Searches for new particles decaying into jet pairs in 2011 ATLAS data

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on behalf of the
ATLAS Collaboration

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Introduction

- *2010* saw **huge** strides being taken in searches for **physics beyond the Standard Model (BSM)**
- Dijet final states **already** allow us to probe many BSM effects
  - How do we tease out potential signals from this final state?
  - What have we be able to learn so far?
- What does the future hold? Results so far from 2011...

Why dijets?

- scattering processes well described within Standard Model (SM) by perturbative Quantum Chromodynamics (pQCD)
- However, it is possible for there to be additional contributions from:
  - new massive particles or
  - new forces, manifesting themselves at large CM energies

As examples of new physics models, we consider:

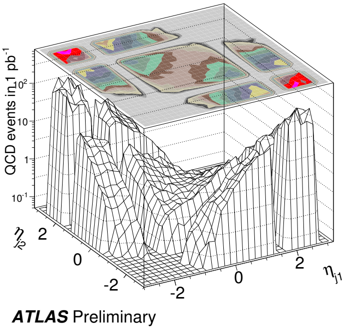
- **Compositeness**
  - Are quarks made from more fundamental particles: "preons"?
- **Excited quarks**
  - $qg \to q^* \to qg$
- TeV-scale gravity and **Quantum Black Holes**
  - generated using BlackMax
- **Axigluon model** - predicted by Chiral colour model
- and many more... [see New J. Phys. 13 (2011) 053044]

Dijet invariant mass: $m_{jj} = \sqrt{(E^{j_1} + E^{j_2})^2 - (\vec{p}^{j_1} + \vec{p}^{j_2})^2}$

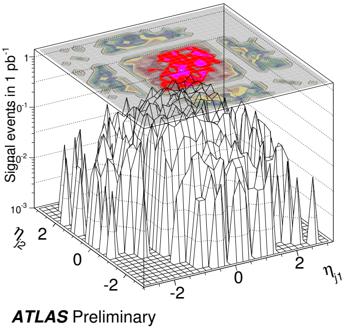
- Are there deviations from SM in m_{jj} spectrum?

But there is also *angular information* to consider...

QCD background:



Excited Quark Signal:



Both **Resonance** and dedicated **Angular Search** aim to take advantage of all of this information...

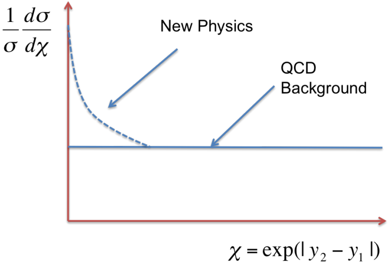
Dijet Angular Search: The χ Variable

$$\chi = exp\,|y_1 - y_2| \quad \text{where} \quad \text{Rapidity}: \; y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

- Related to the Centre of Mass (CM) scattering angle:

$$\cos\hat{\theta} = \tanh|y^*| \text{ where } y^* = (y_1 - y_2)/2$$

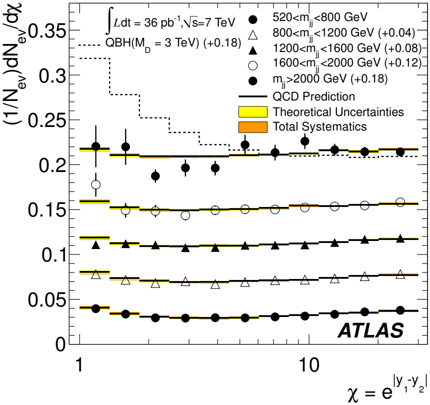
- Consider normalised $dN/d\chi$ distributions in bins of m_{jj}
- QCD $\rightarrow$ dominated by Rutherford-like scattering $\rightarrow$ flat χ
- New physics $\rightarrow$ isotropic scattering $\rightarrow$ excess at low χ



AIM: Find evidence of BSM physics resulting in excess of isotropic processes above certain mass threshold → most sensitive to threshold effects

