Search for Quark Substructure in 7 TeV *pp* Collisions with the ATLAS Detector

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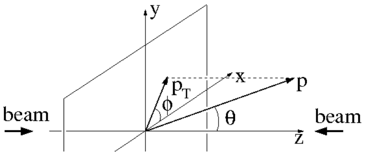
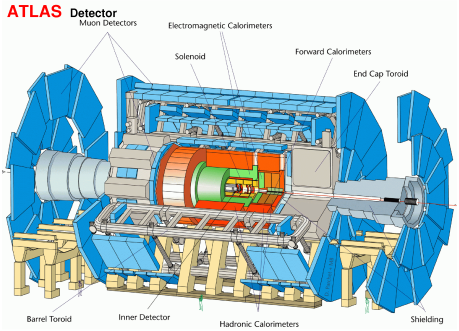
- The LHC provides counter-rotating proton beams each at 3.5 TeV (2010-2011)
- Beams intersect in ATLAS causing collisions of quarks (and/or gluons)





- Decay products of collisions are recorded by ATLAS
- Pseudo-rapidity η is the measure of longitudinal angle:

$$\eta = -\ln \tan(\theta/2)$$

  - Differences in pseudo-rapidity are invariant under longitudinal boost
  - Rapidity (y) of massless particles

Quark Compositeness

- Are quarks fundamental particles or composite objects?
  - Constituents are generally called *preons*
  - Preons may reveal themselves at an energy scale Λ
- Expect to see the effects of composite nature if $\sqrt{\hat{s}}$ is sufficiently high
  - At lower energies quarks appear point-like
- Search for deviation in dijet cross-section from QCD prediction
  - A 4-fermion contact interaction should become evident for an observation of quark compositeness
  - If data agrees well with QCD set a limit on Λ
- Aside: Composite nature could also be observed by finding a quark resonance

Quark Contact Interactions (CI)

- Effects of contact interactions should appear if $\sqrt{\hat{s}}$ is sufficiently large
- If $\Lambda > \sqrt{s}$ interactions between constituents are suppressed, with quarks appearing point-like $\rightarrow$ dominant contribution to cross section from 4-fermion contact term

- 4-fermion contact term in Lagrangian

$$\mathcal{L}_{qqqq}(\Lambda) = \frac{\xi g^2}{2\Lambda^2} \bar{\Psi}_q^L \gamma^\mu \Psi_q^L \bar{\Psi}_q^L \gamma_\mu \Psi_q^L$$

  - $g^2/4\pi = 1$, Ψ are the left handed quarks
  - $\xi = +1$ (-1) is destructive (constructive) interference with QCD
  - Exclusion limits change by $\sim$1 % depending on the choice of ξ

Sensitive Observables

- QCD at LO looks like Rutherford scattering in the centre-of-mass frame:

$$\frac{d\hat{\sigma}}{d\Omega} \sim \frac{1}{\sin^4(\Theta/2)}$$

- Contact interactions are expected to yield a more isotropic spectrum
- Useful angular variable in hadron collider experiment is χ:

$$\chi = e^{|y_1 - y_2|} = \frac{1 + cos\Theta}{1 - cos\Theta}$$

  - y_1 is the rapidity of the leading (in p_T) jet
  - y_2 is the rapidity of the sub-leading (in p_T) jet
  - Invariant under Lorentz boosts along the beam (z)

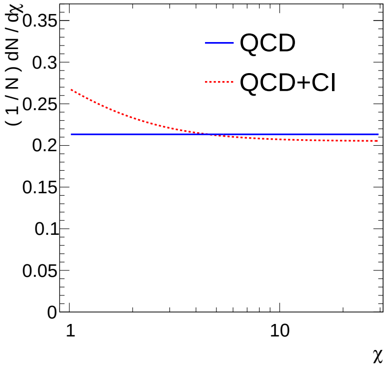
Expected Distribution

- Rutherford scattering (QCD):

$$\frac{d\hat{\sigma}}{d\Omega} \sim \frac{1}{\sin^4(\Theta/2)} \rightarrow \frac{d\hat{\sigma}}{d\chi} \sim 1$$

