The better NMSSM:

Naturaleness and enhanced diphoton rates at Fermi and the LHC

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CERN

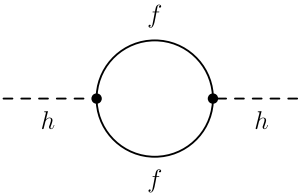
based on

1205.1509, 1208.1683, 1211.2835

DESY Theory Seminar

Motivation

- Higgs finally found! $\Rightarrow$ the hierarchy problem exists.



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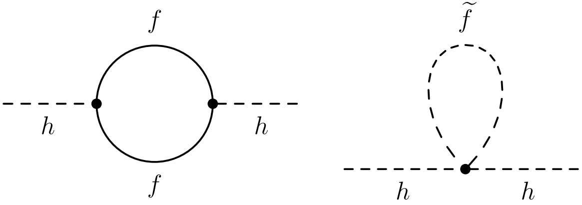

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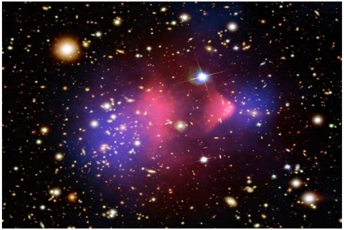

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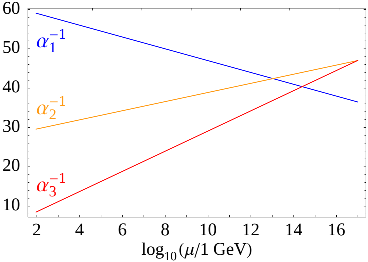

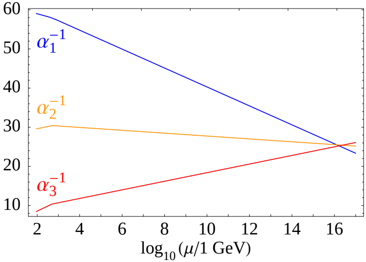

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Renewed interest in the NMSSM

MSSM superpotential

- The gauge-invariant superpotential terms of the MSSM include

$$\begin{aligned}\mathcal{W} \;=\; & \mu H_u H_d + \kappa_i L_i H_u \\ & + Y_e^{ij} H_d L_i E_j^c + Y_d^{ij} H_d Q_i D_j^c + Y_u^{ij} H_u Q_i U_j^c \\ & + \lambda^{(0)}_{ijk} L_i L_j E_k^c + \lambda^{(1)}_{ijk} L_i Q_j D_k^c + \lambda^{(2)}_{ijk} U_i^c D_j^c D_k^c \\ & + \kappa^{(0)}_{ij} H_u L_i H_u L_j + \kappa^{(1)}_{ijk\ell} Q_i Q_j Q_k L_\ell + \kappa^{(2)}_{ijk\ell} U_i^c U_j^c D_k^c E_\ell^c\end{aligned}$$

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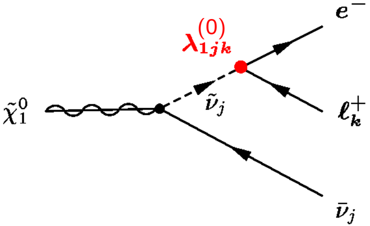
- No stable dark matter candidate



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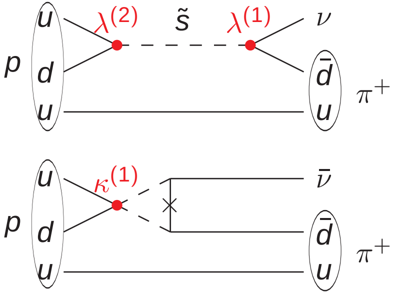

R parity

Standard symmetry in the MSSM:

$\mathbb{Z}_2$ R parity   Farrar & Fayet; Dimopoulos, Raby, Wilczek

$$
\begin{aligned}
\mathcal{W} = \; & \mu H_u H_d + \not{\kappa_i} L_i H_u \\
& + Y_e^{ij} H_d L_i E_j^c + Y_d^{ij} H_d Q_i D_j^c + Y_u^{ij} H_u Q_i U_j^c \\
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\end{aligned}
$$

- Experiment: $\kappa_{ijk\ell} < \frac{10^{-8}}{M_\mathrm{P}}$
- By far not suffient to make the proton stable!
- does not solve the μ problem...

