Candidates for Dark matter

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LAPTH- Annecy

Outline

- Dark matter
  - What is DM ? What are its properties?
- LHC and DM
- Complementarity with Astroparticle
- A few dark matter candidates -
  - Neutralino, vector boson, right-handed neutrino, scalar

What is DM?

- Strong evidence that DM dominates over visible matter. Data from rotation curves, clusters, supernovae, CMB all point to large DM component
- One of the central questions in PP: what is DM (new particle WIMP)?
  - Likely to be related to physics at weak scale
  - New physics at the weak scale can also solve EWSB
  - Many possible solutions – many possible DM candidates
- Dark energy rather related to Planck scale
- NP at weak scale could also explain baryon asymmetry in the universe

Dark matter : a new particle?

- Weakly interacting particle gives roughly the right annihilation cross section to have $\Omega h^2 \sim 0.1$

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

- 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…
  - More phenomenological approaches: extra scalar, Dirac fermion
  - Superweakly interacting particles also work (gravitino)

WIMPS

Spin	DM	Model	Motiv.	Mass (GeV)	LHC: New particles	DD (pb)
1/2 Majorana	χ χ χ χ χ χ χ χ ν_R	SUGRA GUT-scale MSSM CPVMSSM NMSSM nMSSM UMSSM sMSSM Walk. Tech.	SB SB+GUT SB +baryo $+\mu$ +baryo $+\mu$ $+\mu$ SB	50-2000 10-2000 10-2000 10-2000 > 10 < 50 > 50 < 50 30-2000	Sparticles +H +H +H+Z' +H+Z' Techni.	$10^{-11} - 10^{-6}$ $10^{-12} - 10^{-6}$ $10^{-11} - 10^{-6}$ $10^{-9} - 10^{-6}$ $10^{-11} - 10^{-6}$ $10^{-9} - 10^{-6}$?
1/2 Dirac	ν_R ν_R ν	Warped-Xdim LR+Xdim MDM	SB SB DM	50 or > 700 50-3000 > 4000	KK particles fermions/GB	$< 10^{-7}$ $< 10^{-7}$
1	B B	UED Little Higgs	SB SB	400-1200 100-500	KK particles T-quarks, W_H..	$10^{-11} - 10^{-6}$ $< 10^{-10}$
0	H H H γ $\tilde{\nu_R}$	Inert Higgs Twin Higgs xSM UED-6D MSSM $+\nu_R$	DM DM DM SB SB+m_ν	50 or > 500 50-600 100-500 50-2000	Scalar Scalar+Z' Singlet, Hinv KK particles Sparticles + Z'	$10^{-12} - 10^{-7}$ $5.10^{-10} - 10^{-6}$ $10^{-11} - 10^{-9}$ $10^{-10} - 10^{-7}$

GUT-scale models include string inspired models (e.g.moduli-dominated), AMSB, Split SUSY, Compressed SUSY, NUHM, mirage mediation

Identifying Dark matter

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

- Discovery of WIMP -- complementarity LHC – DD

- Determination of properties of new particles (LHC)
  - 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
  - Also compute cross section for dark matter scattering on nuclei -> consistent with direct detection results ?

- Observation of DM in Direct or Indirect Detection -- reconstruct density distribution

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

Detection of DM

- Direct detection
  - 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 nucleon 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 DM annihilation in the galactic halo
    - Photons from DM annihilation in center of galaxy
    - Neutrinos from DM in sun
  - Consistency checks of different signals
  - Check compatibility with NP scenario (SUSY or other)
  - Caveat: assumptions on dark matter distribution

Different approaches to DM

- Complementarity
  - DM signal in DD/ID *or* NP discovery at LHC
    - DD constrains NP models – which DM candidate
    - Potential for DM discovery after LHC
    - LHC constrains NP – missing energy but no direct evidence
- Concurrence
  - Signals in different types of experiments allow cross-checks
  - Possible tests of cosmology, dark matter distribution…

Some examples

- mSUGRA (CMSSM)
- MSSM
- UED
- Right-handed neutrino
- Scalar DM

SUSY – neutralino LSP

- Solution to hierarchy problem : cancel quadratic divergences in Higgs mass
- Unification of gauge coupling
- Boson/fermion symmetry : associate new SUSY particle to each SM particle + extend Higgs sector (additional doublet)
- DM candidate : usually neutralino can also be gravitino

Neutralino LSP

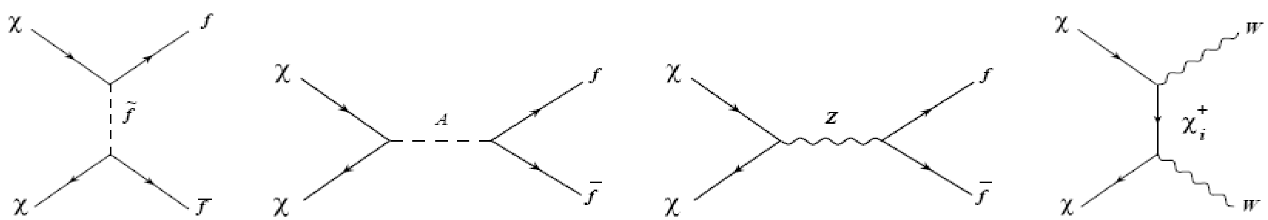
- Neutral spin ½ *SUSY* partner of gauge bosons (Bino, Wino) and Higgs scalars (Higgsinos)