- Data is compared to QCD MC
  - Pythia * bin-wise NLO k-factors
- Anti-k_t jet algo with $R = 0.6$
- $|y_{j1} - y_{j2}| < 3.4$ & $|y_{j1} + y_{j2}| < 2.2$
- $p-$value for each mass bin

mass range (GeV)	$p-$value
$520 < m_{jj} < 800$	0.44
$800 < m_{jj} < 1200$	0.33
$1200 < m_{jj} < 1600$	0.64
$1600 < m_{jj} < 2000$	0.89
$2000 < m_{jj}$	0.44

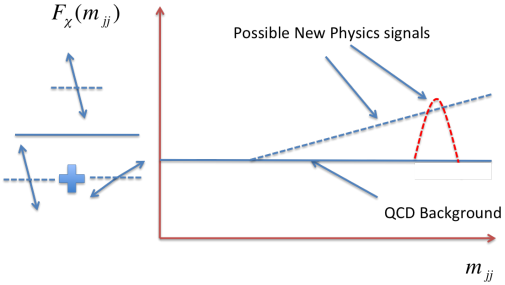


Indicates good agreement → Set limits!

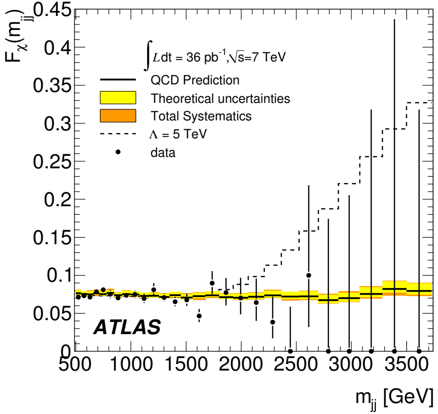
Motivation: Fine binning in dijet mass **maximises sensitivity** to search of **both resonant and non-resonant phenomena**

$$F_\chi(m_{jj}) = \frac{N_{events}(|y^*| < 0.6)}{N_{events}(|y^*| < 1.7)} \text{ where } y^* = (y_1 - y_2)/2$$

Sensitive to mass-dependent change in centrally produced dijets
$\rightarrow$ combines strengths of resonance analysis and χ analysis



- Data is compared to QCD MC (Pythia * bin-wise NLO k-factors)
- Using previous χ event selection with $m_{jj} > 500$ GeV



- Mass bins above 1253 GeV used for searches
- $p-$value $= 0.28$
  - from binned likelihood
  - systematics convolved with PE
- Indicates good agreement $\rightarrow$ Set limits!

* Λ is parameter for Quark Contact Interactions

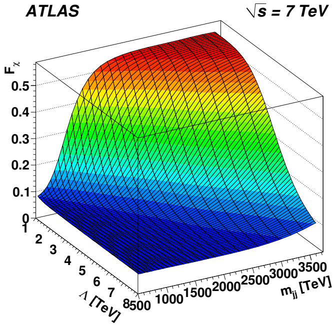
Dijet Angular Search: Limit setting with $F_\chi(m_{jj})$

Limits set using frequentist CL_{s+b} approach with statistic:

$$\text{Likelihood ratio } Q = -2(\ln L(F_\chi(m_{jj})|H_0) - \ln L(F_\chi(m_{jj})|H_1))$$

where H_0 is null hypothesis of QCD, H_1 is a specific signal hypothesis
- $L(F_\chi(m_{jj})|H)$ is binned likelihood for $F_\chi(m_{jj})$ assuming H

- 'data' for given H is taken from fits to fully simulated signal samples (see right)
- For each H throw PE to find expected distribution of Q - inc. variations of all systematic uncert.
- "signal-like" PE (or data) $\rightarrow$ high Q
- "QCD-like" PE (or data) $\rightarrow$ low Q
- construct Neyman Confidence Level



Dijet Angular Search: Limits on Contact Interactions (Λ)

