Searches for Black Holes in ATLAS

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Institute of Physics Half-day Meeting

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Outline

- Extra Dimensions
- Black Hole Formation and Decay
- The ATLAS Experiment at the LHC
- Searches for Black Holes
- Summary

The Hierarchy Problem

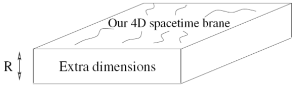
- Why is the fundamental scale for gravity:
  $M_{Pl} \sim 10^{16}$TeV,
  so large compared to the electroweak energy scale:
  $M_{EW} \sim 1$TeV
- Why is gravity so weak?

See e.g.
N.Arkani-Hamed et al. hep-ph/9803315,
L. Randall & R. Sundrum hep-ph/9905221

The Extra Dimensions Solution

Solve with Extra Dimensions

- Assume spacetime is *(4+n)* dimensional.



$$F_{r \ll R} \sim \frac{1}{\mathbf{M^{2+n}_{(4+n)}}\, r^{2+n}}, \qquad F_{r \gg R} \sim \frac{1}{\mathbf{M^{2+n}_{(4+n)} R^n}\, r^2} + KK \ldots$$

Take $M_{EW} \sim 1$,TeV - M_{4+n} as fundamental scale → 4D gravity diluted

Two main classes of models:

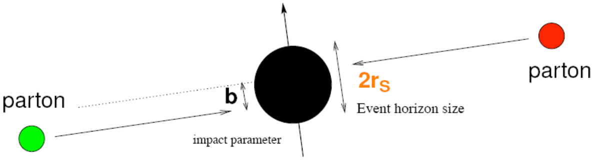
- Large extra dimensions (ADD)
- (Usually a) Single warped extra dimension (RS).

N.B. Deviations at short distances, KK modes.

→ constraints

Black Hole Formation

The black disk approach



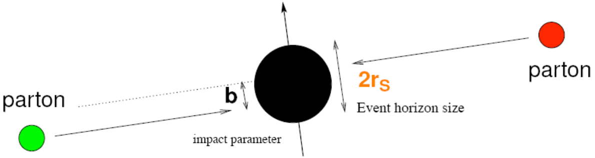
- **Thorne's hoop conjecture** (*Magic without Magic 231 (1972)*): For a given concentration of matter/energy, if it fits inside a hoop with the Schwarzchild radius r_S for that mass, then a black hole forms.
- **Black disk cross section:**

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

S. B. Giddings and S. D. Thomas, hep-ph/0106219

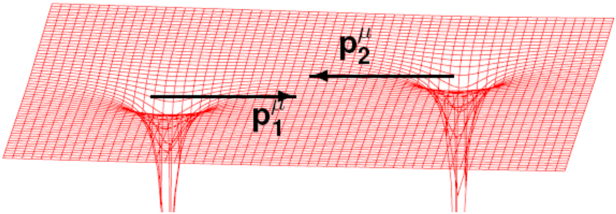
S. Dimopoulos and G. Landsberg, hep-ph/0106295

Production - Short-comings



- Why not $b > 2r_S$?
- Angular momentum?
- Losses in gravitational radiation?
- Spin and charge of the partons.

Production Model I

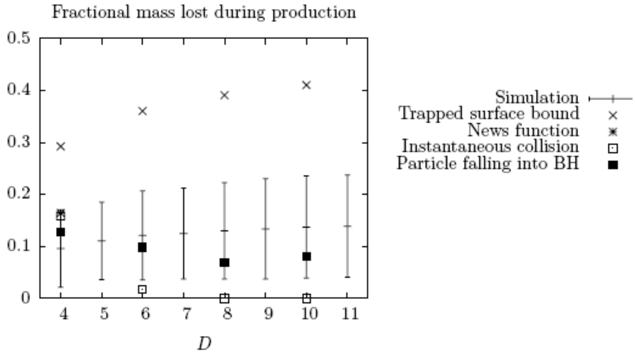


- Ideally, set up the spatial metric for two highly boosted particles (modelled as black holes).
- Include spin and charge.
- Evolve system.
- Obtain final metric and radiation.

Production Model II

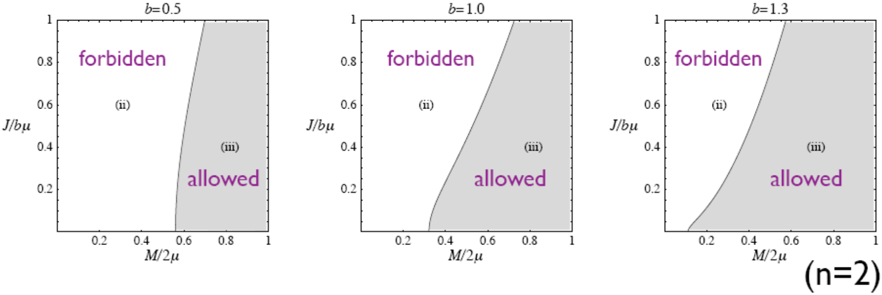
Trapped Surface Results

- Trapped surface methods give bounds on the maximum impact parameter and hence parton-level cross section.
- Bounds on the mass (M) and angular momentum (J) trapped for a given impact parameter, b.
- Mass bounds compared with approximate methods for b=0



