Experimental Beyond-the-SM projects at the HL-LHC

Kerstin Hoepfner (RWTH Aachen)
on behalf of the ATLAS and CMS collaborations
Motivation

Many ongoing searches at present LHC. Indications here and there but no conclusive sign of new physics yet.

BSM searches at HL not a linear extrapolation from presence. Rather **widen the scope**, e.g.:
- Rare processes, weaker couplings
- New models upcoming including observed LHC results
- Go more model-independent not to miss something

How to prepare for phase-2 physics?
- Continue benchmark analyses
- Develop new analysis strategies

SCOPE of this talk: show selected examples
Keep Searching

New bosons

Flavour-related

Exotic Signatures

Where is SUSY?

New phenomena

See backup for references
Analysis Techniques

**ATLAS**
- Generate truth-only 14 TeV event
- Overlay with jets (full sim) from pileup library, $<PU> = 200$
- Reconstruct particles from truth+overlay
- Smear their energy and $p_T$ using appropriate smearing functions, incl. Eff for genuine objects and rates from mis-identified objects.

**CMS (two types, projections and full analyses)**

**Projections from a present analysis**
- Existing signal and background samples (simulated at 13 TeV) scaled to higher luminosity and $\sqrt{s}=14$ TeV. Different uncertainty scenarios.
- Analysis steps (cuts) from present analyses.

**Full analyses with parametrized detector performance**
- DELPHES with up-to-date phase-2 detector performance and $<PU> = 200$
- Analysis steps guided by present analysis. Limited optimization for HL conditions. Cross checks with present analyses.
- Dedicated simulation of signal and bkgr samples
Dijet (bump hunt)

Discovery reach for excited quarks (q*) and quantum black holes (QBH)

Powerful search technique for new physics, **model-independent** as long as a sharp resonance. Many interpretations possible.

**Bump-hunter algorithm** (Similar technique for other analyses)

---

ATLAS simulation preliminary

\( \sqrt{s} = 14 \text{ TeV} \)

- **Simulated data**
- **Background**

\( \int L \, dt = 200.0 \text{ fb}^{-1} \)

Injected 6 TeV q* signal

Leads to a 5\( \sigma \) excess

---

8 TeV @ 3/ab

QBH

>10 TeV @ 3/ab
Searches for Heavy Bosons

ATLAS and CMS are working on $Z'/W'$ searches in general.

$W' \rightarrow \mu \nu$ (ATLAS Muon TDR)
Cumulative acceptance as fct($\eta$) with upgraded detector. With additional RPC gain in trigger efficiency 70% -> 90%.

$W' \rightarrow e\nu$ (CMS-PAS-EXO-14-007)
Weaker coupling are domain of HL
Shown here study of coupling strength

Discovery up to 7 TeV

ATLAS Simulation

CMS Delphes Simulation

$\sqrt{s} = 14$ TeV
TP performance
Where is SUSY?

Present LHC has excluded large part of the natural SUSY parameter space

• Limits for strong SUSY production are above 1 TeV
• Top and bottom squarks highly constrained

Still lots of opportunities in the electroweak sector

• May dominate if squarks and gluinos are heavy
• In most SUSY breaking scenarios EWK-inos are expected O(100 GeV) mass based on naturalness
• EWK-inos are produced via EWK production → small cross sections. HL-LHC has potential to increase sensitivity by 3000/80 ~40x
Search of EWK-inos into WW

Search for \( \tilde{\chi}_2^\pm \tilde{\chi}_4^0 \) decaying to same-sign WW. In some models large visible cross section (25%).

**Signature:** same-sign leptons. Small mass difference yields soft W and soft leptons.

Baseline SR binned into 7 \( m_{T,\text{min}} \) based regions.
Direct Production of stau Pairs

If chargino and neutralino NLSP are heavy, direct stau pair production can become dominant EWK production. Assume 100% BR to SM tau and LSP.

**Signature:**
- 2 tau jets (hadronically decaying tau)
- Large MET (from $\tilde{\chi}_1^0$)

**Main background:** W+jets, ttbar

**Selection:** 2 OS taus, loose jet and Z-veto, MET>280 GeV

**Define signal region (SR) in** $m_{\tau_1}(\tau_1) + m_{\tau_2}(\tau_2)$

**Discovery reach**
430-520 GeV @ 3/ab depending on bkg
Exotic Signatures

- More and more models with **long-lived particles**
- One signature can originate from different models → search signature-based rather than model-driven
- Experimental issues: needs dedicated triggers and algorithms to detect these **non-standard signatures**. Efficiencies depend on kinematics, decay length, etc.

What is exotic?

- Anomalous dE/dx
- Decay after long lifetime
- Appearance of tracks
- Timing measurements
Detection via Anomalous $dE/dx$

Slow moving particles ($\beta \ll 0.9$) can be identified from their anomalous $dE/dx$

Similar method for fractionally and multiply charged particles
Detection via Time-Of-Flight

Slow moving particles deviate sufficiently from relativistic TOF → allows to target low beta at trigger level

HSCP = heavy stable charged particle

Phase-2 sensitive to $0.25 < \beta < 0.5$

Relativistic SM particle

Slow moving stau
Sensitivity for Displaced Muons

Search for muons with large displacement $O(1-10 \text{ m})$ such that tracker does not contribute to trigger and reconstruction only in muon system.

