Searches for TeV-scale Gravity

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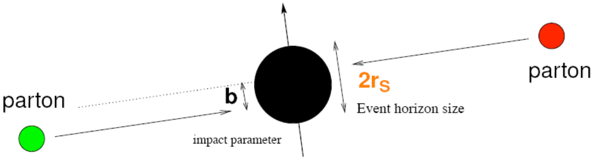
Outline

- Black Hole Models and Properties
- Search for Black Holes in pp Collisions at $\sqrt{s} = 7$ TeV with 1 fb^{-1} Data Set (CMS)
- Searches for TeV-scale gravity signatures in final states with leptons and jets (ATLAS)
- Search for Black Holes in Same-sign Dimuons (ATLAS)
- Summary

Overview

- ADD Extra-dimensional models with low scale gravity allow for the production of non-perturbative gravitational states such as black holes and string balls.
- A fundamental gravity scale M_D in the TeV range would allow exploration of such states at the LHC.
- In such models the produced black hole mass ranges from M_{TH} to $\sqrt{s}$.
- These states decay to multiple high p_T particles, of all SM types.
- Expect a range of multiplicities from signal - this is model-dependent but relatively high - not below 3 particles emitted, usually much higher.

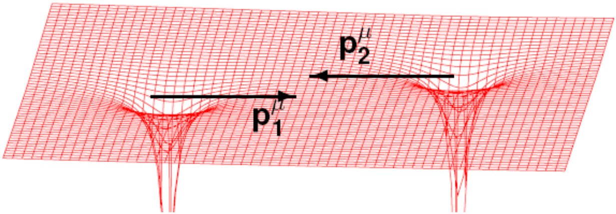


- **Thorne's hoop conjecture** (*Magic without Magic 231 (1972)*): For a given concentration of matter/energy, if it fits inside a hoop with the Schwarzchild radius r_S for that mass, then a black hole forms.
- **Black disk cross section:**

$$\sigma_{\mathbf{disk}} \sim \pi \mathbf{r_S^2}, \quad \mathbf{r_s} = \frac{C_n}{M_{4+n}} \left(\frac{\sqrt{s}}{M_{4+n}} \right)^{\frac{1}{n+1}}$$

S. B. Giddings and S. D. Thomas, hep-ph/0106219
S. Dimopoulos and G. Landsberg, hep-ph/0106295

Ideal Production Model



- Ideally, set up the spatial metric for two highly boosted particles (modelled as black holes).
- Include spin and charge.
- Evolve system.
- Obtain final metric and radiation.

Black Hole Production

- Though numerical relativity methods are beginning to make rapid progress in the area, this is still not realised.
- Trapped surface methods give bounds on the maximum impact parameter (and hence parton-level cross-section). (Yoshino Rychkov hep-th/0503171).
- Also on the maximal losses of M and J from the black hole, for given impact parameter.

- Black hole cross-sections can be large.
- **But** assuming the maximum allowed losses can reduce the differential cross section strongly (arXiv:0904.0979, hep-ph/0609055).
- Models use semi-classical approximation, the validity of which is suspect when the BH mass at production is not much larger than M_D, motivating the use of a lower production mass threshold (M_{TH}).

The Hawking Phase

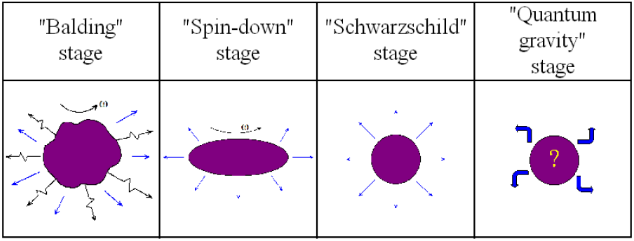
Particle Creation

- Thermal, Hawking radiation is thought to be emitted by black holes due to quantum effects.
- Black hole looses mass and evaporates
- All SM particles are emitted, primarily according to their SM degrees of freedom.
- The spectrum is that of a grey-body, with a characteristic temperature, and spectrum modified by transmission (grey-body) factors, which depend upon n, spin and properties of the black hole itself.

- Microscopic black holes have high Hawking temperatures
- Expect multiple emissions of high-energy particles, particularly jets.

Black Hole Lifecycle

- Black holes formed will be rapidly rotating, asymmetric, and "hairy".
- Four stages of subsequent evolution.
  - Balding Phase
  - Spin-down Phase
  - Schwarzschild Phase
  - Planck (Quantum) Phase



Tools and Limitations

- During the 2000s, there has been much progress in the theory describing these phenomena.
- Encoded in several Monte-Carlo generators to simulate these events and allow their analysis in greater detail.
  - Charybdis 2 JF et al. arXiv:0904.0979,
  - BlackMax D. Dai et al. arXiv:0902.3577,
  - QBH D. Gingrich arXiv:0911.5370
- There are, however, still considerable uncertainties over some modelling aspects.
- Need careful consideration in experimental searches
  - Production - losses in production, cross-section uncertainty.
  - Graviton emission in Hawking phase.
  - Remnant modelling - Quantum gravity important - can have a large effect on multiplicity, often targeted by experimental searches.

Experimental Signature

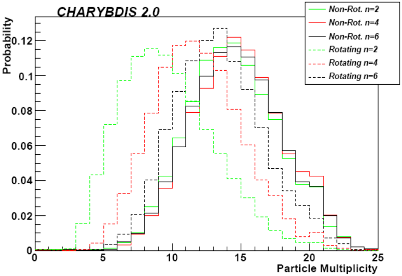
What's different about black holes?

