# Phenomenology of light neutralinos in view of recent results at the CERN Large Hadron Collider

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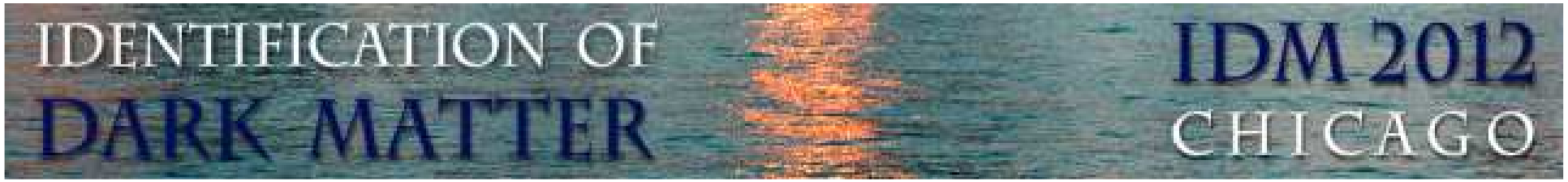

# Searching for susy dark matter is not for the faint of heart

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**Particle physics**

## The dark at the end of the tunnel?

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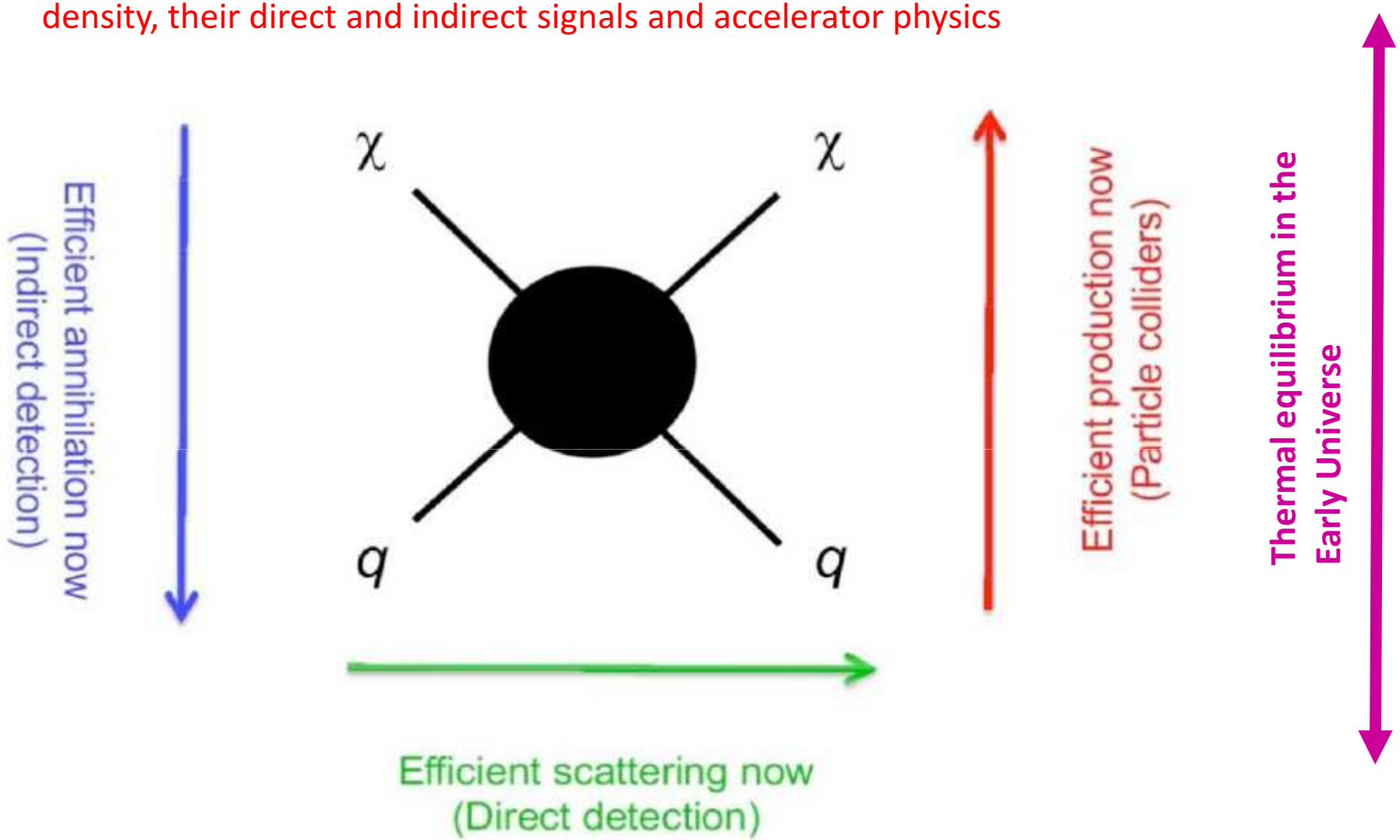
## LHC results put supersymmetry theory 'on the spot'

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.**

The logic connection between Weakly Interacting Massive Particles (WIMPs) relic density, their direct and indirect signals and accelerator physics




The same class of interactions that kept WIMPS in thermal equilibrium in the early Universe could allow their detection today

**is it possible to get correlations in a model independent way?**

The LHC-direct-detection connection: three possible quantitative approaches:

1. Minimal SUGRA
2. Effective theory
3. <u>Your (my) favorite model</u>

# The specific scenario of and effective MSSM

# *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
- $\mu$ 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 $H^{\pm}$)
- $m_q$ 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→$R$=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 $N_\nu$ 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

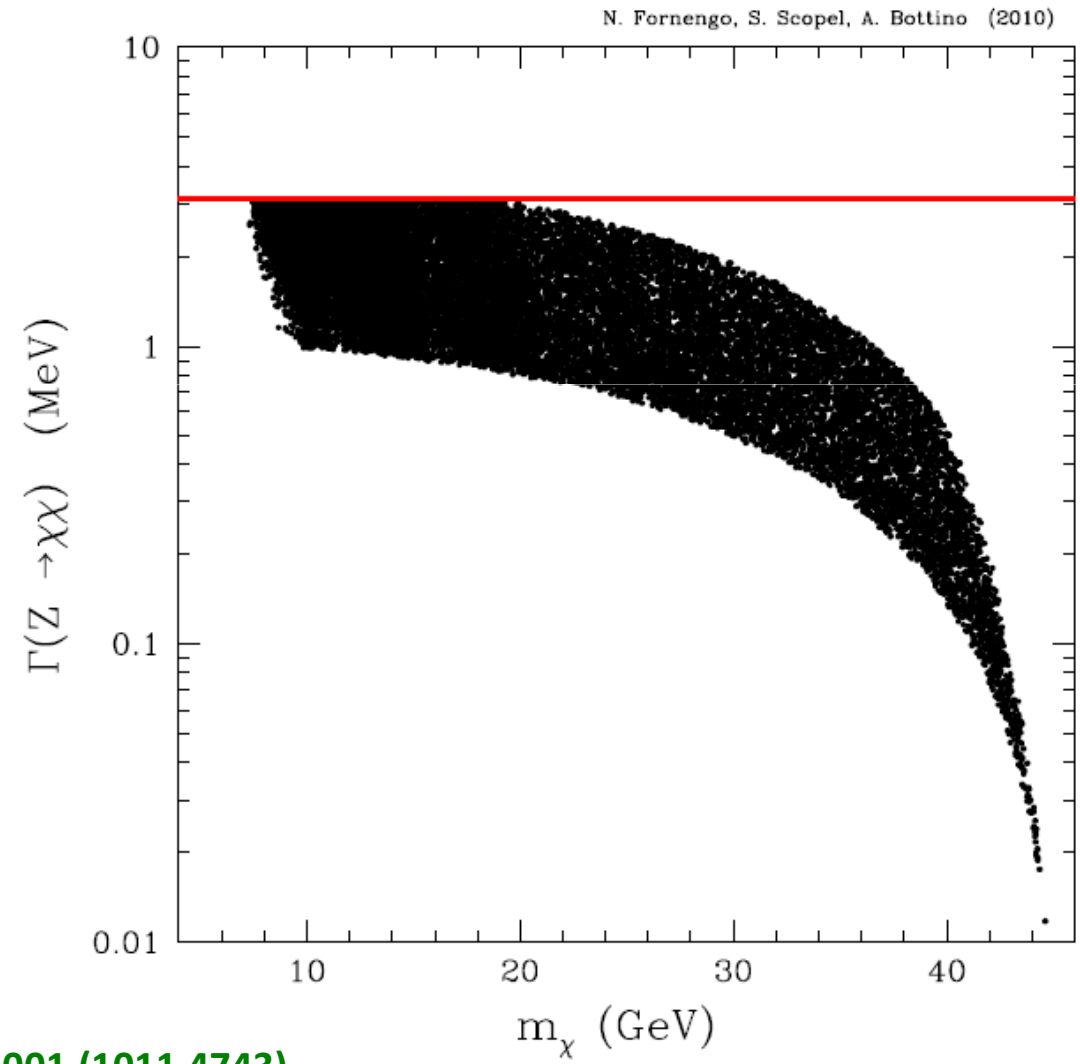
➠ No absolute direct lower bounds on $m_\chi$

## Constraint from the invisible width of the Z boson at LEP

$$\Gamma(Z \to \chi\chi) = 166 \text{ MeV } [1 - (2m_\chi)^2/M_Z^2]^{3/2}\, a_3^4$$

Assuming: $\Gamma(Z \to \chi\chi) < 3$ MeV

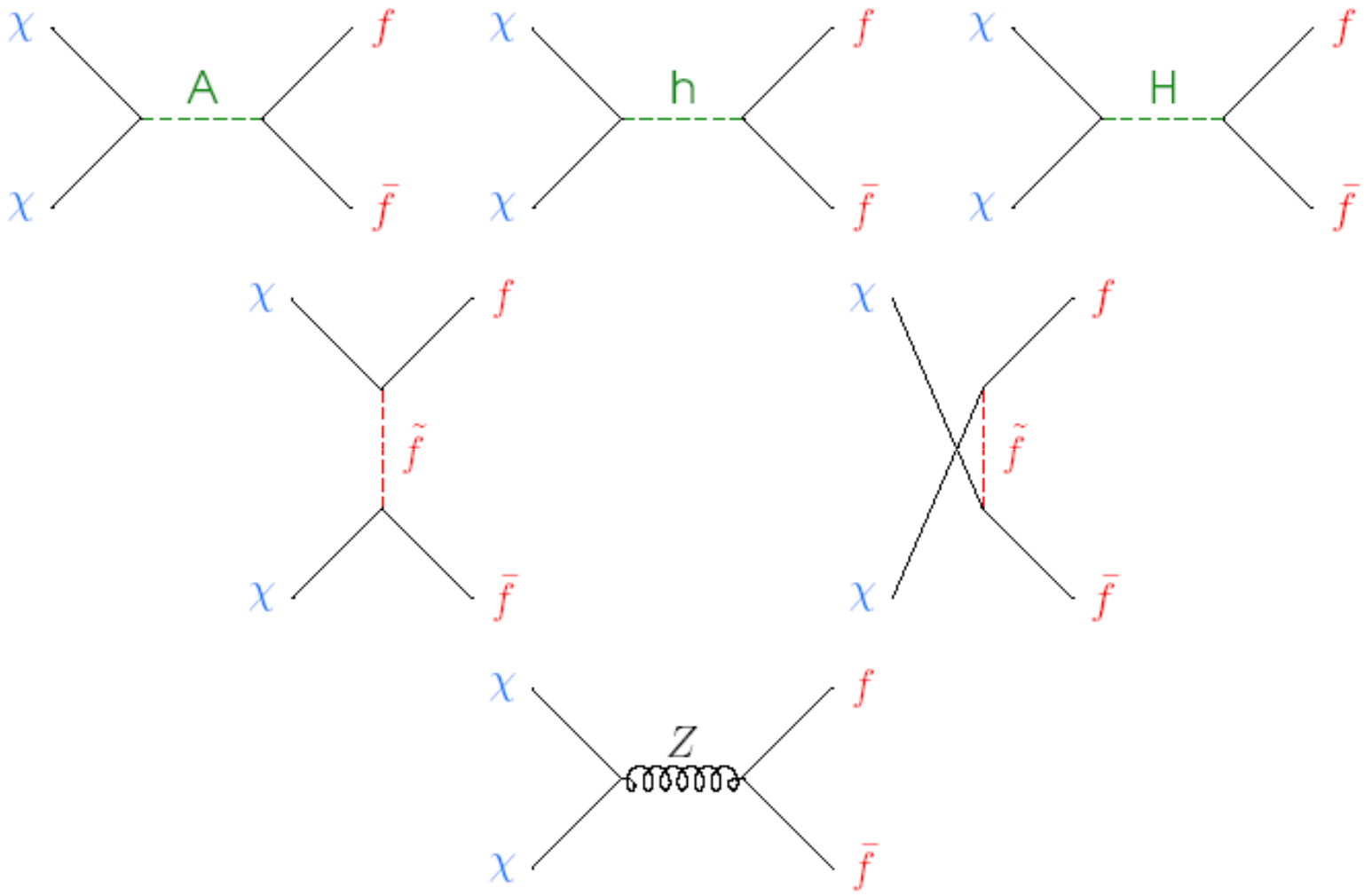
$a_1^2 a_1^2 < 0.12$




Fornengo, Scopel, Bottino, PhysRevD.83.015001 (1011.4743)

In relic abundance:

## $\chi$–$\chi \to f\bar{f}$ annihilation cross section - Diagrams (low $m_\chi$)




$(m_\chi \leq M_W)$

## Approximate analytic expressions at small $m_\chi$

- The dominant terms in $\langle \widetilde{\sigma_{\rm ann}\, v} \rangle_{\rm int}$ are the contributions due to Higgs-exchange in the $s$ channel and sfermion-exchange in the $t, u$ channels of the annihilation process $\chi + \chi \to \bar{f} + f$.

