Physics prospects of the high luminosity LHC with the ATLAS detector

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9-11th May 2016, Phenomenology 2016 Symposium
University of Pittsburgh.
LHC High-Luminosity Prospects

OUTLOOK

HL-LHC PLANS

CONDITIONS & STATUS & MOTIVATION

SM HIGGS COUPLINGS

UPGRADE

BSM PHYSICS IN HIGGS COUPLINGS

HIGGS PAIR PRODUCTION

SUSY

CONCLUSIONS
Run1: -> Higgs discovery
Run2: -> Design energy & lumi
Run3: -> 2x Design luminosity
HL-LHC: -> 10x Design luminosity
LS1: Magnet splice update
LS2: Injectors
LS3: IP focusing
LHC High-Luminosity Conditions

- 14 TeV centre of mass energy
- $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ nominal (ultimate) inst. luminosity
- 40 MHz maximal bunch crossing rate
- Pile-up $\mu = 140 \ (200)$ p-p interactions per bunch crossing
- 3000 fb$^{-1}$ in order ten years

SIMULATED ATLAS INNER DETECTOR EVENT WITH 230 PILEUP
European Strategy 2012: “Europe’s top priority should be the exploitation of the full potential of the LHC, including the high luminosity upgrade of the machine and the detectors with a view to collecting 10 times more data than in the initial design, by around 2030”

- Phase II LoI [CERN-LHCC-2012-022] - detector upgrade
- ECFA HL-LHC workshop 2014
- Public results: UpgradePhysicsStudies
- Most simulations are using $\mu = 140$ and not yet using full Inner Detector coverage of 4.0 pseudo rapidity
• Trigger and Data Acquisition
  • Hardware trigger with L0 ≤ 1 MHz and L1 ≤ 400 KHz
  • High-Level Trigger with 10 kHz output (permanently recorded data)
  • “Custom hardware” triggers for data streaming at rates 1-40 MHz
  • New Inner Tracker, Calorimeters and Muon Triggers

• Calorimeters
  • LAr forward electromag. calorimeter replaced with high-granularity
  • High Granularity Timing Detector installed in front of LAr Cal end-caps, 2.4 ≤ |η| ≤ 4.3
  • Readout electronics of LAr and Tile Calorimeters replaced

• Muon Spectrometer
  • NSW in the end-cap at Phase I
  • Addition of RPCs in the barrel, |η| < 1

• Inner Tracker
  • Completely new, all-silicon tracker
  • Extending coverage to |η| < 4
• **EWSB Understanding:**
  - Precise 125 GeV Higgs couplings to bosons & fermions
  - Precise Yukawa couplings measurements (especially direct top Yukawa coupling), search for rare Higgs decays
  - HH production studies: aim to estimate Higgs potential (self-coupling $\lambda_{hhh}$), the ultimate test for SM EWSB
  - Testing vector-boson scattering probes composite nature of the Higgs

• **BSM Physics couplings to Higgs, direct searches for:**
  - Partners of the 125 GeV Higgs boson
  - SUSY
  - Other BSM objects (Dark Matter, etc.)
h → γγ
h → ZZ* → 4l
h → WW* → lνlν
h → Zγ
h → bb
h → ττ
h → μμ

- Using zero-width approximation, i.e. model-independent, as not using Higgs width, not measurable at LHC
- Some parametrisations measure ratios $\lambda_{ij} = \kappa_i / \kappa_j$
- Minimal coupling fit assumes common coupling for all bosons, $\kappa_V$, and for all fermions, $\kappa_f$.
- Uncertainties given with & w/o theory uncertainties
- Searches for “invisible Higgs” decays

all production modes
all production modes
0-, 1-, 2-jet final states
inclusive
in Wh and Zh production
VBF production
inclusive and in tth production
### ATLAS Simulation Preliminary

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

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Experimental precision (with theor. unc.) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow \gamma\gamma ) (comb.)</td>
<td>300 fb^{-1} 3000 fb^{-1}</td>
</tr>
<tr>
<td>( H \rightarrow ZZ ) (comb.)</td>
<td>( \kappa_V ) 2.5 (4.3) 1.7 (3.3)</td>
</tr>
<tr>
<td>( H \rightarrow WW ) (comb.)</td>
<td>( \kappa_f ) 7.1 (8.8) 3.2 (5.1)</td>
</tr>
<tr>
<td>( H \rightarrow Z\gamma ) (incl.)</td>
<td></td>
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</table>
Fermions: 
\[ y_i = k_i \, m_i \, v^{-1} \]
Bosons: 
\[ y_i = \sqrt{k_i} \, m_i \, v^{-1} \]
Minimal Composite Higgs is pseudo-Nambu-Goldstone boson