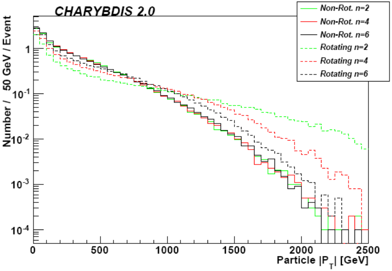
Signatures of semi-classical black holes:

- Potentially very high cross sections.
- High multiplicity events, with multiple very high p_T objects.
- Rotation $\rightarrow$ slightly reduced multiplicity but harder spectrum
- Wide range of SM particles - many hadronic jets, but also highly boosted photons and leptons $\rightarrow$ hard to replicate through other BSM scenarios.
- Potentially large missing energy from losses in formation.

Phenomenology

Rotating versus Non-rotating black holes

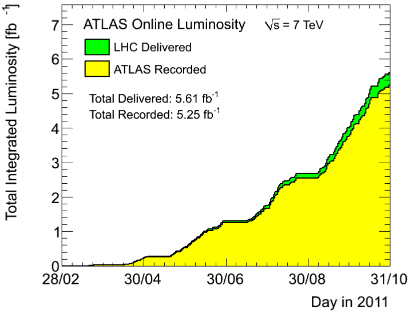




- Very high p_T objects.
- Multiple objects in the final states.
- Harder spectrum, but correspondingly lower multiplicity from rotating black holes

The LHC in 2011

2011 has been a very successful year for the LHC. The LHC Experiments have been taking data very efficiently - we now have recorded over 5 fb^{-1}!
- summer results shown here are based on the first $\sim$ 1 fb^{-1}



Introducing Analysis One

Search for Black Holes in *pp* Collisions at $\sqrt{s} = 7$ TeV with 1 fb^{-1} Data Set

CMS PAS EXO-11-071

also for 2010 data: arXiv:1012.3375 (PLB 429 (2011) 434-453)

Search for Black Holes in *pp* Collisions at $\sqrt{s} = 7$ TeV with 1 fb^{-1} Data Set

CMS PAS EXO-11-071

- Search for deviation from Standard Model expectations in high multiplicity final states.
- For such events, construct the scalar E_T sum of the objects (reconstructed and selected leptons, photons and jets), including only those above 50 GeV (note E_T^{miss} is also included if it exceeds this value), hereinafter S_T.

- Consider a series of signal regions, requiring a minimum event multiplicity, N, greater than X (with X varying from 3 to 8).
- The predominant background is inevitably multi-jet processes, with a small component of direct photon production and prompt lepton processes.

Analysis Details

CMS PAS EXO-11-071

- H_T triggers used to collect a sample of 1.09 fb^{-1} of 2011 collision data, with a threshold of 350-550 GeV depending upon the period.
- Event Selection
  - Jets, reconstructed using the Anti-k_T algorithm, with R=0.5 and $|\eta| < 2.6$
  - Electrons and photons with $E_T > 20$ GeV and $|\eta| < 1.44$ or $1.56 < |\eta| < 2.4$.
  - Muons with $p_T > 20$ GeV and $|\eta| < 2.1$.
- This trigger selection is fully efficient above the minimum offline H_T requirement used, of 700 GeV.
- A set of rotating and non-rotating black hole benchmark samples generated by BlackMax used to give limits for two specific models.

S_T Invariance

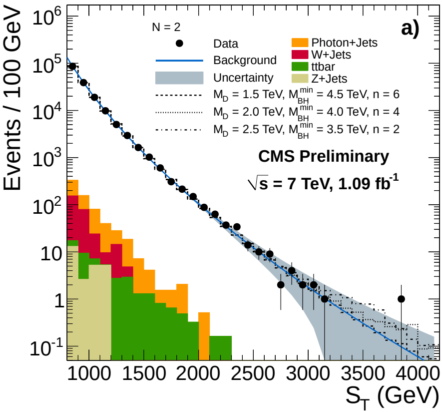
CMS PAS EXO-11-071

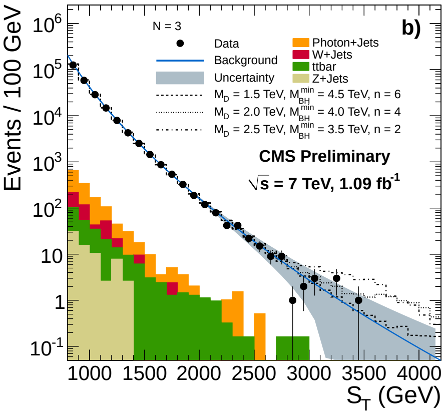
- Dominant multijet background estimated using the S_T multiplicity invariance method.
- This relies on the independence of the shape of S_T with respect to the number of final state objects, N.
- Tested extensively empirically.
- The dijet (N=2) and N=3 S_T distributions are fitted with a function at low S_T (800-2500): $\frac{p_0(1+x)^{p_1}}{x^{p_2+p_3 \ln x}}$
- Other choices of fit functions give a systematic uncertainty, as does the difference between the N=2 and N=3 fits.
- Can then apply this fit function and its uncertainties to the distributions for $N \geq 2$, $N \geq 3$, etc.
- Systematic uncertainty varies from 7% to 165%.

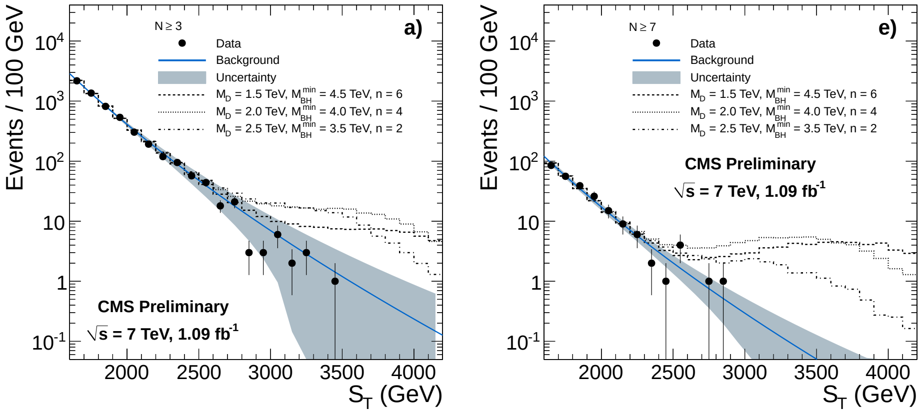
Validating S_T Invariance

Exclusively 2-object (left) and 3-object final states (right)