Production Losses

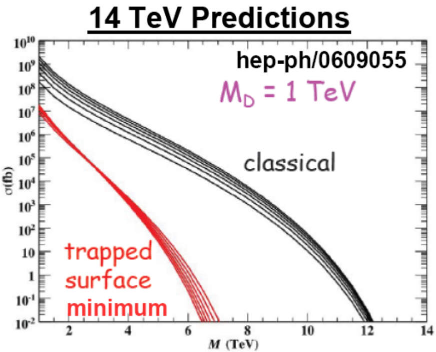
H. Yoshino, V. S. Rychkov hep-th/0503171



- For each value of impact parameter b, a maximum bound can be placed on the fraction of the black hole mass and angular momentum lost in radiation.

Inelasticity

- Black hole cross-sections can be large.
- **But** assuming the maximum allowed losses reduces the differential cross section dramatically.
- Large uncertainties.



- **When is the semi-classical approach valid-how far above M_{Pl}?**
- Can argue the Compton wavelength of colliding particle of energy E/2 must lie within the Schwarzschild radius → bounds on E/M_{Pl}, particularly in the RS case.
- Expect interactions, with lower entropy and multiplicity below this - with similar cross sections. Randall, Meade arXiv:0708.3017

Open Issues

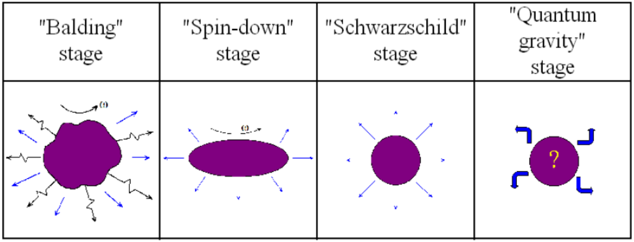
Formation

- Numerical relativity simulations in (3+1) and higher dimensions, Shibata and Yoshino arXiv:0907.2760, Sperhake et al. arXiv:0907.1252,1006.3081
- Effects of brane tension, thickness and extra dimensional geometry not completely modelled.
- Quantum gravity effects (see Xavier's talk) - input partons have charges.
- What is the threshold for equilibrium black hole production? Randall, Meade arXiv:0708.3017

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

Question: Is this still true for very light black holes?



The central result of Hawking's calculation is:

- Classically, black hole do not emit, only accrete.
- However, in 1974, Hawking found a quantum instability.
- Effectively, the large gravitational field leads to spontaneous emission of particle via pair creation at the event horizon (cf. e^+e^- pairs in a strong electric field).
  $\rightarrow$ Black hole evaporates and slowly loses mass
- Gravity couples universally, so all SM particles can be emitted.
- The spectrum is that of a grey-body, with a characteristic temperature T_H (non-rotating case):

$$T_H = \frac{n+1}{4\pi r_S}$$

Hawking Radiation

Non-rotating case

$$\frac{\mathbf{dN}_h}{\mathbf{dtd}\omega\mathbf{d}\Omega} = \frac{1}{2\pi}\sum_{j=|h|}^{\infty}\sum_{m=-j}^{j}\frac{\mathbb{T}_k^{(n)}(\omega)}{\exp(\omega/\mathbf{T_H}) \pm \mathbf{1}}\left|{}_hY_j^m(\Omega)\right|^2$$

- Has a thermal, black-body character, with Planckian factor and temperature T_H...
- ... modified by a transmission coefficient (grey-body factor), codifying the probability of escaping the gravitational field.
- Spin-dependent - through helicity label h.
- Isotropic angular distribution.

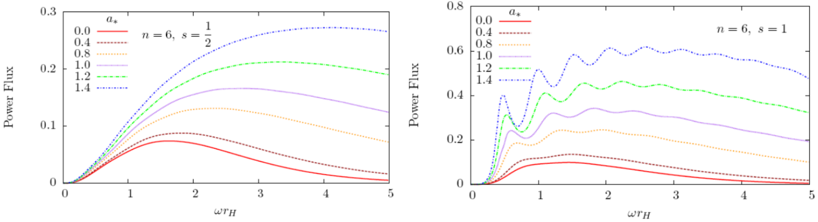
- Universal thermal spectrum for particles emitted (modulo spin).

Particle type	spin-0	spin-1/2	spin-1
Quarks	0	72	0
Gluons	0	0	16
Charged Leptons	0	12	0
Neutrinos	0	6	0
Photon	0	0	2
Z^0	1	0	2
W^+ and W^-	2	0	4
Higgs boson	1	0	0
Total	4	90	24

- Integrating the spectrum gives a high multiplicity.
- Implications for colliders - expect signature to have multiple hadronic jets.

Rotation Effects I

- Once the grey-body factors are known, the power fluxes and angular distributions can be determined.

