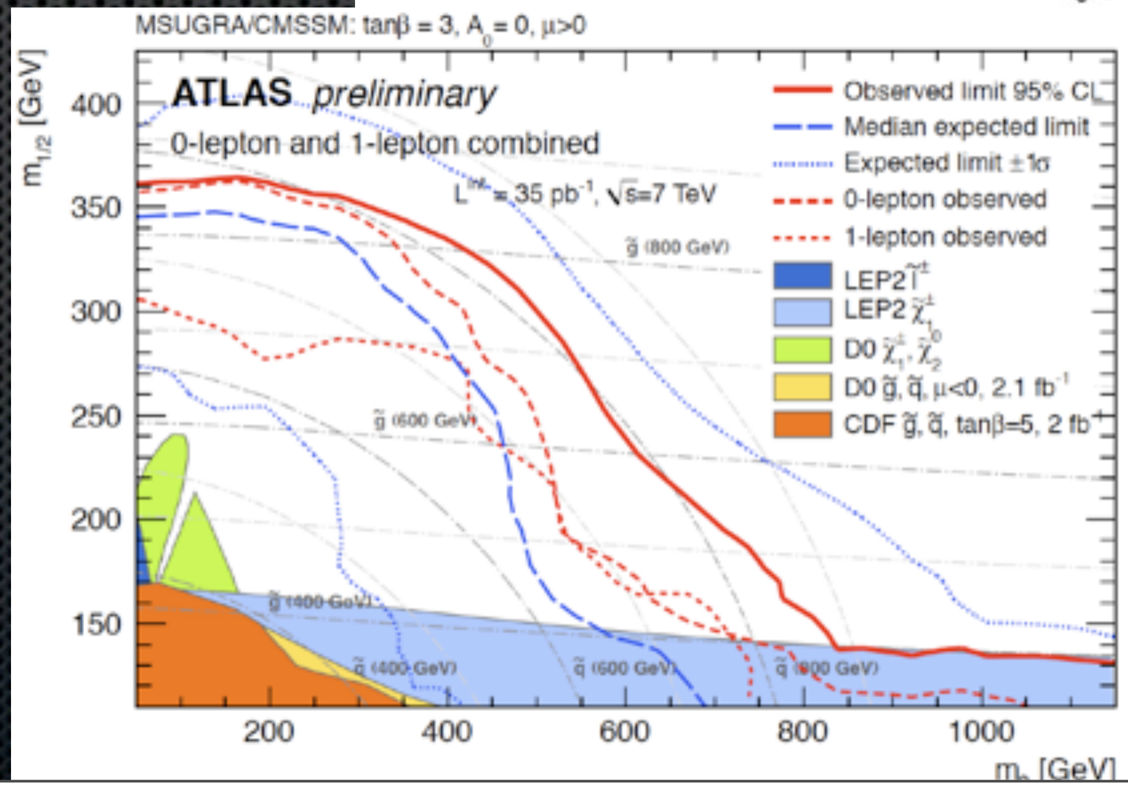
Effect of Early Results from LHC

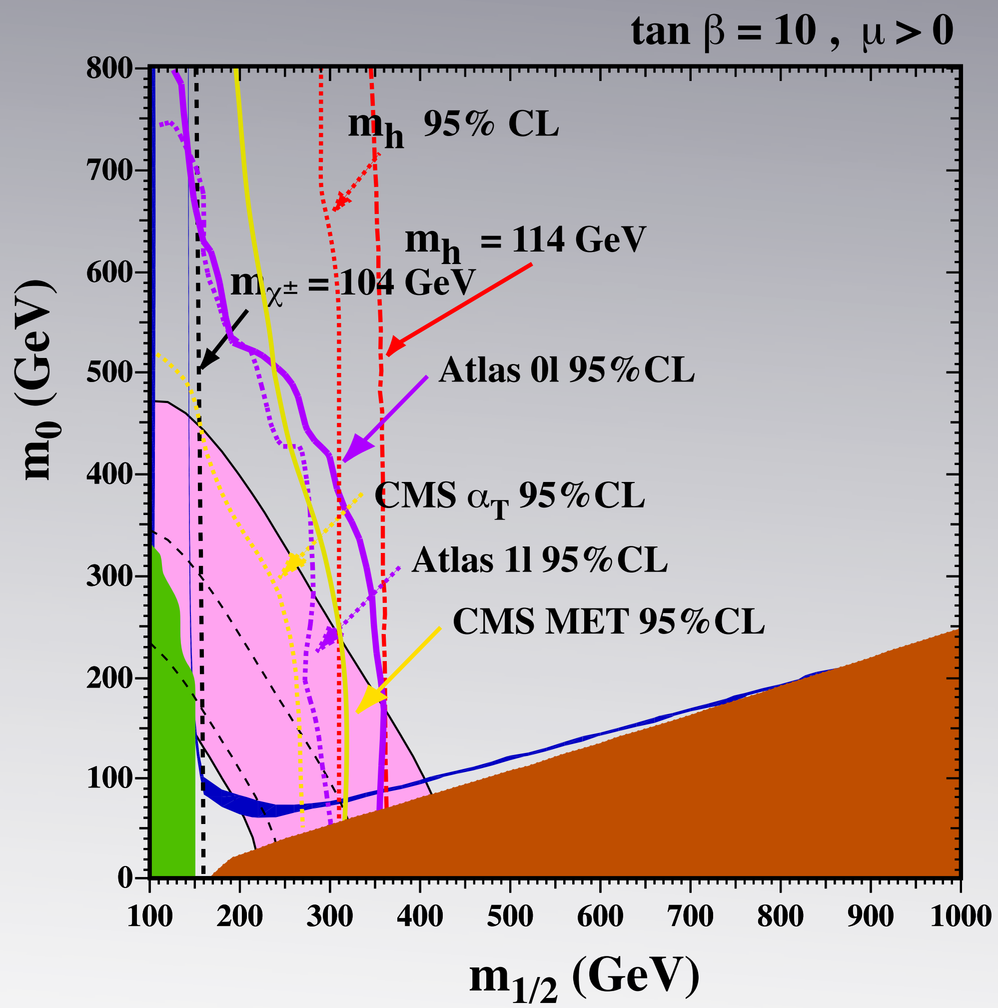
35 pb^{-1} @ 7 TeV

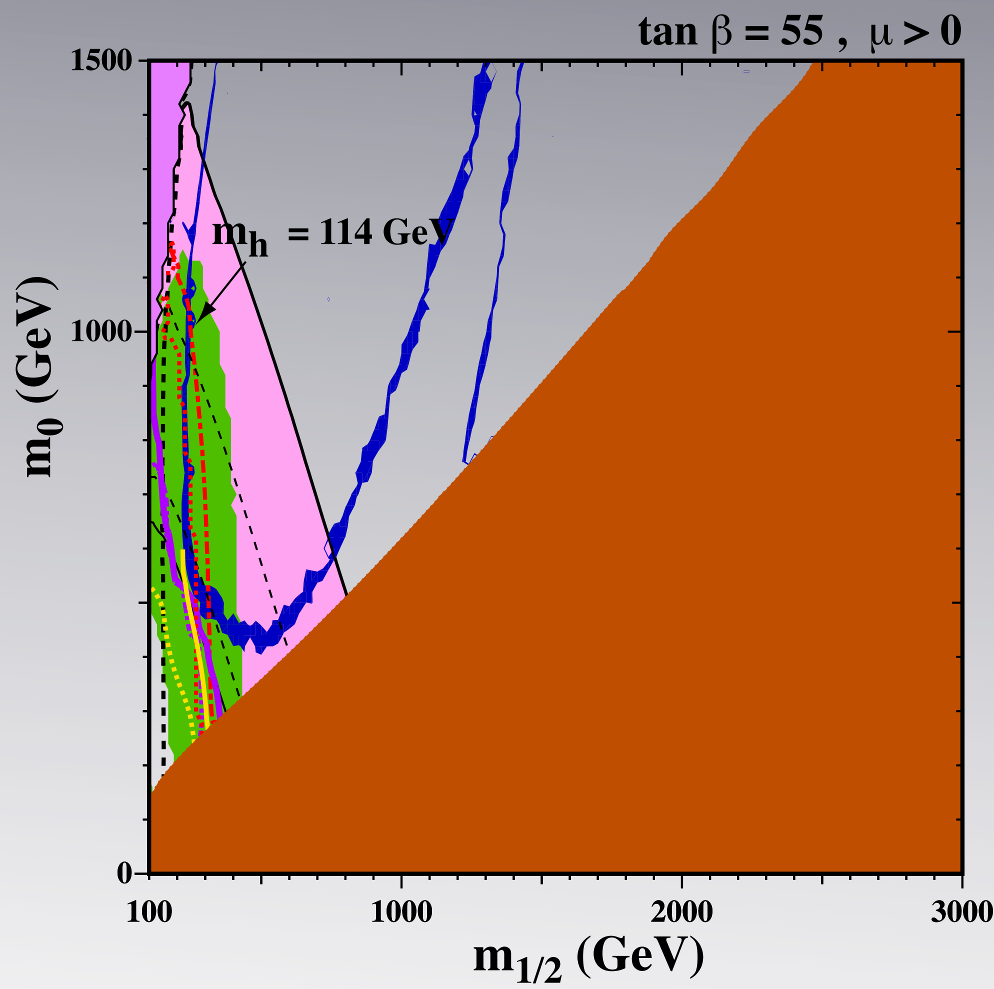
- CMS α_T
- ATLAS 1-lepton
- ATLAS 0-lepton
- CMS MET





