QCD Studies with the ATLAS Detector

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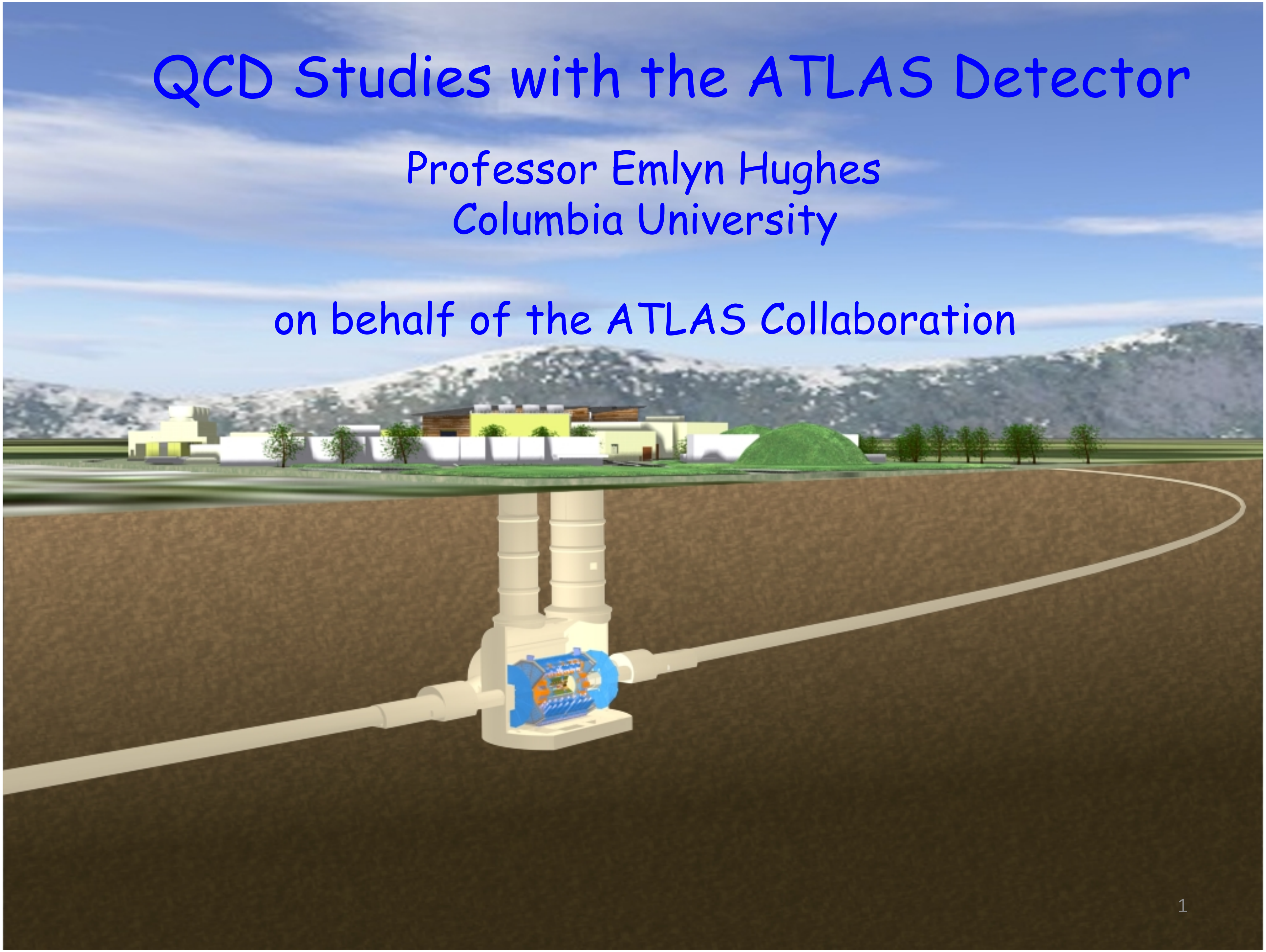
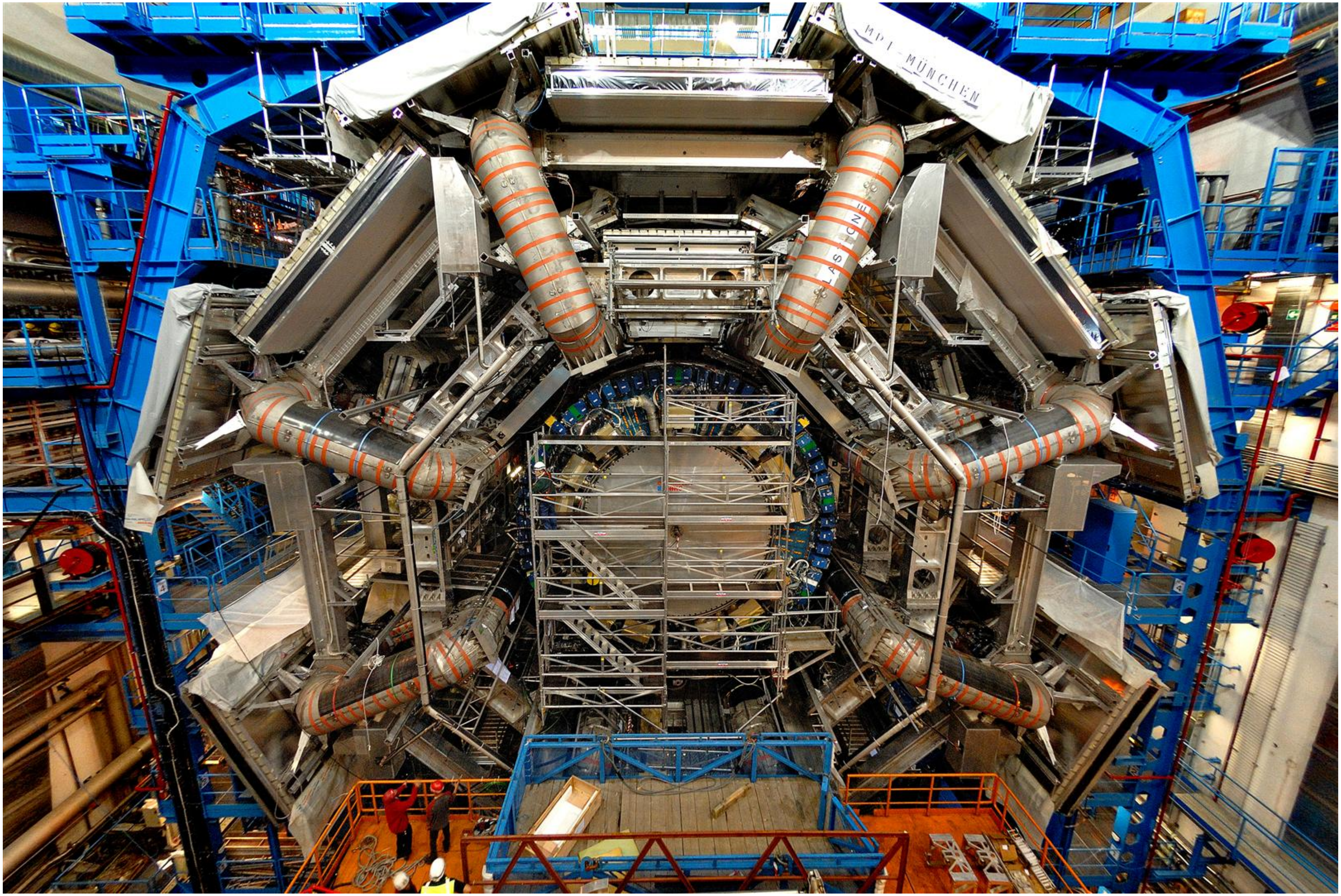
Columbia University

on behalf of the ATLAS Collaboration




MPI-MÜNCHEN

Motivation for QCD Studies

- * Fundamental tests of QCD in a new energy regime
  - → comparison to NLO pQCD calculations
  - → measurement of α_s
- * Understanding backgrounds in searches
  - → Testing leading-order (LO) and next-to-leading order (NLO) Monte Carlo simulations
  - → ATLAS detector performance

OUTLINE

I. Jets

II. Inclusive Jet Studies

III. Multijet Studies

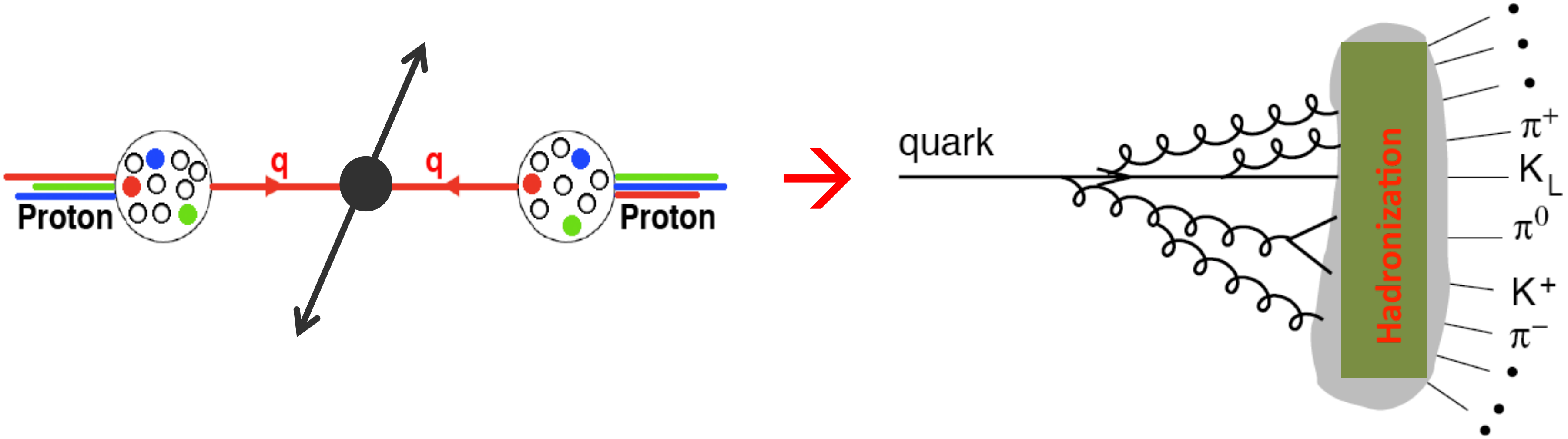
IV. Z + Jets Studies

V. W + Jets Studies

VI. Recent Soft QCD Publications

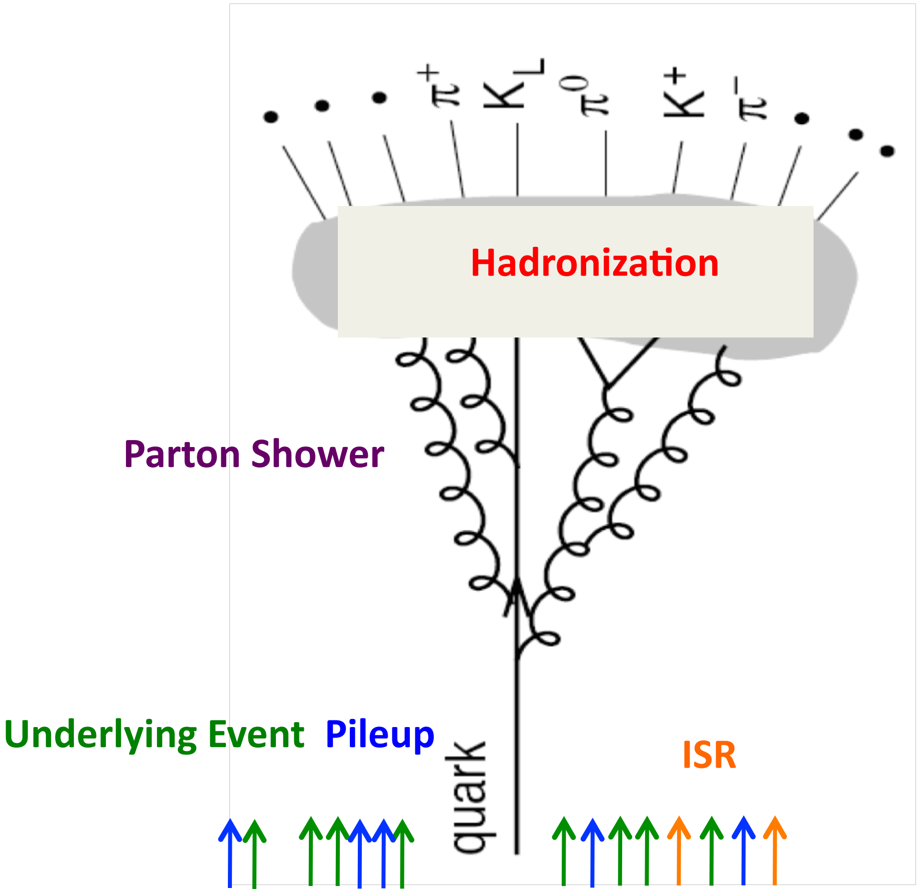
Jets

A jet is a collimated group of particles travelling in the same direction as the original parton:



$$\frac{d^2\sigma}{dp_T dy} = \frac{N_{jets}}{\Delta p_T \Delta y \cdot L}$$

Non-Perturbative QCD



We never observe partons!

- **Parton shower** gluon emission, quark/antiquark pairs
- **Hadronization** partons combine into hadrons
- **ISR**: initial state radiation
- **Underlying event**: parton-parton interactions
- **Pileup**: proton-proton interactions, *only* experimental!

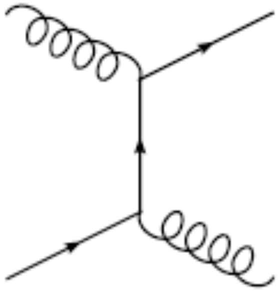
Monte Carlo event generators:
- contain models for parton shower evolution, hadronization, ISR
- “tuned” to reproduce measurements in data

Factorization Theorem

The LHC collides *hadrons*, not *partons*...

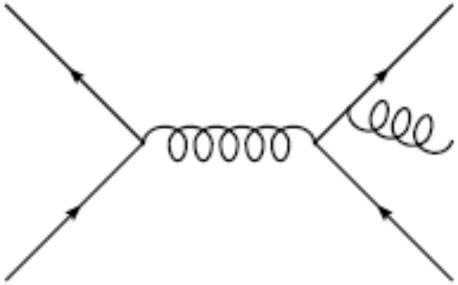
$$\sigma(P_1,P_2)=\underbrace{\sum_{i,j}}\int dx_1 dx_2 f_i(x_1,\mu_f^2)f_j(x_2,\mu_f^2)\hat{\sigma}_{ij}\underbrace{(p_1,p_2,\alpha_s(\mu_r^2),Q^2/\mu_r^2,Q^2/\mu_f^2)}$$

Leading order (LO):



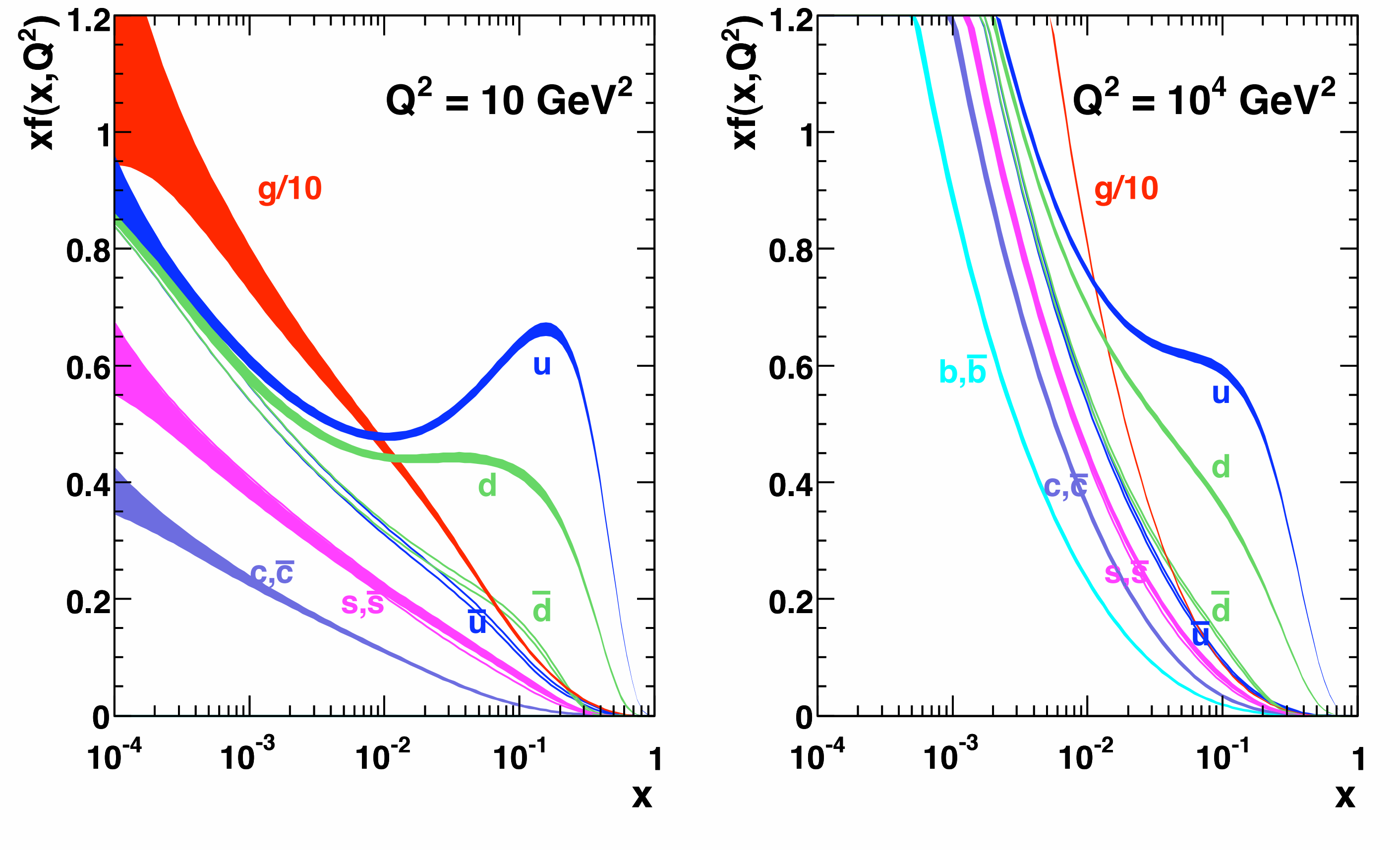
Next-to-leading order (NLO):

