Beyond the standard model physics at the HL-LHC

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On behalf of the ATLAS collaboration
• HL-LHC outlook
• Summary of BSM physics reach at HL-LHC
• Analysis highlights
  – High mass resonances
  – Dark matter searches
• Conclusions
Integrated luminosity goal: 3000/fb at $\sqrt{s}=14$ TeV

- Detailed studies of Higgs boson
- Precision measurements of QCD, EW, Higgs, b-physics
- Probing BSM physics in both precise measurements and rare processes
ATLAS detector upgrades for HL-LHC

Triggers:
L0 (Calo+Muon+ITk): 1 MHz, L1: 400 kHz, HLT: 10 kHz

Calorimeters: new readout electronics
High Granularity Timing Detector: 2.7<|\eta|<4.2, 30 ps timing resolution

Muons: new trigger/readout electronics, additional inner barrel layer

Inner tracker (ITk): new all-Si tracker with |\eta|<4.0
Physics potential of HL-LHC

• It has been recently summarized in reports from HL-HE Physics Workshop
  – final jamboree: https://indico.cern.ch/event/783141/
  – Yellow Report: http://cdsweb.cern.ch/record/2664870

• Highlights of BSM physics from the report on the physics potential of HL-HE LHC:
  – supersymmetry (covered in Alberto's talk)
  – dark matter and dark sectors
  – high mass resonances
  – long-lived particles
Expected mass reach: SUSY

- Gluino mass reach (pair production): 2-3 TeV
- Stop mass reach: ~1 TeV
- Gluino mass reach (LLP→DV_MET): ~3 TeV

arXiv 1812.07831
**Expected mass reach: other BSM**

<table>
<thead>
<tr>
<th>Model</th>
<th>spin</th>
<th>95% CL Limit (solid), 5 σ Discovery (dash)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$KK \to 4b$</td>
<td>2</td>
<td>6.1.1</td>
</tr>
<tr>
<td>$HVT \to VV$</td>
<td>1</td>
<td>6.4.4 6.4.4</td>
</tr>
<tr>
<td>$G_{RS} \to W^+W^-$</td>
<td>1</td>
<td>6.4.6</td>
</tr>
<tr>
<td>$G_{RS} \to t\bar{t}$</td>
<td>1</td>
<td>6.2.2 6.2.2</td>
</tr>
<tr>
<td>$Z_{TPE} \to t\bar{t}$</td>
<td>1</td>
<td>6.2.3 6.4.6</td>
</tr>
<tr>
<td>$Z_{SSM} \to t\bar{t}$</td>
<td>1</td>
<td>6.4.4</td>
</tr>
<tr>
<td>$Z^\prime \to \ell^+\ell^-$</td>
<td>1</td>
<td>6.2.4</td>
</tr>
<tr>
<td>$Z^\prime_{SSM} \to \ell^+\ell^-$</td>
<td>1</td>
<td>6.2.5</td>
</tr>
<tr>
<td>$W_{SSM} \to \tau\nu$</td>
<td>1</td>
<td>6.2.4</td>
</tr>
<tr>
<td>$W_R \to tb \to b\bar{b}\ell\bar{\nu}$</td>
<td>1</td>
<td>6.2.6</td>
</tr>
<tr>
<td>$Q^* \to jj$</td>
<td>$\frac{1}{2}$</td>
<td>6.4.6</td>
</tr>
<tr>
<td>$\nu_{Majorana} \to \ell qq^-$</td>
<td>$\frac{1}{2}$</td>
<td>5.1.3 5.1.3</td>
</tr>
<tr>
<td>$\nu_{Heavy} (m_N = m_E)$</td>
<td>$\frac{1}{2}$</td>
<td>6.3.1</td>
</tr>
<tr>
<td>$\ell^* \to \ell \gamma$</td>
<td>$\frac{1}{2}$</td>
<td>5.2.3 5.2.4</td>
</tr>
</tbody>
</table>

$W',Z'$ to leptons: mass reach 6-8 TeV

ArXiv 1812.07831
Search for $W'$ and $Z'$ resonances

- **Scenarios:**
  - Sequential Standard Model (SM-like fermion couplings)
  - $E_6$-motivated models ($Z'_\psi$, 0.5% width vs 3% width for SM-like $Z'$)

- **$W'\rightarrow e\nu$ ($\mu\nu$) selection:** $p_T^{e(\mu)}>65(55)$ GeV, MET>55(65) GeV, dominant background: SM W DY production

- **$Z'\rightarrow ee$ ($\mu\mu$) selection:** $p_T^{e(\mu)}>25$ GeV, same flavor, dominant background: $Z^*/\gamma$ DY production

- **These searches are statistics limited, systematics is 7%×$m_T (W')$, 6.5%×$m_\parallel (Z')$**
Search for $W'$ and $Z'$: results

- $W'/Z'$ can be discovered / excluded up to 6—7 TeV

<table>
<thead>
<tr>
<th></th>
<th>$W'_\text{SSM}$</th>
<th>$Z'_\text{SSM}$</th>
<th>$Z'_\psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discovery</td>
<td>7.7 TeV</td>
<td>6.4 TeV</td>
<td>5.7 TeV</td>
</tr>
<tr>
<td>Exclusion</td>
<td>7.9 TeV</td>
<td>6.5 TeV</td>
<td>5.8 TeV</td>
</tr>
</tbody>
</table>

