Dark matter models after the LHC, LUX ...

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LAPTH, Annecy-le-Vieux

Introduction

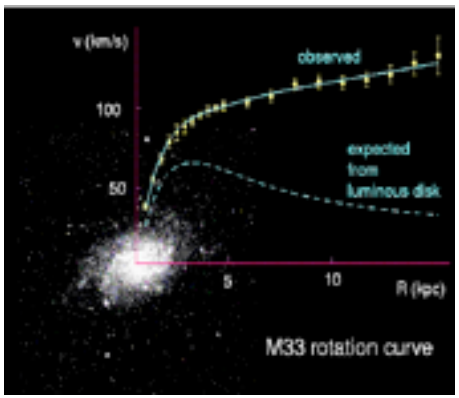
SUSY DM after LHC

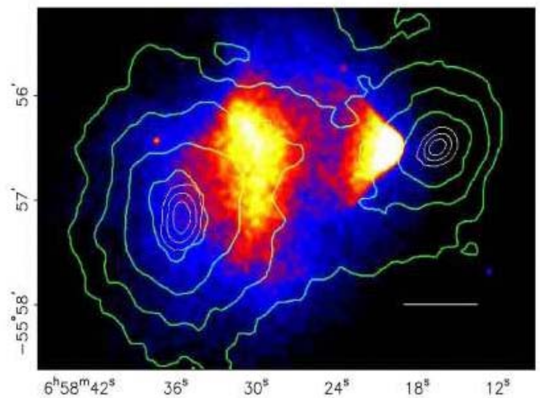
Scalar DM, portals and the Higgs

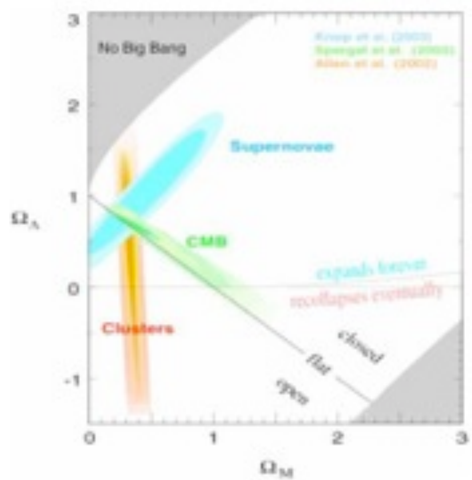
Conclusion

Introduction

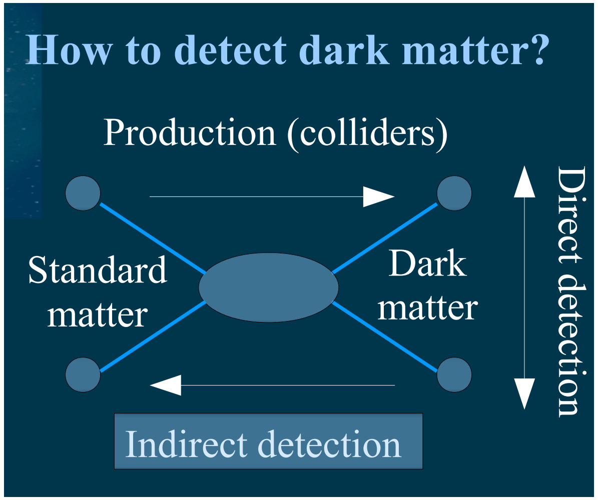
- Strong evidence for dark matter from astrophysical and cosmological observations
- Motivation for new particles from particle physics : symmetry breaking, stabilization of Higgs, unification
- Can one of these new particles explain the dark matter?







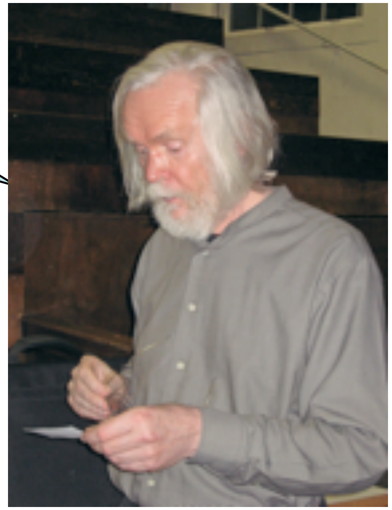
- Recently LHC has probed BSM physics - both Higgs sector, indirect/direct searches for new particles - no clear direction on BSM so far
- Several astroparticle experiments actively search for DM both in direct detection (Xenon, LUX) and indirect detection (PAMELA, FermiLAT, Hess AMS) - some hints



- What is the status of dark matter candidates after LHC8TeV (+LUX..) and before LHC13TeV?
  - LHC can only see neutral particle stable enough to escape the detector (missing E_T): can never tell whether particle stable on cosmological scale

Dark matter a new particle?

CMSSM
Neutralino (bino)

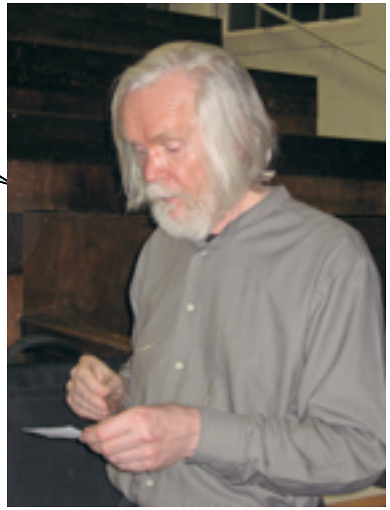


Dark matter a new particle?

CMSSM
Neutralino (bino)

bino/Higgsino

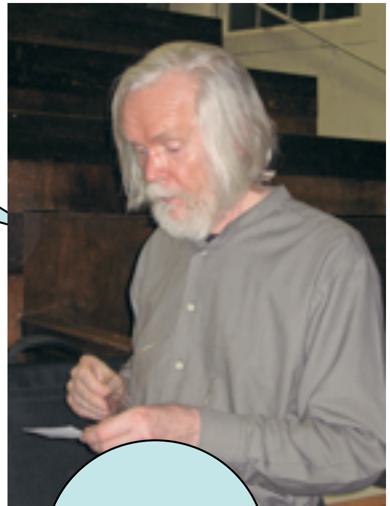
bino/higgsino/wino



gravitino

Dark matter a new particle?

CMSSM
Neutralino (bino)



NMSSM
singlino

Xenonphobic

gravitino

pMSSM
bino/higgsino/wino

FIMPs axion

right-handed neutrino

Dirac fermion

KK-neutrino

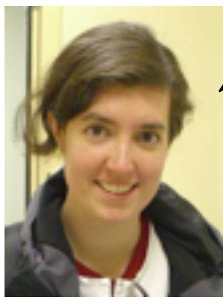
KK-photon

scalar photon

higgsino
sneutrino

axino

Asymmetric



Light DM

Singlet scalar

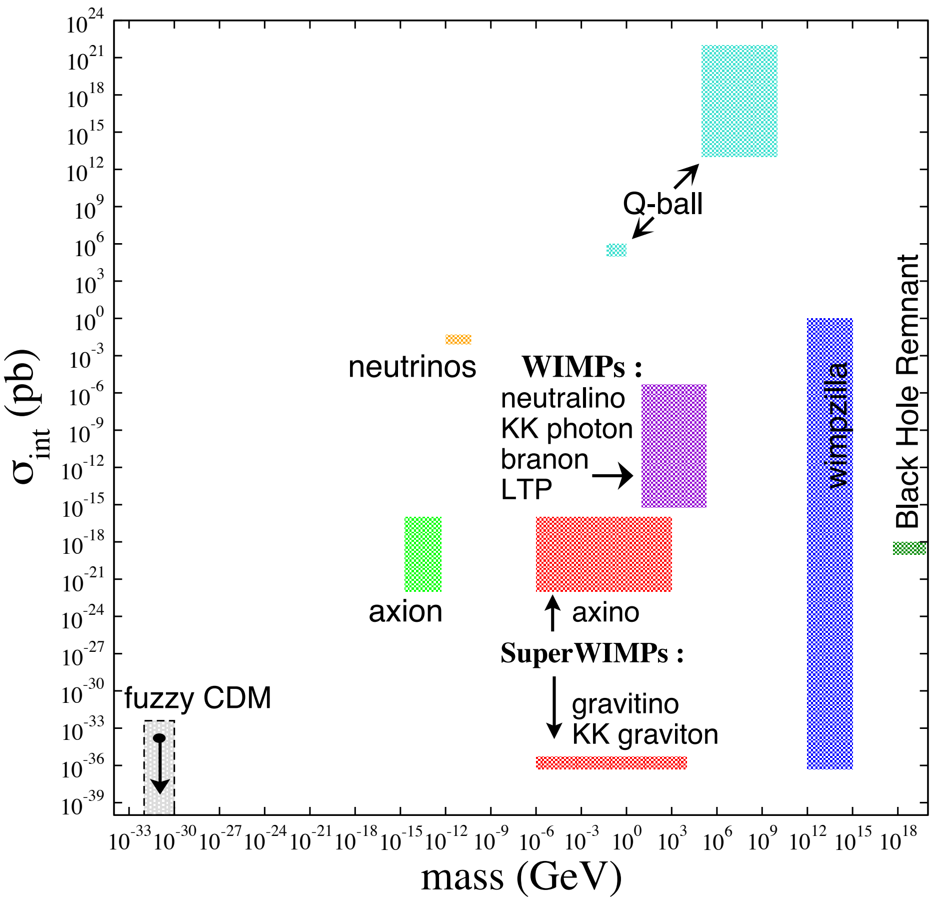
Inert doublet

Hidden sector
Fermion/vector/scalar

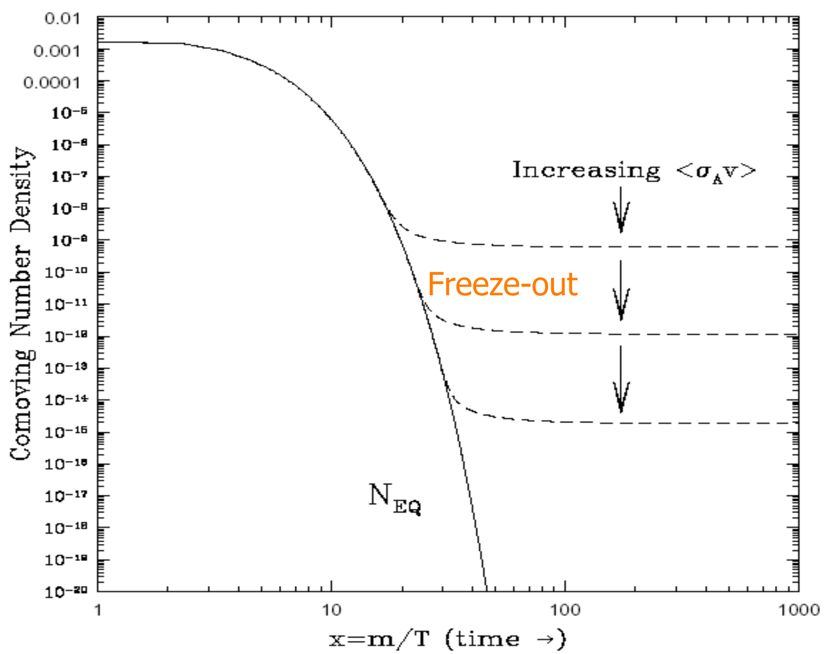
graviton KK

heavy photon

Some Dark Matter Candidate Particles



WIMP 'miracle'



