Neutralino Dark Matter and the 125 GeV Higgs boson measured at the LHC

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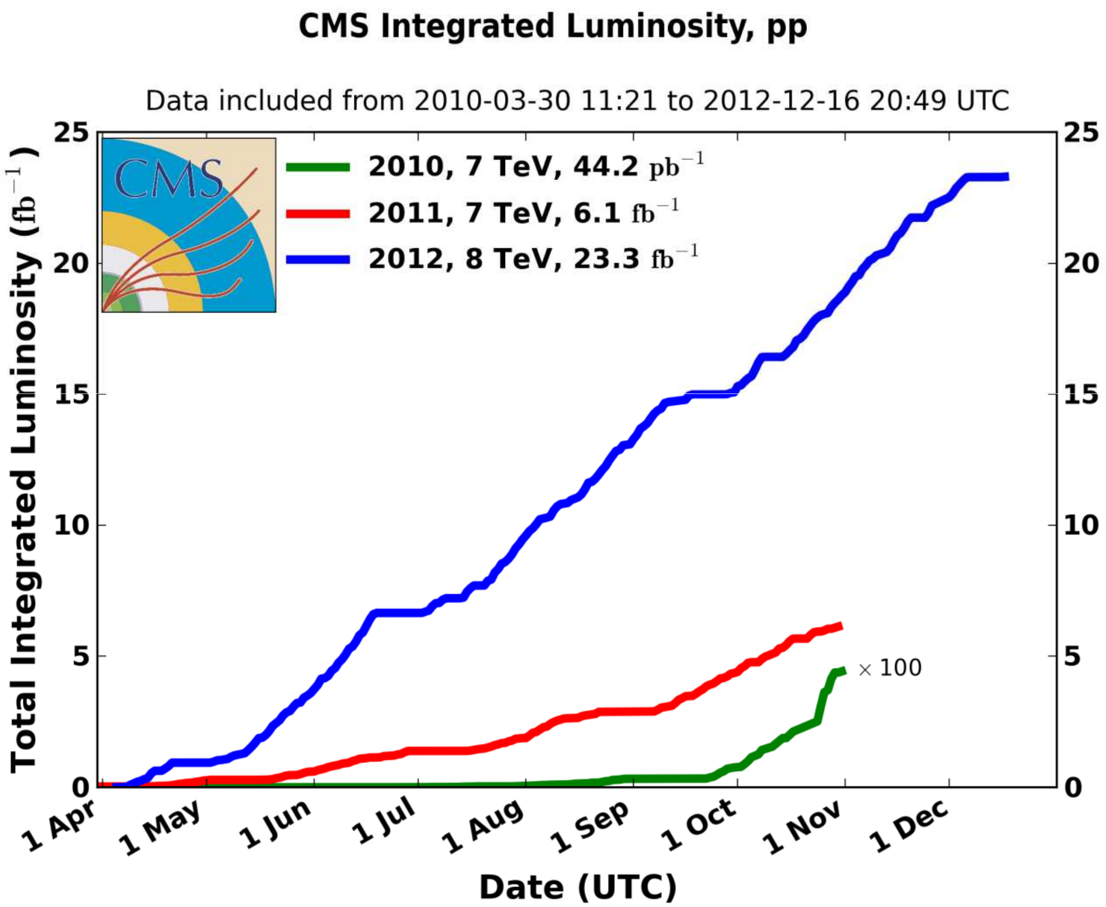
(Based on work done in collaboration with A. Bottino and N. Fornengo)

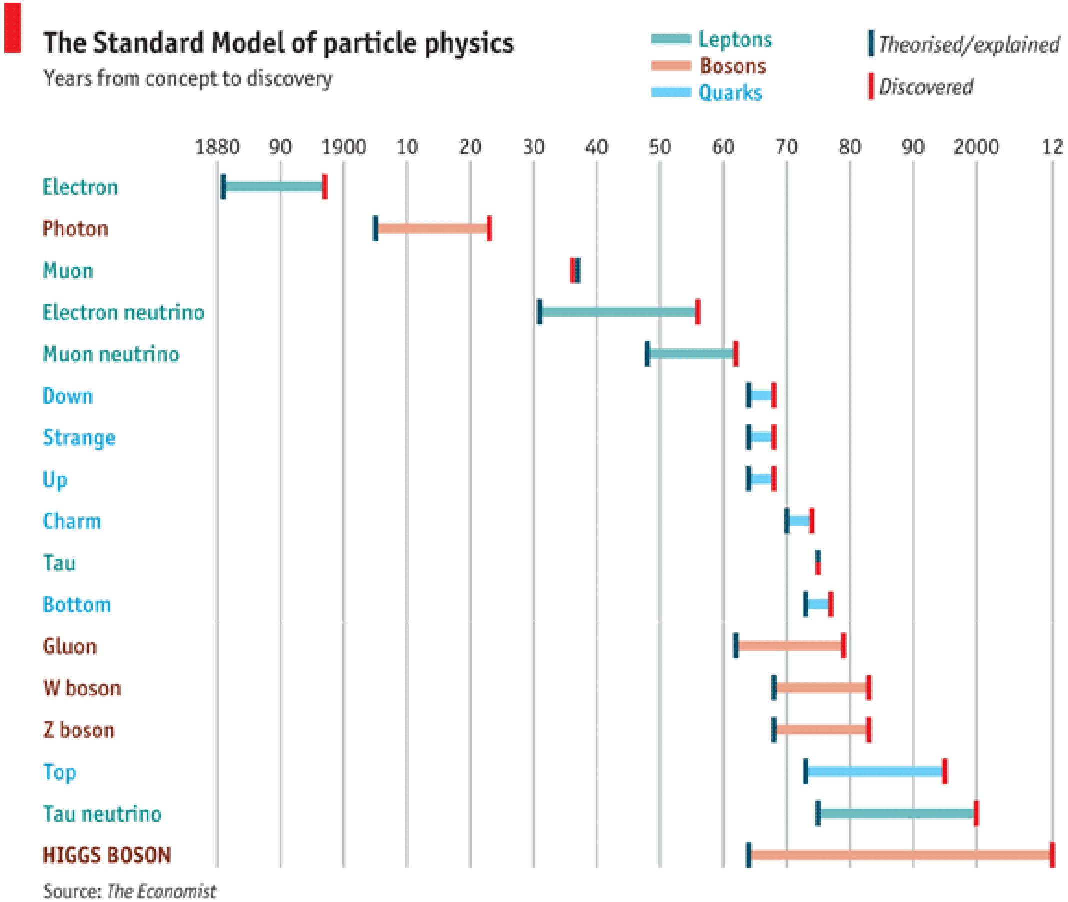
Trieste, 26-31 August 2013

LHC Integrated luminosity 2010-2012



- 2010: **0.04 fb^{-1}**
  - $\sqrt{s}$ = 7 TeV
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - $\sqrt{s}$ = 7 TeV
  - … exploring the limits
- 2012: **23 fb^{-1}**
  - $\sqrt{s}$ = 8 TeV
  - … production

We have entered the LHC era!



After the discovery of the Higgs boson what next?
No direct evidence of physics beyond the standard model until now
What are the consequences for Dark Matter searches?

On the other hand, searching for susy dark matter is not for the faint of heart…

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Particle physics

The dark at the end of the tunnel?

Evidence for the existence of dark matter begins to stack up

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LHC results put supersymmetry theory 'on the spot'

By Pallab Ghosh
Science correspondent, BBC News

Results from the Large Hadron Collider (LHC) have all but killed the simplest version of an enticing theory of sub-atomic physics.

Hot issues in the Dark Matter business today

- DAMA and CoGeNT modulations
- CoGeNT and CRESST spectral "excesses"
- 3-event "excess" in CDMS-Si
- Constraints from XENON, CDMS (Ge –low)
- KIMS bound on WIMP-Iodine cross section
- A SM-like Higgs with m_H~125 GeV: can it be relevant for DM searches?
- Light neutralinos in effective MSSM: are they still viable?

The WIMP low-mass region of direct detection experiments is getting ever more crowded…

Upper bounds:

CDMS-Si (2008+2013)

CDMS-Si (2013)

CDMS-Ge(low threshold)

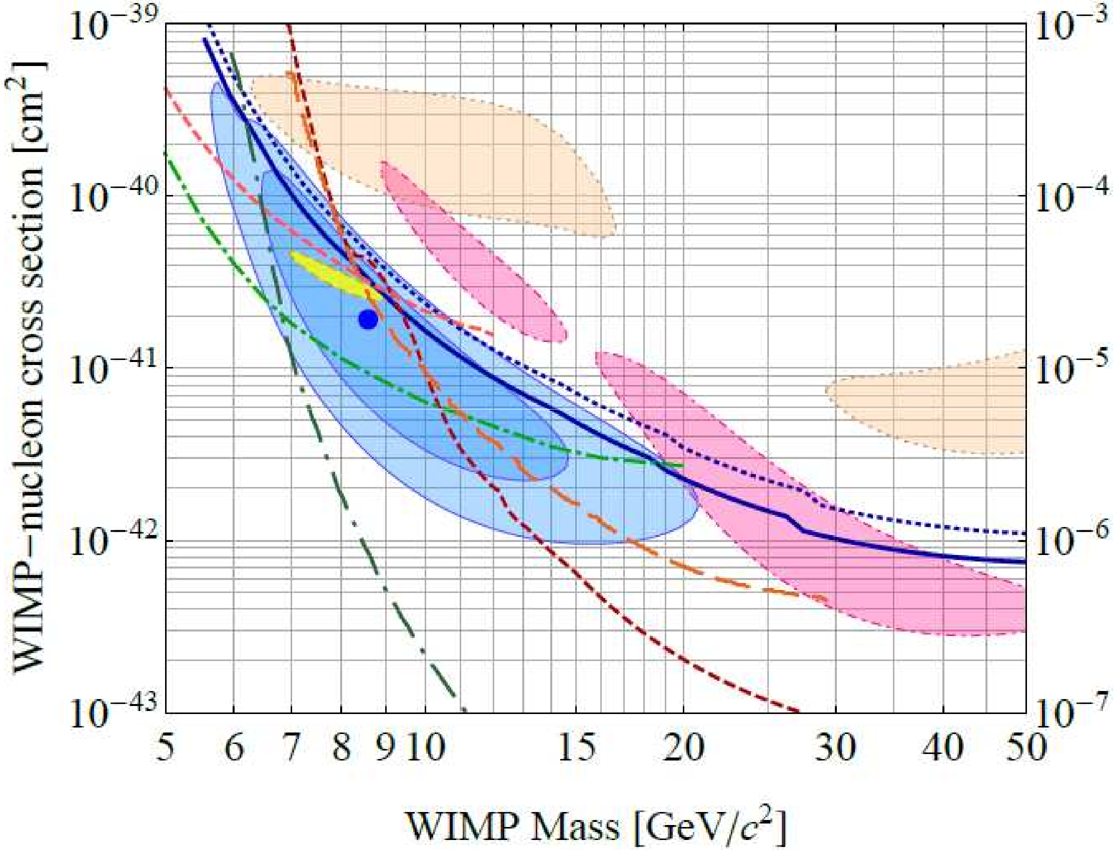
CDMS-Ge(high threshold)

Edelweiss

XENON100

XENON10 (S2 only)

(Updated to May 2013)



Possible signal regions:

DAMA/LIBRA

CoGeNT

CRESST

CDMS-Si

Interestingly, all signal regions qualitatively in the same ball-park
But at face value they are inconsistent to some of the upper bounds

Effective MSSM scheme (effMSSM) – Independent parameters

- M_1 U(1) gaugino soft breaking term
- M_2 SU(2) gaugino soft breaking term
- M_3 SU(3) gaugino soft breaking term
- μ Higgs mixing mass parameter
- $\tan\beta$ ratio of two Higgs v.e.v.'s
- m_A mass of CP odd neutral Higgs boson (the extended Higgs sector of MSSM includes also the neutral scalars h, H, and the charged scalars $H^{\pm}$)
- $m_{\tilde{q}}$ soft mass for squarks of the first two families
- $m_{\tilde{t}}$ soft mass for squarks of 3° family
- $m_{\tilde{l}}$ soft mass common to all sleptons
- A common dimensionless trilinear parameter for the third family ($A_{\tilde{b}} = A_{\tilde{t}} \equiv Am_{\tilde{q}}$; $A_{\tilde{\tau}} \equiv Am_{\tilde{l}}$)
- $R \equiv M_1/M_2$

SUGRA$\rightarrow R=0.5$

Can the neutralino be *light*?

Lower limits on the neutralino mass from accelerators

❒ Indirect limits from chargino production ($e^+e^- \to \chi^+\chi^-$):

$$m_{\chi^\pm} \gtrsim 100 \text{ GeV} \Rightarrow m_\chi \gtrsim 50 \text{ GeV} \quad \text{if} \quad R \equiv \frac{M_1}{M_2} = \frac{5}{3}\tan^2\theta_w$$

❒ Direct limits from $e^+e^- \to \chi_0^i \chi_0^j$ $\quad (\chi_0^1 \equiv \chi,\, m_{\chi_0^1} < m_{\chi_0^2} < m_{\chi_0^3} < m_{\chi_0^4})$ †:

- ➥ Invisible width of the Z boson (upper limit on number N_ν of neutrino families)
- ➥ Missing energy + photon(s) or $f\bar{f}$ from $\chi_0^{i>1} \to \chi_0^1$ decay

❒ Direct limits from $\tilde{t} \to c\,\chi$ and $\tilde{b} \to b\,\chi$ at Tevatron ‡

† small production cross sections

‡ light squark masses ($\lesssim 100$ GeV) required

$$\boxed{\text{➠ No absolute direct lower bounds on } m_\chi}$$

Neutralino – nucleon cross section

(A.Bottino, F.Donato, N.Fornengo and S.Scopel, PRD69,037302 (2004))

Color code:

● $\Omega_\chi h^2 < 0.095$

× $\Omega_\chi h^2 > 0.095$

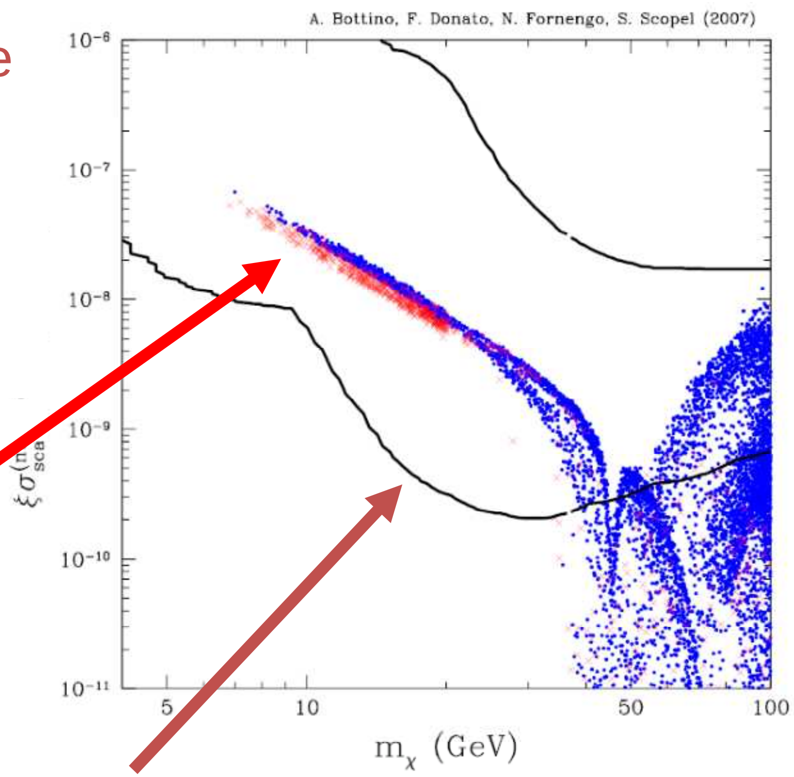
tight correlation between relic abundance and χ-nucleon cross section:

$$\Omega_\chi h^2 \leq (\Omega_{CDM} h^2)_{max}$$

$$\sigma^{(\mathrm{nucleon})}_{\mathrm{scalar}} \gtrsim \frac{10^{-40} cm^2}{(\Omega_{CDM} h^2)_{max}} \frac{\mathrm{GeV}^2}{m_\chi^2\,[1 - m_b^2/m_\chi^2]^{1/2}} \quad \text{for } m_\chi \lesssim 20 \text{ GeV}$$

The elastic cross section is bounded from below

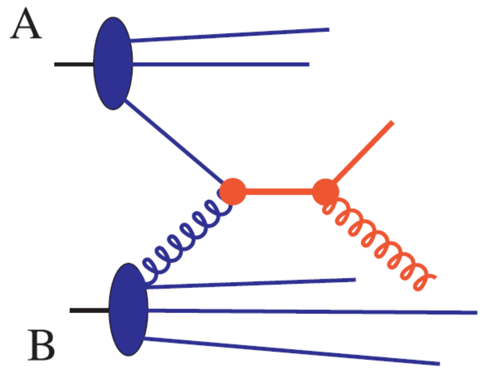
→ "funnel" at low mass



DAMA/NaI modulation region, likelyhood function values distant more than 4 σ from the null result (absence on modulation) hypothesis, Riv. N. Cim. 26 n. 1 (2003) 1-73, astro-ph/0307403