Other important $W'/Z'$ discovery channels:
- $W'_R \rightarrow tb \rightarrow l\nu bb$, $Z'_\text{TC} \rightarrow tt \rightarrow l\nu bbjj$

Improved from current 5.6 TeV
Diboson resonances

- **Scenarios:**
  - weakly coupled heavy vector triplet (HVT) models like extended gauge symmetry
  - strongly coupled HVT models like composite Higgs
  - Randall-Sundrum model with KK excitations of the graviton
  - (empirical) narrow heavy scalar

- **Strategies:** resonance search and VBS search (+2 forward non-tagged jets)

- **Signal:** $VV \rightarrow \ell \nu jj$ ($e/\mu$ with $p_T>27$ GeV, $W \rightarrow jj$ or $W \rightarrow J$ candidate, MET>60 GeV)

- **Background:** $VV$, $V$+jets
Diboson resonances: results

- VBS VV production is expected to be observed at 5\(\sigma\) at 300/fb, and measured at 6.5% uncertainty at 3000/fb
- Reach/limits for VV resonances (heavy gauge bosons / Randall-Sundrum resonances):
  
<table>
<thead>
<tr>
<th></th>
<th>HGB</th>
<th>RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discovery</td>
<td>3.3 TeV</td>
<td>1.7 TeV</td>
</tr>
<tr>
<td>Exclusion</td>
<td>4.9 TeV</td>
<td>3.3 TeV</td>
</tr>
</tbody>
</table>

\(~1\) TeV improvement compared to existing limits
Search for resonant HH production

- Scenario: high mass KK gravitons decaying into HH pairs
- Signal: two back-to-back boosted $H \rightarrow bb$ objects
- Selection: two large-$R$ jets ($p_T > 450, 250$ GeV) – Higgs candidates
- Like the original $HH \rightarrow 4b$ analysis, the extrapolation of Run2 results is complicated since the dominant background is multijets, can only be reliably estimated with data
- The results would benefit from improvement in large-$R$ jet reconstruction and $b$-tagging
DM searches with monojets

- Scenario: pair production of Dirac fermion WIMPs from the s-channel exchange of a spin-1 mediator + associated jet(s) from ISR
- Signal selection: ≥1 jet with $p_T > 250$ GeV + MET > 250 GeV
- This analysis is very sensitive to systematics (ISR / FSR, renormalization / factorization scales, JES)
- With 3000/fb, the discovery potential and the exclusion limits on the mediator mass are 2.2—2.5 TeV depending on uncertainties
DM searches with monotops

- Scenario: non-resonant production of an exotic massive vector-like particle decaying into DM candidates, and a right-handed top quark
- Signal selection: one e/µ + one b-jet (from t→ Wb→ lνb) + MET>100 GeV
- Exclusion limits on \( m_V \) (BDT-based analysis): 4.6 TeV, discovery reach: 4.0 TeV
Dark photon searches in LLP\(\rightarrow\mu\mu\)

- Dark photons can be searched for as long-lived neutral particles decaying into pairs of muons in the muon system
- Scenario: FRVZ vector portal
- Signal: two calo/ITk isolated muonic lepton-jets (|\(\eta\)|<2.4) back-to-back
- The search would benefit from a dedicated L0 multi-muon scan trigger

<table>
<thead>
<tr>
<th>Excluded (c\tau) [mm] muonic-muonic</th>
<th>Run-2</th>
<th>Run-3</th>
<th>HL-LHC</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{BR}(H \rightarrow 2\gamma_d + X)=10%)</td>
<td>(2.2 \leq c\tau \leq 111)</td>
<td>(1.15 \leq c\tau \leq 435)</td>
<td>(0.97 \leq c\tau \leq 553)</td>
<td>(0.97 \leq c\tau \leq 597)</td>
</tr>
<tr>
<td>(\text{BR}(H \rightarrow 2\gamma_d + X)=1%)</td>
<td>-</td>
<td>(2.76 \leq c\tau \leq 102)</td>
<td>(2.18 \leq c\tau \leq 142)</td>
<td>(2.13 \leq c\tau \leq 148)</td>
</tr>
</tbody>
</table>

ATLAS-PHYS-PUB-2019-002
Summary

• The LHC will be upgraded to HL-LHC with a goal to achieve 3000/fb at √s=14 TeV in 10 years
  – the ATLAS detector will receive upgrades to its calorimeter, muon, and trigger systems, as well as an new all-Si inner tracker
  – it will open broad perspectives for searches for new particles, both in precision measurements and rare processes

• The upgrade will allow for a wide range of searches for BSM physics, including supersymmetry, dark matter and dark sectors, high mass resonances, and long-lived particles
  – while some of the channels will get a straightforward boost from increased luminosity and improved detector, others will need more creative effort

• The latest estimations of the HL-LHC physics potential summarized in Yellow report are promising
  – with increased amount of effort dedicated to HL-LHC physics, we can hopefully do even better!
Backup
Displaced vertex signatures

- Search for 0.1-10 ns life time LLPs decaying in the inner tracker
- Requires a dedicated version of ATLAS tracking (“displaced tracking”)
  - Assume that the new ATLAS ITk will match the Run 2 performance (>90% efficiency for tracks with at least 7 silicon hits)
- Scenario: pair production of gluinos hadronizing into R-hadrons
- Signal selection: ≥1 displaced vertex (m_{DV}>10 GeV) + MET>250 GeV
- Results: can discover gluino R-hadrons up to 2.8 TeV or exclude up to 3.4 TeV