Interplay of dark matter and collider physics

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LAPTH- Annecy

Plan

- Dark matter
- Prospects for DM production at LHC
- Determination of DM properties at LHC

Dark matter: a WIMP?

- Strong evidence that DM dominates over visible matter. Data from rotation curves, clusters, supernovae, CMB all point to large DM component
- Structure formation : DM is mostly cold and weakly interacting
- DM stable at cosmological scale
- Is DM a new particle what are its properties?

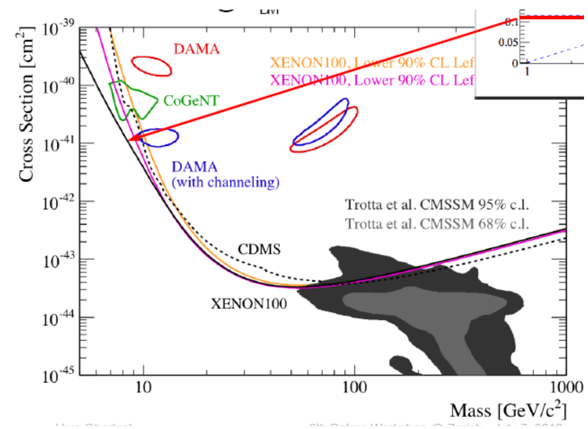
- In standard cosmological scenario where DM particles are thermal equilibrium in early universe and during expansion universe DM “freeze-out” , relic abundance

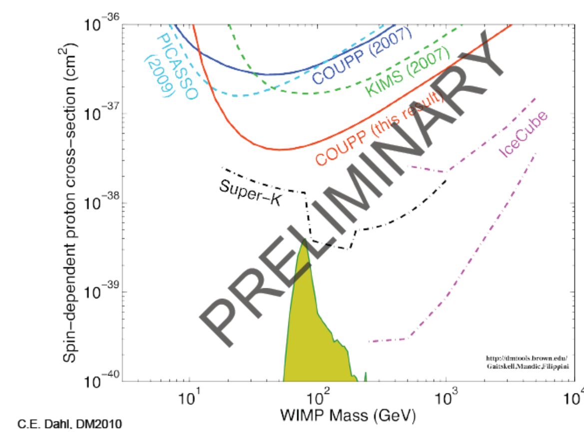
$$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle} .$$

- A WIMP has ‘typical’ annihilation cross section for $\Omega h^2 \sim 0.1$ (WMAP)

Direct Detection: limits/hints

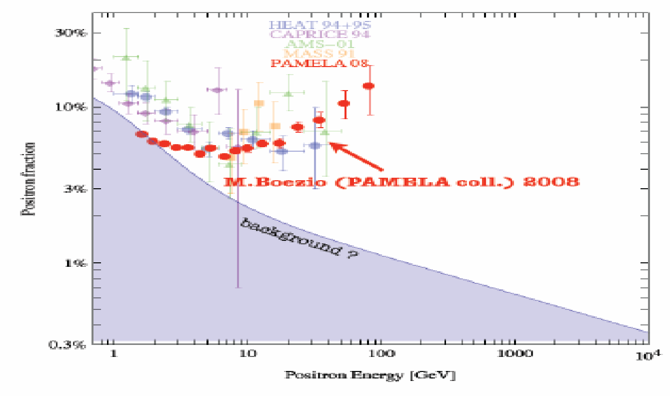
- Direct detection can establish that new particle is DM
- Limits that probe parameter space of several models
- Hints of signals in DAMA, Cogent, CDMS…
- Searches in different nuclei: SI/SD check compatibility with NP scenario
- Caveats:
  - assumption about local density and velocity distribution
  - Uncertainties in nucleon matrix elements



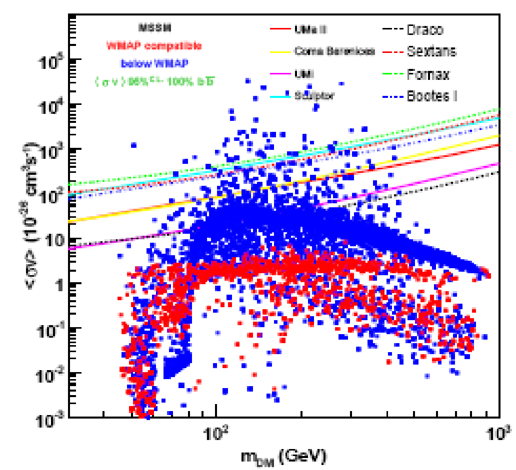


Indirect detection: limits/hints

- Pair of dark matter particles annihilate and their annihilation products are detected in space
- Depend on σv + B.R. in different SM particles
- Caveat: strong dependence on DM distribution + propagation for charged particles
- Several new and upcoming results:
- PAMELA: no excess in antiproton but excess in positron
  - Can be explained by astro source : pulsar
- FermiLAT : photons from DM annihilation in GC and dwarf galaxies
- Neutrino telescopes (IceCUBE, Antares)



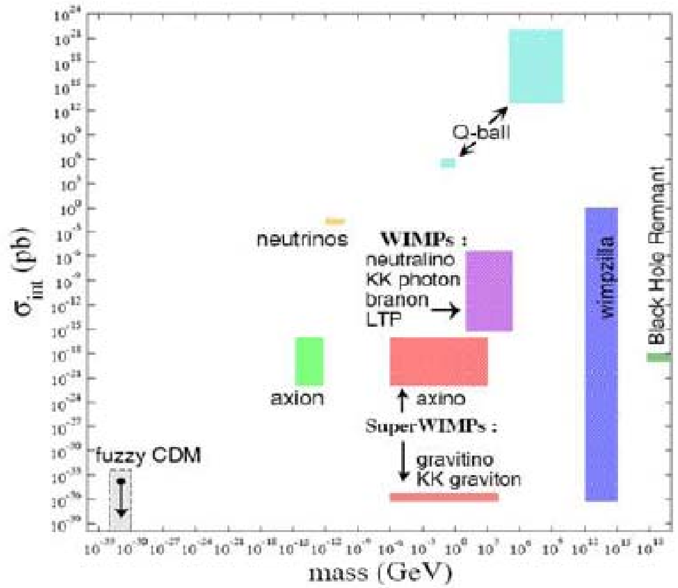
O. Adriani 0810.4995



Fermi 1001.4531

Which Dark matter candidate?

