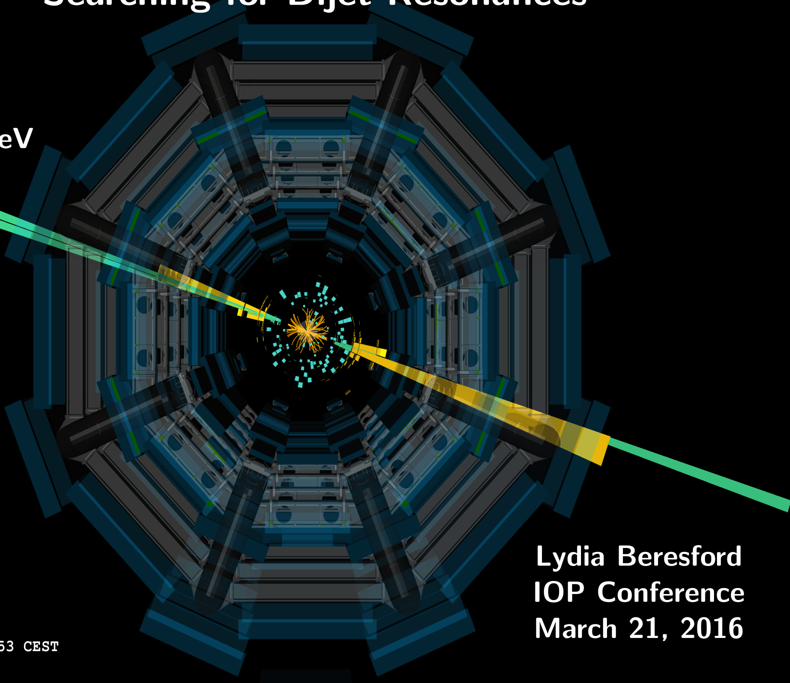
Searching for Dijet Resonances

m_{jj} = 6.9 TeV



ATLAS EXPERIMENT
http://atlas.ch

Run: 280673
Event: 1273922482
2015-09-29 15:32:53 CEST

Lydia Beresford
IOP Conference
March 21, 2016

Outline

Focus of this talk is dijet resonance search:

- Dataset: 3.6 fb^{-1} of 13 TeV proton-proton data

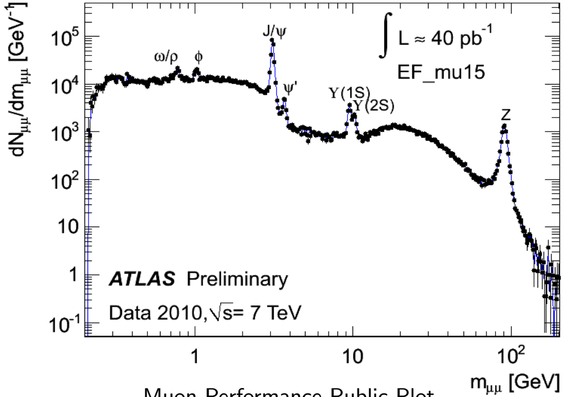
- Collected by the ATLAS detector at the LHC during 2015

- Recently published in Physics Letters B Vol. 754 (2016) Pgs. 302 - 322

- Brief introduction to resonances
- Why dijets?
- Jets in ATLAS
- Search strategy
- Results

The classic bump hunt!

- Decay of heavy particles with short lifetimes → **resonances (bumps)** on top of smooth invariant mass distributions



Muon Performance Public Plot

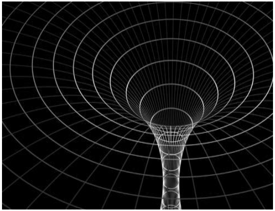
Searching for resonances has proved to be a vital tool in particle physics & lead to discovery of several Standard Model particles

Looking for new particle that decays to two back-to-back jets (dijet)

- LHC is a hadron collider, jets are produced in abundance
- Higher LHC energy (13 TeV) $\rightarrow$ increased senstivity at high mass, even with smaller dataset!
- Sensitive to some of the highest mass scales accessible at the LHC

What could we hope to find?

Dark matter mediator?



Quantum black holes?

