Recent results in Higgs studies and BSM searches at the LHC

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on behalf of the CMS Collaboration
The Higgs boson

BEH mechanism and the Higgs boson
Observation at LHC
Production and decay channels
Couplings to fermions and bosons

Problems of the standard model

Supersymmetry: the solution?

Simplified and natural
Search status, 2018

Extended BEH sector?

The 750 GeV bump

Exotica: summary

Acknowledgement:
Supported by half the world
including Hungarian NKFIH Grants
The Zoo of the Standard Model

3 fermion families:
1 pair of quarks and
1 pair of leptons in each

3 kinds of gauge bosons:
the force carriers
+ the Higgs boson (!)

All identified and studied!
Expt – theory uncertainty

Measurements by all experiments

Left: global EW fit

Right: fit w/o measured value of given parameter

All within statistics

J. Haller et al, arXiv:1803.01853
Production of the SM Higgs boson
in p-p collisions at LHC

SM Higgs production

σ [fb]

10^5

10^4

10^3

10^2

m_h [GeV]

100

200

300

400

500

TeV4LHC Higgs working group

Teo-Phys. Sem., Budapest, 31 Oct 2018
Production of the SM Higgs boson in p-p collisions at LHC (Run 2)

D. de Florian et al. [LHC Higgs Cross Section Working Group], Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector, arXiv:1610.07922

Dezső Horváth: Higgs and BSM physics at LHC

Decay of the SM Higgs boson

At 125 GeV many decay processes compete.

Best identified ($\Delta M/M = 1 \cdots 2\%$):

- $H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$ ($\ell = e, \mu$): $\text{BR} = 1.24 \times 10^{-4}$, $S/B > 1$
- $H \rightarrow \gamma\gamma$: $\text{BR} = 2.27 \times 10^{-3}$, $S/B \ll 1$

LHC Higgs Cross Section Working Group, arXiv:1610.07922
LHC and its main experiments

p 14 TeV p

Dezső Horváth: Higgs and BSM physics at LHC

ELTE Theo-Phys. Sem., Budapest, 31 Oct 2018

- p. 8
# ATLAS vs. CMS

Both optimized to detect (and study!) $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$.

Very different detectors giving very similar results.

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
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<tbody>
<tr>
<td>Magnet</td>
<td>toroid + small (2 T solenoid)</td>
<td>large 3.8 T solenoid</td>
</tr>
<tr>
<td>Tracker</td>
<td>semiconductor + TRD</td>
<td>semiconductor</td>
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<td>E-m calorimeter</td>
<td>LAr with steel and Pb</td>
<td>PbWO$_4$ scint.</td>
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<td>Hadron cal.-m.</td>
<td>steel + scint. tiles</td>
<td>brass + scint. tiles</td>
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<tr>
<td>Far forward h-cal</td>
<td>LAr with Cu and W</td>
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<td>Muon detector</td>
<td>chambers (4 types)</td>
<td>chambers (3 types)</td>
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<td>Size</td>
<td>$\Theta 25$ m $\times$ 46 m ($23000$ m$^3$)</td>
<td>$\Theta 15$ m $\times$ 21.6 m ($3800$ m$^3$)</td>
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<td>Trigger</td>
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<td>Participants (sci)</td>
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<td>2300</td>
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</table>
CMS vs. ATLAS: Run 1 masses

Combined ATLAS + CMS Higgs-boson mass (Run 1):

\[ 125.09 \pm 0.21 \text{(stat)} \pm 0.11 \text{(syst)} \text{ GeV} \]


CMS (2017): 125.26 \pm 0.20 \pm 0.08

PDG (2018): 125.18 \pm 0.16
CMS vs. ATLAS: Higgs mass

Mass averaged for two production and all decay channels

CMS, 2013: $125.7 \pm 0.3^{\text{(stat)}} \pm 0.3^{\text{(syst)}} \text{ GeV}/c^2$

CMS, 2014: $125.03 \pm \begin{cases} +0.26 \\ -0.27 \end{cases}^{\text{(stat)}} \pm \begin{cases} +0.13 \\ -0.15 \end{cases}^{\text{(syst)}} \text{ GeV}/c^2$

ATLAS, 2013: $125.5 \pm 0.2^{\text{(stat)}} \pm \begin{cases} +0.5 \\ -0.6 \end{cases}^{\text{(syst)}} \text{ GeV}/c^2$

