Search for new physics at the LHC & prospects for new discoveries

Géraldine Conti (CERN) on behalf of the ATLAS and CMS collaborations

May 11th, 2015
Introduction

From LHC up to now (2010 - 2012), collision energies of 7 and 8 TeV (Run1):

- An **impressive amount of searches** have been carried out in various physics areas
  - *Disclaimer: not possible to show them all!*

- **No observation of excesses** “Beyond the Standard Model (BSM)” predictions observed
  - A few **legacy 2-3 $\sigma$ discrepancies** remaining

For LHC 2015 - 2018, collision energies of 13 TeV (Run2):

- An **ambitious program** to test further the TeV energy frontier
LHC, ATLAS and CMS

- LHC is a 27km proton accelerator and colliding ring at CERN
- The **LHC Run1 dataset** consists of:
  - 2010: ≈45 pb\(^{-1}\) of √s=7 TeV data
  - 2011: ≈ 5 fb\(^{-1}\) of √s=7 TeV data
  - 2012: ≈ 20 fb\(^{-1}\) of √s=8 TeV data
  - Tevatron got 8 fb\(^{-1}\) of √s~2 TeV data
- ATLAS and CMS are **general purpose experiments**

(see C. Biino presentation)
Particle Physics Objects

Example for $H \rightarrow ZZ \rightarrow \mu\mu qq$

What we calculate: $g \rightarrow t \rightarrow H \rightarrow Z \rightarrow q\bar{q}$

What we measure: $\mu^+ \mu^- q\bar{q}$

Jet = hadrons that are clustered together

Jet

Run1: BSM Higgs searches

- The main goal of Run1 to find the **Higgs boson** was reached:

- In the **Higgs sector**, searches for BSM physics were performed in:

  1) **New Higgs decays**
     - Higgs to *invisible particles*
     - Higgs to $\mu \tau$ (**lepton flavor violation**)
     - ...

  2) **Other Higgs bosons**
     - Two Higgs doublet model
     - Di-Higgs resonances
     - Exotic Higgs
     - ...

**Two Higgs doublet model (2HDM):**

$\begin{align*}
&\begin{aligned}
&M_{h, \, H, \, A, \, H^\pm} \\
&\text{2 CP-even neutral Higgses:} \quad \text{1 CP-odd Higgs:} \quad \text{2 charged Higgses:}
\end{aligned}
\end{align*}$

Motivated by SUSY, axion models, possible to generate a baryon asymmetry of the universe of sufficient size
• Higgs decaying to invisible particles

\[ q \to W^\pm/Z \to \chi^0 \]

Dark matter candidates

Higgs portal model

\[ \text{Higgs boson acts as mediator between the hidden sector and the SM particles} \]

\[ h \to \text{invisible} : \quad \text{BR } h \to \text{invisible} < 29\% \]

\[ Zh \to \text{ll invisible} : \quad \text{BR } h \to \text{invisible} < 75\% \]

\[ \text{at } 19.2 \text{ fb}^{-1} (8 \text{ TeV}) \]

\[ \text{CMS PAS HIG-14-038} \]

\[ \text{CMS PAS HIG-14-038} \]

\[ \text{arXiv:1402.3244} \]
Search results in BSM Higgs (2)

- Charged Higgs boson

\[ H^+ \rightarrow c\bar{s} \]

\[ H^+ \rightarrow \tau_{\text{had}}\nu \]

\[ \tan(\beta) = \text{ratio of the two vacuum values of the 2 CP-even neutral Higgses (h,H)} \]

- No significant excess observed

- Stringent limits on \( \tan(\beta) \), hence on 2HDM

CMS Preliminary. \( \sqrt{s} = 8 \text{ TeV}, \ 19.7 \text{ fb}^{-1} \)

\[ M_{h^+} = 120 \text{ GeV} \]
\[ \text{Br}(t \rightarrow H^+b) = 0.2 \]

\[ \int Ldt = 19.5 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV} \]
Data 2012
MSSM \( m_h^{\text{max}} \) scenario
• **CP-odd Higgs $A$**

$$A \rightarrow Z h \rightarrow llbb$$

Complementarity with $A \rightarrow \tau\tau$ limits

- No excess observed
- di-Higgs resonances

$$H \rightarrow hh \rightarrow b\bar{b}b\bar{b}(b\bar{b}\gamma\gamma)$$

Allows to access higher masses
Run1 : SUSY searches

- Before Run1, **supersymmetry (SUSY)** was one of the most attractive BSM theories
  - Solves the hierarchy problem \((m_H\) unstable at short distances\)
  - Dark matter candidate (R-parity)
  - High-energy unification of weak, strong and EM couplings

- A **natural SUSY** scenario was favored because it involves a small tuning in the theory.
  - **Stop** needed to solve the hierarchy problem \((by\ cancelling\ the\ top\ loop)\)
  - Gluinos and 3rd-generation squarks constrained to be quite light, \(O(\text{TeV})\) \((\text{Higgs mass at } \approx 125 \text{ GeV})\)

- At LHC, the strategy was to look first for **strongly-produced gluinos and 3rd-generation squarks**
  - Should be produced copiously \((\text{hadron collider})\)
Search results in SUSY (1)

- **Strong production**

  - LSP mass [GeV]
    - SUS-13-012: 0-lep ($\tilde{g} \rightarrow t \tilde{\chi}^0_1$) 19.5 fb$^{-1}$
    - SUS-14-011: 0+1+2-lep (razor) 19.3 fb$^{-1}$
    - SUS-13-007: 1-lep ($n_{\text{jet}} = 6$) 19.3 fb$^{-1}$
    - SUS-13-016: 2-lep (OS+b) 19.7 fb$^{-1}$
    - SUS-13-013: 2-lep (SS+b) 19.5 fb$^{-1}$
    - SUS-13-008: 3-lep (3l+b) 19.5 fb$^{-1}$

  - Stop mass [GeV]
    - SUS-13-011: 1-lep (MVA) 19.5 fb$^{-1}$
    - SUS-14-011: 0-lep + 1-lep + 2-lep (Razor) 19.3 fb$^{-1}$
    - SUS-14-011: 0-lep (Razor) + 1-lep (MVA) 19.3 fb$^{-1}$
    - SUS-13-009: (monojet stop) 19.7 fb$^{-1}$ (exists)
    - SUS-13-015: (hadronic stop) 19.4 fb$^{-1}$

