Entering a New Era:

Precision measurements of W/Z+jets at the LHC

Monica Dunford

IPPP, Durham University

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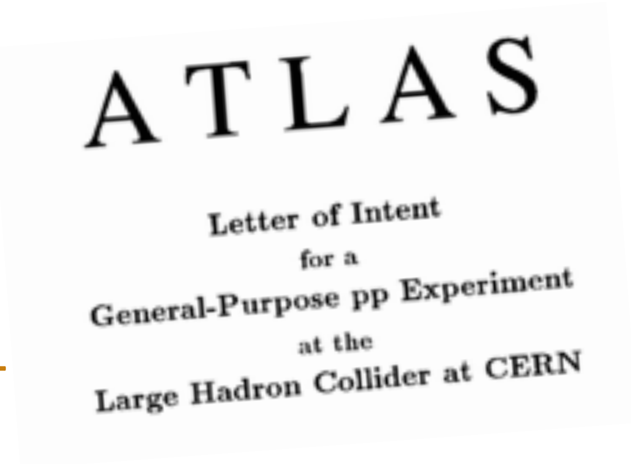
Outline

- An Experimental Challenge
  - An historical interlude
- W/Z+jets as probes of QCD
- Short discussion of backgrounds/uncertainties
- Results
  - Focus on a recent measurement of W+jets
  - http://arxiv.org/abs/1409.8639

The Experimental Challenge

The experimentalists


ATLAS

Letter of Intent
for a
General-Purpose pp Experiment
at the
Large Hadron Collider at CERN

1992

The theorists

1686

Total number of papers on the archive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• 9.5" color active matrix TFT-LCD screen
• 120/200/340MB HDD
• 6.9 lbs.
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T4600
• 9.5" high-contrast, black and white LCD screen
• 120/200MB HDD
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BOTH MODELS
• Intel 486SL/33MHz, 3.3 volt processor with 8K cache
• 4MB RAM expandable to 20MB
• Type II (5mm) and Type "IV" (16mm) PCMCIA slots
• BallPoint™ mouse w/QuickPort™
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The Experimental Challenge

The experimentalists

ATLAS

Letter of Intent
for a
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Large Hadron Collider at CERN

From CERN Courier: Jenni and Virdee

"A prevalent saying was: We think we know how to build a high-energy, high-luminosity hadron collider — but we don't have the technology to build a detector for it"

1992

The theorists

1686

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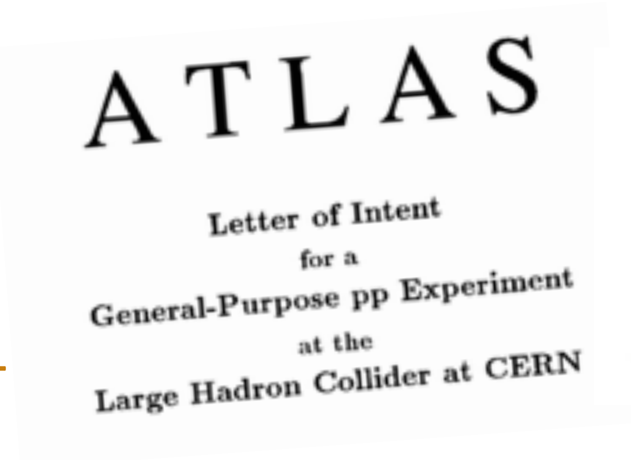
The Experimental Challenge

The experimentalists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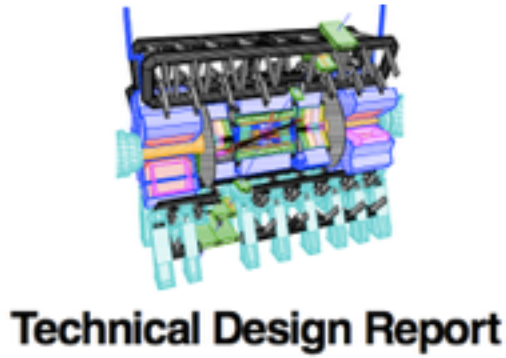

1992 — 1999 — 2000 →

The theorists

1686 **19476** **22621**

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The Experimental Challenge

The experimentalists

Charged-particle multiplicities in pp interactions at $\sqrt{s} = 900$ GeV measured with the ATLAS detector at the LHC

The ATLAS Collaboration

2008 — 10 days later — 2010 →

The theorists

49076 **49162** **55831**

Total number of papers on the archive

The Experimental Challenge

The experimentalists

372

2008 — 10 days later — Today

The theorists

49076 49162 75119

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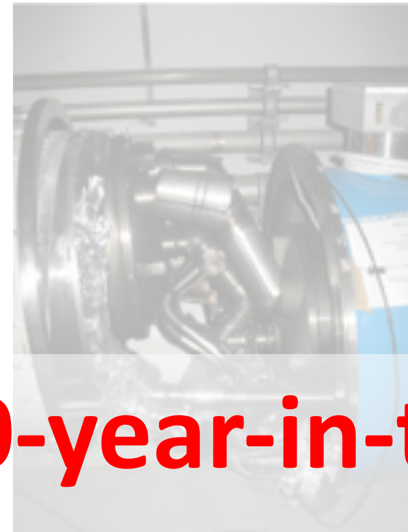
The Experimental Challenge

The experimentalists



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How can a 20-year-in-the-making experiment measure today's physics?

The theorists

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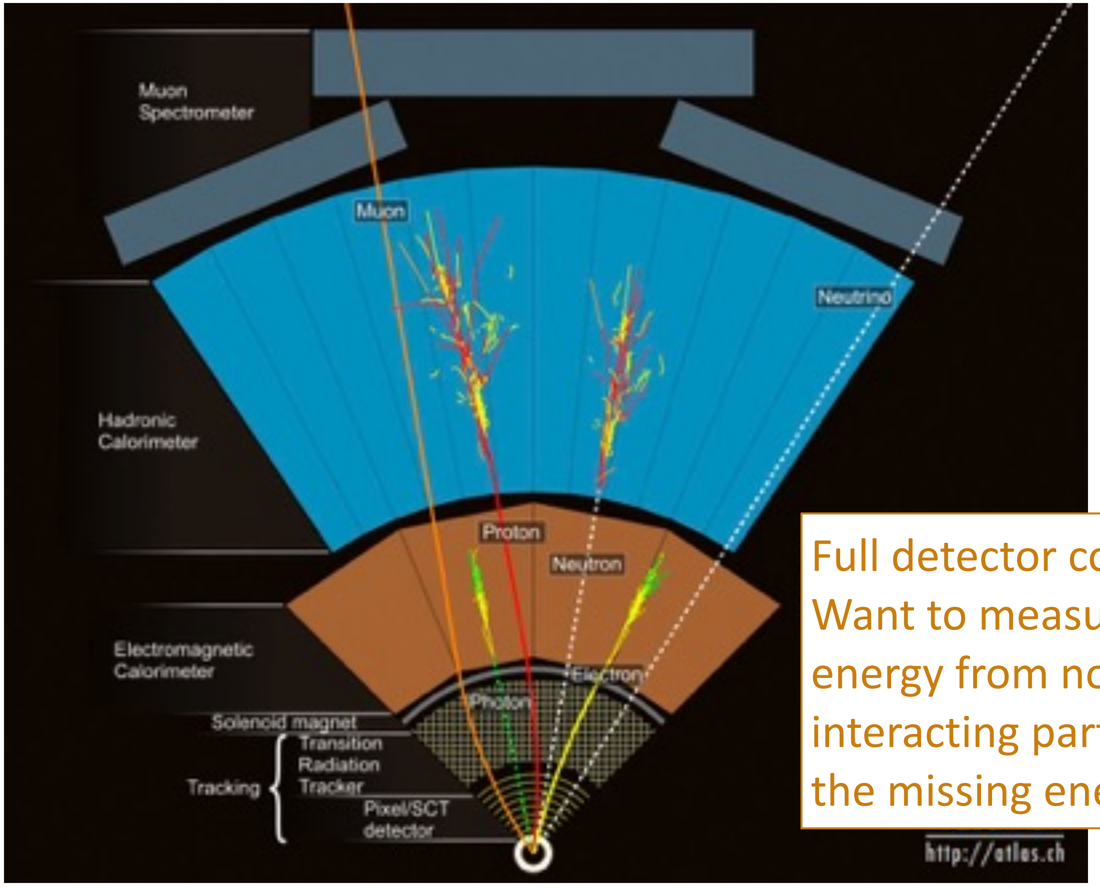
A Collider Experiment in General

- The goal: an excellent measurement of photons, electron, muons, jets and missing energy

Muon spectrometer with toroid magnetic field for measuring momentum of muons

Calorimeter for measuring electron, tau, photon and jet energies over a large energy range

Tracker with solenoid magnetic field to measure momentum of all charged particles

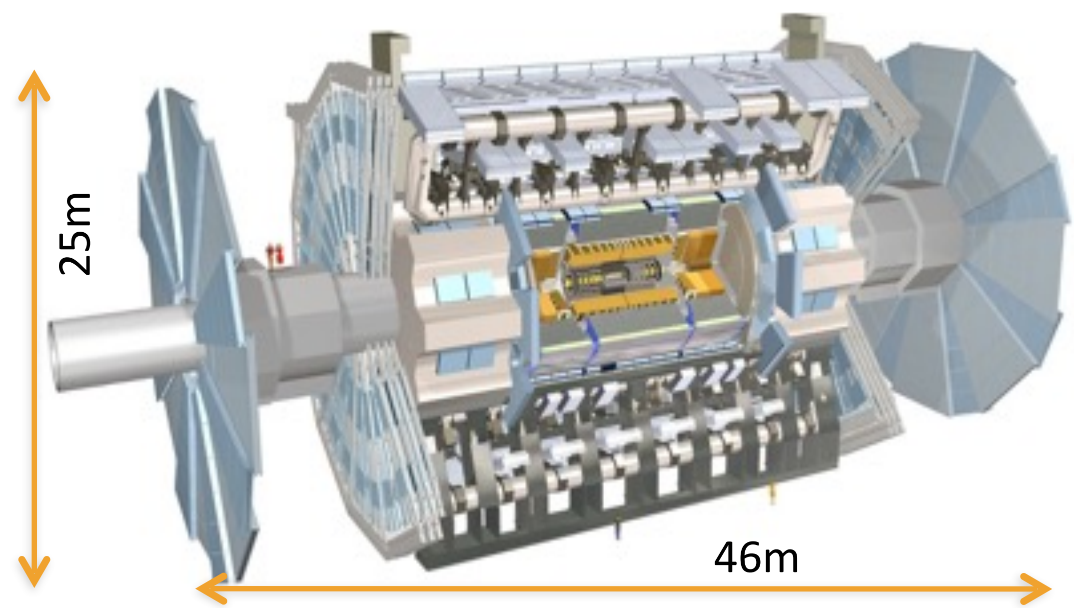


Full detector coverage: Want to measure the energy from non-interacting particles – the missing energy