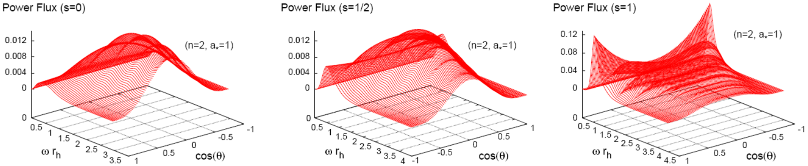


Power spectrum of fields for brane emission with n=6 and a range of BH oblateness.

- Rotation increases the mean energy and total flux dramatically.
- Harder spectrum.

Rotation Effects II

- Rotation breaks the isotropic emission spectrum.
- Higher energy emissions are more equatorial in character.
- Low energy vector emissions are more axial with each polarisation contriubting differently to the angular distribution.
- Azimuthal symmetry remains.

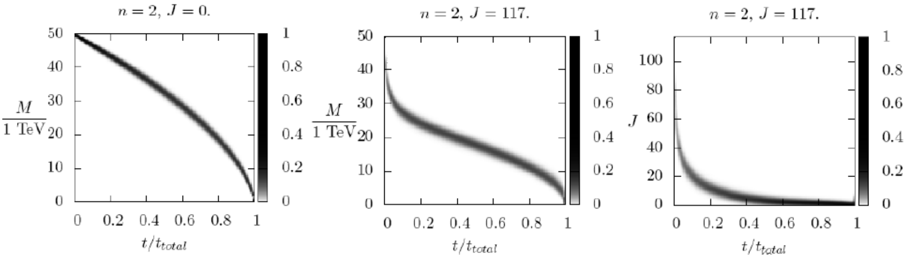


Angular power fluxes for scalars, fermions and vectors.
hep-th/0507274,hep-th/0511163,hep-th/0608193
hep-th/0212108,hep-th/0503052,hep-th/0602188

Black Hole Evolution

Semi-classical limit: BH mass 50 TeV

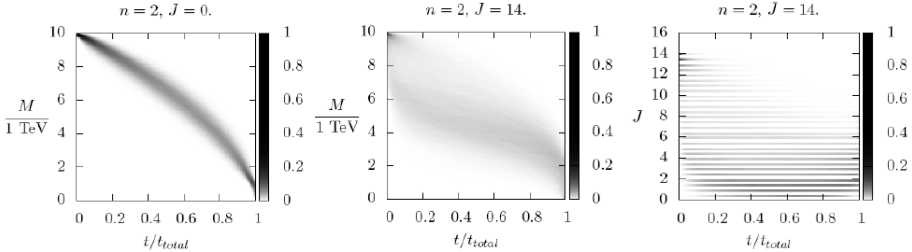
JF et al. arXiv:0904.0797



Non-rotating | **Highly rotating** | **Angular Momentum**

- Shows expected semi-classical behaviour:
- **Schwarzschild:** steady loss of mass until Planck phase.
- **Rotating:** mass lost more rapidly during spin-down phase.

JF et al. arXiv:0904.0797



Non-rotating **Highly rotating** **Angular Momentum**

- Evaporation is less smooth, due to fewer emissions.
- Statistical fluctuations are larger, and trends less definite.

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 - cross-sections, missing energy.
  - Graviton emission in Hawking phase
  - Remnant modelling - Quantum gravity important - can have a large effect on multiplicity, often targeted by experimental searches.
  - Quantum effects...

Experimental Signature

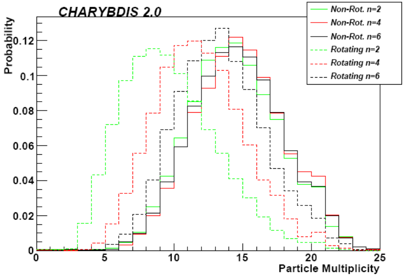
What's different about black holes?

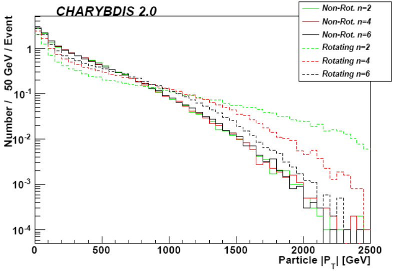
Signatures of semi-classical black holes:

- 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

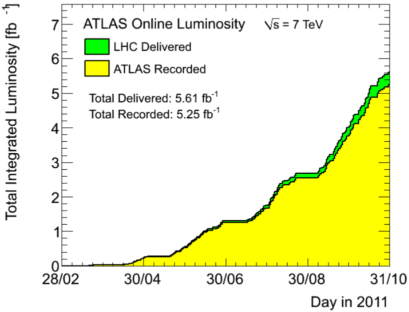


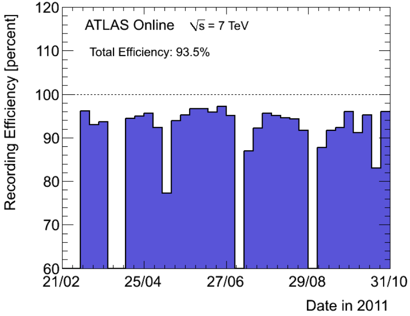


- Very high p_T objects.
- Multiple objects in the final states.
- Harder spectrum, but correspondingly lower multiplicity from rotating black holes

