Light Dark Matter, Baryogenesis
Direct Detection and LHC Searches

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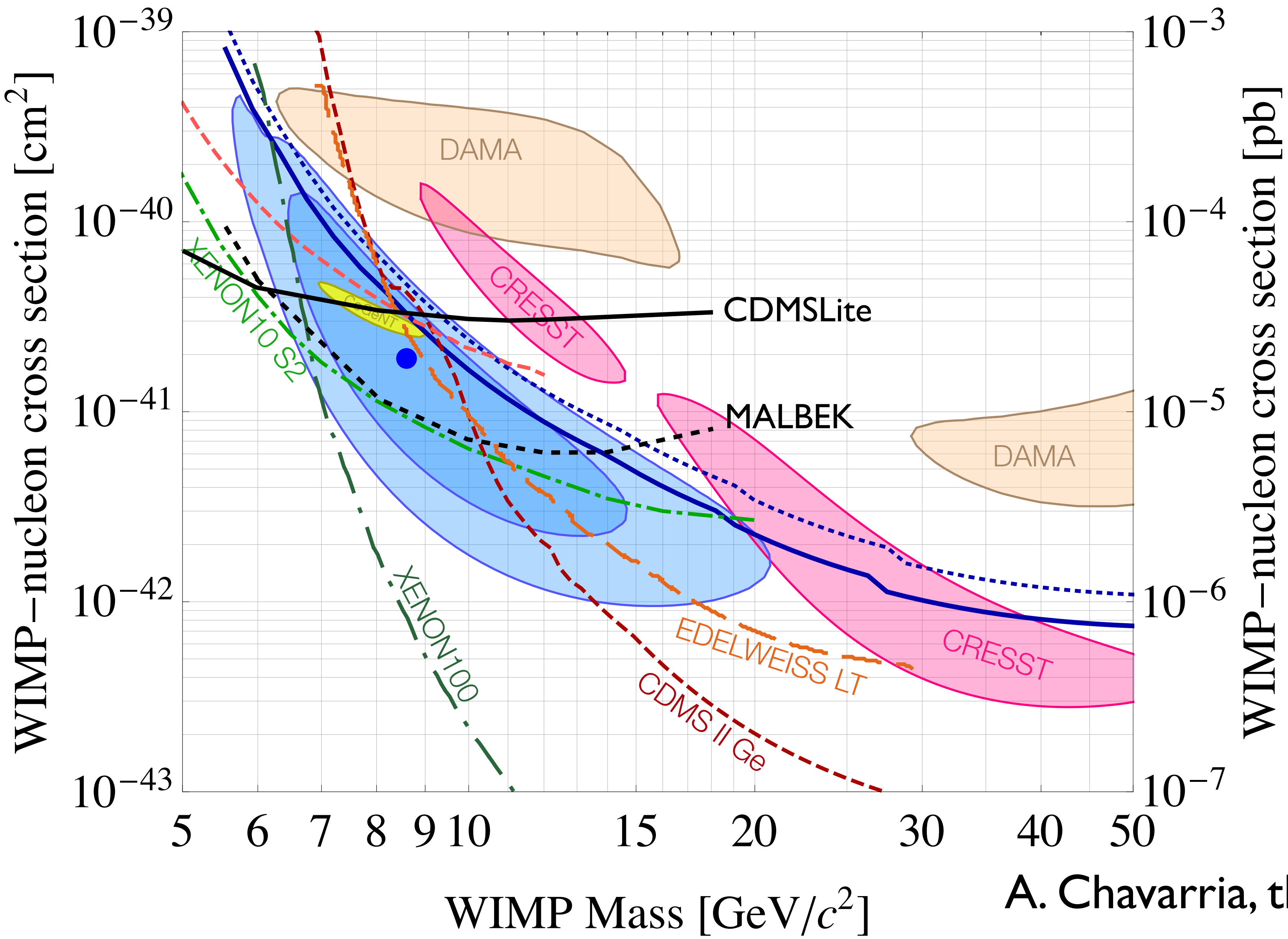
Based on the following works

P. Draper, T. Liu, H. Zhang, C.E.M. Wagner and L.T. Wang, arXiv: 1009.3969, **Phys.Rev.Lett. 106 (2011) 121805**
M. Carena, N. Shah and C.E.M. Wagner, arXiv:1110.4378, **Phys.Rev. D85 (2012) 036003**
M. Carena, S. Gori, N. Shah and C.E.M. Wagner, to appear

KICP Workshop on "Dark Matter at the LHC", University of Chicago, Sep. 21, 2013

In the last year, several Direct Detection experiments have claim possible evidence of light Dark Matter.

Low mass WIMPs



A. Chavarria, this workshop

Evidence is weak, due to the apparent incompatibility of the results of different experiments.

If DM would be light and DD cross sections would be as large as suggested, the minimal supersymmetric model would have a hard time to explain it (light sbottoms may be an exception).

I present here an NMSSM scenario that may lead to such properties, without being in conflict with other experiments.

NMSSM

- It shares all the good properties of the MSSM, but allows the determination of the Higgsino mass parameter μ from the vacuum expectation value of a singlet field
- Apart from the five Higgs physical degrees of freedom of the MSSM, there are one extra neutral CP-odd and one extra CP-even scalar. Moreover, there are five neutralinos in the spectrum, one more than in the MSSM.
- In this work, we shall consider a limit in which these extra particles are naturally light, with masses lower than about 10 to 20 GeV, and a strong singlet component. The neutralino is the LSP and a dark matter candidate.
- Direct Dark Matter cross section may be large in these mode and a strong electroweak phase transition may be obtained
- Model can be probed by collider and also "intensity frontier" constraints
- Searches for electroweakinos at the LHC start to constrain this scenario

The superpotential of the NMSSM is given by

$$W_{NMSSM} = Y_U \mathbf{Q}\mathbf{H}_u\mathbf{U}^c - Y_D\mathbf{Q}\mathbf{H}_d\mathbf{D}^c - Y_E\mathbf{L}\mathbf{H}_d\mathbf{E}^c + \lambda\mathbf{N}\mathbf{H}_u\mathbf{H}_d + \frac{1}{3}\kappa\mathbf{N}^3$$

and, therefore

$$\mu = \lambda\langle N\rangle$$

The corresponding soft supersymmetry breaking parameters in the Higgs sector are

$$V_{soft} = m_{H_d}^2|H_d|^2 + m_{H_u}^2|H_u|^2 + m_N^2|N|^2 - (\lambda A_\lambda H_u H_d N + \text{h.c.}) + \left(\frac{\kappa}{3}A_\kappa N^3 + \text{h.c.}\right)$$

When $\kappa \to 0$, there is a new global U(1) symmetry , a PQ symmetry defined by

$$H_u \to H_u \exp(i\phi_{PQ}),\;\; H_d \to H_d \exp(i\phi_{PQ}),\;\; N \to N\exp(-2i\phi_{PQ})$$

Therefore, when the Higgs bosons acquire vacuum expectation values, a massless CP-odd scalar appears in this limit. For small κ, the CP-odd state becomes light.

Dark Light Higgs Scenario

- Close to the PQ limit, the CP-odd scalar acquires a mass

$$m_{a_1}^2 \simeq -\frac{3\kappa A_\kappa \mu}{\lambda}$$

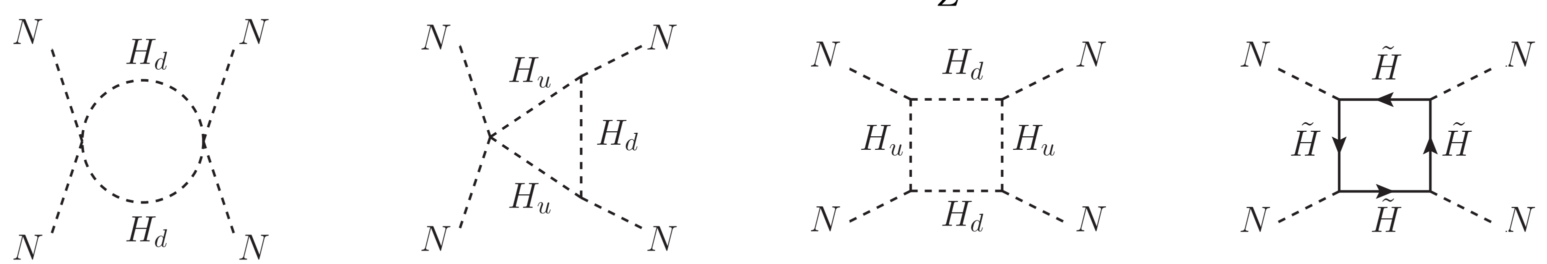
- While for moderate or large $\tan\beta$, the CP-even scalar mass is governed by how far $A_\lambda/\mu\tan\beta$ is from 1. Defining

$$\epsilon = \frac{\lambda\mu}{M_Z}\left(\frac{A_\lambda}{\mu\tan\beta} - 1\right)$$ and taking $A_\lambda \to \mu\tan\beta, \quad \kappa \ll \lambda < 1$

at tree level, for small epsilon, the scalar mass contributions are small

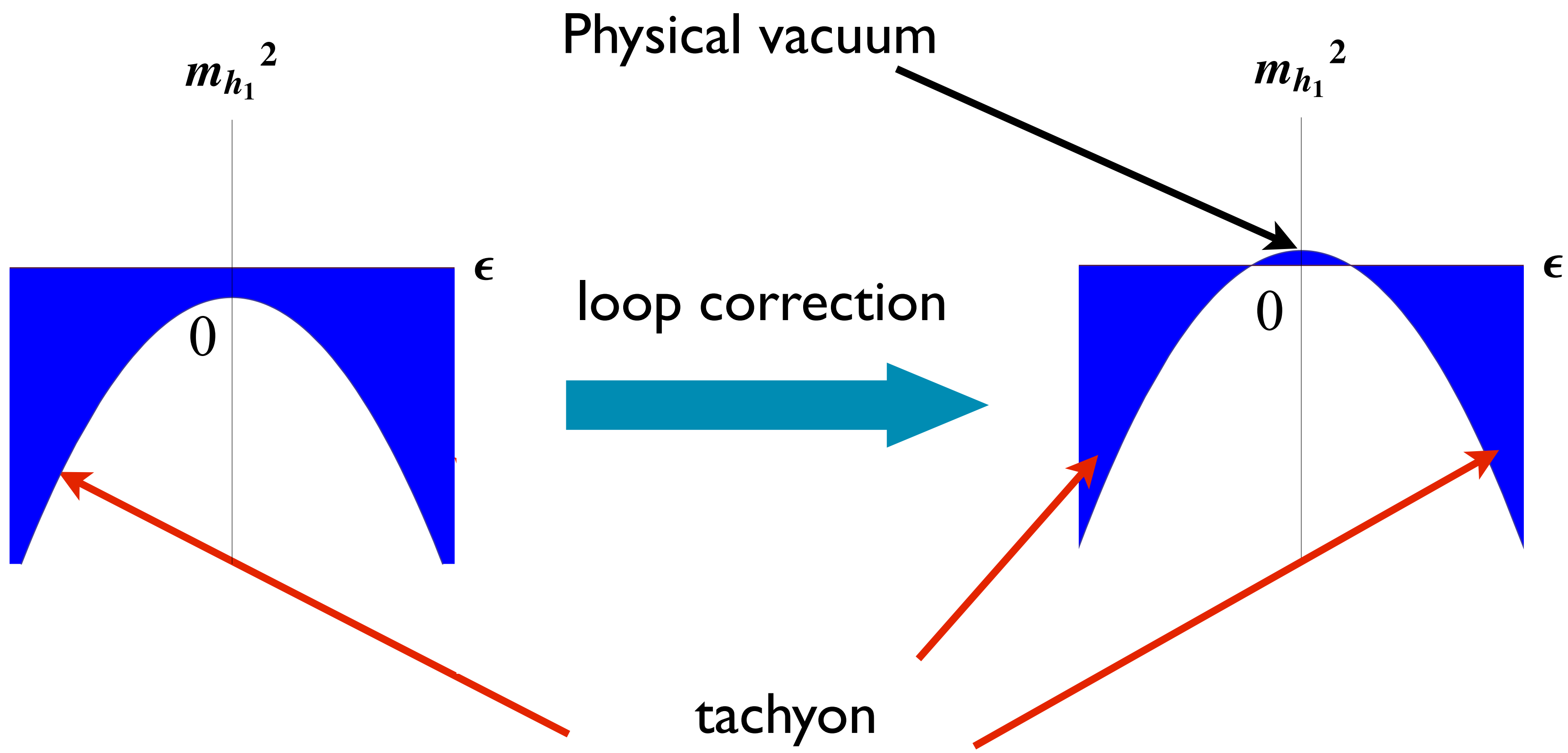
$$m_{h_1}^2 \approx -4v^2\varepsilon^2 + \frac{4v^2\lambda^2}{\tan^2\beta} + \frac{\kappa A_\kappa \mu}{\lambda} + \frac{4\kappa^2\mu^2}{\lambda^2}.$$

At loop level, $\Delta m_{h_1}^2 \approx \frac{\lambda^2\mu^2}{2\pi^2}\log\frac{\mu^2\tan\beta^3}{m_Z^2}.$



The Dark Light Higgs Scenario

- The positive loop correction can cancel the tree level negative contribution of the lightest CP-even Higgs mass square.
- Small ε is not a result of the fine-tuning, but a result of the vacuum stability.

