LHC and Dark Matter – A Theorist's Perspective

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Outline

- Introduction
- Why LHC
- Supersymmetric dark matter
- Impact of LHC ~5/fb results
- Prospects for DM direct detection search
- Impact of FermiLAT dSphs data
- Prospects for DeepCore
- Summary

Based on:

- Fowlie, et al, (arXiv:1206.0264)
- Fowlie, Kalinowski, Kazana, Roszkowski, Tsai (arXiv:1111.6098)
- Roszkowski, Sessolo, Tsai (arXiv:1202.1503)

Dark matter and the LHC

In elucidating the nature of dark matter, the role of the LHC will not be just helpful, or complimentary.

It will be absolutely essential!

Let's assume that DM signal is eventually measured in underground searches (direct detection)...

What shall we learn from this?

- WIMP elastic scat. cross section

...within an order of magnitude, or so

- WIMP mass

...within a factor of two, or so
signal in more than one detector with different targets will help a lot
(Drees+Shan, Green, 2008,...)

$\Rightarrow$ The nature of DM WIMP would remain a mystery

...need info from colliders

What is the DM?

- non–baryonic
- cold (CDM)

  or possibly (?) warmish
- no electric nor (preferably) color interactions
- relic from the Big Bang
- element of some sensible particle theory

plausible choice $\Rightarrow$ WIMP

(weakly interacting massive particle)

...a very broad class, not a single candidate

...How weak can weak be?

WIMP: most likely an unknown particle

Some WIMP candidates for Cold DM

No shortage of ideas... ...but few good ones, ...and even fewer longer-lasting

- lightest neutralino χ of supersymmetry
- lightest Kałuża-Klein (KK) state from warped/universal extra dimensions
- massive (almost) sterile neutrino ν_R or sneutrino $\tilde{\nu}_R$
- axion a
- axino $\tilde{a}$, gravitino $\tilde{G}$

extremely-weakly interacting relics

not necessarily stable

- add your own...

several other interesting candidates: well-tempered neutralino, multiple DM, little Higgs DM, mirror DM, shadow DM, sequestered DM, secluded DM, flaxino DM, Higgs portal DM, inflation and DM, modulus DM, asymmetric DM, inelastic DM, etc etc. – no nonsense but not superior either

Strategies for WIMP Detection

- direct detection (DD): measure WIMPs scattering off a target

  go underground to beat cosmic ray bgnd

- indirect detection (ID):
  - HE neutrinos from the Sun (or Earth)

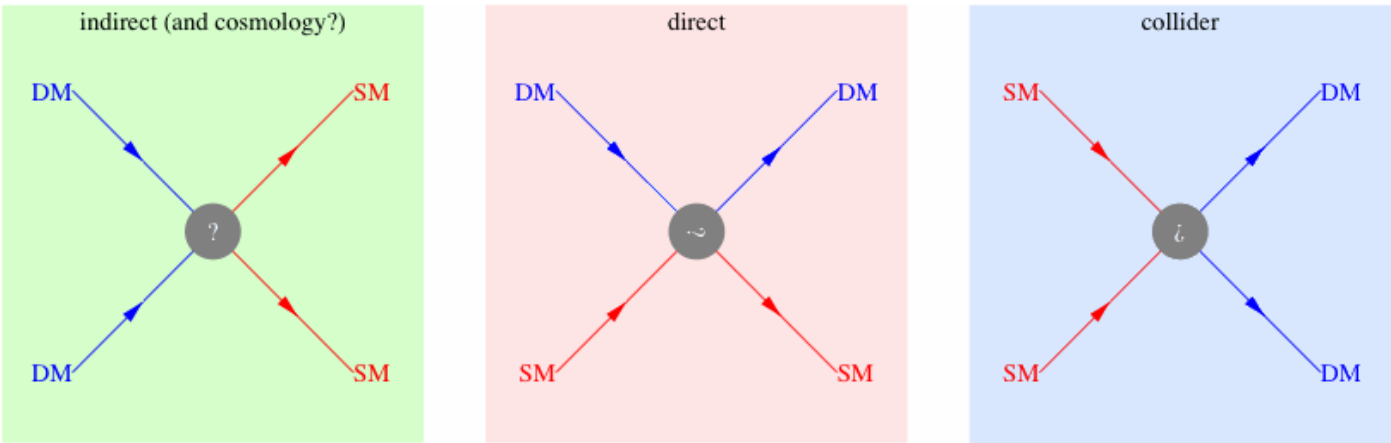
    WIMPs get trapped in Sun's core, start pair annihilating, only ν's escape
  - antimatter (e^+, $\bar{p}$, $\bar{D}$) from WIMP pair-annihilation in the MW halo

    from within a few kpc
  - gamma rays from WIMP pair-annihilation in the Galactic center

    depending on DM distribution in the GC
  - other ideas: traces of WIMP annihilation in dwarf galaxies, in rich clusters, etc

    more speculative
- the LHC

Indirect, direct, collider



(figure from Strumia)

but... usually NO crossing symmetry to help

reason: in each case different diagrams dominate

- DD: XENON, CDMS, CoGeNT, ...
- ID: Fermi, Pamela, ACT, ...
- colliders: LHC

Dark matter at colliders

- direct WIMP production $pp \to \chi\chi +$ hadronic debris: undetectable

only missing energy, nothing to tag on

- DM WIMP is expected to be part of “new physics” at/above EW scale

like neutralino and SUSY

- LHC will probe “new physics” up to a few TeV
- one will need to measure several processes, perform detailed spectroscopy,...