- **Limits on gluino mass** at ≈1.3 TeV (302 GeV pre-LHC), limits on stop mass at ≈750 GeV (for m(LSP) = 0 GeV and for the most sensitive scenario)
Run1 : SUSY searches

In the **absence** of strongly-produced SUSY particles in Run1, **two alternatives** became more popular:

1) **electroweak (EWK) production**

![Graph showing pair-production cross section of SUSY particles]

- **Pair-production cross section of SUSY particles:**
  - **Gluino limit**
  - Average mass of the pair-produced SUSY particles
  - Could be the **dominant production process** at the LHC, hence search for EW-inos pairs

2) **Split SUSY**

- **Gluino lifetime** depends on squark masses ($m_0$):
  - **Search for long-lived strongly interacting particles**

- **Split SUSY**
  - Reason for splitting:
    - Fermions carry R-parity, scalars don’t
  - **Unification** ✓
  - **Dark Matter** ✓
  - No Flavor, CP, moduli... problems

- **only sfermions** within LHC reach (gluinos, EW-inos)

- Some level of **fine tuning** accepted as stop mass can be quite high
Search results in SUSY (2)

- **Electroweak production**: decays via W/Z bosons or sleptons

Limit on $\chi_1^0$ mass up to $\approx 80$ GeV (for $m(\chi_2^0/\chi_1^\pm) = 100$ GeV and WZ scenario)
Search results in SUSY (3)

- **Long-lived particles**:

  ![Diagram of SUSY particles](image)

  \[ \tilde{g} \text{ R-hadron} \rightarrow g/qq \tilde{\chi}_1^0 ; \ m_{\tilde{\chi}_1^0} = 100 \text{ GeV} \]

  Status: March 2015

  - Displaced vertices: arXiv:1504.05162
  - Jets+E_{T}^{miss}: arXiv:1405.7875, ATLAS-CONF-2014-037
  - Stable charged: arXiv:1411.6795
  - Stopped gluino: arXiv:1310.6584

  - Expected limits
  - Observed limits

  95% CL limits, c_{\text{theory}}^\text{SUSY} not included

  - Prompt: 18.4-20.3 fb^{-1}, \ L_{\text{s}}=8 \text{ TeV}

  ATLAS Preliminary

- **Nice complementarity** of searches covering different lifetimes
- **Strongest limit** on gluinos with the displaced vertices analysis (≈1550 GeV)

**Candidate event display**:

![Candidate event display](image)

### Run1: Exotics searches

<table>
<thead>
<tr>
<th><strong>Leptoquarks</strong> <em>(carry both L and B quantum numbers)</em></th>
<th><strong>RS gravitons</strong> <em>(Randall-Sundrum (RS) model)</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Appear in <strong>various models</strong></td>
<td>- <strong>Randall-Sundrum (RS) model</strong> <em>(explains hierarchy with a warped extra dimension)</em></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Long-lived particles</strong></th>
<th><strong>Dark Matter</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Appear in <strong>various models</strong></td>
<td>- All the models try to accommodate for it</td>
</tr>
<tr>
<td>Example given for SUSY in p.13</td>
<td>will be discussed in p.16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Heavy gauge bosons <em>(W’,Z’)</em></strong></th>
<th><strong>Large Extra Dimensions</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>- In models with extended gauge sectors to achieve gauge coupling unification</td>
<td>- Appear in <strong>string theories</strong> <em>(provides link to gravity missing in the SM)</em></td>
</tr>
<tr>
<td></td>
<td>Di-lepton mass distributions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Excited fermions</strong> <em>(couple to ordinary SM fermions)</em></th>
<th><strong>Compositeness (Model)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>- in <strong>compositeness models</strong></td>
<td>- quarks/leptons are made of more fundamental constituents (addresses the <strong>number of quark/lepton generation, charges and masses</strong>)</td>
</tr>
<tr>
<td></td>
<td>high energy part of the di-lepton/jet mass spectra <em>(non-resonant)</em></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Multijet resonances</strong></th>
<th><strong>Events with lots of jets</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Appear in <strong>various models</strong></td>
<td></td>
</tr>
</tbody>
</table>

+ searches for **Higgs resonances** *(Vh with V=W,Z)*
Dark Matter Detection

- Dark Matter creation

If WIMP interactions are sensitive to the spin of the nucleus, the cross section is spin-dependent. If not, the cross section is spin-independent.

- At the LHC, look for an energetic object and missing energy

Energetic jet:

Energetic photon:

1.7σ effect, not seen by CMS (arXiv:1408.3583)

http://www.quantumdiaries.org/2014/10/22/have-we-detected-dark-matter-axions/

arXiv:1502.01518
Effective Field Theory (EFT) approach

- SM-WIMP coupling via a contact interaction:
  - $M_{\text{med}}$ = mass of the mediator
  - $Q_{\text{tr}}$ = scale of the interaction ($=\text{invariant mass of the two } \chi$)

- Condition: $M_{\text{med}} > Q_{\text{tr}}$
  - to ensure that the mediator cannot be produced directly in LHC collisions and can be integrated out with an EFT formalism
  - in the next slide: truncated = remove events that do not satisfy the condition
  - $M_{\text{med}}$ depends on the couplings of the mediator to the SM/DM particles

- Interaction couplings: WIMPs-SM
  - WIMPs = scalars
  - WIMPs = Dirac fermions

- EFT allows for direct comparison with (in)direct DM results
  - improvements expected for Run2

http://moriond.in2p3.fr/QCD/2015/WednesdayAfternoon/Landsberg.pdf
LHC allows for access to **low-mass WIMP scenario**, which is nicely **complementary** to other types of experiments.
LHC has the best limits for the whole range of WIMP masses.
LHC has the best limits for \textbf{WIMP masses below }m_H/2\textbf{ (vector DM)}

\begin{itemize}
  \item WIMPs of \textbf{different nature considered} (scalar, vector or fermion)
  \item Direct detection: \textbf{spin-independent} results from searches for nuclei recoils from elastic scattering of WIMPs
\end{itemize}

\textbf{Higgs portal model}
**Run1 : A few small excesses left (1)**

As of May 11th, 2015 :