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

- Lightest neutralino is stable because of R-parity (also stabilizes the proton)
- Neutralino is Majorana particle

- Exact nature of neutralino (model dependent) will determine its annihilation properties – relevant for relic density, for indirect detection rate, for direct detection through interaction with nuclei in large detector

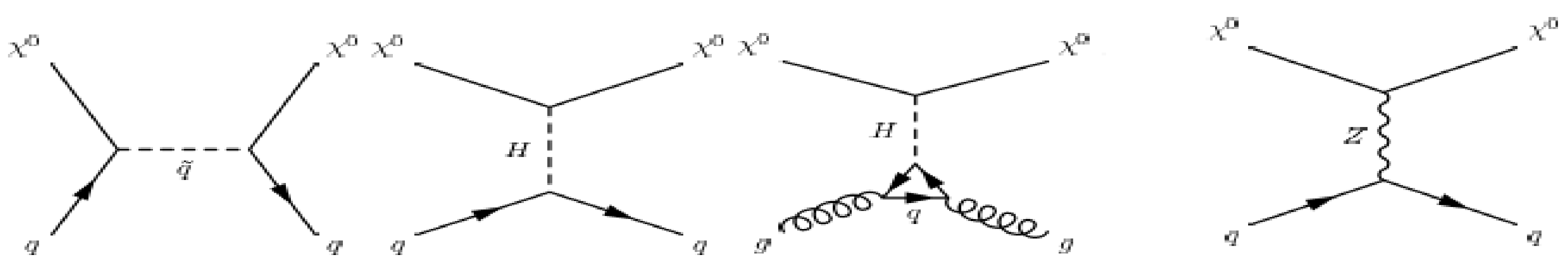
Neutralino annihilation



+coanni.

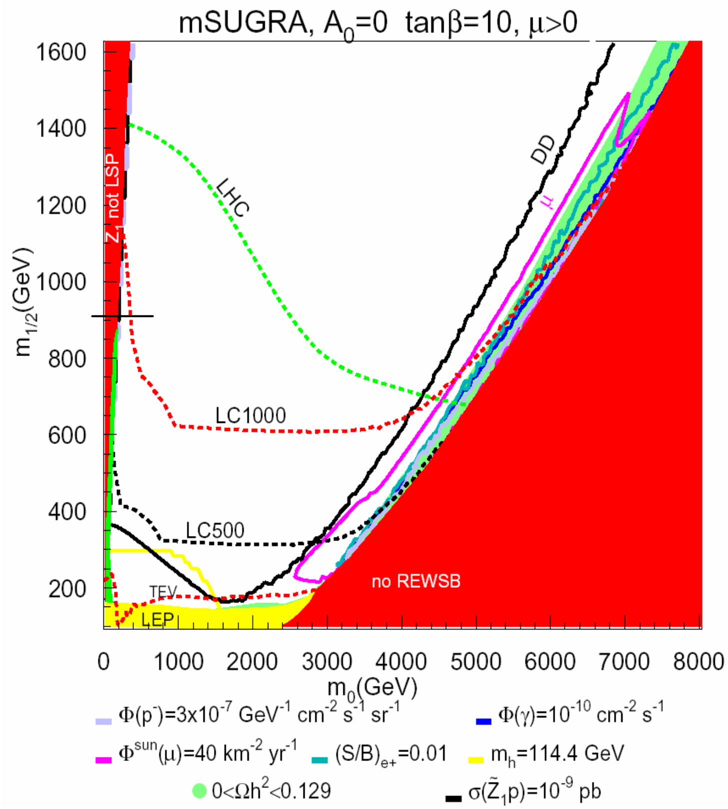
- Annihilation of LSP in W pairs enhanced for mixed bino/Higgsino – also favoured for indirect detection
- Annihilation of bino dominantly into fermions
- Annihilation through Higgs if some Higgsino component
- DD: often dominate by Higgs exchange diagram (except when squarks are light)
  - Higgsino component is necessary to have LSP coupling to Higgs