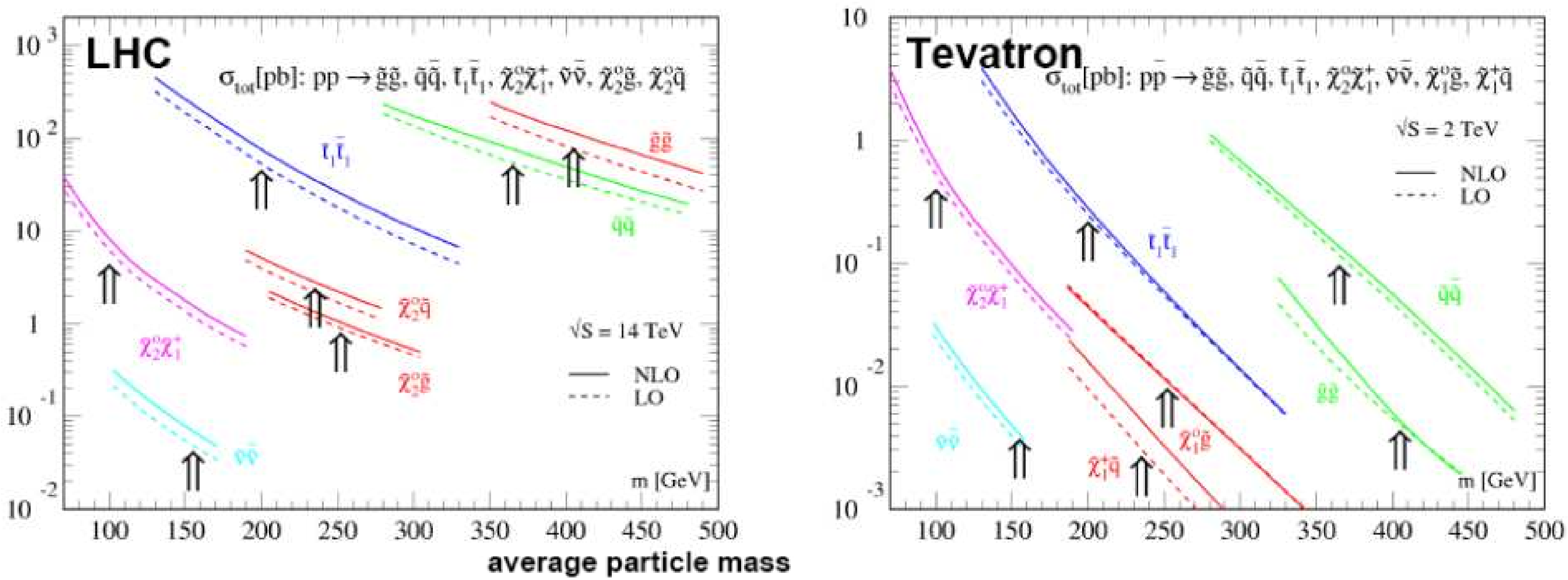
Light relic neutralinos have (roughly) the right mass and cross section to explain DAMA/LIBRA, CoGeNT, CDMS II, CDMS-Si and CRESST

Production of susy particles @ LHC & Tevatron



$$pp, p\bar{p} \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$$

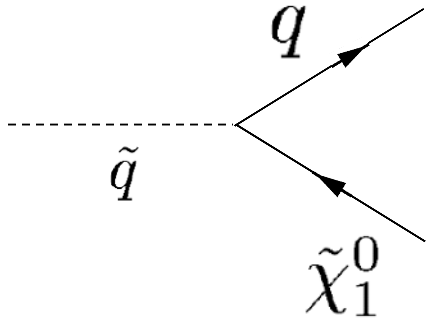
- Cross sections calculated to NLO, typically in pb range at LHC
  - Masses depend on how SUSY is broken, but otherwise, cross section is model-independent
- Production cross section at LHC increases dramatically relative to Tevatron, especially for squark/gluino



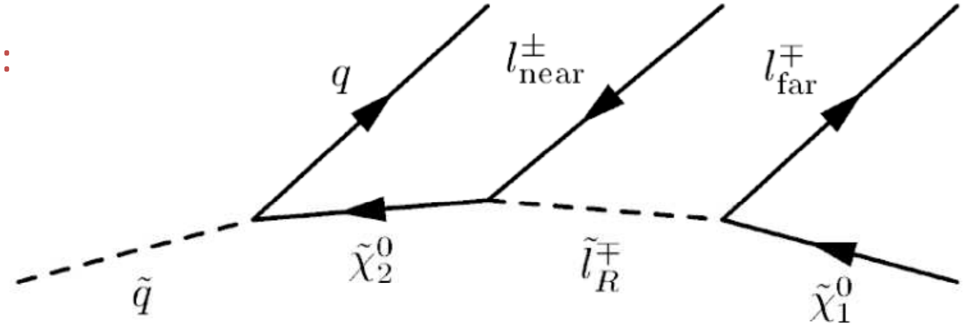
[Prospino]

The fate of a squark…

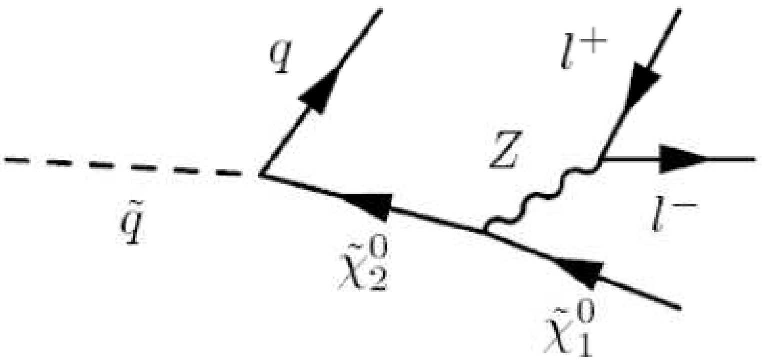
direct decay to a neutralino:
(early discovery channel, easy to see if kinematically accessible (acoplanar jets+missing energy)

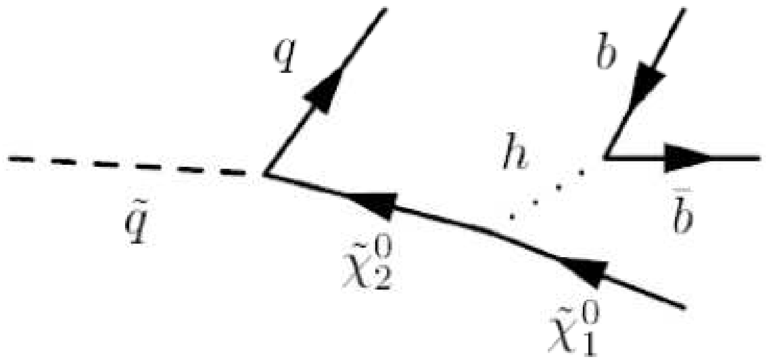


“sequential” chain through sleptons:



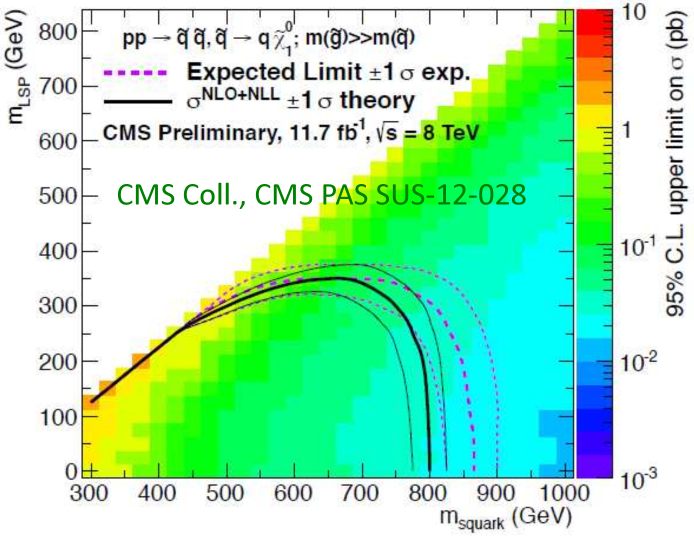
“branched” chain through gauge and Higgs bosons:



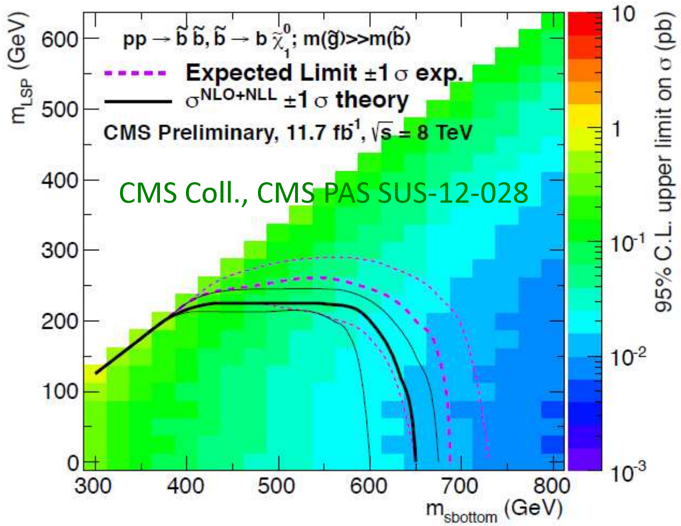


LHC bounds constrain gluino and squark masses

squarks of first two families

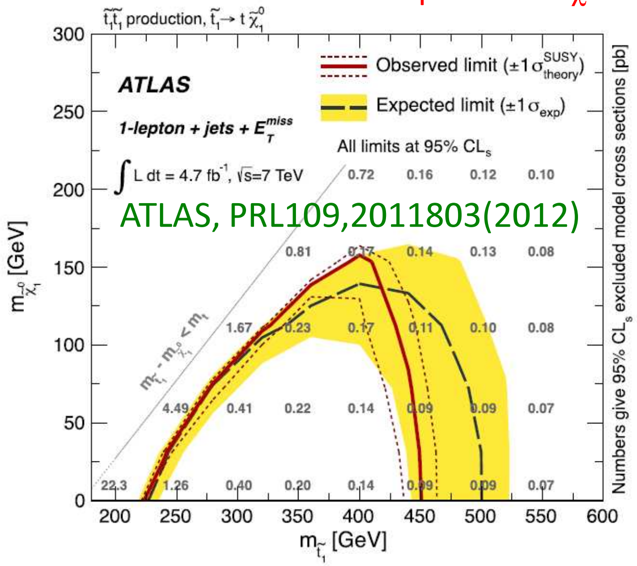


sbottom

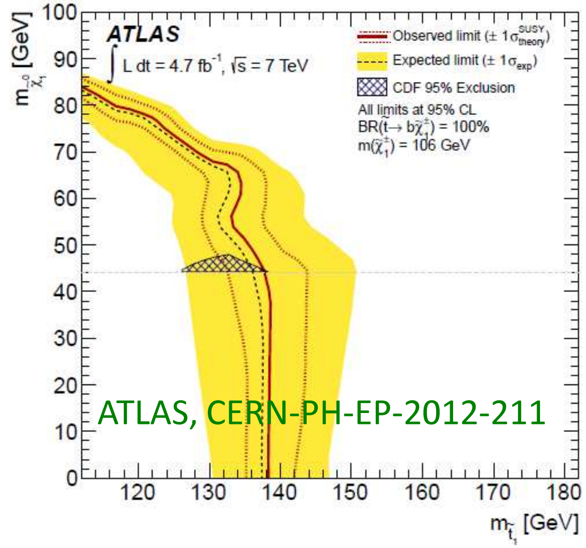


(“simplified model”, valid for decoupled gluino, $M_3 >> m_{squark}$)

heavy stop ($m_{stop} > m_t + m_\chi$)

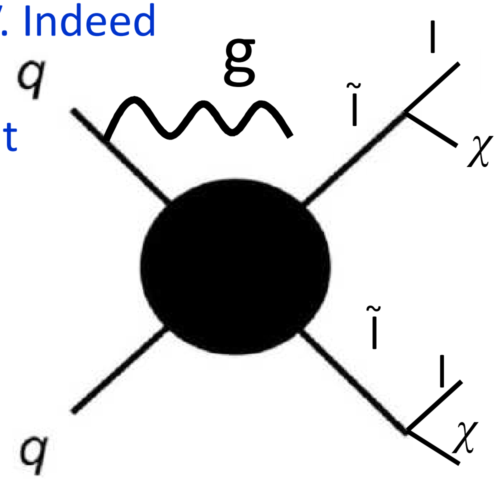


light stop ($m_{stop} < m_t + m_\chi$)

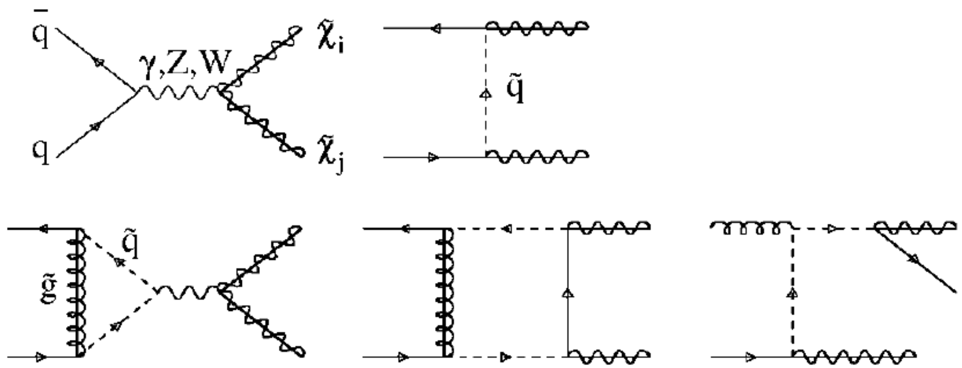


In light of the stringent bounds from the LHC in the following we will assume that M_3 (gluino mass) and m_q (soft mass for the first two families) are heavy.
N.B. bounds on sbottom and stop are less constraining because the top and bottom flavours are scarce in the proton.

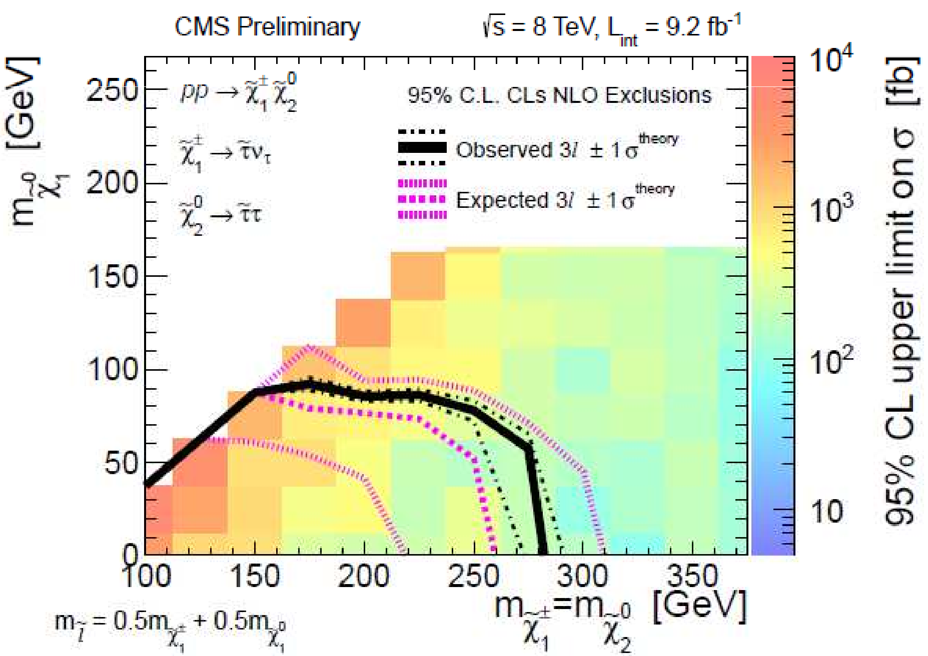
For the lower bound on the slepton masses we used the LEP values $m_{slepton}$ *> 80-100 GeV (depending on flavour). These* lower bounds actually depend on the condition that $m_{slepton} - m_{\chi} >$ O(3-15) GeV. If these conditions are not met, it has been claimed by C. Boehm et al.,(arXiv:1303.5386) that the slepton lower bound can decrease to about 40 GeV. Indeed this may have relevant implications for the neutralino phenomenology (but what about monojet+missing energy bounds?)