The ATLAS Experiment in Particular

Design Goal: Precision measurements of the Standard Model and New Physics discovery

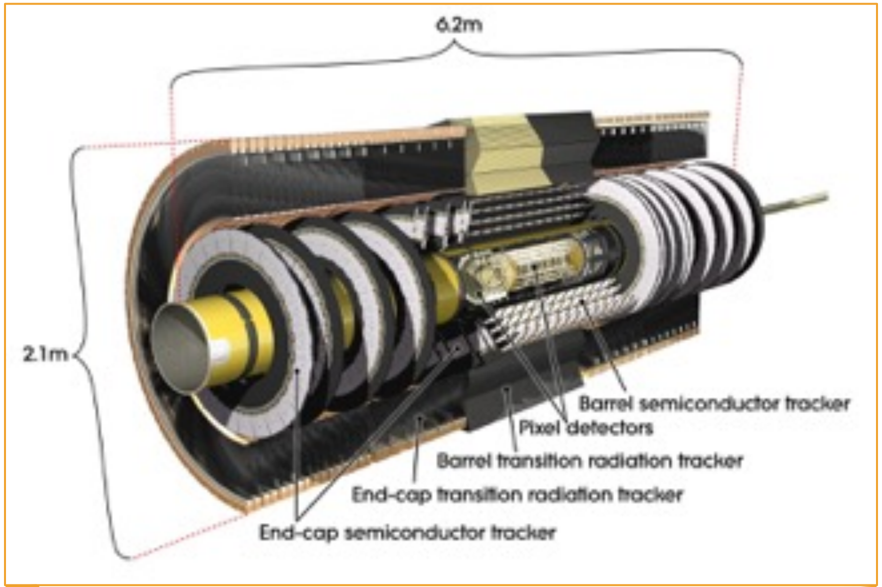
- ATLAS: A Toroidal LHC ApparatuS
- Unique feature is two large magnets
  - 2T solenoid field
  - 4T Toroid field
- Roughly 100 million electronics channels
- 30 pages of authors

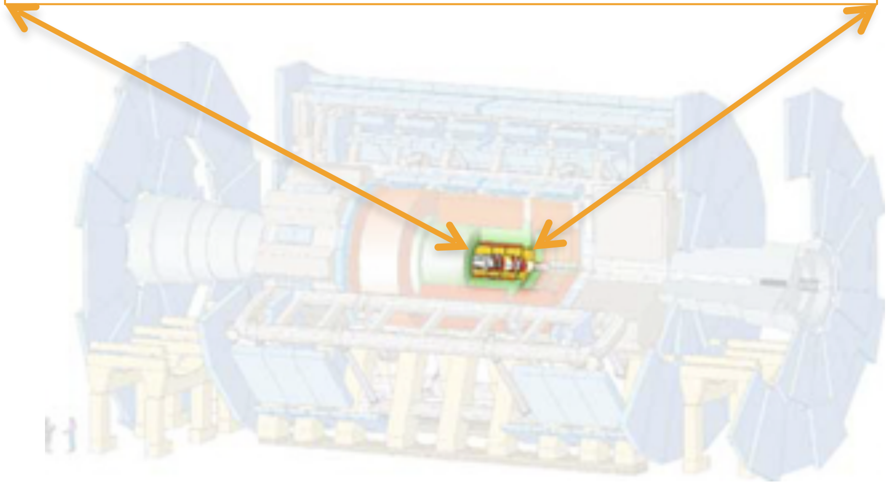


Lepton energy scale ~ 0.02%
Jet energy scale ~ 1%
Absolute luminosity < 5%

The Inner Detector

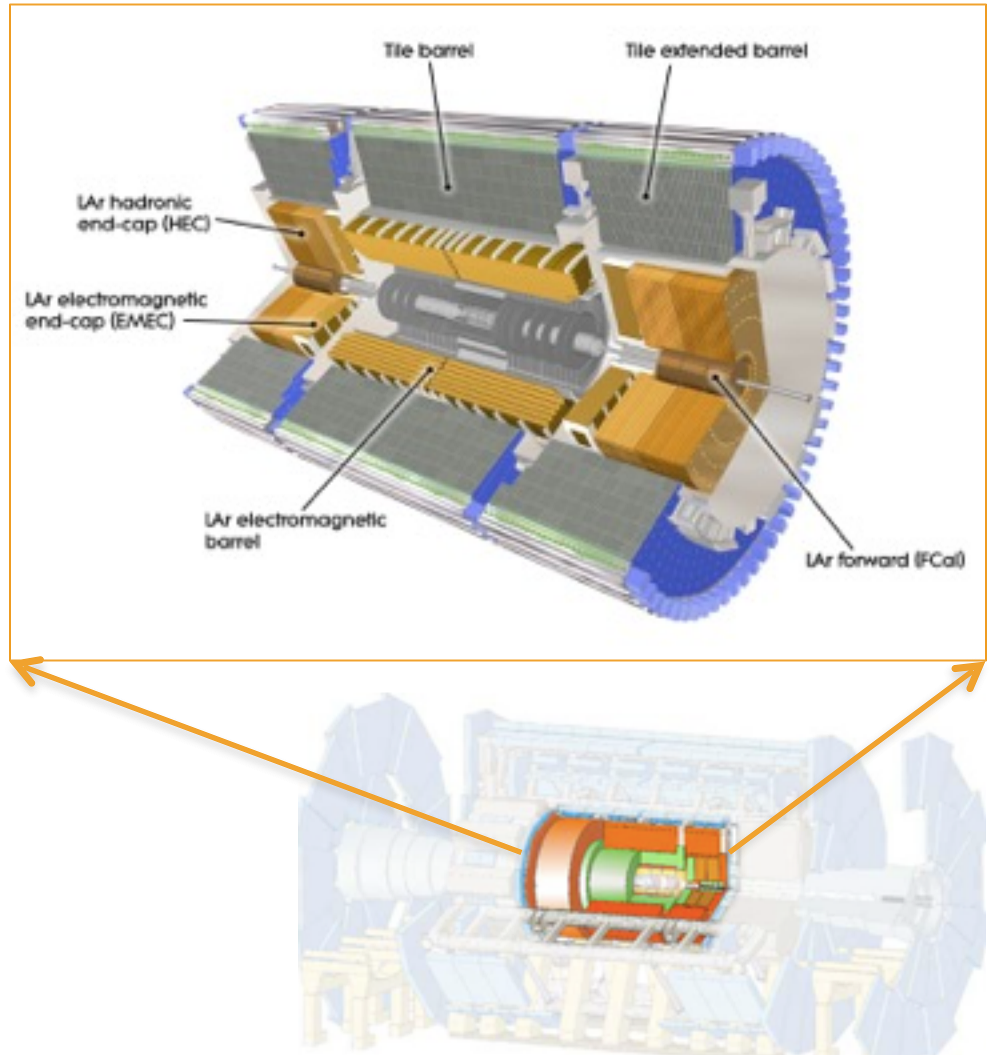
- Three main detector elements
  - Pixels
  - Semiconductor tracker
  - Transition Radiation Tracker
- Surrounded by a 2 Tesla solenoid magnet
- Total η coverage out to 2.5
- Ability for secondary vertex, b-tagging
- Challenges:
  - Have on average 20 simultaneous interactions = lots of tracks





The Calorimeters

- EM: Liquid argon detector with accordion-shaped Kapton electrodes and lead absorber plates
- Hadronic Calorimeter: scintillating tiles with steel absorbers
- Coverage up to $|\eta| = 4.9$



The Muon System

For Track Measurement

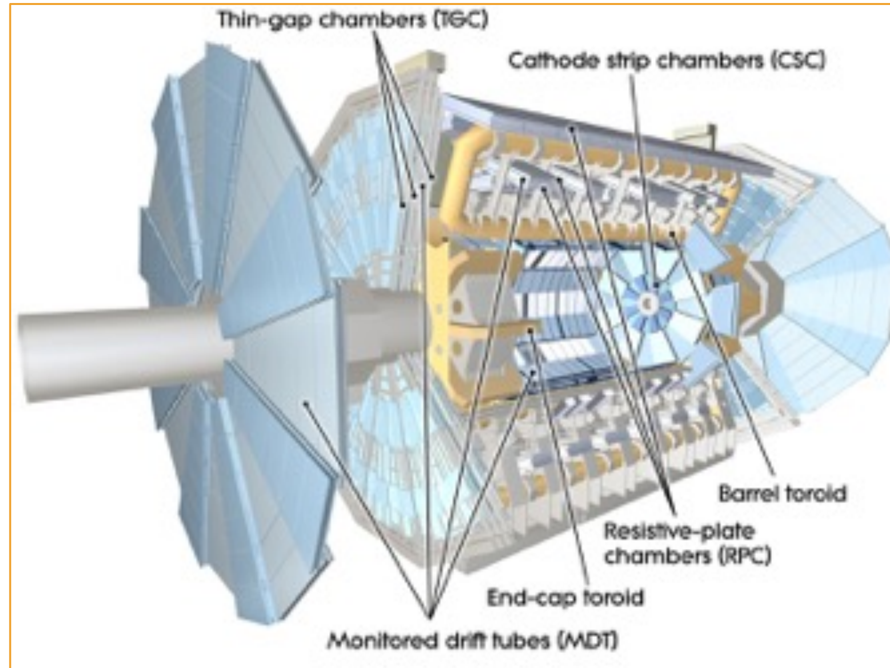
- Monitoring drift tubes
- Cathode Strip Chambers
- Resolution: σ_{pt} = 10% at p_t=1TeV

