ATLAS Searches for TeV-scale gravity with multi-body final states

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TeV-Scale Gravity

• Scenario: large or warped extra dimensions exist into which gravitons can propagate
• Motivation: reduces the effective Planck-scale to something on the order of the Electroweak scale and resolves the hierarchy problem
  – A lower Planck scale ($M_D$) leads to a stronger gravitational interactions
• At some threshold value $M_{\text{TH}}$ above $M_D$ regions of space-time from which nothing can escape classically can form and be detected in ATLAS
• Goal: to set limits on the Planck mass and the number of extra dimensions
Simulated Black Hole Event in ATLAS
The ATLAS Detector
Phenomenology

• TeV-scale gravity interactions are mediated by gravitons and couple to SM particles democratically
• We search for many very active, high invariant mass events in ATLAS
• We aim to take advantage of universality and require a high $p_T$ lepton
• We are hoping to see a new interaction threshold for multi-body final states with leptons
Signal MC Samples

- Samples produced for both rotating and non-rotating black holes (BH) and stringballs (SB) for 2-7 extra dimensions
- Charybdis2
  - Both low and high multiplicity remnants for BHs and SBs
- BlackMax
  - Final burst remnant model for BH (no SBs)
    - High multiplicity remnant states
    - No form factor in the cross-section
    - Brane width = 0
    - Both baryon number and lepton number conserved
- Shower evolution and hadronisation uses Pythia 6.421
  - With the CTEQ6.6 PDF sets
  - $M_{BH}$ is used as the QCD scale
- Charybdis and BlackMax samples are used to guide the analysis and illustrate the potential signal properties:
  - Non-rotating BH sample with $1 \text{ TeV} < M_D < 3 \text{ TeV}$ and $M_{TH} \geq 4 \text{ TeV}$
  - Rotating SB sample with $M_{TH} = 3 \text{ TeV}$, $M_D = 1 \text{ TeV}$ and string coupling $g_S = 0.4$
Monte Carlo Background Samples

• QCD jet events generated with Pythia
  – MRST2007LO* w/modified LO PDF
• Production of top pairs and single top simulated with MC@NLO
  – $m_{\text{top}} = 172.5$ GeV
  – NLO PDF set CTEQ6.6
• Samples of $W$ and $Z/\gamma^*$ produced with Alpgen
• Di-boson ($WW, WZ, ZZ$) production simulated with Herwig
• Fragmentation and hadronization for the Alpgen and MC@NLO samples performed with Herwig
  – Jimmy is used for the underlying event
• All samples use a specific ATLAS parameter tune and the ATLAS full GEANT4 detector simulation
ATLAS detection

- For TeV-scale gravity searches in ATLAS, we observe:
  - \(N\) - the number of objects (electrons, photons, muons, jets) passing selections in the final state
  - \(\Sigma |p_T|\) - the scalar sum of the transverse momenta of the objects selected

\[\Sigma p_T \equiv \Sigma_{i=\text{objects}} p_{Ti}\]
Multi-jet Search Strategy

• PYTHIA MC samples are normalized to data in a control region (CR)
  – Signal already excluded in this region by previous short-scale gravity and particle collider experiments

• MC predictions are then extrapolated to the signal region (SR)

• Search for deviation from SM prediction in the jet distributions
Multiplicity and Momenta

- Pythia QCD bg prediction compared to various BH models for 35 pb-1
High Multiplicity Event in ATLAS

6 Jet Event in 7 TeV Collisions
ATLAS Reconstruction

- **Electrons**
  - ATLAS reconstruction algorithm based on calorimeter shower shape, track quality and track matching algorithm
  - Cluster $p_T > 40$ GeV and $|\eta_{cl}| < 2.47$, excluding $1.37 < |\eta_{cl}| < 1.52$
  - $\Sigma p_T$ (other) in $\Delta R < 0.2$ must be $< 0.1 p_T(e)$
  - If $0.2 < \Delta R < 0.4$ between $e$ and jet, electron is vetoed

- In 2011 data-taking LAr barrel calorimeter had in a small “dead” region
  - Inside region up to 30% of the incident jet energy may be lost
  - Should any of the four leading jets with $p_T > 40$ GeV fall into this region, the event is vetoed
  - Loss of signal efficiency of $\sim 15 - 20\%$ for the models considered
  - Electrons incident on this region are removed
More ATLAS Reconstruction

- **Muons**
  - $p_T > 40$ GeV
  - Associated ID track with sufficient hits in the pixel, SCT and TRT
  - Hits in at least 3 precision layers of the muon chambers
  - $\Sigma p_T$(other) in \(\Delta R < 0.3\) must be $< 0.05$ $p_T(\mu)$
  - If $\Delta R < 0.4$ between $\mu$ and jet, muon is vetoed
  - Tight cuts applied to the origin of the muons relative to the primary vertex
    - Rejects muons from cosmic rays