$\sigma_{NLO} = \sigma_{LO}(1+\alpha_s c_1)$



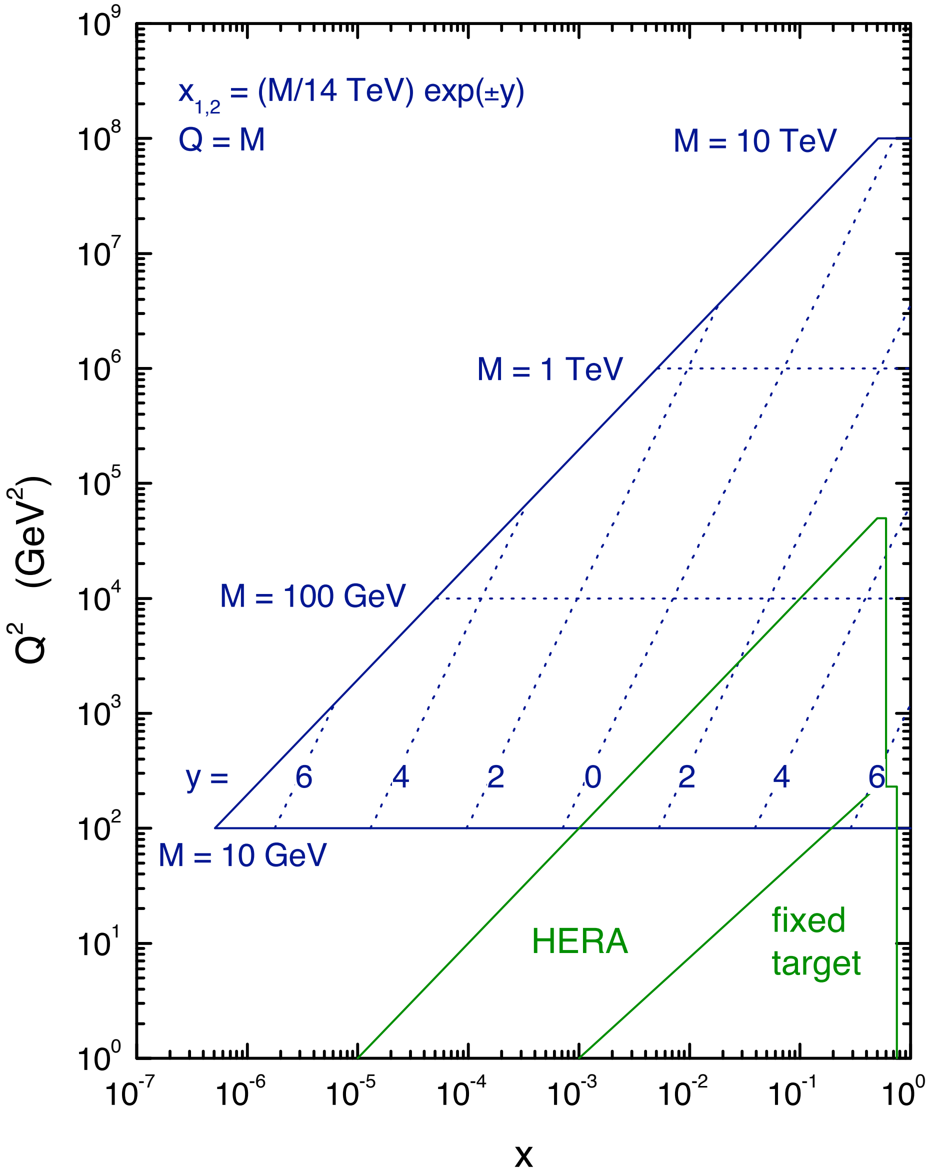
Factorization Theorem

$$\sigma(P_1,P_2)=\sum_{i,j}\int dx_1 dx_2 \underbrace{f_i(x_1,\mu_f^2)f_j(x_2,\mu_f^2)}\hat{\sigma}_{ij}(p_1,p_2,\alpha_s(\mu_r^2),Q^2/\mu_r^2,Q^2/\mu_f^2)$$



Parton
distribution
functions
(PDFs)

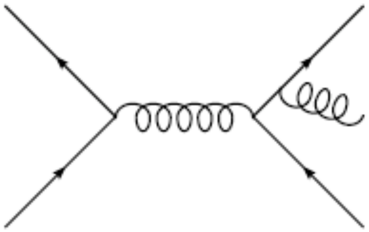
Parton Distribution Function Kinematic Range



Note: $\sqrt{s}$ = 14 TeV

From Particles to Jets

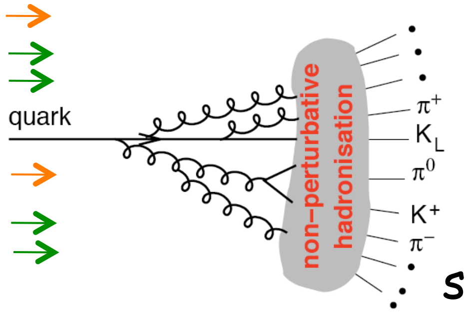
Parton-level jet



→

theory

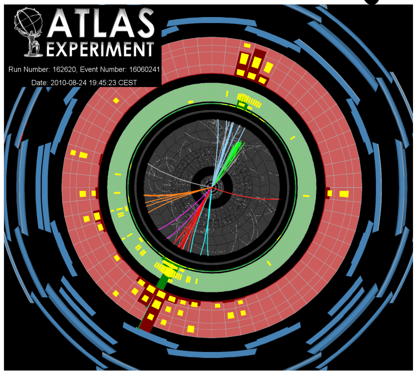
Particle-level jet



←

simulation

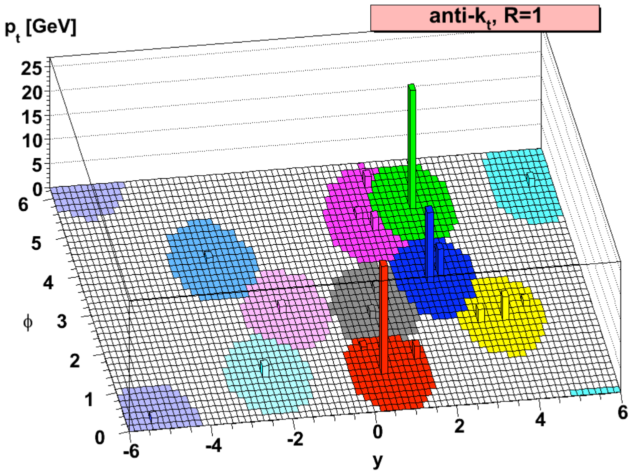
Detector-level jet



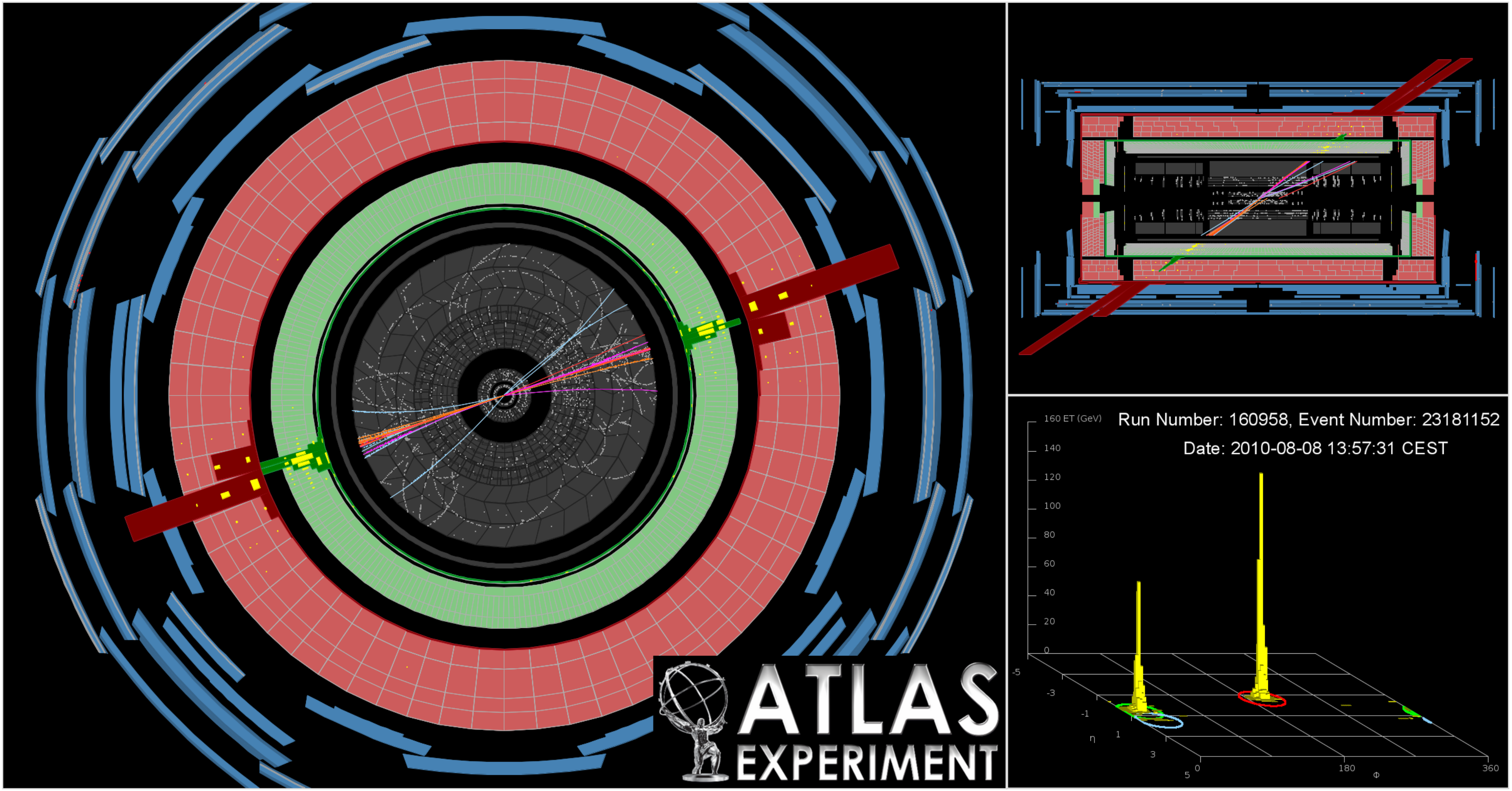
A **jet algorithm** defines how group inputs into objects called **jets**

ATLAS uses the **anti-k_t** algorithm:
- infra-red and collinear safe

Two distance parameters:
- $R = 0.4$ and 0.6, where $R \approx$ radius of jet
- smaller more sensitive to parton shower, larger to underlying event



Jet Reconstruction

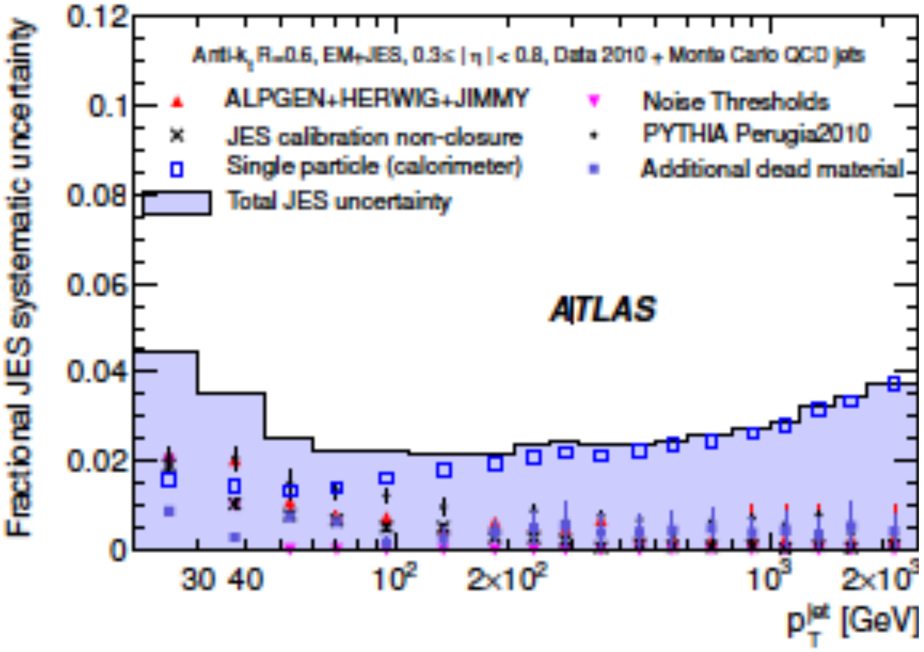


Run Number: 160958, Event Number: 23181152

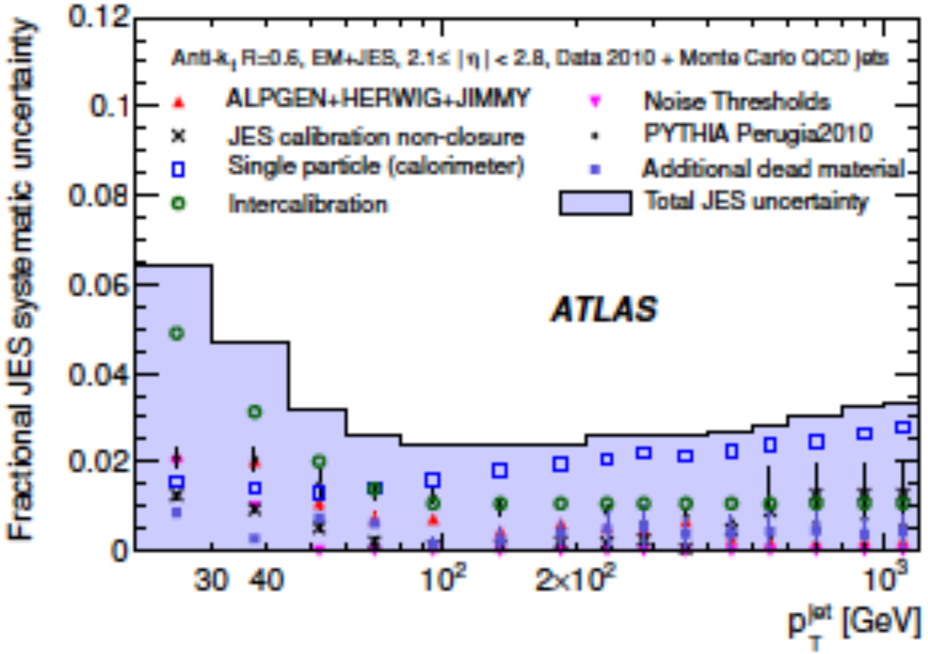
Date: 2010-08-08 13:57:31 CEST

1.9 TeV dijet mass

Jet Energy Scale Uncertainty



$0.3 \le |\eta| < 0.8$



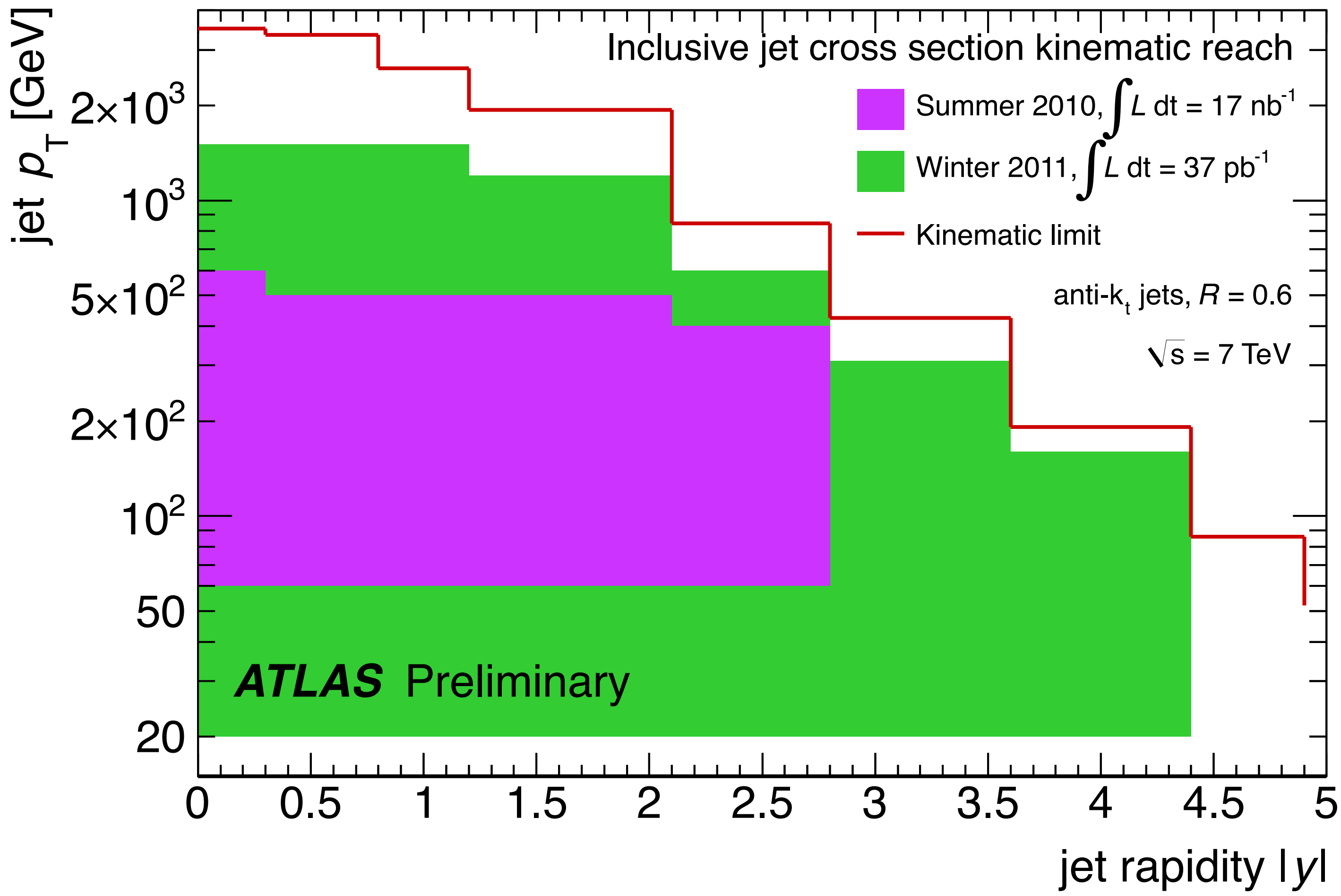
$2.1 \le |\eta| < 2.8$

some studies performed:

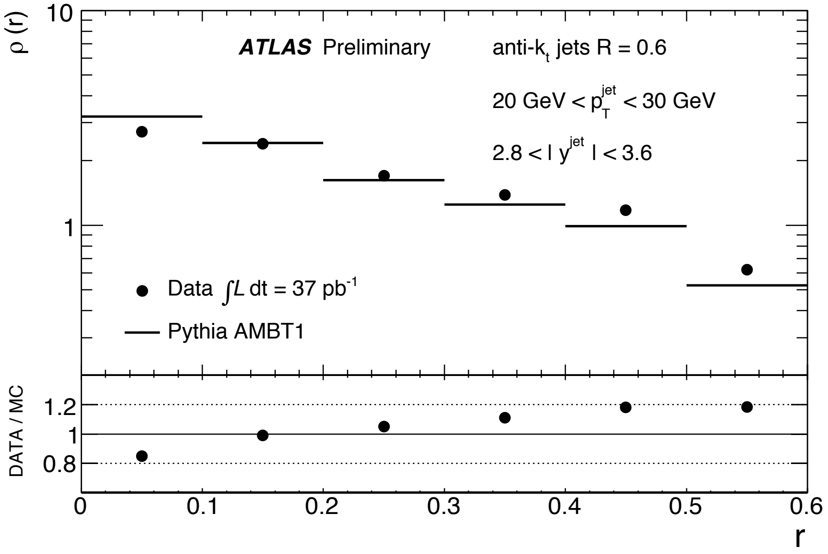
- Single particle
- Test beam
- Track jets
- dijet and γ/jet balance

II. Inclusive Jet Studies

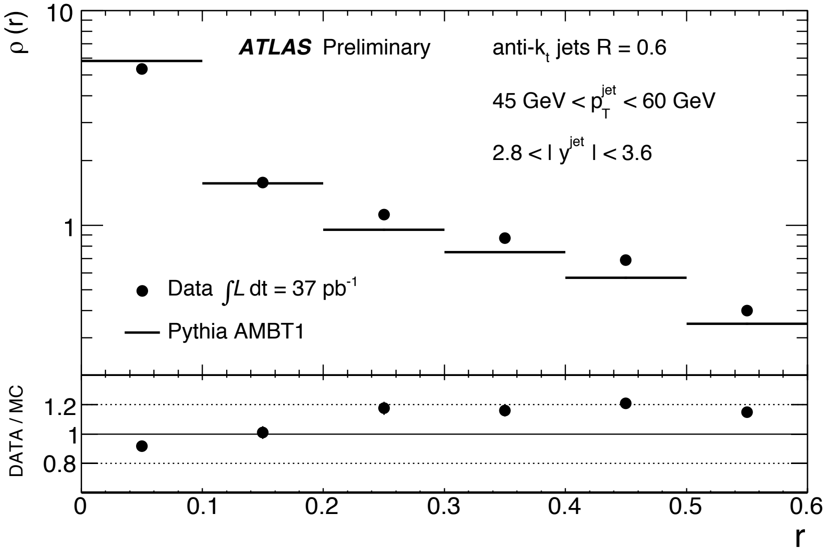
Comparison of kinematic coverage (2010 vs. 2011 results)