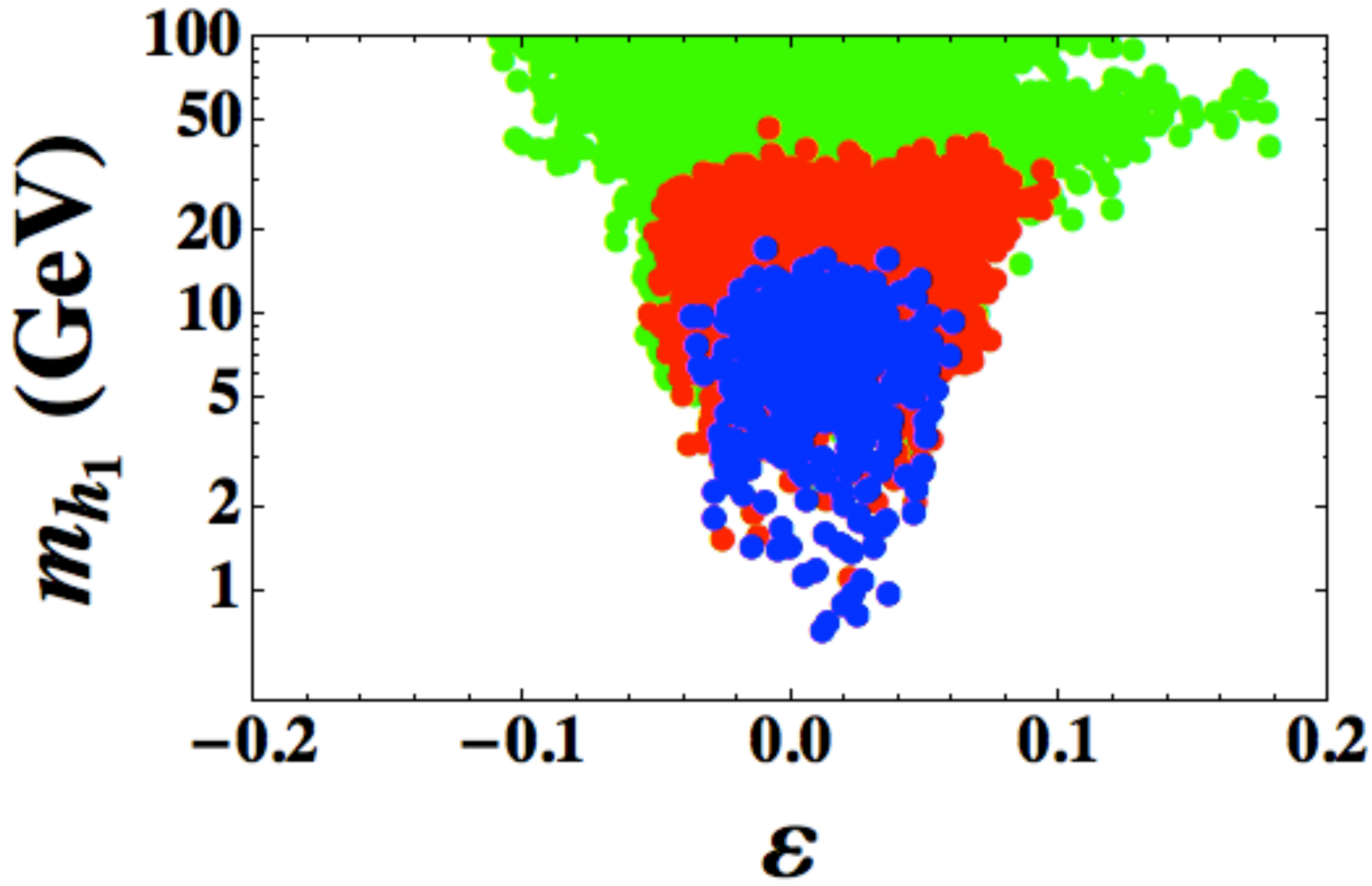


- The upper bound of the ε is

$$\varepsilon^2_{\max} \approx \frac{1}{4v^2}\left(\frac{4\lambda^2 v^2}{\tan^2\beta} + \frac{\kappa A_\kappa \mu}{\lambda} + \frac{4\kappa^2\mu^2}{\lambda^2} + \frac{\lambda^2\mu^2}{2\pi^2}\log\frac{\mu^2\tan^3\beta}{m_Z^3}\right)$$

The Dark Light Higgs Scenario

- Some numerical results (using NMSSMTools 2.3.1and MicrOMEGAS 2.4.Q)



DLH:
Blue Points

$5 \leqslant \tan\beta \leqslant 50,\ 0.05 \leqslant \lambda \leqslant 0.5,\ 0.0005 \leqslant \kappa \leqslant 0.05, -0.8 \leqslant \varepsilon' \leqslant 0.8,\ -40\text{GeV} \leqslant A_\kappa \leqslant 0,\ 0.1\text{TeV} \leqslant \mu \leqslant 1\text{TeV}$

$\lambda < 0.30,\ \kappa/\lambda < 0.05,\ \mu < 400\text{GeV}$

$\lambda < 0.15,\ \kappa/\lambda < 0.03,\ \mu < 250\text{GeV}$

$\varepsilon' = \frac{A_\lambda}{\mu \tan\beta} - 1$

Values of $\epsilon \lesssim 0.05$ are obtained

The Dark Light Higgs Scenario

DLH: Blue Points

- How about other new particles in the DLH scenario?

- A singlino-like light neutralino ~ 1-10 GeV

$$m_{\chi_1} \approx \frac{\lambda^2 v^2}{\mu} \sin 2\beta + \frac{2\kappa\mu}{\lambda}$$

- A light CP-odd Higgs (due to the PQ limit) ~ 10 GeV

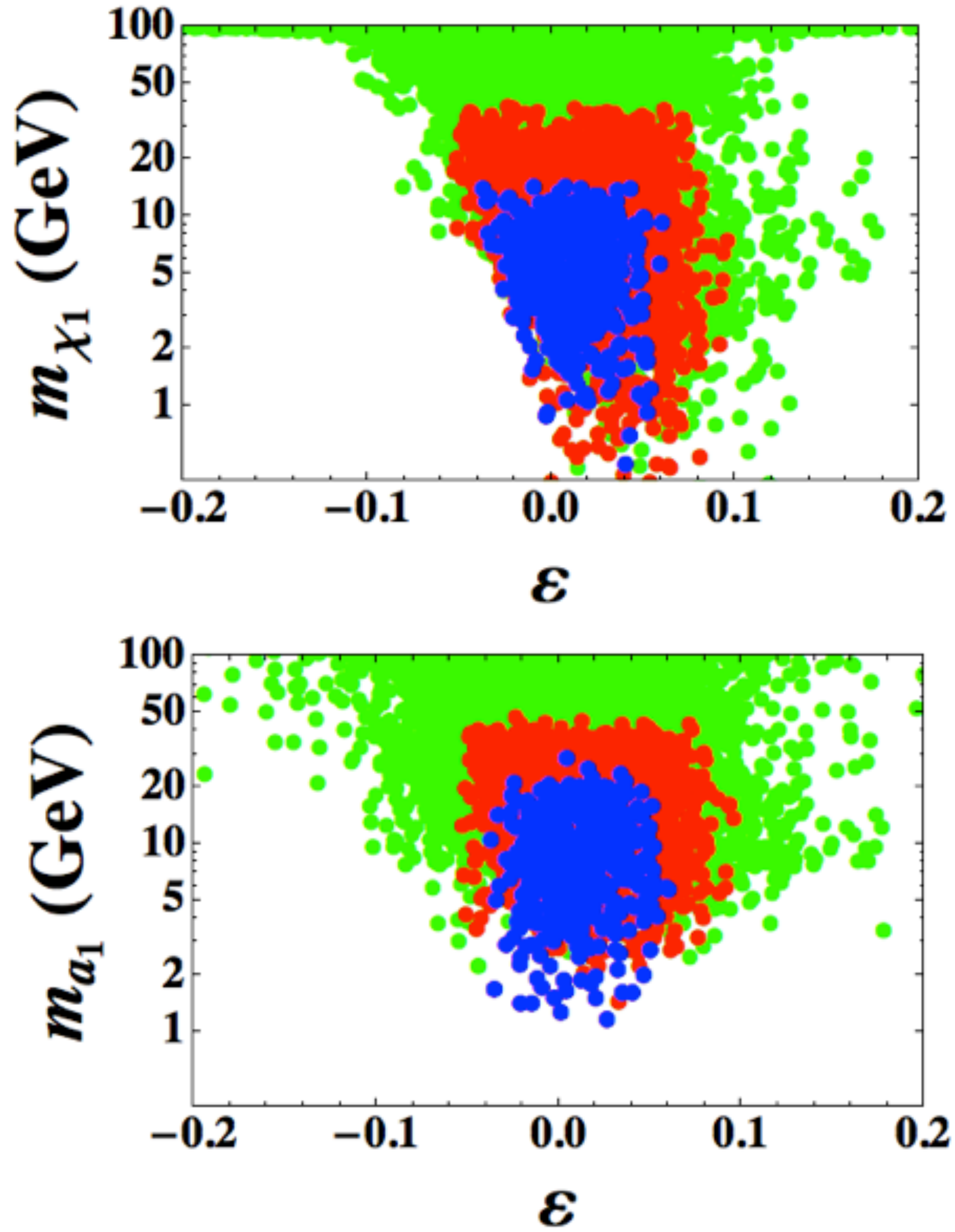
$$m_{a_1}^2 \approx -\frac{3\kappa A_\kappa \mu}{\lambda}$$

- A SM-like Higgs ~ 125 GeV

$$h_2 \sim h_u + h_d \cot\beta - \frac{2\varepsilon v m_Z}{m_Z^2 + \mu^2} h_n$$

- CP-odd and a CP-even non-standard Higgs Bosons

$$m_{h_3}^2 \simeq A_\lambda^2 \gg m_{h_{1,2}}^2$$



Phenomenological Constraints

- Dictated by mixing of mainly singlet state with MSSM Higgs bosons

$$S_{1d} \approx \frac{v}{\mu \tan\beta}\left(\lambda + \frac{2\varepsilon\mu}{m_Z}\right), \quad S_{1u} \approx \frac{2v\varepsilon}{m_Z};$$

- One should consider the possible decays of the SM-like Higgs, which is mainly up-type, into the light states

$$S_{2d} \approx \cot\beta, \quad S_{2s} \approx -\frac{2\varepsilon v m_Z}{m_Z^2 + \mu^2}$$

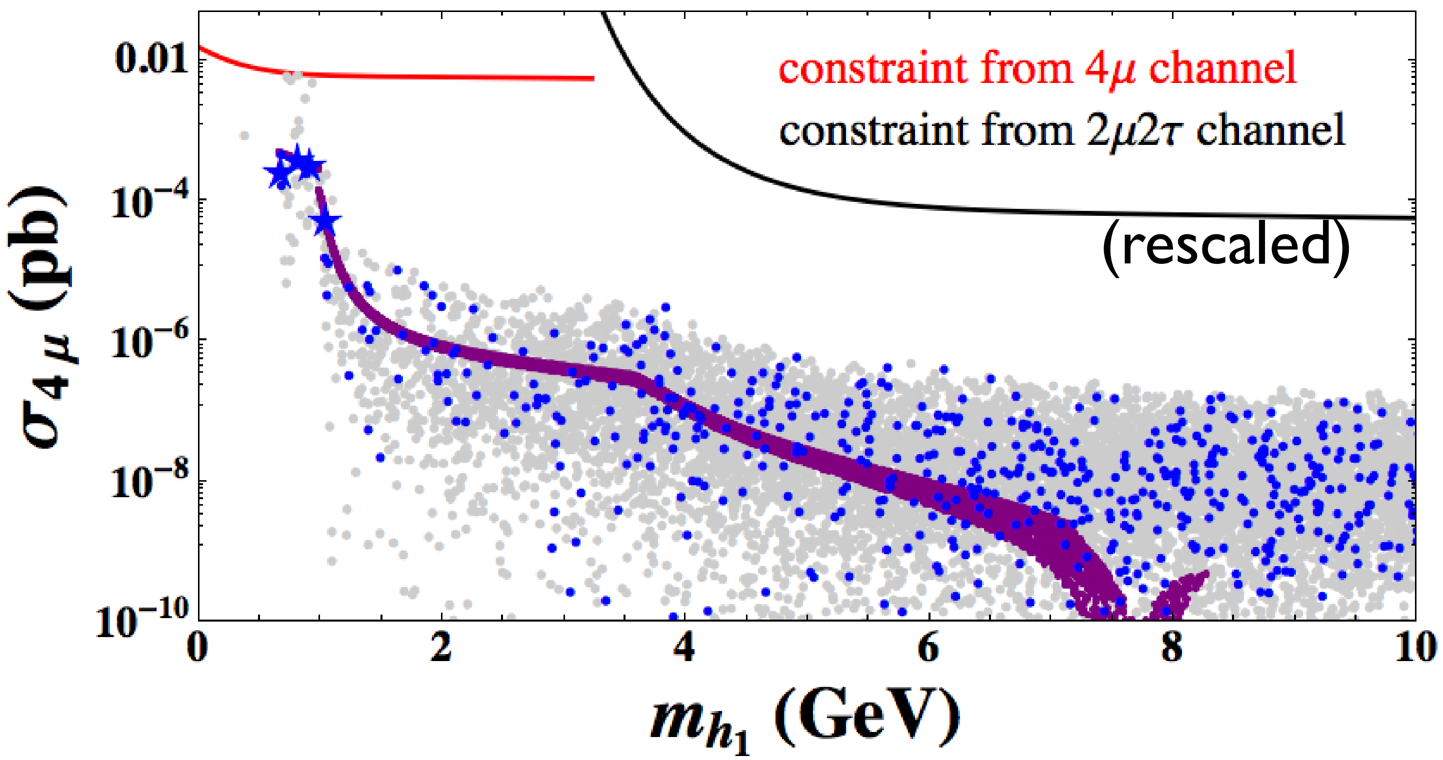
- The effective coupling $y_{h_2 h_1 h_1} \approx -\frac{\lambda v m_Z \varepsilon}{\sqrt{2}\mu}.$

It is suppressed both by small values of lambda and epsilon. The coupling to fermions is easily extracted from the above mixing values.