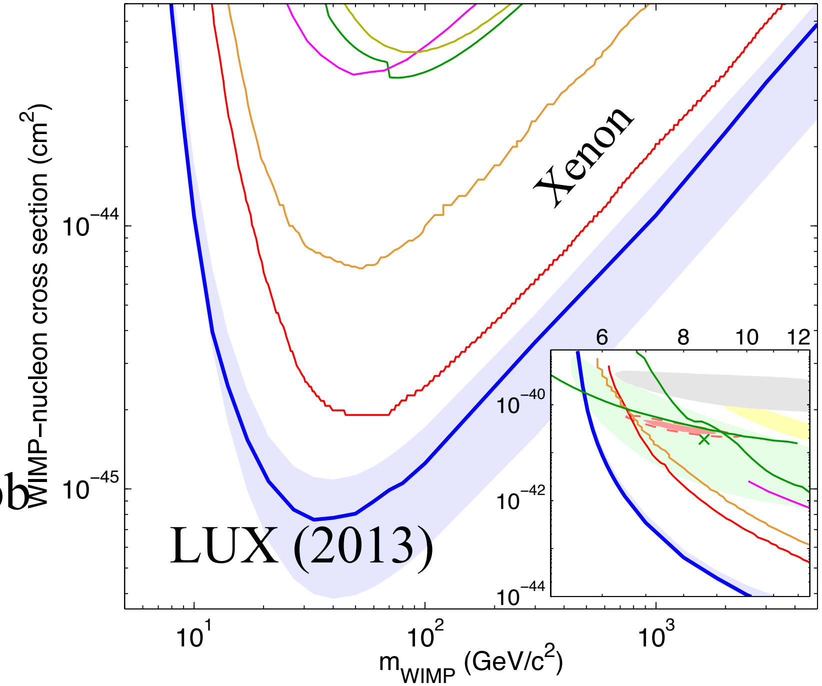
$$\frac{dn}{dt} = -3Hn - < \sigma v > \left[n^2 - n_{eq}^2\right]$$

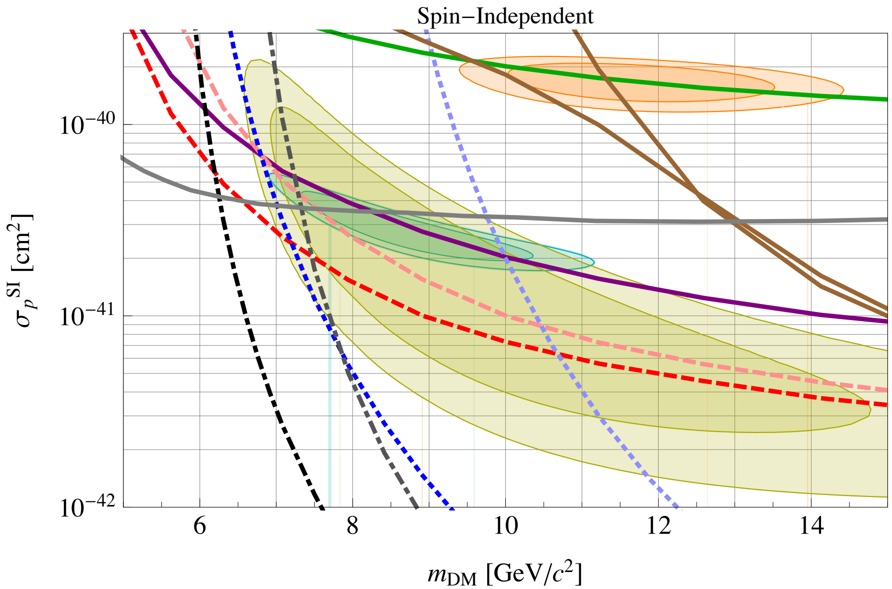
$$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle} \ .$$

- 'Typical' weak interaction cross section --> Ωh^2 ~0.1 (for any mass)
- Precise determination of Ωh^2=0.1199+/-0.0027 (PLANCK)

Direct detection

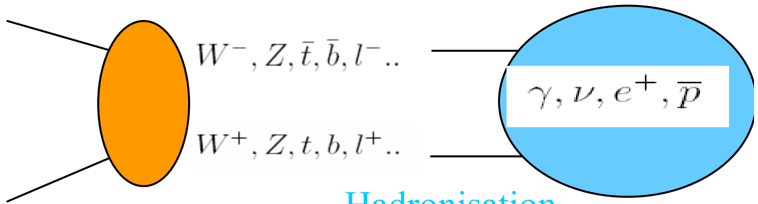
Elastic scattering of WIMPs off nucleons in a large detector





- Much improved limit on SI cross section - LUX
- Assuming $f_p=f_n$, rules out CDMS, CoGENT, DAMA..

Indirect detection



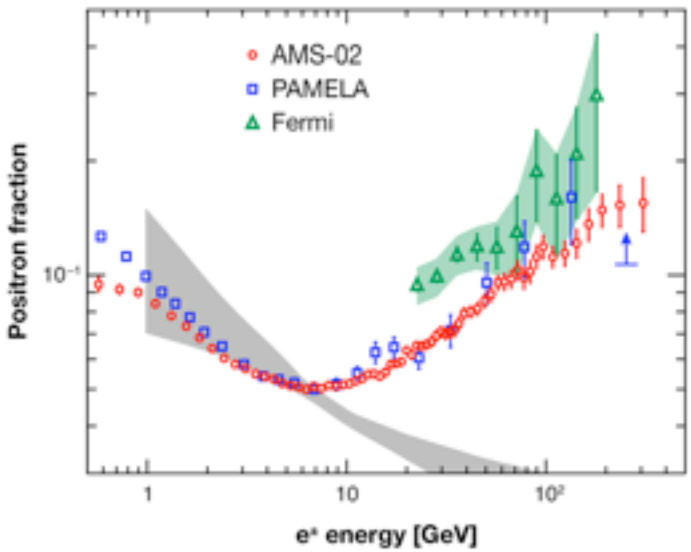
- Annihilation of pairs of DM particles into SM : decay products observed (after propagation)
- Search for DM in e^+, p, γ, ν
- Dependence on the DM distribution (ρ)

$$Q(x, \mathbf{E}) = \frac{< \sigma v >}{2} \left(\frac{\rho(\mathbf{x})}{m_\chi} \right)^2 \frac{dN}{dE}$$

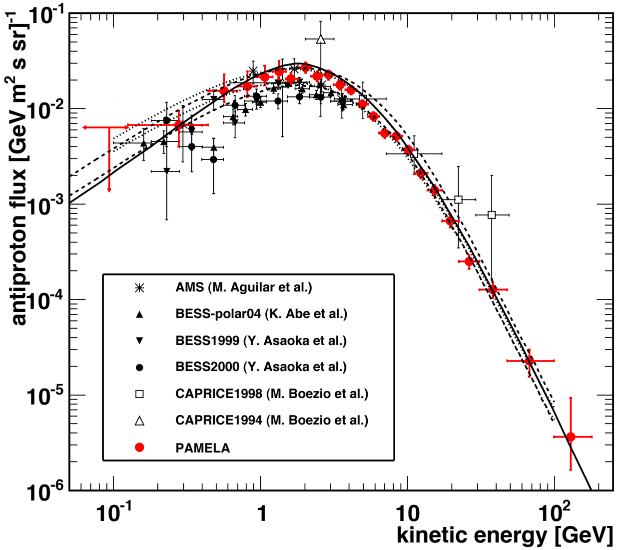
- Typical annihilation cross-section 3 10^{-26} cm^3/s
  - $\sigma v = a + bv^2$ --> σv(galaxy) can be much different σv (early universe)
  - if coannihilation dominates --> σv small

Indirect detection

Aguilar et al 2013

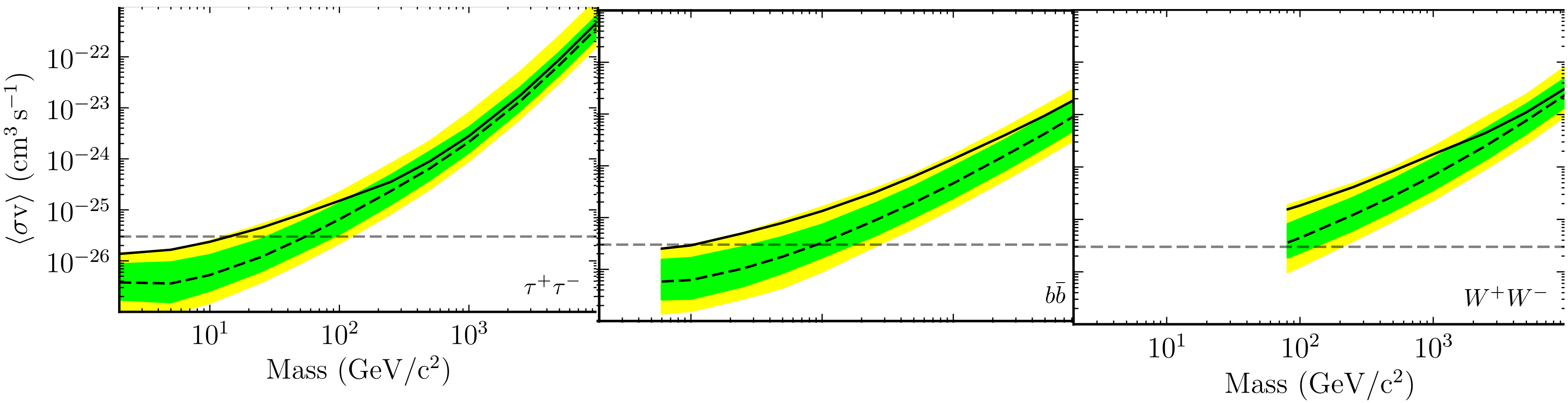


Adriani et al, 1007.0821



Anomaly in positron fraction but no deviation in antiprotons --> could be pulsar, leptophilic dark matter (with large boost factor)