Bounds on Electro-Weak production of neutralinos and charginos



N.B. if squarks of the first two families and gluinos are heavy only the first diagram contributes



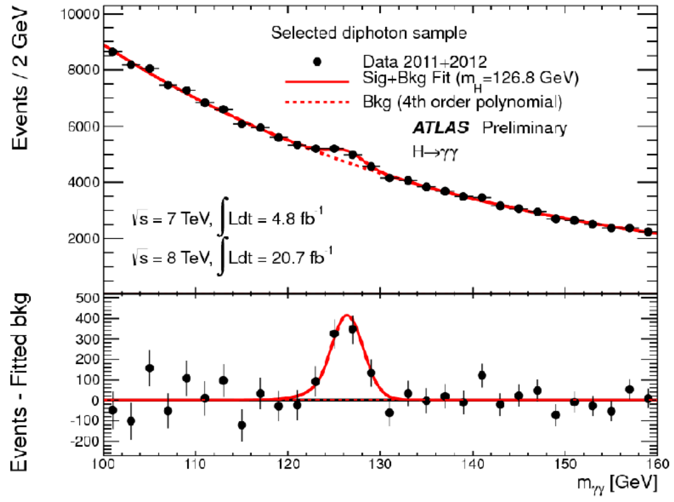
CMS-SUS-12-022

τ-dominated scenario, compatible with next-to-lightest neutralinos and lightest chargino of higgsino type

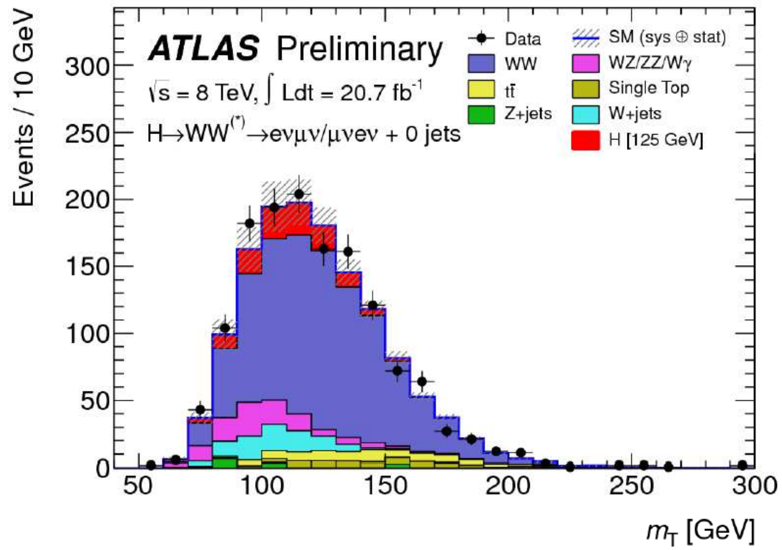
$|\mu|>280$ GeV

Implications of Higgs discovery

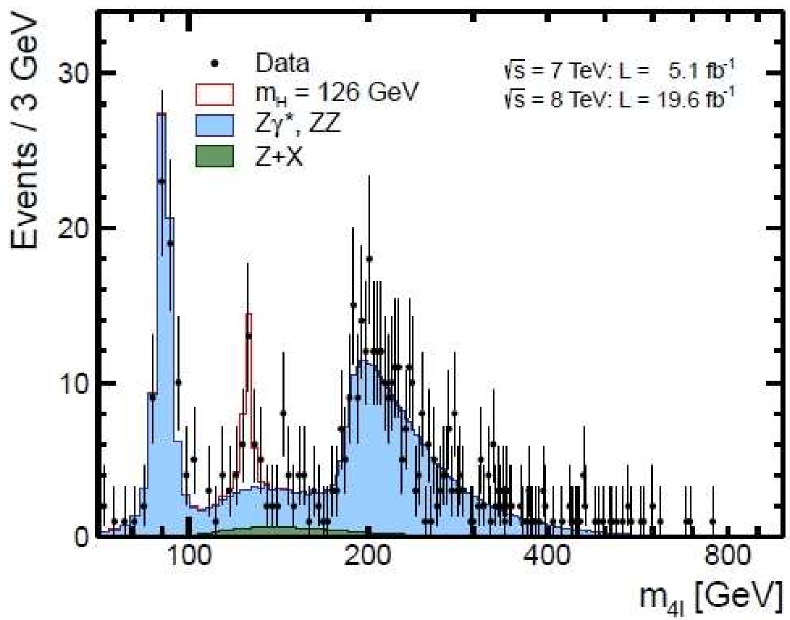
H->γγ



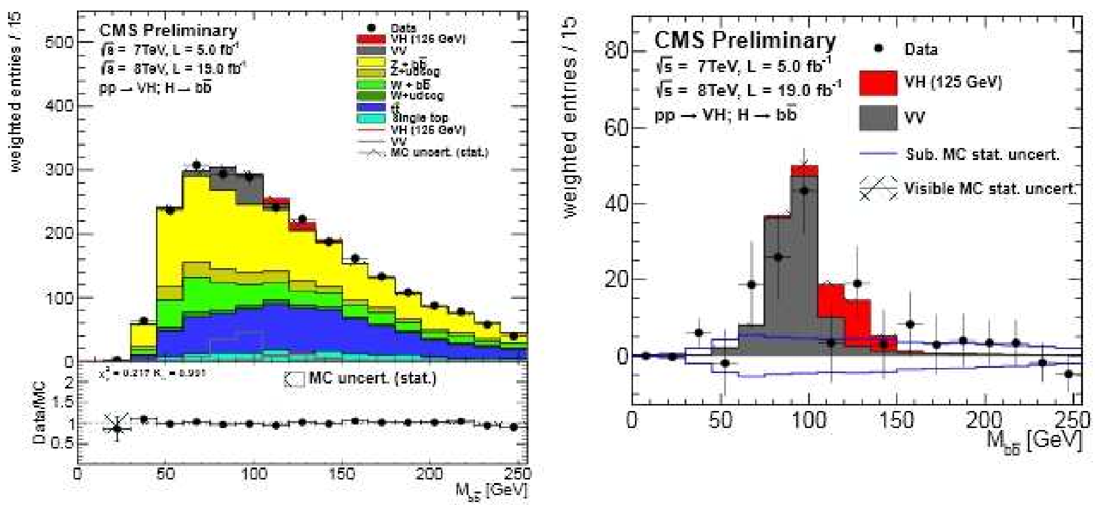
H->WW



H->ZZ

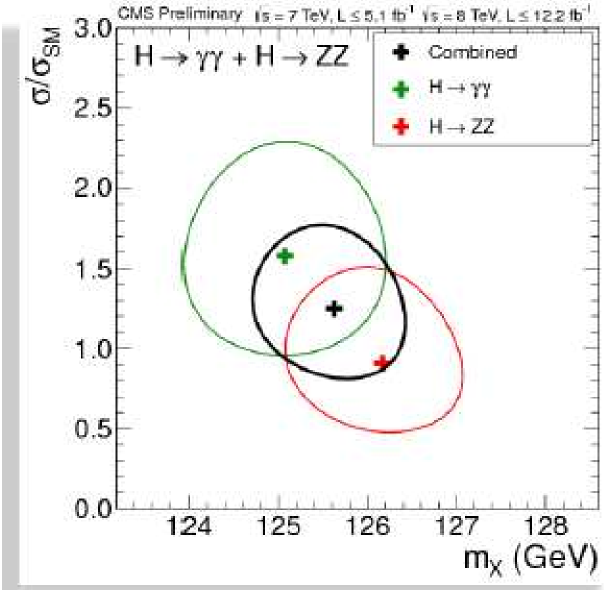


H->bb

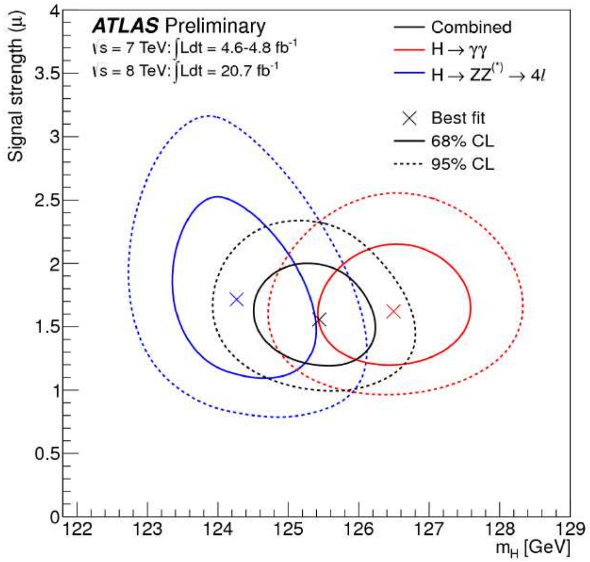


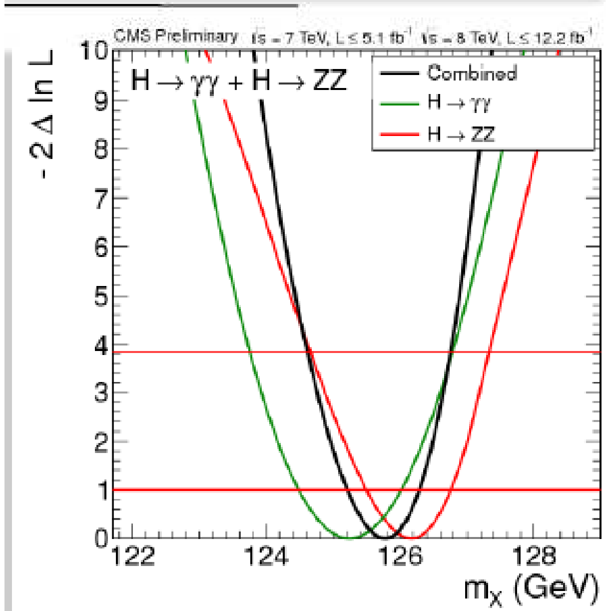
The Higgs mass after Moriond 2013

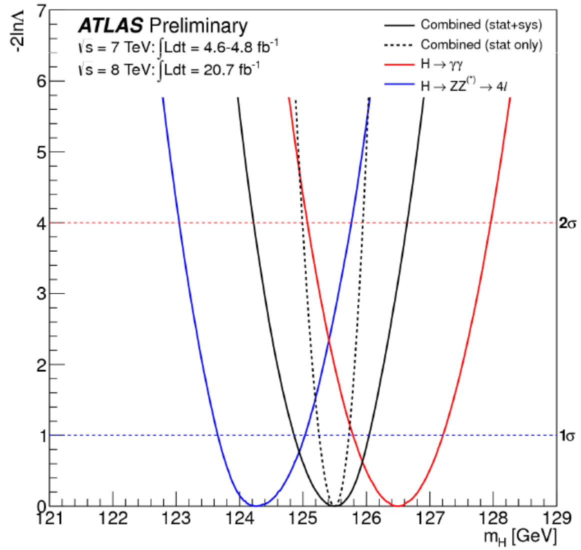
CMS



ATLAS







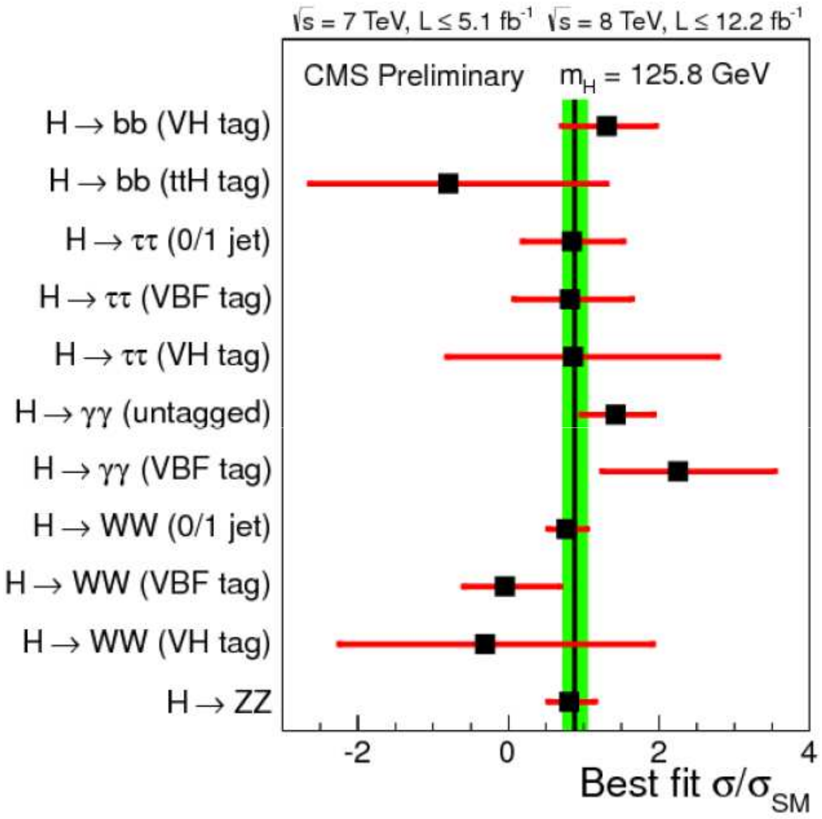
m_H = 125.8 +/- 0.4 (stat) +/- 0.4 (syst) GeV

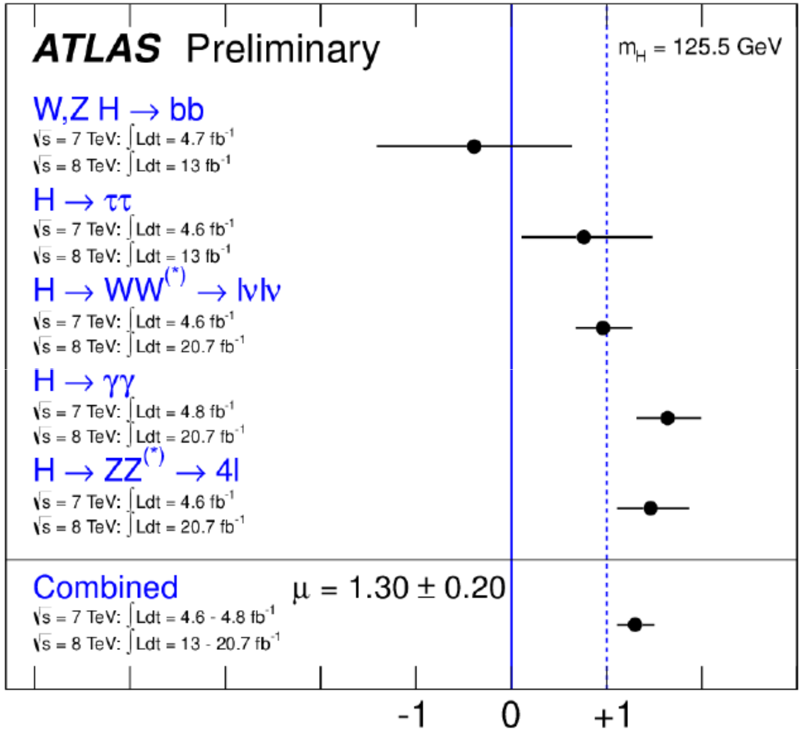
$m_H = 125.5 \pm 0.2\ (\mathrm{stat})\ ^{+0.5}_{-0.6}\ (\mathrm{sys})$ GeV

A. Whitbeck, Moriond QCD 2013

T. Adye, Moriond QCD 2013

Signal strengths: $\sigma(pp \to H \to X)_{MSSM} / \sigma(pp \to H \to X)_{SM}$





- Overall agreement with the Standard Model
- Excess in H→γγ?

We used FeynHiggs to calculate the Higgs spectrum and couplings @ two loops

M. Frank, T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak and G. Weiglein, JHEP 0702, 047 (2007) [hepph/0611326];
G. Degrassi, S. Heinemeyer, W. Hollik,P. Slavich and G. Weiglein, Eur. Phys. J. C 28, 133(2003) [hep-ph/0212020];
S. Heinemeyer, W. Hollik and G. Weiglein, Eur. Phys. J. C 9, 343 (1999) [hepph/9812472];
S. Heinemeyer, W. Hollik and G. Weiglein,Comput. Phys. Commun. 124, 76 (2000)[hepph/9812320].

After the Higgs discovery the SUSY the parameter space is restricted because:

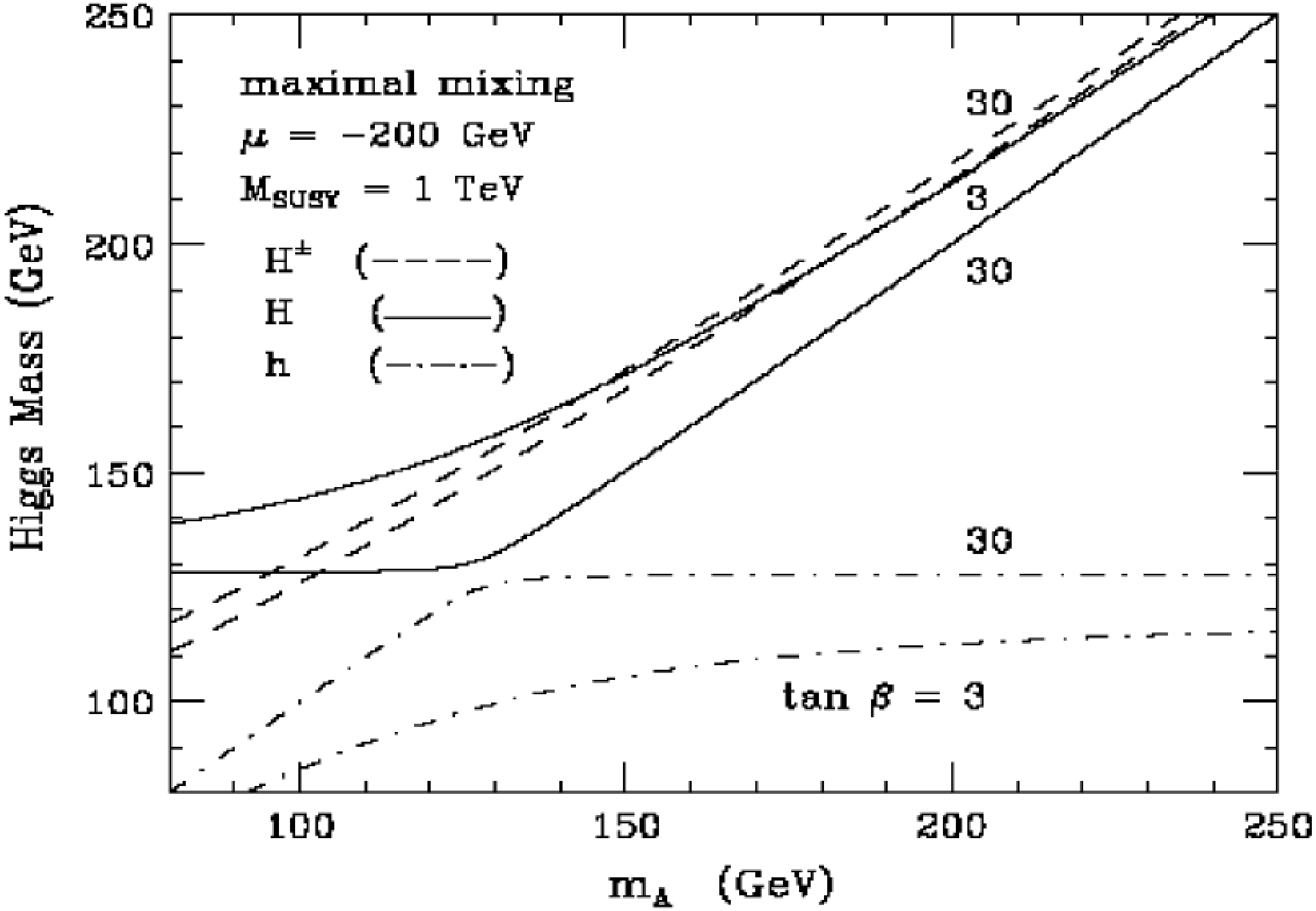
- one of the two the Higgs boson masses is constrained to have mass ~125 GeV and to be Standard-Model like
- the other Higgs boson must be either heavier or lighter. In the latter case it must be very weakly coupled to the Z boson (to evade LEP limits)
- So there are two possibilities: H_{125}=H or H_{125}=h

In light of this we single out two scenarios:

- Scenario I: H_{125}=H (**heavy** Higgs scalar)
- Scenario II: H_{125}=h (**light** Higgs scalar)

Scenario I

Scenario II



$m_h \sim m_A < m_H \sim 125$ GeV

$m_h \sim 125$ GeV $< m_A \sim m_H$

Constraints from signal strengths (abridged…)

•Experimentally slight excess in pp→H→γγ while decays to fermions (b and τ) may possibly be slightly too low.