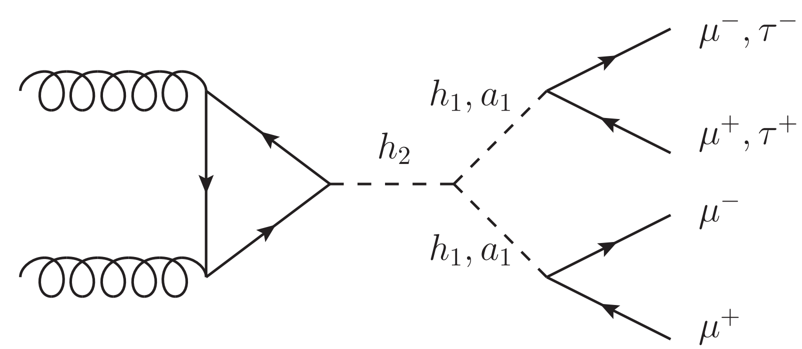
Higgs Decay Bounds

- We consider squark masses of a few TeV, and values of the trilinear soft terms of similar magnitude.

- There are powerful limits from the Tevatron in its possible gluon fusion production and possible decay into light boson states. This puts a very tight upper bound on the rate of these decays.



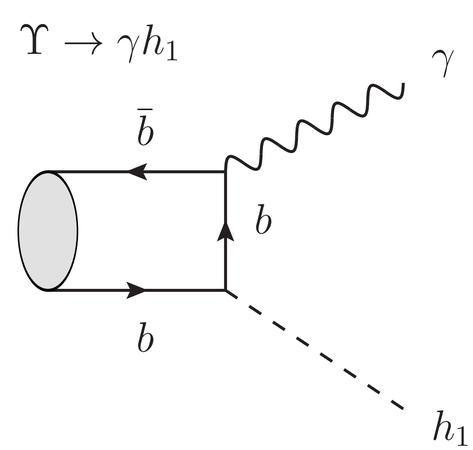
M_a (GeV)	Window (MeV)	Eff.	$N_{\rm bckg}$	$N_{\rm obs}$	$\sigma\times$BR [exp] obs (fb)
0.2143	± 15	17%	0.001 ± 0.001	0	[10.0] 10.0
0.3	± 50	16%	0.006 ± 0.002	0	[9.5] 9.5
0.5	± 70	12%	0.012 ± 0.004	0	[7.3] 7.3
1	± 100	13%	0.022 ± 0.005	0	[6.1] 6.1
3	± 230	14%	0.005 ± 0.002	0	[5.6] 5.6



- These bounds are therefore easily fulfilled in these models

Upsilon Decay Bounds

- The most important bounds for a light scalar come from radiative decays



$$\mathcal{L} = -\frac{h_1}{\sqrt{2}}(\lambda_d m_l \bar{l}l + \lambda_d m_d \bar{d}d + \lambda_u m_u \bar{u}u)$$

$$\frac{\Gamma(\Upsilon \to \gamma h_1)}{\Gamma(\Upsilon \to e^+e^-)} \propto \frac{\lambda_d^2 m_b^2 G_F}{\sqrt{2}\pi}\left(1 - \frac{m_{h_1}^2}{m_\Upsilon^2}\right)$$

- The effective coupling

$$\lambda_d \approx \frac{v}{\mu}\left(\lambda + \frac{2\varepsilon\mu}{m_Z}\right), \;\; \lambda_u \approx \frac{2\varepsilon v}{m_Z}$$

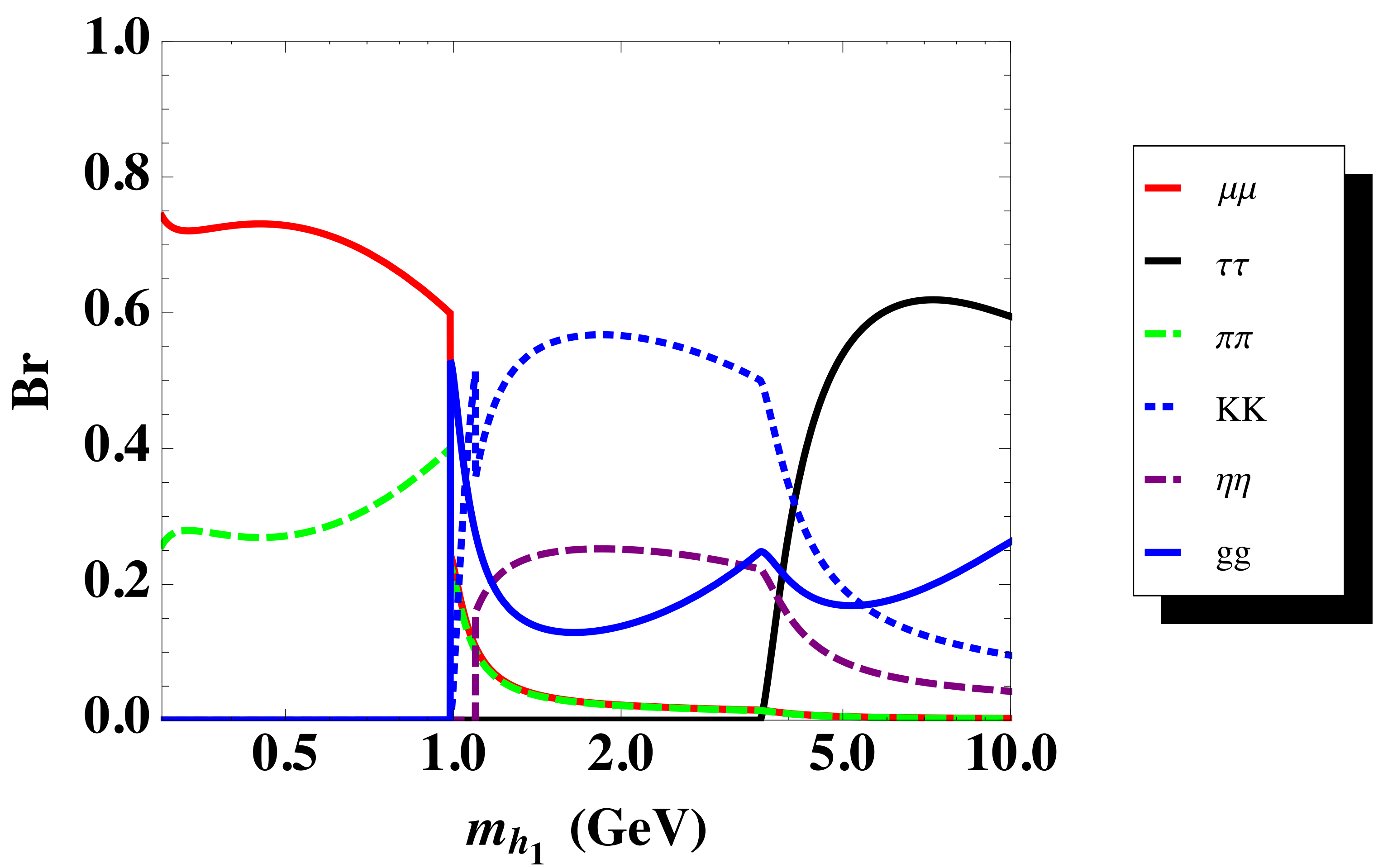
$$\Gamma(h_1 \to l^+l^-) = \frac{\lambda_d^2 m_l^2 G_F}{4\sqrt{2}\pi}\beta_l^3$$

- In addition for masses below the Kaon decay threshold

$$\frac{\Gamma(h_1 \to \mu^+\mu^-)}{\Gamma(h_1 \to \pi\pi)} = \frac{243 m_\mu^2}{m_{h_1}^2}\left[1 + \frac{2\lambda_u}{\lambda_d} + \left(\frac{31\lambda_d + 35\lambda_u}{4\lambda_d}\right)\frac{m_\pi^2}{m_{h_1}^2} + \frac{27}{4}\left(1 - \frac{\lambda_u}{\lambda_d}\right)\frac{\Delta m_K^2}{m_{h_1}^2}\right]^{-2}\frac{\beta_\mu^3}{\beta_\pi}$$

Upsilon decay

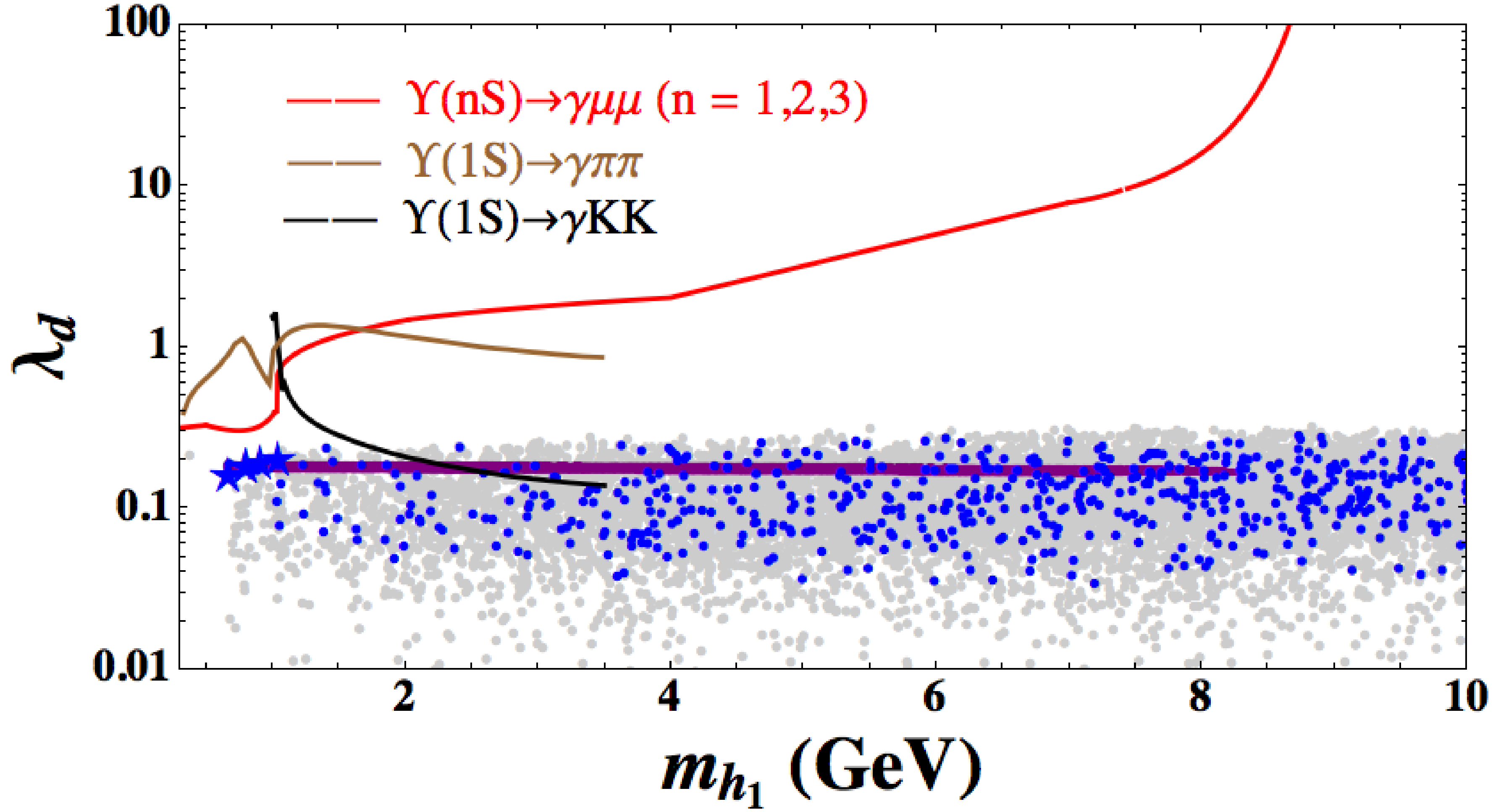
- When $m_{h_1} > 2m_K$, the perturbative spectator model is used to estimate the decay branching ratio of the Higgs.
- Finally, the decay branching ratio of the lightest CP-even Higgs is



David McKeen, Phys Rev D 79, 015007 (2009)