- For light dark matter, FermiLAT probes cross sections expected of a thermal relic with photons from dwarf Spheroidal galaxies



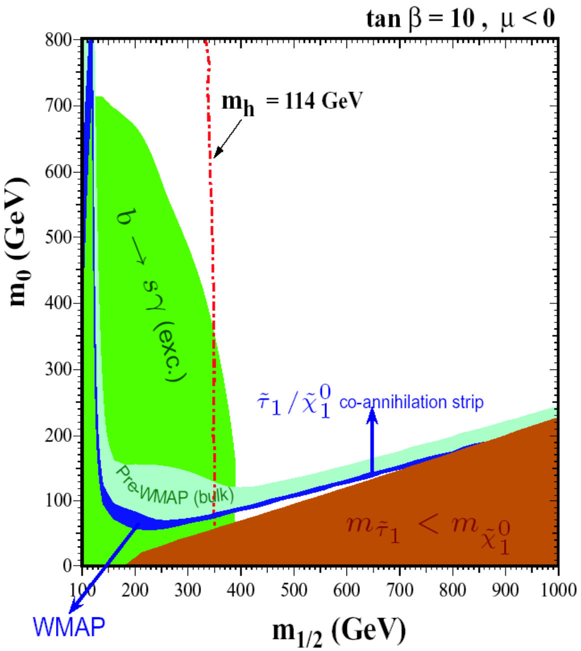
- Evidence of a gamma-ray line (from DM annihilation into two-photons) for m=130GeV weakening

Gauge hierarchy problem and dark matter

Supersymmetry as an example

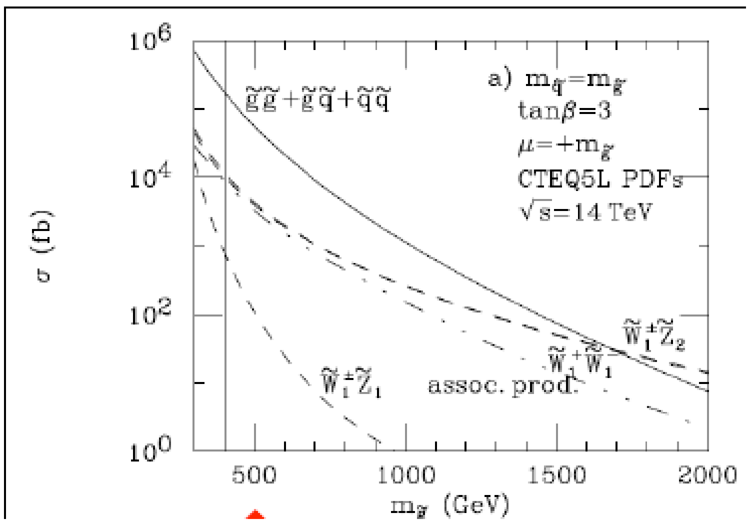
CMSSM neutralino

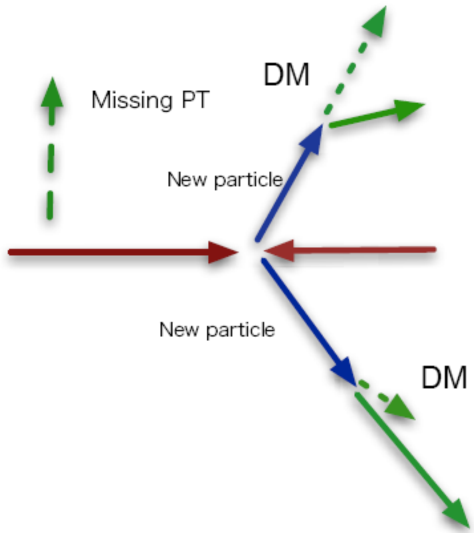
- In CMSSM (symmetry boson/fermion, unification of couplings at GUT scale, universality conditions, supergravity) with R-parity violation - get DM candidate 'for free'
- 4 parameters - relation between different sectors
- Over most of parameter space neutralino bino (-> too much DM)



LHC

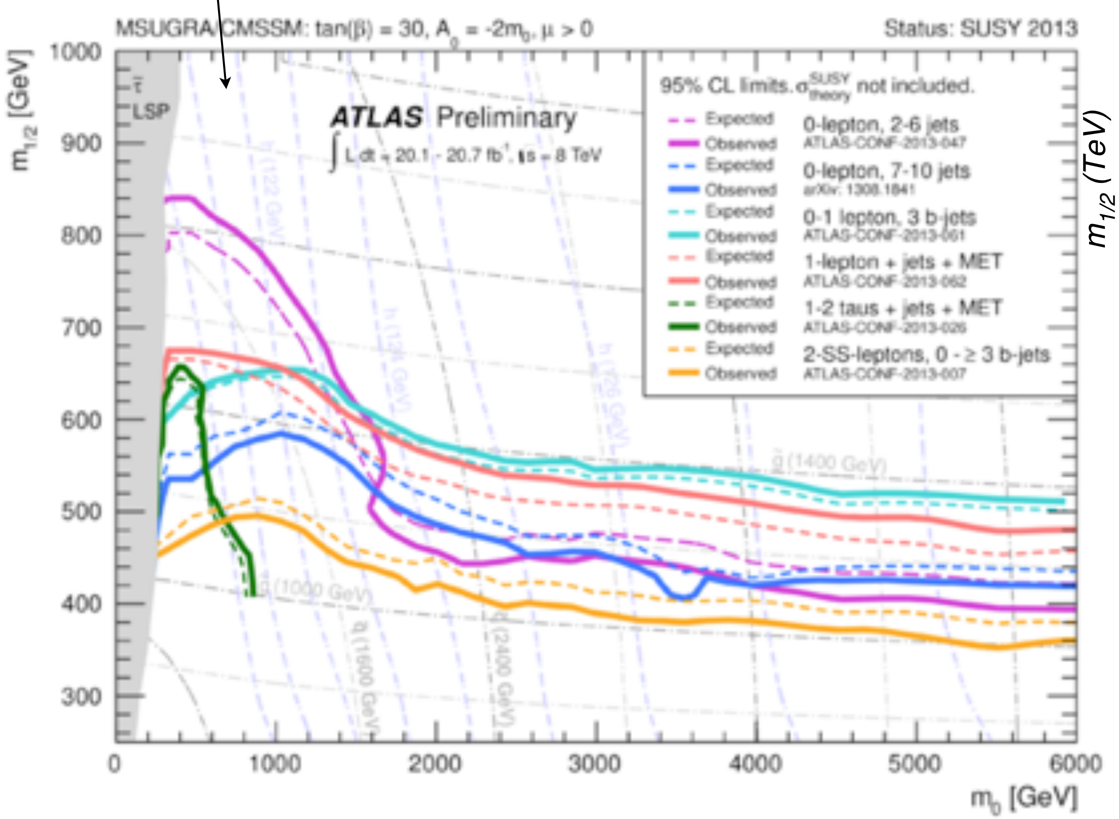
- pp collisions 7-14TeV
- Direct DM production missing energy no trigger
- Largest cross sections: coloured sparticles, DM in decays
- DM signature (missing E_T)