likely to be a very long process

Hide and seek with SUSY

SUSY can (potentially) contribute to various measurable quantities

- signals of supersymmetric and Higgs particles

  direct collider searches: still only lower bounds on masses

- indirect (e.g. loop) contributions
  - electroweak observables: $\sin\theta_W$, m_Z, Γ_Z, ...
  - flavor processes: $b \to s\gamma$, $\mathrm{BR}(\bar{B}_s \to \mu^+\mu^-)$, $\mathrm{BR}(\overline{B}_u \to \tau\nu)$, ...
  - anomalous magnetic moment of the muon $(g-2)_\mu$
  - ...
- neutralino WIMP as dark matter to give correct relic abundance $\Omega_\chi h^2$

Constrained Minimal Supersymmetric Standard Model (CMSSM)

G. L. Kane, C. F. Kolda, L. Roszkowski and J. D. Wells, Phys. Rev. D 49 (1994) 6173

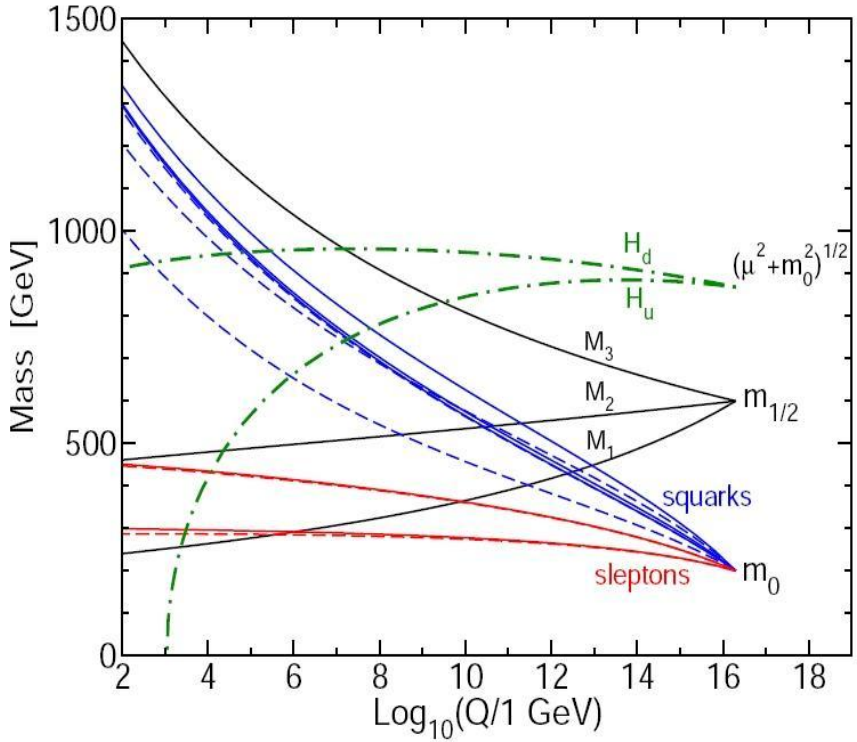


figure from hep-ph/9709356

At $M_{\rm GUT} \simeq 2 \times 10^{16}$ GeV:

- gauginos $M_1 = M_2 = m_{\tilde{g}} = m_{1/2}$
- scalars
  $m^2_{\tilde{q}_i} = m^2_{\tilde{l}_i} = m^2_{H_b} = m^2_{H_t} = m_0^2$
- 3–linear soft terms $A_b = A_t = A_0$
- radiative EWSB
  $\mu^2 = \frac{m^2_{H_b} - m^2_{H_t} \tan^2\beta}{\tan^2\beta - 1} - \frac{m_Z^2}{2}$
- five independent parameters:
  $\boxed{m_{1/2},\ m_0,\ A_0,\ \tan\beta,\ \mathrm{sgn}(\mu)}$
- well developed machinery to compute masses and couplings

Hide and seek with SUSY

Measurement	Mean or Range	Exp. Error	Th. Error	Likelihood Distribution	Ref.
CMS razor 4.4/fb analysis	See text	See text	0	Poisson	[2]
SM-like Higgs mass m_h	117.5 – 118.5 and 122.5-129	0	2	Lower/Upper limit – Error Fn	[9]
	114.4 – 127.5	0	2	Lower/Upper limit – Error Fn	[8]
	> 114.4	0	2	Lower limit – Error Fn	[34]
ζ_h^2	$< f(m_h)$	0	0	Upper limit – Step Fn	[34]
$\Omega_\chi h^2$	0.1120	0.0056	10%	Gaussian	[35]
$\sin\theta_{\rm eff}$	0.23116	0.00013	0.00015	Gaussian	[36]
m_W	80.399	0.023	0.015	Gaussian	[36]
$\delta(g-2)_\mu^{\rm SUSY} \times 10^{10}$	30.5	8.6	1.0	Gaussian	[36, 37]
$\mathrm{BR}(\overline{\mathrm{B}} \to \mathrm{X_s}\gamma) \times 10^4$	3.60	0.23	0.21	Gaussian	[36]
$\mathrm{BR}(\mathrm{B_u} \to \tau\nu) \times 10^4$	1.66	0.66	0.38	Gaussian	[38]
ΔM_{B_s}	17.77	0.12	2.40	Gaussian	[36]
$\mathrm{BR}(\mathrm{B_s} \to \mu^+\mu^-)$	$< 4.5 \times 10^{-9}$	0	14%	Upper limit – Error Fn	[19]