Jet Shapes



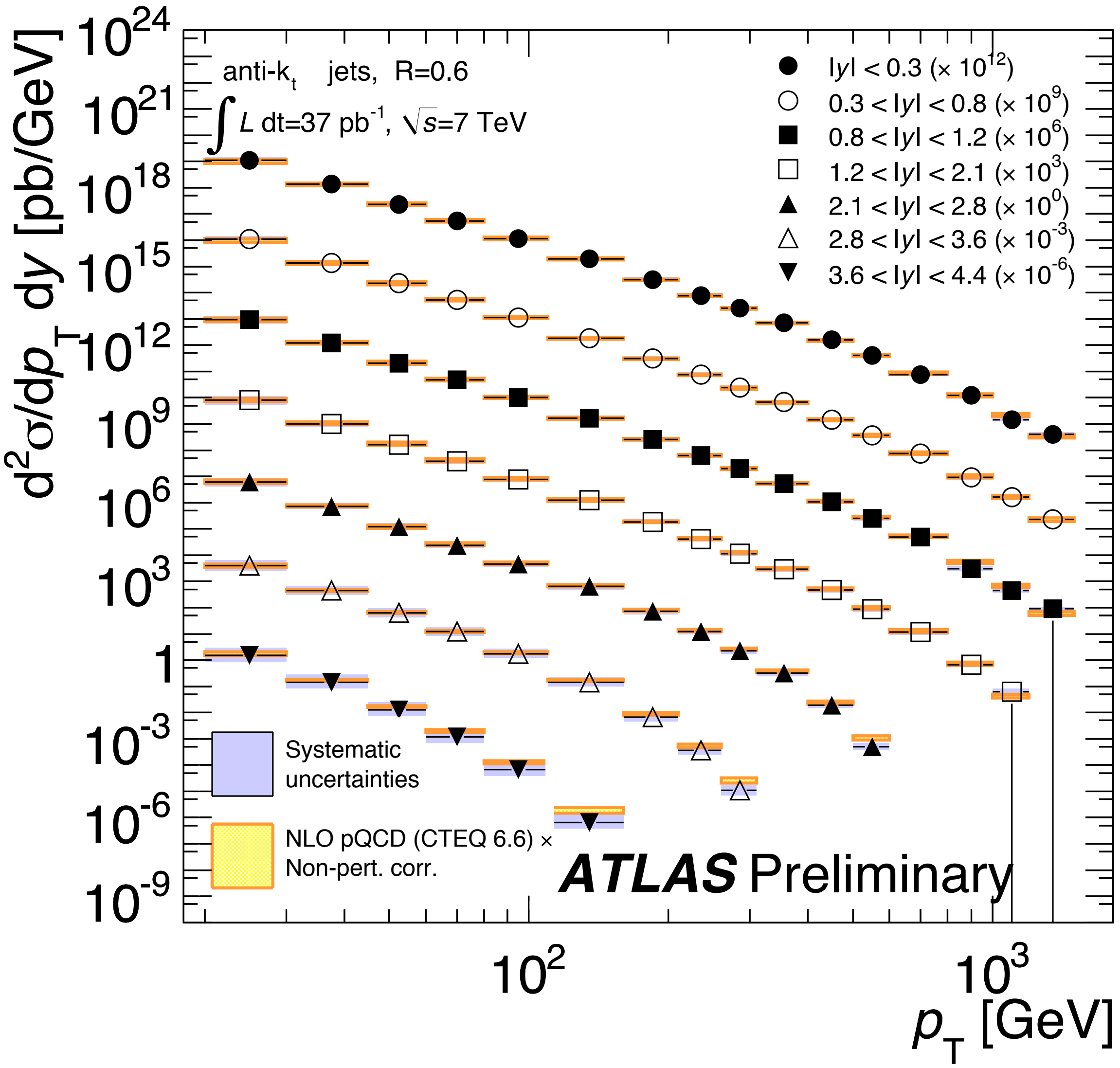
$20\,GeV < p_T^{JET} < 30\,GeV$



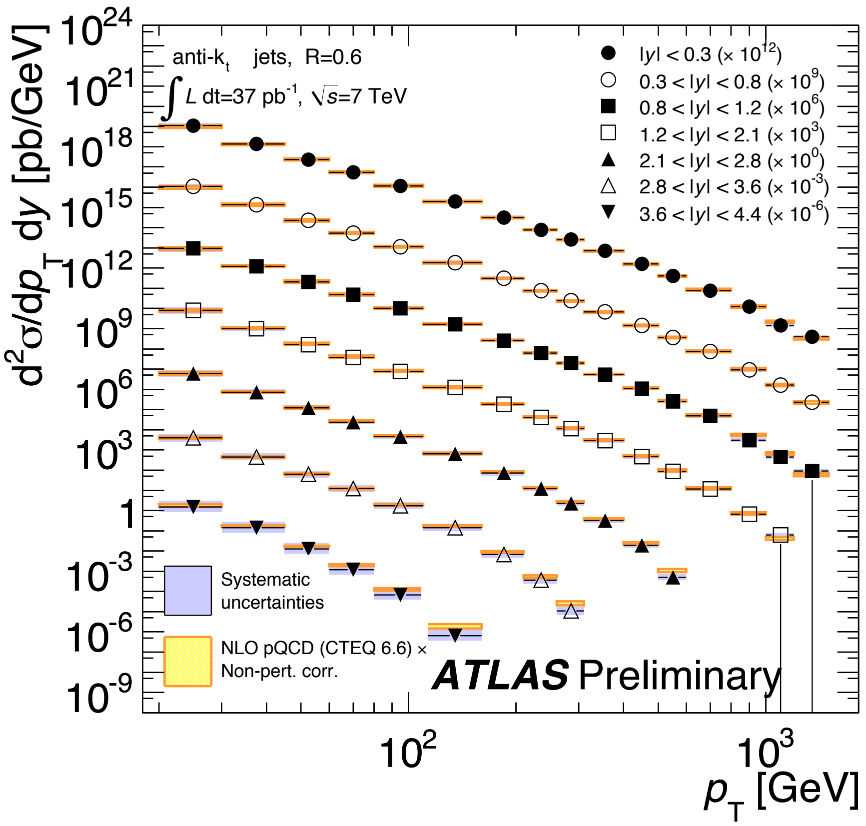
$45\,GeV < p_T^{JET} < 60\,GeV$

~20% difference between AMBT1 tune and measurement

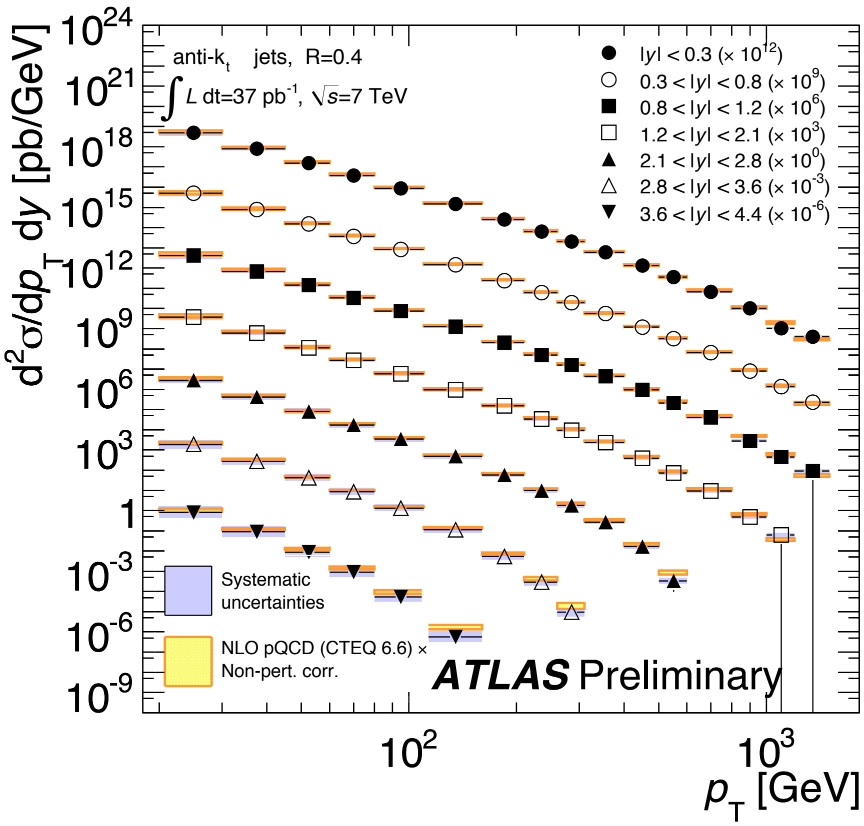
Inclusive Jet cross section results



Inclusive Jet cross section results

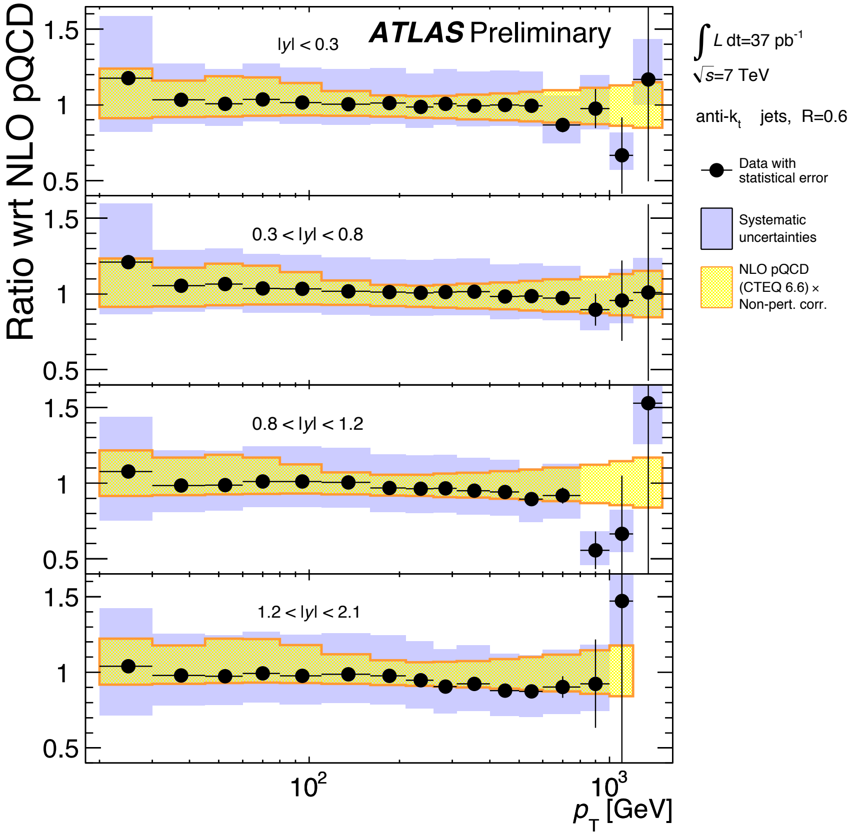


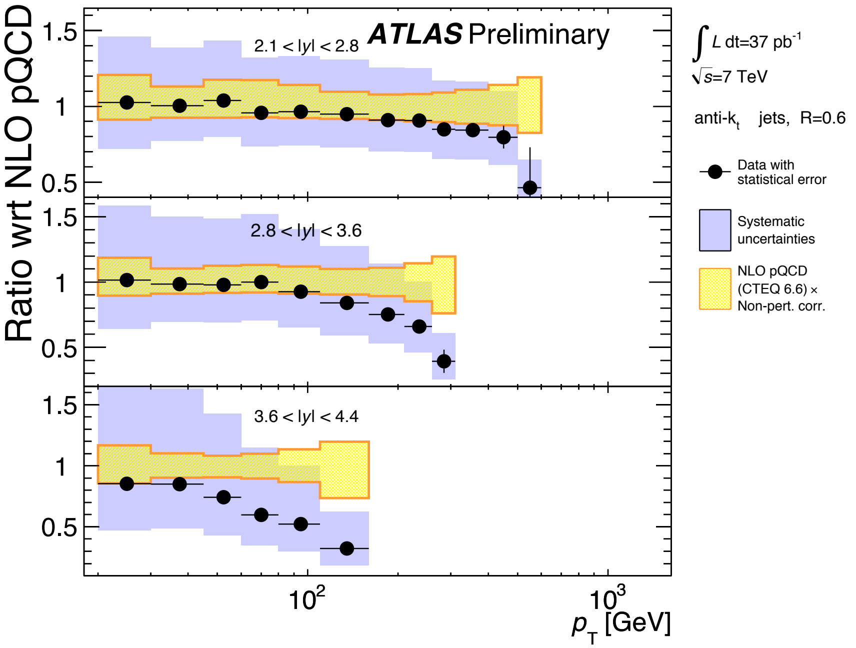
R = 0.6



R = 0.4

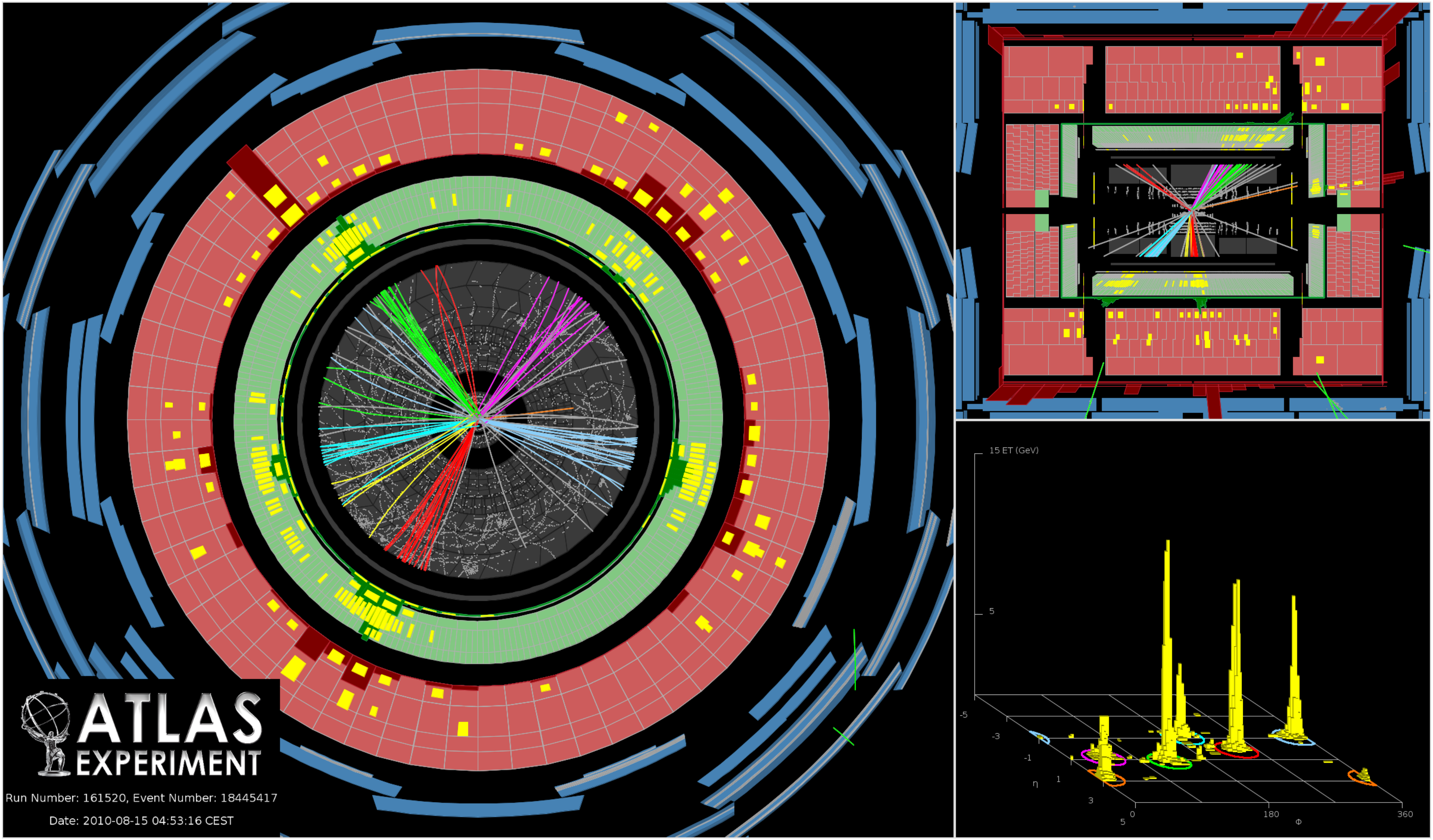
Inclusive Jet cross section ratios





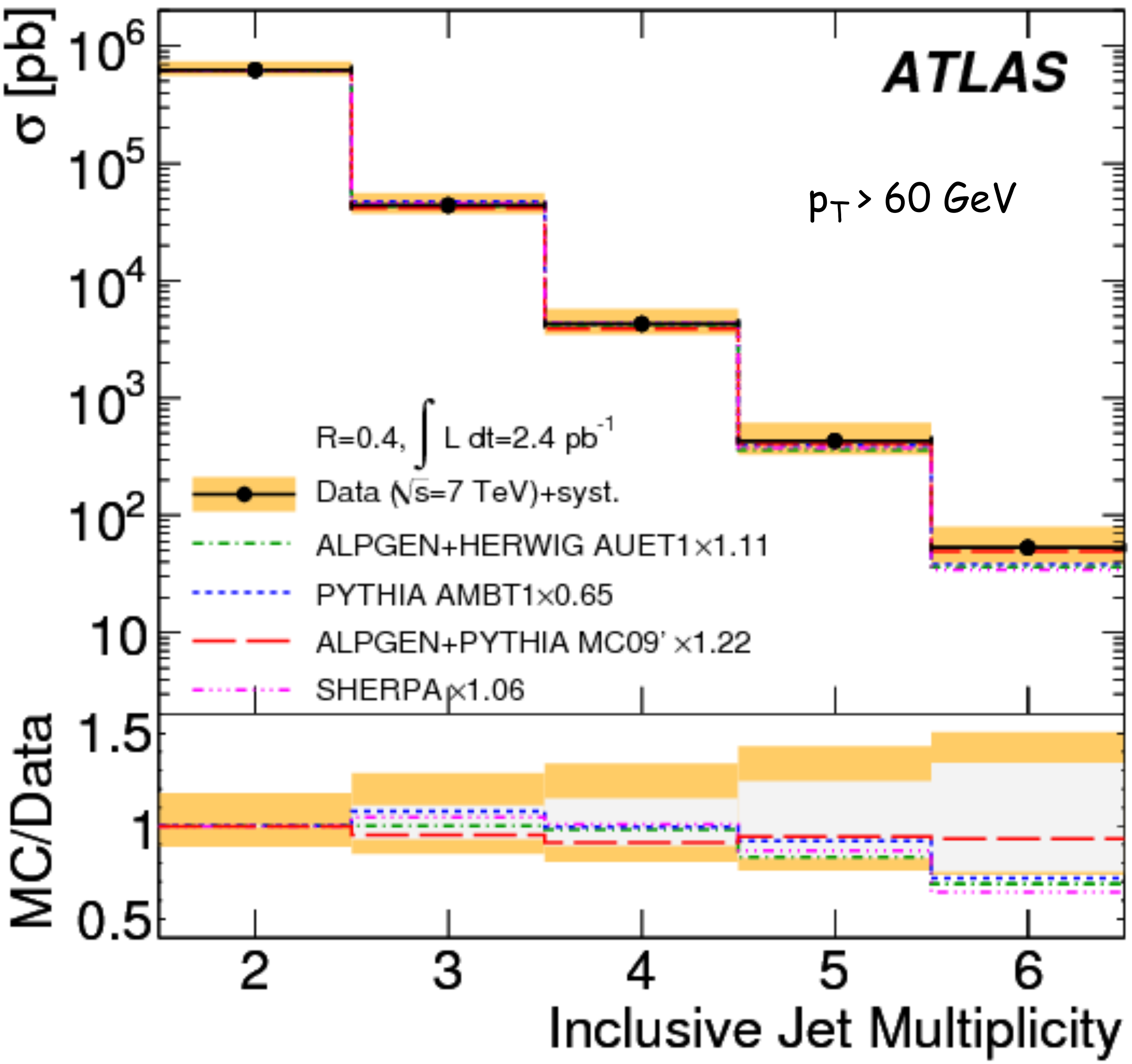
III. Multijet Studies

Six Jet Event

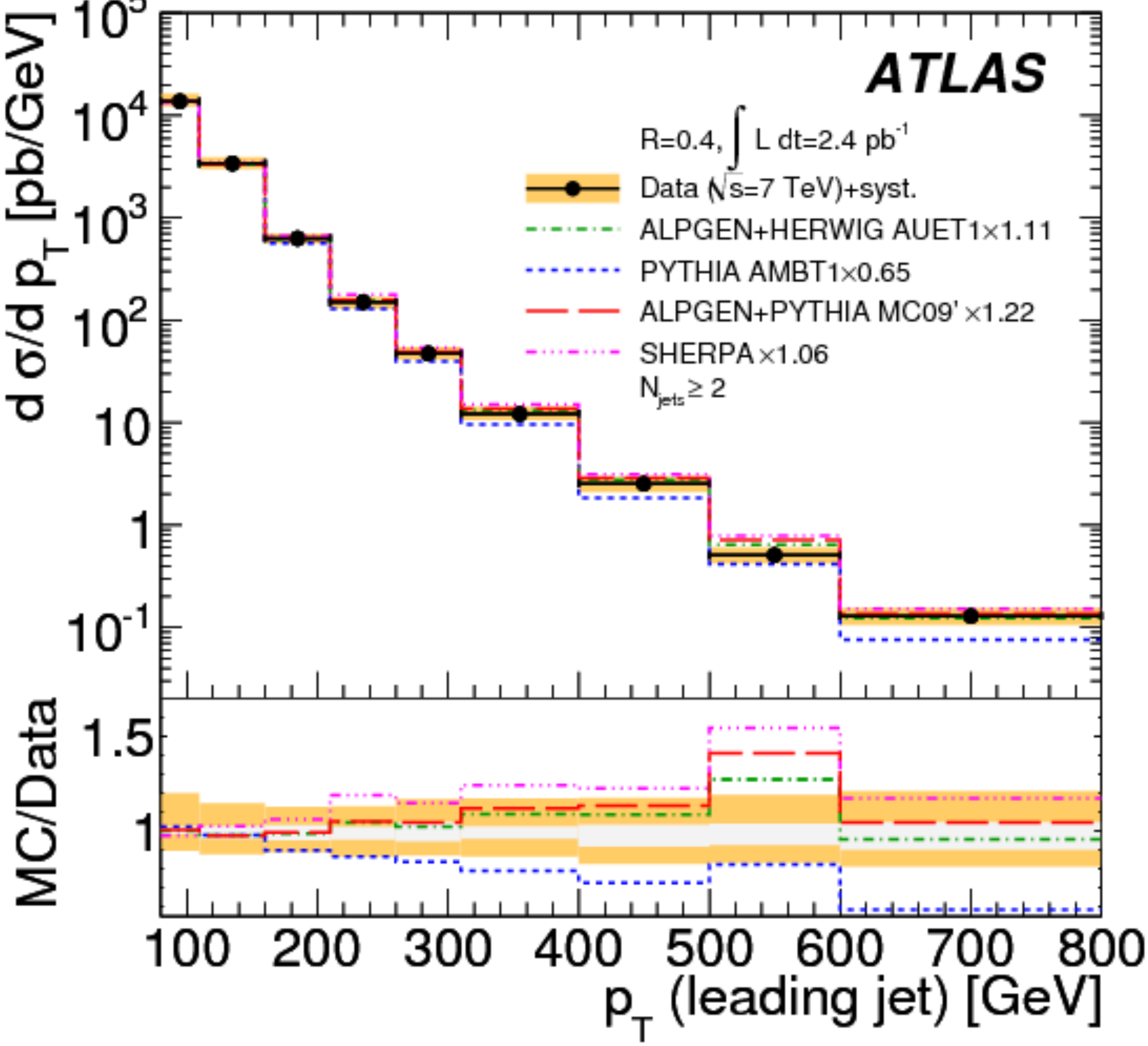


Run Number: 161520, Event Number: 18445417

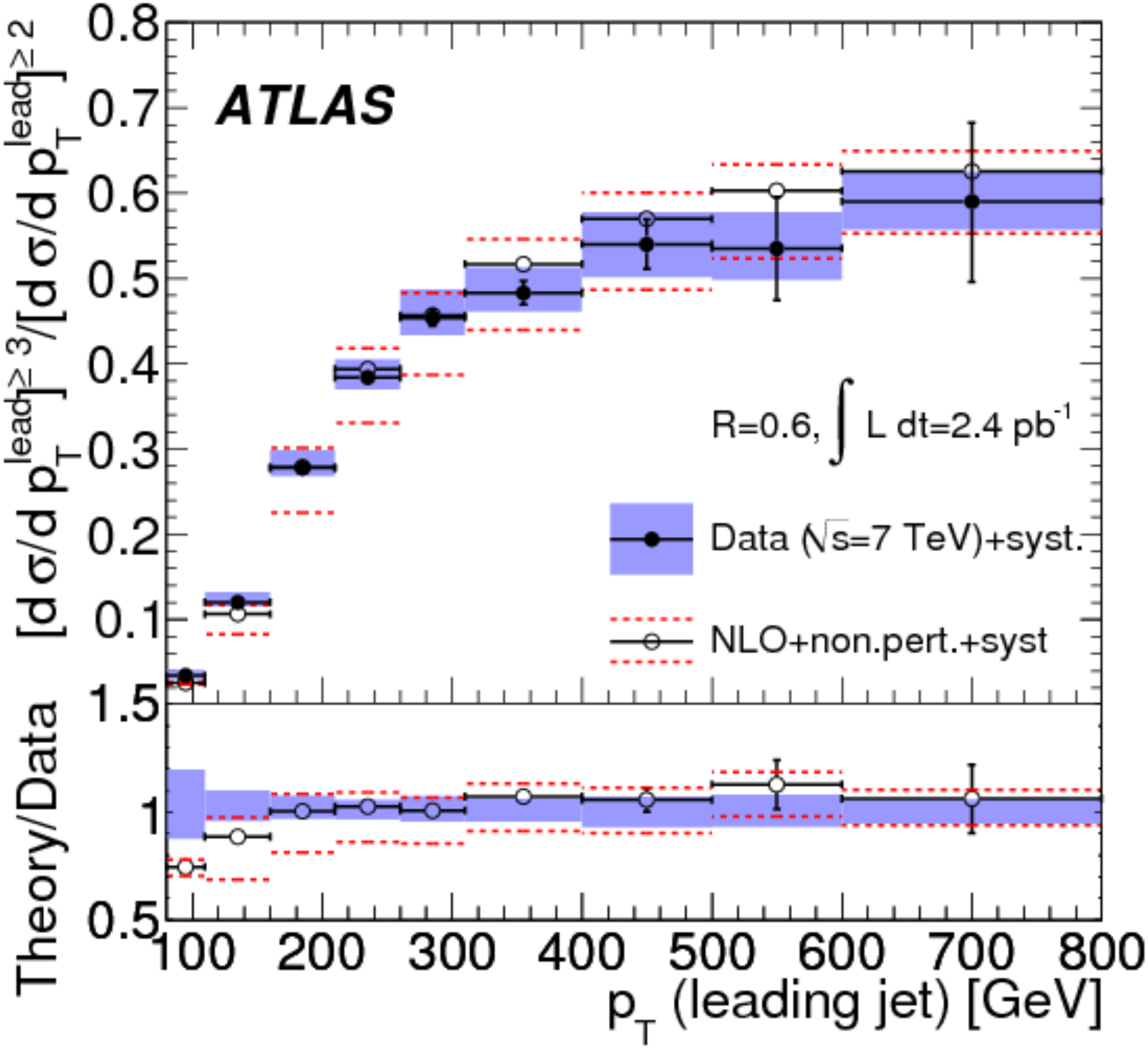
Date: 2010-08-15 04:53:16 CEST


ATLAS
σ [pb]
10^6
10^5
10^4
10^3
10^2
10
R=0.4, $\int L\,dt = 2.4\ pb^{-1}$
Data ($\sqrt{s}$=7 TeV)+syst.
ALPGEN+HERWIG AUET1×1.11
PYTHIA AMBT1×0.65
ALPGEN+PYTHIA MC09' ×1.22
SHERPA ×1.06
MC/Data
1.5
1
0.5
2
3
4
5
6
Inclusive Jet Multiplicity

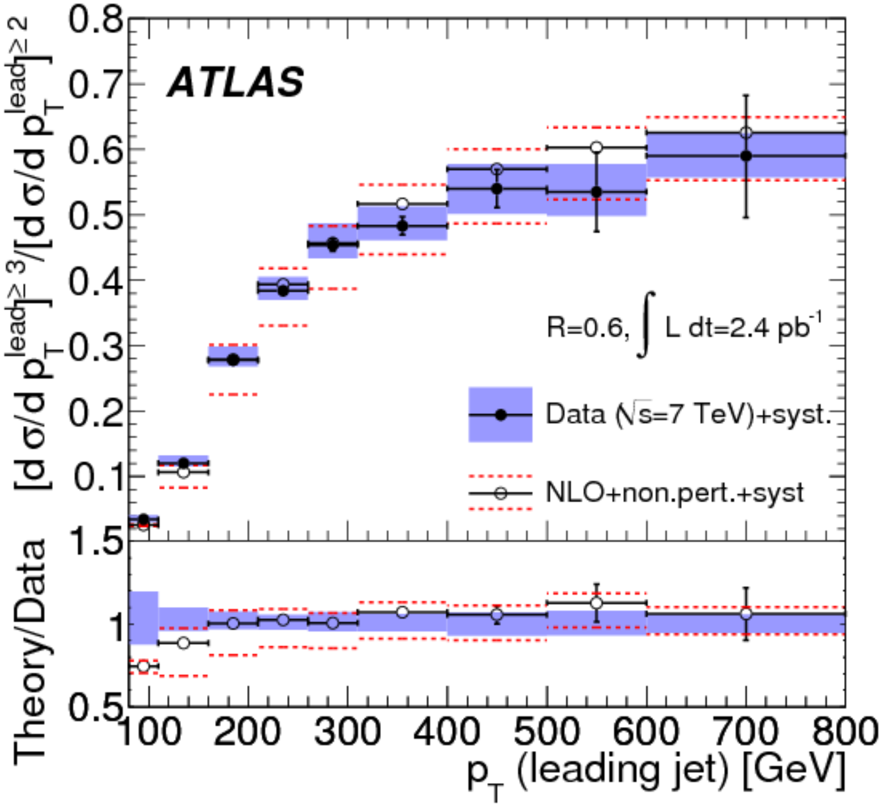
$p_T > 60$ GeV

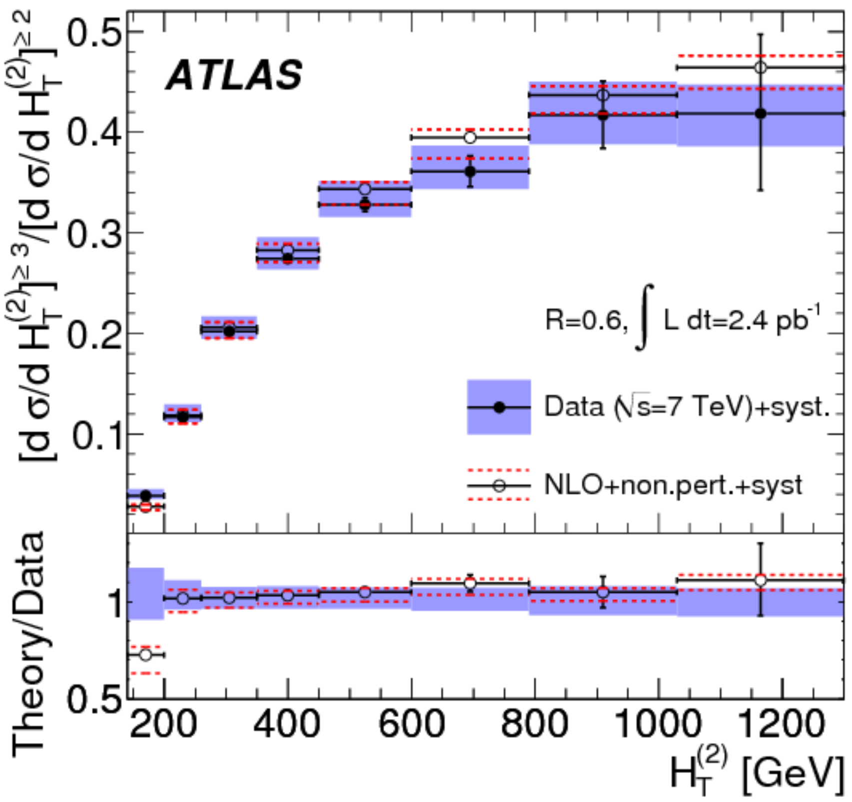


ATLAS
R=0.4, $\int$ L dt=2.4 pb^{-1}
Data ($\sqrt{s}$=7 TeV)+syst.
ALPGEN+HERWIG AUET1×1.11
PYTHIA AMBT1×0.65
ALPGEN+PYTHIA MC09' ×1.22
SHERPA ×1.06
$N_{jets} \geq 2$
d σ/d p_T [pb/GeV]
10^5
10^4
10^3
10^2
10
1
10^{-1}
MC/Data
1.5
1
100
200
300
400
500
600
700
800
p_T (leading jet) [GeV]


