Searches for Heavy Resonances in Fermionic Final States at HL

Summary of existing ATLAS & CMS results for yellow-report-kickoff meeting

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on behalf of the ATLAS and CMS collaborations

Analysis Techniques

ATLAS
- Generate truth-only 14 TeV event
- Overlay with jets (full sim) from pileup library, $<\text{PU}> = 140$ or $200$
- 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 $<\text{PU}> = 200$
- Analysis steps guided by present analysis. Limited optimization for HL conditions. Cross checks with present analyses.
- Dedicated simulation of signal and bkgr samples
ATLAS Dijet (bump hunt)

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

**Bump-hunter algorithm**

- Discriminating variable = $m(jj)$
- Simulated bkgr = QCD (PYTHIA 8).
  - No beam bkgr or detector bkgr.
  - Fit bkgr shape with a smooth 4P-function, normally done to „data“
- No significant PU dependence, used <80>.

- Jets are smeared according to projected Phase-2 performance.
  - Reconstructed with anti-kT, R=0.4

- Bump hunter scans all $m(jj)$ bins with variable window size. Searching for bin with largest deviation from bkgr fit. Signals injected.
ATLAS Dijet (bump hunt)
Reach for excited quarks ($q^*$) and quantum black holes (QBH)

Possible NP signals simulated and injected

- $q^* \rightarrow qV$ ($V=g$ in 83% of the cases) with $c=1$
  PYTHIA 8, $m(q^*) = 2 - 13$ TeV

- QBH $\rightarrow jj$ (BlackMax)
  Planck scale $M_D$ = threshold mass for BH
  ADD model with 6 ED