NMSSM

- MSSM plus extra singlet S
- Standard symmetry for the NMSSM: global $\mathbb{Z}_3$ + R parity

$$\mathcal{W}_{\rm NMSSM} = \mathcal{W}^{\mu=0}_{\rm MSSM} + \lambda\, S\, H_u\, H_d + \frac{1}{3}\kappa\, S^3$$

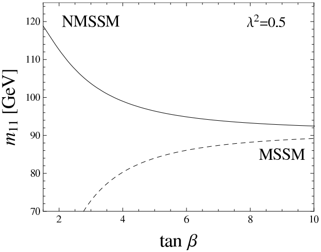
- Original motivation: Solve the μ problem: $\mu_{\rm eff} = \lambda \langle S \rangle$

Nice feature:

Additional tree-level contribution to Higgs mass:

$$M_Z^2 \cos^2(2\beta) + \lambda^2 v^2 \sin^2(2\beta) + \text{radiative corrections}$$

- Upper bound only...
- perturbativity bound: $\lambda \lesssim 0.7$



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- domain wall problem   Abel, Sarkar & White

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- tadpole problem (e.g. from $(H_u H_d)^2$ operator)
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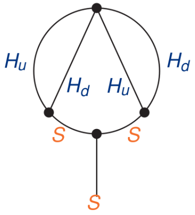

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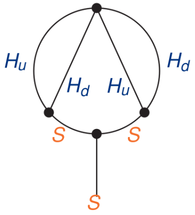

The $\mathbb{Z}_3$ symmetric NMSSM is (basically) excluded!

Need another underlying symmetry!

$\mathbb{Z}_N^R$ symmetries

arXiv:1009.0905

arXiv:1102.3595

N	$\mathcal{W}$	$q_{\mathbf{10}}$	$q_{\overline{\mathbf{5}}}$	q_{H_u}	q_{H_d}	q_S
4	2	1	1	0	0	2
8	2	1	5	0	4	6

The $\mathbb{Z}_4^R$ case: MSSM part

$$
\begin{aligned}
\mathcal{W} \;=\; & \cancel{\mu}\, \underbrace{H_u\, H_d}_{0} + \cancel{\kappa_i}\, \underbrace{L_i\, H_u}_{1} \\
& + Y_e^{ij}\, \underbrace{H_d\, L_i\, E_j^c}_{2} + Y_d^{ij}\, \underbrace{H_d\, Q_i\, D_j^c}_{2} + Y_u^{ij}\, \underbrace{H_u\, Q_i\, U_j^c}_{2} \\
& + \cancel{\lambda_{ijk}^{(0)}}\, \underbrace{L_i L_j E_k^c}_{3} + \cancel{\lambda_{ijk}^{(1)}}\, \underbrace{L_i Q_j D_k^c}_{3} + \cancel{\lambda_{ijk}^{(2)}}\, \underbrace{U_i^c\, D_j^c\, D_k^c}_{3} \\
& + \kappa_{ij}^{(0)}\, \underbrace{H_u\, L_i\, H_u\, L_j}_{2} + \cancel{\kappa_{ijk\ell}^{(1)}}\, \underbrace{Q_i\, Q_j\, Q_k\, L_\ell}_{0} + \cancel{\kappa_{ijk\ell}^{(2)}}\, \underbrace{U_i^c\, U_j^c\, D_k^c\, E_\ell^c}_{0}
\end{aligned}
$$

The $\mathbb{Z}_4^R$ case: MSSM part

$$\begin{aligned}\mathcal{W} &= \frac{1}{M_\mathrm{P}^2}\underbrace{\langle\mathcal{W}\rangle H_u\,H_d}_{2} + \cancel{\kappa_i}\,\underbrace{L_i\,H_u}_{1}\\ &\quad + Y_e^{ij}\,\underbrace{H_d\,L_i\,E_j^c}_{2} + Y_d^{ij}\,\underbrace{H_d\,Q_i\,D_j^c}_{2} + Y_u^{ij}\,\underbrace{H_u\,Q_i\,U_j^c}_{2}\\ &\quad + \cancel{\lambda_{ijk}^{(0)}}\,\underbrace{L_iL_jE_k^c}_{3} + \cancel{\lambda_{ijk}^{(1)}}\,\underbrace{L_iQ_jD_k^c}_{3} + \cancel{\lambda_{ijk}^{(2)}}\,\underbrace{U_i^c\,D_j^c\,D_k^c}_{3}\\ &\quad + \kappa_{ij}^{(0)}\,\underbrace{H_u\,L_i\,H_u\,L_j}_{2} + \frac{1}{M_\mathrm{P}^4}\underbrace{\langle\mathcal{W}\rangle Q_i\,Q_j\,Q_k\,L_\ell}_{2} + \frac{1}{M_\mathrm{P}^4}\underbrace{\langle\mathcal{W}\rangle U_i^c\,U_j^c\,D_k^c\,E_\ell^c}_{2}\end{aligned}$$

- need $\langle\mathcal{W}\rangle \sim m_{3/2}M_\mathrm{P}^2$ to cancel cosmological constant
- $\mu \sim \langle\mathcal{W}\rangle/M_\mathrm{P}^2 \sim m_{3/2}$
- proton decay operators suppressed by $\langle\mathcal{W}\rangle/M_\mathrm{P}^4 \sim 10^{-15}/M_\mathrm{P}$
- matter parity exact

Singlet part

- Allowed superpotential terms for $\mathbb{Z}^R_{4/8}$

$$\mathcal{W}_{\mathbb{Z}^R_{4/8}} = \mathcal{W}^{\mu=0}_{\text{MSSM}} + \lambda\, S\, H_u\, H_d + \kappa\, S^3 + M^2 S$$

$\mathbb{Z}^R_4$: reintroduces hierarchy problem if $M \gtrsim M_{EW}$

- Allowed superpotential terms for $\mathbb{Z}_{4/8}^R$

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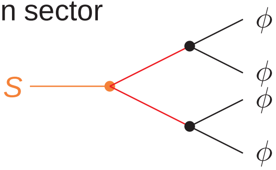
$\mathbb{Z}_4^R$: reintroduces hierarchy problem if $M \gtrsim M_{EW}$

- assume only trilinear couplings in $\mathcal{W}$ and intermediate VEVs $\langle\phi\rangle$ in hidden sector



$$\Rightarrow \quad S\,\underbrace{\langle\phi\rangle^4/M_{\mathrm{P}}^2}_{\sim M_{EW}^2}$$

- However: linear term can also be generated radiatively
- divergent tadpoles arise from even (odd) terms in the super (Kähler) potential   Abel

$\Rightarrow$ Hierarchy problem not reintroduced

The GNMSSM

What about the domain wall problem?

$$\langle \mathcal{W} \rangle \sim m_{3/2} M_{\mathrm{P}}^2 \sim 10^{13}\ \mathrm{GeV}$$

$\Rightarrow$ corresponding domain walls inflated away

$$\begin{aligned}
\Delta \mathcal{W}_{\mathbb{Z}_4^R} &= \langle \mathcal{W} \rangle + \langle \mathcal{W} \rangle^2 S + \langle \mathcal{W} \rangle S^2 + \langle \mathcal{W} \rangle H_u H_d \\
&\sim m_{3/2} M_{\mathrm{P}}^2 + m_{3/2}^2 S + m_{3/2} S^2 + m_{3/2} H_u H_d
\end{aligned}$$

$$\mathcal{W}_{\mathrm{GNMSSM}} = \mathcal{W}_{\mathrm{NMSSM}} + \mu H_u H_d + \frac{1}{2} \mu_s S^2$$

- Phenomenological implications?

The GNMSSM

- Upper bound on the lightest Higgs mass same as in NMSSM
- Difference? Look at naturaleness
- Correct electroweak symmetry breaking requires (MSSM case):

$$m_Z^2 = -2(m_{h_u}^2 + |\mu|^2) + \mathcal{O}(1/\tan\beta^2)$$

- Cancellations of unrelated parameters required
- Standard definition of fine-tuning   Ellis et al;   Barbieri, Giudice

$$\Delta \equiv \max \mathrm{Abs}\big[\Delta_p\big], \qquad \Delta_p \equiv \frac{\partial \ln v^2}{\partial \ln p} = \frac{p}{v^2}\frac{\partial v^2}{\partial p}$$

- p is ‘fundamental’ parameter of the theory

Fine-Tuning in the GNMSSM

- Outcome depends on what is the 'fundamental' theory, i.e. what is assumed for SUSY breaking
- Simplest case: 'CGNMSSM' with $m_{1/2}, m_0, A_0, \tan\beta, \lambda, \kappa, v_s, \mu_s$.
- Full 'state of the art' evaluation with *SPHENO*

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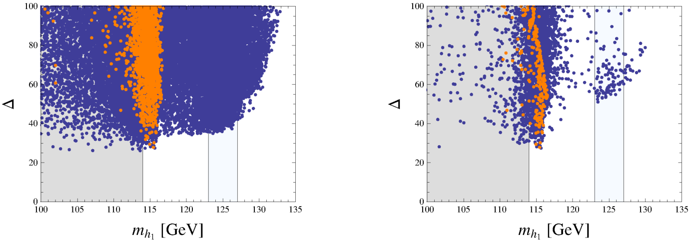

- Pheno: MSSM like with heavier Higgs, singlets rather heavy.
- stau coannihilation region for relic abundance

Fine-Tuning in the GNMSSM

- Other option - allow for non-universal gaugino masses with $M_1 = a \cdot m_{1/2}$, $M_2 = b \cdot m_{1/2}$, $M_3 = m_{1/2}$

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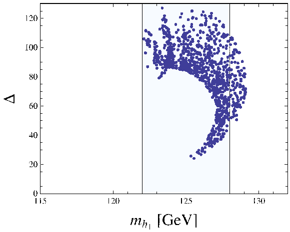
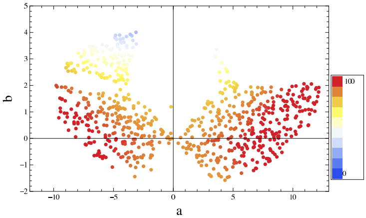
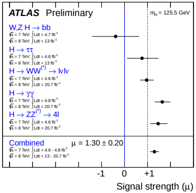




- more freedom in neutralino sector: DM and compressed spectra
- Low fine-tuning requires small tan β and large λ!
- What are the implications for the Higgs sector?

Enhanced diphoton rate



- Two easy options to enhance the di-photon rate
  - suppress partial width into bb to increase BR
  - **light** charged particles in the loop to increase partial width into $\gamma\gamma$
- only option in MSSM: 'light stau scenario' Carena et al
- needs very large $\mu \cdot \tan\beta \Rightarrow$ unnatural, danger of CCB vacuum
- what about $H^{\pm}$ or $\chi^{\pm}$?

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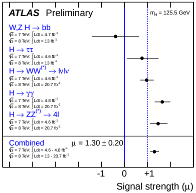

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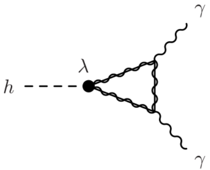

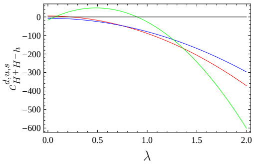

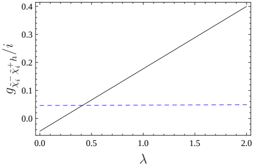

- Enhancemant via charginos requires (small) singlet component

Full Analysis

- Potentially very large effects for large λ
- Use low energy variables to see what is possible
- take into account the Higgs mass, production cross section, ...

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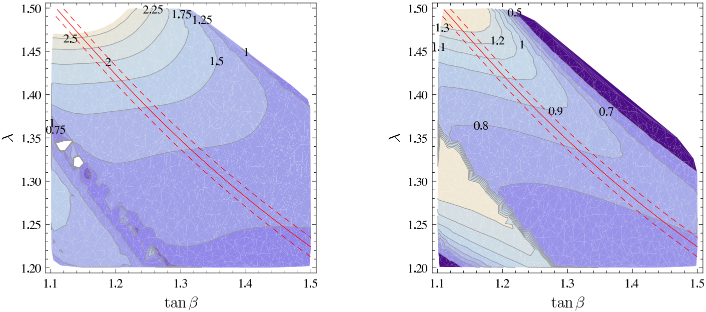
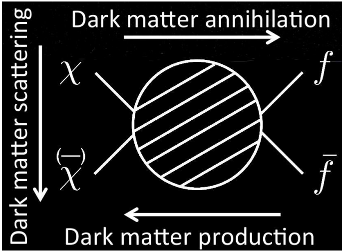


- Enhancement of the diphoton signal by a factor 2 with SM like WW, the correct Higgs mass etc. possible
- main enhancement due to light charginos (higgsinos)...

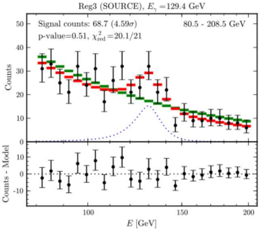
Dark matter indirect detection

- Indirect detection experiments look for the products of DM annihilation in regions of high DM density (e.g. the galactic center)
- Photons particularly interesting - preserve spatial information
- Photon line would be smoking gun for DM



Fermi LAT

- DM annihilation seen by Fermi?



Weniger

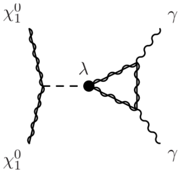
Significance of the signal: around 4 σ

Inferred dark matter properties:

- $m_\chi \sim$ 130 GeV (135 GeV)
- large annihilation cross section into photons, $\langle \sigma v \rangle \sim 10^{-27}$ cm^3/s
- Any particle physics models?

