Quantum Black Hole Model Limit Setting with the ATLAS detector at $\sqrt{s} = 8$ TeV

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Quantum Black Holes

The quantum gravity regime (M_{Pl}-3$\cdot M_{Pl}$) is expected to yield some interesting BSM Physics. If the Planck Scale is lowered to a few TeV, Quantum Black Holes (QBH) could be produced at the LHC.

- Unlike semiclassical black holes, QBH are non-thermal and would decay according to Quantum Gravity
- Couplings are yet unknown, it is hence assumed that QBH decay "democratically" to the known SM particles
- The cross section is taken to be $\sigma = \pi r_g^2$, an extrapolation from the semi-classical regime
- QBH would start being formed at M_{Th}, which is generally taken to be equal to M_D, the extradimensional Planck Scale
- It is assumed that there should be a continous spectra of QBH with masses ranging from M_{Pl}-3$\cdot M_{Pl}$

Quantum Black Holes at the LHC

The model described in arxiV 0912.0826v4 uses the features described above to calculate cross sections and branching ratios for possible QBH decays at the LHC depending on the initial state.

- The angular momentum of the QBH depends only on the spin of the incoming partons, ignoring the possibility of orbital angular momentum due to the impact parameter
- Can have qq, qg and gg combinations. Hence, possible spin combinations are: 0, $\frac{1}{2}$,1,$\frac{3}{2}$ or 2
- QBH would form a continous spectra beyond M_{Th}
- Branching ratios are calculated for the case where Quantum Gravity conserves all global symmetries and for the cases where it can violate them.

QBH Event Generator

Based on the model mentioned, a QBH event generator has been developed[1] and allows for a number of different options:

- Number of extra dimensions and their model (ADD or Randall-Sundrum)
- Conserve or violate global symmetries
- Definition of the extradimensional Planck Scale
- Minimum QBH mass (M_{th})

Monte Carlo samples were generated for spin-0 QBH while conserving all global symmetries. Pythia8 is used to simulate the parton shower

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[1] `http://qbh.hepforge.org`

Expected signal

It is expected that a QBH with spin-0, formed from a $q\bar{q}$ or gg initial state, can decay to an opposite sign dimuon final state

- Fully reconstructable final state
- Relatively well understood SM backgrounds
- New phenomena are expected to modify the dilepton mass spectra
- Use all the 2012 data → 20.5 fb^{-1} at $\sqrt{s} = 8$ TeV for the search
- Signal templates are constructed for the mass spectra. Shape information is used for our statistical analysis.
- Other channels have also been searched (dijet and lepton+jet).
- Parallel analysis for a dielectron final state

Standard Model Background

- The largest SM background is the Drell-Yan.
- All background estimated from Monte Carlo simulation

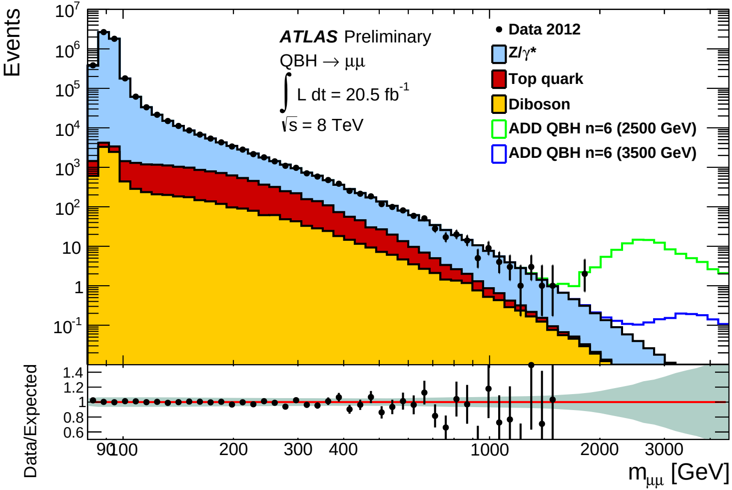
Background	Generator	Comments
DY	Powheg+Pythia8	QCD-EW k-factor and Photon-Induced Corrections
WW-WZ-ZZ	Herwig	Use a mass independent k-factor to bring production to NLO
Top	MC@NLO	Includes $t\bar{t}$+Single Top High mass extrapolation