<table>
<thead>
<tr>
<th>Areas</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Higgs</strong></td>
<td>H → hh → bbγγ (back-up)</td>
<td>Higgs to invisible (p.6)</td>
</tr>
<tr>
<td></td>
<td>ttH</td>
<td>ttH</td>
</tr>
<tr>
<td></td>
<td>LVF H → τμ (back-up)</td>
<td></td>
</tr>
<tr>
<td><strong>SUSY</strong></td>
<td>Z+MET</td>
<td>Di-lepton mass edge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multilepton 3l+τ (back-up)</td>
</tr>
<tr>
<td><strong>Exotics</strong></td>
<td>Dark Matter (p.16)</td>
<td>Di-jet mass search</td>
</tr>
<tr>
<td></td>
<td>Same-sign + b-jets</td>
<td>Di-lepton mass search</td>
</tr>
<tr>
<td></td>
<td>Type III Seesaw heavy leptons (back-up)</td>
<td>Di-boson mass search</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy neutrinos and right-handed W bosons</td>
</tr>
</tbody>
</table>

- Analyses grouped together with color codes will be presented together in the following. For others, you can find information in the back-up slides.
SUSY Excesses (2)

2 leptons (on/off-Z) + jets + missing energy

- ATLAS has an excess ≈at the mass of the Z for the electron channel
- CMS has an excess (edge) at masses below the Z mass

\[
\begin{align*}
3.0\sigma \text{ for } ee \\
1.7\sigma \text{ for } \mu\mu
\end{align*}
\]

CMS does not see an excess at ≈m(Z)

\[
\begin{align*}
\approx2.6\sigma
\end{align*}
\]

ATLAS does not see an excess in the edge

• Both experiments have excesses, but not at the same place in m_|| mass!
Higgs/Exotics Excesses (3)

ATLAS/CMS ttH and ATLAS exotic same-sign+b-jets

3 categories of decays:
1) $H \rightarrow$ hadrons ($bb, \tau\tau$)
2) $H \rightarrow$ photons
3) $H \rightarrow$ leptons (from WW, ZZ, $\tau\tau$)

Largest discrepancy in the same-sign channel:

2$\sigma$

• An excess is also observed in ATLAS (dilepton channel).

$2.5\sigma$

$ttH$ is one of the most dominant bkg's

... different regions designed to target different signals

arXiv:1503.05066

arXiv:1504.04605
Heavy neutrinos and W bosons with right-handed couplings
Exotics Excesses (5)

**RS graviton mass (GeV)**
- 1200
- 1400
- 1600
- 1800
- 2000

**Observed**
- CMS

**Expected**
- 95% CL upper limits
- RS graviton (k/M=0.1)
- Observed
- Expected
- ± 1σ
- ± 2σ

Searches for resonances

**CMS, L = 19.7 fb⁻¹ at \( \sqrt{s} = 8 \text{ TeV} \)**

**G→WW→lνqq**

**G→ZZ→lℓqq**

**G→WW→ hadronic**

**X→di-lepton**

**di-jet : G→gg**

**WW→lνqq**

**W′→WH→lνbb**

**W'→WH**

**WHT B(gv=3):xsec**

**WH→lνqq**

**W′HVT B(gv=3):xsec**

**BR(W′→WH)**

**BR(G→WW),→RS**

**BR(G→ZZ),→RS**

**M [GeV]**
- 500
- 1000
- 1500
- 2000
- 2500
- 3000
- 3500

**σ × B × A (pb)**
- 10⁻²
- 10⁻¹
- 1
- 10

**Resonance mass (TeV)**
- 1
- 1.5
- 2
- 2.5
- 3

**CMS, Preliminary e+e− combined**

**CMS- PAS- EXO- 14- 010**

**25**
Exotics Excesses (5bis)

- **X → di-lepton**
  - No excess in ATLAS
  - (arXiv:1405.4123)

- **di-jet : W' → qq'**
  - ∫L dt = 20.3 fb⁻¹
  - ATLAS
  - Observed 95% CL upper limit
  - Expected 95% CL upper limit
  - 68% and 95% bands

- **W' → WH → lνbb**
  - No excess in ATLAS, but the search stops at ≈1800 GeV
  - (arXiv:1503.08089)

- **G → WW → lνqq**
  - No excess in ATLAS
  - (arXiv:1503.04677)

- **G → ZZ → llqq**
  - No excess in ATLAS
  - (arXiv:1409.6190)

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Searches for resonances

**G → WW → hadronic**

**W' → WH → lνbb**

To appear soon on arXiv
LHC Run 2, ATLAS and CMS

- **18-month LHC shutdown** to consolidate and add new components

- **LHC main improvements**:
  - centre of mass energy increased to $\sqrt{s}=13$ TeV

- **ATLAS main improvements**:
  - Muon system completion with chambers in barrel/endcap transition
  - Additional innermost pixel layer (IBL) to improve tracking, vertexing and b-tagging for high pileup, and smaller radius Be beam pipe

- **CMS main improvements**:
  - new HCAL Outer Barrel photo-detectors
  - Muon system completed (fourth disk for RPC endcap region) and 72 CSC chambers added (on top of the 468 existing ones)

\[ \approx 10 \text{ fb}^{-1} \text{ of data in 2015} \]
Run2 (early data) : SUSY searches

- **Gluino pair production**: large production increase (factor ~15 for 2 TeV gluinos, ~50 for 3 TeV gluinos)

**Run2 discovery potential** for various datasets (from 1 fb$^{-1}$ to 10 fb$^{-1}$):

**Number of sigmas in discovery mode:**

- 3σ for evidence
- 4σ for observation
- 5σ for discovery

**3σ evidence reach with 5 fb$^{-1}$**

for gluino masses < 1500 GeV
Run2 (early data) : Exotics searches

- **Dijet resonances search**
  - With **1 fb^{-1}** of 14 TeV data, **5 \sigma** discovery potential for:
    - excited quarks up to \( \approx 4 \text{ TeV} \)
    - quantum black holes up to \( \approx 7 \text{ TeV} \)
Run2 (and further) : Higgs searches

- Still quite **some room left** from Run1 results for BSM decays of the Higgs

- Both $H^+ \rightarrow \tau \nu$ and $A \rightarrow \tau \tau$ will have better sensitivity with $2-5 \text{ fb}^{-1}$ of data

