Searches for high mass dilepton resonances in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS Experiment

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Theoretical Motivations

- New high mass resonances are predicted in several extensions of the Standard Model
  - Set limits on spin 1 and spin 2 resonances

- **Spin 1**: benchmark is **Sequential Standard Model (SSM)**
  - $Z'$ has same leptonic couplings as SM $Z$
  - Width scales linearly with mass

- Also consider Grand Unification $E_6$-inspired models
  - $E_6$ broken to $SU(5) \times U(1)_\chi \times U(1)_\psi$
  - $Z'$ candidate is linear combination of U(1) gauge bosons:
    \[
    Z'(\theta_{E_6}) = Z'_\chi \cos \theta_{E_6} + Z'_\psi \sin \theta_{E_6}
    \]

- **Spin 2**: benchmark is **Randall-Sundrum (RS) Graviton**
  - See talk by **Evan Wulf** for more info
Large Hadron Collider
Large Hadron Collider

- Located at CERN, Geneva, Switzerland
- pp collider at $\sqrt{s} = 7$ TeV
- Peak instantaneous luminosity:
  - $2 \cdot 10^{33}$ cm$^2$s$^{-1}$ and rising
Large Hadron Collider

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ATLAS Detector
ATLAS Detector

- **Inner Detector**
  - Coverage for $|\eta| < 2.5$

- **Electromagnetic Calorimeter**
  - Central region coverage for $|\eta| < 2.47$
  - Energy resolution (in barrel): 1.1% at 1 TeV

- **Muon Spectrometer**
  - Coverage for $|\eta| < 2.5$
  - Momentum resolution (in barrel): 15% at 1 TeV
Signal and Backgrounds

- Select events with **two leptons of same flavor** (ee, μμ)
- Search for excess above Standard Model expectations in **high invariant mass region**

**Main backgrounds**

- Drell Yan (irreducible)
- Dibosons (WW, WZ, ZZ)
- Top quark pair production
- SM W+jets
- QCD dijets

Non-prompt muons (including cosmic rays) found to be negligible for muon channel
Electron Selection

- Electrons reconstructed as cluster in EM calorimeter matched with track from Inner Detector

**Detailed selection:**
- Trigger requiring single “Medium” electron with $E_T > 20$ GeV
- 2 electrons with:
  - $E_T > 25$ GeV
  - $|\eta| < 2.47$, exclude calorimeter crack region $1.37 < |\eta| < 1.52$
  - “Medium” Electron ID
    - Transverse shower shapes
    - Hadronic calorimeter leakage
    - Track quality
    - Track-cluster matching
  - Hit in first pixel layer (“B-layer”)
- Leading electron isolated:
  - $\sum E_T < 7$ GeV within a cone of $\Delta R < 0.2$

**Total acceptance*efficiency:**
- ~67% for Z' masses above 1 TeV

*Robust selection to suppress instrumental background and ensure well-understood leptons*
Muon Selection

Robust selection to suppress instrumental background and ensure well-understood leptons

- Muons reconstructed from combination of tracks in Inner Detector and Muon Spectrometer

Detailed selection:
- Trigger requiring single Muon with $p_T > 22$ GeV
- Primary vertex with $|z| < 200$ mm
- 2 muons with:
  - $p_T > 25$ GeV
  - $|\eta| < 2.4$
  - Track quality in Inner Detector
  - Precision hits in all 3 muon stations
  - Hit in non-bending plane
  - Veto on overlapping hits in barrel and endcaps
  - $|d_0| < 0.2$ mm, $|z_0| < 1$ mm
  - Isolation: $\sum p_T^{trk} < 0.05 p_T$ within a cone of $\Delta R < 0.3$
  - Opposite charge

Total acceptance*efficiency:
- $\sim 42\%$ for $Z'$ masses above 1 TeV
Electron QCD Dijet Background

