Perspectives of monojet searches at the LHC on supersymmetric dark matter

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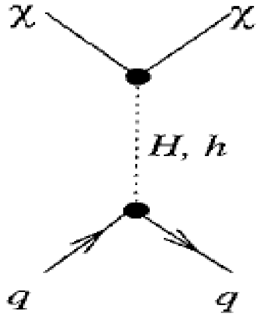
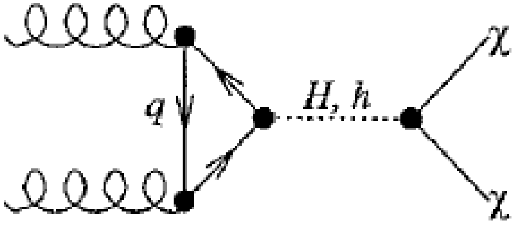
dark matter scattering

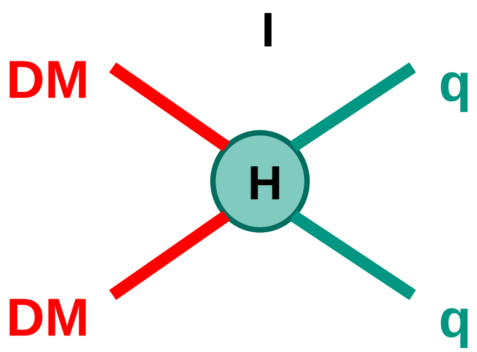


LHC production

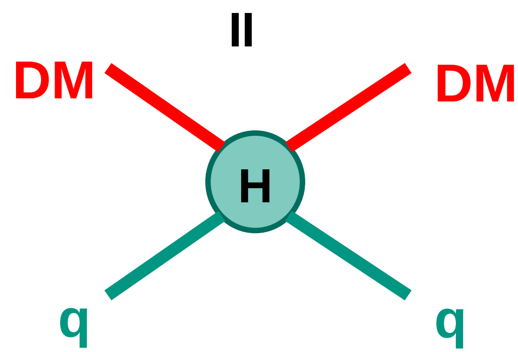


How to detect dark matter?

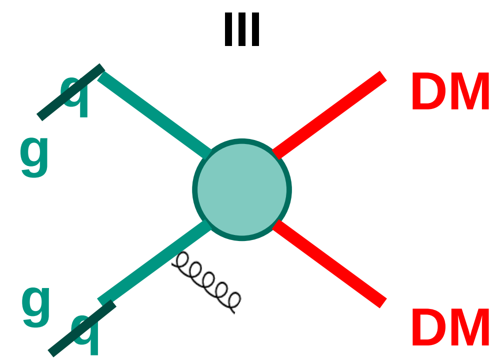
INDIRECT



DIRECT



COLLIDER



σ ≈ $10^{-36}\ cm^2$ from relic density Ωh^2

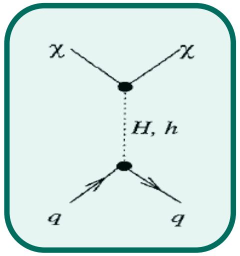
σ < $10^{-46}\ cm^2$ from direct dark matter searches

σ < $10^{-36}\ cm^2$ from monojet searches

Z or Higgs exchange to explain neutral and weak interactions but 10 orders of magnitude between I and II most easily explained by Higgs exchange, since Higgs couples only weakly to light quarks.

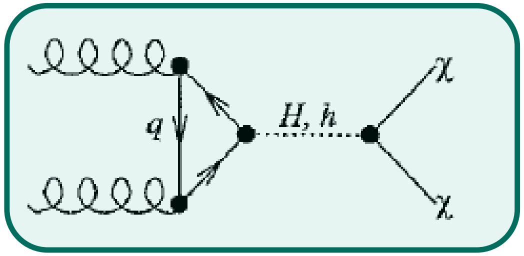
Comparison of monojet and direct DM searches

Scattering of DM with matter



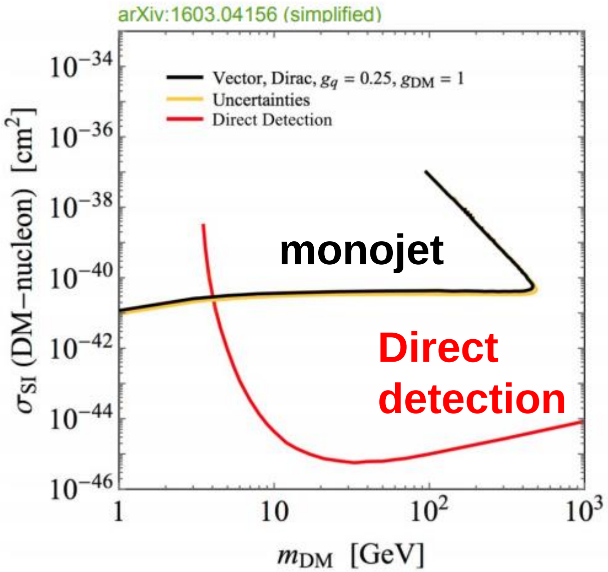
light quarks in protons and form factors essential

DM production at the LHC



Loops with heavy quarks

Monojet sensitivity increases for light dark matter masses. Constraints from monojets are used to compare the results of direct DM searches



Beware: LHC data interpreted within simplified models → since couplings in simplified models are arbitrary, no quantitative comparison with direct scattering experiments possible.

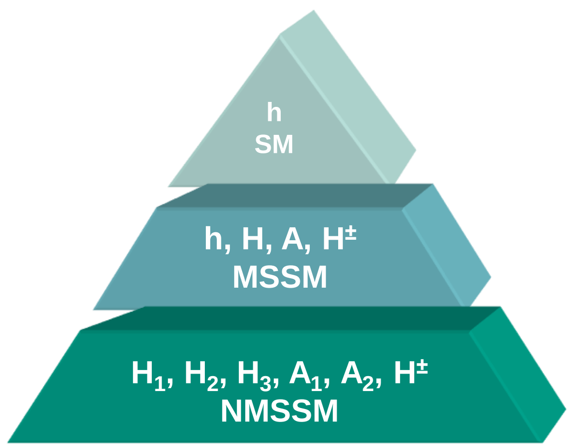
Loops effects can change limits by 2-3 orders of magnitude at LHC (see e.g. 1208.4605) → quantitative comparison between direct DM searches and LHC only possible in complete realistic models, like SUSY

Next-to minimal supersymmetric SM

- **Pros of NMSSM**
  - ✓ 125 GeV Higgs mass possible for TeV stop masses
  - ✓ Describes DM sector for neutralinos at the EW scale
  - ✓ Solves μ-Problem (Kim, Nilles Phys. Lett. B 138, 150 (1984))
- **NMSSM has one additional Higgs singlet → additional terms in superpotential leads to more free parameters**

$$W_{NMSSM} = \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{\kappa}{3}\hat{S}^3 + \cdots$$

