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

Vicki Moeller
On Behalf of the ATLAS Collaboration

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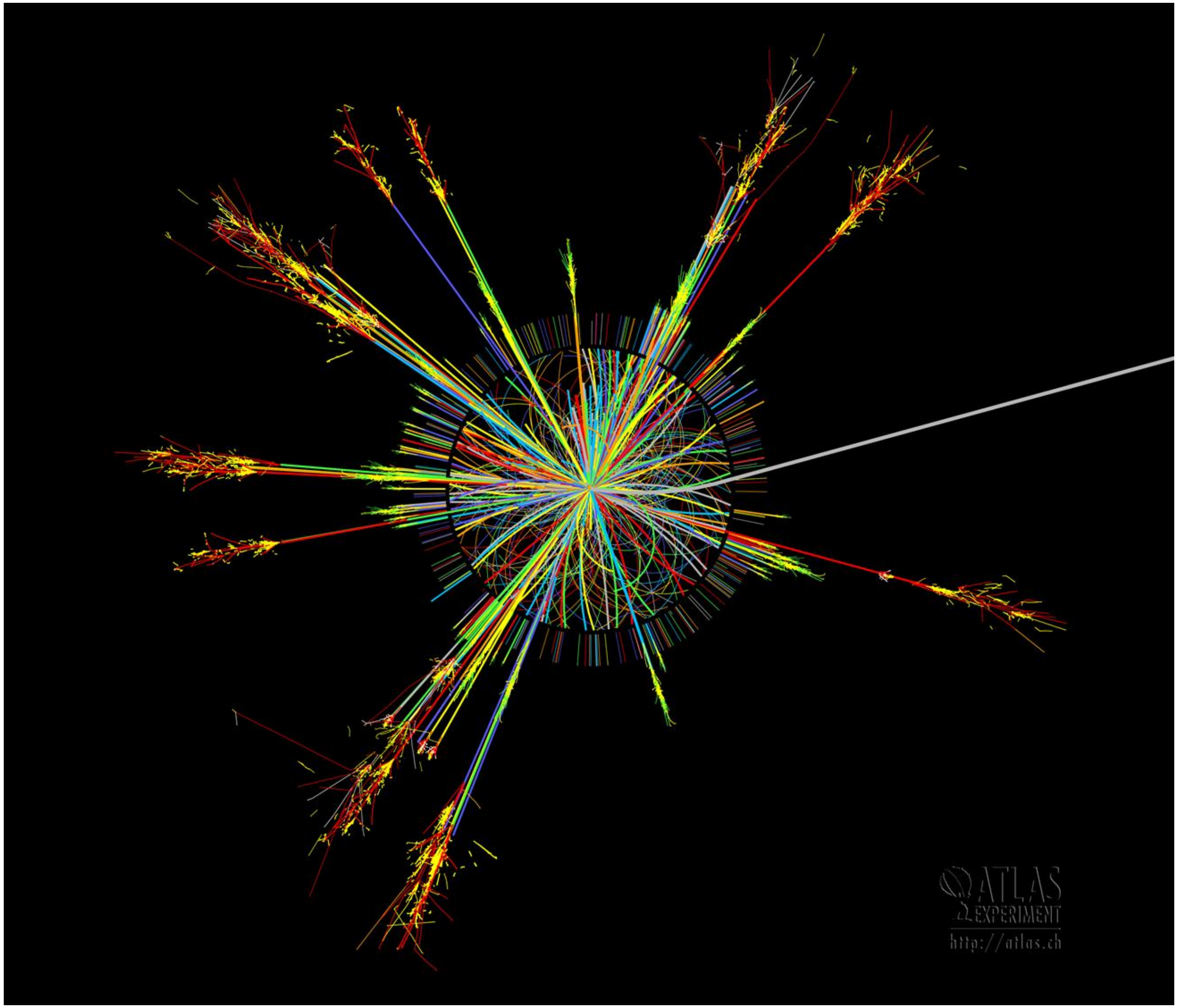
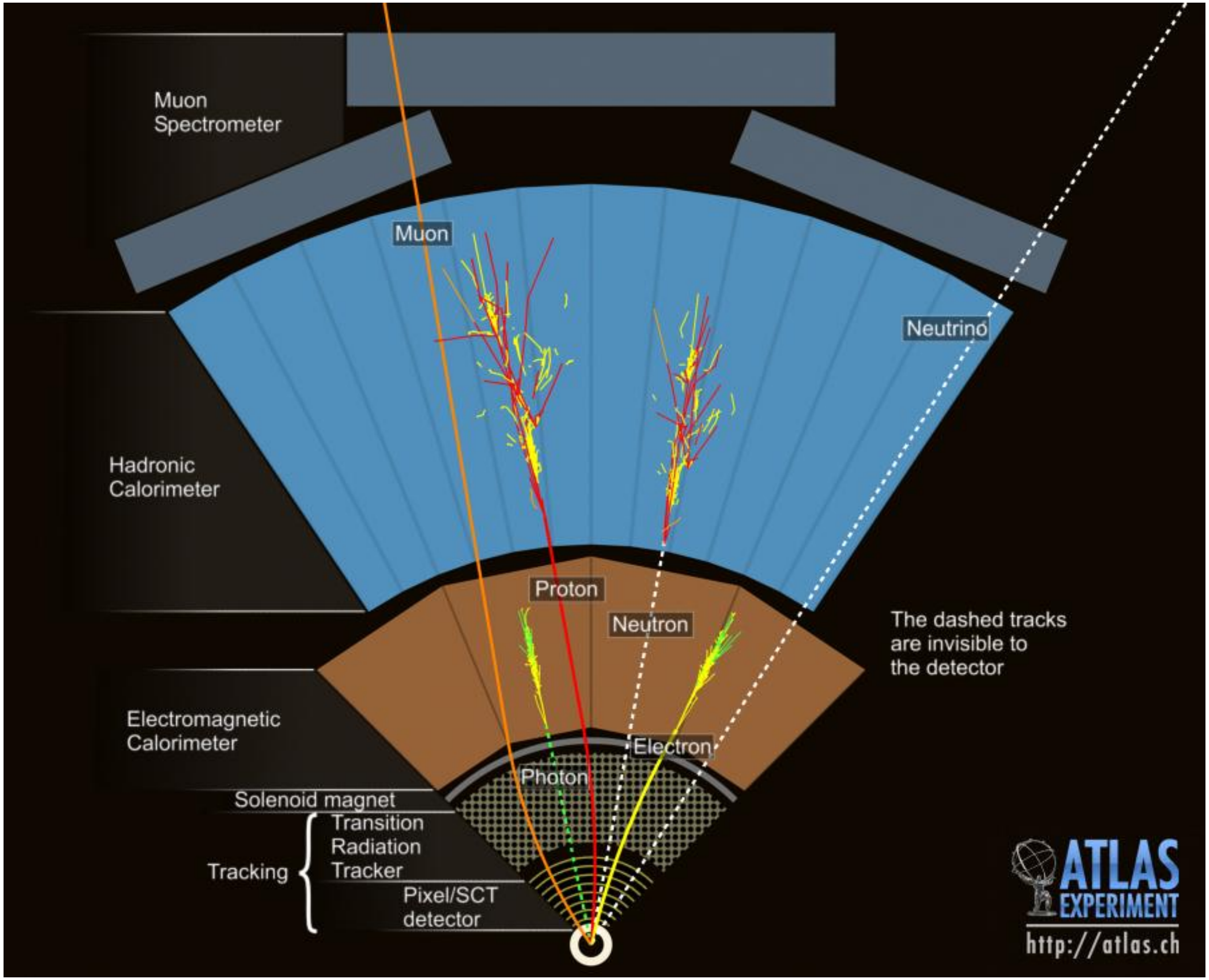
TeV-Scale Gravity