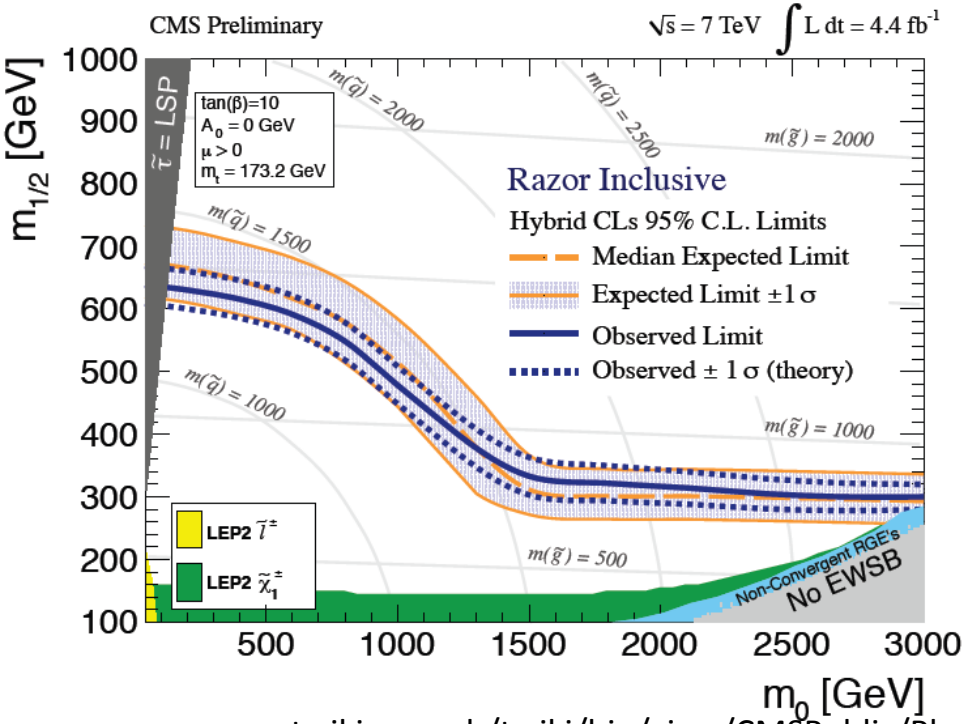
New!

New!

Table III: The experimental measurements that we apply to constrain the CMSSM's and the NUHM's parameters. Masses are in GeV.

LHC: most important constraints:

- **Direct limits**



twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

- **The Higgs:**

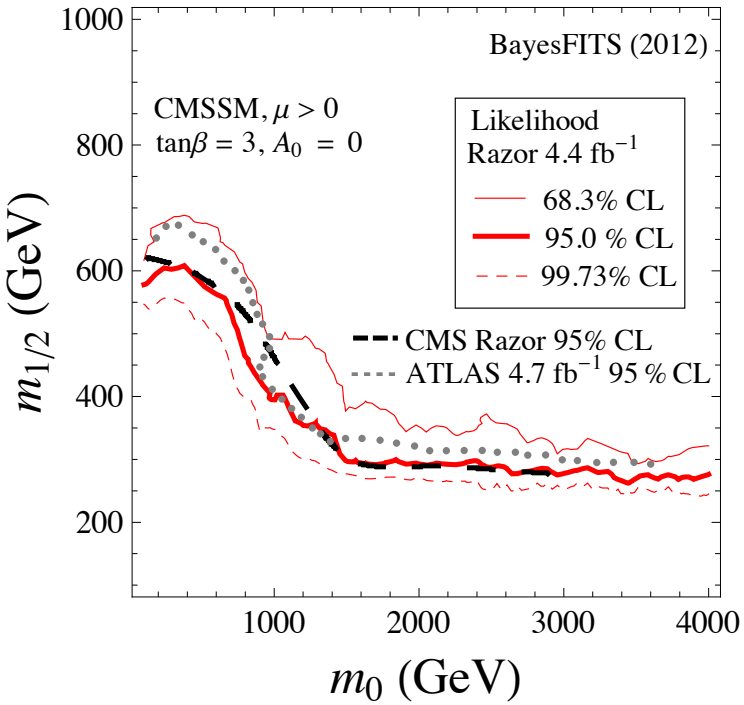
1. Improved ATLAS and CMS limits on the SM-like Higgs boson mass:

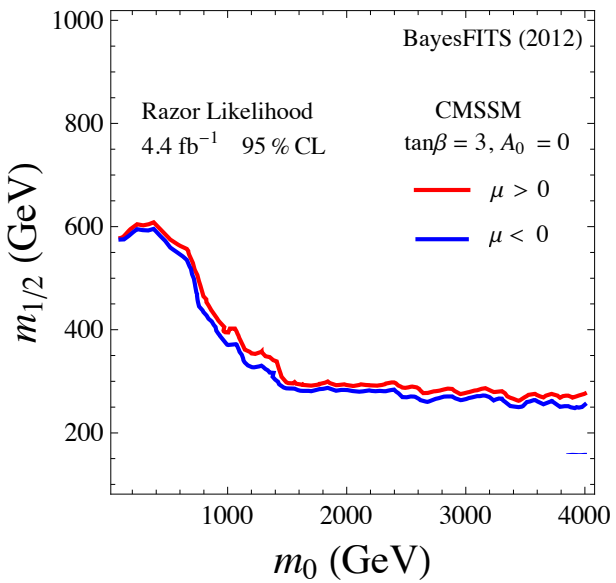
   95% CLs Higgs masses outside the intervals: (117:5; 118:5) GeV or (122:5; 129) GeV (ATLAS) and (114:4; 127:5) GeV (CMS)

2. A possible Higgs signal at 125 GeV

- **BR(B_s -> mu mu) < 4.5 x 10^-9 (LHCb)**

Reproducing the razor likelihood





Works for both signs of mu

Excellent agreement

Implementing the Higgs Constraints

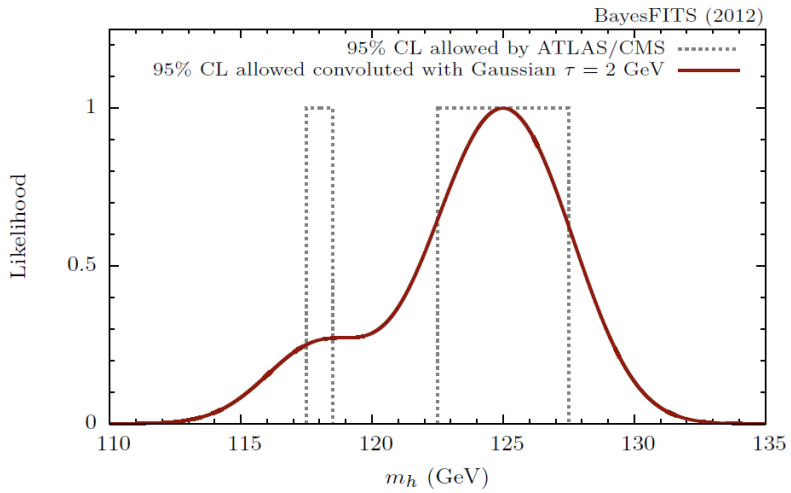
- **Currently allowed (95%)**

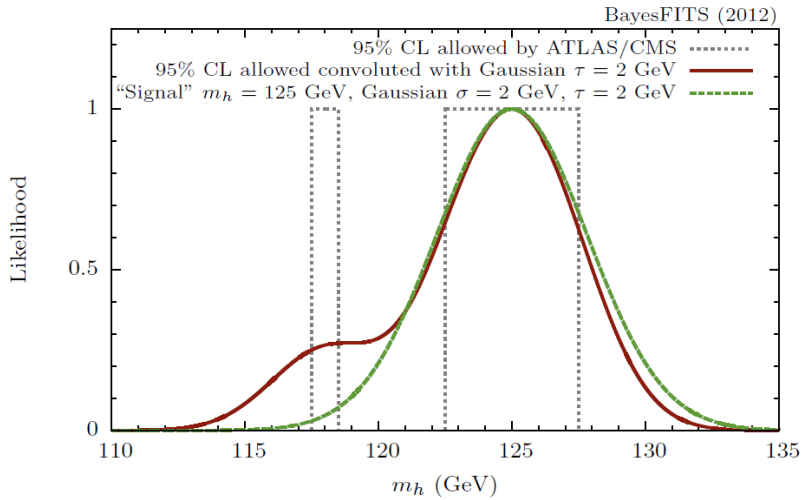
ATLAS: 117.5-118.5 GeV and 122.5-129 GeV

CMS: 114.4 – 127.5 GeV

- **Add tau=2GeV th error**
- **Construct likelihood**

- **Assume mh~125 GeV confirmed**
- **Add tau=2GeV (th) and sigma=2GeV (expt)**





The Like-function only differs in the lower mass window where it is rather small anyway.