Particular SUSY model with TeV smuons with production cross section $\sigma_{\text{prod}} < 10^{-2} \text{ fb}$
Exclude masses $m(\tilde{\mu}) < 220 \text{ GeV}$ with 3000/fb, Phase-2 detector.

Sensitivity in terms of decay length $c\tau$
Also discovery sensitivity.
More interpretations in other models ongoing.
Flavour puzzle

Observed anomalies in B-physics

One possible explanation are leptoquark (LQ)-like mediators. TeV scale and 3rd generation favored.

- Experimentally: LQ pair and singly produced.
- LQ3 -> \( \tau + t \) (\( \tau \tau tt \)) and \( \tau + b \) (\( \tau \tau bb \)).

Another possible explanation are Z´-like mediators. Also here 3rd generation favoured.

Complementary searches in other channels

Many Run-2 searches in all final states. Some projections for HL-LHC.

Ongoing projections for HL-LHC
Selection steps derived from Run-2, simplified. Discriminating variable = m(tt)

Two categories: resolved and boosted, l = e, μ

Signal model: topcolor model with spin-1 Z' boson, width 1.2%. PYTHIA 8. LO xsec * 1.3 (k-factor), Interference signal-background neglected.

Backgrounds simulated to NNLO

Boosted category with heavier Z' signals

Detector effects: parametrized performance estimate of Phase-2 Det

Gain from HL: 3 TeV (300/fb) → 4 TeV (3000/fb)

Similar projection by CMS on Z'→tt
$W' \rightarrow tb \rightarrow e/\mu + b$-jet(s)

Three scenarios to extrapolate systematics from 12.9/fb to 3/ab

1) Leave **systematics unchanged**, simply scale templates with lumi
2) **Reduce** most experimental to percent level, theoretical uncertainties by factor 2, top $p_T$ reweighting by factor 3
3) No systematics (best possible limit)

→ Impact on projected exclusion limit: 4(4.4) TeV for case 1(3)

Exclusion reach depends on systematics

In 14 TeV CMS Preliminary Simulation

- Theory $M_{W'} < M_{W^*}$
- Theory $M_{W'} > M_{W^*}$
- 95% CL expected
- Unchanged Systematics
- Reduced Systematics
- No Systematics

Invariant Mass Analysis $e/\mu + \text{jets } N_{b\text{ tags}} = 1 \text{ or } 2$

Discovery

$\log_{10}(\sigma(pp\rightarrow W'_{R}) \times B(W'_{R}\rightarrow tb\rightarrow lvbb))$ (pb)

- Theory ($M_{W'} < M_{W^*}$)
- Theory ($M_{W'} > M_{W^*}$)
- Current Systematics
- Reduced Systematics
- No Systematics

$W'$ Mass [GeV]

$1000 \quad 1500 \quad 2000 \quad 2500 \quad 3000 \quad 3500 \quad 4000$

Projection in DP-2016/064 and CMS-PAS-FTR-16-005.
See something

What is it?
Study properties of „excess“ in phase-2
Property Measurements

Example: study new physics properties with high statistics in characteristic distributions, e.g. $A_{FB}$

New heavy spin-1 resonance (dilepton channel). Little theoretical constraints on $A_{FB}$ value → any value between -0.75 and +0.75.

<table>
<thead>
<tr>
<th>$Z_0$</th>
<th>$A_{FB}$ up quarks</th>
<th>$A_{FB}$ down quarks</th>
<th>$A_{FB} \sqrt{s} = 13$ TeV pp collisions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$Z'$</td>
<td>(no coupling)</td>
<td>-0.75</td>
<td>-0.75</td>
</tr>
<tr>
<td>$Z'_{SSM}$</td>
<td>0.075</td>
<td>0.105</td>
<td>0.08</td>
</tr>
</tbody>
</table>

More $A_{FB}$ studies by ATLAS and CMS from SM point

Determine lepton charge and direction

Direction
Summary

Future is bright

Rich BSM potential at HL-LHC.

Looking forward to another discovery 😊

Poked just here and there. Many more ongoing studies. Several projections and full analyses for a variety of benchmarks.

With HL rare processes and low couplings become accessible, also new models, signature-driven searches.