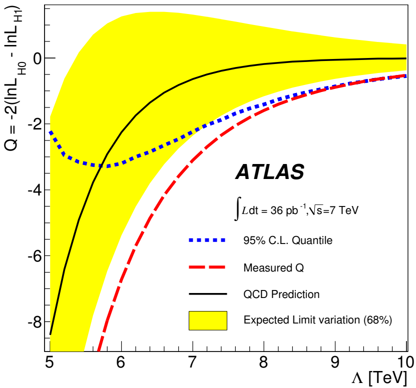
Set limit by comparing measured Q with expected for given Λ

Expected limit: 5.7 TeV   Observed limit: 9.5 TeV

Observed result significantly above expected

\- *due to downward fluctuation in $F_\chi(m_{jj})$*

- Known feature of CL_{s+b} method
- Cross-checks performed with other methods - similar expected limits
- (Bayesian: Expected 5.7 TeV, Observed 6.7 TeV)
- We chose not to exclude CL_{s+b} result *a posteriori*



Dijet Angular Search: Limits on Quantum Black Holes

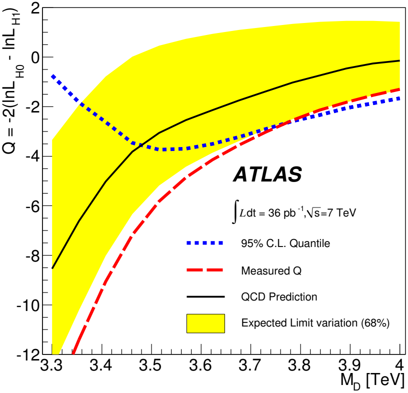
The QBH model

- Low-entropy limit to the popular semi-classical BH models
- Produced at threshold once $\sqrt{s} \geq M_D$ (Planck mass)
- Decay isotropically into 2-body final states (mostly jets)

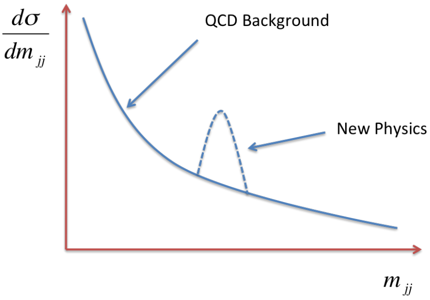
- Signal generated with BlackMax MC generator
- using most basic QBH scenario
- Limit set for $n = 6$ extra dimensions
- For limits on $n = 2 - 7$ see New J. Phys. 13 (2011) 053044

Limits set on the Planck mass, M_D:

- Expected limit: 3.49 TeV
- Observed limit: 3.78 TeV



AIM: Find evidence of new resonances in dijet mass spectrum with emphasis on identifying excess of isotropic processes



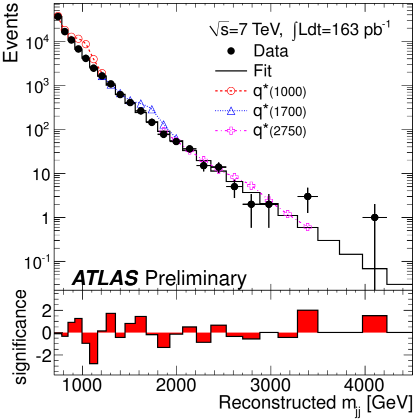
Chose leading two jets with:

- Anti-k_t jets with $R = 0.6$
- $|\eta_1 - \eta_2| < 1.3$
  - boost isotropic component
- $|\eta_{1,2}| < 2.5$
- $m_{jj} > 700$ GeV

$$m_{jj} = \sqrt{(E^{j_1} + E^{j_2})^2 - (\vec{p}^{j_1} + \vec{p}^{j_2})^2}$$

If no resonance found... set limits on specific models *and* generic limits which apply to many models.

NEW results for 163 pb^{-1}!



Background fit

Use smooth function:

$$f(x) = p_1(1-x)^{p_2}x^{p_3+p_4\ln x}$$

where $x = \frac{m_{jj}}{\sqrt{s}}$

Is there a signal?