• a general fit performed in P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein, L. Zeune, arXiv:1211.1955 disfavours production cross sections very different from the standard model ones, so pp→H→γγ is driven by the decay branching ratios

• branching ratios to b and τ fermions are correlated (both down-type) , obviously H→bb dominates

• H→bb and H→γγ are anticorrelated (a small relative decrease in the dominant channel implies a much higher relative increase in subdominant ones and the other way around)

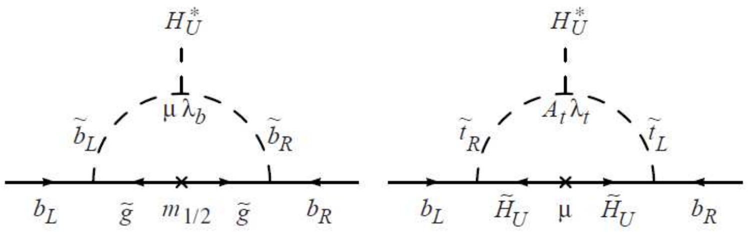
• so in order to boost H→γγ need to suppress H→bb. The corresponding coupling:

$$\frac{g_{hb\bar{b}}}{g_{H_{\rm SM}b\bar{b}}} = \frac{1}{1+\Delta_b}\left(-\frac{\sin\alpha_{\rm eff}}{\cos\beta} + \Delta_b\frac{\cos\alpha_{\rm eff}}{\sin\beta}\right)$$

is suppressed if the correction Δ_b is large and positive

•another mechanism (discussed in M. Carena et al., JHEP 1207 (2012) 175, [arXiv:205.5842]; JHEP 1203 (2012) 014, [arXiv:1112.3336]) is through light sleptons (light squarks modify also the gluon fusion rate, with a compensating effect between the production cross section and the decay branching ratio) → modify $\alpha_{\rm eff}$

Constraints from signal strengths (abridged…)



L. J. Hall, R. Rattazzi, and U. Sarid, Phys. Rev. D50 (1994) 7048–7065, [hep-ph/9306309];

Through a sbottom/gluino or a stop/higgsino loop the bottom quark couples to the “wrong” Higgs doublet through the effective lagrangian:

$$h_b H_1^0 b\bar{b} + \Delta h_b H_2^0 b\bar{b}$$

so the relation between Yukawa coupling and mass is modified:

$$h_b \to \frac{m_b}{v}\frac{1}{1+\Delta_b}\tan\beta \qquad \left(\Delta_b = \frac{\Delta h_b}{h_b}\tan\beta\right)$$

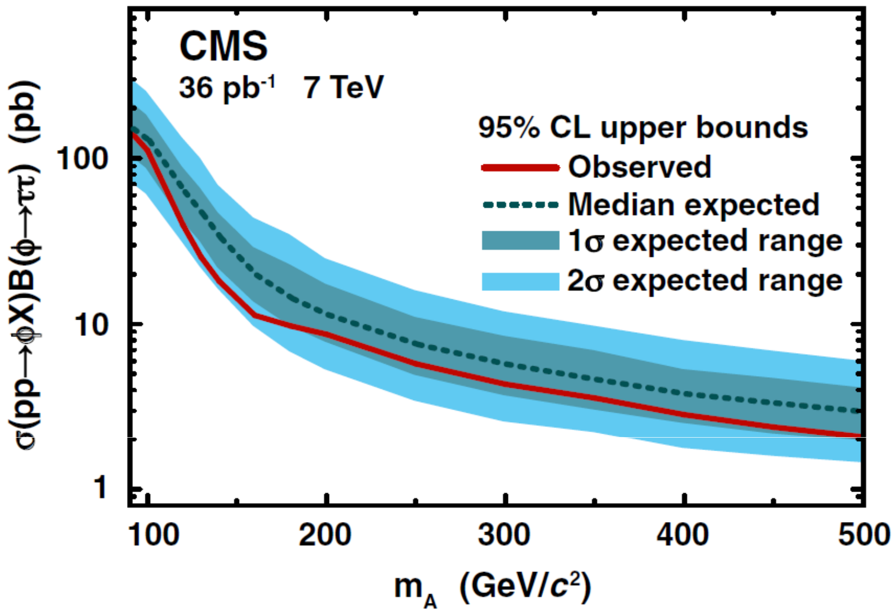
$$\Delta_b = \frac{2\alpha_s}{3\pi} M_3 \mu \tan\beta I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, M_3) + \frac{h_t^2}{16\pi^2}\mu A_t \tan\beta I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)$$

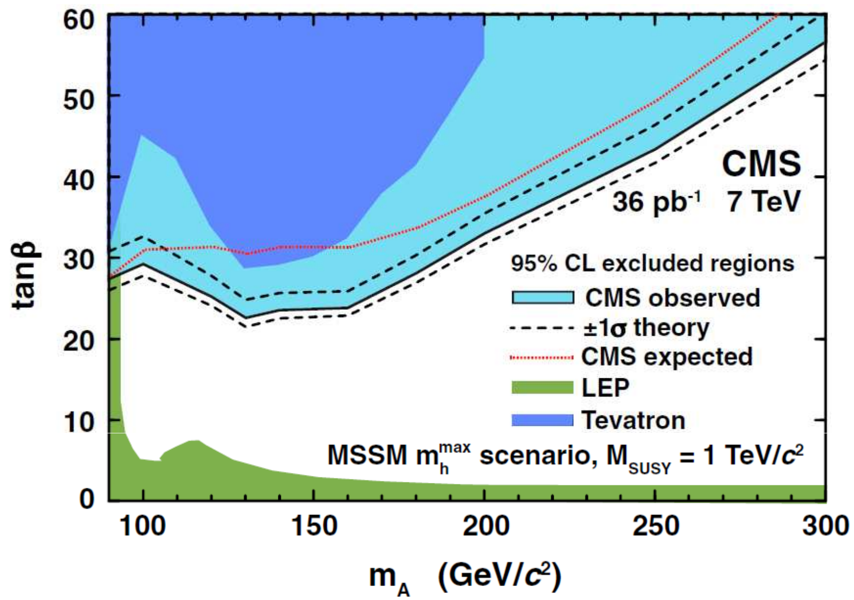
$$I(a,b,c) = \frac{1}{(a^2-b^2)(b^2-c^2)(a^2-c^2)}\left(a^2b^2\log\frac{a^2}{b^2} + b^2c^2\log\frac{b^2}{c^2} + c^2a^2\log\frac{c^2}{a^2}\right)$$

→ to get a large Δ_b need large μ

Actually, the $H \to \tau\tau$ channel strongly constrains the low m_A scenario

S. Chatrchyan et al.(CMS Collaboration), PRL 106, 231801 (2011)



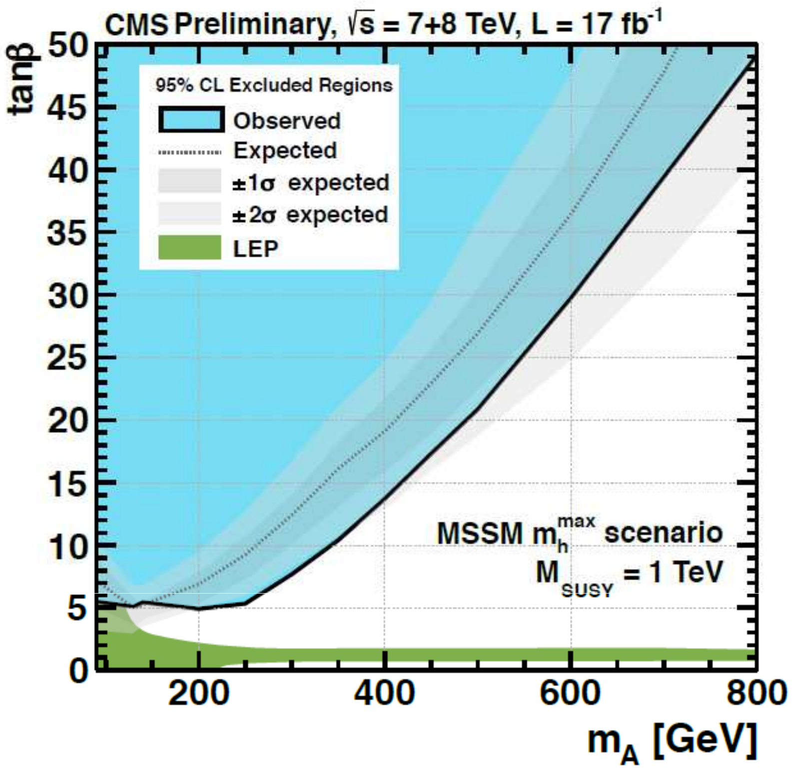


Upper bound on production cross section converted into a constraint on tanβ vs m_A in the m_h^{max} scenario:

$\boxed{\mu=200 \text{ GeV}, X_t=2000 \text{ GeV}, M_2=200 \text{ GeV}, M_3=800, M_{SUSY}=1000 \text{ GeV}}$

To get the limit in a scenario different from m_h^{max} (in particular with large μ) need to recalculate the production cross section and compare it directly to the corresponding upper bound

Latest bound on H→ττ much more constraining (tanβ<5 at low m_A)



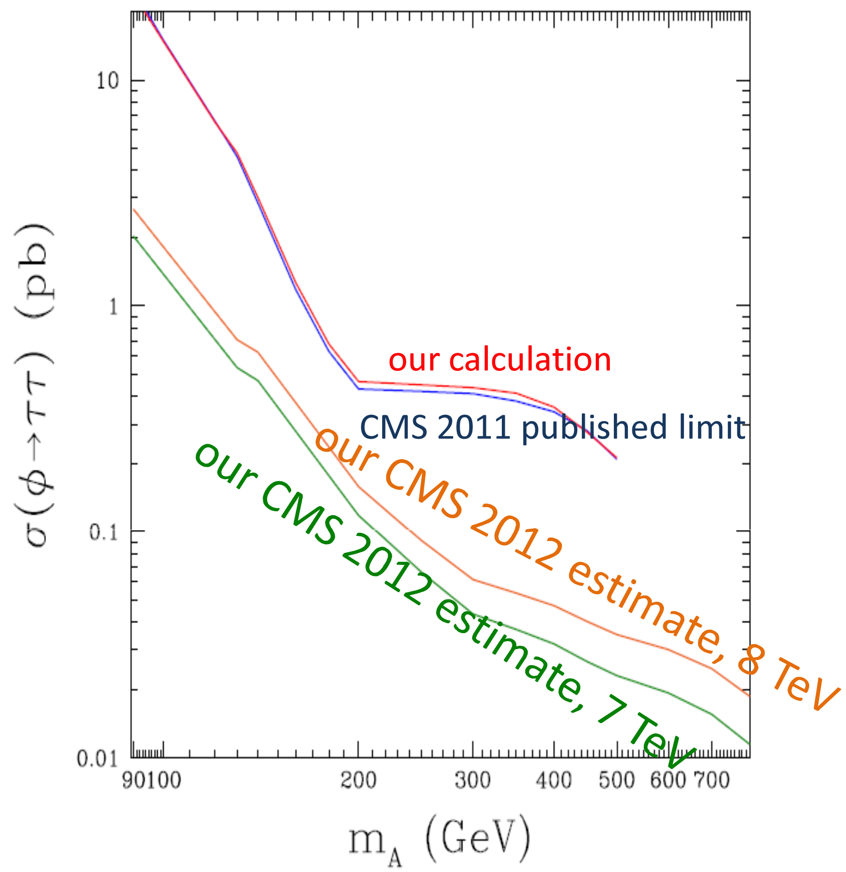
CMS PAS HIG-12-050

This bound is particularly severe for low-mass relic neutralinos because a large value of tanβ is instrumental in enhancing the annihilation cross section (keeping the relic density in the observational range) and the neutralino-nucleon cross section (explaining DAMA, CoGeNT, CDMS-Si, CRESST)

<u>However, CMS does not provide the corresponding upper bound on the production cross section</u>

Since this bound is particularly important, to estimate it we adopted inverse engineering…

We reproduced the 2011 CMS limit in the m_h^{max} scenario by calculating $\sigma(\Phi \rightarrow \tau\tau)$ with m_A and tanβ taken from the CMS upper bound curve

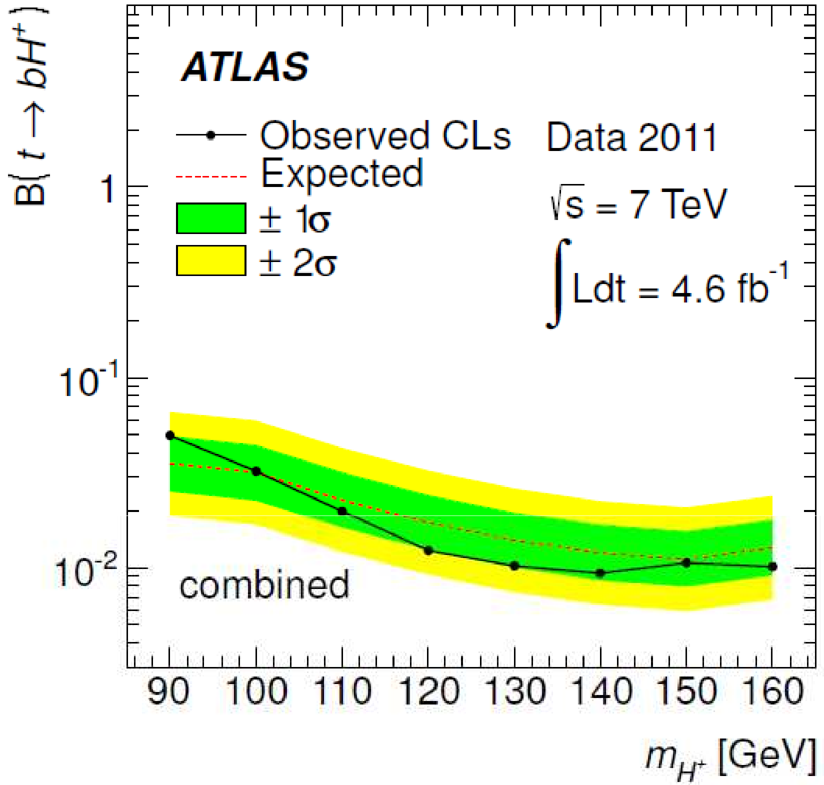


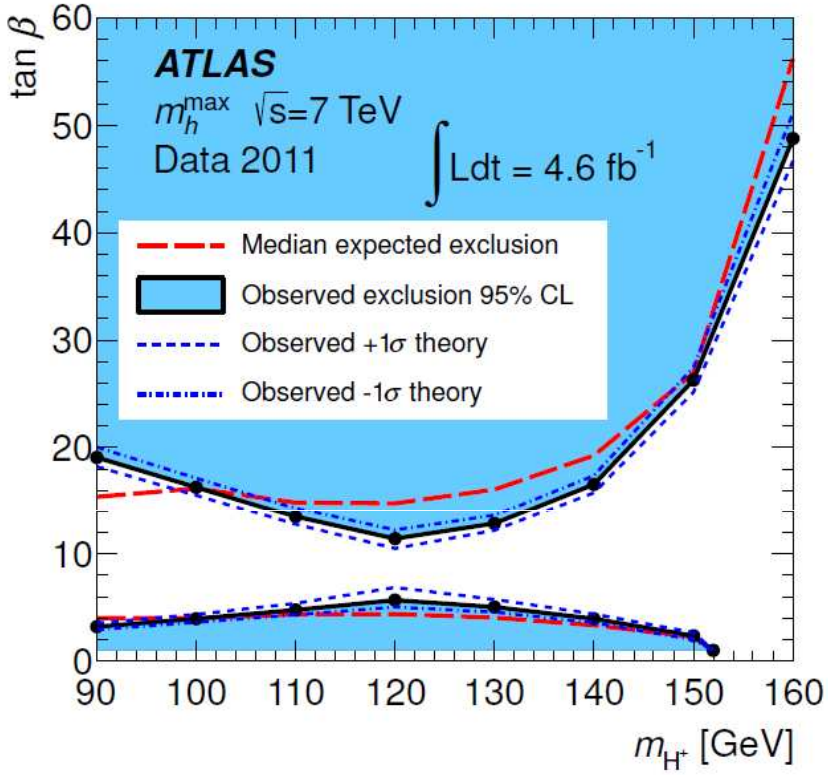
We then estimated the *new* bound on $\sigma(\Phi \rightarrow \tau\tau)$ by repeating the exercise with m_A and tanβ taken from the 2012 CMS constraint curve → the limit on the cross section can now be compared to the theoretical expctation in scenarios which are different from m_h^{max}

N.B. don't know how to combine 7 TeV and 8 TeV data, since the 2012 CMS data combine 4.9 fb^{-1} at 7 TeV and 12.1 fb^{-1} at 8 TeV we adopted the 8 TeV curve

In Scenario I the charged Higgs is light and the decay t→H⁺b is kinematically allowed

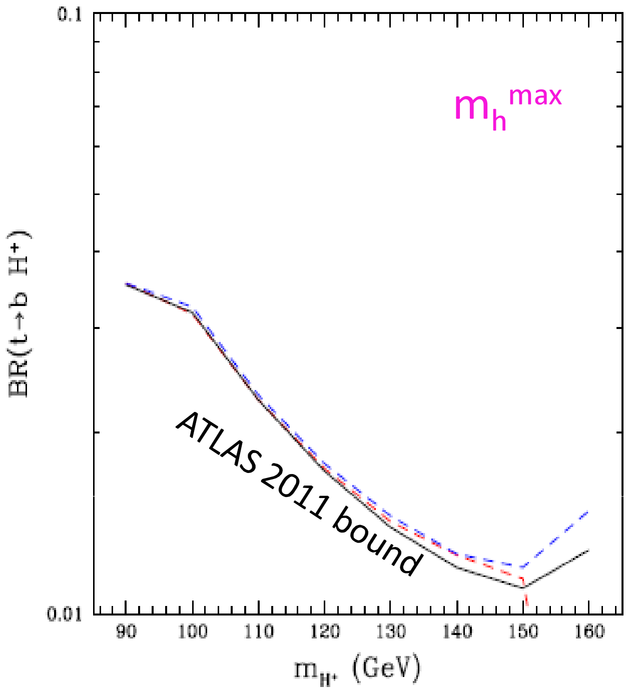
G. Aad et al.[ATLAS Collaboration], JHEP 1206, 039 (2012) [arXiv:1204.2760 [hep-ex]].