- For $m_A \lesssim 200$ GeV Higgs–exchange contribution due to S-wave annihilation into down-type fermions dominates:

$$\langle \widetilde{\sigma_{\rm ann}\, v} \rangle_f^{Higgs} \simeq \tilde{a}_f^{Higgs} \simeq$$

$$\simeq \frac{2\pi\alpha_{e.m.}^2 c_f}{\sin^2\theta_W \, \cos^2\theta_W} a_1^2 a_3^2 \tan^2\beta \, (1+\epsilon_f)^2 \, \frac{\bar{m}_f^2}{m_W^2} \frac{m_\chi^2 \, [1 - m_f^2/m_\chi^2]^{1/2}}{[(2m_\chi)^2 - m_A^2]^2}$$

  - $c_f = 3$ for quarks, $c_f = 1$ for leptons
  - $\bar{m}_f$= fermion running mass evaluated at the energy scale $2m_\chi$
  - $m_f$ = fermion pole mass
  - $\epsilon_f$ = one–loop correction to the relationship between a down–type fermion running mass and the corresponding Yukawa coupling $(m = h \times v \times (1+\epsilon))$

## Cosmological lower bound on $m_\chi$ (low $m_A$ mass)

- $\Omega_\chi h^2 < 0.131$

- $< \widetilde{\sigma_{ann} v} >$ is an increasing function of $m_\chi$

- The maximal value $(< \widetilde{\sigma_{ann} v} >)_{max}$ at fixed $m_\chi$ is obtained by inserting into $< \widetilde{\sigma_{ann} v} >$ the product $a_1^2 a_3^2 \tan^2\beta$ for maximal bino–higgsino mixing:

  - $\frac{|a_3|}{|a_1|} \simeq 0.42 \ \sin\beta$
  - for $m_A \simeq$ 90 GeV, $\tan\beta < 45$ (CDF)

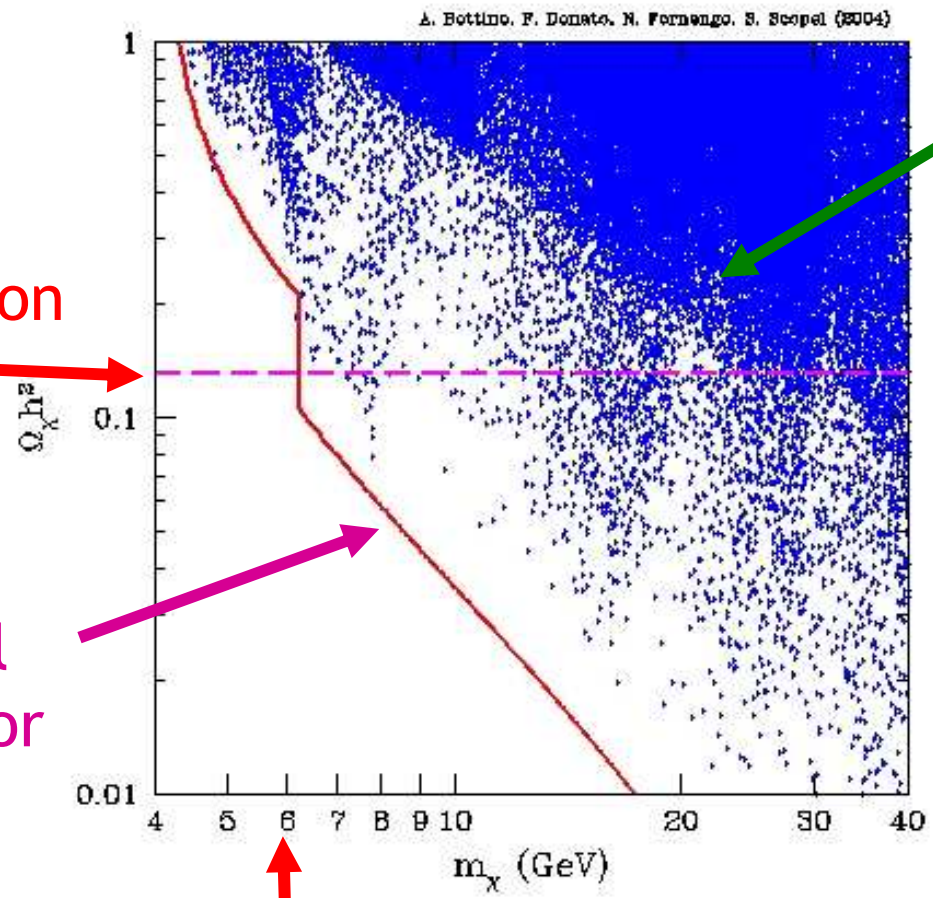
$$\Rightarrow (a_1^2 a_3^2 \tan^2\beta)_{max} \simeq 260$$

- Keeping only the dominant contribution to $b$–$\bar{b}$ final state:

$$m_\chi \, [1 - m_b^2/m_\chi^2]^{1/4} \gtrsim 5.3 \text{ GeV} \left(\frac{m_A}{90 \text{ GeV}}\right)^2$$

# Cosmological lower bound on $m_\chi$ (low $m_A$)

A. Bottino, F. Donato, N. Fornengo, S. Scopel, Phys. Rev. D 68, 043506 (2003)




scatter plot: full calculation

upper bound on $\Omega_{CDM}h^2$

curve: analytical approximation for minimal $\Omega_{CDM}h^2$

$$m_\chi \, [1 - m_b^2/m_\chi^2]^{1/4} \gtrsim 5.3 \text{ GeV} \left(\frac{m_A}{90 \text{ GeV}}\right)^2$$

à la Lee-Weinberg

# Sfermion-exchange contribution

- Important if $m_A \gtrsim 200$ GeV

- Both S-wave and P-wave contributions have to be taken into account in the expression:

$$\widetilde{\langle \sigma_{\rm ann}\, v \rangle}_f^{sfermion} \simeq \tilde{a}_f^{sfermion} + \frac{1}{2x_f}\tilde{b}_f^{sfermion}$$

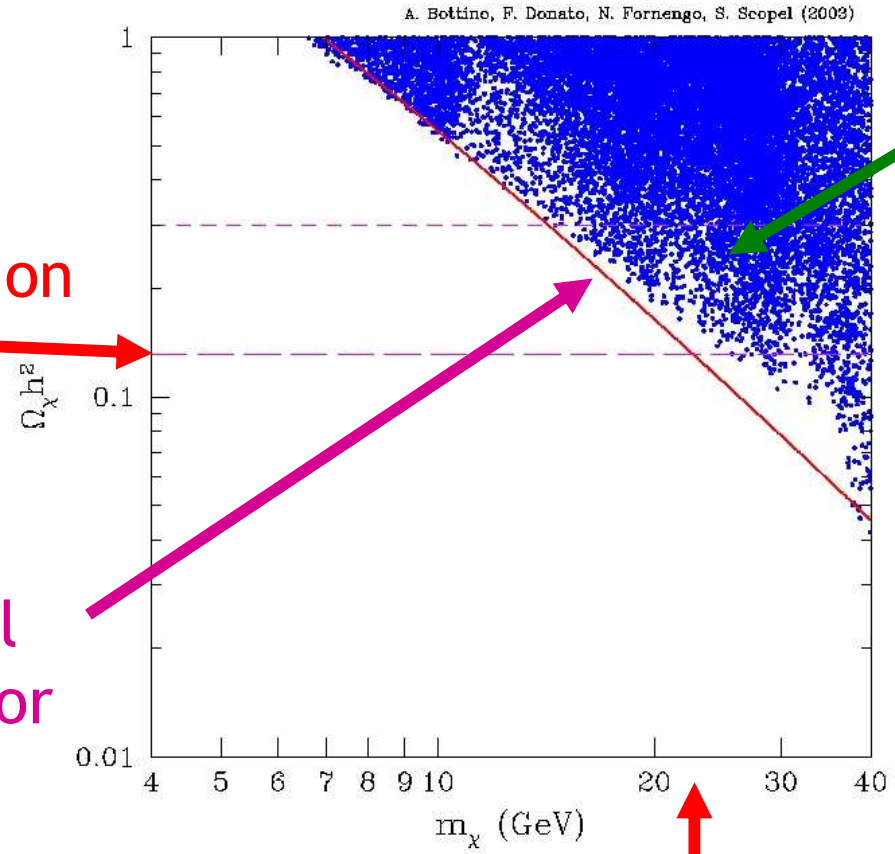
- Lowest $\Omega_\chi h^2$ obtained for $\tilde{\tau}$ exchange. Lightest $\tilde{\tau}$ ($m_{\tilde{\tau}} \simeq$ 87 GeV) if mixing is maximal

- $\widetilde{\langle \sigma_{\rm ann}\, v \rangle}^{sfermion} \simeq \widetilde{\langle \sigma_{\rm ann}\, v \rangle}_\tau^{sfermion}$ maximized by:

$$(\widetilde{\langle \sigma_{\rm ann}\, v \rangle}^{sfermion})_{max} \simeq \frac{\pi \alpha_{e.m.}^2}{8\cos^4\theta_W} \frac{m_\chi^2\,[1-m_\tau^2/m_\chi^2]^{1/2}}{m_{\tilde{\tau}}{}^4} \left[\left(2+\frac{5}{2}\,\frac{m_\tau}{m_\chi}\right)^2 + \frac{23}{2x_f}\right]$$

# Cosmological lower bound on $m_\chi$ ($m_A > 200$ GeV)

A. Bottino, F. Donato, N. Fornengo, S. Scopel, Phys. Rev. D 68, 043506 (2003)




scatter plot: full calculation

upper bound on $\Omega_{CDM}h^2$

curve: analytical approximation for minimal $\Omega_{CDM}h^2$

$$m_\chi \, [1 - m_\tau^2/m_\chi^2]^{1/4} \gtrsim 22 \text{ GeV} \, \left(\frac{m_{\tilde{\tau}}}{90 \text{ GeV}}\right)^2$$

à la Lee-Weinberg

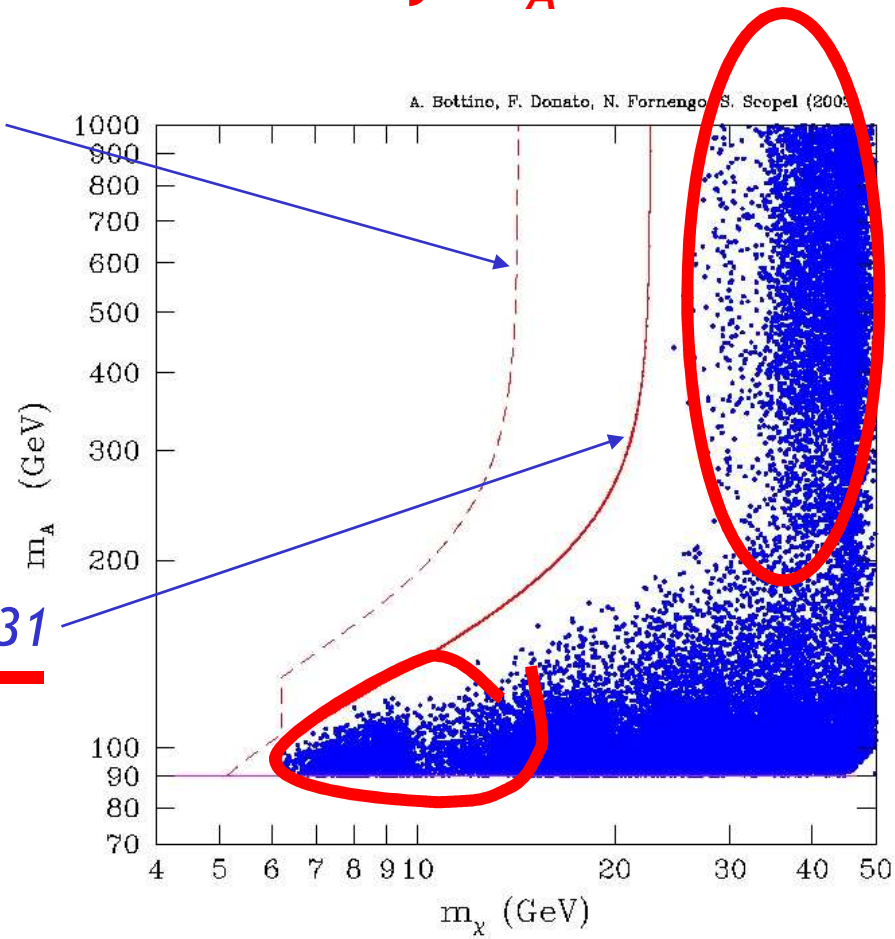
The bottom line: the cosmological lower bound on $m_\chi$ depends on the value of $m_A$:

✓ $m_\chi$ > 6 GeV for light $m_A$

✓ $m_\chi$ > 22 GeV for heavy $m_A$

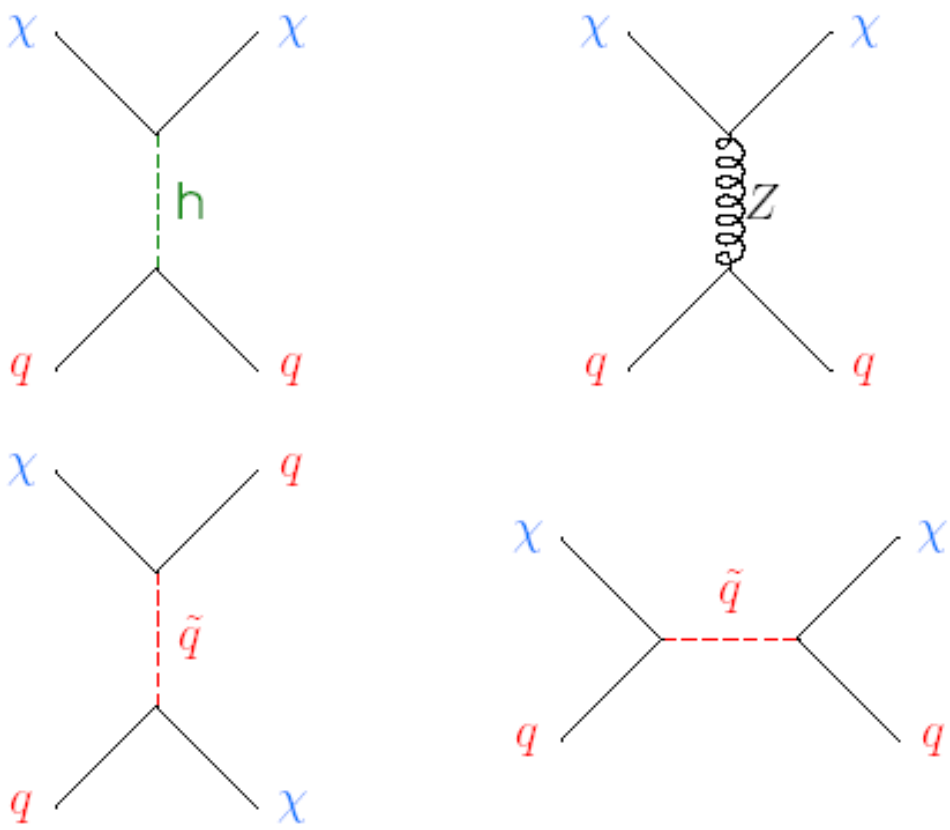
$(\Omega_{CDM}h^2)_{max} = 0.3$

$(\Omega_{CDM}h^2)_{max} = 0.131$



# Light neutralinos in eff-MSSM

## Neutralino–quark cross section - Diagrams




at very low mass same diagrams, correlation between relic density and cross section for direct detection

# Neutralino - nucleon cross section

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

**Color code:**
- $\Omega_\chi h^2 < 0.095$
- $\times\ \Omega_\chi h^2 > 0.095$

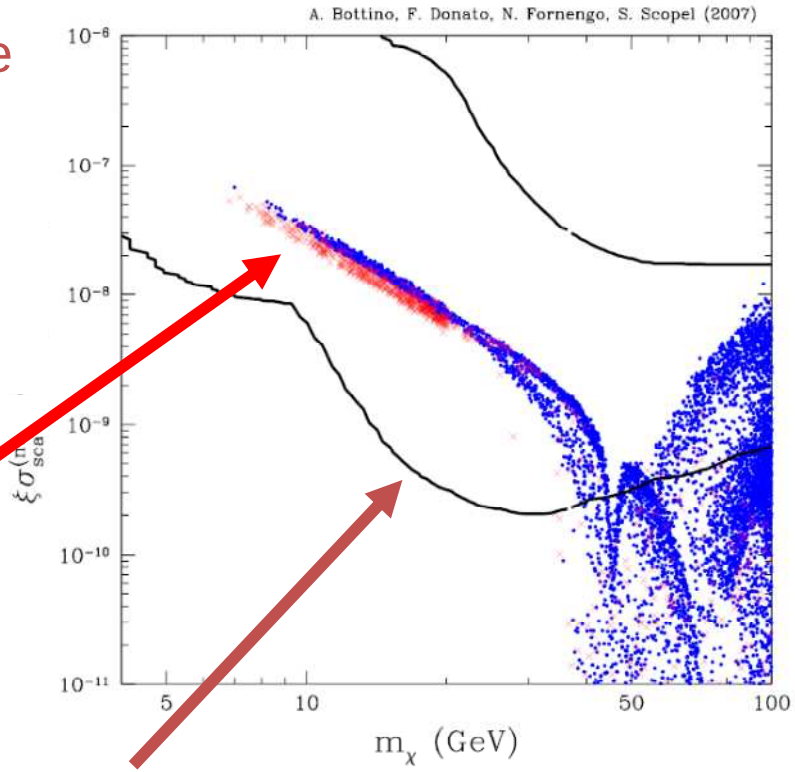
tight correlation between relic abundance and $\chi$-nucleon cross section:

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

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

The elastic cross section is bounded from below

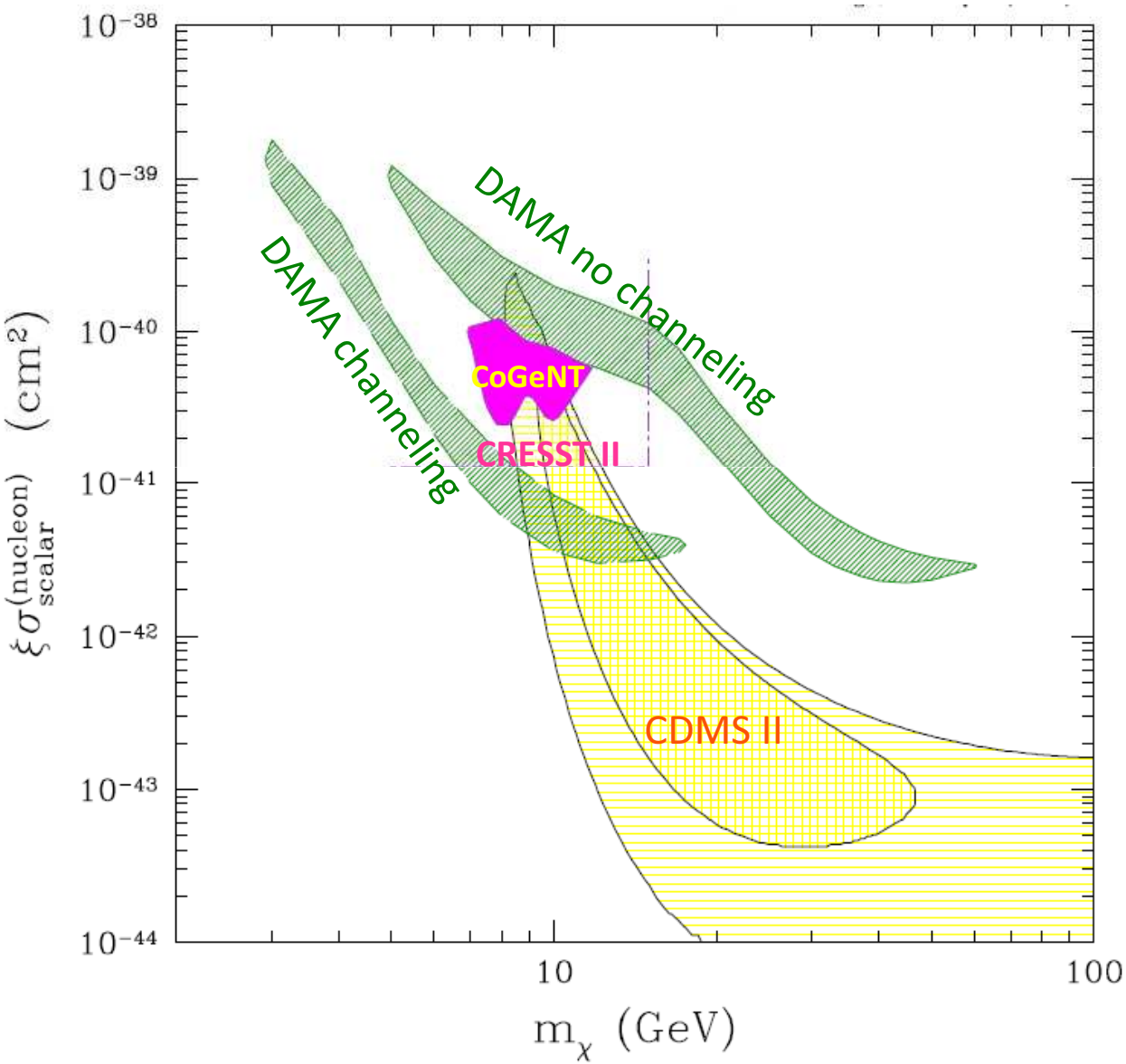
→ "funnel" at low mass




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

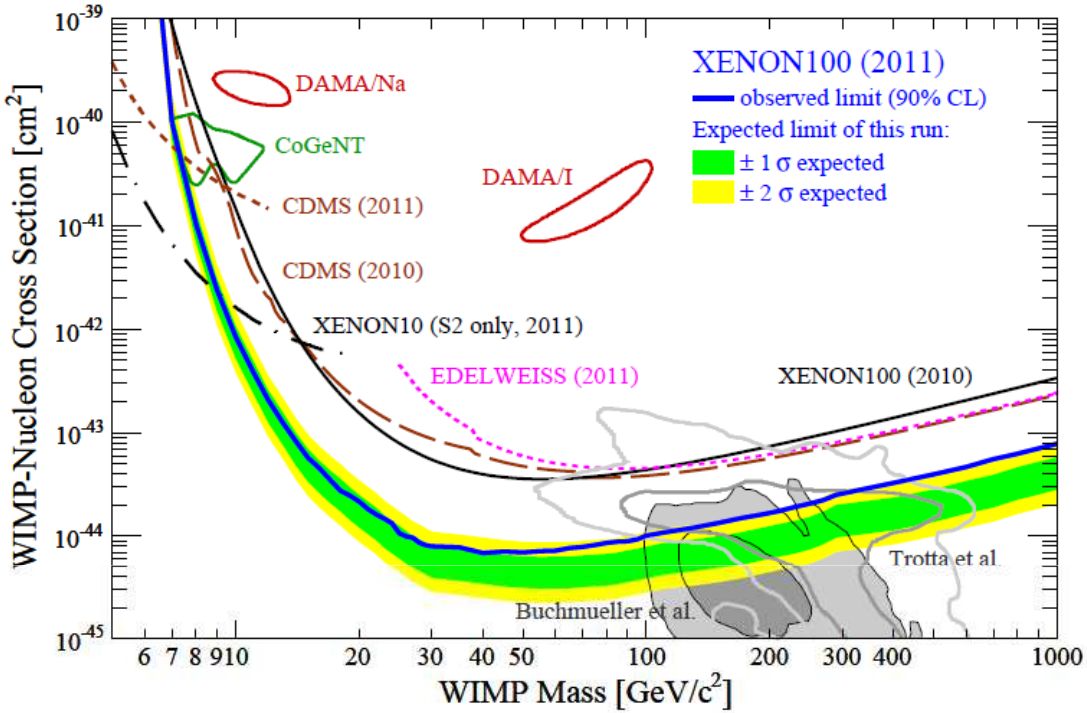
**Light relic neutralinos have (roughly) the right mass and cross section to explain DAMA/LIBRA, CoGeNT, CDMS II and CRESST II!**

CRESST after DAMA and CogeNT (+CDMS2): evidence for light Dark Matter piling up?)




$m_{WIMP}$~10 GeV
$\sigma_{nucleon}$~ $10^{-41}$-$10^{-40}$ $cm^2$

However XENON100 and CDMS exclusion plots taken at face value rule out DAMA+CoGeNT

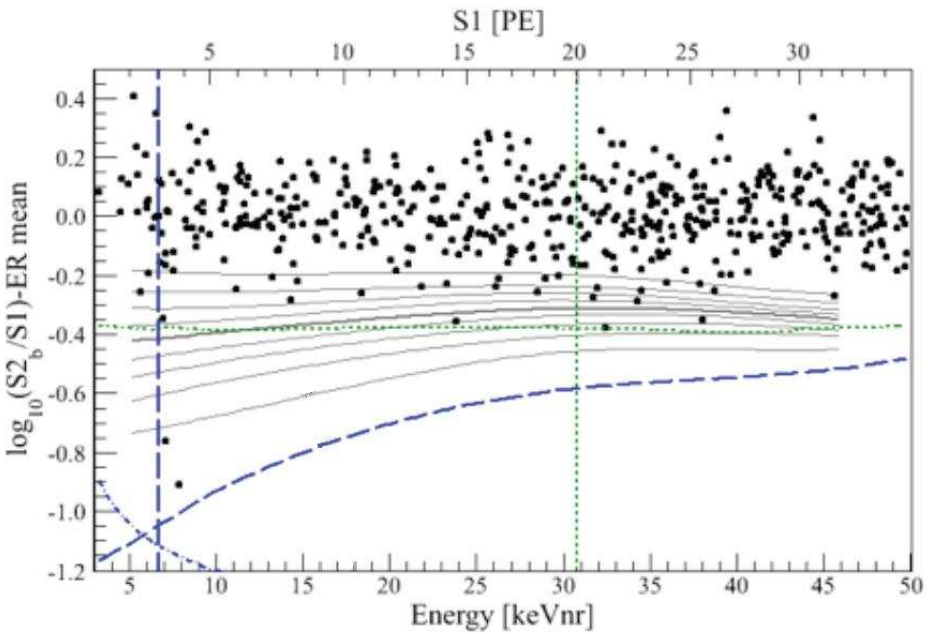


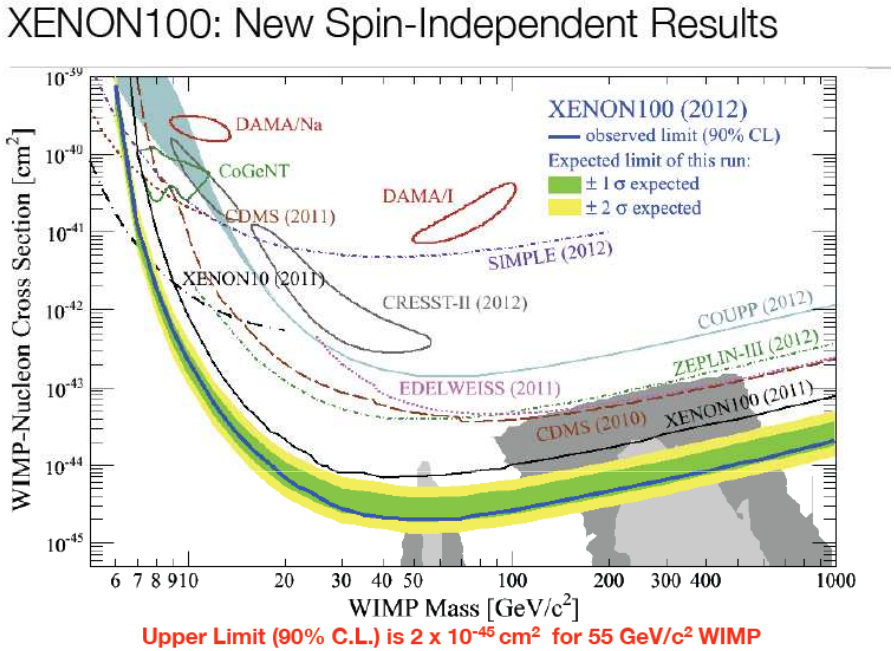

**E. Aprile et al. (XENON100 Coll.), arXiv:1104.2549**

However, robustness of these constraint is questioned at low WIMP masses:

- Liquid Noble gases for Dark Matter searches: a synoptic survey, R. Bernabei et al., 0806.0011
- A Realistic Assessment of the Sensitivity of XENON10 and XENON100 to Light-Mass WIMPs, J. Collar, arXiv:1106.0653
- A comparison between the low-energy spectra from CoGeNT and CDMS, J. Collar, arXiv:1103.3481

# XENON100 bound after 2012 data analysis



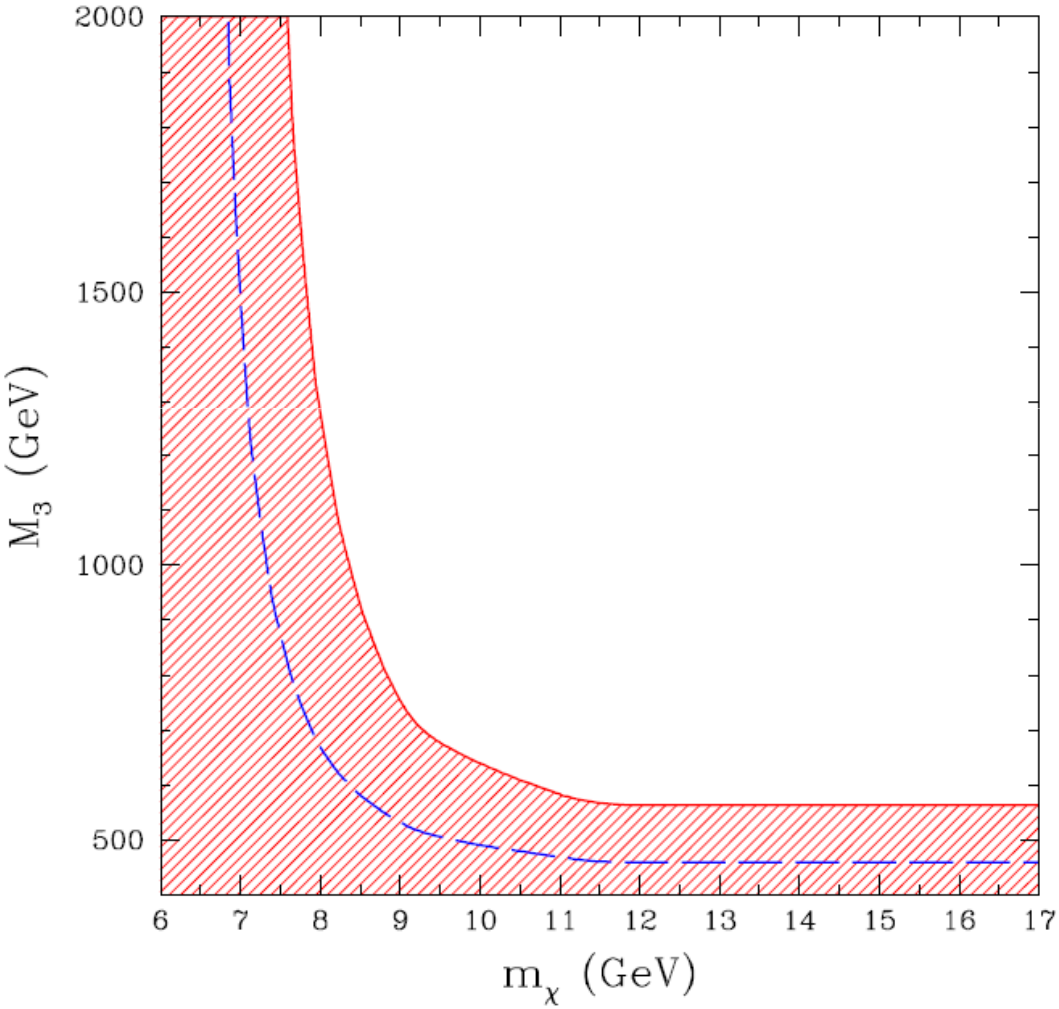

E. Aprile, talk at DarkAttack2012, 18 July 2012

In the following I will not implement these bounds.

If $m_{\tilde{q}}$(squark soft mass for the first two families) $=m_{\tilde{t}}$ (soft mass for the third family) the LHC constraints can be converted in a bound on the neutralino mass (S.Scopel, S. Choi, N. Fornengo and A. Bottino, Phys.Rev. D83 (2011) 095016)

S.Scopel, S. Choi, N. Fornengo and A. Bottino, , Phys.Rev. D83 (2011) 095016)

$m_{\tilde{q}}=m_{\tilde{t}}$



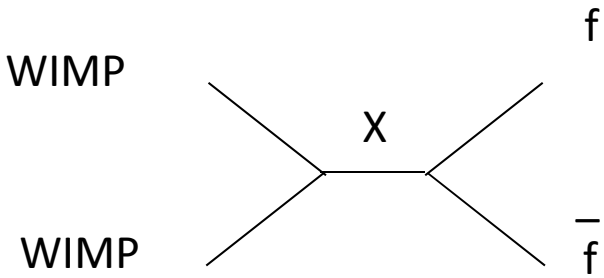

CMS, 35 $fb^{-1}$

Lower bound on $m_\chi$ depends on gluino mass:

7.6 GeV $< m_{\chi,min} <$ 11.8 GeV

## Correlations, correlations…

$$\Omega \sim \frac{1}{\sigma v} \sim \frac{1}{\quad} \qquad \sigma v \simeq \alpha^2 \frac{m^2}{M_X^4} = G_X^2 m^2$$

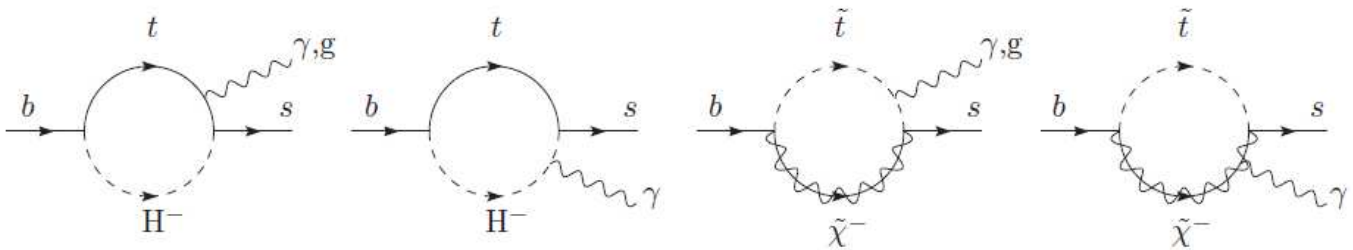



For light neutralinos X=A (pseudoscalar Higgs boson)

small $m_\chi$ requires small $m_A$ to boost σv and keep the relic density below the observational limit

$$m_{H^\pm}^2 \simeq m_A^2 + m_W^2$$

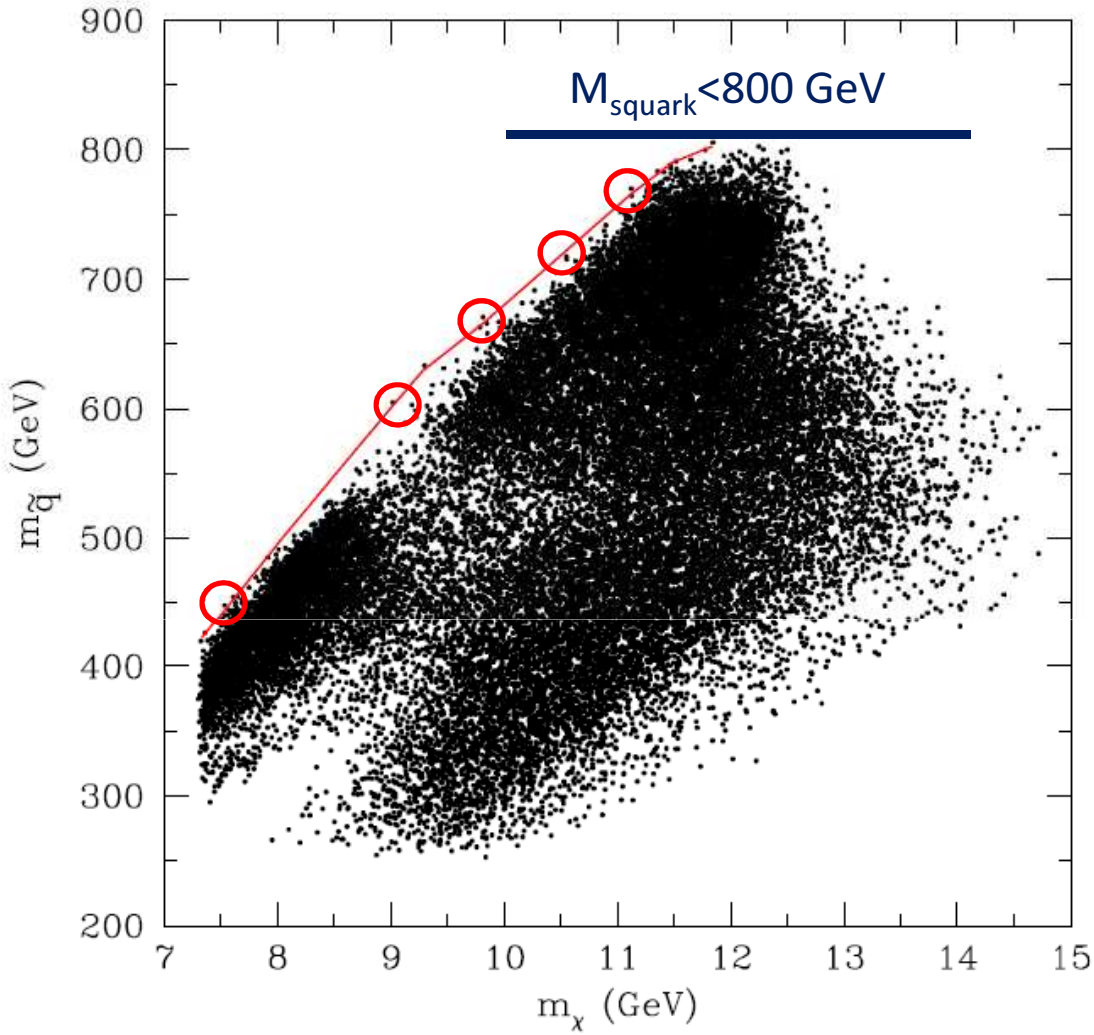
masses of pseudoscalar Higgs boson A and charged Higgs boson $H^+$ strictly correlated so also $H^+$ is light




in b→s γ decay the loop with a top quark and a charged higgs must be canceled by the loop with a stop and a chargino (N.B.: in LNM also chargino is light)

**Lower bound on the stop mass proportional to the neutralino mass**

S.Scopel, S. Choi, N. Fornengo and A. Bottino, , Phys.Rev. D83 (2011) 095016)




Estimate total efficiency ε using ISAJET on a few selected benchmarks at the boundary of the allowed parameter space

