Invisible Higgs Decay to Light Sneutrinos

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PSBD, S. Mondal, B. Mukhopadhyaya and S. Roy, JHEP **1209**, 110 (2012) [arXiv:1207.6542 [hep-ph]].

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Outline

- 125 GeV Higgs vis-a-vis Light DM
- A Supersymmetric Model for Neutrino Mass
- Invisible Higgs Decay
    - A Global Fit
    - Upper limit on Light-Heavy Neutrino Mixing
- Collider Analysis
- Conclusion

125 GeV Higgs – Standard or Non-Standard?

- Experimental results so far show no *significant* deviation from SM expectations.
- However, the possibility of a non-standard Higgs boson still alive.
- A precise measurement of the total decay width is very difficult at the LHC.
- A better way to identify a non-standard Higgs is by studying its decay modes.

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- Experimental results so far show no *significant* deviation from SM expectations.
- However, the possibility of a non-standard Higgs boson still alive.
- A precise measurement of the total decay width is very difficult at the LHC.
- A better way to identify a non-standard Higgs is by studying its decay modes.
- The invisible Higgs decay mode is particularly sensitive to large BSM contributions, since BR($h \to ZZ^* \to 4\nu$) is tiny in the SM.
- The LHC prospects have been analyzed in various Higgs production channels. [Gunion '93; Frederikson, Johnson, Kane, Reid '94; Eboli, Zeppenfeld '00; Godbole, Guchait, Mazumdar, Moretti, Roy '03; Davoudiasl, Han, Logan '05; Bai, Draper, Shelton '12; Ghosh, Godbole, Guchait, Mohan, Sengupta '12;...]
- Current LHC limits are $\mathrm{BR}^h_{\rm inv} < 0.65$ (0.75) at 95% CL from ATLAS (CMS) in the search channel $pp \to Zh \to \ell^+\ell^- \not{E}_T$.
- Global fits to existing LHC Higgs data provide a much stronger constraint: $\mathrm{BR}^h_{\rm inv} < 0.28$ at 95% CL. [Giardino, Kannike, Masina, Raidal, Strumia '13]

The Dark Matter Connection

- Compelling evidence for DM from Cosmology and Astrophysics.
- Given suitable mass and coupling to the Higgs, invisible decay to DM could be significant.
- Can occur in many well-motivated BSM scenarios.
- Renewed interest in view of the recent claims for light DM in the mass range 5 - 50 GeV from DAMA, CoGeNT, CRESST-II and CDMS-II.
- Motivation for examining invisible Higgs decay in BSM scenarios accommodating a *light* DM.

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- Motivation for examining invisible Higgs decay in BSM scenarios accommodating a *light* DM.
- Here we'll focus on an *R*-parity conserving SUSY scenario in which the LSP could be a *natural* WIMP DM candidate.
- In the MSSM, the lightest neutralino ($\widetilde{\chi}_1^0$) is the prime DM candidate.
- Assuming gaugino mass unification,
  - $m_{\widetilde{\chi}_1^0} \gtrsim 50$ GeV from LEP constraints on chargino mass.
  - LHC limits on gluino mass push the lower limit on $m_{\widetilde{\chi}_1^0}$ beyond 150 GeV – exclude the possibility of $h \to \widetilde{\chi}_1^0 \overline{\widetilde{\chi}}_1^0$.
- With non-universal gaugino masses, possible to have light (even massless) neutralino [Dreiner, Heinemeyer, Kittel, Langenfeld, Weber, Weiglein '09; Vasquez, Belanger, Boehm, Pukhov, Silk '10; Bottino, Fornengo, Scopel '11; Arbey, Battaglia, Mahmoudi '12; Belanger *et al* '13;...], but high fine-tuning needed [Grothaus, Lindner, Takanishi '12; Boehm, PSBD, Mazumdar, Pukartas '13]

Light Sneutrino DM

- Neutrino oscillation data require at least two non-zero neutrino masses.
- First (and so far only) experimental evidence for beyond SM/MSSM physics.
- A simple paradigm: seesaw mechanism with SM singlet Majorana fermions. [Minkowski '77; Yanagida '79; Gell-Mann, Ramond, Slansky '80; Mohapatra, Senjanovic '80]
- In its SUSY version, the superpartner of singlet neutrino (by itself or with a small admixture of left-sneutrino) can be a viable (and possibly light) DM candidate. [Arkani-Hamed, Hall, Murayama, Smith, Weiner '01; Gopalakrishna, de Gouvea, Porod '06; Deppisch, Pilaftsis '08; Dumont, Belanger, Fichet, Kraml, Schwetz '09; An, PSBD, Cai, Mohapatra '11;...]
- We consider the possibility of *light* sneutrino DM in a variation of type-I seesaw, namely, inverse seesaw.