- Again, the bound on $\tan\beta$ is given in the m_h^{max} scenario, need to recalculate it for an arbitrary choice of parameters
- N.B. also a *lower* bound on $\tan\beta$, parameter space shrinks at small m_A !

As before we recalculate the branching ratio $t \to H^+ b$ in the m_h^{max} scenario and compare it to the limit published by ATLAS (N.B. now there are two curves, one for the upper bound on tanβ and the other for the lower bound)



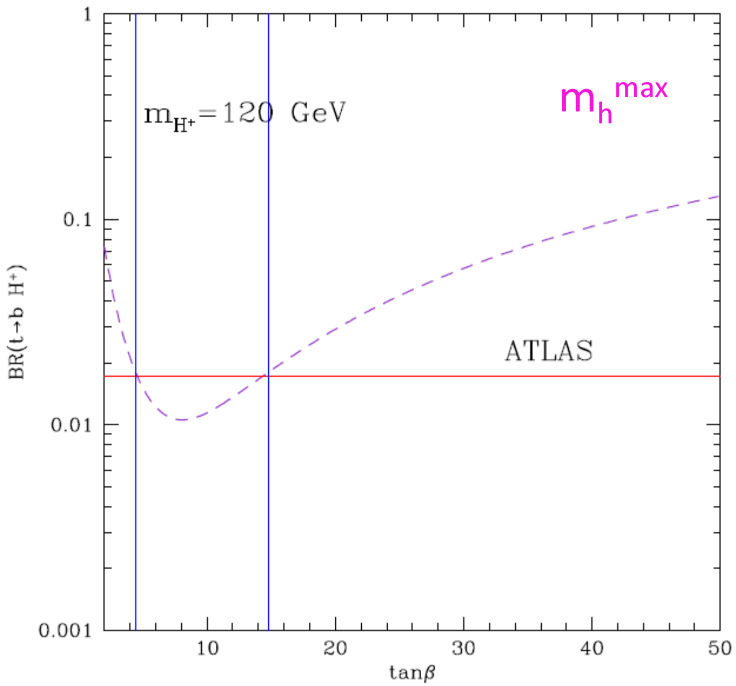
Our estimate upper bound

Our estimate lower bound

$$\Gamma^{tree}(t \to b\, H^+) \;=\; \frac{g^2}{64\pi M_W^2} |V_{tb}|^2 m_t^3\, \lambda^{1/2}\,(1, q_{H^+}, q_b) \times \Big[(1 - q_{H^+} + q_b) \left(\cot^2\beta + q_b \tan^2\beta\right) + 4\, q_b \Big]$$

$$q_{b,H^+} \;=\; m^2_{b,H^+}/m_t^2,\;\; r_{b,t} \;=\; m^2_{b,t}/M^2_{H^+}$$

$$\lambda\,(1, x, y) = 1 + x^2 + y^2 - 2\,(x + y + x\, y)$$



The $B_s \to \mu\mu$ decay

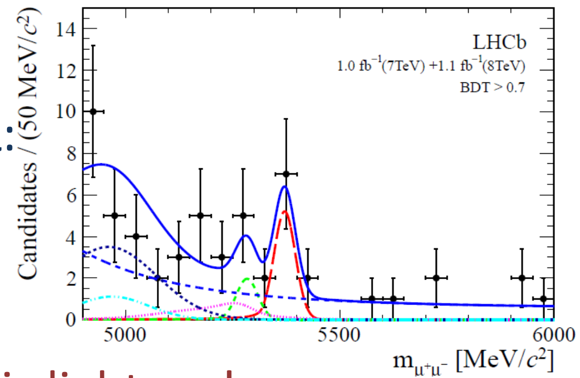
First evidence for the decay $Bs \to \mu\mu$:

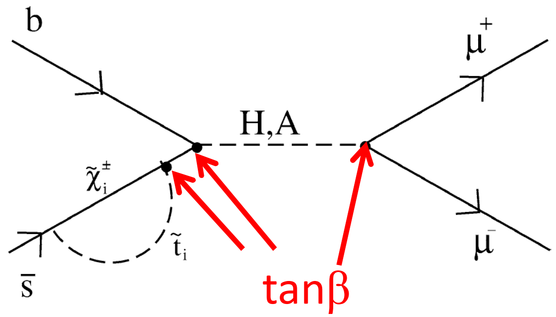
$1.1\times10^{-9} < BR(Bs \to \mu\mu) < 6.4\times10^{-9}$

Compatible with SM expectation:

$BR(Bs \to \mu\mu) \sim 3\times10^{-9}$

Important constraint whenever m_A is light and $\tan\beta$ is large, as in the light neutralino model, since $BR(Bs \to \mu\mu)\ \alpha\ \tan\beta^6/m_A^4$





Example of diagram proportional to $\tan\beta^3$

Dominant term:

$$BR^{(6)}(B_s \to \mu^+\mu^-) \simeq 5.8\times10^{-8}\left(\frac{14\,A\,m_t\,m_{\tilde{q}}}{m_{\tilde{q}}^2+m_t^2}\right)^2\left(\frac{m_{\chi^\pm}}{110\text{ GeV}}\right)^2\left(\frac{90\text{ GeV}}{m_A}\right)^4\left(\frac{\tan\beta}{35}\right)^6$$

To pass the constraint need:

- chargino of higgsino type to be light → small μ or
- trilinear coupling A to be small (leading to stop-quark degeneracy) and respecting the hierarchy :

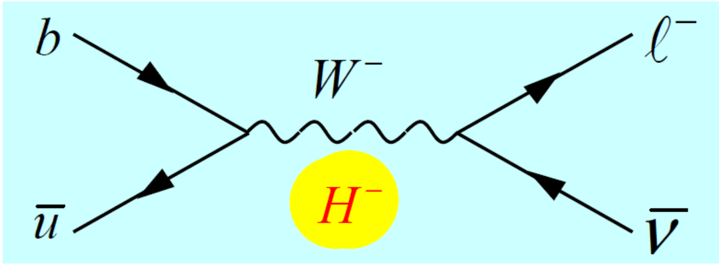
$$\frac{|\mu|}{m_{\tilde{q}}\ \tan\beta} \ll |A| \ll \frac{m_{\tilde{q}}}{m_t}$$

or

- small tanβ

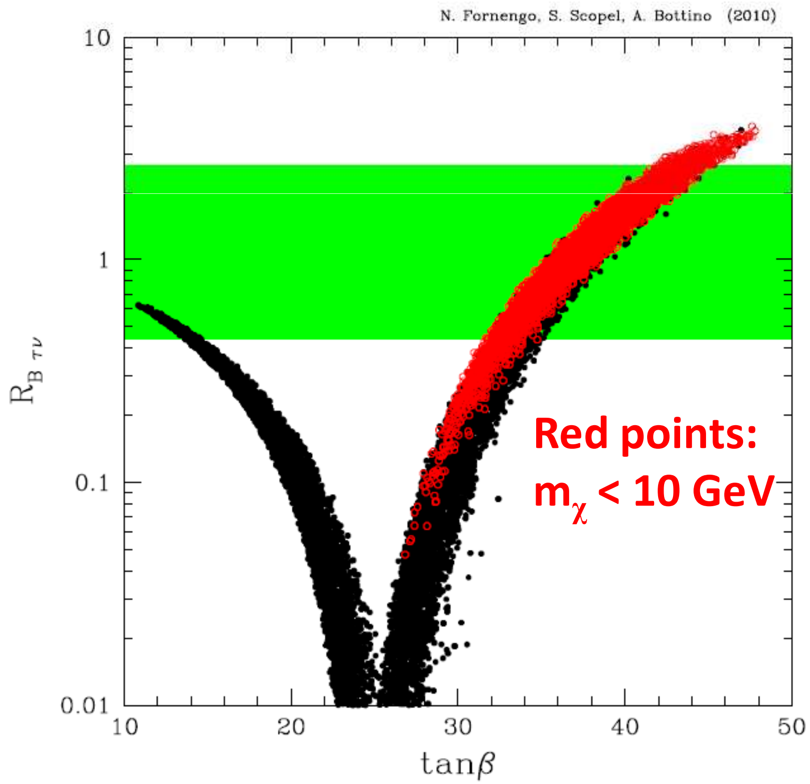
Fornengo, Scopel, Bottino, PRD 83, 015001 (2011)[arXiv:1011.4743]

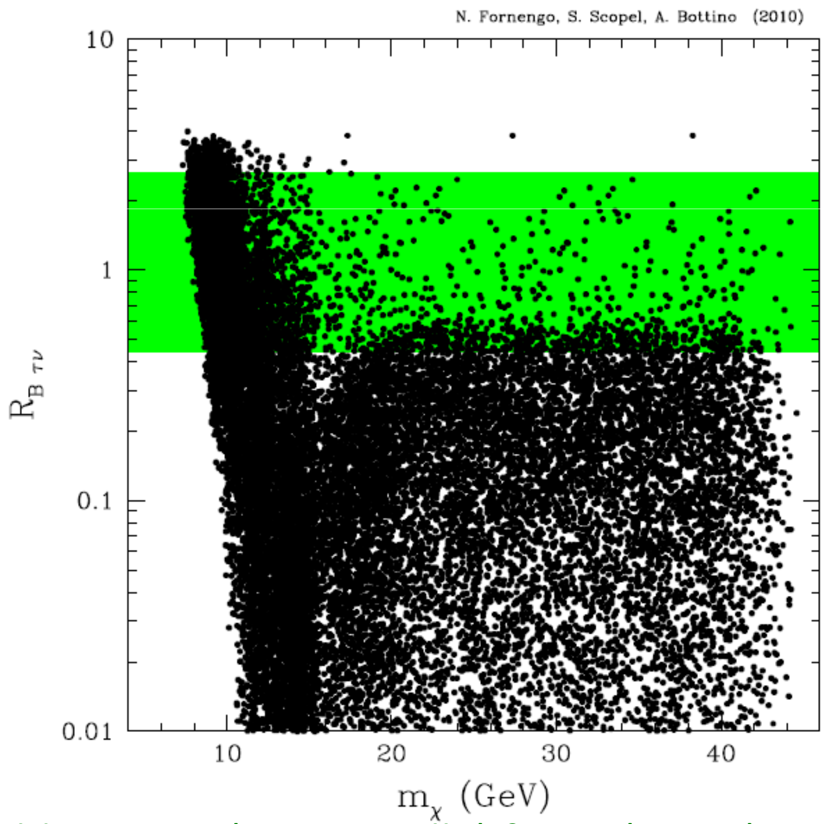
B-meson decays are sensitive to susy particles (charged Higgs, tanβ and susy corrections to the Higgs coupling)



$$R_{B\tau\nu} \equiv \frac{BR_{\rm tot}(B \to \tau\nu)}{BR_{SM}(B \to \tau\nu)}$$

B→τν

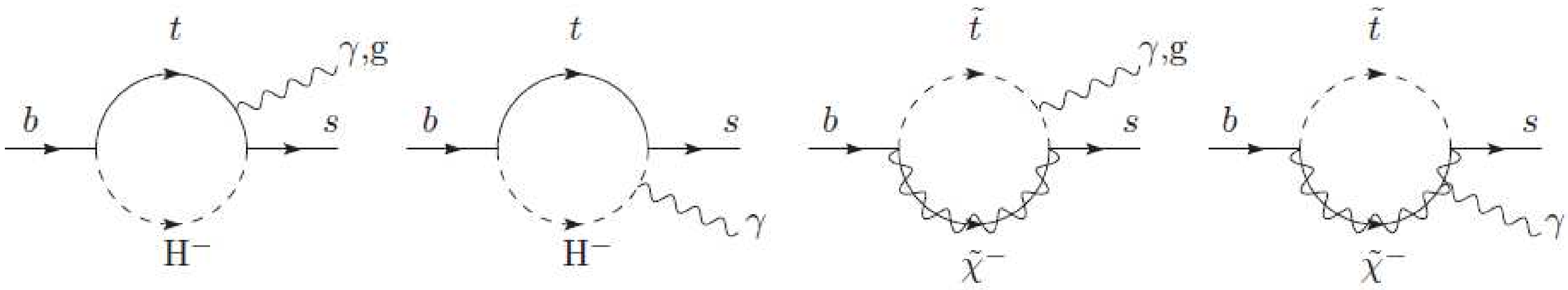




Allowed interval for $R_{B\tau\nu}$ based on world average (BaBar+Belle) for BR(B→τν)

Fornengo, Scopel, Bottino, PRD 83, 015001 (2011)[arXiv:1011.4743]

$b \to s\gamma$ decay



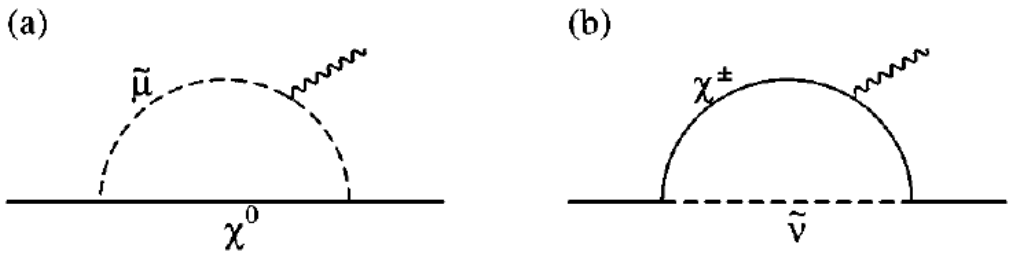
$2.89 \times 10^{-4} < BR(b \to s\gamma) < 4.21 \times 10^{-4}$

N.B. In Scenario I m_A is light so also $m_{H^\pm}^2 \simeq m_A^2 + m_W^2$ is light

Then the loop with a top quark and a charged Higgs must be canceled by the loop with a stop and a chargino → need a light chargino of higgsino type, i.e. $|\mu|$ should be small. However this is not possible because otherwise $pp \to H \to \gamma\gamma$ is too small

Tension in Scenario I between $pp \to H \to \gamma\gamma$ and $b \to s\gamma$

Muon g-2



$$3.1 \times 10^{-10} \leq \Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{theory} \leq 47.9 \times 10^{-10}$$

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

Largest uncertainty is in the determination of the Standard Model hadronic contribution

Large for light sleptons , dominant SUSY contributions proportional to μ tanβ

→light sleptons and large |μ| lead to large muon g-2

Scenario I: parameter scan

H_{125}=H (heavy scalar)

Optimized parameter scan with:

$$123 \text{ GeV} \leq m_{H_{125}} \leq 129 \text{ GeV}$$

(include ~2 GeV theoretical uncertainty)

Scenario I	
$\tan\beta$	$(4,\ 6)$
μ	$(1800,\ 2000)$ GeV
M_1	$(40,\ 80)$ GeV
M_2	$(180,\ 800)$ GeV
M_3	~ 2000 GeV
$m_{\tilde{q}_{12}}$	$(1400,\ 1600)$ GeV
$m_{\tilde{t}}$	$(1400,\ 1600)$ GeV
$m_{\tilde{l}_{12,L}}, m_{\tilde{l}_{12,R}}$	~ 500 GeV
$m_{\tilde{\tau}_L}, m_{\tilde{\tau}_R}$	$(120,\ 200)$ GeV
m_A	$(100,\ 120)$ GeV
$\|A\|$	$(2.5,\ 2.8)$