Event Selection

- $p_T > 25$ GeV
- Require isolated muons
- Muon Station Hits Requirement: require very well reconstructed muons
  - Require consistency (5σ) between the Inner Detector and Muon Spectrometer p_T measurements
  - Tight channel: Require only 3 station muons
  - Loose channel: Allow pairs of 3 and 2 station muons
  - Loose channel brings a relative gain of 8% in acceptance

Require $M_{ll} > 80$ GeV. If more than one lepton pair satisfies the above requirements, the pair with the highest $\sum \mathrm{p}_T$ is selected

Data/MC Comparisons: Invariant Mass Spectra[2]



The uncertainty band covers the effect of all systematic uncertainties

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[2] ATL-CONF-2013-017, `https://indico.cern.ch/event/309903/`

Systematics at $m_{ll} = 3$ TeV

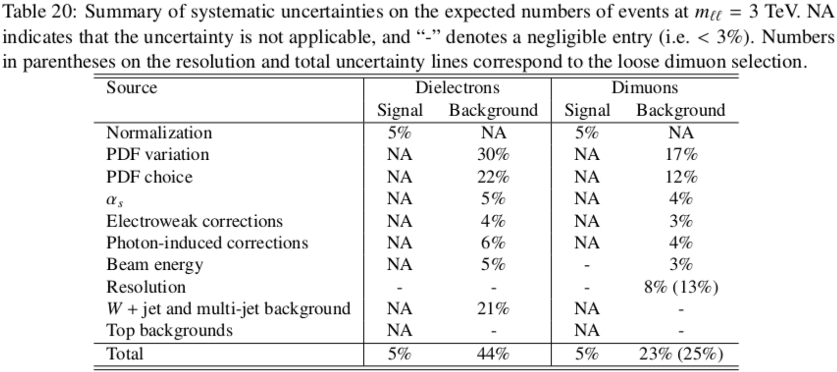

Table 20: Summary of systematic uncertainties on the expected numbers of events at $m_{\ell\ell} = 3$ TeV. NA indicates that the uncertainty is not applicable, and "-" denotes a negligible entry (i.e. < 3%). Numbers in parentheses on the resolution and total uncertainty lines correspond to the loose dimuon selection.

Source	Dielectrons		Dimuons	
	Signal	Background	Signal	Background
Normalization	5%	NA	5%	NA
PDF variation	NA	30%	NA	17%
PDF choice	NA	22%	NA	12%
α_s	NA	5%	NA	4%
Electroweak corrections	NA	4%	NA	3%
Photon-induced corrections	NA	6%	NA	4%
Beam energy	NA	5%	-	3%
Resolution	-	-	-	8% (13%)
W + jet and multi-jet background	NA	21%	NA	-
Top backgrounds	NA	-	NA	-
Total	5%	44%	5%	23% (25%)

- PDF variation sytematics obtained using MSTW NNLO 90% CL

Statistical Analysis

In the absence of signal, we set cross section and model dependent exclusion limits at 95% C.L.

- Build a likelihood function with the product of the poissonian probability of the signal given the data in each of the mass bins considered
- Each of the systematics uncertainties is introduced in the likelihood as a nuisance parameter
- Use the Bayesian Analysis Toolkit[3] to integrate out the dependence on the nuisance parameters by the use of Markov Chain Monte Carlo
- The parameter dependence of the likelihood is reduced to our parameter of interest ($\sigma \cdot BR$)
- The posterior probability distribution for our parameter of interest can then be obtained and 95% C.L. limits are extracted

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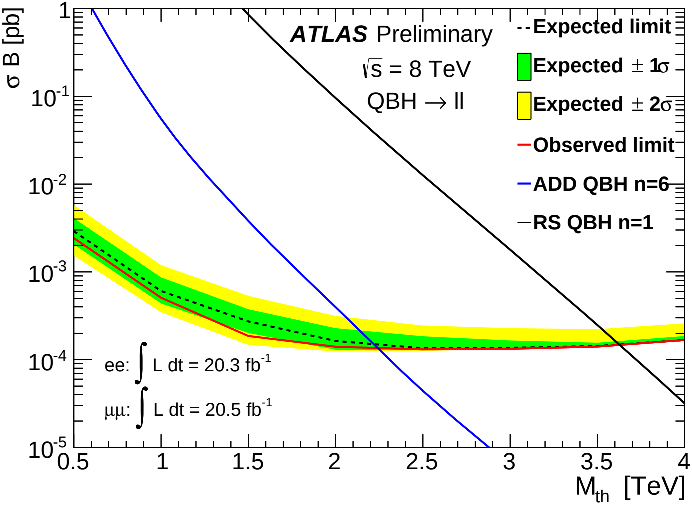
[3] `https://www.mppmu.mpg.de/bat/`

