Models of Dark Matter and constraints from the Large Hadron Collider

Werner Porod

Universität Würzburg
Where do we stand and why do we want to extend the Standard Model

Example: supersymmetry

Dark Matter at the LHC
  - Monojet and monophoton searches
  - SUSY searches and implications for model building

Conclusions
Where do we stand

La physique des particules étudie la matière dans ses dimensions les plus petites.
Particle physics looks at matter in its smallest dimensions.

L'astrophysique étudie la matière dans ses dimensions les plus grandes.
Astrophysics looks at matter in its largest dimensions.

The Two Frontiers of Physics
Les Deux Frontières de la Physique

Microscopes
Jumelles Binoculars
Telescopes optiques & radio
Optical & radio telescopes

Accélérateurs et détecteurs
Accelerators and detectors

L'œil nu.
Naked eye
W boson mass

Comparison of indirect constraints on the Standard Model Higgs boson and the direct measurements of the mass of the new boson discovered by ATLAS and CMS:

Consistent at the 1.3 $\sigma$ level.

In the context of the standard model, the mass of the new boson discovered by ATLAS+CMS is inside this blue band.
Where do we stand: Higgs results in a nut-shell, I

ATLAS, arXiv:1307.1427

CMS, CMS-PAS-HIG-13-005

\[ M_H = 125.5 \pm 0.2_{\text{stat}} \pm 0.6_{\text{sys}} \ \text{GeV} \]

\[ M_H = 125.7 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}} \ \text{GeV} \]

for details see e.g. talks by G. Landsberg and F. Cerutti @ EPS-HEP, Stockholm, 2013
### ATLAS, arXiv:1307.1427

<table>
<thead>
<tr>
<th>Process</th>
<th>m$_H$ = 125.5 GeV</th>
<th>Total uncertainty $\pm 1\sigma$ on $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$\mu = 1.55^{+0.33}_{-0.28}$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4l$</td>
<td>$\mu = 1.43^{+0.40}_{-0.35}$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow ll\nu\nu$</td>
<td>$\mu = 0.99^{+0.31}_{-0.28}$</td>
<td></td>
</tr>
<tr>
<td>Combined $H \rightarrow \gamma\gamma$, $ZZ^<em>$, $WW^</em>$</td>
<td>$\mu = 1.33^{+0.21}_{-0.18}$</td>
<td></td>
</tr>
</tbody>
</table>

**CMS, CMS-PAS-HIG-13-005**

**CMS Preliminary**

<table>
<thead>
<tr>
<th>Process</th>
<th>m$_H$ = 125.7 GeV</th>
<th>$\sigma_{SM} = 0.65$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow bb$</td>
<td>$\mu = 1.15 \pm 0.62$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>$\mu = 1.10 \pm 0.41$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$\mu = 0.77 \pm 0.27$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>$\mu = 0.68 \pm 0.20$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>$\mu = 0.92 \pm 0.28$</td>
<td></td>
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</tbody>
</table>

For details see e.g. talk F. Cerutti @ EPS-HEP, Stockholm, 2013.

Vilnius 18 Sept. 2014

W. Porod, Uni. Würzburg – p. 6
One of the big questions: dark matter

Zwicky: galaxies rotate too fast in comparison to the observed mass.

The universe at the age of $\approx 4 \cdot 10^5$ years

CMB $\approx 13.7 \cdot 10^9$ years later

(WMAP and Planck satellites)
Why do we want to extend the SM

What is the nature of dark matter?

- $\Omega_B \sim 5\%$
- $\Omega_{DM} \sim 23\%$
- $\Omega_{\Lambda} \sim 72\%$

What is the origin of the observed baryon asymmetry?

L. Roszkowski, astro-ph/0404052
Why do we want to extend the SM

How to combine gravity with the SM?
⇒ local Supersymmetry (SUSY) implies gravity

SM particles can be put in multiplets of larger gauge groups
- in $SU(5)$: $1 = \nu_R^c$, $5 = (d_{\alpha,R}^c, \nu_l, L, l_L)$, $10 = (u_{\alpha,L}, u_{\alpha,R}^c, d_{\alpha,L}, l_R)$
- in $SO(10)$: $16 = (u_{\alpha,L}, u_{\alpha,R}^c, d_{\alpha,L}, d_{\alpha,R}^c, l_L, l_R, \nu_l, L, \nu_R^c)$

However there are two problems in the SM but not in SUSY:
- proton decay (also in SUSY $SU(5)$ a problem)
- gauge coupling unification
Why do we want to extend the SM

- SM & $m_h = 125.5$ GeV: potentially meta-stable (G. Degrassi et al., arXiv:1205.6497)

- "Why does electroweak symmetry break?" or "Why is $\mu^2 < 0$ in the SM?"