ATLAS, 2014: $125.36 \pm 0.37^{\text{(stat)}} \pm 0.18^{\text{(syst)}}$

$= 125.36 \pm 0.41 \text{ GeV}/c^2$

Gain in systematics, loss in statistics.
Is it really the SM Higgs boson?

relative signal strengths $\mu = \text{expt/theory in Run 1}$

Excellent agreement in all channels for both experiments

[ATLAS and CMS Collaborations, 5113 authors], JHEP 1608 (2016) 045.
H → 4ℓ

Invariant mass spectra at $\sqrt{s} = 13$ TeV

**ATLAS Preliminary**

$H \rightarrow ZZ^* \rightarrow 4\ell$

13 TeV, 36.1 fb$^{-1}$

**Data**
- Signal ($m_H=125$ GeV)
- Background $ZZ^*$
- Background $t\bar{t}V$, $VVV$
- Background $Z$+jets, $t\bar{t}$
- Uncertainty

**Events / 2.5 GeV**

**CMS**

35.9 fb$^{-1}$ (13 TeV)

**Data**
- $H(125)$
- $qq\rightarrow ZZ$, $Z\gamma^*$
- $gg\rightarrow ZZ$, $Z\gamma^*$
- $Z+X$

Both statistically limited.

$124.79 \pm 0.36$ (stat) $\pm 0.05$ (syst)

ATLAS, arXiv:1806.00242

$125.26 \pm 0.20$ (stat) $\pm 0.08$ (syst)

CMS, JHEP 1711 (2017) 047
A CMS event: $H \rightarrow \gamma\gamma$ candidate
H → γγ, Run 2 (2016 data)

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

$m_H = 125.11$ GeV

$\ln(1 + s/b)$ weighted sum

CMS Preliminary

$H \to \gamma\gamma$

$m_H = 125.4$ GeV, $\hat{\mu} = 1.16$

All categories

S/(S+B) weighted

Data

S+B fit

B component

$\pm 1 \sigma$

$\pm 2 \sigma$

S/(S+B) weighted events / GeV


CMS, arXiv:1804.02716

124.93 ± 0.21(stat) ± 0.34 (syst) GeV

125.4 ± 0.2(stat) ± 0.2(syst) GeV
$H \rightarrow W^+ W^-$

3rd most significant decay channel for the 125 GeV Higgs boson: observed and studied.

When in 2012 added to $\gamma\gamma$ and $4\ell$, increased the observed significance for ATLAS from $5\sigma$ to $6.1\sigma$ and decreased it for CMS to $4.9\sigma$.

- ATLAS, Run 1: $6.8\sigma$ and $\mu = 1.22^{+0.23}_{-0.21}$
- CMS, Run 1: $4.8\sigma$ and $\mu = 0.90^{+0.23}_{-0.21}$
- ATLAS + CMS in Run 1: $\mu = 1.09^{+0.18}_{-0.16}$

ATLAS & CMS: \( H \rightarrow \tau^+\tau^- \), Run 1

- ATLAS: \( 4.4\sigma \) (\( 3.3\sigma \) expected), \( \mu = 1.41^{+0.40}_{-0.36} \)
- CMS: \( 3.4\sigma \) (\( 3.7\sigma \) expected), \( \mu = 0.88^{+0.30}_{-0.28} \)
- ATLAS + CMS: \( 5.5\sigma \) (\( 5.0\sigma \) expected),
  \( \mu = 1.09 \pm 0.11 \) (gen.)

CMS: \( H \rightarrow \tau^+ \tau^-, \) Run 2

Local \( p \)-value:
Prob. that the observed excess is due to random background fluctuations.

Signal 13 TeV: \( 4.9\sigma \),
strength \( \mu = 1.09^{+0.27}_{-0.26} \)

7 + 8 + 13 TeV: \( 5.9\sigma \)

[CMS Collaboration], *Observation of the Higgs boson decay to a pair of tau leptons*,
CMS & ATLAS, signal strengths

Production rate (cross section) ratios:
\[ \mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}} \quad (i = \text{ggF, VBF, WH, ZH, ttH}) \]

Relative decay rates (ratios of branching fractions):
\[ \mu^f = \frac{B^f}{(B^f)_{SM}} \quad (f = ZZ, WW, \gamma\gamma, \tau\tau, bb, \mu\mu) \]

Production and decay cannot be separated, what is really measured:
\[ \mu_{fi} = \frac{\sigma_i B^f}{(\sigma_i)_{SM}(B^f)_{SM}} = \mu_i \mu^f \]

