Physics at the High-Luminosity LHC

Pippa Wells, CERN, on behalf of the ATLAS and CMS Collaborations

DESY Theory Workshop
October 2015
HL-LHC Physics

• HL-LHC program
• Detector configurations
  • Pileup mitigation
• Higgs boson measurements
  • Precision coupling measurements
  • Rare processes
  • Higgs boson pair production
• Beyond the Standard Model
  • In the Higgs sector
  • Dark matter
  • SUSY
  • Exotica
• Conclusions
Full exploitation of LHC is top priority in Europe & US for high energy physics
Operate HL-LHC with 5 (nominal) to 7.5 (ultimate) \(10^{34}\text{cm}^{-2}\text{s}^{-1}\) to collect 3000/fb in order ten years.
Detector upgrades

• In a nutshell - upgrade the detectors to achieve the same or better performance as in Run 1
• Luminosity of 5 (7.5) x10^{34} \text{cm}^{-2}\text{s}^{-1} corresponds to *average* pileup, \( \mu \), of 140 (200) events
• Pileup mitigation a critical element of detector designs
• Collections of public results:
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP
  ECFA HL-LHC workshop 2014: https://indico.cern.ch/event/315626/
Pile-up jet rejection

- Rate of pileup jets/true jets for Particle Flow algorithm (PF)
  Plus rejecting charged hadrons from pileup vertices (CHS)
  Using Puppi algorithm

- Impact on $E_{\text{miss}}$ of using extended tracking information to reject pile-up jets
  - (resolution as a function of $\Sigma E_T$ in $t\bar{t}$ events)
Combined ATLAS & CMS Run 1 Higgs boson

\[ m_H = 125.09 \pm 0.21 \text{(stat.)} \pm 0.11 \text{(syst.)} \text{ GeV} \]
\[ \mu = 1.09 \pm 0.11 \]

- \( J^P \) consistent with \( 0^+ \). Other hypotheses excluded at >99% CL
- Model dependent constraint on width from off-shell \( H \to ZZ: \Gamma_H < 22 \text{ MeV} \)

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HL-LHC Physics
HL-LHC a Higgs boson factory with 3000 fb⁻¹

- Over 100 million SM Higgs bosons in total
- Over 1 million for each of the main production mechanisms (→ production cross sections)

- Spread over many decay modes (→ branching ratios)
  - 20k H → ZZ → llll
  - 400k H → γγ
  - 40k H → μμ
  - Only 50 leptonic H → J/ψγ
    (a very rare mode)
Prospects for the Higgs boson

- Compare prospects with “LHC” 300 fb\(^{-1}\) and “HL-LHC” 3000 fb\(^{-1}\)
  - Results are always given for 1 experiment, not 2 combined
- ATLAS uses detector response functions based on full simulation for
  - Phase I detector with new pixel layer for Run 2, pile-up of 50
  - Phase II detector with pile-up of 140
  - Results are shown with and without theory uncertainty
- CMS extrapolated from the present 7-8 TeV analyses, assuming that the upgrades maintain the detector performance.
  - Scenario 1 - Experimental systematic and theoretical uncertainties unchanged. Statistical uncertainties scale with \(1/\sqrt{L}\)
  - Scenario 2 - Statistical and experimental systematic uncertainties scale with \(1/\sqrt{L}\), theoretical uncertainties reduced by a factor 2.
  - (Newer analyses use other techniques)
- Systematic uncertainties are therefore always included, but with different assumptions on possible detector/algorithm/theoretical improvements.
Signal strength precision

- All production modes can be observed for ZZ and γγ final states
- Combine production modes for best information on branching ratios

**ATLAS** Simulation Preliminary

\[ \sqrt{s} = 14 \text{ TeV: } \int L dt = 300 \text{ fb}^{-1}; \int L dt = 3000 \text{ fb}^{-1} \]

Uncertainties between 0 & 1 jet cancel out in combination

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Signal strength precision

Scenario 1 (present errors). Scenario 2 (scaled errors).