- **Jets**
  - $p_T > 50$ GeV and $|\eta| < 2.8$
  - Anti-$k_t$ jet clustering algorithm with a radius of 0.4
  - If $\Delta R < 0.2$ between $e$ and jet, jet is rejected
Multi-jet Search Event Selection

• 2 triggers during 2010 running
  – As instantaneous luminosity increased need to maintain constant total trigger output rate
    • Lowest full acceptance trigger threshold increased
  – $E_T$ thresholds of 55 GeV or 95 GeV
  – $p_T$(leading jet) > 250 GeV
    • To ensure trigger fully efficient

• Primary vertex must have at least 5 tracks with $p_T > 150$ MeV
  – Reduces non-collision background

• Data is divided into 4 regions in $(N_J, \Sigma p_T)$
  – $R_0 : 1.1 < \Sigma p_T < 1.2$ TeV and $N_J < 5$
  – $R_1 : 1.1 < \Sigma p_T < 1.2$ TeV and $N_J \geq 5$
  – $R_2 : \Sigma p_T > 2$ TeV and $N_J < 5$
  – $R_3 : \Sigma p_T > 2$ TeV and $N_J \geq 5$ *SR
Multi-jet Search Results

- No deviation from the SM expectation is observed
- 35 pb\(^{-1}\) of data
- Upper limit on the cross-section \(\times\) acceptance of 0.29pb
  - Final states with at least 4 jets, \(\Sigma p_T(jets) > 2\) TeV

\(\sqrt{s}=7\) TeV
Data \(\int \mathcal{L} d\tau = 35\) pb\(^{-1}\)

\(N_j \geq 5\)
\(N_j < 5\) normalized
Motivation for Including Leptons

• The current analysis is limited by systematic errors
  – PDFs: MC matched to data in the control region, but poorly understood consistency with SM
  – JES/JER not yet very well measured for high \( M_{\text{inv}} \)
  – Errors magnified by extrapolating from control to signal region

• Notably, in the early data sample, we see very few leptons in the signal region
  – So, we are confident that we don't have a signal from any process that involves democratic decay
Same-Sign Dimuon Final States

• A complementary search using 2010 data with a luminosity of 31 pb$^{-1}$

• Events must pass a single muon trigger
  – $p_T(\mu) > 15$ GeV
  – Trigger efficiency is independent of $p_T$ (trigger plateau) for $p_T(\mu) > 20$ GeV

• All signal MC samples generated with BlackMax 2.01 and hadronized with Pythia
  – 0.5 TeV $< M_D < 2$ TeV
  – 2 TeV $< M_{TH} < 5$ TeV
  – 2, 4, and 6 extra dimensions
Dimuon Search Event Selection

- Primary Vertex must have at least 5 tracks
  - Muon candidates must point back to the primary vertex
- Muon spectrometer (MS) tracks are matched to inner detector (ID) tracks
  - $p_T(\mu_{MS})/p_T(\mu_{ID})$ used to reduce the background from π/K decay-in-flight
  - Muon ID track required to have sufficient hits in the pixel, SCT and TRT
- Leading muon
  - $p_T > 20$ GeV
  - Isolated: $\Sigma p_T(\text{other}) \Delta R(\eta,\phi) < 2.0 < 1.8$ GeV
- At least 2 muon candidates passing these selections are required in each event
Dimuon Search Results

- No excess with respect to the SM observed
- Searching for same-sign dimuons means very small SM background

- With larger dataset, can set a better limit by looking for one very high $p_T$ isolated lepton
From (Lack of) Signal to Cross-Sections

- Model-independent exclusion limits are determined on the effective cross section ($\sigma_{\text{eff}}$) as a function of minimum $\Sigma p_T$ using the CL$_s$ prescription
  
  \[ \sigma_{\text{eff}} = \sigma (pp \rightarrow \ell X) \cdot \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{rec}} \]

  - $\varepsilon_{\text{acc}} \cdot \varepsilon_{\text{rec}}$ varies, depending on the model
    - $63 \pm 6 \%$ for the electron channels considered
    - $30 \pm 4 \%$ for the muon channels considered
      
      - Acceptance for the muon channel is lower because of lower trigger efficiency and more stringent reconstruction requirements

  - $\varepsilon_{\text{acc}} \cdot \varepsilon_{\text{rec}}$ is lowest for the low multiplicity, low mass states (small values of $M_{\text{TH}}/M_D$, or $M_{\text{TH}}$ and $M_D$) that are theoretically or experimentally disfavoured
Results

- Exclusion contours in the plane of $M_D$ and $M_{TH}$
  - From counts of data events and background expectations
- Rotating black holes
- 6 extra dimensions
- Black Max
- Only slopes much larger than 1 correspond to physical models
Limiting Systematic Error: What can we measure well?

