LHC Impact on DM searches

Complementarity between collider and direct searches for DM

David G. Cerdeño

Outline

Introduction (complementarity of DM searches)

Dark Matter signals at the LHC

(missing E_T , jets, etc...)

Particular example: SUSY

LHC potential reach
SUSY WIMPs (neutralino + sneutrino) and eWIMPs

Direct Detection experiments are necessary

Combination with LHC data and determination of WIMP properties

A final note on identification of WIMP DM

WHAT is the Dark Matter? ... WHAT DO WE KNOW...

- Good dark matter candidates must fulfil a number of requirements

- Neutral
- Stable on cosmological scales
- Reproduce the correct relic abundance
- Not excluded by direct or indirect searches
- No conflicts with BBN or stellar evolution

- Many candidates in Particle Physics

- Axions
- Weakly-Interacting massive particles:

  WIMPs

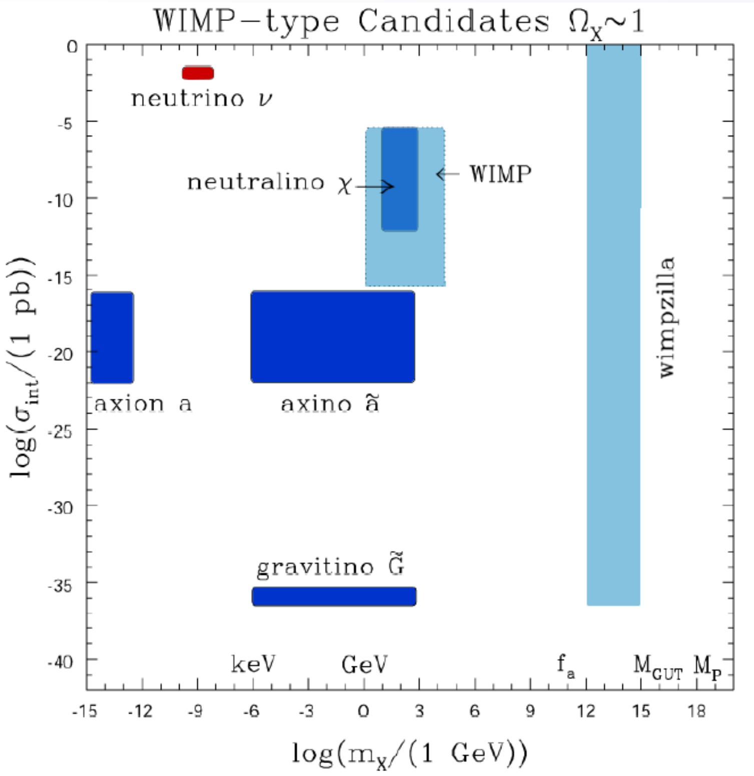
- SuperWIMPs (gravitino, axino)
- Decaying DM
- SIMPs, CHAMPs, SIDMs, WIMPzillas, Scalar DM, Light DM, ...

NEW PHYSICS BEYOND THE STANDARD MODEL OF PARTICLE PHYSICS

WHAT is the Dark Matter?

... WHAT DO WE KNOW...

- These candidates have very different properties!



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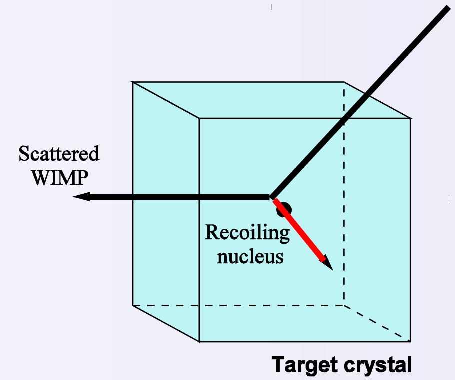
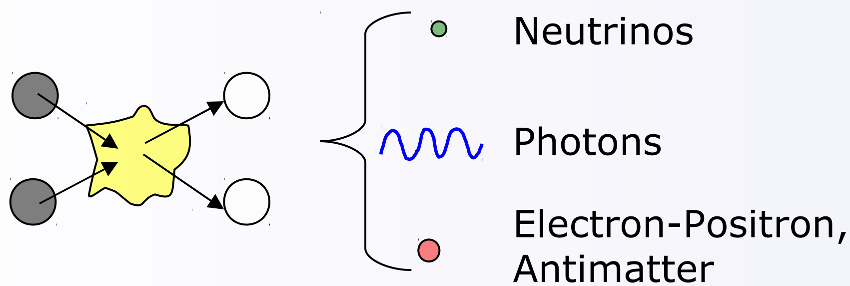
NEW PHYSICS BEYOND THE STANDARD MODEL OF PARTICLE PHYSICS

Detection of Dark Matter

- Direct Detection:

  Look for the elastic scattering of dark matter with nuclei



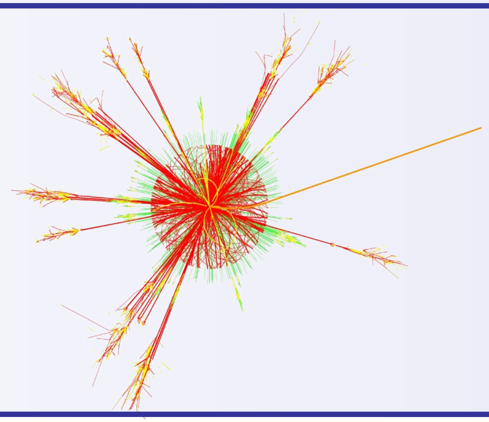


- Indirect Detection:

  Look for the annihilation products

- Accelerator Searches

  Look for signals of new physics



Complementarity of DM searches

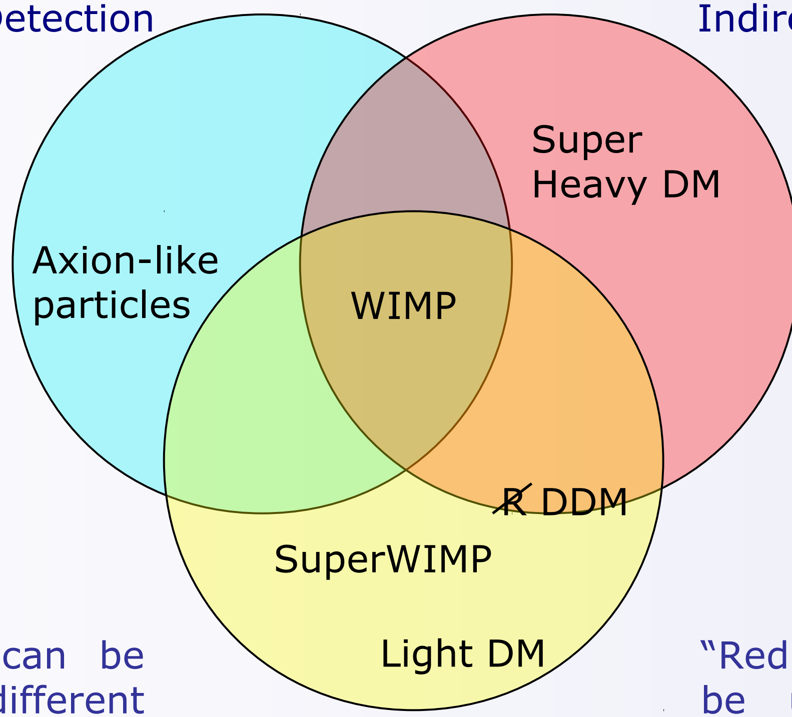
- We are attacking the DM in various fronts:

Direct Detection

DAMA/LIBRA
XENON
CDMS
KIMS
COUPP
ZEPLIN
CoGeNT
...

Indirect Detection

PAMELA
GLAST
MAGIC
AMS
ANTARES
IceCube
...



Many DM models can be probed by the different experimental techniques

Accelerator searches

LHC, ILC, ...

"Redundant" detection can be used to extract DM properties

Direct detection of DM

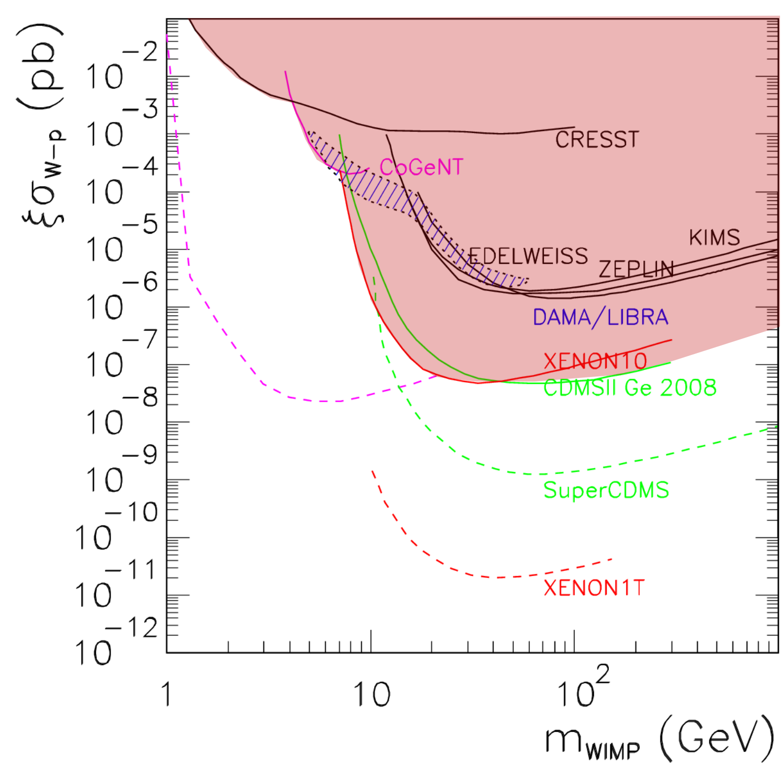
- Most of the experiments nowadays are mostly sensitive to the scalar (spin-independent) part of the WIMP-nucleon cross section

DAMA/LIBRA (based on NaI) claims a potential dark matter signal

Other experiments (XENON10, CDMS and CoGeNT) have not yet confirmed any WIMP in the DAMA region (maybe very light WIMPs?)

The current sensitivity and future predictions will allow to explore models for particle dark matter.

Need to compare with theoretical predictions for WIMP models



Direct detection of DM

- Direct detection experiments may allow to determine some WIMP properties in a model-independent way

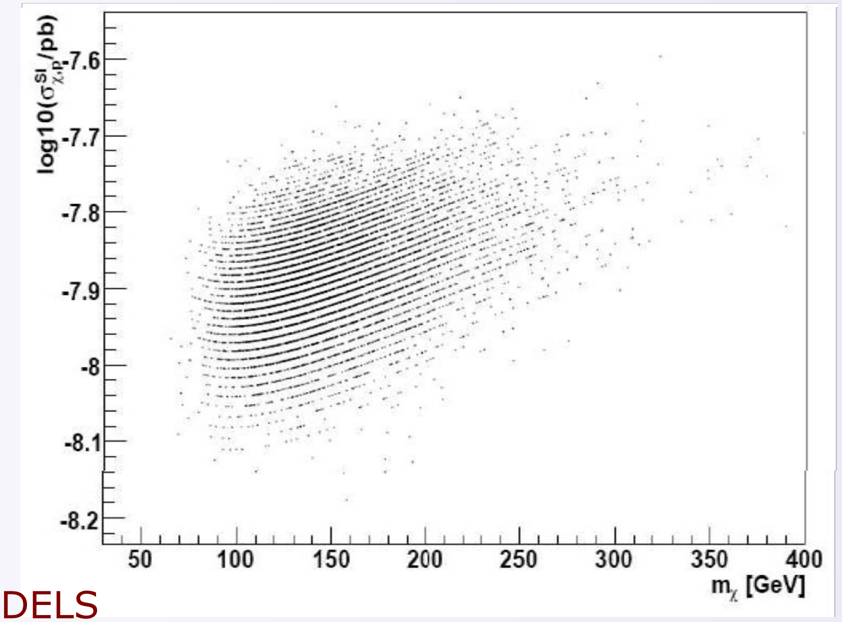
$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

Through the study of the energy-dependence of the detected rate the WIMP mass and cross section might be determined

(see, e.g., A.M. Green '07;'08)

E.g., detection of a 120 GeV WIMP

(courtesy of M. Fornasa)



HOWEVER, DIFFERENT THEORETICAL MODELS CAN REPRODUCE THE SAME SIGNAL

Neutralino in the MSSM

- The neutralino can be within the reach of present and projected direct DM detectors