$0.07<\varepsilon_{CMS}<0.2$

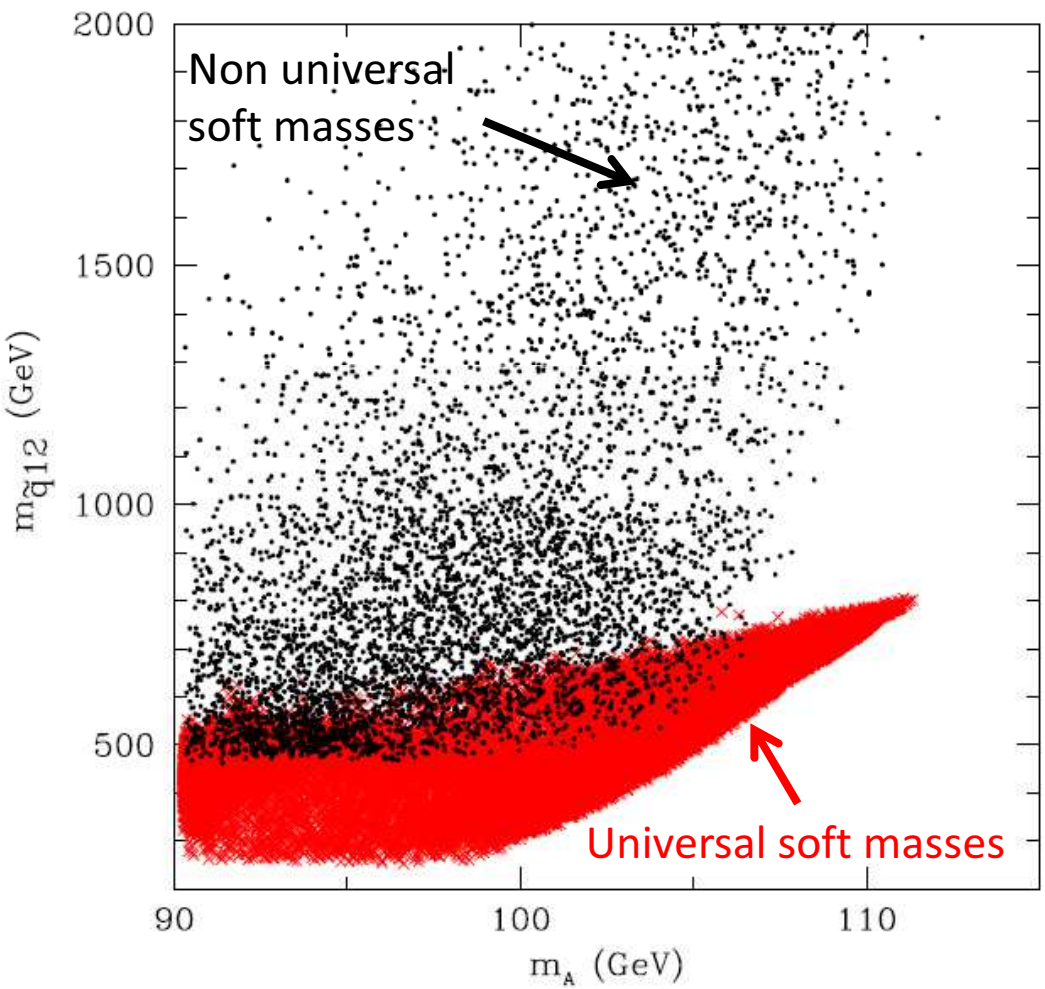
$0.0002<\varepsilon_{ATLAS}<0.005$

Upper bound on $m_{squark}$=800 GeV from b→s γ decay if squark soft masses are universal

In the LNM scenario correlation among the squark mass and the lower bound of the neutralino mass → lower bound on $m_{squark}$ from LHC implies lower bound on $m_\chi$

S.Scopel, S. Choi, N. Fornengo and A. Bottino, , Phys.Rev. D83 (2011) 095016)

N.B. when squark soft masses of the third family are allowed to float independently from those of the first two no upper bound on $m_{squark}$→no constraints on $m_{\chi}$




Tension between LHC and b→s γ desappears because:

- LHC p+p cross section depends on $m_{squark,12}$
- b→s γ depends on stop soft mass

# How to measure light neutralinos at the LHC?

Select a benchmark for sequential decay (LNM-seq) within the effMSSM:

| benchmark | $M_1$[GeV] | $M_2$[GeV] | $M_3$[GeV] | $\mu$ [GeV] | $\tan\beta$ | $m_A$ [GeV] | $m_{\tilde{l}}$ [GeV] | $m_{\tilde{q}}$ [GeV] | $m_{\tilde{t}}$ [GeV] | $A$ |
|---|---|---|---|---|---|---|---|---|---|---|
| LNM-seq | 14 | 500 | 2000 | 126 | 34 | 97 | 300 | 700 | 444 | -0.08 |

S. Choi, S. Scopel, N. Fornengo, A. Bottino, Phys. Rev. D 85, 035009 (2012)

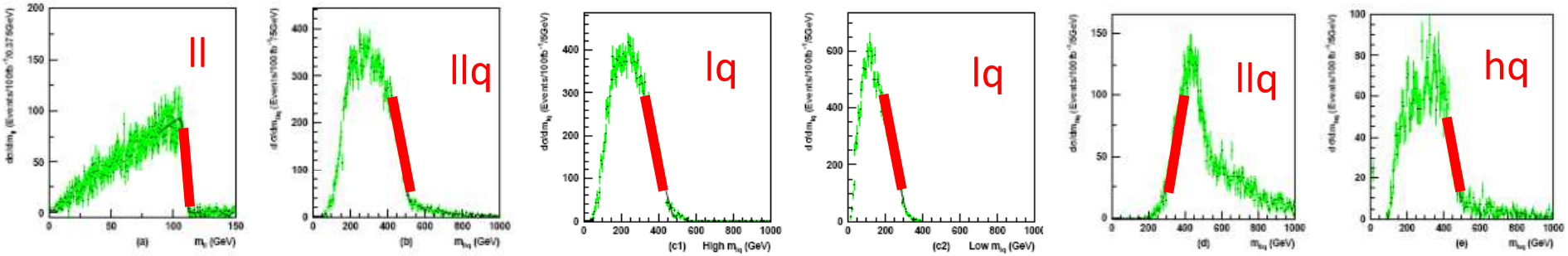
The LSP goes undetected, no complete kinematical reconstruction allowed in direct decay

however, kinematical endpoints in chain decays allow to reconstruct masses in a model-independent way
(no charginos, otherwise neutrinos in final state)

| Related edge | Kinematic endpoint |
|---|---|
| $l^+l^-$ edge | $(m_{ll}^{\max})^2 = (\tilde{\xi}-\tilde{l})(\tilde{l}-\tilde{\chi})/\tilde{l}$ |
| $l^+l^-q$ edge | $(m_{llq}^{\max})^2 = \begin{cases} \max\left[\frac{(\tilde{q}-\tilde{\xi})(\tilde{\xi}-\tilde{\chi})}{\tilde{\xi}}, \frac{(\tilde{q}-\tilde{l})(\tilde{l}-\tilde{\chi})}{\tilde{l}}, \frac{(\tilde{q}\tilde{l}-\tilde{\xi}\tilde{\chi})(\tilde{\xi}-\tilde{l})}{\tilde{\xi}\tilde{l}}\right] \\ \text{except for the special case in which } \tilde{l}^2 < \tilde{q}\tilde{\chi} < \tilde{\xi}^2 \\ \text{and } \tilde{\xi}^2\tilde{\chi} < \tilde{q}\tilde{l}^2 \text{ where one must use } (m_{\tilde{q}}-m_{\tilde{\chi}_1^0})^2. \end{cases}$ |
| $Xq$ edge | $(m_{Xq}^{\max})^2 = X + (\tilde{q}-\tilde{\xi})\left[\tilde{\xi}+X-\tilde{\chi}+\sqrt{(\tilde{\xi}-X-\tilde{\chi})^2-4X\tilde{\chi}}\right]/(2\tilde{\xi})$ |
| $l^+l^-q$ threshold | $(m_{llq}^{\min})^2 = \begin{cases} [2\tilde{l}(\tilde{q}-\tilde{\xi})(\tilde{\xi}-\tilde{\chi})+(\tilde{q}+\tilde{\xi})(\tilde{\xi}-\tilde{l})(\tilde{l}-\tilde{\chi}) \\ -(\tilde{q}-\tilde{\xi})\sqrt{(\tilde{\xi}+\tilde{l})^2(\tilde{l}+\tilde{\chi})^2-16\tilde{\xi}\tilde{l}^2\tilde{\chi}}]/(4\tilde{l}\tilde{\xi}) \end{cases}$ |
| $l^\pm_{\text{near}}\ q$ edge | $(m_{l_{\text{near}}\ q}^{\max})^2 = (\tilde{q}-\tilde{\xi})(\tilde{\xi}-\tilde{l})/\tilde{\xi}$ |
| $l^\pm_{\text{far}}\ q$ edge | $(m_{l_{\text{far}}\ q}^{\max})^2 = (\tilde{q}-\tilde{\xi})(\tilde{l}-\tilde{\chi})/\tilde{l}$ |
| $l^\pm q$ high-edge | $(m_{lq(\text{high})}^{\max})^2 = \max\left[(m_{l_{\text{near}}\ q}^{\max})^2, (m_{l_{\text{far}}\ q}^{\max})^2\right]$ |
| $l^\pm q$ low-edge | $(m_{lq(\text{low})}^{\max})^2 = \min\left[(m_{l_{\text{near}}\ q}^{\max})^2, (\tilde{q}-\tilde{\xi})(\tilde{l}-\tilde{\chi})/(2\tilde{l}-\tilde{\chi})\right]$ |
| $M_{T2}$ edge | $\Delta M = m_{\tilde{l}} - m_{\tilde{\chi}_1^0}$ |

**Table 4:** The absolute kinematic endpoints of invariant mass quantities formed from decay chains of the types mentioned in the text for known particle masses. The following shorthand notation has been used: $\tilde{\chi} = m^2_{\tilde{\chi}_1^0}, \tilde{l} = m^2_{\tilde{l}_R}, \tilde{\xi} = m^2_{\tilde{\chi}_2^0}, \tilde{q} = m^2_{\tilde{q}}$ and $X$ is $m_h^2$ or $m_Z^2$ depending on which particle participates in the "branched" decay.

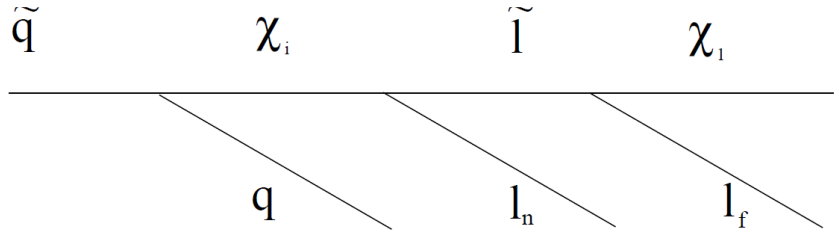
C. Allanach et al., JHEP09(2000)004



In particular, define:

$$m_{j\ell(lo)} \equiv \mathrm{Min}(m_{j\ell_n}, m_{j\ell_f})$$

$$m_{j\ell(hi)} \equiv \mathrm{Max}(m_{j\ell_n}, m_{j\ell_f})$$




(cannot distinguish far lepton $l_f$ from near lepton $l_n$)

In this way one gets a set of 4 measurable kinematic endpoints:

$$(m_{\ell\ell}^{max}, m_{j\ell\ell}^{max}, m_{j\ell(lo)}^{max}, m_{j\ell(hi)}^{max})$$

to measure the 4 unknown masses:

$$(m_\chi, m_{\tilde{l}}, m_{\chi_i}, m_{\tilde{q}})$$

# Two problems in this procedure:

1) In the LNM the four endpoints are not independent. In particular, for $m_\chi<(m_{\tilde{l}})^2/m_{\tilde{q}}$ (as in the LNM-seq benchmark) one has:

$$(m_{j\ell\ell}^{max})^2 = (m_{\ell\ell}^{max})^2 + (m_{j\ell(hi)}^{max})^2$$

Need another independent measurement. Take (Allanach et al., JHEP0009,004, 2000):

$m_{j\ell\ell(\theta>\pi/2)}^{min}$ =lower bound of $m_{jll}$ histogram with the additional constraint:

$$(m_{\ell\ell}^{max})^2/2 < (m_{\ell\ell})^2 < (m_{\ell\ell}^{max})^2$$

2) The solution of the inversion procedure has multiple solutions and in general is not unique

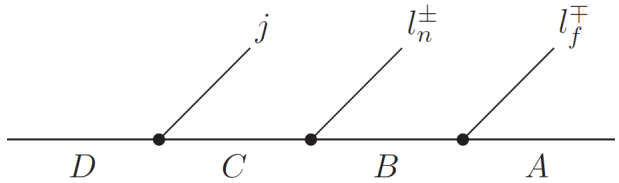
## Duplicate solutions in the inversion procedure for the LNM-seq benchmark

| Variable | LNM-seq | LNM-seq′ |
|---|---|---|
| $m_\chi$ | 11 | 263 |
| $m_{\tilde{l}}$ | 305 | 383 |
| $m_{\chi_i}$ | 515 | 688 |
| $m_{\tilde{q}}$ | 703 | 896 |
| $m_{\ell\ell}^{max}$ | 415 (417.5± 3.5) | |
| $m_{j\ell\ell}^{max}$ | 632 (631.3± 3.8) | |
| $m_{j\ell(lo)}^{max}$ | 338 (342.2 ±4.3) | |
| $m_{j\ell(hi)}^{max}$ | 477 (483± 14) | |
| $m_{j\ell\ell(\theta>\pi/2)}^{min}$ | 400 (399.3 ± 1.7) | |
| $n', p'$ | 282,385 | 232,477 |

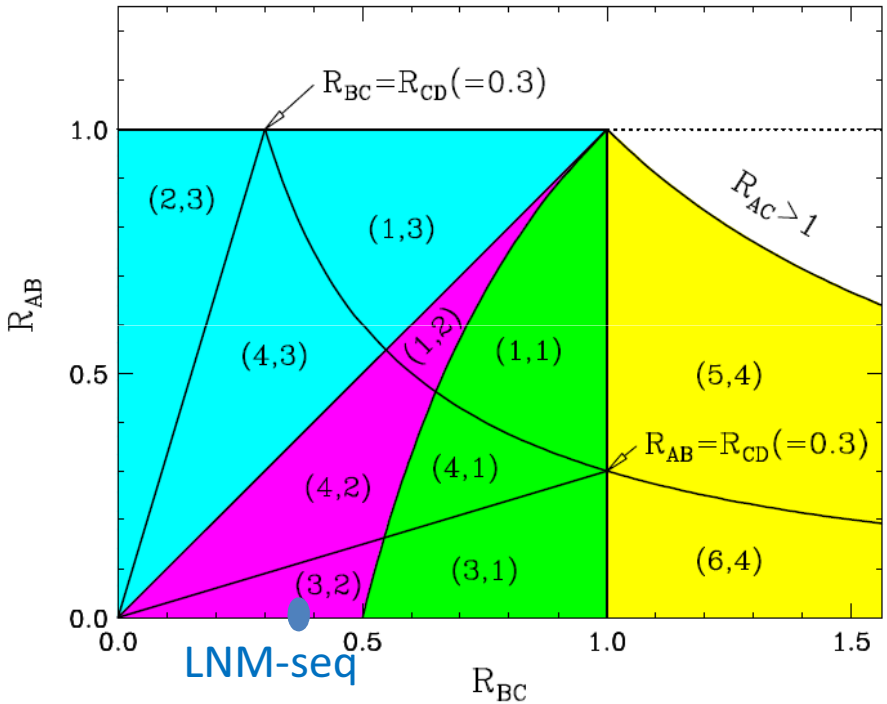
Inversion procedure from kinematic endpoints leads to correct solution plus a duplicate one with a completely different spectrum but identical endpoints!