Fermi LAT and GNMSSM

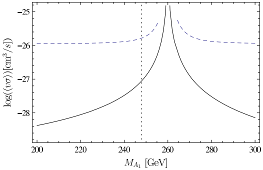
- GNMSSM: charginos show up in similar diagrams as before...

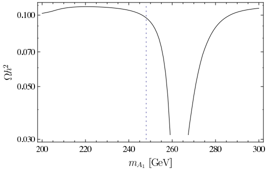


- Picture: mainly singlino neutralino, mainly singlet CP odd Higgs
- NOT possible in the usual NMSSM! Das, Ellwanger
- GNMSSM: possible to realise 130 GeV DM with correct $\langle\sigma v\rangle_{\gamma\gamma}$
  - with correct relic abundance
  - consistent with continuum photon flux
  - consistent with direct detection constraints
  - consistent with electroweak observables
  - 125 GeV Higgs with slightly enhanced diphoton rate

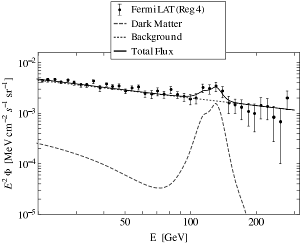
How fine-tuned?

- how much on resonance exactly?





- No cancellations required for singlet like CP odd scalar
- Observational picture...



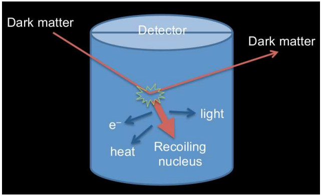
SUSY Summary

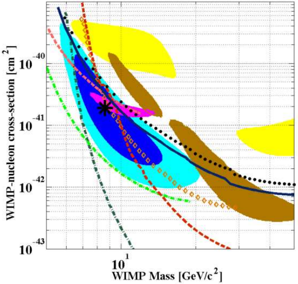
- 125 GeV Higgs makes MSSM singlet extensions very interesting
- $\mathbb{Z}_3$-symmetric NMSSM (basically) excluded
- Interesting NMSSM like structure with additional mass terms based on discrete R symmetry
- Reasonable fine-tuning for measured Higgs mass, correct relic density,...
- Small fine-tuning correrspónds to large λ
- Large λ allows for significant enhancement of $h \to \gamma\gamma$ while keeping $h \to WW$ SM like
- Also allows for a simultaneous explanation of the Fermi line

Still work to be done - join in!

Dark matter in CDMS-Si?

- Recently at the direct detection front...

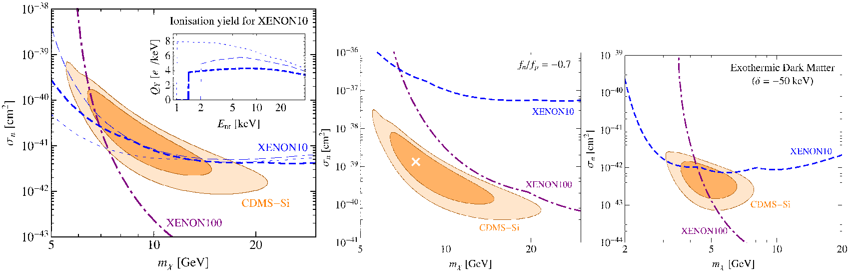




- CDMS-Si has observed three events with a background estimate of < 0.62 events   1304.4279
- Interpretation in terms of dark matter preferred with about 3 σ
- In tension with bounds from XENON10/100

Dark matter in CDMS-Si?

- We find significantly weaker bounds from XENON10 1304.6066
- In contact with the XENON collaboration...



- Take home message: There is a dark matter signal which is not ruled out even with standard assumptions

Dark matter in CDMS-Si?

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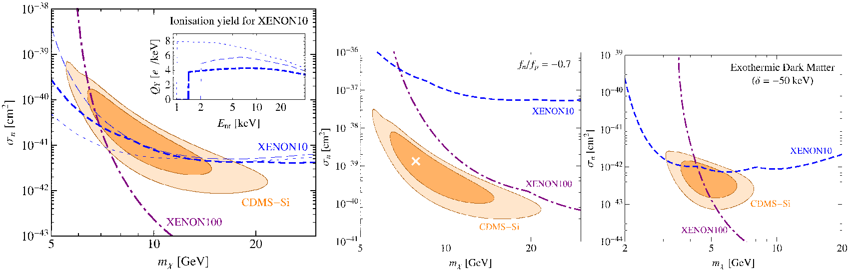

- Take home message: There is a dark matter signal which is not ruled out even with standard assumptions

Thank You!