Summary of precision (%): 4~5% for main channels, 10~20% on rare modes

ATLAS without/with theory uncertainty, CMS Scenario 1 and Scenario 2

<table>
<thead>
<tr>
<th>L(fb⁻¹)</th>
<th>Exp.</th>
<th>γγ</th>
<th>WW</th>
<th>ZZ</th>
<th>bb</th>
<th>ττ</th>
<th>Zγ</th>
<th>μμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>ATLAS</td>
<td>[9, 13]</td>
<td>[8, 13]</td>
<td>[7, 11]</td>
<td>[26, 26]</td>
<td>[18, 21]</td>
<td>[44, 46]</td>
<td>[38, 39]</td>
</tr>
<tr>
<td></td>
<td>CMS</td>
<td>[6, 12]</td>
<td>[6, 11]</td>
<td>[7, 11]</td>
<td>[11, 14]</td>
<td>[8, 14]</td>
<td>[62, 62]</td>
<td>[40, 42]</td>
</tr>
<tr>
<td>3000</td>
<td>ATLAS</td>
<td>[4, 9]</td>
<td>[5, 11]</td>
<td>[4, 9]</td>
<td>[12, 14]</td>
<td>[15, 19]</td>
<td>[27, 30]</td>
<td>[12, 16]</td>
</tr>
<tr>
<td></td>
<td>CMS</td>
<td>[4, 8]</td>
<td>[4, 7]</td>
<td>[4, 7]</td>
<td>[5, 7]</td>
<td>[5, 8]</td>
<td>[20, 24]</td>
<td>[14, 20]</td>
</tr>
</tbody>
</table>
Example - $H \rightarrow ZZ \rightarrow 4$ leptons

- High purity signal. Measure all 5 main production modes with 3000 fb$^{-1}$

<table>
<thead>
<tr>
<th>Signal events</th>
<th>ggH</th>
<th>VBF</th>
<th>ttH</th>
<th>WH</th>
<th>ZH</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000 fb$^{-1}$</td>
<td>3800</td>
<td>97</td>
<td>35</td>
<td>67</td>
<td>5.7</td>
</tr>
</tbody>
</table>

- Vector Boson Fusion and ttH events have extra jets.
- WH, ZH events have extra leptons
**CMS H→4l**

- 20% more 4μ events by extending acceptance to |\(\eta|<3.0\)
- Improved mass resolution resolution (from e and μ)

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**CMS Simulation**

14 TeV, 3000 fb\(^{-1}\), PU = 140

- Phase I PU140 age1k: \(H \rightarrow ZZ^* \rightarrow 4l\)
- Phase II PU140: \(H \rightarrow ZZ^* \rightarrow 4l\)
- Phase I PU140 age1k: \(Z/ZZ \rightarrow 4l\)
- Phase II PU140: \(Z/ZZ \rightarrow 4l\)
ATLAS new result for VBF $H \rightarrow ZZ \rightarrow 4l$

- Old result, PU = 140, cut on $m_{jj} > 350$ GeV
  - $\Delta \mu / \mu$ (stat + experimental) = 0.293
- New result, PU = 200, use a BDT to distinguish ggF and VBF. Also improved pileup jet rejection from forward tracking.
  - $\Delta \mu / \mu$ (stat + experimental) = 0.134

- Just one example - more sophisticated techniques not yet propagated through HL-LHC projections

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**Reference scenario**

$\sqrt{s} = 14$ TeV, $\int L dt = 3.0$ ab$^{-1}$

**BDT bin 3**

<table>
<thead>
<tr>
<th>VBF125</th>
<th>Testing</th>
<th>Training</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF125</td>
<td>Testing</td>
<td>Training</td>
</tr>
</tbody>
</table>

**UO-flow (S:B): (0.0, 0.0)% / (0.0, 0.0)%**
Rare processes

• $H \rightarrow \mu\mu$ - second generation
  • ATLAS and CMS expect >7\sigma significance with 3000 fb$^{-1}$
  • $\rightarrow$ coupling measured to 5-10%