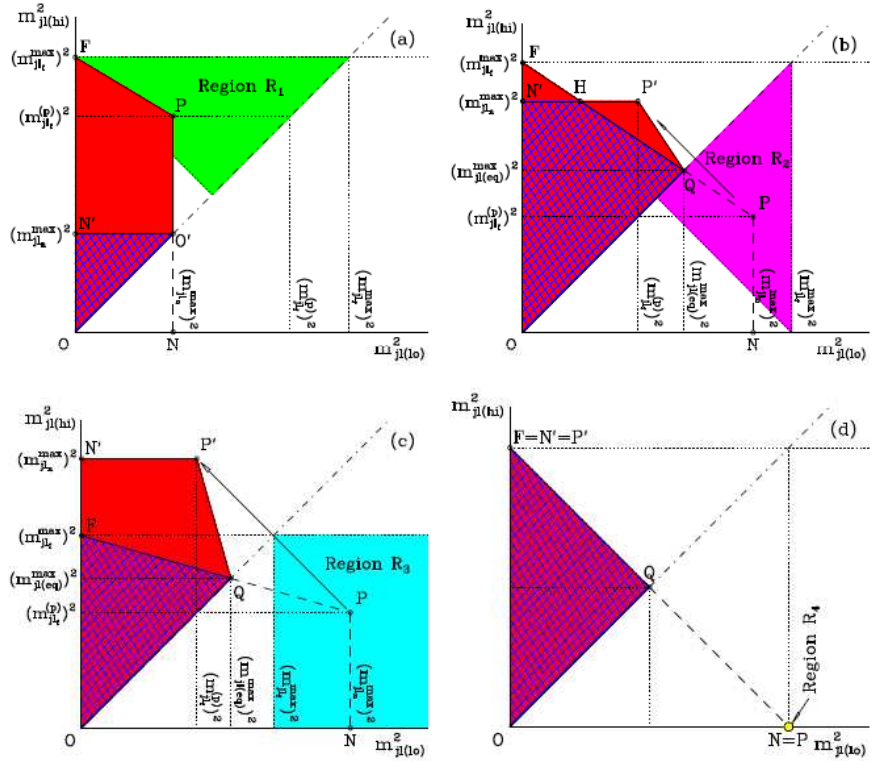
S. Choi, S. Scopel, N. Fornengo, A. Bottino, Phys. Rev. D 85, 035009 (2012)

## Can break the degeneracy by using two-dimensional kinematic distributions




$$R_{ij} \equiv \frac{m_i^2}{m_j^2}$$

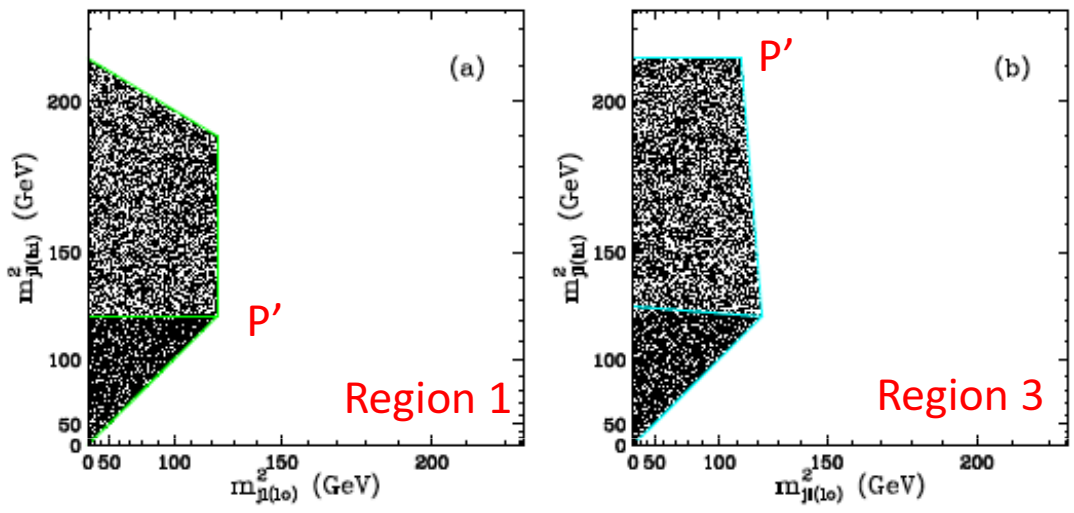


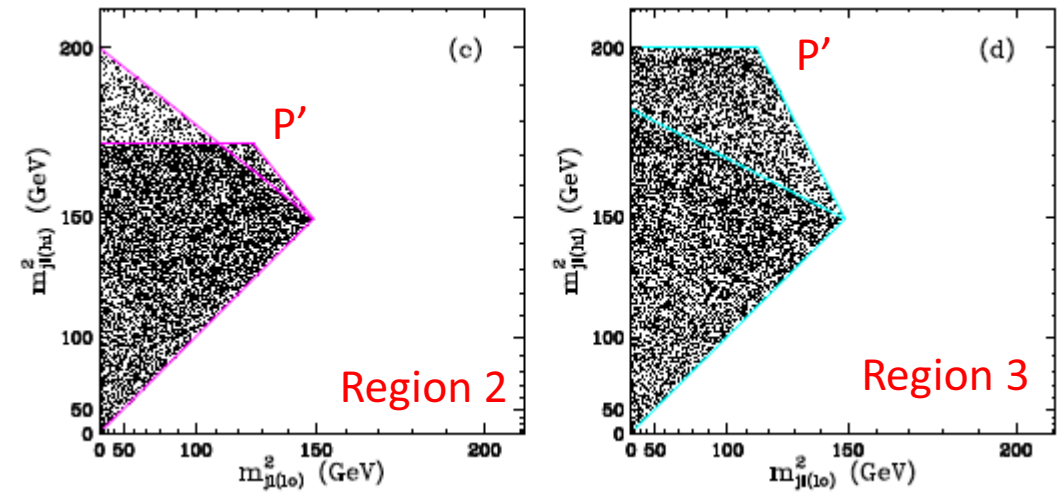

Select 4 kinematic regions ($R_1$, $R_2$, $R_3$, $R_4$) that lead to different shapes in two-dimensional distributions. LNM-seq belongs to region $R_2$

**(M. Burns, K. T. Matchev, M. Park, JHEP0905, 094 (2009)**

In ideal situation (10000 data points in this example) can locate the position of the point P' that allows to break the degeneracy and determine which is the correct solution




Duplicate models: same kinematic endpoints but different mass spectra




Duplicate models: same kinematic endpoints but different mass spectra

(M. Burns, K. T. Matchev, M. Park, JHEP0905, 094 (2009)

## Summary of edge-point determinations (in parenthesis) vs. expected values

| Variable | LNM-seq | LNM-seq′ |
|---|---|---|
| $m_\chi$ | 11 | 263 |
| $m_{\tilde{l}}$ | 305 | 383 |
| $m_{\chi_i}$ | 515 | 688 |
| $m_{\tilde{q}}$ | 703 | 896 |
| $m_{\ell\ell}^{max}$ | 415 (417.5± 3.5) | |
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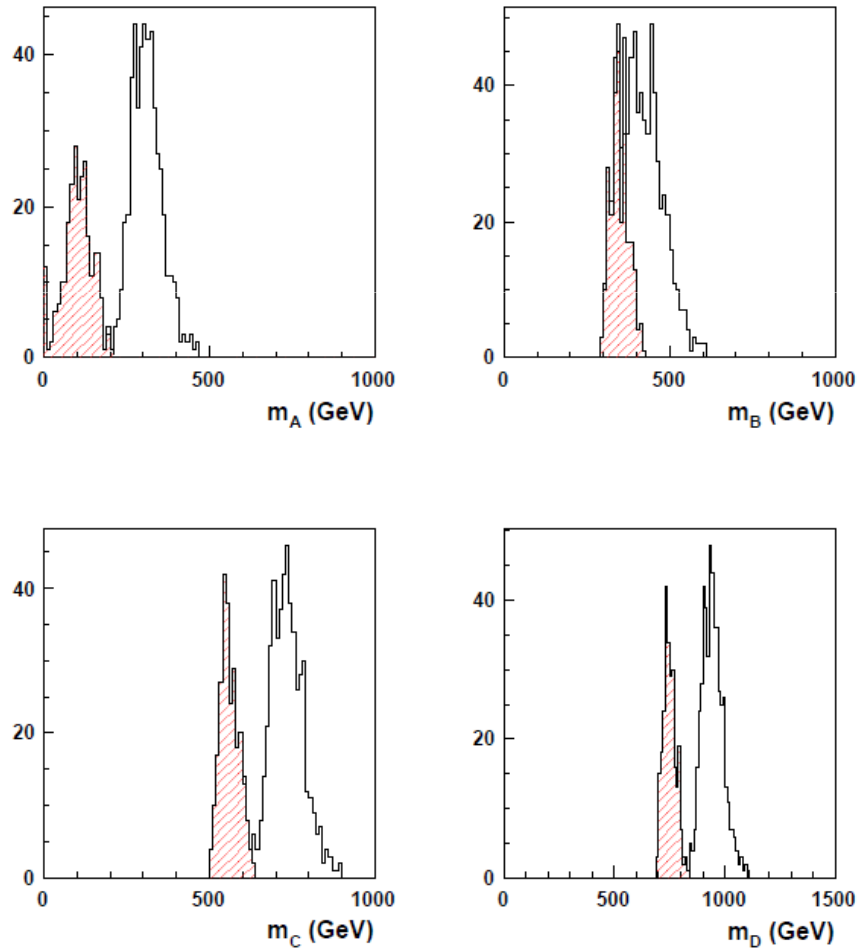
| $n', p'$ | 282,385 | 232,477 |

S. Choi, S. Scopel, N. Fornengo, A. Bottino, Phys. Rev. D 85, 035009 (2012)

Final inversion from $m_{\ell\ell}^{max}$, $m_{j\ell(hi)}^{max}$, $m_{j\ell(low)}^{max}$, $m_{j\ell\ell}^{max}$, $m_{j\ell\ell(\theta<\pi/2)}^{min}$

(only 4 are independent) to $(m_\chi, m_{\tilde{l}}, m_{\chi_i}, m_{\tilde{q}})$

Do that by brutal force, just simulate a large number of random values of the 4 masses and plot the histogram of the mass combinations whose theoretical values of the endpoints fall within the measured ranges.




$$\frac{m_\chi^2}{m_{\tilde{l}}^2} < \frac{m_{\tilde{l}}^2}{m_{\chi_i}^2} < \frac{1}{2 - m_\chi^2/m_{\tilde{l}}^2}$$

(kinematic region $R_2$)

As expected find two solutions. However the correct one can be determined by imposing that the mass pattern has the correct shape in the $m_{jl(lo)}$ - $m_{jl(hi)}$ two-dimensional distribution (i.e. belongs to kinematic region $R_2$)

S. Choi, S. Scopel, N. Fornengo, A. Bottino, Phys. Rev. D 85, 035009 (2012)

# Final mass determination:

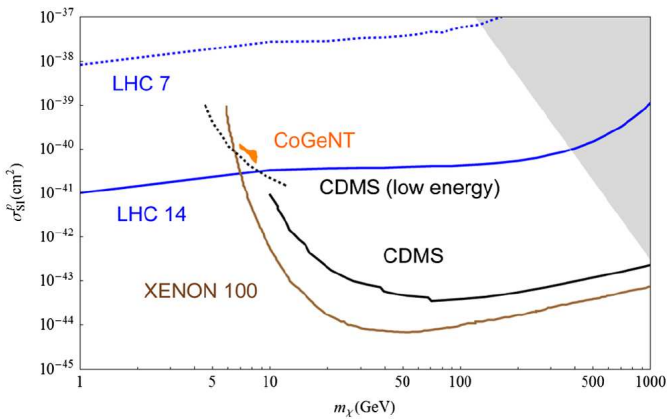
| | | (input values) |
|---|---|---|
| $m_\chi = (103 \pm 43)$ GeV | | (10) |
| $m_{\tilde{l}} = (349 \pm 27)$ GeV | | (300) |
| $m_{\chi_i} = (561 \pm 28)$ GeV | | (500) |
| $m_{\tilde{q}} = (751 \pm 28)$ GeV | | (700) |

S. Choi, S. Scopel, N. Fornengo, A. Bottino, Phys. Rev. D 85, 035009 (2012)

The reconstructed mass of the light neutralino in the LNM-seq benchmark is ~103 GeV, and deviates remarkably from the input value ~10

This can be explained by the fact that the center-of-mass energy available in the sequential decay is set by the squark and is much larger than the neutralino mass → in the LNM the neutralino is produced in the relativistic regime and its kinematics is almost insensitive to $m_\chi$


This is actually quite intuitive. For the same reason LHC constraints in effective theories are almost flat for a low DM mass.