Numerical scans

- Perform random scan over 4 CMSSM +4 SM parameters simultaneously
- Use Nested Sampling algorithm to evaluate posterior
- Use 4 000 live points

- Very wide ranges:

$$100\,\mathrm{GeV} \leq m_0 \leq 4\,\mathrm{TeV}$$

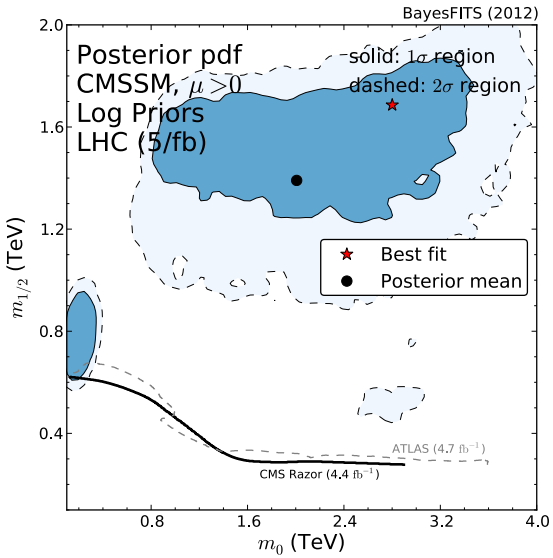
$$100\,\mathrm{GeV} \leq m_{1/2} \leq 2\,\mathrm{TeV}$$

$$-7\,\mathrm{TeV} \leq A_0 \leq 7\,\mathrm{TeV}$$

$$3 \leq \tan\beta \leq 62$$

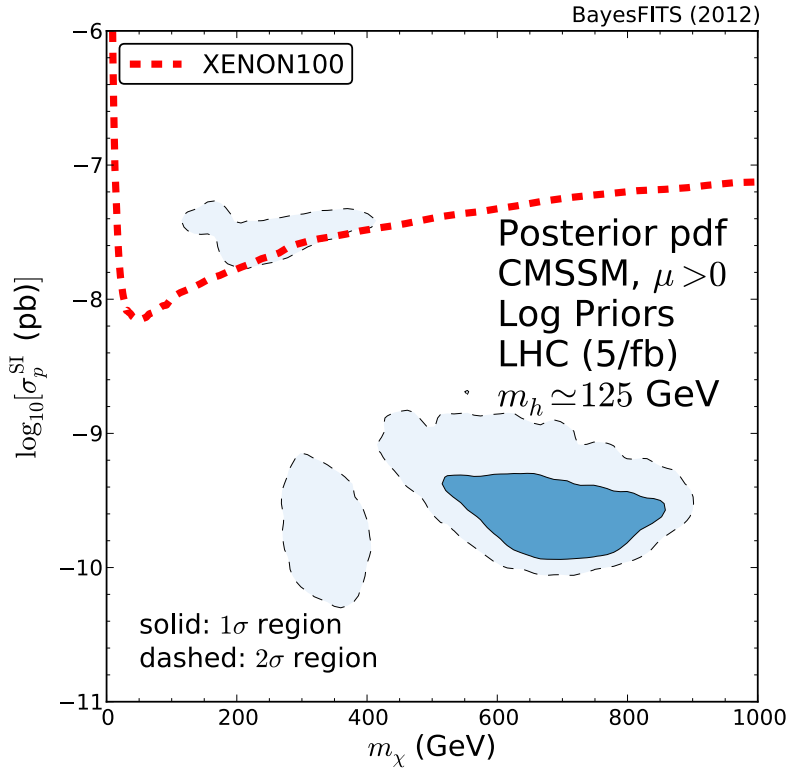
CMSSM parameter	Description	Prior Range	Prior Distribution
m_0	Universal scalar mass	100, 4000	Log
$m_{1/2}$	Universal gaugino mass	100, 2000	Log
A_0	Universal trilinear coupling	-7000, 7000	Linear
$\tan\beta$	Ratio of Higgs vevs	3, 62	Linear
$\mathrm{sgn}\,\mu$	Sign of Higgs parameter	$+1$ or -1	Fixed[a]
Nuisance	Description	Central value $\pm$ std. dev.	Prior Distribution
M_t	Top quark pole mass	172.9 ± 1.1	Gaussian
$m_b(m_b)^{\overline{MS}}_{\mathrm{SM}}$	Bottom quark mass	4.19 ± 0.12	Gaussian
$\alpha_s(M_Z)^{\overline{MS}}$	Strong coupling	0.1184 ± 0.0007	Gaussian
$1/\alpha_{\mathrm{em}}(M_Z)^{\overline{MS}}$	Reciprocal of electromagnetic coupling	127.916 ± 0.015	Gaussian

Impact on DM direct detection



XENON(2011)
limit not applied

(arXiv:1206.0264)

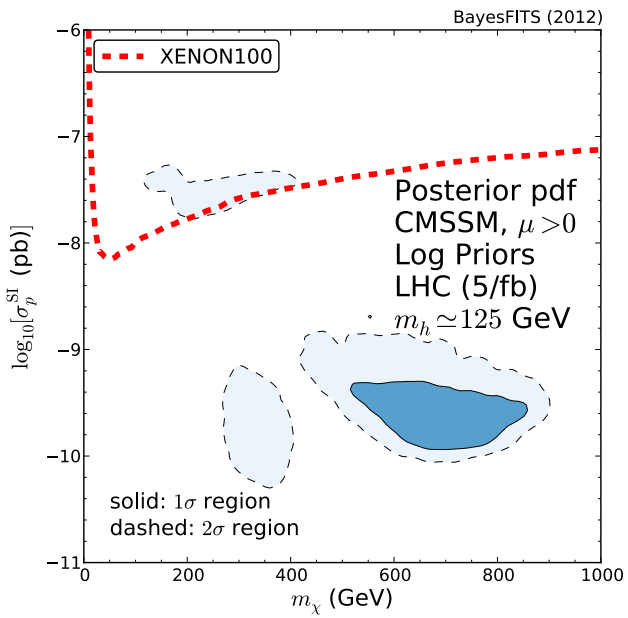


- **LHC limit pushes sigma_p down, mostly below XENON100 limit.**
- **One-tonne detector reach:**
  sigma_p~2x10^-11 pb.