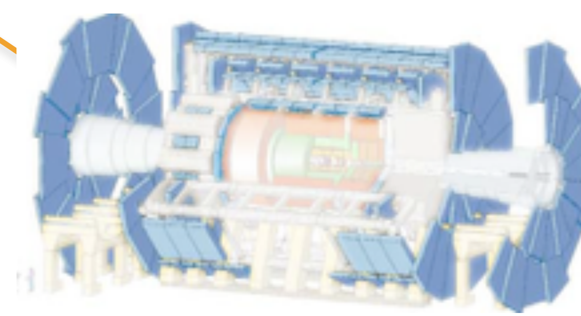
For Triggering

- Resistive plate chambers
- Thin-gap chambers

All inside a 4 Tesla Toroid magnetic field

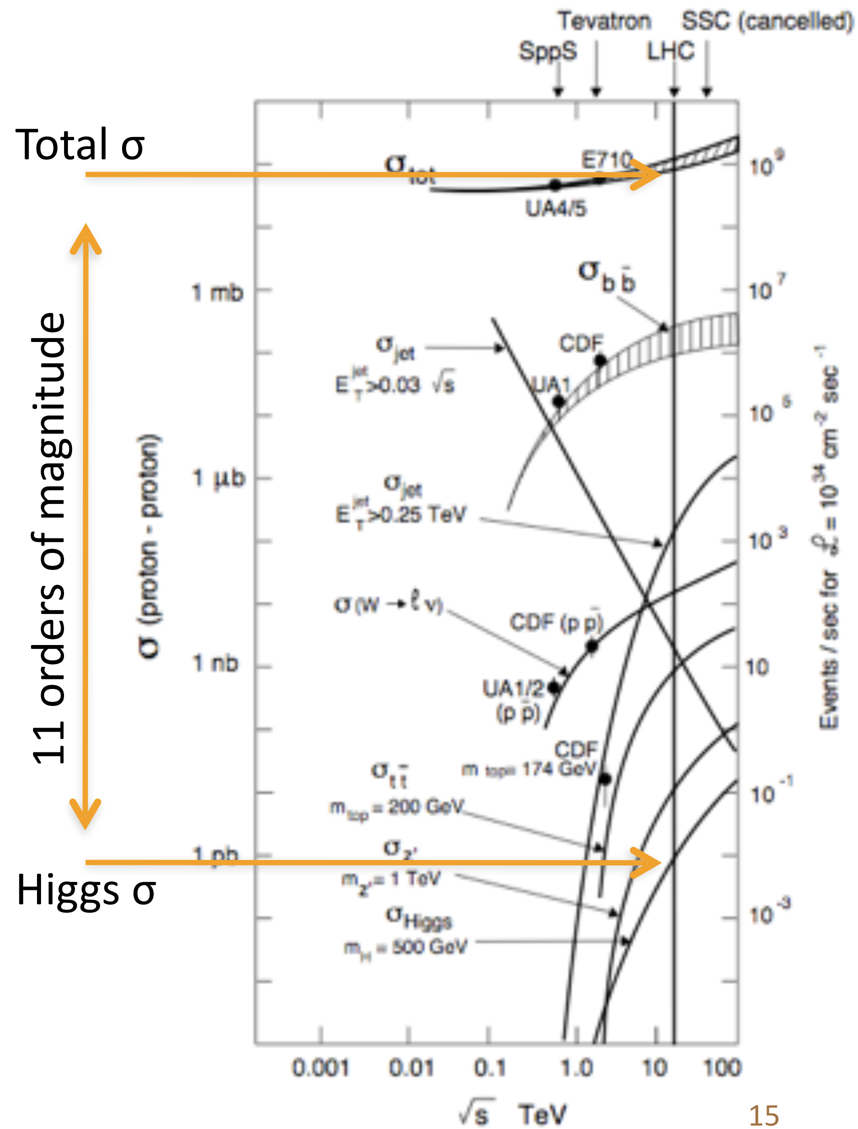
Coverage up to |η| = 2.7





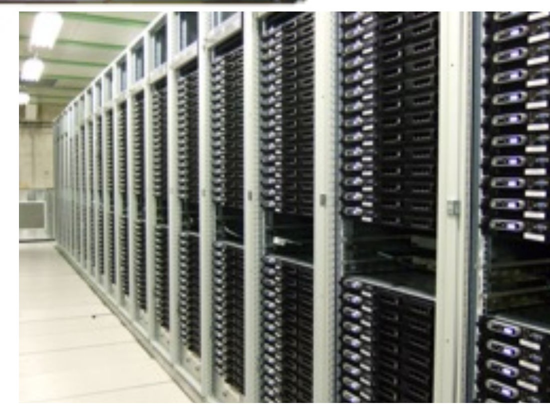
Defining 'Interesting': The Trigger

- First trigger decision must be made within 2.5 µs
- Only write to 'tape' ~400Hz of the original 40MHz
- Still store 1 TB/hr of data



The Trigger Challenge

- Level-1: Fast
  - Specialized hardware
  - Uses only Calorimeter and Muons
  - No tracking, no b-tagging, no vertex/pile-up corrections
- Level-2: Improved
  - Full detector granularity
  - Uses data only in a given Level-1 region-of-interest
  - Tracking is hard (slow)
- Event Filter: Like offline
  - Full detector granularity
  - Alignment and calibration corrections available
  - Full tracking available

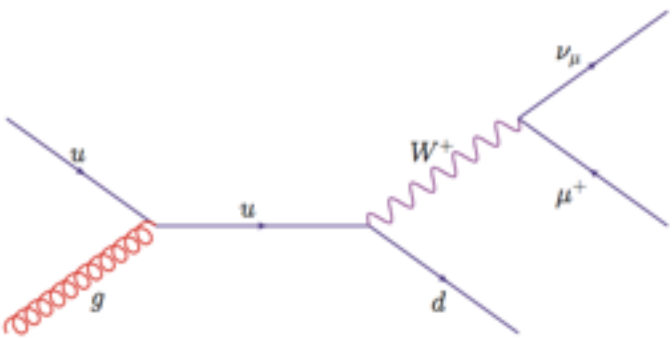


Trigger Level	Output Rate	Decision Time
Level-1	75kHz	2.5μs
Level-2	1kHz	10ms
Event Filter	300-400Hz	1s

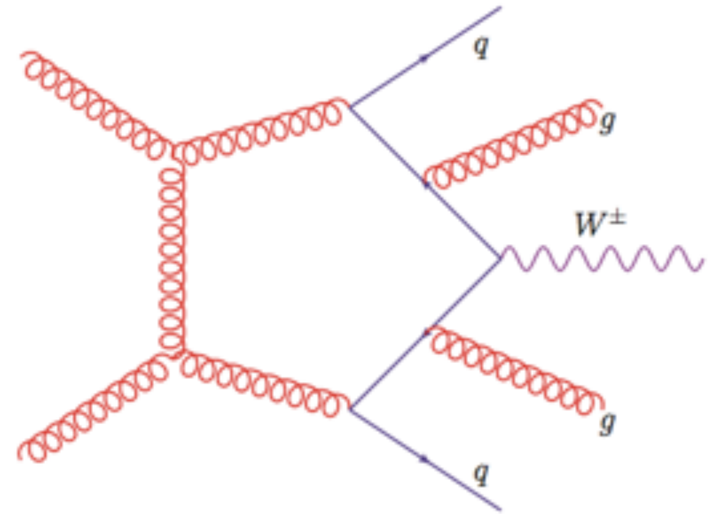
W+jets and Z+jets

V+jets is a test of perturbative QCD

→ This is a jet measurement



W+1 jets



W+4 jets

Interested in the kinematic properties of these the event and jets
→ Differential measurements

What does V+jets Probe?

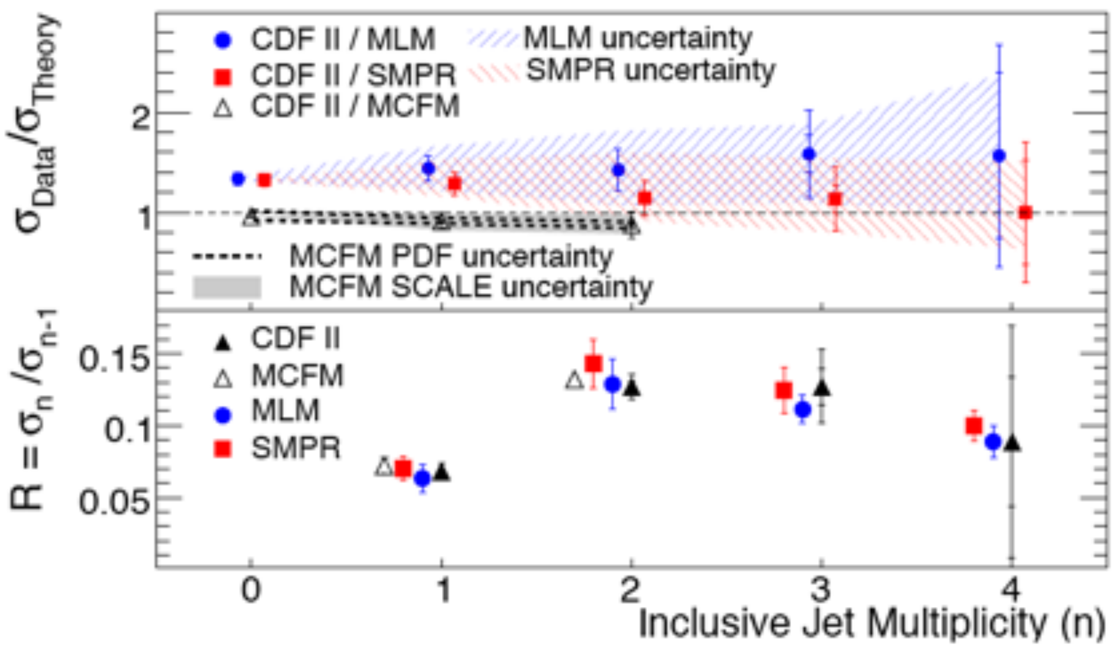
- V+jet production: An important test of perturbative QCD
  - **Scale is large** - in perturbative regime
  - **Test of MC** - test tree-level Matrix Element generators in all corners of phase space
  - **Test of NLO** - In recent years have gone from 2-jet to 5-jet processes
  - **PDF fitting** - where partonic x is large
  - **A major background -** to many Higgs analyses and searches
  - **Jet vetos studies** - of great interest to vector boson fusion studies

V+jets: Pre-LHC

$$\sigma_n = \sigma(W \rightarrow e\nu + \geq n - jet; E_T^{nth-jet} > 25GeV)$$

CDF measurement comparing data to three different W+jet generation models

- MLM (Alpgen), LO
- SMPR (Pythia), LO
- MCFM, NLO



- NLO has small uncertainties but only for Njet=2
- Large stat. uncertainties on the data for Njet=4

Inner error bars are statistical
Outer error bars are systematic

Results from CDF Phy. Rev. D 77 011108 (2008)

NLO Revolution

- The Les Houches NLO wish list (from 2005-2011): calculations that were
  - phenomenologically important for LHC physics
  - feasible
  - difficult to calculate at NLO