ATLAS
R=0.6, ∫ L dt=2.4 pb^{-1}
Data ($\sqrt{s}$=7 TeV)+syst.
NLO+non.pert.+syst
[d σ/d p_T^{lead}]$^{\geq 3}$/[d σ/d p_T^{lead}]$^{\geq 2}$
Theory/Data
p_T (leading jet) [GeV]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1.5
1
0.5
100
200
300
400
500
600
700
800

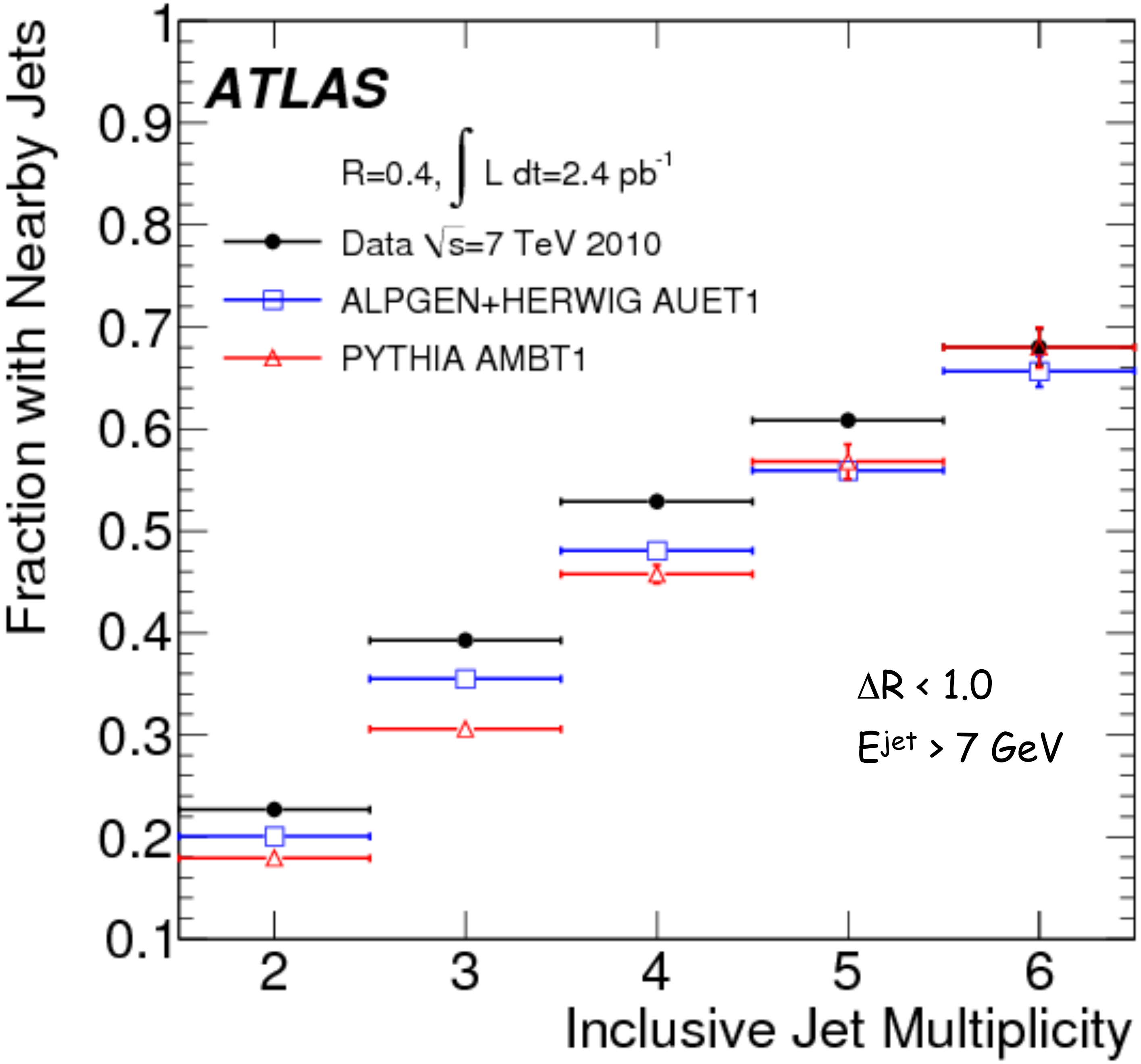
Comparison of p_T(lead) vs p_T(lead) + p_T(second)





p_T(lead) + p_T(second)

→ path to an α_S measurement



$\Delta R < 1.0$

$E^{jet} > 7$ GeV

III. W + Jet Studies

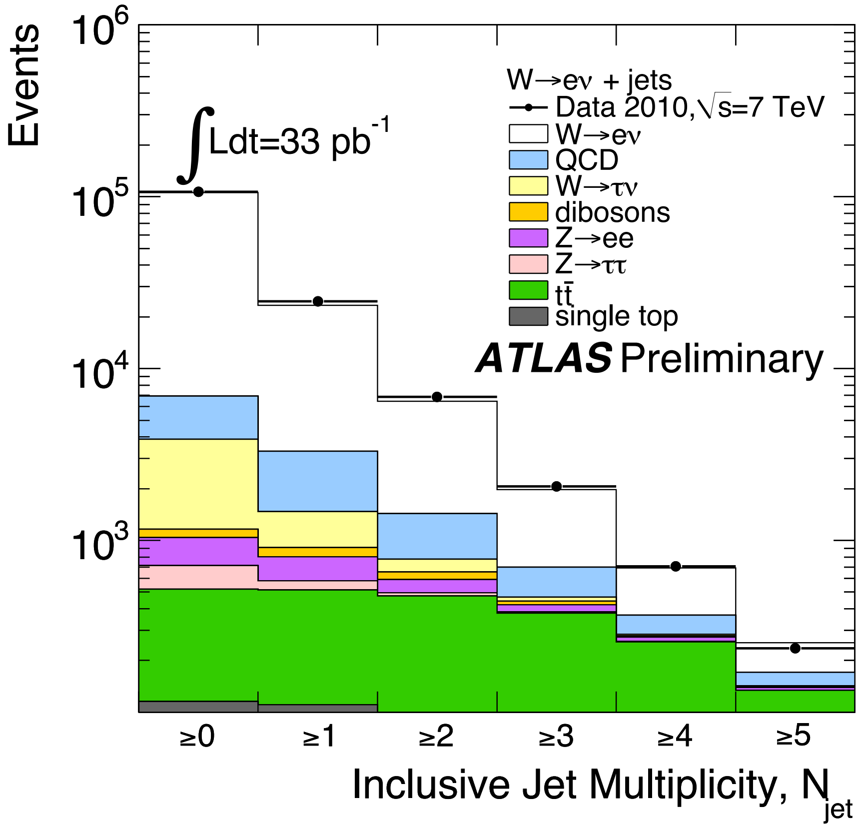
Black Hat (BH)

program to calculate
NLO pQCD corrections
to W+ jet events

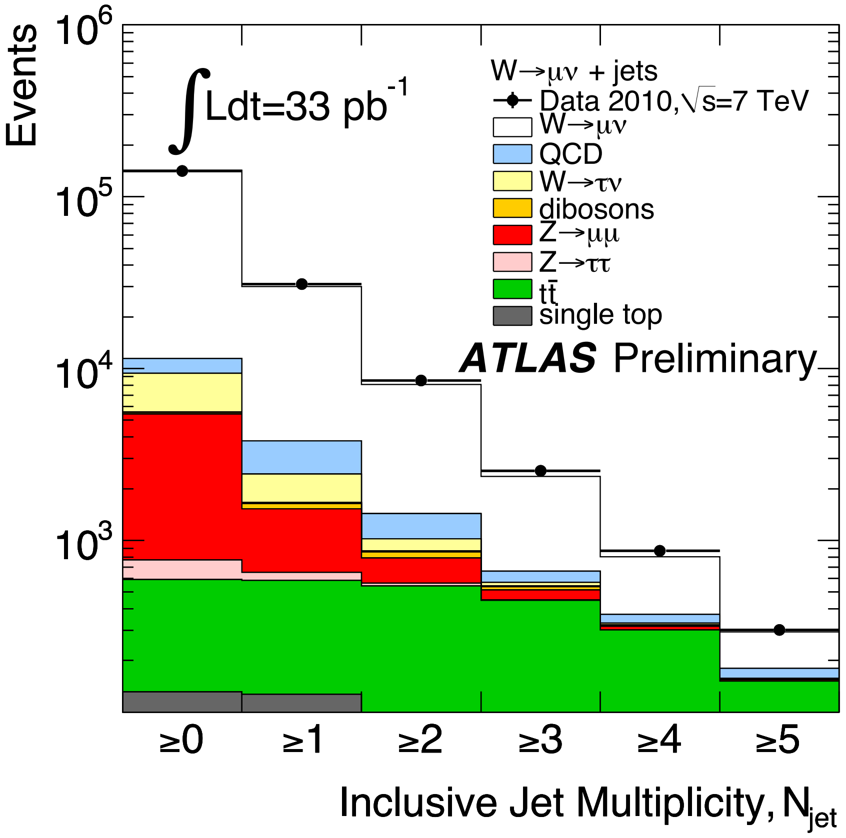
pp → W + 0 jet	1978	Altarelli, Ellis, Martinelli
pp → W + 1 jet	1989	Arnold, Ellis, Reno
pp → W + 2 jets	2002	Campbell, Ellis
pp → W + 3 jets	2009	BH+Sherpa Ellis, Melnikov, Zanderighi
pp → W + 4 jets	2010	BH+Sherpa