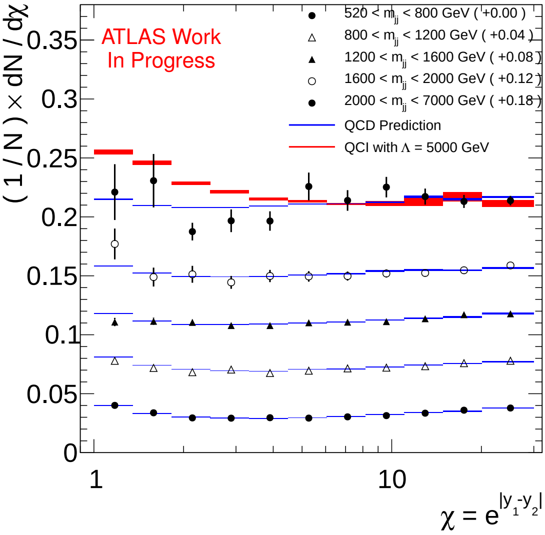
- Isotropic scattering (CI):

$$\frac{d\hat{\sigma}}{d\Omega} \sim 1 \rightarrow \frac{d\hat{\sigma}}{d\chi} \sim \frac{1}{(1+\chi)^2}$$



- Higher order QCD predicts more events at low χ
- Can test NLO QCD using events at low dijet mass

Data Distributions



- 2010 data $\mathcal{L} = 36\,\mathrm{pb}^{-1}$
- Low χ implies large scattering angle
- Data and MC prediction are normalized per m_{jj} bin
- Offset each m_{jj} bin for display
- QCD and CI prediction is corrected to NLO using k-factors derived from QCD
- NLO calculations for CI have recently become available [5]

Likelihood Function

- Counting events in bins of m_{jj} and χ so binned Poisson Likelihood:

$$L(\mathbf{n}|\Lambda) = \prod_{j=0}^{N_{bins}} \left(\frac{\mu_j(\Lambda)^{n_j}}{n_j!} \cdot e^{-\mu_j(\Lambda)} \right)$$

  - n_j is the number of recorded events in bin j
  - $\mu_j(\Lambda)$ is the number of events predicted for bin j at CI scale Λ
- Shape only analysis: The MC is normalized to contain the same number of events as the data in each m_{jj} bin
- Since we only have MC simulation for some discrete points in Λ fit:

$$\mu_j(\Lambda) \sim \underbrace{a_0}_{QCD} + \underbrace{a_1\Lambda^{-4}}_{CI} + \underbrace{a_2\Lambda^{-2}}_{Interference}$$

Test Statistics

Maximum likelihood ratio

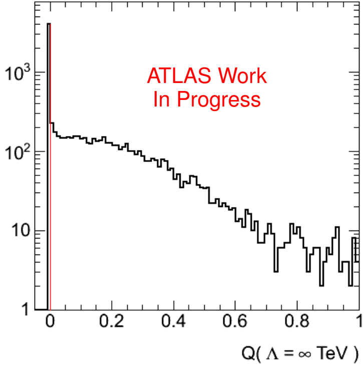
$$Q(\Lambda) = -2\ln\left(\frac{L(\mathbf{n}|\Lambda)}{L(\mathbf{n}|\hat{\Lambda})}\right)$$

- $\hat{\Lambda}$ is the most likely value of Λ found by minimizing $-2\ln L(\mathbf{n}|\Lambda)$

- where **n** stands for the data recorded or pseudo-experiments

p-Value for Q (Maximum Likelihood Ratio)