2009, 2011 wish list

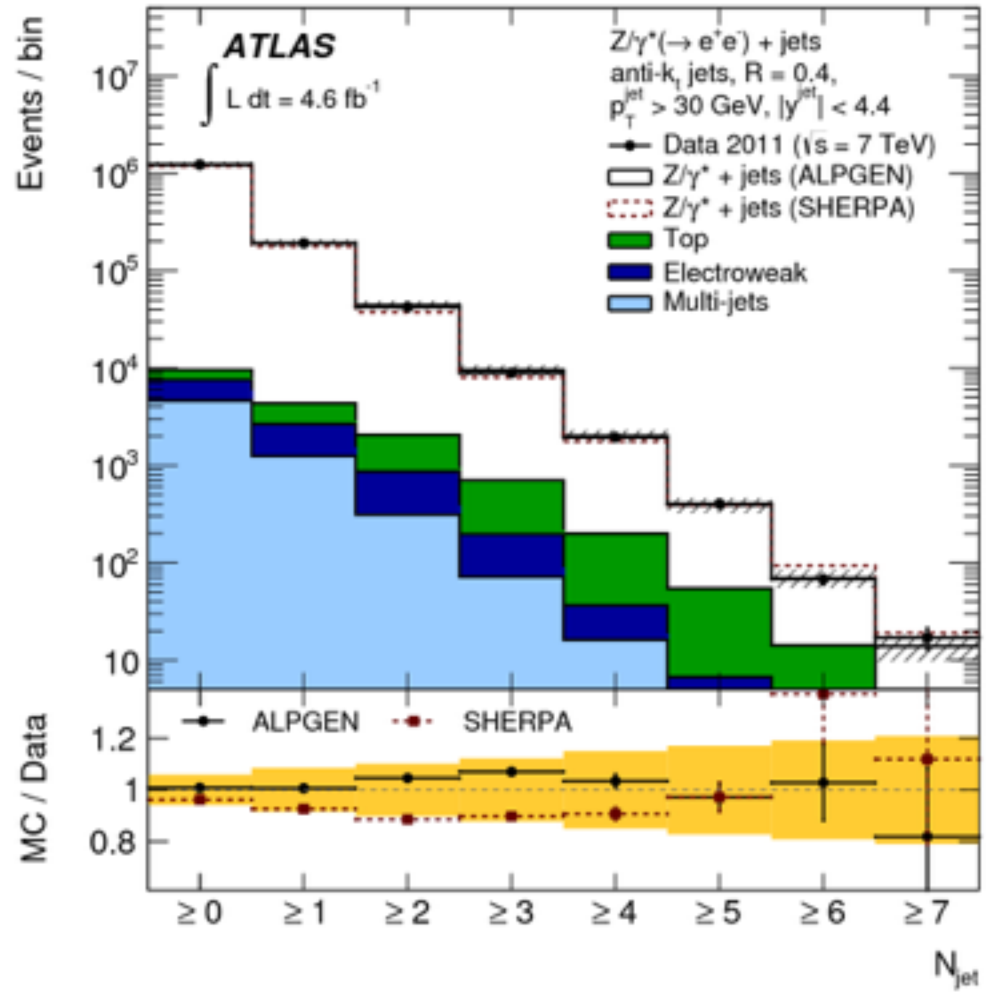
$pp \to W + j$	$pp \to t\bar{t} + 2j$	$pp \to V + 3j$
$pp \to H + 2j$	$pp \to VVb\bar{b}$	$pp \to t\bar{t}b\bar{b}$
$pp \to VVV$	$pp \to VV + 2j$	$pp \to b\bar{b}b\bar{b}$
$pp \to t\bar{t}t\bar{t}$	$pp \to 4j$	$pp \to W + 4j$
$pp \to Z + 3j$	$pp \to Wb\bar{b}j$	

- By 2011, every calculation on the wish list had been determined
- W, Z+jets available to 5-jets, with work ongoing for 6-jet

A plethora of NLO calculations available including: MCFM, MadGraph, MC@NLO, Powheg, HEJ, LoopSim, MEPS@NLO, Blackhat-Sherpa

The Data Revolution

- We have lots of data now!
- Using 2011 data only (~5 fb^{-1}), Z + 7 jets measurement is possible



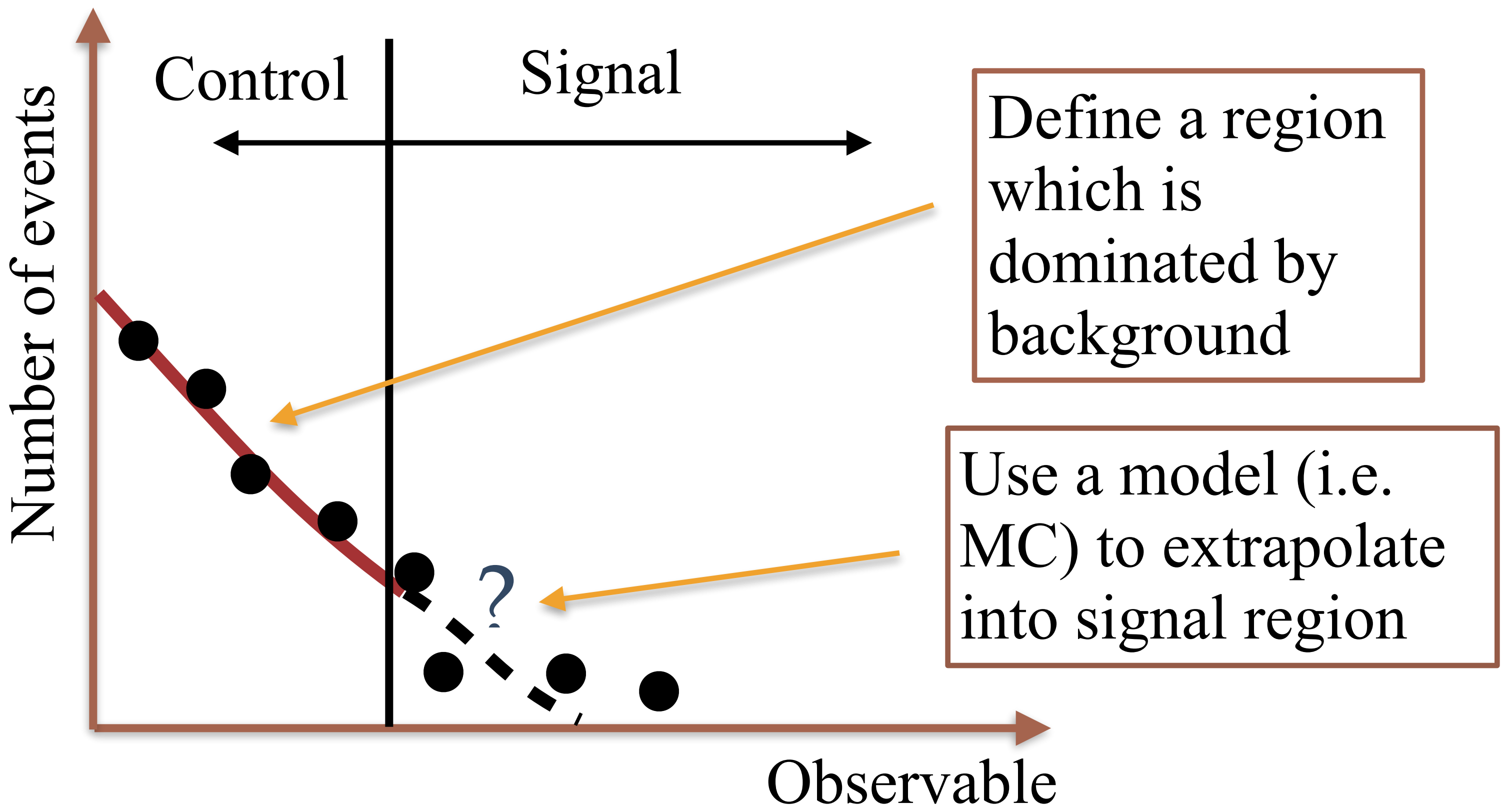
What is Interesting Now

- With much more data from the LHC, the focus is now on
  - Measurements in new phase spaces
    - Such as boosted Z p_T, high jet p_T
  - Measurements for more observables
    - Such as forward jet rapidities
  - Differential measurements in processes with lower cross sections
    - Such as differential cross sections for Z+bb

Important test of the Standard Model in a new phase spaces, especially important for searches, where V+jets are major backgrounds

About Searches

- A common background method:
  - Used to mitigate the dependence on MC

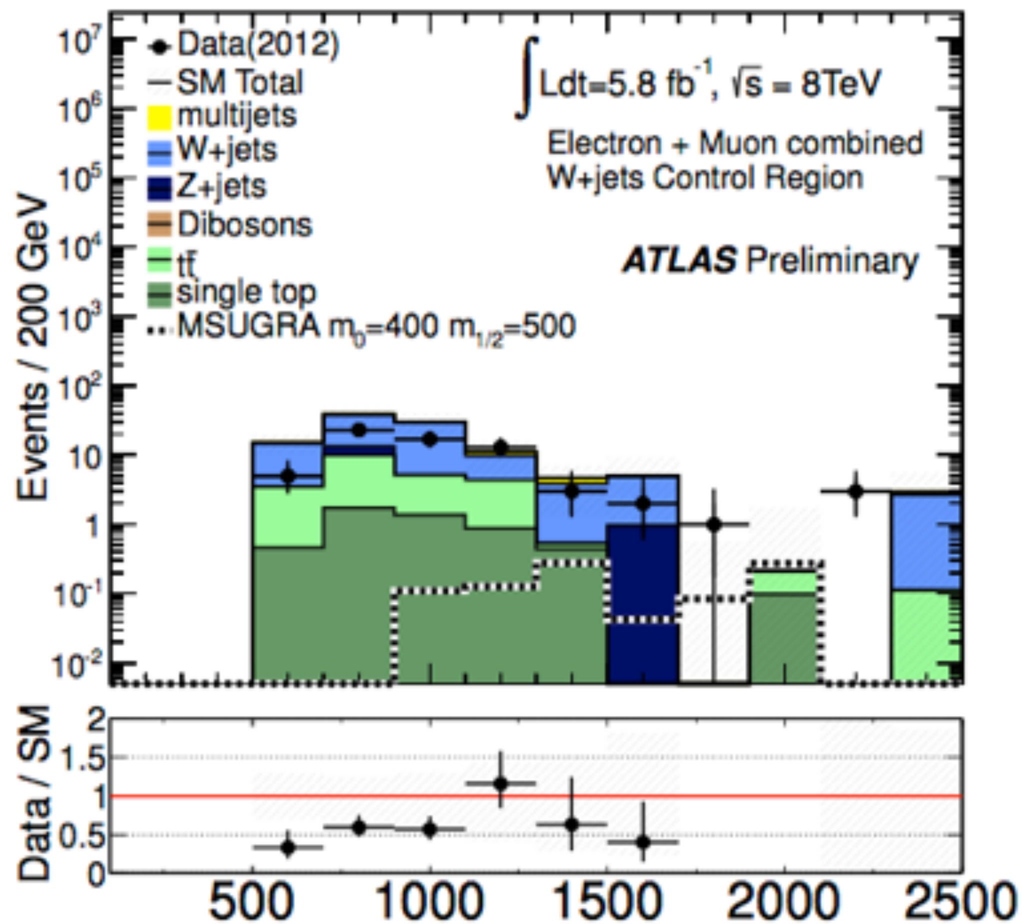


About Searches

- ATLAS SUSY search, chosen at random

Cuts include:

1 lepton, 4+ jets
Missing E_T > 250 GeV
H_T > 800 GeV



H_T (GeV) = scalar sum of all objects

These cuts introduce:

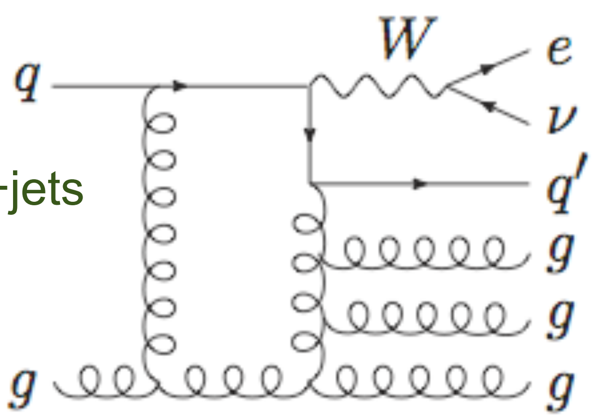
- scales are >> the W/Z mass
- large logarithmic contributions in higher-order QCD corrections

A General Selection

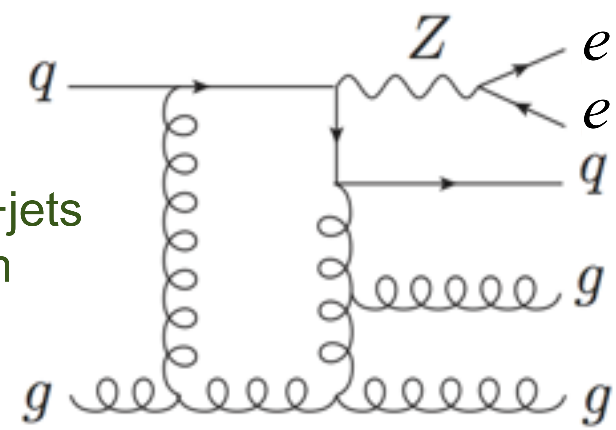
- W+jets
  - 1 high p_T lepton
  - Missing energy and M_T
- Z+jets
  - 2 high p_T leptons
  - Z-mass requirement

For both: High p_T jets

NLO W+jets diagram



NLO Z+jets diagram



In other words, a very general selection with minimal topological cuts

Selecting W Events

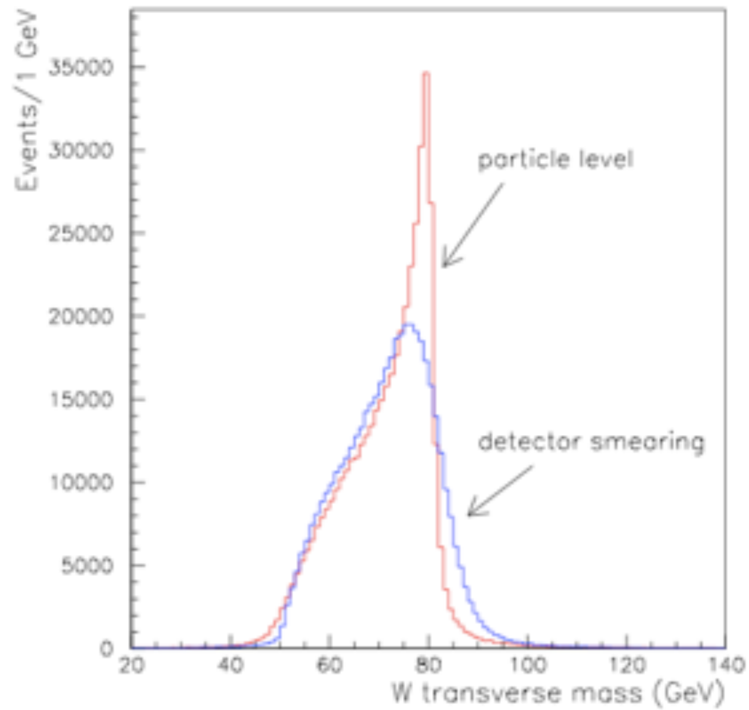
- Leptonically decaying W has missing energy from the neutrino: Cannot reconstruct a mass peak

$$M_T^2(W) = 2 p_T(l) p_T(\nu)[1 - \cos(\Delta\phi)]$$

Lepton transverse momentum

Missing E_t

Angle between lepton and missing E_t in the transverse plane

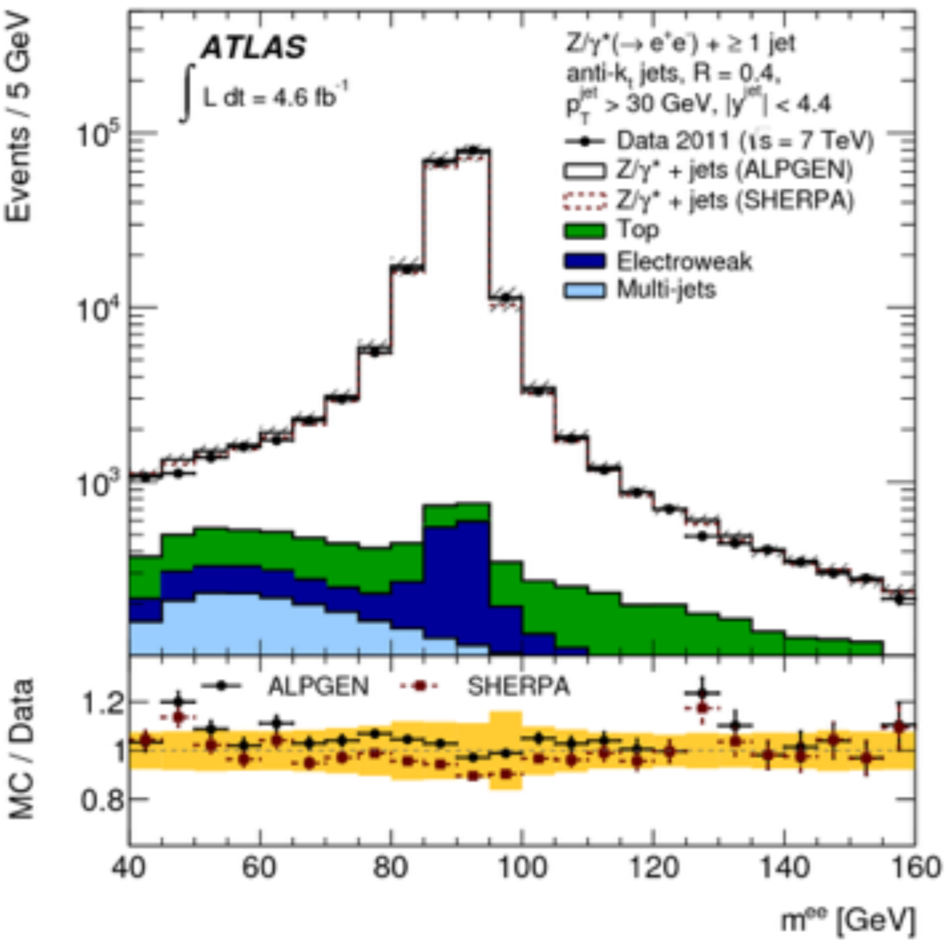


W Boson Selection:

1. Missing E_t > 25 GeV
2. Transverse mass (M_T) > 40 GeV
3. Require one and only one good lepton

Selecting Z Events

- For Z events, can reconstruct the mass of the Z candidate

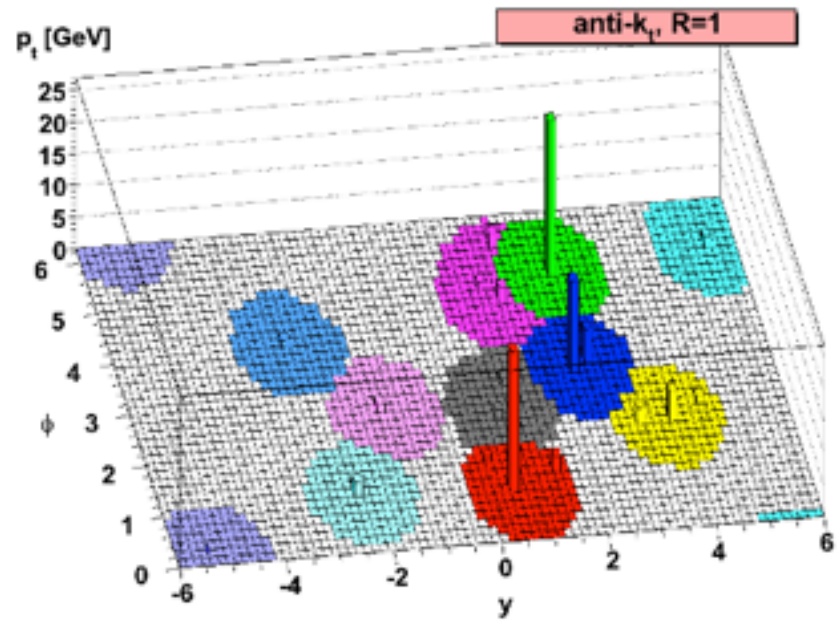


Z Boson Selection:

1. Invariant mass 66 < (M_{ll}) < 116 GeV
2. Require two leptons of opposite charge

Selecting Jets

- A 'jet' depends on your definition
  - Here: Use anti-k_T algorithm, R=0.4
  - Jet p_T > 30 GeV
  - Jet rapidity < 4.4
  - Jets and leptons must be separated by $\Delta R > 0.5$



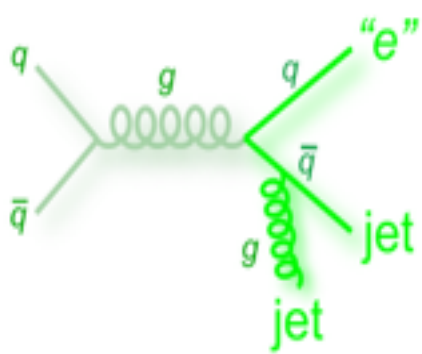
M. Cacciari, G. P. Salam, G.Soyez, JHEP 0804:063,2008