L. Dixon (SLAC)

Raw Distributions for W + jets



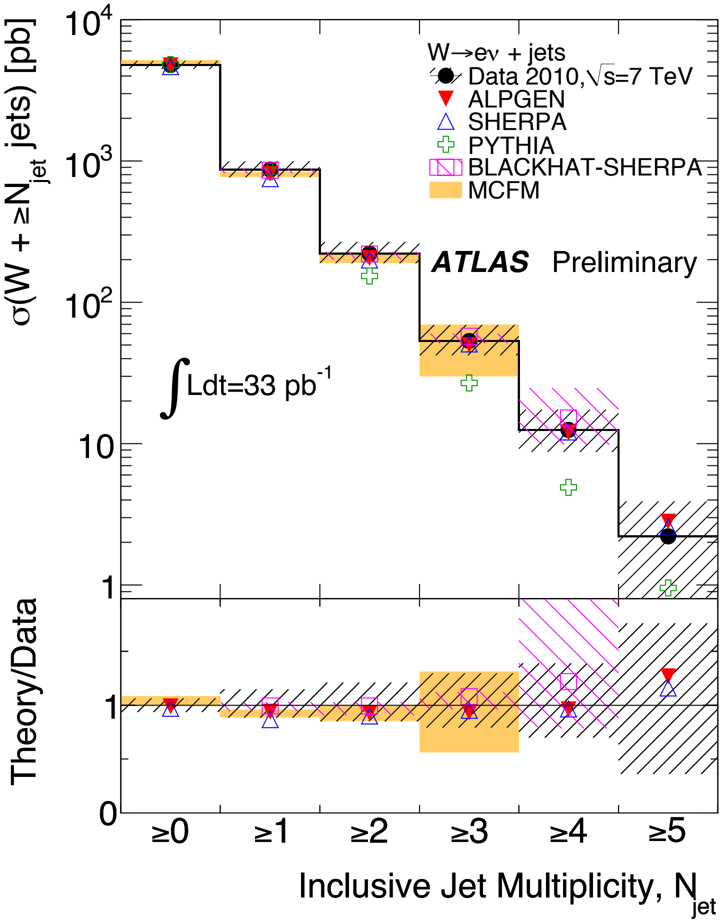
electrons



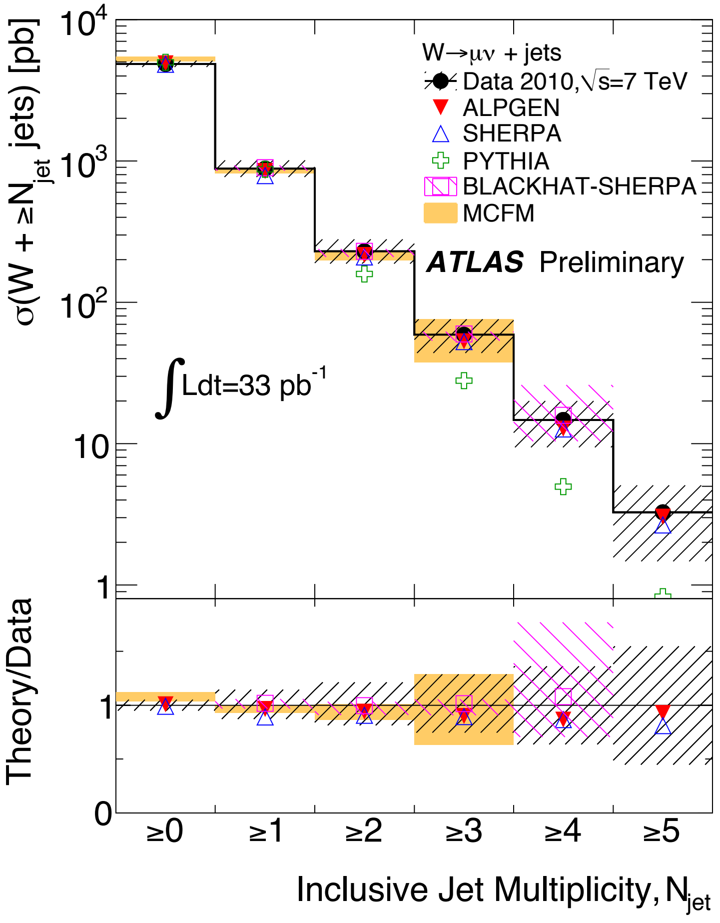
muons

$$p_T^{Jet} > 30\,GeV$$

Total Cross Section vs. Inclusive Jet Multiplicity

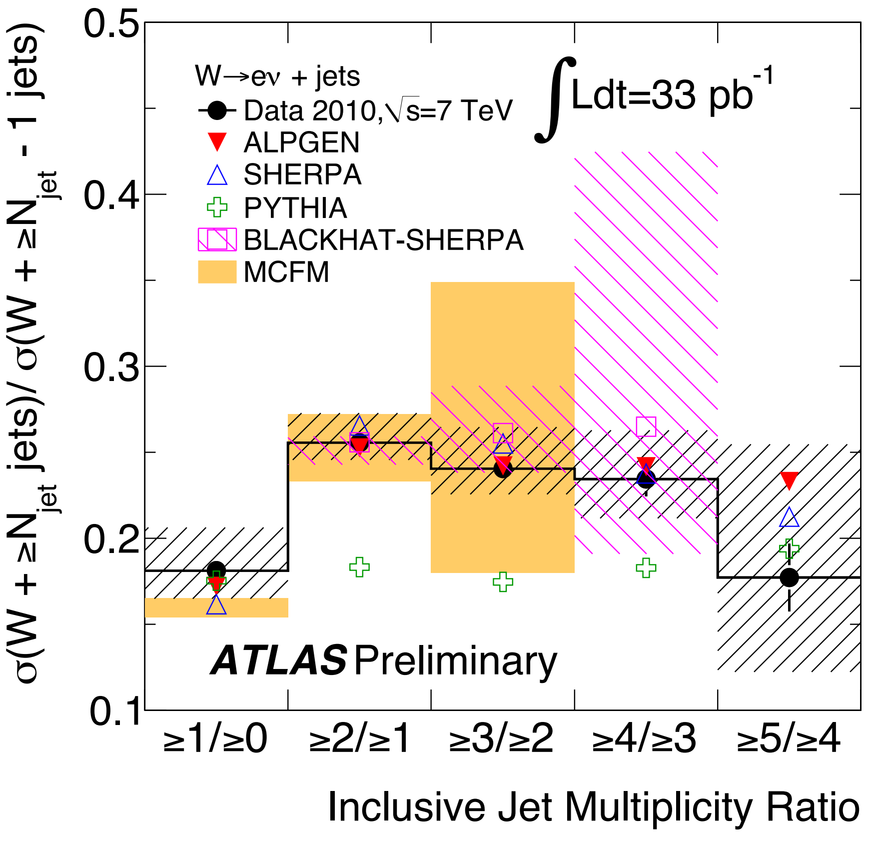


electron

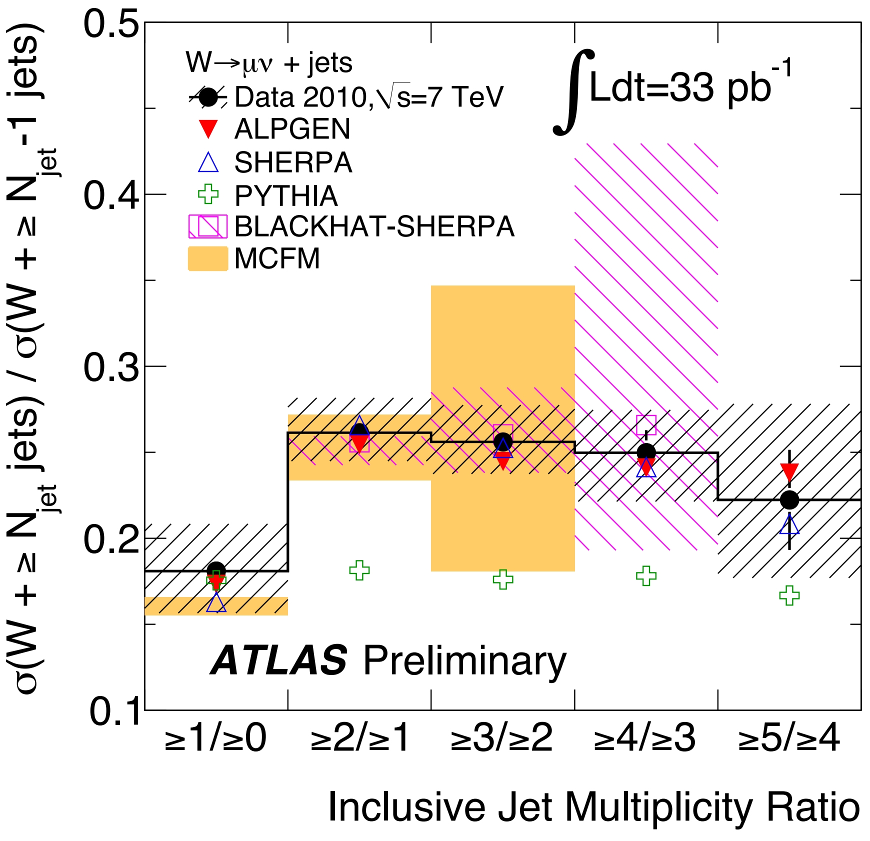


muon

Total Cross Section vs. Inclusive Jet Multiplicity Ratios

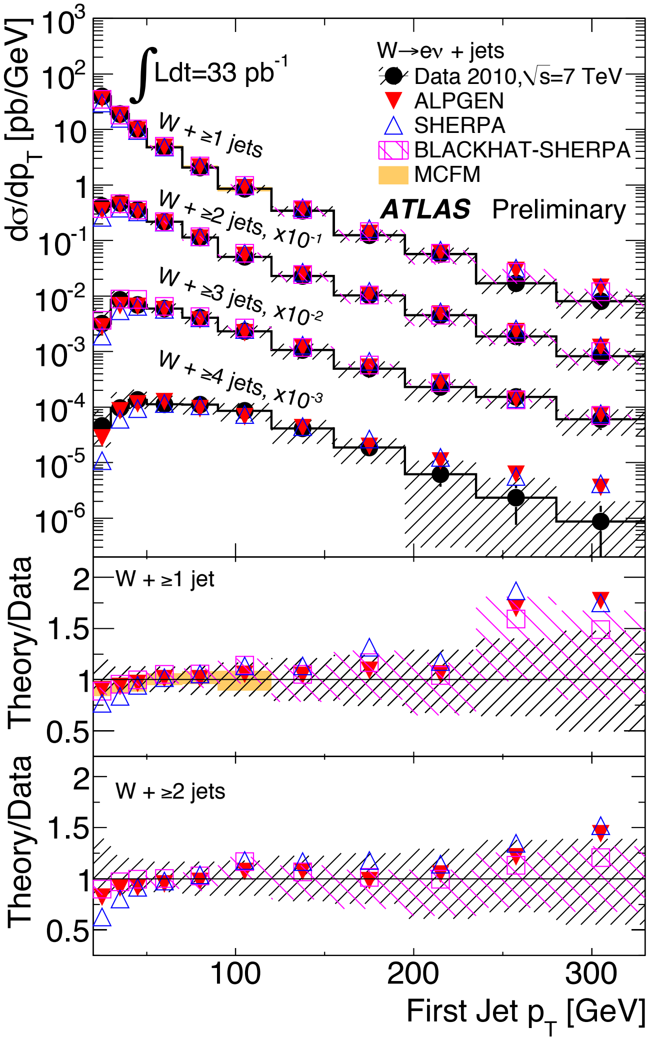


electron

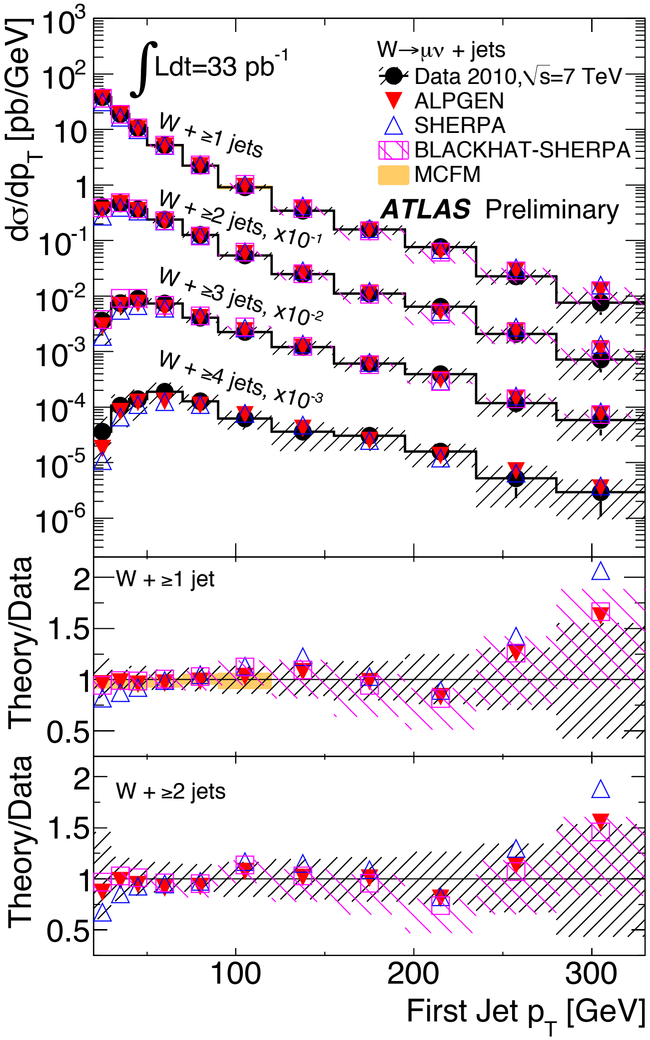


muon

Differential Cross Section vs. Lead Jet p_T



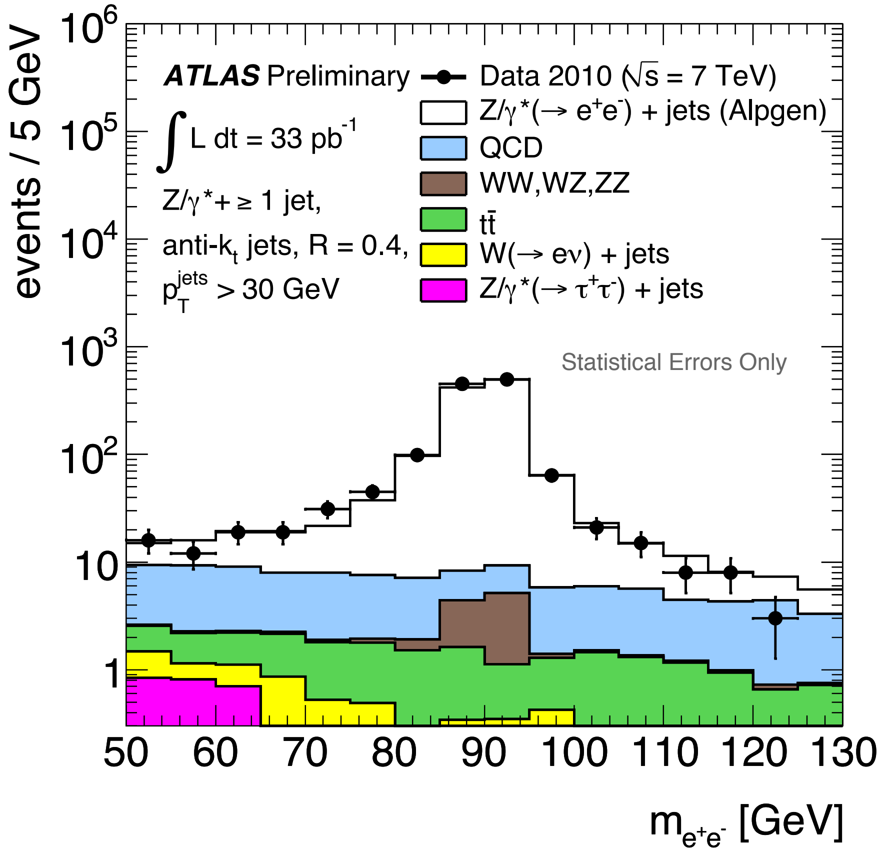
electron



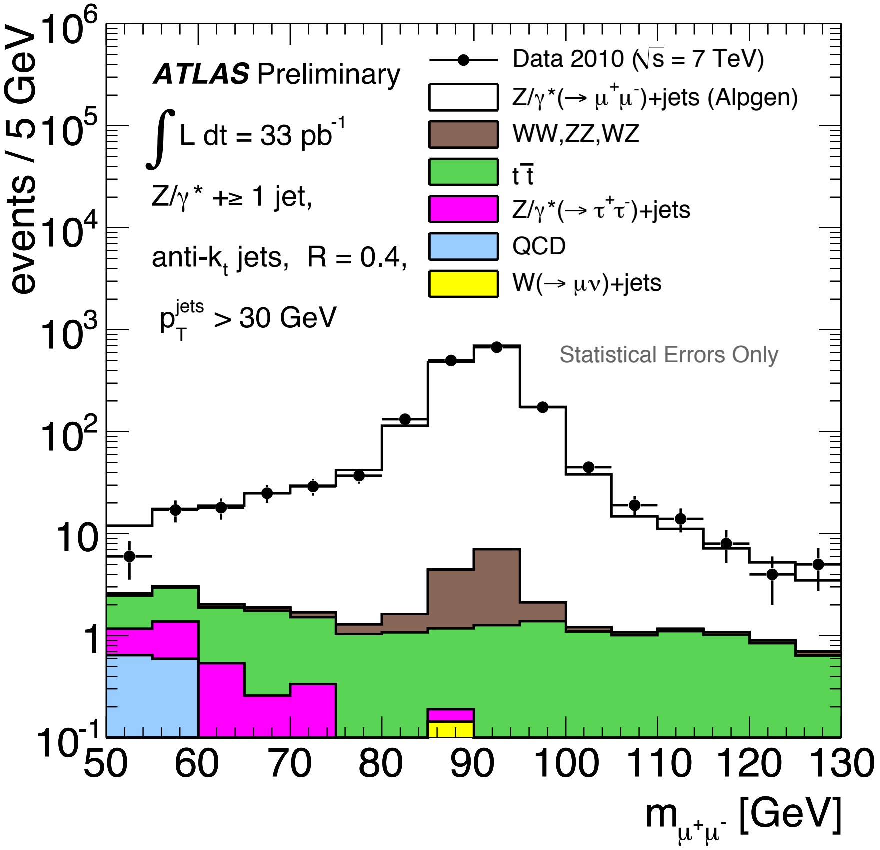
muon

IV. Z/γ^* + Jet Studies

Raw Distributions for Z + jets

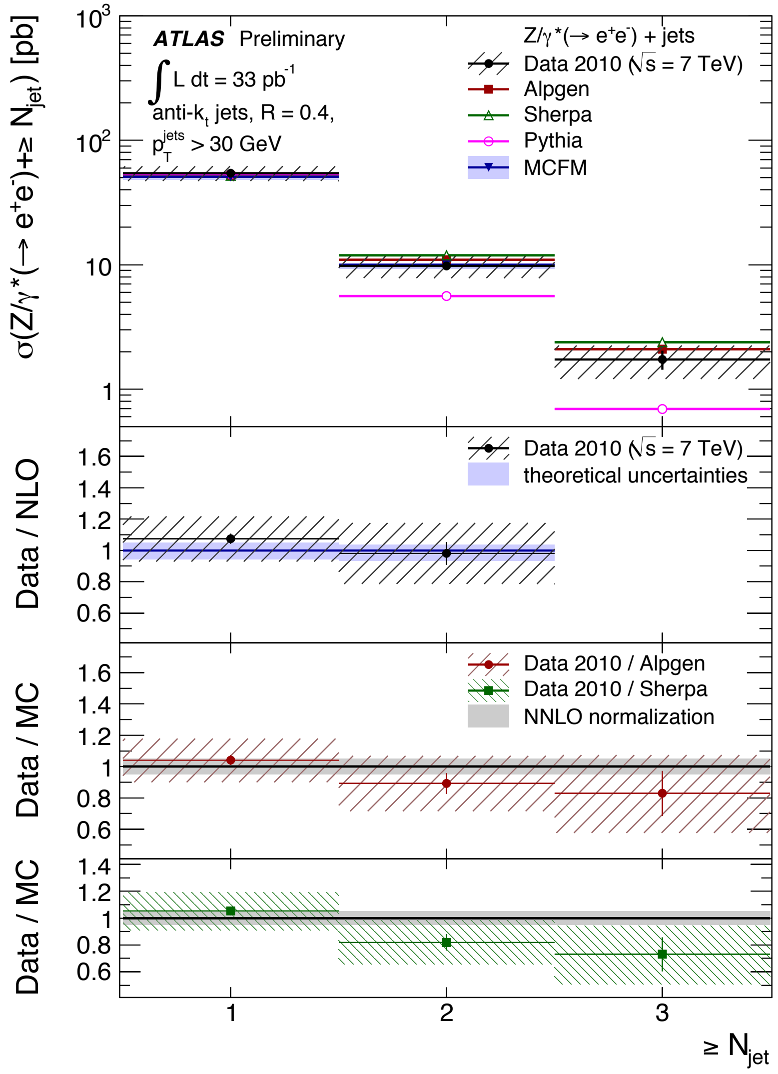


e+e-

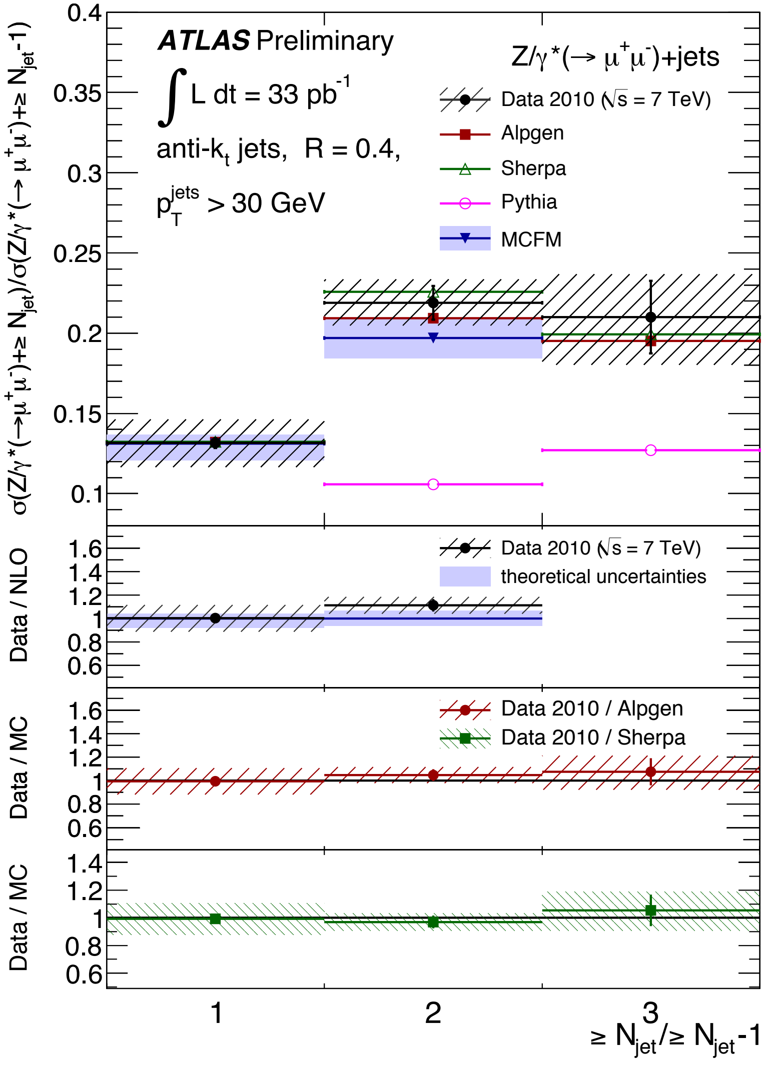


μ+μ−

Multiplicity Distributions for Z + jets

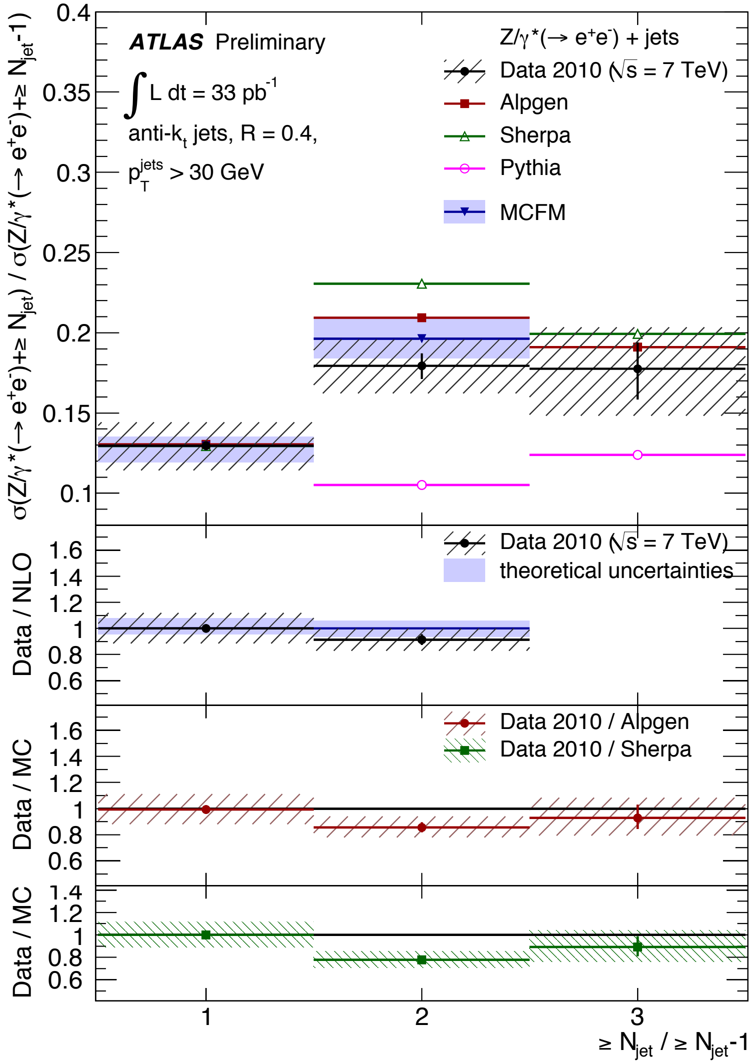


e+e-

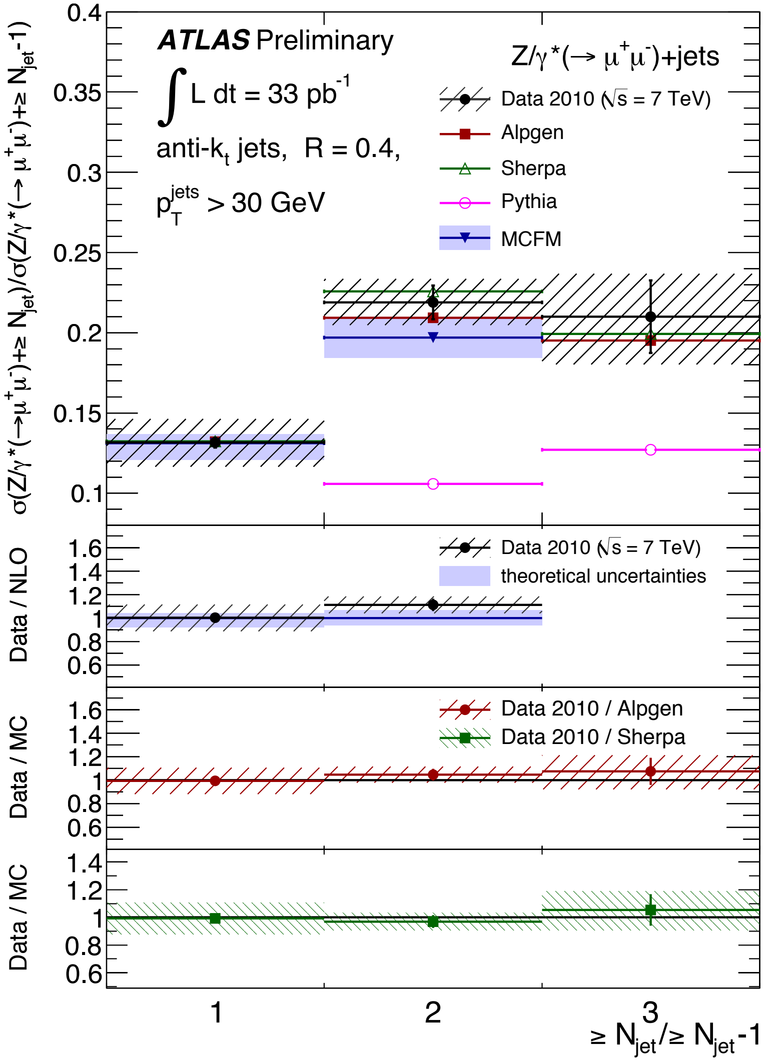


μ+μ−

Multiplicity Ratios for Z + jets

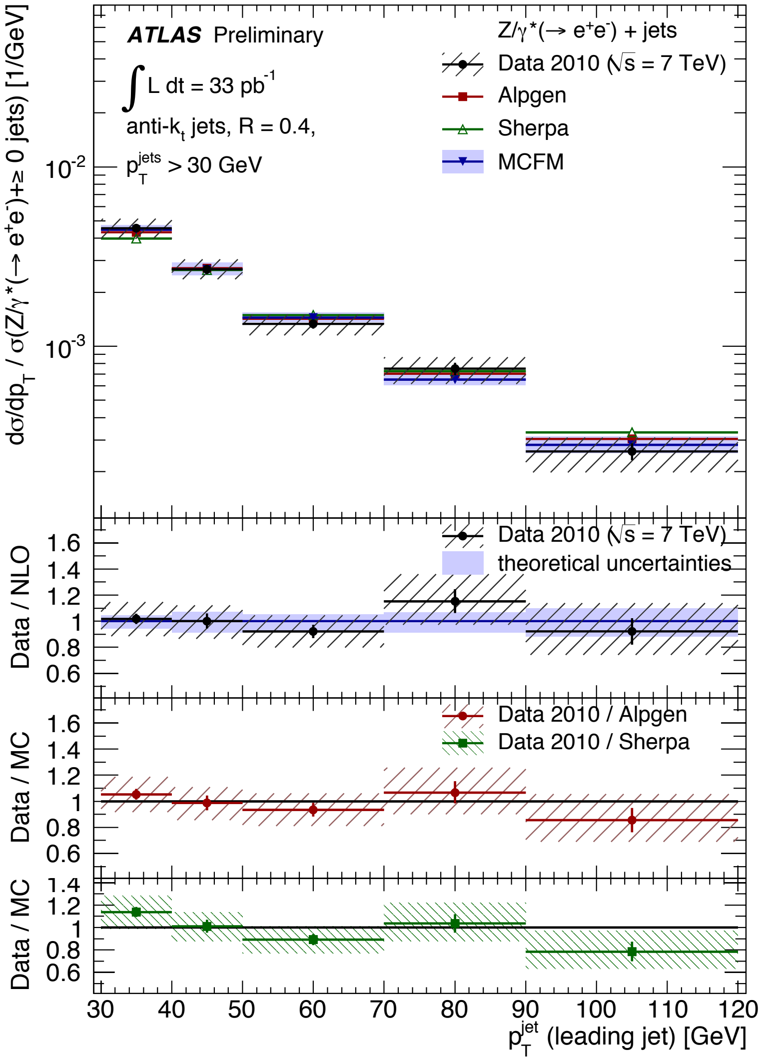


e+e-

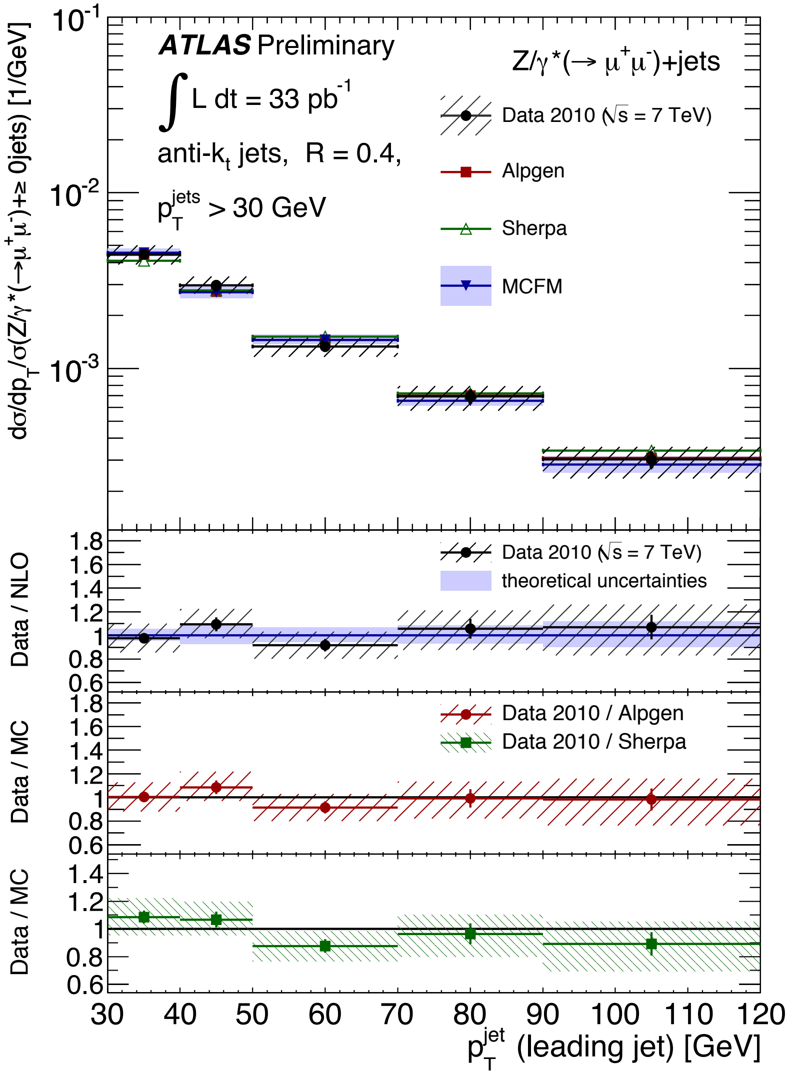


μ+μ−

Differential Cross Section vs. Lead Jet p_T



e+e-

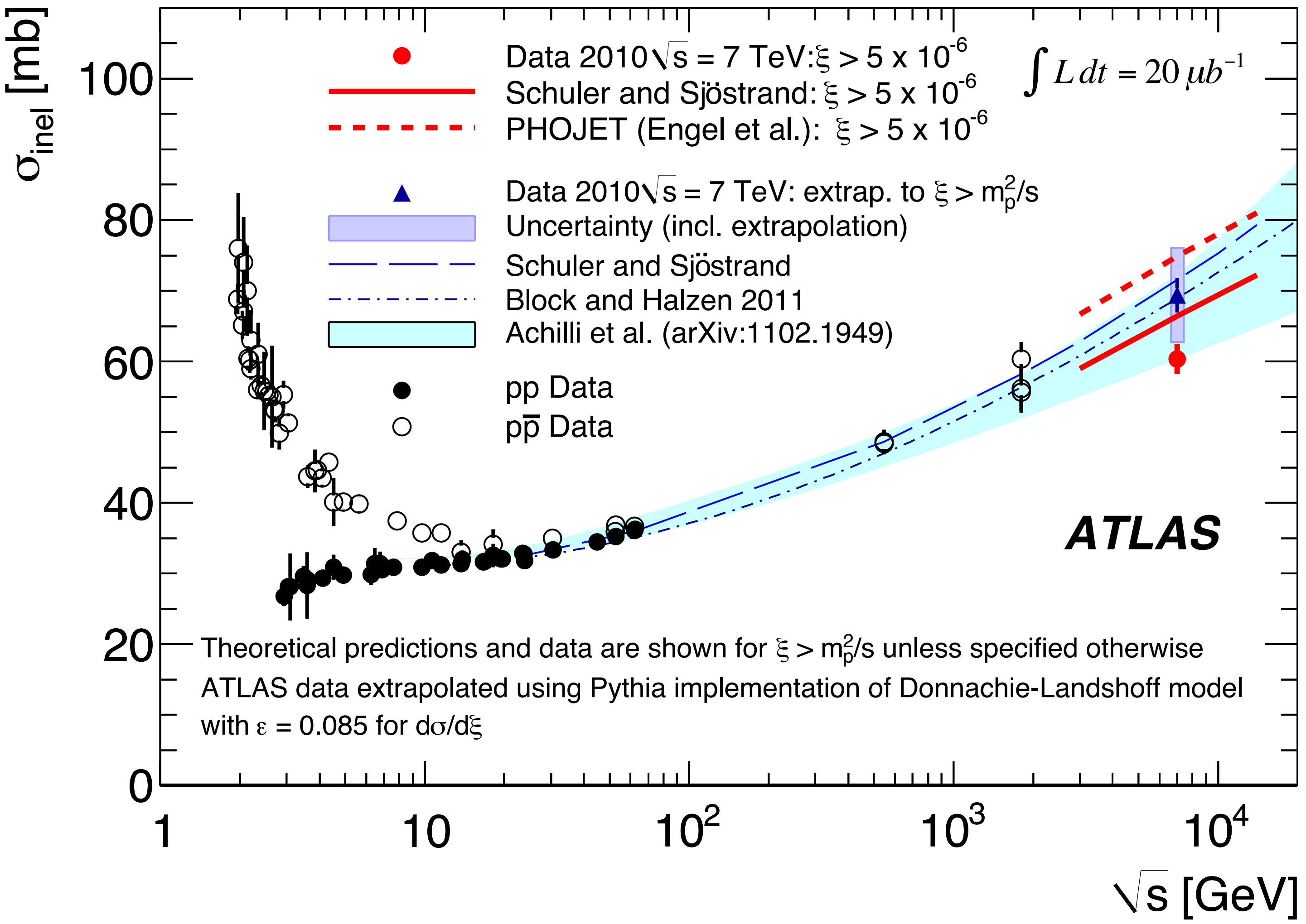