S.S., N. Fornengo, A. Bottino, Phys.Rev. D88 (2013) 023506

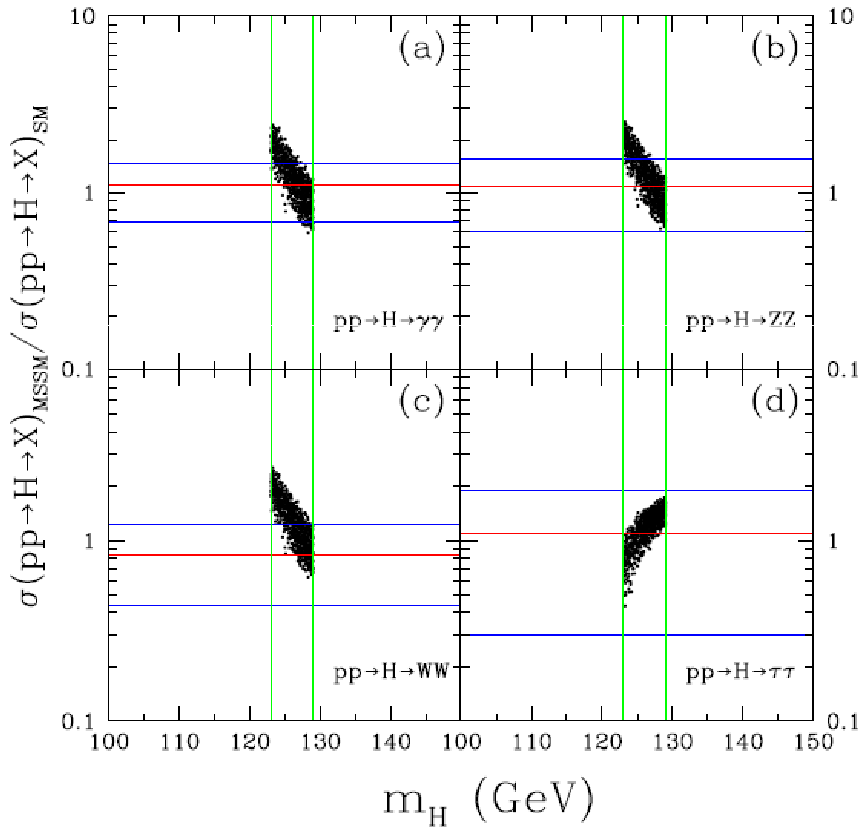
Scenario I: signal strengths

$$R_{\gamma\gamma} = \frac{\sigma(p+p \to H_{125}) BR(H_{125} \to \gamma + \gamma)}{\sigma_{SM}(p+p \to H_{125}) BR_{SM}(H_{125} \to \gamma + \gamma)}$$

same for R_{ZZ},R_{WW} and $R_{\tau\tau}$

CMS+ATLAS 2 σ experimental ranges (Moriond 2013):

$$\begin{aligned} 0.61 &< R_{\gamma\gamma} < 1.57 \\ 0.75 &< R_{ZZ} < 1.47 \\ 0.44 &< R_{WW} < 1.24 \\ 0.21 &< R_{\tau\tau} < 1.90, \end{aligned}$$



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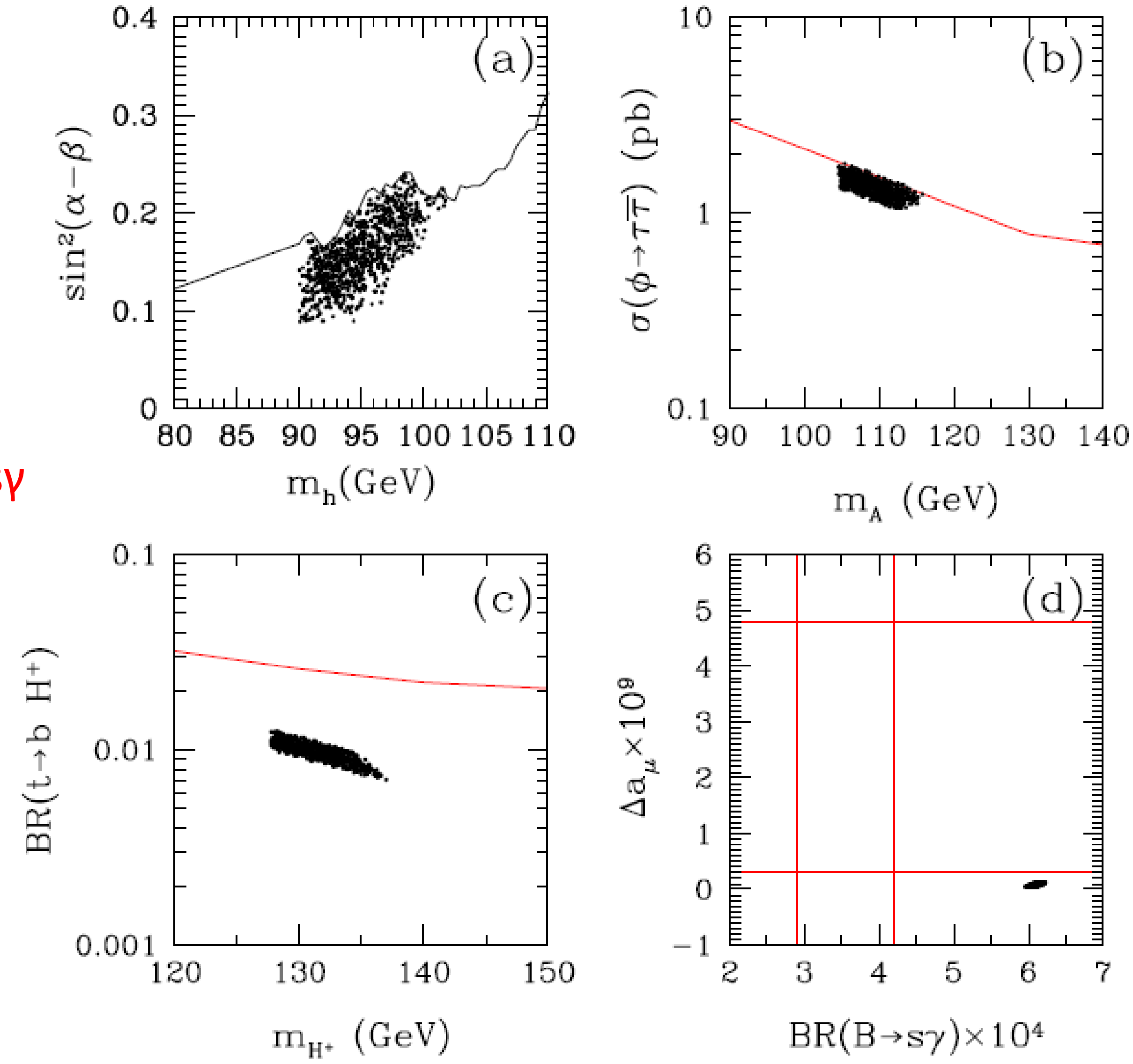
Scenario I: experimental constraints

Tension with g-2 and b→sγ



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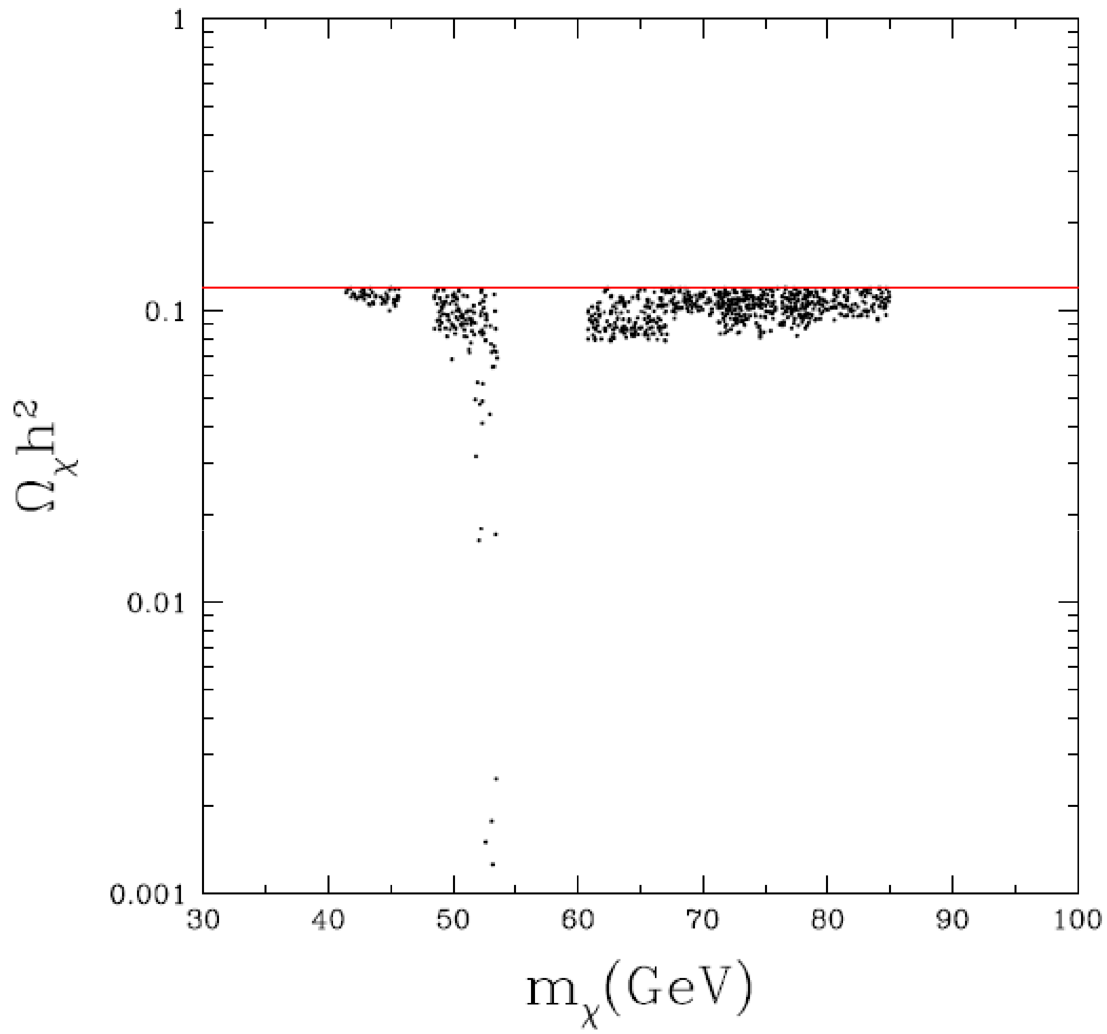
Scenario I: relic abundance

0.11<Ωh^2<0.13
(Planck, arXiv:1303.5076)



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Scenario I: fractional contributions to the annihilation cross section at freeze out of different channels

$$\Omega_\chi h^2 = \frac{x_f}{g_\star(x_f)^{1/2}} \frac{9.9 \cdot 10^{-28}\ \mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v\rangle_{\mathrm{int}}}$$

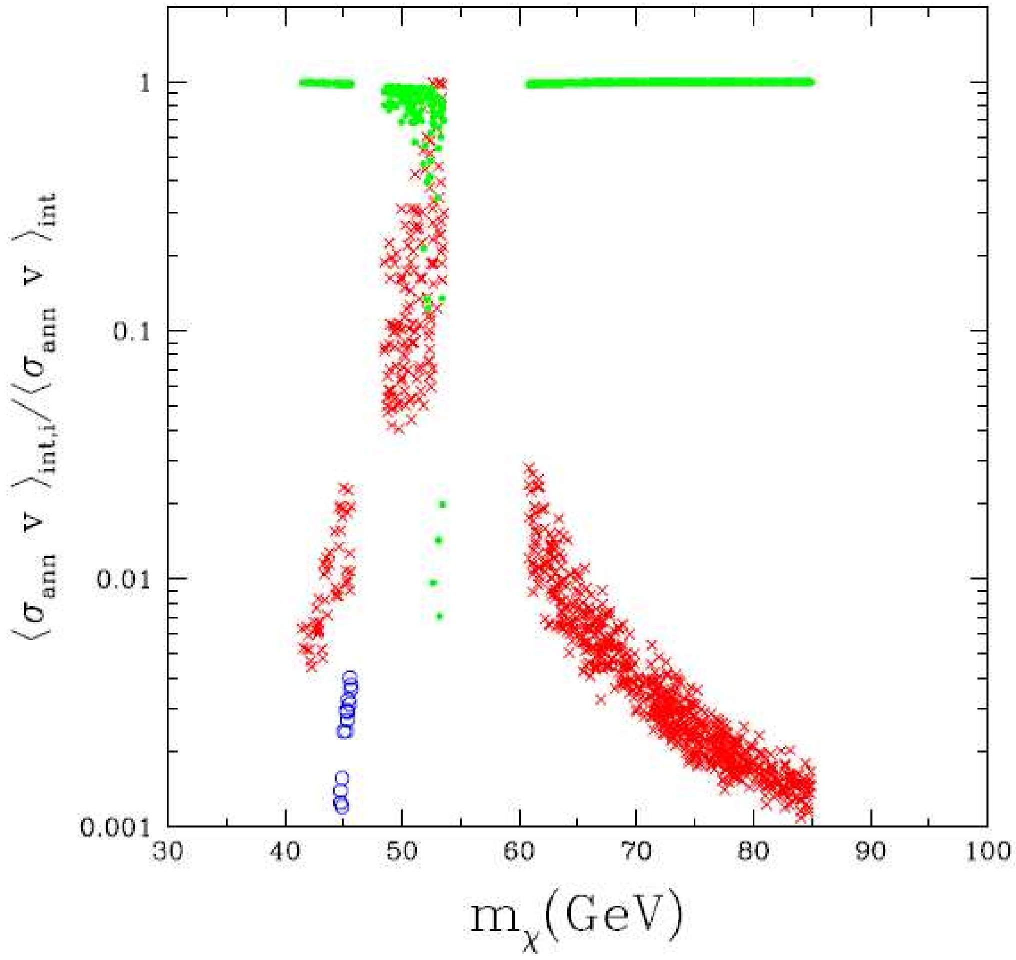
$$x_f \equiv m_\chi / T_f$$

$$<\sigma_{ann} v>_{int} = \int_{x_f}^{x_0} <\sigma_{ann} v> dx$$

T_f=freeze-out temperature

$g_*(x_f)$=# of relativistic degrees of freedom at T_f

- • $\chi\chi \rightarrow$ slepton $\rightarrow$ ff
- x $\chi\chi \rightarrow$ higgs $\rightarrow$ ff
- o $\chi\chi \rightarrow Z \rightarrow$ ff



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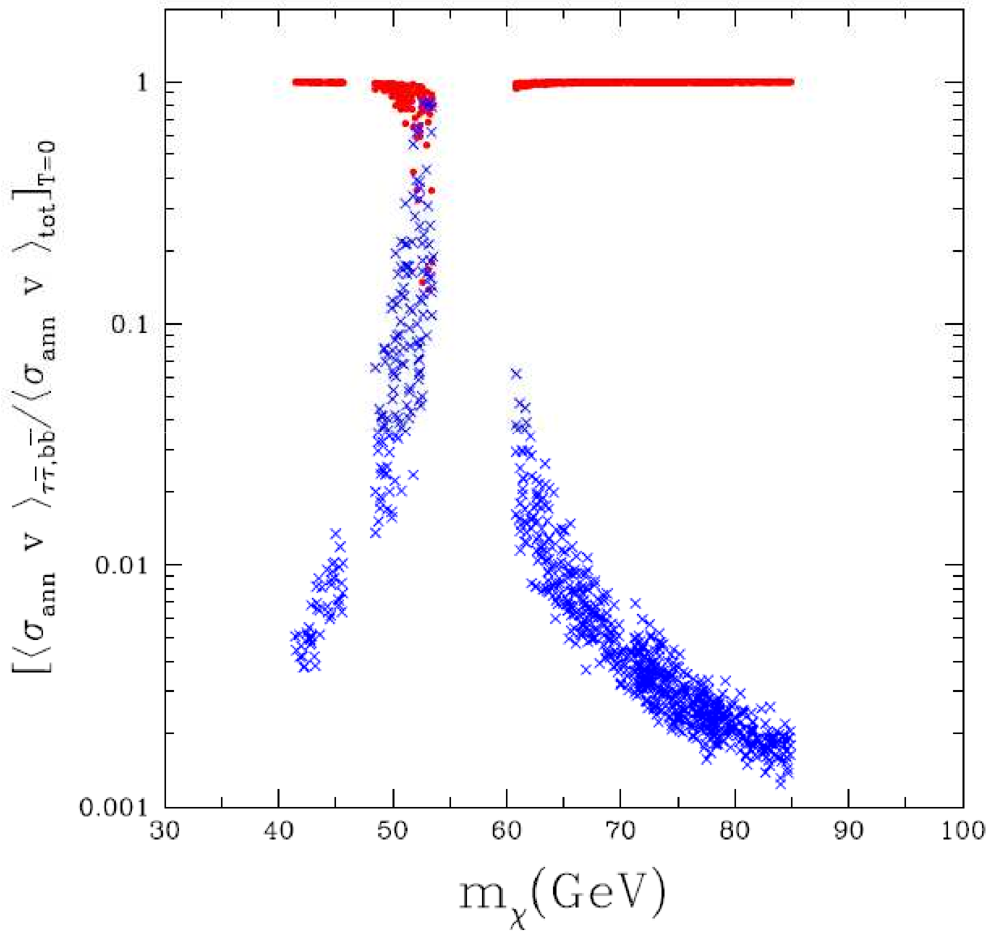
Scenario I: fractional contributions to the annihilation cross section at zero temperature of different final states