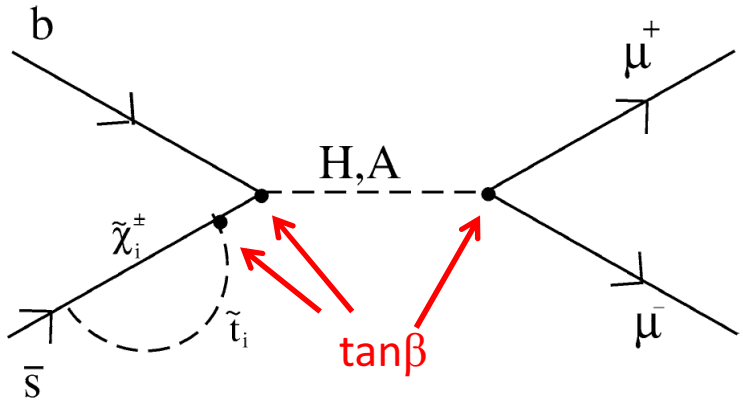



"Maverick DM"

# The $B_s \to \mu\mu$ decay

Combined ATLAS+CMS+LHCb upper bound: BR(Bs→μμ) < $4.2 \times 10^{-9}$

Important constraint whenever $m_A$ is light and tanβ is large, as in the light neutralino model, since BR(Bs→μμ) α $\tan\beta^6/m_A^4$




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

Dominant term:

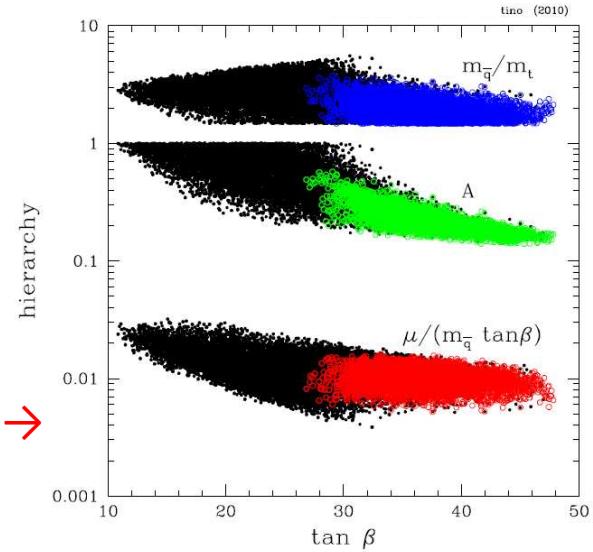
$$BR^{(6)}(B_s \to \mu^+\mu^-) \simeq 5.8 \times 10^{-8} \left(\frac{14\, A\, m_t\, m_{\tilde{q}}}{m_{\tilde{q}}^2 + m_t^2}\right)^2 \left(\frac{m_{\chi^\pm}}{110\ \text{GeV}}\right)^2 \left(\frac{90\ \text{GeV}}{m_A}\right)^4 \left(\frac{\tan\beta}{35}\right)^6$$

To pass the constraint need:

- chargino of higgsino type to be light → small μ (not true in SUGRA where μ is large due to EWSB)
- trilinear coupling A to be small (leading to stop-quark degeneracy) and respecting the hierarchy :

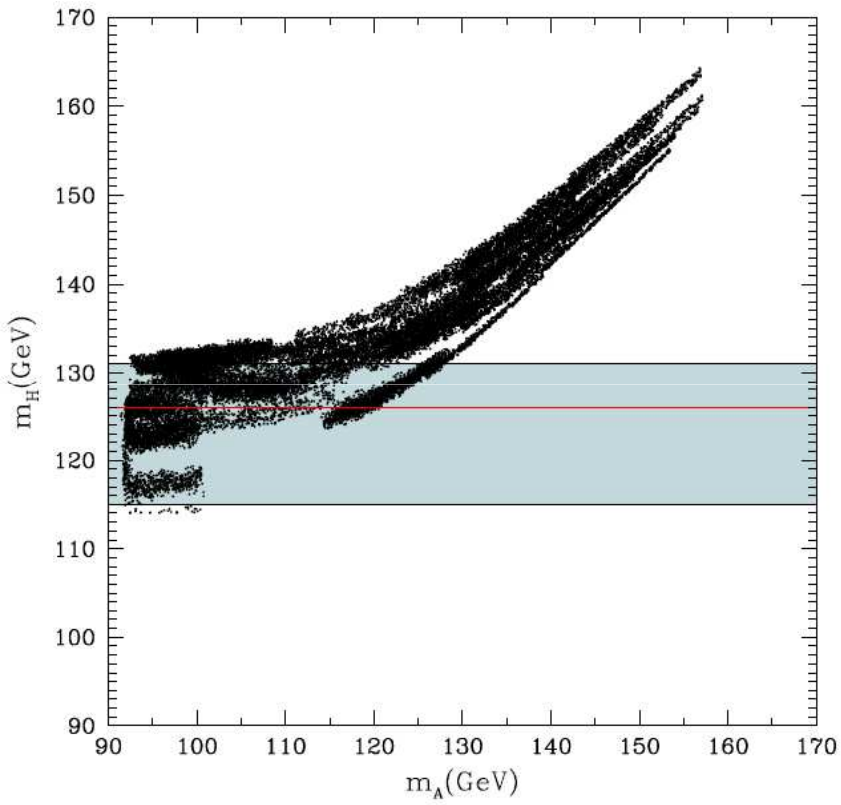
$$\frac{|\mu|}{m_{\tilde{q}}\ \tan\beta} \ll |A| \ll \frac{m_{\tilde{q}}}{m_t}$$

easily verified, no fine tuning→

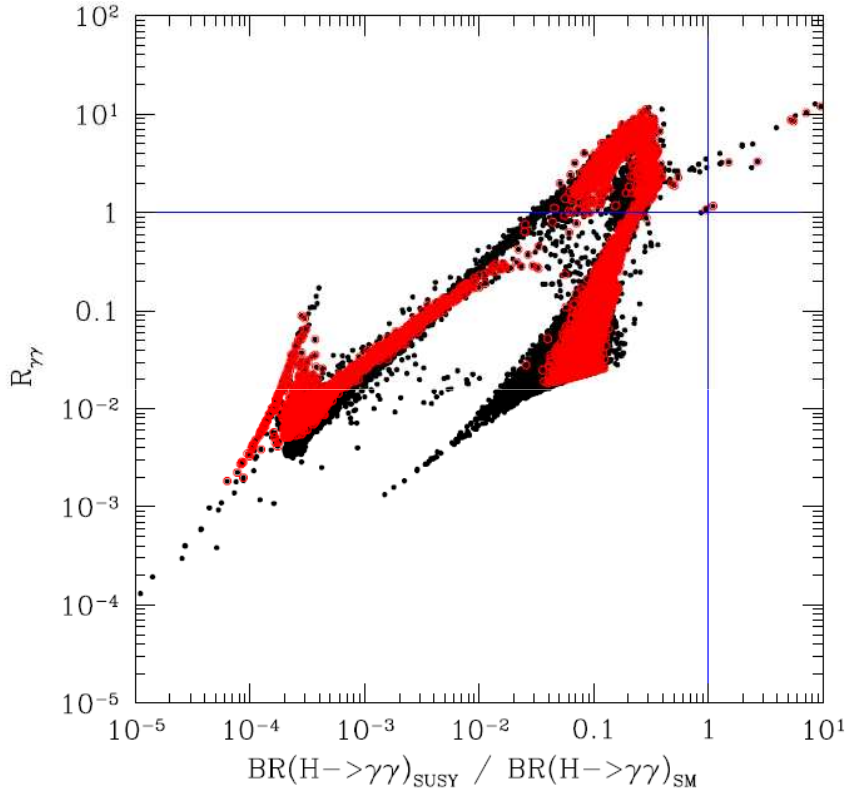



**Fornengo, Scopel, Bottino, PhysRevD.83.015001 (1011.4743)**

In the light neutralino parameter space the mass of the HEAVY Higgs boson mass $m_H$ fall naturally in the range of the LHC excess. Also production rates are roughly OK! The light Higgs h ($m_h$<110 GeV) goes undetected because it is in the decoupling limit

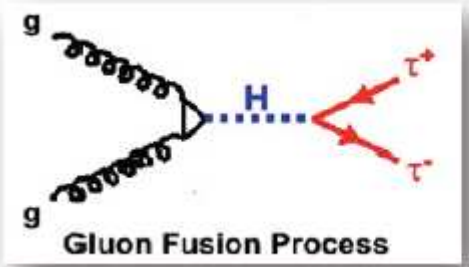


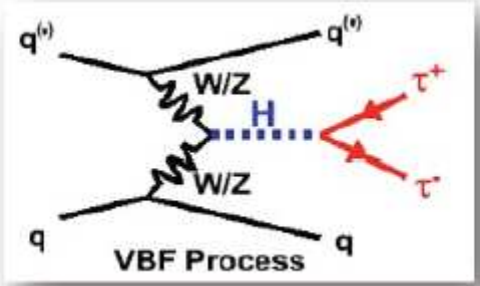

$R_{\gamma\gamma}$ =γγ production (MSSM/SM)

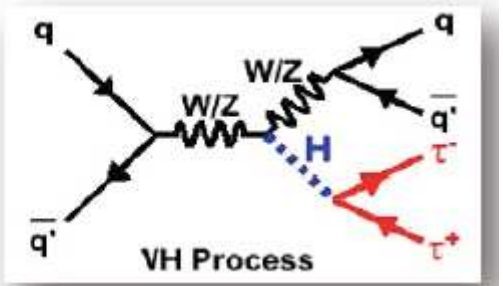


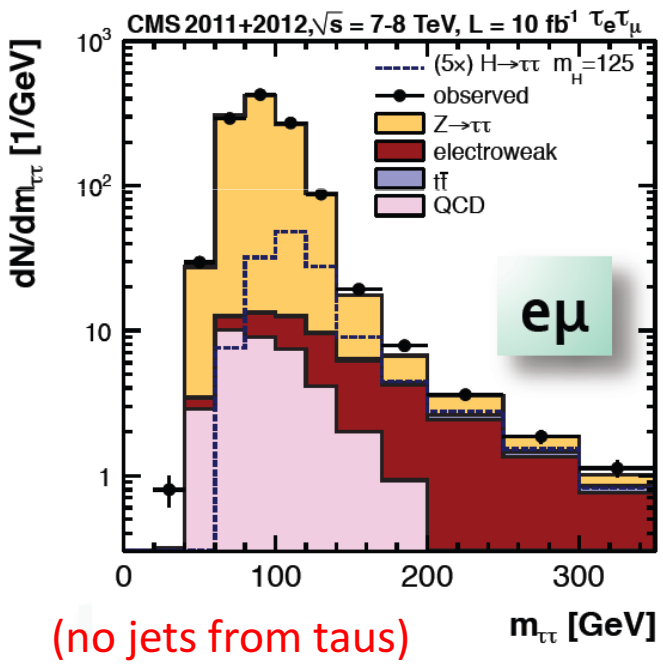

A. Bottino, N. Fornengo, S. Scopel, PRD85(2012)095013

However, stringent bounds on this scenario from CMS constraints on H→ττ:

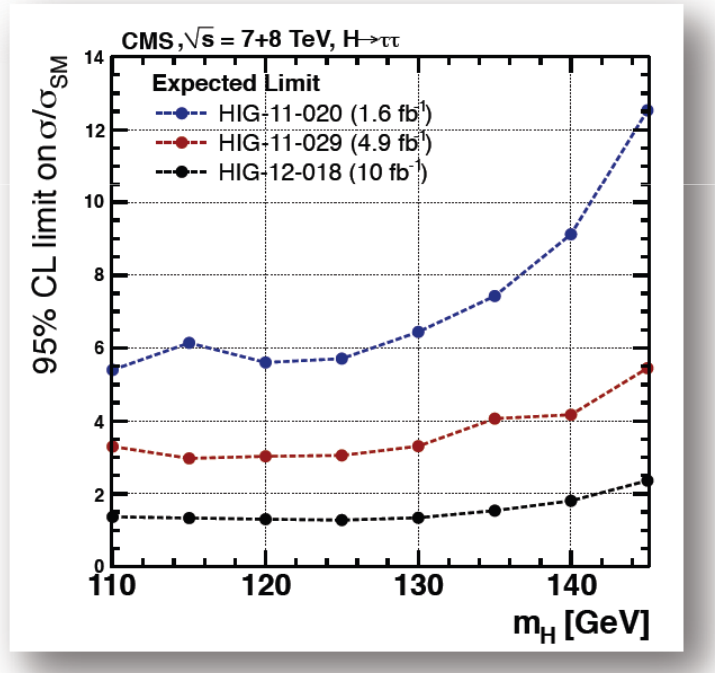



(no jets from taus)



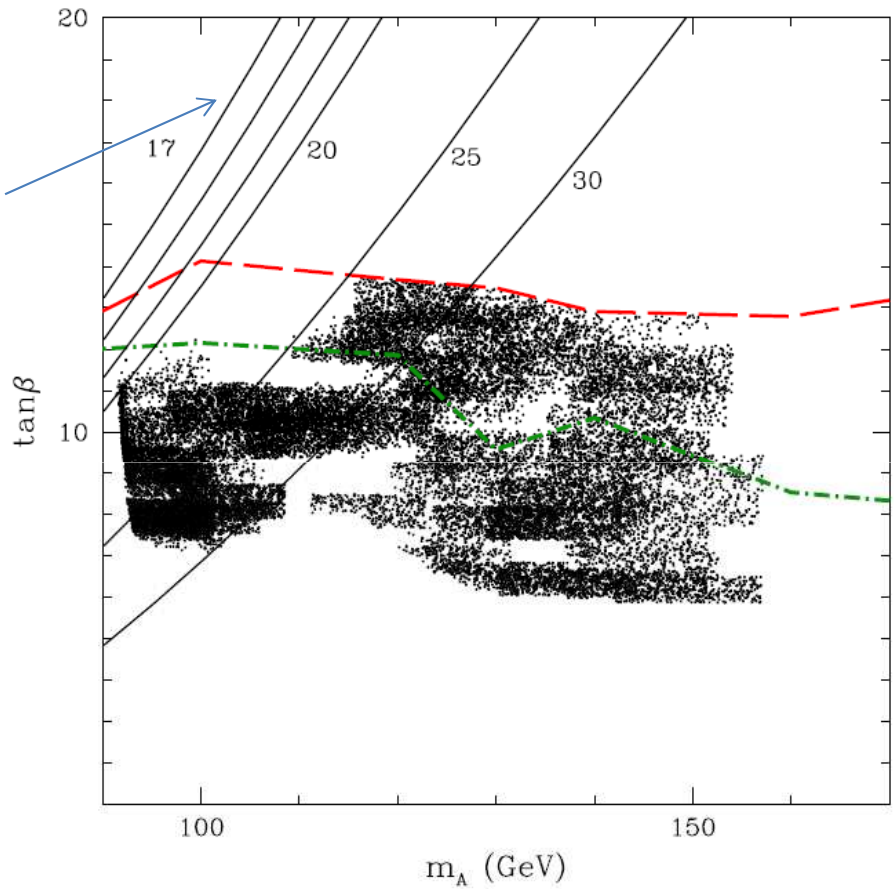

little space from additional contribution from light higgs state→ more stringent limits