Large cross section for a wide range of masses

Very light **Bino-like** neutralinos with masses ~10 GeV

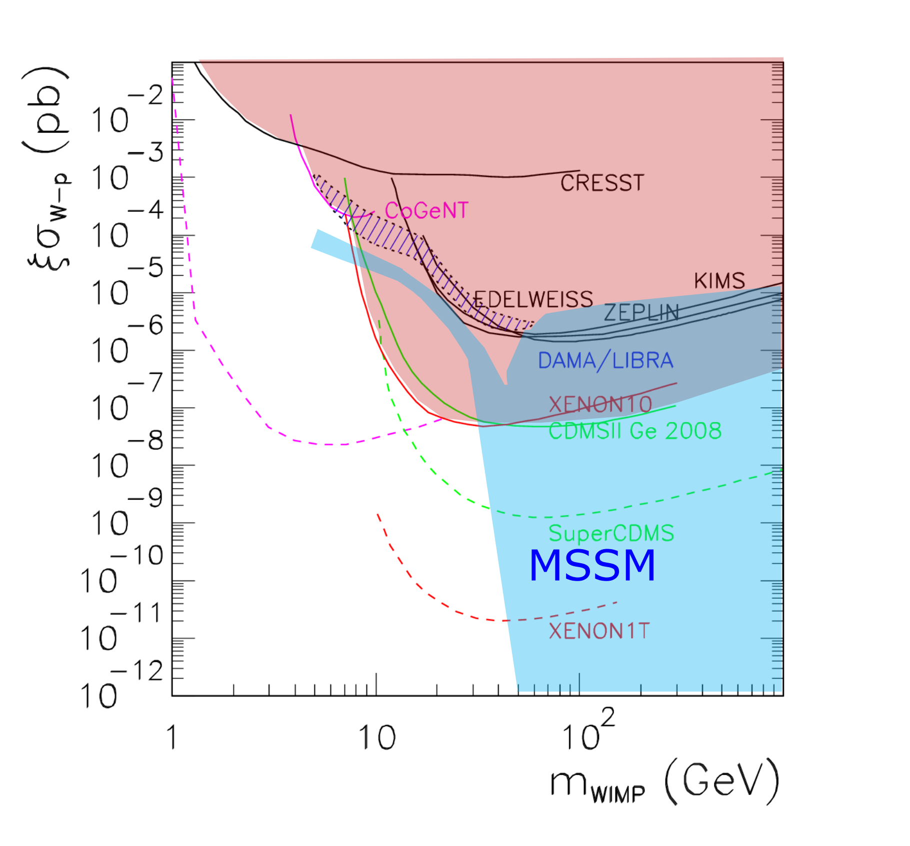
(Bottino, Donato, Fornengo, Scopel '04-'08)

Bayesian analyses show preference for regions within the reach of CDMS and Xenon

(Roszkowski, Ruiz de Austri, Trotta '08)

A frequentist approach may favour different regions

(Buchmüller et al. '09)



Neutralino in the NMSSM

- Different predictions from the MSSM (extensions with extra U(1) are also possible)

The detection cross section can be larger (through the exchange of light Higgses)

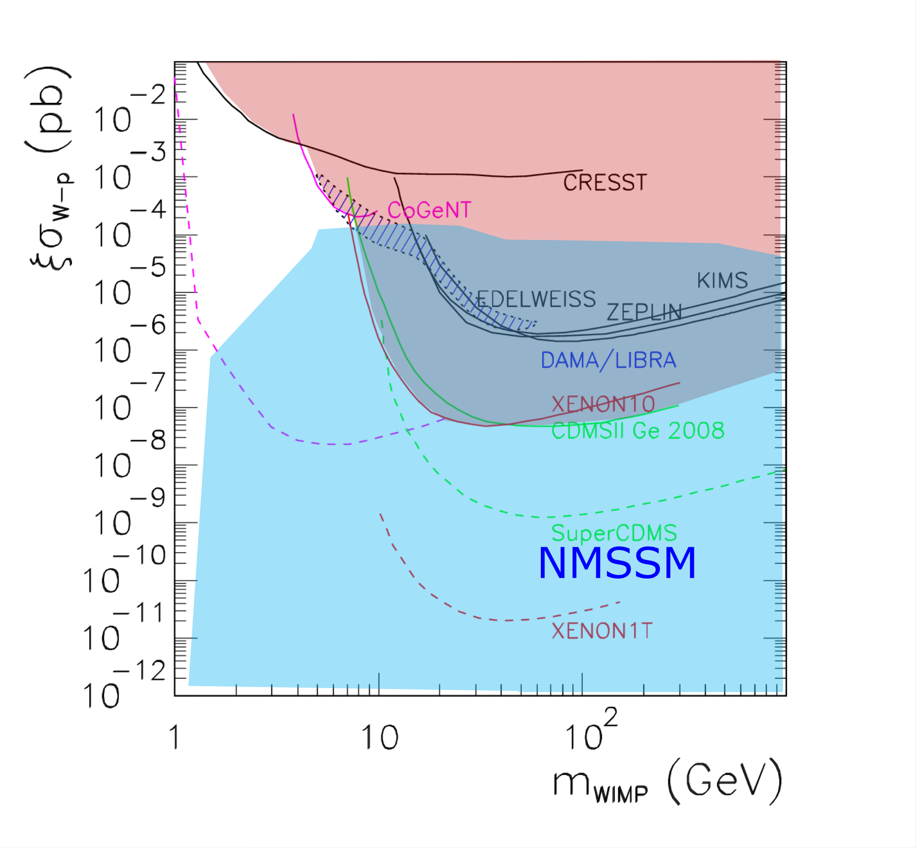
(D.G.C., E. Gabrielli, D.López-Fogliani, A.Teixeira, C.Muñoz ´07)

Very light **Bino-singlino** neutralinos are possible

(Gunion, Hooper, McElrath '05)

And their detection cross section significantly differs from that in the MSSM

(CoGeNT '08)

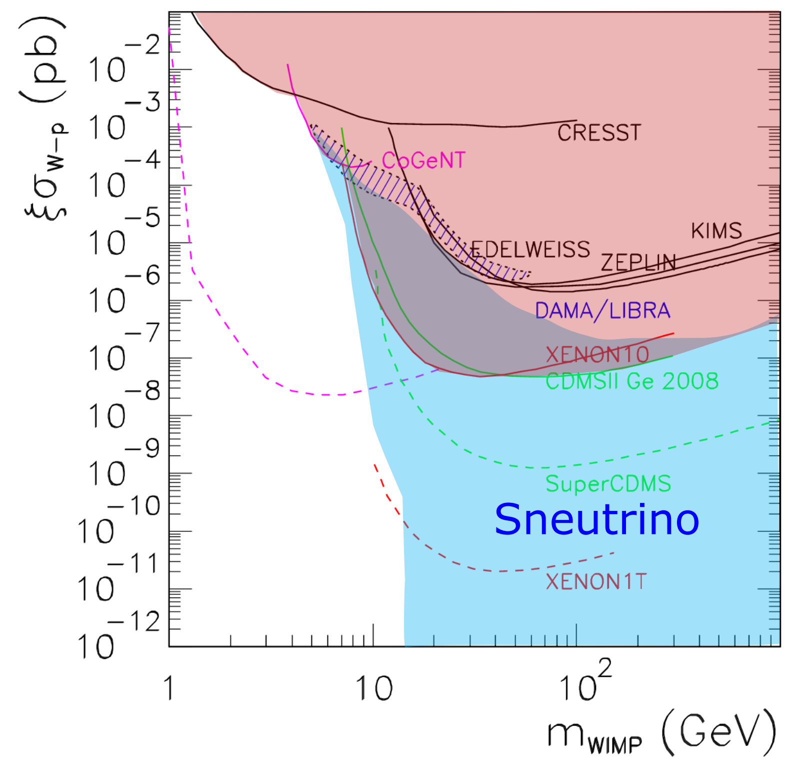


RH-Sneutrino DM overview

- Even different SUSY WIMPs are possible: (Right-handed) sneutrinos in the NMSSM.

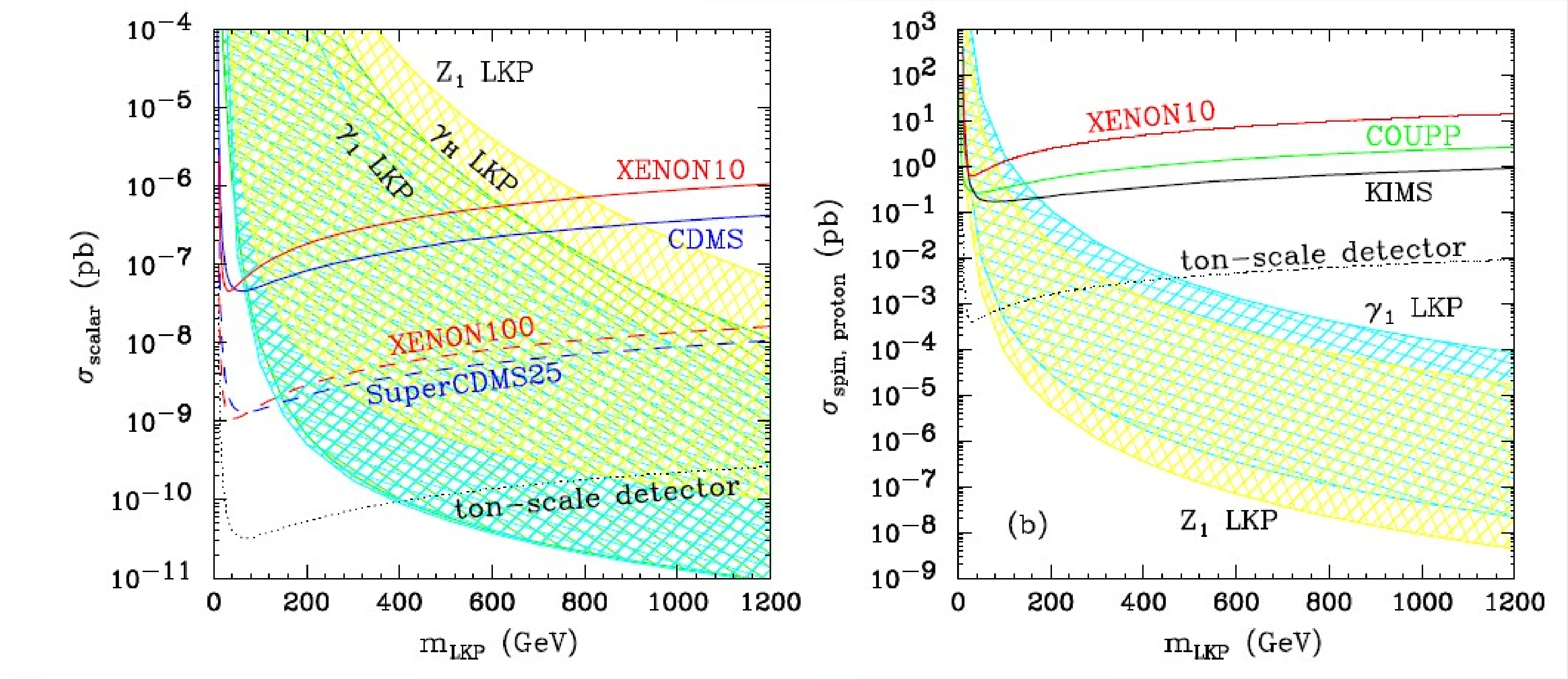
  - Viable, accessible and not yet excluded
    (D.G.C., Muñoz, Seto ‘08)

  - Light sneutrinos are viable and distinct from MSSM neutralinos
    (D.G.C., Seto '09)



KK dark matter

• The Lightest KK particle (LKP) is also a good dark matter candidate in Universal Extra Dimensions models



(Arrenberg et al.'08)

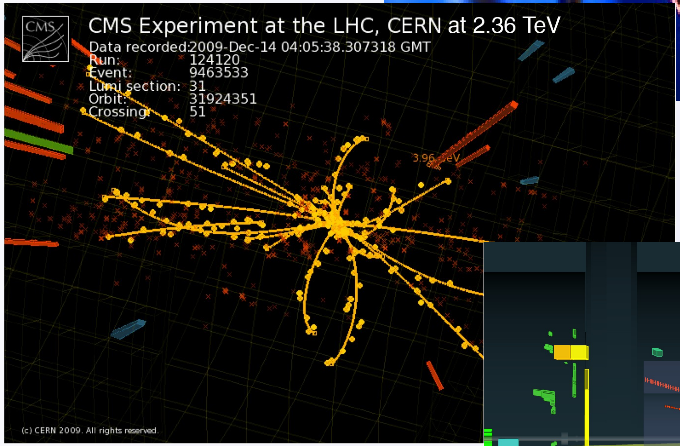
Dark Matter signals at the LHC

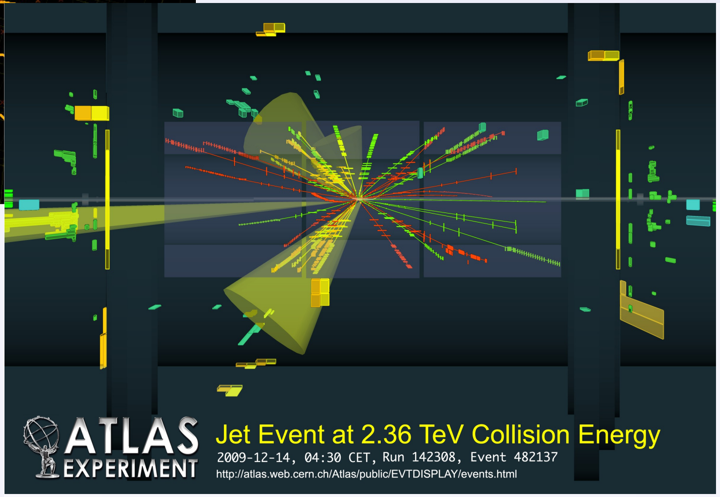
LHC will probe new Physics at the TeV scale

Most of the models for DM appear in extensions of the SM at that scale

The LHC is back!

