HL-LHC Physics

• HL-LHC program
• Detector configurations
  • Pileup mitigation and performance
• 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
Detector upgrades

- Luminosity of 5 (7.5) x10^{34} \text{ cm}^{-2}\text{s}^{-1} corresponds to *average* pileup, $\mu$, of 140 (200) events (interactions in the same bunch crossing)
  - Higher occupancy, larger integrated radiation dose
  - Need to distinguish particles from hard scatter vertex
- ATLAS and CMS will fully replace their inner trackers
  - All silicon trackers, with higher granularity
  - Pixel detectors extended to $|\eta|=4.0$ (ATLAS), 3.8 (CMS)
- Calorimeter upgrades - including precise timing
  - CMS will fully replace the end cap calorimeter (1.5 < $|\eta|$ < 3.0), with precise timing information from each layer, plus improved timing information in the barrel region
  - ATLAS propose a high granularity timing detector between the barrel and endcap LAr calorimeter cryostats (2.4 < $|\eta|$ < 4.3)
  - For both experiments, the timing aspects are not yet fully integrated in simulation and/or reconstruction algorithms
  - ATLAS may also replace the forward calorimeter (3.2 < $|\eta|$ < 4.9)
- Additional improvements to improve triggers and increase bandwidth
References


• ATLAS Phase II Letter of Intent [CERN-LHCC-2012-022], CMS Technical Proposal [CERN-LHCC-2015-010]

• 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/

• Next steps: Technical Design Reports (TDRs)
Track and vertex reconstruction

- Pion tracking efficiency in ttbar events for ATLAS full and reduced scenarios, PU of 200
- ttbar events reconstructed with the CMS Phase II detector

- For both experiments, fake rates are well under control
- Muon tracking efficiency is uniformly high (about 99%)
- Efficiency for picking the right primary vertex depends on process
**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
Jets and pileup

- Particles from pileup events make a significant contribution to the jet energy of true low $p_T$ jets.
- Pileup events can also produce additional QCD-like jets (usually at low $p_T$), and jets from random combinations of particles from several pileup events.

- Plot shows additional energy from pileup overlaid on low energy QCD jets with radius 0.4 in $\eta$-$\phi$ space.
- Reconstructed jet energy depends on detector specific algorithms which reject/correct pileup.
- Jet energy scale correction is applied to estimate true jet energy.
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 $E_T^{miss}$ of using extended tracking information to reject pile-up jets
  - (resolution as a function of $\Sigma E_T$ in ttbar events)
Higgs boson measurements
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 \( H \to ZZ \): \( \Gamma_H < 22 \text{ MeV} \)

10 to 20% precision for main channels

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HL-LHC Physics 13
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 \( H \rightarrow ZZ \rightarrow 4l \)
  - 400k \( H \rightarrow \gamma\gamma \)
  - 40k \( H \rightarrow \mu\mu \)
  - Only 50 leptonic \( H \rightarrow J/\psi\gamma \) (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

Uncertainties between 0 & 1 jet cancel out in combination

ATLAS Simulation Preliminary
√s = 14 TeV: ∫Ldt=300 fb⁻¹ ; ∫Ldt=3000 fb⁻¹

H→γγ (comb.)
  (0j)
  (1j)
  (VBF-like)
  (WH-like)
  (ZH-like)
  (ttH-like)

H→ZZ (comb.)
  (0j)
  (1j)
  (VBF-like)
  (ggF-like)

H→WW (comb.)
  (0j)
  (1j)
  (VBF-like)

H→Zγ (incl.)

H→b¯b (comb.)

H→ττ (VBF-like)

H→μμ (comb.)
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→ZZ→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

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HL-LHC Physics
**CMS H→4l**

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

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

**CMS Simulation**

- Phase I PU140 age1k: H → ZZ* → 4 l
- Phase II PU140: H → ZZ* → 4 l
- Phase I PU140 age1k: Z/ZZ → 4 l
- Phase II PU140: Z/ZZ → 4 l
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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HL-LHC Physics
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)
  - ~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 $H \rightarrow \gamma\gamma$)
  - ~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