- **Further into the future**:
  - LHC Run3 planned in 2020-2022 ($300 \text{ fb}^{-1}$ of data)
  - High-luminosity LHC (HL-LHC) in $\approx2025-2035$ ($3000 \text{ fb}^{-1}$ of data)

**Limit on production times branching fraction for $A \rightarrow \tau \tau$**

**factor $\approx5$-10 gain**

**mass of the CP-odd Higgs**

**Limit on production times branching fraction for $A \rightarrow \tau \tau$**
Dark Matter further into the future

Result in p.20 from $Z_h \rightarrow ll$ invisible:

One order of magnitude gain in DM-nucleon cross section at $m_\chi = 1$ GeV
Alternatives: Intensity Frontier

- **SHiP fixed target experiment** at the SPS?

  ideal for $\nu_\tau$ physics ($D_S \rightarrow \tau \nu_\tau$)

- Explore **heavy neutral leptons (HNL)** with masses below $O(10)$GeV:

- Detector construction, 5 years of data taking (from 2022) and data analysis of $2 \times 10^{20}$ pot can be achieved in $\sim 10$ years

400 GeV protons from SPS

arXiv:1504.04855
Conclusions

• New physics searched for **in a lot of places during Run1**
  • *Not possible to highlight all of them today*

• The Higgs boson seems to be the **one predicted by the SM**
  • *Still room for new decays, new Higgses,…*

• “Natural” SUSY has suffered a lot with Run1, **split-SUSY** is now gaining more attention for Run2
  • *Analogy to EWSB model (by theorist N. Craig) ? minimal SU(2)xU(1) structure of the Glashow model (1961) is correct, but the model was missing a scalar field (Higgs) for EWSB (Weinberg in 1967) → non-minimal realization in nature*

• **A few excesses remaining,** some of them reported by both ATLAS/CMS !

• **pp collisions at 13 TeV** of Run2 will happen very shortly.
  • confirm/rule out the Run1 excesses
  • Explore a new window in energy with the **2015 dataset,** sensitivities will increase significantly in particular in **high mass regions** !
Back-Up Slides
LHC, ATLAS and CMS
LHC goal for 2015 and for Run 2 and 3

Integrated luminosity goal:
2015 : 10 fb$^{-1}$

Run2: $\sim$100-120 fb$^{-1}$
(better estimation by end of 2015)

300 fb$^{-1}$ before LS3
### ATLAS and CMS: More details

- **The main differences** between the ATLAS and CMS detectors are:

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>B-field</strong></td>
<td>2T solenoid (Inner Tracker inside, HCAL outside of B-field) + toroid: 0.5T (barrel), 1T (endcap)</td>
<td>4T solenoid + return yoke (ECAL and part of HCAL inside)</td>
</tr>
<tr>
<td></td>
<td>→ good for jet resolution, worse for e/γ</td>
<td>→ good for e/γ resolution, worse for jet</td>
</tr>
<tr>
<td><strong>Tracker</strong></td>
<td>Si pixels and strips + transition radiation tracker</td>
<td>Si pixels and strips (fully Silicon)</td>
</tr>
<tr>
<td><strong>π with pT=1GeV</strong></td>
<td>σ/p_T ~ 5 x 10^{-4}p_T + 0.01</td>
<td>σ/p_T ~ 1.5 x 10^{-4}p_T + 0.005</td>
</tr>
<tr>
<td><strong>e with pT=5GeV</strong></td>
<td>84% reco efficiency (material budget, B-field)</td>
<td>80% reco efficiency</td>
</tr>
<tr>
<td></td>
<td>90% reco efficiency</td>
<td>85% reco efficiency</td>
</tr>
<tr>
<td><strong>EM calo</strong></td>
<td>Liquid argon + Pb absorbers → high granularity</td>
<td>PbWO_4 crystals → high resolution</td>
</tr>
<tr>
<td>100 GeV γ</td>
<td>σ/E ~ 10%/√E + 0.007</td>
<td>σ/E ~ 3%/√E + 0.003</td>
</tr>
<tr>
<td>50 GeV e</td>
<td>1.0 - 1.5% E resolution</td>
<td>0.8% E resolution</td>
</tr>
<tr>
<td></td>
<td>1.3 - 2.3% E resolution</td>
<td>2.0% E resolution</td>
</tr>
<tr>
<td><strong>Had calo</strong></td>
<td>Fe + scintillator / Cu+Lar (10λ)</td>
<td>Brass + scintillator (7λ + catcher)</td>
</tr>
<tr>
<td>1000 GeV jets</td>
<td>σ/E ~ 50%/√E + 0.03 GeV</td>
<td>σ/E ~ 100%/√E + 0.05 GeV</td>
</tr>
<tr>
<td>2000 GeV MET</td>
<td>2%</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>20 Gev</td>
<td>40 Gev</td>
</tr>
<tr>
<td><strong>Muon</strong></td>
<td>σ/p_T~2% at 50 GeV to 10% at 1 TeV (Inner Tracker + muon system)</td>
<td>σ/p_T~1% at 50 Gev to 10% at 1 TeV (Inner Tracker + muon system)</td>
</tr>
</tbody>
</table>
The ATLAS Detector

- **Inner tracker** → electrons, muons, jets
- **Solenoid B-field** → electrons, muons
- **Electromagnetic calorimeter** → electrons, photons, jets, missing energy
- **Hadronic calorimeter** → jets, missing energy
- **Toroid B-field** → muons
- **Muon chambers** → muons

Searches for SM Deviations
Run1: Search for deviations from the SM

- In the **Standard Model**, deviations were looked for in:
  - Cross section measurements
  - Anomalous couplings
  - Resonances (ttbar,...)
  - Indirect effects (B-physics)

- **WW production cross section** that was puzzling during Run1
  - **NNLO theory calculations** could explain the discrepancy observed
Anomalous couplings:

Quartic couplings in the SM:

- **Add anomalous** quartic couplings via effective Lagrangian (independent of the SM ones)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limits</th>
<th>L</th>
<th>$\sqrt{s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW^+\gamma\gamma$</td>
<td>[-15000, 15000]</td>
<td>0.43fb$^{-1}$</td>
<td>0.20 TeV</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow WW$</td>
<td>[-430, 430]</td>
<td>9.70fb$^{-1}$</td>
<td>1.96 TeV</td>
</tr>
<tr>
<td>$WW^+\gamma\gamma$</td>
<td>[-21, 20]</td>
<td>19.30fb$^{-1}$</td>
<td>8.0 TeV</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow WW$</td>
<td>[-4, 4]</td>
<td>5.05fb$^{-1}$</td>
<td>7.0 TeV</td>
</tr>
</tbody>
</table>