- Many WIMPs proposed : best motivated also solve hierarchy problem
  - Supersymmetry, Extra dimensions, Little Higgs, Extended Higgs
- Others motivated by hints in DM detection
  - PAMELA : leptophilic
  - Light DM (DAMA/Cogent/CDMS)
- Superwimps also work – talks of L. Covi and T. Moroi
  - Gravitino, axion, axino



For now not enough to determine the mass of DM and/or new particles

Which Dark matter candidate?

- Can invent a new particle that fits DM observables
- Harder to propose a new physics model that solves outstanding issues in SM + DM + satisfy all constraints
- Constraints on new physics from various precision observables (B physics, g-2, M_W, $\sin^2\theta_{eff}$), collider limits
- LHC will probe the new physics at TeV scale
- If new particles are found : provide better understanding of particle physics dependence in DM observables

LHC and dark matter

- Search for new particles (including Higgs)
  - What is the discovery potential at LHC (within specific models)
- B physics : indirect constraints on new physics
- How well can the properties of dark matter be determined?
  - Strongly depends on the particle physics model and on details of given model, mass of new particles, couplings etc..
- Signals in different types of experiments allow cross checks
  - Possible tests of cosmology, dark matter distribution…
- 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

SUSY as a test case

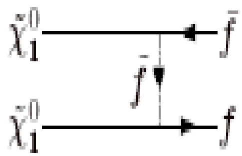
- Well-motivated
  - SUSY: solution to hierarchy problem cancellation of divergences in Higgs mass
  - LSP is stable because of R-parity (also stabilizes the proton)

- Well studied at colliders

- Cover several possibilities for DM candidates (neutralino, gravitino, sneutrino), DM annihilation mechanisms, DM interaction with nuclei
  - Neutralino LSP (Majorana)
  - Neutral spin ½ *SUSY* partner of gauge bosons (Bino, Wino) and Higgs scalars (Higgsinos)

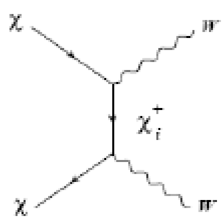
$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_1 + N_{14}\tilde{H}_2$$

The neutralino



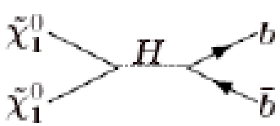
- Bino: annihilates into fermions – sfermions must be light

$$\sigma v \propto m_{\tilde{\chi}}^2 / m_{\tilde{l}}^4$$



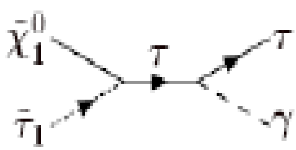
- Mixed B/Higgs-ino : efficient into WW
- Mixed W/B/H-ino

$$\sigma v \propto 1 / m_{\tilde{\chi}}^2$$



- All (not pure bino): annihilation Higgs resonance

$$\sigma v \propto m_{\tilde{\chi}}^2 / (4 m_{\chi}^2 - m_H^2)^2$$

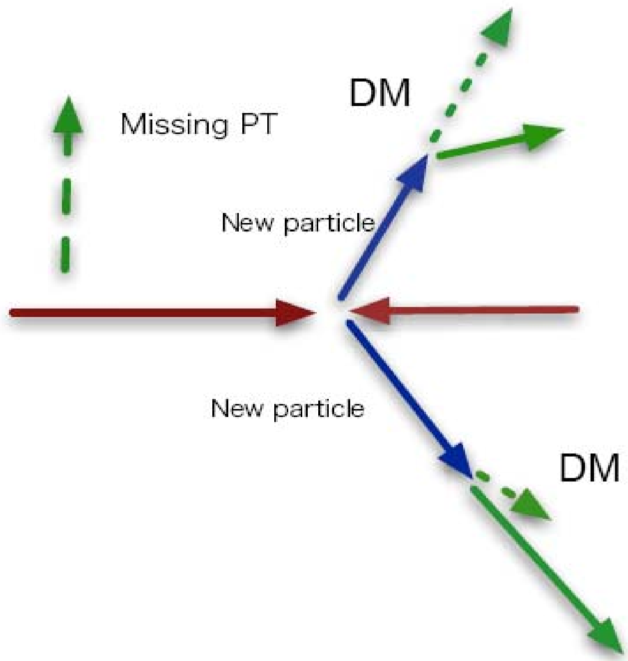


- All: coannihilation possible suppression exp(-ΔM/T)

DM production at LHC

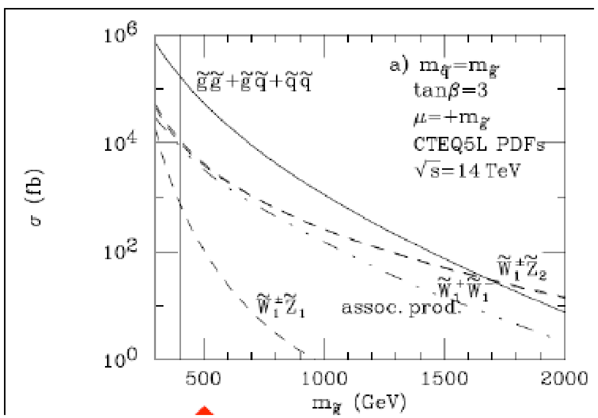
- pp collider 7-14TeV
- Direct production : missing energy no trigger
- Production of coloured particles: DM in decay chain