- Create pseudo-experiments by drawing Poisson random numbers in each bin centred on the MC-prediction for $\Lambda = \infty$
- Fill likelihood distribution with Q from each pseudo-experiment
- Determine the fraction of pseudo-experiments with Q greater than the data



p-Value from ATLAS data: 0.95

The p-value is the probability of observing a more extreme Q given QCD than the data: $P_{\mathrm{QCD}}(Q(\infty) \geq Q_{\mathrm{data}}(\infty))$

Definition of Confidence Limits

- Extend the idea of the p-value to be computed from our prediction at some Λ [6]:

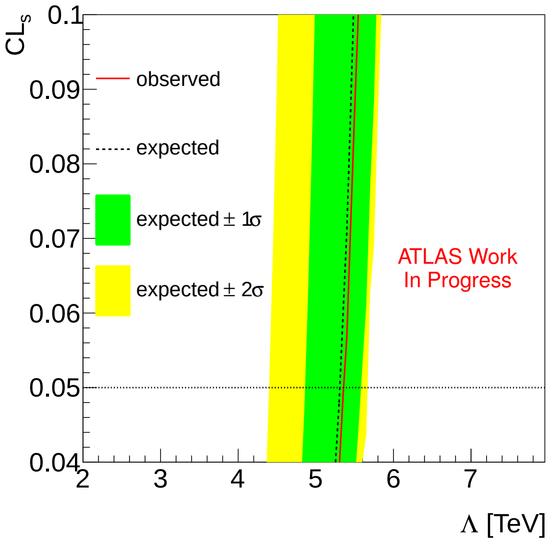
$$CL_{s+b}(\Lambda) = P_{\mathrm{QCD+CI}}(Q(\Lambda) \geq Q_{\mathrm{data}}(\Lambda))$$

- Previous ATLAS exclusion limit was set at $CL_{s+b} < 0.05$ (the 95 % exclusion limit)
- A more conservative approach corrects for the QCD likelihood distribution assuming Λ:

$$CL_{s}(\Lambda) = \frac{P_{\mathrm{QCD+CI}}(Q(\Lambda) \geq Q_{\mathrm{data}}(\Lambda))}{1 - P_{\mathrm{QCD}}(Q(\Lambda) \leq Q_{\mathrm{data}}(\Lambda))}$$

- CMS used this definition in their recent paper

Λ Limit using CL_s with Q



- Using 2010 ATLAS data $\mathcal{L} = 36\,\mathrm{pb}^{-1}$
- Test statistic

$$Q = -2 \ln \frac{L(\mathbf{n}|\Lambda)}{L(\mathbf{n}|\hat{\Lambda})}$$

- Observed 95 % CL_s limit = 5.36 TeV
- Expected 95 % CL_s limit = 5.31 TeV

Systematic Effects

- Experimental
  - Jet Energy Scale ($\sim$ 0.1% change to CL_s)
    - Could cause excess of events at high $_{jj}$
  - Jet p_T resolution ($\sim$ 0.1% change to CL_s)
    - Minimal bin-to-bin migration in m_{jj}
- Theoretical:
  - Factorization (μ_f) and renormalization (μ_r) scale choice ($\sim$ 1.3% change to CL_s)
    - Dominant effect
  - Parton distribution function errors ($\sim$ 0.2% change to CL_s)
- Angular observable minimizes the effect of all of these uncertainties
- Systematic effects are included through **Bayesian integration**

Effect on Limits

ATLAS Work In Progress

	CL_s		CL_{s+b}	
Effect	Obs [TeV]	Exp [TeV]	Obs [TeV]	Exp [TeV]
No Systematics	5.36	5.31	5.60	5.48
MC Statistics	5.36	5.31	5.59	5.49
Jet p_T Resolution	5.37	5.31	5.60	5.49
Jet Energy Scale	5.37	5.31	5.60	5.49
μ_f/μ_r Scale Choice	5.29	5.21	5.54	5.40
PDF Fit Errors	5.37	5.32	5.60	5.50
All[1]	5.29	5.20	5.52	5.41