Allowing for BSM interpretation:
\[ \sigma_i B^f = \sigma_i(\kappa) \cdot \Gamma^f(\kappa) / \Gamma_H \]
\[ \Gamma_H, \Gamma^f: \text{total and frac. decay widths,} \]
Coupling modifiers:
\[ \kappa_j^2 = \sigma_j / \sigma_j^{SM} \text{ (prod.)}; \quad \kappa_j^2 = \Gamma^j / \Gamma_j^{SM} \text{ (decay)} \]

CMS & ATLAS, signal strengths, Run 1

\[ \mu = 1.09 \pm 0.07\text{ (stat)} \pm 0.04\text{ (expt)} \pm 0.03\text{ (thbgd)} \{^{+0.07}_{-0.06}\text{ (thsig)}\} \]


↑ \( \sigma(\text{ggF}) \)!
Production channels: CMS, $H \rightarrow \gamma \gamma$

CMS Preliminary

$H \rightarrow \gamma \gamma$

**Untagged 0**
45.8 expected events

**Untagged 1**
480.6 expected events

**Untagged 2**
670.4 expected events

**Untagged 3**
610.1 expected events

**VBF 0**
10.0 expected events

**VBF 1**
8.6 expected events

**VBF 2**
27.8 expected events

**ttH Hadronic**
5.8 expected events

**ttH Leptonic**
3.8 expected events

**ZH Leptonic**
0.5 expected events

**WH Leptonic**
3.6 expected events

**VH Leptonic**
2.8 expected events

**VH Hadronic**
9.7 expected events

**VH MET**
4.2 expected events

35.9 fb$^{-1}$ (13 TeV)

Best-fit average signal strength (at a floating H mass):

$$\mu = \left( \frac{\sigma \times BR_{\text{meas}}}{\sigma \times BR_{\text{SM}}} \right) = 1.18 \left\{ \begin{array}{c} +0.12 \\ -0.11 \end{array} \right\} \text{ (stat.)} \left\{ \begin{array}{c} +0.09 \\ -0.07 \end{array} \right\} \text{ (syst.)} \left\{ \begin{array}{c} +0.07 \\ -0.06 \end{array} \right\} \text{ (theo.)}$$

CMS, arXiv:1804.02716, 2018
Coupling modifiers, Run 1

EW vs. QCD production

QCD vs. EM decay

ATLAS & CMS: coupling mod’s, Run 1

Coupling to fermions & bosons: per expt. and average per decay mode

CMS: $H \rightarrow \bar{b}b$

**CMS**

*Preliminary*

$$pp \rightarrow VH; H \rightarrow b\bar{b}$$

$$\mu = 1.01 \pm 0.18 \text{ (stat.)} \pm 0.14 \text{ (syst.)}$$

Run 2 $\mu = 1.06 \pm 0.20 \text{ (stat.)} \pm 0.17 \text{ (syst.)}$

(2016) $\mu = 1.20 \pm 0.40$

(2017) $\mu = 1.08 \pm 0.35$

Run 1 $\mu = 0.89 \pm 0.38 \text{ (stat.)} \pm 0.24 \text{ (syst.)}$

All prod. channels: VH, gluon fusion, VBF, ttH

All LHC energies: 7, 8 and 13 TeV

Signal excess $5.6\sigma$ ($5.5\sigma$ expected) $\mu = \sigma / \sigma_{SM} = 1.04^{+0.20}_{-0.19}$

The CMS Collaboration: *Observation of Higgs boson decay to bottom quarks,*

CMS PAS HIG-18-016
CMS: $\bar{t}tH$ production

2011+2012+2016, all channels

5.2σ observed, 4.2σ expected, $\mu = 1.26^{+0.31}_{-0.26}$

Mass of the top quark: vacuum stability

G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori and A. Strumia,
“Higgs mass and vacuum stability in the Standard Model at NNLO,” JHEP 1208 (2012) 098

How stable is our EW vacuum? Depends on the masses of the Higgs boson and of the top quark
Measuring the mass of the top quark

CMS Collaboration, “Measurement of the top quark mass in the all-jets final state at $\sqrt{s} = 13$ TeV” CMS-PAS-TOP-17-008.
Problems of the Standard Model – 1