- Hierarchy problem

\[ \delta m_h^2 \propto \Lambda^2: \text{Sensitivity to highest mass scale of unknown physics} \]
### Supersymmetry, MSSM

<table>
<thead>
<tr>
<th>Standard Model</th>
<th>MSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Matter:</strong></td>
<td></td>
</tr>
<tr>
<td>$e$ $d$ $d$ $d$</td>
<td>$\tilde{e}$ $\tilde{d}$ $\tilde{d}$ $\tilde{d}$</td>
</tr>
<tr>
<td>$\nu_e$ $u$ $u$ $u$</td>
<td>$\tilde{\nu}_e$ $\tilde{u}$ $\tilde{u}$ $\tilde{u}$</td>
</tr>
</tbody>
</table>

| **Gauge Sector:** |      |
| $\gamma$ $Z^0$ $W^\pm$ $g$ | $\tilde{\gamma}$ $\tilde{z}^0$ $\tilde{w}^\pm$ $\tilde{g}$ |

| **Higgs Sector:** |      |
| $h$ $H$ $A$ $H^\pm$ | $\tilde{h}^0_d$ $\tilde{h}^0_u$ $\tilde{h}^\pm$ |

**$R$-Parity:** $(-1)^{(3(B-L)+2s)}$

$$ (\tilde{\gamma}, \tilde{z}^0, \tilde{h}^0_d, \tilde{h}^0_u) \rightarrow \tilde{\chi}^0_i, (\tilde{w}^\pm, \tilde{h}^\pm) \rightarrow \tilde{\chi}^\pm_j $$

**DM particle:** $\tilde{\chi}^0_1$
Dark Matter candidates

- neutrinos: $\Omega_\nu h^2 < 0.0067$ @ 95% CL
- sterile neutrinos (with respect to $SU(3)_C \times SU(2)_L \times U(1)_Y$)
- axions
- SUSY
  - neutralino $\tilde{\chi}_1^0$
  - gravitinos
  - $\tilde{\nu}_R$ (in models with sterile neutrinos)
  - axinos
- models with extra dimensions: KK-states
  - first vector boson KK state $V_1^Y$
  - first graviton KK state $G^1$

...
requirements

- electrically neutral (‘dark’)
- either stable: usually via discrete symmetry: R-parity, KK-parity, $Z_n$, \ldots or life-time larger than age of universe
- massive and weakly interacting as $\Omega_{DM} h^2 \simeq 0.1$

Note: there might be more than one component, we have at least neutrinos

generic signal at high energy colliders

- large missing transvers momentum / transverse energy
Dark matter, annihilation processes

- bino
  - bulk region

- wino, higgsino
  - focus-point region

- funnel region

- wino, higgsino
  - focus-point region

- stau co-annihilation

- stop co-annihilation
How to produce DM particles at the LHC

- **Direct production**: $\chi\chi + \text{SM particles}
  - includes monojet, monophoton, mono-$b$, mono-$Z$, mono-$W$, mono-$H$

- **Associated production** with a heavier exotic $E$: $\chi + E$, then $E \rightarrow \chi + \text{SM}$

- **Pair of heavier exotics** $E + E$, then both $E \rightarrow \chi + \text{SM}$

- **SM decays** to $\chi$: $Z \rightarrow \chi\chi$, $h \rightarrow \chi\chi$, $t \rightarrow c\chi\chi$

- **Exotic resonance decays**: $E \rightarrow \chi\chi$

- **Heavier metastable exotic**, decay of $E \rightarrow \chi$ not seen in the detector

SUSY give a lots of examples of all of these, so this is a good place to start with, even if DM has nothing to do with SUSY
Moreover: usually exotics of other BSM extensions have large cross sections at LHC due to higher spin
Besides heavier unstable relatives of the DM particle, one is also interested in the particle(s) which mediate the non-gravitational interactions of the DM-particle with SM particles.

- SM: the only $s$-channel mediators are $Z$ and $h$.

- Exotic mediators may be very heavy $\Rightarrow$ DM-SM interactions described by contact interactions.

- If mediators are lighter, produce and identify them at LHC, not necessarily in association with DM-particles, e.g. the heavy Higgs-boson in SUSY.
A very broad and powerful program of MET-related searches at ATLAS and CMS.
These are the ‘SUSY’ searches.