[1] Assuming effects are independent

Previous Limits

with $\xi = -1$

			Limits [TeV]		
Experiment	$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	observed	expected	Stat
ATLAS	7	4.8	7.8	8.7	CL_{s+b}
CMS	7	2.2	10.5	9.7	CL_s
D0	1.96	0.7	2.82	2.75	binned χ^2
CDF[2]	1.96	0.106	1.4	-	binned χ^2

- All limits based on χ and m_{jj} [1, 2, 3, 4]
- ATLAS also performed measurement using the centrality ratio finely binned in m_{jj} to get a 95 % CL_{s+b} exclusion of 7.6 TeV (expected 8.2 TeV)

[2] CDF paper is from 1996, while D0's is from 2009

Summary

ATLAS Work In Progress

- An exclusion limit for quark compositeness has been obtained from the 2010 data-set

$$\Lambda > 5.29\,\mathrm{TeV\ at}\ 95\%\ CL_s\ 7\,\mathrm{TeV\ Collisions}\ \mathcal{L} = 36\,\mathrm{pb}^{-1}$$

Accounted For:

- Jet energy scale uncertainty
- Jet p_T resolution
- Factorization and renormalization scale uncertainty
- PDF fit errors
- Statistical limitations of simulated events

Event Cleaning and Selection

- GRL: Require LHC stable beam, good conditions for the Inner detector and calorimeters
- Using single jet triggers on efficiency plateau
- Cleaning cuts:
  - One primary vertex with at least five tracks
  - All jets pass quality cuts
- Selection Cuts
  - Leading jet $p_T > 60$ GeV
  - Sub-leading jet $p_T > 30$ GeV
  - Dijet rapidity separation $|y^\star| = |(y_1 - y_2)/2| < 1.7$
  - Dijet boost $|\bar{y}| = |(y_1 + y_2)/2| < 1.1$

Total Data For Analysis

ATLAS Work In Progress

m_{jj} Bin [TeV]		Periods A-E		Periods F-I	
min	max	L1 Item	$\mathcal{L}$ [pb^{-1}]	EF Item	$\mathcal{L}$ [pb^{-1}]
.52	.8	J30	2.00	j50_jetNoEF	0.25
.8	1.2	J55	3.11	j77_jetNoEF	6.46
1.2	1.6	J55	3.11	j95_NoAlg	33.17
1.6	2.0	J55	3.11	j95_NoAlg	33.17
2.0	∞	J55	3.11	j95_NoAlg	33.17

- Trigger selection guarantees $\sim$100 % efficiency in each m_{jj} bin
- Total 2010 data: $\sim$36 pb^{-1}

Test Statistics

Likelihood ratio (reference to most probable)

$$Q(\Lambda) = -2\ln\left(\frac{L(\mathbf{n}|\Lambda)}{L(\mathbf{n}|\hat{\Lambda})}\right)$$

- $\hat{\Lambda}$ is the most likely value of Λ found by minimizing $-2\ln L(\mathbf{n}|\Lambda)$

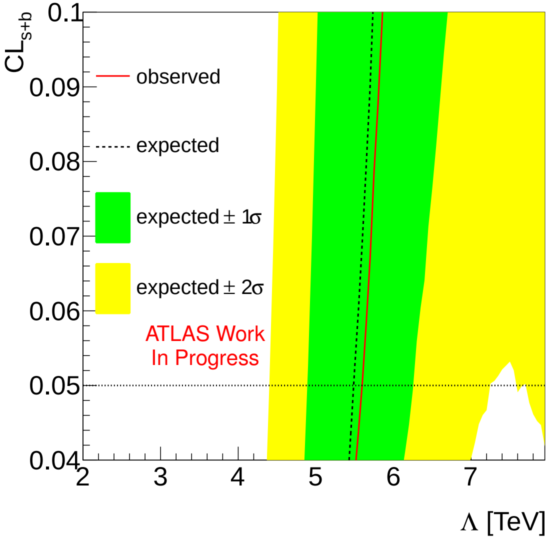
Likelihood ratio (reference to QCD)

$$q(\Lambda) = -2\ln\left(\frac{L(\mathbf{n}|\Lambda)}{L(\mathbf{n}|\infty)}\right)$$