• $ttH, H \rightarrow \mu\mu$ (ATLAS)
  • $\sim$30 signal events in 3000 fb$^{-1}$ but good signal:background

• $H \rightarrow Z\gamma$
  • Tests the loop structure of the decay (compare with $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$)
  • $\sim$4\sigma significance possible with 3000 fb$^{-1}$ despite the challenging background

CMS $H \rightarrow \mu\mu$ coupling precision improves from 8% to 5% with Phase II upgrade
Interpretation as coupling scale factors

- Experiments measure cross section times branching ratio
- Interpretation with coupling scale factors, $\kappa$, is model dependent

<table>
<thead>
<tr>
<th>Gluon-gluon fusion</th>
<th>Vector boson fusion, VBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g$ $b,t$ $\kappa_{b,t}$ $H$</td>
<td>$q$ $W,Z$ $\kappa_{W,Z}$ $H$</td>
</tr>
<tr>
<td>$g$ or $\kappa_g$</td>
<td>$q$ $W,Z$ $\kappa_{W,Z}$ $H$</td>
</tr>
<tr>
<td>$q$ $W,Z$ $\kappa_{W,Z}$ $H$</td>
<td>$g$ $t$ $\kappa_t$ $H$</td>
</tr>
<tr>
<td>$q$ $W,Z$ $\kappa_{W,Z}$ $H$</td>
<td>$g$ $t$ $\kappa_{t}$ $H$</td>
</tr>
</tbody>
</table>

Production → cross section

Decay → branching ratio

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Coupling fits - the small print...

- The cross section times branching ratio for initial state \( i \) and final state \( f \) is given by

\[
\sigma \cdot Br(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}
\]

- The total width \( \Gamma_H \) is too narrow to measure directly
  - Assume it is the sum of the visible partial widths - no additional invisible modes
  - (Charm coupling is assumed to scale with top coupling)
- Cross sections and branching ratios scale with \( \kappa^2 \) (\( \Delta \kappa \sim 0.5 \Delta \mu \))
- Gluon and photon couplings can be assumed to depend on other SM couplings, or to be independent to allow for new particles in the loop
General coupling fit

- Photon, gluon, heavy fermions each have their own scale factor

ATLAS and CMS general coupling fits compared (%)

### CMS Projection

**Expected uncertainties on Higgs boson couplings**

<table>
<thead>
<tr>
<th>L(fb⁻¹)</th>
<th>Exp.</th>
<th>κ_γ</th>
<th>κ_W</th>
<th>κ_Z</th>
<th>κ_g</th>
<th>κ_b</th>
<th>κ_t</th>
<th>κ_τ</th>
<th>K_{Zγ}</th>
<th>K_{μμ}</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>ATLAS</td>
<td>[9, 9]</td>
<td>[9, 9]</td>
<td>[8, 8]</td>
<td>[11, 14]</td>
<td>[22, 23]</td>
<td>[20, 22]</td>
<td>[13, 14]</td>
<td>[24, 24]</td>
<td>[21, 21]</td>
</tr>
<tr>
<td></td>
<td>CMS</td>
<td>[5, 7]</td>
<td>[4, 6]</td>
<td>[4, 6]</td>
<td>[6, 8]</td>
<td>[10, 13]</td>
<td>[14, 15]</td>
<td>[6, 8]</td>
<td>[41, 41]</td>
<td>[23, 23]</td>
</tr>
<tr>
<td>3000</td>
<td>ATLAS</td>
<td>[4, 5]</td>
<td>[4, 5]</td>
<td>[4, 4]</td>
<td>[5, 9]</td>
<td>[10, 12]</td>
<td>[8, 11]</td>
<td>[9, 10]</td>
<td>[14, 14]</td>
<td>[7, 8]</td>
</tr>
<tr>
<td></td>
<td>CMS</td>
<td>[2, 5]</td>
<td>[2, 5]</td>
<td>[2, 4]</td>
<td>[3, 5]</td>
<td>[4, 7]</td>
<td>[7, 10]</td>
<td>[2, 5]</td>
<td>[10, 12]</td>
<td>[8, 8]</td>
</tr>
</tbody>
</table>
**Coupling ratios**