- ≈20 times better than Tevatron
- ≈2 orders of magnitude better than LEP
More material on mono-object searches
DM annihilation rate:

![Graph showing the DM annihilation rate versus WIMP mass](image)

- **ATLAS**
- 95% CL, $\sqrt{s}=8$ TeV, 20.3 fb$^{-1}$

- $2 \times$ (Fermi-LAT dSphs ($\chi\chi$) $\rightarrow u\bar{u}$, 4 years)
- $2 \times$ (HESS 2011 ($\chi\chi$) Majorana $\rightarrow q\bar{q}$, Einasto profile)
- $2 \times$ (HESS 2011 ($\chi\chi$) Majorana $\rightarrow q\bar{q}$, NFW profile)

- D5: $\chi\gamma^\mu\gamma^\nu q \rightarrow (\chi\chi)_{\text{Dirac}}$
- D8: $\chi\gamma^\mu\gamma^5\gamma^\nu q \rightarrow (\chi\chi)_{\text{Dirac}}$

- Truncated, coupling = 1
- Truncated, max coupling
- Thermal relic

```latex
\begin{align*}
\langle \sigma v \rangle _{\chi\chi \rightarrow q\bar{q}} \text{ [cm}^3\text{s]} & \ 
\end{align*}
\end{equation}
```
Mono-phot: Limits on SUSY

Limit on SUSY compressed result (from energetic photon)

$$\sigma(pp \rightarrow \tilde{q}\tilde{q}^* \gamma + X)$$

- Squark masses excluded up to 250 GeV
General search
Run1: Model-Independent General Search

- **697 final states** put together

- Compare data to backgrounds
  - Number of events
  - Distributions, like missing energy

No significant deviation found
More material on excesses
2 leptons (on/off-Z) + jets + missing energy (ATLAS)

Background description ok everywhere
CMS ttH

arXiv:1408.1682v2 [hep-ex]
Majorana Neutrinos

Heavy neutrinos and W bosons with right-handed couplings

Same-sign analysis:

No excess observed in ATLAS nor CMS

to appear soon on ArXiv

arXiv:1501.05566
Searches for resonances

VV Combined Results

Full combination of $X \rightarrow VV$ results in the Bulk Graviton model

- Improves sensitivity to new physics!
- Best sensitivity from lepton+$E_T^{miss}$+V-jet channel over the whole mass range, followed by the all-hadronic channel at higher masses.
- Good sensitivity from the 2 leptons+V-jet channel at low masses.
- Interesting deviation from expected background (1.3σ) in all channels at $M \sim 1.8$ - 2 TeV!
• CMS LFV $H \rightarrow \mu\tau$

- CMS preliminary, $19.7 \text{ fb}^{-1}$, $\sqrt{s} = 8 \text{ TeV}$

- 2.5\sigma excess

- ATLAS result in preparation
Type III See-Saw heavy leptons in 2L+2J final state:

No excess observed by CMS (3L final state):

To appear soon on arXiv
ATLAS Higgs excess

- Di-Higgs resonances

\[ G^* \rightarrow HH \rightarrow b\bar{b}b\bar{b} \text{ (or } b\bar{b}\gamma\gamma) \]

**bbγγ** final state:

Small statistics

Excess not seen by CMS

(CMS PAS HIG-13-032)
**CMS SUSY Excess**

**Multilepton 3l+\(\tau\)**

- **Right-handed stau lepton** is (N)NLSP

- **Signal regions with off-shell Z, hadronic taus without b-jets**

<table>
<thead>
<tr>
<th>Missing energy (GeV)</th>
<th>H(_T)&gt;200 GeV, observed</th>
<th>H(_T)&gt;200 GeV, expected</th>
<th>H(_T)&lt;200 GeV, observed</th>
<th>H(_T)&lt;200 GeV, expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 100</td>
<td>1</td>
<td>0.25±0.11</td>
<td>3</td>
<td>0.60±0.24</td>
</tr>
<tr>
<td>[50,100]</td>
<td>1</td>
<td>0.29±0.13</td>
<td>4</td>
<td>2.1±0.5</td>
</tr>
<tr>
<td>[0,50]</td>
<td>0</td>
<td>0.27±0.12</td>
<td>15</td>
<td>7.5±2.0</td>
</tr>
</tbody>
</table>

\(\sqrt{s} = 8 \text{ TeV}, \int L dt = 19.5 \text{ fb}^{-1}\)

**NLSP case**

- **Stau-NLSP and Stau-NNLSP**
  - Observed 95% CL limits
  - Theoretical uncertainty (NLO)
  - Expected 95% CL limits
  - Expected ±1\(\sigma\) experimental
  - Expected ±2\(\sigma\) experimental
  - Expected ±3\(\sigma\) experimental

**NNLSP case**

- **3\(\sigma\) for NLSP case**
- **2\(\sigma\) for NNLSP case**
### ATLAS SUSY Searches - 95% CL Lower Limits