- 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_{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

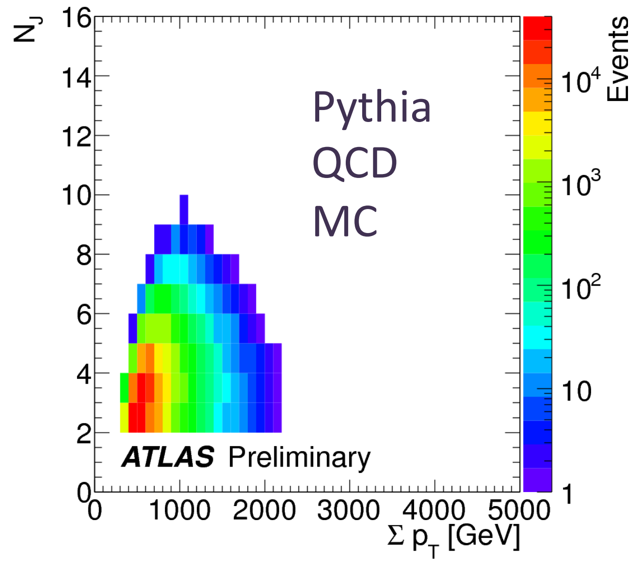
- Samples produced for both rotating and non-rotating black holes (BH) and stringballs (SB) for 2-7 extra dimensions
- Charybdis2
  - Both low and high multiplicity remnants for BHs and SBs
- BlackMax
  - Final burst remnant model for BH (no SBs)
    - High multiplicity remnant states
  - No form factor 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 1TeV < M_{D} < 3 TeV and M_{TH} >= 4 TeV
  - Rotating SB sample with M_{TH} = 3 TeV, M_{D} = 1 TeV and string coupling g_{S}=0.4

