Phenomenology of the MRSSM.

A light singlet in the dark and at the LHC

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HARMONIA Meeting

and Theory Particle Physics Seminar

Warsaw, May 29th 2017

HELMHOLTZ
GEMEINSCHAFT

DESY

Outline

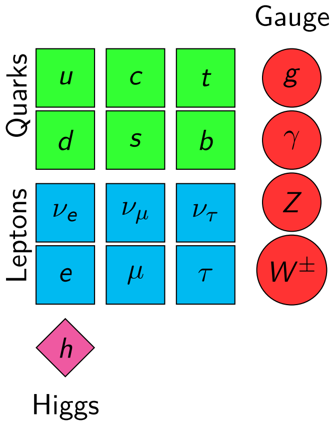
Introduction
- R-Symmetry
- MRSSM

Higgs sector
- Higgs boson mass
- Light singlet phenomenology

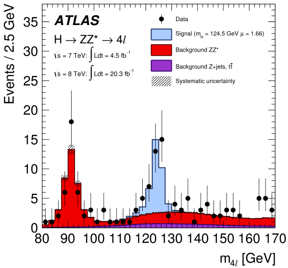
LHC phenomenology

Dark matter
- Direct detection
- Relic density

The Standard Model of particle physics



Success!



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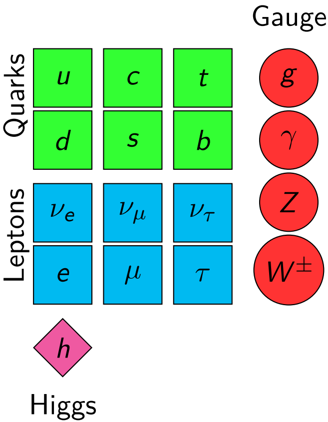

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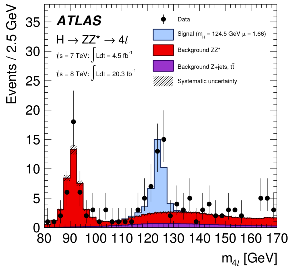
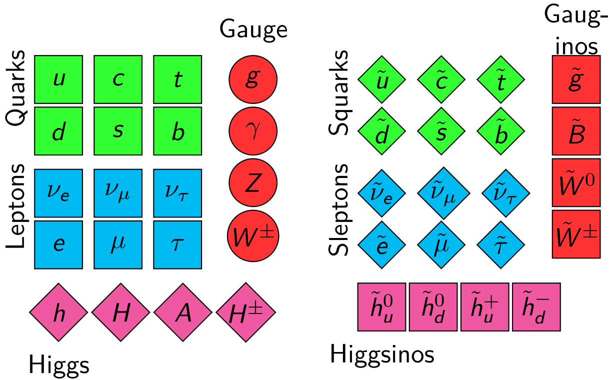


And trouble

- Hierarchy problem
- Dark matter
- Including Gravity
- ...

The MSSM



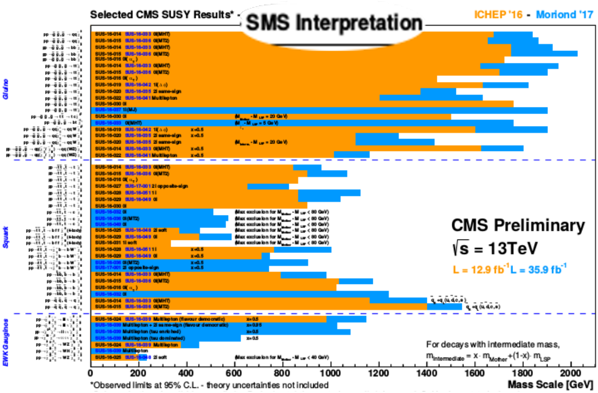
> SUSY solves hierarchy problem

> LSP can be DM

Caveat: Expect SUSY states to directly show up at LHC

Going beyond the MSSM

- LHC Run 2 on-going
- So far no obvious sign of MSSM



Going beyond the MSSM

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- Look into non-minimal models for range of alternative predictions

Possibilities

- More Higgs (NMSSM, TMSSM)
- More gauge (UMSSM, BLMSSM, E_6SSM)
- Less symmetry (RPV)
- ...