- Gravity? $S = 2$ graviton?
- Asymmetries: right $\Leftrightarrow$ left World $\Leftrightarrow$ Antiworld
- Artificial mass creation: Higgs-field *ad hoc*
- Charge quantization: $Q_e = Q_p$, $Q_d = Q_e/3$
- Why the 3 fermion families?
- Nucleon spin: how 1/2 produced?
- 19 free parameters (too many ??):
  - 3 couplings: $\alpha$, $\Theta_W$, $\Lambda_{QCD}$; 2 Higgs: $M_H$, $\lambda$
  - 9 fermion masses: $3 \times M_\ell$, $6 \times M_q$
  - 4 parameters of the CKM matrix: $\Theta_1$, $\Theta_2$, $\Theta_3$, $\delta$
  - QCD-vacuum: $\Theta$
Problems of the Standard Model – 2

- Neutrino mysteries
  - $M_\nu > 0 \Rightarrow +3$ masses, $+4$ mixing matrix
    - The SM does not like them...
  - What makes them oscillate?
  - Are they Majorana particles $\bar{\nu} \equiv \nu$?

- Gravitational mass of the Universe:
  - 4% ordinary matter (stars, gas, dust, $\nu$)
  - 23% invisible dark matter (out of SM!)
  - 73% mysterious dark energy

- Naturalness (hierarchy):
  - The mass of the Higgs boson quadratically diverges due to radiative corrections. Cancelled if fermions and bosons exist in pairs.
Many-many different models

Alternative models
Beyond the Standard Model


Dezső Horváth: Higgs and BSM physics at LHC
ELTE Theo-Phys. Sem., Budapest, 31 Oct 2018
Supersymmetry (SUSY)

Hypothesis: Fermions and bosons exist in pairs:

\[ Q|F> = |B>; \quad Q|B> = |F> \quad m_B = m_F \]

Identical particles, just spins different

Broken at low energy, partners: much larger mass?

SUSY should solve many problems
2 Higgs doublets $\Rightarrow$ masses to upper and lower fermions

Extended left–right asymmetry:

$m_L = m_R$, but $\tilde{m}_L \neq \tilde{m}_R$

8 Higgs fields $\Rightarrow$ 5 Higgs bosons: $h^0, H^0, A^0, H^\pm$

Higgs-parameters: $\tan \beta = v_1/v_2$, masses

Mass hierarchy: heavy gluino, light (?) scalar top quark
LSP = dark matter?

SUSY’s quantum number: $R$ parity $R = (-1)^{3B-L+2S}$

($B$: baryon charge, $L$: lepton charge, $S$: spin)

$R = +1$ particle, $R = -1$ SUSY partner

Parity-like: $R^2 = +1$

If $R$ conserved, lightest SUSY particle (LSP) is stable

$R$ parity may not be much violated: we would detect LSP decays

Neutral LSP: excellent dark matter candidate
SUSY: coupling constants

Minimal Supersymmetric Standard Model: Unification!
Bend at low energies: SUSY enters with many new particles ⇒ more loop corrections
Natural SUSY?

- Light ($\sim 1\ \text{TeV}$) SUSY particles help to eliminate the hierarchy problem and keep the lightest Higgs-boson light ($\tilde{h}_0^0_{\text{MSSM}} = H_{\text{SM}}$).

- Heavy SUSY particles add huge 2nd-order (log) corrections, ruining the hierarchy elimination.

- Unfortunately, naturalness is less and less probable as the lower limits on SUSY masses grow.

E.g., $\tilde{t}$ is assumed to be the lightest squark, now having $m(\tilde{t}) \gtrsim 1\ \text{TeV}$, and a possible decay of the gluino is to $t\tilde{t}$...
CMS SUSY summary plot, 2017

### Simplified Model Spectrum (SMS) topologies

*Selected CMS SUSY Results - SMS Interpretation*

ICHEP '16 - Moriond '17

**Glino**

- $m_{glino} < 100$ GeV
- $m_{glino} < 120$ GeV

**Squark**

- $m_{s} < 100$ GeV
- $m_{s} < 120$ GeV

**EMK Gaugino**

- $m_{emk} < 100$ GeV
- $m_{emk} < 120$ GeV

---

**CMS Preliminary**

- $\sqrt{s} = 13$ TeV
- $L = 12.9$ fb$^{-1}$
- $L = 35.9$ fb$^{-1}$

**For decays with intermediate mass,**

$$m_{intermediate} = x \cdot m_{mass} + (1-x) \cdot m_{LSP}$$

---

*Observed limits at 95% C.L. - theory uncertainties not included.

Only a selection of available mass limits. Probe “up to” the quoted mass limit for $m_{LSP} = 0$ GeV unless stated otherwise.