μ+μ−

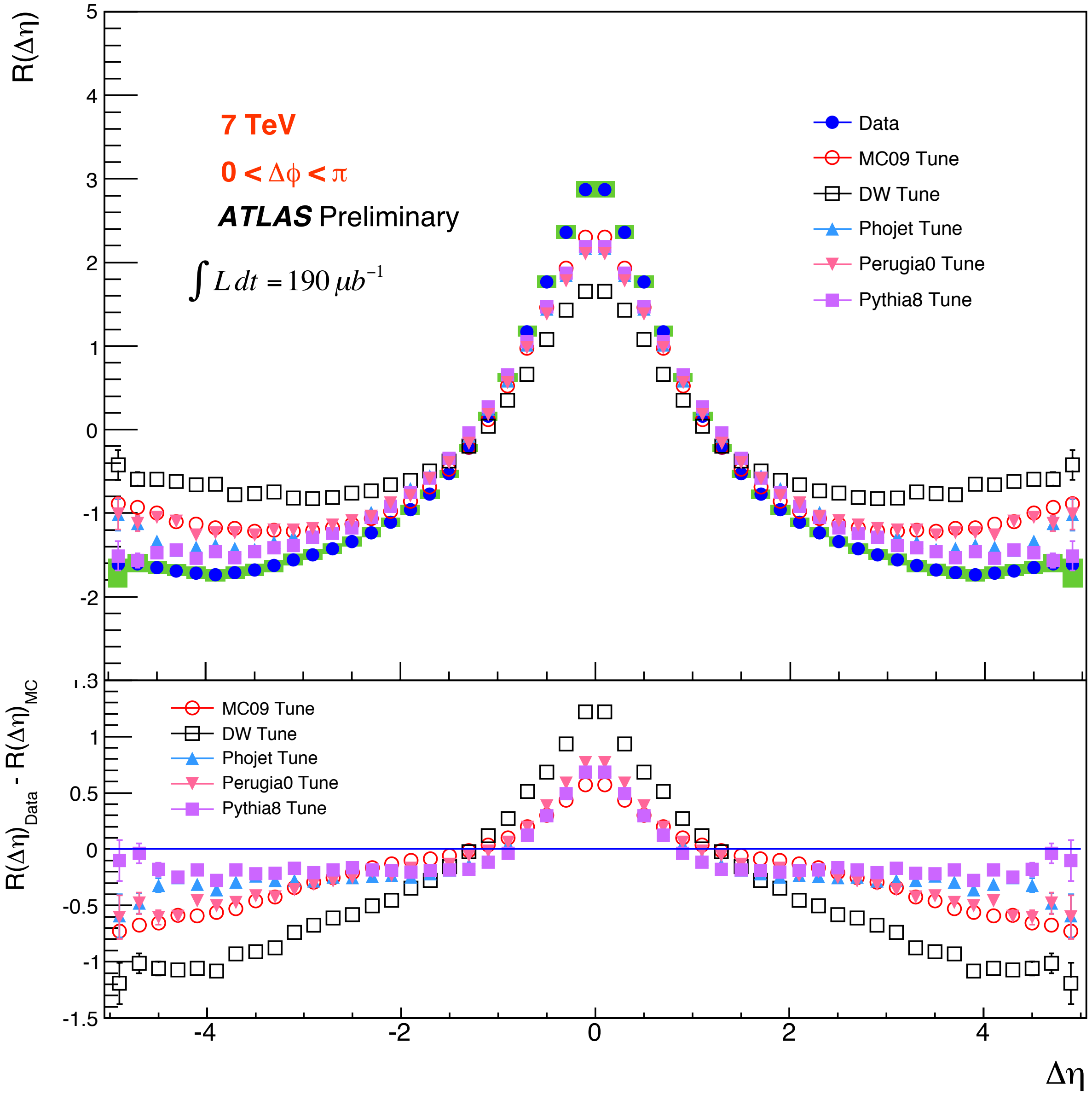
V. Soft QCD

New Publications

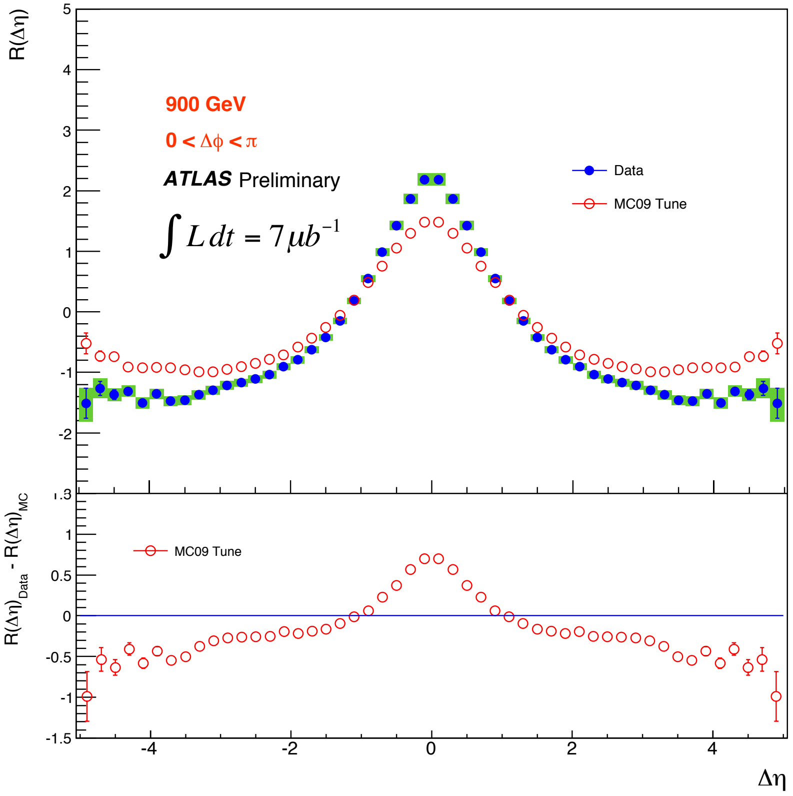
Total Inelastic Cross Section



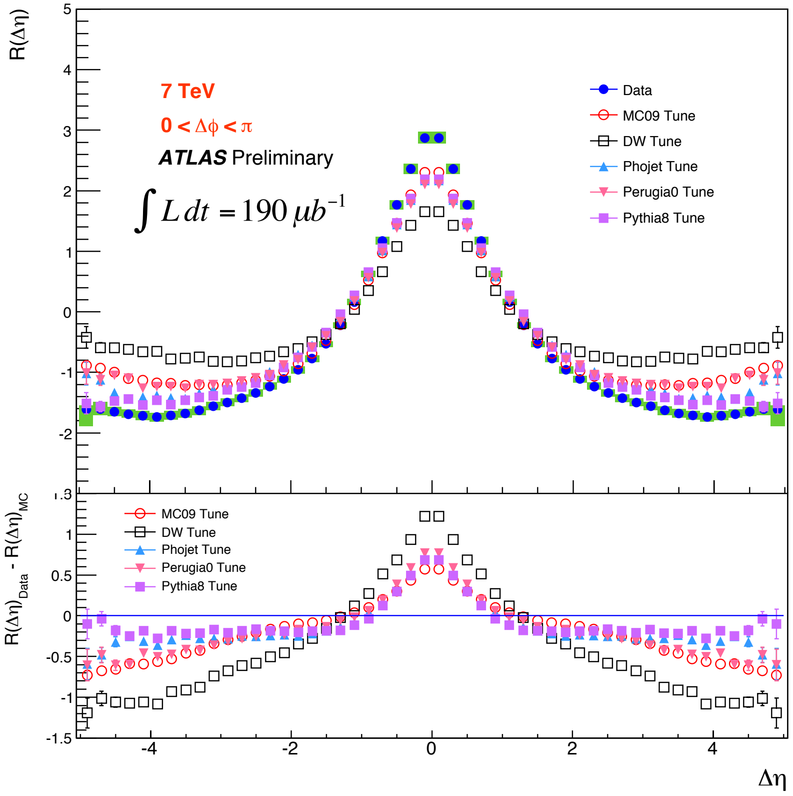
Two particle angular correlations



Two particle angular correlations

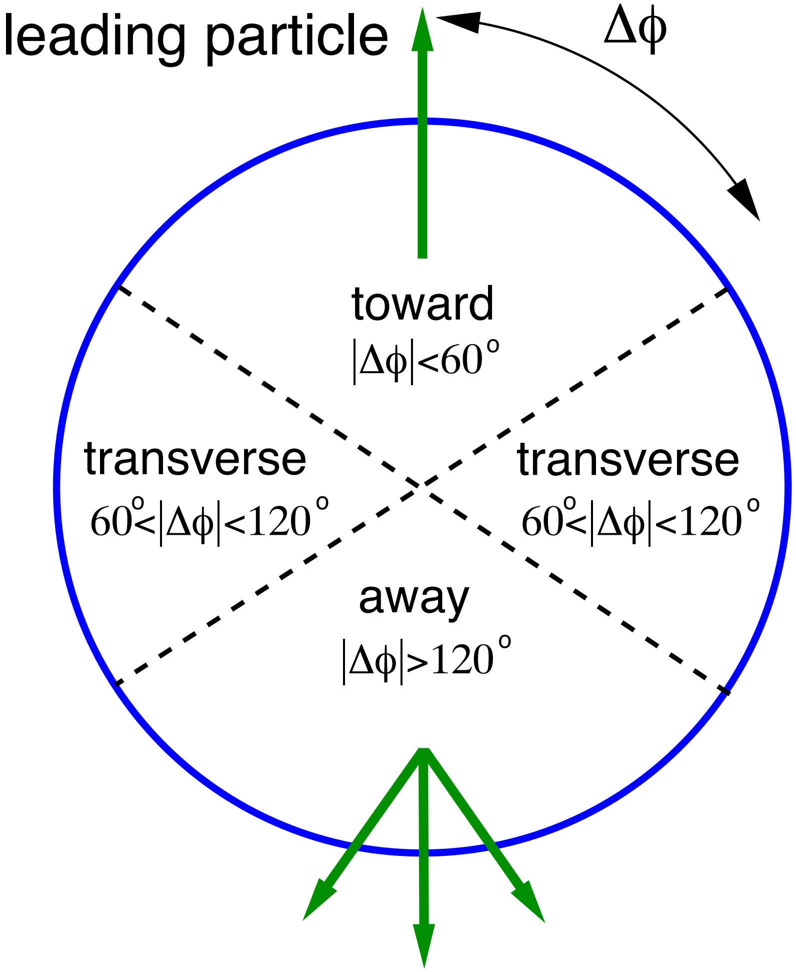


900 GeV

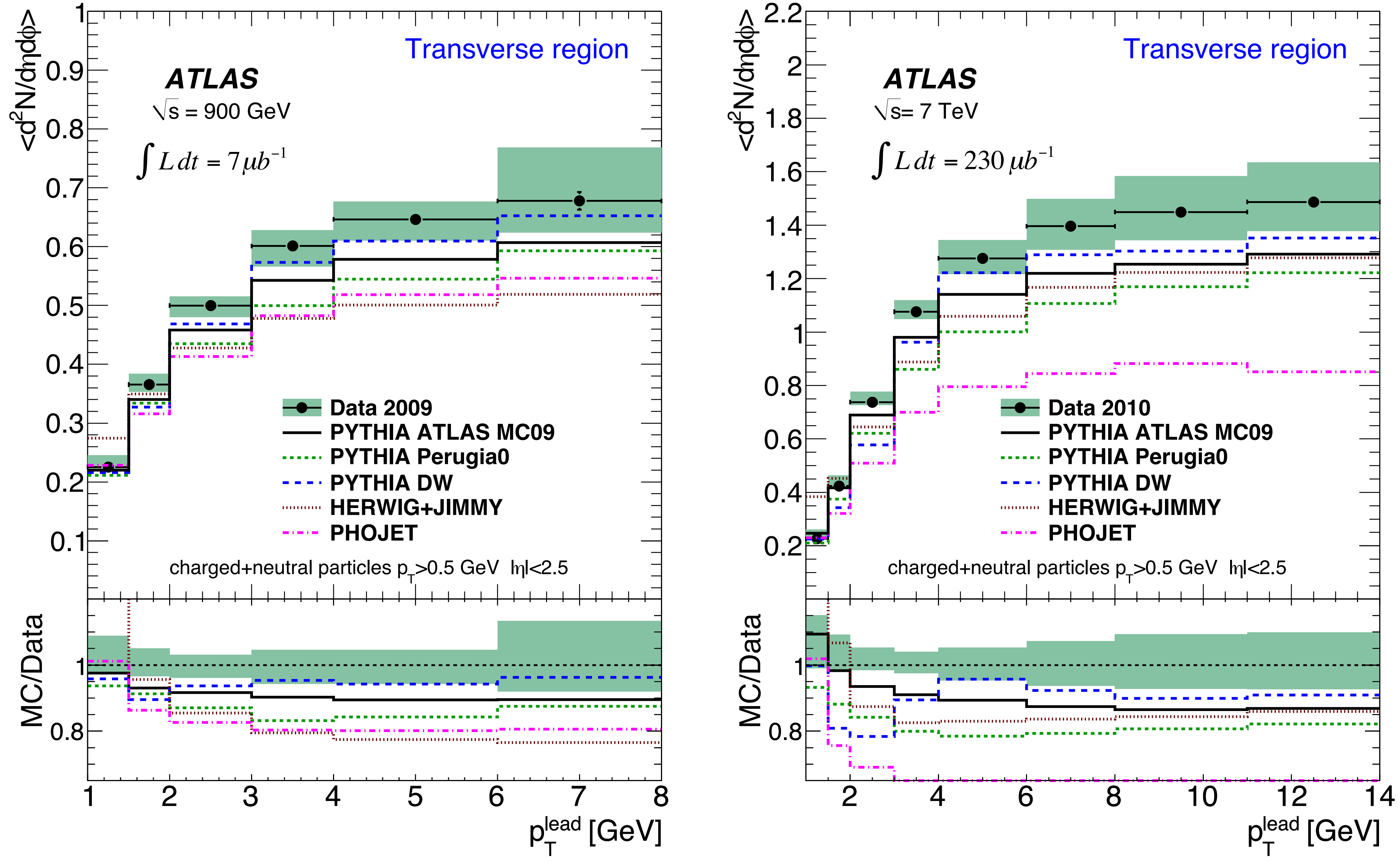


7 TeV

Further Underlying Event Studies



Underlying Event



Soft Physics Tunes General Comments

* Still at the stage where different tunes have different levels of success depending on the process studied

* Differences in UE cross sections at ~20% still in play

* Generally, tunes optimized for 7 TeV data due better than older Tevatron based tunes

(For multijet studies, 2→6 LO MCs do better than 2 → 2 LO MCs)

Summary

- From the QCD perspective, huge data samples
- Pushed the limits/quality in energy, kinematic range, event reconstruction compared to past hadron colliders
- Should have reasonably accurate determinations of α_s from ATLAS soon. . .
- Future data will extend the kinematic reach ($\sqrt{s} \sim 14$ TeV)