- Systematic uncertainties partly cancel
- Ratios are almost model independent

This results in better agreement between the two experiments
- Can achieve 2~3% precision in main channels if systematic uncertainties are controlled
- HL-LHC yields a factor 2~3 improvement in coupling ratio determination
Mass scaled couplings

- Coupling factors plotted as a function of particle mass

\[ y_{V,i} = \sqrt{\kappa_{V,i}} \frac{g_{V,i}}{2v} = \sqrt{\kappa_{V,i}} \frac{m_{V,i}}{v} \]

\[ y_{F,i} = \kappa_{F,i} \frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i} \frac{m_{F,i}}{v} \]
Theoretical uncertainties

- **ATLAS:** Deduced size of theory uncertainty to increase total uncertainty by <10% of the experimental uncertainty
  - (MHOU - missing higher order uncertainty)

### Scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Status 2014</th>
<th>Deduced size of uncertainty to increase total uncertainty by ≤10% for 300 fb⁻¹</th>
<th>Deduced size of uncertainty to increase total uncertainty by ≤10% for 3000 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Theory uncertainty (%)</strong></td>
<td>[10–12]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$gg \rightarrow H$</td>
<td></td>
<td>$\kappa_{gZ}$</td>
<td>$\lambda_{gZ}$</td>
</tr>
<tr>
<td>PDF</td>
<td>8</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>incl. QCD scale (MHOU)</td>
<td>7</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>$p_T$ shape and 0j → 1j mig.</td>
<td>10–20</td>
<td>-</td>
<td>3.5–7</td>
</tr>
<tr>
<td>1j → 2j mig.</td>
<td>13–28</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1j → VBF 2j mig.</td>
<td>18–58</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>VBF 2j → VBF 3j mig.</td>
<td>12–38</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>VBF</td>
<td></td>
<td>3.3</td>
<td>-</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDF</td>
<td>9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>incl. QCD scale (MHOU)</td>
<td>8</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

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HL-LHC Physics
Higgs boson pair production

- Higgs boson pair production includes destructive interference between two types of processes:

- ~factor 2 increase in cross section if \( \lambda \to 0 \)

\[ \sigma_{pp \rightarrow HH} \] vs. \( \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} \)

NNLO \( \sigma_{SM} = 40.8 \text{ fb} \)

Number of events:

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>( bbWW )</td>
<td>30000</td>
</tr>
<tr>
<td>( bb\tau\tau )</td>
<td>9000</td>
</tr>
<tr>
<td>WWWWW</td>
<td>6000</td>
</tr>
<tr>
<td>( \gamma\gamma \text{ bb} )</td>
<td>320</td>
</tr>
<tr>
<td>( \gamma\gamma\gamma )</td>
<td>1</td>
</tr>
</tbody>
</table>

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HL-LHC Physics 21
**HH→bbγγ**

- Parametrised object performances
  - CMS 2d fit of $m(bb)$ and $m(γγ)$ distributions (control background from data)
  - ATLAS cut based analysis
  - $bb$ mass peak is broad. $γγ$ shows narrow resonance

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**ATLAS Simulation**

- Preliminary
- $\sqrt{s}=14$ TeV, 3000 fb$^{-1}$
- $H(bb)H(γγ)$
- $tfH(γγ)$
- $bH(γγ)$
- $tX$
- $bbH(γγ)$
- $Z(bb)H(γγ)$
- Others

**CMS Simulation**

- Toy data
- Combined fit
- $HH→bbγγ$
- Resonant bkg
- Non-resonant bkg

$\sqrt{s}=14$ TeV, PU=140

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HL-LHC Physics
**bbγγ results**