- $\Lambda = \infty$ implies the likelihood of QCD given the data

- where **n** stands for the data recorded or pseudo-experiments

Λ Limit using CL_{s+b} with Q

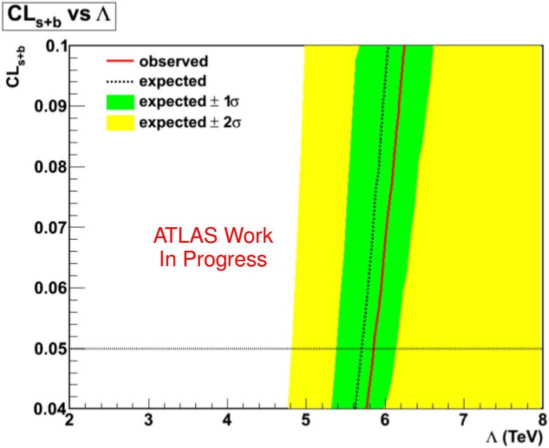


- Using 2010 ATLAS data $\mathcal{L} = 36\ \mathrm{pb}^{-1}$
- Using test statistic

$$Q = -2 \ln \frac{L(\mathbf{n}|\Lambda)}{L(\mathbf{n}|\hat{\Lambda})}$$

- Observed 95 % CL_{s+b} limit = 5.60 TeV
- Expected 95 % CL_{s+b} limit = 5.48 TeV

Λ Limit using CL_{s+b} with q

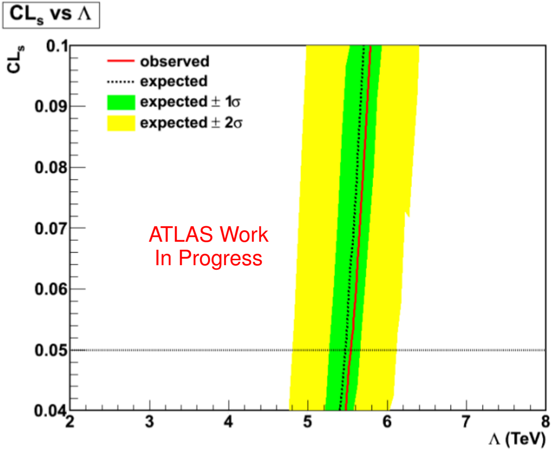


- Using 2010 ATLAS data $\mathcal{L} = 36\,\mathrm{pb}^{-1}$
- Using test statistic

$$q = -2 \ln \frac{L(\mathbf{n}|\Lambda)}{L(\mathbf{n}|\infty)}$$

- Observed 95 % CL_{s+b} limit = 5.85 TeV
- Expected 95 % CL_{s+b} limit = 5.70 TeV

Λ Limit using CL_s with q



- Using 2010 ATLAS data $\mathcal{L} = 36\,\mathrm{pb}^{-1}$
- Using test statistic