With non-SM fermion & boson couplings

\[ \xi = \frac{v^2}{F^2}, \]  
with compositeness scale F VEV \( v \)
Higgs Pair Production

\( gg \rightarrow hh \rightarrow bb\gamma\gamma \) limits on \( \lambda_{hhh} \)

\( gg \rightarrow hh \rightarrow bb\tau\tau \) limits on \( \lambda_{hhh} \)

\( gg \rightarrow hh \rightarrow bbbb \) resonant search for \( G^{*}_{KK} \)

- Dominant production at LHC gluon fusion - \( \sigma(hh)^{NNLO+NNLL} = 45.34 \text{ fb} \)
- Other production modes \( \sim 30 \) times smaller cross-sections (not yet investigated)
- 10\% theory uncertainties
  (6\% scale, 2\% PDF, 2\% \( \alpha_s \))
- All analyses used old calculation with \( \sigma(hh) = 40.8 \text{ fb} \)
**Higgs Pair Production**

- 3 sub-channels:
  - $\tau_{lep}\tau_{lep}$,
  - $\tau_{lep}\tau_{had}$,
  - $\tau_{had}\tau_{had}$

  different triggers & event selections

- Track confirmation used to suppress pile-up

- Distributions of $m_{bb}$ and $p_{Tbb}$ in the $\tau_{had}\tau_{had}$ channel:

Cross-section limit:

$$4.3 \times \sigma(HH \rightarrow bb\bar{\tau}+\tau-)$$ at 95% CL
Improvements possible by better b-tagging efficiency & light jet rejection rate

<table>
<thead>
<tr>
<th>Channel</th>
<th>Significance</th>
<th>Combined in channel</th>
<th>Total combined</th>
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</thead>
<tbody>
<tr>
<td>$e + \text{jets}$</td>
<td>0.31</td>
<td>0.43</td>
<td>0.60</td>
</tr>
<tr>
<td>$\mu + \text{jets}$</td>
<td>0.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_{\text{had}} + \tau_{\text{had}}$</td>
<td>0.41</td>
<td>0.41</td>
<td></td>
</tr>
</tbody>
</table>
Graviton Resonance Search $HH \rightarrow bbbb$

- $\mu=200$
- 3000 fb$^{-1}$
- 3 update scenarios
- 2 systematic uncertainties: 2.5% & 5%
- High 180 GeV jet threshold - pileup negligible
- 3 jet collections: large R, track & trigger jets

B-tagging performance increases significance - Significance for $G_{KK}^*$ with 2 TeV: 4.4
Supersymmetry
Wh-mediated

\[ \chi^\pm \chi^0_2 \rightarrow \ell b b + E_T^{\text{miss}} \]

- Pair-produced charginos & neutralinos
- Heavy sleptons & neutrinos
- Conservation of R-parity
- Lightest neutralino is stable LSP
- Mass eigenstates of SUSY partners from superposition of Higgs & EW gauge bosons

- Charginos and neutralinos have masses \( \sim \) 100 GeV
- With 100% branching ratio:
  - \( \chi^\pm_1 \rightarrow W^\pm \chi^0_1 \)
  - \( \chi^0_2 \rightarrow h \chi^0_1 \)

ATL-PHYS-PUB-2014-010
Electro-Weakinos Discovery Prospects

- \( \mu = 200 \)
- Min. \( p_{T}^{e,\mu} = 22,20 \) GeV
- Object selection
- Calo & ITK upgrades improve b-tagging efficiency
- Total background systematic uncertainty 30%
- Trigger improvements not included

Discovery potential: \( X^{\pm 1} X^{0 2} \) mass 800 GeV
Conclusions

- Precise Higgs sector measurements necessary to understand EWSB - including vector boson scattering
- Higgs Couplings to elementary Fermions & Bosons
  - 2–3 smaller uncertainties $300 \text{ fb}^{-1} \rightarrow 3000 \text{ fb}^{-1}$
  - highest improvement potential: VH & ttH production
  - meas. precision limited by theo. uncert. $\sigma(gg \rightarrow h)$
- Di-Higgs production
  - First Observation at HL-LHC possible
  - given tiny rates we should study as many channels as possible, but $O(1)$ limit set by $\lambda_{hhh}$ (with room for analysis optimisation)
- Direct searches for New Physics can be extended further
  - Limits on Higgs compositeness scale in 1 TeV range
  - Up to 2TeV sensitivity for Kaluza-Klein Graviton
  - Sensitivity to electro-weakinos in 800 GeV range
- Theory input crucial to decrease uncertainties

MANY STUDIES WITH DIFFERENT LAYOUTS, ETA=4 AND MU=200 ARE ONGOING