Searches for New Physics with Jets in ATLAS

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on behalf of the ATLAS collaboration

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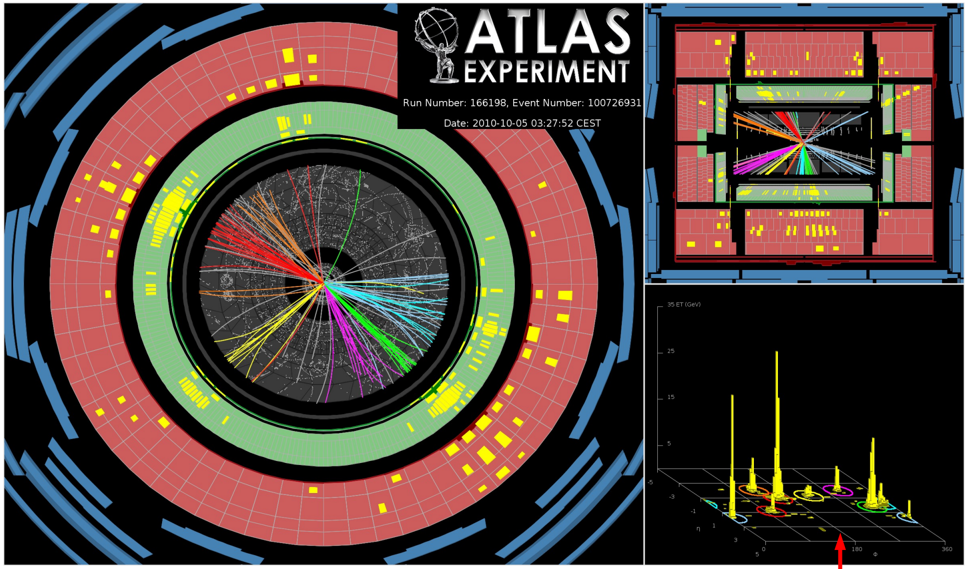
Introduction

Physics of Interest

- Many new physics models have jet final states.
- Covered in this talk:
  - Composite quark
    - Di-jet angular distribution (χ distribution) [arXiv:1009.5069v1]
  - TeV scale gravity
    - Multi-object final states with large M_{inv} [ATLAS-CONF-2010-088]
- Covered in other Kruger2010 contributions:
  - SUSY
    - Jets + MET (Xuai Zhuang's Talk)
  - Composite quark
    - Di-jet resonances & centrality ratio (Reyhaneh Rezvani's talk)

Jet Reconstruction

- Anti-Kt algorithm
  - R=0.6 (0.4) for di-jet (multi-object) analysis
  - Collinear & infrared safe
- Jet input: topological clusters
  [JINST 3 S08003 (2008)]
  - Provides noise suppression
- Calibration:
  - EM scale
  - Correction derived from MC
    [ATLAS-CONF-2010-056]
    - η & p_T dependent
- Jet Energy Scale
  [ATLAS-CONF-2010-056]
  - Main systematic uncertainty
  - η/p_T dependent
  - 5-7% for di-jet analysis
  - Up to 9% for multi-body analysis



How to group energy deposits into jets?

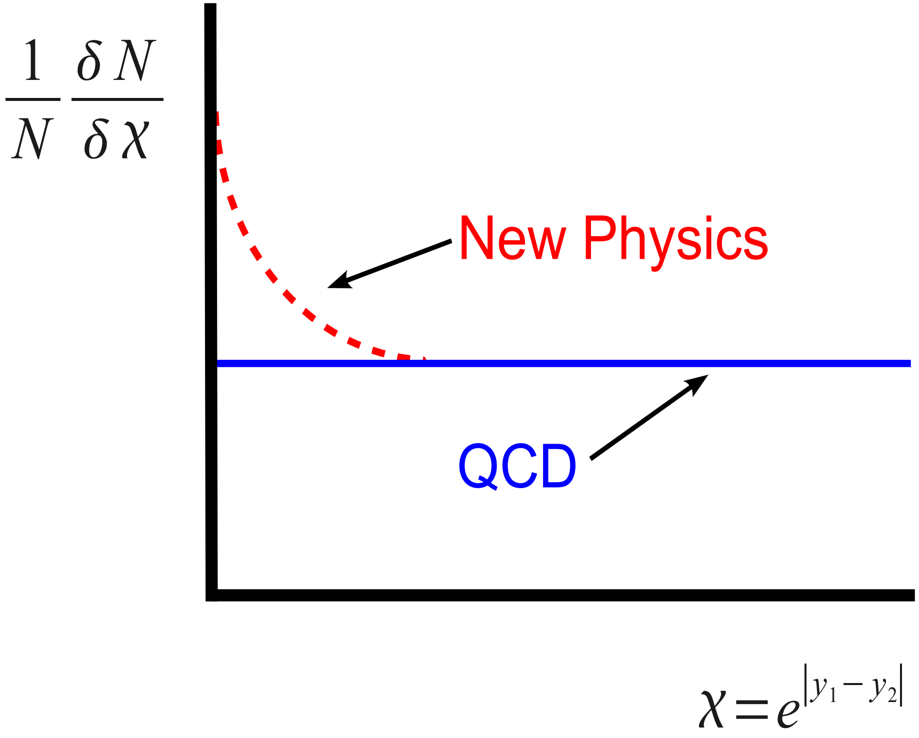
Composite Quark Search

Quark Compositeness

- Are quarks composite objects?
  - For example, made of “preons?”
- If so, expect to see effects of this above an energy scale (Λ)
  - Below Λ quarks appear point like
- Search for deviations in di-jet angular distributions from QCD predictions.
  - Evidence of 4 fermion contact interaction if this is seen.
  - If not, set a limit on Λ

Di-Jet Angular Distribution

- Observable: χ
- ~Flat for LO QCD
  - Rutherford Scattering!
- Expect rise at low χ for compositeness
  - Due to a more isotropic angular distribution
  - The mathematical details are in the backup slides
- Note: also an excess of events at low χ from higher order QCD
  - Can test NLO QCD predictions through events with low invariant mass.



Event Selection

- Pre-selection: Data quality requirements, non-collision background cleaning cuts, reject events with poorly reconstructed jets
  - Details in the backup slides
- Additional constraints:
  - $y^* \leq 1.7$ and $y_B \leq 0.75$, where $y^* = ½(y_1 - y_2)$ and $y_B = ½(y_1+y_2)$
    - This limits the jets to $|\eta|<2.45$, and $\chi<30$
    - **Acceptance flat in χ for this region**

Binning

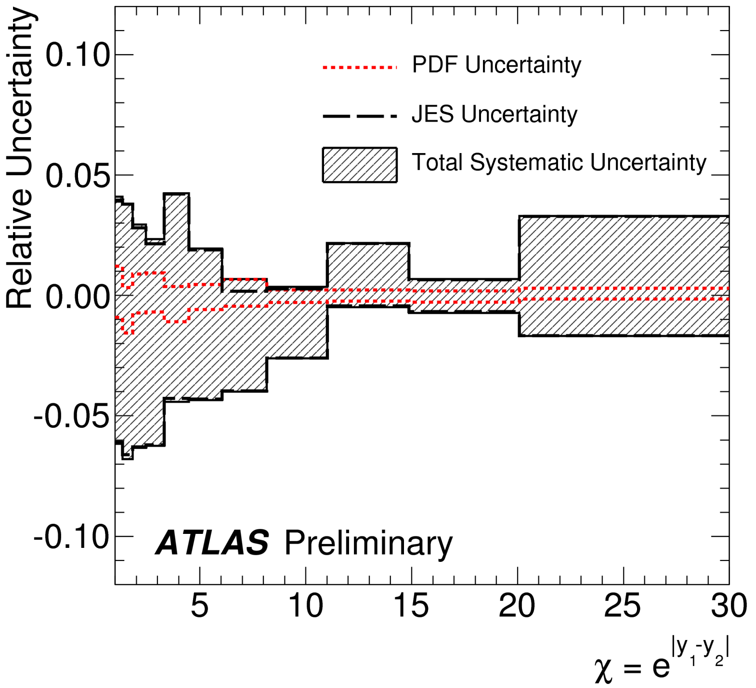
- Angular Binning
  - Fine binning corresponding to detector segmentation
- Invariant Mass (m_{jj}) Binning
  - Low m_{jj} bins give QCD shape
  - High m_{jj} bins sensitive to new physics
  - Different trigger per bin → effective luminosity varies by bin

Invariant Mass Bin	∫L (pb^{-1})
340 GeV < m_{jj} < 520 GeV	0.12
520 GeV < m_{jj} < 800 GeV	0.56
800 GeV < m_{jj} < 1200 GeV	2.0
1200 GeV < m_{jj}	3.1

$$m_{jj} = \sqrt{(E^{j1} + E^{j2})^2 - (\vec{p}^{\,j1} + \vec{p}^{\,j2})^2}$$

Systematic Uncertainties

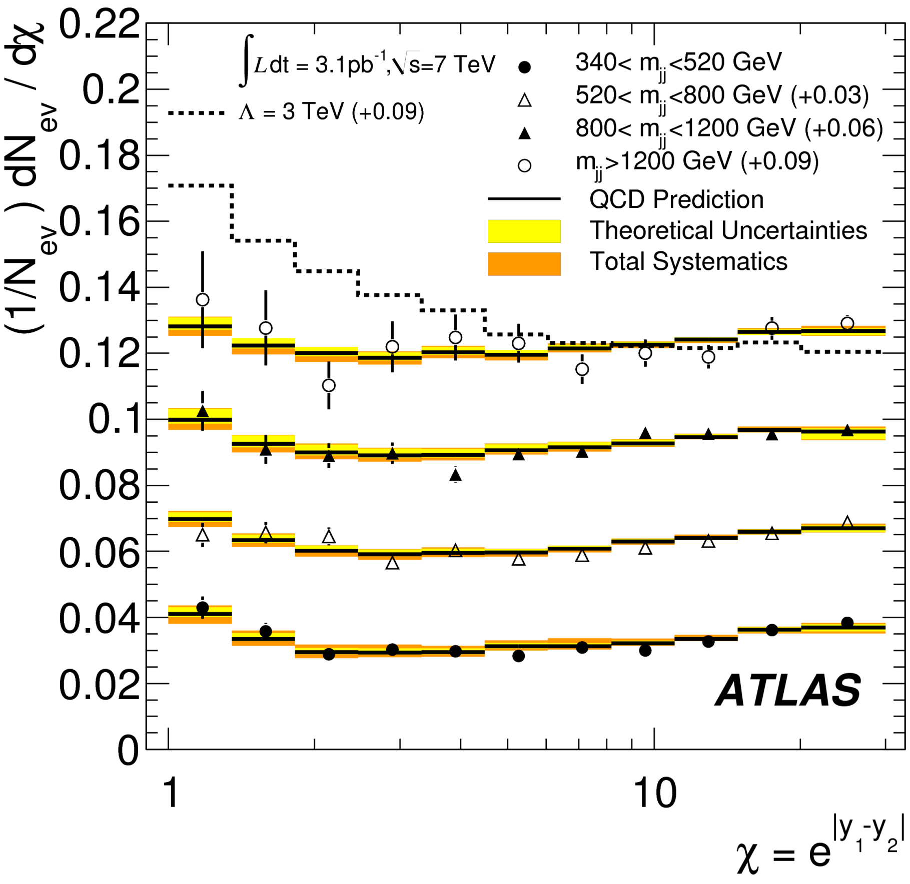
- Jet Energy Scale: 5-7%
  - **Dominant uncertainty**
  - up to 9% uncertainty/bin
- Theoretical Uncertainties
  - NLO QCD renormalization & factorization scales
    - μ_R & μ_F varied independently between 0.5, 1 & 2 times the average jet p_T
    - 3% uncertainty/bin
  - PDFs
    - Use CTEQ6.6 PDF error sets
    - 1% uncertainty/bin
- Total Uncertainty
  - Convolute uncertainties via MC pseudo-experiments
  - Gives 1 σ error bands on MC prediction



Relative systematic uncertainties of QCD χ spectra prediction for 520 < M_{jj} < 680 GeV.

Data vs. Theory

- Each m_{jj} bin given an offset for display purposes
  - Only interested in the shape
- Errors:
  - 1 σ error bands from pseudo-experiments
  - Statistical error from Poisson distribution
- Good agreement with QCD.
  - Chi-square is ~ 1 per degree of freedom for all m_{jj} bins

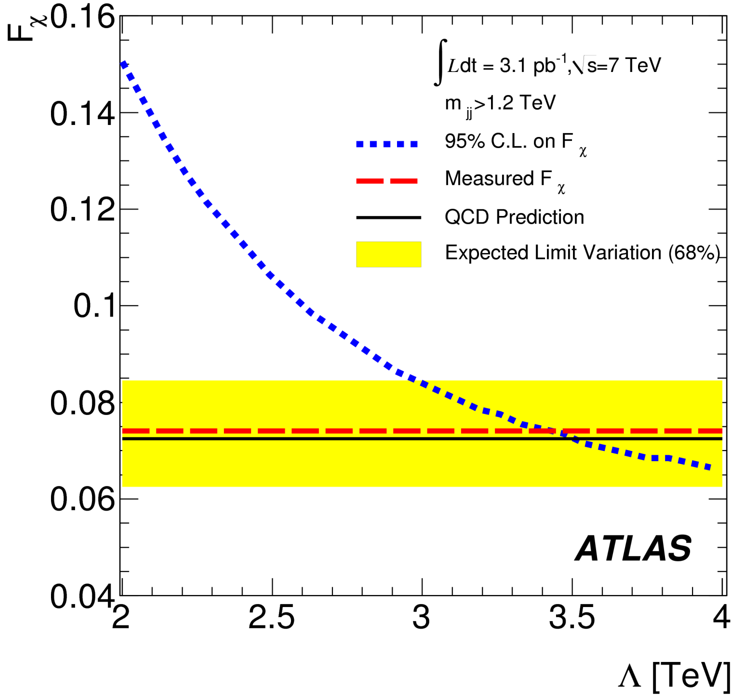


Exclusion limit

- Frequentist analysis
- Define variable F_χ:

$$F_\chi = \frac{N_{events}(\text{first 4 bins})}{N_{events}(\text{all bins})}$$

  - $0<\chi<3.32$ for first 4 bins
  - $0<\chi<30$ for all bins
- Simulate several samples with various $1/\Lambda^2$ values and interpolate between their 95% confidence level intervals for F_χ
  - QCD equivalent to $\Lambda=\infty$
- Exclusion where F_χ 95% CL curve crosses measured F_χ
- Expected limit where F_χ 95% CL curve crosses Monte Carlo F_χ



achieved limit: $\Lambda \geq$ 3.4 TeV
(length scale of 6×10^{-5} fm)
expected limit: $\Lambda \geq$ 3.5 TeV

TeV Gravity Search

TeV Scale Gravity

- Hierarchy problem: $M_{EW} \sim 100$ GeV vs $M_{Pl} = (\hbar c / G)^{1/2} \sim 10^{19}$ GeV
- Large Extra Dimensions (ADD models):
  - N extra dimensions of size R where only gravity can propagate
- Get a new scale $M_D \sim 1$ TeV
- Continuous spectrum of black holes possible above M_D
- Other phenomena (such as sting balls) are also possible

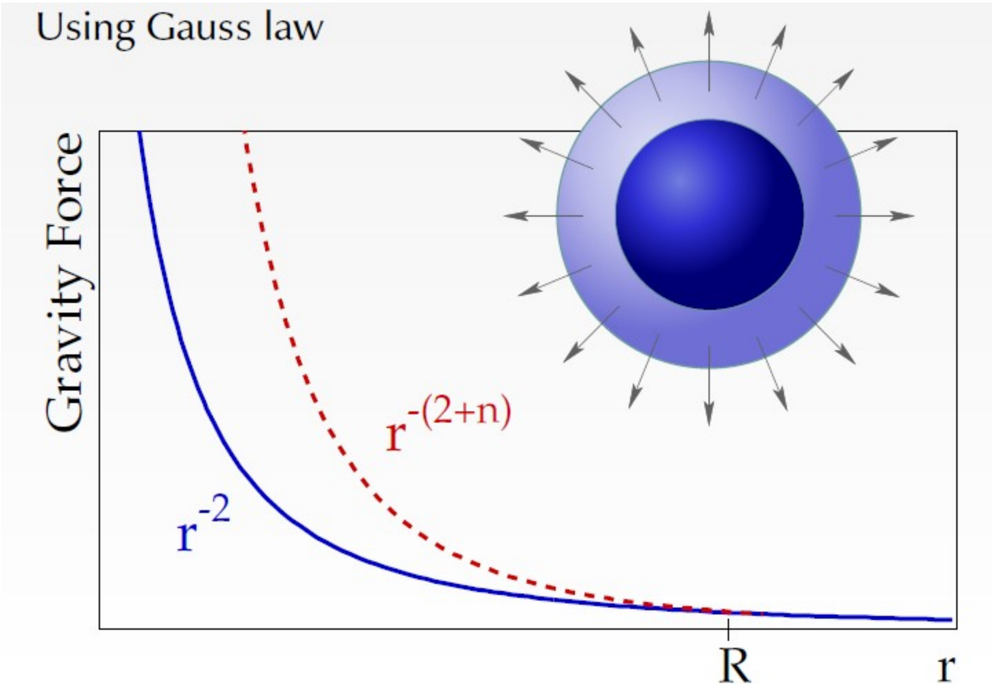


Image credit: Victor Lendermann

$$M_{Pl}^2 \sim M_D^{n+2} R^n$$

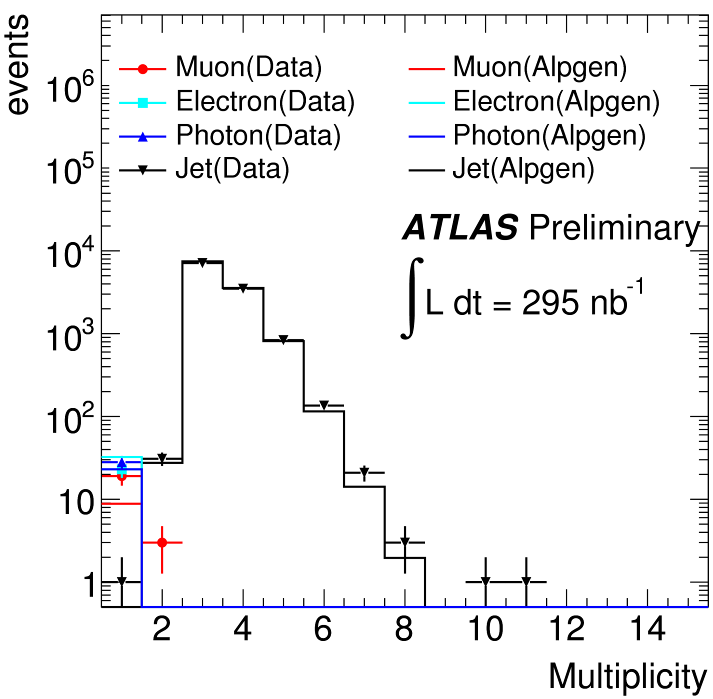
Multi-Body Final States

- General signature of TeV gravity models
  - Black holes and string balls decay by Hawking Radiation
- Expect large deviation from the Standard Model
- Observable:

  Invariant mass (**M_{inv}**) in high multiplicity events

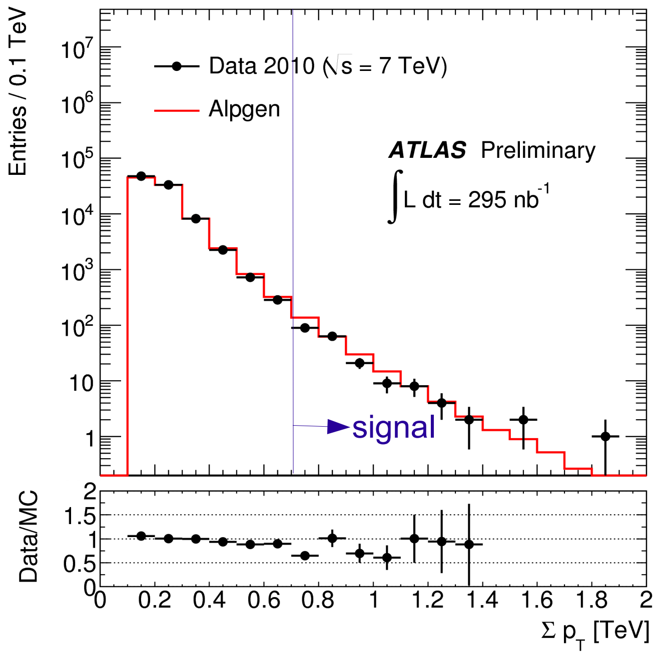
$$M_{inv} = \sqrt{|p^{\mu} p_{\mu}|} \text{ where:}$$
$$p^{\mu} = \sum_{i=objects} p_i^{\mu} + (E_T^{miss}, E_x^{miss}, E_y^{miss}, 0)$$

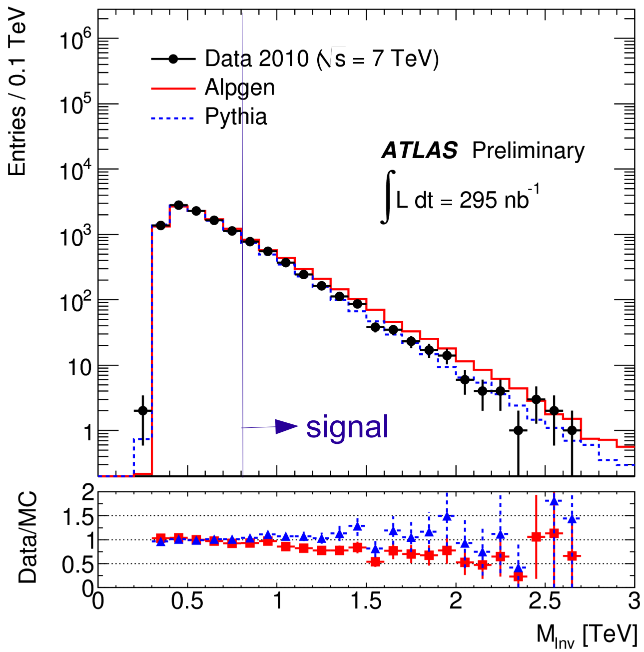
- Select events with ≥ 3 high p_T objects.
  - e/γ (p_T>20 GeV)
  - Jets (p_T>40 GeV)
  - μ (p_T>20 GeV)
- Dominated by jets!



Signal vs Control Region

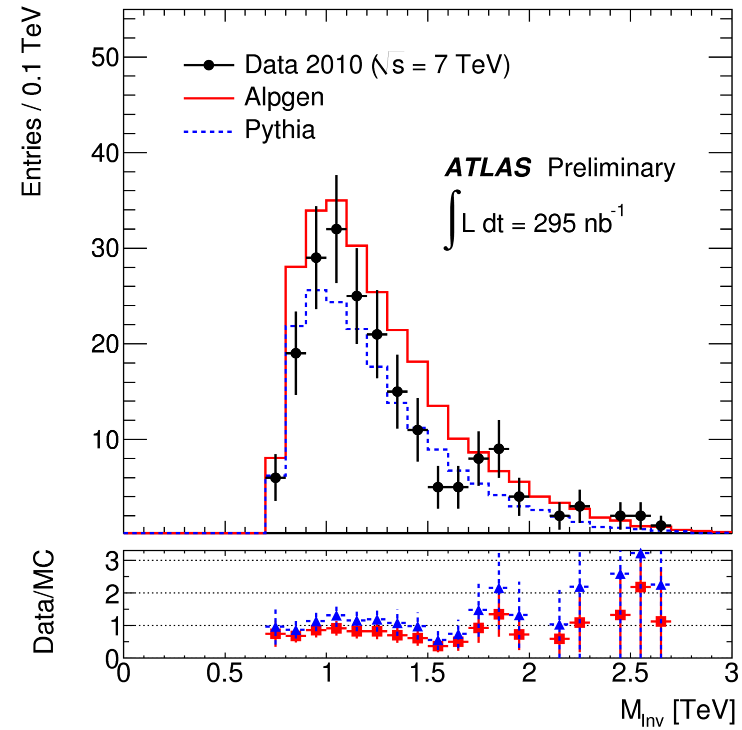
- Previous limits constrain M_D>800 GeV
- Signal Region: $\sum p_T$ > 700 GeV, M_{inv} >800 GeV
  - 193 events (all jets!) for a integrated luminosity of 295±32 nb^{-1}
- Control Region: $\sum p_T$ > 300 GeV, 300 GeV > M_{inv} >800 GeV
- Normalize QCD MC to data in control region
  - 254 events





Systematic Uncertainties

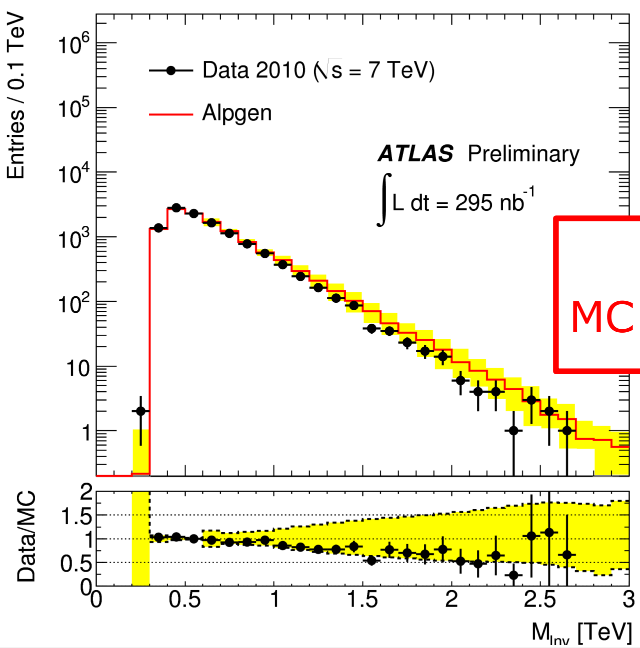
Quantity	Value	Uncertainty	Uncertainty [%]
	Data		
Observed events	193		
Luminosity [nb^{-1}]	295	± 32	$\pm 11\%$
	Estimated Background		
ALPGEN	254	± 18	6.9%
PYTHIA	174	± 11	6.2%
Background (statistical)	254	± 18	6.9%
	Systematic Uncertainties		
Background (QCD)		± 66.5	26%
PDF (choice)			$\pm 12\%$
PDF (error set)			$+6.8\%$
PDF (error set)			-5.2%
Control region			$\pm 10\%$
Un-simulated backgrounds			$\pm 0.6\%$
Including e, γ, μ			$\pm 0.2\%$
Missing transverse energy			$\pm 0.02\%$
JES			$\pm 11.0\%$
JES (MET)			$\pm 0.5\%$
JER			$\pm 0.6\%$
Systematic uncertainty		$+84$	$+33\%$



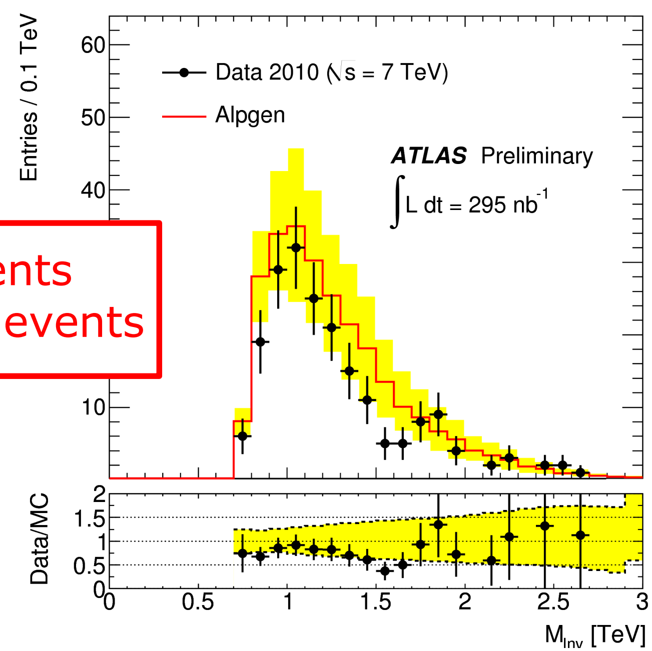
Shown here are the Alpgen and Pythia QCD predictions after normalizing the Monte Carlo to data in the control region.

Results

- The M_{inv} distribution for $\Sigma p_T > 300$ (700) GeV is shown on the left (right)
- The Monte Carlo is normalized to the data in the control region ($\Sigma p_T > 300$ GeV, 300 GeV < M_{inv} < 800 GeV)
- Good agreement is seen between data and Monte Carlo
  - Next: set a limit on new physics



Data: 193 events
MC: 254±18±84 events



Limit on New Physics

- Bayesian analysis
  - Flat prior p.d.f. for # of signal events
- Upper limit obtained for σ·A=0.34 nb at 95% CL
  - 0.32 nb if pile up contribution is subtracted
- Benchmark models used to estimate upper limit on σ
  - CHARYBDIS 2 and BLACKMAX 2 event generators [arXiv:0904.0979], [arXiv:0711.3012]
  - 58% acceptance for BLACKMAX
    - CHARYBDIS samples give similar acceptance (within 4%)
- Suggests upper limit on σ of ~0.6 nb
  - Significantly lower than some optimistic theoretical models (predict σ~100 nb)

Conclusions

- Di-jet angular distributions were used to constrain the quark compositeness scale (Λ)
  - **Λ > 3.4 TeV**
  - Compare with:
    - D0 limit of Λ>2.8 TeV [PRL 103:191803,2009]
    - CMS limit of Λ>4.0 TeV [arXiv:1010.4439v1]
- Multi-body final states were used to set a limit on σ·A for new physics decaying into these states
  - **σ·A < 0.34 nb**
- These limits were set using only part of the currently available statistics
  - Stay tuned for updates!

Backup Slides

Event Generators & PDFs I

- Di-jet analysis
  - QCD Simulation
    - Event Generator: Pythia 6.4.21
    - Parameter Tune: ATLAS MC09
    - PDFs: MRST2007 (modified LO PDF)
  - Correcting for NLO effects
    - Create bin-by-bin correction factors (K-factors) from the ratio of $NLO_{ME}/Pythia_{SHOW}$
      - NLO_{ME} uses NLOJET++ event generator and the NLO PDFs from CTEQ6.6
      - $Pythia_{SHOW}$ uses Pythia restricted to LO matrix elements and parton showering using the modified LO MRST2007 PDF
    - Multiply full Pythia angular distribution prediction by K-factors
      - Spectrum now includes NLO matrix element corrections while keeping non-perturbative effects from Pythia.
      - Change distributions by up to 6% (similar for all invariant mass bins)

Event Generators & PDFs II

- Multi-body analysis:
  - QCD Event Generators: Pythia6.421 & Alpgen2.06
    - Alpgen combined with Jimmy 4.3 for underlying event simulation and Herwig 6.510 for the parton shower.
    - LO Herwig and Herwig++ also used for comparison
    - Note: Pythia produces 2 hard jets using LO matrix elements, Alpgen produces up to 6 jets in the final state.
  - ttbar Event Generator: MC@NLO
  - Parameter Tune:
    - ATLAS MC09 Pythia tune is the baseline
    - Alternative fragmentation model for uncertainty calculation
    - Alternative underlying event model for uncertainty calculation (Perugia0 tune for Pythia)
  - PDFs:
    - MRST 2007 LO* used with Pythia, Herwig and Herwig++
    - CTEQ 6 L1 used for Alpgen
    - CTEQ 6.6 used for MC@NLO, BLACKMAX and Charybdis

Event Selection (Di-jet Analysis)

- Require:
  - Stable LHC beam and ATLAS conditions
  - Single jet trigger
  - 1 primary collision vertex with # tracks ≥ 5 and $|z|<30$ cm
  - Leading jet p_T > 60 GeV, sub-leading jet p_T > 30 GeV
    - Both jets with $|\eta|<2.8$
    - Both jets passing quality cuts (i.e. in time)
  - No poorly reconstructed jets with p_T > 15 GeV
- Additional constraints:
  - $y^* \leq 1.7$ and $y_B \leq 0.75$, where $y^* = ½(y_1-y_2)$ and $y_B = ½(y_1+y_2)$
    - This limits the jets to $|\eta|<2.45$. Note this is larger eta range than for R_c

(back to the talk)

Contact Interaction Model

- For composite quarks, effects should appear below a energy scale (Λ)
- If $\Lambda > \sqrt{s}^{1/2}$ these interactions would be suppressed & quarks appear point like → dominant effect then from 4 fermion contact term
- 4 fermion contact interaction Lagrangian:

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

  - $g^2/4\pi = 1$, Ψ left handed
  - Destructive interference with QCD ($\xi = +1$)
    - Exclusion limits change by ~1% depending on choice of constructive/destructive
- This model may also apply to other BSM processes, but with difference in coupling.

(back to the talk)

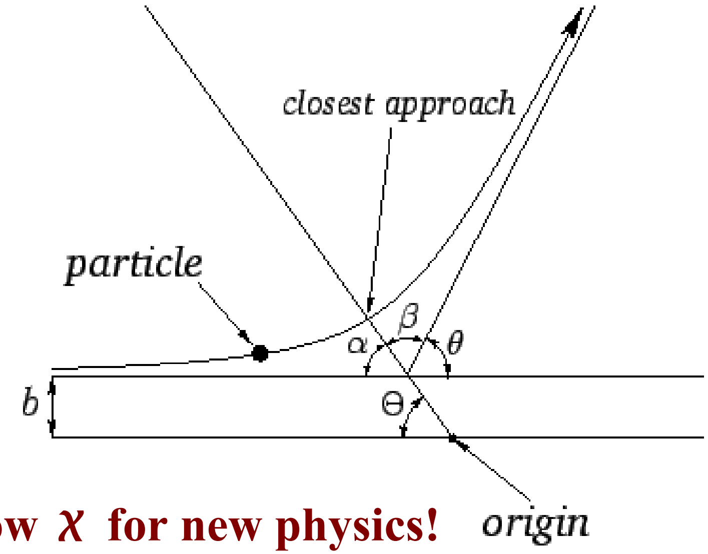
Chi Distributions

- For LO QCD, get Rutherford scattering in the center-of-mass frame:

$$\frac{d\hat{\sigma}}{d\cos\theta^*} \sim \frac{1}{\sin^4(\theta^*/2)}$$

- New physics expected to be more isotropic.
- Useful variable is χ: removes Rutherford singularity, uses variables in the lab frame & is invariant under a Lorentz boost:

$$\chi = \exp(2|y^*|) = \exp(|y_1 - y_2|) = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$



- For Rutherford scattering:

$$\frac{d\hat{\sigma}}{d\chi} \sim \text{constant} \Rightarrow$$ **flat distribution for LO QCD!**

- For isotropic distribution

$$\frac{d\hat{\sigma}}{d\cos\theta^*} \sim constant \Rightarrow \frac{d\hat{\sigma}}{d\chi} \sim \frac{1}{(1+\chi)^2} \Rightarrow$$ **expect rise at low χ for new physics!**

(back to the talk)

Event Selection (Multi-Body Analysis)

- Require:
  - Stable LHC beam and ATLAS conditions
  - L1 (hardware) jet trigger p_T>15 GeV
  - 1 primary collision vertex with # tracks ≥ 5 and |z|<15 cm
  - 3 high p_T objects:
    - e (p_T>20 GeV, $|\eta|<2.47$)
    - γ (p_T>20 GeV, $|\eta|<2.37$)
    - Jets (p_T>40 GeV, $|\eta|<2.8$)
      - Jets need to pass quality cuts
    - μ (p_T>20 GeV, $|\eta|<2.0$)

(back to the talk)

Clustering Jet Algorithms

(back to the talk)

- Start with list of vectors (topoclusters, towers, etc)
- Define a distance:

$$D_{ij} = min(P_{Ti}^{2p}, P_{Tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \quad D_i = P_{Ti}^{2p}$$

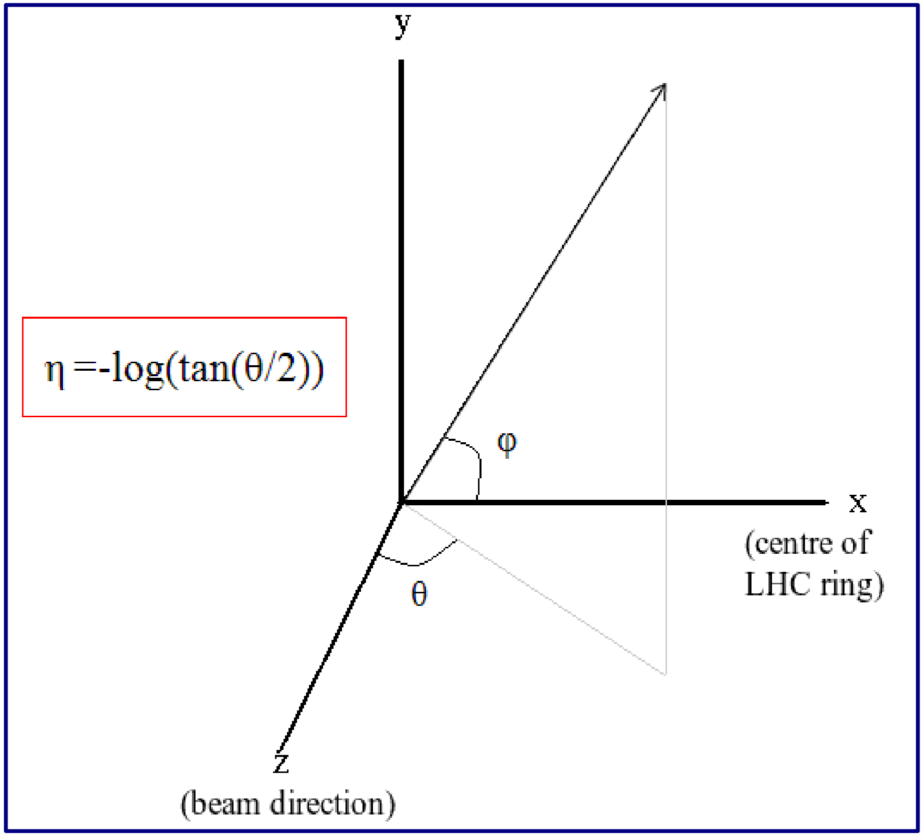
  where R_{ij} is the distance in eta-phi space and R is a size parameter (typically 0.4 or 0.6 in ATLAS)
- Compute $\{D_{ij}, D_i\}$ and $d = min(\{D_{ij}, D_i\})$ for all input vectors
  - if $d = D_{ij}$, combine vector i with vector j and return to the list of vectors
  - if $d = D_i$, vector i is a final jet
- Continue until all input vectors are clustered into final jets
- Three different variants:
  - p=1: Standard kt algorithm
  - p=0: Cambridge algorithm
  - p=-1: Anti-kt algorithm → **used in ATLAS!**
- The anti-kt algorithm essentially starts with the highest p_T input and checks if there is another input within R. If so, it merges them and starts the process again. If not, this input is added to the list of jets.

ATLAS Coordinate System

The ATLAS coordinate system measures position in terms of pseudorapidity (η) and ϕ with a distance measure given by:

$$\Delta R = (\Delta\eta^2 + \Delta\phi^2)$$

These variables are as described on the plot below.



Pseudorapidity may also be written as:

$$\eta = \frac{1}{2}\ln\left(\frac{|\vec{p}|+p_z}{|\vec{p}|-p_z}\right)$$

In the limit of a massless particle, this is the same as the rapidity (y):

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

Note Δy is relativistically invariant.