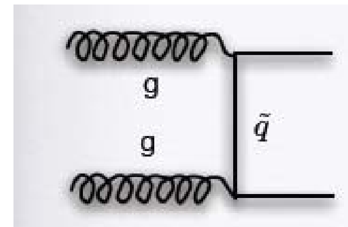
- pT : transverse p lepton, jets
- E_T(miss) : sum all pT
  - DM, neutrinos
  - Particle missed
  - …
- Meff: P_T of first 4 jets+ $E_T$miss

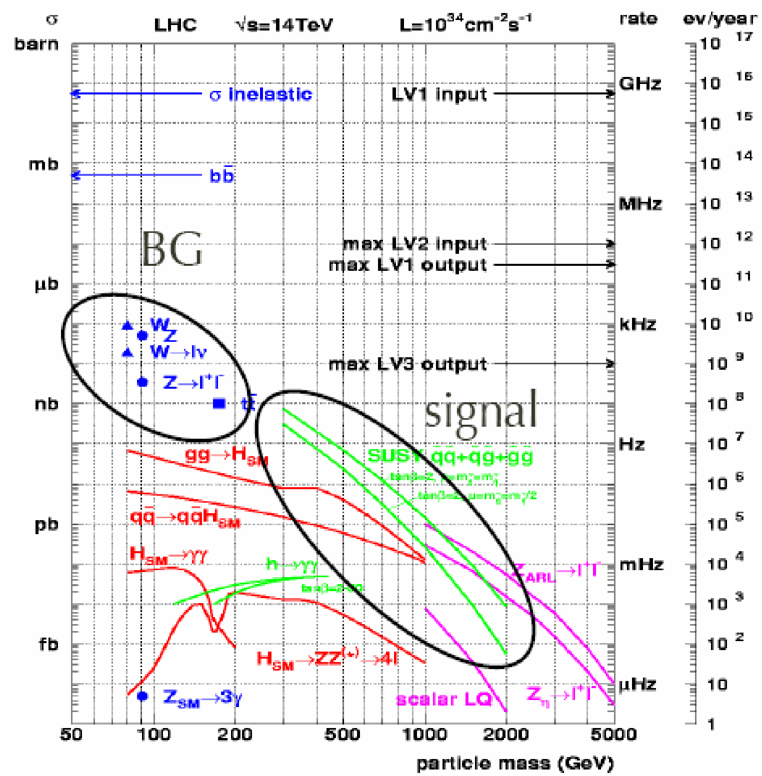


SUSY production at LHC

- Production cross sections for coloured particles are large







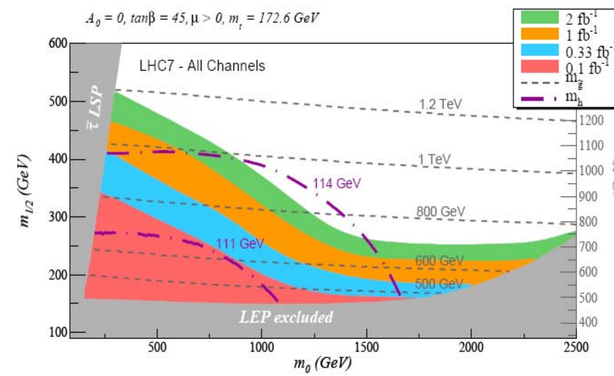
- If squarks heavy : direct chargino/neutralino dominate
- Background is an issue – cuts to enhance signal

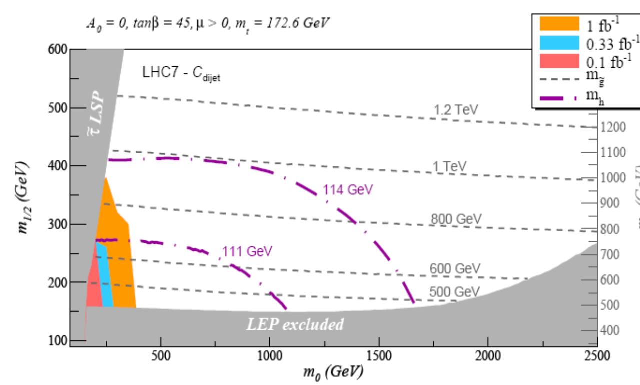
LHC reach

- Production squarks/gluinos
- Signatures: missing E_T + multiple hard jets (generic or b) + isolated leptons or photons
  - One Lepton
  - Dileptons same/opposite
  - trilepton
  - Four(+) leptons
- Cuts to reject background

- To exploit first data avoid signatures with E_T miss (require good knowledge of detector performance)
  - Jets, b/τ jets, di/trileptons
  - Limited reach – extend LEP

LHC – 7 TeV





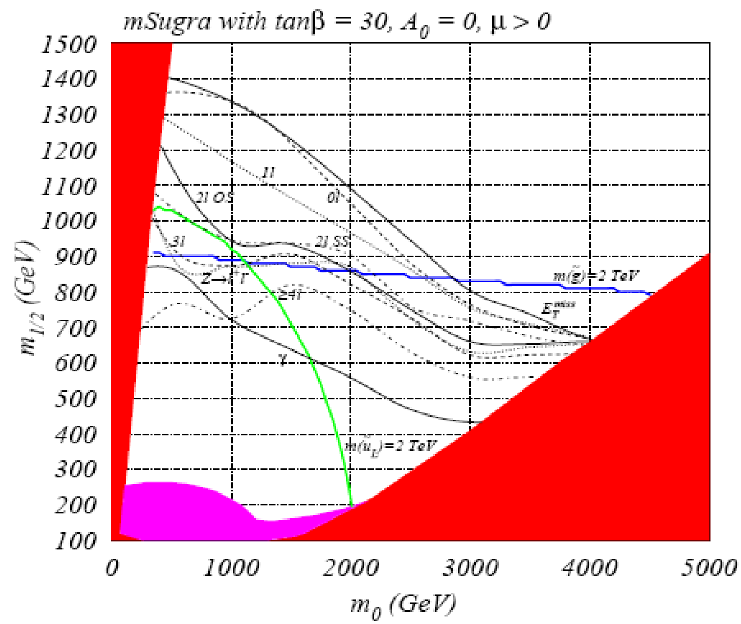
Baer et al 1004.3594

LHC14 reach

- Production squarks/gluinos
- Signatures: missing E_T + multiple hard jets (generic or b) + isolated leptons or photons
  - One Lepton
  - Dileptons same/opposite
  - trilepton
  - Four(+) leptons
- Cuts to reject background