Going beyond the MSSM

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R-Symmetry

- Includes solution to flavor problem of the MSSM
- Dirac gauginos (esp. gluino) might explain SUSY non-discovery
- Extended Higgs sector, different predictions than (N)MSSM
- Salam '74, Fayet '74

R-Symmetry

- Additional symmetry allowed by SUSY algebra described in "Haag-Łopuszański-Sohnius-Theorem"
- For $N = 1$ SUSY it is a global $U(1)_\mathrm{R}$ symmetry
  $\rightarrow$ charged Spinor coordinates:
  $Q_\mathrm{R}(\theta) = 1$, $Q_\mathrm{R}(\bar{\theta}) = -1; \quad (\theta \rightarrow e^{i\tau}\theta, \bar{\theta} \rightarrow e^{-i\tau}\bar{\theta})$
- Lagrangian has to be invariant:
  - superpotential has $Q_\mathrm{R} = 2$; $\mathcal{L}_\mathcal{W} = \int \mathrm{d}^2\theta \mathcal{W}$
  - softbreaking terms have $Q_\mathrm{R} = 0$
- SM fields have $Q_\mathrm{R} = 0$

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	Q_R	scalar	vector	fermionic
vector superfield	0	-	0	1
chiral superfield	Q	Q	-	$Q-1$

$\rightarrow$ Higgs superfield: $Q_\mathrm{R} = 0$; matter superfields: $Q_\mathrm{R} = 1$

Symmetry or Parity?

Transformation of superfield

$$\exp(i\tau R)F(x^\mu,\theta,\overline{\theta})\exp(-i\tau R)=\exp(i\tau Q_R)F(x^\mu,\exp(-i\tau)\theta,\exp(i\tau)\overline{\theta})$$

$\tau \in \{0, 2\pi\}$

For R-parity τ fixed, as Z_2: $\tau = n\pi$

$$n \text{ odd} \Rightarrow \exp(-i\tau)=\exp(i\tau)=-1$$
$$n \text{ even} \Rightarrow \exp(-i\tau)=\exp(i\tau)=1$$

End up with matter parity ($(-1)^{3B+L+2S}$)

Consequences for model building

Symmetry forbids terms in Lagrangian

- Superpotential ($Q_R = 2$): $\mu \hat{H}_u \hat{H}_d$, $\lambda \hat{E}\hat{L}\hat{L}$, $\kappa \hat{U}\hat{D}\hat{D}$
- Soft breaking ($Q_R = 0$): $M_i \tilde{\lambda}_i \tilde{\lambda}_i$, $A y_e h_d \tilde{l} \tilde{e}_R$, $A y_u h_u \tilde{q} \tilde{u}_R$, $A y_d h_d \tilde{q} \tilde{d}_R$

Relaxes flavor problem, but no masses for gauginos and higgsinos

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Relaxes flavor problem, but no masses for gauginos and higgsinos

Solution: Dirac masses

$$\mathcal{L} \supset M^D \tilde{\lambda}_a \chi_a$$

$\tilde{\lambda}$ from vector superfield, χ from chiral superfield

How to get it

D-term breaking

spurion field strength $\mathcal{W}^\alpha = \theta^\alpha D$

$$\int \mathrm{d}^2\theta \, \frac{\sqrt{2}\mathcal{W}^\alpha}{\Lambda} W_\alpha^a \Phi^a \overset{\text{vev}}{=} -M^D \left(\lambda^a \psi^a - \sqrt{2} D^a \phi^a\right)$$

with mass given by vev of D: $M^D = \frac{\langle D \rangle}{\Lambda}$ (Λ breaking scale)

