

Latest results from Mastercode

Kazuki Sakurai

IPPP, Durham University

Experimentalists

O.Buchmueller, R.Cavanaugh, M.Citron, A.De Roeck, H.Flacher, S.Mallik, J.Marrouche, D.Martinez-Santos, K.J.de Vries,

Theorists

E.Bagnaschi, M.Dolan, J.Ellis, S.Heinemeyer, G.Isidori, K.Olive, K.Sakurai, G.Weiglein

15/12/2015 @ University of Heidelberg

Global fit | SM

• confront theory predictions with the experimental values

$$
\chi^2 = \sum_i \Big(\frac{\mathcal{O}_i^{theo.} - \mathcal{O}_i^{meas.}}{\sigma_i} \Big)^2
$$

- the *status of the model*
- min $χ²$ after marginalising other parameters
- the *most likely values* for *unconstrained parameters* and *unmeasured observables*

search strategies implication to the model

increase \mathbf{u} **²artic**
.. \mathbf{r} is the model of the model \mathbf{r} **Particularly important after NP discovery**

Theo. E.Bagnaschi, M.Dolan, J.Ellis, S.Heinemeyer, G.Isidori, K.Olive, G.Weiglein \blacksquare **inductade MasterCode**

des and sample efficiently around the small χ^2 region us Exp. O.Buchmueller, R.Cavanaugh, M.Citron, A.Roeck, H.Flacher, S.Mallik, J.Marrouche, D.Martinez-Santos, K.J.Vries in-house codes and sample efficiently around the small χ^2 region using Multinest **MasterCode** algorithm. masteRcope. \bullet Master C construction \bullet from various \bullet from various \bullet calculated \bullet in9house-codes-and-sample-efficiently-around-the-small-year-small-year-small-year-small-year-small-year-small-EW precision observables SoftSUSY, SDecay FeynWZ EW precision observables SoftSusy, Susy, Su Sampling Dark Matter Multinest B-Physics MicrOmega, SSARD Sampling $(P_i - \mathcal{O}_i)^2$ SuFla, SuperIso Dark Matter

 $\chi^2 = \sum$

 $\chi^2 = \sum$

(*Pⁱ ^Oi*)² 2 *i*

i

 $\overline{}$

i

 $\overline{ }$

 $\sqrt{2}$

LIGHT, DOOI PION Atom, Scorpion

LHC SUSY searches

Atom, Scorpion

Mass spectra: SoftSUSY Decays: SDecay

MicrOmega, SSARD

FeynHiggs, Higgssignals, Higgsbounds

21

Higgs sector and (g-2)**^μ**

 \mathcal{F}_{max}

 σ_i^2 *i*

- The spectrum is used for calculation of other observables.
- The decay info is used for the direct SUSY search constraints.

 $\overline{1.5}$

EW precision obs: FeynWZ where the theoretical uncertainty follows [33].

DM relic : MicrOmega $\sigma^{SI}{}_{\chi\text{-}N}$: SSARD

Require

thermal neutralino = observed DM

B-Physics: SuFla, SuperIso *O*SUSY*/*SM. *O*EXP*/*SM, which are used to constrain the relative enhancement due to SUSY contributions

measured rate. Since the signal strength modifier is measured relative to its SM value

 \lim_{Area} \lim_{Area}

FeynHiggs, Higgssignals, Higgsbounds and and Conserved and Computer of the previous for details the previous for the previous for the previous for the p
Experimental conservative previous for the previous formulation of the previous formula for the previous f $\mathbb{F}_{\mathcal{C}}$ is measured value, $\mathbb{F}_{\mathcal{C}}$ is measured value. In our fits we take the take the take the take the take the take the take take the take take the take take take take the take take take take take take ta

 $M_h = 125.09 \pm 0.24_{\text{EXP}} \pm 1.5_{\text{SUSY}}$ GeV

 $m_t = 173.2 \pm 0.87$ GeV

 \sim 3.6 σ deviation in (g-2)_μ **The discovery of the discovery set the SUSY scale low** $\overline{\mathcal{L}}$ $\overline{\mathcal{L}}$

Theo. E.Bagnaschi, M.Dolan, J.Ellis, S.Heinemeyer, G.Isidori, K.Olive, G.Weiglein \blacksquare **inductade MasterCode**

LHC SUSY searches:

Atom, Scorpion

important constraints but challenging to estimate

Sampling: Multinest

reduce the effective dim. of parameter space

GUT inspired Models

 $m_{1/2}$ A_0 $\tan \beta$ m_{II}^2 m_{II}^2 $\tan 4$ search by ATLAS α **NUHM2**: $m_0, m_{1/2}, A_0, \tan \beta, m_{H_u}^2, m_{H_d}^2$ [1408.4060] $CMSSM: m_0, m_{1/2}, A_0, \tan \beta$ $\textsf{NUM1}: \ m_0, m_{1/2}, A_0, \tan\beta, m_{H_u}^2 = m_{H_d}^2 \quad \texttt{[1312.5250]}$ $\textsf{NUMM2:}~~ m_0, m_{1/2}, A_0, \tan\beta, m_{H_u}^2, m_{H_d}^2$ [1408.4060] [1312.5250]

out depende (olmeet) enly en the 12 state ; constraint depends (almost) only on m_0 , m $\overline{}$ LHC constraint depends (almost) only on m_0 , $m_{1/2}$.

shaped by **DM**, **Jet + MET**, *mh*

mq˜1*,*² 6= *mq*˜³ , a common slepton mass *m*`

5 -- GUT inspired Models coupling combinations include the focus-point region all'unità di un acquire a significa a significa a significa a significa a significa a significa a signifi global analyses. Here we discuss systematically which DM mechanisms are dominant in which distributed by \mathcal{L} $s\,=\,-\,$. The CMSSM $\,$ in $N_{\rm H}$ and pms $N_{\rm H}$ and pms $N_{\rm H}$ parameters 10 the relevances of these DM mechanisms for \mathbf{A} $- -$ and \blacksquare and \blacksquare and \blacksquare which DM mechanisms are dominant in which distributed in the dominant in which distributed in the dominant in

5 5 $-$ GUT inspired Models coupling combinations include the focus-point region all'unità di un acquire a significa a significa a significa a significa a significa a significa a signifi Higgsino component. global analyses. Here we discuss systematically which DM mechanisms are dominant in which distribute $s\,=\,-\,$. The CMSSM $\,$ in \mathcal{L} and possible parameters \mathcal{L} and possible parameters \mathcal{L} the relevances of these DM mechanisms for \mathbf{r} $- -$ and \blacksquare and \blacksquare and \blacksquare which DM mechanisms are dominant in which distributed in the dominant in which distributed in the dominant in \star - $-$

| stau coan. | \n $\left(\frac{m_{\tilde{\tau}_1}}{m_{\tilde{\chi}_1^0}} - 1\right) < 0.15$ \n |
|-------------------|--|
| hybrid | \n $\left \frac{M_A}{m_{\tilde{\chi}_1^0}} - 2\right < 0.4$ \n |
| focus point | \n $\left(\frac{\mu}{m_{\tilde{\chi}_1^0}}\right) - 1 < 0.3$ \n |
| chargingino coan. | \n $\left(\frac{m_{\tilde{\chi}_1^{\pm}}}{m_{\tilde{\chi}_1^0}} - 1\right) < 0.1$ \n |

mq˜1*,*² 6= *mq*˜³ , a common slepton mass *m*`

5 5 $-$ GUT inspired Models coupling combinations include the focus-point region all'unità di un acquire a significa a significa a significa a significa a significa a significa a signifi Higgsino component. global analyses. Here we discuss systematically which DM mechanisms are dominant in which distribute $s\,=\,-\,$. The CMSSM $\,$ in \mathcal{L} and possible parameters \mathcal{L} and possible parameters \mathcal{L} the relevances of these DM mechanisms for \mathbf{r} $- -$ and \blacksquare and \blacksquare and \blacksquare which DM mechanisms are dominant in which distributed in the dominant in which distributed in the dominant in \star - $-$

Figure 10. *As in Fig. 8, for M^A (left panel) and for µ (right panel).* of possibilities. Studies have been carried out for a variety of models where the models where the models where the models where the studies of models where the studies where the studies where the studies where the studie parameters are specified. Here we give a generic discussion primarily intended to the specified to the specifi illustrate the strong likelihood that evidence for supersymmetry can be inferred from of possibilities. Studies have been carried out for a variety of models where the models where the models where parameters are specified. Here we give a generic discussion primarily intended to the specified to the specifi **GUT inspired Models**

\mathcal{L} and may in fact be the natural explanation for the apparent deviation for the apparent deviation from SMM theory reported by E821. \mathbf{d}^{III} and \mathbf{d}^{III} and \mathbf{d}^{III} difficult to explain *(g-2)_μ*

phenomenological MSSM

phenomenological approach

- MSSM has >120 parameters but most are $\bm{\mathsf{off\text{-}diagonal}}$ entries of $\ m_{\tilde{f}}, A_f$ and CP phases. \rightarrow set them zero
- FCNC constraints (1-2 gen.)

$$
\longrightarrow \ \ m_{\tilde f_1} = m_{\tilde f_2}
$$

left with 19 parameters $=$ pMSSM-19

pMSSM-10

pMSSM-10

Universal Mass Limit

Universal Mass Limit

"If the variety of channels are combined, the limit becomes insensitive to the topology."