Plans to run at 7 TeV until 2011 and then there are plans to try to go for 14 TeV





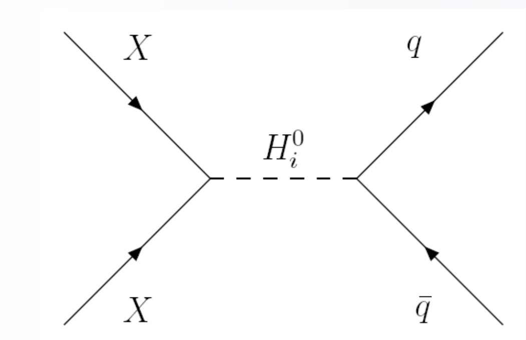
Will probe new Physics at the TeV scale

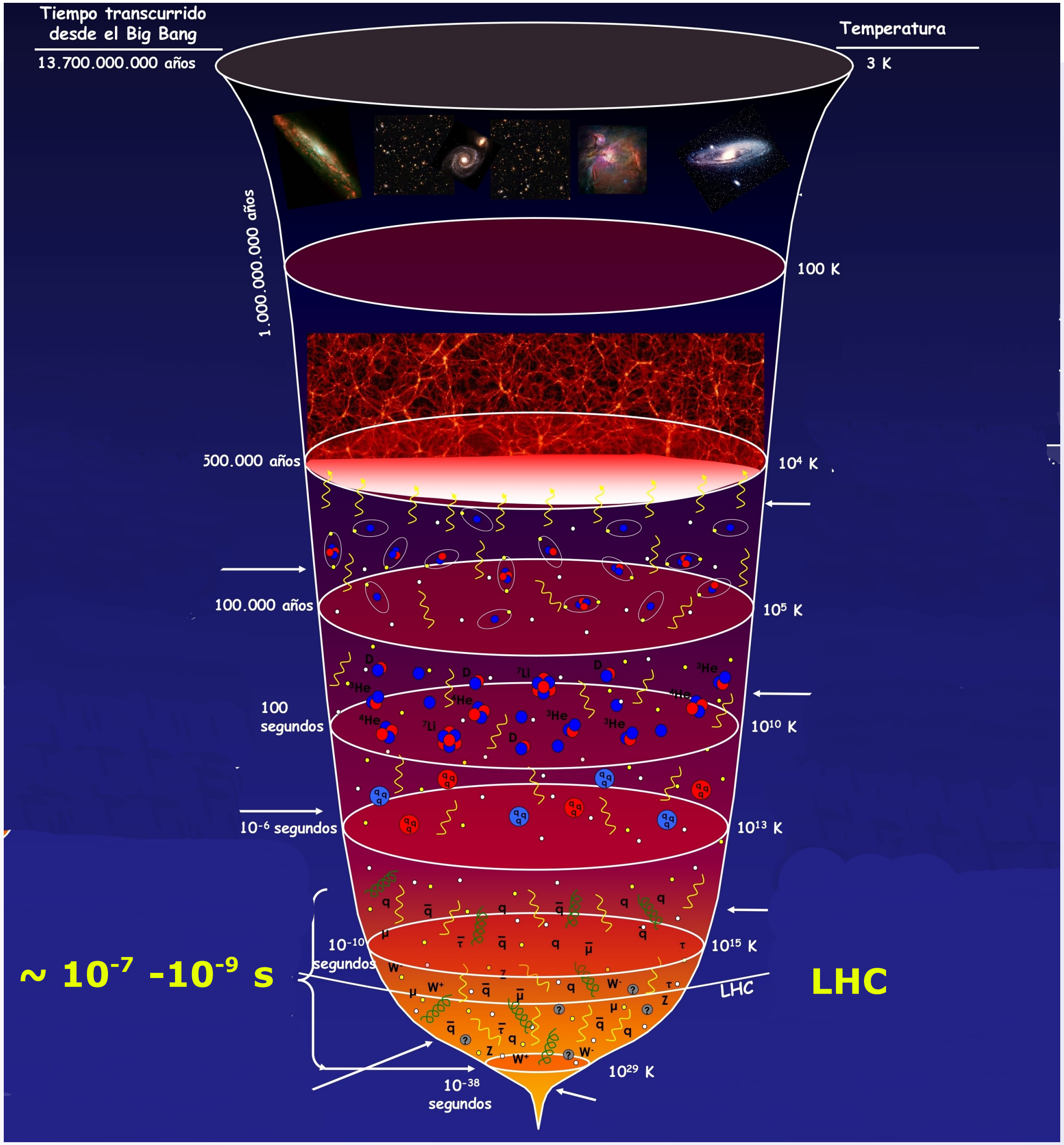
Higgs boson, SUSY, Extra Dimensions... Dark Matter?

Exploring the nature of Physics at the TeV scale

Understanding the origin of EW symmetry breaking

Probing the scale at which (thermal) DM is created

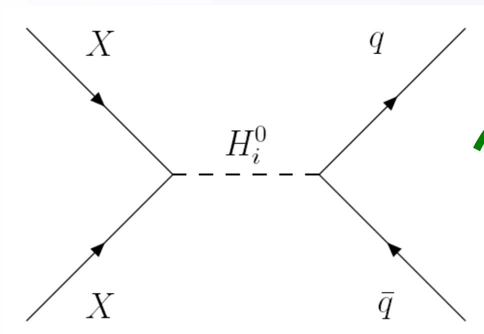




DM Signals in colliders

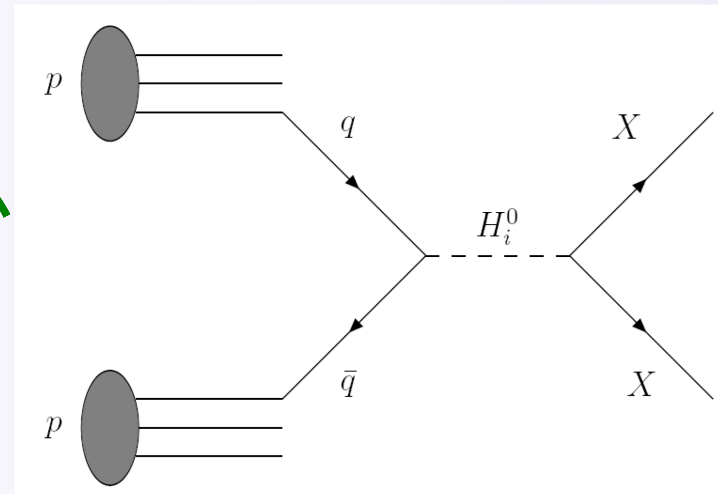
- Direct production of DM (pp → XX)

DM annihilation (Early Universe)



Inverse process

DM Production in colliders?



Missing transverse energy

Potential problems in measuring missing E_T:

- Energy loss due to uninstrumented regions of the detector or dead cells
- Noisy channels in calorimeter (e.g., hot cells)
- Mis-measurements in calorimeters or muon detectors (e.g. escaping muons)
- Mis-identified cosmic rays

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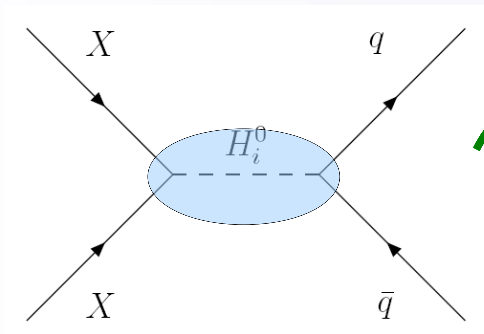

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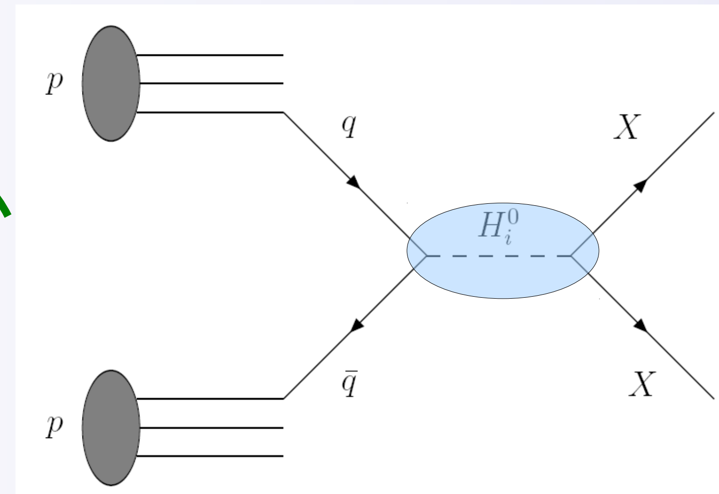


Missing transverse energy

Problematic: does not leave a good signal (no hard energy deposition for detectors to trigger upon)

We might not be able to test directly the DM couplings to SM matter (problem for estimating the relic abundance)

MAKES IT DIFFICULT TO TAKE A MODEL INDEPENDENT APPROACH.

DM Signals in colliders

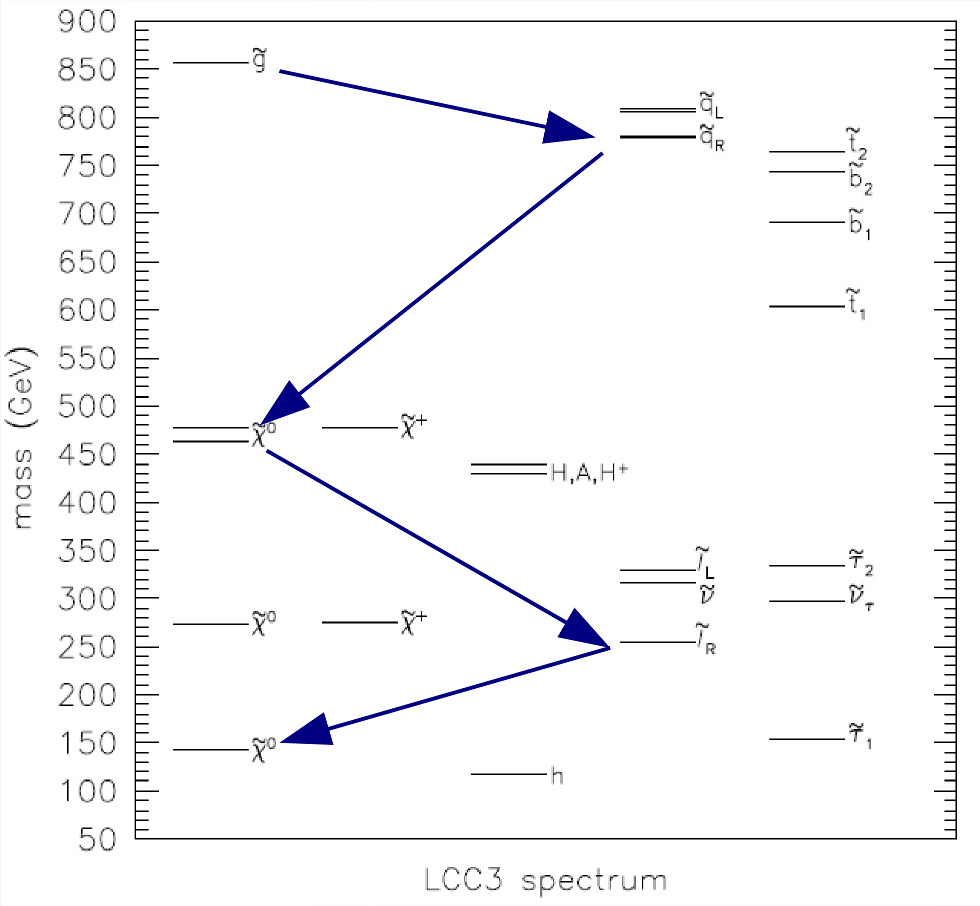
- Look for jets + extra leptons

New coloured particles are expected to be produced through their couplings with SM quarks and gluons

E.g., in Supersymmetric theories dominant production will be in

$$\tilde{g}\,\tilde{g} \qquad \tilde{q}\,\tilde{q} \qquad \tilde{g}\,\tilde{q}$$

These heavy particles subsequently decay into lighter ones and finally into the LSP



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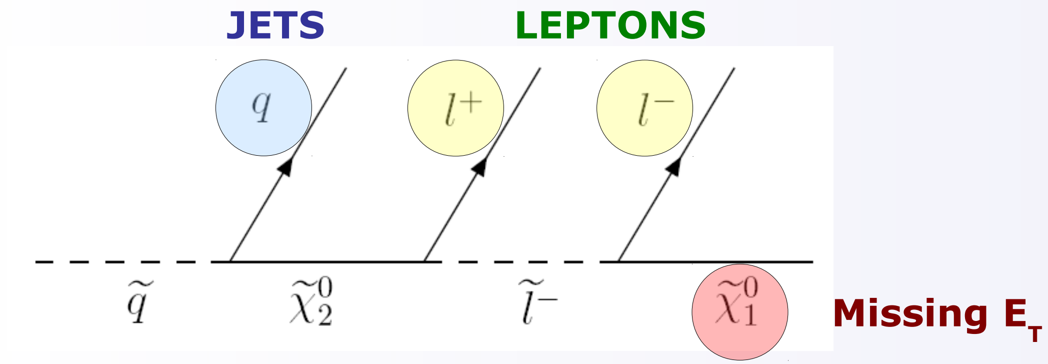
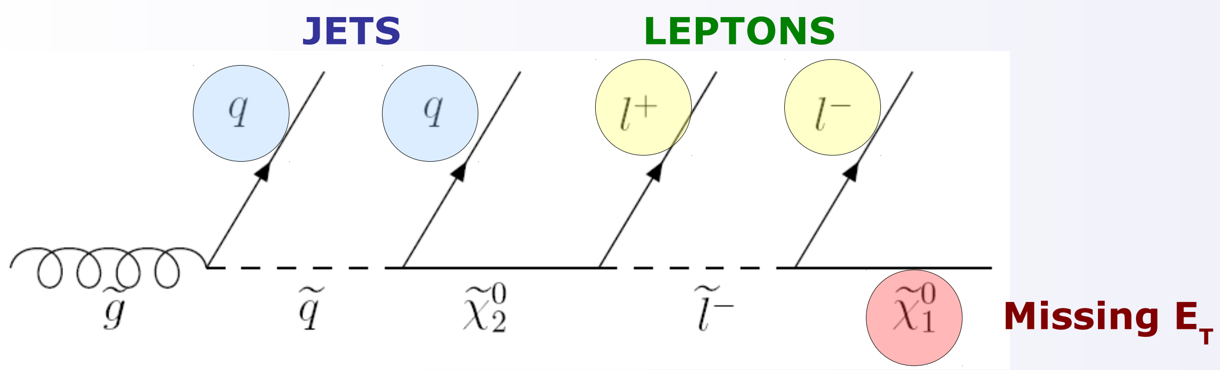