Supersoftness Fox, et.al. hep-ph/0206096

Finite threshold contribution to scalar soft breaking masses :

$$m^2 \sim \frac{C_i(r)\alpha_i M_D}{\pi}$$

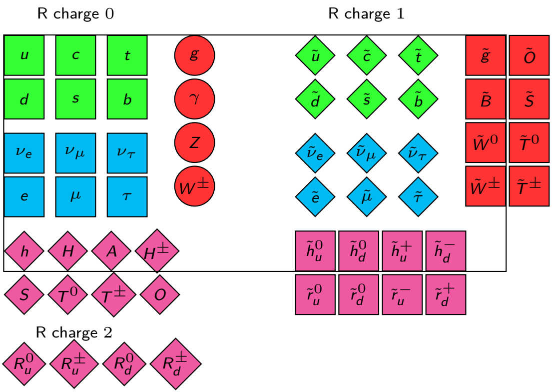
Minimal R-Symmetric Supersymmetric Standard Model

		$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_\mathrm{R}$
Singlet	$\hat{S}$	1	1	0	0
Triplet	$\hat{T}$	1	3	0	0
Octet	$\hat{O}$	8	1	0	0
R-Higgses	$\hat{R}_u$	1	2	$-1/2$	2
	$\hat{R}_d$	1	2	$1/2$	2

Kribs et.al. 0712.2039

Other realisations possible: Frugiuele et.al. 1107.4635, Davies et.al. 1103.1647, Riva et.al. 1211.4526

Minimal R-Symmetric Supersymmetric Standard Model



New interactions

Superpotential

$$\begin{aligned}\mathcal{W} =& y_e \hat{H}_d \hat{L} \hat{E} + y_d \hat{H}_d \hat{Q} \hat{d} - y_u \hat{H}_u \hat{Q} \hat{U} + \\ & \mu_d \hat{H}_d \hat{R}_d + \mu_u \hat{H}_u \hat{R}_u + \\ & \lambda_d \hat{H}_d \hat{R}_d \hat{S} + \lambda_u \hat{H}_u \hat{R}_u \hat{S} + \Lambda_d \hat{H}_d \hat{T} \hat{R}_d + \Lambda_u \hat{H}_u \hat{T} \hat{R}_u\end{aligned}$$

New interactions

Superpotential

$$\mathcal{W} = y_e \hat{H}_d \hat{L} \hat{E} + y_d \hat{H}_d \hat{Q} \hat{d} - y_u \hat{H}_u \hat{Q} \hat{U} +$$
$$\mu_d \hat{H}_d \hat{R}_d + \mu_u \hat{H}_u \hat{R}_u +$$
$$\lambda_d \hat{H}_d \hat{R}_d \hat{S} + \lambda_u \hat{H}_u \hat{R}_u \hat{S} + \Lambda_d \hat{H}_d \hat{T} \hat{R}_d + \Lambda_u \hat{H}_u \hat{T} \hat{R}_u$$

Soft SUSY Breaking

$$-\mathcal{L}_{\text{soft}} = M_i^D \tilde{\lambda}_i^a \psi_j^a - \sqrt{2} M_i^D D_j^a \phi_i^a + m_k^2 \phi_k \phi_k^* + B\mu h_u h_d$$
$$+ h.c.$$
$$\{i, j\} \in \{\{G, O\}, \{W, T\}, \{B, S\}\};$$
$$k \in \{q, u, d, l, e, H_d, H_u, R_d, R_u, S, T, O\}$$

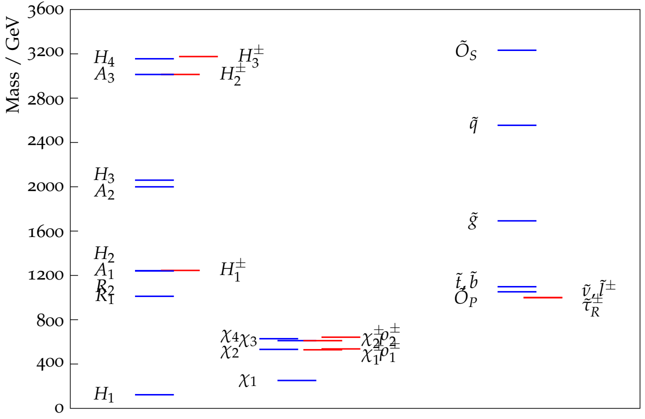
Other soft breaking terms related to S, T, O possible but for simplicity excluded here