SD only



CMSSM - complementarity

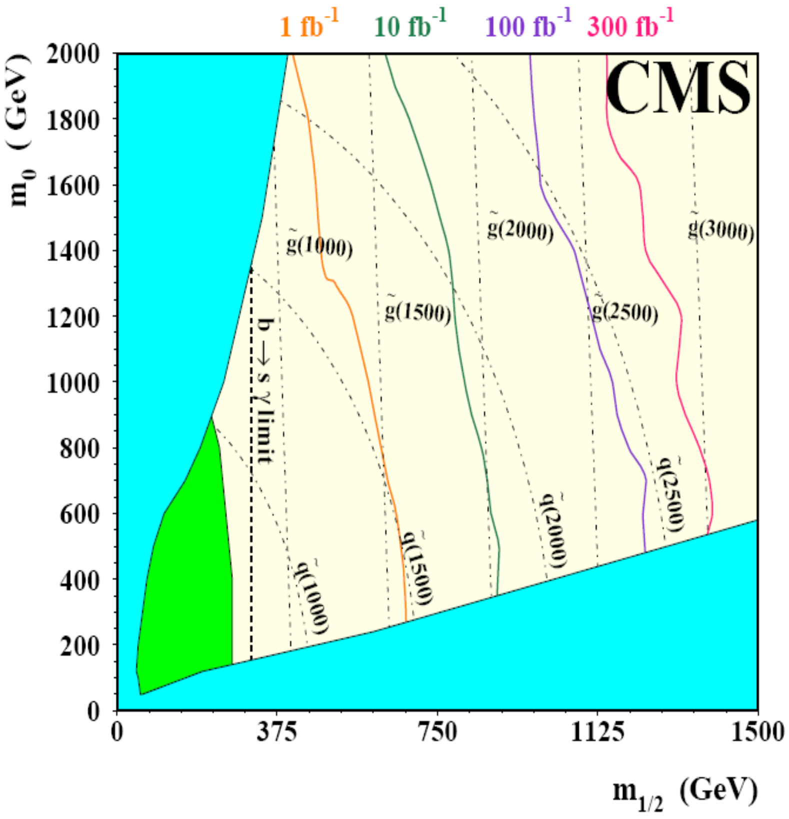
- Most studies at colliders done within context of CMSSM (small number of parameters: 4 ½ instead 100)
  - Convenient, good for tuning analyses, but not general
  - Somewhat fine tuned from DM perspective – neutralino is in general bino
- LHC
  - Good for discovery of coloured particles
  - Limited reach 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

Potential for SUSY discovery at LHC

- pp collider @14TeV
- Operation starts 2008
- Good for discovery of coloured particles: squarks, gluinos < 2-2.5 TeV
- Sparticles in decay chains
- Higgs searches
- Limited reach when all squarks heavy – only chargino/neutralino "light"
- Other models : similar reach in masses for coloured particles



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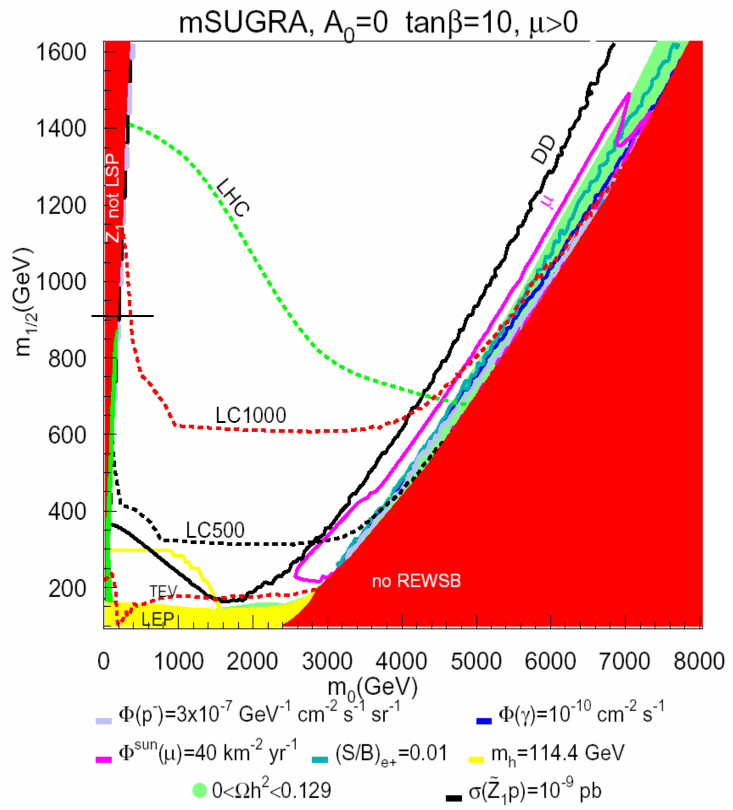
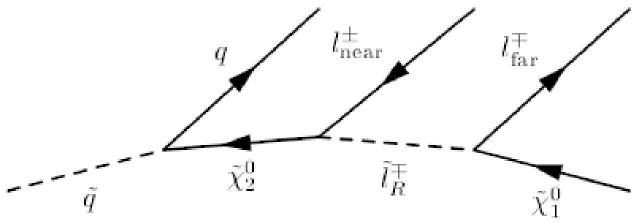