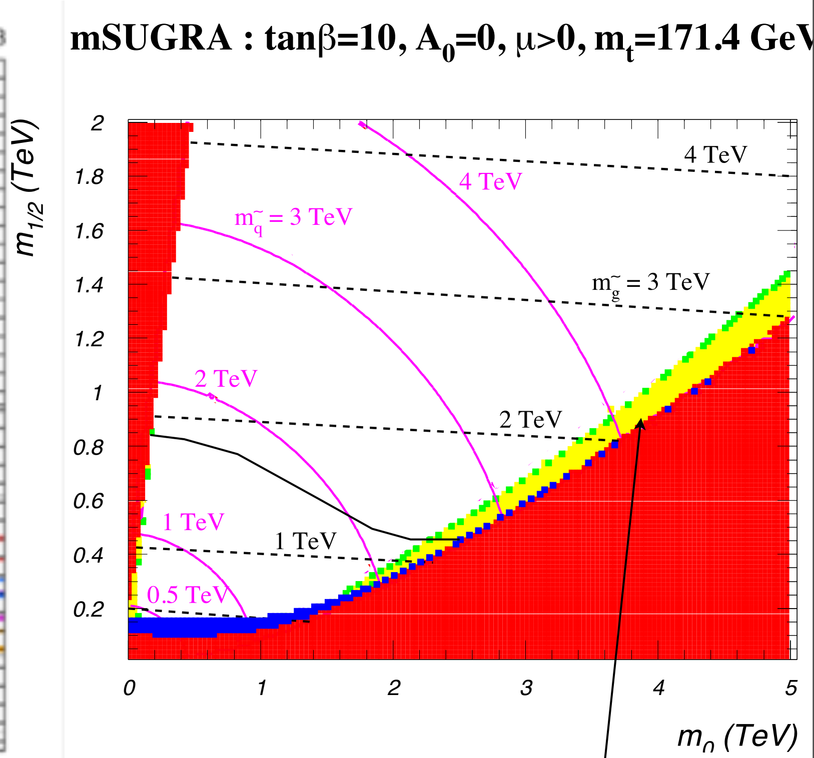




LHC limits on CMSSM

mh>122 GeV

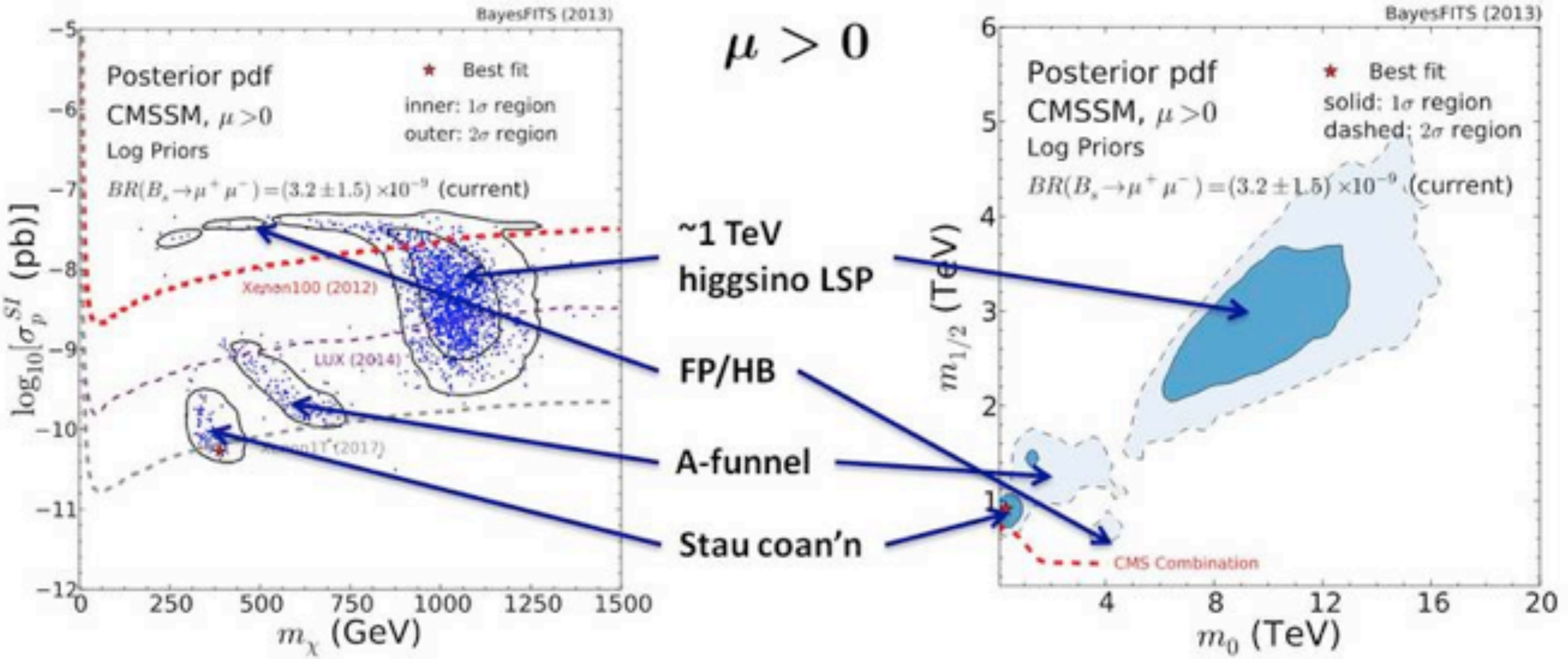




higgsino LSP

- gluino,squark > 1.4 TeV -> bino cannot be light --> higgsino DM or coannihilation or Higgs funnel

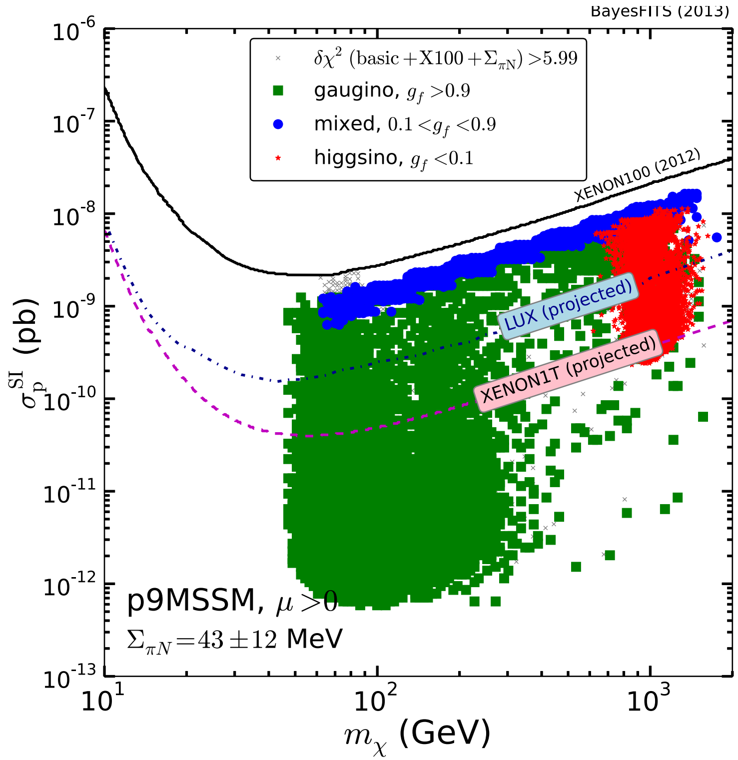
What's left



L. Roszkowski

Funnel : enhanced annihilation since $m_{LSP} \sim m_A/2$

- Near the end of neutralino DM era?
- Relic density suggests a more natural DM candidate is mixed bino/higgsino/wino (non-universality or pMSSM)
  - more efficient annihilation in W - but challenged by LUX
- Decouple squark/gluino from neutralino LSP



Fowlie et al, 1306.1567
include LHC searches

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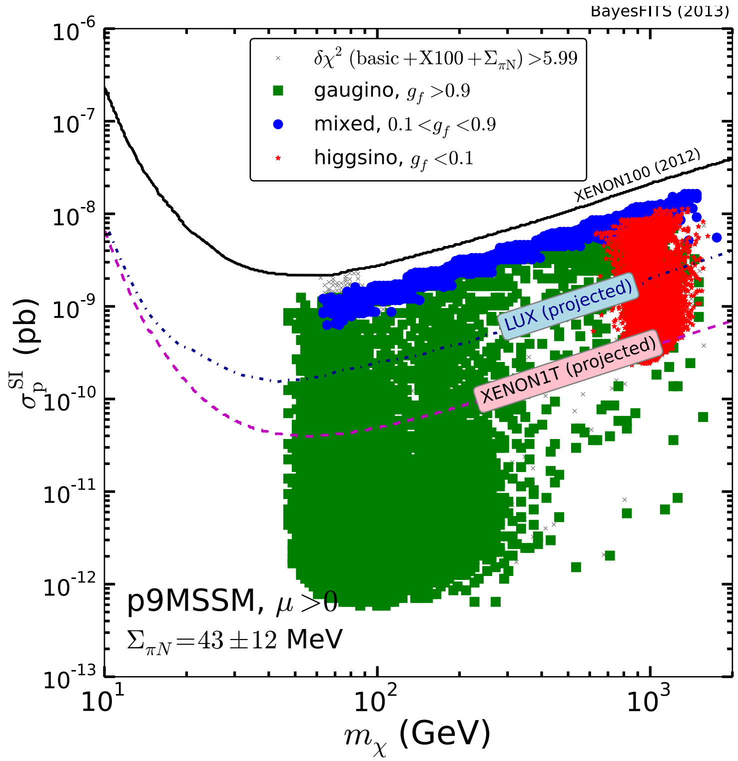
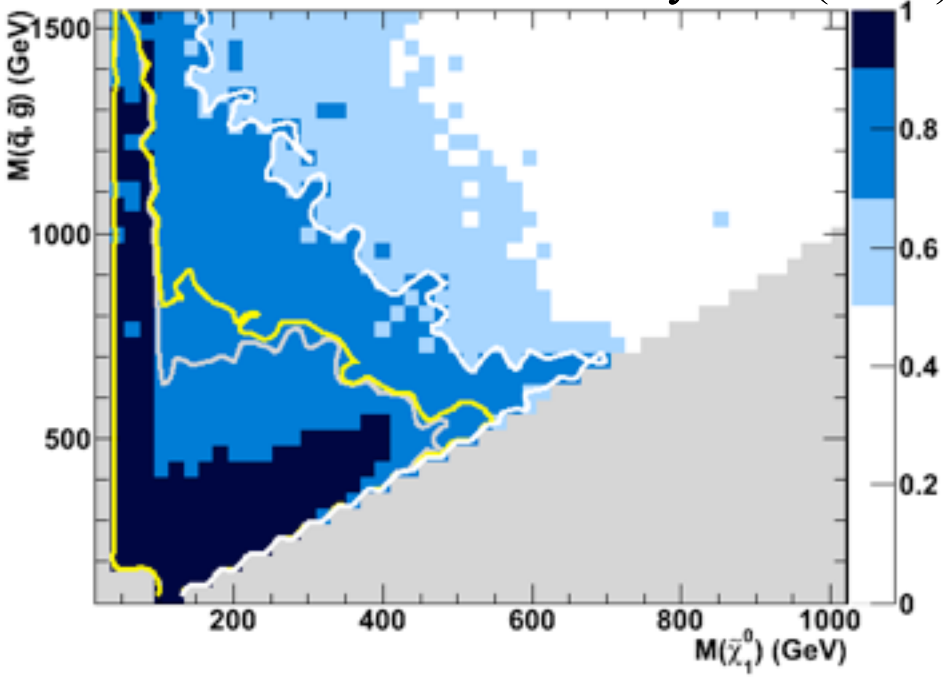


Fowlie et al, 1306.1567
include LHC searches

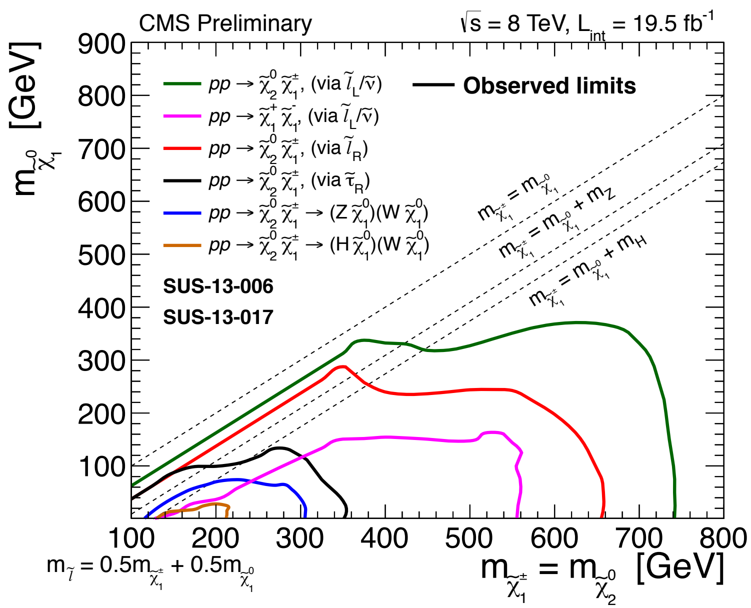
Arbey et al (2013)