- To exploit first data avoid signatures with E_T miss (require good knowledge of detector performance)
  - Jets, b/τ jets, di/trileptons
  - Limited reach – extend LEP

LHC14 - 100fb^{-1}



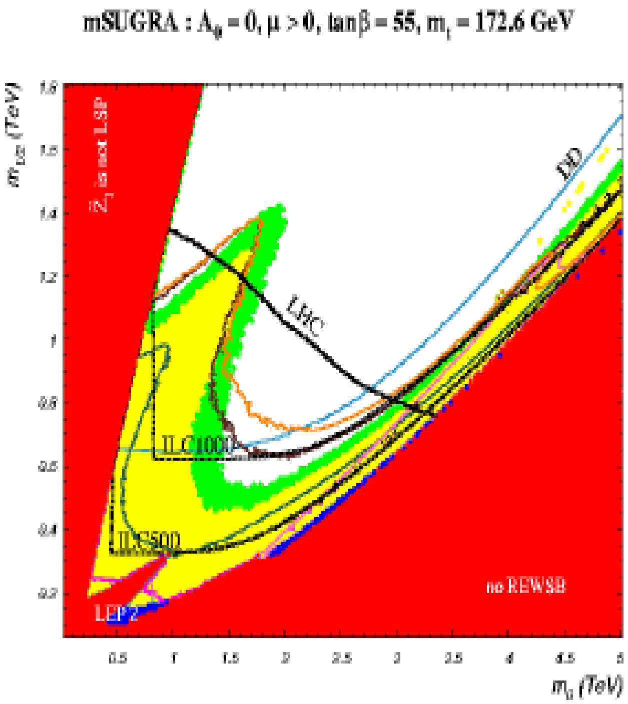
Baer, Tata, 0805.1905

- Squarks < 2.5TeV, gluinos<2TeV

LHC and DM in CMSSM

- LHC14: good discovery potential for model in agreement (or not) with WMAP
  - Nothing guaranteed

- The hard cases :
  - very heavy squarks and only light gluino neutralino/ chargino – good signature in DD
  - heavy Higgs and neutralino annihilation on resonance (LSP rather heavy)



Baer, Park, Tata 0903.0555

Constraints on New physics

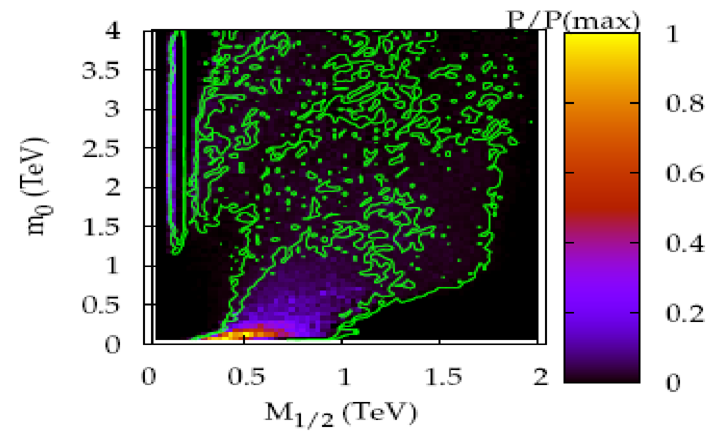
- Precision, B physics, g-2, Ωh^2

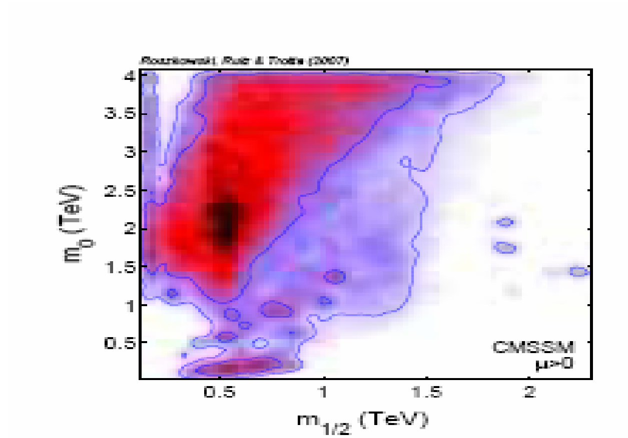
$\sin^2\theta_w^\ell(Q_{fb})$	0.2324 ± 0.0012
M_W [GeV]	80.399 ± 0.025
$BR^{exp}_{b\to s\gamma}/BR^{SM}_{b\to s\gamma}$	$1.117 \pm 0.076_{exp} \pm 0.082_{th(SM)}$
$BR(B_s \to \mu^+\mu^-)$	$< 4.7 \times 10^{-8}$
$BR^{exp}_{B\to\tau\nu}/BR^{SM}_{B\to\tau\nu}$	$1.25 \pm 0.40_{[exp+th]}$
$BR(B_d \to \mu^+\mu^-)$	$< 2.3 \times 10^{-8}$
$a_\mu^{exp} - a_\mu^{SM}$	$(30.2 \pm 8.8) \times 10^{-10}$
M_h [GeV]	> 114.4 (see text)
$\Omega_{CDM}h^2$	0.1099 ± 0.0062