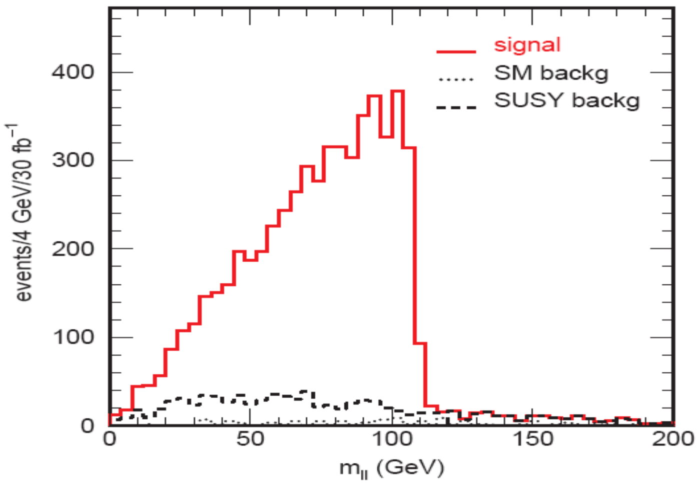
Baer et al., hep-ph/0405210

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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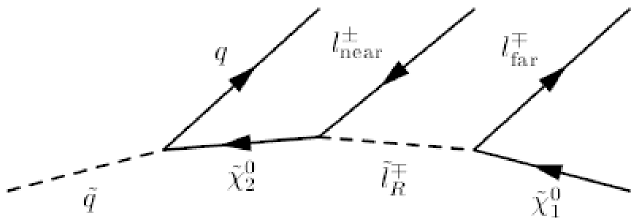
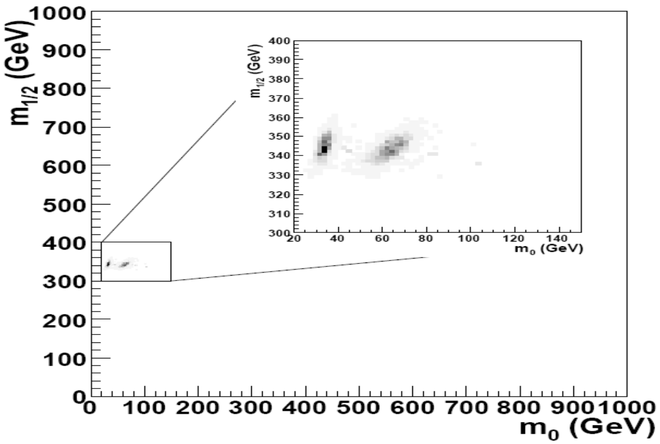
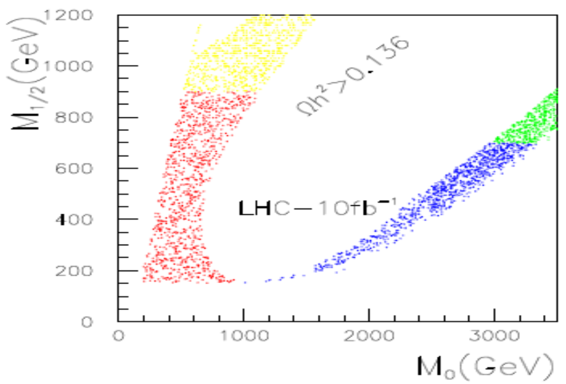


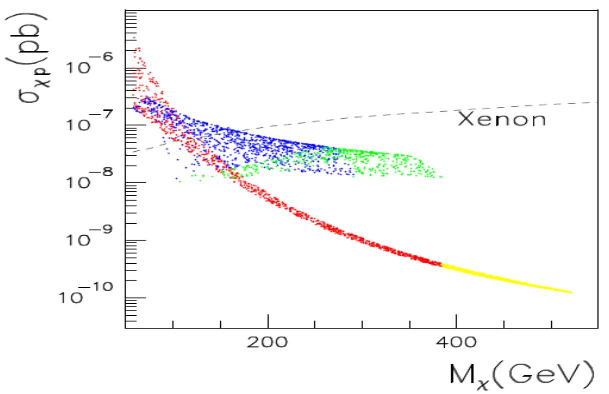


White, hep-ph/0605065

CMSSM or mSUGRA



tβ=50, A_0=0



- By 2010 – if LHC has discovered SUSY in mSUGRA –> signal in DD accessible to ton-size detectors (few 10^{-10}pb) or even before
- At LHC can distinguish type of SUSY model + can measure mass of SUSY particles→ better prediction of the range for DD rate
- No signal at LHC : if bino/Higgsino LSP will have signal in DD

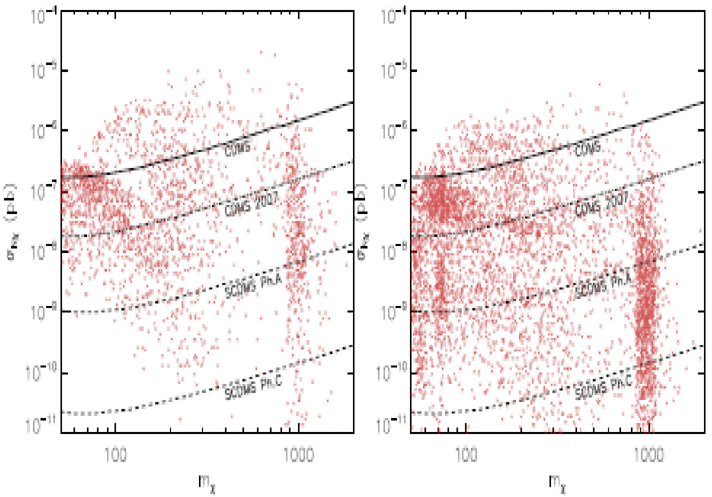
LHC vs DD in MSSM

- In MSSM, neutralino can have any composition, Higgsino component not only associated with heavy squarks as in CMSSM
- Harder to make general statement about correlation signal at LHC with DD.