**Status:** Feb 2015

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell', \mu', \tau', \gamma$ Jets</th>
<th>$E_T^{\text{miss}}$</th>
<th>$\sqrt{s} , dt$ [mb$^{-1}$]</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSMSS</td>
<td>0 2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>(1.5 \text{ TeV})</td>
<td>1405.7875</td>
</tr>
<tr>
<td>(q_1 \rightarrow q_0 l^+l^-) (compressed)</td>
<td>0 2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>(250 \text{ GeV})</td>
<td>1405.7875</td>
</tr>
<tr>
<td>(q_2 \rightarrow q_0 l^+l^-)</td>
<td>1 0-1 jet</td>
<td>Yes</td>
<td>20.3</td>
<td>(1.2 \text{ TeV})</td>
<td>1405.7875</td>
</tr>
<tr>
<td>(g \rightarrow q_0 q_0 l)</td>
<td>0 2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>(1.2 \text{ TeV})</td>
<td>1405.7875</td>
</tr>
<tr>
<td>GSMSSB (NLSP)</td>
<td>1 0-3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>(1.6 \text{ TeV})</td>
<td>1405.7875</td>
</tr>
<tr>
<td>GGM (bino NLSP)</td>
<td>2 0-2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>(1.28 \text{ TeV})</td>
<td>1405.7875</td>
</tr>
<tr>
<td>GGM (higgsino NLSP)</td>
<td>3 0-2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>(0.9 \text{ TeV})</td>
<td>1405.7875</td>
</tr>
<tr>
<td>Gravitino LSP</td>
<td>2 0-3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>(0.8 \text{ TeV})</td>
<td>1405.7875</td>
</tr>
<tr>
<td>BMH (M_{\chi}^{1})</td>
<td>3 0-3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>(0.7 \text{ TeV})</td>
<td>1405.7875</td>
</tr>
<tr>
<td>GGM (higgsino NLSP)</td>
<td>3 0-2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>(0.6 \text{ TeV})</td>
<td>1405.7875</td>
</tr>
<tr>
<td>Gravitino LSP</td>
<td>3 0-3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>(0.5 \text{ TeV})</td>
<td>1405.7875</td>
</tr>
<tr>
<td>BMH (M_{\chi}^{1})</td>
<td>3 0-3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>(0.4 \text{ TeV})</td>
<td>1405.7875</td>
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<tr>
<td>BMH (M_{\chi}^{1})</td>
<td>3 0-3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>(0.3 \text{ TeV})</td>
<td>1405.7875</td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1$\sigma$ theoretical signal cross section uncertainty.*
Summary of CMS SUSY Results* in SMS framework

<table>
<thead>
<tr>
<th>m(mother)-m(LSP)=200 GeV</th>
<th>m(LSP)=0 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS-13-012 SUS-12-028 L=19.5 11.7 /fb</td>
<td>SUSY 2013</td>
</tr>
<tr>
<td>SUS-12-005 SUS-11-024 L=4.7 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-11-011 L=4.98 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-12-004 L=4.98 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-12-010 L=4.98 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-13-008 SUS-13-013 L=19.5 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-11-010 L=4.98 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-11-021 SUS-12-002 L=4.98 4.73 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-13-013 L=19.5 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-12-001 L=4.93 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-12-001 SUS-13-004 L=19.5 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-13-008 SUS-13-013 L=19.5 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-13-012 SUS-12-028 L=19.5 11.7 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-12-005 SUS-11-024 L=4.7 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-13-011 SUS-13-004 L=19.5 19.3 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-11-024 SUS-12-005 L=4.7 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-13-011 L=19.5 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-11-030 L=4.98 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-13-014 L=19.5 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-12-028 L=11.7 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-13-008 SUS-13-013 L=19.5 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-13-008 L=19.5 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-13-006 L=19.5 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-13-006 L=19.5 /fb</td>
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<tr>
<td>SUS-13-006 L=19.5 /fb</td>
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<tr>
<td>SUS-13-017 L=19.5 /fb</td>
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<tr>
<td>SUS-13-006 L=19.5 /fb</td>
<td></td>
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<tr>
<td>SUS-13-006 L=19.5 /fb</td>
<td></td>
</tr>
<tr>
<td>SUS-13-014 L=19.5 /fb</td>
<td></td>
</tr>
</tbody>
</table>

CMS Preliminary

For decays with intermediate mass, m_{intermediate} = x m_{mother} \cdot (1-x) \cdot m_{lsp}

*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe "up to" the quoted mass limit

Run1 : CMS SUSY searches (1)
Run1: CMS SUSY searches (2)

Summary of CMS RPV SUSY Results*

<table>
<thead>
<tr>
<th>Process</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{g} \rightarrow q\ell\nu$</td>
<td>SUS-12-027 L=9.2 /fb</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow q\ell\nu$</td>
<td>SUS-12-027 L=9.2 /fb</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow q\ell\nu$</td>
<td>SUS-12-027 L=9.2 /fb</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow qbt\mu$</td>
<td>SUS-12-027 L=9.2 /fb</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow qbt\mu$</td>
<td>SUS-12-027 L=9.2 /fb</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow qbt\mu$</td>
<td>SUS-12-027 L=9.2 /fb</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow qbt\mu$</td>
<td>SUS-12-027 L=9.2 /fb</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow qbt\mu$</td>
<td>SUS-12-027 L=9.2 /fb</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow qbt\mu$</td>
<td>SUS-12-027 L=9.2 /fb</td>
</tr>
</tbody>
</table>

*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe "up to" the quoted mass limit
## ATLAS Exotics Searches* - 95% CL Exclusion

**Status:** March 2015

### ATLAS Preliminary

\[
\int dL = (1.0 - 20.3) \, \text{fb}^{-1} \quad \sqrt{s} = 7, 8 \, \text{TeV}
\]