Masses are determined by measuring endpoints in kinematic distributions



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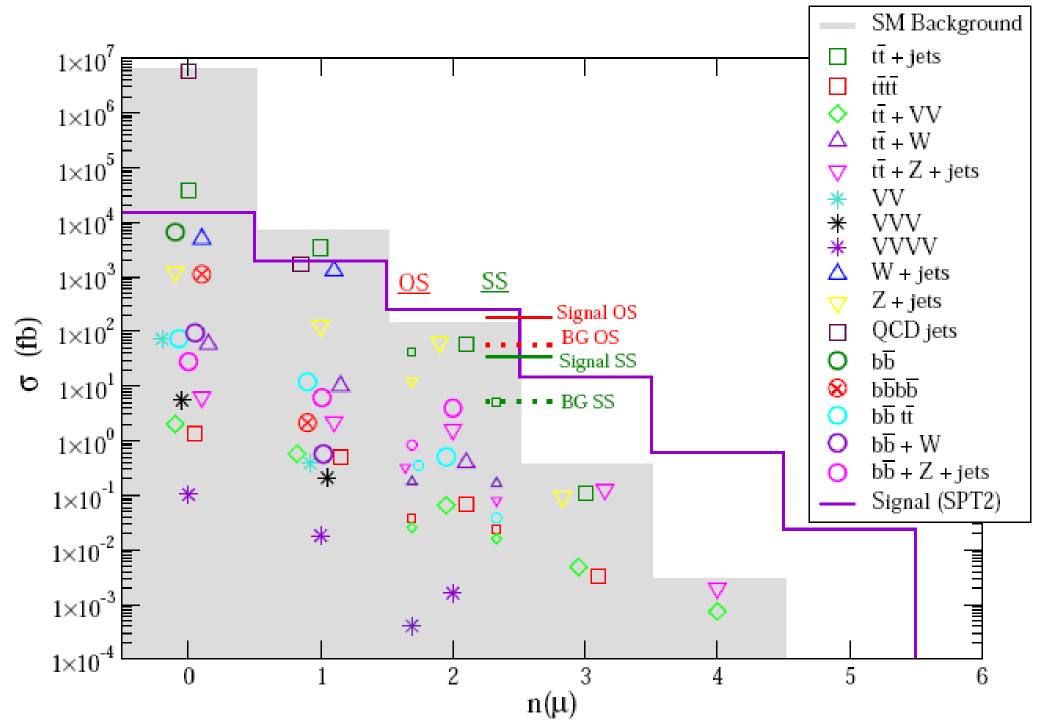
E.g., in Supersymmetric theories dominant production will be in $\tilde{g}\,\tilde{g}\quad \tilde{q}\,\tilde{q}\quad \tilde{g}\,\tilde{q}$

The background for this kind of processes is smaller in the SM (especially for large lepton multiplicity)

Estimation of the SM background for 4 jets + n leptons



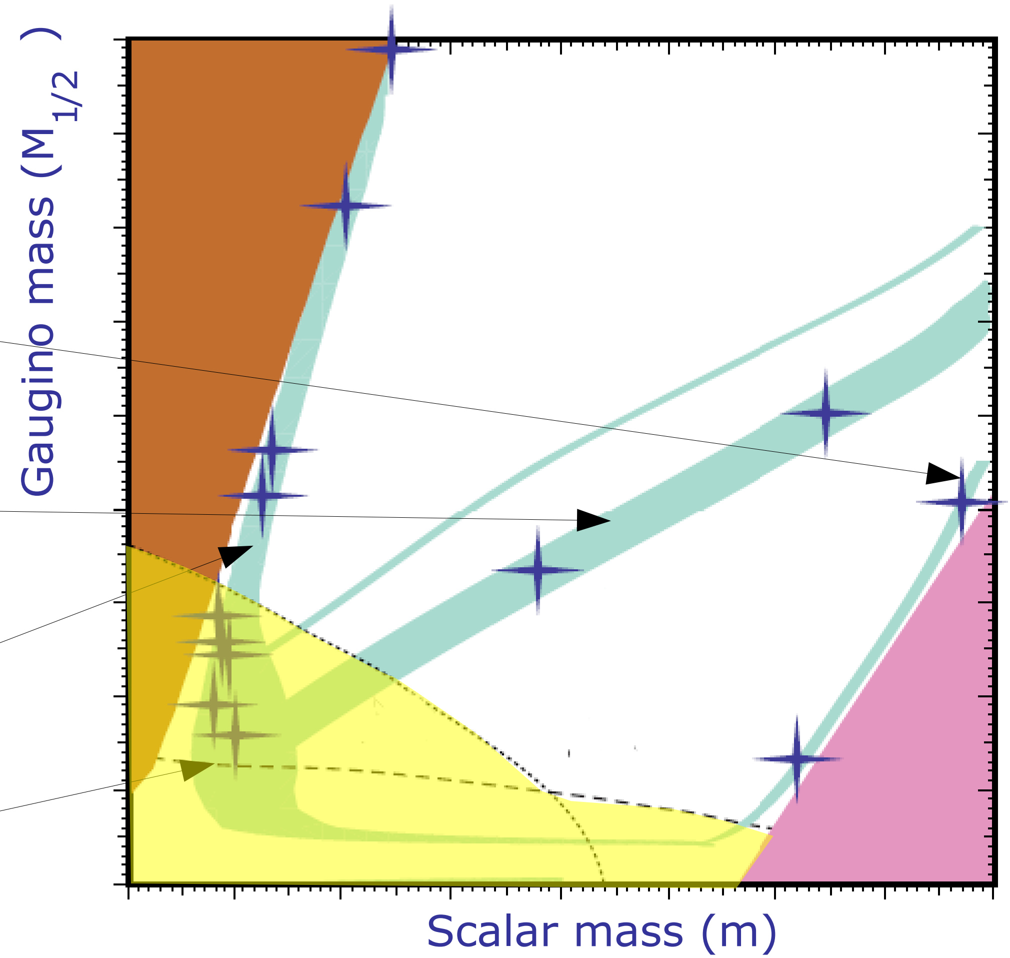
(Baer, Barger, Lessa, Tata '09)

LHC reach in the SUSY parameter space (example CMSSM – A, M, m, tanβ, μ)

Regions compatible with Neutralino DM (having correct relic density)

- Focus-Point region (Higgsino-Bino neutralino)
- Resonant annihilation (with pesudoscalar Higgs
- Coannihilation region (small LSP-NLSP mass difference)
- Bulk (small SUSY masses)

Mostly excluded by LEP constraints (still available in non-minimal models)



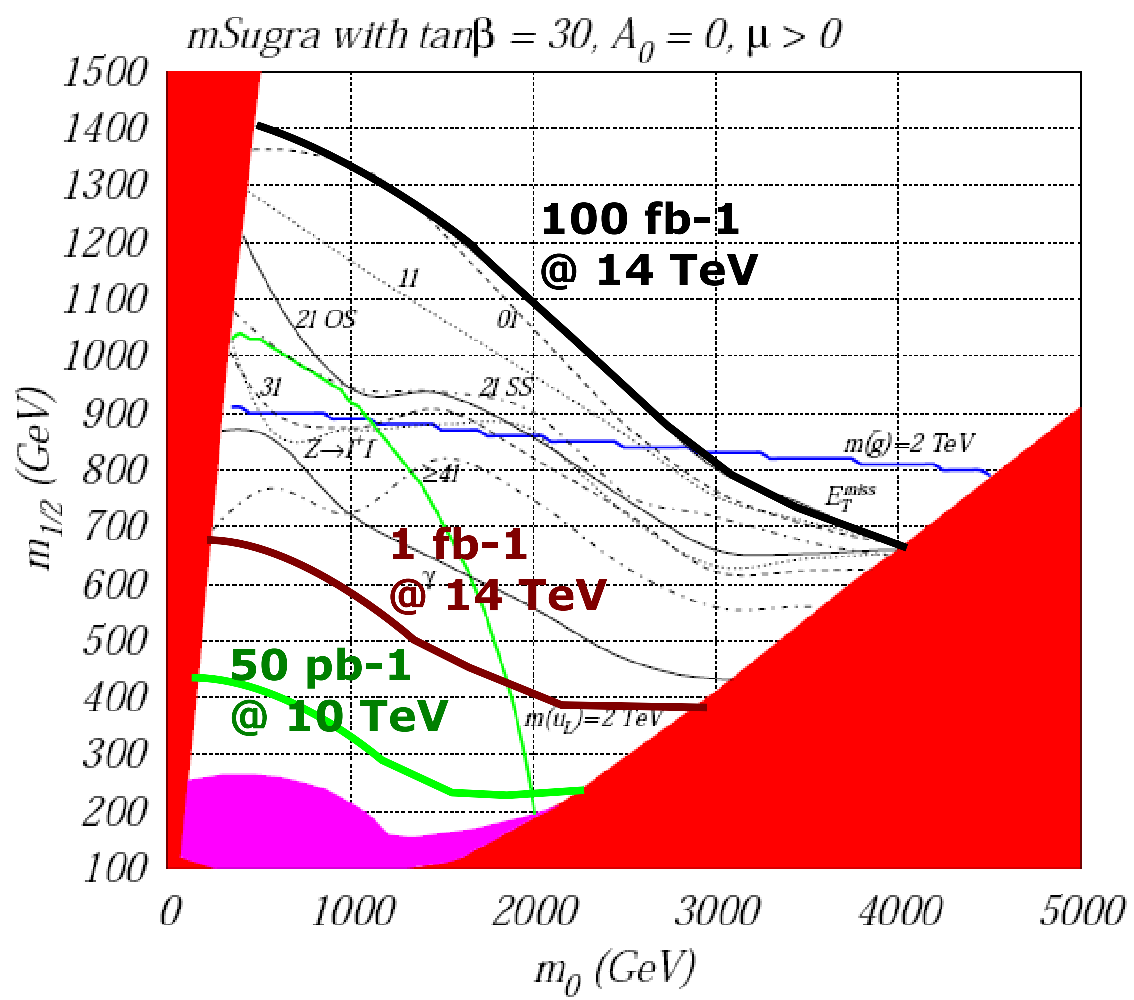
(see e.g., Ellis, Ferstl, Olive)

LHC reach in the SUSY parameter space (example CMSSM)

LHC (at its best) might be able to probe the SUSY parameter space with

$$m_{\tilde{g}} \sim 2-3\,TeV$$

Depending on the topology of the event



(Baer, Belyaev, Kuprovnikas, o'Farrill ' 04)

(Buchmüller et al. '08)

LHC reach in the SUSY parameter space (example CMSSM)

Some regions compatible with Neutralino DM can be probed

- Focus-Point region (Higgsino-Bino neutralino)

NOT ACCESSIBLE

- Resonant annihilation (with pesudoscalar Higgs

MOSTLY ACCESSIBLE

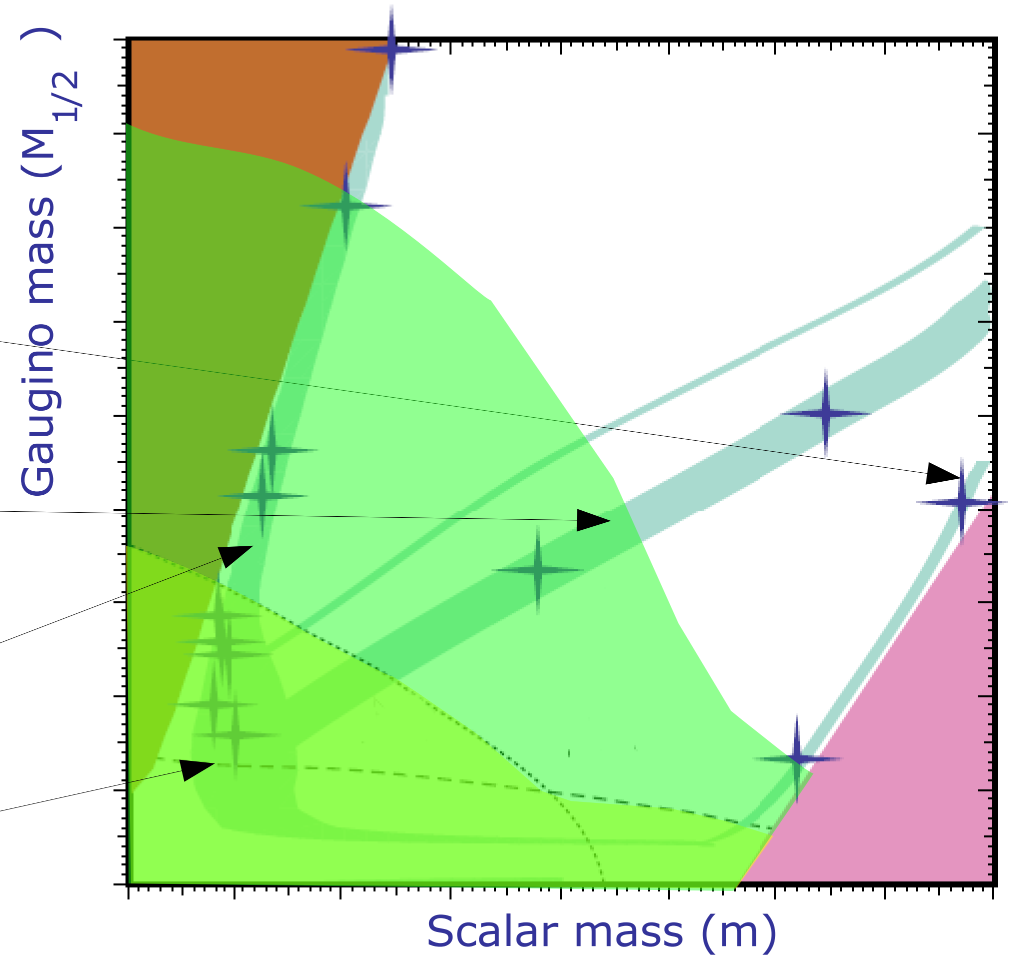
- Coannihilation region (small LSP-NLSP mass difference)