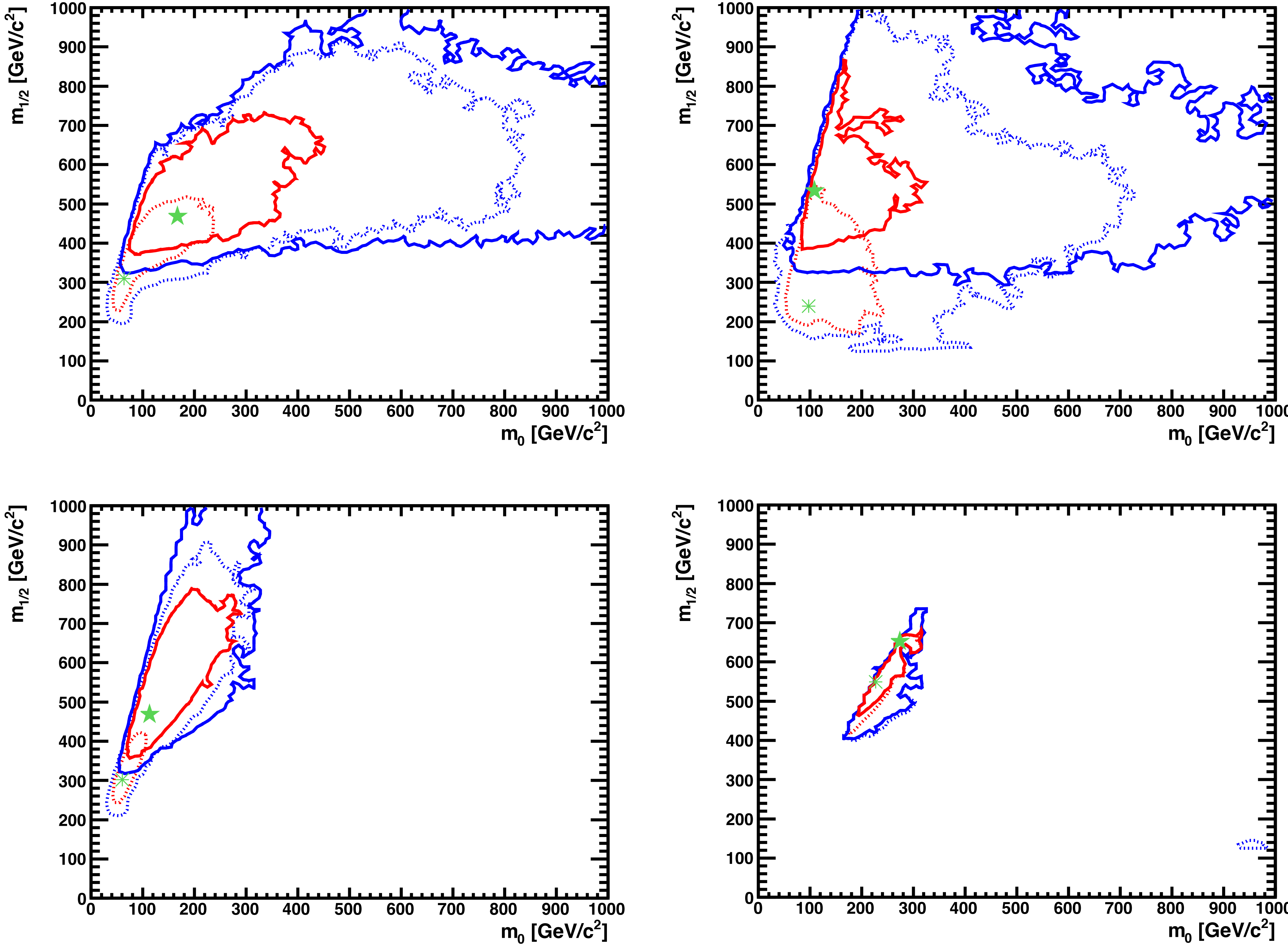
$m_{1/2}$ - m_0 planes incl. LHC





- CMSSM

Ellis, Olive, Santoso, Spanos

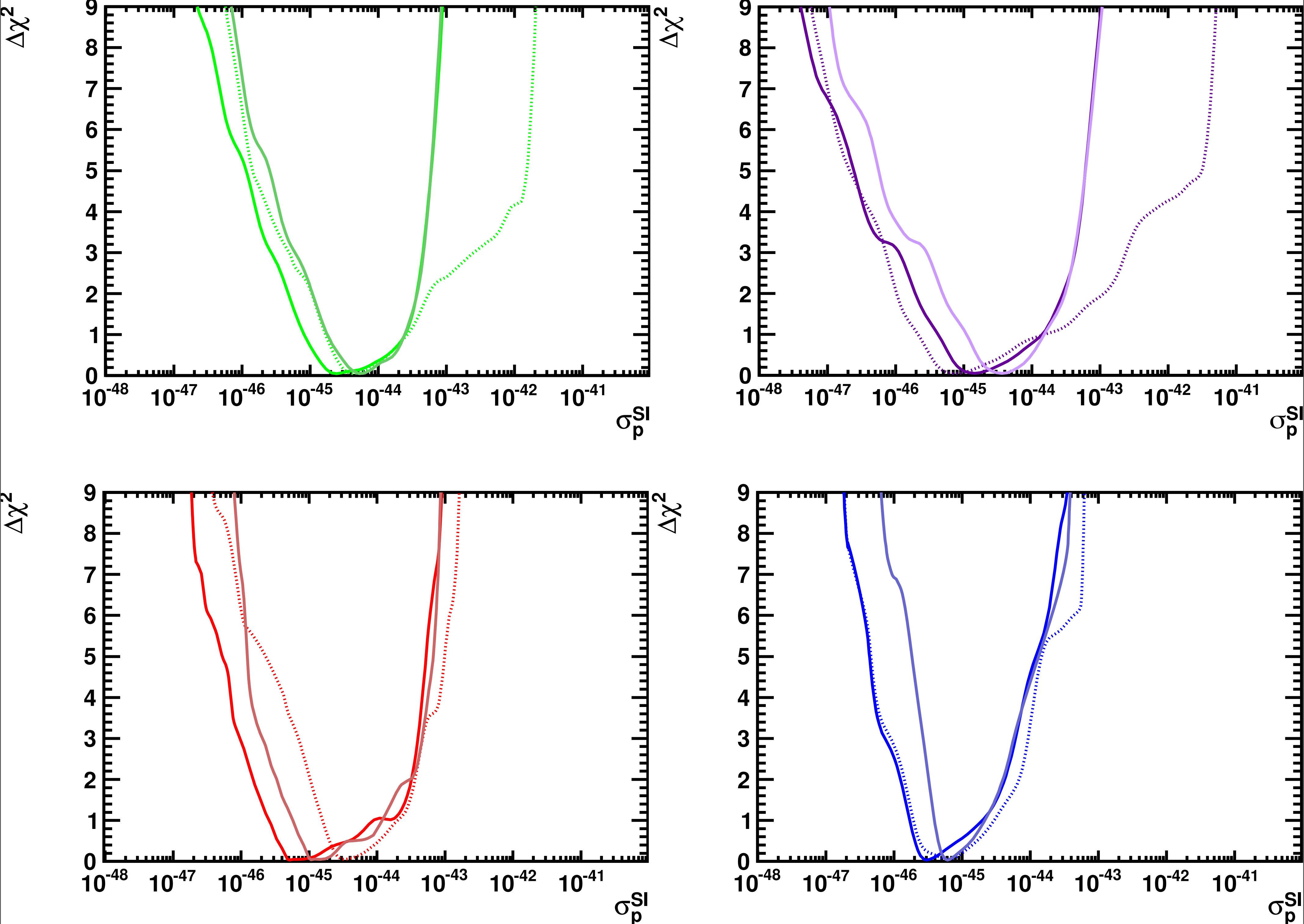


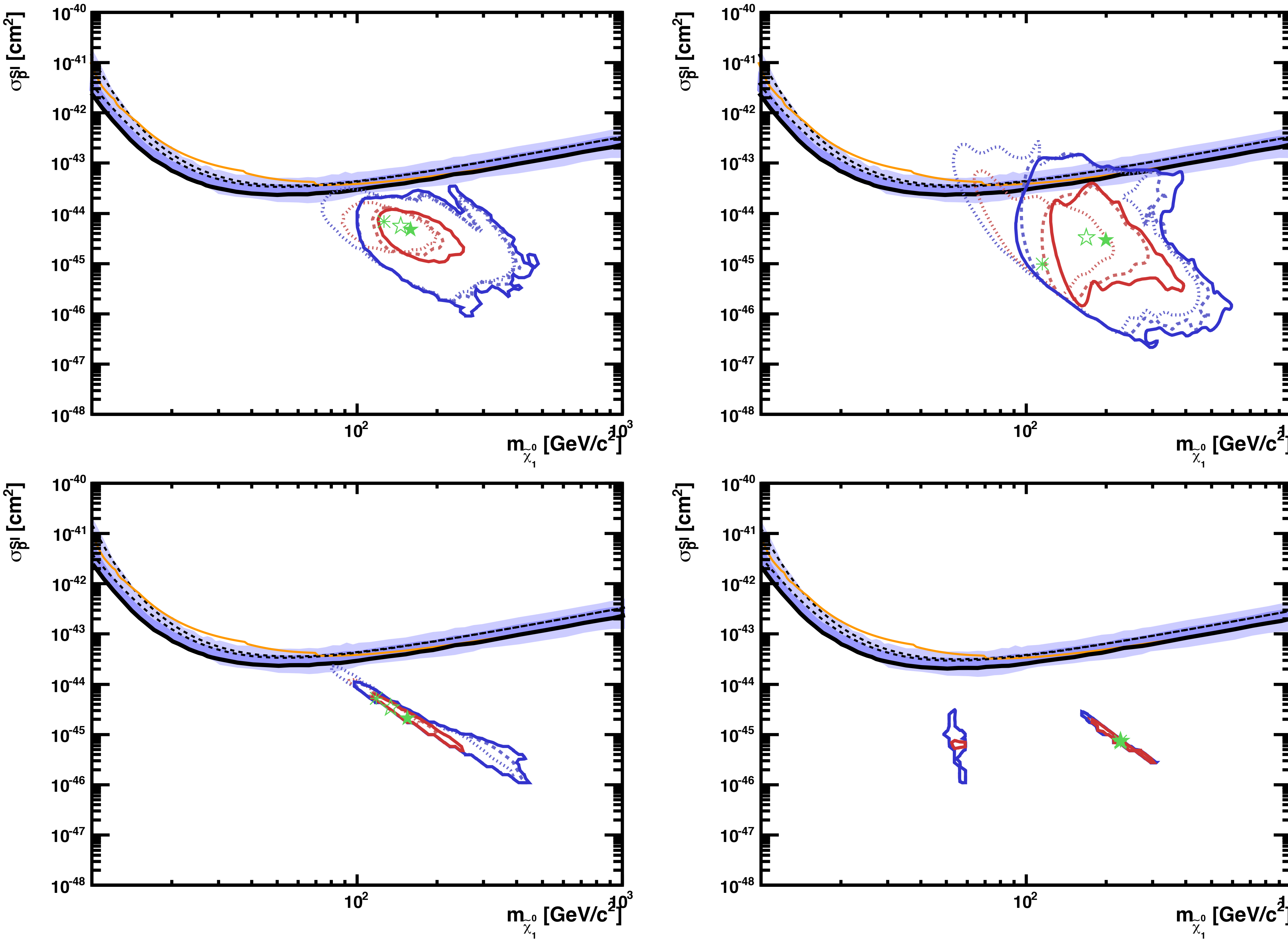
Thursday, July 7, 2011

Comparison of best fit points pre and post LHC

Model	Minimum χ^2/dof	Probability	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	M_h (GeV) (no LEP)
CMSSM pre-LHC	22.5/19	26%	310^{+120}_{-50}	60^{+90}_{-10}	-60^{+410}_{-840}	10^{+10}_{-4}	108.6
post-2010-LHC	26.1/19	13%	470^{+140}_{-70}	170^{+330}_{-80}	-780^{+1410}_{-820}	22^{+27}_{-13}	115.7
post-Xenon (50 ± 14)	26.2/20	16%	470^{+140}_{-70}	170^{+330}_{-80}	-780^{+1410}_{-820}	22^{+27}_{-13}	115.7
NUHM1 pre-LHC	20.5/17	25%	240^{+150}_{-50}	100^{+70}_{-40}	920^{+360}_{-1260}	7^{+11}_{-2}	119.4
post-2010-LHC	24.1/18	15%	530^{+220}_{-90}	110^{+80}_{-20}	-370^{+1070}_{-1000}	27^{+24}_{-10}	117.9
post-Xenon (50 ± 14)	24.2/19	19%	530^{+220}_{-90}	110^{+80}_{-20}	-370^{+1070}_{-1000}	27^{+24}_{-10}	117.9
VCMSSM pre-LHC	22.6/20	31%	300^{+60}_{-40}	60^{+20}_{-10}	30^{+50}_{-30}	8^{+3}_{-1}	110.0
post-2010-LHC	27.9/20	11%	470^{+150}_{-80}	110^{+110}_{-30}	120^{+300}_{-190}	13^{+14}_{-8}	115.0
post-Xenon (50 ± 14)	28.1/21	14%	470^{+150}_{-80}	110^{+110}_{-30}	120^{+300}_{-190}	13^{+14}_{-8}	115.0
mSUGRA pre-LHC	29.4/19	6.0%	550^{+170}_{-90}	230^{+80}_{-40}	430^{+190}_{-90}	28^{+5}_{-2}	107.8
post-2010-LHC	30.2/20	6.7%	650^{+70}_{-130}	270^{+50}_{-50}	530^{+130}_{-130}	30^{+4}_{-3}	122.2
post-Xenon (50 ± 14)	30.3/21	8.6%	650^{+70}_{-130}	270^{+50}_{-50}	530^{+130}_{-130}	30^{+4}_{-3}	122.2