### gluon-gluon fusion

Production $\rightarrow$ cross section

### vector boson fusion, VBF

Decay $\rightarrow$ branching ratio
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 $\kappa^2$ ($\rightarrow \Delta\kappa \sim 0.5 \Delta\mu$)
- 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

### 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>κ_{Zγ}</th>
<th>κ_{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>

- ATLAS and CMS general coupling fits compared (%)
### 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

<table>
<thead>
<tr>
<th>$L(fb^{-1})$</th>
<th>Exp.</th>
<th>$\frac{K_g \cdot K_Z}{K_H}$</th>
<th>$\frac{K_Y}{K_Z}$</th>
<th>$\frac{K_W}{K_Z}$</th>
<th>$\frac{K_b}{K_Z}$</th>
<th>$\frac{K_T}{K_Z}$</th>
<th>$\frac{K_Z}{K_g}$</th>
<th>$\frac{K_T}{K_Z}$</th>
<th>$\frac{K_u}{K_Z}$</th>
<th>$\frac{K_{Z\gamma}}{K_Z}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>ATLAS</td>
<td>[4,6]</td>
<td>[5,6]</td>
<td>[5,5]</td>
<td>[17,18]</td>
<td>[11,12]</td>
<td>[10,13]</td>
<td>[15,17]</td>
<td>[20,20]</td>
<td>[23,23]</td>
</tr>
<tr>
<td></td>
<td>CMS</td>
<td>[4,6]</td>
<td>[5,8]</td>
<td>[4,7]</td>
<td>[8,11]</td>
<td>[6,9]</td>
<td>[6,9]</td>
<td>[13,14]</td>
<td>[22,23]</td>
<td>[40,42]</td>
</tr>
<tr>
<td>3000</td>
<td>ATLAS</td>
<td>[2,6]</td>
<td>[2,3]</td>
<td>[2,3]</td>
<td>[7,10]</td>
<td>[8,9]</td>
<td>[5,9]</td>
<td>[5,9]</td>
<td>[6,6]</td>
<td>[14,14]</td>
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<tr>
<td></td>
<td>CMS</td>
<td>[2,5]</td>
<td>[2,5]</td>
<td>[2,3]</td>
<td>[3,5]</td>
<td>[2,4]</td>
<td>[3,5]</td>
<td>[6,8]</td>
<td>[7,8]</td>
<td>[12,12]</td>
</tr>
</tbody>
</table>
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)**

<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>by ≤10% for 3000 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory uncertainty (%)</td>
<td>[10–12]</td>
<td>( \kappa_{gZ} )</td>
<td>( \lambda_{gZ} )</td>
</tr>
<tr>
<td>gg ( \rightarrow ) H</td>
<td></td>
<td></td>
<td></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 ( \rightarrow ) 1j mig.</td>
<td>10–20</td>
<td>-</td>
<td>3.5–7</td>
</tr>
<tr>
<td>1j ( \rightarrow ) 2j mig.</td>
<td>13–28</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1j ( \rightarrow ) VBF 2j mig.</td>
<td>18–58</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>VBF 2j ( \rightarrow ) 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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[10-12] LHC Higgs Cross Section Working Group

Pippa Wells, CERN

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 $\lambda \to 0$

Higgs triple self-coupling $\lambda$

NNLO $\sigma^{SM}=40.8$ fb

Number of events

<table>
<thead>
<tr>
<th>Process</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bbWW$</td>
<td>30000</td>
</tr>
<tr>
<td>$bb\tau\tau$</td>
<td>9000</td>
</tr>
<tr>
<td>$WWWW$</td>
<td>6000</td>
</tr>
<tr>
<td>$\gamma\gamma bb$</td>
<td>320</td>
</tr>
<tr>
<td>$\gamma\gamma\gamma$</td>
<td>1</td>
</tr>
</tbody>
</table>
• Parametrised object performances
  • CMS 2d fit of $m(bb)$ and $m(\gamma\gamma)$ distributions (control background from data)
  • ATLAS cut based analysis
  • $bb$ mass peak is broad. $\gamma\gamma$ shows narrow resonance
**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>ccγγ, 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$\rightarrow$bbττ

- Major background from ttbar, with $t\rightarrow\tau vb$
  - Kinematic variables to distinguish signal from background

- Combining $\tau_h\tau_h$ and $\tau_h\tau_\mu$ gives 105% signal uncertainty
- Combining bbγγ and bbττ: 1.9σ significance, 54% signal uncertainty

- HH$\rightarrow$bbWW, 37.1 signal events with 3875 background (ttbar) $\rightarrow$ 200% uncertainty on signal strength
Beyond the Standard Model
Vector Boson Scattering

• Explore electroweak symmetry breaking through VBS
  • Distinguish electroweak and QCD induced processes
  • Same sign WW pair production and WZ final states
  • CMS: interpretation as limits on dimension-eight operators $f_X/\Lambda^4$ [arXiv:hep-ph/0606118].