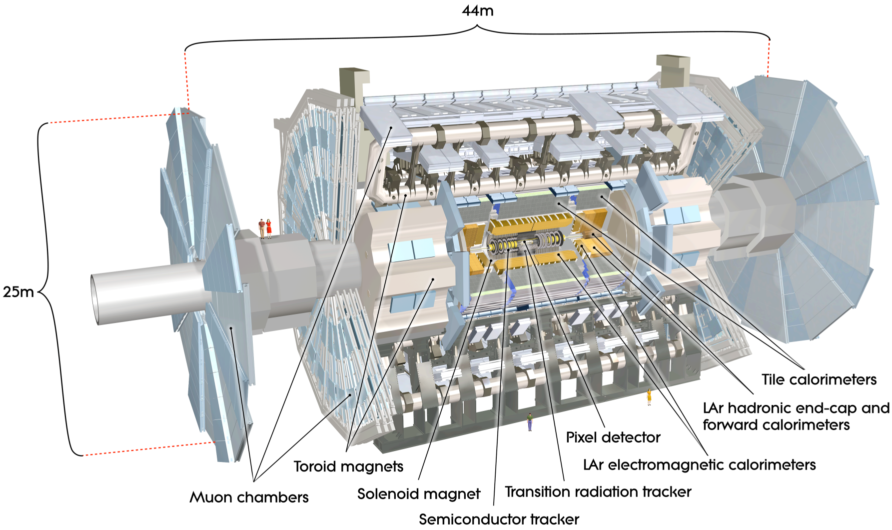
The ATLAS Experiment in 2011

2011 has been a very successful year for the ATLAS and for the LHC generally. The ATLAS Experiment has 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}

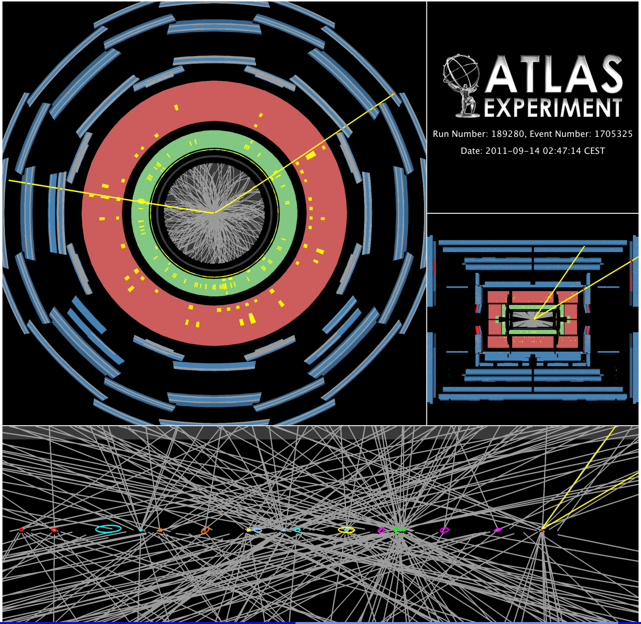




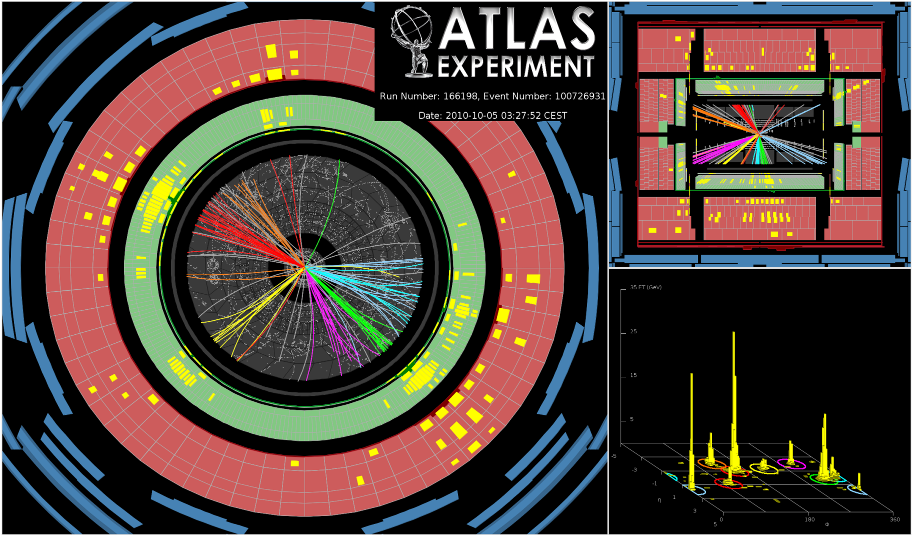
The ATLAS Detector



Collision Events in 2011



Collision Events - many jets, even in 2010



Models

- 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.