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\begin{align*}
\text{QBH} & \quad \text{QBH} \\
\text{BumpHunter p-value} & \quad \text{QBH}
\end{align*}
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\begin{align*}
\text{ATLAS simulation preliminary} & \quad \text{ATLAS simulation preliminary} \\
\text{Luminosity [fb$^{-1}$]} & \quad \text{Luminosity [fb$^{-1}$]}
\end{align*}
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\begin{align*}
\text{ATLAS simulation preliminary} & \quad \text{ATLAS simulation preliminary} \\
\text{m_{QBH} = 10 TeV} & \quad \text{m_{QBH} = 10 TeV}
\end{align*}
```
MSSM $\phi \rightarrow \tau \tau$

- MSSM $\phi (=h, H, A)$ from gg$\phi$ and bb$\phi$ production with decays $\tau\tau \rightarrow \mu\tau_h, \epsilon\tau_h, \tau_h\tau_h, \epsilon\mu$. Discriminating variable M($\tau\tau$)
- Di-tau channel most sensitive direct search for additional Higgs’es
- Projection to 3000/fb based on 2015 result with 2.3/fb with two interpretations

\[ \begin{align*}
\text{CMS Projection} & \quad \text{MSSM } \phi \rightarrow \tau\tau \text{ (13 TeV)} \\
\end{align*} \]

95% CL limit on $\sigma(b(b)\phi)$ as $B(\phi \rightarrow \tau\tau)/(pb)$

95% CL Expected exclusion:
- Expected
- ±1σ Expected
- ±2σ Expected

Projections:
- Scenario 1 (300 fb$^{-1}$)
- Scenario 2 (300 fb$^{-1}$)
- Stat. Only (300 fb$^{-1}$)
- Scenario 1 (3000 fb$^{-1}$)
- Scenario 2 (3000 fb$^{-1}$)
- Stat. Only (3000 fb$^{-1}$)

\[ \begin{align*}
\text{CMS Projection} & \quad \text{MSSM } \phi \rightarrow \tau\tau \text{ (13 TeV)} \\
\end{align*} \]

Projection of $bb\phi$

\[ \begin{align*}
\text{Projection of } bb\phi \\
\text{56} \quad \text{60} \quad \text{tan}\beta \\
\text{Projection of } mm^{mod+}_h \text{ scenario} \\
\text{Excluded regions in the MSSM} \\
m^{mod+}_h \text{ benchmark scenario.}
\end{align*} \]
W' Projected Discovery Reach

Benchmark analysis with max discovery sensitivity. DELPHES analysis.

W'→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.

\[
M_T = \sqrt{2p_T E_T^{miss}(1 - \cos[\Delta\phi(p_T, E_T^{miss})])} \quad M_t \ (GeV)
\]
Study Weak Couplings

Weaker couplings is a domain of high luminosity. Example of $W'$ shown here, would work equally well for other models.

Coupling strength impacts widths, reweighted at GEN level. Detector performance from DELPHES (TP performance)
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 $O(1 \text{ TeV})$
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)

Projection in DP-2016/064 and CMS-PAS-FTR-16-005
CMS Z’→tt Projection from 2.6/fb to 3/ab

Z’→ttbar studied in two distinct channels distinguished by decay of W (from t→Wb)
• Semileptonic (l + b-jet + jet + MET)
• All-hadronic channel (jets)
12 orthogonal categories

Pure projection
- Scale existing run-2 signal and bkgr expectations to 14 TeV and 3000/fb
- Discriminating variable = m(tt)

Two scenarios of systematic uncertainties:
• Current Run-2 baseline analysis without scaling of uncertainties
  • E.g. Non-top multijet bkgr (dominant bkgr in all-hadronic) derived from data, should improve with L
  • Uncertainties on ttbar simulation (10-20%). Uncert. on other xsec’s will improve.
  • JES, resolution and lepton ID efficiencies should improve
• Without any systematics, include only statistical uncertainties = best case
Z’ → tt Projected Sensitivity

Two signal models: Narrow resonance (Z’) with 1% width
RS KK gluon resonance with width ~16% of mass

Exclusion limit
\[ \Gamma = 1\% \]

Discovery for \( \Gamma = 1\% \)

Exclusion limit
\[ \Gamma = 16\% \]

Discovery for \( \Gamma = 16\% \)
ATLAS Z’→tt→WbWb→lvbqqb

- 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-bkgr 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)
What if we discovered something in Phase-I?

Example of $Z' \rightarrow ee$

**Case-1:** assume a hint of a signal has been seen at the end of Phase-I and its properties are studied in Phase-II. E.g. spin or production mode, $A_{FB}$

**Case-2:** model-independent search for a deviation of the $A_{FB}$ asymmetry in the high-mass

$$A_{FB} = \frac{\sigma_{\theta<\pi/2} - \sigma_{\theta>\pi/2}}{\sigma_{\theta<\pi/2} + \sigma_{\theta>\pi/2}}$$

DY AFB = +0.6

BSM AFB might be anything between -0.75... +0.75,

e.g. $Z'_{SSM}$ AFB $\approx$ 0.08, $Z'_I \approx$ -0.75

Used fullsim samples with knowledge of $\sim$2013 (no HGCAL yet) and tuned electron ID.
Property Measurements

New heavy spin-1 resonance. Little theoretical constraints on $A_{FB}$ value $\rightarrow$ any value between -0.75 and +0.75. Experimentally determine lepton charge and direction of incoming quark.