SM Higgs
h = 125 GeV
H_1 or H_2 = 125 GeV



$$\Rightarrow \quad \tilde{\chi}_1^0 = \tilde{B} + \tilde{W} + \tilde{H}_1 + \tilde{H}_2$$

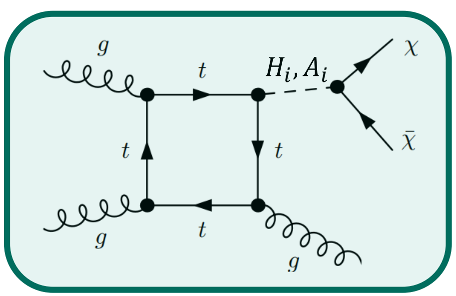
$$\Rightarrow \quad \tilde{\chi}_1^0 = \tilde{B} + \tilde{W} + \tilde{H}_1 + \tilde{H}_2 + \tilde{S}$$

Sampling of NMSSM parameter space

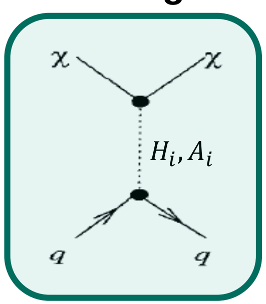
Scanning strategy for accepted points: select a point in the 3D Higgs parameter space, fit the corresponding masses with the 7 free NMSSM parameters using the following constraints: $M_{H1/H2} = 125$ GeV with SM-like couplings to quarks, leptons and gauge bosons (8 constraints from reduced XS), apply LHC and LEP Higgs mass limits. The relation between the NMSSM parameters and masses is encoded in NMSSMTools. Repeat the fit in a grid of all Higgs mass combinations of M_{A1} , M_{H1}, M_{H3} (for $M_{A1/H2} < 500$ GeV and $M_{H3} < 2$ TeV).
For more details see backup slides, *PLB782 (2018) 69-76*/arXiv:1712.02531 and C.B. Mon 15.00-15.20

micrOMEGAs

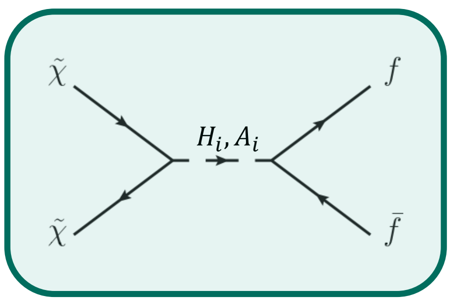
Monojet XS



Scattering XS

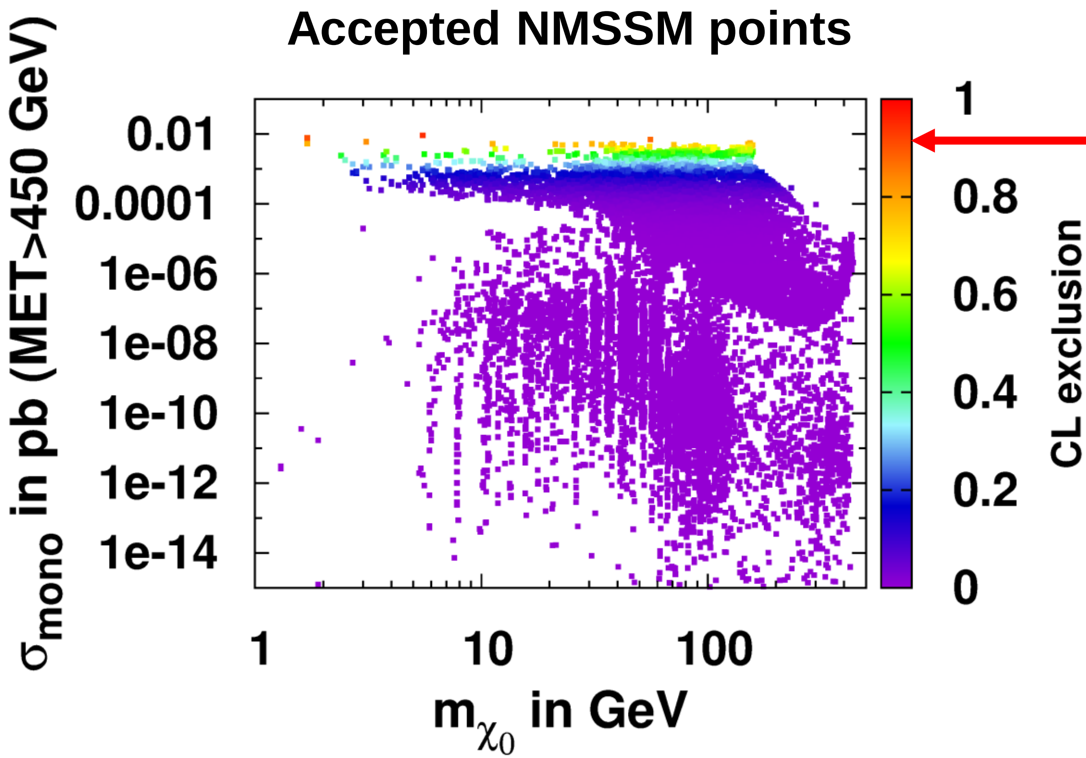


Annihilation XS

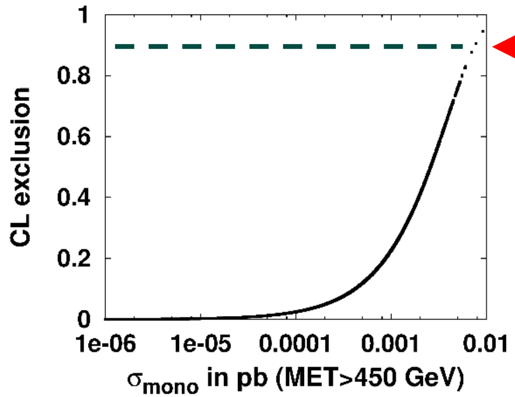


Monojet cross section in NMSSM

- Accepted points translated to monojet cross section (for MET > 450 GeV) versus WIMP mass plane



Only a few excluded points at 90% CL from monojet searches



Present results from monojet searches

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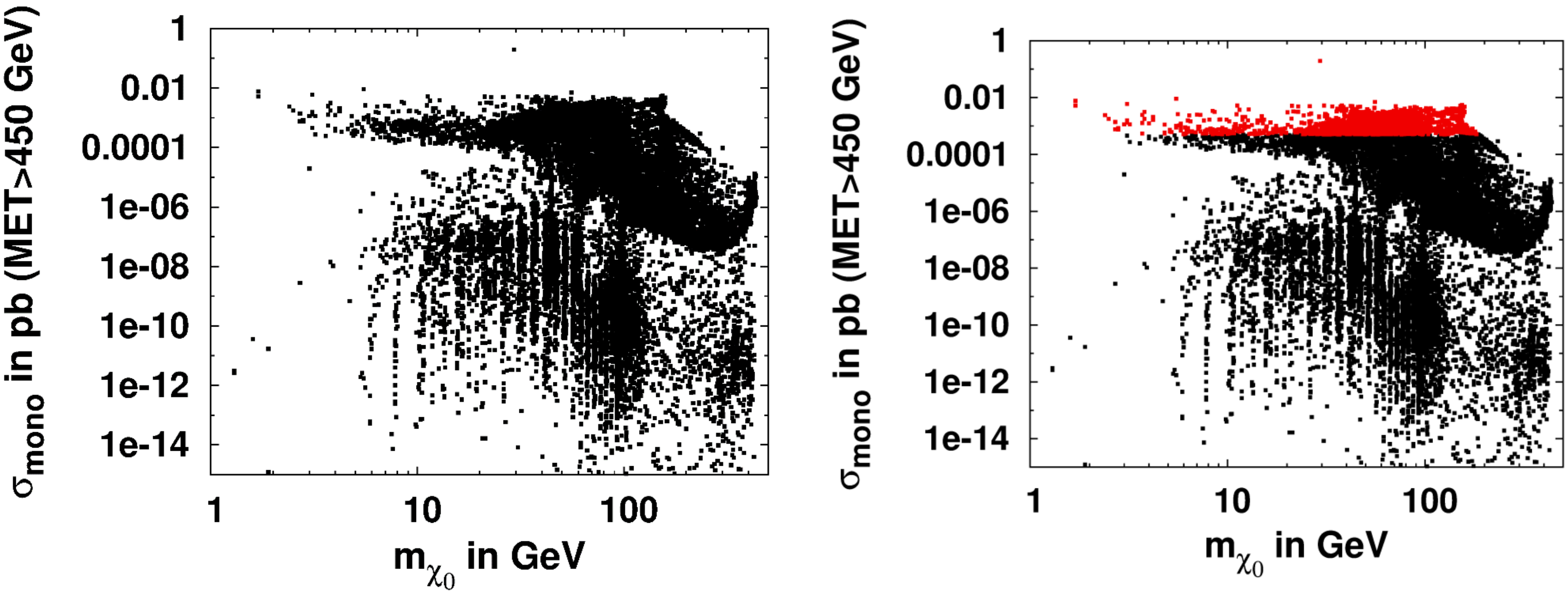
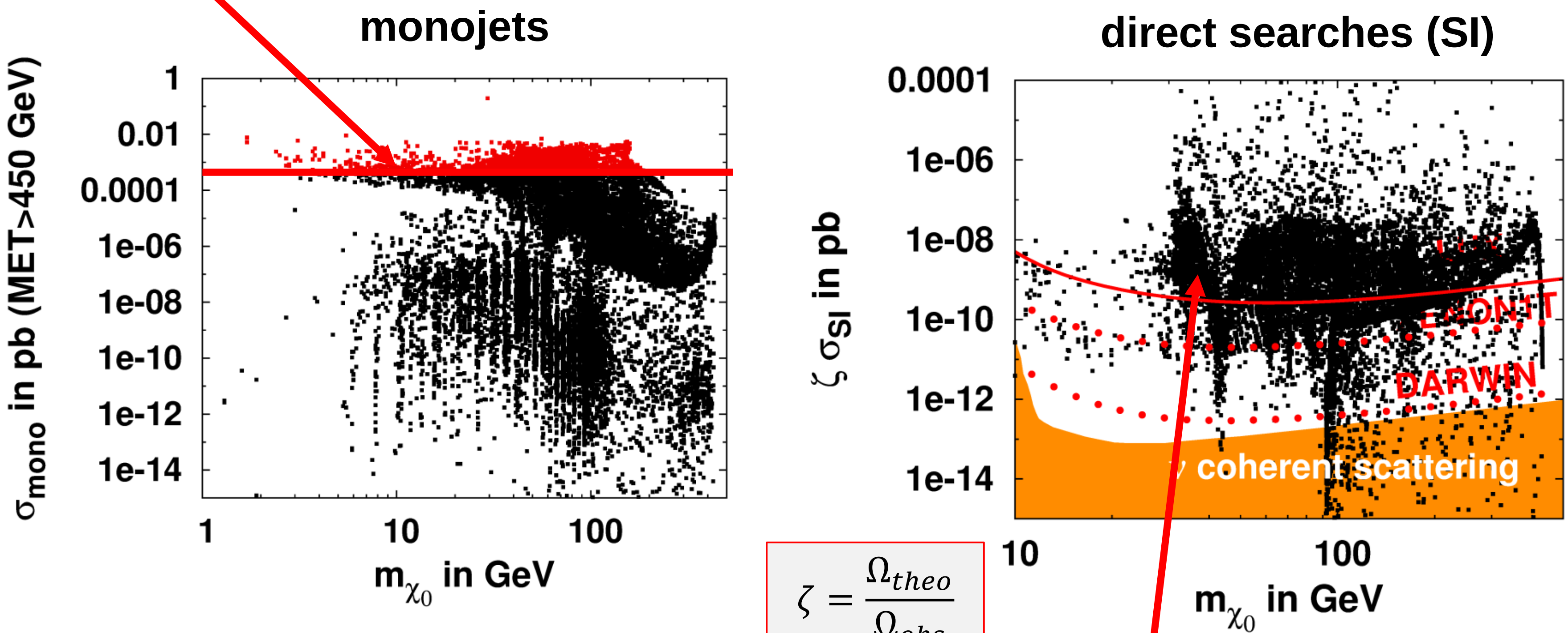


● **NMSSM accepted point** ● **excluded by monojets @90% C.L. and 3000fb^{-1}**

Present results from monojet searches hardly exclude accepted points at 90% C.L..

Assuming that the discovery potential scales with the luminosity L as $\sqrt{L}$ and the efficiency stays constant the present results can be scaled to 3000fb^{-1}

How would these excluded points compare with expected DARWIN sensitivity for SI and SD limits?



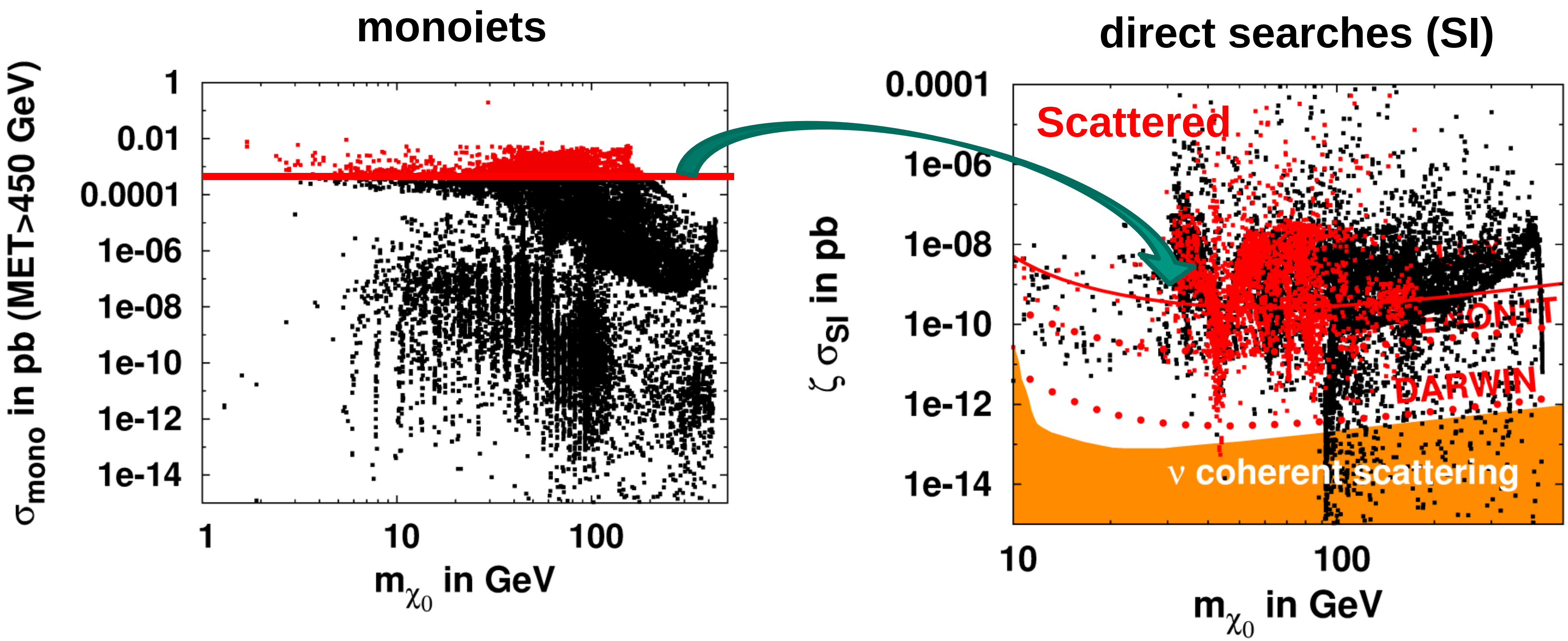
$$\zeta = \frac{\Omega_{theo}}{\Omega_{obs}}$$

Results from direct DM searches exclude large fraction of accepted points.

The orange area is below the neutrino coherent scattering cross section from solar, atmospheric and diffuse supernova neutrinos on nuclei, providing a high background for future DM searches.

Excluded points translation to direct searches

● NMSSM accepted point ● excluded by monojets @90% C.L. and $3000 fb^{-1}$

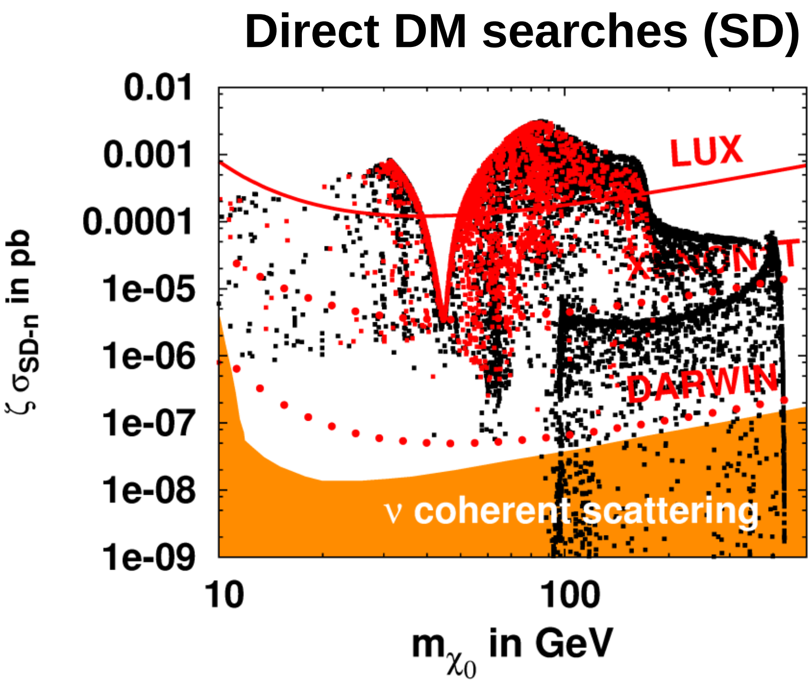


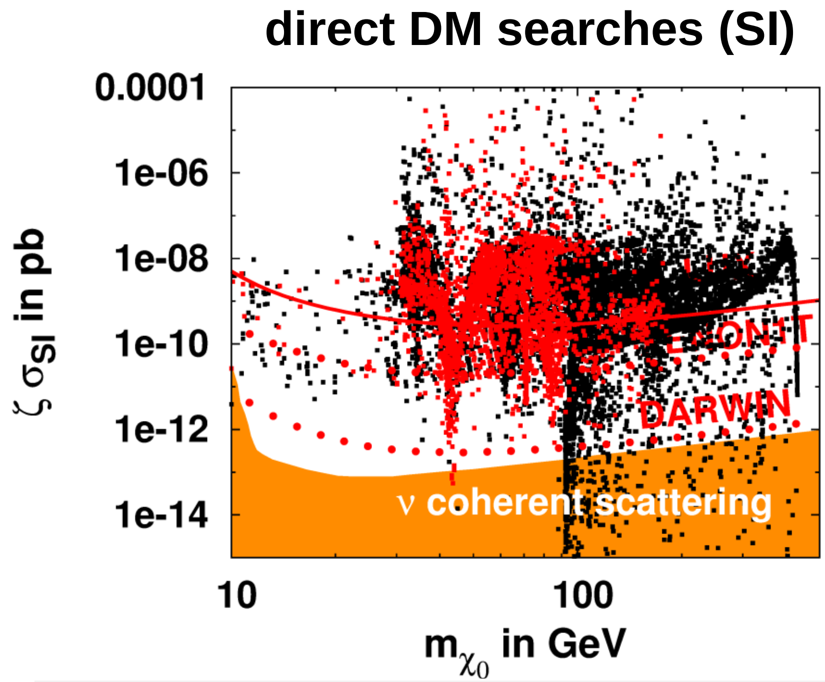
Peaks = resonant DM annihilation

In realistic SUSY models the XS limits from monojets are not a simple line in direct DM XS plane but depend on the DM mass.