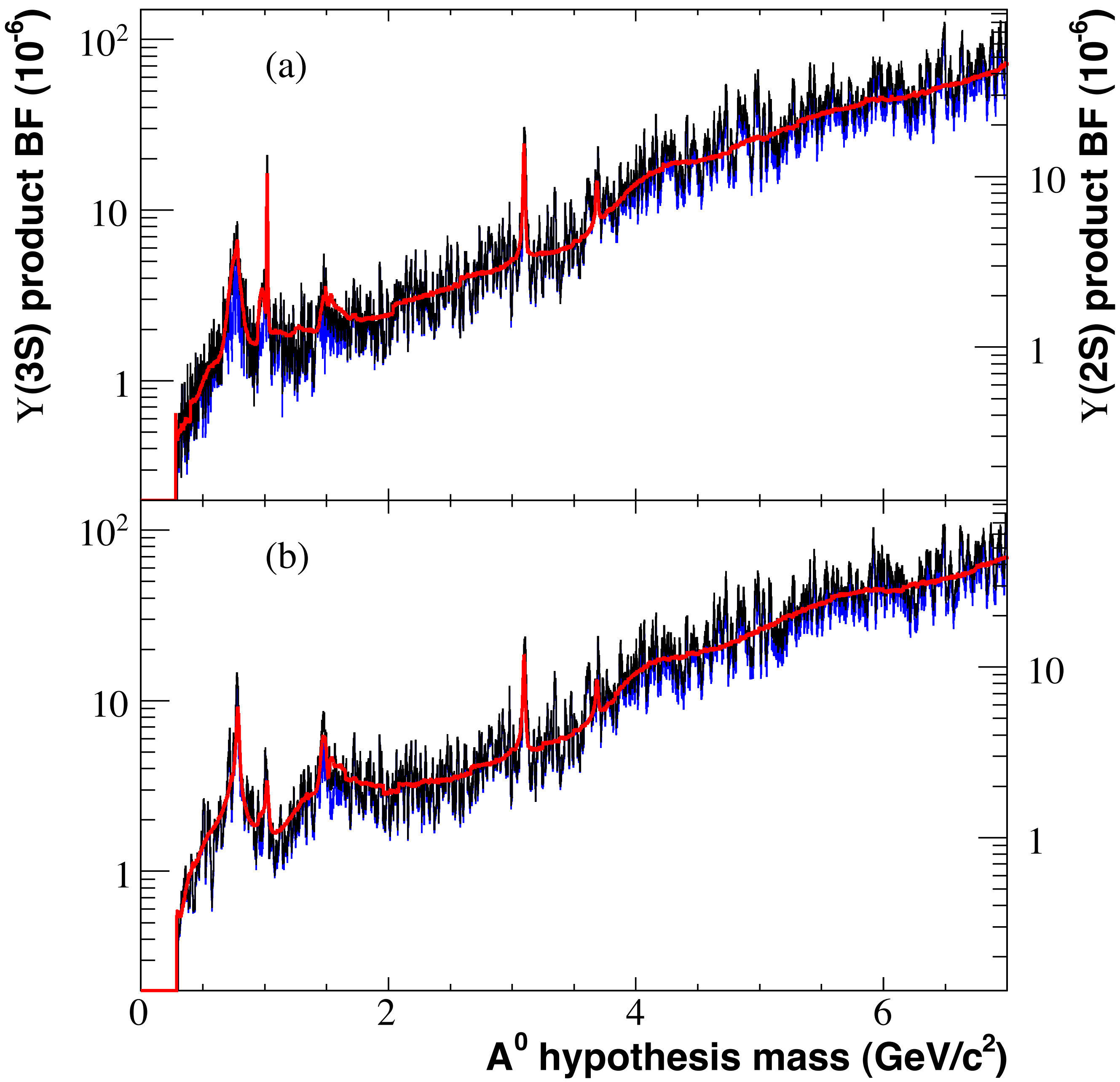
J. F. Gunion, H. E. Haber, G. L. Kane, and S. Dawson, The Higgs Hunter's Guide (Addison-Wesley, Reading, Massachusetts, 1990)

Upsilon Decay : CLEO Bounds



For masses below 2GeV, bounds are satisfied even for relatively large values of the effective down fermion coupling.

New BABAR Bounds



$$BF(Y \to \gamma + s) \simeq 2 \times 10^{-4}\ \lambda_d^2\ F_{QCD}$$

$$F_{QCD} \simeq 0.3$$

Bound on λ_d larger than 0.25 may be obtain from these considerations.

Typical value of $\lambda_d \simeq 0.1$ in this model, so it comfortably satisfies the bound.

Other constraints from lepton, Higgs and flavor physics

Constraints on this model also come from $g-2$ of the muon at the one and two-loop level, from rare B decays and from the Zh_1 production at LEP2.

The first ones put constraints on λ_d and the two-loop $g-2$ as well as the last one on λ_u. Bounds depend also on the SUSY spectrum.

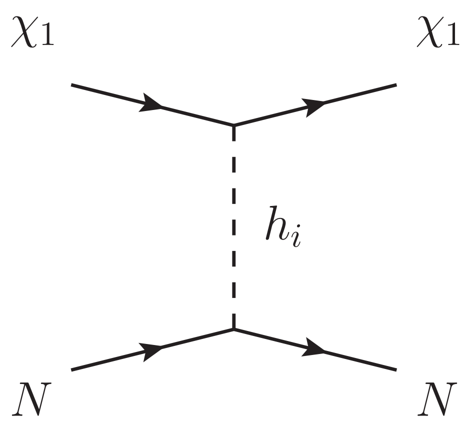
Values of λ_d and λ_u smaller than 10^{-1} tend to satisfy these constraints.

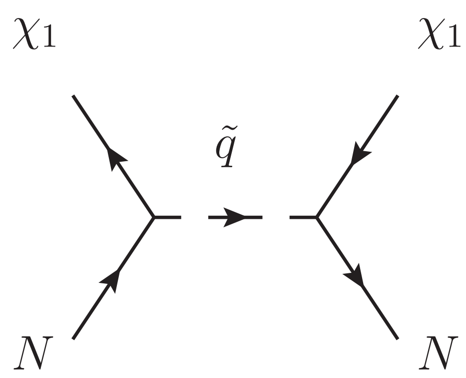
How about the implications for cosmology?

Dark Matter in the DLH Scenario

SI Direct Dark Matter Cross Section

Production dominated by t-channel interchange of light scalar Higgs.
Contribution of non-standard Higgs bosons suppressed by large mass

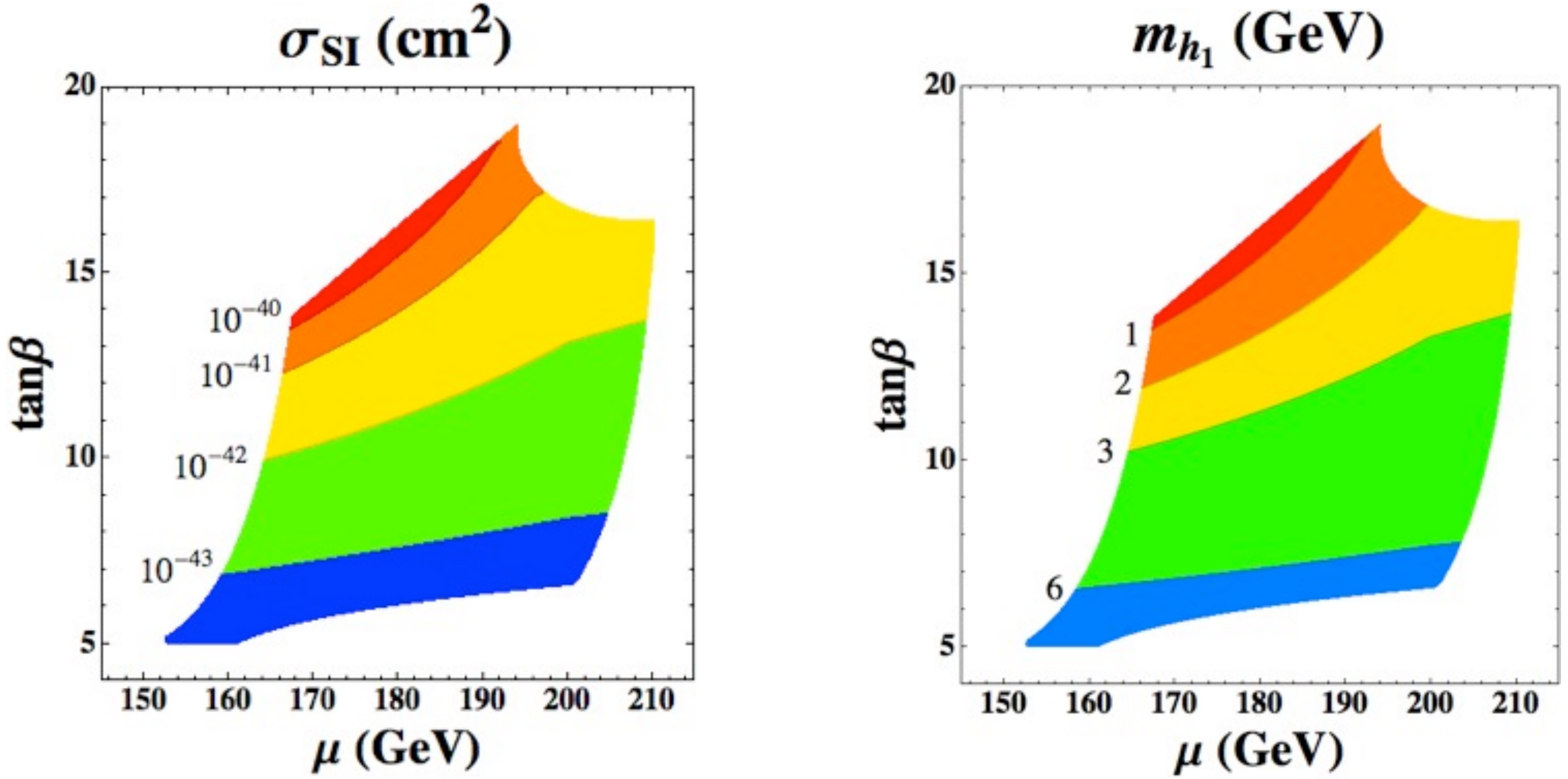




$$\sigma_{\rm SI} \approx \frac{\left(\left(\frac{\varepsilon}{0.04}\right) + 0.46\left(\frac{\lambda}{0.1}\right)\left(\frac{v}{\mu}\right)\right)^2 \left(\frac{y_{h_1\chi_1\chi_1}}{0.003}\right)^2 10^{-40}{\rm cm}^2}{\left(\frac{m_{h_1}}{1{\rm GeV}}\right)^4}.$$

$$y_{h_1\chi_1\chi_1} \approx -\sqrt{2}\kappa$$

Simple correlation between light scalar mass and SI Cross Section



Dark Matter Relic Density

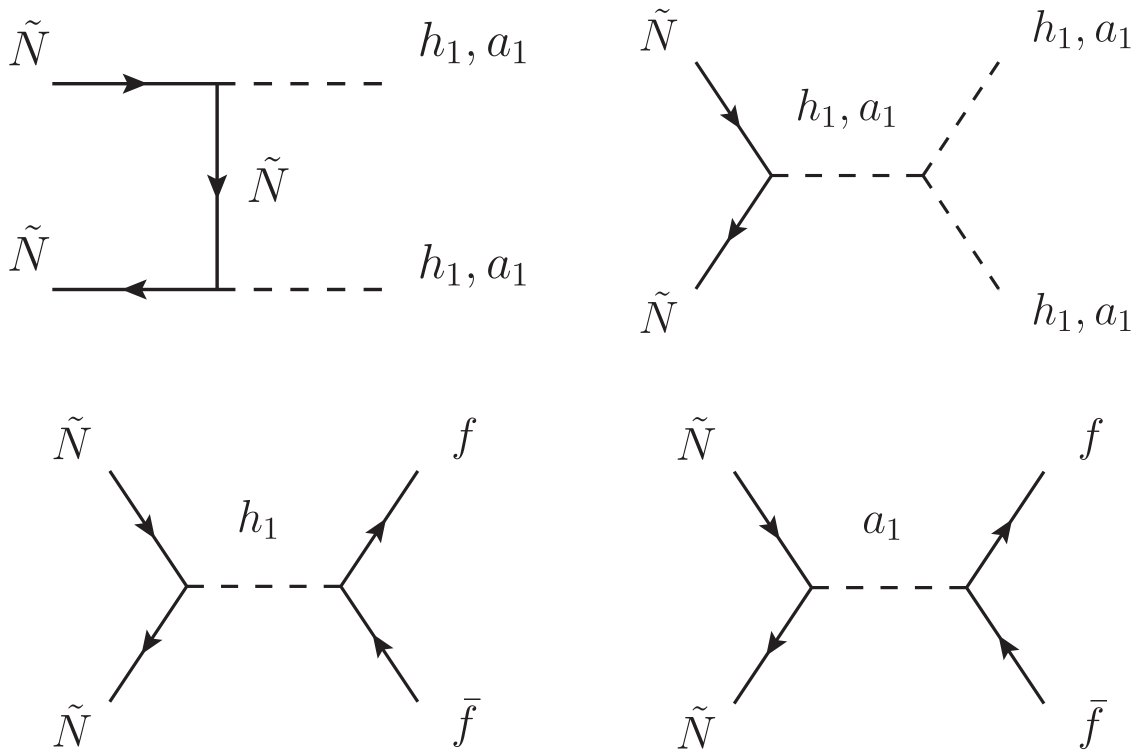
Dominant Annihilation Cross Sections

- Channel I

  $\kappa^4 m_{\chi_1}^{-2}$ suppressed

- Channel II

  $\kappa^2 Y_b^2 S_{1d}^2 m_{\chi_1}^{-2}$ $(\kappa^2 Y_b^2 P_{1d}^2 m_{\chi_1}^{-2})$



S-channel annihilation from light pseudoscalar dominant annihilation channel

Resonant effects at finite T should be properly taken into account while computing the thermal average cross section.