ACCESSIBLE

- Bulk (small SUSY masses)

  Mostly excluded by LEP constraints (still available in non-minimal models)

ACCESSIBLE



(see e.g., Ellis, Ferstl, Olive)

LHC reach in the SUSY parameter space (example CMSSM)

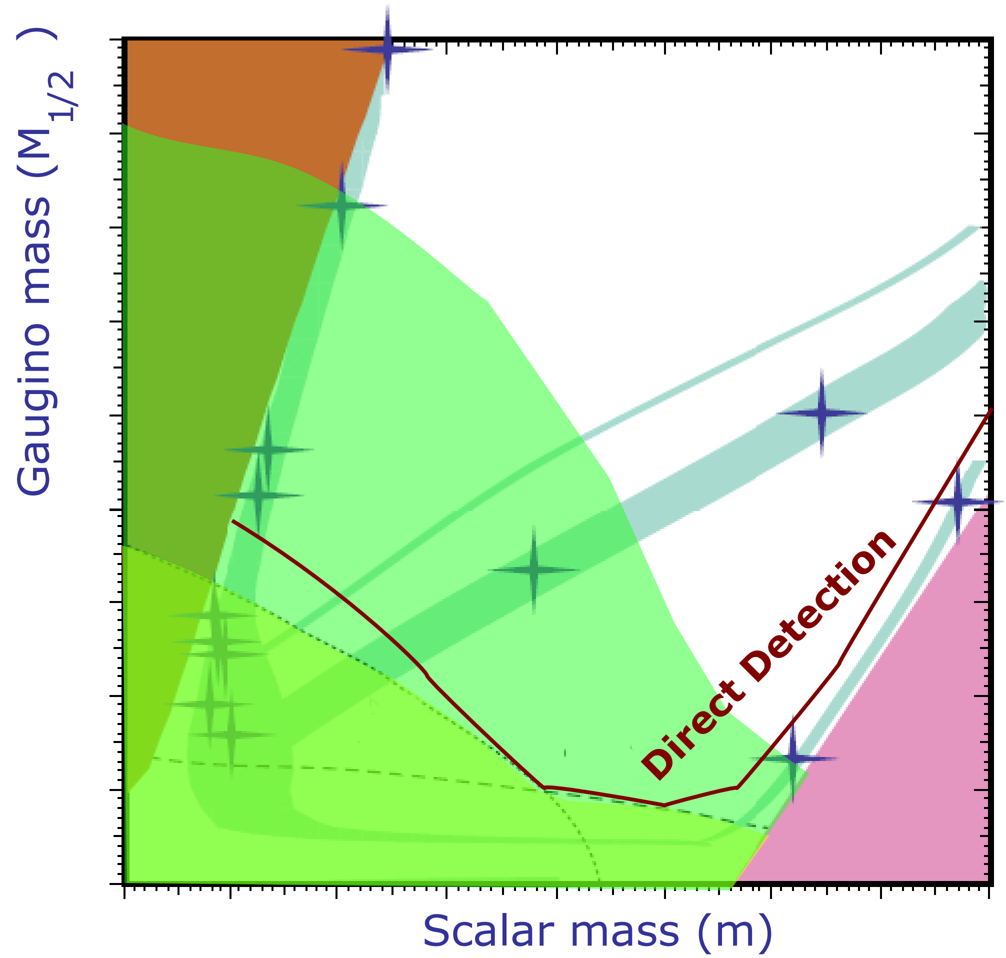
Some regions compatible with Neutralino DM can be probed

• Focus-Point region (Higgsino-Bino neutralino)

NOT ACCESSIBLE

However, Direct Detection experiments (also indirect searches) can probe the FP region

ACCESSIBLE



COMPLEMENTARITY OF LHC AND DIRECT DETECTION

LHC reach in the SUSY parameter space (example CMSSM)

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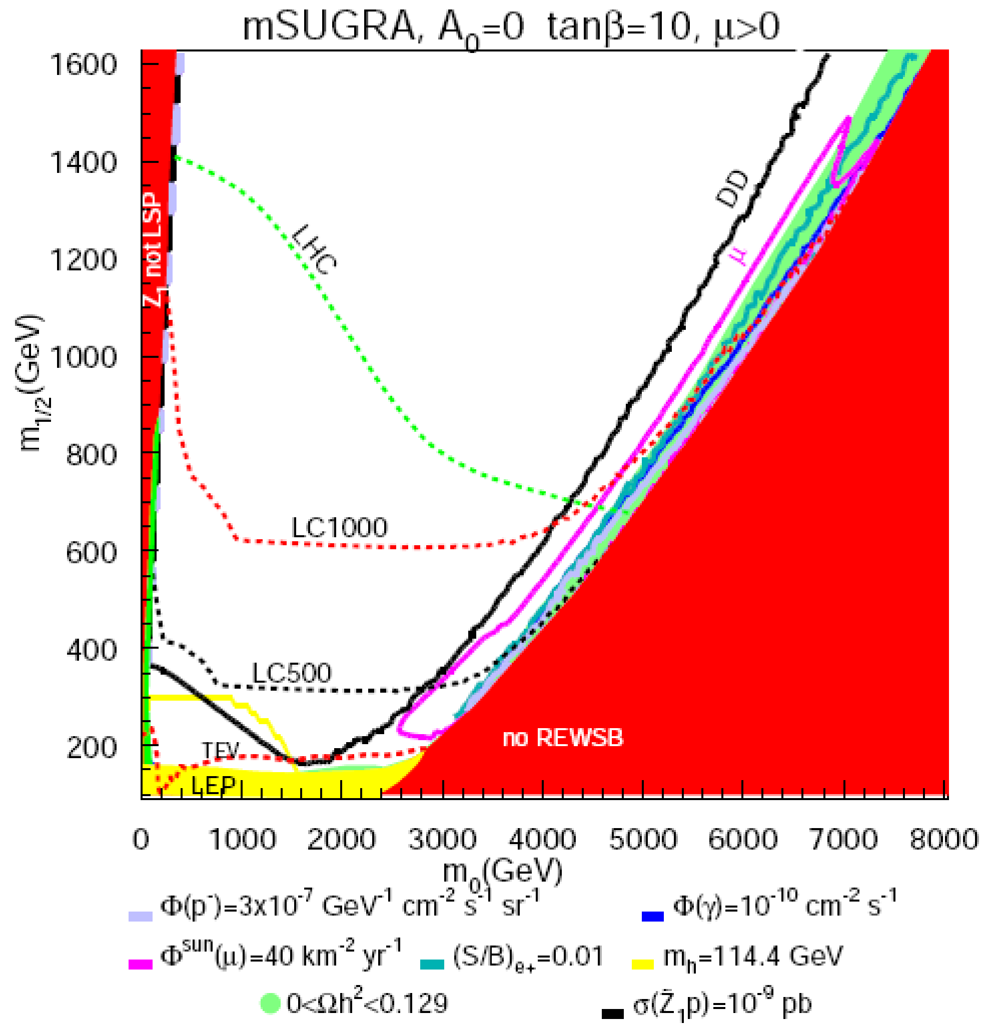
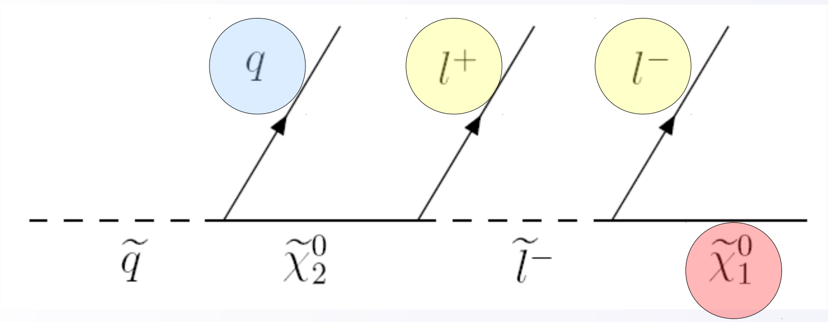


COMPLEMENTARITY OF LHC AND DIRECT DETECTION

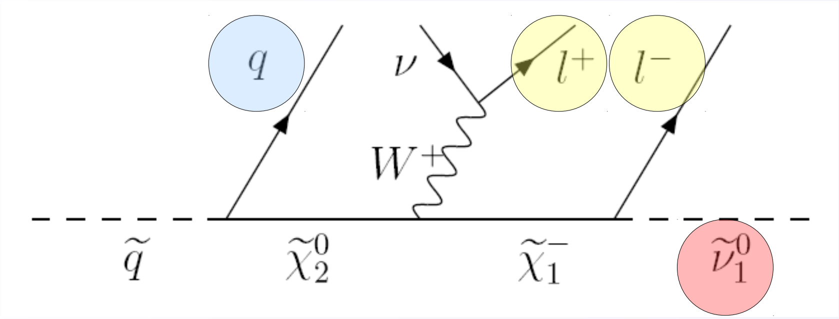
DM Signals in colliders

- Look for jets + extra leptons

However, similar decay chains can correspond to very distinct WIMPs (LSPs)



Neutralino DM



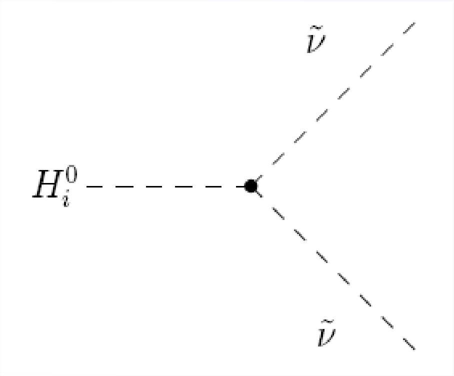
Sneutrino DM

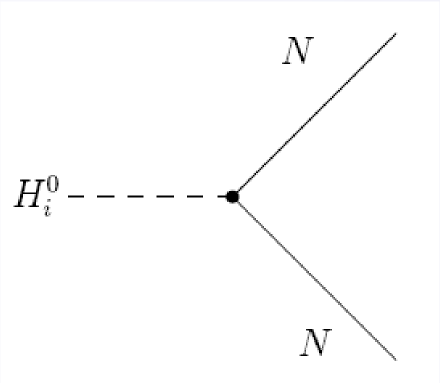
The study of some kinematical variables M(T2) can help determining the spin of the particle

(Cho, Choi, Kim, Park '09)

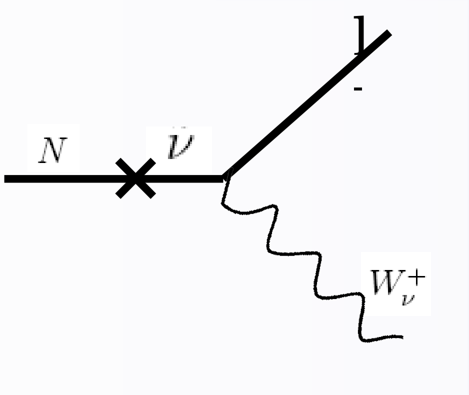
Less standard signatures of DM (model dependent but useful to discriminate theories)

- Invisible Higgs decays (decays into DM or extra particles from the DM model)





- Displaced vertices

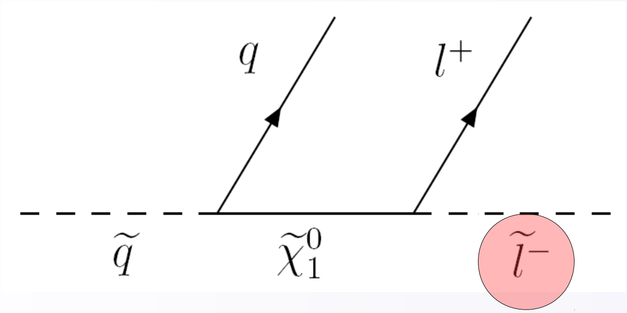


EXAMPLES OF NEW PHENOMENOLOGY WITH SNEUTRINO DM

COMPLEMENTARITY OF LHC AND DIRECT DETECTION

Colliders could also be sensitive to other DM models

E.g. SuperWIMPs such as gravitino (or axino) DM might lead to long-lived charged particles.



Long-lived stau NLSP

Might get constraints on cosmological parameters (e.g., reheating temperature) from estimations of NLSP relic abundance.

(see e.g., Covi, Roszkowski, Ruiz de Austri '08)

A final word of caution... Can LHC **DISCOVER** dark matter?

- A "stable" particle at the LHC does not imply stability in Cosmological scales

How can we test it is the DM?

- Calculate its relic abundance (possible to some extent if the spectrum is measured)

  The uncertainty can be large (more than 1 order of magnitude)

Is it compatible with the WMAP result?

- Yes — Cross-check with other experiments
- No — Non-thermal dark matter?

  Non-standard Cosmological history?

  Subdominant component of dark matter?

Confirmation from other source of experiments (e.g., Direct Detection) is crucial.