Models

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.
- Much more 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 One

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.
- Such deviations are predicted in scenarios of low scale gravity.
- 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 experimental 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

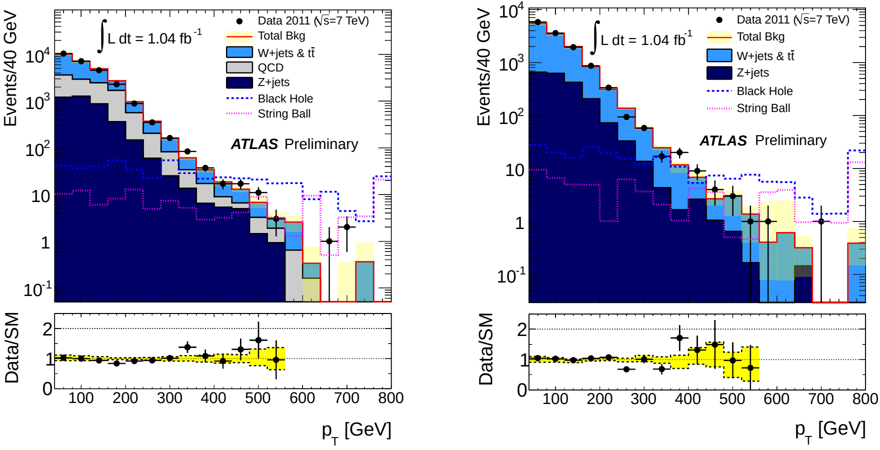
ATLAS-CONF-2011-147

- 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 energdy scales and resolutions.

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

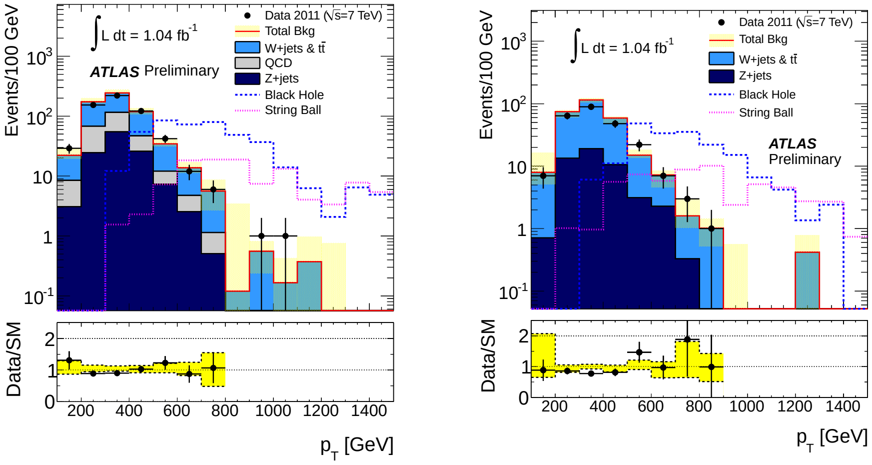
$\sum p_T$ (GeV)	QCD	W+jets/$t\bar{t}$	Z+jets	Total SM	Data
> 700	$137 \pm 10 \pm 45$	$371 \pm 10 \pm 77$	$119 \pm 4 \pm 22$	$627 \pm 15 \pm 92$	586
> 800	$75 \pm 7 \pm 25$	$210 \pm 6 \pm 42$	$74 \pm 4 \pm 13$	$358 \pm 10 \pm 51$	348
> 900	$42 \pm 5 \pm 14$	$122 \pm 5 \pm 28$	$46.9 \pm 2.8 \pm 8.6$	$210 \pm 8 \pm 33$	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.

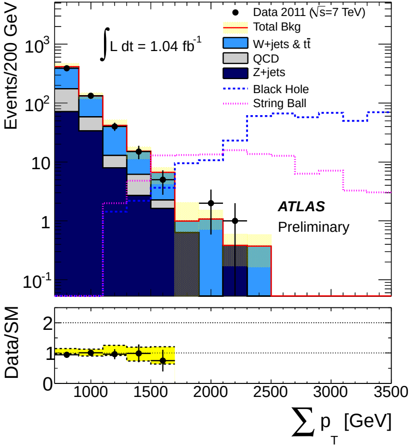
Final Distributions I - leading object p_T

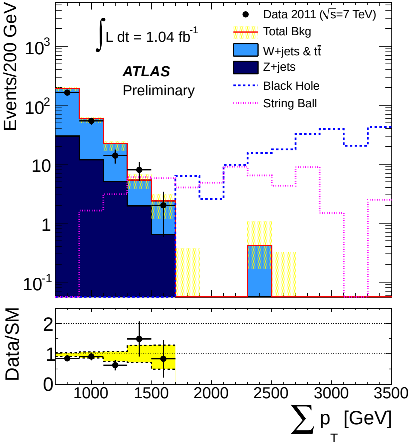
Electron Channel - left, Muon Channel - right



Final Distributions II - Σp_T

Electron Channel - left, Muon Channel - right





Interpretation I

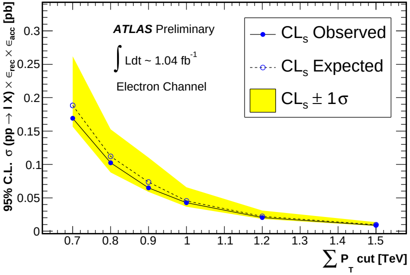
Model-independent limits Electron Channel - left, Muon Channel - right

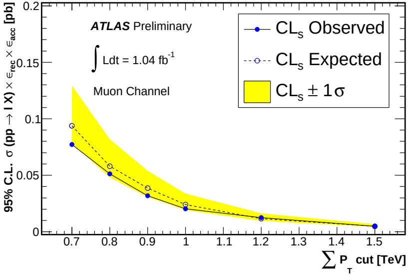
Effective cross section limits set:

$$\sigma_{\text{eff}} = \sigma\left(pp \to \ell X\right) \cdot \epsilon_{\text{rec}} \cdot \epsilon_{\text{acc}}.$$

For the electron (muon) channel $\epsilon_{\text{rec}} \cdot \epsilon_{\text{acc}}$ is $(74 \pm 6)\,\%$ $((51 \pm 5)\,\%)$.