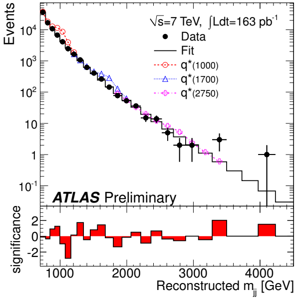
$p-$value of the fit to the data $= 0.016$

$p-$value of the fit without highest m_{jj} events $= 0.26$

- using χ^2 from PE with Poisson fluctuations around background fit

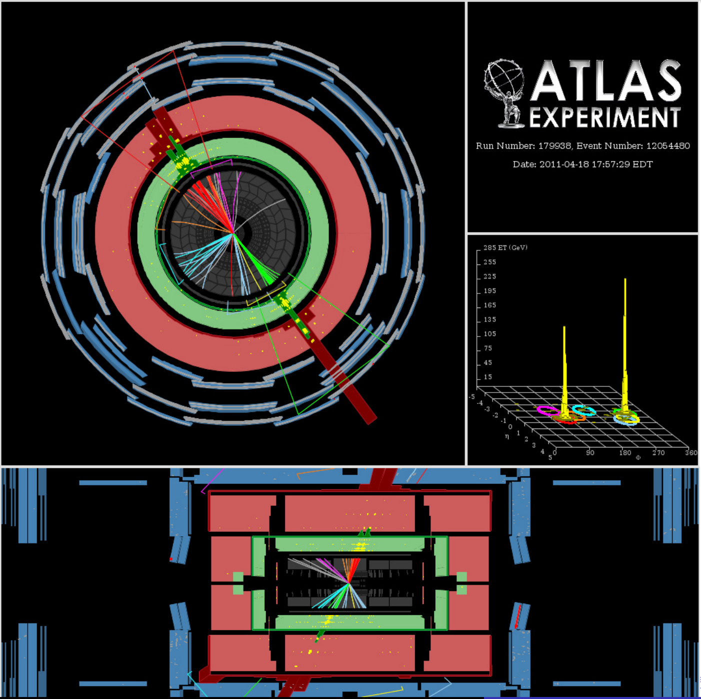
Can we do better?

- BumpHunter systematically looks for "bumps"
  - signal window increased and shifted to include *all* bin intervals (up to half m_{jj} range)
  - Identify most significant discrepancy
    - Find set of bins with smallest prob. of arising from background fluctuation (assuming Poisson stats)
  - include "trials factor" for significance of finding
    - Use PE to find prob. of excess due to background fluctuations



- **Most discrepant region**:
  due to last 4 events (4 bins) with p-value $= 0.26$
- *No evidence for a resonance signal...*

Set limits!



High energy candidate

$m_{jj} = 4.04$ TeV
$p_T^{j1} = 1.85$ TeV
$p_T^{j2} = 1.84$ TeV

Dijet Resonance: Setting limits on new processes

- Bayesian method used to set Credibility Levels (CL):

$$P(s|d) = \prod_i \mathrm{Poisson}(d_i; s_i + b_i) \times \frac{\pi(s)}{\mathcal{N}}$$

- $\prod_i \mathrm{Poisson}(d_i; s_i + b_i)$: likelihood function for observed mass spectrum
  - - obtained from fit to BG and a signal shape from MC
- Use a flat prior, $\pi(s)$, in s (signal events)
- Integrate to find upper limit at the 95% CL
- Systematics:
  - JES (2 - 4%), lumi (4.5%) and Background fit (3% at 600 GeV - 40% at 3500 GeV)
  - Each varied as Gaussian and convolved with Bayesian posterior
  - Halving and doubling of μ_R and μ_F varies limit by ~ 0.1 TeV