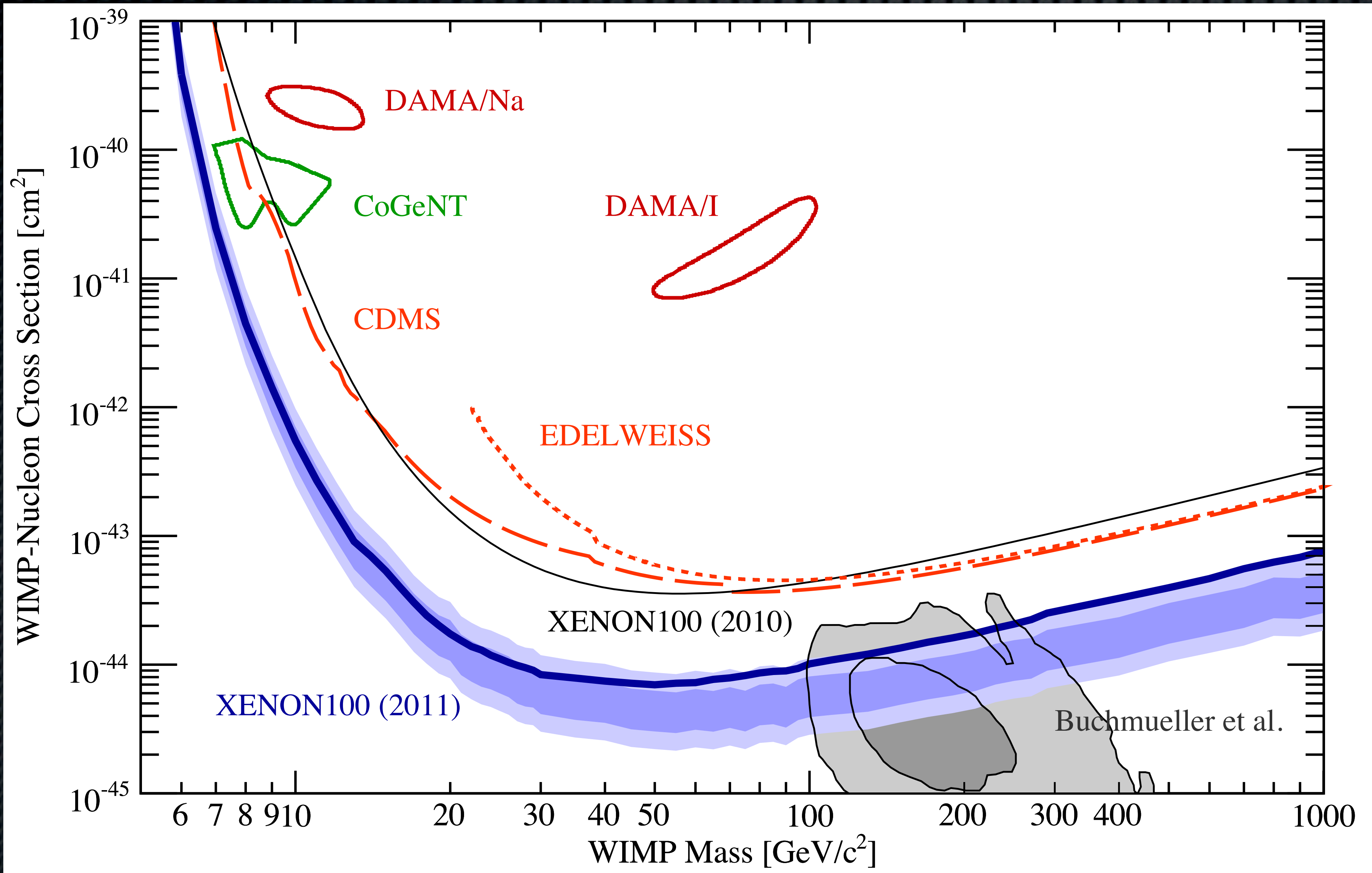
Buchmueller, Cavanaugh, Colling, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Olive, Rogerson, Ronga, Weiglein


Δχ²
σ_p^SI
0 1 2 3 4 5 6 7 8 9
10^-48 10^-47 10^-46 10^-45 10^-44 10^-43 10^-42 10^-41

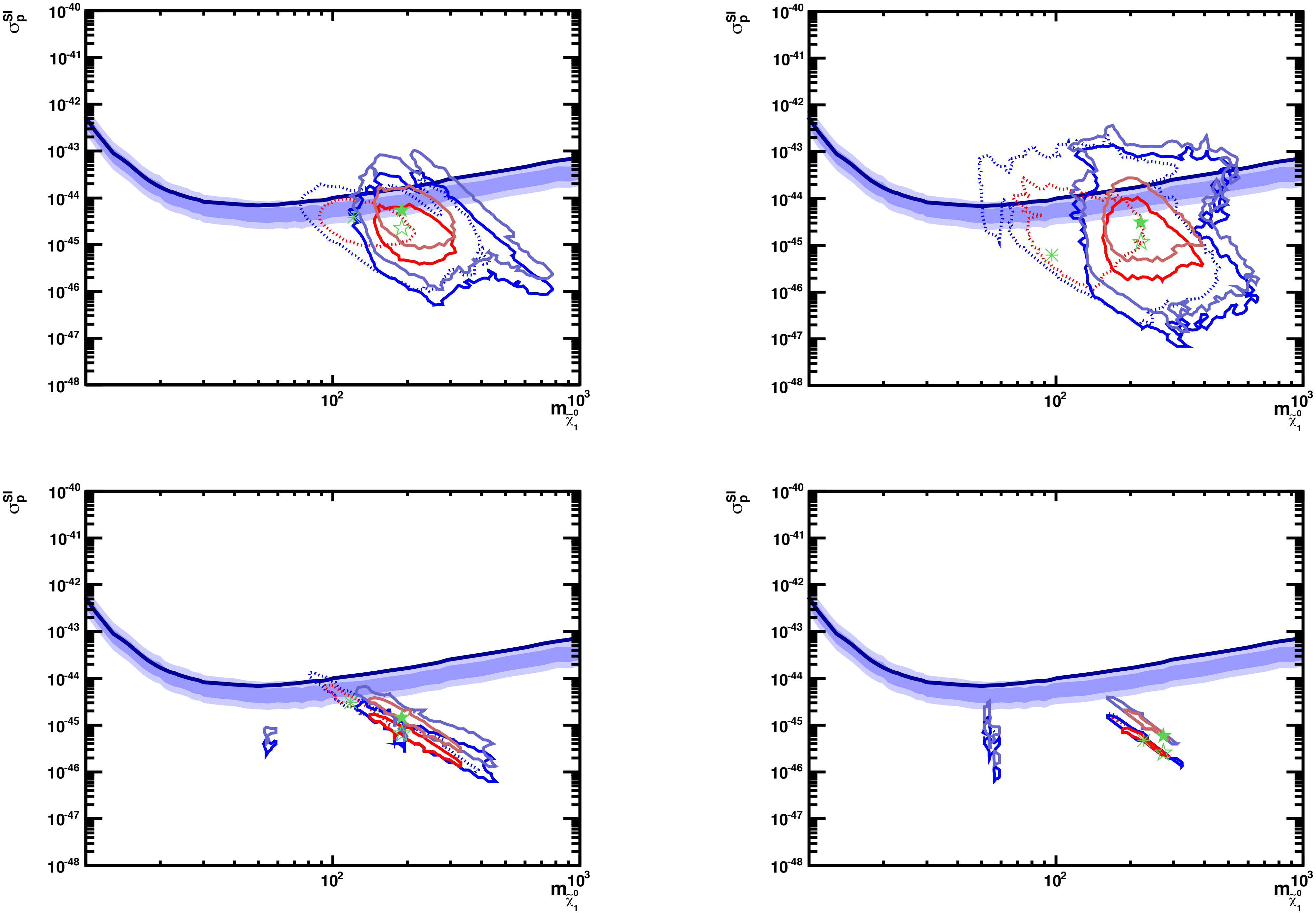


Buchmueller, Cavanaugh, Colling, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Olive, Rogerson, Ronga, Weiglein

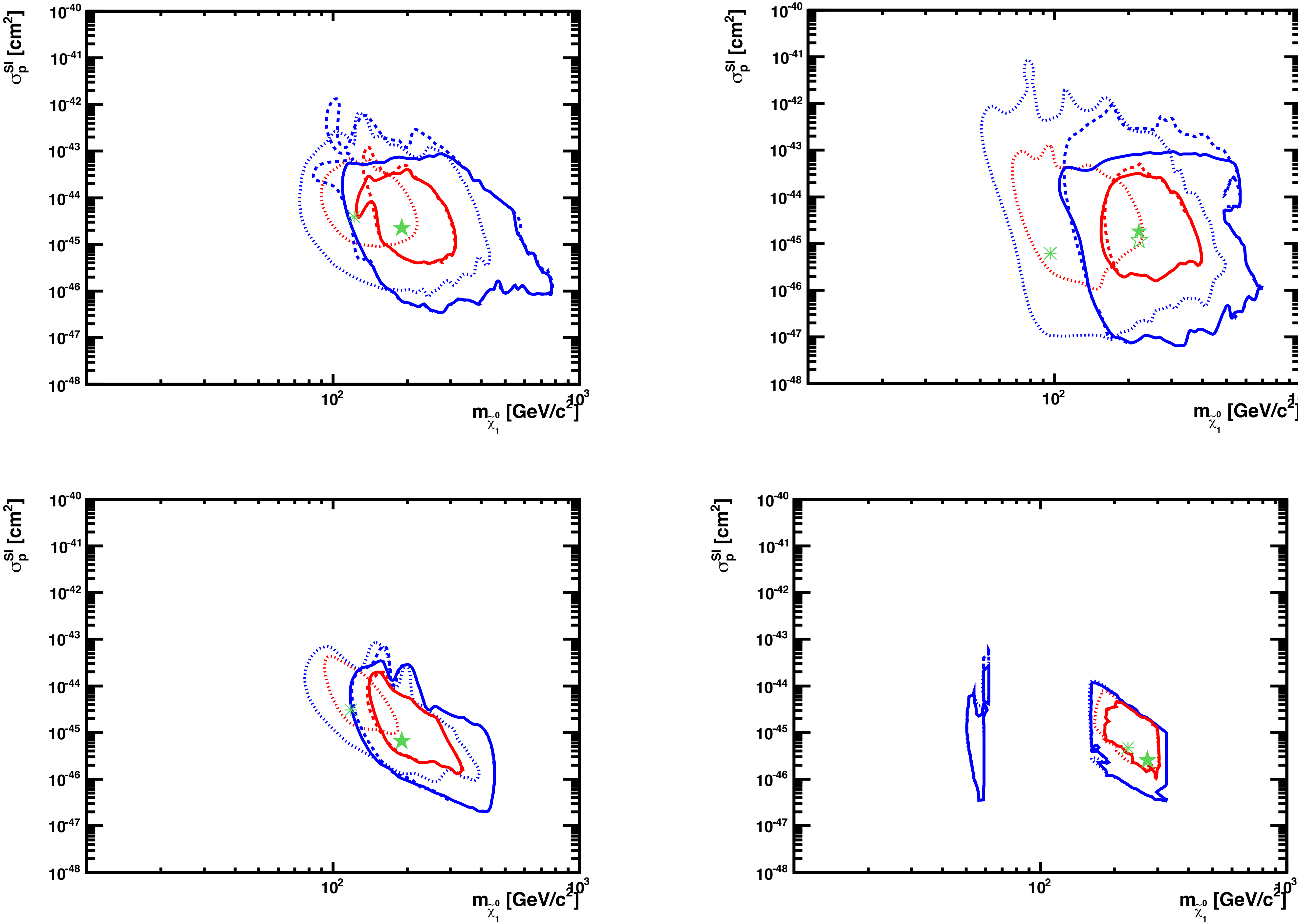
Most recent result from Xenon100



Aprile et al.