Measure $\cos\theta$. Its shape depends on production mode ($gg$, $qq$) and spin (0,1,2). CLs test of hypotheses.
Model-Independent Search for New Physics Using DY $A_{FB}$

**Concept:** Measure DY $A_{FB}$ with high precision. Search for deviation from new physics. At low masses high SM bkgr, at high masses nearly bkgr free.

Expect $A_{FB}$ to be affected by performance of forward regions, maximum sensitivity for events $\cos \theta \approx \pm 1$. With phase-2 detector extended coverage and improved performance in forward.

Gain in Phase-II from extended acceptance

For low masses, $M(ee) < 500$ GeV, about 5% of events recovered with upgraded tracker → very important forward region! $A_{FB}$ uncertainty reduced by $\approx 40\%$ at 500 GeV and by $\approx 15\%$ at 2 TeV, based on recovered events (plot in backup).
High energy will be VERY beneficial for new physics, significantly increased reach for new & heavy particles. Much more than HL.

Not yet many projections of BSM studies.

Likely needs new detectors, as ours will be too old by then.

Detector performance has to be considered. E.g. expected mass range would yield leptons (e, mu) where saturation effects come into effect.

- Electron energy saturation (for CMS in the ballpark O(2-3 TeV))
- Muon momentum measurement becomes difficult for $p_T \gg 2$ TeV (bending too small with present magnetic field)
Summary

Rich BSM potential at HL-LHC. Looking forward to another discovery.

Poked just here and there. Many more potential studies which would be interesting.

Several projections and full analyses for a variety of existing benchmark channels.

With HL rare processes and low couplings become accessible. New models also welcome.

Reducing systematic uncertainties impacts sensitivity.
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-EXO-14-007] Enhanced scope of a Phase 2 CMS detector for the study of exotic signatures at the HL-LHC
- [CMS-PAS-FTR-16-005] Estimated Sensitivity for New Particle Searches at the HL-LHC
- Additional material for ECFA 2014
CMS $Z' \rightarrow tt$ Discovery Sensitivity

**W' \rightarrow 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>
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<tr>
<td>Luminosity</td>
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<tr>
<td>Trigger Efficiency ($e/\mu$)</td>
<td>2%/5%</td>
<td>1%/1%</td>
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<tr>
<td>Lepton ID Efficiency ($e/\mu$)</td>
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<td>Bosonic cross section</td>
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<td>5%</td>
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</table>

Theoretical uncertainties comparable to experimental

Exclusion limit $m(W') > 4$ TeV @3/ab
ATLAS $Z' \to tt \to WbWb \to l\nu bqqb$

- Selection steps derived from run-2, simplified. Discriminating variable = $m(tt)$
- Two categories: resolved and boosted
- Backgrounds simulated to NNLO

Resolved category with 1 TeV $Z'$ signal

Boosted category with heavier $Z'$ signals

- Detector effects: parametrized performance estimate of Phase-2 Det
ATLAS Z' \rightarrow tt

Signal model: topcolor model with spin-1 Z' boson, width 1.2%.
PYTHIA 8. LO xsec * 1.3 (k-factor), Interference signal-bkgr neglected.
For limits: LLH function based on binned ttbar mass spectrum with two hypothesis (s+b)(b). For each simulated signal mass.

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

Same upgraded detector and PU for 300/fb and 3000/fb.
Property Measurements – Tools and Methods

- Fullsim samples with knowledge of ~2013 (no HGCAL yet)
- For phase-2 tuned the high-$E_T$ electron ID to an efficiency comparable to run-1 with fake rate below 2x run-1 fake rate → reduced electron efficiency, especially in endcaps
- Extended acceptance increases forward sensitivity
- Charge-misID in forward regions would suffer from aging while opposite charge is required for AFB study

- Consider different models (all with sharp resonance) with their typical properties.
- Statistical method: CLs test between two hypothesis H1 and H0. Dice pseudo-experiments for each.
Model-Independent Search for new physics in high-mass DY tail

Concept:
• Measure DY AFB with high precision.
• Search for deviation from new physics
• At low masses high SM background. High masses nearly background free.

Some numbers:
DY $A_{FB} = +0.6$
BSM $A_{FB}$ might be anything between -0.75... +0.75,
e.g. $Z^\prime$ _SSM AFB ≈ 0.08,
$Z^\prime$ _I ≈ -0.75

Large impact: AFB uncertainty reduced with phase-II geometry
by ≈ 40% at 500 GeV and by ≈ 15% at 2 TeV. Based on recovered events.