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ELTE Theo-Phys. Sem., Budapest, 31 Oct 2018
# CMS limits, 2018: gluino pairs

## Overview of SUSY results: gluino pair production

<table>
<thead>
<tr>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$</td>
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<tr>
<td>$\tilde{g} \rightarrow t\bar{t} \rightarrow t\bar{t}\tilde{\chi}_1^0$</td>
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<tr>
<td>$\tilde{g} \rightarrow t\bar{t} \rightarrow t\bar{t}\tilde{\chi}_1^+$</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow t\bar{b}\tilde{\chi}_1^+ \rightarrow t\bar{b}f^+f^-\tilde{\chi}_1^0$</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow \tilde{\chi}_1^+ / \tilde{b} \tilde{\chi}_1^0 / \tilde{t} \tilde{\chi}_1^0 / \tilde{t} \tilde{\chi}_1^0$</td>
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<tr>
<td>$\tilde{g} \rightarrow \tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 / \tilde{\chi}_2^0$</td>
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<td>$\tilde{g} \rightarrow \tilde{b} \tilde{\chi}_1^0 \rightarrow \tilde{b} \tilde{\chi}_1^0$</td>
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<tr>
<td>$\tilde{g} \rightarrow \tilde{b} \tilde{\chi}_1^+ \rightarrow \tilde{b} \tilde{\chi}_1^+$</td>
</tr>
</tbody>
</table>

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probes up to the quoted mass limit for light LSPs unless stated otherwise. The quantities $\Delta M$ and $x$ represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to $\Delta M$, respectively, unless indicated otherwise.
CMS limits, 2018: squark pairs

Overview of SUSY results: squark pair production

\( \sqrt{s} = 13 \text{ TeV} \)

**\( pp \rightarrow \tilde{t}\tilde{\bar{t}} \)**

- \( \tilde{t} \rightarrow b\tilde{\chi}_1^+ \rightarrow bW^{\pm}\tilde{\chi}_1^\mp \)
  - \( \Delta M_{\tilde{t}} < 3 \text{ GeV (mass exclusion)} \)
  - \( x = 0.5 \)

- \( \tilde{t} \rightarrow b\tilde{\chi}_1^0 \rightarrow bW^{\pm}\tilde{\chi}_1^\mp \)
  - \( \Delta M_{\tilde{t}} < 3 \text{ GeV (mass exclusion)} \)
  - \( x = 0.5 \)

**\( pp \rightarrow \tilde{\ell}\tilde{\bar{\ell}} \)**

- \( \tilde{\ell} \rightarrow b\tilde{\chi}_1^+ \rightarrow bZ^{\pm}\tilde{\chi}_1^0 \)
  - \( \Delta M_{\tilde{\ell}} < 3 \text{ GeV (mass exclusion)} \)
  - \( x = 0.5 \)

**\( pp \rightarrow \tilde{b}\tilde{\bar{b}} \)**

- \( \tilde{b} \rightarrow b\tilde{\chi}_1^0 \rightarrow bH^0 \)
  - \( \Delta M_{\tilde{b}} < 3 \text{ GeV (mass exclusion)} \)
  - \( x = 0.5 \)

Selection of observed limits at 95\% C.L. (theory uncertainties are not included). Under \( x \) is the quoted mass limit for light LPs unless stated otherwise.

The quantities \( \Delta M \) and \( x \) represent the absolute mass difference between the primary squark and the LSP, and the difference between the intermediate sparticle and the LSP relative to \( \Delta M \), respectively, unless indicated otherwise.
Overview of SUSY results: electroweak production
36 fb⁻¹ (13 TeV)

$\mathbf{pp \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^\pm_1}$

- $\mathbf{3\ell}$: arXiv:1709.05406
- $\geq 3\ell + 2\ell$ same-sign: arXiv:1709.05406
- $\geq 3\ell + 2\ell$ same-sign: arXiv:1709.05406

$\mathbf{pp \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^0_1}$

- $\mathbf{3\ell}$: arXiv:1709.05406
- $\mathbf{r}$ enriched, $x = 0.5$

$\mathbf{pp \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^0_1}$

- $\mathbf{3\ell}$: arXiv:1709.05406
- $\mathbf{3\ell}$: arXiv:1709.05406
- $\mathbf{r}$ enriched, $x = 0.95$

$\mathbf{pp \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^0_1}$

- $\mathbf{3\ell}$: arXiv:1709.05406
- $\mathbf{r}$ dominated, $x = 0.2$

$\mathbf{pp \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^0_1}$

- $\mathbf{3\ell}$: arXiv:1709.05406
- $\mathbf{3\ell}$: arXiv:1709.05406
- $\mathbf{1\ell + j}$: arXiv:arXiv:1709.05406