CMS PAS EXO-11-071



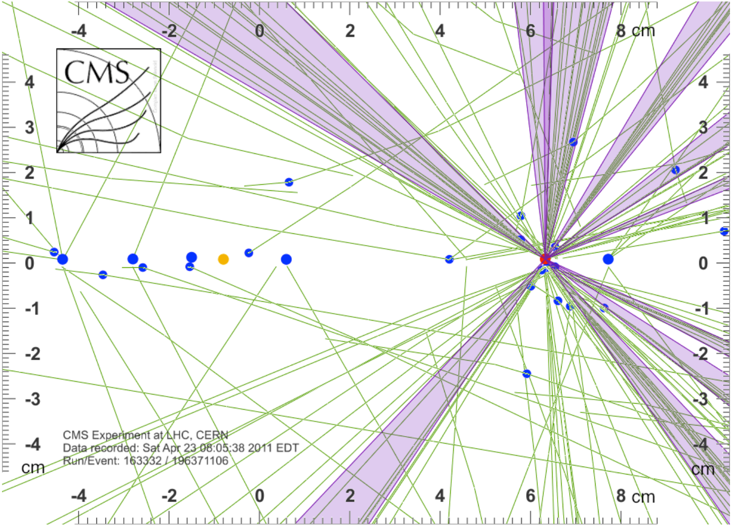




- No evidence of a signal - proceed to set limits on the cross-section times acceptance for new physics production of these final states.

A sample candidate event

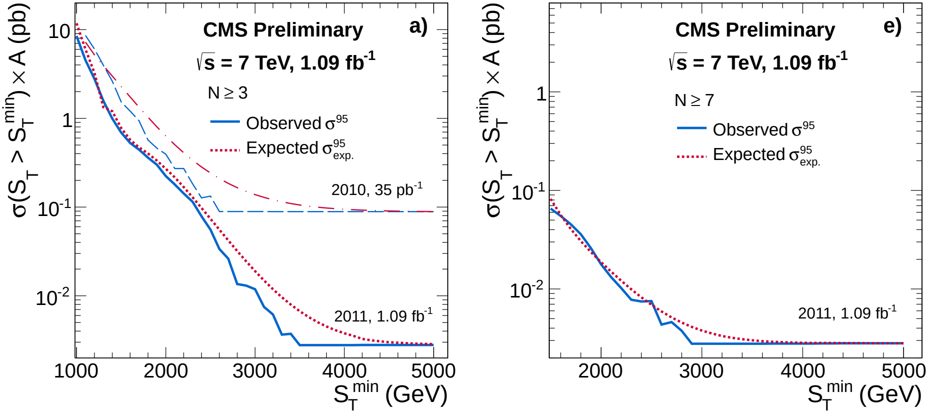
CMS PAS EXO-11-071



- Ten-object (jets) candidate event, with $S_T = 1.1$ TeV.

95% C.L. cross-section limits on multi-object final states

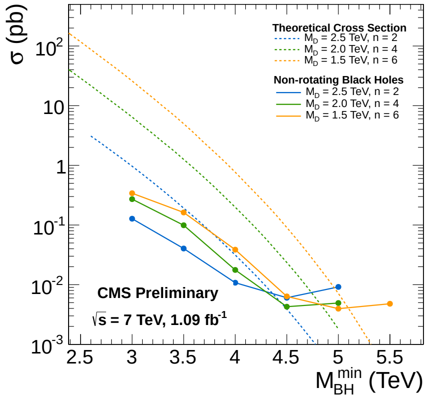
CMS PAS EXO-11-071

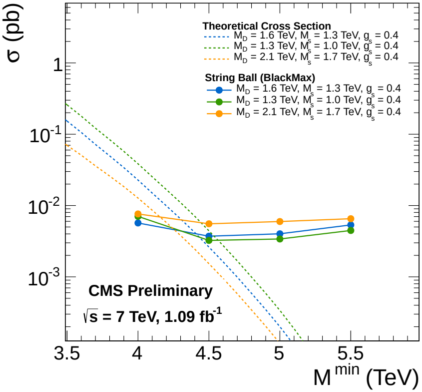


Moving towards 95% C.L. limits on the models directly...

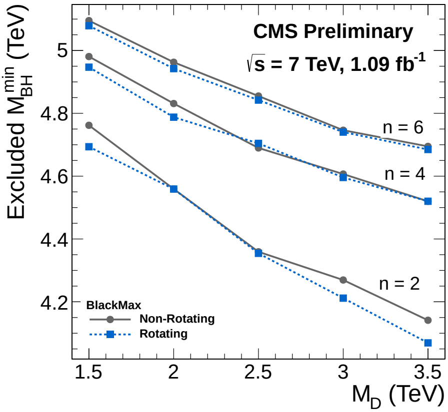
CMS PAS EXO-11-071

- For each signal sample, optimise the signal region definition (minimum S_T and N) using $\frac{S}{\sqrt{(S+B)}}$.





- Search for high multiplicity final states
- No deviations from SM expectations observed.
- Derive model-independent limits on the production of high multiplicity final states, as a function of N and S_T^{min}.
- Also a model-specific exclusion in the 2-D model parameter space.



Leptonic Searches

Why look for TeV-scale gravity with leptons?