$\sum p_{\mathrm{T}}$ (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)

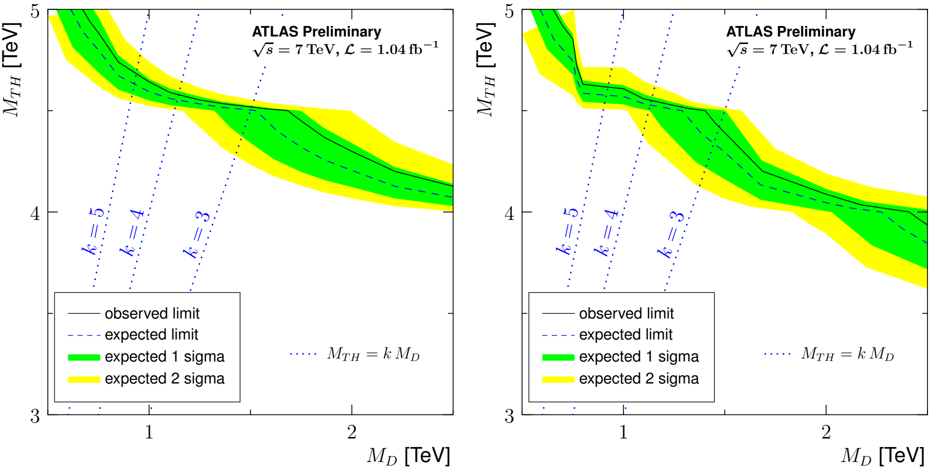




Interpretation II

Benchmark model limits - Rotating Black Holes

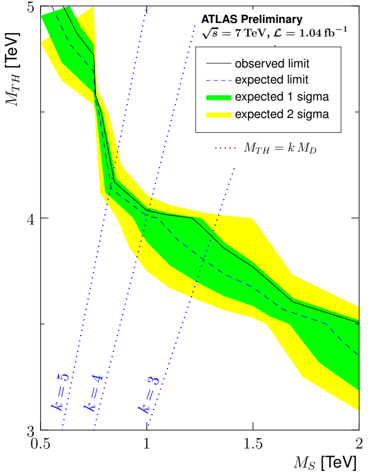
Models using a high (left) and low (right) multiplicity remnant model

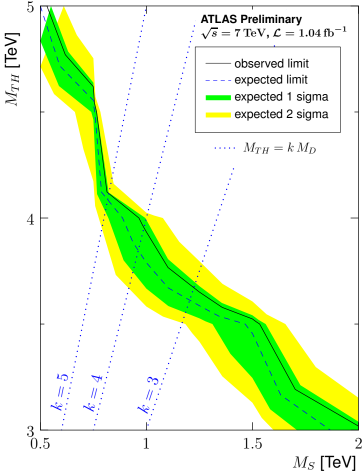


Interpretation II

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 Two

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

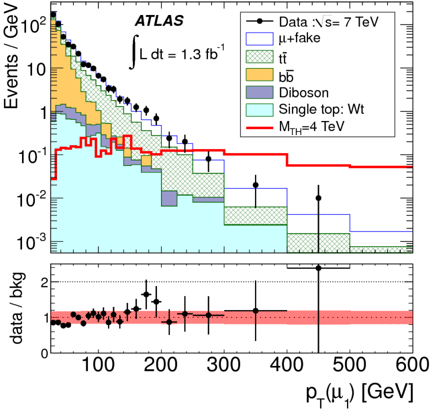
arXiv:1111.0080

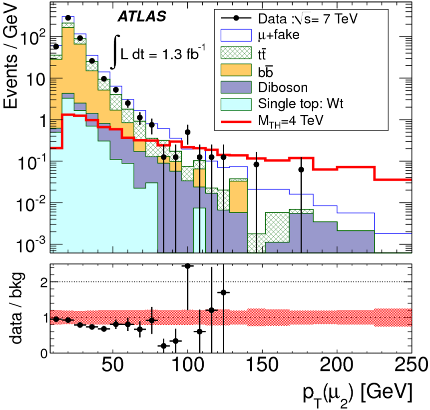
- Black hole events should have a relatively high multiplicity of high energy particles, and consequently many tracks in the events.
- Use the event track multiplicity to discriminate between signal-rich and background-rich regions.
- Perform a counting experiment in a pre-defined signal region.
- Use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

