LHC: links with cosmology and astroparticle

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LAPTH- Annecy

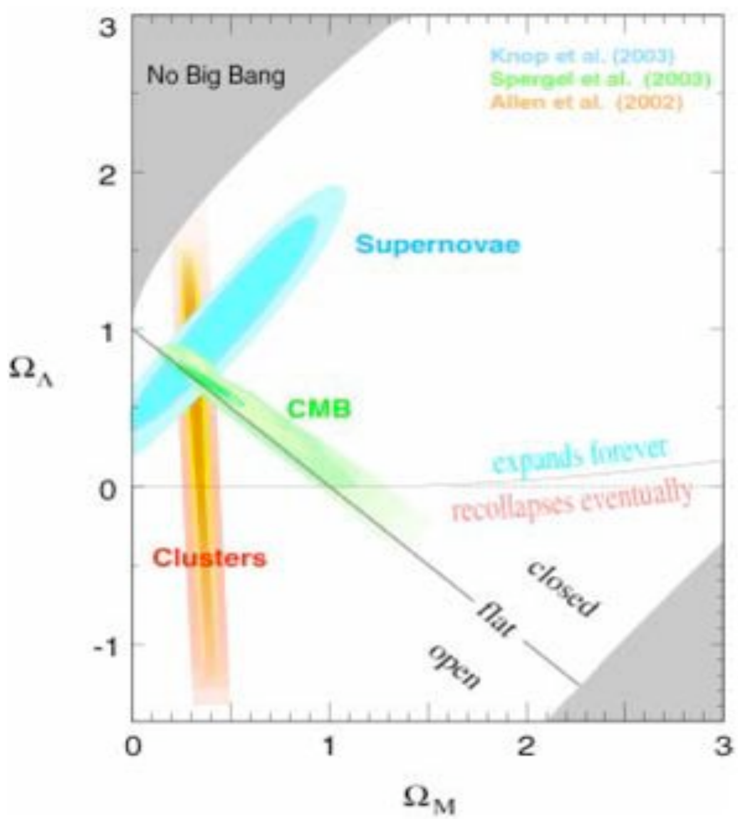
Outline

- Dark matter
- LHC and DM
- Astroparticle/cosmology and DM
- The links: supersymmetry as an example
- Other dark matter candidates
- Baryon asymmetry

What is the universe made of?

- Dark matter inferred from rotation curve of galaxy
- In recent years : new precise determination of cosmological parameters
- Data from CMB (WMAP) agree with the one from clusters and supernovae
    - Dark matter: 23+/- 4%
    - Baryons: 4+/-.4%
    - Dark energy 73+/-4%
    - Neutrinos < 1%

- *Dark matter dominates over visible matter*



What is dark matter/dark energy

- Dark matter
  - Related to physics at weak scale
  - New physics at weak scale can also solve EWSB
  - Many possible solutions
- Dark energy
  - Related to Planck scale physics
  - NP for dark energy might affect cosmology and dark matter
- Baryon asymmetry
  - New physics at weak scale could also explain baryon asymmetry of the universe, eg. electroweak baryogenesis and MSSM with CP violation
  - Leptogenesis may be connected to some higher scale

Dark matter : a new particle?

- Weakly interacting particle gives roughly the right annihilation cross section to have _h^2 ~0.1

$$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle} \quad .$$

- Many candidates for weakly interacting neutral stable particles
  - best known is neutralino in SUSY
  - Other models with NP at TeV scale have candidates, only need some symmetry to ensure that lightest particle is stable: UED, Warped Xtra-Dim, Little Higgs…
  - Superweakly interacting particles might also work (gravitino)

…. a new particle

- To know if these new stable particles give precisely the required amount of DM (or less) one needs to know the details of the underlying model. At 2 sigma (with conservative error bars):

$$.087 < \_{CDM}h^2 < .138$$

- We have no evidence of what NP could be but LHC which will probe symmetry breaking mechanism will help

- Direct/Indirect detection : search for dark matter → establish that new particle is dark matter → constrain models
- Cosmology → precise measurement of relic density → constrain models

What can LHC tell us about DM ?

- Discover new particles
- Determine the underlying model for NP at the weak scale + consistency checks of underlying model at high scale, e.g. SUGRA
- Determination of properties of new particles
  - From this deduce annihilation cross sections for dark matter
    - Prediction for relic density – compare with measurement, if "collider prediction" precise enough it means
      - Testing underlying cosmological model
      - When comparing with signals from indirect detection-information on dark matter distribution….
  - Also compute cross section for dark matter scattering on nuclei -> consistent with direct detection results ?
    - Information on velocity distribution of DM ….

LHC and dark matter

- How well can the properties of dark matter be determined?
  - Strongly depends on the particle physics model (SUSY or Xtra-Dim or…)
  - Strongly depends on details of given model, mass of new particles, couplings etc..

- What the LHC cannot do:
  - Produce directly large numbers of weakly interacting particle, mainly in decay products of strongly interacting particles
  - Cannot know for sure there is stable particle (missing energy)
  - Say anything directly about dark matter spatial and velocity distributions

Cosmology/Astroparticle

- What can we learn from cosmology
  - Establish DM
  - Determination of _h^2
  - Constrain PP models assuming •ÀCDM cosmology
  - Improve determination of _h^2 (PLANCK)
    - More constraints on PP models

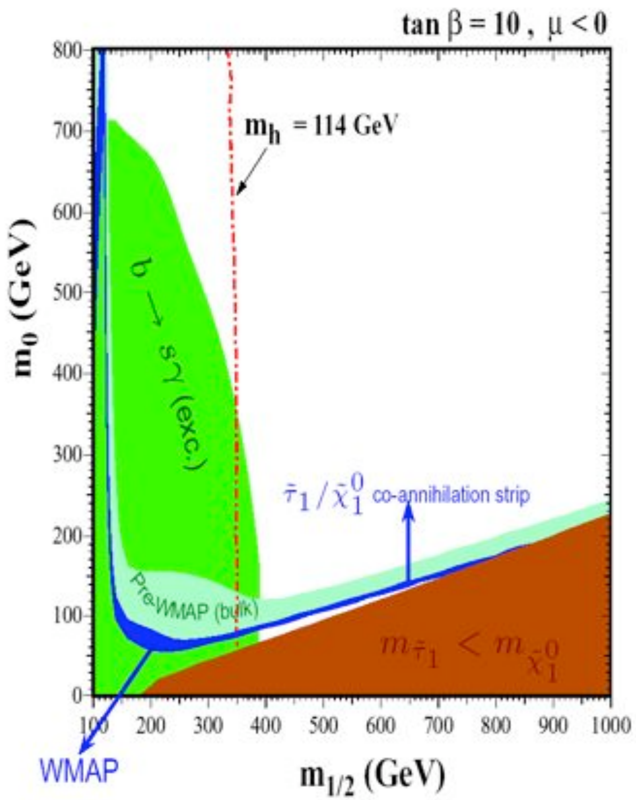
- What can we learn from DD
  - Establish that a new particle is DM
  - Measurement of cross section in different nuclei : compatibility with NP scenario (SUSY or other)
  - Some information on the mass of DM candidate
  - Caveats:
    - assumption about local density and velocity distribution
    - Uncertainties in nuclear matrix elements

…

- Indirect detection
  - Pair of dark matter particles annihilate and their annihilation products are detected in space
  - Search for DM in different channels
    - Positrons from neutralino annihilation in the galactic halo
    - Photons from neutralino annihilation in center of galaxy
    - Neutrinos from neutralino in sun
  - Consistency checks of different signals
  - Check compatibility with NP scenario (SUSY or other)
  - Caveat: assumptions on dark matter distribution

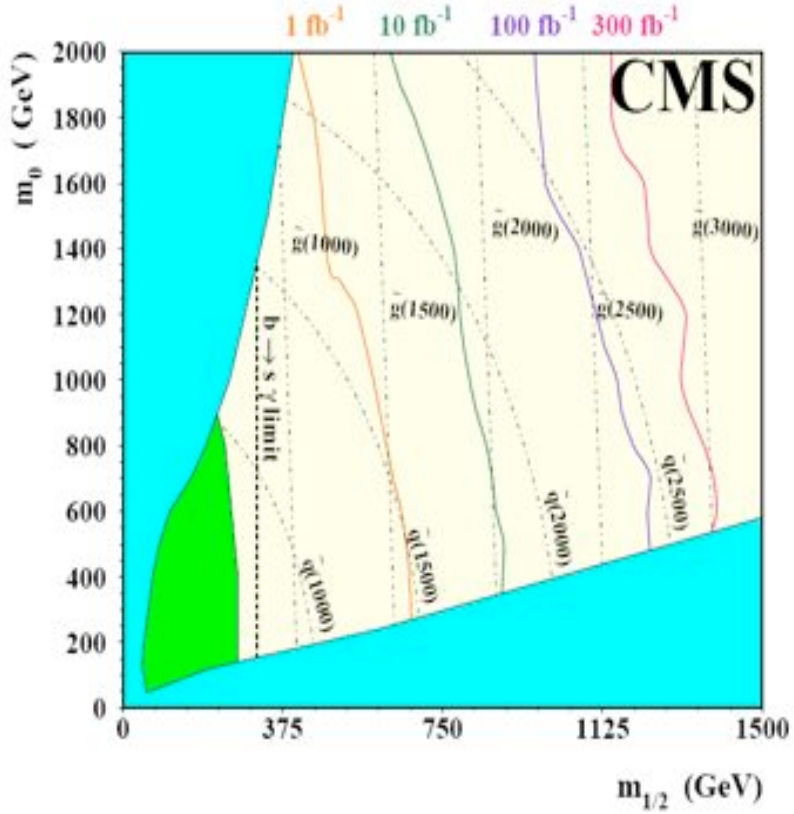
Supersymmetry as an example

- The case of neutralino LSP
- Most studies at colliders done within context of CMSSM or mSUGRA (small number of parameters: 4 _ instead 100)
  - Convenient, good for tuning analyses, but not completely general
  - Somewhat fine tuned from DM perspective – neutralino is in general bino
- Potential of discovery at LHC



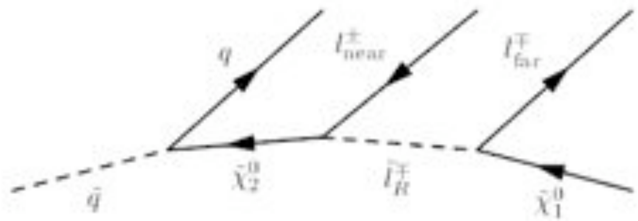
Potential for SUSY discovery at LHC

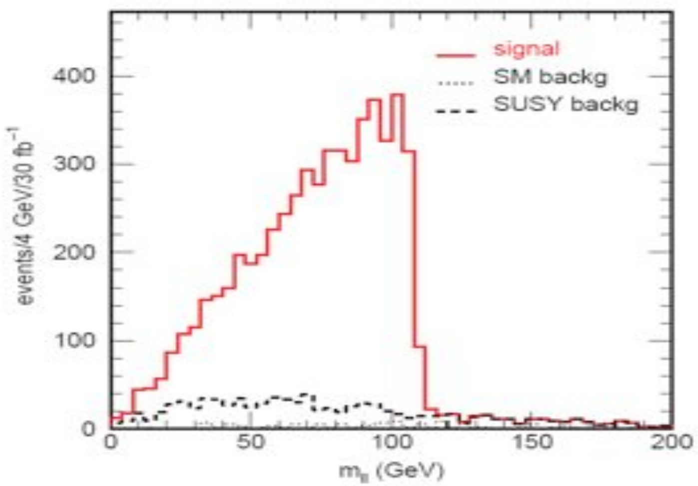
- pp collider @14TeV
- Operation starts late 2007
- Squarks, gluinos < 2- 2.5 TeV
- Sparticles in decay chains
- Higgs searches
- CMSSM: probe significant parameter space, large m_0-$m_{1/2}$ difficult
- Other models : similar reach in masses for coloured particles



LHC and DM

- How will LHC see dark matter?
  - Missing energy
  - Sample decay chain
- What can LHC measure?
  - Mass differences (using endpoints) – percent level
  - Masses (endpoints +cross-sections + theory) more difficult – Lester,Parker, White '05
  - Some properties of particles: spin.. (Barr –hep-ph/0511115)
  - Reconstruct underlying model parameters especially if theoretical assumption





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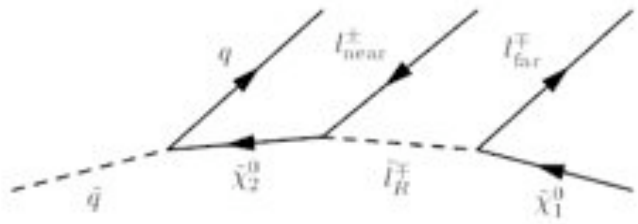
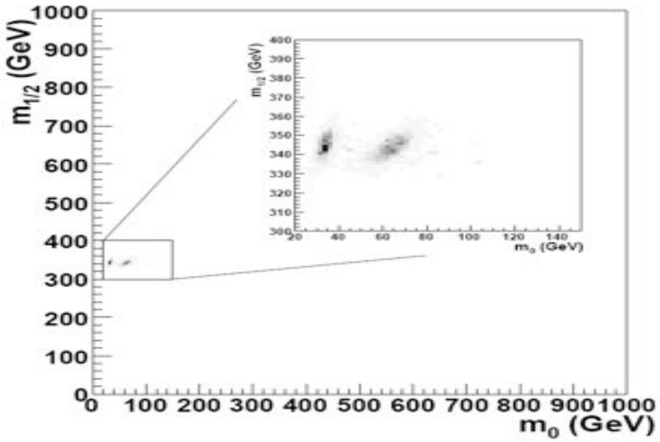




White, hep-ph/0605065

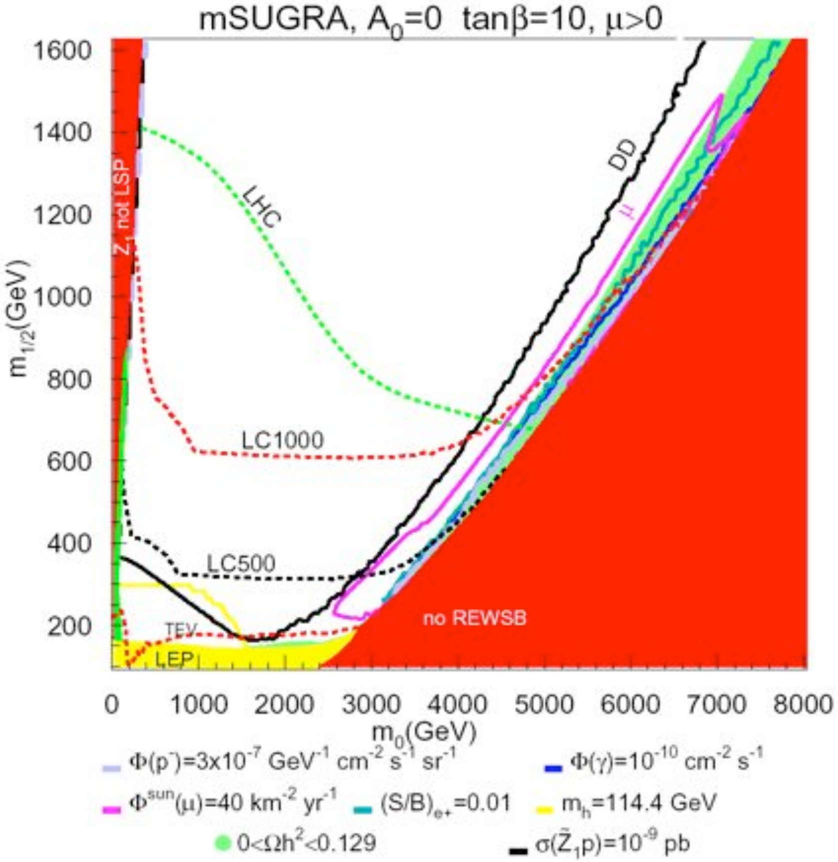
Why different approaches to DM

- Complementarity
  - No experiment cover full parameter space of all models (even SUSY model)

- Concurrence
  - Signals in different types of experiments allow cross-checks
  - Possible tests of cosmology, dark matter distribution…

Complementarity

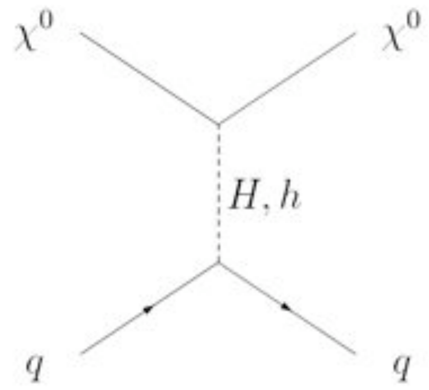
- LHC
  - Good for discovery of coloured particles
  - Limited reach when all squarks heavy – only chargino/neutralino “light”
  - In CMSSM this occur when LSP is mixed bino/Higgsino
- Direct and indirect detection
  - Good prospects for mixed bino/Higgsino

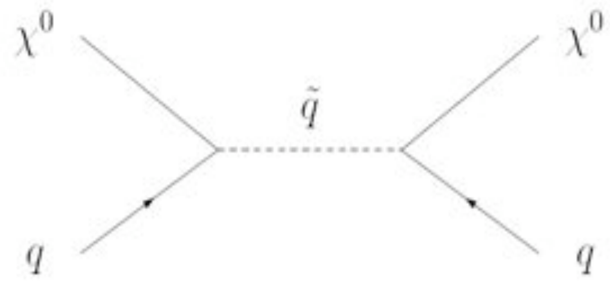


Baer et al., hep-ph/0405210

Complementarity - DD

- Detect dark matter through interaction with nuclei in large detector
- Often dominate by Higgs exchange diagram (except when squarks are light)
- Higgsino component is necessary to have LSP coupling to Higgs
- With next generation of detectors (10^{-9}pb), direct searches can probe regions of CMSSM parameter space inaccessible to LHC
- Annihilation of LSP in W pairs enhanced for mixed bino/Higgsino – also favoured for indirect detection



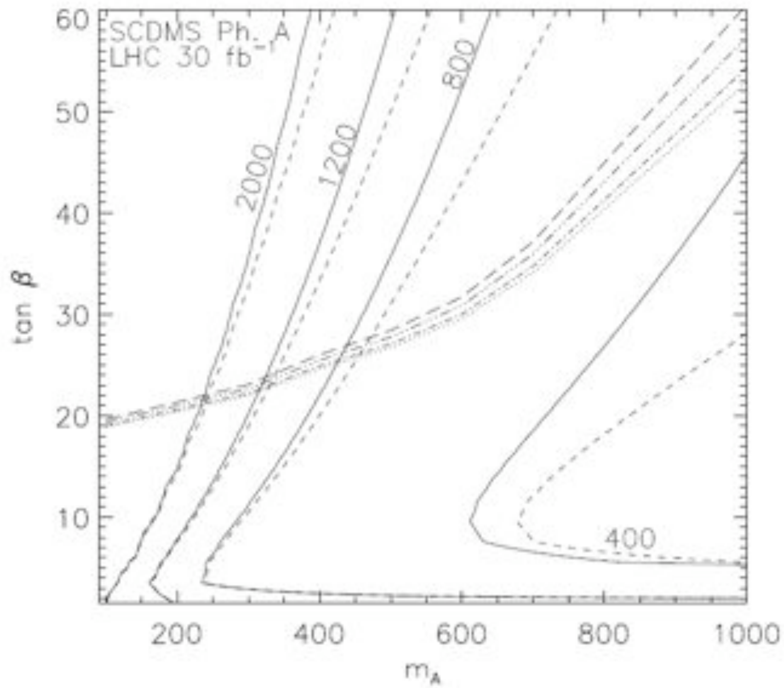


Complementarity– LHC/DD

- If squarks dominate (below 1TeV) they will be quickly found at LHC

- If Higgs dominate, LHC (even Tevatron) might see a heavy Higgs signal
  - pp-> A/H+X-> __ +X

- a fraction of the MSSM models that predict a signal in SCDMS (~10^{-9} pb) will also give a Higgs signal at colliders



Carena et al, hep-ph/0611065

Probing cosmology using collider information

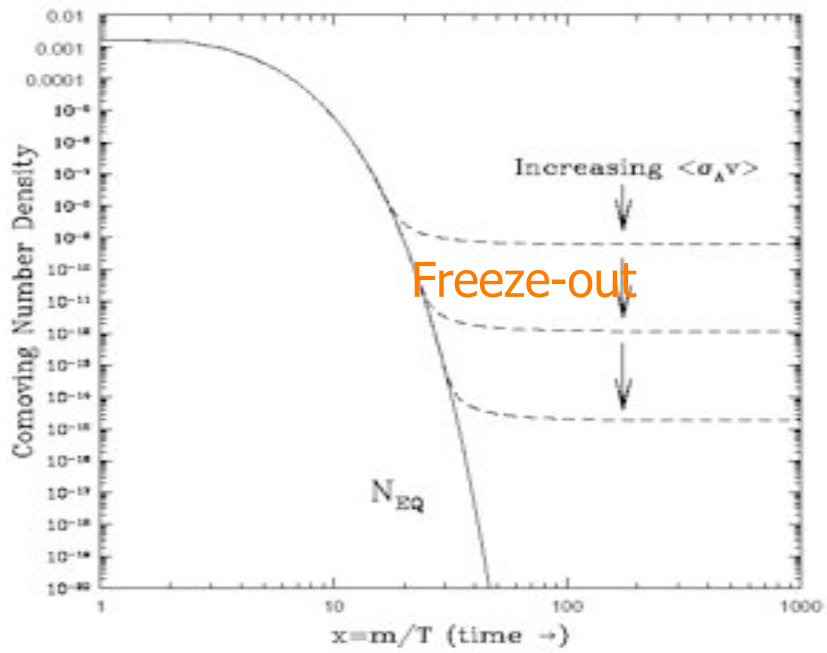
- Within the context of a given model can one make precise predictions for the relic density at the level of WMAP(10%) and even PLANCK (3%) therefore test the underlying cosmological model.
  - Assume discovery SUSY/Higgs, precision from LHC? Precision for ILC?

- Answer depends strongly on underlying NP scenario, many parameters enter computation of relic density, only a handful of relevant ones for each scenario – work is going on in North America, Asia and Europe both for LHC and ILC

- A few benchmark scenarios studied in detail
  - 1^{st} step : CMSSM scenario that predict relic density in agreement with WMAP.
  - 2^{nd} step : MSSM scenarios
  - Other scenarios

Reminder: Relic density of wimps

- In early universe WIMPs are present in large number and they are in thermal equilibrium
- As the universe expanded and cooled their density is reduced through pair annihilation
- Eventually density is too low for annihilation process to keep up with expansion rate
  - Freeze-out temperature



- LSP decouples from SM particles, density depends only on expansion rate of the universe

$$\frac{dn}{dt} = -3Hn - <\sigma v> \left[n^2 - n_{eq}^2\right]$$

One sample benchmark: SPA1A

- bino+ stau coannihilation
  - Annihilation into fermions
  - Coannihilation with staus

- Relevant parameters : LSP mass, couplings, slepton masses
  - stau-neutralino mass difference (for coannihilation processes – factor e $^{-\_M}$)

M_0=70, $M_{1/2}$=250, A0=-300,tan_=10

Sparticle	mass (GeV)	Sparticle	mass (GeV)
$\tilde{\chi}_1^0$	97.2	$\tilde{\chi}_2^0$	180.1
$\tilde{\chi}_3^0$	398.4	$\tilde{\chi}_4^0$	413.8
$\tilde{\ell}_L$	189.4	$\tilde{\ell}_R$	124.1
$\tilde{\tau}_1$	107.7	$\tilde{\tau}_2$	194.2
$\tilde{t}_1$	347.3	$\tilde{t}_2$	562.3
$\tilde{u}_L$	533.3	$\tilde{g}$	607.0
h	116.8	A	424.6

Process	Fraction
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \ell^+\ell^-$	40%
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau^+\tau^-$	28%
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \nu\bar{\nu}$	3%
$\tilde{\chi}_1^0\tilde{\tau}_1 \to Z\tau$	4%
$\tilde{\chi}_1^0\tilde{\tau}_1 \to A\tau$	18%
$\tilde{\tau}_1\tilde{\tau}_1 \to \tau\tau$	2%

Determination of parameters LHC : SPA1A

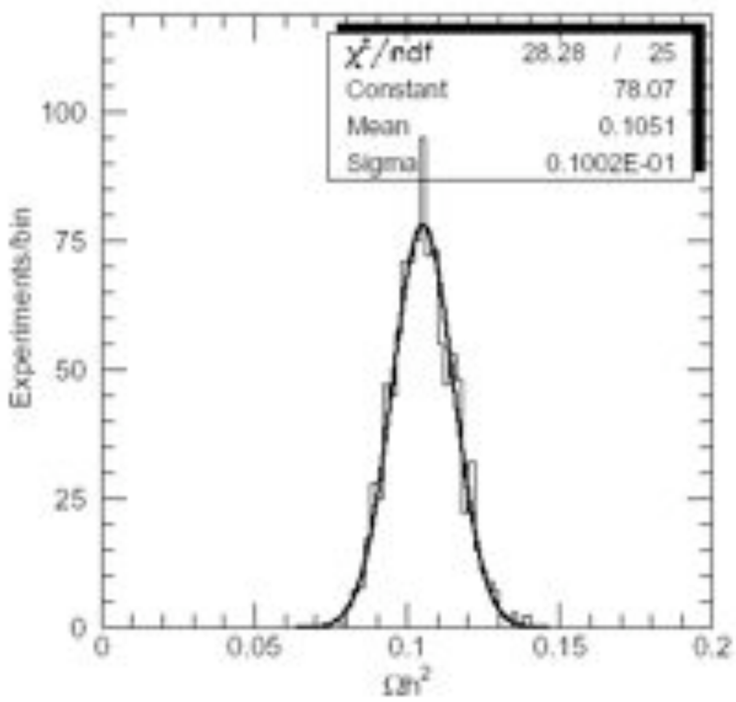
- Decay chain
$$\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\ell}^{\pm}\ell^{\mp} \to q\ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$$
- Signal: jet +dilepton pair
- Can reconstruct four masses from endpoint of ll and qll
  - In particular stau-neutralino mass difference
- Here _m (NLSP-LSP) = 10.5GeV

- Mixing in the stau sector obtained from
$$BR(\tilde{\chi}_2^0 \to \tilde{\ell}_R\ell)/BR(\tilde{\chi}_2^0 \to \tilde{\tau}_1\tau)$$
- For LSP couplings need 3 masses (_[1] _[2] _[4]) and assume tan_
- Assume tan_ known + limit on heavy stau and on heavy Higgs

LHC: SPA1A

- Estimate error from LHC measurements+ vary all MSSM parameters within these errors
- LHC: roughly the WMAP precision can be achieved within MSSM
- Also important to measure sfermion/ neutralino parameters and setting limits on Higgs, other coannihilation particles …
- Other mSUGRA and even more so other MSSM scenarios can be hard for LHC

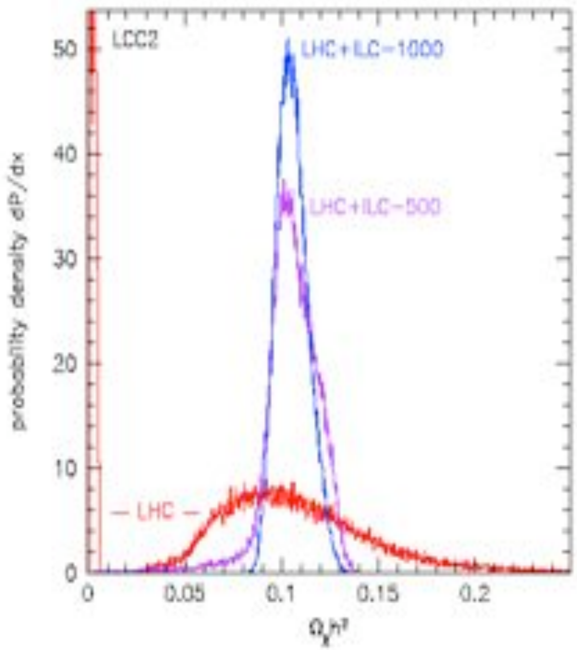
Nojiri et al, hep-ph/0512204



Example : Higgsino- LCC2

- **If squarks are heavy difficult scenario for LHC**
  - **only gluino accessible, chargino/neutralino in decays**
  - mass differences could be measured from neutralino leptonic decays,
  - Relic density of DM depend on parameters of neutralino, need to be determine at % level
    - Recent study shows that necessary precision cannot be reached

Point	m_0	$m_{\frac{1}{2}}$	$\tan\beta$	A_0	sign mu
LCC2	3280	300	10	0	+

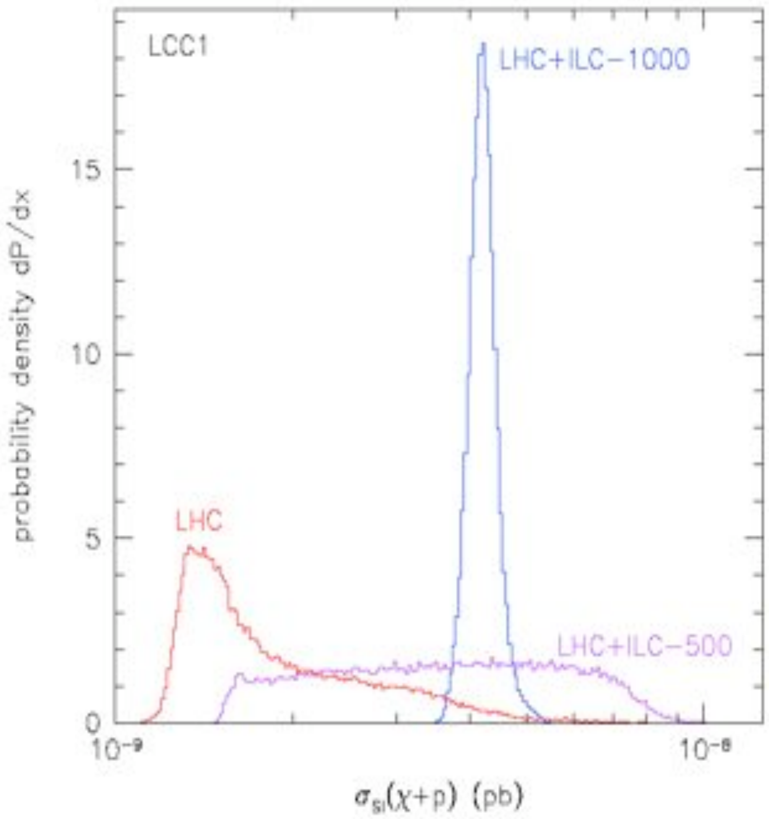


- **Light Higgsinos →possibly many accessible states at ILC**
- chargino pair production sensitive to bino/Higgsino mixing parameter

- Baltz, et al , hep-ph/0602187

LHC + direct detection

- With measurements from LHC can we refine predictions for direct/indirect detection?
- Consider our first example:
  - SPA1A
- Prediction for spin-independent cross-section
  - Observable by 2010
- Factor of 3 uncertainty, improves significantly at ILC1000 (heavy Higgs mass)



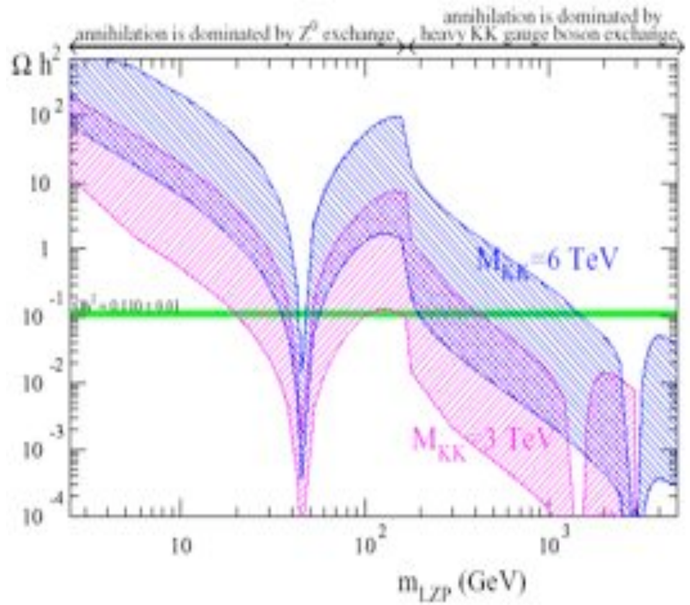
Other DM candidates: KK

- UED
  - Minimal UED: LKP is $B^{(1)}$, partner of hypercharge gauge boson
  - s-channel annihilation of LKP (gauge boson) typically more efficient than that of neutralino
  - Compatibility with WMAP means rather heavy LKP
  - Within LHC range

- Warped Xtra-Dim (Randall-Sundrum)
  - GUT model with matter in the bulk
  - Solving baryon number violation in GUT models → stable Kaluza-Klein particle
  - Example based on SO(10) with Z3 symmetry: LZP is KK right-handed neutrino
    - Agashe, Servant, hep-ph/0403143

Dark matter in Warped X-tra Dim

- Compatibility with WMAP for LZP range 50GeV-> 1-2TeV
- LZP is Dirac particle, coupling to Z through Z-Z' mixing and mixing with LH neutrino
- Large cross-sections for direct detection
  - Signal for next generation of detectors in large area of parameter space
- What can be done at colliders :
  - Signal for KK quarks (Dennis et al. hep-ph/071158) and for Z'
  - Identify model, determination of parameters and confronting cosmology??



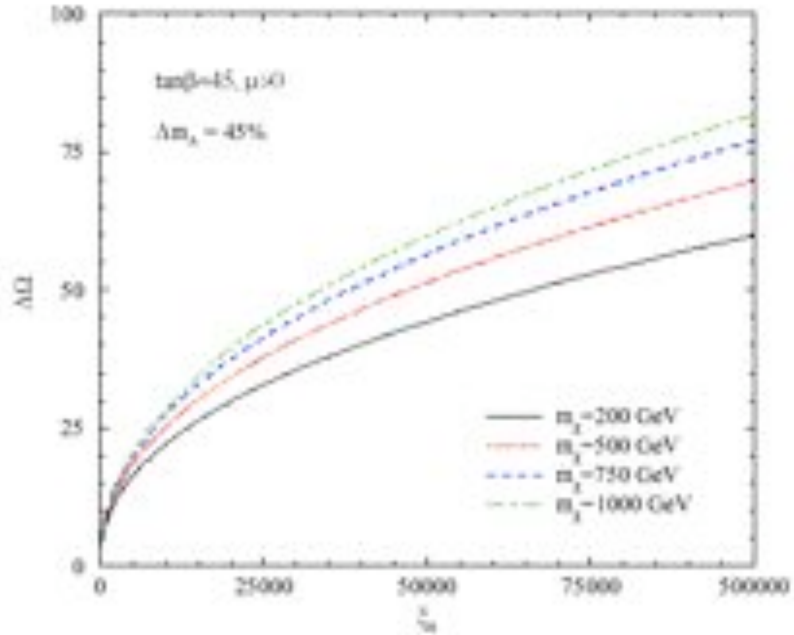
Agashe, Servant, hep-ph/0403143

Cosmological scenario

- Different cosmological scenario might affect the relic density of DM

- Example: quintessence
  - Quintessence contribution forces universe into faster expansion
  - Annihilation rate drops below expansion rate at higher temperature
  - Increase relic density of WIMPS - possible large enhancements in MSSM

- Other scenarios could give a suppression of relic density-> good for LHC, easier to make precise predictions in models where _h^2>0.1, less fine tuning.



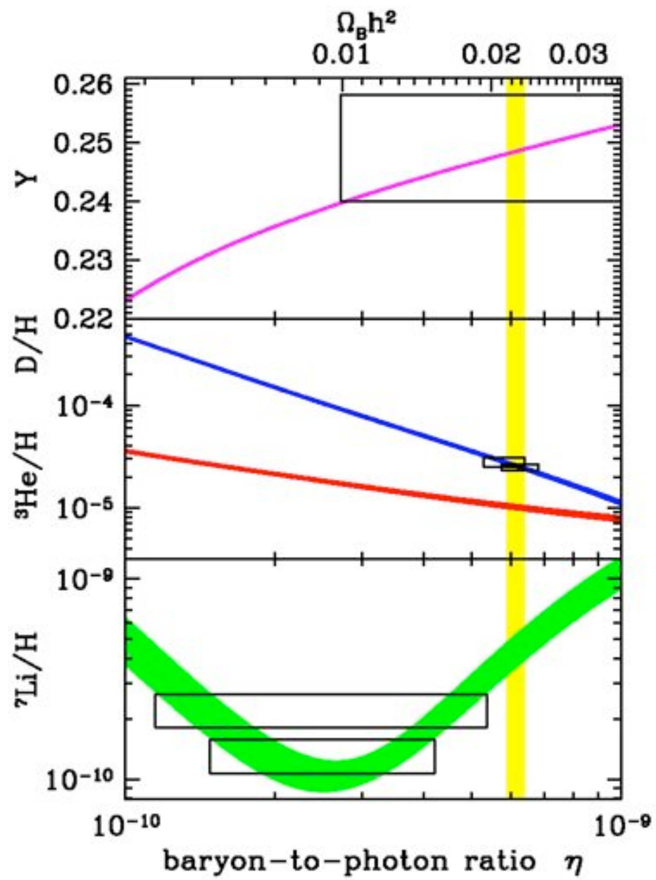
Profumo, Ullio, hep-ph/0309220

Baryon asymmetry of universe

- Small excess of particles over antiparticles in the universe
- Both Big Bang Nucleosynthesis (BBN) and measurements of CMB agree

$$\eta \equiv \frac{n_B}{n_\gamma} = \begin{cases} 3.4 - 6.9 \times 10^{-10}, & \text{BBN} \\ 5.9 - 7.3 \times 10^{-10}, & \text{CMB} \end{cases}$$

- Conditions to create an excess
  - Baryon number violation
  - C and CP violation
  - Out of thermal equilibrium
  - Non-vanishing B-L
- *Need physics Beyond the SM*



Electroweak baryogenesis

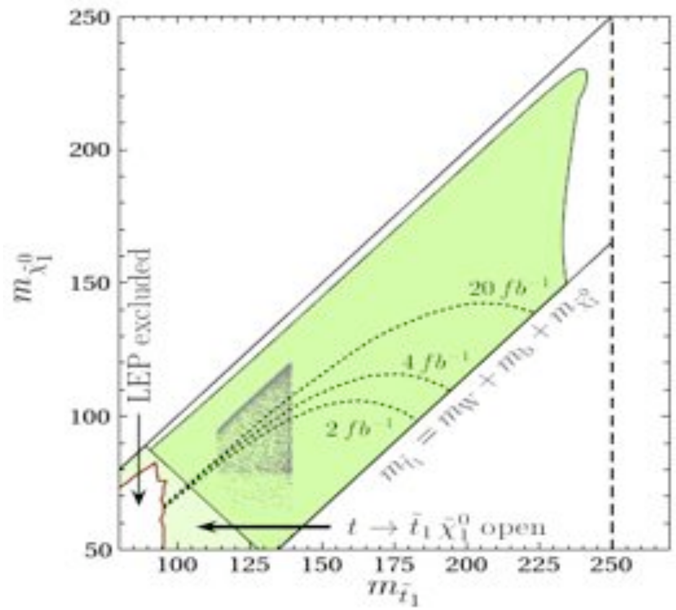
- Baryon number generation at electroweak phase transition
- Need strong first order phase transition
- Finite temperature effective potential
  - V= AT^2_^{2} - ET _^{3}+ __^{4} , condition : 2E/_>1
  - In SM requires Higgs mass < 50 GeV
- New physics solution:
  - Bosonic loops: light stops in MSSM (Carena et al..)
  - New strongly coupled fermions
  - Modification of tree-level potential
    - NMSSM, SUSY with U(1)' (Kang et al, 2005)
    - Higher-order operators in Higgs-potential
      - Kanemura, Okada, Senaha (2004)
      - Grojean, Servant, Wells (2004)

Electroweak baryogenesis and Colliders

- Whether electroweak baryogenesis is realised with new particles or modification of the Higgs sector, there will be signals at colliders (and also in CP violation)

- Well-defined scenario in MSSM : Light RH stop + light Higgs+ light neutralino/chargino +CPV
  - Complementarity: discovery potential at Tevatron/LHC + DD + EDM
  - Signals for CP violation at colliders
  - "Prediction" for relic density of DM in this model (hard for LHC)
    - Freitas et al. hep-ph/0508152

- Modification of Higgs potential → measurement of triple Higgs coupling



Carena et al., hep-ph/0508152

Conclusions

- If LHC discover new particles, will give precious information on NP model and on potential DM candidate – complementarity with direct/indirect detection.

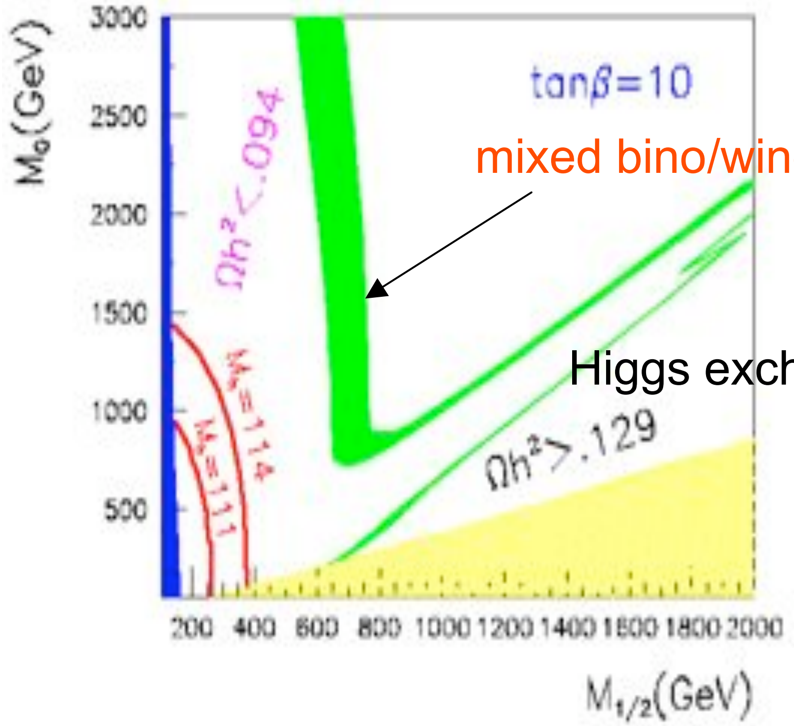
- In more favourable cases, detailed measurements of new particle properties can reduce (PP) uncertainty in prediction of relic density and/or cross-sections in direct/indirect detection –might even test cosmological model – many detailed analyses are going on

- Models to explain Baryon asymmetry in the universe can be tested at LHC

Some examples

- mSUGRA-focus
- Non universal SUGRA, e.g. non universal gaugino masses
  - GB, Boudjema, Cottrant, Pukhov, Bertin,Nezri, Orloff, Baer, Birkedal-Hansen, Nelson, Mambrino, Munoz…
- String inspired moduli-dominated : generically LSP has inportant wino component
  - Binetruy et al, hep-ph/0308047
- Split SUSY
  - Large M_0
  - Higgsino/wino/bino LSP
  - Masiero, Profumo, Ullio, hep-ph/0412058
- NMSSM

$M_1=1.8M_2|_{GUT}$

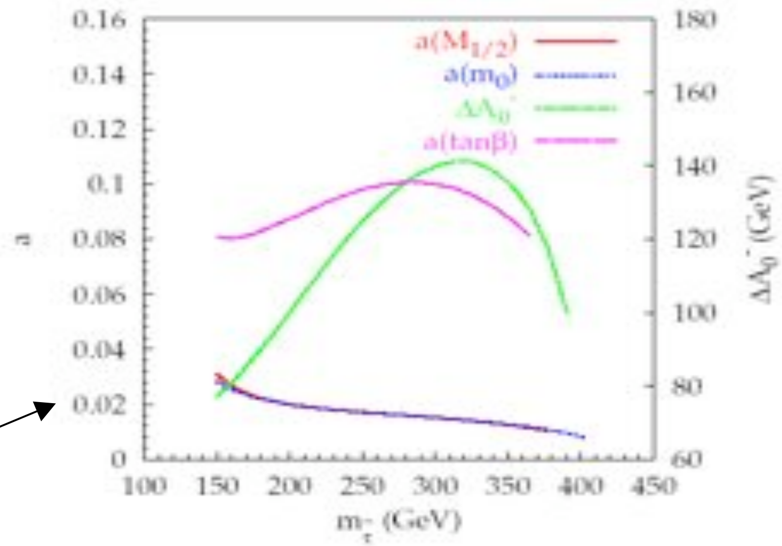


GB, et al, NPB706(2005)

The simplest example: mSUGRA/coannihilation (staus)

- Challenge: measuring precisely mass difference
- Why? _h^2 dominated by Boltzmann factor exp(- _M/T)
  - Although masses are predicted at 1-2% level, still leads to large uncertainties in relic density
- Precision required on mSUGRA parameters to predict _h^2 at 10% level
  - M_0, $M_{1/2}$ ~2%
- LHC: roughly this precision can be achieved in “bulk” region
  - Tovey, Polesello, hep-ph/0403047

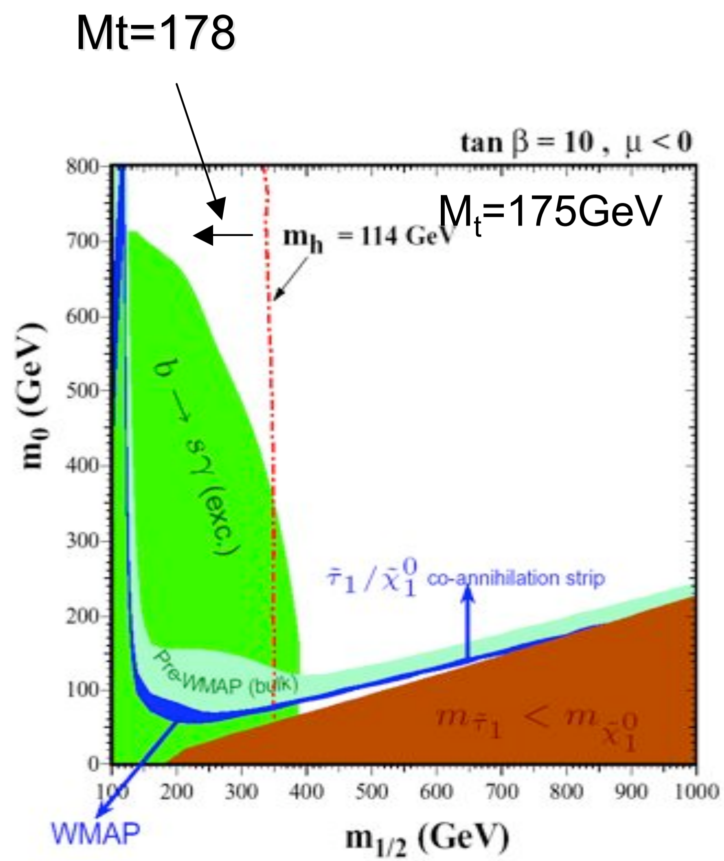
Allanach et al, JHEP 2005



- For coannihilation region errors on mass could be larger (more difficult with staus

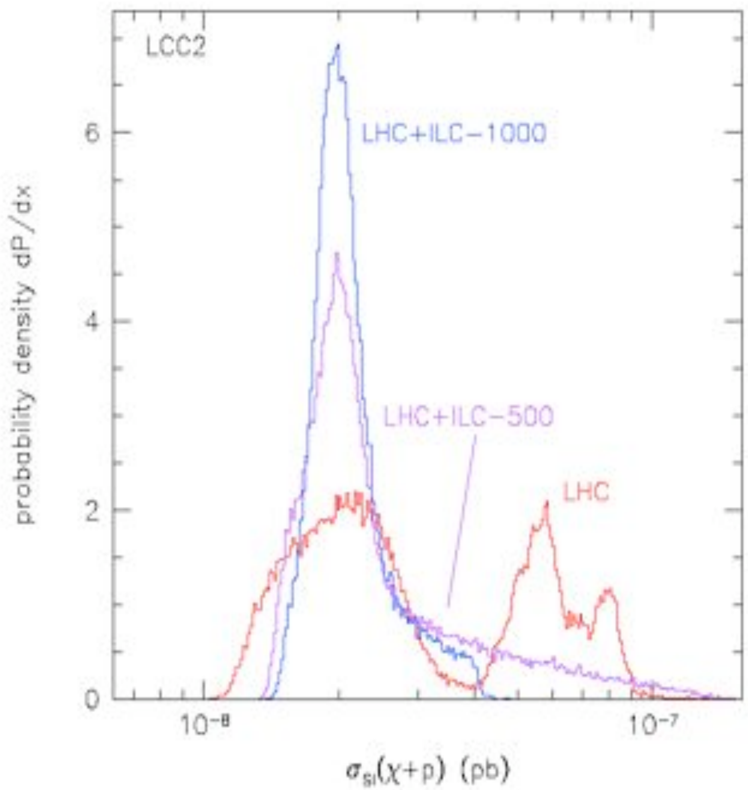
WMAP constraining NP: mSUGRA example

- bino – LSP
  - In most of mSUGRA parameter space
  - Annihilation in fermion pairs
  - Works well for light sparticles but hard to reconcile with LEP/Higgs limit (small window open)
- Sfermion coannihilation
  - Staus or stops
  - More efficient, can go to higher masses
- Mixed bino-Higgsino: annihilation into W/Z/t pairs
- Resonance (Z, light/heavy Higgs)



LHC+ILC+direct detection

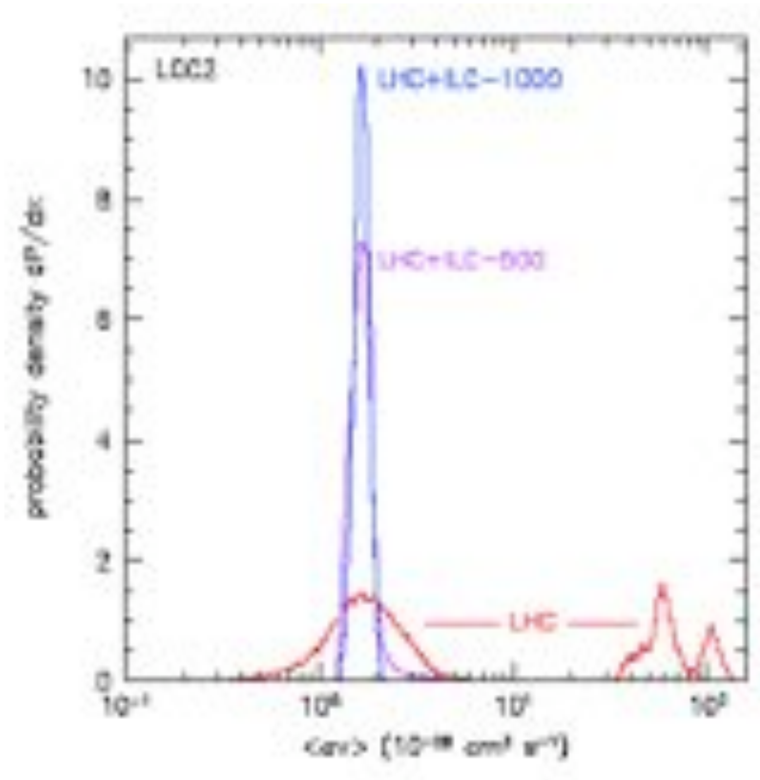
- Favourable example: LCC2 (Higgsino)
- Large spin-independent cross-section
  - e.g. observable at CDMS2
- Ambiguities at LHC



LHC+ILC + indirect detection

- With measurements from LHC+ILC can we refine predictions for indirect detection?

- Consider our Higgsino example (LCC2)
- Prediction for annihilation cross-section at v=0
- For GLAST with NFW profile expect 8600 photons (Background=43000)



E. Baltz et al hep-ph/0602187

Comparisons of DM scenarios

Scenario		SUSY1 bino	SUSY2 higgsino	SUSY3 gravitino	LZP ν_R	LTP heavy photon
LHC	Discovery	***	*	**	*	**
	precision	*	No	?	?	?
ILC	Discovery	***	**	**	*	**
	precision	***	*	?	?	?
Direct		*	***	No	***	No
Indirect	γ or ν	*	***	No	**	***

WMAP – constraining mSUGRA

- Bino – LSP
- Sfermion Coannihilation
- Mixed Bino-Higgsino
  - Annihilation into W pairs
  - In mSUGRA unstable region, m_t dependence, works better at large tan_
- Resonance (Z, light/heavy Higgs)
  - LEP constraints for light Higgs/Z
  - Heavy Higgs at large tan_ (enhanced Hbb vertex)