Combination with Direct Detection

LHC might be unable to determine whether DM has been detected

Confirmation from other experiments is needed (e.g., Direct Detection)

Combination of DD and LHC data can help determining the DM properties

(Bertone, Cerdeño, Fornasa, Trotta, de Austri – in preparation)

Direct detection of DM

- Direct detection experiments may allow to determine some WIMP properties in a model-independent way

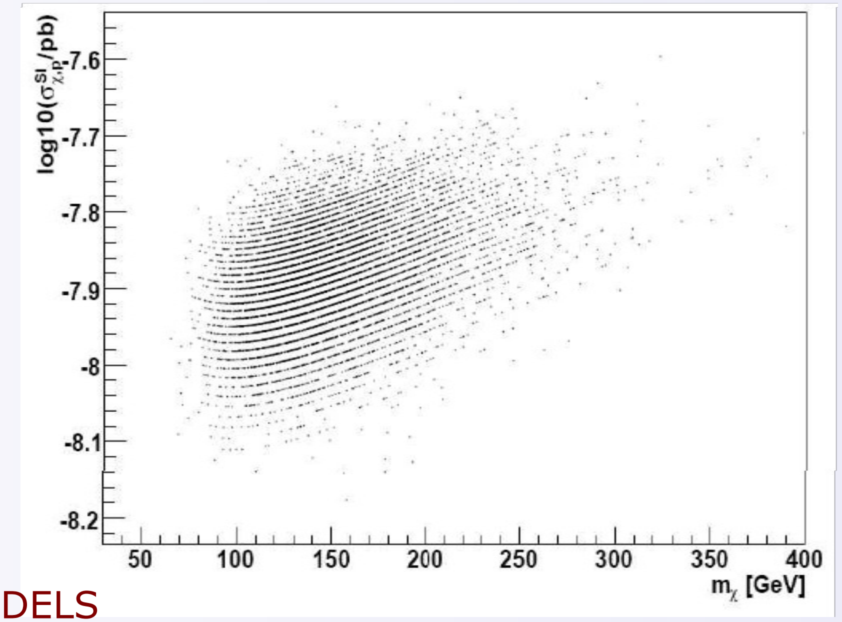
$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

Through the study of the energy-dependence of the detected rate the WIMP mass and cross section might be determined

(see, e.g., A.M. Green '07;'08)

E.g., detection of a 120 GeV WIMP

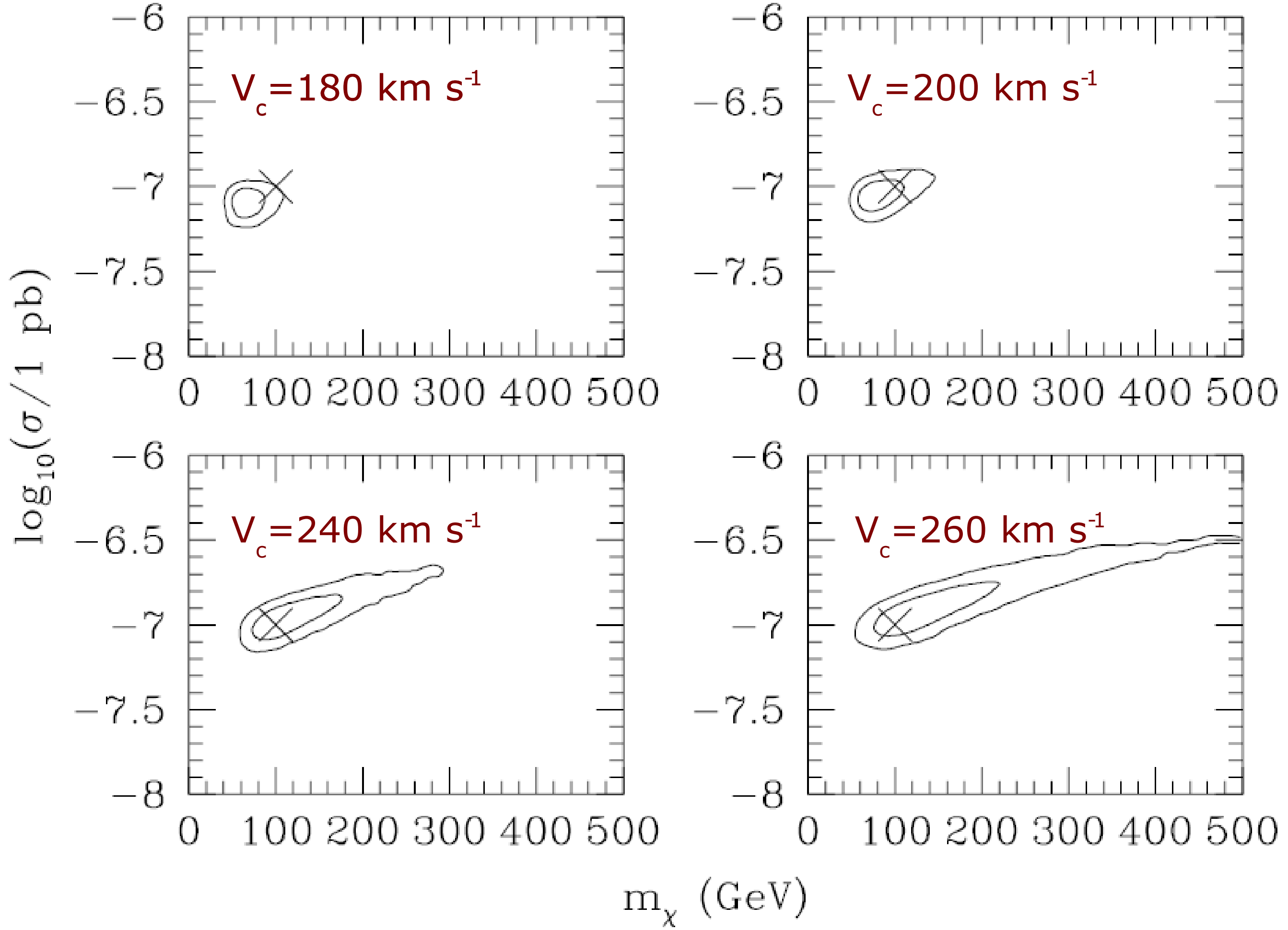
(courtesy of M. Fornasa)



HOWEVER, DIFFERENT THEORETICAL MODELS CAN REPRODUCE THE SAME SIGNAL

The reconstructed mass and cross section are sensitive to the astrophysical uncertainties in the detection rate

E.G:, variations in the central velocity can lead to a mis-reconstruction of the mass

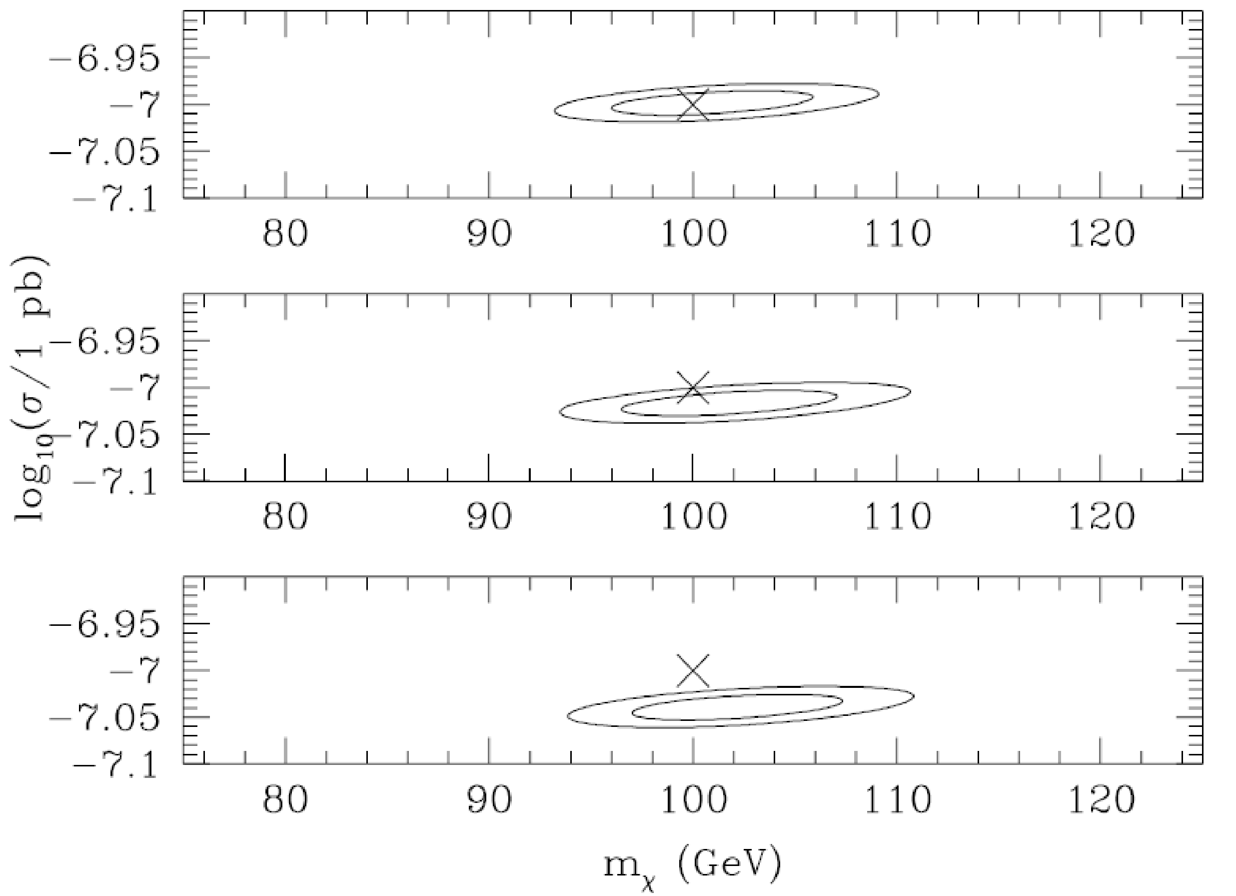


(A.M. Green '07)

The reconstructed mass and cross section are sensitive to the astrophysical uncertainties in the detection rate

E.G:, variations in the central velocity can lead to a mis-reconstruction of the mass

Variations in the halo model can also lead to a mis-reconstructed cross section



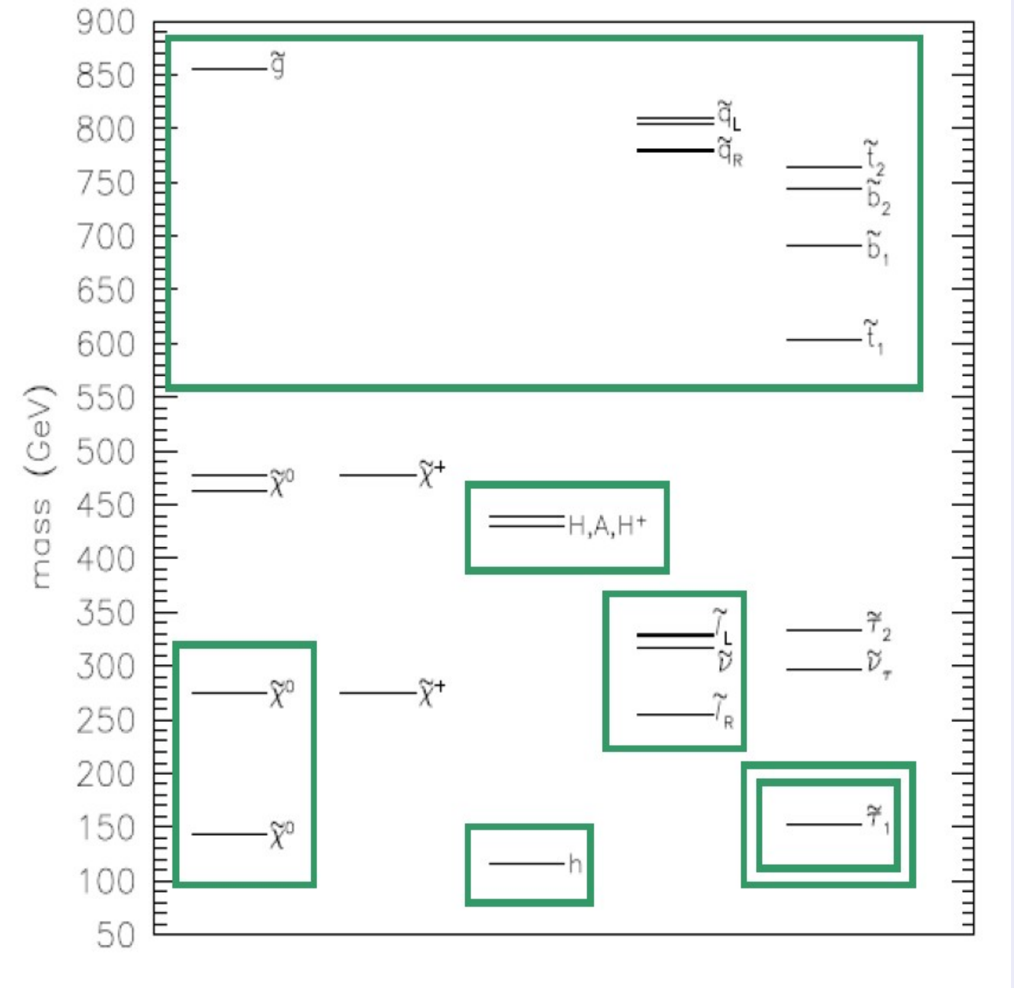
(A.M. Green '07)

• LHC might be able to determine part of the SUSY spectrum... but not all

Some masses can be accurately determined through the study of kinematical endpoints

Even the mass difference between the LSP and NLSP could be accurately reconstructed

However... the neutralino composition might not be determined!