Something else …

Jets in ATLAS

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Analysis uses jets reconstructed with the anti-k_T R = 0.4 algorithm

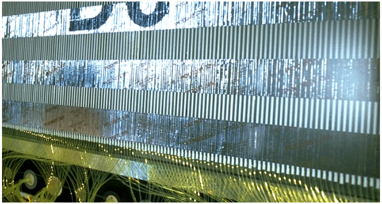
$\rightarrow$ Clusters together energy deposits, based on distances and transverse momentum, to form jets

ATLAS calorimeter:

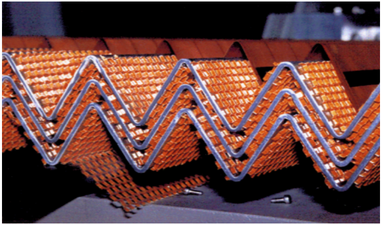
Sampling: layers of absorber and active material $\rightarrow$ Can't measure energy deposited in absorber

Non-compensating: calorimeter responds differently to EM and hadronic parts of the jet

$\rightarrow$ **Calibrate jets to obtain correct jet energy!**



Hadronic calorimeter



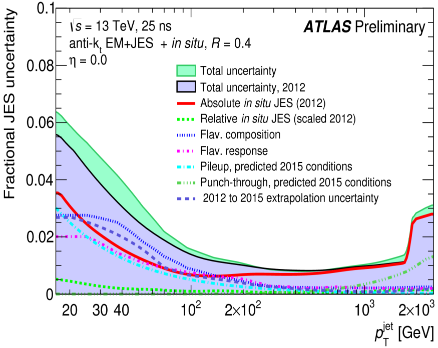
EM calorimeter

Jet calibration:

Will not go through the various stages involved in calibrating jets (more info in backup)

Instead, showing the **uncertainties** associated with 'Jet Energy Scale' calibration

→ Indicates how precisely we can calibrate our jets!



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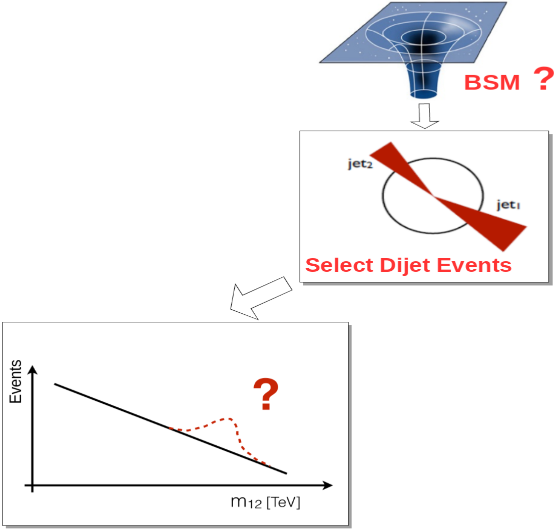


- **Select Dijet events**

  - Data quality criteria
  - 2 clean jets
  - Pass trigger (HLT_j360)
  - Lead jet pT > 440 GeV
  - $|y^*| = |y1-y2|/2 < 0.6$
  - m_{jj} 1.1 TeV

- **Obtain Dijet invariant mass spectrum**

- **Fit spectrum with smooth function**
  →Background estimate

- **Is there a bump?**

Resonance (bump hunt): Looks for resonance bumps on smooth QCD background

QCD background smoothly falling → Compare data to background estimate (smooth fit) & assess compatibility

3 Parameter fit function:

$$f(z) = p_1 (1 - z)^{p_2} (z)^{p_3}$$

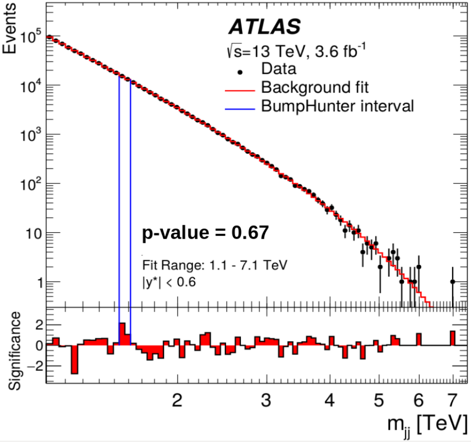
where $z = m/\sqrt{s}$

BumpHunter algorithm:

- Scan each possible range of bins (window) from 2 bins to half the mjj spectrum

- Identify window with max value of test statistic (1.53 - 1.61 TeV)

→ **Shape independence!**



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QCD background smoothly falling → Compare data to background estimate (smooth fit) & assess compatibility

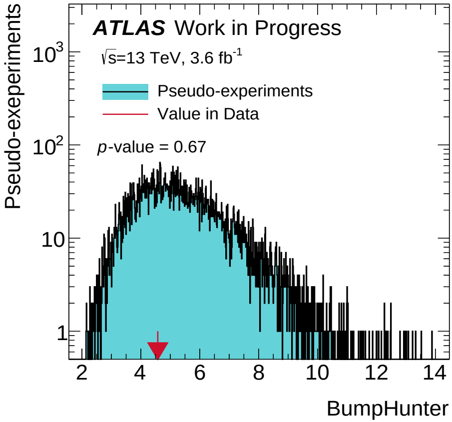
Is the bump significant?