- All backgrounds taken from MC except QCD dijets
- Baseline method is inverted identification:
  - Require two electrons passing looser cuts but failing Medium Electron ID cuts to derive shapes for QCD dijet background
  - QCD dijet invariant mass shape is fit with an empirical function to allow extrapolation to high mass: \( f(x) = p_0 x^{p_1} x^{p_2} \log x \)
  - Normalization is determined using a binned likelihood fit in invariant mass, in the range 70 < \( m_{ee} \) < 200 GeV

| \( m_{ee} \) [GeV] | QCD Events |
|-------------------|------------|
| 70 – 110          | 332 +/- 59 |
| 110 – 200         | 191 +/- 75 |
| 200 – 400         | 36 +/- 29  |
| 400 – 800         | 1.8 +/- 1.4|
| 800 – 3000        | < 0.05     |

\[ \int L \, dt = 1.08 \text{ fb}^{-1} \]
\( s = 7 \text{ TeV} \)
Electron QCD Dijet Background

- Cross checks and systematics from two other methods:
  - **Fake rates** method derives fake rate for jets to pass Z' selection in dijet data, applies fake rate to dielectron events where one electron passes jet-like cuts
  - **Isolation fit** uses binned likelihood fits in calorimeter isolation
    - **Signal templates** taken from W electrons in data
    - **Background templates** taken from reversing ID cuts in data
    - Leading and subleading electrons are fit separately in bins of invariant mass
    - Results of fits are combined using a system of equations to obtain event level background predictions

![Electron Dijet Background](image-url)
Muon QCD Dijet Background

- All backgrounds also taken from MC except QCD dijets
- Use a **reversed isolation** method:
  - **QCD shapes** from data events with both muons non-isolated:
    - $0.1 < \left( \sum p_T^{trk} \right) / p_T^{\mu \text{on}} < 1.0$ for tracks within a cone of $\Delta R < 0.3$
  - **Normalization** taken from the ratio of isolated to non-isolated dimuon events in QCD (bbar/ccbar) MC

![Graph of ATLAS data and background contributions]

$\int L \, dt = 1.21 \text{ fb}^{-1}$

\( \sqrt{s} = 7 \text{ TeV} \)
Results: Invariant Mass

MC normalized to data in Z peak region
(70 < m_{ℓℓ} < 110 GeV)

No excess observed over SM expectations:
set limits on σB
Event Details:
- Leading electron:
  - $E_T$: 257 GeV
  - $\eta, \phi$: (-0.76, 1.14)
- Subleading electron:
  - $E_T$: 207 GeV
  - $\eta, \phi$: (2.05, -2.05)
- $m_{ee}$: 933 GeV
Systematic Uncertainties

- Reduce background systematics by normalizing MC to data in Z peak region ($70 < m_{\ell\ell} < 110$ GeV)
  - Luminosity and other mass-independent systematics cancel
  - Normalization factor: 0.99
- Uncertainties treated as correlated across all mass bins

| Source                | dielectrons | dimuons |
|-----------------------|-------------|---------|
|                       | signal      | background | signal | background |
| Normalization         | 5%          | NA       | 5%     | NA         |
| PDFs/$\alpha_s$       | NA          | 10%      | NA     | 10%        |
| QCD K-factor          | NA          | 3%       | NA     | 3%         |
| Weak K-factor         | NA          | 4.5%     | NA     | 4.5%       |
| Trigger/Reconstruction| negligible  | negligible| 4.5%   | 4.5%       |
| Total                 | 5%          | 11%      | 7%     | 12%        |

Systematic uncertainties on numbers of expected events at $m_{\tau\tau} = 1.5$ TeV
Statistical Method

- Use template shape fitting and Bayesian statistics
- Log likelihood ratio for discovery statistics: \( LLR = -2 \ln \frac{L(S+B)}{L(B)} \)
  - Systematics: nuisance parameters, marginalized
  - 2D likelihood fit in bins of \( \sigma_Z \) and \( M_Z \)
  - Marginalized posterior probability density shown on z-axis below
- P-values: electrons: 24%, muons: 54%
  - No excess: set limits
Spin 1 Combined Limits