Monojet vs direct DM searches (SD & SI)

- NMSSM accepted point
- excluded by monojets @90% C.L. and $3000 fb^{-1}$





Peaks = resonant DM annihilation

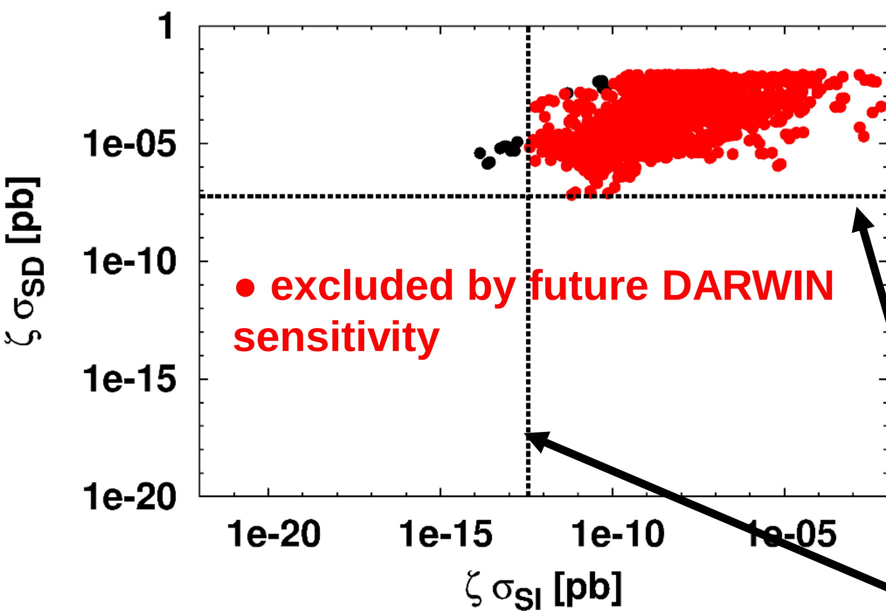
Monojet searches most sensitive for the resonant region → they exclude comparable XSs compared to the future direct DM searches.

Comparison of monojet and direct DM searches

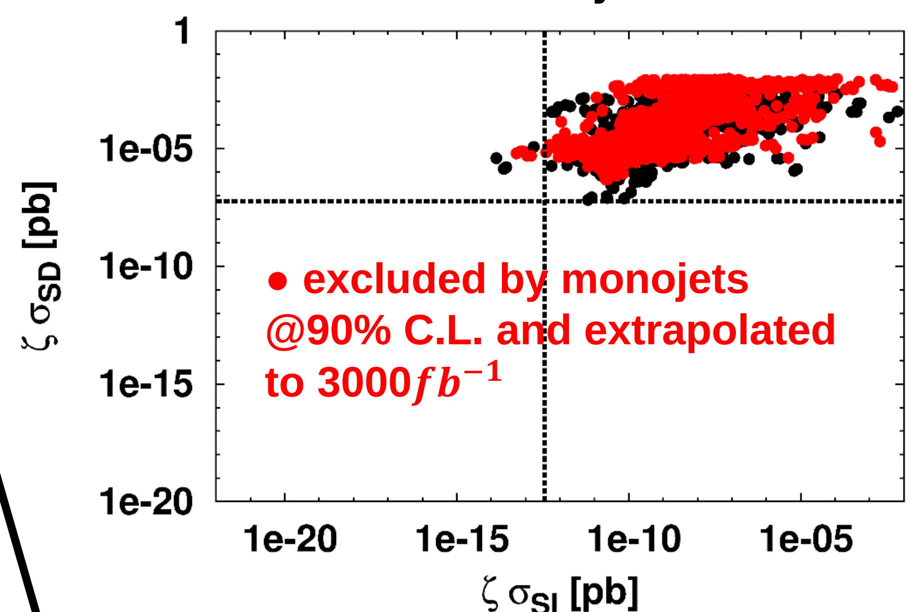
- **NMSSM accepted point**

$30\ GeV < m_{\tilde{\chi}} < 60\ GeV$

direct searches



monojet



Neutrino background

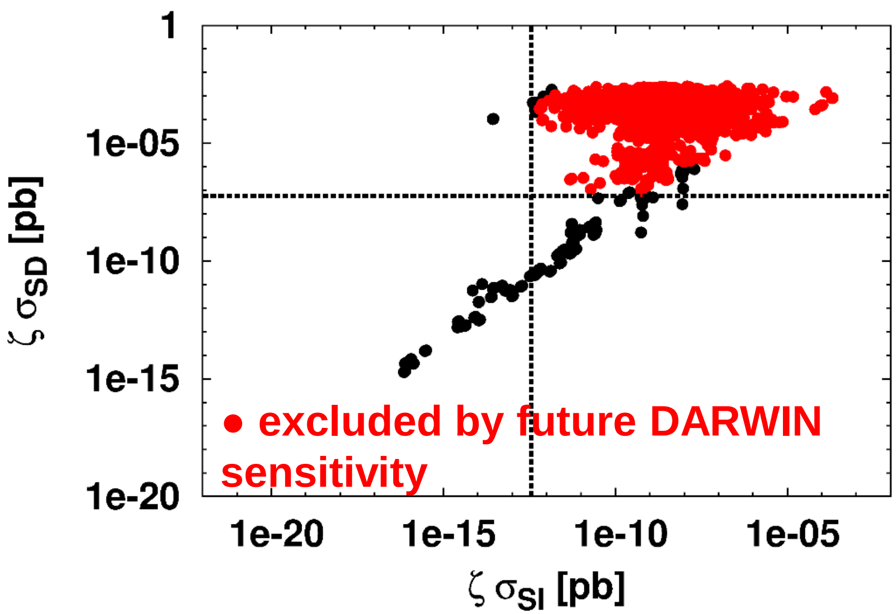
For light DM masses the monojets searches show similar sensitivity and coverage as the combination of for SI and SD searches.