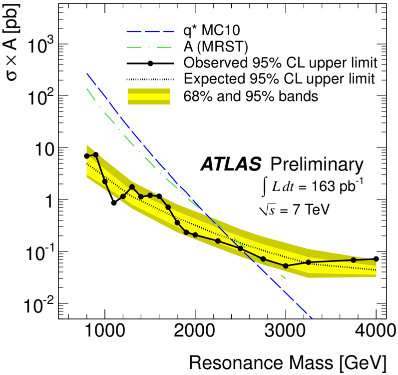
Dijet Resonance: Updates with 2011 data. *New limits*

NEW limits on m_{q^*}:

	Stat. ⊕ Syst.	Stat. only
Exp. [TeV]	**2.40**	2.46
Obs. [TeV]	**2.49**	2.51

NEW limits on Axigluon mass:

	Stat. ⊕ Syst.	Stat. only
Exp. [TeV]	**2.48**	2.56
Obs. [TeV]	**2.67**	2.76



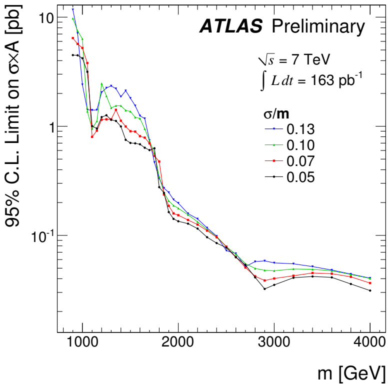
Dijet Resonance: Limits to Gaussian pseudo-signals

Added extra: we also set limits on simplified Gaussian models...

- Use Gaussian profile with
  - $\mu = 800 - 4000$ GeV
  - $\sigma = (5 - 13\%) \times \mu$
- Syst. uncert. convolved through PE

In order to find limit for a model:

- Calculate $\mathcal{A}$ (based on MC)
- ensure Gaussian profile after p_T and η requirements
- Remove long tails to ensure Gaussian shape
- Calculate exp. N_{events} for 163 pb^{-1}



For full table of σ/m for various m see ATLAS-CONF-2011-081

Summary

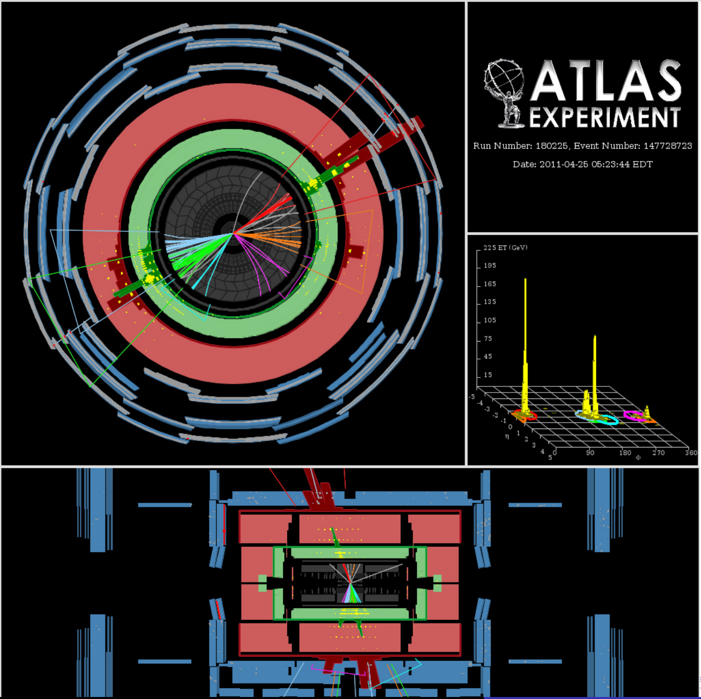
- Presented results from ATLAS searches for New Physics in the inclusive dijet channel - *No evidence found!*