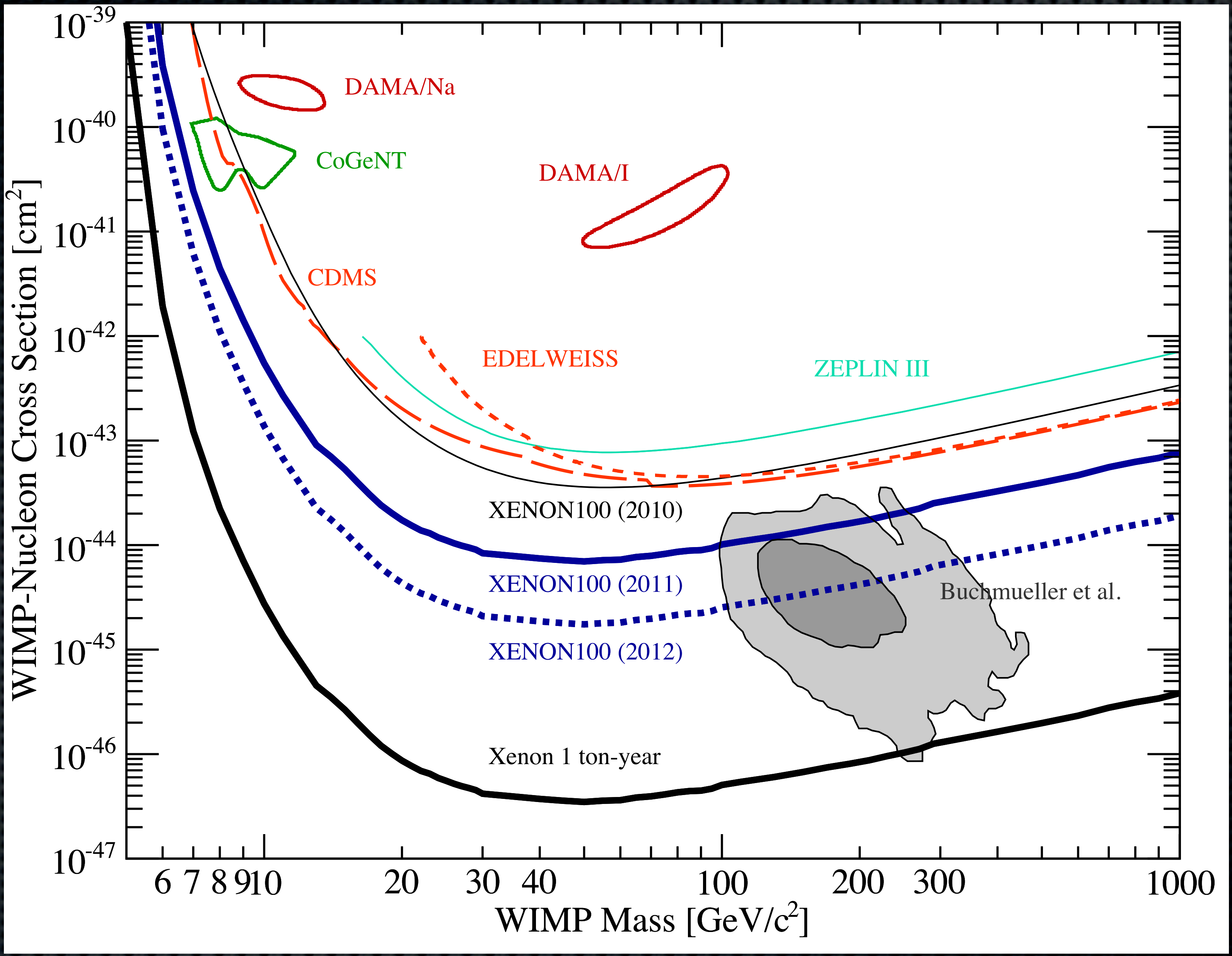


Buchmueller, Cavanaugh, Colling, De Roeck, Dolan, Ellis,
Flacher, Heinemeyer, Isidori, Olive, Rogerson, Ronga, Weiglein



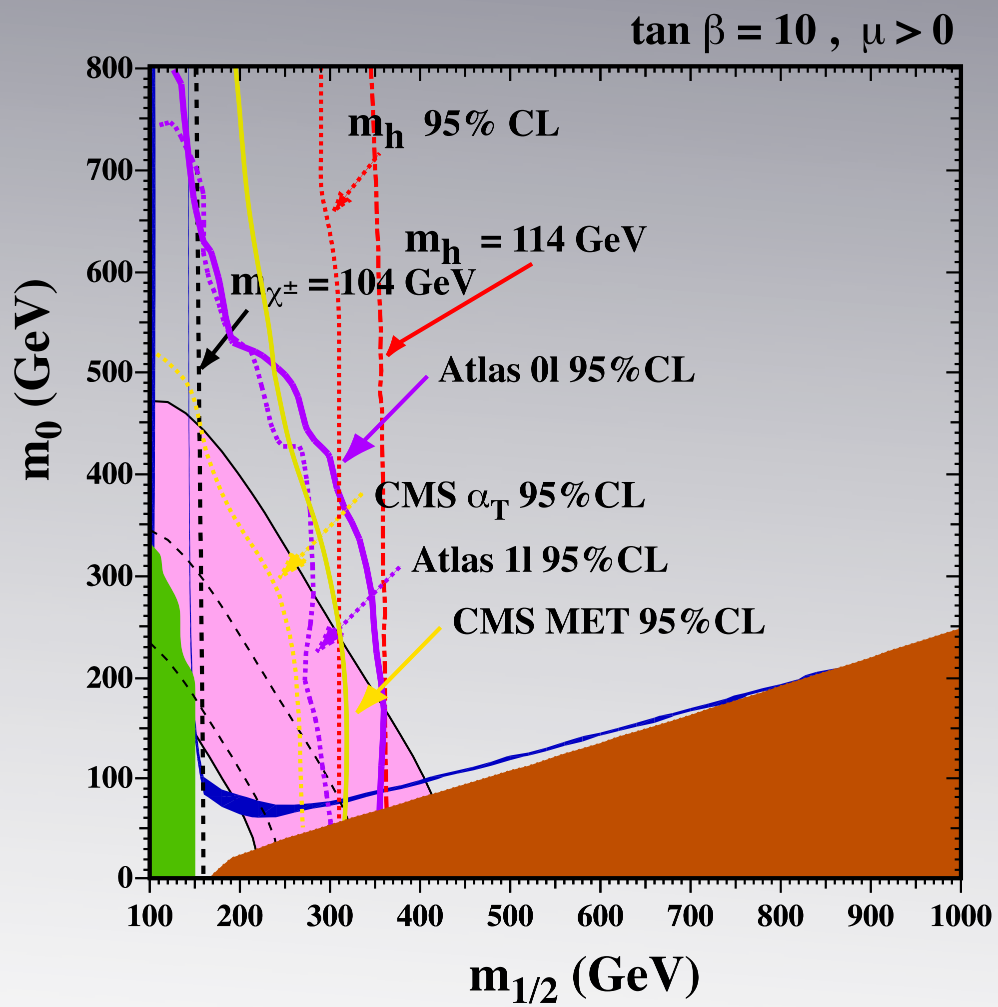
Buchmueller, Cavanaugh, Colling, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Olive, Rogerson, Ronga, Weiglein