Comparison of monojet and direct DM searches

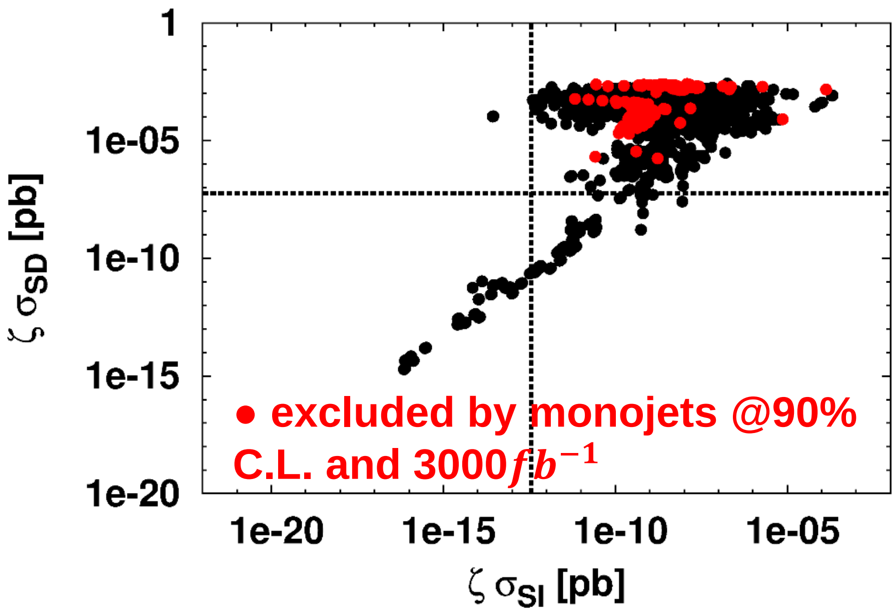
- **NMSSM accepted point**

$150\ GeV < m_{\tilde{\chi}} < 200\ GeV$

direct searches



monojet



For heavy DM masses the coverage and sensitivity from monojet searches decreases compared to direct searches.

Summary

- Up to now the results from monojet searches are interpreted in the framework of simplified models and compared to results from direct DM searches
- But the LHC is a gluon collider, so using arbitrary couplings leads only to a qualitative comparison
- A quantitative comparison is possible in realistic SUSY models

Limits from monojet searches at the LHC form exclusion lines as function of the DM mass but they do not form a line in the SI/SD XS vs DM mass plane in realistic SUSY models

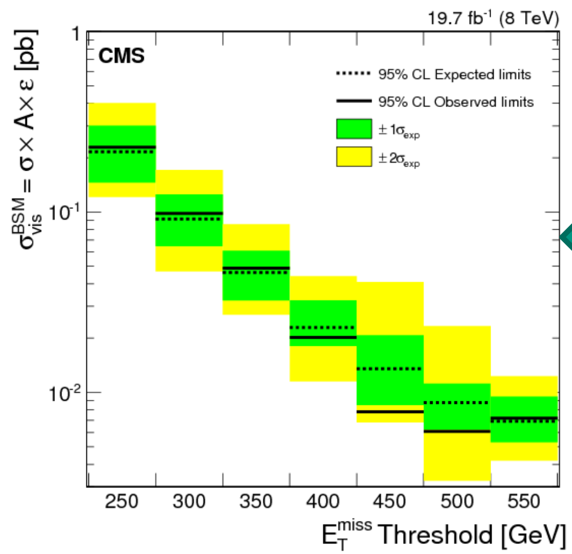
Extrapolating present results from monojet searches to 3000fb^{-1} leads to a comparable sensitivity and coverage compared to direct dark matter searches for light DM masses.

Backup

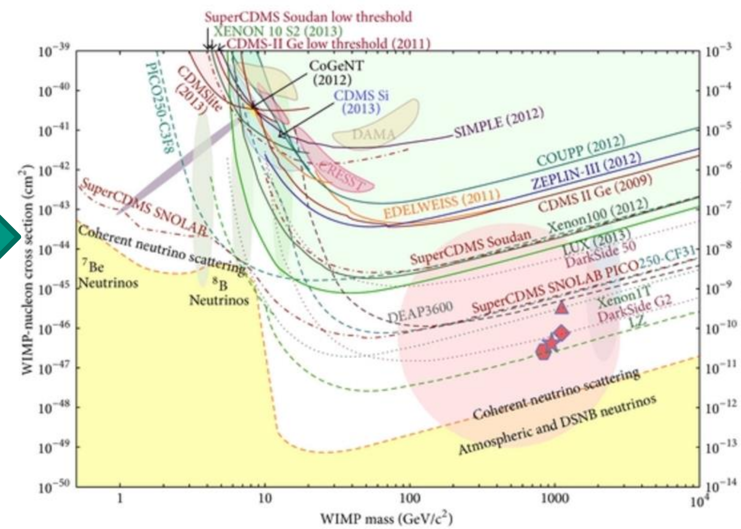
Searches for Dark Matter

Monojet, events characterized by the emission of a single hard jet, used as signature to probe the direct production of invisible dark matter particles in pp collisions.

arXiv:1408.3583



Can they be compared?

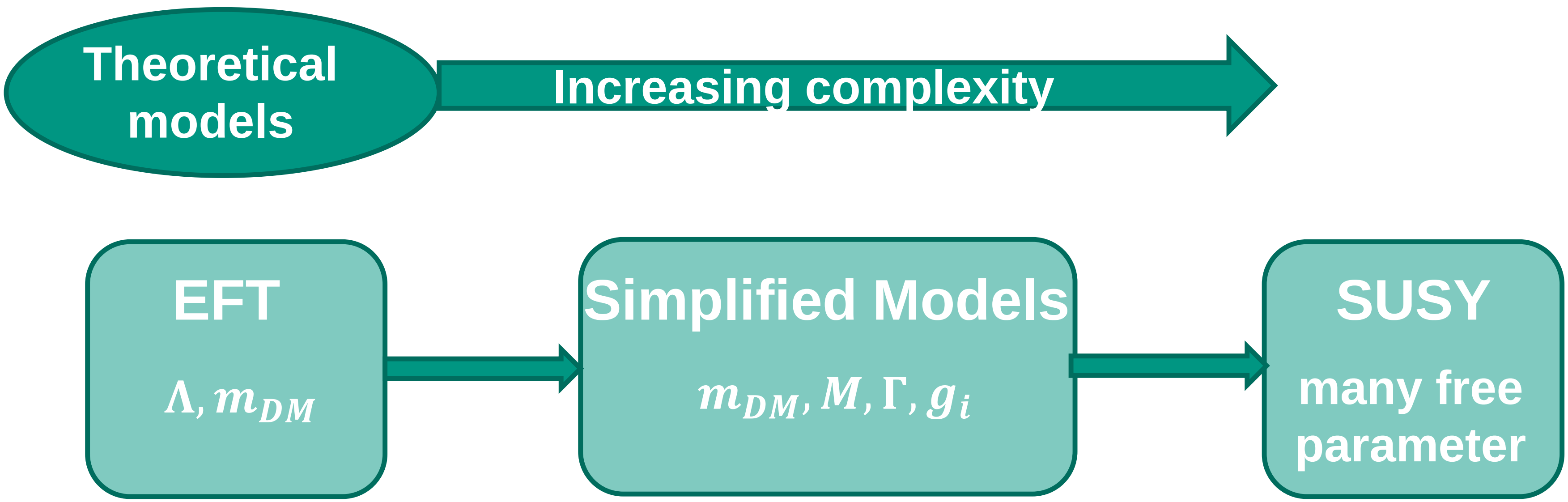


arXiv:1310.8327

Constraints from monojets are used to compare the results of direct DM searches (DDMS) by computing the scattering cross section of DM with matter.