Dark Matter Relic Density

- The annihilation cross section is given by

$$\sigma_{f\bar{f}} v_{\chi_1} \approx \frac{3|\, y_{a_1\chi_1\chi_1}\, y_{a_1 f f}|^2 (1 - m_f^2/m_{\chi_1}^2)^{1/2}}{32\pi m_{\chi_1}^2 \left(\delta^2 + \left|\frac{\Gamma_{a_1} m_{a_1}}{4 m_{\chi_1}^2}\right|^2\right)}$$

$$\delta \equiv |(1 - v_{\chi_1}^2/4)^{-1} - m_{a_1}^2/(4m_{\chi_1}^2)|$$

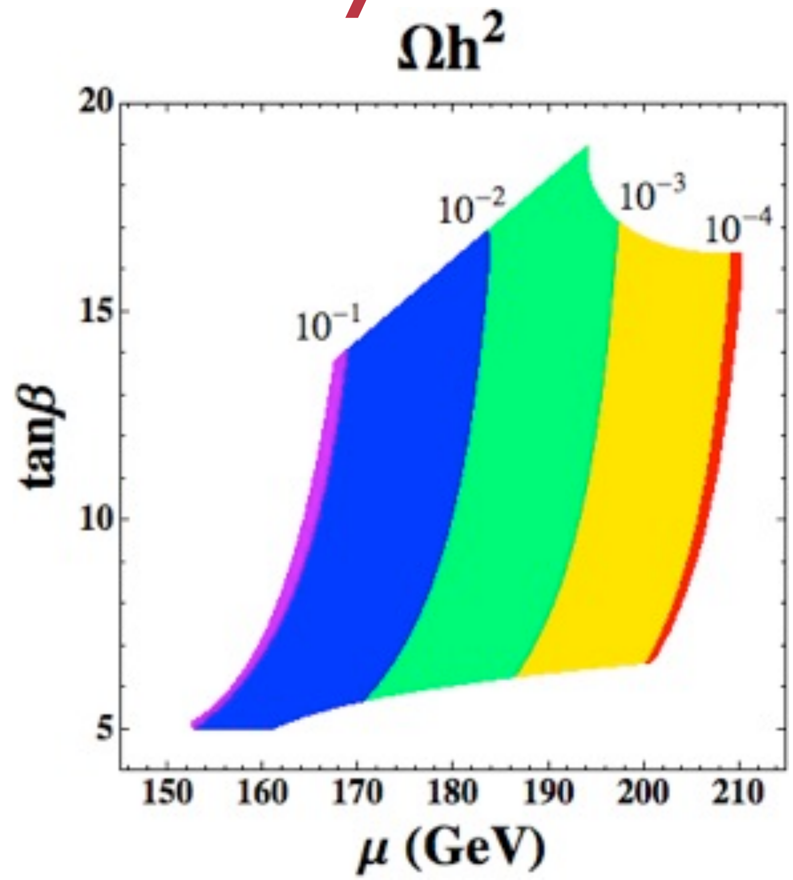
- Due to the resonance effect, we have

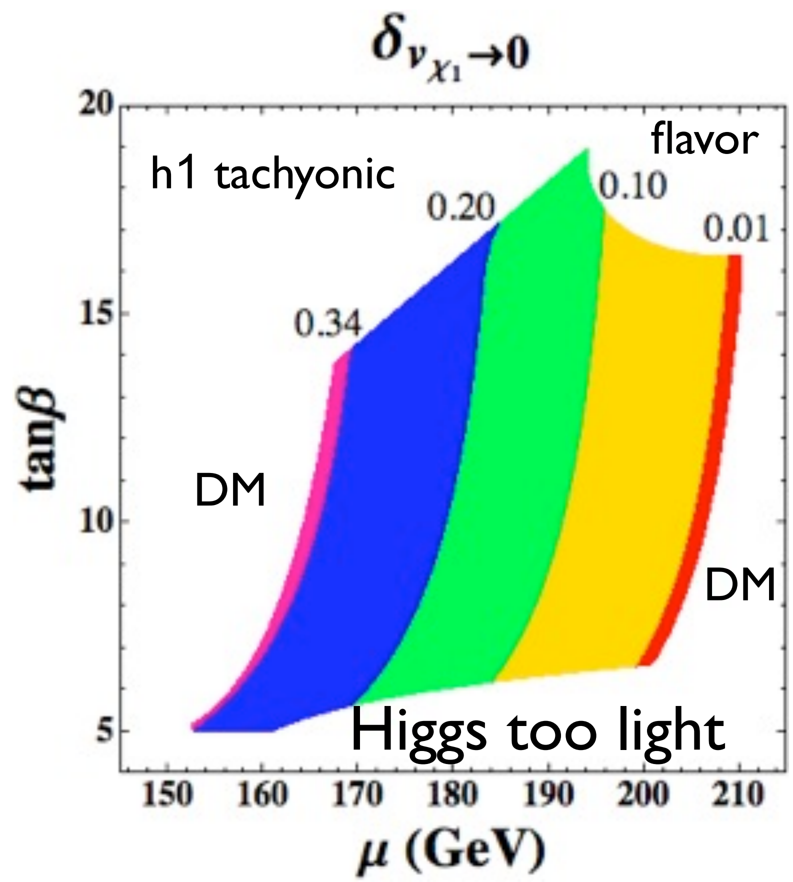
$$\Omega h^2 \approx \frac{0.1\left(\frac{m_{a_1}}{15\text{GeV}}\right)\left(\frac{\Gamma_{a_1}}{10^{-5}\text{GeV}}\right)\left(\frac{\mu}{v}\right)^2\left(\frac{0.003}{\kappa}\right)^2\left(\frac{0.1}{\lambda}\right)^2}{\text{erfc}\left(\frac{2m_{\chi_1}}{m_{a_1}}\sqrt{x_f \delta_{v_{\chi_1}\to 0}}\right)/\text{erfc}(2.2)}$$

- The numerical result shows a $\delta_{v_{\chi_1}\to 0} \simeq 0.3 - 0.35$ is needed to give a correct relic abundance.

- This will constrain the soft parameter A_κ since

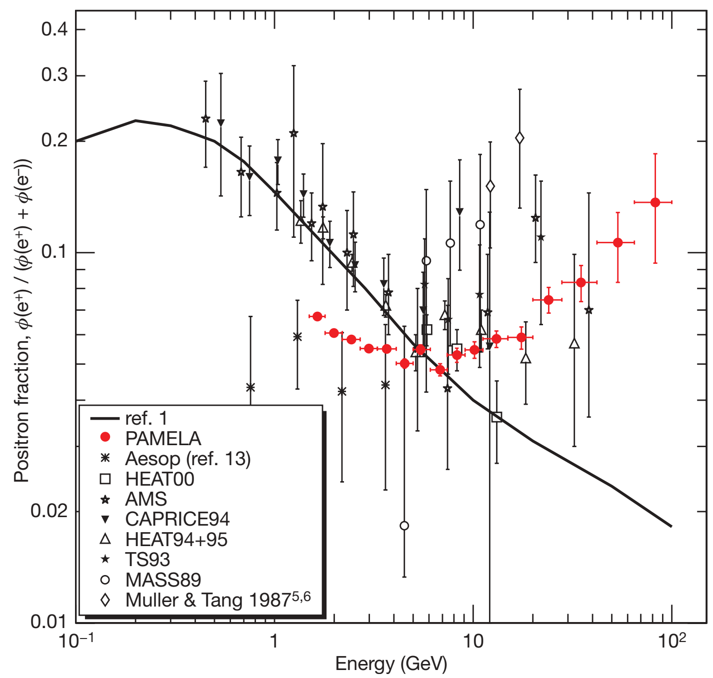
$$1 - \delta_{v_{\chi_1}\to 0} \approx -\frac{3\lambda A_\kappa}{16\kappa\mu}$$

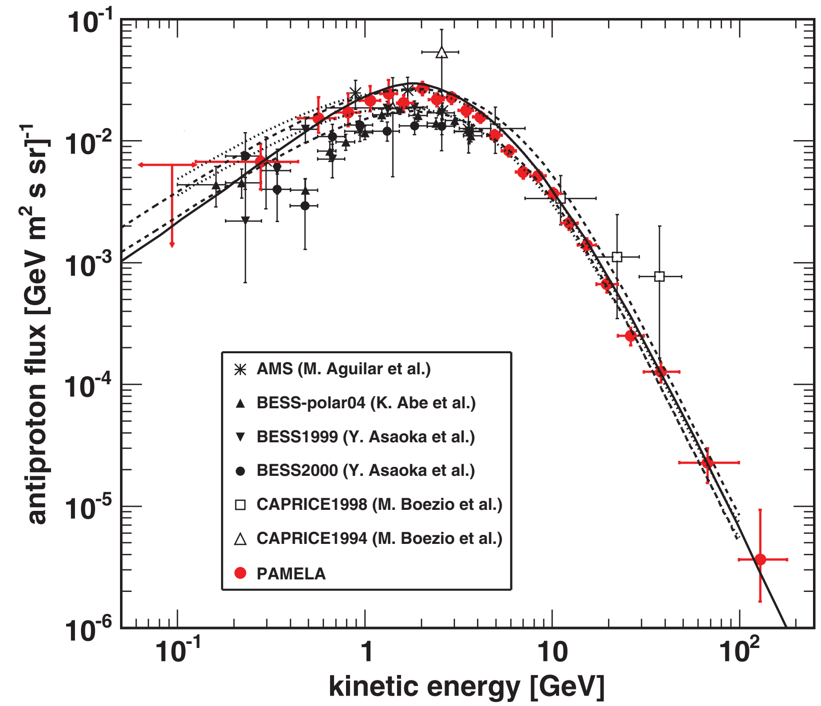


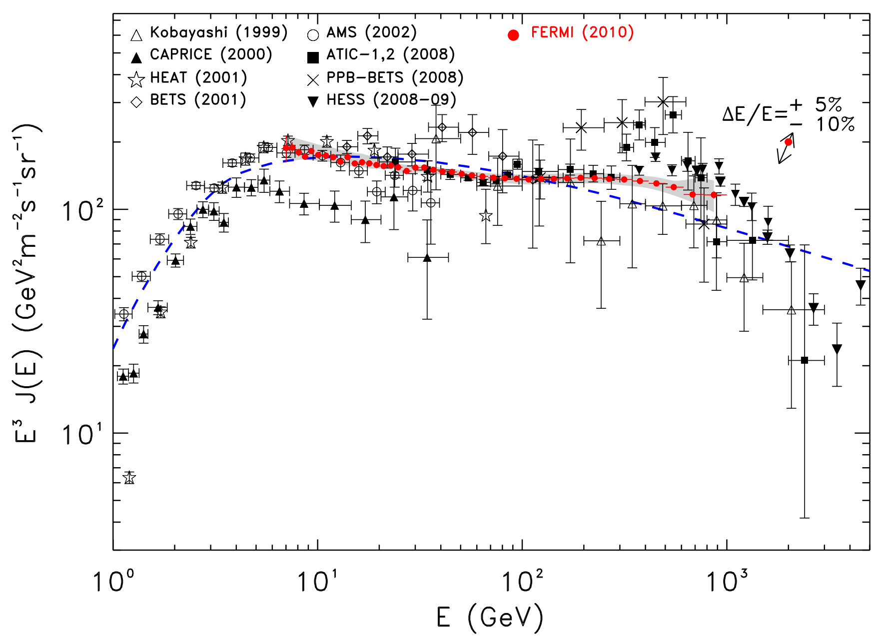


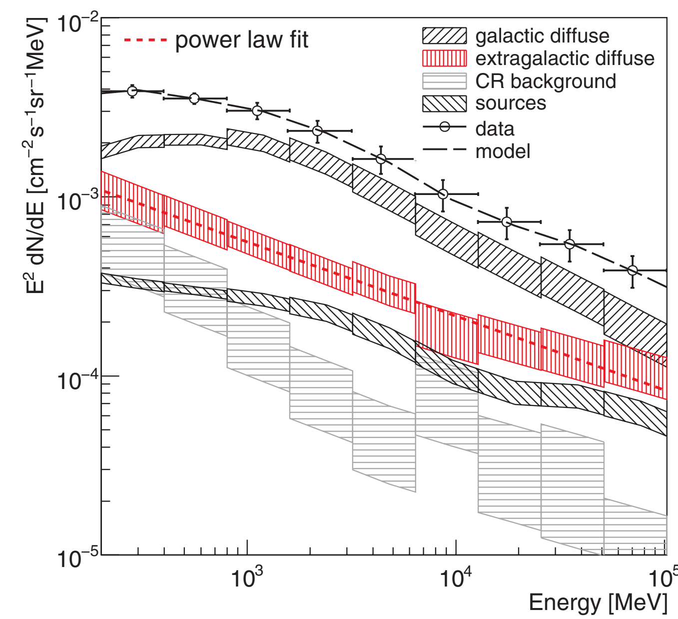
$\lambda = 0.12, \quad \kappa = 2.7\ 10^{-3}, \quad A_\kappa = -24$ GeV

Indirect Dark Matter detection









O. Adriani etc., Nature Vol 458 607, 2009; O. Adriani etc., Phys Rev Lett 105, 121101 (2010)

Fermi LAT Collaboration, arXiv: 1008.3999 [astro-ph.HE]; Fermi LAT Collaboration, Phys Rev Lett 104, 101101 (2010)

Indirect Dark Matter Detection Constraints

- We cannot explain the Pamela or Fermi "excesses", that should come from other sources.