\[ \text{Observed limit} \begin{array}{cc}
\text{mass [TeV]} & \text{Expected limit [TeV]} \\
Z'_{\text{SSM}} \rightarrow e^+e^- & 1.70 & 1.70 \\
Z'_{\text{SSM}} \rightarrow \mu^+\mu^- & 1.61 & 1.61 \\
Z'_{\text{SSM}} \rightarrow \ell^+\ell^- & 1.83 & 1.83
\end{array} \]

| Model       | \( Z'_\psi \) | \( Z'_N \) | \( Z'_\eta \) | \( Z'_l \) | \( Z'_S \) | \( Z'_\chi \) |
|-------------|---------------|------------|---------------|-------------|-------------|----------------|
| Mass limit [TeV] | 1.49         | 1.52       | 1.54          | 1.56        | 1.60        | 1.64           |

95% CL limits set with \textbf{Bayesian method}, flat prior in \( \sigma_{Z'} \).
Spin 2 Combined Limits

Limits for varying coupling $k/M_{pl}$

| Coupling | RS Graviton |
|----------|-------------|
| 0.01     | 0.03 0.05 0.1 |
| Mass limit [TeV] | 0.71 1.03 1.33 1.63 |

95% CL limits set with **Bayesian method**, flat prior in $\sigma_{G^*}$.  

| Process          | Observed limit | Expected limit |
|------------------|----------------|----------------|
| $G^* \rightarrow e^+ e^-$ | 1.51           | 1.50           |
| $G^* \rightarrow \mu^+ \mu^-$ | 1.45           | 1.44           |
| $G^* \rightarrow \ell^+ \ell^-$ | 1.63           | 1.63           |

**ATLAS**
\[ \sqrt{s} = 7 \text{ TeV} \]
$G^* \rightarrow \ell^+ \ell^-$

Limits for a coupling of $k/M_{pl} = 0.1$

| Process          | Observed limit | Expected limit |
|------------------|----------------|----------------|
| $G^* \rightarrow e^+ e^-$ | 1.51           | 1.50           |
| $G^* \rightarrow \mu^+ \mu^-$ | 1.45           | 1.44           |
| $G^* \rightarrow \ell^+ \ell^-$ | 1.63           | 1.63           |
Conclusions

- No excess above Standard Model expectations seen in high mass dilepton events
  - Set limits on spin 1 and spin 2 models
- With much more data to be collected this year, discoveries may still be lurking...

Required luminosity to see 10 signal events

This talk
Bonus Slides


## More details on MC processes

| Process       | Generator | Order                                                                 |
|---------------|-----------|----------------------------------------------------------------------|
| SSM Z'        | PYTHIA    | LO*, mass dependent k-factors for NNLO QCD corrections                |
| RS Graviton   | PYTHIA    | LO*                                                                  |
| Drell Yan     | PYTHIA    | LO*, mass dependent k-factors for NNLO QCD and higher order EW corrections |
| Dibosons      | HERWIG    | LO*, scaled to NLO cross section                                      |
| W+jets        | ALPGEN    | LO*, scaled to NNLO cross section                                     |
| Top quark pairs | MC@NLO  | NLO, scaled to NNLO cross section                                     |
## Expected/Observed Events

| $m_{e^+e^-}$ [GeV] | 70-110  | 110-200 | 200-400 | 400-800 | 800-3000 |
|-------------------|---------|---------|---------|---------|----------|
| DY                | $258482 \pm 410$ | $5449 \pm 180$ | $613 \pm 26$ | $53.8 \pm 3.1$ | $2.8 \pm 0.1$ |
| $t\bar{t}$       | $218 \pm 36$  | $253 \pm 10$  | $82 \pm 3$  | $5.4 \pm 0.3$ | $0.1 \pm 0.0$ |
| Diboson           | $368 \pm 19$  | $85 \pm 5$    | $29 \pm 2$  | $3.1 \pm 0.5$ | $0.3 \pm 0.1$ |
| W+jets            | $150 \pm 100$ | $150 \pm 26$ | $43 \pm 10$ | $4.6 \pm 1.8$ | $0.2 \pm 0.4$ |
| QCD               | $332 \pm 59$  | $191 \pm 75$  | $36 \pm 29$ | $1.8 \pm 1.4$ | $< 0.05$ |
| **Total**         | $259550 \pm 510$ | $6128 \pm 200$ | $803 \pm 40$ | $68.8 \pm 3.9$ | $3.4 \pm 0.4$ |
| **Data**          | $259550$      | $6117$        | $808$      | $65$      | $3$       |