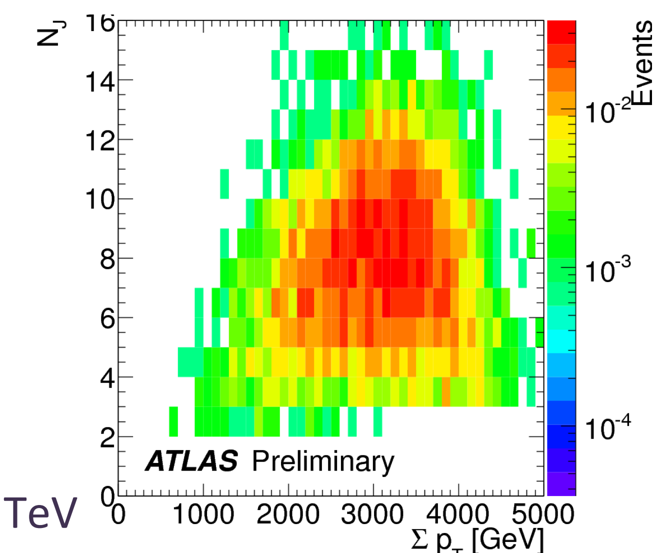
Monte Carlo Background Samples

- QCD jet events generated with Pythia
  - MRST2007LO* w/modified LO PDF
- Production of top pairs and single top simulated with MC@NLO
  - m_{top} = 172.5 GeV
  - NLO PDF set CTEQ6.6
- Samples of *W* and *Z*/γ* 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
    - $\Sigma p_T \equiv \Sigma_{i\,=\text{objects}}\, p_{Ti}$



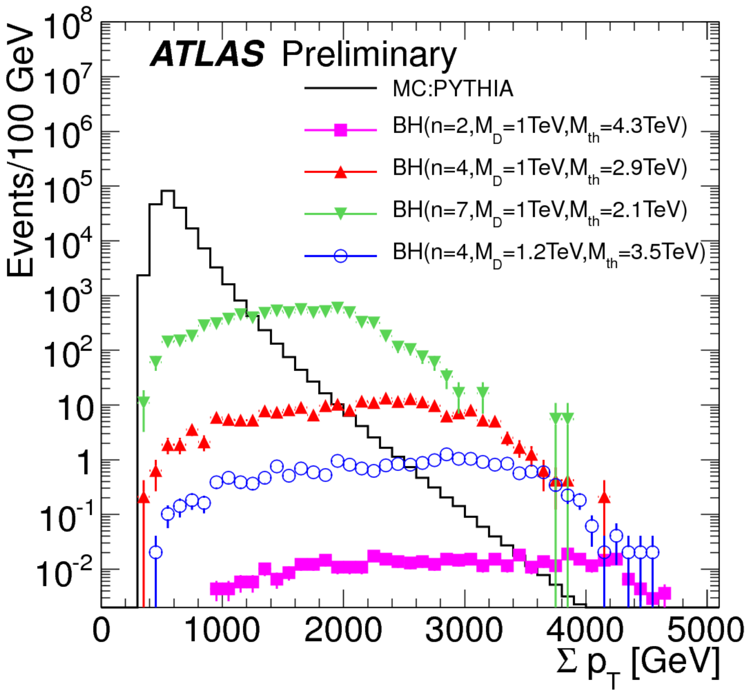


$N_{XD} = 2$
$M_D = 1$ TeV
$M_{TH} = 4.3$ TeV

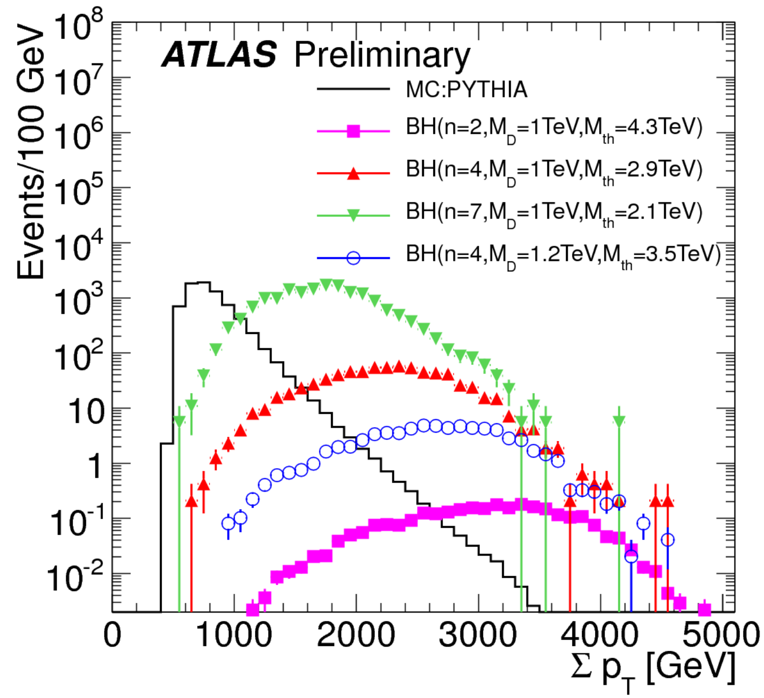
Multi-jet Search Strategy

- 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



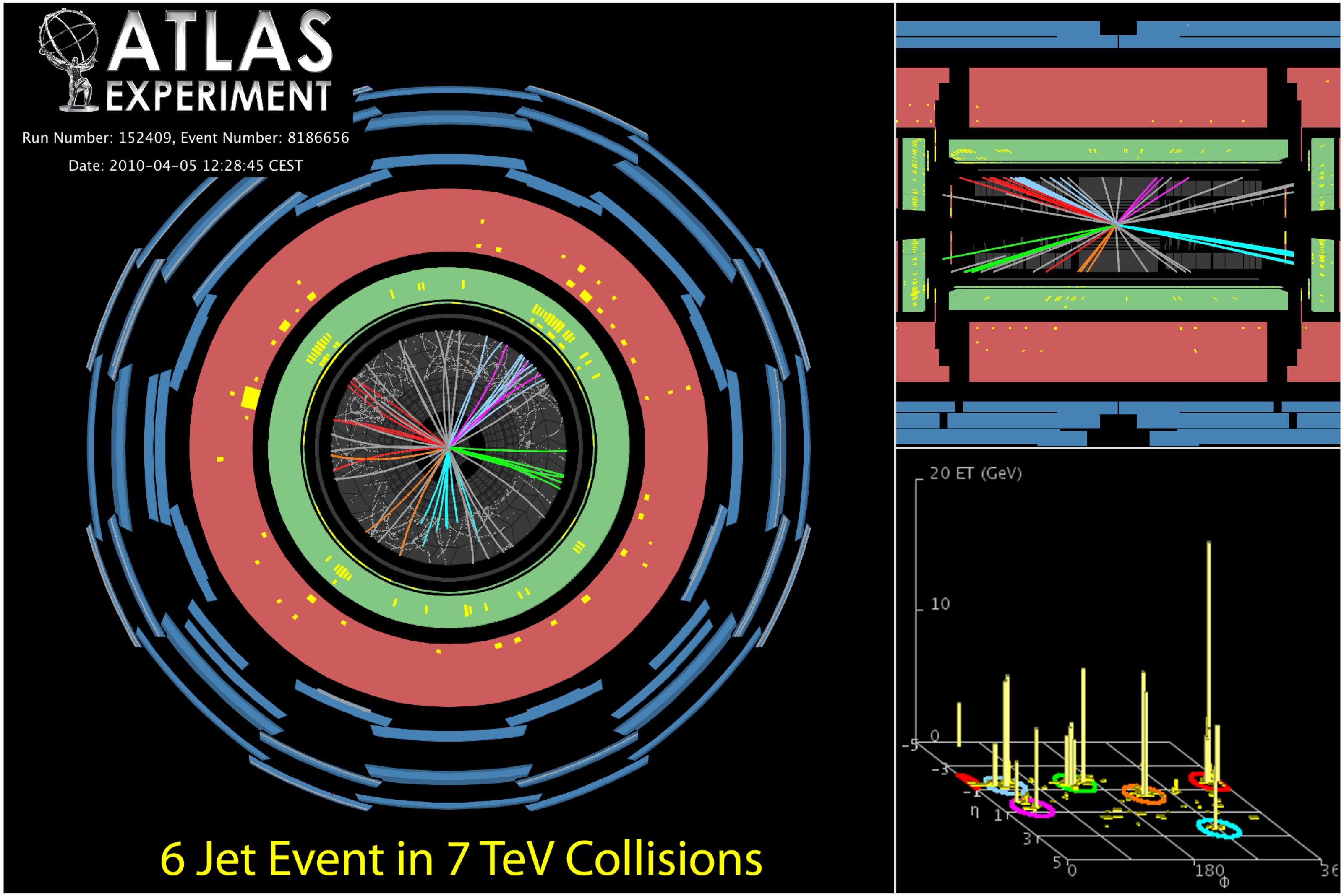
N < 5



N ≥ 5

- Pythia QCD bg prediction compared to various BH models for 35 pb-1

High Multiplicity Event in ATLAS

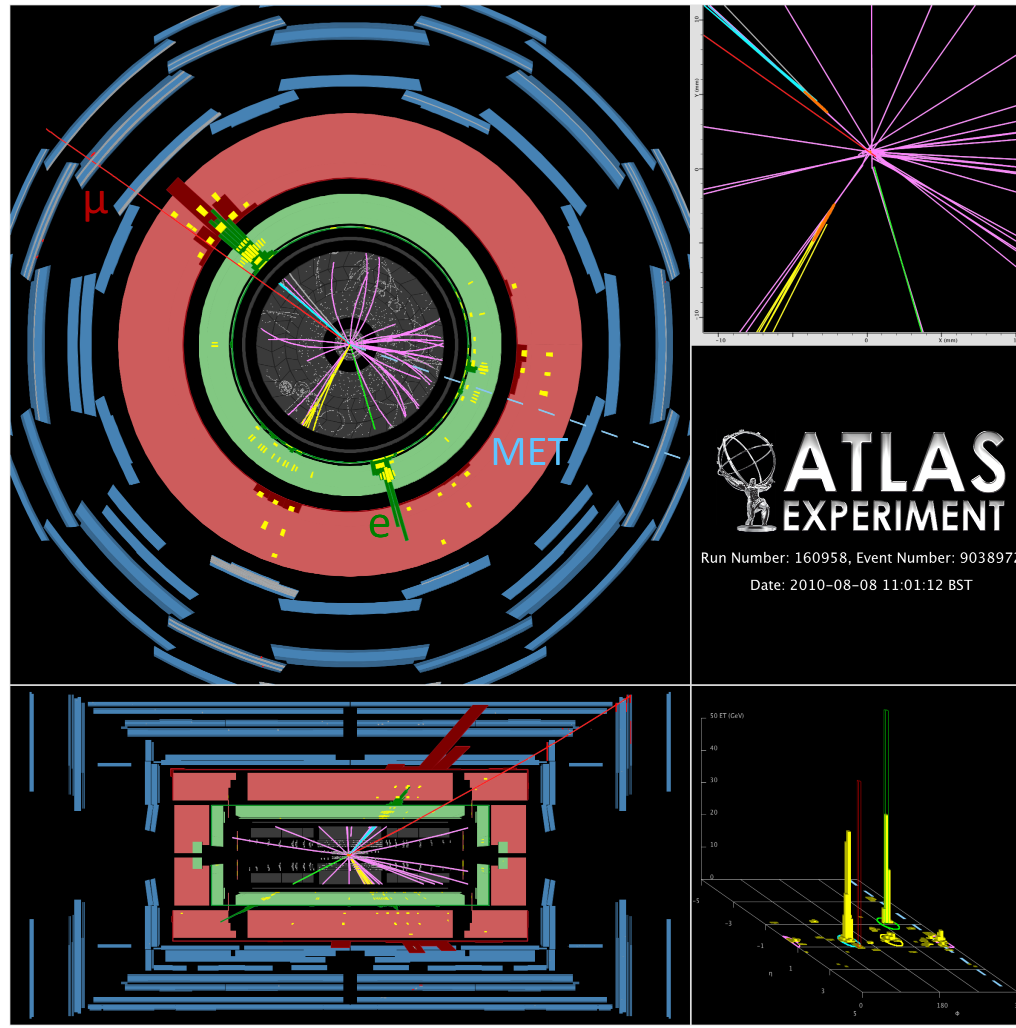


ATLAS Reconstruction

- 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 $1.37 < |\eta_{cl}| < 1.52$
  - Σp_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 ~ 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
  - Σp_T(other) in ΔR <0.3 must be < 0.05 $p_T(\mu)$
  - If ΔR < 0.4 between μ 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 ΔR< 0.2 between e and jet, jet is rejected

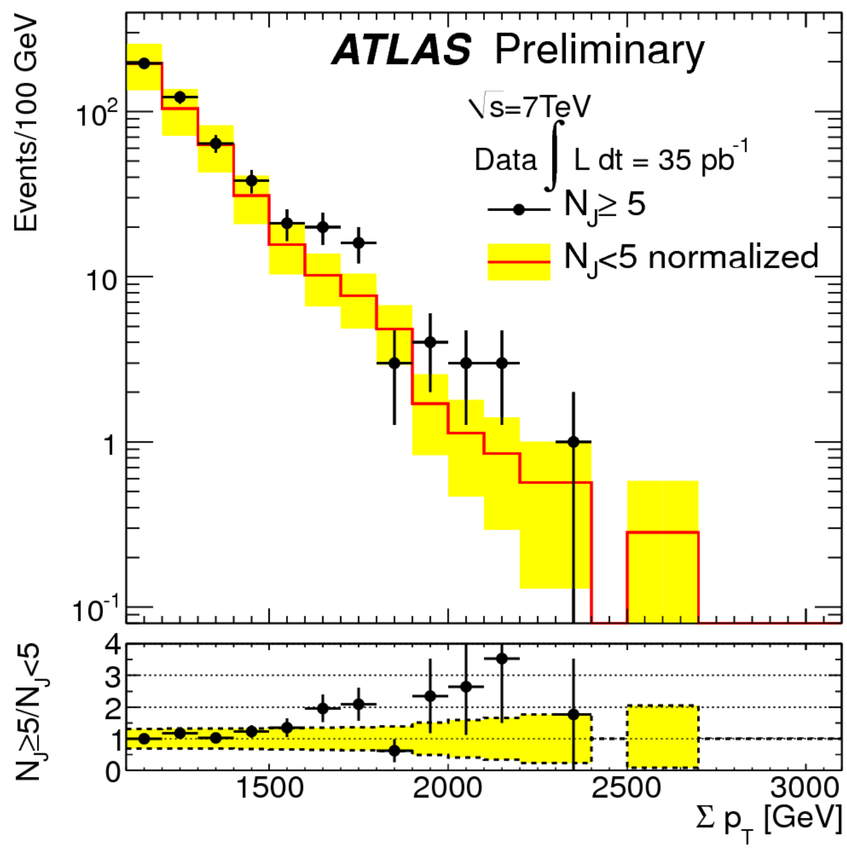


Multi-jet Search Event Selection

- 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 × acceptance of **0.29pb**
  - Final states with at least 4 jets, Σp_T(jets) > 2 TeV



Motivation for Including Leptons

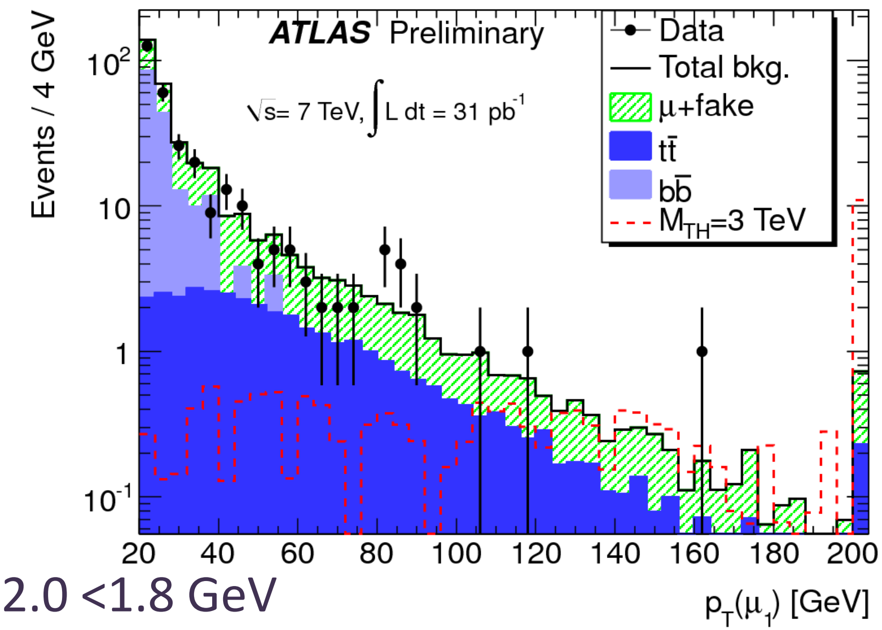
- The current analysis is limited by systematic errors
  - PDFs: MC matched to data in the control region, but poorly understood consistency with SM
  - JES/JER not yet very well measured for high M_{inv}
  - Errors magnified by extrapolating from control to signal region
- Notably, in the early data 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
  - 0.5TeV < M_D < 2TeV
  - 2TeV < M_{TH} < 5TeV
  - 2, 4, and 6 extra dimensions

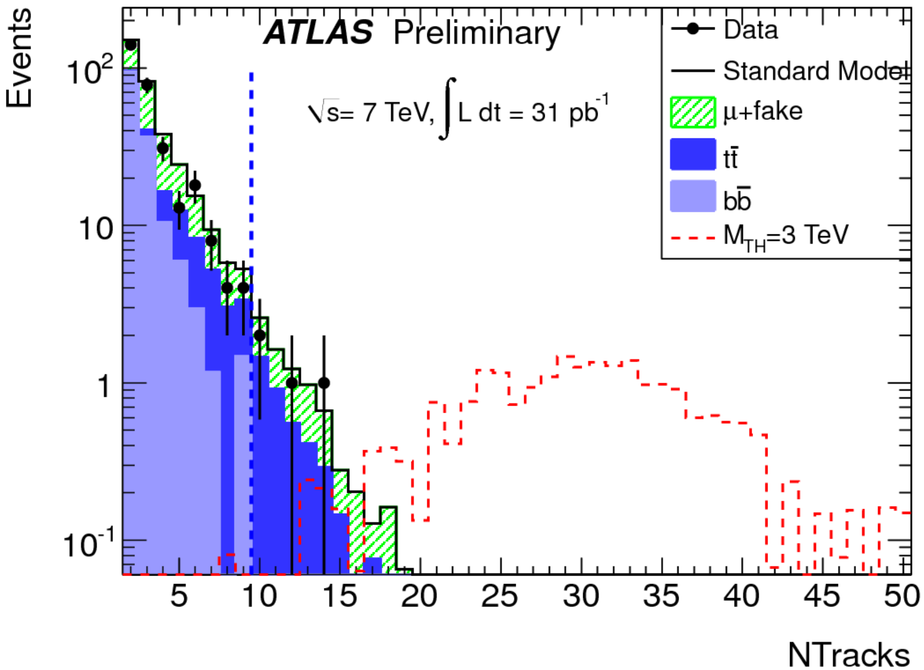
Dimuon Search Event Selection

- 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

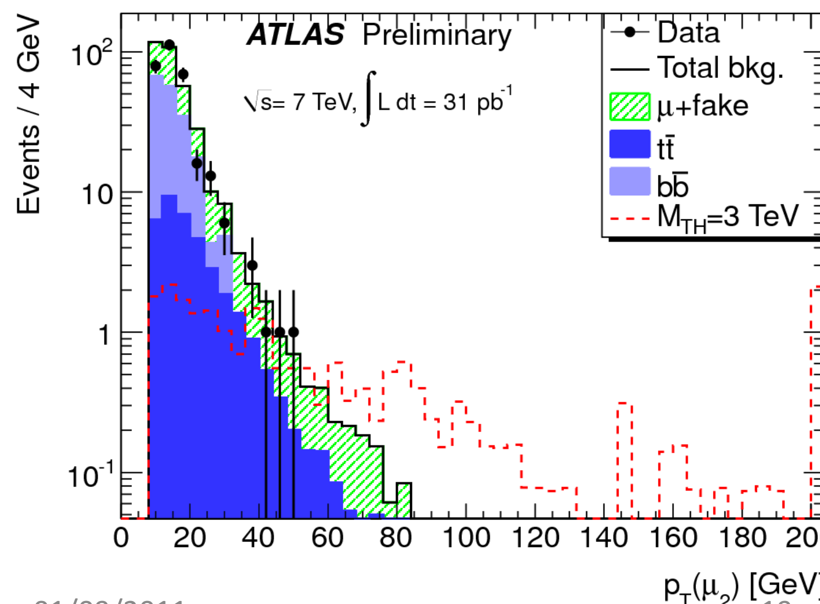


- Leading muon
  - p_T> 20GeV
  - Isloated: Σp_T(other) $\Delta R(\eta,\phi)$ < 2.0 <1.8 GeV
- At least 2 muon candidates passing these selections are required in each event

Dimuon Search Results



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



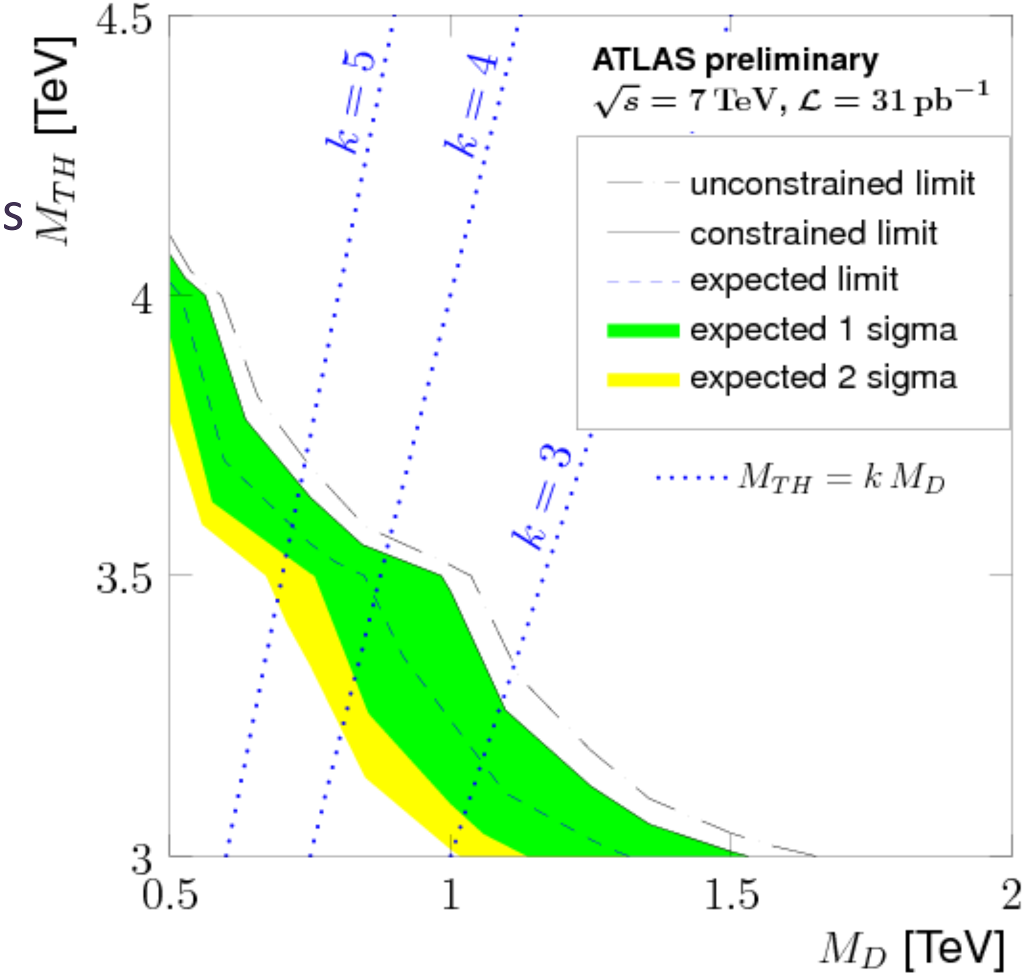
- With larger dataset, can set a better limit by looking for one very high p_T isolated lepton