$\mathbf{pp \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^0_1}$

- $\mathbf{3\ell}$: arXiv:1709.05406
- $\mathbf{3\ell}$: arXiv:1709.05406
- $\mathbf{2\ell}$ opposite-sign: arXiv:1709.05406

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Selection of observed limits at 95% C.L. (theory uncertainties are not included). Please refer to the quoted mass limit for light LSPs unless stated otherwise. The quantities $\delta M$ and $\delta$ represent the absolute mass difference between the primary particle and the LSP and the difference between the intermediate particle and the LSP relative to $\Delta M$, respectively, unless indicated otherwise.
ATLAS SUSY summary plot, 2017

For all results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
### ATLAS SUSY summary plot, 2018

#### ATLAS SUSY Searches* - 95% CL Lower Limits

<table>
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<tr>
<th>Model</th>
<th>$\phi^{0} \rightarrow q\bar{q}$</th>
<th>Dilept 2 $\ell$</th>
<th>$\phi^{0} \rightarrow W^{+}W^{-}$</th>
<th>$\phi^{0} \rightarrow ZZ^{(*)}$</th>
<th>$\phi^{0} \rightarrow 4\ell$</th>
<th>$\phi^{0} \rightarrow \tau^{+}\tau^{-}$</th>
<th>$\phi^{0} \rightarrow jjjj$</th>
<th>$\phi^{0} \rightarrow j\tau^{+}\tau^{-}$</th>
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<td>mono-jet 1 jet 1 $\ell$</td>
</tr>
</tbody>
</table>

#### ATLAS Preliminary

| $\sqrt{s} = 7, 8, 13$ TeV |

#### Reference

- ATLAS-CONF-2018-003
- ATLAS-CONF-2018-002
- ATLAS-CONF-2018-001

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.*
The 750 GeV/$c^2$ excess in 2015

$X \rightarrow \gamma\gamma$

CMS: Barrel-barrel and barrel-endcap
CMS event: $M_{\gamma\gamma} = 745$ GeV

Diphoton event with $m(\gamma\gamma) = 745$ GeV
Excess at 750 GeV/c², December 2015

Local $p$-value: Probability that the observed excess is due to random background oscillation

ATLAS, 13 TeV: $3.6\sigma$

CMS, 8 + 13 TeV: $3.0\sigma$
750 GeV excess: excitement ends

ATLAS and CMS, end of 2015, Spring 2016:
Let us have more data!

Theory: avalanche of papers for interpretation:
2015: 150, 2016: 350 papers

World press: Death of the standard model?!

Excited waiting for new data at start of LHC in 2016.

$M_{\gamma\gamma} \approx 750$ GeV blinded in both experiments.

Unblinding for ICHEP, Chicago (July 2016).

The excess disappeared in the SM background

Be careful about discoveries
(both unexpected and expected)!
Conclusion

- We have observed the Standard Model Higgs boson or (unfortunately, much less probably) a Higgs boson of a more general model.

- All measured properties are consistent with the predictions for the SM Higgs-boson with a mass of 125 GeV.

- Let us hope for some deviation from the Standard Model (although none seen yet).

- The simplest SUSY models do not seem to be supported by experimental data (g-2, LEP, WMAP, LHC, ...)

- The promising 750 GeV diphoton resonance was background oscillation.

- We are looking for and hoping to find new physics (Dark Matter!) at the LHC.

Thanks for your attention!
Spare slides for questions
The SM Higgs boson

Production – decay cross sections depend on masses only
E.g. of decay to fermion pair:

$$\Gamma(H \rightarrow f\bar{f}) = \frac{N_c g^2 m_f^2}{32 \pi m_W^2} \beta^2 m_H$$

$N_c$ colours (leptons: 1; quarks: 3)
$g^2 \sim 0.425$ SU(2) coupling
$\beta^2 = 1 - 4 \frac{m_f^2}{m_H^2}$ fermion velocity.