- Generate **pseudoexperiments** (PEs) from background fit

- Compare PEs to their bkg fit and quantify using test statistic

- Calculate fraction of PEs with larger test statistic than data value → p-value

p-value = 0.67, not significant!



Set limits on benchmark models
$\rightarrow$ quantify search reach & compare to previous results!

Systematics:

Background

Statistical uncertainty on fit

Fit function choice uncertainy

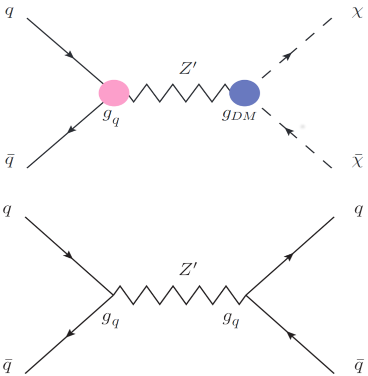
Signal

Luminosity: 9%

PDF acceptance: 1%

Jet Energy Scale: $\sim$ 10%
(For 6 TeV signal)

Z' dark matter mediator



Model dependent limits

Set limits in benchmark models
→ quantify search reach & compare to previous results!

Systematics:

Background

Statistical uncertainty on fit

Fit function choice uncertainy

Signal

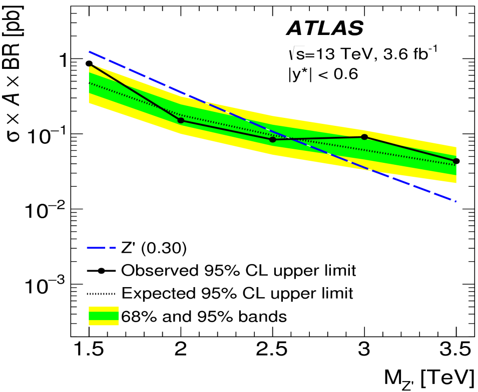
Luminosity: 9%

PDF acceptance: 1%

Jet Energy Scale: ∼ 10%

(For 6 TeV signal)

Limits on **Z' dark matter mediator**



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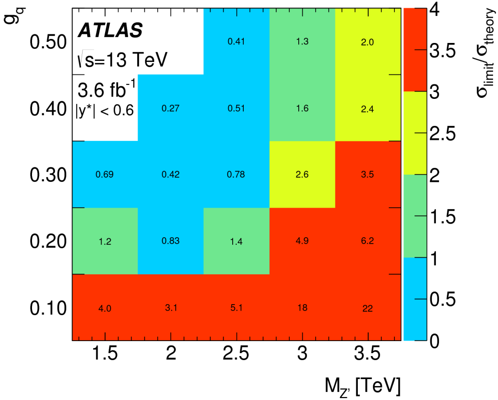

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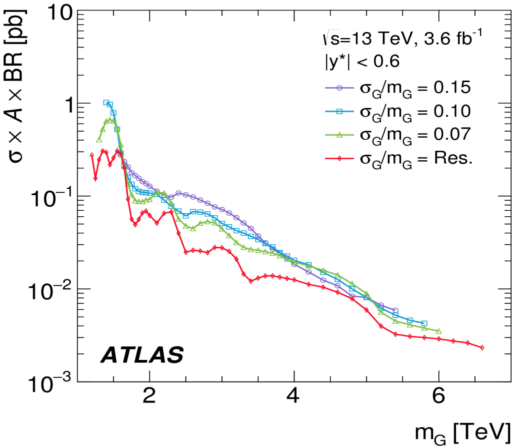
Model independent limits



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Model independent limits on **Gaussian** signal → Can be reinterpreted by theorists to set limits on their own pet models!

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Searches for new physics in dijet channel using 3.6 fb^{-1} 13 TeV proton-proton collision data collected with ATLAS detector:

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- Looked for resonant signals, using the dijet invariant mass

  Paper also includes non-resonant search using angular distribution
- No evidence for new physics has been found
- Setting strong limits on models + probing the highest dijet masses!