Expected 95% C.L. limits for QBH→ll[4]



Expected/Observed M_{th} Limit for ADD and RS QBH: 3.62 and 2.22 TeV

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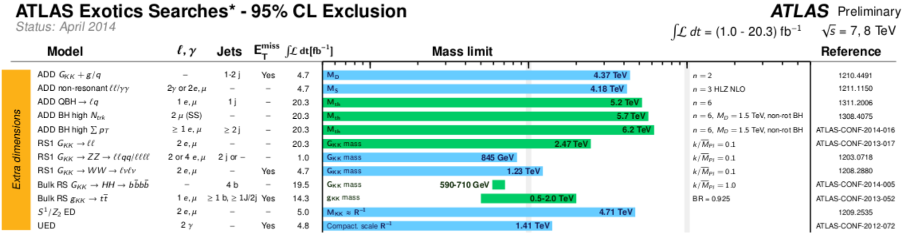
[4] ATL-CONF-2013-017, `https://indico.cern.ch/event/309903/`

Current Results[5]



ATLAS Exotics Searches* - 95% CL Exclusion

Status: April 2014

ATLAS Preliminary

$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D	4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell/\gamma\gamma$	2γ or $2e, \mu$	–	–	4.7	M_S	4.18 TeV	$n = 3$ HLZ NLO	1211.1150
	ADD QBH $\to \ell q$	$1\ e, \mu$	1 j	–	20.3	M_{th}	5.2 TeV	$n = 6$	1311.2006
	ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	M_{th}	5.7 TeV	$n = 6,\ M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	20.3	M_{th}	6.2 TeV	$n = 6,\ M_D = 1.5$ TeV, non-rot BH	ATLAS-CONF-2014-016
	RS1 $G_{KK} \to \ell\ell$	$2\ e, \mu$	–	–	20.3	G_{KK} mass	2.47 TeV	$k/\overline{M}_{Pl} = 0.1$	ATLAS-CONF-2013-017
	RS1 $G_{KK} \to ZZ \to \ell\ell qq/\ell\ell\ell\ell$	2 or 4 e, μ	2 j or –	–	1.0	G_{KK} mass	845 GeV	$k/\overline{M}_{Pl} = 0.1$	1203.0718
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	$2\ e, \mu$	–	Yes	4.7	G_{KK} mass	1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass	590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass	0.5-2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\ e, \mu$	–	–	5.0	$M_{KK} \approx R^{-1}$	4.71 TeV		1209.2535
	UED	$2\ \gamma$	–	Yes	4.8	Compact. scale R^{-1}	1.41 TeV		ATLAS-CONF-2012-072

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[5] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

BACKUP SLIDES

Resonant Analysis: Electron Selection

- All-Good GRL
- >1 primary vertex with more than 2 tracks
- EF_g35_loose_g25_loose
- LArError Error Check
- Author 1 or 3
- $|\eta| < 2.47$, excluding $1.37 < |\eta| < 1.52$
- Leading electron $p_T > 40$ GeV and subleading $p_T > 30$ GeV
- Medium++ ID
- Leading Electron Isolated (E_TCone20_p_T_NPV corrected $< 0.007 \cdot \mathrm{E}_T + 5.0$ (GeV))
- Subleading Electron Isolated (E_TCone20_p_T_NPV corrected $< 0.022 \cdot \mathrm{E}_T + 6.0$ (GeV))
- $M_{ee} > 80$ GeV (No OS requirement is used)

If more than one electron pair satisfies the above requirements, the pair with the highest $\sum \mathrm{p}_T$ is selected

Resonant Analysis: Tight+Loose Muon Selection

- MCP GRL
- > 1 primary vertex with more than 2 tracks
- EF_mu24_tight EF_mu36_tight
- Only Combined MuID muons
- ID hits: MCP guidelines
- $p_T > 25$ GeV
- $p_T\mathrm{Cone30}/p_T < 0.05$
- $|d_0| < 0.2$ mm & $|z_0| < 1.0$ mm
- MS Hits Requirement
  - p_TID-p_TMS consistency (5σ)
  - Tight Channel: Require only 3 station muons
  - Loose Channel: Allow 2 station muons if the other one is 3 station
  - Relative gain of 8% in acceptance for a Z' mass of 2.5 TeV