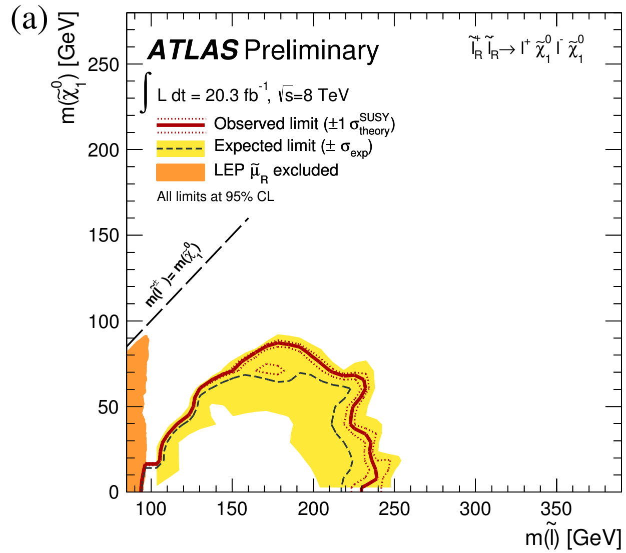


Exclusion jets/l/MET -LUX

Electroweak-inos

- Direct connection with neutralino DM
- Reach dependent on search channel (here simplified model approach)





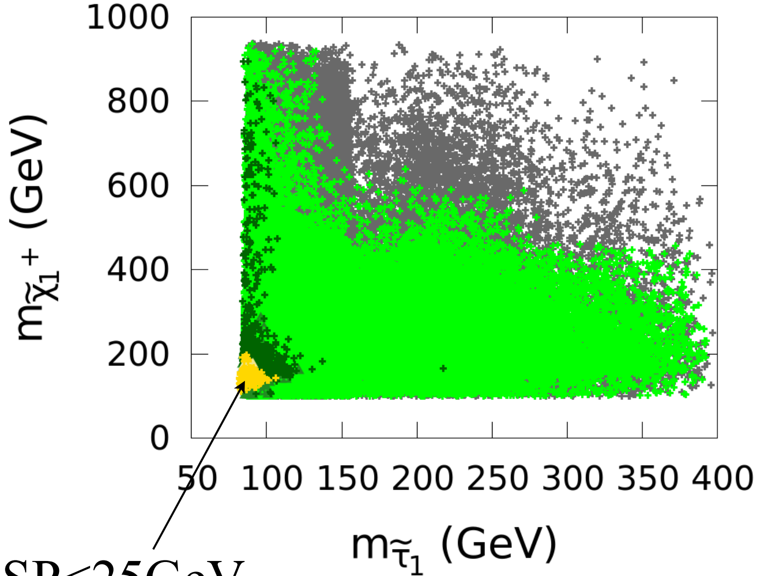
- Weak constraints on higgsino LSP (small mass splitting) and when dominant decay into gauge bosons
- At first sight neutralino ~100GeV is pretty severely constrained

MSSM with light neutralino

- Light neutralino (< 70 GeV) explored by many groups
  - Bottino,Fornengo,Scopel,Donato,Plehn,GB,Boudjema,Godbole,Roszkowski, R. de Austri, Cumberlach, Dreiner, Heinemeyer, Kittel, AlbornozVasquez, Boehm, Calibbi, Ota, Takanishi, Gunion, Belikov, Arbey, Battaglia, Mahmoudi, Dev, Mazumdar, Pukartas, Han, Liu, Natarajan....
- Motivated in part by direct detection hints
- Need large enough annihilation rate to satisfy PLANCK bound.
- Annihilation of LSP pairs:
  - $\chi\chi$->Z->ff
  - $\chi\chi$->h->XX or $\chi\chi$->A->bb (ruled out by searches for heavy Higgs at LHC + various astro constraints)
  - into fermion pairs through sfermion exchange (stau/selectron)
  - light sbottom (Arbey et al, 1308.2153)

After LHC limits

- $\tilde{\ell}_L^{\pm}\tilde{\ell}_L^{\mp} \to \ell^{\pm}\tilde{\chi}_1^0\ell^{\mp}\tilde{\chi}_1^0$; $\tilde{\ell}_R^{\pm}\tilde{\ell}_R^{\mp} \to \ell^{\pm}\tilde{\chi}_1^0\ell^{\mp}\tilde{\chi}_1^0$, ATLAS-CONF-2013-049,CMS-PAS-SUS-12-022
- $\tilde{\chi}_2^0\tilde{\chi}_1^{\pm} \to Z^{(*)}\tilde{\chi}_1^0 W^{(*)}\tilde{\chi}_1^0$, ATLAS-CONF-2013-035, CMS-PAS-SUS-12-022
- $\tilde{\chi}_2^0\tilde{\chi}_1^{\pm} \to \tilde{\ell}_R^{\pm}\nu\tilde{\ell}_R^{\pm}\ell^{\mp} \to \ell^{\pm}\tilde{\chi}_1^0\nu\ell^{\pm}\tilde{\chi}_1^0\ell^{\mp}$ CMS-PAS-SUS-12-022, $(l = e, \mu, \tau)$



LSP<25GeV

- Flavour + DM +Higgs constraints
- LHC constrains many models but light neutralino still possible

After LHC limits

- $\tilde{\ell}_L^{\pm}\tilde{\ell}_L^{\mp} \to \ell^{\pm}\tilde{\chi}_1^0\ell^{\mp}\tilde{\chi}_1^0$; $\tilde{\ell}_R^{\pm}\tilde{\ell}_R^{\mp} \to \ell^{\pm}\tilde{\chi}_1^0\ell^{\mp}\tilde{\chi}_1^0$, ATLAS-CONF-2013-049,CMS-PAS-SUS-12-022
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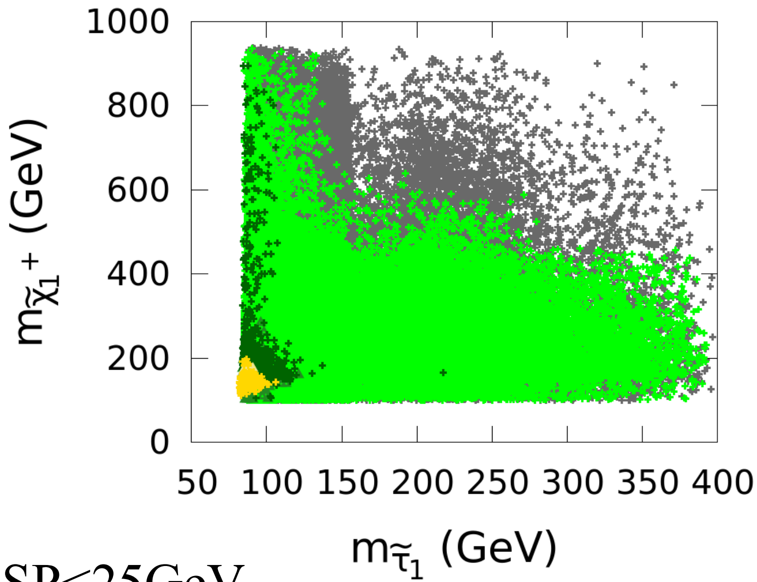
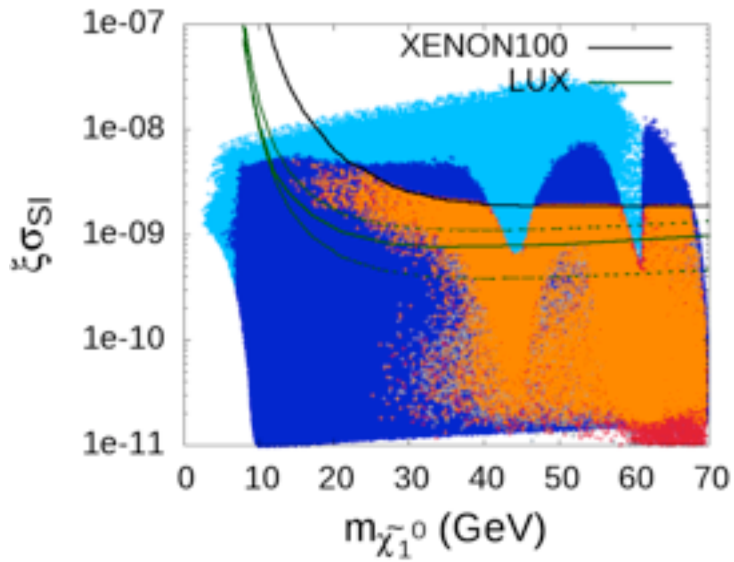




LSP<25GeV

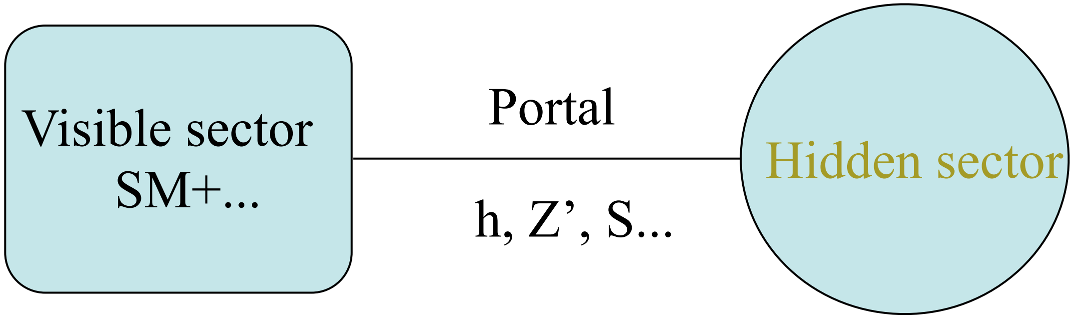
- Lightest neutralinos (<25 GeV) excluded by LUX

- Neutralino DM in MSSM alive and well even with several new particles below TeV scale although direct detection also constrain parameter space
- More possibilities for DM in MSSM extensions
- Other models motivated by hierarchy (UED, little Higgs) subject to same set of constraints
- mUED predicts compressed spectra : challenging for LHC

Scalar dark matter and portals

Higgs sector

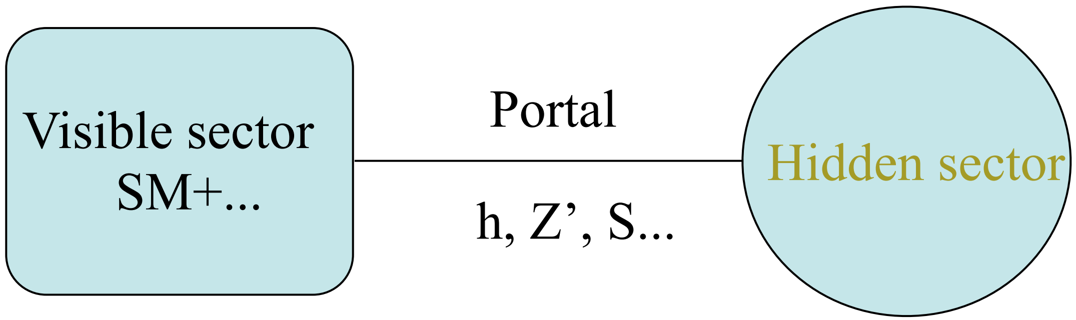
Portals



Higgs-field portal into hidden sectors
Patt, Wilczek 0605188

We present examples that are neither grotesque nor unnatural.