Model	95% CL Exclusion limit		
	Run 1 Observed	Observed 13 TeV	Expected 13 TeV
Quantum black holes, ADD (BlackMax generator)	5.6 TeV	8.1 TeV	8.1 TeV
Quantum black holes, ADD (QBH generator)	5.7 TeV	8.3 TeV	8.3 TeV
Quantum black holes, RS (QBH generator)	—	5.3 TeV	5.1 TeV
Excited quark	4.1 TeV	5.2 TeV	4.9 TeV
W'	2.5 TeV	2.6 TeV	2.6 TeV
Contact interactions ($\eta_{LL}=+1$)	8.1 TeV	12.0 TeV	12.0 TeV
Contact interactions ($\eta_{LL}=-1$)	12.0 TeV	17.5 TeV	18.1 TeV

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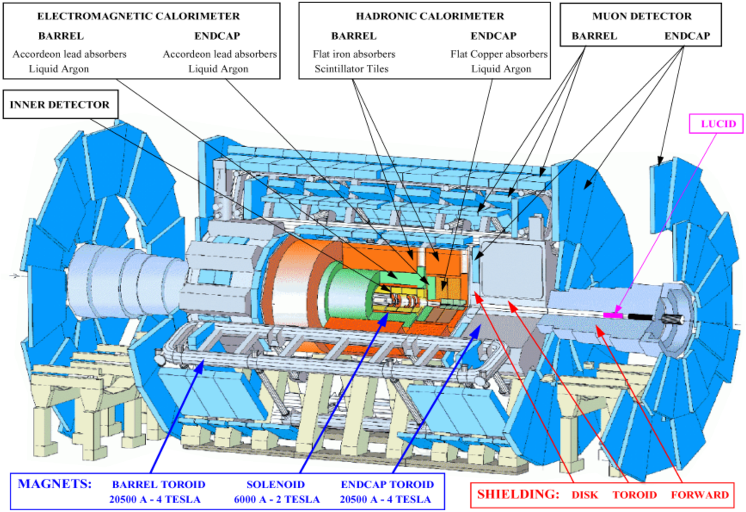
Thank you for listening!

Any questions?

BACKUP

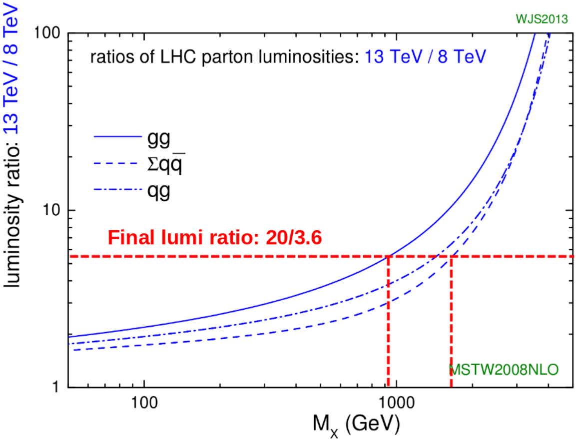
ATLAS Detector



http://hedberg.web.cern.ch/hedberg/home/atlas/atlas.html

Motivation

Looking for new particle that decays to two back-to-back jets (dijet)



W.J. Stirling, private communication

Reminder, 8 TeV dataset: 20 fb^{-1}

Jets in ATLAS

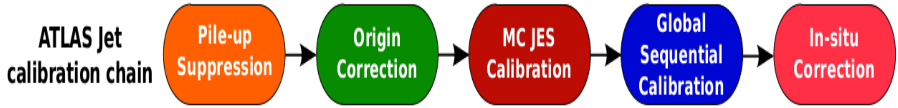
Anti-k_T algorithm used to cluster
together EM-scale topoclusters to form jets of radius R $= \sqrt{\Delta\eta^2 + \Delta\phi^2}$ $= 0.4$

Jet calibration basic ideas

- Use MC, truth and reco level comparisons to derive corrections for missing energy

- Compare data and MC to bring them into agreement & derive uncertainties

Jets in ATLAS



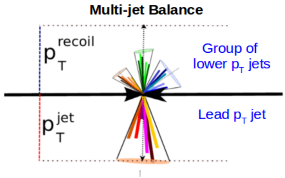
Calibration steps:

- **Pile-up**: Corrects for energy changes introduced by pile-up
- **Origin**: Changes jet direction to point to primary vertex instead of centre of the detector, jet energy unchanged
- **MC JES**: Corrects the jet energy and pseudorapidity to the particle jet scale, derived using MC
- **GSC**: Sequence of corrections applied at jet level that reduces JES dependence on the flavour of initiating parton (gluon vs quark)
- **In-situ**: Exploits pT balance of jet recoiling against a well calibrated reference object like Z, γ or multi-jets. Derived using data and MC, applied to data only