- • $\chi\chi \to \tau\tau$
- x $\chi\chi \to bb$



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Scenario II: parameter scan

H_{125}=h (light scalar)

Optimized parameter scan with:

$$123 \text{ GeV} \leq m_{H_{125}} \leq 129 \text{ GeV}$$

(include ~2 GeV theoretical uncertainty)

Scenario II	
$\tan\beta$	(4, 20)
$\lvert\mu\rvert$	(100, 400) GeV
M_1	(40, 170) GeV
M_2	(100, 1000) GeV
M_3	$\sim$ 2000 GeV
$m_{\tilde{q}12}$	(700, 2000) GeV
$m_{\tilde{t}}$	(700, 1200) GeV
$m_{\tilde{l}_{12,L}}, m_{\tilde{l}_{12,R}}, m_{\tilde{\tau}_L}, m_{\tilde{\tau}_R}$	(80, 1000) GeV
m_A	(200, 1000) GeV
$\lvert A\rvert$	(1.5, 2.5)

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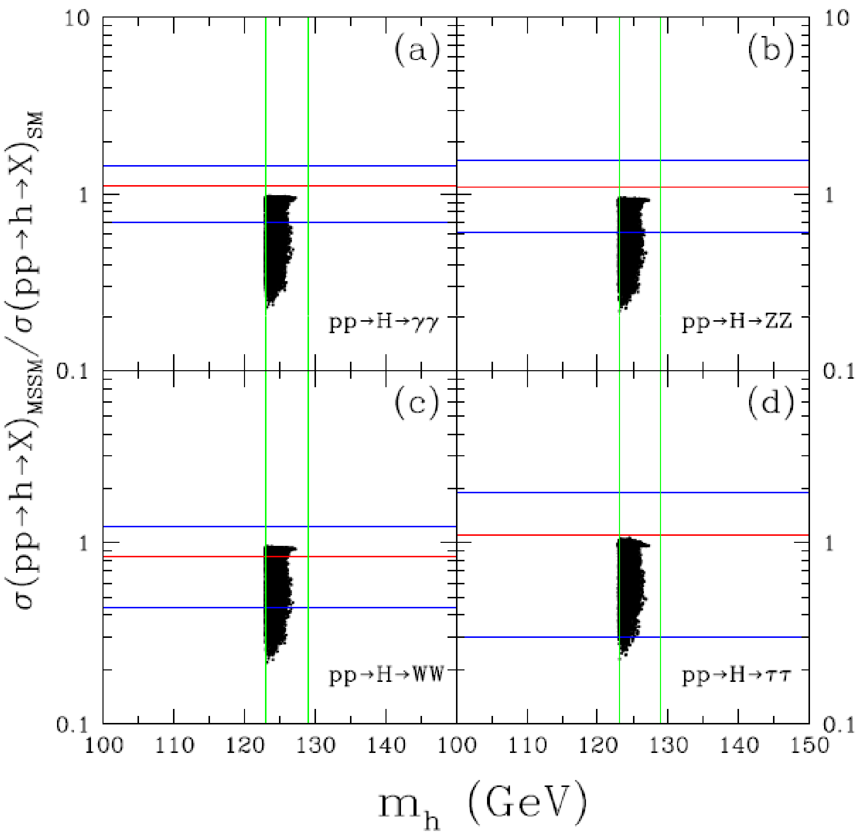
Scenario II: signal strengths

$$R_{\gamma\gamma} = \frac{\sigma(p+p\to H_{125})BR(H_{125}\to\gamma+\gamma)}{\sigma_{SM}(p+p\to H_{125})BR_{SM}(H_{125}\to\gamma+\gamma)}$$

same for R_{ZZ},R_{WW} and $R_{\tau\tau}$

CMS+ATLAS 2 σ experimental ranges (Moriond 2013):

$$\begin{array}{rcccl} 0.61 & < & R_{\gamma\gamma} & < & 1.57 \\ 0.75 & < & R_{ZZ} & < & 1.47 \\ 0.44 & < & R_{WW} & < & 1.24 \\ 0.21 & < & R_{\tau\tau} & < & 1.90, \end{array}$$



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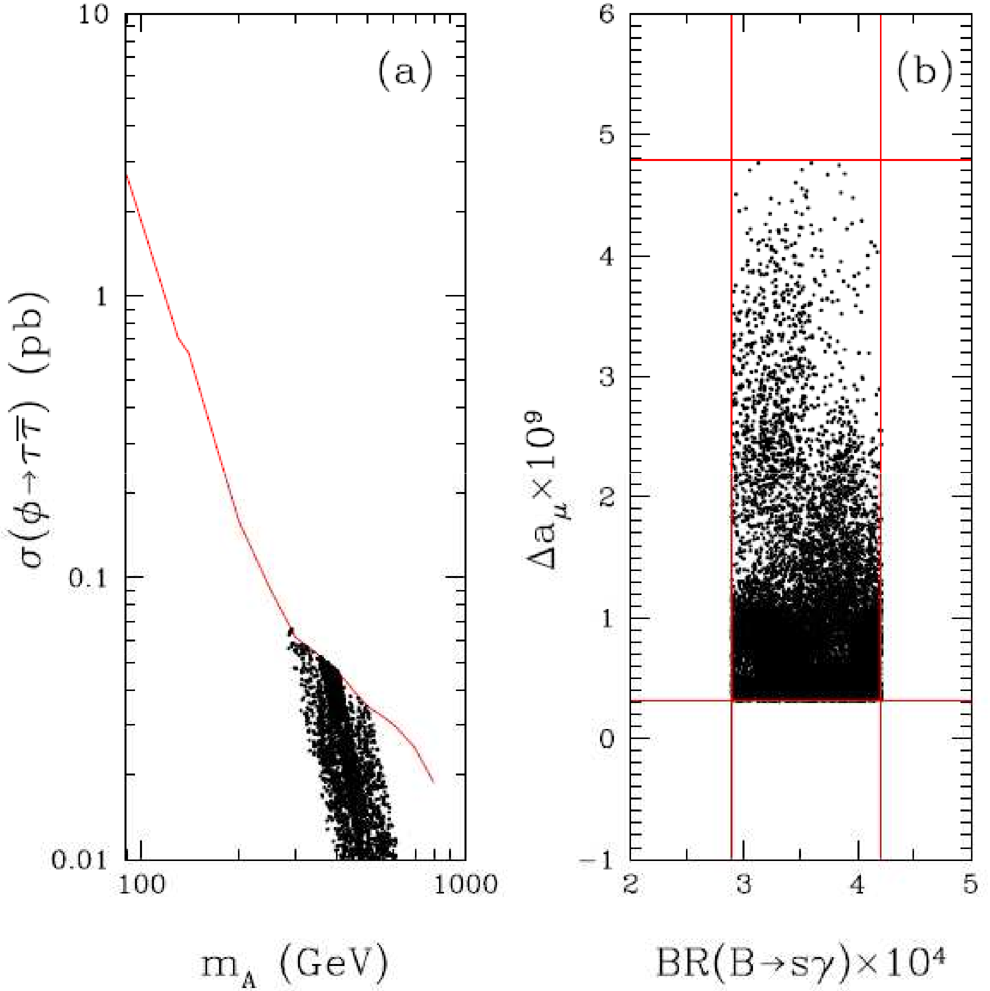
Scenario I: experimental constraints

The configurations plotted in this Scenario satisfy all constraints



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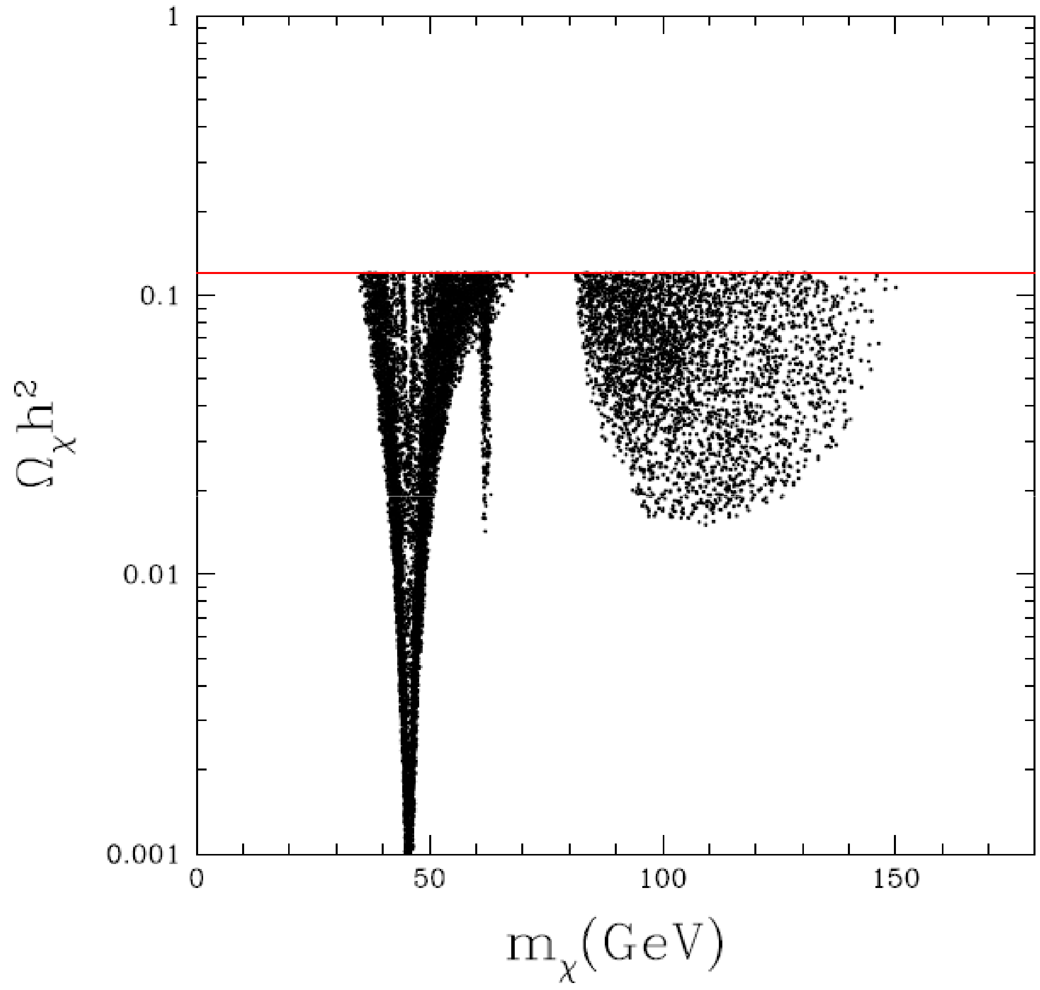
Scenario II: relic abundance

$0.11 < \Omega h^2 < 0.13$
(Planck, arXiv:1303.5076)



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Scenario II: fractional contributions to the annihilation cross section at freeze out of different channels

$$\Omega_\chi h^2 = \frac{x_f}{g_\star(x_f)^{1/2}} \frac{9.9 \cdot 10^{-28}\ \mathrm{cm^3 s^{-1}}}{\langle \sigma_{\mathrm{ann}} v \rangle_{\mathrm{int}}}$$

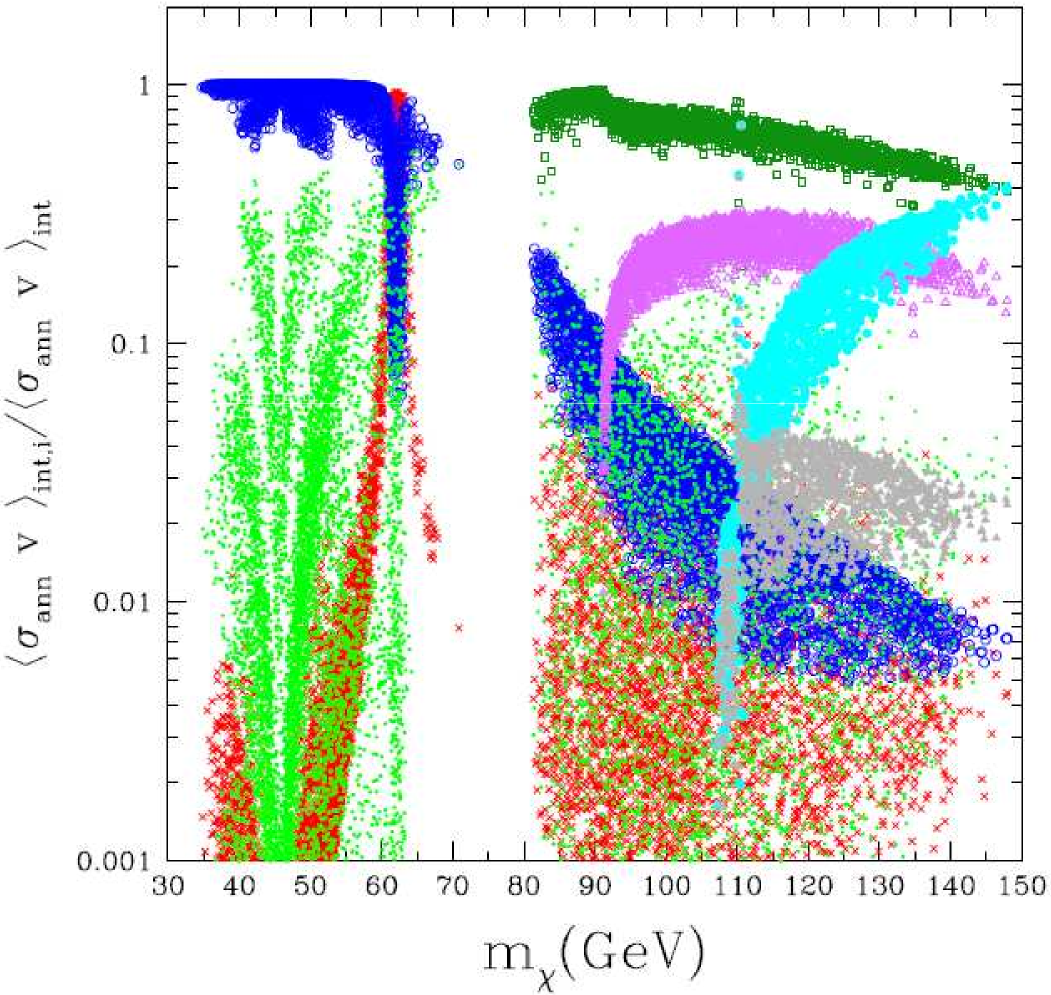
$$x_f \equiv m_\chi / T_f$$

$$<\sigma_{ann} v>_{int} = \int_{x_f}^{x_0} <\sigma_{ann} v> dx$$

T_f=freeze-out temperature

$g_*(x_f)$=# of relativistic degrees of freedom at T_f

- • $\chi\chi \rightarrow$ slepton $\rightarrow$ ff
- x $\chi\chi \rightarrow$ higgs $\rightarrow$ ff
- o $\chi\chi \rightarrow$ Z $\rightarrow$ ff
- □ $\chi\chi \rightarrow$ WW
- Δ $\chi\chi \rightarrow$ ZZ
- ● $\chi\chi \rightarrow$ Zh
- ▲ $\chi\chi \rightarrow$ hh



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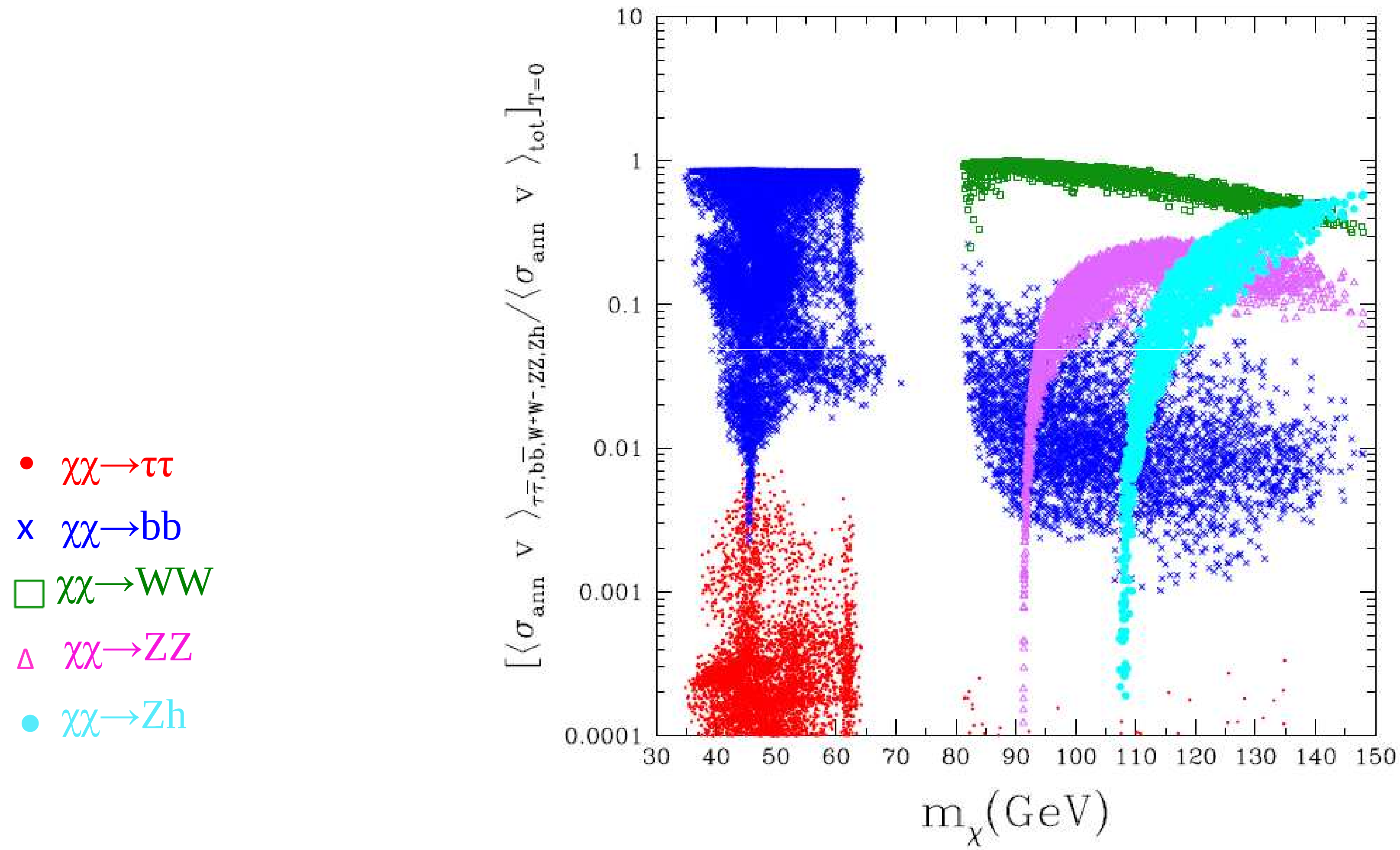
Scenario I: fractional contributions to the annihilation cross section at zero temperature of different final states