- If squarks dominate DD (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-> ττ +X
- A fraction of the MSSM models that give a Higgs signal at colliders also predict a signal in SCDMS (~10^{-9} pb)

- Even if no signal at LHC – large uncertainties in prediction of DD rate

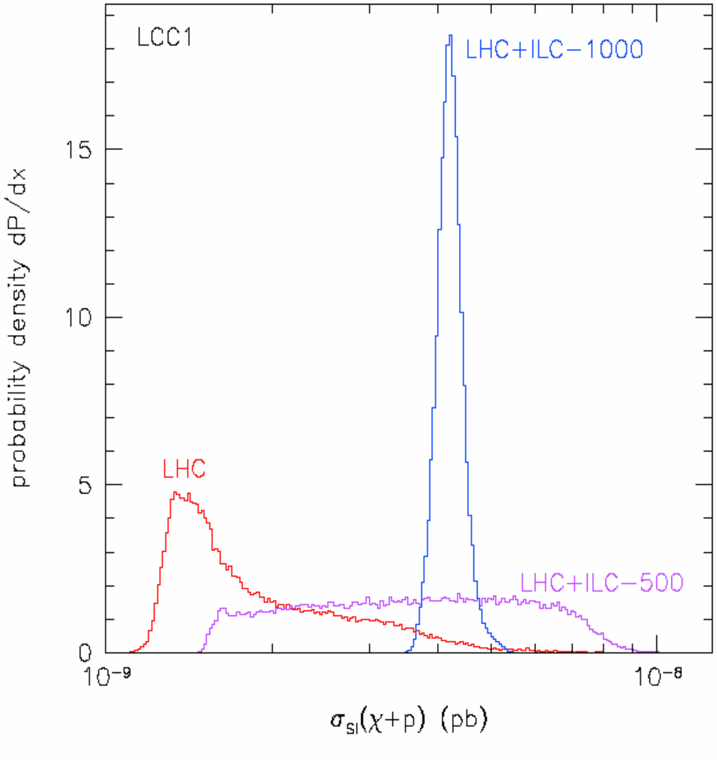
Within reach LHC   No LHC reach



Carena et al hep-ph/0611065

Case study : SPA1a

- Situation better in specific case study
- Assume a model, compute spectrum, estimate error from LHC measurements+ vary all MSSM parameters within these errors
- SPA1A : Annihilation into fermions and Coannihilation with staus
- Relevant parameters : LSP mass, couplings, slepton masses
- LHC: roughly the WMAP precision on Ωh^2 ~10% can be achieved within MSSM
- Prediction for spin-independent cross-section
  - Observable by 2010
- Factor of 3 uncertainty, improves significantly if know heavy Higgs mass



Baltz, Battaglia, Peskin..

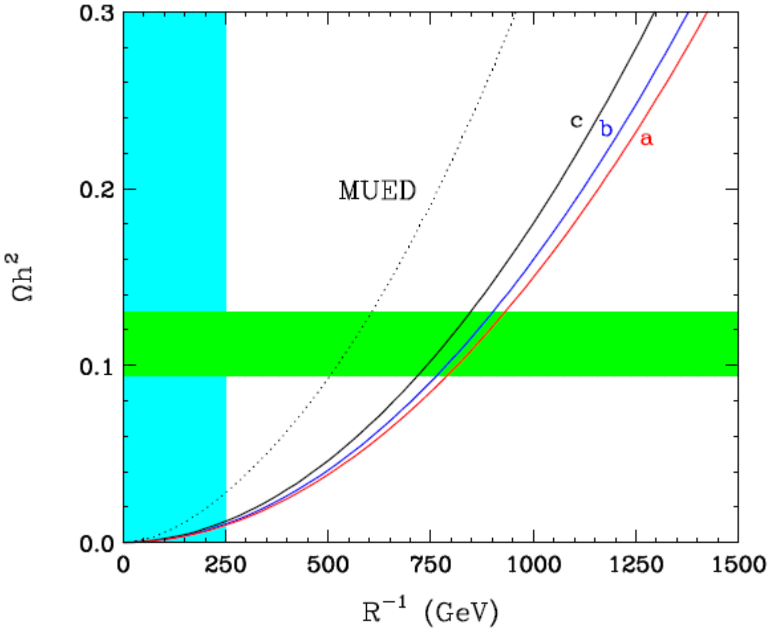
DM in UED

- String theory and M theory : best candidate for consistent theory of quantum gravity and unification of all interactions
- Xtra dim models solve the hierachy problem either with compactified dim on circles of radius R effectively lowering the Planck scale near EW scale or introducing large curvature (warped)

- UED: flat Xdim , all fields propagate in the "bulk"
- Each bulk field has tower of KK states , $m_n \sim n/R$
- Explain:
  - 3 families from anomaly cancellation
  - Dynamical EWSB
  - No rapid proton decay