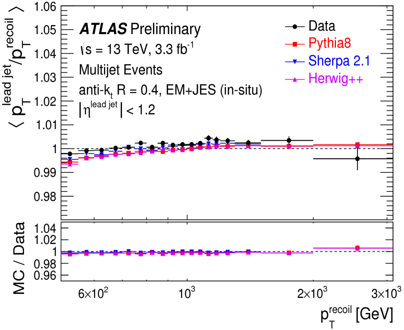
Jets in ATLAS

In-situ corrections:

- Forward & central jets: η-intercalibration, check pT of forward jets wrt central jets Increasing in p_T as go down
- Z + jet balance
- γ + hadronic recoil balance
- Multi-jet balance, balance lead jet + group of lower pT calibrated jets



Validation of jet calibration at multi-TeV



Dijet resonance - Choosing a fit function

- Use Wilk's test

Test statistic: - $2log\,(\Lambda) = -2log\left(\frac{L(H_0|x)}{L(H_1|x)}\right)$ 3 Parameter fit used as H_0

Probability distribution assuming null is true, given by Wilk's theorem: As sample size $\rightarrow \infty$, the test statistic will approach a χ^2 distribution with Ndof = the difference in number of dimensions of the 2 models Use value of test statistic and Wilk's theorem to calculate a p-value

Plot evolution of p-value with lumi

Dijet resonance - Uncertainties

Systematics used in limit setting:

Lumi uncertainty: 9%

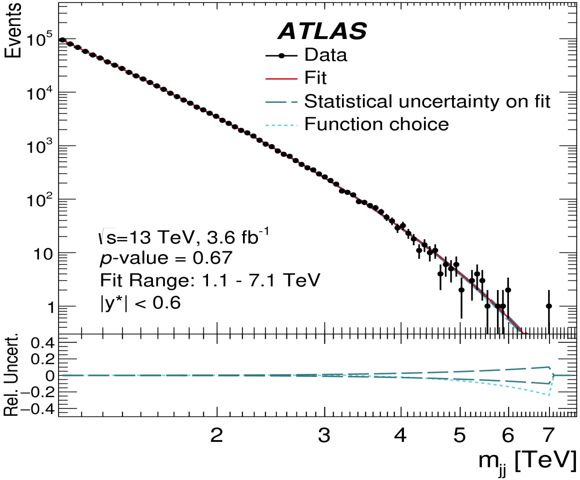
Fit Error: Uncertainty on the background fit, fit pseudo experiments (PEs) and in each mjj bin calculate the RMS of the function value for all PEs

PDF Acceptance: 1% Using a different PDF could change acceptance of a signal (i.e. amount of it we measure)

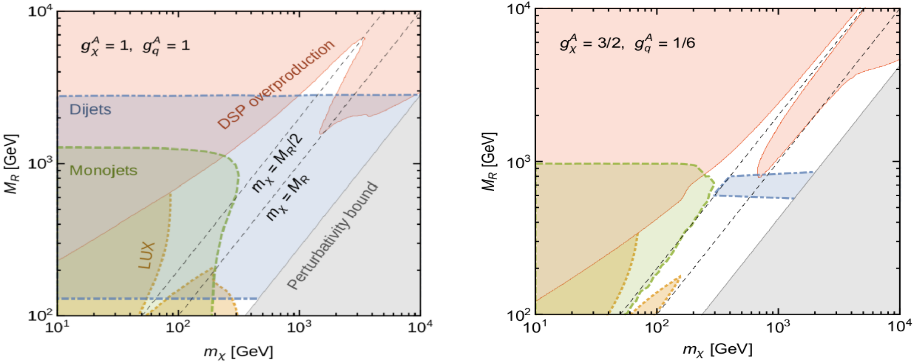
Fit Function Choice Error: Throw toys from data itself + record the RMS of the difference between the nominal and alternative fit in each bin. The difference between the two original fits to data is then scaled to the RMS of the corresponding bin.

JES Uncertainty: Uncertainty associated with the jet energy scale calibration, using reduced set of 3 components with templates to calculate uncertainty

Fit function uncertainties

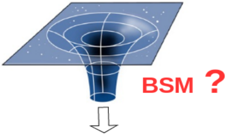


Z' constraints



Constraining Dark Sectors with Monojets and Dijets

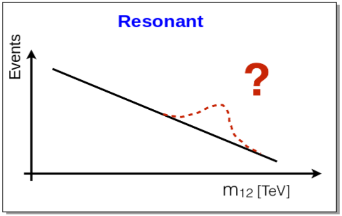
The dijet searches - Resonance and Angular!