More details in references next page
References

- [ATL-PHYS-PUB-2017-002] Study on the prospects of a $tt^-$ resonance search in events with one lepton at a High Luminosity LHC
- [ATL-PHYS-PUB-2015-004] Dijet resonance searches with the ATLAS detector at 14 TeV LHC
- [CMS-PAS-FTR-16-005] Estimated Sensitivity for New Particle Searches at the HL-LHC
- CMS-TDR-17-007 HGCAL performance for high-mass $tt$ resonances
- [CMS-PAS-FTR-16-005] Estimated Sensitivity for New Particle Searches at the HL-LHC
- [CERN-LHCC-2017-017] ATLAS Muon upgrade TDR
- [CMS-PAS-EXO-14-007] Enhanced scope of a Phase 2 CMS detector for the study of exotic signatures at the HL-LHC
- CMS-TDR-17-003 CMS Muon upgrade TDR
- CMS-TDR-17-006 CMS ECAL barrel TDR
- CMS-TDR-17-007 CMS Forward calorimeter TDR

Talk by Gino Isidori at CMS week December 6th 2017
**W' Projected Discovery Reach**

Benchmark analysis with max discovery sensitivity. DELPHES analysis.

\( W' \rightarrow ev \) Electron channel with good **resolution at very high mass** and rather constant resolution. Discriminating variable = \( M_t \) from (e, MET)

Key: understand the \( M_t \) tail and performance of high \( p_T \) leptons.

Assume systematics from run-2.

---

### Discovery of SSM W' masses up to 7 TeV @ 3/ab

**Discovery sensitivity**
Exotic states of HH to bbb

High-Mass Kaluza-Klein gravitons with each of the Higgs bosons decaying to $b\bar{b}$. 
- Large Jet: anti-Kt $R=1.0$
- Track Jet: anti-Kt $R=0.2$. Used as proxy for “track jet” that are b-tagged.
- Trigger Jet anti-Kt $R=0.4$

Dominant background from QCD production.
Needs b-tagging → impact from upgrade scenario for medium masses
Technique similar to dijet analysis, looking for bump from a sharp resonance in spectrum. Sliding mass window around resonance mass for each signal mass point.

![Graphs showing dijet mass and resonance mass distributions](http://cds.cern.ch/record/2055248/files/LHCC-G-166.pdf)
CMS $W' \rightarrow tb$

Probe scenarios such $m(v_R) > m(W') \rightarrow$ forbidden for $W' \rightarrow lv$

- Projection from 12.9/fb
- Four search categories in leptonic decays: e/mu plus 1 or 2 bjets
  - Use standard lepton IDs
  - Jets are reconstructed with anti-kT, R=0.4, $|\eta|<2.4$
  - B-tagging eff = 80% with 10% mistagging probability
- Discriminating variable M(tb)
- Trigger threshold O(1 TeV)
**W' → tb Impact of Systematics**

Three scenarios to extrapolate systematics from 12.9/fb to 3/ab

1) **Leave systematics unchanged**, simply scale templates with lumi

2) **Reduce** most experimental to percent level, theoretical uncertainties by factor 2, top $p_T$ reweighting by factor 3

3) No systematics (best possible limit)

→ Impact on projected exclusion limit: 4(4.4) TeV for case 1(3)

<table>
<thead>
<tr>
<th>Source</th>
<th>Rate Uncertainty (Flat)</th>
<th>Rate Uncertainty (Scaled)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>6.2%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Trigger Efficiency ($e/\mu$)</td>
<td>2%/5%</td>
<td>1%/1%</td>
</tr>
<tr>
<td>Lepton ID Efficiency ($e/\mu$)</td>
<td>5%/2%</td>
<td>1%/1%</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>3.8%</td>
<td>1%</td>
</tr>
<tr>
<td>Jet Energy Resolution</td>
<td>1%</td>
<td>0.07%</td>
</tr>
<tr>
<td>$b/c$-tagging</td>
<td>2.7%</td>
<td>1%</td>
</tr>
<tr>
<td>light quark mis-tagging</td>
<td>1.2%</td>
<td>1.2%</td>
</tr>
<tr>
<td>W+jets Heavy Flavor Fraction</td>
<td>2.3%</td>
<td>1.1%</td>
</tr>
<tr>
<td>Top $p_T$ Reweighting</td>
<td>18%</td>
<td>6%</td>
</tr>
<tr>
<td>Pileup</td>
<td>1.3%</td>
<td>0.09%</td>
</tr>
<tr>
<td>PDF</td>
<td>6.1%</td>
<td>3%</td>
</tr>
<tr>
<td>Matrix element $Q^2$ scale</td>
<td>18.9%</td>
<td>9.5%</td>
</tr>
<tr>
<td>tt Parton matching $Q^2$ scale</td>
<td>1.7%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Top cross section</td>
<td>15%</td>
<td>7.5%</td>
</tr>
<tr>
<td>Bosonic cross section</td>
<td>10%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Impact on exclusion limit:
- **Case 1 (Leave systematics unchanged)**: 4 TeV
- **Case 2 (Reduce systematics)**: 4.4 TeV
- **Case 3 (No systematics)**: Best possible limit

Theoretical uncertainties comparable to experimental

---

Reach depends on systematics

Exclusion limit $m(W') > 4$ TeV @3/ab
Detection via Anomalous dE/dx

Slow moving particles ($\beta << 0.9$) can be identified from their anomalous dE/dx.

Similar method for fractionally and multiply charged particles.

Without dE/dx no improvement in phase-II.

End of phase-I.

Without dE/dx no improvement in phase-II.