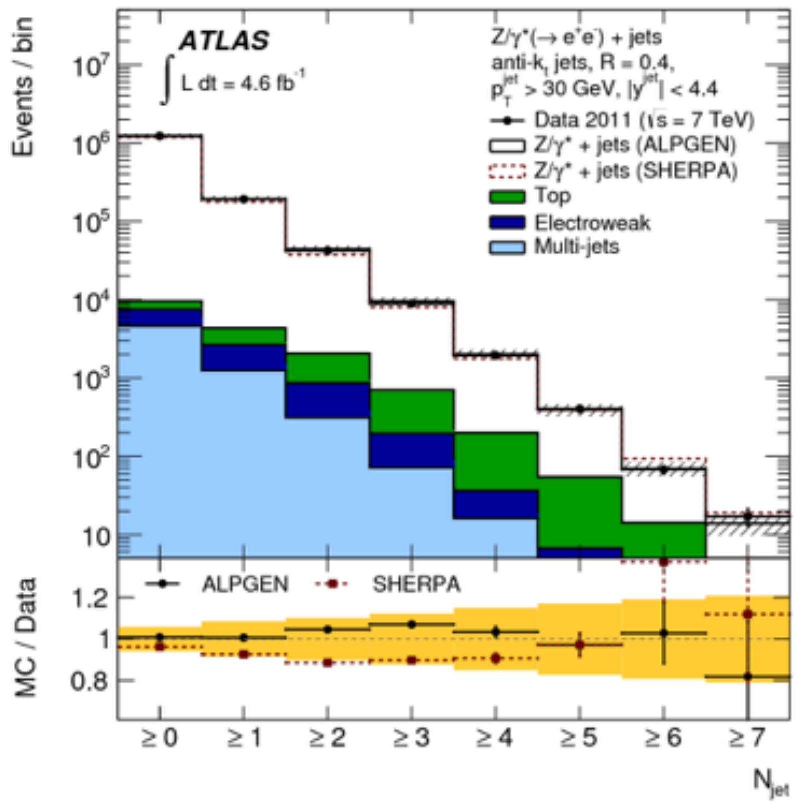
Z+jets: Major Backgrounds

Low Jet multiplicities → High Jet multiplicities

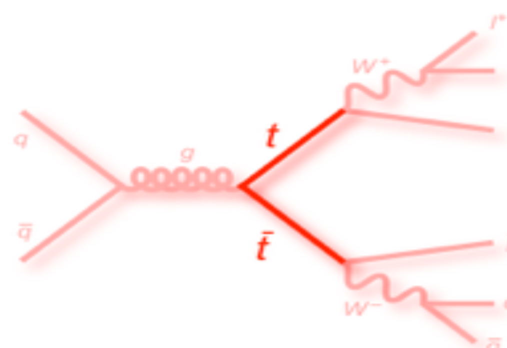
Data-driven estimates reduce systematic uncertainties

Multi-jet: qq, bb





top pair

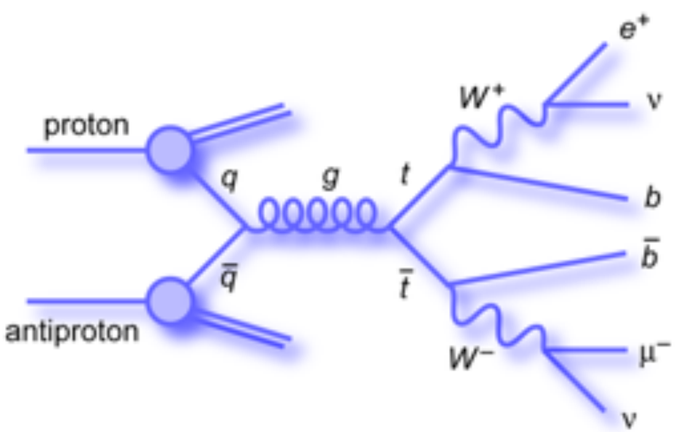


Electroweak Bkgs: WW, WZ, ZZ

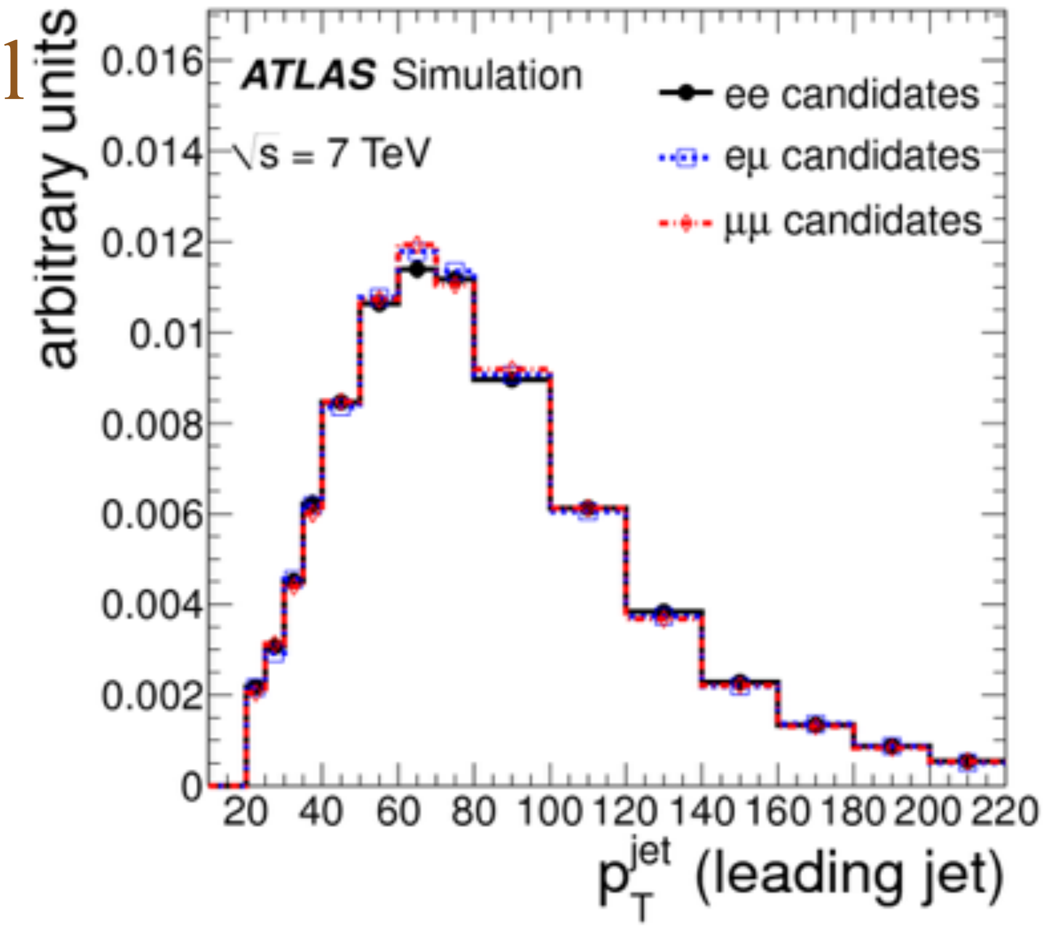
Diagrams complements of D0

Z+jets: Top

- To estimate the ttbar, have the ideal control sample



- For normalization, use MC to estimate eμ to ee/μμ



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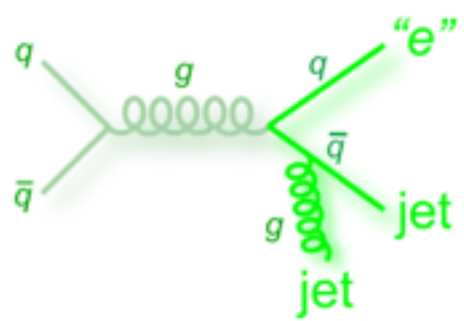

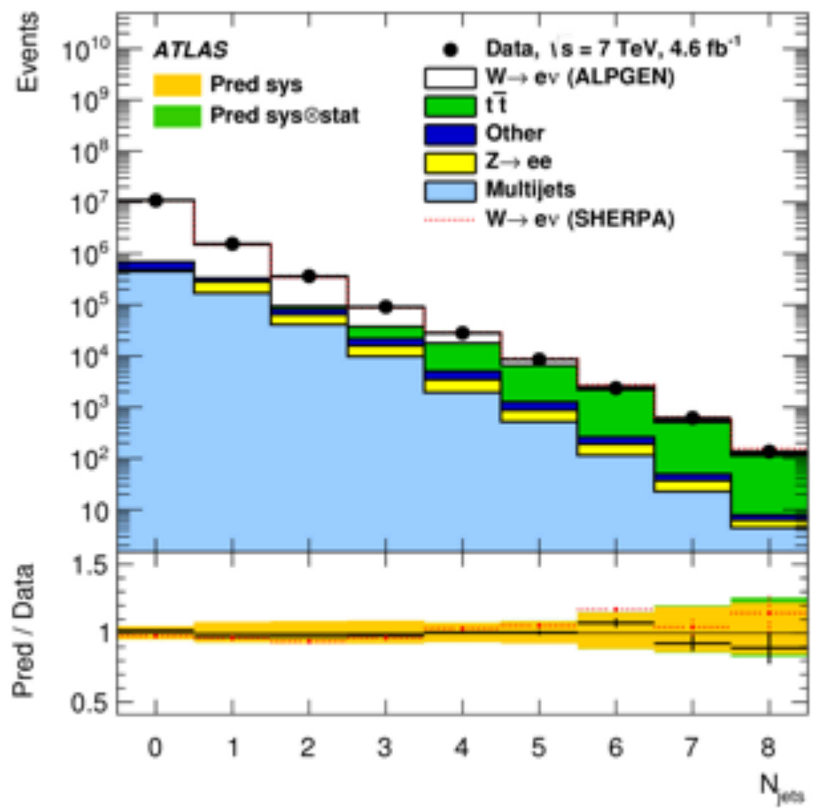

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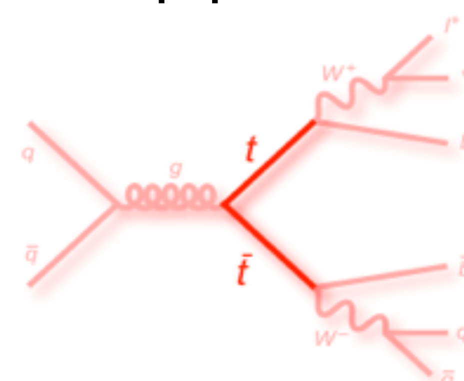
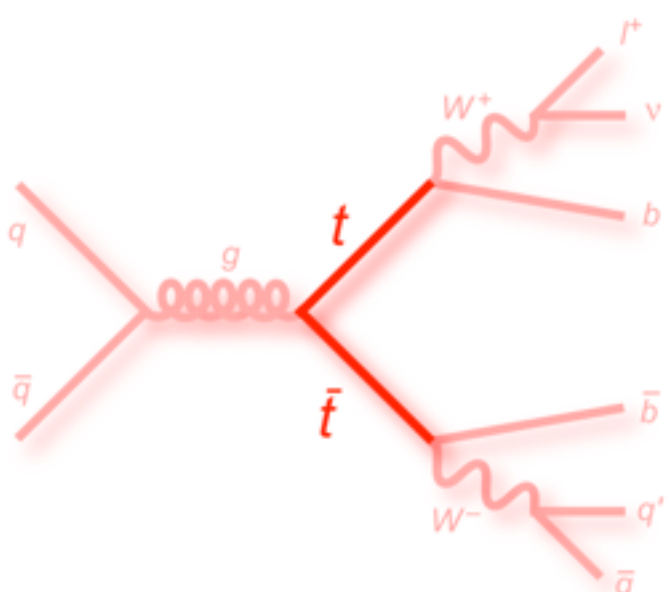