• Using hypothetical LHC data, we have tested the reconstruction of the relic abundance

1) Choose a point in the SUSY parameter space

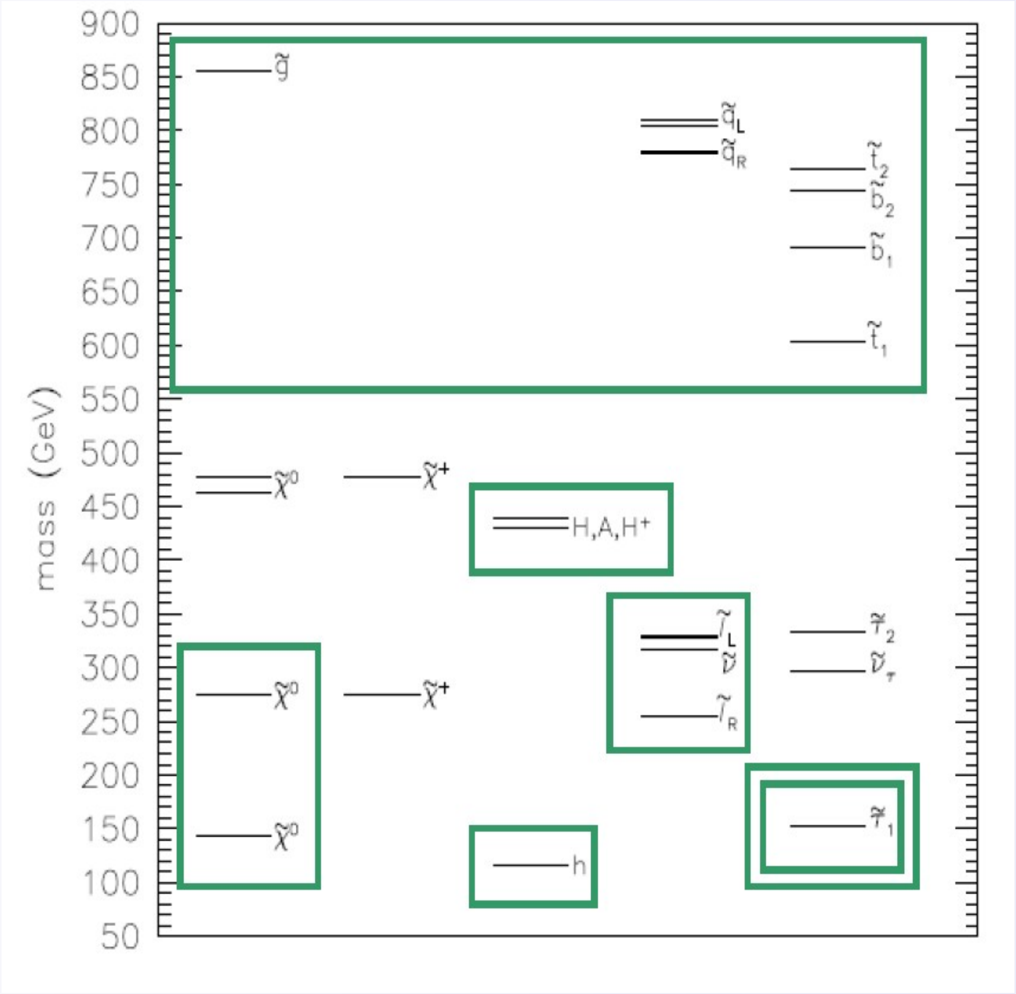
Benchmark point LCC3 in the Constrained MSSM

2) Use determination of masses as experimental constraints

3) Perform a scan in a general MSSM (with 24 parameters) in order to find the regions with the best fit to the "data"

Using MCMC techniques and Bayesian techniques

4) Determine the posterior distribution of the predicted relic abundance

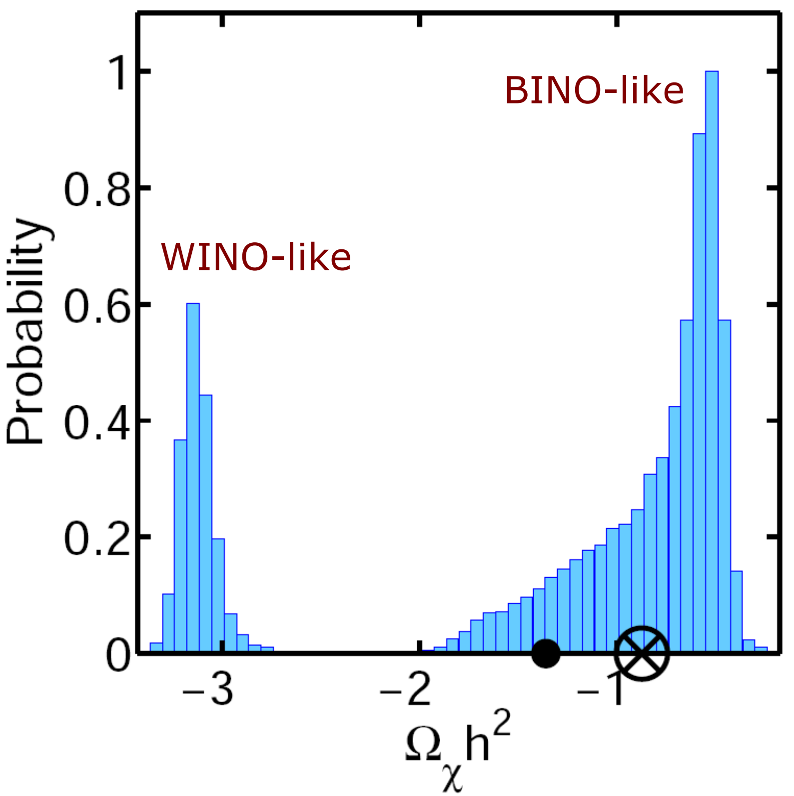


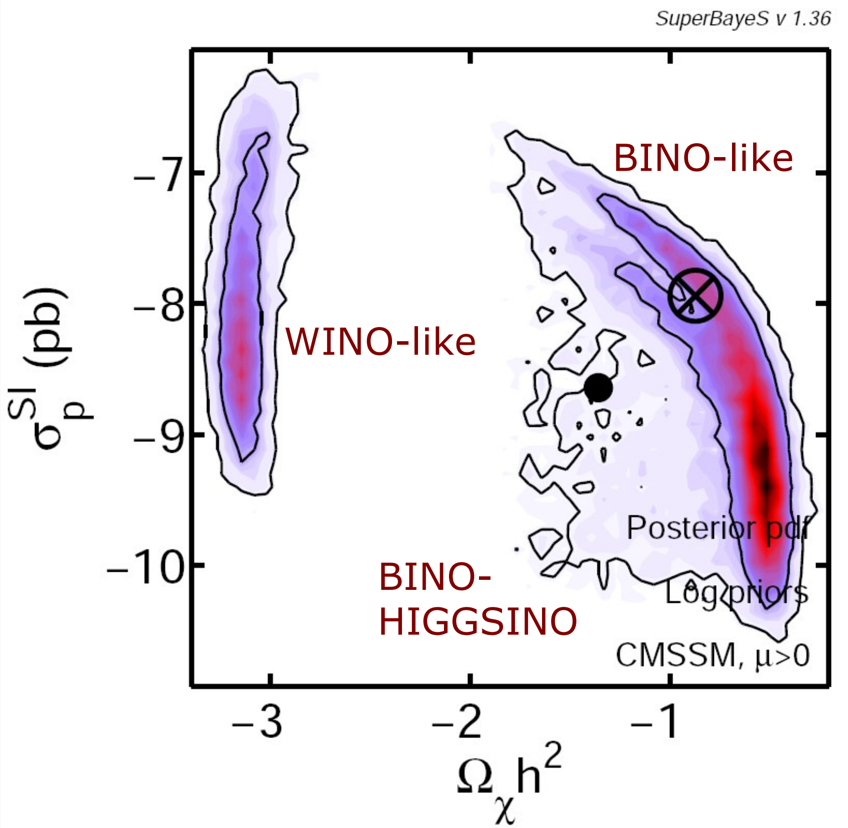
- LHC might be able to determine part of the SUSY spectrum... but not all

This leads to a large uncertainty when attempting to reproduce the relic density

More importantly, fitting the LHC data can lead to the occurrence of several maxima

This uncertainty leads to an indetermination of the scattering cross section





- The combination of LHC data with Direct Detection data can resolve the degeneracy

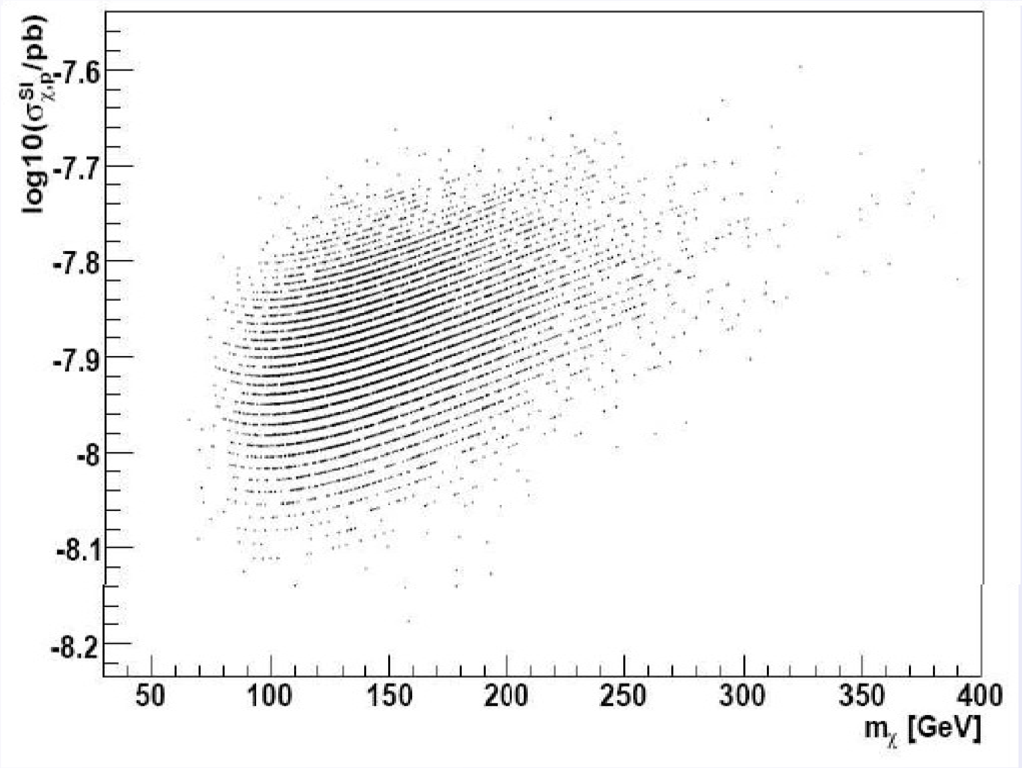
Finally, we assume a positive signal in a direct detection experiment

Using the theoretical predictions of our benchmark point (LCC3) we simulate a number of events with a given energy distribution

The number of events and energy spectrum are used as an extra constraint

This is implemented in the calculated likelihood

A new MCMC scan in the 24-dimensional parameter space is done

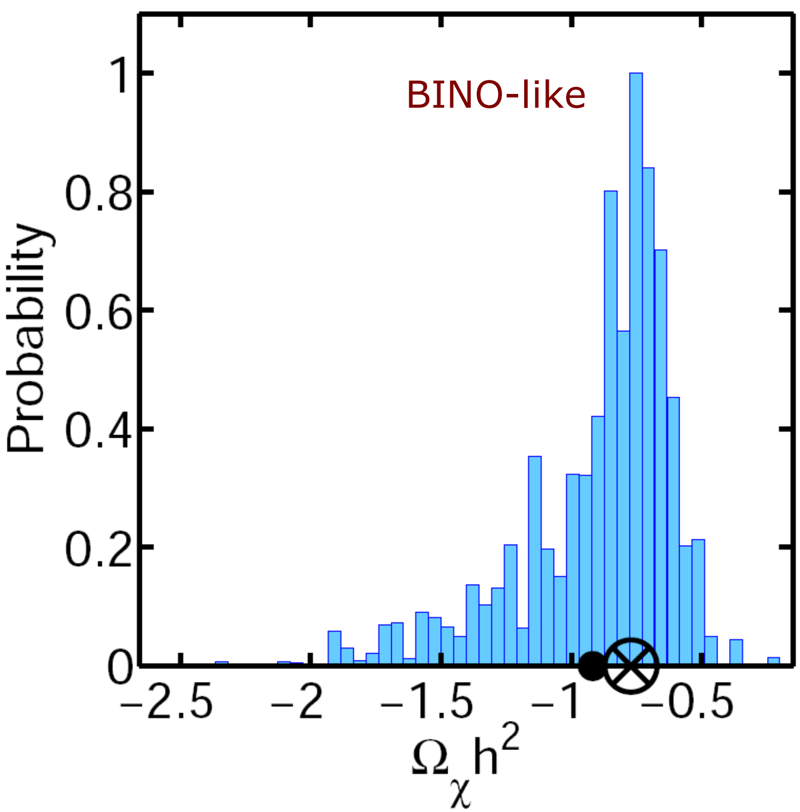


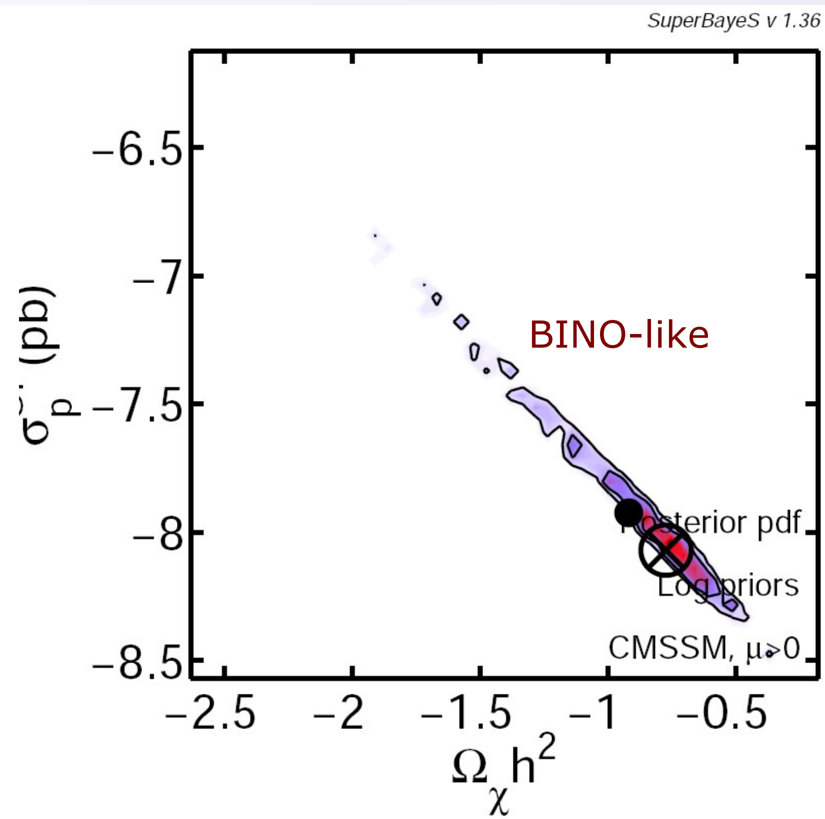
• LHC might be able to determine part of the SUSY spectrum... but not all