- LEP constraints + Tevatron..
- Several groups have performed global analysis to determine parameter space of CMSSM and more general models

The CMSSM

Allanach et al. 2007





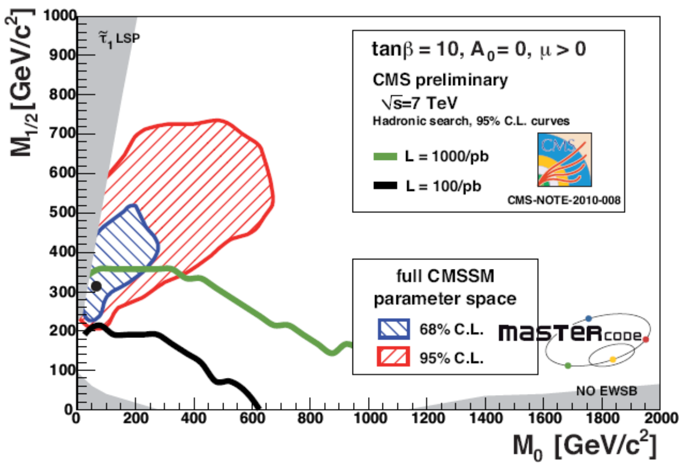
Roszkowski et al 0705.2012

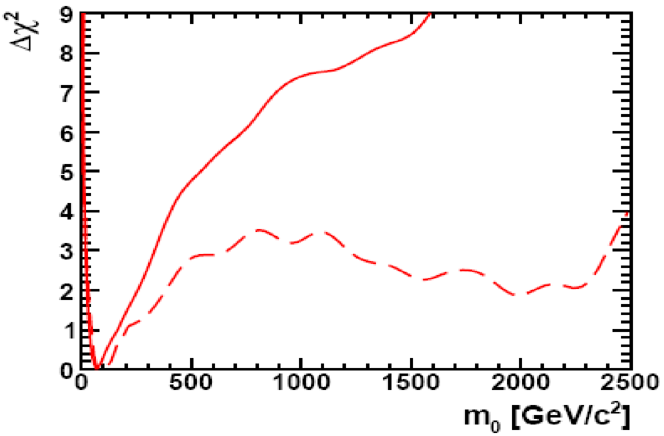
- MCMC analysis
  - m0, m1/2, A0, tanβ,sign(μ) + SM (mt mb,alpha)
  - covers large area of parameter space
- Allowed regions: bino or bino/Higgsino LSP, stau coannihilation.
- Not yet precise information on DM properties even in the context of a well-defined model
- Frequentist vs Bayesian statistics, prior dependence

The CMSSM

- Frequentist + Chi2 with MCMC sampling

O. Buchmuller et al 2010





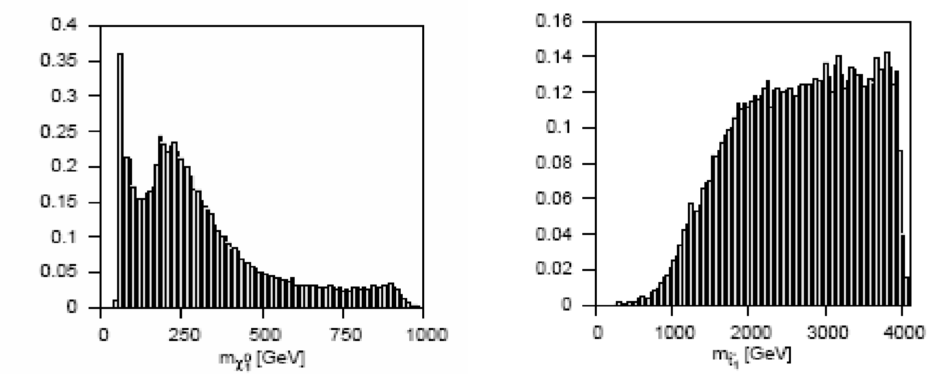
- Preferred region in low m_0-$m_{1/2}$ plane for tb=10
- Slight preference for light SUSY scale even in g-2 is removed from the fit
- Comparison with CMS reach for 0.1-1fb^{-1} at 7TeV (F. Ronga)

Going beyond CMSSM

- NUHM
  - Buchmuller et al (0905.5568)
- MSSM7 : from DM point of view μ and M_A are free parameters
  - DM can be bino/Higgsino and can be rather heavy
  - GB et al (0906.5048)
- MSSM19-25 : allow for non-universal gaugino mass in particular wino LSP
  - AbdusSalam et al (0904.2548)
  - Berger et al (0812.0980)
- CNMSSM: singlet extension of MSSM , LSP singlino
  - Roszkowski et al

MSSM7

- No guarantee of signal at LHC in squark/gluino or Higgs or B physics
  - heavy sparticles



- Good complementarity with DD/Higgs search

If coloured particles very heavy

Heavy Higgs at LHC	$\sigma^{SI}_{\chi p}$(pb)	$B(B_s \to \mu^+\mu^-)$ $> 5. \times 10^{-9}$	$< 5. \times 10^{-9}$
Yes	20.6% ($> 10^{-9}$)	5.6%	15%
24.2%	3.6%($< 10^{-9}$)	1.7%	1.9%
No	54.9%($> 10^{-9}$)	0.3%	54.6%
75.8%	20.9%($< 10^{-9}$)	0.7%	20.2%

