Study of Weak Boson Scattering with Pile-up with the ATLAS Detector at the LHC

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A Toroidal LHC ApparatuS (ATLAS)

- Excellent particle reconstruction and identification performance
- Precise calorimeters with large coverage (up to $|\eta| \approx 4.9$ for jets)
- Toroidal magnetic field for muon $p_T$
Vector Boson Scattering

- Naive Standard Model without Higgs: Scattering of longitudinal $W$ bosons rises infinitely:

$$\sigma (W_L W_L \rightarrow W_L W_L) \xrightarrow{\sqrt{s_{WW}} \rightarrow \infty} \infty$$

- Intimately related to electro-weak symmetry breaking
- Perturbation theory violates unitarity above $\sqrt{s_{WW}} \approx 1.2$ TeV
- Vector Boson Scattering at LHC reaches this limit in parts of the phase space
Flagship solution: Higgs Mechanism

- Also solves problem of masses in the Standard Model
- Introduction of a new scalar particle: Higgs boson

But: Higgs boson not discovered in experiment up to now
No Higgs observed

Unitarity conservation requires physics beyond the Standard Model

- Strong Electroweak Symmetry Breaking (*review e.g. hep-ph/0203079*)
- Advantage: Particular signals
- Disadvantage: A lot of them
Motivation

EWChL and Unitarization

- Effective Electroweak Chiral Lagrangian (EWChL):
  - $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{LO}} + \alpha_4 (\text{Tr}[V_\mu V_\nu])^2 + \alpha_5 (\text{Tr}[V_\mu V^\mu])^2 + \ldots$
  - Approximates the rising edge of a resonance beyond the accessible mass range (anomalous couplings)

- No longer valid at LHC energies

  - "Resonances and Unitarity in Weak Boson Scattering"
    A. Alboteanu, W. Kilian and J. Reuter (arXiv:0806.4145v1)
  - Need resonance(s) with masses $M$ and couplings $g$ to weak bosons

<table>
<thead>
<tr>
<th>weak isospin $I$</th>
<th>$I = 0$</th>
<th>$I = 1$</th>
<th>$I = 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>strong isospin $J$</td>
<td>$J = 0$</td>
<td>$J = 1$</td>
<td>$J = 2$</td>
</tr>
<tr>
<td>$\sigma^0$</td>
<td>$\rho^0$, $\rho^\pm$</td>
<td>$\phi^0$, $\phi^\pm$, $\phi^{\pm\pm}$</td>
<td></td>
</tr>
<tr>
<td>$f^0$</td>
<td></td>
<td>$t^0$, $t^\pm$, $t^{\pm\pm}$</td>
<td></td>
</tr>
</tbody>
</table>

- K-matrix formalism guarantees unitarization
Experimental Signature

- Tagjets (large $p_T$, large distance in $\eta$)
- Few jets between tagjets
- Final state $l\nu l\nu$:
  - Missing $E_T$
  - Decay products between tagjets
Signal and Background Processes

- **Signal: Resonance**
- **Irreducible BG: EW**
- **Irreducible BG: QCD**
- **Also all SM triple and quartic boson vertices (except Higgs) included**
- **Single top (Wt)**
- **Top pairs t\bar{t}**
- **W/Z + jets**
Event Generator Whizard


- Only generator that implements K-matrix unitarization with resonances
- [http://projects.hepforge.org/whizard/](http://projects.hepforge.org/whizard/)

No Effective $W$ Approximation


Full matrix element for the six-fermion final state

- Angular correlations preserved
- Irreducible backgrounds included
Analysis

- Assumed integrated luminosity: $100 \text{ fb}^{-1}$ (not an early study)
- All samples with 14 TeV
- Athena release 14.2.25

Pile-up

- In-time pile-up: More than one proton-proton interaction per bunch crossing
- First studies with available samples to see general influence of pile-up
  - Poisson-distributed mean number of pile-up collisions: 6.9
  - Luminosity: $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ (low luminosity pile-up)
- Goal: High luminosity pile-up
Boosted Decision Tree

TMVA (Toolkit for Multivariate Analysis), Release 4.0.6
http://tmva.sourceforge.net