Mass spectrum calculation

- Take Standard Model input at Z mass scale
- Convert everything consistently to $\overline{DR}$
- Run to M_{SUSY}
- Take MRSSM input parameters and calculate one-loop corrected masses
- Add further corrections to Higgs mass
- Tools: `SARAH`, `SPheno`,`FlexibleSUSY`,
- Automatizing for such a model complicated, many cross checks required

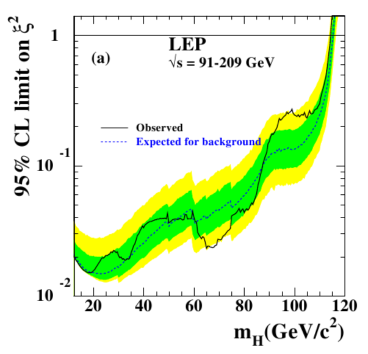
PD, Jan Kalinowski, Wojciech Kotlarski, Dominik Stöckinger
JHEP 1412 124, Adv.High Energy Phys. 2015 760729,
JHEP 1603 007

Example mass spectrum



Lighter Higgs boson

Experiment

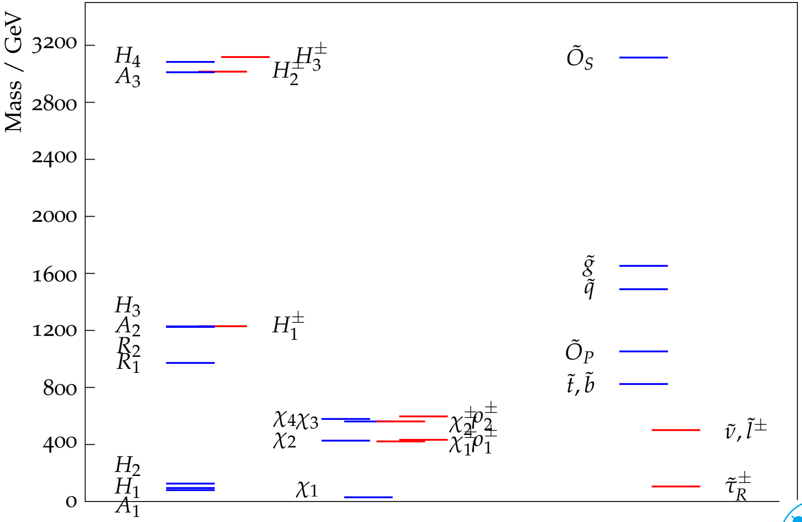


LEP Higgs Working Group

Theory

- Singlet extended SM
- 2HDM
- MSSM
- NMSSM

Mass spectrum with light singlet



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Higgs boson mass

- In SM Higgs boson mass is a free parameter
- In SUSY it is prediction of SUSY parameters as quartic coupling connected to gauge couplings
- Experimental value: 125.1 ± 0.3 GeV

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(Assuming no lighter state)

$$m_h^2 < m_Z^2 \cos^2 2\beta - v^2 \left(\frac{\left(g_1 M_B^D + \sqrt{2}\lambda\mu\right)^2}{4(M_B^D)^2 + m_S^2} + \frac{\left(g_2 M_W^D + \Lambda\mu\right)^2}{4(M_W^D)^2 + m_T^2} \right) \cos^2 2\beta$$

Radiative corrections

$$0 \stackrel{!}{=} \det\left[p^2\delta_{ij} - \hat{m}^2_{ij} + \Re(\hat{\Sigma}_{ij}(p^2))\right]_{p^2=m^2_{\text{pole}}} ,$$

Well-known one-loop loop corrections:

$$\Delta m^2_{h,Y_t} = \frac{6v^2}{16\pi^2}\left[Y_t^4 \log\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right]$$

No stop mixing

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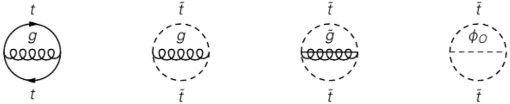
No stop mixing