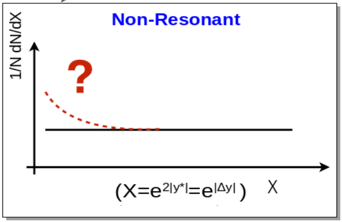


- GRL, 2 clean jets
- Trigger on HLT_j360
- Lead jet pT > 440 GeV

- Resonance: $|y^*| < 0.6$, $m_{jj} > 1.1$ TeV
  Angular: $|y^*| < 1.7$, $m_{jj} > 2.5$ TeV, $|y^B| < 1.1$

  Recall:
  y_1: rapidity of leading jet
  y^*: $(y_1 - y_2)/2$
  y^B: $(y_1 + y_2)/2$





- **Resonance** (bump hunt): Looks for resonance bumps on smooth QCD background

- **Angular**: Looks for variations in dijet separation angle from the QCD expectation

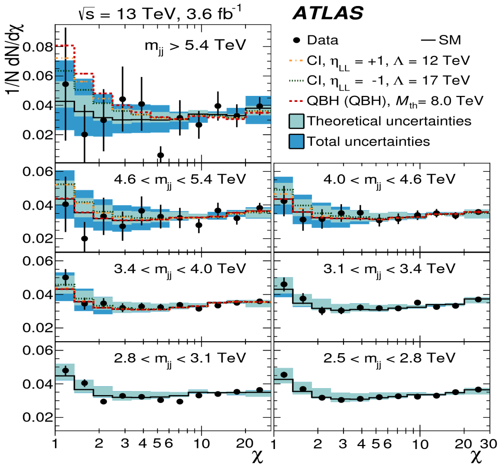
Dijet angular - χ binned in m_{jj}

Shape analysis (QCD $\sim$ flat) $\rightarrow$ Data-MC comparison of χ in different m_{jj} regions

MC : NLO Corrected (QCD and EW) Pythia, normalised to data

Perform search in bins with $m_{jj} > 3.4$ TeV

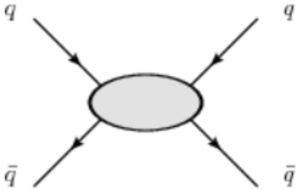
CL_s method used to test compatibility of data with MC prediction: **p-value = 0.35**



Dijet angular - Limits

Set limits on non-resonant CI signals with angular analaysis!

Calculate limits on the ratio of σ/σ_{th}, where σ_{th} is predicted cross-section, as a function of compositeness scale, Λ

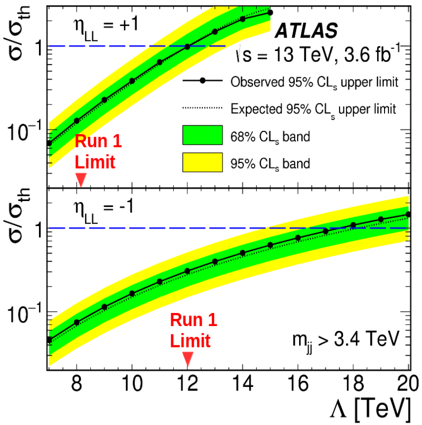


$$\Lambda >> \sqrt{\hat{s}}$$

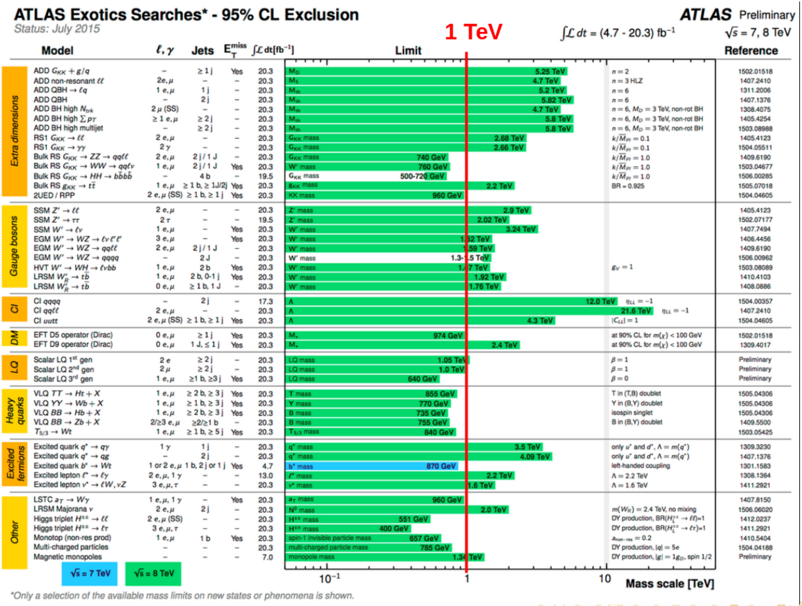
Limits on **quark contact interaction** constructive (destructive) interference