Supersymmetric Inverse Seesaw Model (SISM)

- Add two sets of MSSM singlet superfields: One Dirac ($\hat{N}_i$) and one Majorana ($\hat{S}_i$). [Mohapatra '86; Mohapatra, Valle '86]

$$\mathcal{W}_{\rm SISM} = \mathcal{W}_{\rm MSSM} + \epsilon_{ab} y_\nu^{ij} \hat{L}_i^a \hat{H}_u^b \hat{N}_j + M_{R_{ij}} \hat{N}_i \hat{S}_j + \mu_{S_{ij}} \hat{S}_i \hat{S}_j,$$

$$\mathcal{M}_\nu = \begin{pmatrix} \mathbf{0} & M_D & \mathbf{0} \\ M_D^T & \mathbf{0} & M_R \\ \mathbf{0} & M_R^T & \mu_S \end{pmatrix}$$

$$\boxed{M_\nu = \left[M_D (M_R^{-1})^T\right] \mu_S \left[M_R^{-1} M_D^T\right] + \mathcal{O}(\mu_S^2) \ \text{ for } \|\mu_S\| \ll \|M_R\|}$$

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$$\left(\frac{m_\nu}{0.1 \text{ eV}}\right) \simeq \left(\frac{M_D}{10 \text{ GeV}}\right)^2 \left(\frac{\mu_S}{1 \text{ keV}}\right) \left(\frac{M_R}{1 \text{ TeV}}\right)^{-2}$$

- TeV scale M_R possible even with large M_D – huge implications for seesaw phenomenology. [Deppisch, Valle '05; Hirsch, Kernreiter, Romao, del Moral '09; PSBD, Mohapatra '09; Mondal, Biswas, Ghosh, Roy '12; Abada, Das, Vicente, Weiland '12; PSBD, Mondal, Mukhopadhyaya, Roy '12; Bandyopadhyay, Chun, Okada, Park '12; ...]

- Smallness of μ_S is technically natural in 't Hooft sense.

Sneutrino Mass in SISM

$$\mathcal{L}^{\rm soft}_{\rm SISM} = \mathcal{L}^{\rm soft}_{\rm MSSM} - \left[m_N^2 \widetilde{N}^\dagger \widetilde{N} + m_S^2 \widetilde{S}^\dagger \widetilde{S}\right] - \left[\epsilon_{ab} A_\nu^{ij} \widetilde{L}_i^a \widetilde{N}_j H_u^b + B_{M_R}^{ij} \widetilde{N}_i \widetilde{S}_j + B_{\mu_S}^{ij} \widetilde{S}_i \widetilde{S}_j + {\rm h.c.}\right].$$

$$\mathcal{L}_{\widetilde{\nu}} = \frac{1}{2}(\phi^R, \phi^I) \begin{pmatrix} \mathcal{M}_+^2 & \mathbf{0} \\ \mathbf{0} & \mathcal{M}_-^2 \end{pmatrix} \begin{pmatrix} \phi^R \\ \phi^I \end{pmatrix},$$

where $\phi^{R,I} = (\widetilde{\nu}_{L_i}^{R,I}, \widetilde{N}_j^{c\,R,I}, \widetilde{S}_k^{R,I})$ $(i,j,k = 1,2,3)$ and

$$\mathcal{M}_\pm^2 = \begin{pmatrix} m_{\widetilde{L}}^2 + M_D M_D^\dagger + \frac{1}{2} m_Z^2 \cos 2\beta & \pm(v_u A_\nu - \mu M_D \cot \beta) & M_D M_R^\dagger \\ \pm(v_u A_\nu - \mu M_D \cot \beta)^T & m_N^2 + M_R M_R^\dagger + M_D M_D^\dagger & \mu_S M_R^\dagger \pm B_{M_R} \\ (M_D M_R^\dagger)^T & (\mu_S M_R^\dagger \pm B_{M_R})^T & m_S^2 + \mu_S^2 + M_R M_R^\dagger \pm B_{\mu_S} \end{pmatrix}$$