- Since dominant annihilation channel is into bottom quarks, then the antiproton flux constraints could be important.

- However, these signals become weak, orders of magnitude smaller than the current bounds.

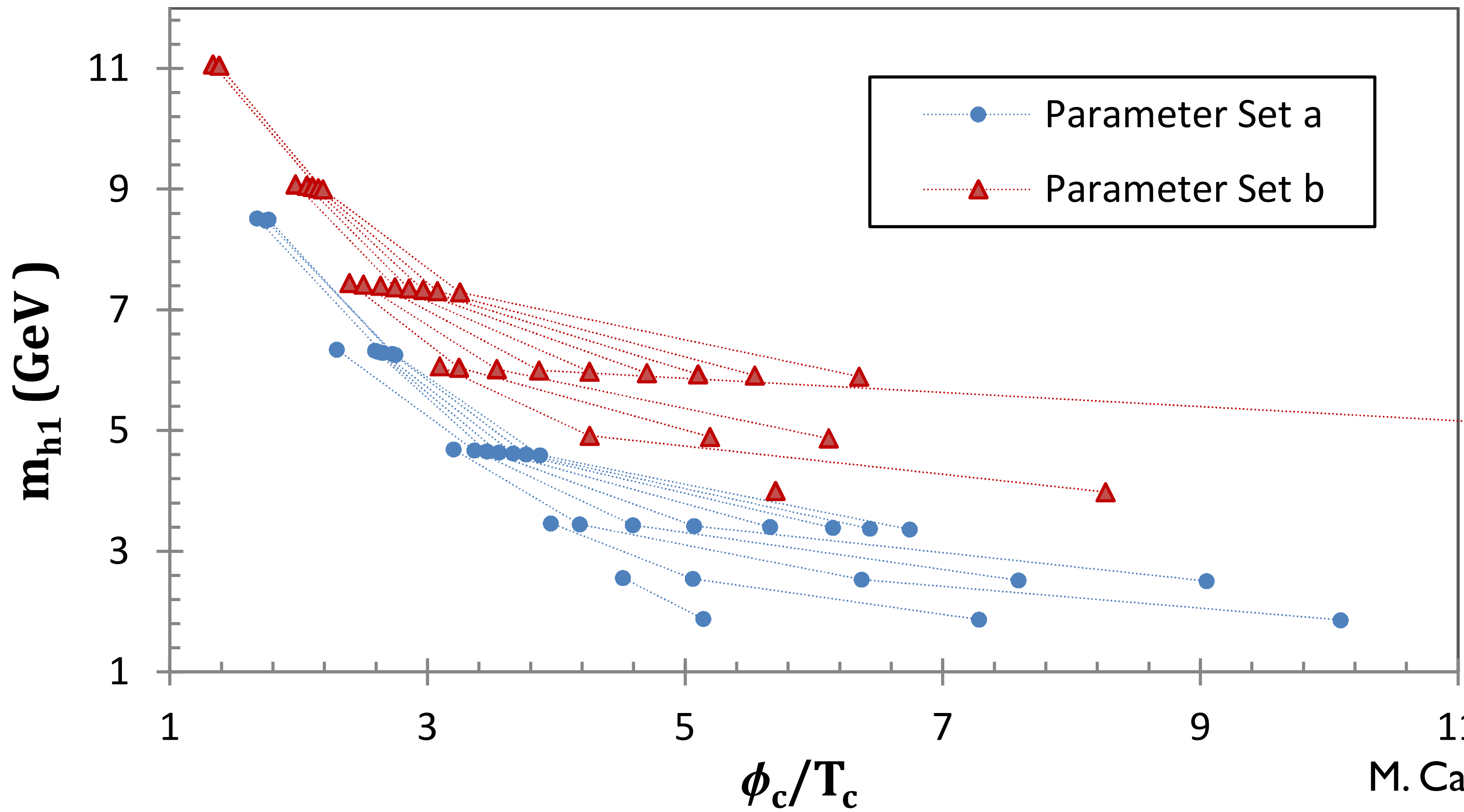
- The reason is that the cross section is considerably suppressed with respect to the thermal average one, since masses are away from resonance

$$\langle \sigma v \rangle_{\text{today}} \ll \langle \sigma v \rangle_{\text{freezing out}}$$

Light Dark Matter and the Electroweak Phase Transition

A strong electroweak phase transition allows the realization of the mechanism of electroweak baryogenesis

Kuzmin, Rubakov and Shaposhnikov, '85—'87

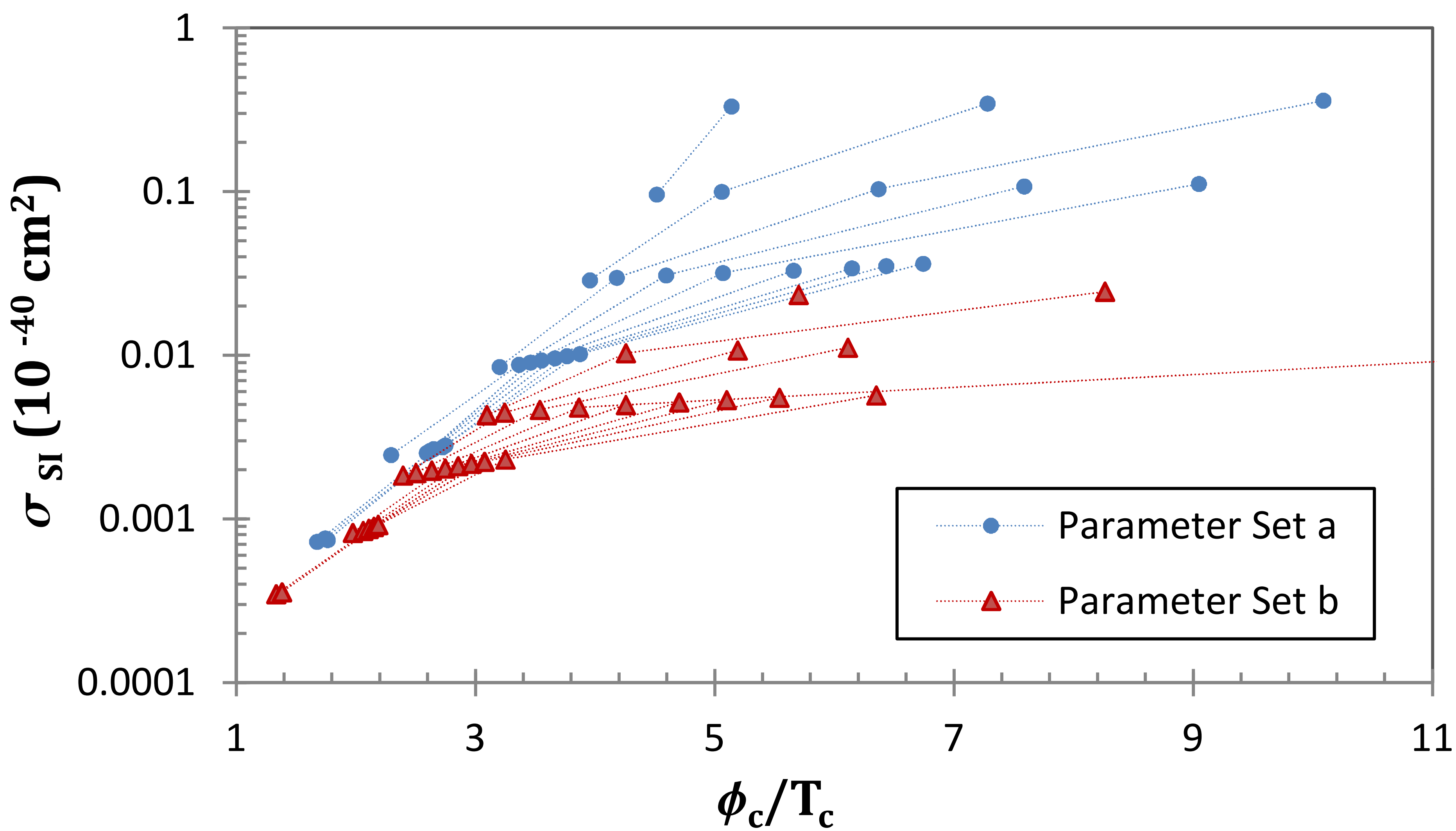


M. Carena, N. Shah, C.W.'11

Interesting correlation between the mass of lightest CP-even Higgs mass and phase transition strength

Correlation between SI cross section and phase transition strength

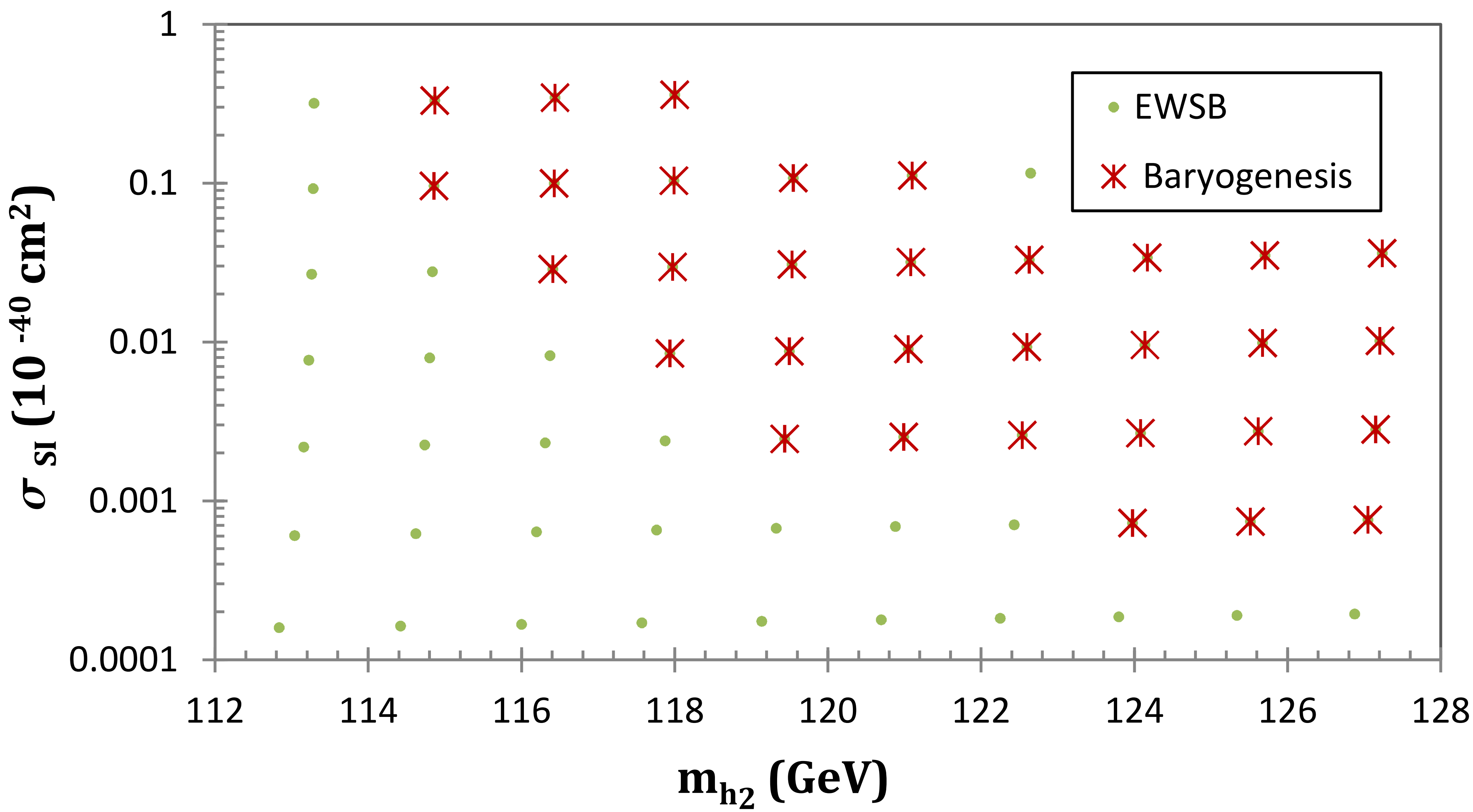
M. Carena, N. Shah, C.W.'11



Correlation induced by the dependence of the
SI cross section on the lightest CP-even Higgs mass