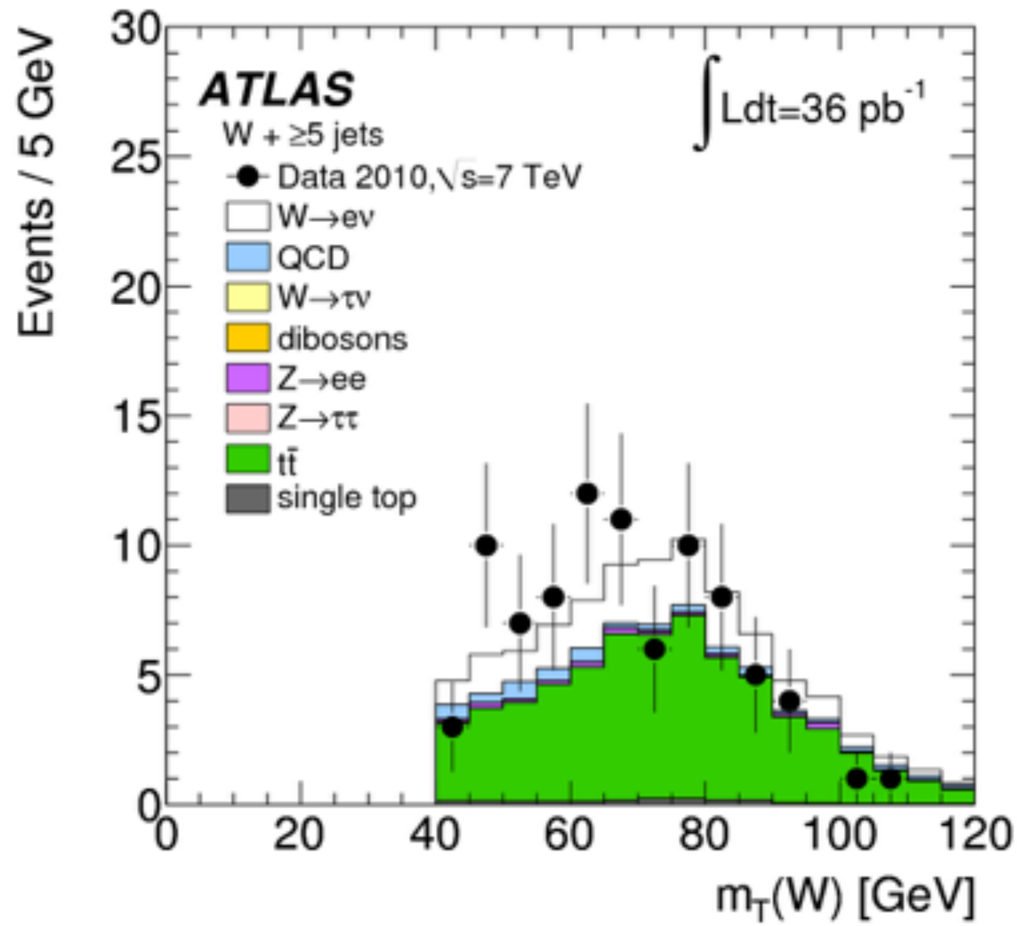
Top is 60% of +5jet events

Others: Z→ll, WW, WZ, ZZ, single-top, W→τν

W+jets: Top

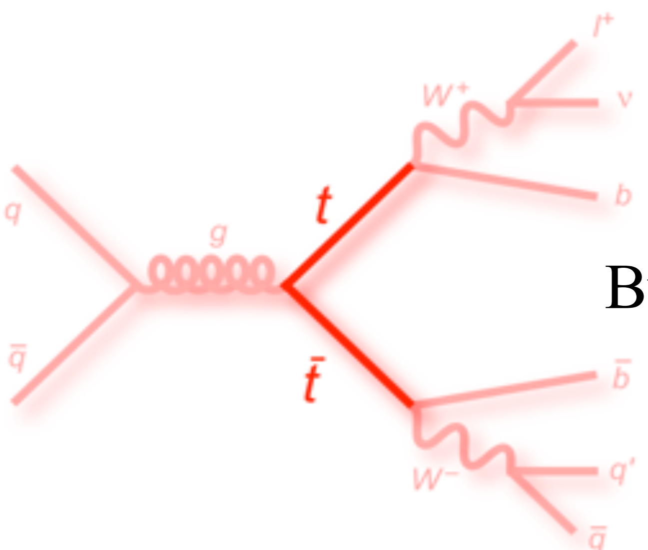
- Unlike Z+jets, no ideal top control sample
- Top events have Ws
  So, no surprise,
  they look like Ws!



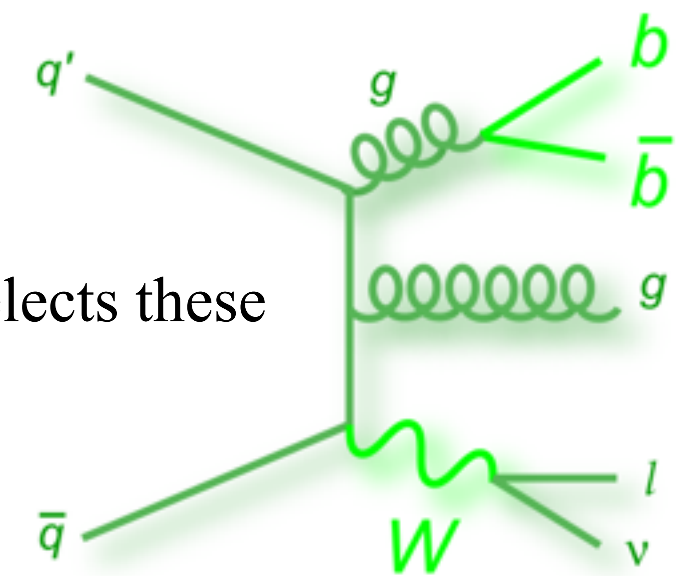


W+jets: Top

- Use b-tagging to select a top control sample



But… also selects these



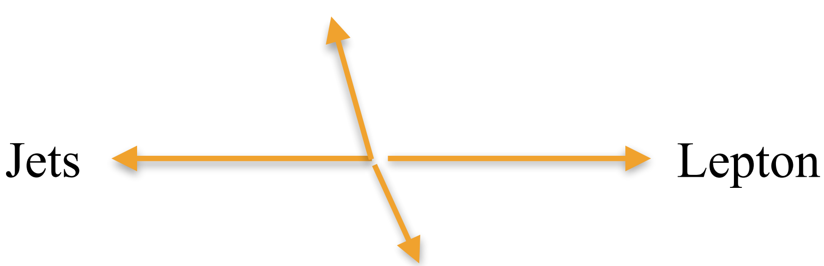
Use MC to remove these from control sample, but uncertainties are large

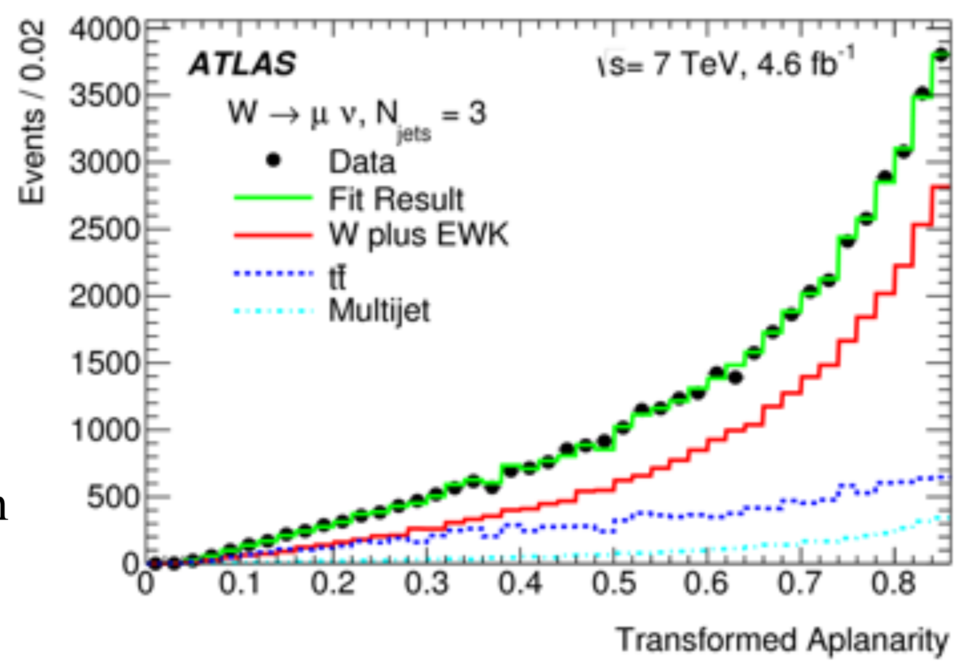
W+jets: Top

- For normalization, have to exploit the topologies
- Use Aplanarity: A measure of the amount of energy outside of the event plane