- Expect a wide range of particle types to be produced, determined primarily by the SM degrees of freedom and gravitational transmission factors.
- Expect leptons in signal, with a reasonable (15-50%) chance per event.
- Powerful channel (SM bkgs dramatically reduced), at the cost of little inclusivity (few leptons in e.g. split brane scenarios).
- Most robust signatures suggest (relatively) high multiplicity and presence of leptons.

Introducing Analysis Two

Searches for TeV-gravity signatures in final states with leptons and jets
http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-147/

Searches for TeV-gravity signatures in final states with leptons and jets

http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-147/

- Search for deviations from the Standard Model in final states with multiple, high-p_T objects including at least one lepton.
- Construct the scalar p_T sum of objects (jets and leptons) in the event, requiring 3 high p_T objects - the signal is manifest as an excess at high values.
- Perform a counting experiment in several high Σp_T signal regions.
- In the absence of a signal set CLs 95% C.L. limits on the effective cross section for high-$\sum p_{\mathrm{T}}$ multi-object final states containing a high-p_T ($>$ 100 GeV) isolated lepton inside acceptance.
- For black hole and string ball benchmark samples, set exclusion contours from the combination of the channels in a plane of M_D and M_{TH}.

Datasets

ATLAS-CONF-2011-147

- Data: integrated luminosity 1.04 fb^{-1} for e/γ and muon streams.
- Event Selection
  - Single lepton triggers.
  - Select reconstructed physics objects
    - High quality electrons and muons with $p_T > 40$ GeV, and $|\eta| < 2.47$ (electrons), $|\eta| < 2.0$ (muons).
    - Jets reconstructed using the Anti-k_T algorithm, with an R parameter $R = 0.4$, and $p_T > 40$ GeV and $|\eta| < 2.8$.
- Signal MC:
  - Use both Charybdis and BlackMax generators.
  - Two samples used to guide the analysis and illustrate signal event properties.
  - Benchmark samples produced for both string balls and black holes.
  - Different models for some important theoretical modelling uncertainties.

Preselection, Signal and Control regions

ATLAS-CONF-2011-147

- Main discriminating observable:
  - $\sum p_{\mathrm{T}}$ - Scalar p_T sum of all selected leptons and jets ($p_T > 40$ GeV).
- Preselection requirements are used to select an event sample with similar kinematics and composition to the signal regions for this search. Events are required to have:
  - At least 3 objects (e,μ,jet) above a 40 GeV p_T threshold.
  - $\sum p_{\mathrm{T}} > 300$ GeV.
  - Electron channel events require the leading electron to be tight.
  - Most control regions, used to estimate and determine the backgrounds, consider subsets of these events.
- Signal Regions raise the object and $\sum p_{\mathrm{T}}$ requirements further:
  - At least 3 objects (e,μ,jet) above a 100 GeV p_T threshold.
  - Several signal regions defined with $\sum p_{\mathrm{T}}$ thresholds ranging from 700 – 1500 GeV.

Background Estimation

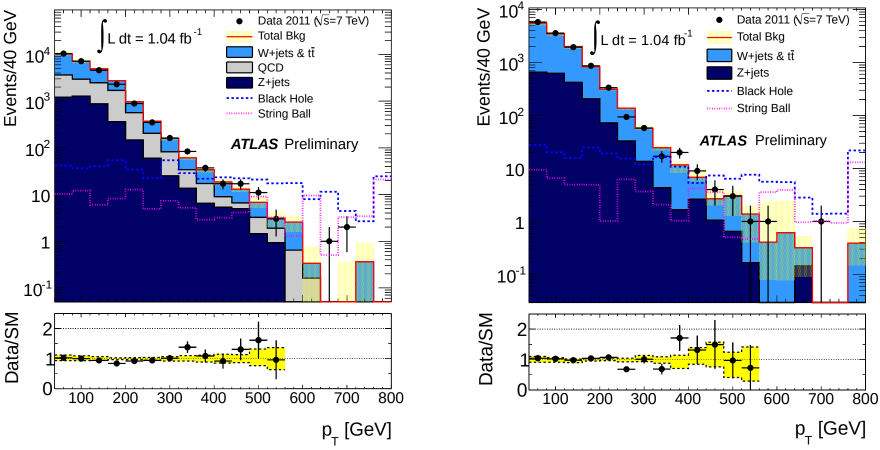
ATLAS-CONF-2011-147

- The dominant Standard Model sources of background are: W+jets, Z/γ^*+jets, $t\bar{t}$ and QCD multijet processes (e only).
  - QCD - electron channel: Estimated by a data-driven matrix method, considering the signal region with the tight electron requirement, and by relaxing it to medium.
  - QCD - muon channel: Predicted to be negligible by MC simulations and ABCD method in data.
  - Z+jets - estimated using a partially data-driven method.
    - Monte Carlo predictions are normalised to the data in a control region and extrapolated to the signal region using Monte Carlo simulations.
    - Events with 2 opposite-sign electrons (muons) with $80 < m_{ll} < 100$ GeV, and $300 < \sum p_{\mathrm{T}} < 700$ GeV.
  - W-jets and $t\bar{t}$ processes - combined estimate, due to their similar behaviour in $\sum p_{\mathrm{T}}$.
    - Normalised according to data in a control region with one e (μ), $40 < m_T < 100$ GeV, $30 < E_T^{miss} < 60$ GeV and $300 < \sum p_{\mathrm{T}} < 700$ GeV.

Preselection Distributions - leading lepton p_T

Electron Channel - left, Muon Channel - right

ATLAS-CONF-2011-147



Yellow band indicates uncertainties from finite statistics, jet and lepton energy scales and resolutions.

Results

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- Event yields following the data-driven background estimates described.