$$q = -2 \ln \frac{L(\mathbf{n}|\Lambda)}{L(\mathbf{n}|\infty)}$$

- Observed 95 % CL_s limit = 5.54 TeV
- Expected 95 % CL_s limit = 5.47 TeV

Previous Limits

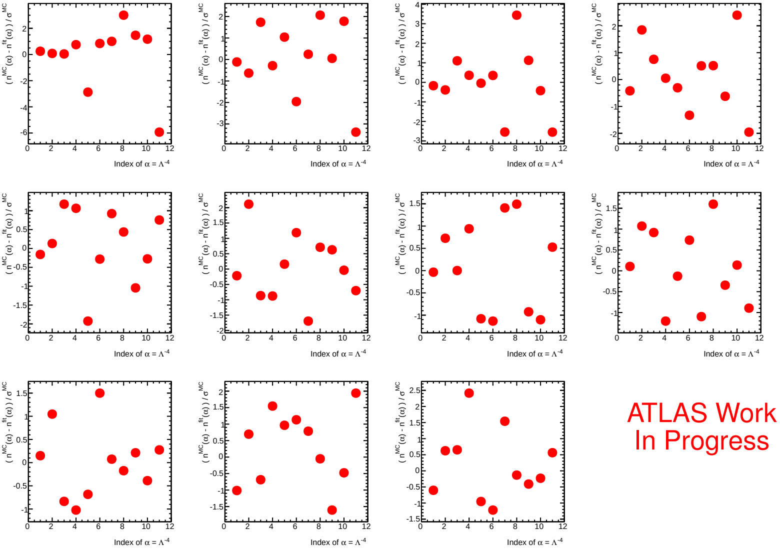
with $\xi = +1$

			Limits [TeV]		
Experiment	$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	observed	expected	Stat
ATLAS	7	–	–	–	CL_{s+b}
CMS	7	2.2	7.5	7.0	CL_s
D0	1.96	0.7	2.84	2.76	binned χ^2
CDF[3]	1.96	0.106	1.6	–	binned χ^2

- ATLAS currently has no MC simulation to make this measurement

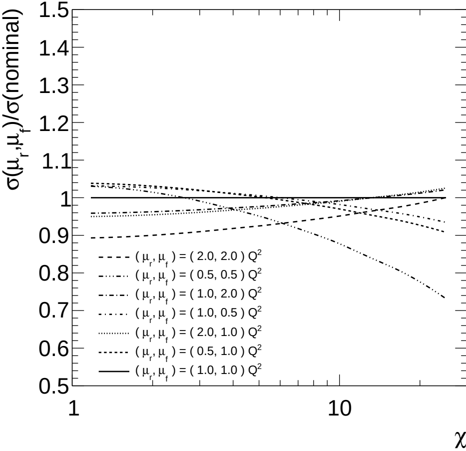
[3] CDF paper is from 1996, while D0's is from 2009

QCI Simulation Fits Residuals



Factorization/renormalization Scale Choice

- Large ($\sim$ 20%) variation across χ
- Dominant effect
- *Prior:*
  - μ_r and μ_f picked from $\frac{1}{x}$ between 0.5 and 2.0 each



PDF Fit Error

- Errors fully correlated across χ
- Large ($\sim$ 20%) effect absorbed by normalization
- Variation of error across χ is $\sim$ 4%
- *Prior:*
  - significance of PDF error follows Gaussian
  - Use same sign error bars to absorb asymmetry

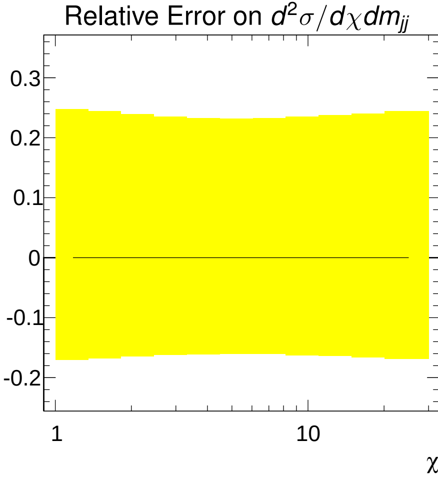


Table to Calculated Exclusion Limits

ATLAS Work In Progress

Stat	$Q = -2\ln\frac{L(\mathbf{n}\vert\Lambda)}{L(\mathbf{n}\vert\hat{\Lambda})}$		$q = -2\ln\frac{L(\mathbf{n}\vert\Lambda)}{L(\mathbf{n}\vert\Lambda=\text{inf})}$	
	obs [TeV]	exp [TeV]	obs [TeV]	exp [TeV]
CL_{s+b}	5.60	5.48	5.85	5.70
CL_s	5.36	5.31	5.54	5.47

- As presented above

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