Observed limits: 17.5 (12.0) TeV

Expected limits: 18.1 (12.0) TeV



Run I Limits


ATLAS Exotics Searches* - 95% CL Exclusion
Status: July 2015
ATLAS Preliminary
1 TeV
∫L dt = (4.7 - 20.3) fb⁻¹
√s = 7, 8 TeV
Model | ℓ, γ | Jets | E_T^miss | ∫L dt[fb⁻¹] | Limit | Reference
Extra dimensions
ADD G_KK + g/q | – | ≥ 1 j | Yes | 20.3 | M_D 5.25 TeV | n = 2 | 1502.01518
ADD non-resonant ℓℓ | 2e, μ | – | – | 20.3 | M_S 4.7 TeV | n = 3 HLZ | 1407.2410
ADD QBH → ℓq | 1 e, μ | 1 j | – | 20.3 | M_th 5.2 TeV | n = 6 | 1311.2006
ADD QBH | – | 2 j | – | 20.3 | M_th 5.82 TeV | n = 6 | 1407.1376
ADD BH high N_trk | 2 μ (SS) | – | – | 20.3 | M_th 4.7 TeV | n = 6, M_D = 3 TeV, non-rot BH | 1308.4075
ADD BH high Σ p_T | ≥ 1 e, μ | ≥ 2 j | – | 20.3 | M_th 5.8 TeV | n = 6, M_D = 3 TeV, non-rot BH | 1405.4254
ADD BH high multijet | – | ≥ 2 j | – | 20.3 | M_th 5.8 TeV | n = 6, M_D = 3 TeV, non-rot BH | 1503.08988
RS1 G_KK → ℓℓ | 2 e, μ | – | – | 20.3 | G_KK mass 2.68 TeV | k/M̄_Pl = 0.1 | 1405.4123
RS1 G_KK → γγ | 2 γ | – | – | 20.3 | G_KK mass 2.66 TeV | k/M̄_Pl = 0.1 | 1504.05511
Bulk RS G_KK → ZZ → qqℓℓ | 2 e, μ | 2 j / 1 J | – | 20.3 | G_KK mass 740 GeV | k/M̄_Pl = 1.0 | 1409.6190
Bulk RS G_KK → WW → qqℓν | 1 e, μ | 2 j / 1 J | Yes | 20.3 | W' mass 760 GeV | k/M̄_Pl = 1.0 | 1503.04677
Bulk RS G_KK → HH → bb̄bb̄ | – | 4 b | – | 19.5 | G_KK mass 500-720 GeV | k/M̄_Pl = 1.0 | 1506.00285
Bulk RS g_KK → tt̄ | 1 e, μ | ≥ 1 b, ≥ 1J/2j | Yes | 20.3 | g_KK mass 2.2 TeV | BR = 0.925 | 1505.07018
2UED / RPP | 2 e, μ (SS) | ≥ 1 b, ≥ 1 j | Yes | 20.3 | KK mass 960 GeV | 1504.04605
Gauge bosons
SSM Z' → ℓℓ | 2 e, μ | – | – | 20.3 | Z' mass 2.9 TeV | 1405.4123
SSM Z' → ττ | 2 τ | – | – | 19.5 | Z' mass 2.02 TeV | 1502.07177
SSM W' → ℓν | 1 e, μ | – | Yes | 20.3 | W' mass 3.24 TeV | 1407.7494
EGM W' → WZ → ℓνℓ'ℓ' | 3 e, μ | – | Yes | 20.3 | W' mass 1.52 TeV | 1406.4456
EGM W' → WZ → qqℓℓ | 2 e, μ | 2 j / 1 J | – | 20.3 | W' mass 1.59 TeV | 1409.6190
EGM W' → WZ → qqqq | – | 2 J | – | 20.3 | W' mass 1.3-1.5 TeV | 1506.00962
HVT W' → WH → ℓνbb | 1 e, μ | 2 b | Yes | 20.3 | W' mass 1.47 TeV | g_V = 1 | 1503.08089
LRSM W'_R → tb̄ | 1 e, μ | 2 b, 0-1 j | Yes | 20.3 | W' mass 1.92 TeV | 1410.4103
LRSM W'_R → tb̄ | 0 e, μ | ≥ 1 b, 1 J | – | 20.3 | W' mass 1.76 TeV | 1408.0886
CI
CI qqqq | – | 2 j | – | 17.3 | Λ 12.0 TeV | η_LL = −1 | 1504.00357
CI qqℓℓ | 2 e, μ | – | – | 20.3 | Λ 21.6 TeV | η_LL = −1 | 1407.2410