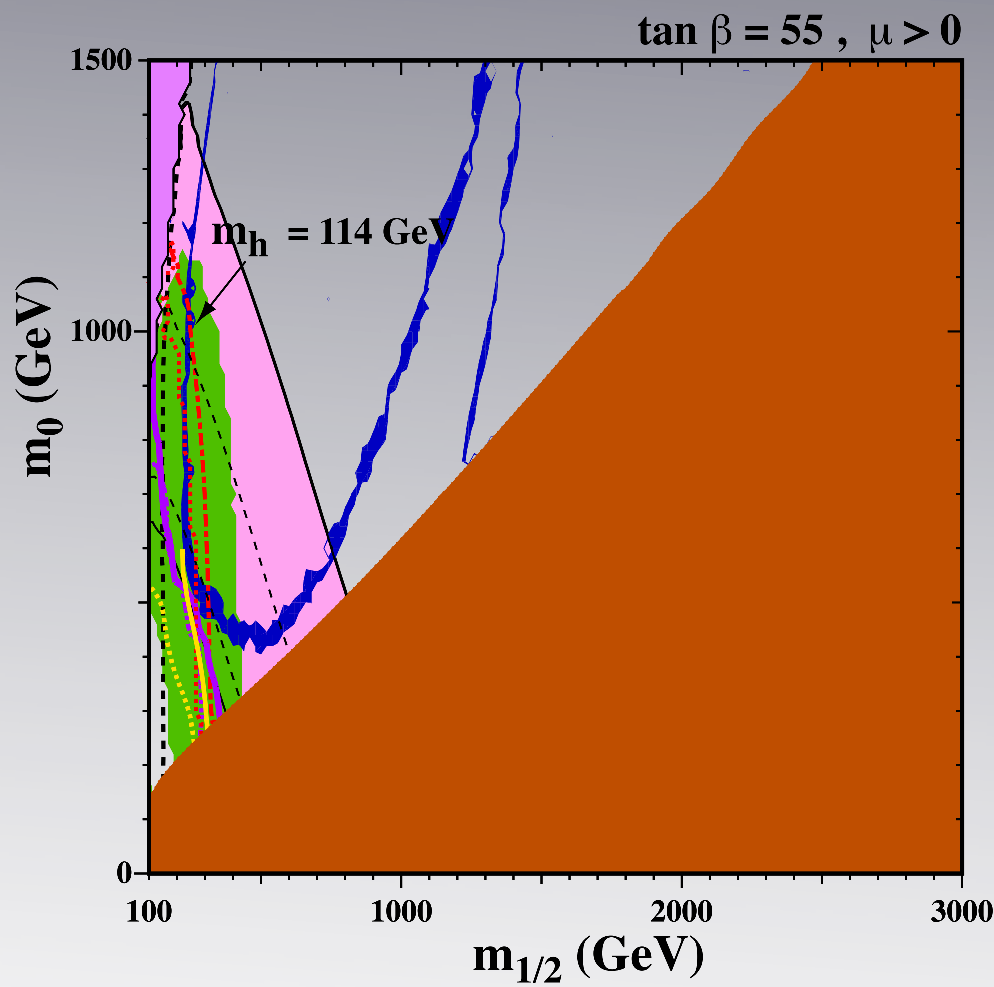
Most recent result from Xenon100



Aprile

$m_{1/2}$ - m_0 planes incl. LHC

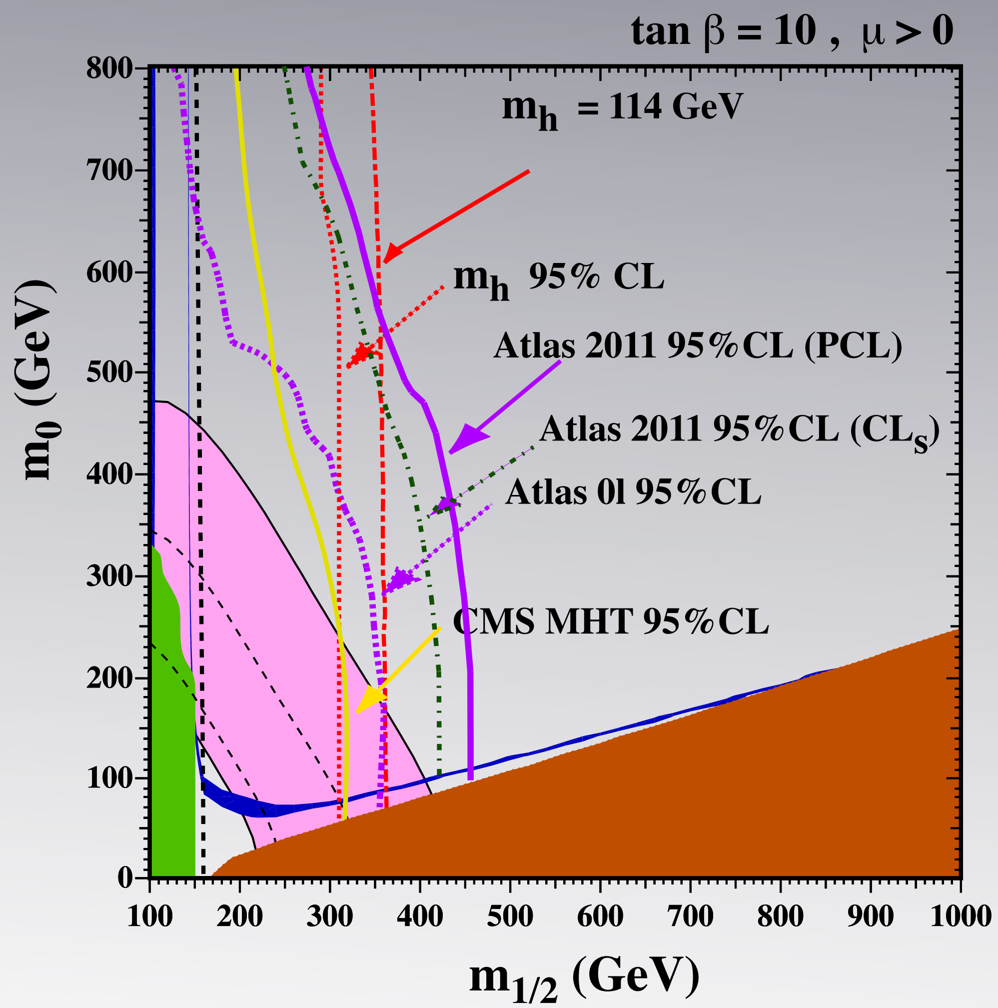


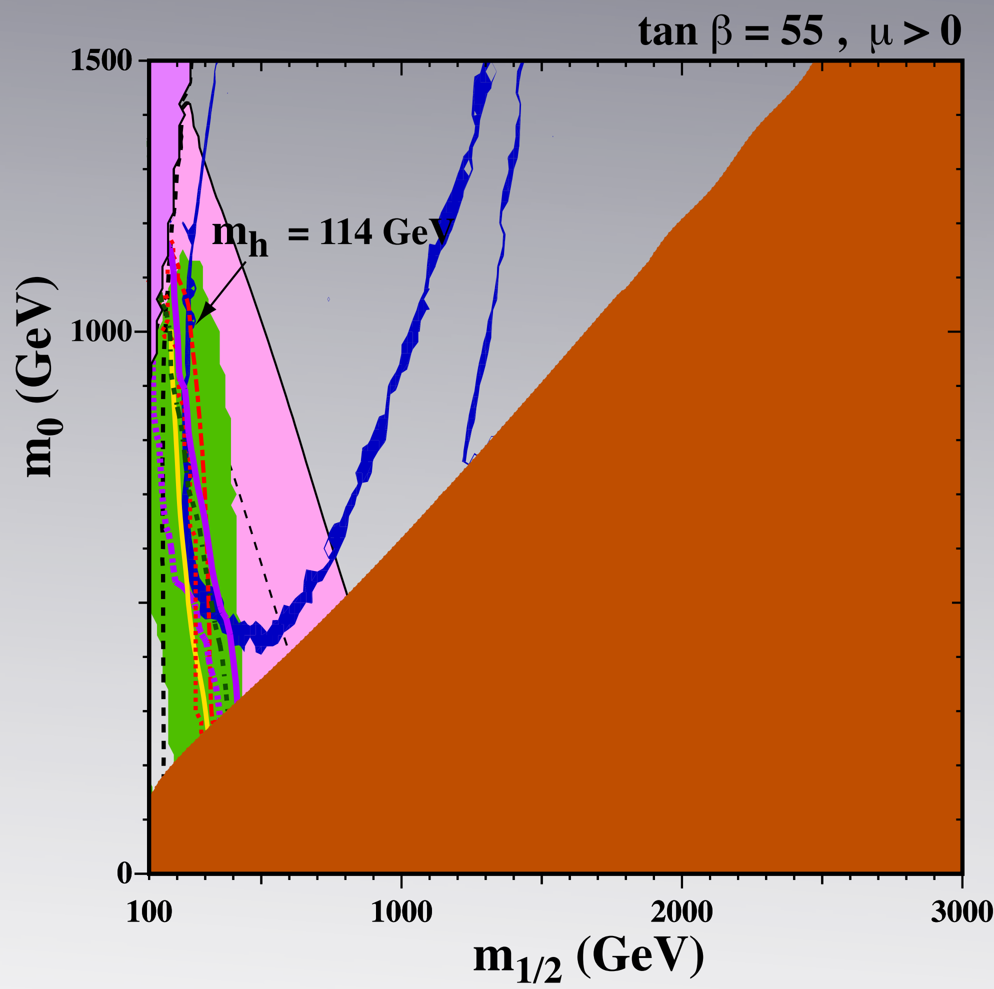


- CMSSM

Ellis, Olive, Santoso, Spanos

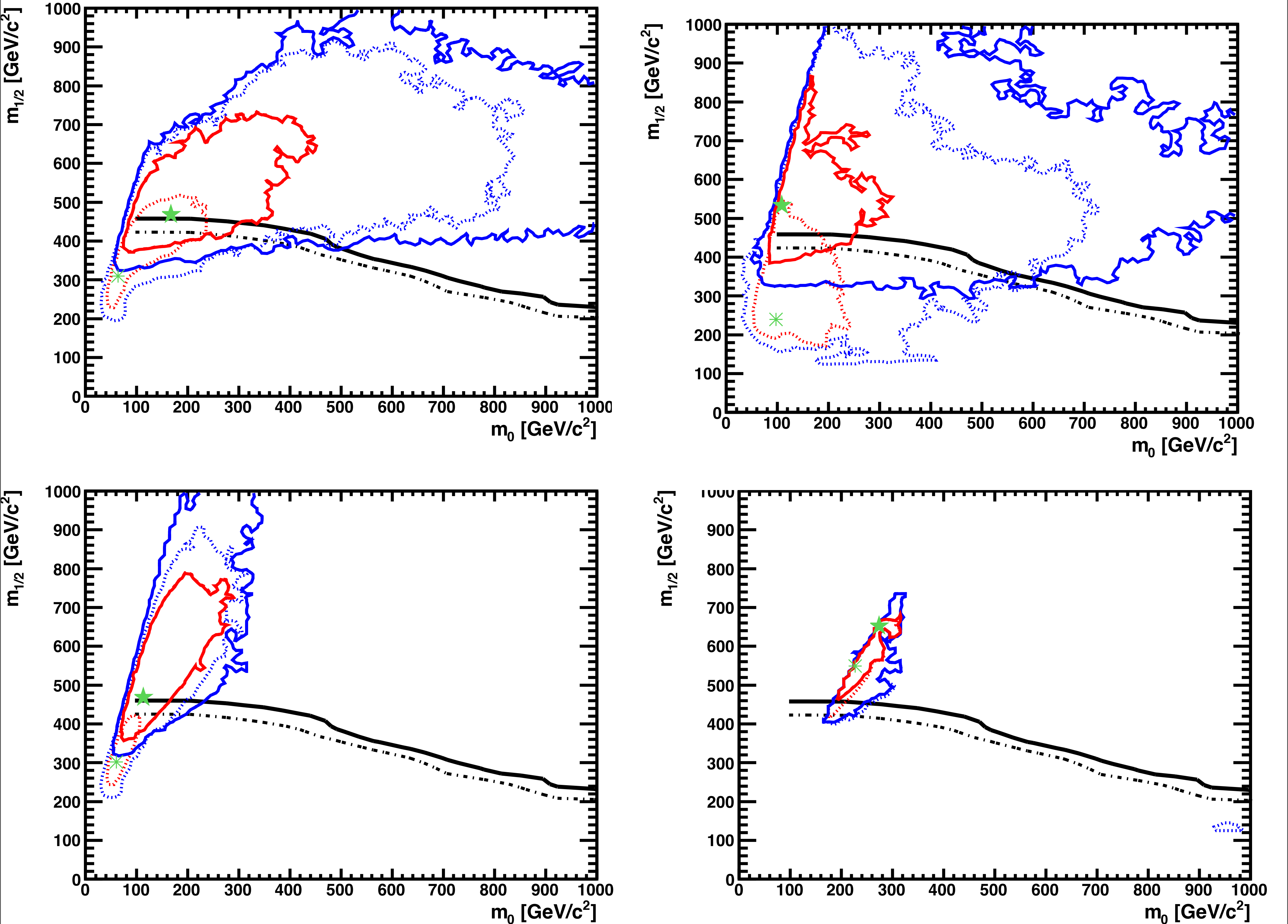
$m_{1/2}$ - m_0 planes incl. LHC





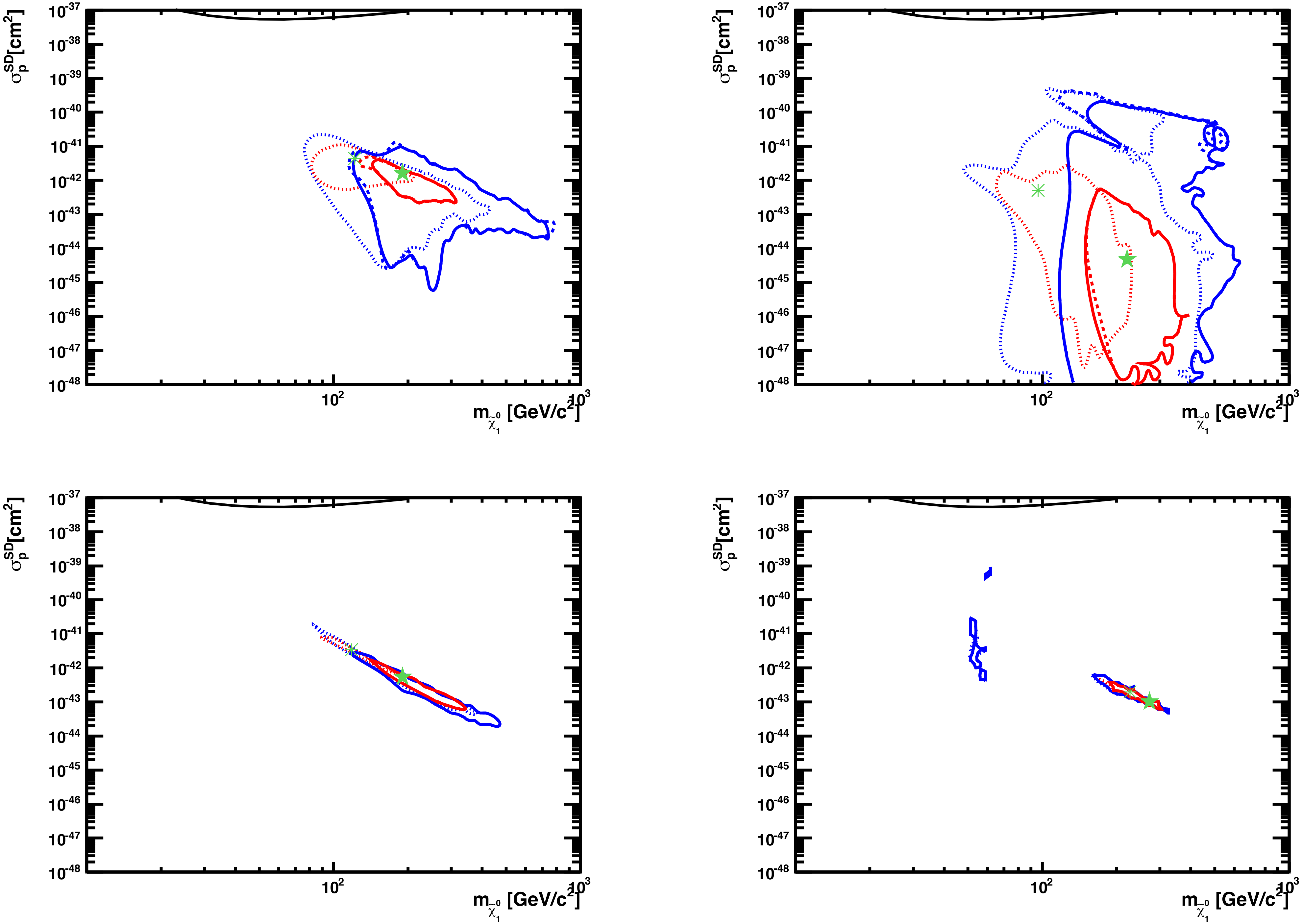
- CMSSM

Ellis, Olive, Santoso, Spanos


m_{1/2} [GeV/c^2]
m_0 [GeV/c^2]
0
100
200
300
400
500
600
700
800
900
1000

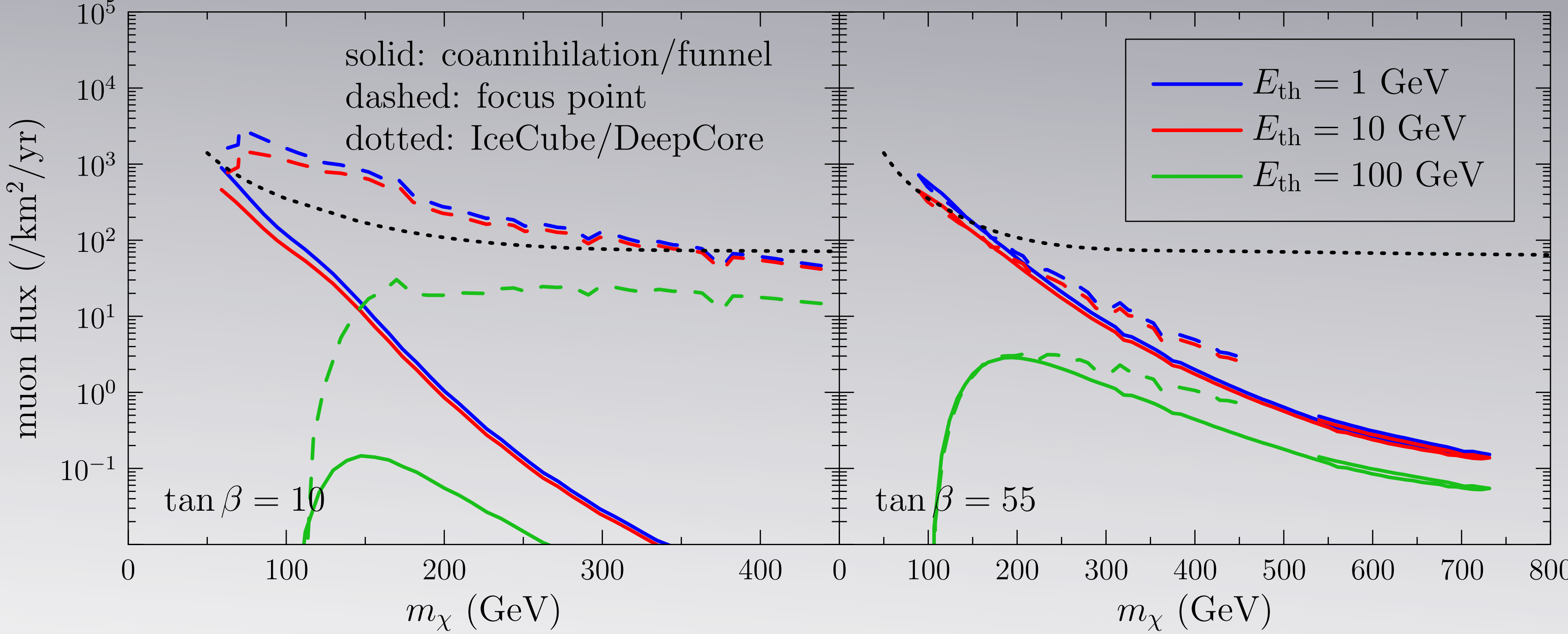
Indirect Detection

- Neutrinos from Neutralino Annihilations in the Sun
- Gamma-rays from Annihilations in the Galactic Halo



Buchmueller, Cavanaugh, Colling, De Roeck, Dolan, Ellis,
Flacher, Heinemeyer, Isidori, Olive, Rogerson, Ronga, Weiglein

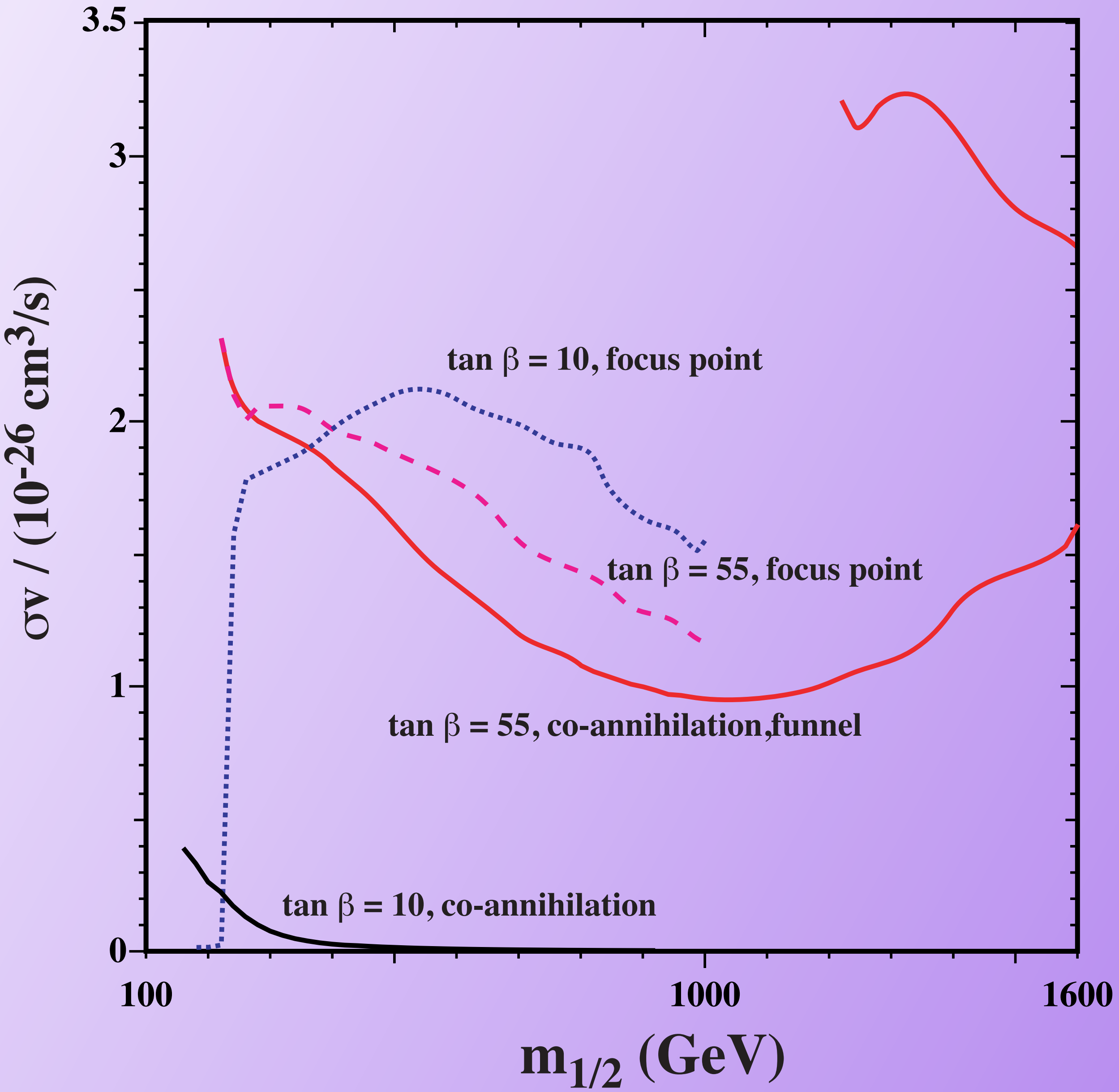
Indirect Detection in the CMSSM



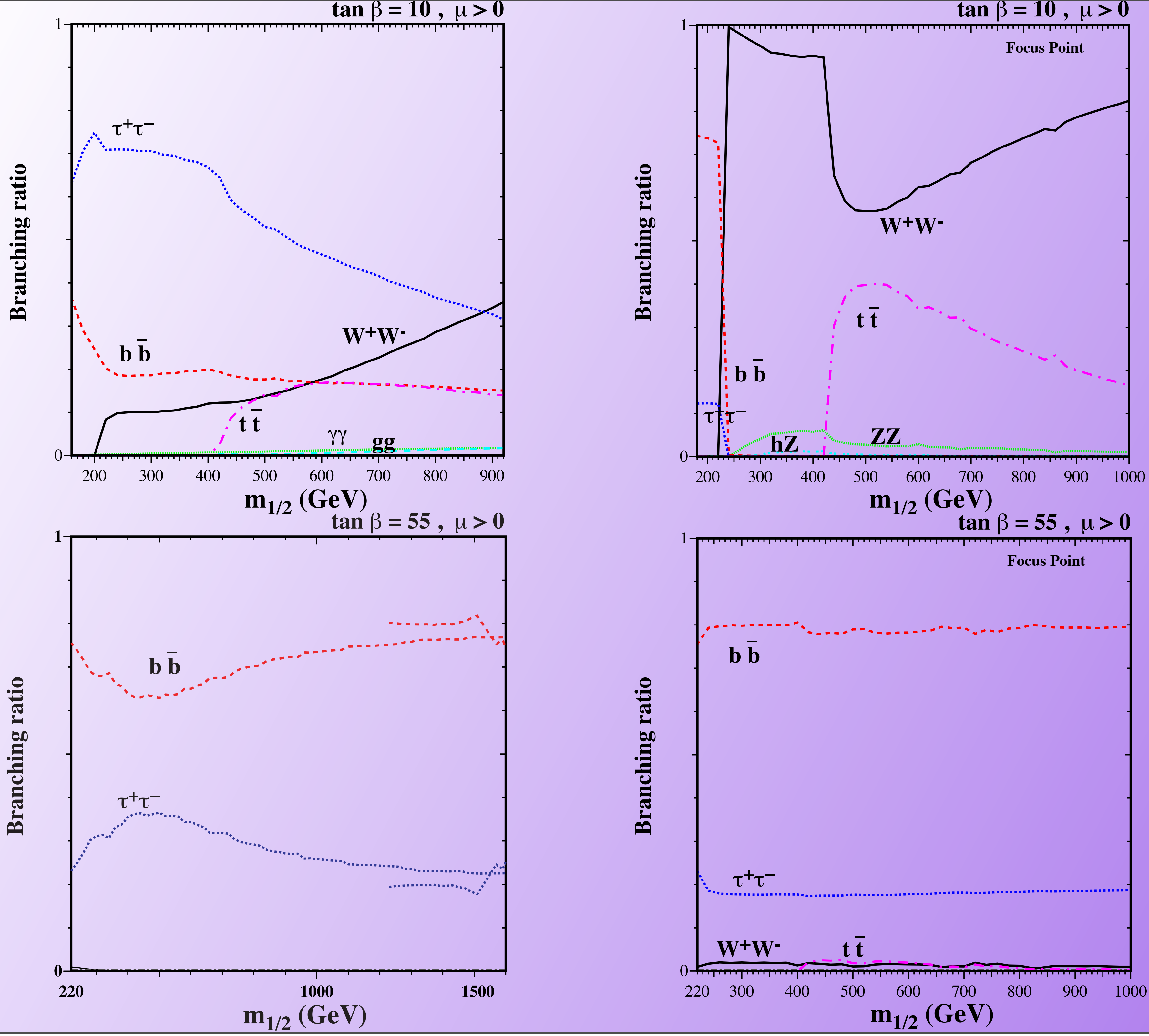
Ellis, Olive, Savage, and Spanos

Annihilations in the Halo

Annihilations in the Halo

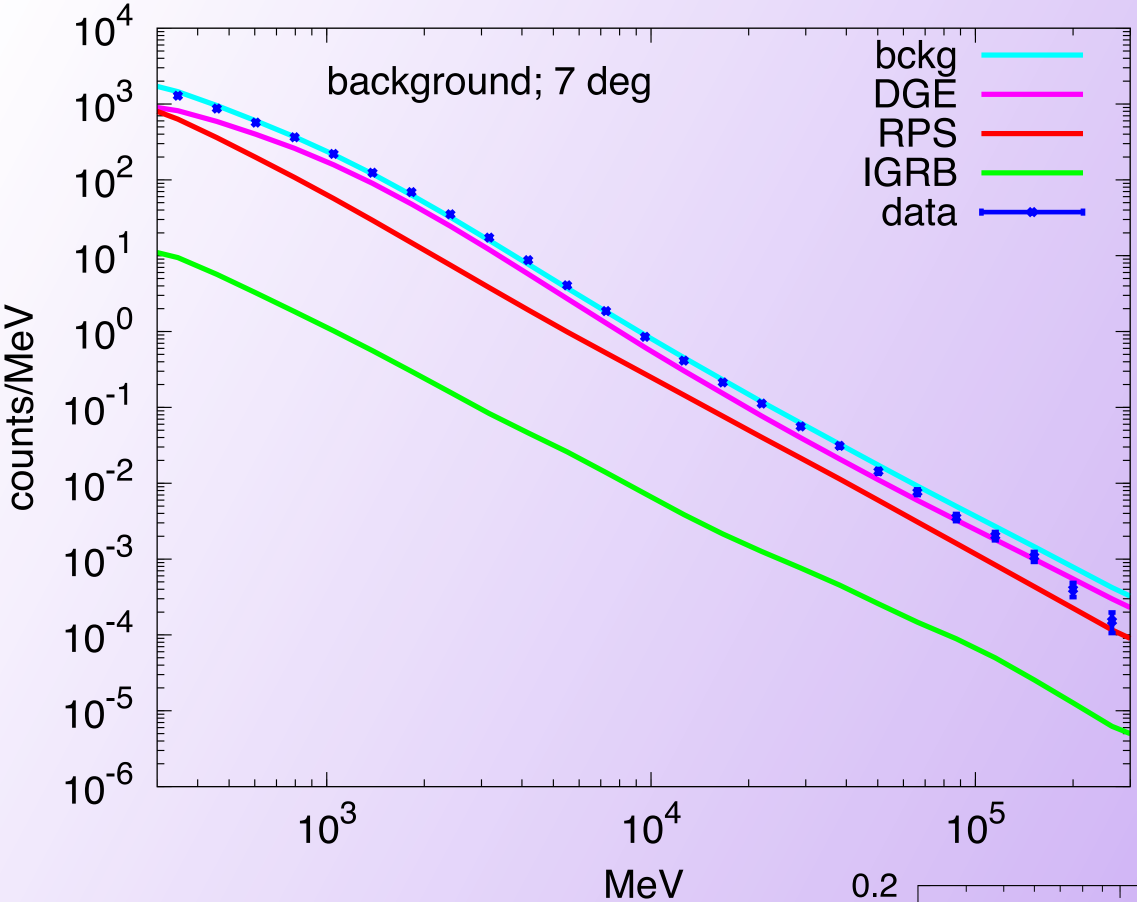


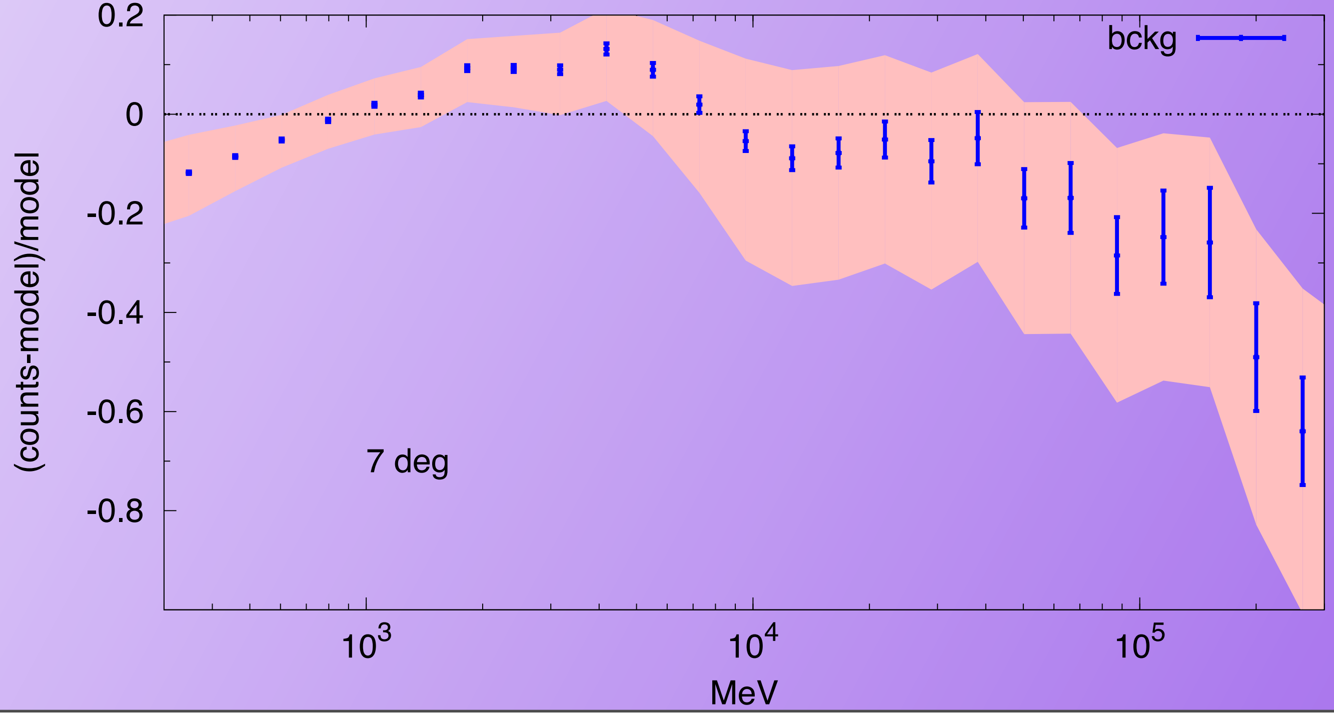
S-wave annihilation cross sections



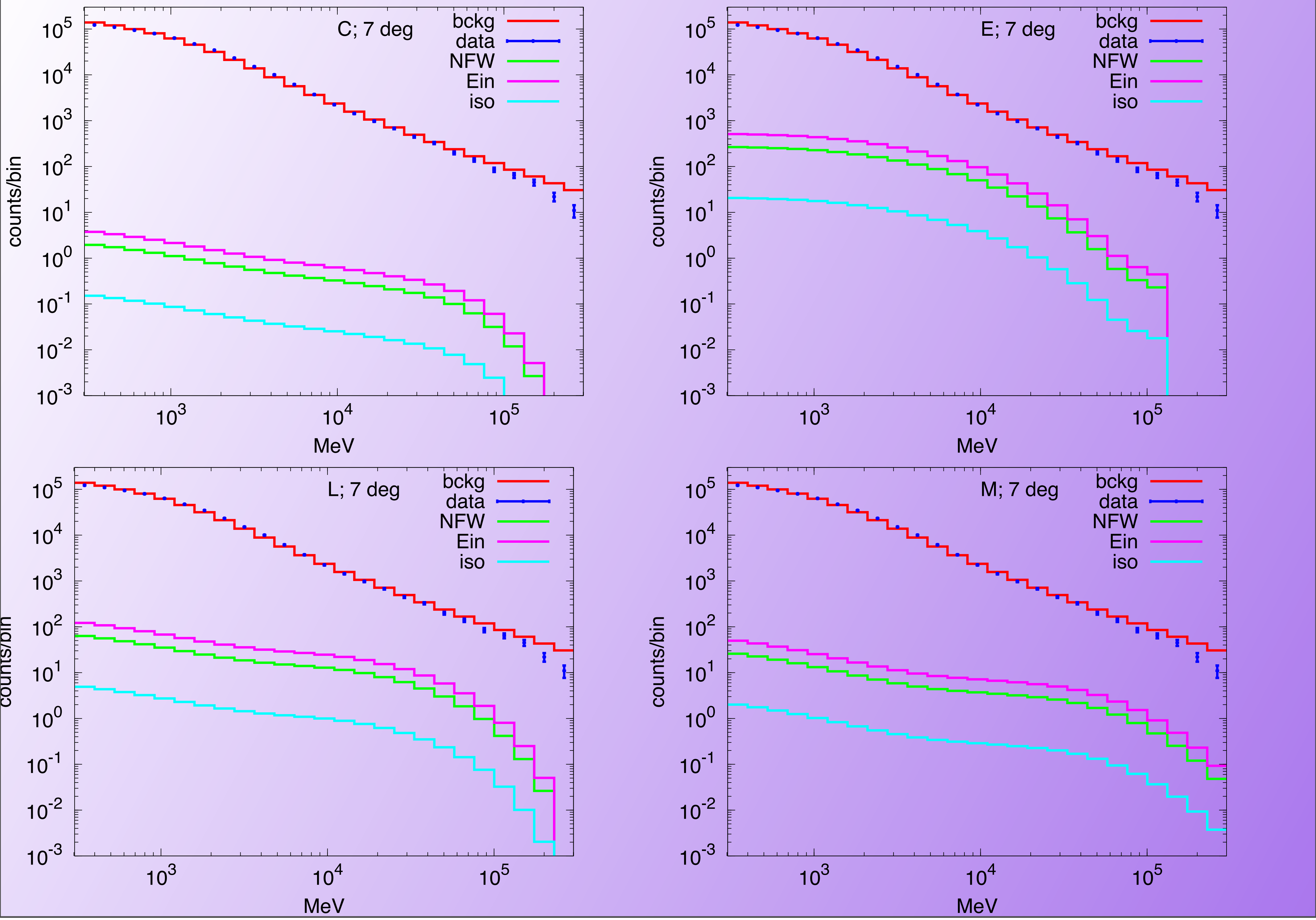
tan β = 10 , μ > 0
Branching ratio
τ+τ−
b b̄
W+W-
t t̄
γγ
gg
m1/2 (GeV)
tan β = 10 , μ > 0
Focus Point
Branching ratio
W+W-
t t̄
b b̄
τ+τ−
hZ
ZZ
m1/2 (GeV)
tan β = 55 , μ > 0
Branching ratio
b b̄
τ+τ−
m1/2 (GeV)
tan β = 55 , μ > 0
Focus Point
Branching ratio
b b̄
τ+τ−
W+W-