From (Lack of) Signal to Cross-Sections

- Model-independent exclusion limits are determined on the effective cross section (σ_{eff}) as a function of minimum Σp_T using the CL_s prescription
- $\sigma_{eff} = \sigma\,(pp \rightarrow \ell X) \cdot \varepsilon_{acc} \cdot \varepsilon_{rec}$
- $\varepsilon_{acc} \cdot \varepsilon_{rec}$ varies, depending on the model
  - 63 ± 6 % for the electron channels considered
  - 30 ± 4 % for the muon channels considered
    - Acceptance for the muon channel is lower because of lower trigger efficiency and more stringent reconstruction requirements
  - $\varepsilon_{acc} \cdot \varepsilon_{rec}$ is lowest for the low multiplicity, low mass states (small values of M_{TH}/M_D, or M_{TH} and $_{MD}$) 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

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

$$= \frac{R_{lep}^{SM} + \frac{\sigma_{sig}}{\sigma_{SM}} * R_{lep}^{sig}}{1 + \frac{\sigma_{sig}}{\sigma_{SM}}}$$

- These equations do not yet include detector effects

- 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

We Can Measure Two Things

- The ratio of the signal cross-section to the standard model cross-section
- The absolute value of the cross-section for your favorite model, but it will include the luminosity error

$$\frac{N_{lep}}{N_{TOT}} = \frac{R_{lep}^{SM} + \frac{\sigma_{sig}}{\sigma_{SM}} * R_{lep}^{sig}}{1 + \frac{\sigma_{sig}}{\sigma_{SM}}}$$

$$\text{for } R_{lep}^{SM} \approx 0 \ , \ = \frac{\frac{\sigma_{sig}}{\sigma_{SM}}}{1 + \frac{\sigma_{sig}}{\sigma_{SM}}} * R_{lep}^{sig}$$

$$\text{and for } \sigma_{sig} << \sigma_{SM} \ , \ = \frac{\sigma_{sig}}{\sigma_{SM}} * R_{lep}^{sig}$$

Simple Example of Measuring σ_{sig}/σ_{SM}

- For ε=0.400, R^{sig}_{lep}=6.7%, ratio σ_{sig}/σ_{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 σ_{sig}, but only slightly

$$\frac{\frac{N_{lep}}{\epsilon}}{N_{TOT}} = \frac{\sigma_{sig}}{\sigma_{SM}} * R^{sig}_{lep}$$

$$\frac{\sigma_{sig}}{\sigma_{SM}} = \frac{N_{lep}}{N_{TOT}} * \frac{1}{\epsilon * R^{sig}_{lep}}$$

$$\frac{\sigma_{sig}}{\sigma_{SM}} = 0.001 * \frac{1}{0.400 * 0.067} = 0.03$$

Simple Example of Measuring Absolute σ_{sig}

- The upper limit on the cross-section was **0.34 nb** for an ATLAS note with 232 nb^{-1}
- Using the Σp_T and $N_{objects}$ 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

$$\frac{3.0}{N_{TOT} * \epsilon} = \frac{\sigma_{sig}}{\frac{N_{TOT} * \epsilon}{\mathbf{L}}} * R^{sig}_{lep}$$

$$\sigma_{sig} = \frac{3.0}{\mathbf{L} * R^{sig}_{lep}}$$

$$\sigma_{sig} = \frac{3.0}{232 * \frac{8}{119}} \approx 0.20 \text{ nb}$$

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