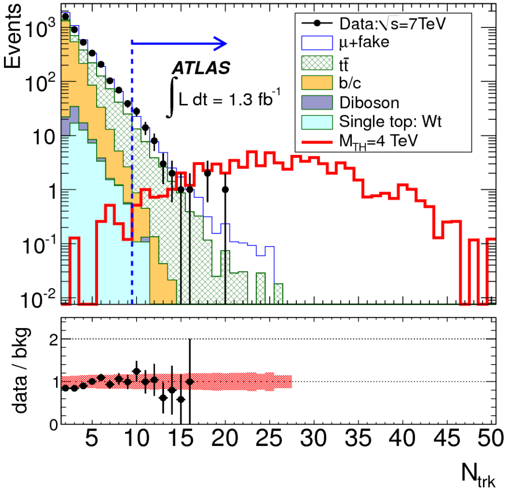




Track Multiplicity

arXiv:1111.0080

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

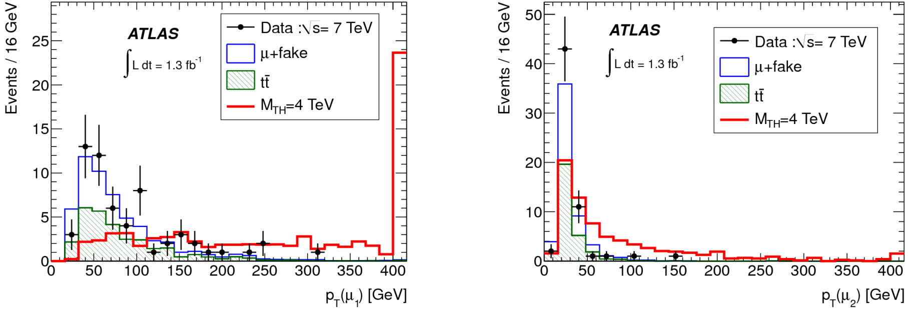
Process	Events
b/c	0.77 ± 0.77(syst)
$t\bar{t}$	29.2 ± 4.1(syst) $\pm$ 1.1(lumi)
μ+fake	25.6$\pm$ 0.3(stat) $\pm$ 5.2(syst)
Other backgrounds	0.25 ± 0.11(syst)
Predicted	55.8 ± 0.3(stat) $\pm$ 6.7(syst) $\pm$ 1.1(lumi)
Observed	60
Signal $M_{TH} = 4$ TeV	72.1 ± 4.5(syst)

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

Signal region Muon p_T distributions

arXiv:1111.0080

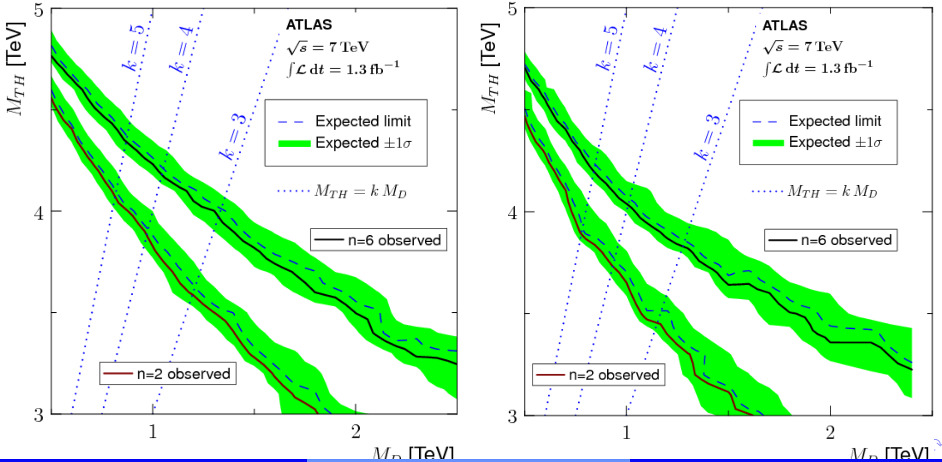
- Inevitably, limited data/background statistics in signal region
- Data agreement with the background estimate is good.



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

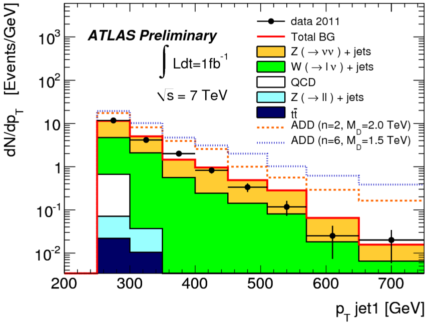
- Search undertaken for black holes in a dimuon final state
- Using track multiplicity to separate signal and background processes.
- No excess over Standard Model expectations observed in 1.3 fb^{-1} of 2011 collision data.
- Exclusion limits placed in a plane of M_D and M_{TH} for black holes.