O.Buchmueller, J.Marrouche '14

Universal Mass Limit

We create **4D lookup table 1**, **E** Using the full simulation chain.

 $\sum_{\mathbf{q}} \left| \cdot \right|_6$ Grid: $(m_{\tilde{g}}, m_{\tilde{q}_{1,2}}, m_{\tilde{q}_3}, m_{\tilde{\chi}_1^0})$

I validated with the full simulation I chain using random 10³ points

EW SUSY searches

The universal mass limit does not work well for EW SUSY particles.

The EW SUSY sector is comprised of a few particles (effectively simplified model).

We construct χ^2 as

Validation 14

Comparison using random 103 points

Compressed stop searches and the absence of an interpretation for the *t* **istop** searches

The universal mass limit does not work well for the compressed stop region. he universal mass limit does not work

Eq. 3.9, for the compressed-stop region. Note that this time *µl,r* and *l,r* depend on *m*˜⁰ ve construct χ^2 as based on
implified models *l*, *a l*, *d*, *a d*, *a* We construct χ^2 as based on simplified models

$$
\chi_{\text{stop}}^2 = \sum_i f_i(m_{\tilde{t}}, m_{\tilde{\chi}_1^0}) \times B_i
$$

these limits we use values of µl,r and l,r in Eq. (2) that in some cases depend on m˜⁰ *values of these parameters are specified for di*↵*erent values of m*˜⁰ ¹ *, the parameters for intermediate values* ¹ *are obtained by linear interpolation, and taken as constants elsewhere.* ¹ *are obtained by linear interpolation, and taken as constants elsewhere. these limits we use values of µl,r and l,r in Eq. (2) that in some cases depend on m*˜⁰ *values of these parameters are specified for di*↵*erent values of m*˜⁰ ¹ *, the parameters for intermediate values* ¹ *are obtained by linear interpolation, and taken as constants elsewhere.* **Validation**

Result

pMSSM10 mass spectrum and the spectrum of the **Best Fit Best Fit**

pMSSM10 mass spectrum and the spectrum of the **Best Fit Best Fit**

… Larger freedom allow to fullfill the (*g* 2)*^µ* constraint without being in tension with

. Poor determination of the mass of the mass of colored sparticles (only lower bound from LHCC) μ … Left-handed fermion decay chains evolve via ˜*[±]* 1.
2 and 2 "prediction"

 \mathcal{L} discovery after the LHC Run 1 Emanuele A. Bagnaschi (DESY) 9 \mathcal{L} $|p| < 1$ TeV Figure 12. *Summary of mass ranges predicted in the pMSSM10. The light (darker) peach shaded bars* $M_1 \simeq M_2 < 500$ GeV $m_{\tilde{\ell}} < 1\,\text{TeV}$

pMSSM10 mass spectrum and the spectrum of the **Best Fit Best Fit**

1.
2 and 2 "prediction"

 $\vert \mathcal{D}: \quad |\mu| < 1 \text{ TeV}$ $M_1 \simeq M_2 < 500 \,\text{GeV}$ $m_{\tilde{\ell}} < 1\,\text{TeV}$

> *indicate the 95% (68%) CL intervals, whereas the blue horizontal lines mark the values of the masses at M*¹ *<* 500 GeV 2σ: $m_{\tilde{\ell}} < 1\,\text{TeV}$

Discovery @ ILC

- The 500 GeV ILC can explore a large part of the low χ^2 region.
- \bullet The 1 TeV II C can explore the low y^2 region ² line I lev led call explore the low X legit ³ *production. Lower right panel: The* • The 1 TeV ILC can explore the low χ^2 region.

tanβ

Figure 17. *The 68% and 95% CL regions in the* (*mµ*˜*^R ,*tan) *plane before (dashed lines) and after (solid* **Higgses**

No tension with the Higgs mass

Heavy Higgses may be around the corner

Gluinos

Stop, Chargino

- Light stop (<500GeV) @ 2σ
- 10 \longleftarrow after LHC constraints *gluino, the first- and second-generation squarks, the lighter stop and sbottom squarks, the lighter chargino* \cdot Stop mass > 800 GeV @ 1 σ
- Chargino1 ~ Neutralino1 @ 1 σ after LHC constraints