Comparison of Monojets and direct DM searches

Beware: LHC data interpreted within effective theories or simplified models. Both not appropriate to compare with direct scattering experiments, because of different diagrams.



LHC is a gluon collider, so diagrams between direct DM searches and LHC searches different.

Why we are interested in the NMSSM

- **MSSM**

Loop corrections Δ_{rad} $< m_Z^2$

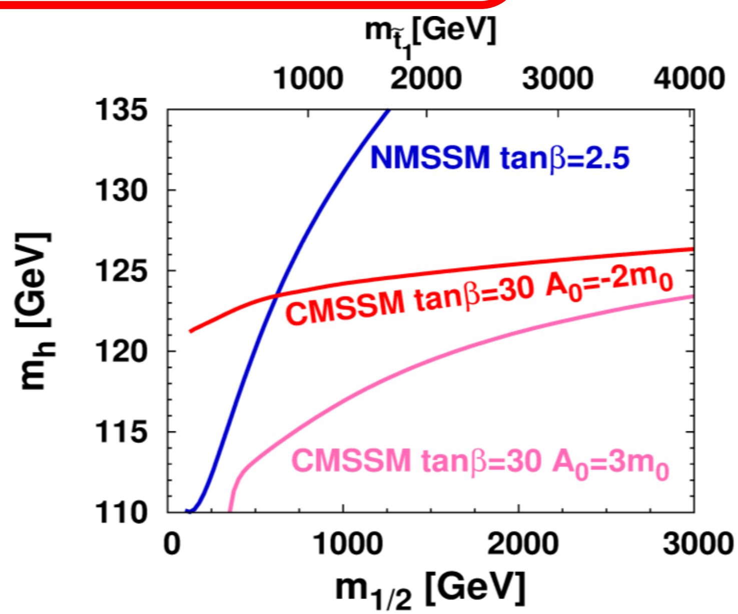
$$\underbrace{m_h^2}_{< m_Z^2} \approx \underbrace{m_Z^2 \cos^2 2\beta}_{} + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

- **NMSSM: Mixing with singlet**

$$m_h^2 \approx \lambda^2 v^2 \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta_{rad}$$

Increases Higgs mass for large values of λ already at Born level

Ellwanger, arXiv 1108.0157

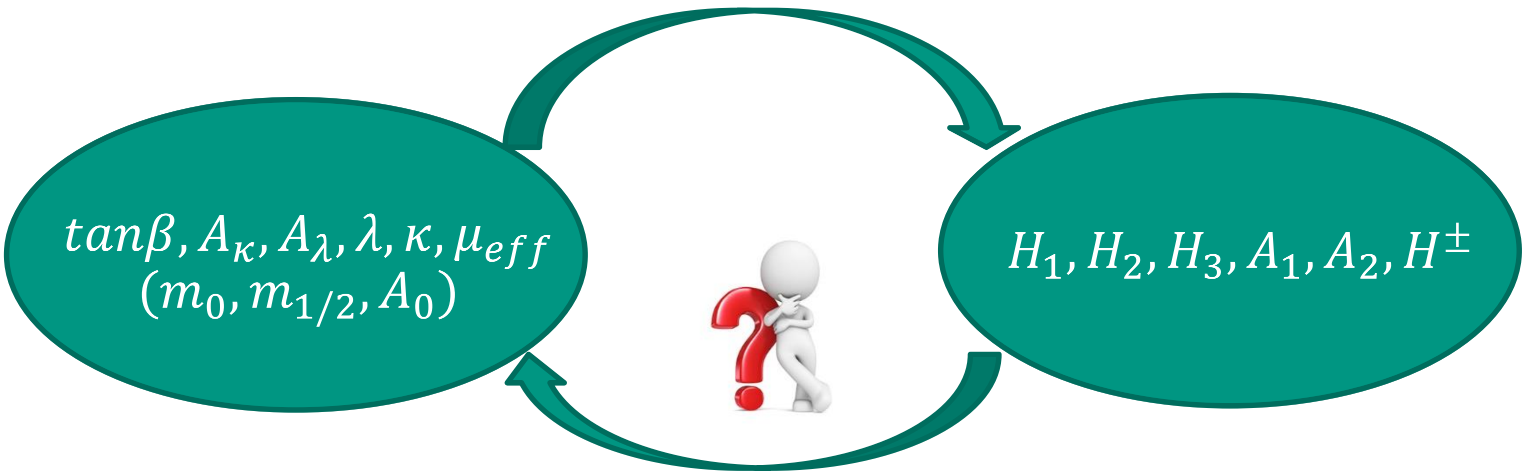


NMSSM: m_h=125 GeV for TeV instead of multi-TeV stops

Principle Fitting procedure

- 6 free parameter (6D) are needed to describe the Higgs sector in the NMSSM consisting of 6 Higgs bosons (6D)

calculated with NMSSMTools*



Question: Can we invert the problem and fit the free couplings and NMSSM parameters for fixed Higgs masses to determine range for BRs?