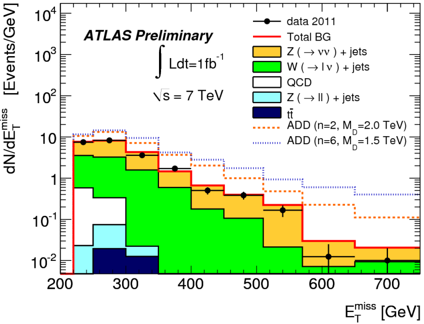
Jet Searches

Monojet plus Missing Energy Final States (1)

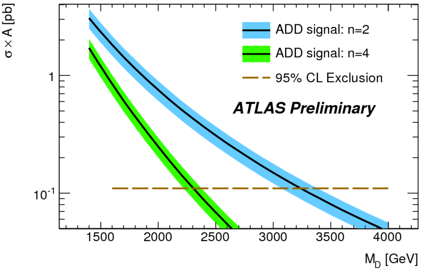
[ATLAS-CONF-2011-096]

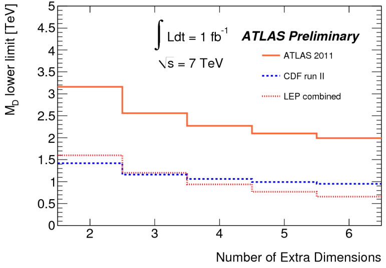
- Search for events with large E_T^{miss} and exactly 1 high p_T jet
- Veto events with a reconstructed lepton (e or μ)
- Search dominated by $Z/W+$jets Standard Model Backgrounds
- ‘high p_T’ search region shown below:
  - Jet $p_T > 250$ GeV, $|\eta| < 2.0$, $E_T^{miss} > 220$ GeV.
  - No second (third)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





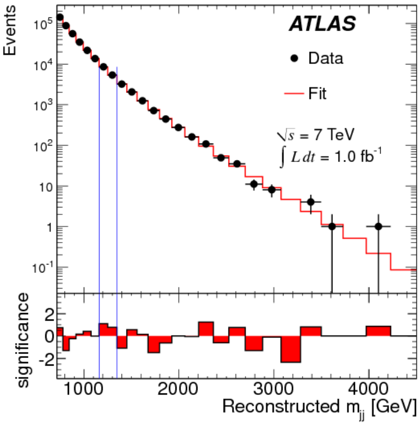
- No excess observed
- Look to exclude ADD models and set limits on the (4+n) dimensional Planck scale, M_D:
  - n=2, $M_D > 3.16$ TeV.
  - n=4, $M_D > 2.27$ TeV
  - n=6, $M_D > 1.99$ TeV





Jet Searches

Dijet Resonances (1) [arXiv:1108.6311]



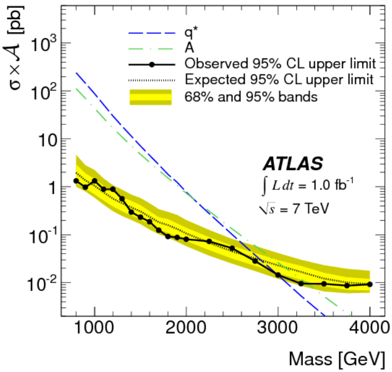
- Anti-$K_\perp$ $R = 0.6$ jets.

- 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

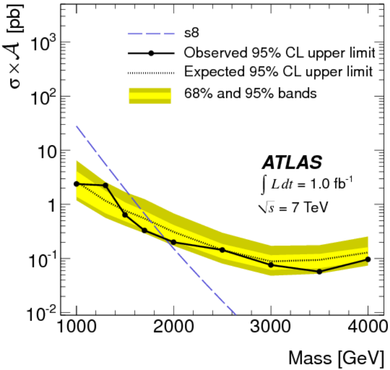
Jet Searches

Dijet Resonances (2) [arXiv:1108.6311]

Limits for Excited Quarks and Axigluons

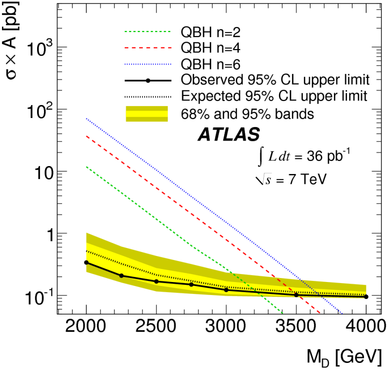


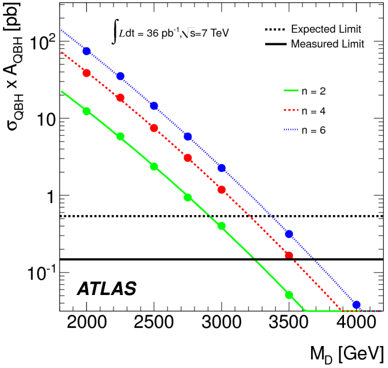
Limits for Colour Octet Scalar Resonances



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





Summary

- The LHC has performed superbly during 2011.
- Efficient ATLAS data-taking has recorded an integrated luminosity exceeding 5 fb^{-1}.
- Searches in ATLAS for black hole signatures have found no excesses beyond the Standard Model so far in the first 1 fb^{-1} of this data, however....
- Increased luminosity rapidly opening up new model phase spaces for searches.
- Many more results to come in the coming days, weeks and beyond!

- 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 $3 - -5$ TeV range.
- However, these often assume the black disc cross-section and high multiplicity.

BACKUP SLIDES