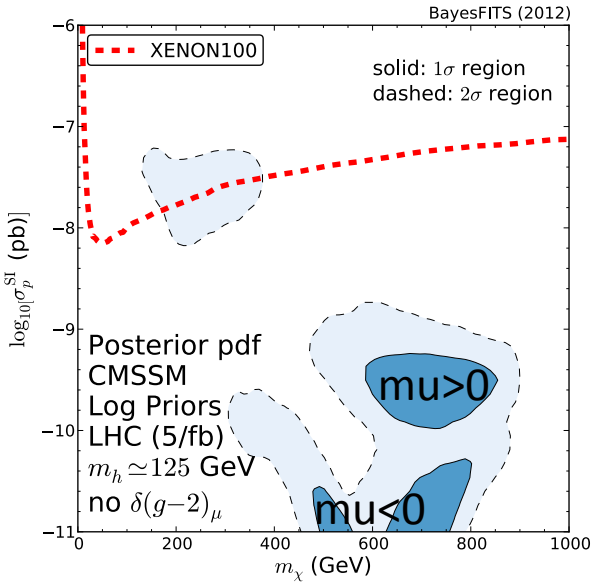
One will need 1 tonne DM detectors to probe favored ranges.

Direct detection of DM

mu>0, m_h~125 GeV



Both signs of mu combined,
no g-2, m_h~125 GeV



XENON(2011) limit not applied

- **LHC limit pushes sigma_p down, well below XENON100 limit.**
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Impact of FermiLAT dSphs gamma

arXiv:1108.3546

- Add FermiLAT dSph 90%CL limit

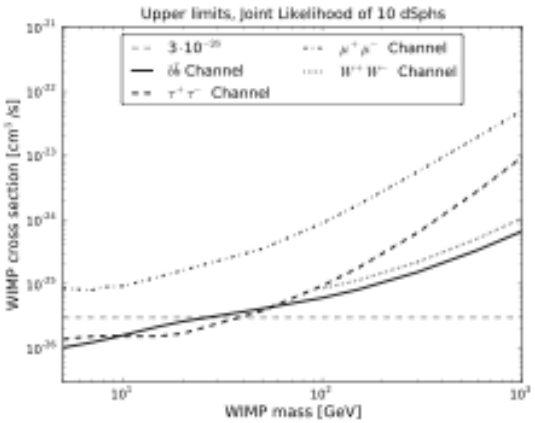


FIG. 2. Derived 95% C.L. upper limits on a WIMP annihilation cross section for the $b\bar{b}$ channel, the $\tau^+\tau^-$ channel, the $\mu^+\mu^-$ channel, and the W^+W^- channel. The most generic cross section ($\sim 3\cdot10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}$ for a purely s-wave cross section) is plotted as a reference. Uncertainties in the J factor are included.

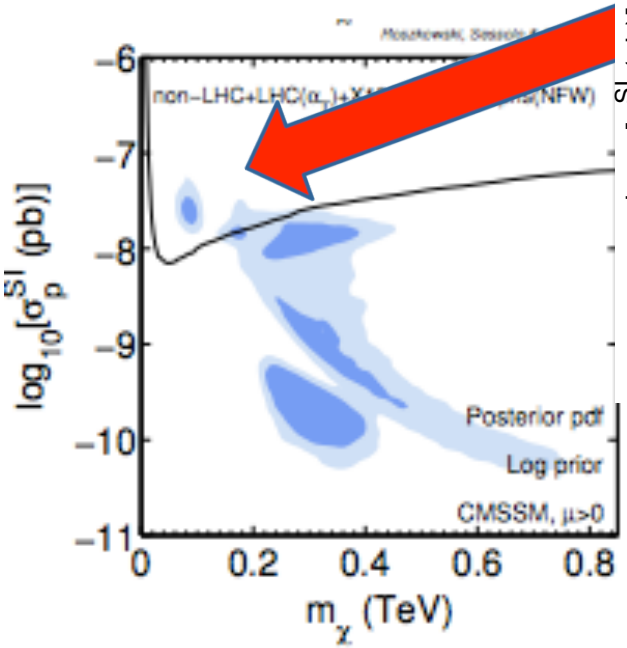
$$J(\psi) = \frac{1}{8.5\,\mathrm{kpc}}\left(\frac{1}{0.3\,\mathrm{GeV/cm^3}}\right)^2 \int_{\mathrm{l.o.s.}} dl\, \rho_\chi^2(r(l,\psi))$$