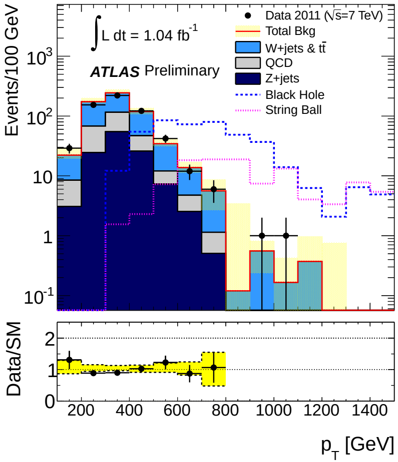
$\sum p_T$ (GeV)	QCD	W+jets/$t\bar{t}$	Z+jets	Total SM	Data
> 700	$137 \pm 10 \pm 45$	$371 \pm 10 \pm 77$	$119 \pm 4 \pm 22$	$627 \pm 15 \pm 92$	586
> 800	$75 \pm 7 \pm 25$	$210 \pm 6 \pm 42$	$74 \pm 4 \pm 13$	$358 \pm 10 \pm 51$	348
> 900	$42 \pm 5 \pm 14$	$122 \pm 5 \pm 28$	$46.9 \pm 2.8 \pm 8.6$	$210 \pm 8 \pm 33$	196
> 1000	$24.6 \pm 4.2 \pm 8.0$	$73 \pm 3 \pm 17$	$22.2 \pm 1.8 \pm 4.5$	$119 \pm 5 \pm 20$	113
> 1200	$8.1 \pm 2.5 \pm 2.7$	$28.5 \pm 1.8 \pm 7.6$	$9.1 \pm 1.0 \pm 1.9$	$45.7 \pm 3.2 \pm 8.3$	41
> 1500	$1.3 \pm 1.1 \pm 0.4$	$6.3 \pm 0.8 \pm 2.5$	$2.6 \pm 0.5 \pm 0.5$	$10.2 \pm 1.4 \pm 2.6$	8

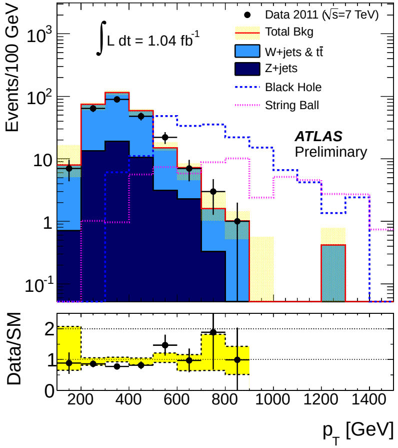
$\sum p_T$ (GeV)	W+jets/$t\bar{t}$	Z+jets	Total SM	Data
> 700	$236 \pm 7 \pm 43$	$49 \pm 3 \pm 11$	$285 \pm 8 \pm 44$	241
> 800	$129 \pm 4 \pm 25$	$32.0 \pm 2.4 \pm 7.5$	$161 \pm 5 \pm 26$	145
> 900	$71 \pm 3 \pm 16$	$19.5 \pm 1.7 \pm 5.0$	$91 \pm 3 \pm 16$	78
> 1000	$38.9 \pm 2.3 \pm 8.3$	$13.1 \pm 1.3 \pm 3.1$	$52.0 \pm 2.6 \pm 8.9$	46
> 1200	$9.9 \pm 1.2 \pm 3.6$	$4.0 \pm 0.6 \pm 1.2$	$14.0 \pm 1.3 \pm 3.8$	15
> 1500	$2.2 \pm 0.5 \pm 1.1$	$0.6 \pm 0.2 \pm 0.4$	$2.8 \pm 0.5 \pm 1.1$	2

- No evidence of a signal - p-values for all signal regions lie between 0.43–0.47.

Final Distributions I - leading object p_T

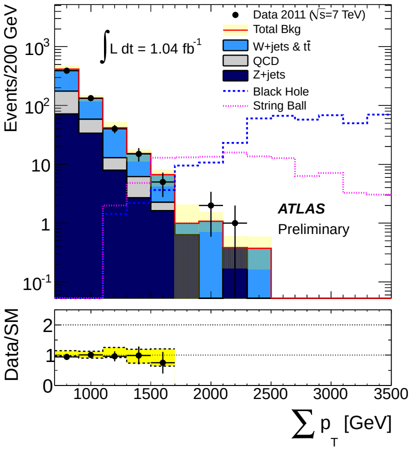
Electron Channel - left, Muon Channel - right

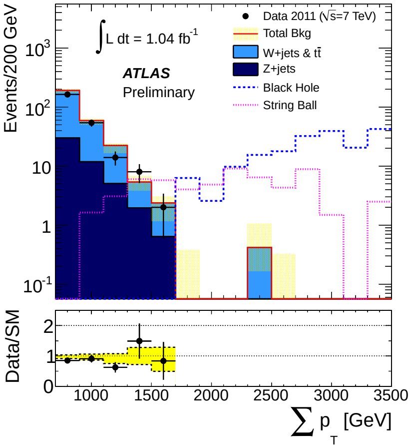




Final Distributions II - Σp_T

Electron Channel - left, Muon Channel - right





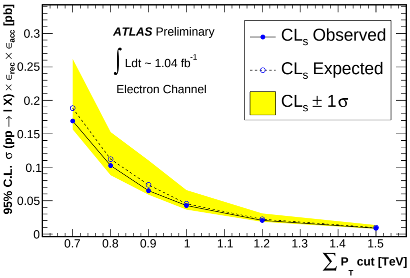
Interpretation I

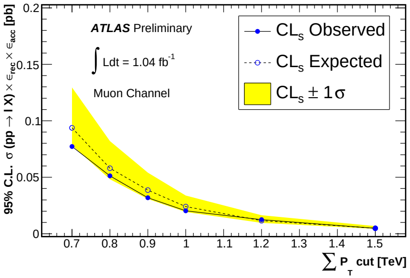
Model-independent limits Electron Channel - left, Muon Channel - right

Effective cross section limits set:
$\sigma_{\text{eff}} = \sigma\left(pp \rightarrow \ell X\right) \cdot \epsilon_{\text{rec}} \cdot \epsilon_{\text{acc}}$.