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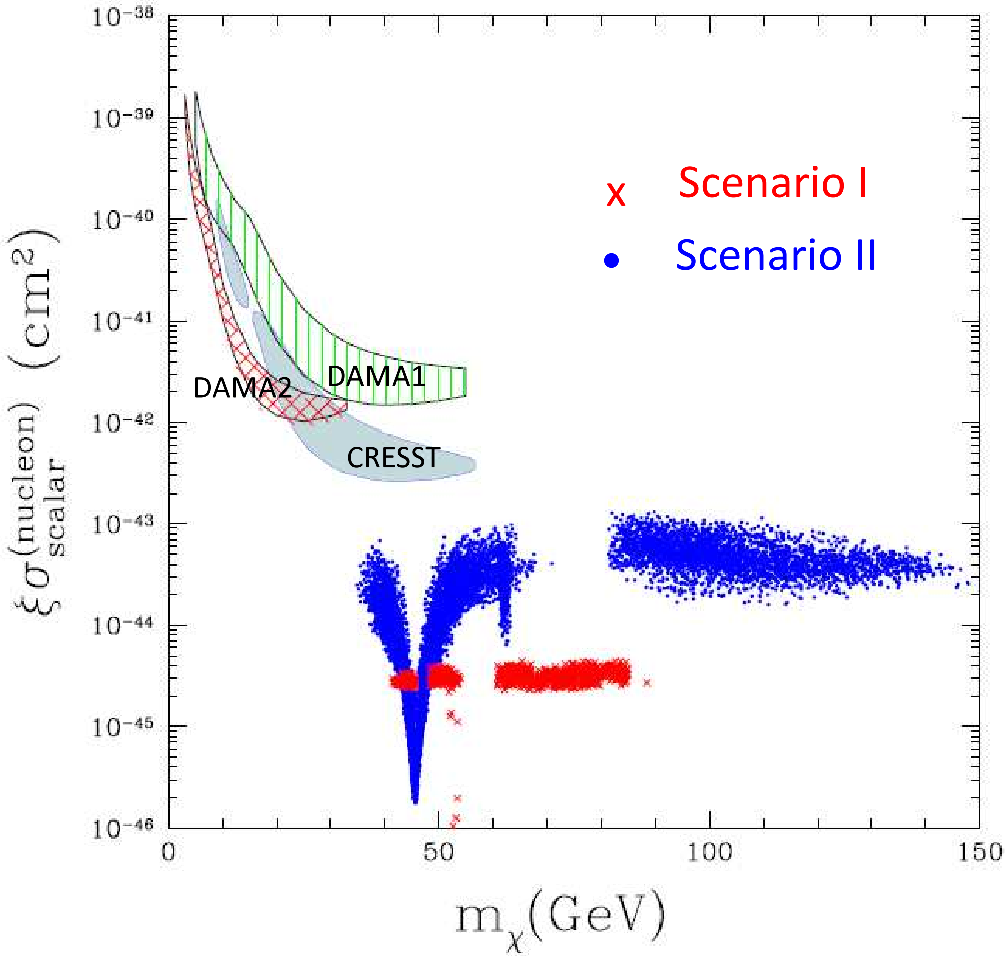
Direct detection

The local density ρ_χ is rescaled with the coefficient ξ defined as:

$$\xi = \min\left\{1, \frac{\Omega_\chi h^2}{(\Omega_{CDM}h^2)_{min}}\right\}$$

and $(\Omega_{CDM}h^2)_{CDM}$=0.11 (Planck 2013)

Due to rescaling the cross section is suppressed whenever the relic density is law, i.e. whenever the annihilation cross section <σv> is large (for instance, can easily see a dip corresponding to resonant annihilation $\chi\chi\rightarrow Z\rightarrow$ff)



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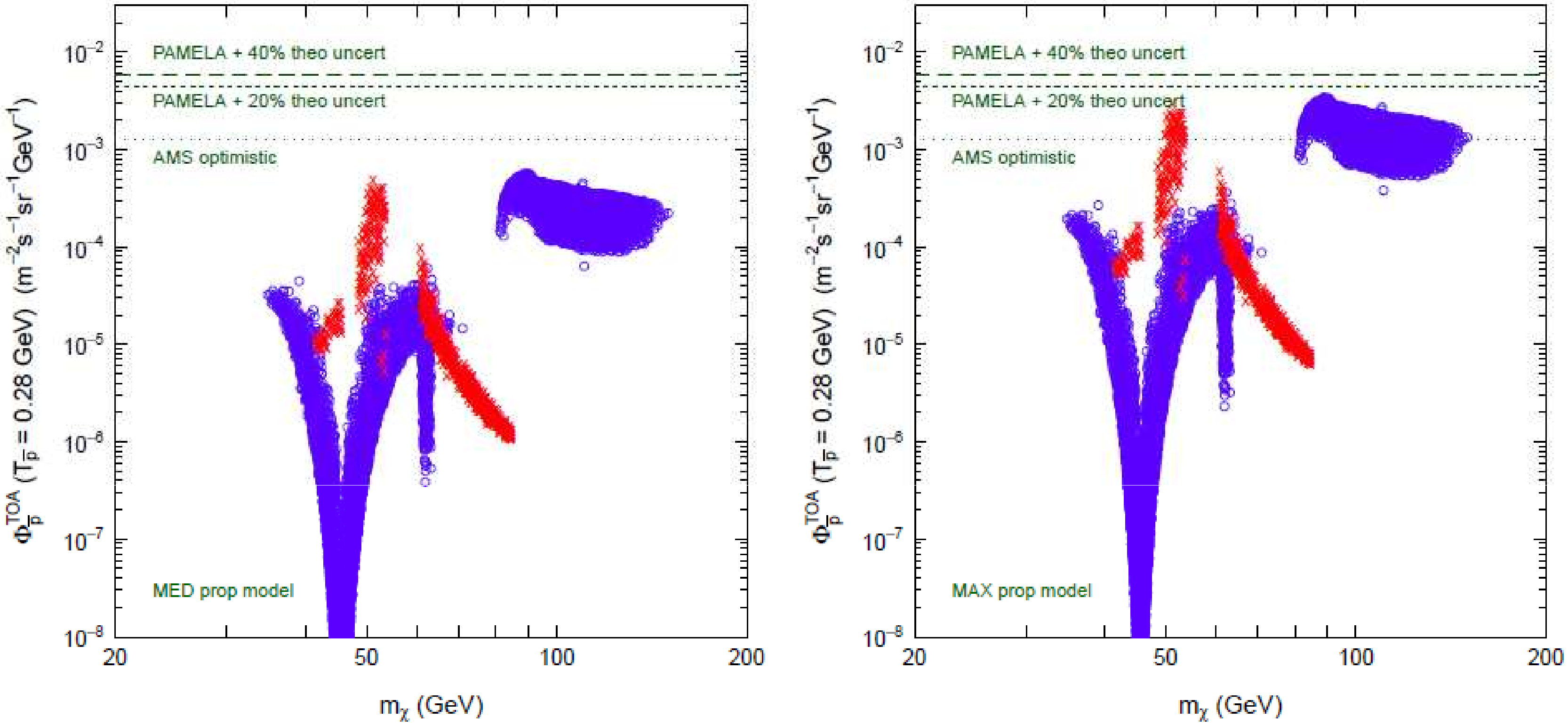
Top-of-atmosphere antiproton flux in the first energy bin of PAMELA ($T_{\bar{p}}$=0.28 GeV)



x Scenario I

o Scenario II

Low expected signals in large parts of the configuration space because the dominant annihilation channel is a leptonic one ($\tau\tau$).

More sizeable expected signals only for resonant $\chi\chi \rightarrow A \rightarrow bb$ (m_χ~m_A/2) and for m_χ >m_W when the $\chi\chi \rightarrow WW$ channel opens up

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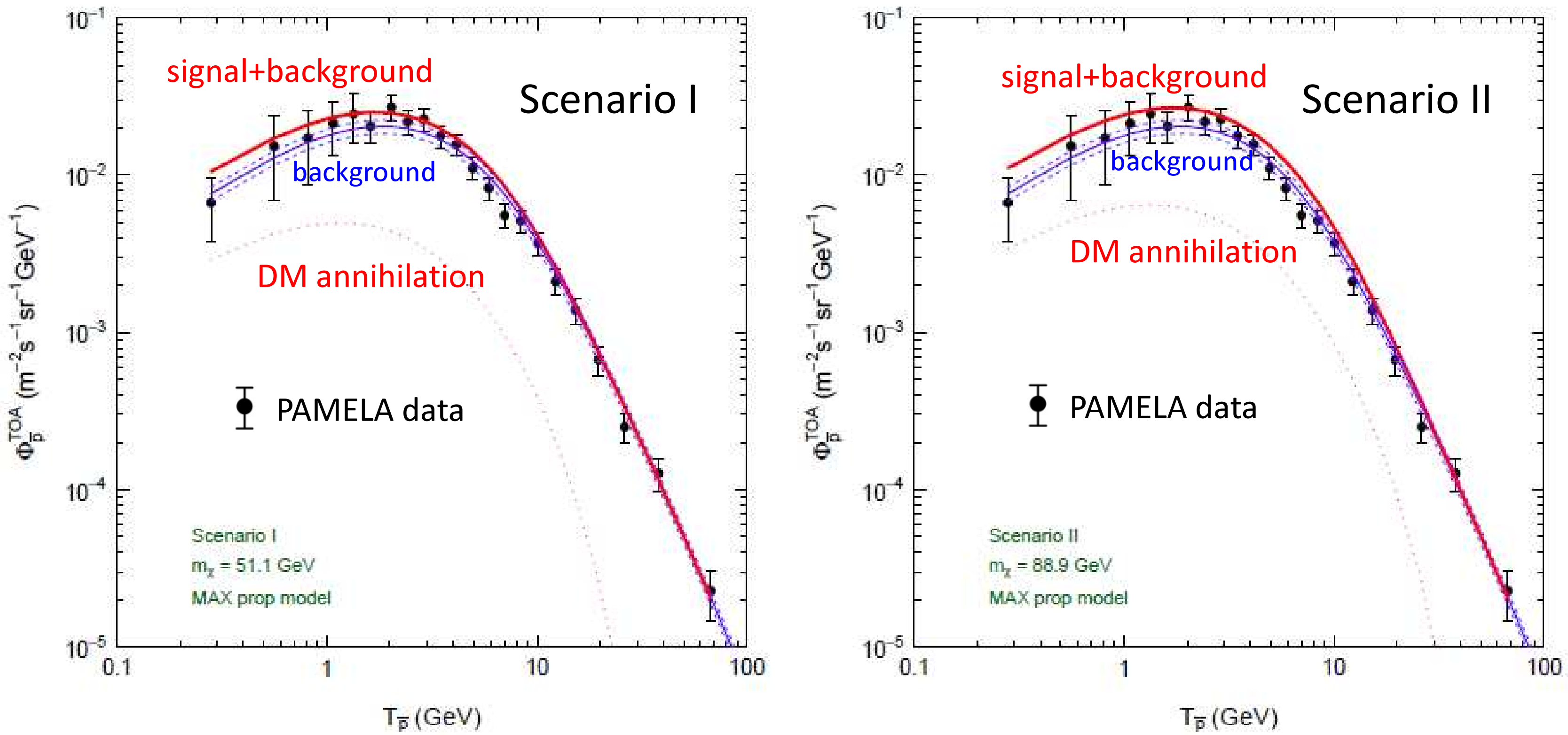
Top-of-atmosphere antiproton flux: two examples of high flux



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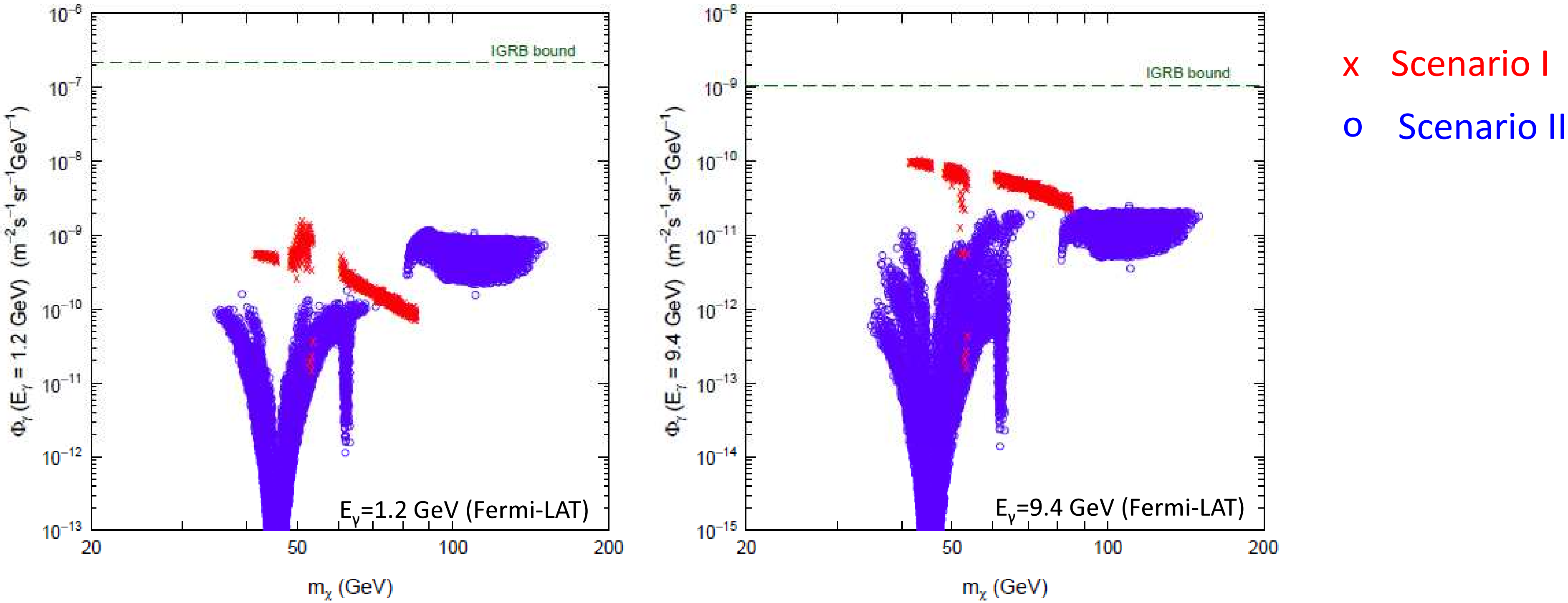
Contribution to the Isotropic Gamma-Ray Background (IGRB) produced by galactic dark matter annihilation at high latitudes



$$\Phi_\gamma(E_\gamma, \psi) = \frac{1}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle}{m_\chi^2}\frac{dN_\gamma}{dE_\gamma}\frac{1}{2}I(\psi)$$

Integration along the line of sight:

$$I(\psi) = \int_{\rm l.o.s} \rho^2(r(\lambda,\psi))\, d\lambda(\psi)$$

$\rho(r) \rightarrow$ Einasto profile

, ψ=angle between l.o.s and source

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Conclusions

- there are now 4 direct detection experiments (DAMA, CoGeNT, CRESST, CDMS-Si) that claim some kind of excess over the background. They all point to approximately the same WIMP mass ($10<m_w<20$) and cross section (10^{-39} cm^2 $<\sigma_{W,nucleon}<10^{-41}$ cm^2).
- Relic neutralinos in an effective MSSM without unification of gaugino masses can explain these excesses, requiring low $|\mu|$ and m_A and large $\tan\beta$ (to enhance both the annihilation cross section and direct detection at low neutralino mass)
- The 2011-2012 runs of the Large Hadron Collider have led to very stringent lower bounds (~TeV range) on the gluino mass and on the masses of squarks of the first two families. Limits on sbottoms and stops are less stringent (in the range of a few hundreds GeV)
- The discovery of the Higgs particle at m_h~125 GeV with production cross sections compatible to the standard model have constrained the available parameter space further, in particular implying large $|\mu|$. The CMS bound on $pp\rightarrow h,H,A\rightarrow\tau\tau$ is particularly stringent on $\tan\beta$ (<5) at low m_A. The combination of these limits is in tension with an explanation of direct detection excesses in terms of relic neutralinos in a minimal MSSM.
- Relic neutralinos with m_χ>40 GeV remain viable DM candidates, possibly detectable with indirect methods