- Numbers of events in 3000 fb$^{-1}$ in signal mass windows
  - CMS preferred result uses a likelihood fit in a larger mass range, which gives 67% relative uncertainty on the signal
  - Differences understood - due to assumptions in b/γ performance

<table>
<thead>
<tr>
<th>process</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM HH → bbγγ</td>
<td>8.4 ± 0.1</td>
<td>9.0</td>
</tr>
<tr>
<td>bbγγ</td>
<td>9.7 ± 1.5</td>
<td>γγ+jets</td>
</tr>
<tr>
<td>ccγγγ, bbγj, bbjj, jjγγ</td>
<td>24.1 ± 2.2</td>
<td>γ+jets, jets</td>
</tr>
<tr>
<td>top background</td>
<td>3.4 ± 2.2</td>
<td>1.2</td>
</tr>
<tr>
<td>ttH(γγ)</td>
<td>6.1 ± 0.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Z(bb)H(γγ)</td>
<td>2.7 ± 0.1</td>
<td>3.4</td>
</tr>
<tr>
<td>bbH(γγ)</td>
<td>1.2 ± 0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Total background</td>
<td>47.1 ± 3.5</td>
<td>27.4</td>
</tr>
<tr>
<td>S/√B (barrel+endcap)</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>S/√B (split barrel and endcap)</td>
<td>1.3</td>
<td></td>
</tr>
</tbody>
</table>
**CMS HH→bbττ**

- Major background from ttbar, with t→τνb
- Kinematic variables to distinguish signal from background

- Combining τ_hτ_h and τ_hτ_μ gives 105% signal uncertainty
- Combining bbγγ and bbττ: 1.9σ significance, 54% signal uncertainty

- HH→bbWW, 37.1 signal events with 3875 background (ttbar) → 200% uncertainty on signal strength
Vector Boson Scattering

- Explore electroweak symmetry breaking through VBS
  - Distinguish electroweak and QCD induced processes
  - Same sign WW pair production and WZ final states

<table>
<thead>
<tr>
<th>Coeff.</th>
<th>Channel</th>
<th>Limit [TeV$^{-4}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>WZ (3\sigma)</td>
<td>0.45</td>
</tr>
<tr>
<td>S0</td>
<td>WW (95% CL)</td>
<td>1.07</td>
</tr>
<tr>
<td>S1</td>
<td>WW (95% CL)</td>
<td>3.55</td>
</tr>
<tr>
<td>T1</td>
<td>WW (95% CL)</td>
<td>0.033</td>
</tr>
</tbody>
</table>

CMS Projection: $\sqrt{s} = 14$ TeV, $L = 3000$ fb$^{-1}$

WZ Transverse Mass, GeV/c$^2$

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BSM Higgs direct/indirect searches

- Models such as supersymmetry require more Higgs bosons
  - Neutral: h, H, A; Charged: H^+, H^- ("2 Higgs doublet model")
- Direct searches complemented by constraints from coupling fits
  - If the 125 GeV Higgs boson (which is "h" in this model) looks very like the SM Higgs, it rules out some other possibilities

Coupling fits constrain parameters $\alpha$ and $\beta$. Direct search results for $A \rightarrow Zh$ depend on the mass of the A
Higgs portal to Dark Matter

- BR of Higgs decays to invisible final states
  - ATLAS: BR_{inv} < 0.13 (0.09 w/out theory uncertainties) at 3000fb^{-1}
  - CMS: BR_{inv} < 0.11 (0.07 in Scenario 2) at 3000fb^{-1}
- The coupling of WIMP to SM Higgs is taken as the free parameter
- Translate limit on BR to the coupling of Higgs to WIMP

- LHC complements direct DM search experiments in the lower mass range
Mono-X searches for dark matter

- DM pair production with eg. initial $W \rightarrow lv$
  - Also probes contact interactions in $qq \rightarrow lv$ and $W'$ production
- Shape discrimination in transverse mass distribution
  - Significant separation between a DM model and Standard Model only achieved at HL-LHC

Distinction between DM $\xi=0$ and other models

![Graph showing events/bin vs. $M_t$ (GeV) for different models and $\xi$ values with CMS simulation results and pseudo experiments at 3000 fb⁻¹ for $\sigma=1$ fb]
Supersymmetry

Motivated by naturalness, dark matter...