### Table of Mass Limits

<table>
<thead>
<tr>
<th>Model</th>
<th>(\ell, \gamma)</th>
<th>Jets</th>
<th>(E_{\text{miss}}) (T)</th>
<th>(fL dt) [fb(^{-1})]</th>
<th>Mass Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADO (gS + g/g)</td>
<td>–</td>
<td>(\geq 1)</td>
<td>Yes</td>
<td>20.3</td>
<td>3.25 GeV</td>
</tr>
<tr>
<td>ADO non-resonant (\ell\ell)</td>
<td>(2e, \mu)</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>3.25 GeV</td>
</tr>
<tr>
<td>ADO (gS \rightarrow \ell\gamma)</td>
<td>(1e, \mu)</td>
<td>(1)</td>
<td>–</td>
<td>20.3</td>
<td>5.2 TeV</td>
</tr>
<tr>
<td>ADO (gS \rightarrow \ell)</td>
<td>(1)</td>
<td></td>
<td></td>
<td>20.3</td>
<td>3.25 GeV</td>
</tr>
<tr>
<td>ADO BH high (M_{\ell\ell})</td>
<td>(2\mu)</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>5.2 TeV</td>
</tr>
<tr>
<td>ADO BH high (\ell\ell)</td>
<td>(\geq 1)</td>
<td>(\geq 2)</td>
<td>–</td>
<td>20.3</td>
<td>5.2 TeV</td>
</tr>
<tr>
<td>ADO BH high multijet</td>
<td>(\geq 2)</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>5.2 TeV</td>
</tr>
<tr>
<td>RS1 (gS \rightarrow \ell\ell)</td>
<td>(2\mu)</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>5.2 TeV</td>
</tr>
<tr>
<td>RS1 (gS \rightarrow \gamma)</td>
<td>(2\gamma)</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>5.2 TeV</td>
</tr>
<tr>
<td>Bulk RS (gS \rightarrow ZZ \rightarrow q\bar{q}+\gamma)</td>
<td>(2e, \mu)</td>
<td>(2)</td>
<td>(1/1)</td>
<td>20.3</td>
<td>7.6 GeV</td>
</tr>
<tr>
<td>Bulk RS (gS \rightarrow WW \rightarrow q\bar{q}+\gamma)</td>
<td>(1e, \mu)</td>
<td>(2)</td>
<td>(1/1)</td>
<td>Yes</td>
<td>20.3</td>
</tr>
<tr>
<td>Bulk RS (gS \rightarrow HH \rightarrow b\bar{b}b\bar{b})</td>
<td>(4b)</td>
<td>–</td>
<td>(1/1)</td>
<td>20.3</td>
<td>7.6 GeV</td>
</tr>
<tr>
<td>Bulk RS (gS \rightarrow t\bar{t})</td>
<td>(1\mu, \mu)</td>
<td>(1)</td>
<td>(1)</td>
<td>20.3</td>
<td>7.6 GeV</td>
</tr>
<tr>
<td>SSIM (Z' \rightarrow \ell\ell)</td>
<td>(2\ell)</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>5.2 TeV</td>
</tr>
<tr>
<td>SSIM (Z' \rightarrow \tau\tau)</td>
<td>(2\tau)</td>
<td>–</td>
<td>–</td>
<td>19.3</td>
<td>5.2 TeV</td>
</tr>
<tr>
<td>EGM (W' \rightarrow ZW \rightarrow \ell\ell)</td>
<td>(3e, \mu)</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>5.2 TeV</td>
</tr>
<tr>
<td>EGM (W' \rightarrow WZ \rightarrow q\bar{q}+\gamma)</td>
<td>(2e, \mu)</td>
<td>(2)</td>
<td>(1/1)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>HVT (W' \rightarrow WH \rightarrow c\bar{b}b)</td>
<td>(1\ell)</td>
<td>(2)</td>
<td>(b)</td>
<td>Yes</td>
<td>20.3</td>
</tr>
<tr>
<td>URSM (W_{L} \rightarrow tb)</td>
<td>(1\ell)</td>
<td>(2b, 0)</td>
<td>(1/1)</td>
<td>Yes</td>
<td>20.3</td>
</tr>
<tr>
<td>URSM (W_{R} \rightarrow tb)</td>
<td>(0\ell)</td>
<td>(1b, 1)</td>
<td>(1/1)</td>
<td>Yes</td>
<td>20.3</td>
</tr>
</tbody>
</table>

### Exotics

<table>
<thead>
<tr>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ci (qq)</td>
</tr>
<tr>
<td>Ci (q\gamma)</td>
</tr>
<tr>
<td>Ci (\ell\nu)</td>
</tr>
</tbody>
</table>

### DM

<table>
<thead>
<tr>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar LG 1(^{st}) gen</td>
</tr>
<tr>
<td>Scalar LG 2(^{nd}) gen</td>
</tr>
<tr>
<td>Scalar LG 3(^{rd}) gen</td>
</tr>
</tbody>
</table>

### Happy quarks

<table>
<thead>
<tr>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLO (T' \rightarrow H'(X)+Wb')</td>
</tr>
<tr>
<td>VLO (T' \rightarrow Z+X)</td>
</tr>
<tr>
<td>VLO (H' \rightarrow Zb+X)</td>
</tr>
<tr>
<td>VLO (H' \rightarrow W'X)</td>
</tr>
<tr>
<td>(\ell\ell) (T' \rightarrow W')</td>
</tr>
</tbody>
</table>

### Exotic fermions

<table>
<thead>
<tr>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excited quark (q' \rightarrow q\gamma)</td>
</tr>
<tr>
<td>Excited quark (q' \rightarrow q\ell)</td>
</tr>
<tr>
<td>Excited quark (q' \rightarrow q\ell)</td>
</tr>
<tr>
<td>Excited lepton (\ell' \rightarrow \ell W)</td>
</tr>
<tr>
<td>Excited lepton (\ell' \rightarrow \ell W)</td>
</tr>
</tbody>
</table>

### Other

<table>
<thead>
<tr>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSTG (a' \rightarrow W\gamma)</td>
</tr>
<tr>
<td>URSM Majamana (a' \rightarrow W\gamma)</td>
</tr>
<tr>
<td>Higgs triplet (H^{++} \rightarrow WH)</td>
</tr>
<tr>
<td>Higgs triplet (H^{++} \rightarrow HW)</td>
</tr>
<tr>
<td>Triplet (non-res prod)</td>
</tr>
<tr>
<td>Multi-charged particles</td>
</tr>
<tr>
<td>Magneto monopoles</td>
</tr>
</tbody>
</table>

**Note:** Only a selection of the available mass limits on new states or phenomena is shown.

---

Image: Run1: ATLAS Exotics searches (1)
Run 1: ATLAS Exotics searches (2)