* D. Das, U. Ellwanger, and A. M. Teixeira, arXiv:1106.5633

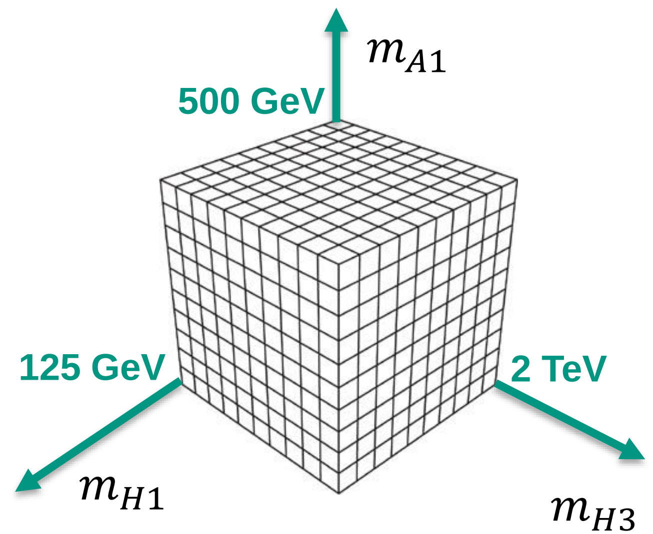
Reduction of the 6D Higgs mass space

- $H_3, H^{\pm}$ and A_2 are considerd to be degenerate in mass
- One observed 125 GeV Higgs with SM couplings

→ 3 undetermined free Higgs masses in the NSSM (3D)

- Provide 3D grid for unknown m_{H1}-m_{H3}- m_{A1} masses
- For each mass combination MINUIT* is used to determine corresponding NMSSM parameters

Efficient sampling of the parameter space and determination of the couplings



* F. James and M. Roos, Comput.Phys.Commun. 10 (1975) 343-367

χ^2 Function $\chi^2_{tot} = \chi^2_{H_1} + \chi^2_{H_2} + \chi^2_{H_3} + \chi^2_{LEP} + \chi^2_{\boldsymbol{LHC}}$

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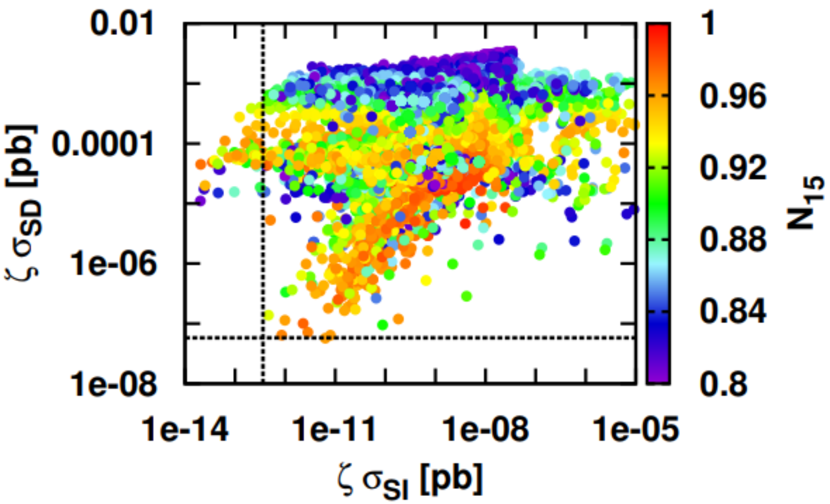
- $\chi^2_{H_1} = \frac{(m_{H_1} - m_{grid,H_1})^2}{\sigma^2_{H_1}}$
  - m_{grid,H_1} : Chosen point in the 3D mass space
  - m_{H_1}: below observed Higgs boson, $\sigma^2_{H_1}$ set to 2 GeV
- $\chi^2_{H_2} = \frac{(m_{H_2} - m_{obs})^2}{\sigma^2_{SM}} + \sum_i (c^i_{H_2} - c_{obs})^2 / \sigma^2_{coup}$
  - 125 GeV Higgs boson with SM couplings , $c^i_{H_2}$: reduced couplings of H_2, ratio of couplings of H_2 to particle $i = f_u, f_d, W, Z, \gamma$. Observed coupling c_{coup} agree within 10% with the SM couplings, so $\sigma^2_{coup} = 0.1$.
- $\chi^2_{H_3/A_1} = \frac{(m_{H_3/A_1} - m_{grid,H_3/A_1})^2}{\sigma^2_{H_3/A_1}}$
- χ^2_{LEP}: includes the LEP constraints on the couplings of a light Higgs boson below 115 GeV and the limit on the chargino mass
- χ^2_{LHC}: includes the LHC constraints as implemented in NMSSMTools

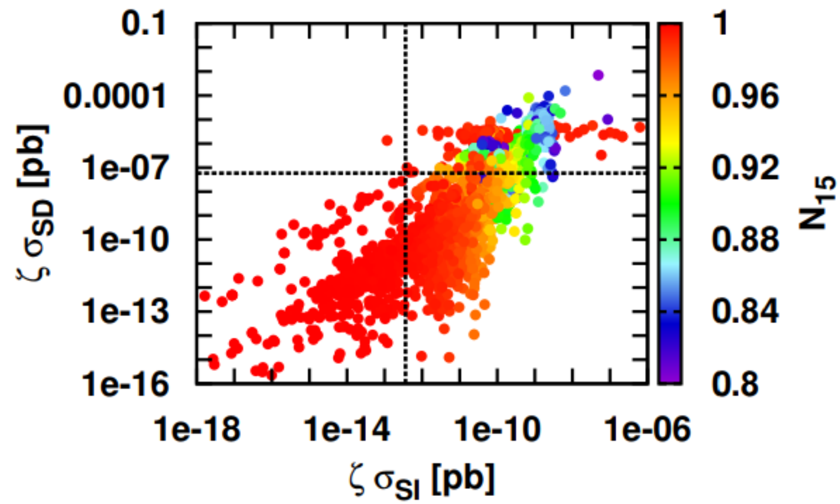
Efficient sampling of Parameter Space - Example

- Dividing the axis of the 3D space into X~100 bin require a total of X^3 Minuit fits, which is quite feasible instead of random sampling in the 6D parameters of the Higgs parameters
- E.g. efficient sampling of parameter space allows to find points in parameter space which will elude the future searches for dark matter at the Darwin experiment

Scenario I (large λ, κ, small $\tan\beta$)



Scenario II (small λ, κ, large $\tan\beta$)



NMSSM – neutralino sector

- **Mass matrix M_0 has an additional singlino component in NMSSM**

$$M_0 = \begin{pmatrix} \mathbf{M_1} & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ 0 & \mathbf{M_2} & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_2 v_d}{\sqrt{2}} & 0 & -\mu_{eff} & -\lambda v_u \\ \frac{g_1 v_u}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & -\mu_{eff} & 0 & -\lambda v_d \\ 0 & 0 & -\lambda v_u & -\lambda v_d & \sqrt{2}\frac{\kappa}{\lambda}\mu_{eff} \end{pmatrix}$$

MSSM

NMSSM

$$M_1 \approx 0.4 m_{1/2}, M_2 \approx 0.8 m_{1/2}, M_3 \approx 2.7 m_{1/2}$$

Small ratio $\frac{\kappa}{\lambda}$ and small μ_{eff} needed

5x5 neutralino mixing matrix

$$\Rightarrow \quad \tilde{\chi}_1^0 = \tilde{B} + \tilde{W} + \tilde{H}_1 + \tilde{H}_2 + \tilde{S}$$

LSP and A1 < 60 GeV possible but small region in parameter space