Stop, sbottom, gluino and higgsino tend to be light in natural models.

Consider simplified and full-spectrum models
Electroweak processes eg \( \chi^+_1 \chi^0_2 \) production

- Weak process - benefit from high luminosity

### Chargino mass 5\( \sigma \) discovery, simplified model

<table>
<thead>
<tr>
<th>Process</th>
<th>[ATLAS]</th>
<th>[CMS]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WZ (3l analysis)</td>
<td>300 fb(^{-1})</td>
<td>3000 fb(^{-1})</td>
</tr>
<tr>
<td></td>
<td>Up to 560 GeV</td>
<td>Up to 820 GeV</td>
</tr>
<tr>
<td>WZ (3l analysis)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Up to 600 GeV</td>
<td>Up to 900 GeV</td>
</tr>
<tr>
<td>WH (3l analysis)</td>
<td>[ATLAS]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(&lt;5( \sigma ) reach)</td>
<td>Up to 650 GeV</td>
</tr>
<tr>
<td>WH (bb analysis)</td>
<td>[ATLAS] (new in 2015)</td>
<td>(&lt;5( \sigma ) reach)</td>
</tr>
<tr>
<td>WH (bb analysis)</td>
<td>[CMS]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>350-460 GeV</td>
<td>Up to 950 GeV</td>
</tr>
</tbody>
</table>

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HL-LHC Physics
Example of scoping exercise, WH(bb)

- Lepton and 2 b-jets with $E_T^{\text{miss}}$
- Main backgrounds $t\bar{t}b$, single top, $W$+jets, $ttW$, $ttZ$
  - Sensitive to modelling of leptons, b-tagging, $E_T^{\text{miss}}$ resolution
- Three scenarios, Reference, Middle, Low

Mass reach in GeV:
- 850 (Ref), 770 (Mid), 675 (Low)
- Need 6000 (12000)/fb in Mid. (Low) to match the reach of Ref.
Stop and sbottom

- Naturalness motivates stop/sbottom searches where the third family squarks are lightest
  - ATLAS stop & sbottom pair production
  - CMS gluino pair production with decay via stop to $t\bar{t}\chi$

<table>
<thead>
<tr>
<th>5σ discovery, simplified model</th>
<th>300 fb$^{-1}$</th>
<th>3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>stop mass from direct production [ATLAS]</td>
<td>Up to 1.0 TeV</td>
<td>Up to 1.2 TeV</td>
</tr>
<tr>
<td>gluino mass with decay to stop [CMS]</td>
<td>Up to 1.9 TeV</td>
<td>Up to 2.2 TeV</td>
</tr>
<tr>
<td>sbottom mass from direct production [ATLAS]</td>
<td>Up to 1.1 TeV</td>
<td>Up to 1.3 TeV</td>
</tr>
</tbody>
</table>
**ATLAS stop/sbottom**

- Results in $m(LSP)-m(\text{squark})$ plane from simplified models

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**ATL-PHYS-PUB-2013-011**

**ATL-PHYS-PUB-2014-010**
Summary of simplified models

<table>
<thead>
<tr>
<th>ATLAS projection</th>
<th>gluino mass</th>
<th>squark mass</th>
<th>stop mass</th>
<th>sbottom mass</th>
<th>$\chi_1^+$ mass WZ mode</th>
<th>$\chi_1^+$ mass WH mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 fb$^{-1}$</td>
<td>2.0 TeV</td>
<td>2.6 TeV</td>
<td>1.0 TeV</td>
<td>1.1 TeV</td>
<td>560 GeV</td>
<td>None</td>
</tr>
<tr>
<td>3000 fb$^{-1}$</td>
<td>2.4 TeV</td>
<td>3.1 TeV</td>
<td>1.2 TeV</td>
<td>1.3 TeV</td>
<td>820 GeV</td>
<td>650 GeV</td>
</tr>
</tbody>
</table>