Results with 36 pb^{-1} - updated with new results at 163 pb^{-1}

Model and Analysis Strategy	95% C.L. Limits (TeV) Expected	Observed
Excited Quark q^*		
Resonance in m_{jj}	**2.40**	**2.49**
$F_\chi(m_{jj})$	**2.12**	**2.64**
Randall-Meade Quantum Black Hole for $n = 6$		
Resonance in m_{jj}	**3.64**	**3.67**
$F_\chi(m_{jj})$	3.49	3.78
θ_{np} Parameter for $m_{jj} > 2$ TeV	3.37	3.69
11-bin χ Distribution for $m_{jj} > 2$ TeV	3.36	3.49
Axigluon		
Resonance in m_{jj}	**2.48**	**2.67**
Contact Interaction Λ		
$F_\chi(m_{jj})$	**5.7**	**9.5**
F_χ for $m_{jj} > 2$ TeV	5.2	6.8
11-bin χ Distribution for $m_{jj} > 2$ TeV	5.4	6.6

All plots from New J. Phys. 13 (2011) 053044 and ATLAS-CONF-2011-081

BACK-UP SLIDES



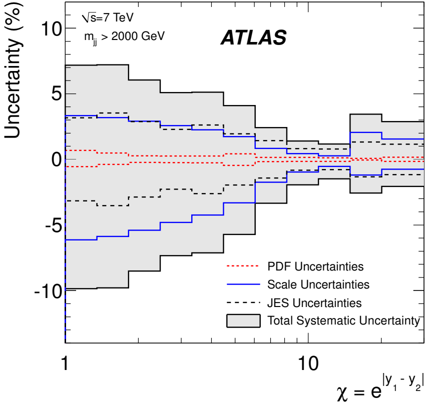
High energy candidate

$m_{jj} = 3.36$ TeV

$p_T^{j1} = 1.64$TeV

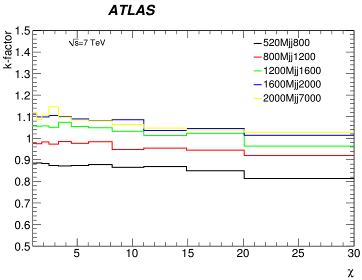
$p_T^{j2} = 1.60$ TeV

Dijet Angular Search: Systematic Uncertainties



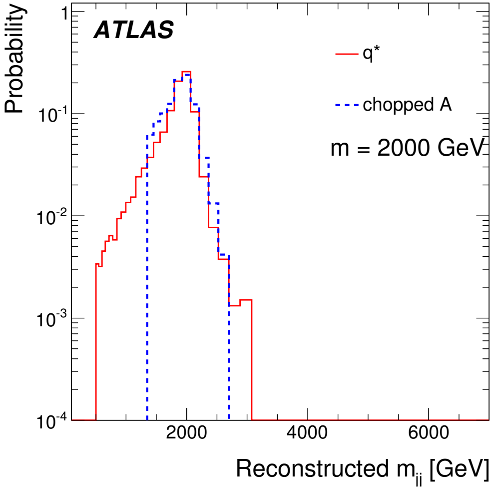
- QCD MC: Pythia 6.4.21 with MC09 tune
- PDF: MRST2007LO*

k-factors for χ distributions

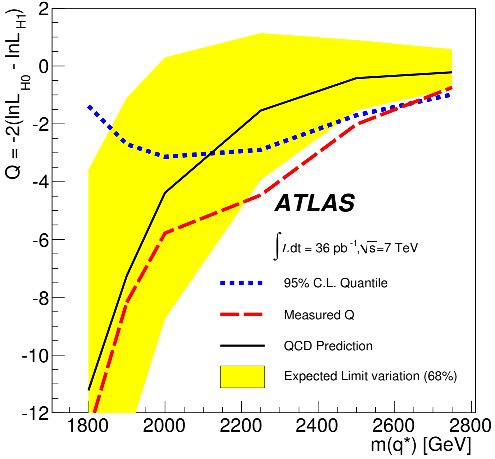


- *k*−factors:
  - $\mathrm{NLO_{ME}/PYT_{SHOW}}$
  - $\mathrm{NLO_{ME}}$ produced with $\mathrm{NLOJET++}$ with $\mathrm{NLO\ PDF\ CTEQ6.6}$
  - $\mathrm{PYT_{SHOW}}$ produced as above.
  - max effect 6% on norm spectra.
  - negligible mass bin migrations

Signal shapes for q^* and axigluon



Limits on m_{q^*} using $F_\chi(m_{jj})$



Explaining significance...