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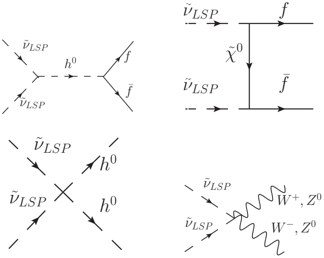
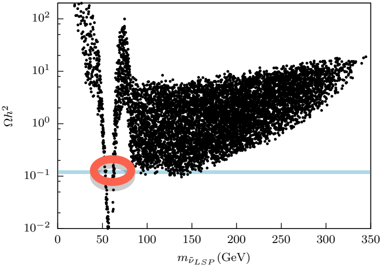
To find a viable sparticle spectrum with *minimum* inputs, we assume mSUGRA boundary conditions for the MSSM sector and low-energy inputs for the singlet sector (without necessarily imposing any GUT features). [Arina, Bazzocchi, Fornengo, Romao, Valle '08; PSBD, Mondal, Mukhopadhyaya, Roy '12]

Sneutrino DM Relic Density





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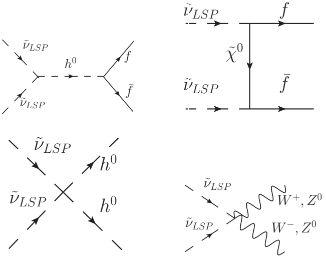

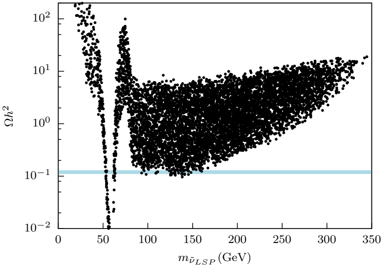

Input Parameters:

$$m_0 \in [0.1, 2.5] \text{ TeV}, \; m_{1/2} \in [0.65, 2.5] \text{ TeV}, \; A_0 \in [-3, 3] \text{ TeV},$$
$$\text{diag}(y_\nu) \in [0.01, 0.2], \; (M_R)_{11} \in [100, 800] \text{ GeV}, (M_R)_{22,33} = 1 \text{ TeV},$$
$$\tan\beta = 10, \; \text{sign}(\mu) = +1, \; , \; B_{\mu_S} = 100 \text{ MeV}^2, B_{M_R} = 1 \text{ TeV}^2$$

Constraints: $m_h = 125 \pm 2$ GeV, LHC constraints (on sparticle masses), and flavor constraints.

Global Analysis of $h \to 2\widetilde{\nu}_{\rm LSP}$

$$\Gamma_{\rm inv} = \frac{\epsilon}{1-\epsilon}\sum \Gamma_{\rm vis} \, .$$

$$\chi^2 = \sum_i \frac{(\mu_i - \hat{\mu}_i)^2}{(\delta\hat{\mu}_i)^2} ,$$

$$\mu_i = R_i^{\rm prod} \times \frac{R_i^{\rm decay}}{R^{\rm width}} ,$$

$$R_i^{\rm prod} = \frac{\left(\sigma_i^{\rm prod}\right)_{\rm SISM}}{\left(\sigma_i^{\rm prod}\right)_{\rm SM}} ,$$

$$R_i^{\rm decay} = \frac{\left(\Gamma_i^{\rm decay}\right)_{\rm SISM}}{\left(\Gamma_i^{\rm decay}\right)_{\rm SM}} ,$$

$$R^{\rm width} = \frac{\left(\Gamma^{\rm width}\right)_{\rm SISM}}{\left(\Gamma^{\rm width}\right)_{\rm SM}} .$$