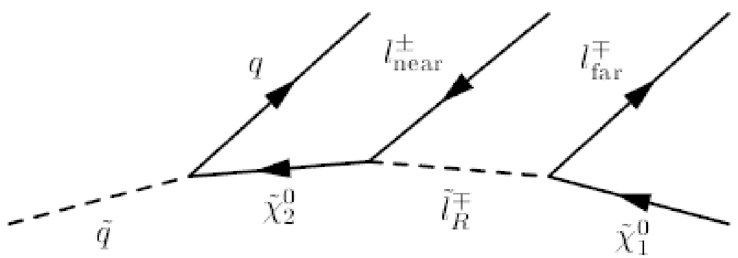
DM properties at LHC

- How well can the properties of dark matter be determined?
- Why we need that ?
  - Compare with signals in DD or ID –LSP is DM -- reconstruct DM density, velocity distributions…
  - compare with Ωh^2 extracted from cosmo, test standard picture : e.g. in scenarios with low reheat temperature relic density very different Drees et al 0704.1590

- What needs to be measured at colliders?
  - Mass and couplings of LSP
    - In MSSM : measure neutralino and chargino masses to determine $M_1, M_2, \mu, \tan\beta$
  - Mass of new particles that contribute to (co)annihilation (or lower limits)
    - In MSSM: stau, squark(stop), other slepton
  - Mass of Higgs (or any other potential resonance)

Parameter determination LHC

- E_{Tmiss} -> no mass peak
- Exploit end-points in kinematic distribution for mass determination
- Assume particles in decay chain are correctly identified



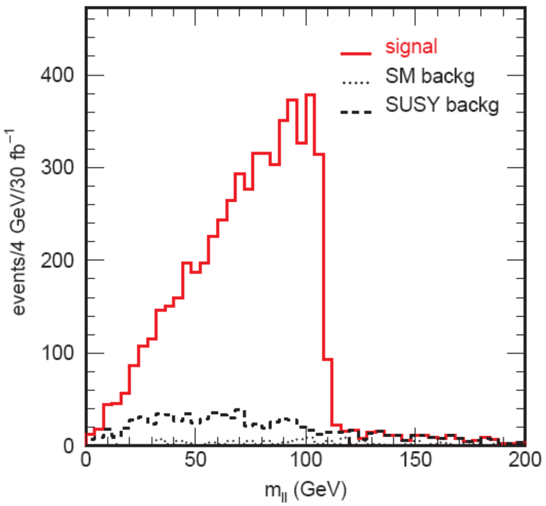
$l^+ l^-$	edge	m_{ll}^{max}
$l^+ l^- q$	edge	m_{llq}^{max}
$l^+ l^- q$	threshold	m_{llq}^{min}
$l^\pm q$	high-edge	m_{lq}^{high}
$l^\pm q$	low-edge	m_{lq}^{low}

Bachacou, Hinchliffe Paige 1999
Allanach et al 2000

Endpoints

$$m_{ll}^{\max} = \sqrt{\frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{e}_R}^2)(m_{\tilde{e}_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{e}_R}^2}}$$

$$m_{jl}^{\min} = \sqrt{\frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{e}_R}^2 - m_{\tilde{\chi}_1^0}^2)}{2m_{\tilde{e}_R}^2 - m_{\tilde{\chi}_1^0}^2}}$$



- Mass differences– (few) percent level
- Masses typically 10%
- Also possible combine endpoints +cross-sections – Lester,Parker, White ’05

Parameter determination

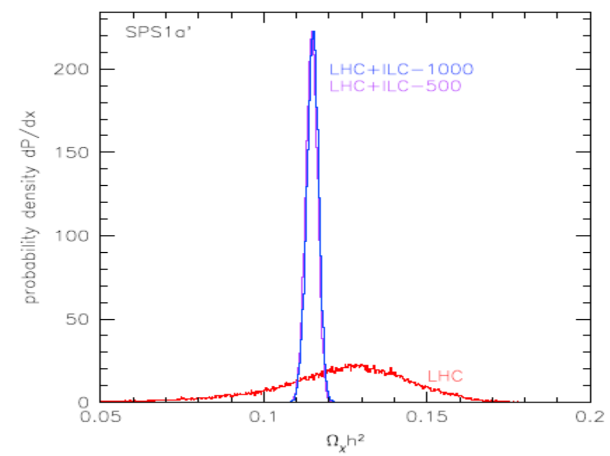
- Strategy: measure as many masses, couplings, branching fractions as possible → constrain model parameters
- See if fits DM observables (Ωh^2,DD)
- Many case studies
  - Nojiri, Tovey, Polesello; Baltz et al. Arnowitt, Dutta, Kamon; Barr Lester, White, Gunion et al, Raklev, Kraml, Matchev et al, Matsumoto et al,

Parameter determination

$$\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\ell}^\pm\ell^\mp \to q\ell^\pm\ell^\mp\tilde{\chi}_1^0$$

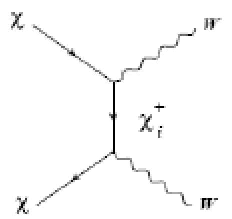
- First results found for favourable cases (SPS1a) with light spectrum and long decay chains
  - Mass LSP 20% level
  - tanβ from Higgs sector
  - Stau mixing

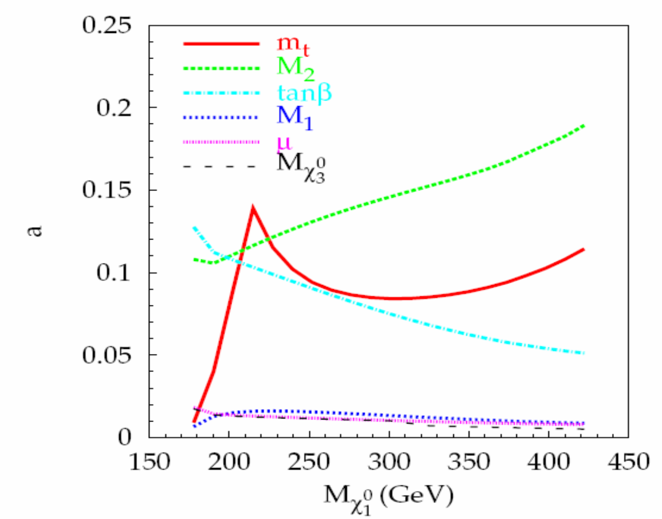
- From LHC about 15% precision on relic abundance
- Order of magnitude on DD