- HL-LHC increases discovery reach by
  - ~20% for gluino, squark, stop
  - ~50 to 100% for electroweak production of $\chi_1^+\chi_2^0$

![Summary of CMS SUSY Projections with SMS](image)

Pippa Wells, CERN

HL-LHC Physics
Full spectrum SUSY models

- 5 different full-spectrum SUSY models which respect DM relic density
  - 3 pMSSM models motivated by naturalness, different LSPs: NM1(2): bino-like with low(high) slepton mass; NM3: higgsino-like
  - 2 p(C)MSSM models with $\chi_1^0$ coannihilation with different nearly mass-degenerate particle: STC = stau ; STOC = stop

- Explored 9 different experimental signatures
- Different models lead to different patterns of discoveries in different final states after different amounts of data

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Luminosity (fb^{-1})</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>all-hadronic ($H_T - H_T^{\text{miss}}$) search</td>
<td>300 3000</td>
<td>NM1</td>
</tr>
<tr>
<td>all-hadronic ($M_{T2}$) search</td>
<td>300 3000</td>
<td></td>
</tr>
<tr>
<td>all-hadronic $b_1$ search</td>
<td>300 3000</td>
<td></td>
</tr>
<tr>
<td>1-lepton $t_1$ search</td>
<td>300 3000</td>
<td></td>
</tr>
<tr>
<td>monojet $t_1$ search</td>
<td>300 3000</td>
<td></td>
</tr>
<tr>
<td>$m_{\ell\ell}$ kinematic edge</td>
<td>300 3000</td>
<td></td>
</tr>
<tr>
<td>multilepton + b-tag search</td>
<td>300 3000</td>
<td></td>
</tr>
<tr>
<td>multilepton search</td>
<td>300 3000</td>
<td></td>
</tr>
<tr>
<td>ewkino WH search</td>
<td>300 3000</td>
<td></td>
</tr>
</tbody>
</table>

<3\sigma  3-5\sigma  >5\sigma
**Exotica - dilepton resonances**

- Many extensions of the SM predict new resonances
  - Heavy gauge bosons $W'$ and $Z'$
  - KK excitations of vector bosons
- Clean decay channels, eg $Z' \rightarrow e^+e^-$ or $\mu^+\mu^-$

**Discovery up to 6.2 TeV (for SSM $Z'$)**

*ATLAS Preliminary

\[
\int L \, dt = 3000 \text{ fb}^{-1}
\]

**CMS Projection, 14 TeV**
Mass reach for exotic signatures

- Sensitivity in multi-TeV range increases by ~20% with HL-LHC

### HL-LHC Physics
**Pippa Wells, CERN**

<table>
<thead>
<tr>
<th>ATLAS @14 TeV</th>
<th>$Z' \rightarrow ee$ SSM 95% CL limit</th>
<th>$g_{KK} \rightarrow t\bar{t}$ RS 95% CL limit</th>
<th>Dark matter $M^*$ 5σ discovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 fb$^{-1}$</td>
<td>6.5 TeV</td>
<td>4.3 TeV</td>
<td>2.2 TeV</td>
</tr>
<tr>
<td>3000 fb$^{-1}$</td>
<td>7.8 TeV</td>
<td>6.7 TeV</td>
<td>2.6 TeV</td>
</tr>
</tbody>
</table>
Model discrimination after a discovery

- Ability to discriminate improves dramatically with HL-LHC
  - Separation between spin-1 ($Z'$) and spin-2 ($G_{KK}$) interpretation or other interpretations ranges from ~2 to 5 $\sigma$
  - Use 2d likelihood with dilepton angular and rapidity distributions or forward-backward asymmetry
Conclusion and outlook