Vector boson DM – UED

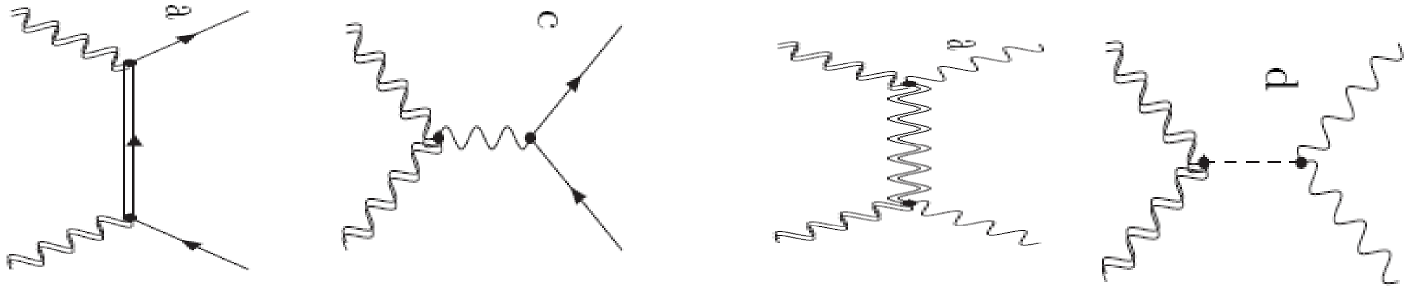
- UED : All SM field propagate through all dim. of space $R \sim TeV^{-1}$
- KK parity for proton stability
- Minimal UED: LKP is $B^{(1)}$, partner of hypercharge gauge boson (spin 1)
- s-channel annihilation of LKP (gauge boson) typically more efficient than that of neutralino LSP
- **Compatibility with WMAP means rather heavy LKP, 500-900 GeV**
  - **Tait, Servant (2002)**



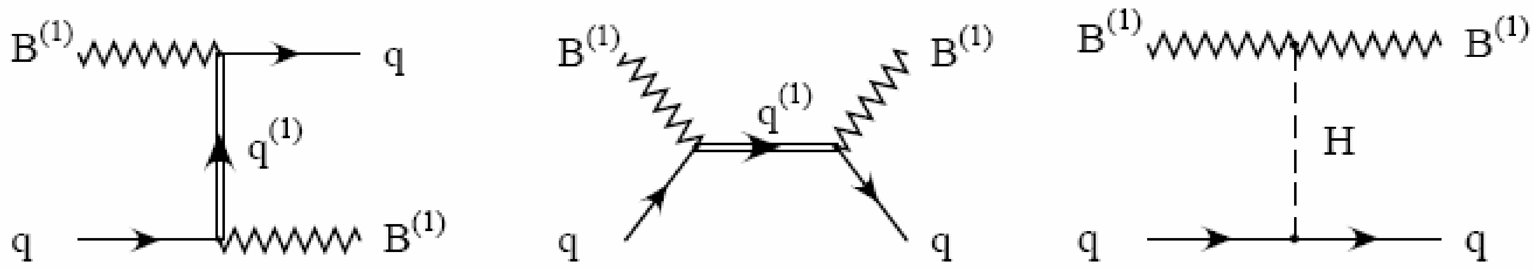
Kong, Matchev, hep-ph/0509119

Annihilation of B

- Annihilation channels: WW, ZZ, ll, qq, hh



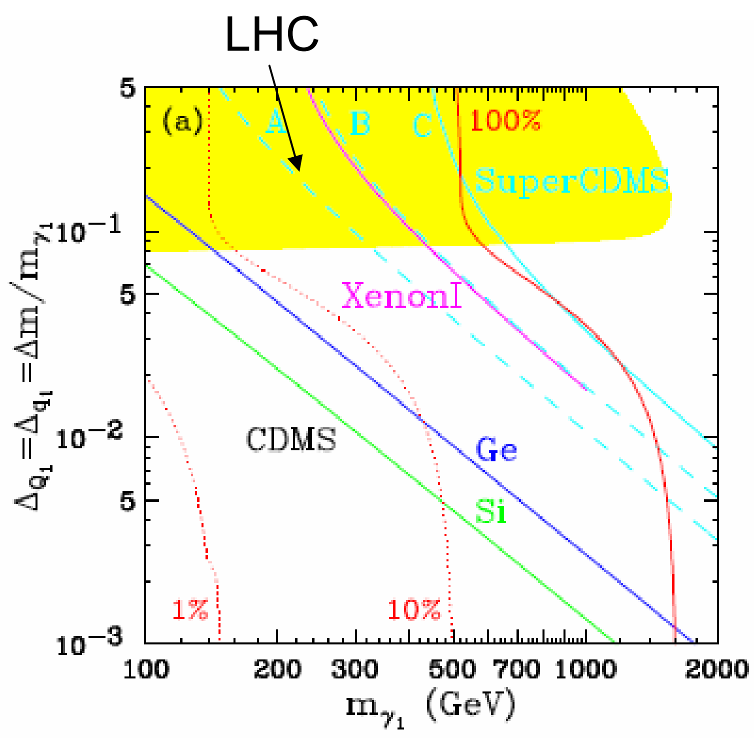
- No need for resonance annihilation
- Also many coannihilation channels
- Direct detection : Higgs or KK quark exchange