SM limits its mass:
30 GeV < $m_H$ < 500 GeV (unitarity)

If SM is perturbative to $E_{\text{GUT}} = 10^{16}$ GeV:
(GUT: Grand Unification Theory)
130 GeV < $m_H$ < 190 GeV
CMS: $H \rightarrow \tau^+ \tau^-$, Run 2

VBF: $\mu \tau_h$, $e \tau_h$, $e \mu$

All other channels

Experimental limits, constraints

No SUSY phenomenon observed, the data limit the parameter space

- LEP, Tevatron, LHC: Higgs sector
  - Mass of SM Higgs from direct searches
    \[ M_H = 125 \text{ GeV}; \quad H \sim h^0 \]
  - Fitting electroweak data
  - Search for neutral Higgs bosons (h and A)

- \( BR(b\rightarrow s\gamma) \) measurements at B-factories

- Anomalous magnetic moment of the muon (BNL)

- Satellite expts WMAP and Planck: density of dark matter (DM), indirect

- Direct searches for DM with \( \nu \)-detectors and AMS2
MSSM mass spectrum: preconceptions

Even if we remain sceptic it is worthwhile to know what do most of the model constructors think (after S.P. Martin)

- R parity is barely violated
- LSP: $\tilde{\chi}_1^0$ or gravitino
- Gluino mass $M_3 \equiv m(\tilde{g}) \gg m(\tilde{\chi}_1^0), m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^\pm)$
- $m(\tilde{u}_i) \sim m(\tilde{d}_i) \sim m(\tilde{c}_i) \sim m(\tilde{s}_i) \gg m(\tilde{\ell}_i)$
- $m(\tilde{u}_i) \sim m(\tilde{d}_i) \sim m(\tilde{c}_i) \sim m(\tilde{s}_i) > (0.6_{\text{MSUGRA}} \ldots 0.8_{\text{GMSB}}) m(\tilde{g})$
- $m(\tilde{u}_L) \geq m(\tilde{u}_R) \ldots m(\tilde{s}_L) \geq m(\tilde{s}_R)$ and $m(\tilde{e}_L) \geq m(\tilde{e}_R), m(\tilde{\mu}_L) \geq m(\tilde{\mu}_R)$ as $M_L^2 \sim M_R^2 + 0, 5m_{1/2}^2$.
- $\tilde{t}_1, \tilde{b}_1$ lightest squarks and $\tilde{\tau}_1$ lightest charged slepton (mixing, Higgs coupling)
- $m(h^0) \lesssim 150 \text{ GeV} \ll m(A), m(H^\pm), m(H^0)$
Simplified Models

Few on-shell particles, simple topology and decays
Not model-independent, but possibly associated with several models.
Possible new physics on well understood SM-base

What can we learn of such analysis?

- Boundaries of search sensitivity, both for data analysis and for new theories.
- Characterizing new physics signals: what models can be associated?
- Limits on more general models: from possible cross-sections.
CMS strategies for discovery

- $\alpha_T$ search for early discovery in (forced) 2-jet events ($E_T(J_1) > E_T(J_2)$):

  Cut $\alpha_T = \frac{E_T(J_2)}{M_T(J_1,J_2)}$

  $$= \frac{E_T(J_2)}{\sqrt{(E_T(J_1) + E_T(J_2))^2 - (p_x(J_1) + p_x(J_2))^2 - (p_y(J_1) + p_y(J_2))^2}}$$

  Exclusive 2-jet, inclusive 3-jet search

- Jets + $H_T$ for > 2 jets, inclusive

  Scalar mom. sum: $H_T = \sum_i |p_T(J_i)|$

  Missing transverse mom.:

  $MHT = H_T = | - \sum_i p_T(J_i)|$

- Razor search: test kinematic consistency for pair production of heavy particles

  Two jets (inv. mass $M_R$) + 0 or 1 lepton
Minimal Supersymmetric SM

Electroweak symmetry breaking ⇒
MSSM-fermions mix into mass eigenstates

\{\text{Electroweak gauginos + higgsinos}\} \Rightarrow \{\text{charginos and neutralinos}\}

\{\tilde{B}(=\tilde{\gamma}), \tilde{W}^\pm, \tilde{W}^0(=\tilde{Z}); \tilde{h}^0, \tilde{H}^0, \tilde{H}^\pm\} \Rightarrow \{\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm; \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0\}

(mass grows with index)

Lightest SUSY particle (LSP) depends on model, e.g.
mSUGRA: \tilde{\chi}_1^0 \text{ or GMSB: gravitino (}\tilde{G})

SUSY breaking (how?) ⇒ many (>100) new parameters
masses, couplings, mixing angles

Lots of model variants, huge parameter space, different constraints invented.
## The missing MSSM menagerie