SM-Like Higgs and SI cross section

M. Carena, N. Shah, C.W.'11



Large SI cross sections can be obtained for acceptable SM-like Higgs masses

LHC Tests : Search for Electroweakinos

M. Carena, S. Gori, N. Shah, C.W., to appear

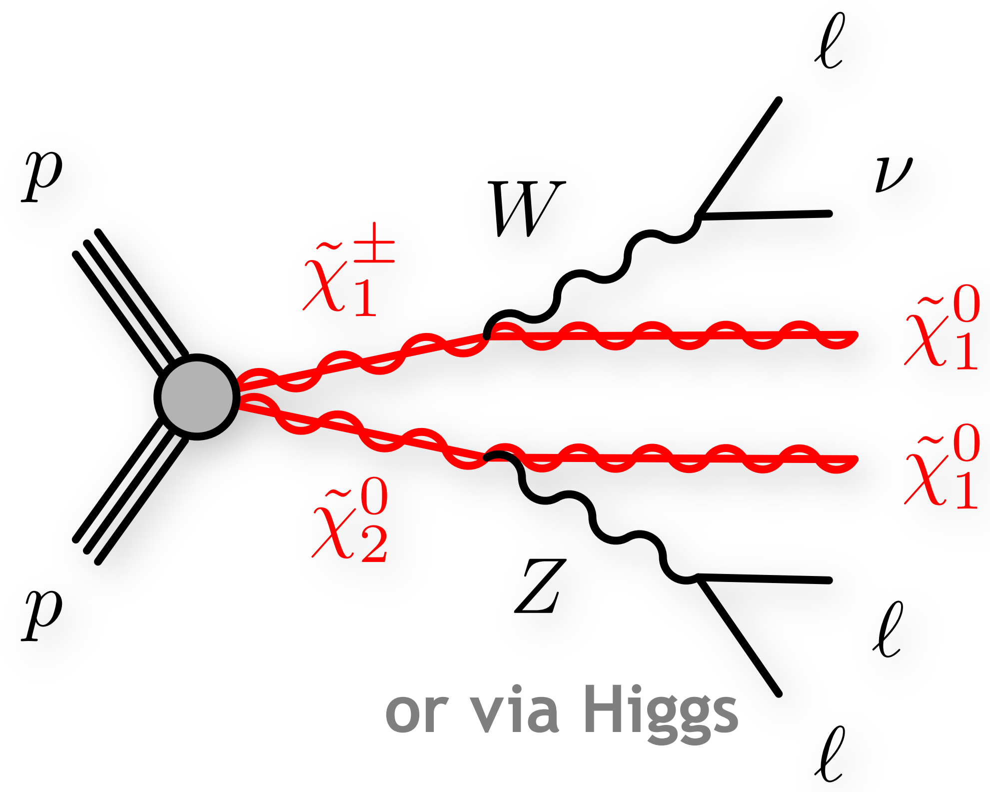
One important feature of this model is that μ cannot be too large, since it is related to $A_\lambda \simeq \mu \tan\beta$. The Higgsino mass parameter should be smaller than a few hundred GeV.

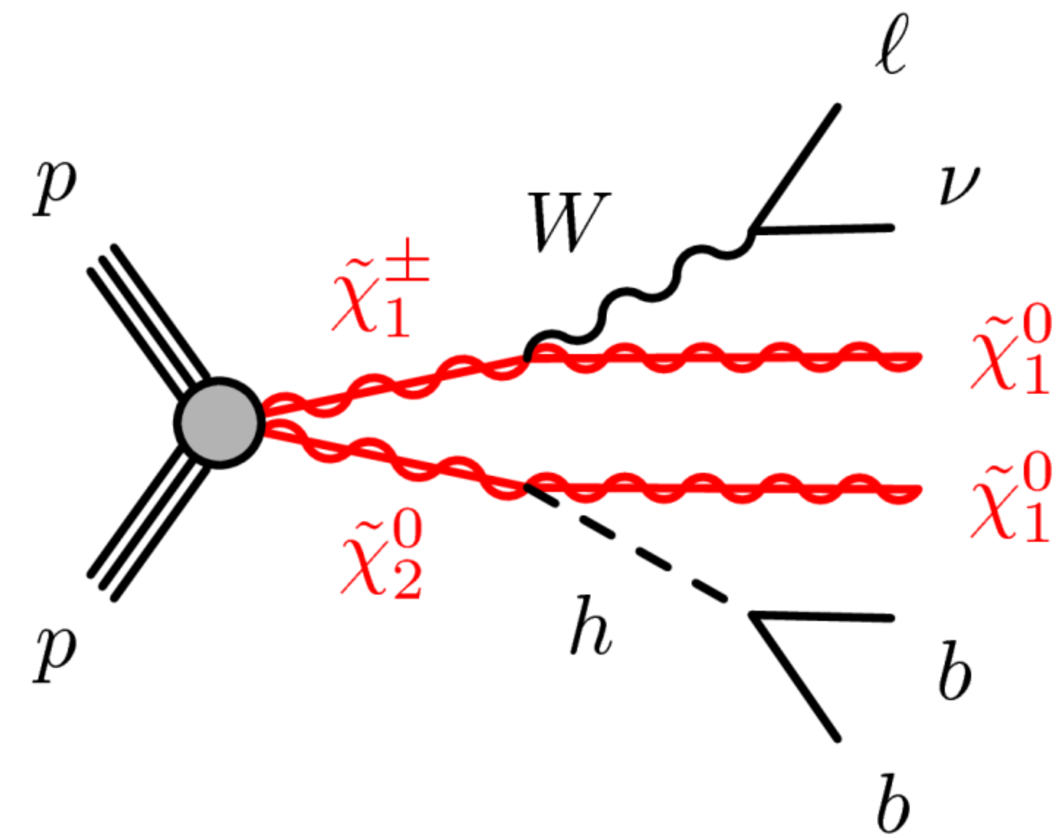
Small values of μ implies light Higgsinos.

Light Higgsinos may be tested at the LHC, mainly in the trilepton channel

Exact gaugino masses have an impact on this scenario, with lighter gauginos leading to more decays of the lightest neutralino into Higgs bosons.

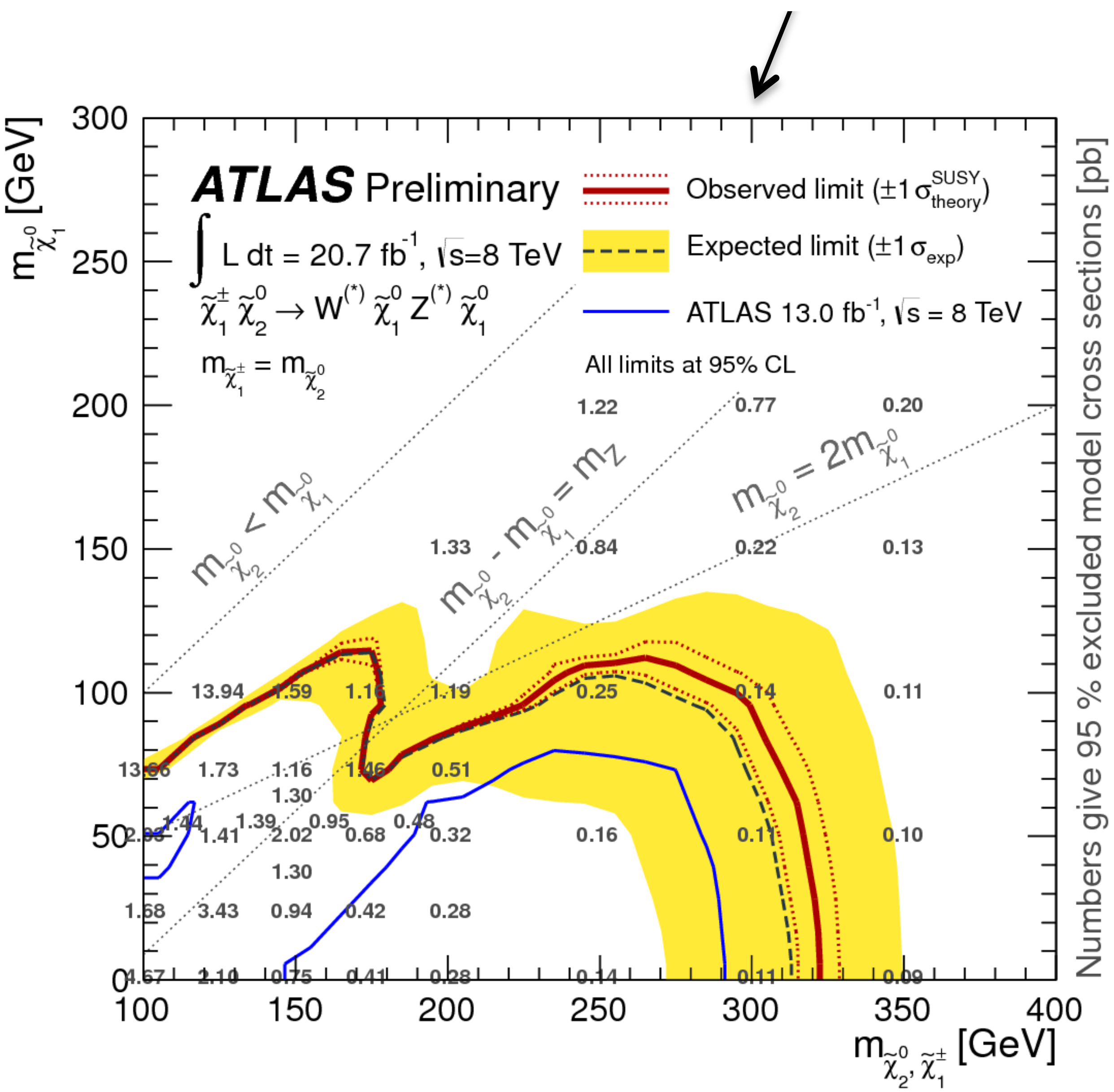
Relevant production channels

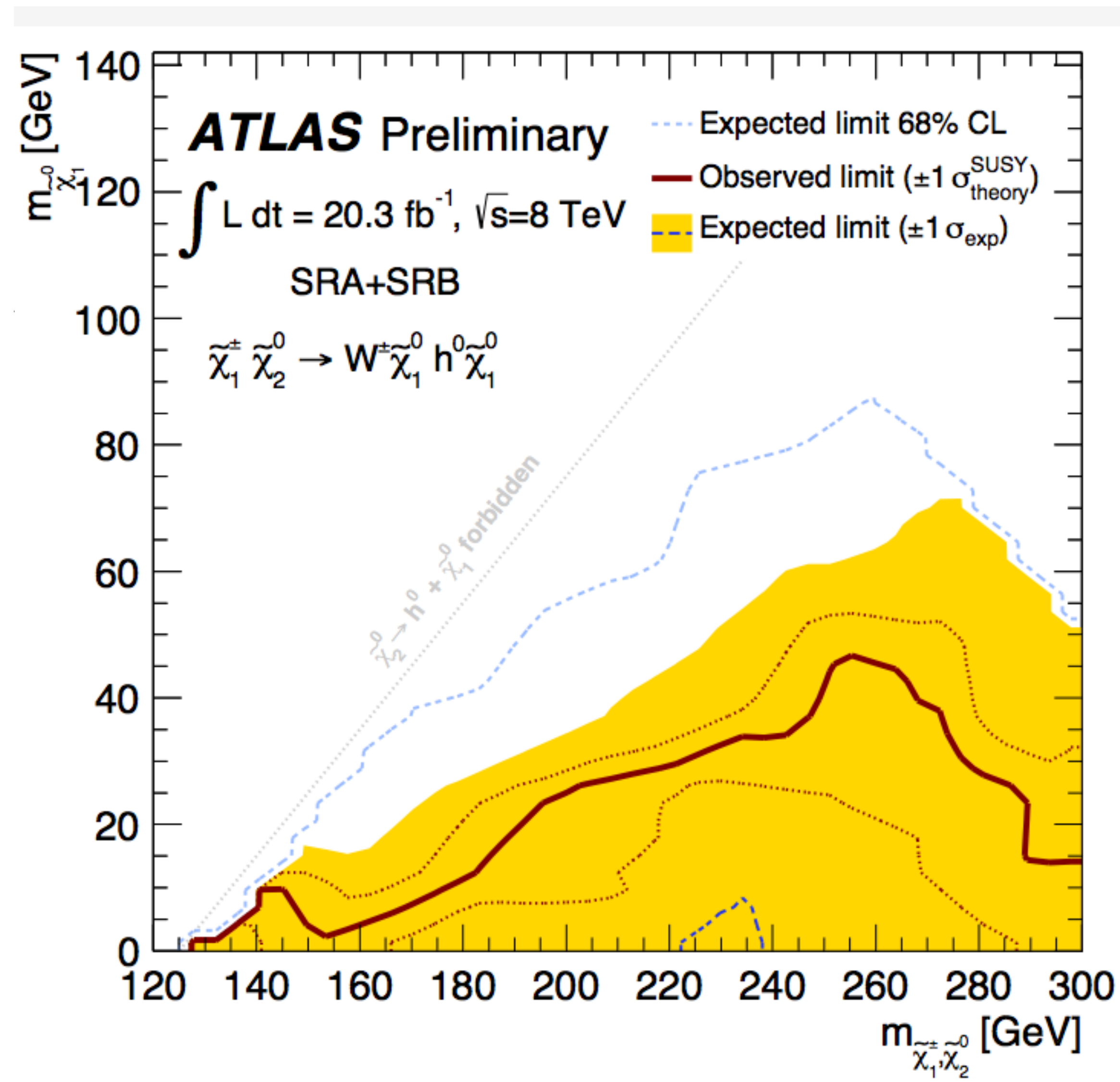




Trileptons coming from gauge bosons constitute the most important search channel, but Higgs channel is starting to be explored.