Channel	$\hat{\mu}$	Experiment
$h \to \gamma\gamma$	$1.55^{+0.33}_{-0.28}$	ATLAS
	$0.78^{+0.28}_{-0.26}$	CMS
$h \to ZZ^* \to 4l$	$1.43^{+0.40}_{-0.35}$	ATLAS
	$0.9^{+0.30}_{-0.20}$	CMS
$h \to WW^* \to 2l2\nu$	$0.99^{+0.31}_{-0.28}$	ATLAS
	$0.80^{+0.20}_{-0.20}$	CMS
$h \to b\bar{b}$	$0.20^{+0.70}_{-0.60}$	ATLAS (VH)
	$1.00^{+0.50}_{-0.50}$	CMS (VH)
$h \to \tau\bar{\tau}$	$0.7^{+0.7}_{-0.6}$	ATLAS
	$1.10^{+0.4}_{-0.4}$	CMS

[EPS 2013]

Upper limit on $\mathrm{BR}^h_{\rm inv}$

Input parameter	BP1	BP2	BP3
m_0 (GeV)	996.45	745.48	614.00
$m_{1/2}$ (GeV)	750.00	1014.17	1083.00
A_0 (GeV)	-2858.00	-2775.09	-2600.00

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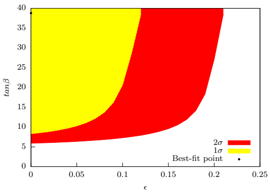
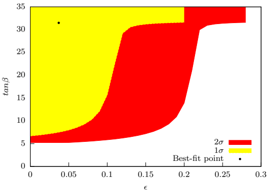
A_0 (GeV)	-2858.00	-2775.09	-2600.00

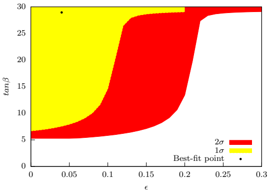
Parameter	BP1		BP2		BP3	
	1σ	2σ	1σ	2σ	1σ	2σ
ε	< 0.07	< 0.16	< 0.15	< 0.24	< 0.15	< 0.25
$\tan\beta$	12.0-38.8	6.9-38.8	14.5-31.6	5.7-31.6	12.3-29.1	5.6-29.2



BP1



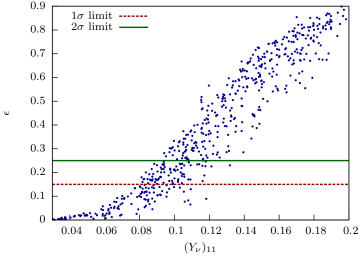
BP2



BP3

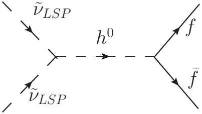
Upper Limit on Dirac Yukawa Coupling

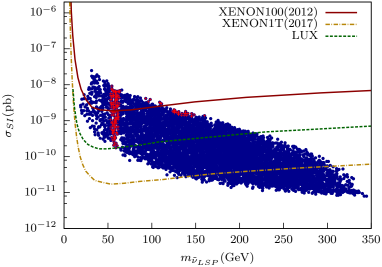
- Invisible decay width to sneutrinos increases with increase in Yukawa coupling.
- An upper limit on $BR_{\rm inv}$ puts an upper limit on Y_ν.



- Comparable with limits obtained from visible Higgs decay $h \to \nu N \to \nu \ell W \to 2\ell 2\nu$ [PSBD, Franceschini, Mohapatra '12], and from charged lepton flavor violating decays [Dinh, Ibarra, Molinaro, Petcov '12].

Direct Detection Cross Section





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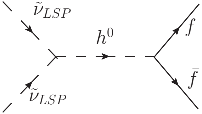

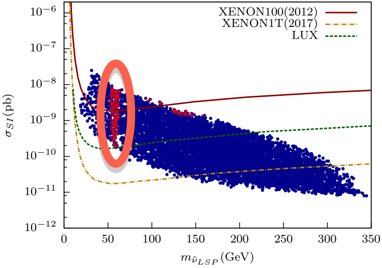

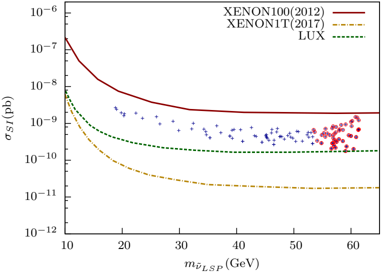

Can be *completely* probed by next generation DM direct detection experiments.