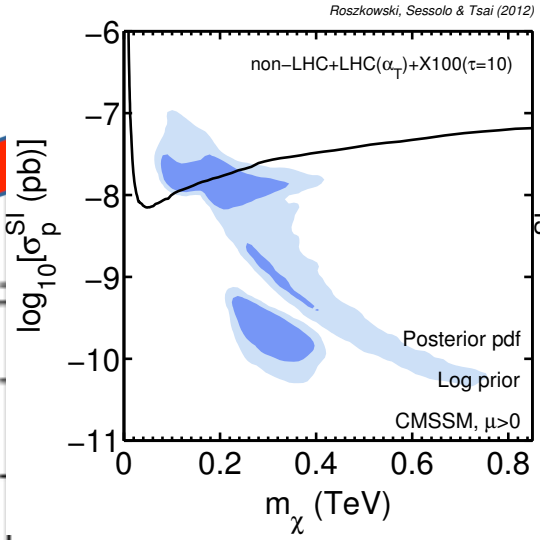
Limits depend on assumed halo profile.

(FermiLAT assume NFW)

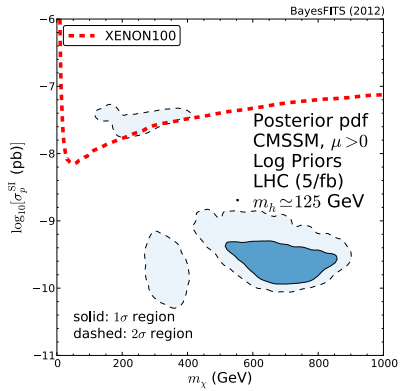
Based on ~1/fb of data

arXiv:1202.1503

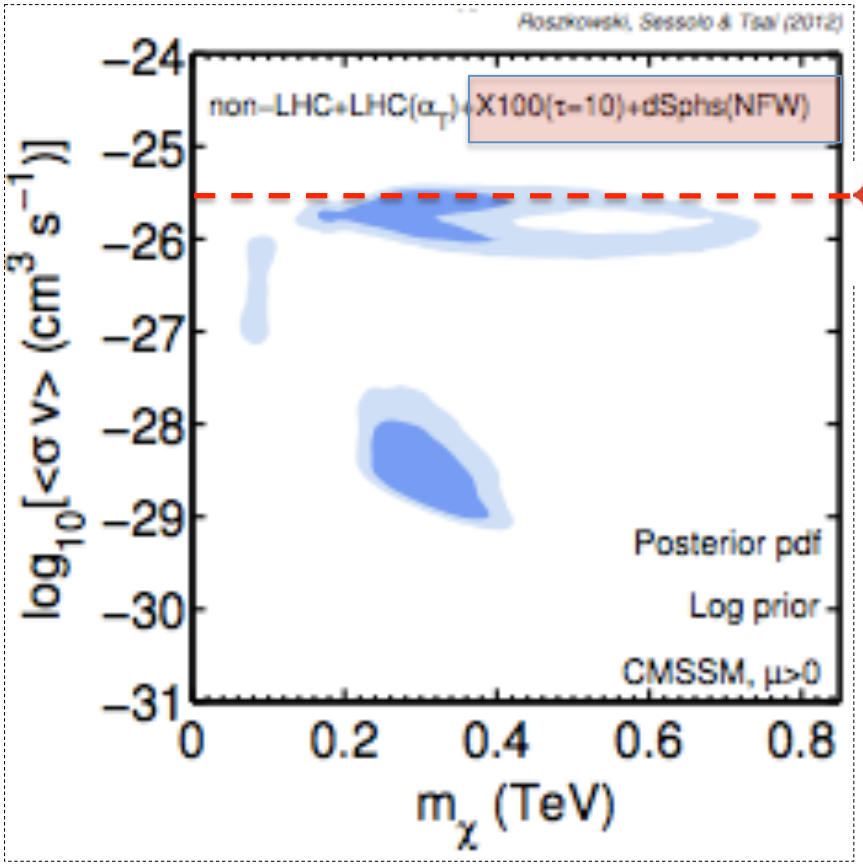




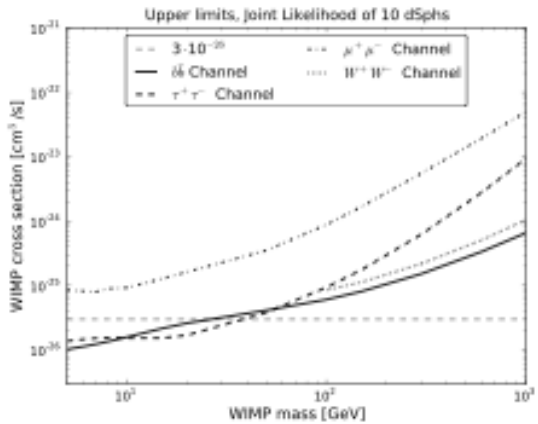
New LHC limits (~5/fb) kill it all



$\langle \sigma v \rangle$ in the CMSSM



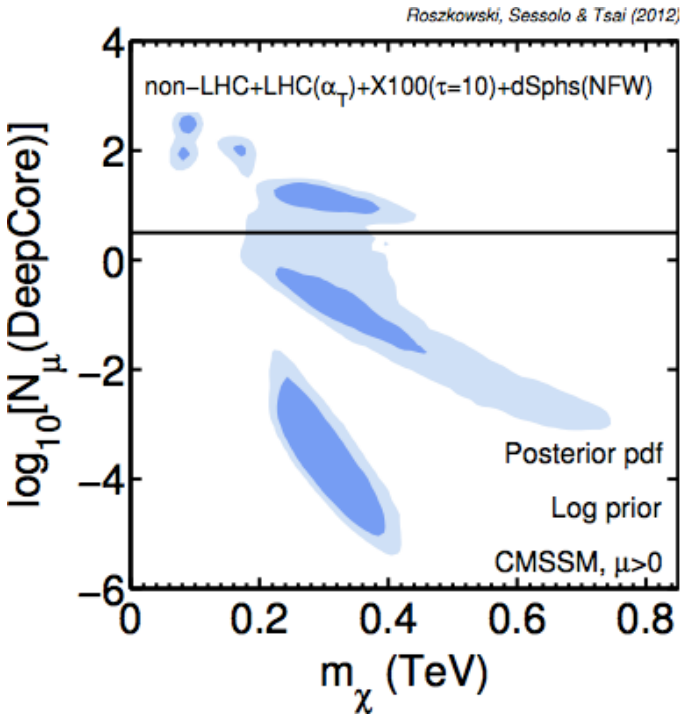
3×10^{-26} cm^3/sec
is NOT a "typical" value

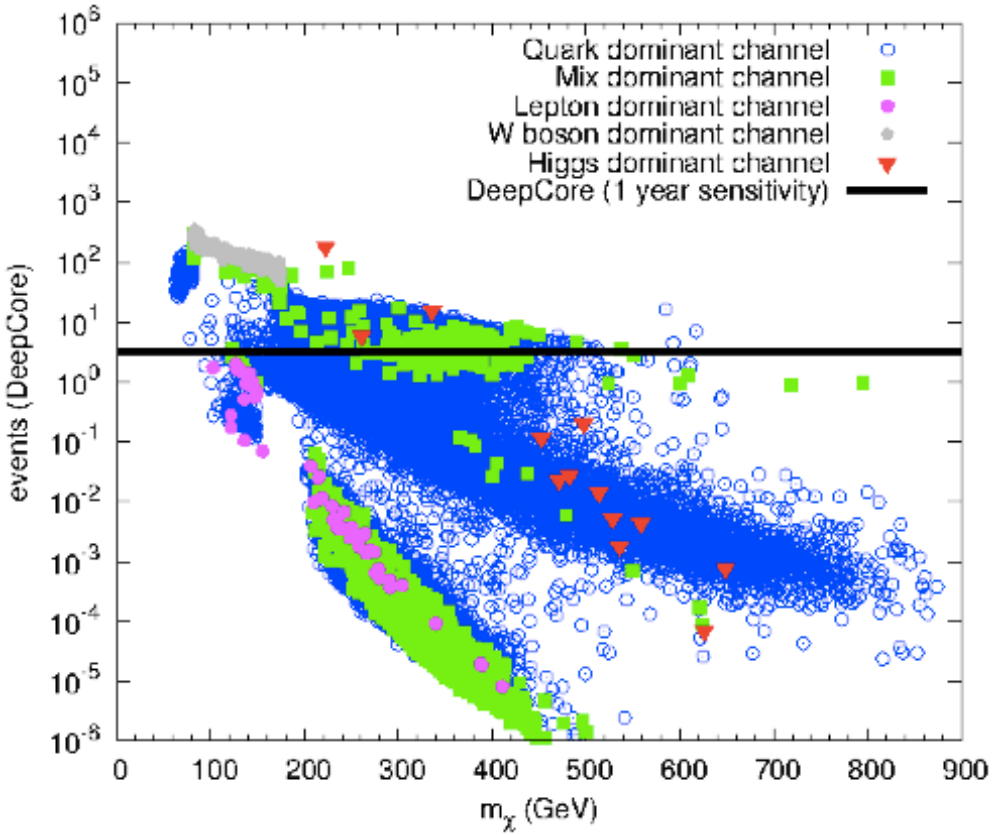


arXiv:1108.3546

SUSY: <sigma v> will be hard to constrain.

CMSSM DM: Prospects for DeepCore





IceCube contained events: slightly worse.

DeepCore will rule out WW annihilation channel, independently of the LHC.

DeepCore will be sensitive to FP/HB region.

Summary

- ✧ The LHC is the place where the nature of dark matter WIMPs can be elucidated.
- ✧ Prime DM suspect: neutralino in unified SUSY models, like Constrained MSSM.
- ✧ Current (~5/fb of data) LHC limits on SUSY particle masses place VERY strong constraints on direct detection,

  sigma_p<~ 10^-9 pb

  → need 1 tonne targets.

Constraints from direct detection of dark matter are currently much weaker than from the LHC.

- ✧ Also impact of sigma*v limit from dSphs (Fermi) weaker than from the LHC.

- ✧ In less constrained SUSY models prospects are likey to be more encouraging.