Strong results from monojet and monophoton searches.
These are ‘Exotic searches’

Weak constrains on invisible decays of the Higgs boson
Monojets

\[ Z \rightarrow \nu\nu \] background

DM Signal

\[ p_T^{\text{jet}1} = 852 \text{ GeV}, \ E_T^{\text{miss}} = 863 \text{ GeV} \]
Estimating the $Z \rightarrow \nu\nu$ background

- Muons are minimum ionizing particles
  - They leave almost no energy in the calorimeter
  - Instead, they are measured by the muon spectrometer
- Neutrinos leave no energy in the calorimeter or spectrometer
- Consider a calorimeter-based $E_T^{\text{miss}}$: muons and neutrinos are similar
- Identify $Z \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$ events in data with the spectrometer
  - Use MC ratios to “transfer” to $Z \rightarrow \nu\nu$ estimate in data

$Z \rightarrow \mu\mu + \text{jet}$  \hspace{1cm}  $W \rightarrow \mu\nu + \text{jet}$  \hspace{1cm}  $Z \rightarrow \nu\nu + \text{jet}$
control region (ATLAS-CONF-2012-147)
signal region SR1 (ATLAS-CONF-2012-147)
\( \sigma(pp \rightarrow \tilde{G} + \tilde{q}/\tilde{g}) \propto \frac{1}{m_{\tilde{G}}^2} \)

(ATLAS-CONF-2012-147; similar results by CMS, see arXiv:1408.3583)
\[ \sigma(pp \rightarrow G^1 + j) \quad \quad M_{\text{Planck}}^2 \sim M_{D}^{2+n} R^n \]

\[
\begin{align*}
\text{95\%CL Observed limit} & \quad \quad \text{95\%CL Expected limit} (\pm 1 \pm 2 \sigma_{\text{exp}}) \\
\text{ADD n = 2} & \quad \quad \text{ADD n = 6}
\end{align*}
\]

\( \sqrt{s} = 8 \text{ TeV}, \int L = 10.5 \text{ fb}^{-1} \)

(ATLAS-CONF-2012-147; similar results by CMS see arXiv:1408.3583)
Monophotons

control region

signal region

(ATLAS-CONF-2014-151)
Monophotons

\[ \Phi \]

\[ T \]

\[ P_2 \]

\[ (\text{ATLAS-CONF-2014-151}) \]
Pair production of SUSY particles

\[ \sigma_{\text{Tot}} [\text{pb}] \]
\[ \sqrt{s} = 8 \text{ TeV} \]

Nathaniel Craig, arXiv 1309.0528
Bounds on charginos and neutralinos

ATLAS arXive:1403.5294

\[ pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_2^0 + X \]

Observed and expected 95% CL exclusion regions

followed by \( W \) and \( Z \)-mediated decays

assumption: specific nature of \( \tilde{\chi}_1^+ \), \( \tilde{\chi}_2^0 \) and mass hierarchies

combine with three-lepton of arXiv:1402.7029
Very sensitive SUSY searches

CMS Preliminary, $L = 19.3 \text{ fb}^{-1}$, $\sqrt{s} = 8 \text{ TeV}$

- fully inclusive except of for requirement of $\geq 1$ b-tag
- the exclusion of $m_{\tilde{g}} = 1.35 \text{ TeV}$ corresponds to only 8 signal events after a 30% efficient selection
- this corresponds cross section $\times BR$ of 1.3 fb
- for comparison: Higgs boson cross section $\times BR(h \to \gamma\gamma)$ is about 10 fb

(CMS-SUS-14-011-pas)
exclusive search with small backgrounds
but also excludes cross section $\times$ BR as small as 1.3 fb
also other BSM searches, so far nothing ...
LHC searches at 7 and 8 TeV have so far excluded a sizable part of the pMSSM and a small fraction of the NMSSM. Too soon to tell from LHC exclusions if SUSY (or also other BSM extensions) is related to electroweak scale and dark matter.
Concluding remarks

Puzzling situation

- collider data agree very well with SM expectations
- cosmological and astrophysical observations as well as theory arguments point to new physics in the TeV range
- I do not expect significant SUSY signals at LHC@13/14 TeV before $L \sim 10 \text{ fb}^{-1}$ but potentially an $s$-channel resonance such as a $Z'$

- despite severe bounds: huge model parameter space in various BSM models still open