The combination of LHC data with Direct Detection data can resolve the degeneracy

The reconstruction of the relic abundance has a similar accuracy but spurious maxima disappear

(Bertone, Cerdeño, Fornasa, Trotta, de Austri – in preparation)





A final note on WIMP Identification

Direct detection experiments alone might also provide information about the nature of the WIMP

Combination of spin-dependent and spin-independent searches

- The interaction of a generic WIMP with nuclei has several contributions

These can be understood at the level of the effective Lagrangian describing the interaction of WIMPs and quarks, e.g., for a fermionic WIMP (as the neutralino)

σ_{WN}

<u>Axial-Vector</u>

$$\mathcal{L} \supset \alpha_q^A (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$$

$$\frac{(\mathrm{J}+1)}{\mathrm{J}}$$

SPIN-DEPENDENT (Nucl. Angular mom)

<u>Scalar</u>

$$\mathcal{L} \supset \alpha_q^S \bar{\chi}\chi\bar{q}q$$

$$\mathrm{A}^2$$

SPIN-INDEPENDENT (Nucleon #)

<u>Vector</u>

$$\mathcal{L} \supset \alpha_q^V \bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

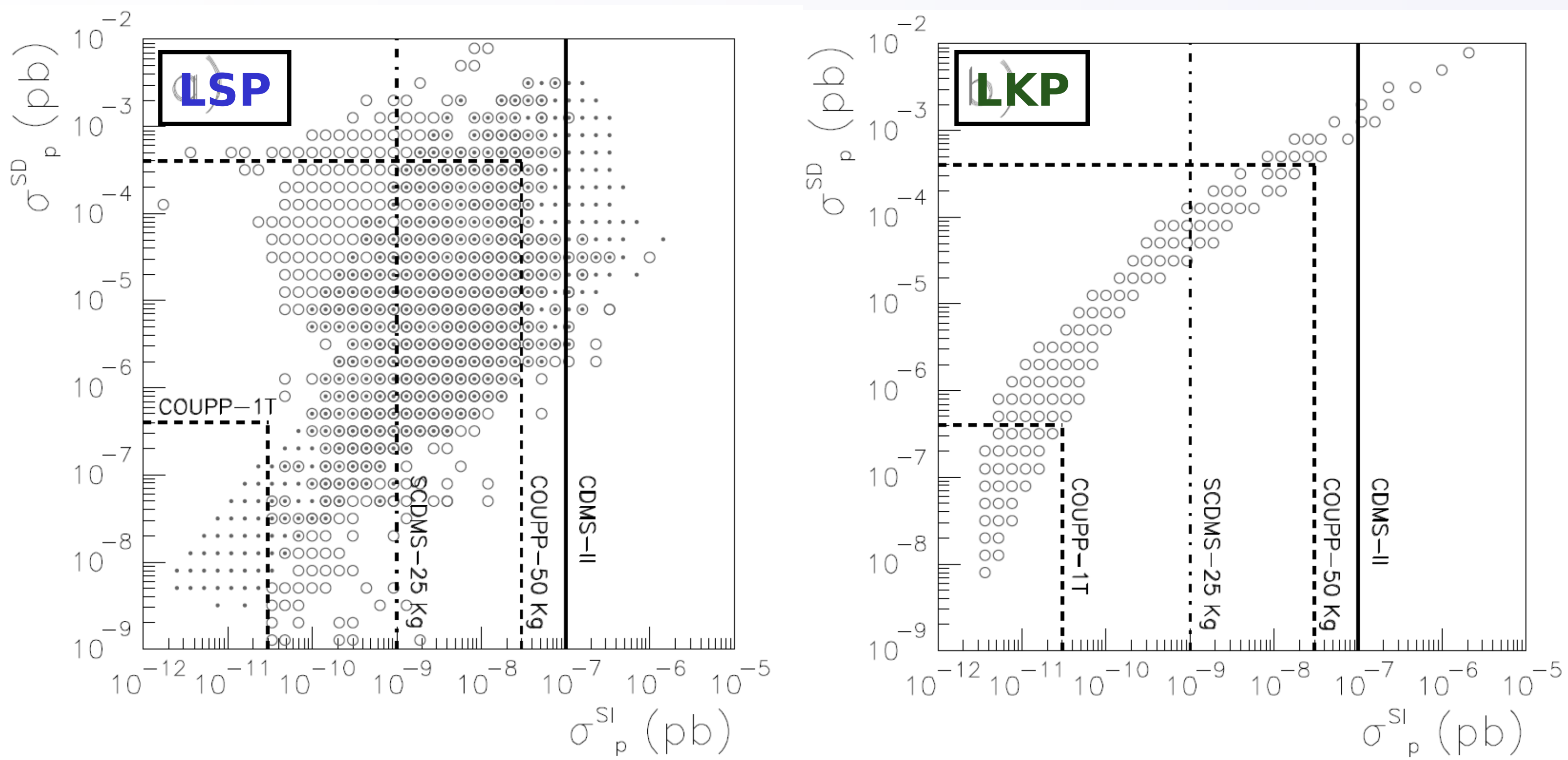
$$\mathrm{A}^2$$

- Only for non-Majorana WIMPs

SPIN-INDEPENDENT

Discriminating Neutralino vs LKP

• The predictions from neutralino dark matter and KK dark matter have a different distribution in the SI-SD cross-section plane

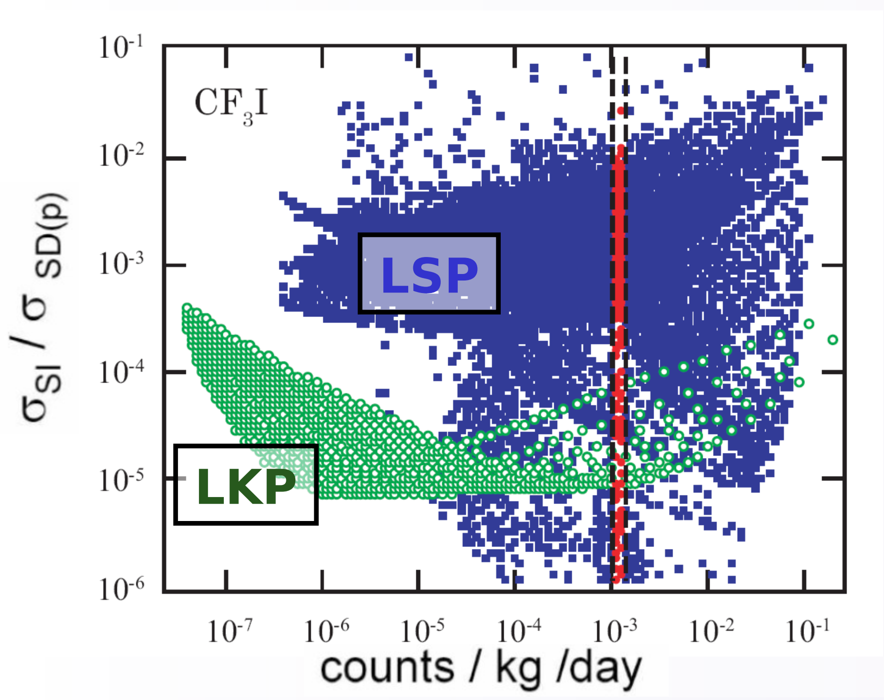


(G.Bertone, D.G.C., J.I.Collar, B.Odom´07)

Complementarity of DM searches

- A simultaneous measurement of the spin-dependent and independent couplings can help discriminating among dark matter experiments (e.g., in COUPP or KIMS)

(Bertone, D.G.C, Collar, Odom '07)



The hypothetical detection of a DM signal with a CF_3I detector loosely constrains DM candidates.

Complementarity of DM searches

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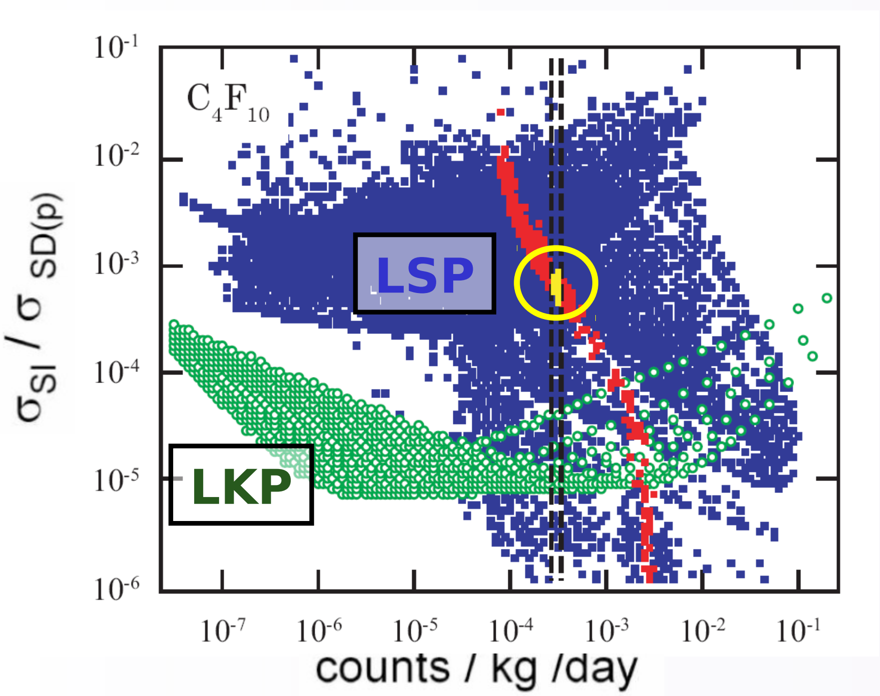

The hypothetical detection of a DM signal with a CF_3I detector loosely constrains DM candidates.

Using then a second detection fluid, C_4F_{10}, with lower sensitivity to spin-independent couplings, reduces the number of allowed models.

The sneutrino (scalar) has no spin-dependent coupling

Conclusions

DM searched with various strategies (LHC, Direct, Indirect)

Raising the hope of a detection in the future (or already detected?)

LHC will probe new physics at the TeV scale

Thereby being sensitive to many DM models

Cannot determine on its own the detection of DM

LHC and Direct (and Indirect) detection are COMPLEMENTARY

Probing more models of DM and discriminating among them

Probe non-standard cosmologies?

Allowing to determine the properties of the DM halo?

Event rate for WIMP direct detection

$$R = \int_{E_T}^{\infty} dE_R \frac{\boxed{\rho_0}}{m_N\, m_\chi} \boxed{\int_{v_{min}}^{\infty} v f(v)} \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

- Astrophysics input

  Local density of dark matter ρ_0

  Velocity distribution function $f(v)$

Event rate for WIMP direct detection

$$R = \int_{E_T}^{\infty} dE_R \frac{\boxed{\rho_0}}{m_N\, m_\chi} \boxed{\int_{v_{min}}^{\infty} v f(v)} \boxed{\frac{d\sigma_{WN}}{dE_R}(v, E_R)}\, dv$$

- Astrophysics input
  - Local density of dark matter ρ_0
  - Velocity distribution function $f(v)$
- Particle Physics input
  - WIMP-nucleus cross section $\frac{d\sigma_{WN}}{dE_R}$

Event rate for WIMP direct detection

$$R = \int_{\boxed{E_T}}^{\infty} dE_R \frac{\boxed{\rho_0}}{m_N\, m_\chi} \boxed{\int_{v_{min}}^{\infty} v f(v)} \boxed{\frac{d\sigma_{WN}}{dE_R}(v, E_R)}\, dv$$

- Astrophysics input
  - Local density of dark matter ρ_0
  - Velocity distribution function $f(v)$
- Particle Physics input
  - WIMP-nucleus cross section $\frac{d\sigma_{WN}}{dE_R}$
- Detector-dependence
  - Threshold energy E_T
  - Choice of material affects $\frac{d\sigma_{WN}}{dE_R}$