- We can measure what fraction of the cross-section can be coming from new physics
- We can move out in phase space without burying new physics in theoretical uncertainties
- The current analysis can only be extended by moving the control region to higher mass
- Using the current signal region as the control region for the next step out in mass has a risk of any new physics signal being absorbed into the control sample
Fraction of Events with Leptons

\[
\frac{N_{lep}}{N_{TOT}} = \frac{\sigma_{SM} \cdot R_{lep}^{SM} + \sigma_{sig} \cdot R_{lep}^{sig}}{\sigma_{SM} + \sigma_{sig}}
\]

\[
= R_{lep}^{SM} + \frac{\sigma_{sig}}{\sigma_{SM}} \cdot R_{lep}^{sig} \cdot \frac{1 + \frac{\sigma_{sig}}{\sigma_{SM}}}{1 + \frac{\sigma_{sig}}{\sigma_{SM}}}
\]

• Many of the same theoretical uncertainties are present in both the Monte Carlo and the signal cross-section predictions
  – Taking the ratio cancels a large part of the uncertainty

• These equations do not yet include detector effects
We Can Measure Two Things

• The ratio of the signal cross-section to the standard model cross-section

\[
\frac{N_{lep}}{N_{TOT}} = \frac{R_{lep}^{SM} + \frac{\sigma_{sig}}{\sigma_{SM}} \cdot R_{lep}^{sig}}{1 + \frac{\sigma_{sig}}{\sigma_{SM}}}
\]

for \( R_{lep}^{SM} \approx 0 \), \( = \frac{\sigma_{sig}}{\sigma_{SM}} \cdot R_{lep}^{sig} \)

and for \( \sigma_{sig} \ll \sigma_{SM} \), \( = \frac{\sigma_{sig}}{\sigma_{SM}} \cdot R_{lep}^{sig} \)

• The absolute value of the cross-section for your favorite model, but it will include the luminosity error
Simple Example of Measuring $\sigma_{\text{sig}} / \sigma_{\text{SM}}$

- For $\epsilon=0.400$, $R_{\text{sig,lep}}=6.7\%$, ratio $\sigma_{\text{sig}} / \sigma_{\text{SM}}=0.001$
- The most conservative way to set the limit is to attribute all the leptons we see to signal
- This will increase the best limit on $\sigma_{\text{sig}}$, but only slightly

$$\frac{N_{\text{lep}}}{N_{\text{TOT}}} = \frac{\sigma_{\text{sig}}}{\sigma_{\text{SM}}} * R_{\text{lep}}$$

$$\sigma_{\text{sig}} = \frac{N_{\text{lep}}}{N_{\text{TOT}}} * \frac{1}{\epsilon * R_{\text{lep}}^{\text{sig}}}$$

$$\frac{\sigma_{\text{sig}}}{\sigma_{\text{SM}}} = 0.001 * \frac{1}{0.400 * 0.067} = 0.03$$
Simple Example of Measuring Absolute $\sigma_{\text{sig}}$

- The upper limit on the cross-section was **0.34 nb** for an ATLAS note with 232 nb$^{-1}$
- Using the $\Sigma p_T$ and $N_{\text{objects}}$ cuts from this early multi-jet search, there are 0 lepton events in the signal region
  - For a 95% CL, the upper bound on 0 is 3.0
- Taking the most pessimistic value for the luminosity error, we can still improve the measurement with the same dataset

\[
\frac{3.0}{N_{TOT} \times \epsilon} = \frac{\sigma_{sig}}{N_{TOT} \times \epsilon} \times R_{lep}^{sig}
\]

\[
\sigma_{sig} = \frac{3.0}{L \times R_{lep}^{sig}}
\]

\[
\sigma_{sig} = \frac{3.0}{232 \times \frac{8}{119}} \approx 0.20 \text{ nb}
\]

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Conclusions

• No deviation from the Standard Model has been observed in jets or lepton channels

• In the future, we can set model-independent limits on the fraction of the cross-section due to TeV-Scale gravity interactions
  – We can also use the efficiency and acceptance of a particular signal model to rule out a range of $M_D$ $M_{TH}$ phase space
References

• Search for Microscopic Black Holes in Multi-Jet Final States with the ATLAS Detector at $\sqrt{s} = 7$ TeV
  – ATLAS-CONF-2011-068, 30 April 2011

• Search for strong gravity effects in same-sign dimuon final states
  – ATLAS-CONF-2011-065, 20 April 2011