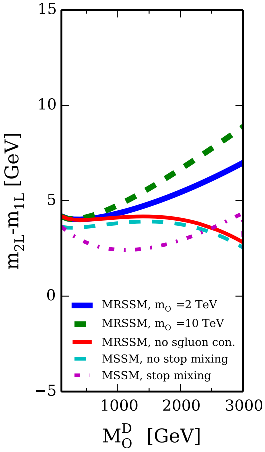
Also, for new Yukawa-like couplings ($\Lambda = \Lambda_u = \Lambda_d$, $\lambda = \lambda_u = -\lambda_d$):

$$\Delta m^2_{H_1,\text{eff.pot},\lambda} = \frac{2v^2}{16\pi^2}\left[\frac{\lambda^4}{2}\left(\log\frac{m^2_{R_u}}{(M^D_B)^2} + \log\frac{m^2_S}{(M^D_B)^2}\right) + \frac{5\Lambda^4}{8}\left(\log\frac{m^2_{R_u}}{(M^D_W)^2} + \log\frac{m^2_T}{(M^D_W)^2}\right)\right]$$

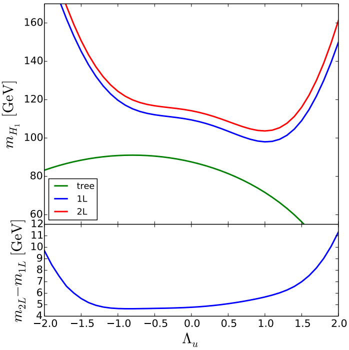
Two-loop effects



- around 5 GeV in size
- QCD effects most important
- Sgluon effects mimic MSSM A-terms



General Higgs mass summary



- Get correct Higgs mass without stop mixing
- Light stops possible
- Uncertainty is under discussion; ≈ 5 GeV

Singlet to the lightest

$$m_{h,\text{tree}}^2 \approx m_Z^2 \cos^2 2\beta - v^2 \cos^2 2\beta \left(\frac{\left(g_1 M_B^D + \sqrt{2}\lambda\mu\right)^2}{|m_S^2 + 4(M_B^D)^2 - m_Z^2 \cos^2 2\beta|} \right)$$

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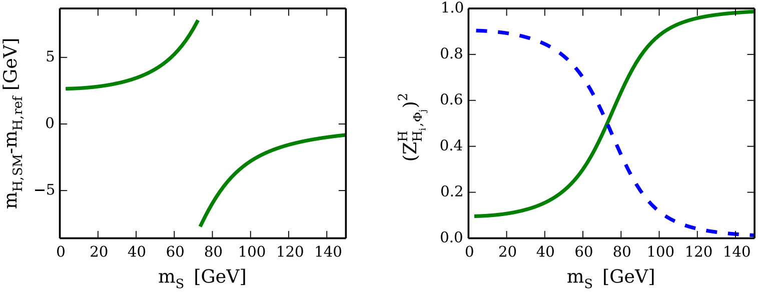
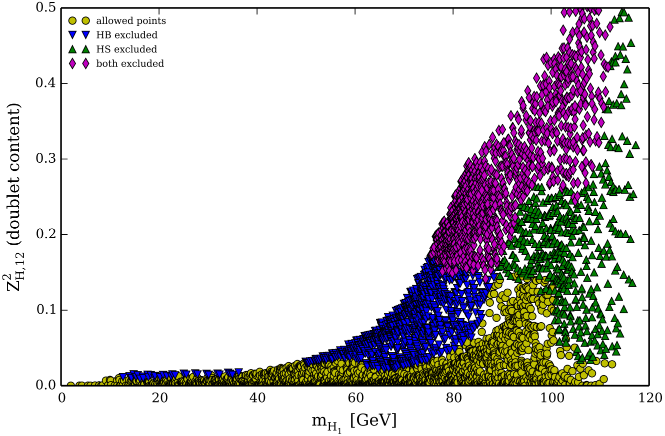