Stop, Chargino

- radivory oriengino ocarimination, *(lower left) and the pMSSM10 (lower right). The red and blue solid lines are the* ² = 2*.*30 *and 5.99 contours, and the solid purple lines show the projected 95% exclusion sensitivity of the LUX-Zepelin* $\frac{1}{2}$ and $\frac{1}{2}$, the computation of the NUHM2 (upper right), the NUHM2 • 10: exclusively chargino coannihilation
- Figure 5. *The* (*m*˜*[±] , m*˜⁰ *(lower left) and the pMSSM10 (lower right). The red and blue solid lines are the* ² = 2*.*30 *and 5.99 contours, and the solid purple lines show the projected 95% exclusion sensitivity of the LUX-Zepelin (LZ) experiment [35]. The green and black lines show the current sensitivities of the XENON100 [33] and LUX [34] experiments, respectively, and the dashed orange line shows the astrophysical neutrino (LZ) experiment [35]. The green and black lines show the current sensitivities of the XENON100 [33] and LUX [34] experiments, respectively, and the dashed orange line shows the astrophysical neutrino (lower left) and the pMSSM10 (lower right). The red and blue solid lines are the* ² = 2*.*30 *and 5.99* • 2σ: stau coannihilation, h/Z funnel
- $\frac{1}{2}$, the CMSSM (upper ratio of $\frac{1}{2}$, the NUHM2 (upper right), the NUHM2 (upper right), the NUHM2 • large part of stau and funnel regions will be explored at LHC ¹) *planes in the CMSSM (upper left), the NUHM1 (upper right), the NUHM2* \bullet large part of stau and funnel regio *(LZ) experiment [35]. The green and black lines show the current sensitivities of the XENON100 [33] and LUX [34] experiments, respectively, and the dashed orange line shows the astrophysical neutrino 'floor' [37], below which astrophysical neutrino backgrounds dominate (yellow region).* · large part of stau and funnel regions will be evplore • large part of stau and funnel regions will be explored at LHC

No Tachyon @ GUT scale

Figure 23. *The impacts of the optional anti-tachyon cut on the two-dimensional profile likelihood functions* Require **no negative m2 at GUT scale**

excludes small sfermion masses at low energy

• Stop mass > 800GeV @ 2σ

• Chargino1 \sim Neutralino1 @ 2 σ

LHC Run-2

HL-LHC can cover most of the 2σ region

1 Standard searches are not $\frac{1}{\tilde{\chi}_1^{\pm} \rightarrow W \tilde{\chi}_1^0 / \tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0}}$ sensitive to the 1 σ region $\frac{\tilde{\chi}_1^{\pm} \rightarrow W \tilde{\chi}_1^0 / \tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0}{\tilde{\chi}_1^{\pm} \rightarrow \nu_{\ell} \tilde{\ell}_L (\tilde{\nu}_{\ell}) / \tilde{\chi}_2^0 \rightarrow \tilde{\ell} \tilde{\ell}_L (\nu_{\ell} \tilde{\nu}_{\ell})}}$

1 *plane of the should look for soft objects W[±]* should look for soft objects

DM direct detection

- viii be explored by LZ *(lower left) and the pMSSM10 (lower right). The red and blue solid lines are the* ² = 2*.*30 *and 5.99 (lower left) and the pMSSM10 (lower right). The red and blue solid lines are the* ² = 2*.*30 *and 5.99 contours, and the solid purple lines show the projected 95% exclusion sensitivity of the LUX-Zepelin (lower left) and the pMSSM10 (lower right). The red and blue solid lines are the* ² = 2*.*30 *and 5.99 contours, and the solid purple lines show the projected 95% exclusion sensitivity of the LUX-Zepelin* **•** 10: WIII be explored by LZ *(lower left) and the pMSSM10 (lower right). The red and blue solid lines are the* ² = 2*.*30 *and 5.99* • 1σ: will be explored by LZ
- *P* COMPIGNIGITIC COMBING (UPPER RIGHT), the LITTLE OUTPER SEARC *contours, and the solid purple lines show the projected 95% exclusion sensitivity of the LUX-Zepelin (LZ) experiment [35]. The green and black lines show the current sensitivities of the XENON100 [33] and LUX [34] experiments, respectively, and the dashed orange line shows the astrophysical neutrino 'floor' [37], below which astrophysical neutrino backgrounds dominate (yellow region). and LUX [34] experiments, respectively, and the dashed orange line shows the astrophysical neutrino 'floor' [37], below which astrophysical neutrino backgrounds dominate (yellow region). contours, and the solid purple lines show the projected 95% exclusion sensitivity of the LUX-Zepelin (LZ) experiment [35]. The green and black lines show the current sensitivities of the XENON100 [33] and LUX [34] experiments, respectively, and the dashed orange line shows the astrophysical neutrino* • complementarity with the LHC SUSY searches

Global fit

tells us the status of models helps us to come up with strategy of discovery becomes more important after the discovery

Summary

pMSSM 10 fit

Result

Implication

- M1 < 500GeV, Mslepton < 1TeV @ 2σ **HL-LHC** and **LZ** DM
- Chargino1 ~ Neutralino1 @ 1σ

detection can explore the preferred region!

sampled 10⁹ points fast calculation of LHC limit

pMSSM10 looks healthy

 \blacksquare Higgs **M** Dark Matter σ (g-2)_μ **M** LHC SUSY limit