UED : LHC vs DD

- LHC :
  - Search for KK quarks and gluons
  - Masses of KK particles nearly degenerate-> with LKP ~TeV, KK quarks easily seen unless too degen.
  - Similar to SUSY : missing E signal
  - How to differentiate? spin determination + search 2nd KK particles
- DD :
  - Higgs and KK quark exchange
  - Typically smaller than SUSY (scale)

    σ (SI) ~10^{-9} -10^{-11}pb
- *Even SuperCDMS(1t) can barely probe favoured mass range unless Δm small*



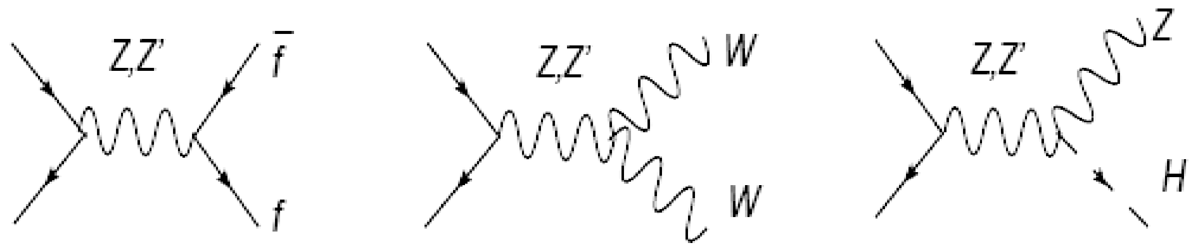
Kong, Matchev, hep-ph/0610057

Right-handed Dirac neutrino

- Can be found in models with warped extra dimension : those models also provide solution to hierarchy problem

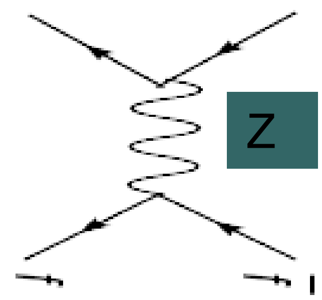
Right-handed Dirac neutrino

- Typical framework: sterile Dirac neutrino under SM but charged under $SU(2)_R$
- Phenomenologically viable model with warped extra-dimensions and right-handed neutrino (GeV-TeV) as Dark Matter was proposed (LZP)
  - Agashe, Servant, PRL93, 231805 (2004)
- Stability requires additional symmetry , but symmetry might be necessary for EW precision or for stability of proton
- Either only SM+ ν_R or extra symmetry
- ν_R can couple to Z through ν'_L- ν_R or Z-Z' mixing –naturally small
- Main annihilation channel – Z/Z' exchange

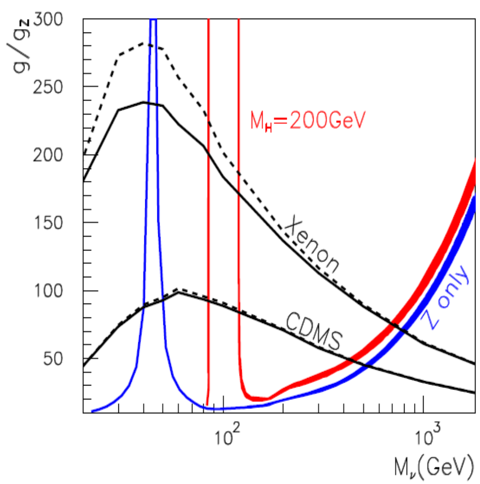


Direct detection : Dirac neutrino

- Dirac neutrino: spin independent interaction dominated by Z exchange (vector-like coupling) → very large cross-section for direct detection
  - coupling $Z\nu_R\nu_R$ cannot be too large
- Current DM experiments already restricts ν_R to be
  - $\sim M_Z/2$, $\sim M_H/2$ or $M(\nu_R) > 700$GeV



- Z exchange: also main mechanism for annihilation of ν_R
- Vectorial coupling : elastic scattering on proton << neutron
- Direct detection is best way to probe this type of model
- At LHC: if new particles (KK) at TeV scale, need high luminosity

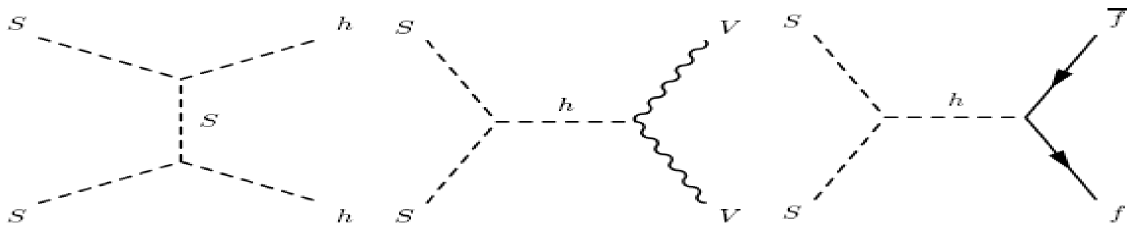


Scalar dark matter (singlet)