Collider Analysis

- Two promising channels: (see M. Guchait's talk)
  - VBF: $pp \to hjj \to jj + \not{E}_T$.
  - Zh: $pp \to Zh \to \ell^+\ell^- + \not{E}_T$.

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  - VBF: $pp \to hjj \to jj + \not{E}_T$.
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- Event generation:
  - SUSY Inverse Seesaw Model implementation by `SARAH`
  - SUSY spectrum generated by `SPheno`
  - SLHA file fed to `PYTHIA` for parton showering, hadronization, etc.
  - Jet reconstruction using cone algorithm via `PYCELL`
  - Include jet energy smearing by a Gaussian probability density function
  - Contributions from non-VBF processes (e.g. hard QCD processes) were also taken into account.

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- Background generation by `Alpgen`. MLM matching while interfacing to `PYTHIA`.
  - Main background for VBF are:
    - $W+$ jets, where $W^+ \to \ell^+\nu$ and ℓ escapes detection.
    - Z + jets, where $Z \to \nu\bar{\nu}$.
    - mismeasured QCD events giving fake $\not{E}_T$.

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    - mismeasured QCD events giving fake $\not{E}_T$.
  - Dominant background for Zh:
    - WW production, where both W's decay leptonically.
    - WZ production, where $Z \to \ell^+\ell^-$ and $W^+ \to \ell^+\nu$, and one ℓ misses detection.
    - ZZ, where one $Z \to \ell^+\ell^-$ and the other $Z \to \nu\bar{\nu}$.
    - $t\bar{t}$ production followed by $t \to Wb$, where both the W's decay leptonically and

VBF Channel

- Selection cuts:
  - $|\eta_{j_1} - \eta_{j_2}| > 4.0$ and $\eta_{j_1} \cdot \eta_{j_2} < 0$.
  - A jet veto with $p_T > 40$ GeV in the central region. Discard jets with $|\eta| < 2.5$.
  - $M_{jj} > 1.8\ \mathrm{TeV}$ for two leading jets.
  - $\not{E}_T > 100\ \mathrm{GeV}$.

Channel	Production cross section (pb)	Cross section after cuts (fb)
BP1 (VBF)	3.76	0.99
BP1 (others)	125.9	0.16
BP2 (VBF)	3.72	1.55
BP2 (others)	125.4	0.25
BP3 (VBF)	3.73	1.72
BP3 (others)	125.7	0.25
W + n-jets	56848.54	46.57
Z + n-jet	10198.72	24.90

- For BP1 with $\mathrm{BR}_{\mathrm{inv}}^{\mathrm{max}} = 0.14$, 3σ signal significance ($S/\sqrt{S+B}$) at 500 fb^{-1}, whereas for BP2 and BP3 with $\mathrm{BR}_{\mathrm{inv}}^{\mathrm{max}} = 0.2$ and 0.22 respectively, 3σ significance at 200 fb^{-1} for $\sqrt{s} = 14$ TeV LHC.

Zh Channel

- Basic selection criteria for leptons:
  - $p_T^e > 15$ GeV and $p_T^\mu > 10$ GeV. For both, $|\eta^\ell| < 2.4$.
  - $\Delta R_{\ell\ell} > 0.2$.
  - $\Delta R_{\ell j} > 0.4$.
  - Scalar sum of E_T deposits by hadrons within a cone of $\Delta R \leq 0.2$ around a lepton must be less than $0.2 p_T^\ell$ to ensure lepton isolation.
- Background reduction cuts:
  - A jet veto with $p_T > 20$ GeV and $|\eta^j| < 4.5$.
  - Dilepton invariant mass $|M_Z - M_{\ell\bar{\ell}}| < 10$ GeV.
  - $M_T^{\ell\ell} \geq 150$ GeV, where $M_T^{\ell\ell} = \sqrt{p_T^{\ell\ell} \not{E}_T [1 - cos\phi(p_T^{\ell\ell}, \not{E}_T)]}$.
  - $\not{E}_T > 100$ GeV.