t t̄
m1/2 (GeV)

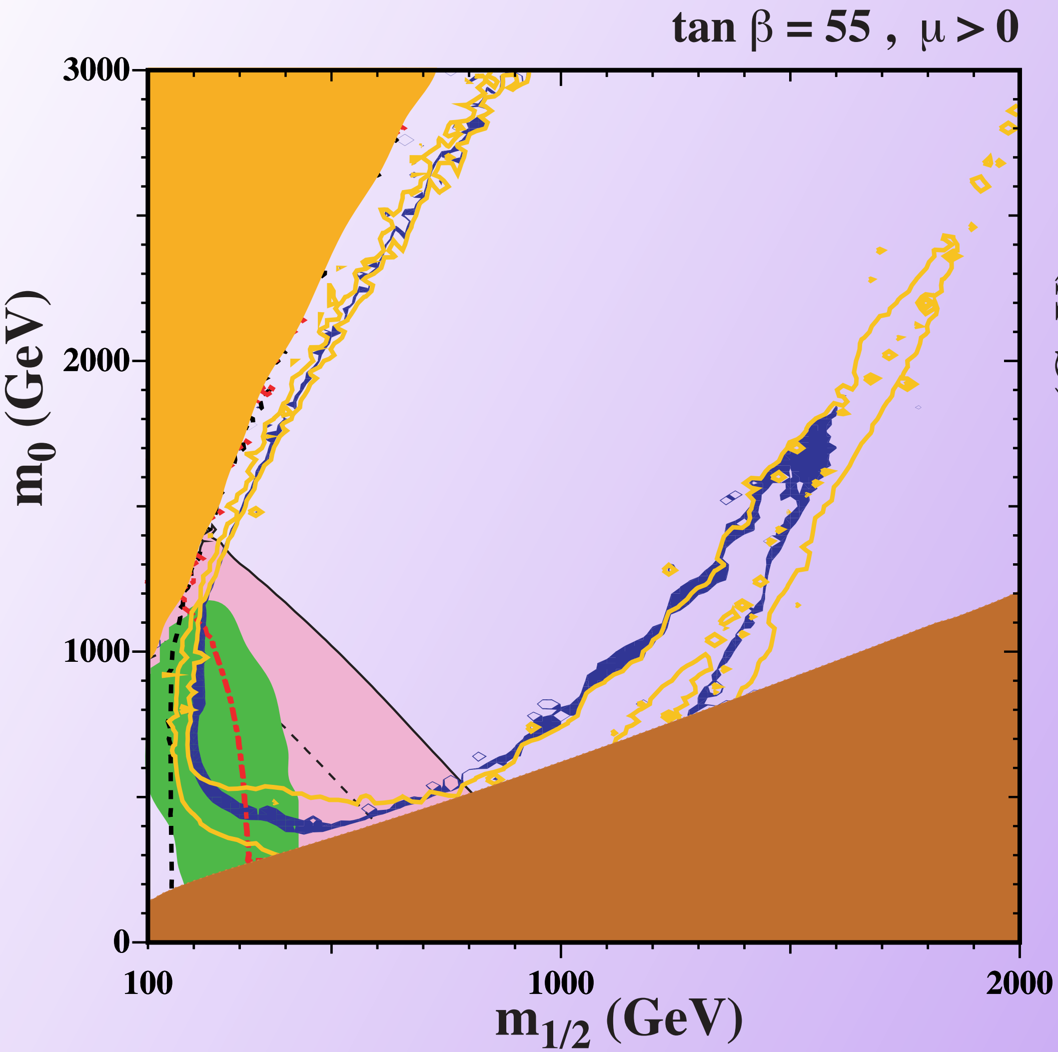
Backgrounds

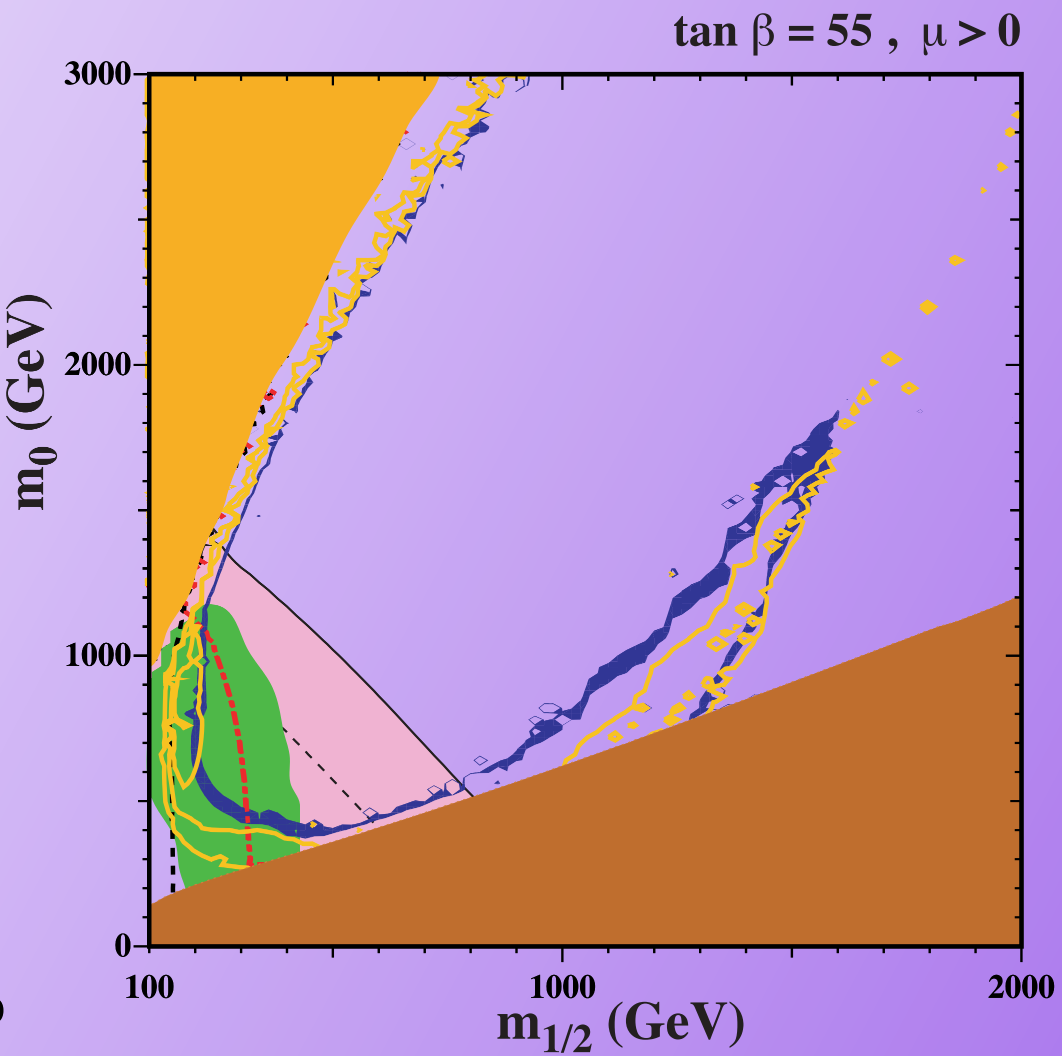




Gamma-ray signals




tan β = 55 , μ > 0
3000
2000
1000
0
100
1000
2000
m0 (GeV)
m1/2 (GeV)


tan β = 55 , μ > 0
3000
2000
1000
0
100
1000
2000
m0 (GeV)
m1/2 (GeV)

Summary

- Frequentist method (no priors) shows strong preference for relatively light neutralinos, low tan β, and co-annihilation region
- LHC beginning to make in significant inroads
- XENON100 also making inroads (cf. value of $\Sigma_{\pi N}$)
- Indirect Detection more difficult - typically sensitive to focus point region where cross sections are higher