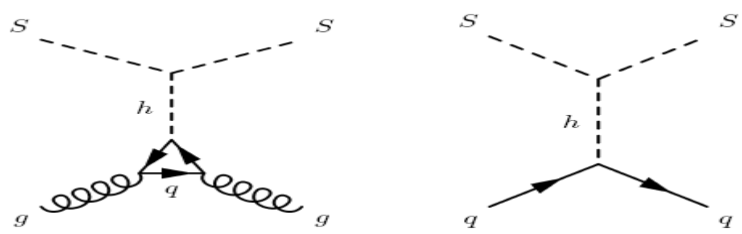
- Extensions of SM Higgs sector that can affect Higgs phenomenology
- No strong theoretical motivation

Scalar DM

- Simplest extension : add scalar singlet to SM + discrete symmetry-> stable scalar
- Singlet couples to Higgses –responsible for annihilation



- Higgs exchange also gives spin-independent direct detection



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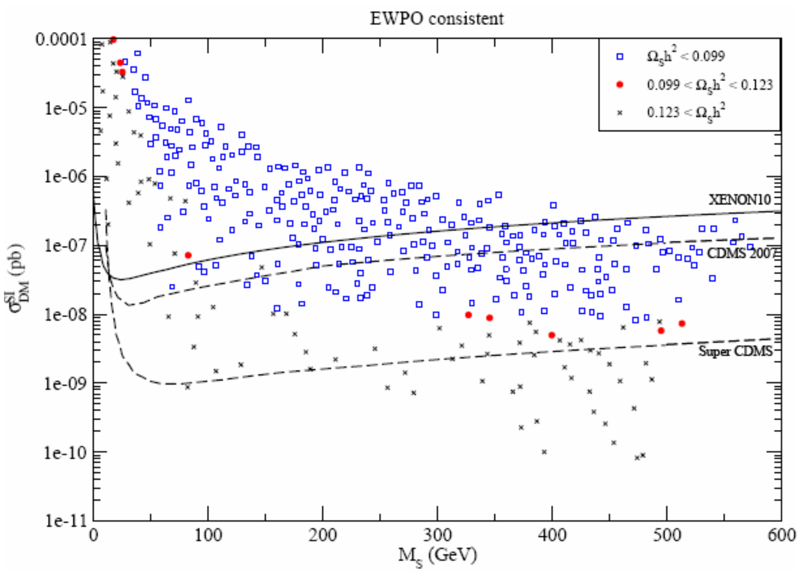
Scalar DM -

- No resonance annihilation needed→ DD directly related to annihilation cross-section
  - Good prospects for direct detection
- LHC : singlet modify properties of Higgs decays, (invisible decay)
- LHC can look for those, need high luminosity
- *No early signs of NP at LHC, yet possible signal in Direct detection*



Barger et al 0706.4311

Indirect detection - remarks

- To have correct relic density must have

$$\langle \sigma v \rangle \approx 3 \times 10^{-26}$$

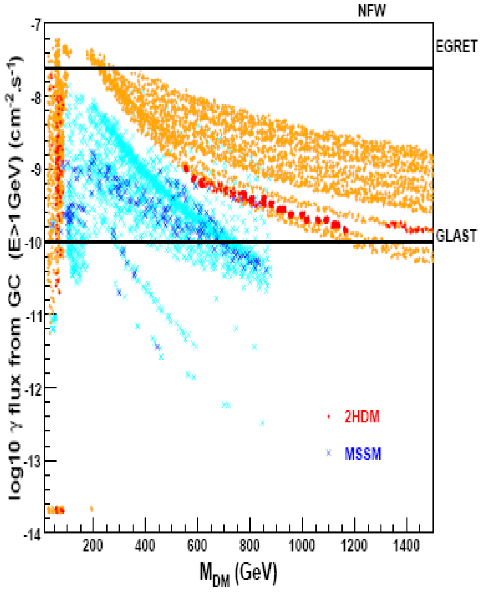
- For indirect detection, v->0 , cross-section might be different than the one at freeze-out
  - Typically in UED and ν_R model, $\sigma v(0) \sim \sigma v(FO)$
  - MSSM : depends on parameter, if coannihilation dominant $\sigma v(0) < \sigma v(FO)$

- For certain models can have line at m_{LSP} coming from annihilation into 2 photons – model dependent

- In UED models or Dirac neutrino model – annihilation into light fermions important whereas this is suppressed in MSSM –harder positron and neutrino spectrum

Indirect detection - remarks

- In ν_R model : good prospects for detecting HE neutrinos from the sun – $M_{\nu'}$ <100GeV, ν' pairs annihilate directly into ν pairs : accessible to AMANDA (max 5-10 events/yr) and Antares
  - Hooper, Servant, hep-ph/050224
- Also good signal in positron –Pamela
- For photons: good prospects for scalar DM while MSSM more model dependent (coannihilation models have small flux)



Lopez, Nezri, Tytgat

Conclusions

- Many dark matter candidates (WIMPS) often motivated by NP models introduced to solve the hierarchy problem
- Beyond theoretical prejudice : if LHC discover new particles, might 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
- If no signal at LHC can still expect large cross-sections for direct/indirect detection (model dependent)