Channel	Production cross section (pb)	Cross section after cuts (fb)
BP1	0.53	0.35
BP2	0.51	0.51
BP3	0.51	0.52
WW	76.51	0.38
ZZ	10.58	7.77
WZ	28.95	8.83
$t\bar{t}$	370.20	0.92

- For BP2 and BP3, 3σ signal significance at 600 fb^{-1}, whereas for BP1, need to go beyond 1300 fb^{-1} at 14 TeV LHC.

Distinction from Neutralino LSP at the LHC

- Cascade decay of $\widetilde{q}$ and $\widetilde{g}$ through $\widetilde{\chi}_1^\pm$ and $\widetilde{\chi}_0^\pm$, which further go to $\widetilde{\nu}_1$ LSP in our case.

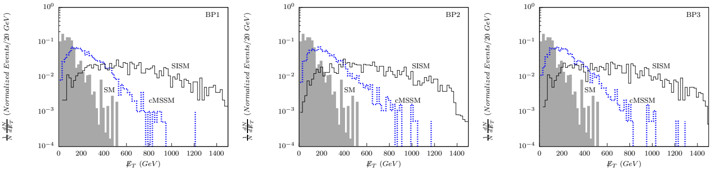
$$\widetilde{\chi}_1^\pm \to \ell^\pm \widetilde{\nu}_1, W^\pm \widetilde{\chi}_1^0; \quad \widetilde{\chi}_1^0 \to \nu \widetilde{\nu}_1$$

whereas for neutralino LSP, $\widetilde{\chi}_1^\pm \to W^\pm \widetilde{\chi}_1^0$ (dominant),$f\bar{f}\widetilde{\chi}_1^0$.

- Sneutrino case has an enhanced SSD rate and larger r value, where

$$r = \frac{\sigma(\ell^\pm \ell^\pm + \geq 2j + \not{E}_T)}{\sigma(0\ell + \geq 3j + \not{E}_T)}$$

- Also harder $\not{E}_T$ spectrum compared to the neutralino LSP case. [PSBD, Mondal, Mukhopadhyaya, Roy '12]



- "Residual MSSM backgrounds" can be reduced/removed by studying

$$M_{\rm eff} = \sum |p_T^\ell| + \sum |p_T^j| + \not{E}_T$$

which will be considerably harder in the pure MSSM case than in our case.

Conclusion

- Supplementing cMSSM with Inverse Seesaw mechanism for neutrino masses can give a light scalar DM candidate, consistent with all existing collider, low-energy and cosmological constraints.
- This leads to the possibility of invisible decay of the lightest *CP*-even Higgs to a pair of sneutrinos.
- We performed a global analysis of this scenario, and derived $2\sigma(1\sigma)$ upper limits of 0.25 (0.15) on $\mathrm{BR}^h_{\rm inv}$.
- This puts an upper limit of order 0.1 on the Dirac Yukawa coupling.
- The model parameter space allowed by $\mathrm{BR}^h_{\rm inv}$ can be *completely* ruled out in case of future null results from DM direct detection experiments (e.g., LUX, XENON1T).
- Also explored the prospects at 14 TeV LHC for a few benchmark points.
- 3σ signal significance possible in the VBF channel with $\int \mathcal{L}dt$ as low as 200 fb^{-1}, whereas requires at least 600 fb^{-1} in the *Zh* channel.

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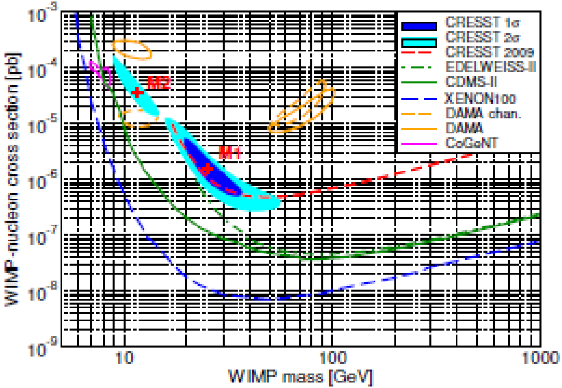
Thank You.

Backup Slide



[Angloher *et al.* (CRESST-II Collaboration) '11]