• Excellent progress with evaluating the HL-LHC physics case
• The main Higgs couplings can be measured to a few percent precision
  • Also sensitivity to rare processes
• HL-LHC extends discovery reach in strongly motivated areas
  • If discoveries or hints observed in Runs 2 & 3, HL-LHC will be crucial to unravel what is seen

\[ m_{ee} = 2.9 \text{ TeV} \]

\[ m_{jj} = 6.9 \text{ TeV} \]
Additional material
B-tagging performance

- Example from the ATLAS Scoping Document
  - Use a Run 1 b-tagging algorithm out-of-the box
  - With $\mu=140$, better performance than Run 1
  - With $\mu=200$, similar performance to Run 1 (for Reference scenario)
  - Useful b-tagging capability in large $\eta$ region in Reference scenario

![Graphs showing b-jet efficiency and light-jet rejection for different $\mu$ values and regions](image)
CMS HH→bbWW

- Only consider dominant ttbar background with t→lvb (l=e,µ)
  - Based on Delphes smearing
  - Signal region: Neural Network output > 0.97
    →37.1 signal events with 3875 background
- Result quoted as a function of background systematic uncertainty
  - Expect to constrain this to ~1% from data driven methods, giving 200% uncertainty on the signal yield.
Chapter 10. Exploring the High Luminosity LHC Physics Program

are applied to five full-spectrum benchmark SUSY models, which include three natural SUSY scenarios, as well as stau and stop coannihilation scenarios. The features of these models, and the selection requirements of the nine analyses are briefly described. Section 10.3.3 presents the results obtained from the nine analyses. We consider not only the discovery sensitivity, but also how, in the event of a discovery, the pattern of signals and the associated kinematic distributions can provide many clues to understanding the nature of the underlying particle spectrum. From these studies, it is clear that the full HL-LHC data sample will provide critical information, even if discoveries are made much earlier. Section 10.3.4 summarizes the main results and conclusions of these studies.

10.3.1 SUSY models, searches with Run 1 data, and simplified-model projections to higher energies

10.3.1.1 SUSY models used in the interpretation of searches

This section compares full-spectrum SUSY models, which are used in the new studies presented in later sections, with simplified-models, which have been used in many of the interpretations of CMS Run 1 data. Figure 10.19 shows the mass spectra for two of the SUSY models, NM3 and STC. The left-most column shows the particles that make up the Higgs sector, with the neutral, CP-even Higgs boson fixed at the observed mass, $m_{H^0} = 125$ GeV. (All five models share this feature, but other aspects of their Higgs sectors can vary from model to model.) SUSY particles with electroweak interactions (only) are shown in the two middle columns. These are the scalar leptons and scalar neutrinos (sleptons and sneutrinos) and an electroweak sector consisting of the charginos and neutralinos, which are spin-1/2 fermions. The SUSY partners in the electroweak sector, sometimes referred to as ewkinos, are superpositions of higgsinos and gauginos of the same charge. The far-right-hand column shows the strongly interacting sector, with the gluino and the squarks. Because quarks are spin-1/2 objects, they each have two SUSY partners, corresponding to the $L$- and $R$-handed chiral projections, which have different gauge quantum numbers. Thus, $e^q_L$ and $e^q_R$ are distinct particles. Mixing is expected to be significant in the third generation of squarks, leading to mass eigenstates designated $e^t_1$, $e^t_2$, $e^b_1$, and $e^b_2$.

Figure 10.19: Examples of SUSY full-spectrum models: (a) the natural SUSY model NM3 and (b) the stau coannihilation model STC, which are among the five full-spectrum scenarios used in the studies presented here. In NM3, the masses of the $\tilde{g}$, $\tilde{t}_1$, $\tilde{t}_2$, and $\tilde{b}_1$ are all below 2 TeV. The $\tilde{\chi}^0_1$ is higgsino-like. In the STC model, the gluino is much heavier than the top squarks, and the slepton sector is light, with the $\tilde{\tau}$ nearly degenerate with the $\tilde{\chi}^0_1$. The lines between different states indicate transitions with branching fractions greater than 5%.