J. Incandela, talk at CERN, 4 July 2012

# Light neutralinos after the LHC

Lines at constant neutralino mass

The bound on light neutralinos moves now to ~20 GeV




J. Baglio and A. Djouadi, arXiv:1103.6247

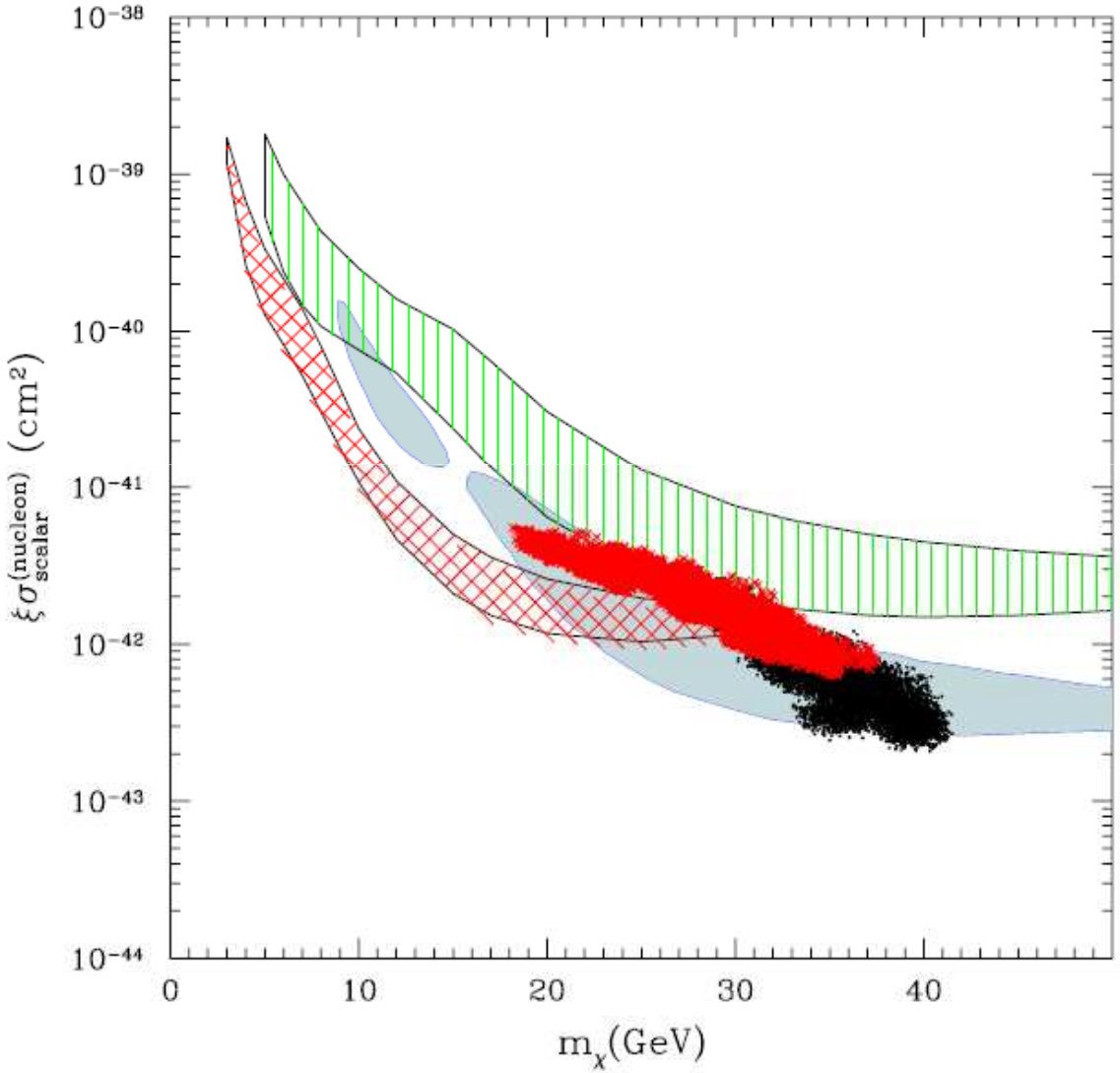
CMS

Stronger bounds on tanβ (<15) from h→ττ searches @LHC (CMS, report CMS PAS HIG-11-029.)

(A. Bottino, N. Fornengo, S. Scopel, PRD85, 095013 (2012)

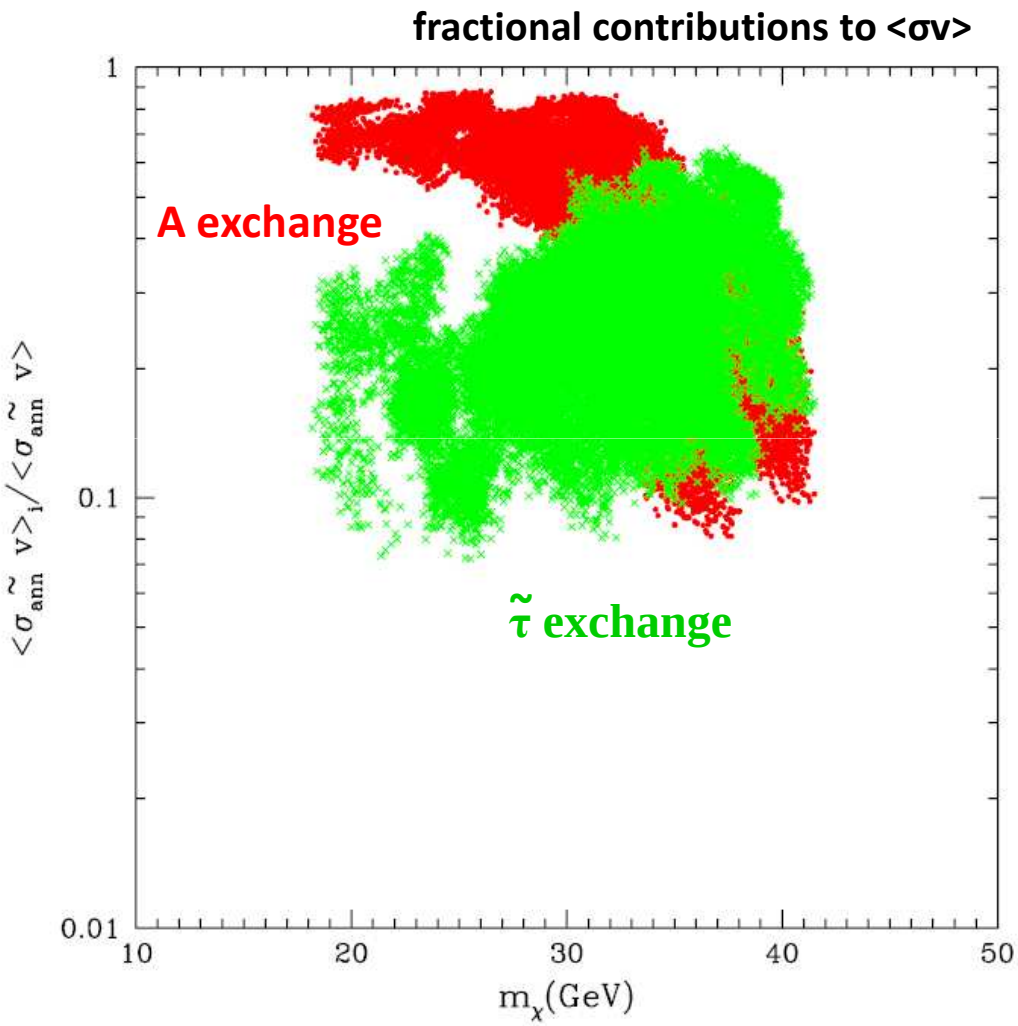
# Updated light neutralino funnel after LHC bounds on h→ττ

Red crosses:
115.5 GeV<$m_H$ <131 GeV




(A. Bottino, N. Fornengo, S. Scopel, PRD85, 095013 (2012)

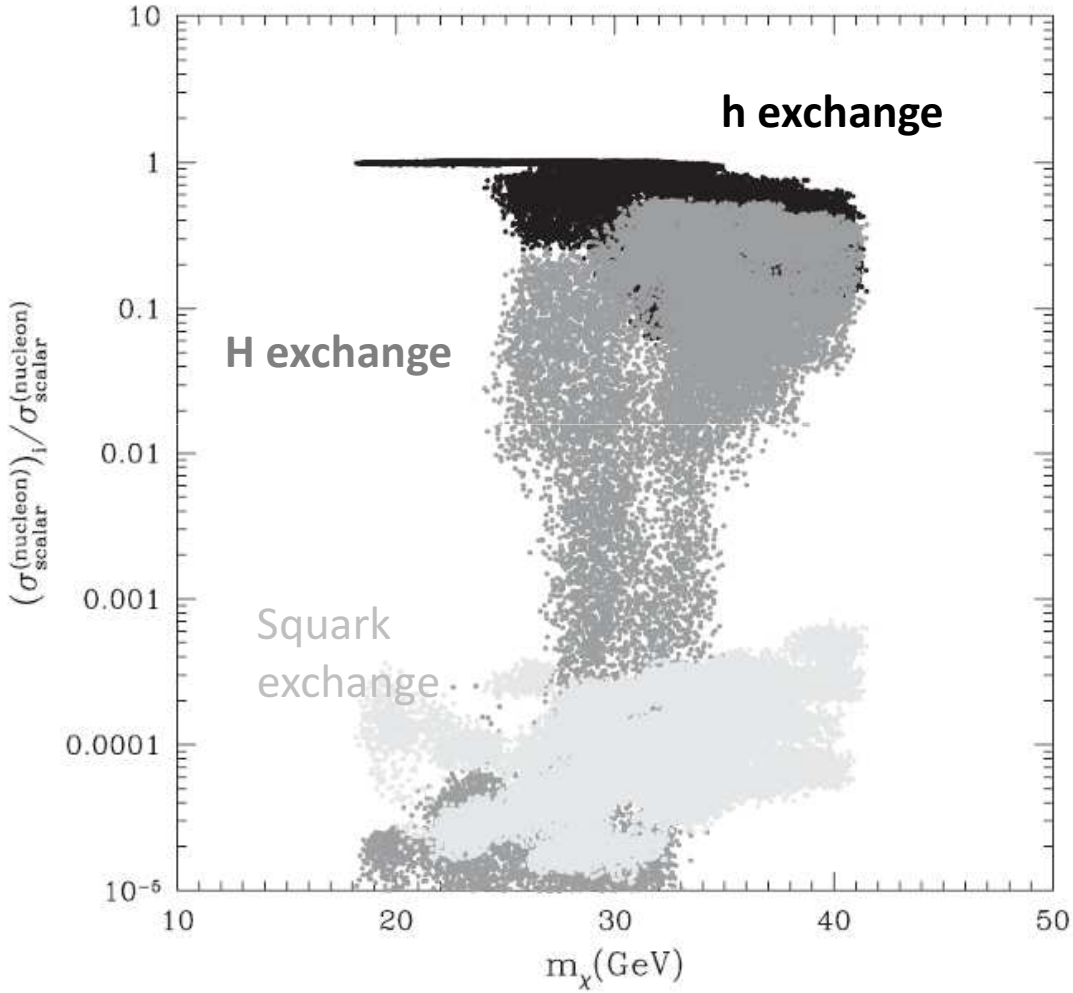
In the surviving parameter space of light neutralinos ($m_\chi$>20 GeV) the annihilation cross section at decoupling that drives the relic abundance takes comparable contributions from A exchange and stau exchange, the former still dominating at the lowest masses




(A. Bottino, N. Fornengo, S. Scopel, PRD85, 095013 (2012)

Anyway, neutralino-nucleon cross section still dominated by exchange of lightest Higgs scalar h

**fractional contributions to neutralino-nucleon cross section**




(A. Bottino, N. Fornengo, S. Scopel, PRD85, 095013 (2012)

# Conclusions

- An effective MSSM scenario (effMSSM) with no unification of gaugino masses at the GUT scale allows neutralinos as light as ~20 GeV taking into account the latest constraint from CMS on the tanβ parameter from $h \to \tau\tau$
- Could roughly explain some excesses in Dark Matter direct searches (DAMA, CRESST). Probably too heavy to explain CoGeNT .
- This scenario is compatible in a very natural way (no particular fine tuning required) to the heavy Higgs scalar being the particle measured at the LHC with a mass $m_H$~125 GeV
- In this case the lightest scalar h should be not far from discovery
- This scenario is in tension with XENON100 and CDMS bounds, but the robustness of these constraints has been put into question
- Difficult to pinpoint the mass of the neutralino if it is light from kinematic measurements at the LHC