- Soft QCD measurements will become more challenging in the higher energy and higher luminosity environment, where large pileup rates may dominate

BACKUP

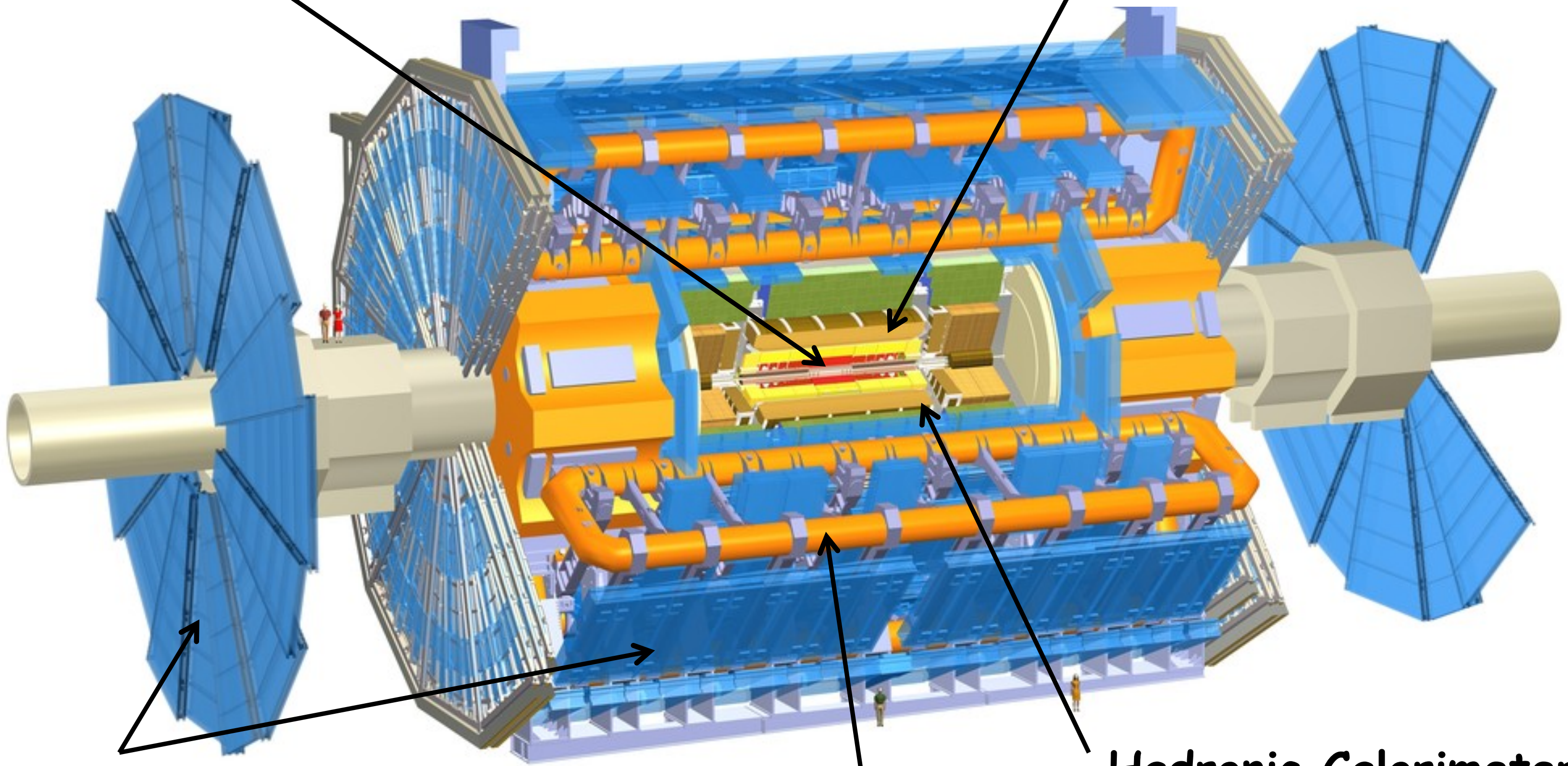
$$R\left(\Delta\eta,\Delta\phi\right)=\frac{\left\langle\left(N_{ch}-1\right)F\left(N_{ch},\Delta\eta,\Delta\phi\right)\right\rangle_{ch}}{B\left(\Delta\eta,\Delta\phi\right)}-\left\langle N_{ch}-1\right\rangle_{ch}$$

The foreground correlation distribution F in η and ϕ between emitted particle pairs is given by

$$F\left(\Delta\eta,\Delta\phi\right)=\left\langle\frac{2}{N_{ch}\left(N_{ch}-1\right)}\sum_{i}\sum_{j\neq i}\delta_{\eta_i-\eta_j-\Delta\eta}\delta_{\phi_i-\phi_j-\Delta\phi}\right\rangle,$$

$$B\left(\Delta\eta\right)=\int_{-2.5}^{2.5}\int_{-2.5}^{2.5}\mathrm{d}\eta_1\mathrm{d}\eta_2\delta\left(\eta_1-\eta_2-\Delta\eta\right)\left.\frac{\mathrm{d}N_{ch}}{\mathrm{d}\eta}\right|_{\eta=\eta_1}\left.\frac{\mathrm{d}N_{ch}}{\mathrm{d}\eta}\right|_{\eta=\eta_2}$$

ATLAS



Electromagnetic Calorimeter

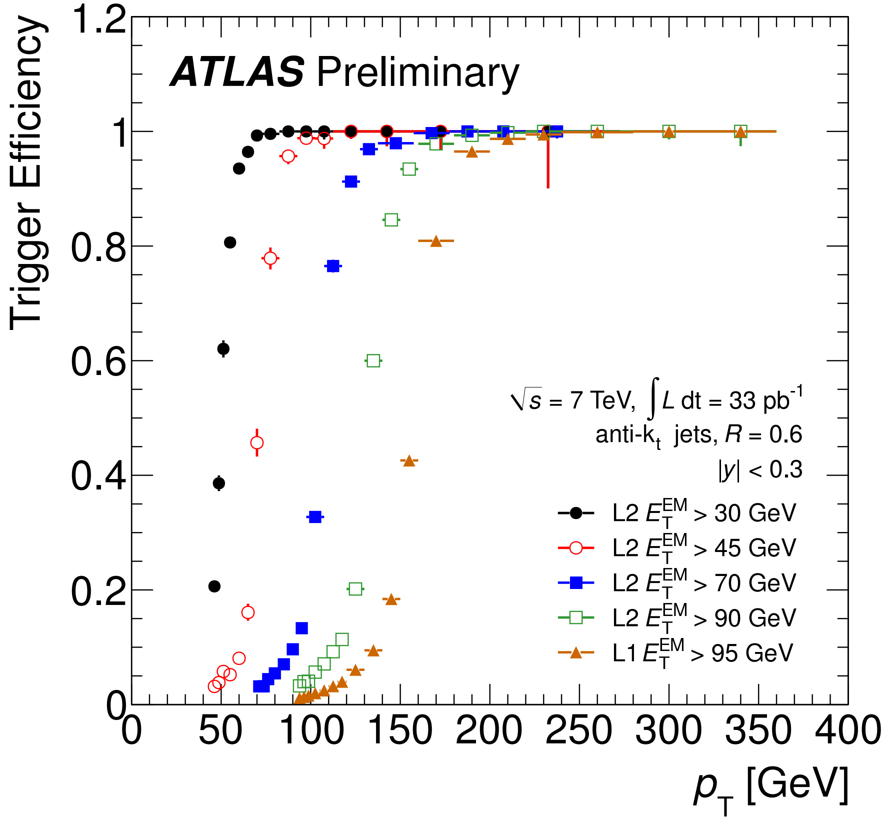
Inner Detector

Muon System

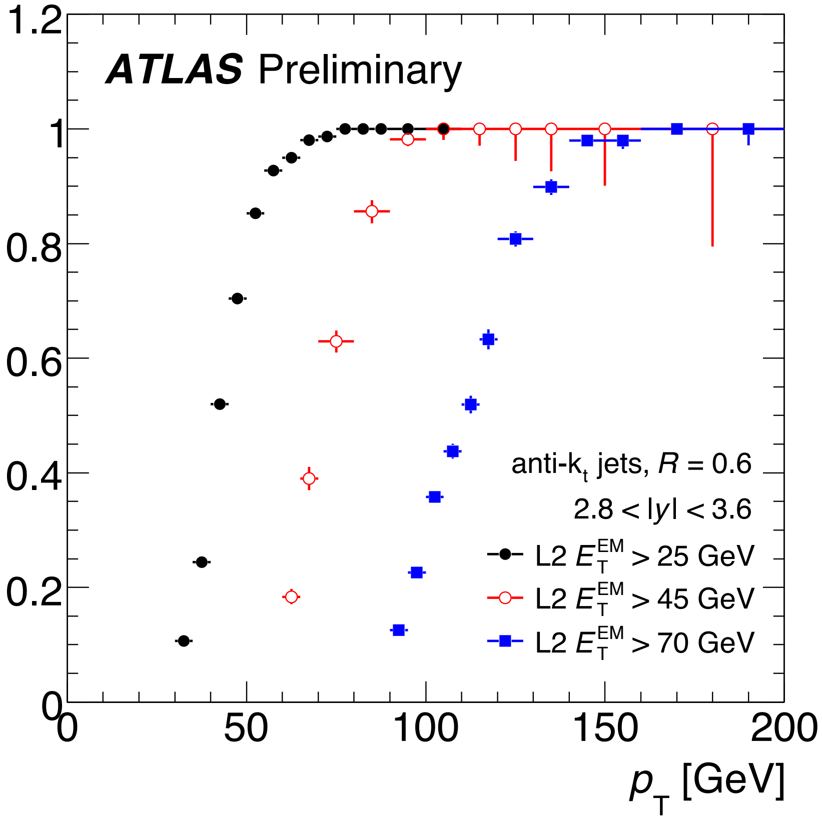
Hadronic Calorimeter

Toroid Magnets

L2 trigger efficiency versus jet p_T



$0.3 < |y|$



$2.8 < |y| < 3.6$