For the electron (muon) channel $\epsilon_{\text{rec}} \cdot \epsilon_{\text{acc}}$ is $(74)\,\%$ ($(51)\,\%$).

$\sum p_T$ (GeV)	σ_{eff} 95% C.L. Upper Limit (fb) Observed (Expected) Muon Channel	Electron Channel
> 700	77 (94)	169 (188)
> 800	51 (58)	102 (112)
> 900	32 (39)	65 (73)
> 1000	20 (24)	43 (45)
> 1200	13 (12)	20 (22)
> 1500	4.8 (4.8)	8.7 (9.7)

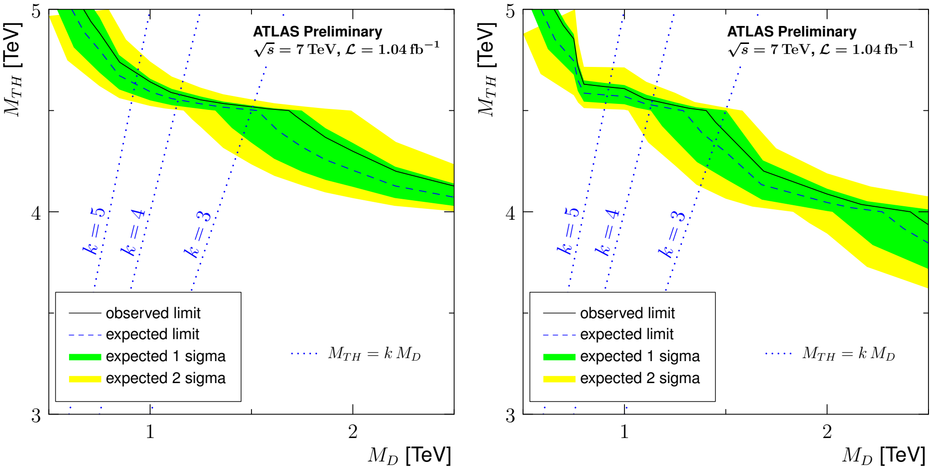




Interpretation II

Benchmark model limits - Rotating Black Holes

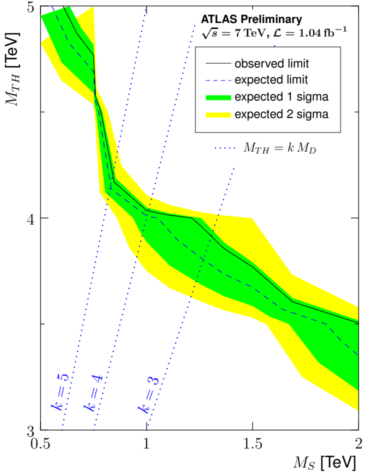
Models using a high (left) and low (right) multiplicity remnant model

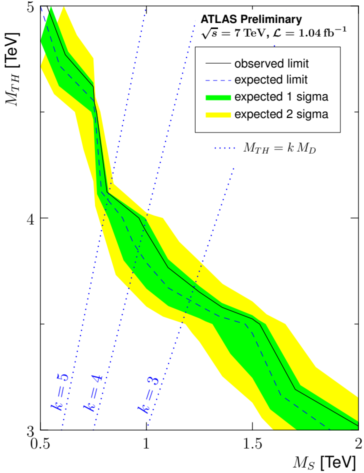


Interpretation II

Benchmark model limits - Stringballs

Non-rotating (left) and Rotating (right) models.





Summary

ATLAS-CONF-2011-147

- A search for TeV-scale gravity signatures (black holes and string balls) in final states with at least 3 high p_T objects, including one lepton, using a luminosity of 1 fb^{-1}.
- No deviation from Standard Model predictions is observed.
- Limits are set on models of TeV-scale gravity:
  - As exclusion contours for benchmark models as functions of the fundamental gravity scale and mass threshold.
  - On the effective cross section for new physics in these final states.

Introducing Analysis Three

Search for Strong Gravity Signatures in Same-sign Dimuon Final States using the ATLAS detector at the LHC

http://arxiv.org/abs/1111.0080

Search for black holes with same-sign dimuons

arXiv:1111.0080

- Look for final states that are prevalent in black hole events with low rates from Standard Model processes.
- One candidate is same-sign dilepton events - here look in the muon channel for dimuon candidates.
- Require two muons with leading $p_T > 25$ GeV, subleading $p_T > 15$ GeV and $|\eta| < 2.4$
- Require the muon leading in p_T to be isolated.
- Maintain signal efficiency by dropping this requirement on the sub-leading muon.
- Require the event to have at least 10 tracks.

Same-sign dimuon search: Strategy

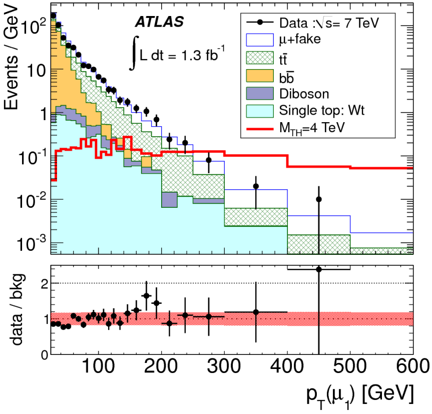
arXiv:1111.0080

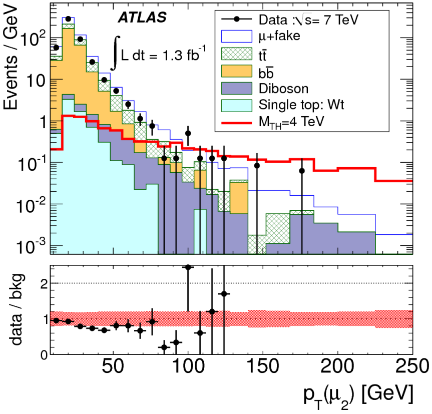
- Black hole events should have a relatively high multiplicity of high energy particles, and consequently many tracks in the events.
- Use the event track multiplicity to discriminate between signal-rich and background-rich regions.
- Perform a counting experiment in a pre-defined signal region.
- Use 1.3 fb^{-1} of 2011 collision data.