Portals



Higgs-field portal into hidden sectors
Patt, Wilczek 0605188

We present examples that are neither grotesque nor unnatural.

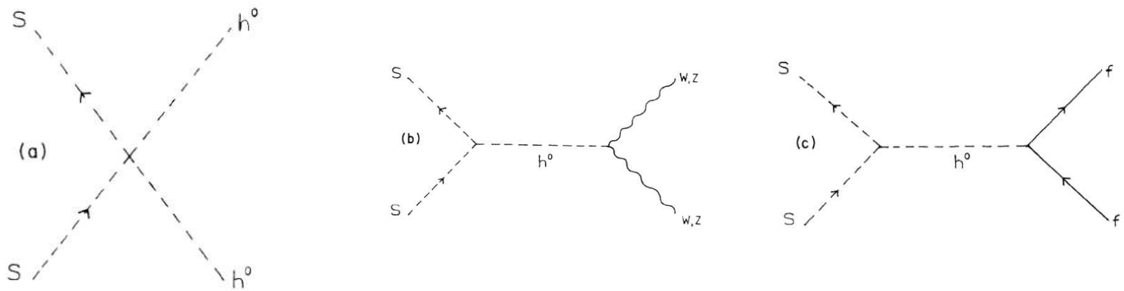
- DM and the Higgs portal
  - Bertolami,Rosenfeld, 0708.1794; March-Russell et al, 0801.3440; J. Mcdonald, Sahu, 0802.3847, 0905.1312; Tytgat, 0906.1100; Aoki et al, 0912.5536; Andreas et al, 1003.3295; Arina et al, 1004.3953; Cheug,Nomura (singlet)1008.5153; Djouadi et al, 1112.3299 ..
- DM and the Z' or A' portal
  - Krokilowski, 0712.0505; Chu et al, 1112.0493; Dudas et al, 0904.1745....

Minimal Extended scalar sector

- Minimal extension of SM - singlet scalar - stability guaranteed by some discrete symmetry
  - Silveira, Zee (1985); J. McDonald, PRD (1994) and hep-ph/0702143

$$L_S = \partial^\mu S_i^\dagger \partial_\mu S_i - m^2 S_i^\dagger S_i - \lambda_S S_i^\dagger S_i H^\dagger H$$

- Adjust λ_S to achieve correct relic density - fix direct detection rate



Extended scalar sector

- Extended scalar sector generic in extensions of the SM
  - not LHC-friendly - no new coloured particles - can only probe Higgs sector
- Models with extended scalar sector much studied from the Higgs point of view (e.g. two-Higgs-doublet model- compatible with all Higgs data)
- To also provide a DM candidate - impose discrete symmetry to guarantee the stability of the lightest neutral particle from the 'dark' sector.
- Usually a Z_2 symmetry (R-parity in SUSY, KK-parity...)
- Can also consider larger symmetries like Z_3, Z_4, new phenomena : semi-annihilation, interactions between two DM candidates.

‘Inert’ models

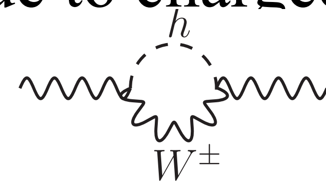
- Two-Higgs doublet model with Z_2 symmetry
  - Deshpande, Ma, PRD18(1978) 2574; Barbieri, Hall, Rychkov, PRD74 (2006) 015007
  - Although suggested as alternative to light Higgs model (natural to have mh >>100 GeV) compatible with light Higgs and provide alternative to neutralino dark matter
  - Lopez Honorez, Nezri,Oliver, Tytgat, JCAP 0702(2007) 028; Arina et al (2009); Lopez Honorez ,Yaguna (2011); Goudelis et al (2013)
- SM + doublet
  - odd under Z_2 --> H or A stable
  - no coupling of H_2 to fermions

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2^2| + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + \mathrm{h.c.}\right] ,$$

- SM + doublet + singlet ...

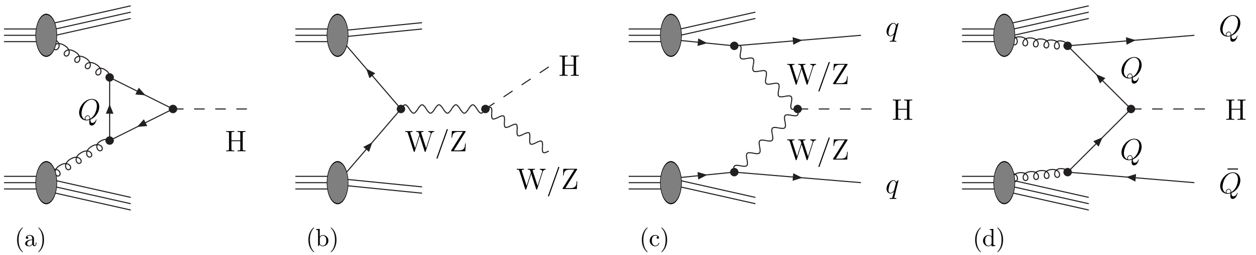
Constraints

- Theoretical : vacuum stability, perturbativity, globality of vacuum, unitarity
- Electroweak precision tests (corrections due to charged Higgs and/or doublet/singlet mixing)
  - S = 0.05+/-0.10 T=0.08+/- 0.07

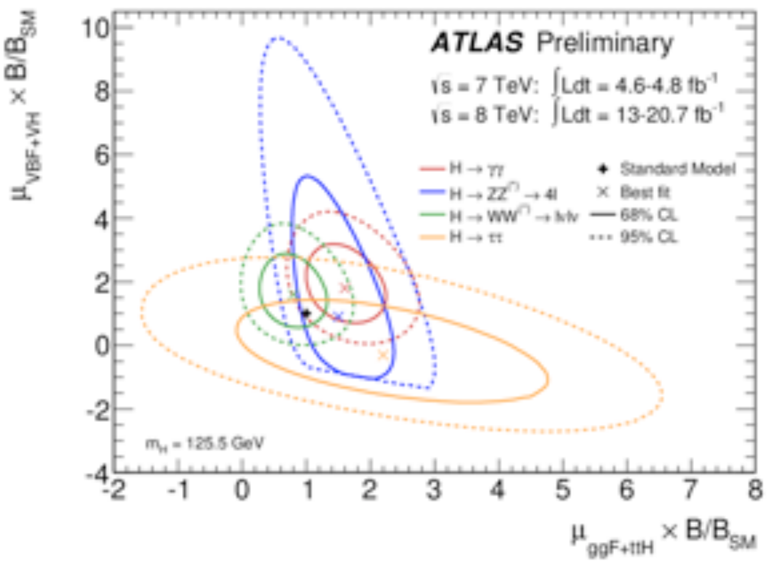


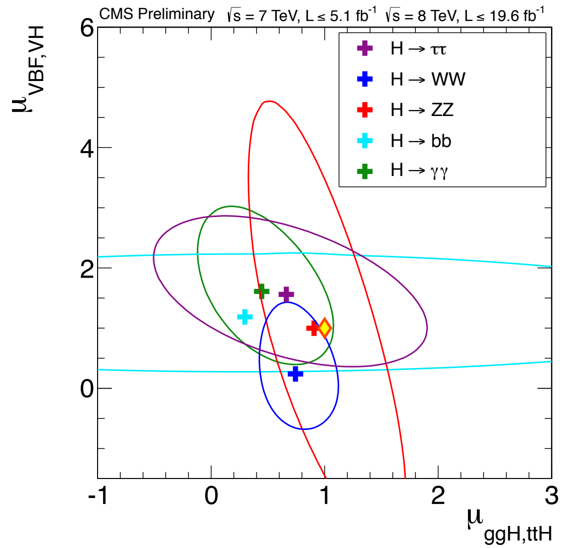
- LEP limits (Z invisible < 3MeV)
- LHC Higgs couplings + invisible width

Higgs at LHC



- two independent production modes VBF+VH, ggF+ttH and four independent final states: γγ,VV, bb,ττ
- Consistent with SM but also room for non-standard contributions