Explanation behind new plotting convention for significance

- Previous convention ($(D-B)/\sqrt{B}$) has little meaning for low statistics
- Consider $z-$value where *[See PDG, Statistics Review, Eq33.33]*

$$p - \text{value} = \int_{z-\text{value}}^{\text{inf}} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) dx$$

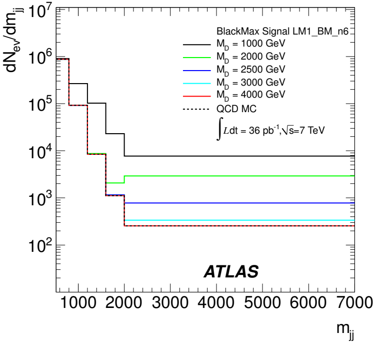
- For $p-$value $< 0.5 \rightarrow z-$value > 0 - interesting cases
- We remove all bins with $p-$value < 0.5 *by hand*
- We reverse signs of $z-$values for deficits
- Therefore,
  - Significance $+2$ means 2σ excess
  - Significance -2 means 2σ deficit

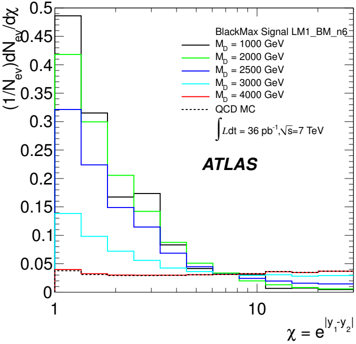
The q^* model

- Produced via $qg \to q^*$
- spin 1/2 with quark-like couplings relative to SM $SU(2)$, $U(1)$ and $SU(3)$ gauge groups
  - $(f = f' = f_s = 1)$ respectively
- Compositeness scale set to $\Lambda = 1$
- Generated using Pythia with MRST2007LO* PDF
- $\mu_R = \mu_F = p_T$ of two leading jets
- Decays to all SM particles (predominantly qg) inc. qW, qZ and $q\gamma$

The QBH model

- Low-entropy limit to the popular semi-classical BH models
- Produced at threshold once $\sqrt{s} \geq M_D$ (Planck mass)
- Decay isotropically into 2-body final states (mostly jets)
- Generated using the BlackMax MC Generator



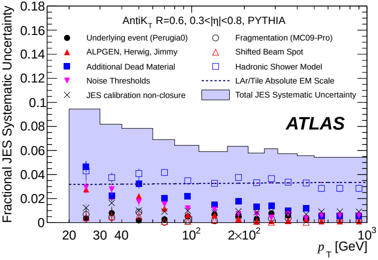


Estimate of the jet energy scale uncertainty

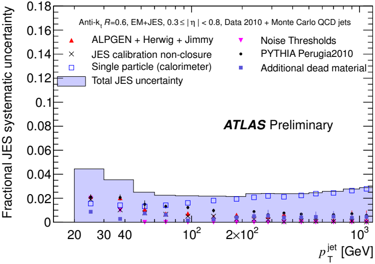
Estimate JES uncertainty using:

- single particle uncertainties (in-situ/test beam)
- Monte Carlo samples with systematic variations
- p_T balance in dijet events
- in-situ measurements in case of pile-up (added separately)

ICHEP, 07/2010:
$<$**6.5%** for central jets, p_T $>$200 GeV



Moriond QCD, 03/2011:
$<$**2.5%** for central jets, 60$<$ p_T $<$800 GeV



Endcap region ($0.8 < |\eta| < 3.6$): $< 9\%$ for whole p_T range
Forward region ($3.6 < |\eta| < 4.5$): $< 14\%$ for whole p_T range