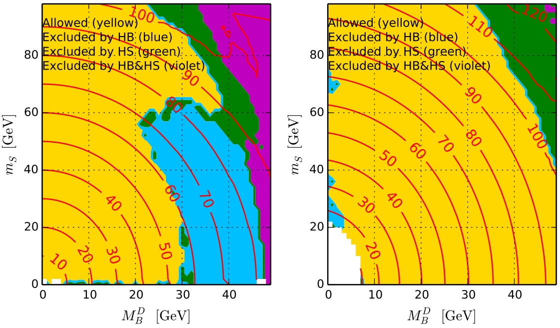
$$m_{H_S} \approx \sqrt{m_S^2 + 4(M_B^D)^2}$$

General light contraints

Via `HiggsBounds` and `HiggsSignals`
Depends on physical mass and mixing angle:



Bounds on the singlet



varying λ_u from zero to -0.01

> Depends on exactness of alignment

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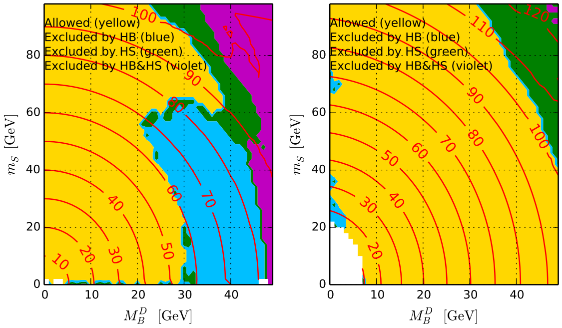


varying λ_u from zero to -0.01

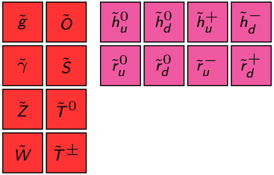
- Depends on exactness of alignment
- $m_{H_S} \approx \sqrt{m_S^2 + 4(M_B^D)^2}$ (red)
- Upper limit on singlet mass ~ 110 GeV
- $M_B^D \lesssim 55$ GeV

Connection bosonic and fermionic sector

$$m_{H_S} \approx \sqrt{m_S^2 + 4(M_B^D)^2}$$

Λ and λ important for Higgs loop corrections and doublet-singlet mixing

$$m_\chi = \begin{pmatrix} M_B^D & 0 & -\frac{1}{2} g_1 v_d & \frac{1}{2} g_1 v_u \\ 0 & M_W^D & \frac{1}{2} g_2 v_d & -\frac{1}{2} g_2 v_u \\ -\frac{1}{\sqrt{2}} \lambda_d v_d & -\frac{1}{2} \Lambda_d v_d & -\mu_d & 0 \\ \frac{1}{\sqrt{2}} \lambda_u v_u & -\frac{1}{2} \Lambda_u v_u & 0 & \mu_u \end{pmatrix};$$



Doubled number of states compared to MSSM

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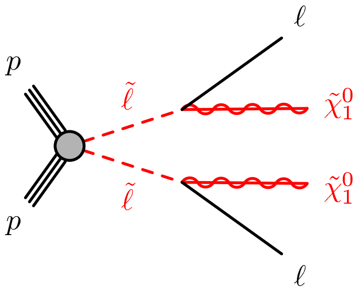
LHC searches

Electroweak production

- Upper limit on $M_B^D \Rightarrow$ Clear LSP candidate in χ_1^0
- Collider constraints on electroweak production
- LHC searches studied using `Herwig++` and `CheckMATE`
- Experimental analyses used: 2 or 3 lepton + E_{miss}^T from ATLAS 8 TeV

  [ATLAS, JHEP05(2014)071; JHEP04(2014)169]
- Strong production very sensitive to NLO corrections, not done here

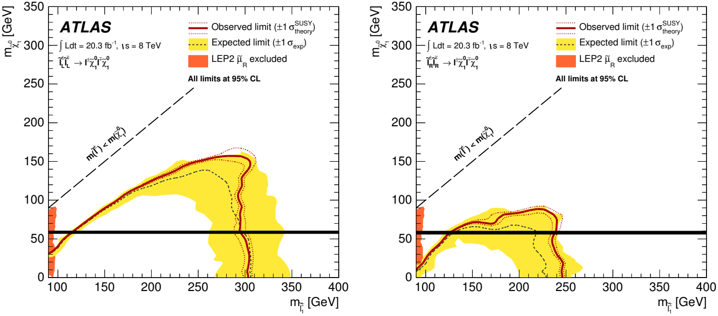
Sleptons at the LHC



- only same chirality slepton production
- Third generation relevant for other observables, but no results
- No update for 13 TeV