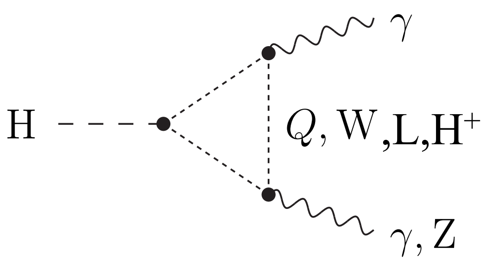


Generic Higgs couplings

- Scaling SM tree-level couplings

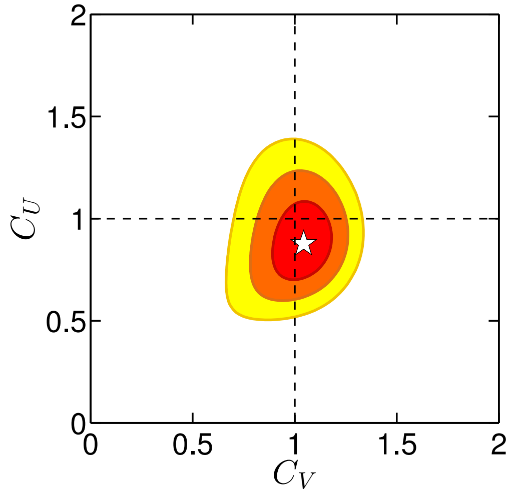
$$\mathcal{L} = g\left[C_V\left(m_W W_\mu W^\mu + \frac{m_Z}{\cos\theta_W} Z_\mu Z^\mu\right) - C_U \frac{m_t}{2m_W}\bar{t}t - C_D \frac{m_b}{2m_W}\bar{b}b - C_D \frac{m_\tau}{2m_W}\bar{\tau}\tau\right] H$$

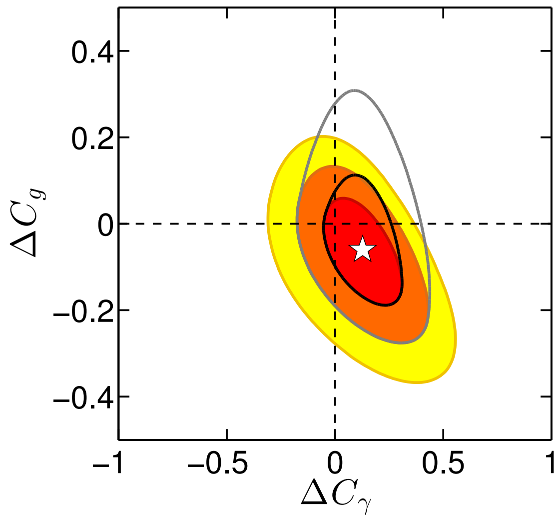
- Loop-induced couplings: hgg, hγγ
  - modified if tree-level couplings are modified
  - contributions from new particles
  - 6 free parameters $C_U, C_D, C_V, \Delta C_g, \Delta C_\gamma$ + Br(inv)



Global fits to ATLAS/CMS

GB,Dumont, Ellwanger, Gunion, Kraml
1306.2941



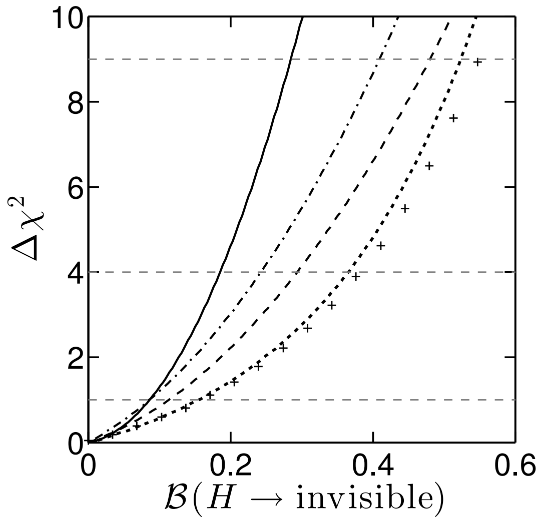


No new loop contributions
No invisible decays

Standard tree-level couplings
No invisible decays

- Compatible with SM and largish new physics contributions

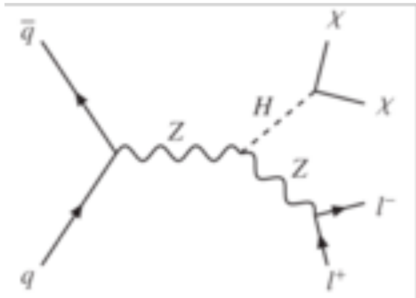
How much invisible Higgs?

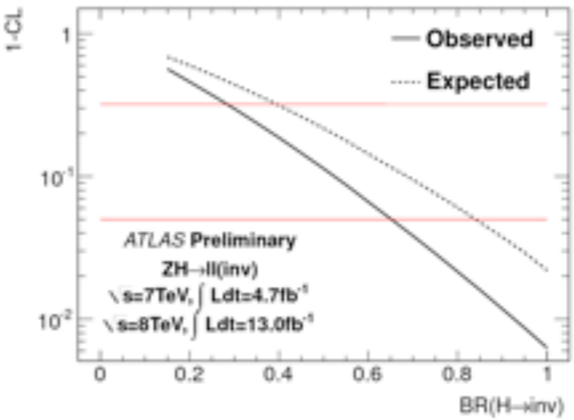


GB et al, 1306.2941

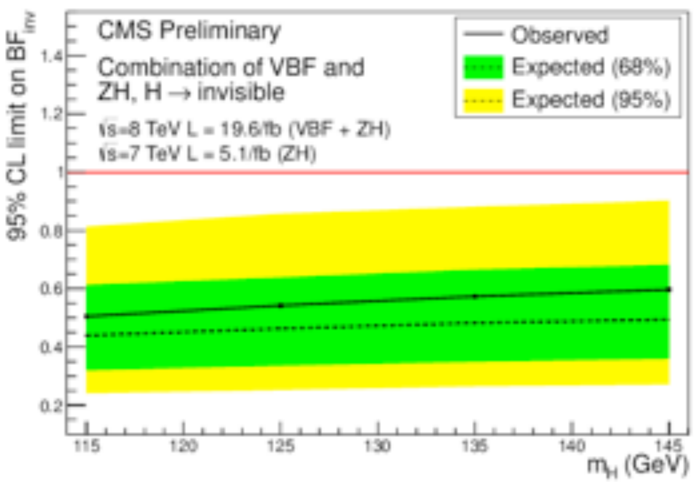
- Best fit at 0 - the 95%CL allows B_{inv} up to 19% (only SM + invisible) or 38% (C_U,C_D,C_V,ΔC_g,ΔC_γ)
- *There is still plenty of room for non standard Higgs decays (invisible +others)*

Direct search for invisible Higgs





ATLAS CONF-2013-011

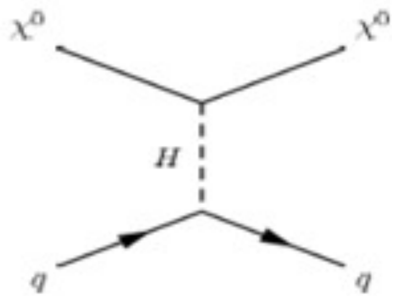


CMS-HIG-13-013

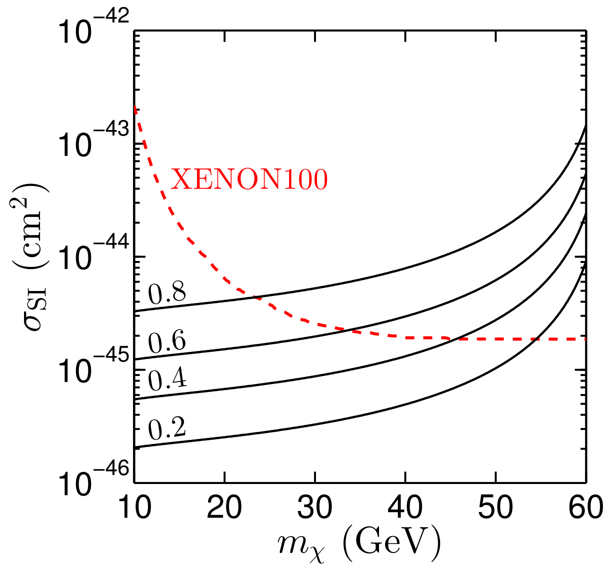
Combination of VBF and VH
CMS 95%CL limit : Brinv < 0.54

- What are the implications for dark matter?
- Both the invisible width and SI cross section (direct detection) depend on h coupling to DM
- Constraints on Higgs portal models

Djouadi et al, arXiv:1112.3299



Fermion DM



$$\sigma_{\rm SI} = \eta \mu_r^2 m_p^2 \frac{g^2}{M_W^2} \Gamma_{\rm inv} \left[C_U(f_u^N + f_c^N + f_t^N) + C_D(f_d^N + f_s^N + f_b^N) + \frac{\Delta C_g}{\widehat{C}_g} f_g^N \right]^2$$

- # What are the implications for dark matter?
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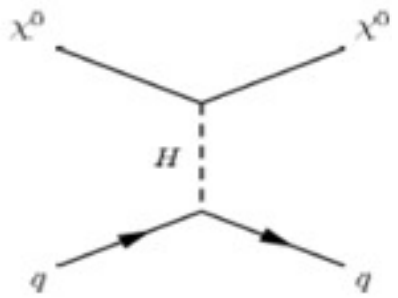
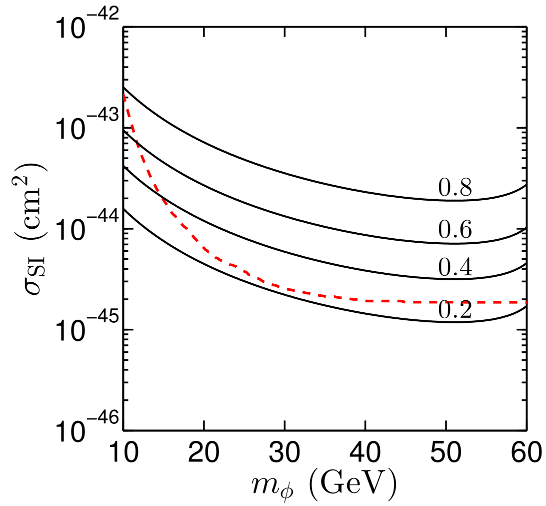