Input variables

- $b$ tag
- $p_T$ of leptons
- invariant tagjet mass
- $\Delta \eta$ between tagjets
- transverse mass
- $p_T$ of tagjets
- missing $E_T$
- lepton centrality $\zeta$
- $p_T$ balance
- minijet veto

Training: Pile-up samples trained with pile-up samples and vice versa
**Cutflow of Boosted Decision Tree Output**

- Whizard irreducible background most important background
- Reducible backgrounds disappear for BDT cuts > 0.3
- Separate backgrounds...
Discovery Significance

- Example: Discovery significance for $\varphi$ resonance with $m = 850 \text{ GeV}$ and pile-up
- Profile likelihood method
- Cut on BDT output: $r^{\text{cut}} > 0.2$
- Assumed experimental luminosity: $100 \text{ fb}^{-1}$
- Amount of Monte Carlo scaled to $100 \text{ fb}^{-1}$
- Optimal BDT cut for best $5\sigma$ discovery significance
Discovery Significance Results for 850 GeV

Minimal couplings discoverable with 5σ and effect of pile-up:

<table>
<thead>
<tr>
<th></th>
<th>gmin</th>
<th>pile-up</th>
<th>pile-up effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ</td>
<td>0.44</td>
<td>0.41</td>
<td>-6.3%</td>
</tr>
<tr>
<td>ϕ</td>
<td>0.65</td>
<td>0.71</td>
<td>10.1%</td>
</tr>
<tr>
<td>ρ</td>
<td>1.64</td>
<td>1.64</td>
<td>0%</td>
</tr>
<tr>
<td>f</td>
<td>1.02</td>
<td>1.04</td>
<td>2.3%</td>
</tr>
<tr>
<td>t</td>
<td>1.27</td>
<td>1.40</td>
<td>10.1%</td>
</tr>
</tbody>
</table>

- Pile-up trained with pile-up and no pile-up trained with no pile-up

5σ discovery sensitivity for:

- All resonances with $g \lesssim 2.5$
- SM Higgs ($σ, g = 1$)
Systematic Uncertainties (not all included yet)

Minimal couplings discoverable with $5\sigma$ including systematic uncertainties and pile-up:

<table>
<thead>
<tr>
<th>$g_{\text{min}}$</th>
<th>Systematics effect</th>
<th>Pile-up effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>0.58</td>
<td>40.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13.7%</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>0.92</td>
<td>28.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.0%</td>
</tr>
<tr>
<td>$\rho$</td>
<td>1.95</td>
<td>18.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.3%</td>
</tr>
<tr>
<td>$f$</td>
<td>1.17</td>
<td>12.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.3%</td>
</tr>
<tr>
<td>$t$</td>
<td>1.60</td>
<td>14.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.9%</td>
</tr>
</tbody>
</table>

$5\sigma$ discovery sensitivity for:

- All resonances with $g \lesssim 2.5$
- SM Higgs ($\sigma, g = 1$)
Summary

This Analysis:

- ATLAS has discovery potential in the Vector Boson Scattering two lepton channel at 100 fb$^{-1}$ at 850 GeV in relevant coupling range $g \lesssim 2.5$
- Effect of systematic uncertainties: $\approx 20\%$ (will increase with all uncertainties included)
- Contribution of low luminosity pile-up: $\approx 15\%$

Analysis of Jan Schumacher:

- Upper limit setting potential
- Discoverable minimal couplings for $m = 1150$ GeV up to 100% worse compared to $m = 850$ GeV
Thank you!
BACKUP
Signal and Irreducible Backgrounds

- **Signal:** Resonance
- **Background:** EW
- **Background:** QCD

- All generated with **WHIZARD** for 14 TeV
- Signal entangled with irreducible background
- **WHIZARD** $qql\nu l\nu$ samples available:
  - EW . . . Resonances and QCD switched off
  - Signal + EW . . . QCD switched off
  - QCD + EW . . . Resonances switched off
- Realistic detector simulation using **GEANT**
- Assumed Monte Carlo Luminosites: $100 \text{ fb}^{-1}$
- Pile-up and no pile-up samples available
- Five resonance types at 850 GeV and 1150 GeV each
Reducible Backgrounds