Sleptons II

Direct production of Sleptons similar to MSSM/simplified model:



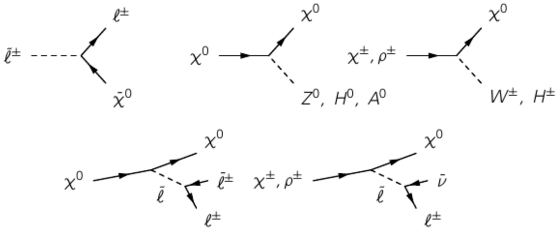
Taken from ATLAS, JHEP05(2014)071; 2l+ETmiss

- For LSP masses here, low mass region very constrained
- Limits for selectrons and smuons
- No limits on direct stau production

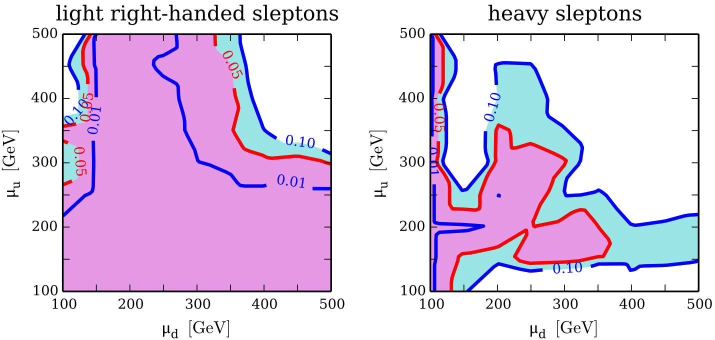
Production of electroweakinos

Differences to the MSSM

- Dirac neutralino
- Doubled number of degrees of freedom
- But also R-charge conservation for process
- Higgsinos have different masses:
  $\mathcal{W} \supset \mu_d \hat{H}_d \hat{R}_d + \mu_u \hat{H}_u \hat{R}_u$



Recasting searches



$m_{\text{LSP}} = 50$ GeV

- Down- and up-Higgsino don't mix as strongly as in MSSM
- Decay to LSP and SM particles also different because of composition with new states
- Competing decay chains don't allow for universal limit

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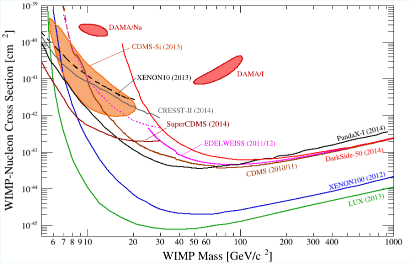
Dark matter

Direct detection



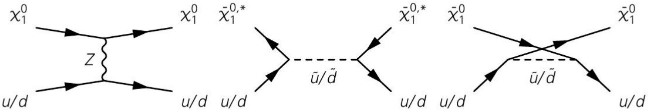
(LUX 2013 result)

Relic density

After freeze-out
$\Omega h^2 = 0.1187 \pm 0.0017$
(PLANCK)

R-Symmetric dark matter first studied in Buckley, et. al. 1307.3561

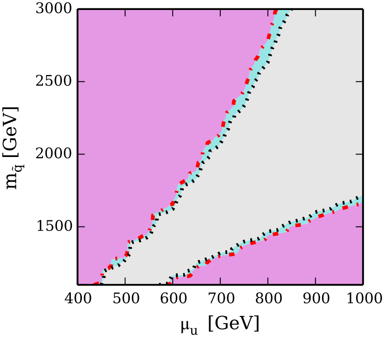
Direct Detection



- Neutralino is mainly bino-like, with some higgsino components
- Squark and Z-boson exchange
- Dirac LSP has vector interaction $\rightarrow$ couples to valence quarks
- Spin-independet scattering