### ATLAS Exotics Long-lived Particle Searches* - 95% CL Exclusion

Status: March 2015

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>$[\mathcal{L}dt] [\text{fb}^{-1}]$</th>
<th>Lifetime limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hidden Valley $H \rightarrow \pi, \pi \pi$</td>
<td>2 low-EMF trackless jets</td>
<td>20.3</td>
<td>$\tau_{\pi}$ lifetime, $0.31-7.59 \text{ hr}$</td>
<td>$m(\pi) = 25 \text{ GeV}$</td>
</tr>
<tr>
<td>Hidden Valley $H \rightarrow \pi, \pi \pi$</td>
<td>2 ID/MS vertices</td>
<td>16.5</td>
<td>$\tau_{\pi}$ lifetime, $0.21-25.4 \text{ mm}$</td>
<td>$m(\pi) = 25 \text{ GeV}$</td>
</tr>
<tr>
<td>FRVZ $H \rightarrow 2\gamma + X$</td>
<td>2 $e, \mu, \tau$-jets</td>
<td>20.3</td>
<td>$\tau_{\gamma}$ lifetime, $1.4-14.4 \text{ mm}$</td>
<td>$H \rightarrow 2\gamma + X, m(\gamma \gamma) = 400 \text{ MeV}$</td>
</tr>
<tr>
<td>FRVZ $H \rightarrow 4\gamma + X$</td>
<td>2 $e, \mu, \tau$-jets</td>
<td>20.3</td>
<td>$\tau_{\gamma}$ lifetime, $15-200 \text{ mm}$</td>
<td>$H \rightarrow 4\gamma + X, m(\gamma \gamma) = 400 \text{ MeV}$</td>
</tr>
<tr>
<td>Hidden Valley $H \rightarrow \pi, \pi \pi$</td>
<td>2 low-EMF trackless jets</td>
<td>20.3</td>
<td>$\tau_{\pi}$ lifetime, $0.65 \text{ m}$</td>
<td>$m(\pi) = 25 \text{ GeV}$</td>
</tr>
<tr>
<td>Hidden Valley $H \rightarrow \pi, \pi \pi$</td>
<td>2 ID/MS vertices</td>
<td>19.5</td>
<td>$\tau_{\pi}$ lifetime, $0.48-11.1 \text{ m}$</td>
<td>$m(\pi) = 25 \text{ GeV}$</td>
</tr>
<tr>
<td>FRVZ $H \rightarrow 2\gamma + X$</td>
<td>2 $e, \mu, \tau$-jets</td>
<td>20.3</td>
<td>$\tau_{\gamma}$ lifetime, $28-154 \text{ m}$</td>
<td>$H \rightarrow 2\gamma + X, m(\gamma \gamma) = 400 \text{ MeV}$</td>
</tr>
<tr>
<td>Hidden Valley $\Phi \rightarrow \pi, \pi \pi$</td>
<td>2 low-EMF trackless jets</td>
<td>20.3</td>
<td>$\tau_{\pi}$ lifetime, $0.29-7.9 \text{ m}$</td>
<td>$m(\Phi) = 500 \text{ GeV}$</td>
</tr>
<tr>
<td>Hidden Valley $\Phi \rightarrow \pi, \pi \pi$</td>
<td>2 ID/MS vertices</td>
<td>19.5</td>
<td>$\tau_{\pi}$ lifetime, $0.19-31.9 \text{ m}$</td>
<td>$m(\Phi) = 500 \text{ GeV}$</td>
</tr>
<tr>
<td>Hidden Valley $\Phi \rightarrow \pi, \pi \pi$</td>
<td>2 low-EMF trackless jets</td>
<td>20.3</td>
<td>$\tau_{\pi}$ lifetime, $0.15-4.1 \text{ m}$</td>
<td>$m(\Phi) = 500 \text{ GeV}$</td>
</tr>
<tr>
<td>Hidden Valley $\Phi \rightarrow \pi, \pi \pi$</td>
<td>2 ID/MS vertices</td>
<td>19.5</td>
<td>$\tau_{\pi}$ lifetime, $0.11-18.3 \text{ m}$</td>
<td>$m(\Phi) = 500 \text{ GeV}$</td>
</tr>
<tr>
<td>GMSB</td>
<td>non-pointing or delayed $\gamma$</td>
<td>20.3</td>
<td>$\tau_{\gamma}$ lifetime, $0.08-5.4 \text{ m}$</td>
<td>SPS8 with $A = 200 \text{ TeV}$</td>
</tr>
<tr>
<td>Stealth SUSY</td>
<td>2 ID/MS vertices</td>
<td>19.5</td>
<td>$\phi$ lifetime, $0.12-6.6 \text{ m}$</td>
<td>$m(\phi) = 500 \text{ GeV}$</td>
</tr>
<tr>
<td>HV $Z'(1 \text{ TeV}) \rightarrow q, q\bar{q}$</td>
<td>2 ID/MS vertices</td>
<td>20.3</td>
<td>$\tau_{\phi}$ lifetime, $0.11-4.9 \text{ m}$</td>
<td>$m(\phi) = 500 \text{ GeV}$</td>
</tr>
<tr>
<td>HV $Z'(2 \text{ TeV}) \rightarrow q, q\bar{q}$</td>
<td>2 ID/MS vertices</td>
<td>20.3</td>
<td>$\tau_{\phi}$ lifetime, $0.11-10.1 \text{ m}$</td>
<td>$m(\phi) = 500 \text{ GeV}$</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 8 \text{ TeV}$

*Only a selection of the available lifetime limits on new states is shown.*
Run 1: CMS Exotics searches (2)

CMS Searches for New Physics Beyond Two Generations (B2G)

95% CL Exclusions (TeV)

- Vector-like T'
- Vector-like B'
- Dark matter
- tt̄ Resonances
- tb Resonances
- Excited tops
- Displaced tops
Run1: Limits on SUSY (1)

- Strong production

![Graph showing limits on SUSY particles](image)

Except for dark matter, the 5 sigma discovery reach in terms of particle mass is shown. Selected models include new resonances $Z'$ and $W'$, heavy stable charged particles (HSCP) such as gluino or stau, and pair-produced T-quarks.

For the EFT description of pair-produced dark matter, the interesting parameter is the cut-off scale $\Lambda = M/\sqrt{g_{DM} g_{SM}}$ with $M$ being the mediator mass (assumed to be high) and $g$ being the DM and SM couplings, respectively. The chosen dark matter monolepton channel allows to study potentially different couplings to up- and down-type quarks parametrized by $\xi$. 

https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsFP/ECFA-CMSPublicResults.pdf
Run2 (and further) : Higgs searches

\begin{align*}
\text{ATLAS Simulation Preliminary} \\
\text{Combined } h \rightarrow \gamma\gamma, ZZ^*, WW^* \\
h \rightarrow Z\gamma, \mu\mu, \tau\tau, b\bar{b} \\
\text{Exp. 95\% CL at } \sqrt{s} = 14 \text{ TeV} \\
\text{Simplified MSSM } [\kappa_\gamma, \kappa_u, \kappa_d] \\
\int L dt = 300 \text{ fb}^{-1} : \text{all unc.} \\
\int L dt = 300 \text{ fb}^{-1} : \text{No theo.} \\
\int L dt = 3000 \text{ fb}^{-1} : \text{all unc.} \\
\int L dt = 3000 \text{ fb}^{-1} : \text{No theo.} \\
\end{align*}

≈ Run1 exclusion from p.12