- Top pairs $t\bar{t}$
- MC@NLO
- Two-lepton filter
- ATLFAST-II

- Single top ($Wt$)
- AcerMC
- Two-lepton filter
- ATLFAST-II
- no pile-up available

- $W/Z + \text{jets}$
- Alpgen
Training options

- Number of trees: 1000
- Boosting type: Gradient
- Shrinkage: 0.3
- Separation type: Gini index
- Pruning method: Cost Complexity
- Pruning strength: 50
- Maximum number of nodes: 5
Event Selection - Fiducial Precuts

- $\Delta\eta$ between tagjets $> 3.0$
- $p_T$ of tagjets $> 20$ GeV
  - Generator level
- $p_T$ of 1st and 2nd lepton $> 30$ GeV
  - Generator level
  - Trigger plateau
- $m_{\text{leplep}} > 150$ GeV
  - Removing $Z$+jets background
  - Caveat: Sample has a cut $m_{\text{leplep}} < 200$ GeV
- Triggers:
  - Electron trigger: 25 GeV
  - Muon trigger: 20 GeV
Input Variables Distributions

Backup

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WW Scattering including Pile-up

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Input Variables Distributions

Transverse Mass $m_{T1}^{VBS}$ [GeV/c²]

Missing Transverse Momentum $p_T^{miss}$ [GeV/c]

Flavour Tag Weight $b_1$

Flavour Tag Weight $b_2$

Lepton $p_{T1}$ [GeV/c]

Lepton $p_{T2}$ [GeV/c]

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WW Scattering including Pile-up

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Input Variables Distributions

Minijet Transverse Momentum $p_{T1}$ [GeV/c]

Minijet Transverse Momentum $p_{T2}$ [GeV/c]

Lepton Momentum Fraction $x_1$

Lepton Momentum Fraction $x_2$
Boosted Decision Tree Results

W+jets background  Z+jets background  WHIZARD QCD

WHIZARD EW  t\bar{t} background  Wt background
TMVA Training Tests

Trust a multivariate method?

Retraining with equivalent subsamples of the same size

Retraining with random picking of training events inside TMVA

Retraining with samples with different number of events

$\varphi$ resonance with $m = 850$ GeV and pile-up
Luminosity studies

\[
\int L dt = 1 \text{ fb}^{-1}
\]
\[
\int L dt = 10 \text{ fb}^{-1}
\]
\[
\int L dt = 100 \text{ fb}^{-1}
\]
\[
\int L dt = 1000 \text{ fb}^{-1}
\]

pile-up
Angular Separation of Leptons

- Signal shows clear lepton angular separation
  - Preserved by Whizard
  - Motivation for $l\nu l\nu$ final state
- Lepton angular separation $\Delta \varphi^{leplep}$ no input variable of BDT
- No cut on BDT output $\rightarrow$ Possible control region at low $\Delta \varphi^{leplep}$
- After cut on BDT output $\rightarrow$ Separation power of $\Delta \varphi^{leplep}$ lost
Disentangling Signal and Irreducible Backgrounds

- Samples reweighted from high to low coupling values
- $S(g) = n_{\text{Signal+EW}}(g) - n_{\text{Signal+EW}}(g = 0)$
- Reasonable couplings for strong EWSB: $g \lesssim \sqrt{2\pi} \approx 2.5$
Jet-energy resolution: $E' = E + e_2 \Delta E$ with
  ▶ $\Delta E$ randomly drawn from a Gaussian with:
    ▶ $\sigma(E) = 0.45\sqrt{E \times 1\text{ GeV}}$ for $|\eta| \leq 3.5$
    ▶ $\sigma(E) = 0.63\sqrt{E \times 1\text{ GeV}}$ for $|\eta| > 3.5$

Electron-energy scale: $E'_e = (1 + e_3)E_e$ with $e_3 = 0.5\%$

Electron-energy resolution: $E'_e = \frac{E_T + e_4 \Delta E_T}{E_T}E_e$ with
  ▶ $\Delta E_T$ randomly drawn from a Gaussian with:
    ▶ $\sigma(E_T) = 0.0073E_T$

Muon-energy scale: $E'_\mu = (1 + e_5)E_\mu$ with $e_5 = 1\%$