Direct Detection

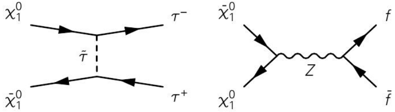
- Because of vector interaction naively TeV scale bounds
- But deconstructive interference **very important!**
- $m_{\tilde{q}} = \sqrt{\frac{7+11\frac{A-Z}{Z}}{3}}\mu_u \overset{\text{Xe}}{\approx} 2.2\mu_u$

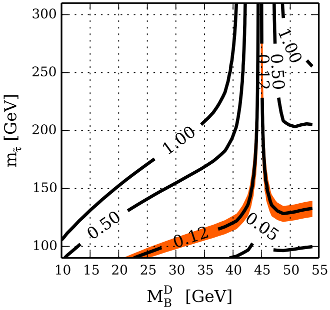


Relic density

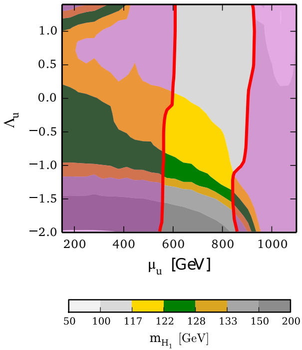
Dark matter candidate

- Bino-Singlino is LSP
- Dirac fermion
- Annihilation using right-handed staus favored





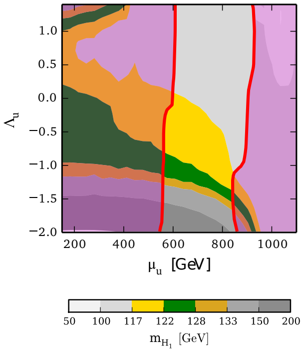
Correlations in Parameter space



> Light singlet pops up at LHC
> fermionic superpartner is LSP
> Prediction for squark masses
> Prediction other electroweakinos
> Prediction BSM-couplings

This scenario is very predictive

Correlations in Parameter space



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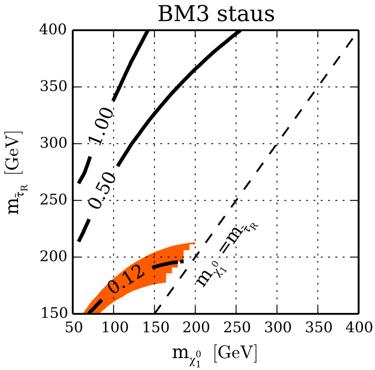
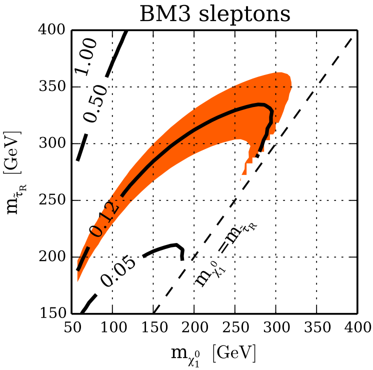
Alternative: Evade direct detection by heavy squarks and higgsino

Dark matter beyond light singlet

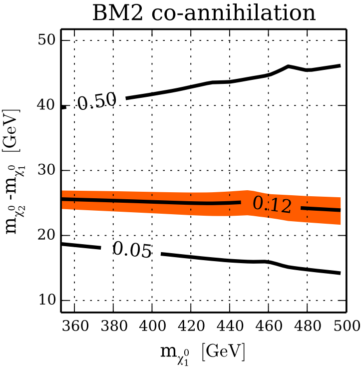
LSP heavier than 50 GeV:
Direct detection does not change much
Upper limit on slepton masses as seen





Coannihilation

- Alternative to sleptons needed
- Co-annihilation possible
- Bino still good candidate with wino



Conclusions

- R-Symmetry interesting building block for SUSY model
  - Extended Higgs sector allows for unconventional phenomenology
  - Dirac neutralinos and gluino
- Spectrum with multitude of light states not ruled out
  - Scenario with a light singlet is very predictive
  - Tested by both dark matter and LHC experiments
- Include LHC constraints on strong sector

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Thanks for your attention!

In Memoriam

Prof. Maria Krawczyk