- $M_{\mu\mu} > 80$ GeV

If more than one muon pair satisfies the above requirements, the pair with the highest $\sum p_T$ is selected

QBH MC Samples

The samples were produced using the output from QBH, a Quantum Black Hole event generator, with the following settings[6]:

- Beam 1 energy = 4.0 TeV
- Beam 2 energy = 4.0 TeV
- reduced Planck mass = minimum BH mass
- maximum BH mass = Minimum of 3 times Planck mass and center-of-mass energy
- BH type: ADD
- Total number of dimensions: 10
- 21000 MSTW 2008 LO
- PDG definition of Planck scale
- Using black hole radius as QCD scale

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[6] `https://twiki.cern.ch/twiki/bin/view/AtlasSandbox/QuantumBlackHole#MC12a`

Phase Space Available

- Totally inelastic cross section used
- Yoshinio-Rychkov factors not used
- Two-particle decay probability not include
- Include a SM Higgs as particle
- Include graviton as particle
- Assuming neutrinos are only left-handed
- Assuming Dirac neutrinos
- Electric Charge = 0
- Assuming global gauge symmetries can be violated
- Spin-0 QBH such that initial states can only be gg or $q\bar{q}$

Statistical Analysis

- Cross section and mass limits:

In the absence of any significant signal, we set cross section and model dependent exclusion limits at 95 % C.L.

- Make use of well established procedures:

✓ Bayesian inference using the Bayesian Analysis Toolkit (BAT)
✓ Sources of systematic uncertainty incorporated in terms of nuisance parameters

$$L\left(data\,|\,\sigma B_{Z'},\theta_i\right) = \prod_{k=1}^{N} \frac{\mu_k^{n_k} e^{-\mu_k}}{n_k!} \prod_{i}^{Sys} G(\theta_i,0,1) \qquad \mu_k = \sum_j N_j T_{jk}\left(1+\theta_i \varepsilon_{ijk}\right)$$

where, $N_1=(A\varepsilon)(\sigma B)_{Z'}$xLumi $\quad N_2=N_{bkg} \quad \sum_{k=1}^{N} T_k = 1$

$\sigma B_{Z'}$	normalization parameter of signal ($j=1$)
Θ_i	nuisance parameter for each systematic effect
T_{jk}	fractional template shape expectation of template j in bin k
ε_{ijk}	systematic uncertainty in bin k due to source i on template j

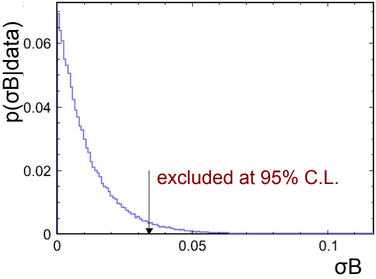
Limit Setting

The parameter dependence of the likelihood function is reduced to *one parameter* of interest by marginalizing (using *Markov Chain MC*)

$$\mathcal{L}'(data|\sigma B) = \int \mathcal{L}(\sigma B, \theta_1, ..., \theta_N) d\theta_1, ..., d\theta_N$$

In Bayesian statistics, all knowledge about the parameter of interest is summarized by the posterior p.d.f.
Obtained through Bayes' theorem:

$$p(\boldsymbol{\theta}|\boldsymbol{x}) = \frac{L(\boldsymbol{x}|\boldsymbol{\theta})\pi(\boldsymbol{\theta})}{\int L(\boldsymbol{x}|\boldsymbol{\theta}')\pi(\boldsymbol{\theta}')\, d\boldsymbol{\theta}'}$$



here, θ=σB (parameter of interest)

Integrate p.d.f. to obtain exclusion limits

Black Holes at the LHC

Some BSM Physics searches have focused on searching for semiclassical black holes

- If the Planck Scale (M_{Pl}), due to the existence of extradimensions, was reduced to a few TeV black holes could be created in pp collisions at the LHC
- It is expected that semiclassical black holes could be formed at 3-5$\cdot M_{Pl}$
- Similarly to stellar black holes, they would lose mass and decay through Hawking Radiation, but their lifetime is expected to be small (10^{-25} s)
- The expected signal would be an excess of high $\sum p_T$ events