Muon Distributions

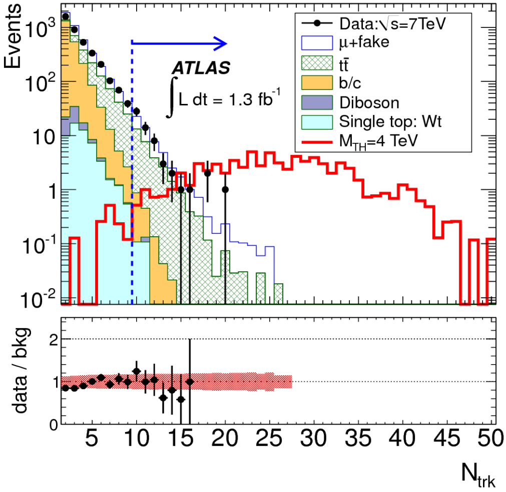
Distributions for same-sign dimuon events before N_{track} cut

- Same-sign dimuons from uncorrelated decays - W+jets, Z+jets, low p_T QCD.
- Same-sign dimuons from correlated decays - $t\bar{t}$, $b\bar{b}$
- In signal region, $t\bar{t}$ dominates, followed by μ+fake.





- Use track multiplicity ($p_T > 10$ GeV, $|\eta| < 2.4$) to separate signal and background processes.
- Define signal region as $N_{\mathrm{track}} >= 10$.
- Use lower multiplicity region to estimate and constrain backgrounds.



Background Estimation

arXiv:1111.0080

- $t\bar{t}$ derived from Monte-Carlo
- μ+fake - fake rate determined per track from W events in data, then applied to muon+track events to get dimuon estimate.
- $b\bar{b}$ - estimated from data in background region and extrapolated into signal regime using $\mathrm{N_{tracks}}$.

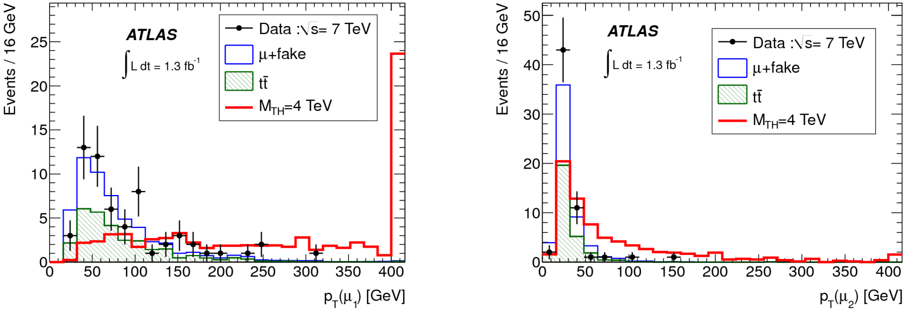
Process	Events
b/c	0.77 ± 0.77(syst)
$t\bar{t}$	29.2 ± 4.1(syst) $\pm$ 1.1(lumi)
μ+fake	25.6 ± 0.3(stat) $\pm$ 5.2(syst)
Other backgrounds	0.25 ± 0.11(syst)
Predicted	55.8 ± 0.3(stat) $\pm$ 6.7(syst) $\pm$ 1.1(lumi)
Observed	60
Signal $M_{TH} = 4$ TeV	72.1 ± 4.5(syst)

- No sign of a signal $\rightarrow$ set limits on black hole models.

Signal region Muon p_T distributions

arXiv:1111.0080

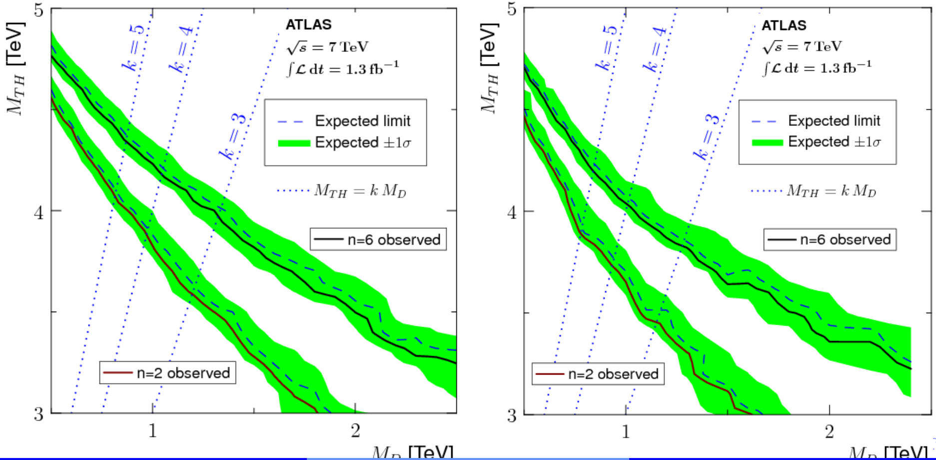
- Inevitably, limited data/background statistics in signal region
- Data agreement with the background estimate is good.



Model-dependent Limits

arXiv:1111.0080

- 95% C.L. exclusions for non-rotating (left) and rotating (right) black hole models with 2 and 6 extra dimensions, using the CL_s prescription.



Conclusions

arXiv:1111.0080

- Search undertaken for black holes in a dimuon final state
- Using track multiplicity to separate signal and background processes.
- No excess over Standard Model expectations observed in 1.3 fb^{-1} of 2011 collision data.
- Exclusion limits placed in a plane of M_D and M_{TH} for black holes.

Summary

- The LHC has performed superbly during 2011.
- Searches in both ATLAS and CMS for black hole signatures have found no excesses beyond the Standard Model so far in the first 1 fb^{-1} of this data.

- Many different search strategies and approaches to looking for black holes.
- Increasingly stringent limits are being placed upon the possible cross-section for these states.
- Exclusion bounds extend into the $M_{TH} = 3 - 5$ TeV range, depending upon the model parameters.
- However, these often assume the black disc cross-section and high multiplicity.
- Searches are beginning to have the power to cover these modelling/theoretical uncertainties more concretely.

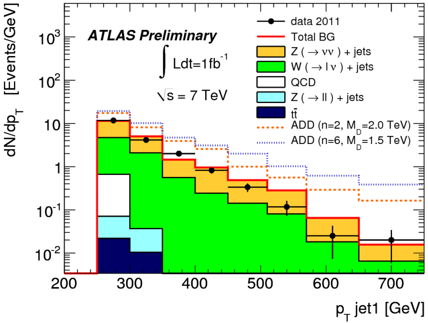
BACKUP SLIDES

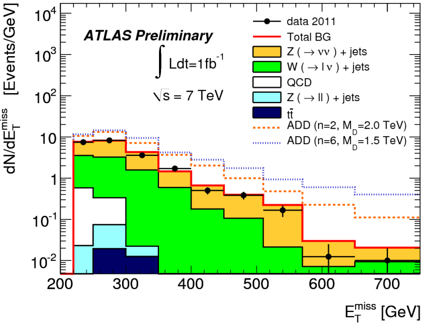
Jet Searches

Monojet plus Missing Energy Final States (1)

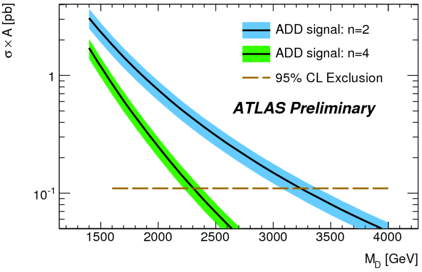
[ATLAS-CONF-2011-096]

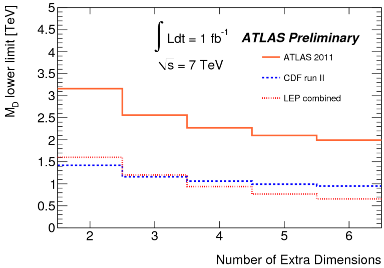
- Search for events with large E_T^{miss} and exactly 1 high p_T jet
- Veto events with a reconstructed lepton (e or μ)
- Search dominated by $Z/W+$jets Standard Model Backgrounds
- 'high p_T' search region shown below:
  - Jet $p_T > 250$ GeV, $|\eta| < 2.0$, $E_T^{miss} > 220$ GeV.
  - No second (third) jet above $p_T > 60$ (30) GeV, $\Delta\phi(jet, E_T^{miss}) < 0.5$.





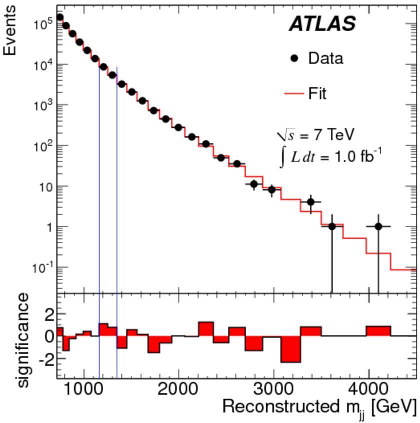
- No excess observed
- Look to exclude ADD models and set limits on the (4+n) dimensional Planck scale, M_D:
  - n=2, $M_D > 3.16$ TeV.
  - n=4, $M_D > 2.27$ TeV
  - n=6, $M_D > 1.99$ TeV





Jet Searches

Dijet Resonances (1) [arXiv:1108.6311]



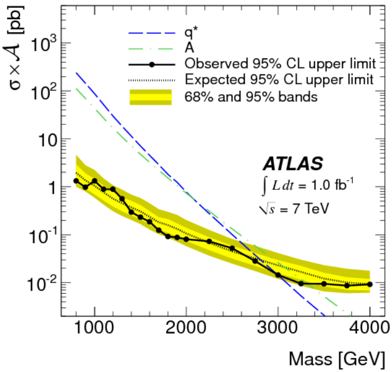
- Anti-K$_\perp$ $R = 0.6$ jets.

- Select events with two high p_T jets with $|y^*| < 0.6$.
- Require highest jet $p_T > 180$ GeV $\rightarrow m_{jj} > 717$ GeV.
- Compare data dijet mass distribution with a binned QCD background distribution, described by a smooth functional form.
- Search for resonances in the spectrum.
- Most significant discrepancy in blue - p-value of 0.62

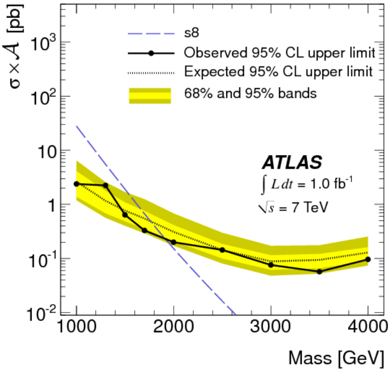
Jet Searches

Dijet Resonances (2) [arXiv:1108.6311]

Limits for Excited Quarks and Axigluons



Limits for Colour Octet Scalar Resonances



Model	Observed Limit	Expected Limit
Excited quarks (q*)	M > 2.99 TeV	M > 2.81 TeV
Axigluons	M > 3.32 TeV	M > 3.07 TeV
Color Octet Scalar	M > 1.92 TeV	M > 1.77 TeV

2010 results on quantum black holes