| $m_{\mu^+\mu^-}$ [GeV] | 70-110  | 110-200 | 200-400 | 400-800 | 800-3000 |
|-------------------------|---------|---------|---------|---------|----------|
| DY                      | $236319 \pm 320$ | $5171 \pm 150$ | $483 \pm 22$ | $40.3 \pm 2.5$ | $2.0 \pm 0.3$ |
| $t\bar{t}$              | $193 \pm 21$  | $193 \pm 20$  | $63 \pm 6$  | $4.2 \pm 0.4$ | $0.1 \pm 0.0$ |
| Diboson                 | $307 \pm 16$  | $69 \pm 5$    | $25 \pm 2$  | $1.7 \pm 0.5$ | $< 0.05$ |
| W+jets                  | $1 \pm 1$     | $1 \pm 1$     | $< 0.5$     | $< 0.05$     | $< 0.05$ |
| QCD                     | $1 \pm 1$     | $< 0.5$       | $< 0.5$     | $< 0.05$     | $< 0.05$ |
| **Total**               | $236821 \pm 487$ | $5434 \pm 150$ | $571 \pm 23$ | $46.1 \pm 2.6$ | $2.1 \pm 0.3$ |
| **Data**                | $236821$      | $5406$        | $557$      | $51$       | $5$       |
Highest $m_{\mu\mu}$ Event

Event Details:
- Leading muon:
  - $p_T$: 510 GeV
  - $\eta, \phi$: (0.37, 3.01)
- Subleading muon:
  - $p_T$: 437 GeV
  - $\eta, \phi$: (0.72, -0.12)
- $m_{\mu\mu}$: 959 GeV
Spin 1 Individual Channel Limits

\[
\text{ee: } \int L \, dt = 1.08 \, \text{fb}^{-1}
\]

\[
\text{μμ: } \int L \, dt = 1.21 \, \text{fb}^{-1}
\]

| \(Z'_\text{SSM} \rightarrow e^+e^-\) | 1.70 | 1.70 |
| \(Z'_\text{SSM} \rightarrow \mu^+\mu^-\) | 1.61 | 1.61 |
| \(Z'_\text{SSM} \rightarrow \ell^+\ell^-\) | 1.83 | 1.83 |
Spin 2 Individual Channel Limits

**ATLAS**
\(\sqrt{s} = 7 \text{ TeV} \)
G* → ee

**Observed limit**
- \(k/M_{pl} = 0.1\)
- \(k/M_{pl} = 0.05\)
- \(k/M_{pl} = 0.03\)
- \(k/M_{pl} = 0.01\)

**Expected limit**
- Expected ± 1σ
- Expected ± 2σ

\(\sigma B [pb]\)

For a coupling of \(k/M_{pl} = 0.1\), the limits are as follows:

| Process            | Observed limit mass [TeV] | Expected limit mass [TeV] |
|--------------------|----------------------------|----------------------------|
| \(G^* \rightarrow e^+e^-\) | 1.51                       | 1.50                       |
| \(G^* \rightarrow \mu^+\mu^-\) | 1.45                       | 1.44                       |
| \(G^* \rightarrow \ell^+\ell^-\) | 1.63                       | 1.63                       |

\(\ell: \int L \, dt = 1.08 \text{ fb}^{-1}\) for ee channel

\(\mu: \int L \, dt = 1.21 \text{ fb}^{-1}\) for \(G^* \rightarrow \mu\mu\) channel
Sensitivity: Limit Setting

ATLAS Preliminary (simulation)

95%CL Limit $Z' \rightarrow ee, \mu\mu$

Luminosity [pb$^{-1}$]

$Z'$ Mass [TeV]

- 7 TeV
- 8 TeV
- 9 TeV