<table>
<thead>
<tr>
<th>Kind</th>
<th>spin</th>
<th>R parity</th>
<th>gauge eigenstate</th>
<th>mass eigenstate</th>
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</thead>
<tbody>
<tr>
<td>Higgs bosons</td>
<td>0</td>
<td>+1</td>
<td>$H_1^0, H_2^0, H_1^+, H_2^-$</td>
<td>$h^0, H^0, A^0, H^\pm$</td>
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<tr>
<td>squark</td>
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<td>$\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R$</td>
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<td>same</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{b}_R$</td>
<td>$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$</td>
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<tr>
<td>slepton</td>
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<tr>
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<td></td>
<td>$\tilde{\mu}_L, \tilde{\mu}<em>R, \tilde{\nu}</em>\mu$</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{\tau}_L, \tilde{\tau}<em>R, \tilde{\nu}</em>\tau$</td>
<td>$\tilde{\tau}_1, \tilde{\tau}<em>2, \tilde{\nu}</em>\tau$</td>
</tr>
<tr>
<td>neutralino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{B}_1^0, \tilde{W}_1^0, \tilde{H}_1^0, \tilde{H}_2^0$</td>
<td>$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$</td>
</tr>
<tr>
<td>chargino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{W}_1^\pm, \tilde{H}_1^+, \tilde{H}_2^-$</td>
<td>$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$</td>
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<td>gluino</td>
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<td>-1</td>
<td>$\tilde{g}$</td>
<td>same</td>
</tr>
<tr>
<td>goldstino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{G}$</td>
<td>same</td>
</tr>
<tr>
<td>gravitino</td>
<td>3/2</td>
<td>-1</td>
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</table>
Search for other (heavier) Higgs bosons

SM extensions predict more Higgs-like bosons.

Minimal Supersymmetric SM:
  2 BEH-doublets, 8 fields, 5 Higgs-bosons
  $h^0$, $H^0$, $A^0$, $H^\pm$

Higgs-like parameters: masses and vacuum exp. values: $\tan \beta = v_2/v_1$
  $h^0$ should be close to $H_{SM}$, $M(H^0) \gg M(h^0)$
  LEP excluded all below $M(W)$. Above?

Popular model: hMSSM where $h^0 \sim H_{SM}$

Some links to hundreds of papers:

ATLAS Collaboration:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome

CMS Collaboration:
Hunting the Higgs boson

- Compose a complete SM background using Monte Carlo simulation taking all types of possible events normalized to their cross-sections.
- Higgs signal: simulation of all possible production and decay processes with all possible Higgs-boson masses
- Put all these through the detector simulation to get events analogous to the measured ones.
- Optimize the event selection: reduce $B$ background, enhance $S$ signal via maximizing e.g.
  \[ \frac{N_S}{\sqrt{N_B}} \text{ or } \frac{N_S}{\sqrt{N_S + N_B}} \]
  or see the approximate formula of G. Cowan et al. [https://arxiv.org/abs/1007.1727].
- Calculate at experimental luminosity the expected nr. of events for signal and background at various conditions.
- SM background $\sim$ experiment? (YES $\downarrow$ / NO $\uparrow$).
Search for charged Higgs bosons

Just two examples from the 13 TeV exclusion plots

ATLAS

\[ \sqrt{s} = 13 \text{ TeV}, \ 3.2 \text{ fb}^{-1} \]

- Observed (CLs)
- Expected (CLs)
- ± 1σ
- ± 2σ
- \( H^+ \) hMSSM \( \tan\beta = 60 \)

CMS

\[ \sigma \left( pp \rightarrow [b|H^+] \times BR(H^+) \times \tau \nu \right) \]

\[ \sigma_{VBF} \times B(H^+ \rightarrow W^+Z) \]

M. Aaboud et al. [ATLAS Collaboration], Search for charged Higgs bosons produced in association with a top quark and decaying via \( H^\pm \rightarrow \tau \nu \) using \( pp \) collision data recorded at \( \sqrt{s} = 13 \text{ TeV} \) by the ATLAS detector, Phys. Lett. B 759 (2016) 555

A. M. Sirunyan et al. [CMS Collaboration], Search for charged Higgs bosons produced in vector boson fusion processes and decaying into a pair of W and Z bosons using proton-proton collisions at \( \sqrt{s} = 13 \text{ TeV} \), arXiv:1705.02942 [hep-ex].
750 GeV excess: strange features

- $X(750) \rightarrow \gamma\gamma$: $S_X = 0$ vagy $S_X = 2$. Scalar?
- Decays to photons only, why not to $\bar{f}f$ and $WW$, $ZZ$?
- For a scalar (Higgs-like) boson $WW$ and $ZZ$ dominate.
- Fifth interaction governs its decay?
- It does not fit in the Standard Model!
- Plus: ATLAS sees wide peak, CMS a narrower one.