A harder one : heavy scalars

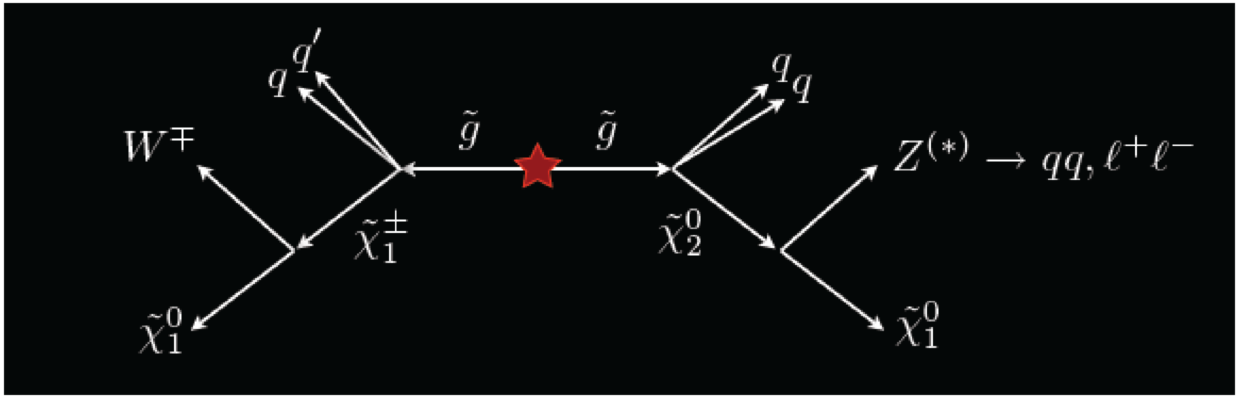
- Precision required on SUSY parameters for $\delta\Omega/\Omega$=10%
- Bino/Higgsino scenario in MSSM with heavy squarks
- Annihilation gauge bosons, tt
- Couplings sensitive to Higgsino fraction depend M_1,μ both same order
- need precise M_1,μ ($m\chi_3$) at least %
- Lower limits on squarks and Higgs





Allanach, et al, hepph/0410091

… bino/Higgsino



- Gluino only accessible, 3 neutralinos + chargino in decay
- mass differences could be measured from m(ll) 2 edges : χ_2, χ_3
  - deSanctis, Lari, Montesano, Troncon, 0704.2515 (hep-ex)
- Also m(bb), m(bbll) + total cross section with M_{eff} : sensitive to m(gluino)
  - About 10% accuracy on masses
  - *Not enough for precise neutralino fraction nor for relic density*

Determining neutralino mixing

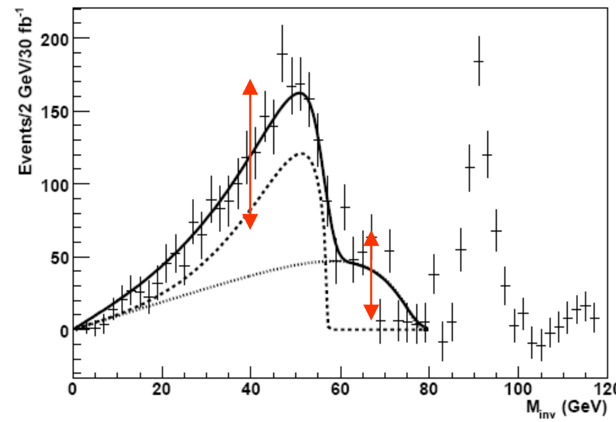
- Add new observables: shape of dilepton invariant mass spectrum

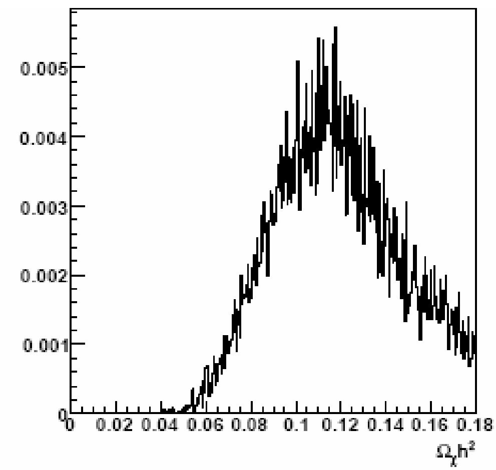
- Changing LSP component : modifies the shape

$$\frac{BR(\tilde{g} \to ... \to \tilde{\chi}_2^0 + X) \times BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+ l^-)}{BR(\tilde{g} \to ... \to \tilde{\chi}_3^0 + X) \times BR(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 l^+ l^-)}$$

- Significantly improves constraint on neutralino mixing and prediction of relic density and DD rate