CI uutt | 2 e, μ (SS) | ≥ 1 b, ≥ 1 j | Yes | 20.3 | Λ 4.3 TeV | |C_LL| = 1 | 1504.04605
DM
EFT D5 operator (Dirac) | 0 e, μ | ≥ 1 j | Yes | 20.3 | M* 974 GeV | at 90% CL for m(χ) < 100 GeV | 1502.01518
EFT D9 operator (Dirac) | 0 e, μ | 1 J, ≤ 1 j | Yes | 20.3 | M* 2.4 TeV | at 90% CL for m(χ) < 100 GeV | 1309.4017
LQ
Scalar LQ 1st gen | 2 e | ≥ 2 j | – | 20.3 | LQ mass 1.05 TeV | β = 1 | Preliminary
Scalar LQ 2nd gen | 2 μ | ≥ 2 j | – | 20.3 | LQ mass 1.0 TeV | β = 1 | Preliminary
Scalar LQ 3rd gen | 1 e, μ | ≥1 b, ≥3 j | Yes | 20.3 | LQ mass 640 GeV | β = 0 | Preliminary
Heavy quarks
VLQ TT → Ht + X | 1 e, μ | ≥ 2 b, ≥ 3 j | Yes | 20.3 | T mass 855 GeV | T in (T,B) doublet | 1505.04306
VLQ YY → Wb + X | 1 e, μ | ≥ 1 b, ≥ 3 j | Yes | 20.3 | Y mass 770 GeV | Y in (B,Y) doublet | 1505.04306
VLQ BB → Hb + X | 1 e, μ | ≥ 2 b, ≥ 3 j | Yes | 20.3 | B mass 735 GeV | isospin singlet | 1505.04306
VLQ BB → Zb + X | 2/≥3 e, μ | ≥2/≥1 b | – | 20.3 | B mass 755 GeV | B in (B,Y) doublet | 1409.5500
T_5/3 → Wt | 1 e, μ | ≥ 1 b, ≥ 5 j | Yes | 20.3 | T_5/3 mass 840 GeV | 1503.05425
Excited fermions
Excited quark q* → qγ | 1 γ | 1 j | – | 20.3 | q* mass 3.5 TeV | only u* and d*, Λ = m(q*) | 1309.3230
Excited quark q* → qg | – | 2 j | – | 20.3 | q* mass 4.09 TeV | only u* and d*, Λ = m(q*) | 1407.1376
Excited quark b* → Wt | 1 or 2 e, μ | 1 b, 2 j or 1 j | Yes | 4.7 | b* mass 870 GeV | left-handed coupling | 1301.1583
Excited lepton ℓ* → ℓγ | 2 e, μ, 1 γ | – | – | 13.0 | ℓ* mass 2.2 TeV | Λ = 2.2 TeV | 1308.1364
Excited lepton ν* → ℓW, νZ | 3 e, μ, τ | – | – | 20.3 | ν* mass 1.6 TeV | Λ = 1.6 TeV | 1411.2921
Other
LSTC a_T → Wγ | 1 e, μ, 1 γ | – | Yes | 20.3 | a_T mass 960 GeV | 1407.8150
LRSM Majorana ν | 2 e, μ | 2 j | – | 20.3 | N⁰ mass 2.0 TeV | m(W_R) = 2.4 TeV, no mixing | 1506.06020
Higgs triplet H^±± → ℓℓ | 2 e, μ (SS) | – | – | 20.3 | H^±± mass 551 GeV | DY production, BR(H_L^±± → ℓℓ)=1 | 1412.0237
Higgs triplet H^±± → ℓτ | 3 e, μ, τ | – | – | 20.3 | H^±± mass 400 GeV | DY production, BR(H_L^±± → ℓτ)=1 | 1411.2921
Monotop (non-res prod) | 1 e, μ | 1 b | Yes | 20.3 | spin-1 invisible particle mass 657 GeV | a_non-res = 0.2 | 1410.5404
Multi-charged particles | – | – | – | 20.3 | multi-charged particle mass 785 GeV | DY production, |q| = 5e | 1504.04188
Magnetic monopoles | – | – | – | 7.0 | monopole mass 1.34 TeV | DY production, |g| = 1g_D, spin 1/2 | Preliminary
√s = 7 TeV
√s = 8 TeV
10⁻¹
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown.