Determination of the strong coupling constant from multi-jet production with the ATLAS detector

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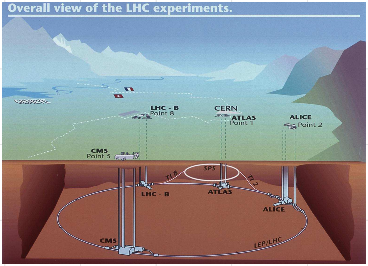
ATLAS & LHC

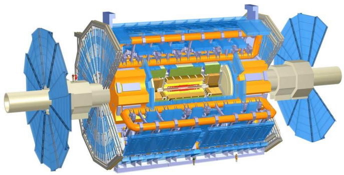
LHC

- Proton-proton collider with 7 TeV center-of-mass energy
- Currently in operation
- Located 50-150m under the Swiss-French border just outside Geneva



ATLAS

- One of 4 main experiments taking place at the LHC
- Multi-purpose particle detector
- Collaboration of $\sim$3000 scientists from 38 countries & 174 universities and labs



Analysis

Goals

- Measure the QCD strong coupling constant α_S
- Study the running of the strong coupling at energies $>$ 209 GeV

Approach

1. Calculate the inclusive ratio distribution

$$R_{3/2} = \frac{\sigma_{N_{jets} \geq 3}}{\sigma_{N_{jets} \geq 2}}$$

   in data at the particle level
2. Match $R_{3/2}$ to next-to-leading order (NLO) predictions at particle level & extract a value for QCD's strong coupling α_S
   - Predictions generated from the ratio are largely independent of PDFs, allowing the study of α_S at energies $>$ 209 GeV

Analysis Cuts and Parameters

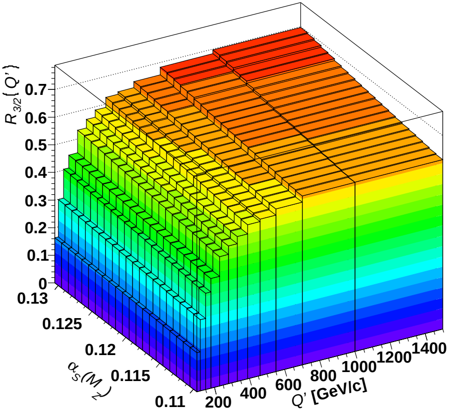
Analysis Cuts

- All jets $p_T > 40$ GeV & $|\eta| < 2.8$
- Leading jet $p_T > 60$ GeV
- Exactly 1 primary vertex with more than 5 tracks
- ATLAS' pre-defined loose jet quality cuts (hadronic end-cap spikes, coherent noise, non-collision background) (bad/ugly jets)
- Data quality cuts recommended by ATLAS' standard model group

Analysis Parameters

- **Data**: ATLAS' 2010 periods A to I ($\sim 38\mathrm{pb}^{-1}$)
- **Triggers**: A combination of all of ATLAS' single jet triggers
- **Jet algorithm**: Anti-$\mathrm{k_t}$ 0.6 jets built from topological clusters & corrected for η offset and jet energy scale (JES)
- **Independent variable**: $Q' = \sqrt{\sum_{j=0}^{N_{jets}} \left(p_T^{(j)}\right)^2}$

NLO Predictions

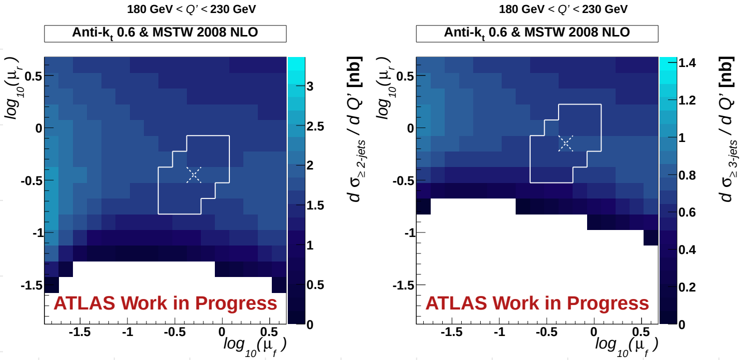


ATLAS Work in Progress

NLOJet++

- Generate 2 & 3 jet NLO samples with different $\alpha_S(M_Z)$ values & matching PDF
  - 100M events / sample
- Use MSTW08nlo90cl PDF set ($0.110 \leq \alpha_S(M_Z) \leq 0.130$)
- Compute $R_{3/2}(Q')$ for each $\alpha_S(M_Z)$ value
- Hard scale parametrization choice consistent with independent variable (Q')

NLO Calculations



Application of the principle of minimal sensitivity

Find the renormalization ($\mu_R = \mu_r \cdot Q'$) and factorization ($\mu_F = \mu_f \cdot Q'$) scales corresponding to the most stable NLO predictions, i.e. the saddle point.

NLO Uncertainties

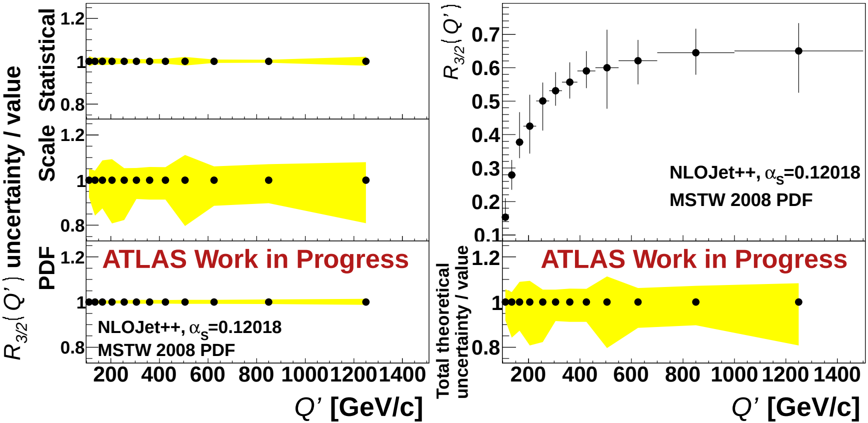
Relative uncertainties

- **Scale**: Obtained by varying the renormalization and factorization scales independently according to
  - $\mu_r^{(saddle)}/2 \leq \mu_r \leq 2 \cdot \mu_r^{(saddle)}$
  - $\mu_f^{(saddle)}/2 \leq \mu_f \leq 2 \cdot \mu_f^{(saddle)}$
  - $\mu_r/2 \leq \mu_f \leq 2\mu_r$
- **PDF**: Obtained by generating 100M events with the full eigenvector PDF sets and combining the resulting $R_{3/2}$ values with the 'master' equation

$$\Delta X^+_{max} = \sqrt{\sum_{i=0}^{N} \left[max\left(X_i^+ - X_0, X_i^- - X_0, 0\right)\right]^2} \quad (1)$$

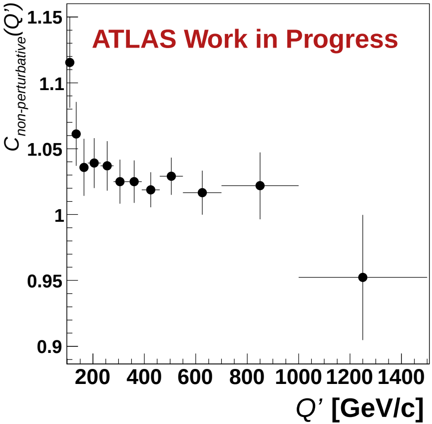
$$\Delta X^-_{max} = \sqrt{\sum_{i=0}^{N} \left[max\left(X_0 - X_i^+, X_0 - X_i^-, 0\right)\right]^2} \quad (2)$$

NLO Uncertainties (continued)



NLO theoretical uncertainties are dominated by the scale uncertainty

AlpGen Parton $\rightarrow$ Particle (Truth) Level

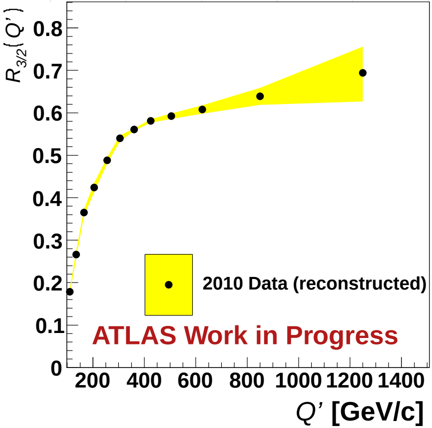


Details

- NLO results do not include any hadronization or underlying event (UE)
- Use AlpGen+Herwig/Jimmy samples to calculate corrections, and AlpGen+Pythia samples to estimate a model uncertainty
- Compute a correction factor $C_{non-perturbative}$ as $\frac{R_{3/2}(particle+UE, AlpGen)}{R_{3/2}(parton+noUE, AlpGen)}$

$$R_{3/2}(particle) = C_{non-pertubative} \cdot R_{3/2}(parton)$$

Accounting for Trigger

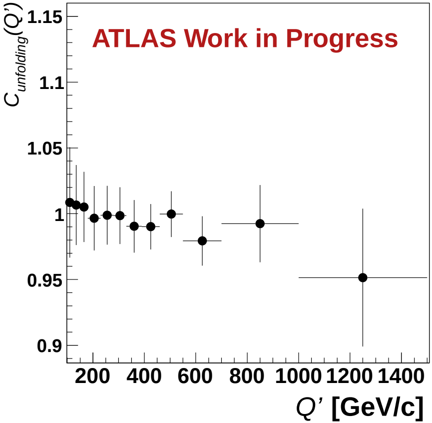


Details

- Use single jet triggers
  - Jet p_T selection criteria range from 10 to 95 GeV
- Use a single trigger per bin
  - Trigger must be fully efficient
  - Use trigger with smallest prescale
- Assign each event a weight

$$w = \frac{1}{\text{prescale}}$$

Detector → Particle (Truth) Level Unfolding

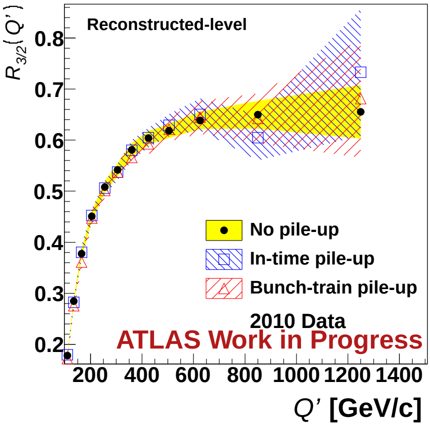


Approach

- Use AlpGen+Herwig/Jimmy sample to compute unfolding factor's value $C_{unfolding}$ as $\frac{R_{3/2}(particle)}{R_{3/2}(reconstructed)}$
- Estimate uncertainty on factor by computing it from AlpGen+Pythia and Pythia samples
- Take maximum shift in each bin used as symmetric uncertainty

$$R_{3/2}(particle) = C_{unfolding} \cdot R_{3/2}(reconstructed)$$

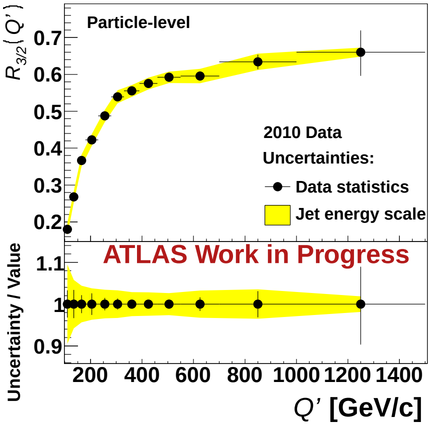
Estimating Pile-Up Effect in Unfolding



Approach

- Use Monte-Carlo sample without pile-up for unfolding
  - Calculate an uncertainty on reconstructed $R_{3/2}$ due to pile-up
- Compute $R_{3/2}$ with in-time & bunch-train pile-up samples
- Take the maximum shift in each bin as additional uncertainty due to pile-up on reconstructed $R_{3/2}$
- Propagate additional uncertainty to unfolded ratio

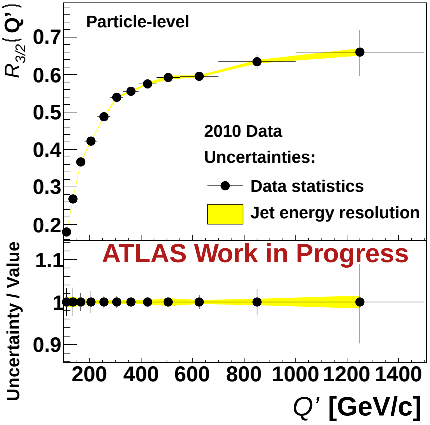
Jet Energy Scale (JES)

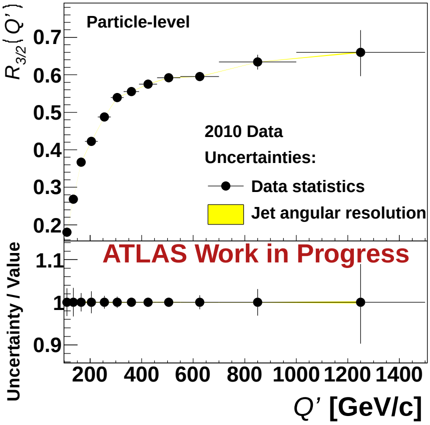


Toy Monte-Carlo Approach

- Vary jet p_T in AlpGen by an amount proportional to the jet's JES uncertainty
- Use the same proportionality factor for all jets per toy MC iteration
- Unfold the data using the modified MC sample
- The standard deviation is calculated for each point and used as JES uncertainty on the unfolded ratio

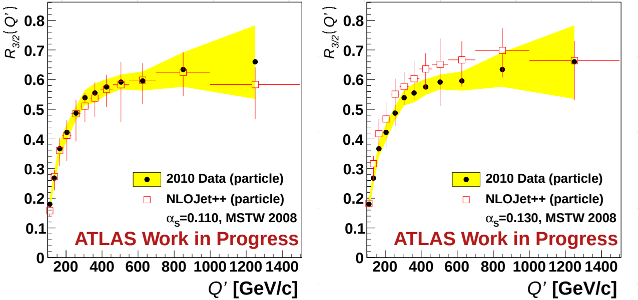
Jet Energy Resolution (JER) & η Resolution





- A similar toy MC approach to the JES calculation is used
- The jet p_T and η are varied independently in Monte-Carlo

α_S Measurement Procedure



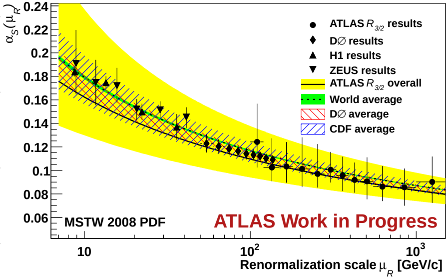
Least-squares fit with Hessian approach

Define the chi-squared function as

$$\chi^2 = \sum_i \frac{\left[R_{3/2}^{(theory)}(\alpha_S(M_Z), i) - R_{3/2}^{(measured)}(i) + \sum_\lambda s_\lambda \Delta_{i\lambda}^{(correlated)}\right]^2}{\sum_{\lambda'} \left[\Delta_{i,\lambda'}^{(uncorrelated)}\right]^2} + \sum_\lambda s_\lambda^2,$$

where $\Delta_{i\lambda}$ are correlated and uncorrelated uncertainties for each Q' bin i, and s_λ are nuisance parameters associated with each correlated source of uncertainty λ.

α_S Measurement Procedure



$\alpha_S(M_Z)$ results:

ATLAS $R_{3/2}$ fit: $0.111^{+0.029}_{-0.016}$

World average: 0.1184 ± 0.0007

DØ: $0.1161^{+0.0041}_{-0.0048}$

CDF: $0.1178^{+0.0081}_{-0.0095}$

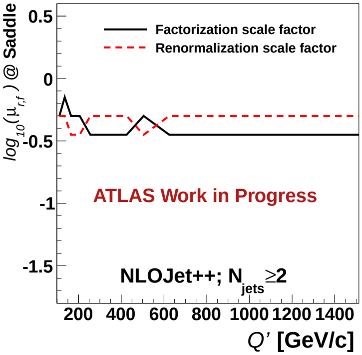
- Obtain an $\alpha_S(M_Z)$ measurement in each Q' bin, then evolve it with a 2-loop approximation of the renormalization group equation solution
- Obtain an overall $\alpha_S(M_Z)$ measurement by fitting all bins simultaneously

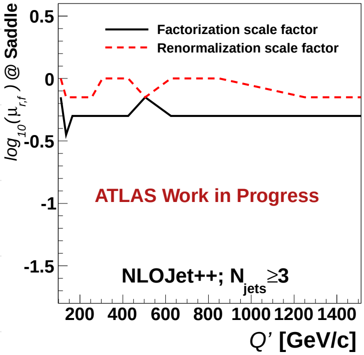
Conclusion

Summary

- Measured $R_{3/2}$ distributions in good agreement with with NLO predictions from NLOJet++
  - The application of the principle of minimal sensitivity is a robust method to tune renormalization and factorization scales in NLO predictions
- $\alpha_S(M_Z)$ results in statistical agreement with the world average and results from similar measurements at CDF and DØ
- Results are consistent with the running of the coupling as predicted by the RGE
  - Running of the coupling observed for the first time at energy scales > 209 GeV
- ATLAS note & paper preparation in progress for 2012 approval

Backup - Variations in optimal μ_r & μ_f

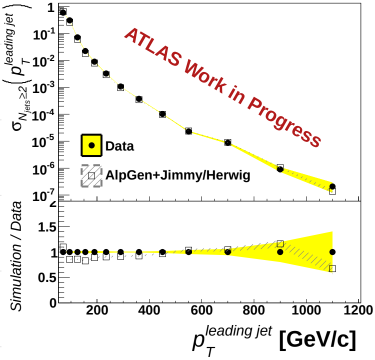


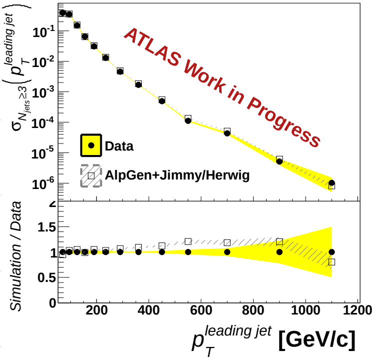


Details

Renormalization (μ_r) and factorization (μ_f) scales optimized by applying the principle of minimal sensitivity

Backup - Raw differential cross-section distributions





Details

- Uncertainties are only statistical
- Distributions are corrected for triggering effects but are otherwise un-altered

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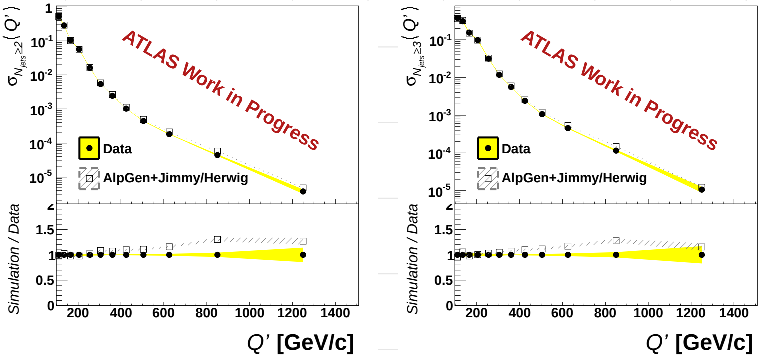

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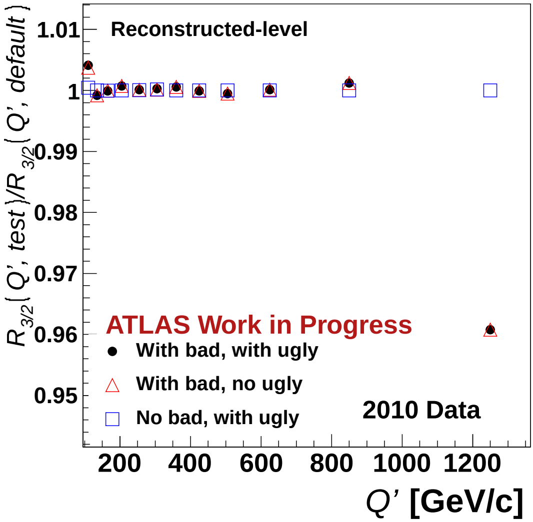
- Distributions are corrected for triggering effects but are otherwise un-altered

Backup - Systematic uncertainties

	Type of Uncertainty		Correlated
Data Measurement	Data Statistics		No
	Trigger Selection		Yes
	Jet Energy Scale		Yes
	Jet Energy Resolution		Yes
	Angular Resolution		Yes
	Jet Quality		Yes
	Unfolding Correction	Jet Energy Scale	Yes
		Jet Energy Resolution	Yes
		Angular resolution	Yes
		Pile-up	No
		Monte-Carlo Modelling	No
		ALPGEN Statistics	No
Theoretical Predictions	NLOJET++ Statistics		No
	Scale		Yes
	PDF		Yes
	Non-pQCD correction factor	ALPGEN Statistics	No
		Monte-Carlo Modelling	Yes

List of all sources of uncertainties considered in the analysis, and whether they are treated as correlated between Q' bins.

Backup - Uncertainty from jet quality requirements



Backup - $R_{3/2}$ agreement between data and NLO predictions