- Main uncertainty Higgs mass

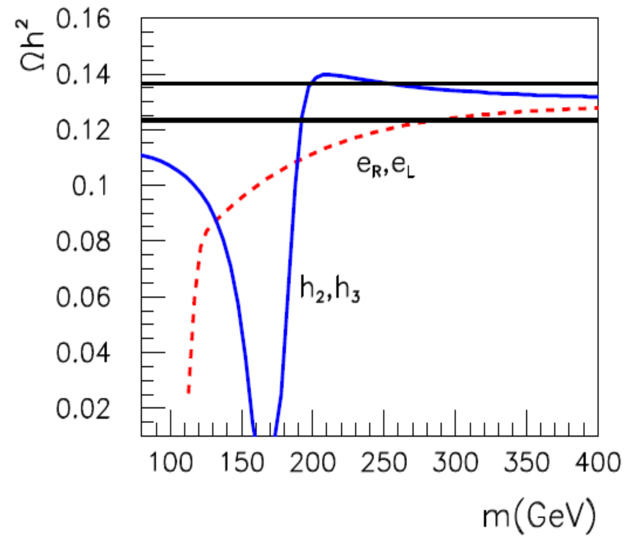




White Feroz 1002.1922

Importance of Higgs search

- Light or heavy Higgs exchange can dominate DM annihilation – resonance effect – need to check whether or not Higgs contribute
  - Search for h
  - Search for heavy Higgs
    - bbH, H->ττ
    - Good at Large tanβ
  - SUSY to Higgs decay
    - Under investigation



- Direct detection rate often dominate by interaction of DM with nuclei via light Higgs exchange- coupling of DM to light Higgs important parameter

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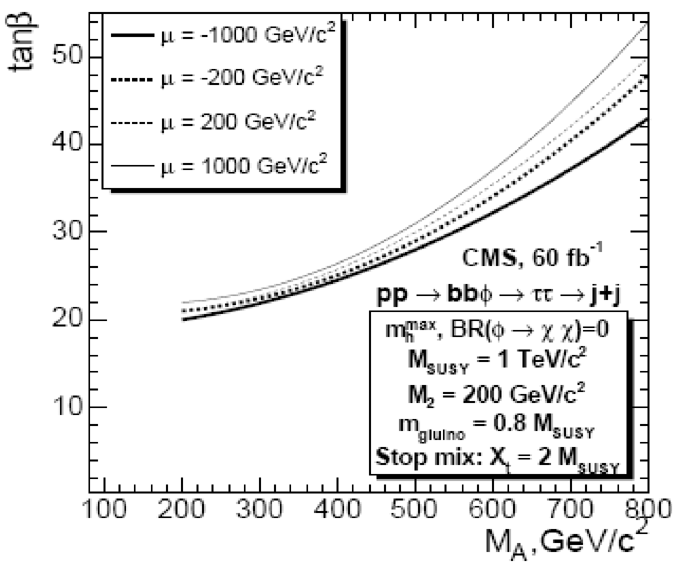

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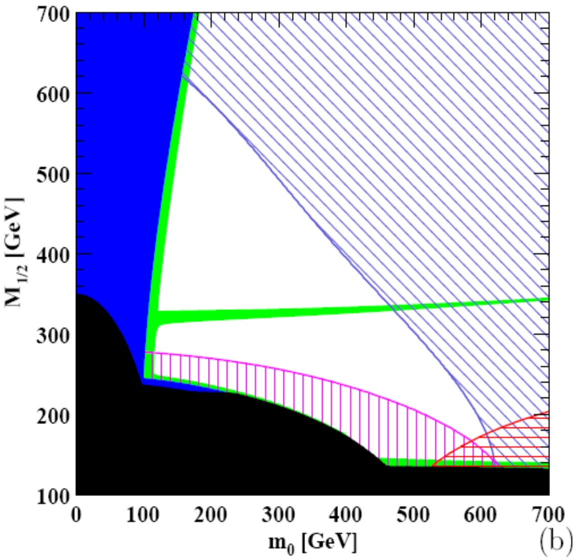
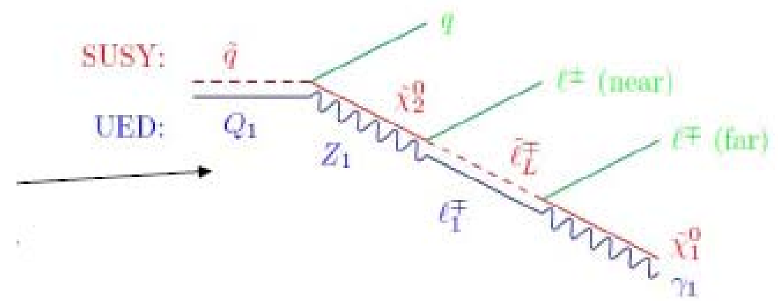
A difficult case with Ω~1

- MSSM with additional singlet superfield – provide naturally μ of weak scale : NMSSM
- Higgs sector: 3 scalars, 2 pseudoscalars – extra fields are dominantly singlet
- Neutralino sector: 5 neutralinos
- Annihilation near new resonance : Ωh^2 ~0.1 in region of parameter space where Ωh^2 ~1 in CMSSM
- After measurement of parameters would likely conclude that "collider relic abundance" does not match cosmological measurement
  - Non-standard cosmological scenario or new particle?
  - Search extra Higgs : possible only in a few cases



G.B., Hugonie, Pukhov, 0811.3224

Other models



- Dark matter in MUED with KK parity for proton stability : photon partner- spin1
- DM rather heavy (500-900 GeV) – Tait Servant 2002: not for LHC7
- Many similarities to SUSY – partner for each SM particle (same spin)
- Production and decay of coloured particles analog to SUSY
- Spin determination is crucial to differentiate with SUSY
  - Alves Eboli,Plehn, hep-ph/0605.067, Barr, hep-ph/0511115
- Also new resonances

$$f_0 f_0 \rightarrow Z^{(2)} \rightarrow l^+ l^-$$

- In general in NP model if light coloured particles good prospects, e.g. littlest Higgs model with new quarks < TeV scale : discovery guaranteed + collider prediction of relic abundance~10% (Matsumoto 2008)

Conclusions

- Understanding the nature of Dark matter : an exciting challenge for the LHC
- Prospects for discovering physics beyond the standard model : excellent
- "Testing cosmology and DM" at colliders : more difficult but useful information in many cases
  - *This is not the final answer: with data experimentalists usually do better than expected*
- Colliders complementary to direct/indirect detection – better control of particle physics aspects