<table>
<thead>
<tr>
<th>Coeff.</th>
<th>Channel</th>
<th>Limit [TeV$^{-4}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>WZ (3σ)</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>
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 angles \(\alpha\) 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: $\text{BR}_{\text{inv}} < 0.13$ (0.09 w/out theory uncertainties) at 3000fb$^{-1}$
  - CMS: $\text{BR}_{\text{inv}} < 0.11$ (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 $W\rightarrow lv$
- Shape discrimination in transverse mass distribution
  - Also probes contact interactions in $qq\rightarrow lv$ and $W'$ production
  - Significant separation between a DM model and Standard Model only achieved at HL-LHC

![Graph showing distinction between DM $\xi=0$ and other models](image-url)
**Supersymmetry**

Motivated by naturalness, dark matter...

![Graph showing cross-sections and mass distributions](image)

Followed prescriptions in 1206.2892 [hep-ph]

- Strong prod. of gluinos
- Strong prod. of squarks
- Strong prod. of stops

EW prod. of $\chi_1^+\chi_2^0$

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

Consider simplified and full-spectrum models

Pippa Wells, CERN

HL-LHC Physics
**Electroweak processes eg $\chi_1^{\pm} \chi_2^0$ production**

- Weak process - benefit from high luminosity

<table>
<thead>
<tr>
<th>Chargino mass 5σ discovery, simplified model</th>
<th>300 fb$^{-1}$</th>
<th>3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WZ (3l analysis) [ATLAS]</td>
<td>Up to 560 GeV</td>
<td>Up to 820 GeV</td>
</tr>
<tr>
<td>WZ (3l analysis) [CMS]</td>
<td>Up to 600 GeV</td>
<td>Up to 900 GeV</td>
</tr>
<tr>
<td>WH (3l analysis) [ATLAS]</td>
<td>(&lt;5σ reach)</td>
<td>Up to 650 GeV</td>
</tr>
<tr>
<td>WH (bb analysis) [ATLAS] (new in 2015)</td>
<td>(&lt;5σ reach)</td>
<td>Up to 800 GeV</td>
</tr>
<tr>
<td>WH (bb analysis) [CMS]</td>
<td>350-460 GeV</td>
<td>Up to 950 GeV</td>
</tr>
</tbody>
</table>
Example of scoping exercise, WH(bb)

- Lepton and 2 b-jets with $E_T^{\text{miss}}$
- Main backgrounds ttbar, 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 $m(\text{LSP})$-$m(\text{squark})$ plane from simplified models

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 $\chi_1^+\chi_2^0$
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^{miss})) search</td>
<td>300 3000</td>
<td>NM1   NM2 NM3 STC STOC</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>
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, e.g. $Z' \rightarrow e^+e^-$ or $\mu^+\mu^-$

Discovery up to 6.2 TeV (for SSM $Z'$)
Mass reach for exotic signatures

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

### ATLAS @14 TeV

<table>
<thead>
<tr>
<th>ATLAS @14 TeV</th>
<th>$Z' \rightarrow ee$ SSM 95% CL limit</th>
<th>$g_{KK} \rightarrow t\overline{t}$ 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>

Pippa Wells, CERN

HL-LHC Physics
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

**Z’_{\psi}, M = 4 \text{ TeV/}c^2**
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

\[ m_{ee} = 2.9 \text{ TeV} \]
\[ m_{jj} = 6.9 \text{ TeV} \]
Two examples of full spectrum SUSY models

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 \( \tilde{\chi}_1^0 \) 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 \( \tilde{\chi}_1^0 \). The lines between different states indicate transitions with branching fractions greater than 5%.