Scalar DM



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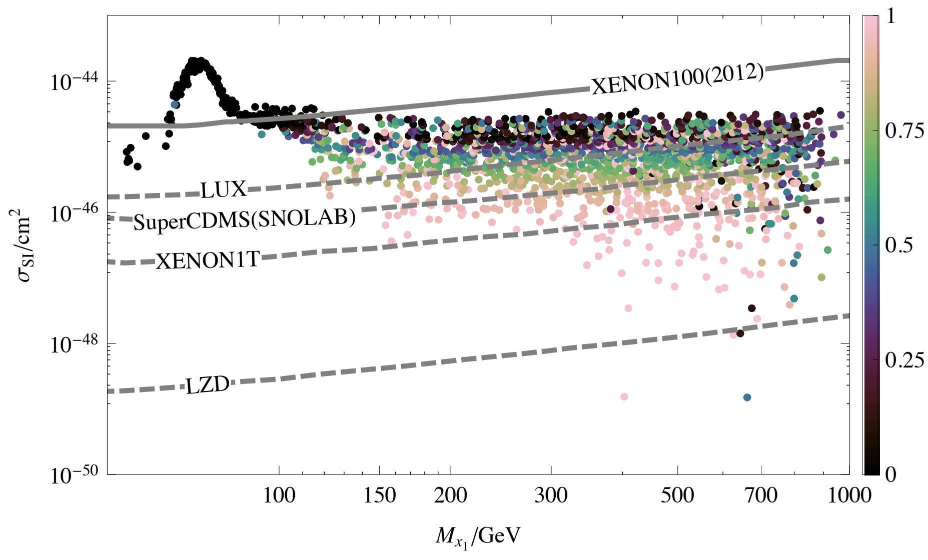
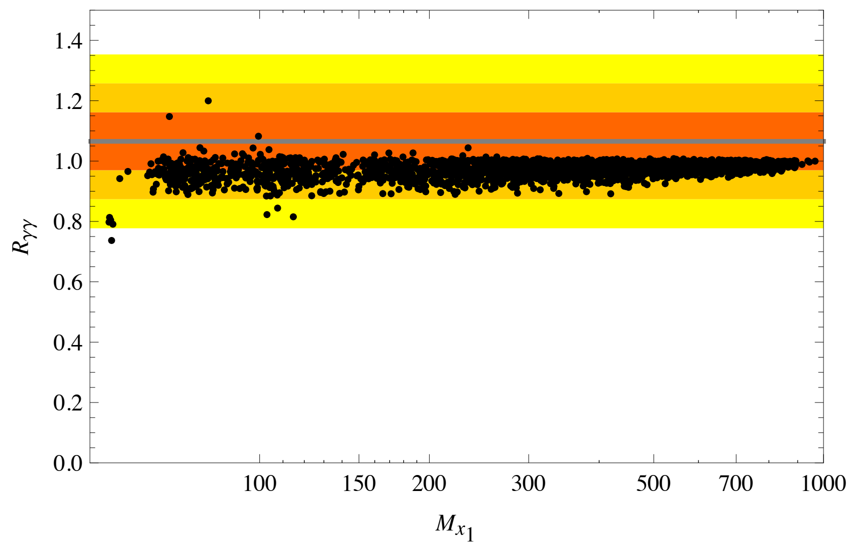
SM+doublet+ singlet

- Z_3 symmetry
- Light DM constrained by invisible Higgs AND direct detection
- Small modifications of Higgs couplings



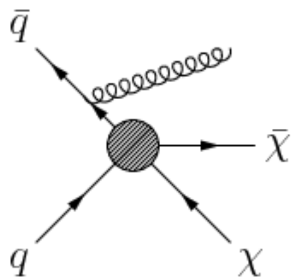


– GB, Kannike, Pukhov, Raidal, (1202.2962, 1211.1014)

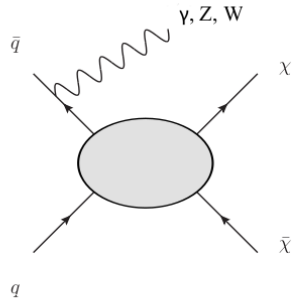
Model-independent

Model independent approach

- Direct production of pairs of DM + radiation : high E_T miss + single jet/photon/boson



(a) $q\bar{q} \to \chi\chi + g$

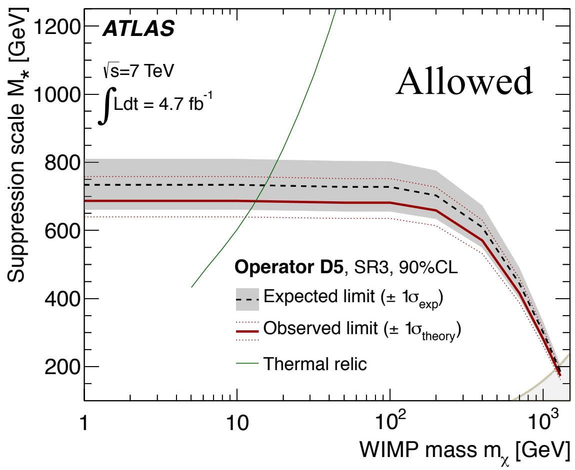


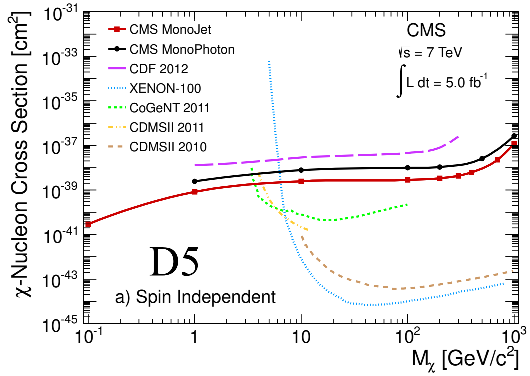
(b) $q\bar{q} \to \chi\chi + \gamma, Z, W$

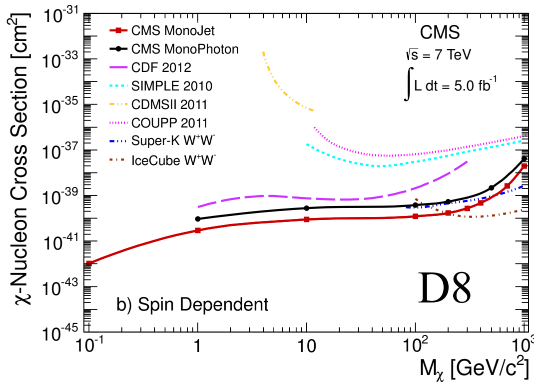
Effective interaction operators

Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^\mu q$
D9	qq	tensor	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s(G_{\mu\nu}^s)^2$

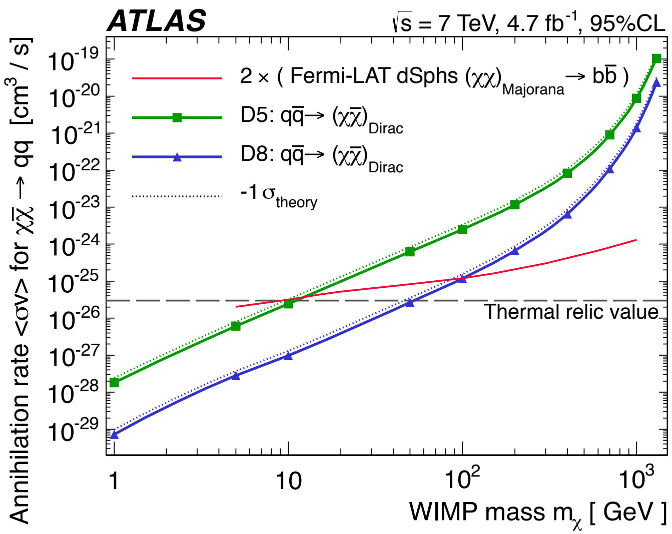
- For each operator : monojet limit --> limit on direct detection
- Caveats : monojet limit valid assuming scale NP large
  - LHC not very sensitive to scalar operators with couplings proportional to mass



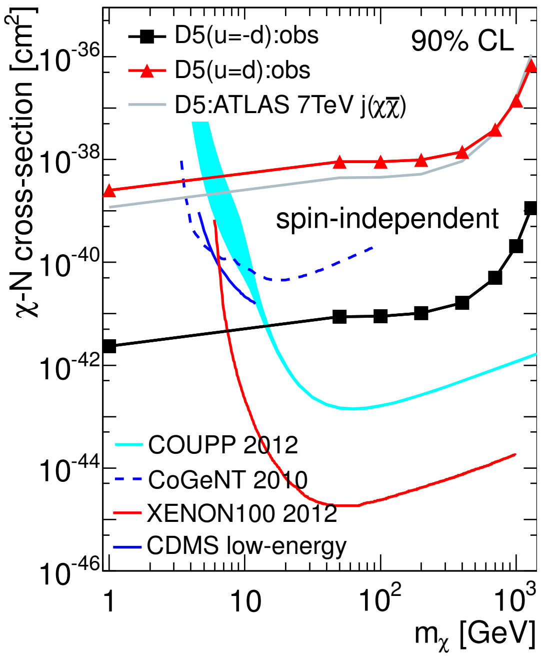


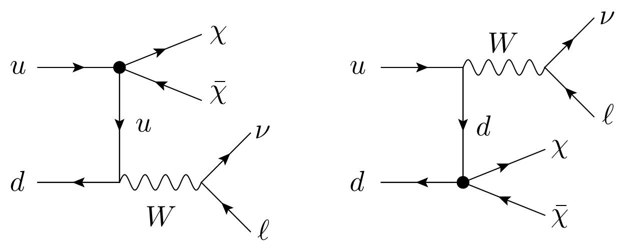


- Assuming DM annihilation into qq with only one effective operator monojet --> limit on indirect detection
- For light DM mass : more sensitive than FermiLAT



- mono Z/W --> single lepton, somewhat less sensitive than monojet
- mono Z/W --> quarks --> constructive interference for opposite sign u and d operator



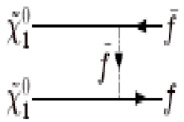


Bai,Tait,1208.4361

CONCLUSION

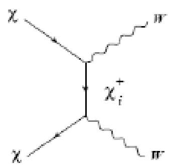
- Variety of well-motivated DM models - even if only consider wimps
- LHC started to probe these models both through the Higgs and searches for new particles
- A signal at collider/direct/indirect -- would lead to interesting cross checks
- DM might live in hidden sector - could be hard to find at LHC

Recall : the neutralino in the MSSM



- Bino: annihilates into fermions – sfermions must be light

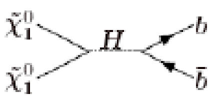
$$\sigma v \propto m_{\tilde{\chi}}^2 / m_{\tilde{l}}^4$$



- Mixed B/Higgs-ino : efficient into WW

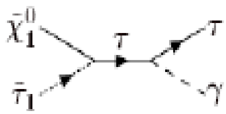
$$\sigma v \propto 1/m_{\tilde{\chi}}^2$$

- Mixed W/B/H-ino



- All (not pure bino): annihilation Higgs resonance

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



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