ATLAS results in trileptons and Higgs + W searches

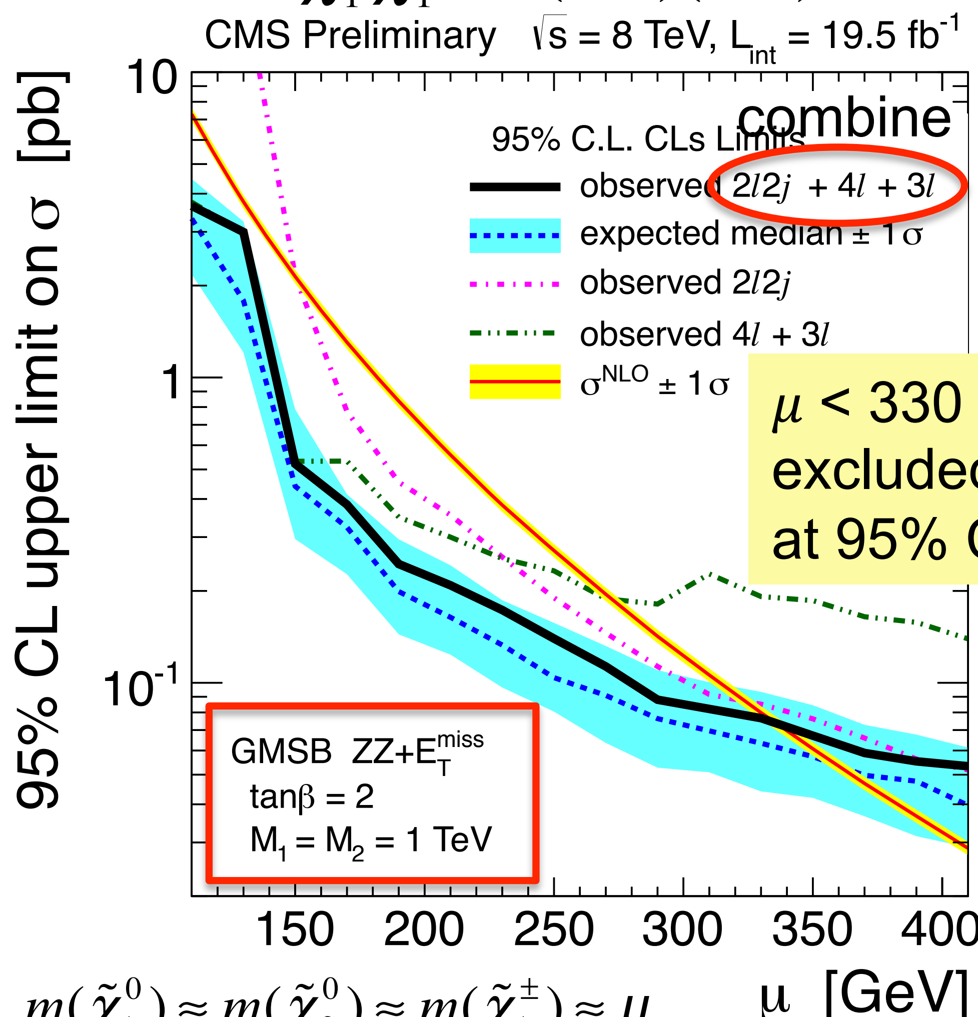




CMS Results. Impact of light sleptons

GMSB Z-enriched higgsino scenario

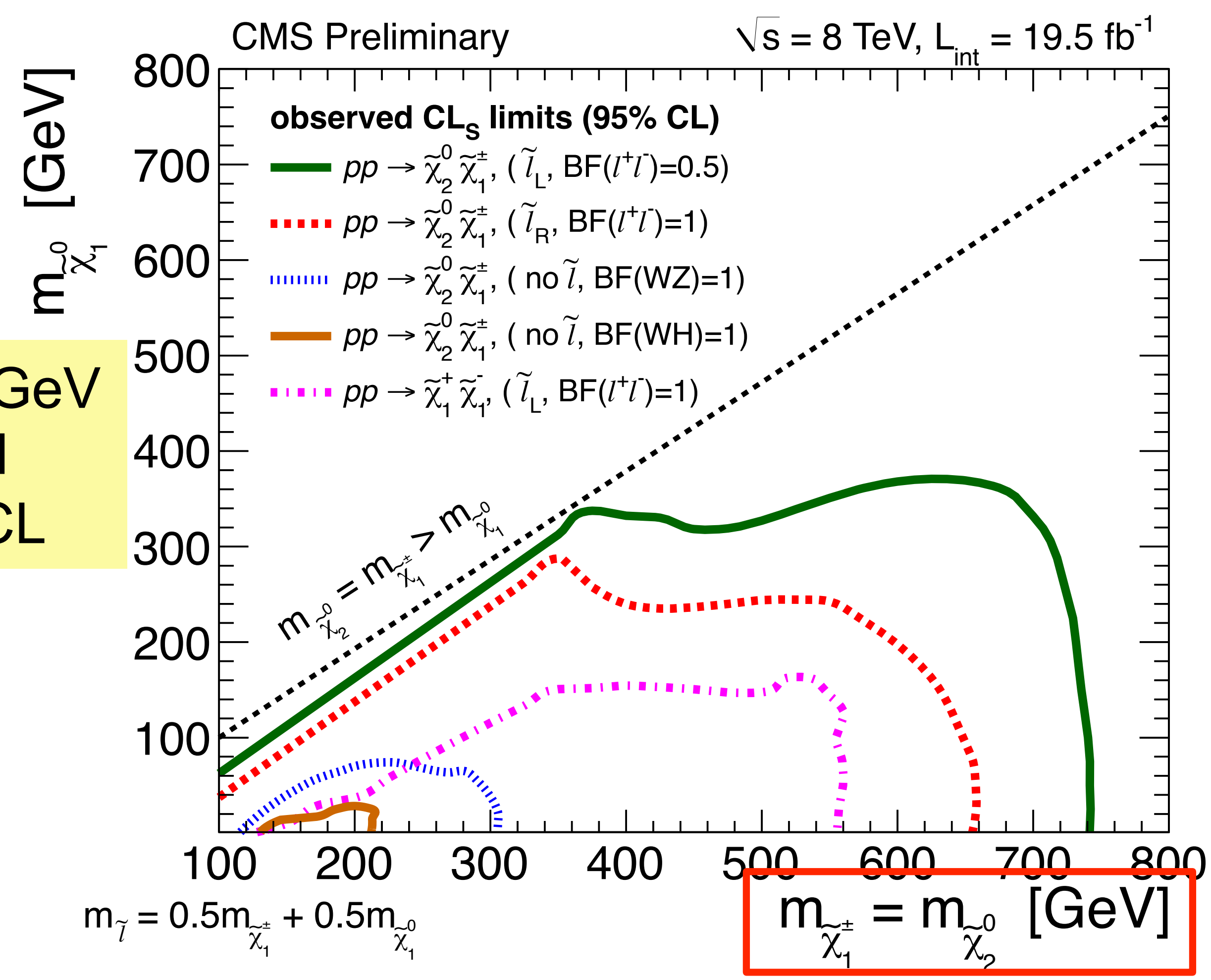
$$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow (Z\tilde{G})(Z\tilde{G})$$



μ < 330 GeV excluded at 95% CL

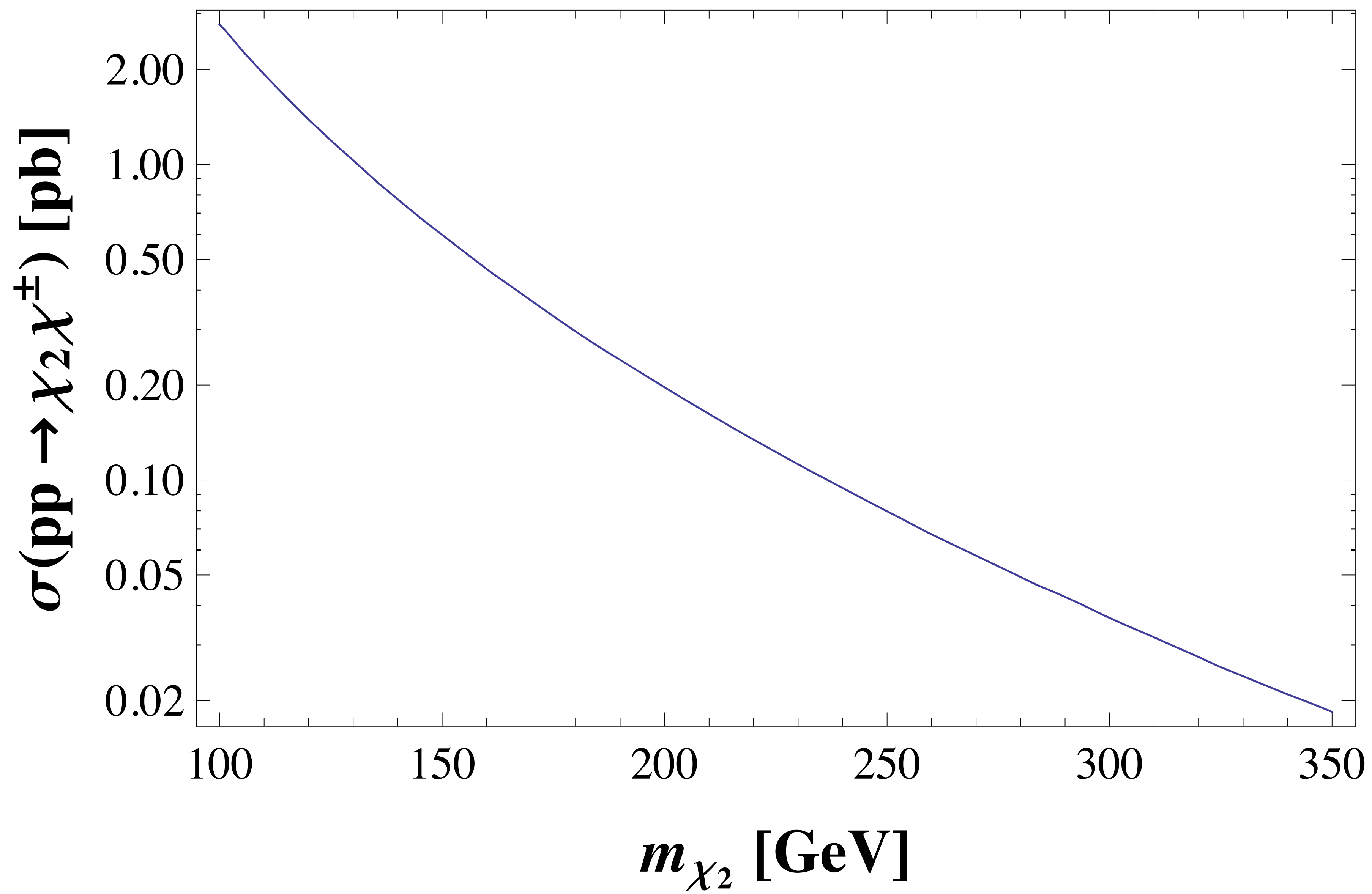
$$m(\tilde{\chi}_1^0) \approx m(\tilde{\chi}_2^0) \approx m(\tilde{\chi}_1^\pm) \approx \mu$$

Chargino-Neutralino production/decay scenarios



Higgsino Cross Sections

Bounds before relevant for charginos and second lightest neutralinos with dominant wino component. Higgsino production cross section a factor 4 smaller (per neutral Higgsino) !



Decay Branching Ratios

- In this model, the lightest chargino decays one hundred percent of the time into a W and a light neutralino
- The second lightest neutralinos, instead, tend to decay in average about 60 percent of the time into a neutralino and a Z, and 40 percent of the time into a Higgs and a neutralino
- The bounds are therefore further weakened with respect to the ones found by ATLAS and CMS.

We found that the current bound on the Higgsino mass parameter is of about
$\mu > 250$ GeV at both ATLAS and CMS

Bounds tend to be weakened for lighter binos (keeping the winos heavy)
due to an increase of decays into Higgs bosons.

Conclusions

- Dark Light Higgs scenario is a region of parameters in the MSSM, where one finds
- A light, mostly singlet scalar Higgs, with mass below about 10 GeV
- A light, mostly singlet pseudoscalar Higgs with mass below about 20 GeV
- A light, mostly singlet, neutralino, with mass below about 10 GeV
- This scenario is in agreement with all experimental constraints coming from high energy collider as well as flavor experiments. It can lead to the proper relic density, with indirect dark matter annihilation signatures well within current bounds.
- Furthermore, for a sufficiently light scalar Higgs it can lead to a large direct dark matter cross section, consistent with values suggested by COGENT, DAMA and CMDS (Si) (but challenged by XENON).
- Strength of the electroweak phase transition correlated with the SI cross section one.
- This scenario is being probed by LHC searches for Higgsinos in trilepton final states. Higgs states abundantly produced from SUSY particle decays.