Value =1: Pencil-like

Value =0: Spherical

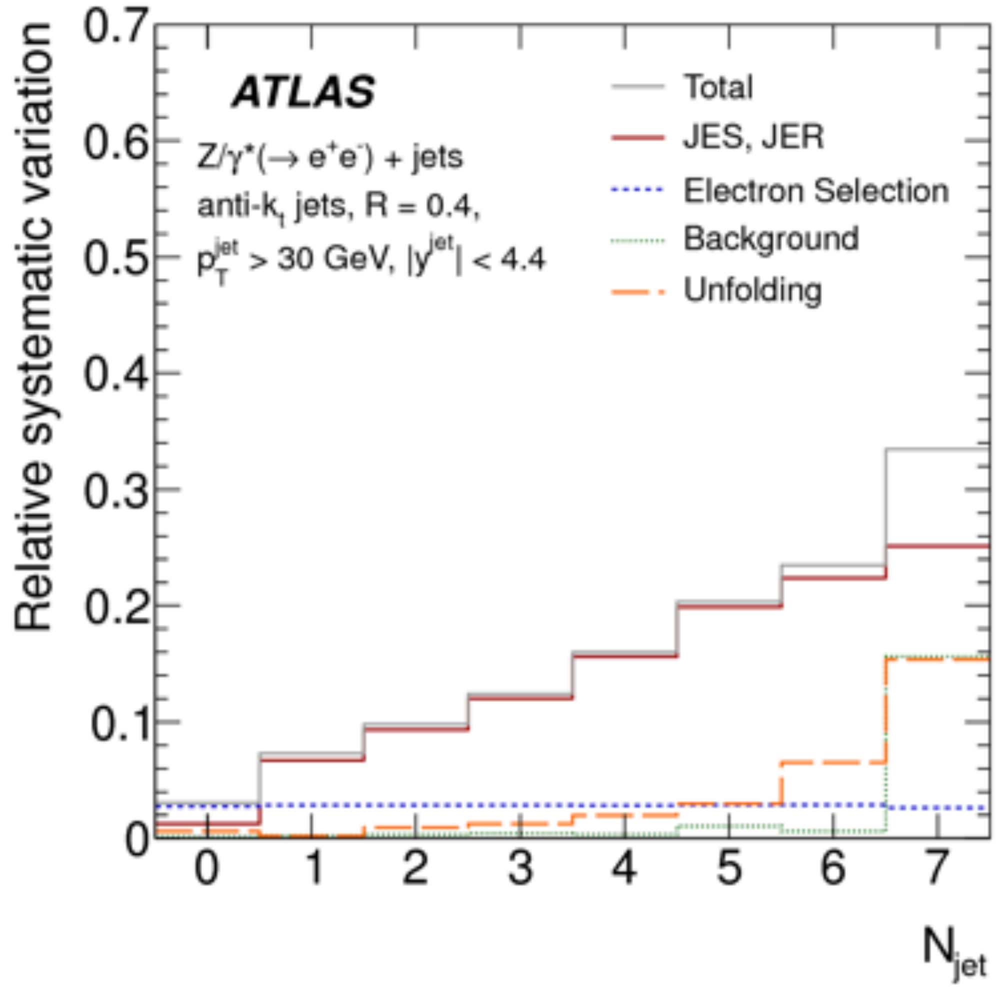




A data-drive top estimates reduces uncertainties by ~ factor of 2

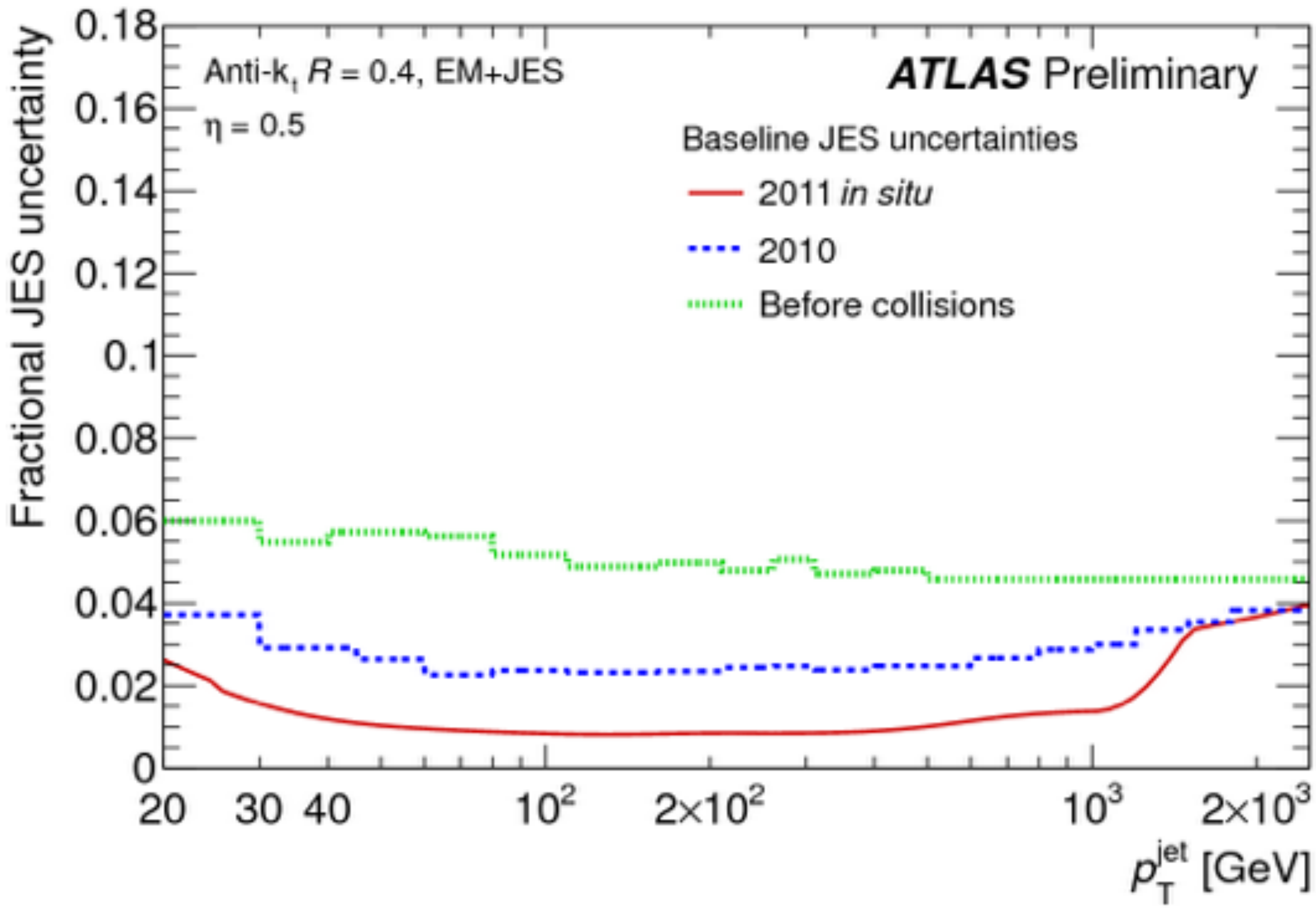
Major Uncertainties

- Measurement is always limited by the jet energy uncertainties
- For W+jets, at high multiplicities, top background uncertainties also large



Jet Uncertainties

- For only three years of running, our JES is great
  - For central jets at pT ~ 100 GeV, 1% uncertainty on the jet energy

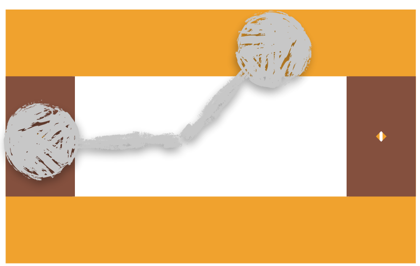


Jet Uncertainties

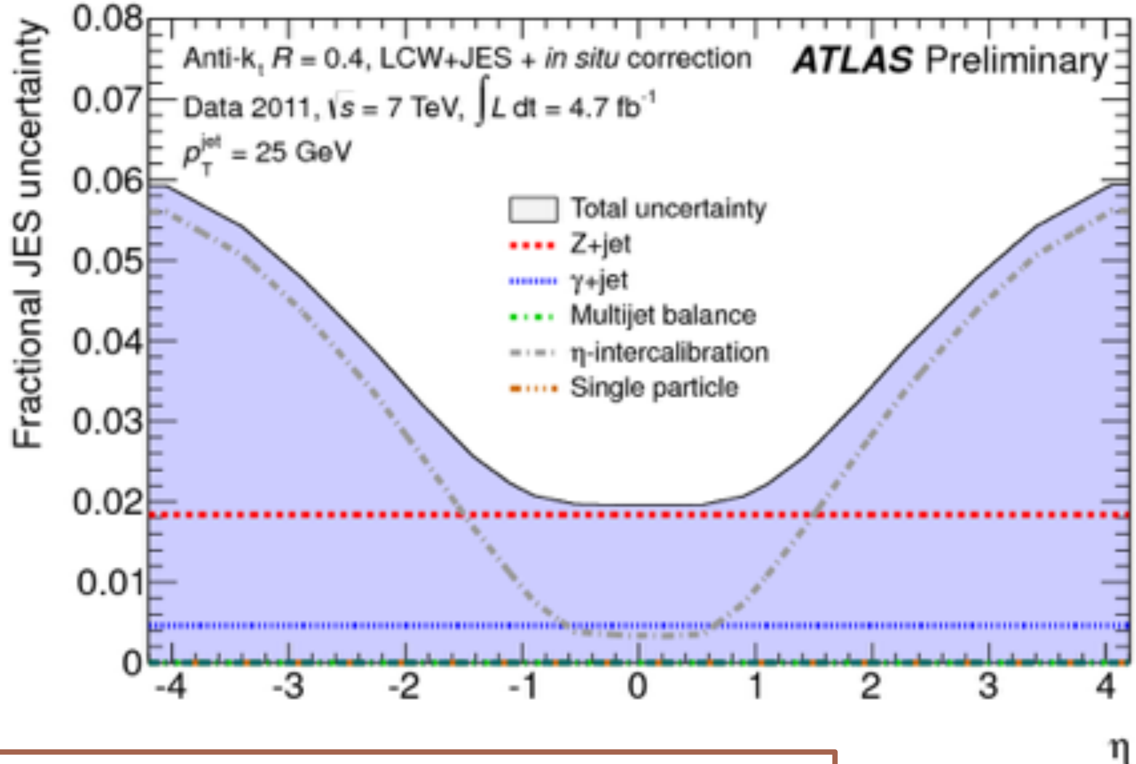
- For only three years of running, our JES is great
  - For central jets at pT ~ 100 GeV, 1% uncertainty on the jet energy

Uncertainty is larger in more interesting regions, like forward jets

Central



Forward



The dijet balance technique dominates: due to the modeling of the additional parton radiation altering the dijet balance.

What is Interesting Now

- With much more data from the LHC, the focus is now on
  - Measurements in new phase spaces
    - Such as boosted Z p_T, high jet p_T
  - Measurements for more observables
    - Such as forward jet rapidities
  - Differential measurements in processes with lower cross sections
    - Such as differential cross sections for Z+bb

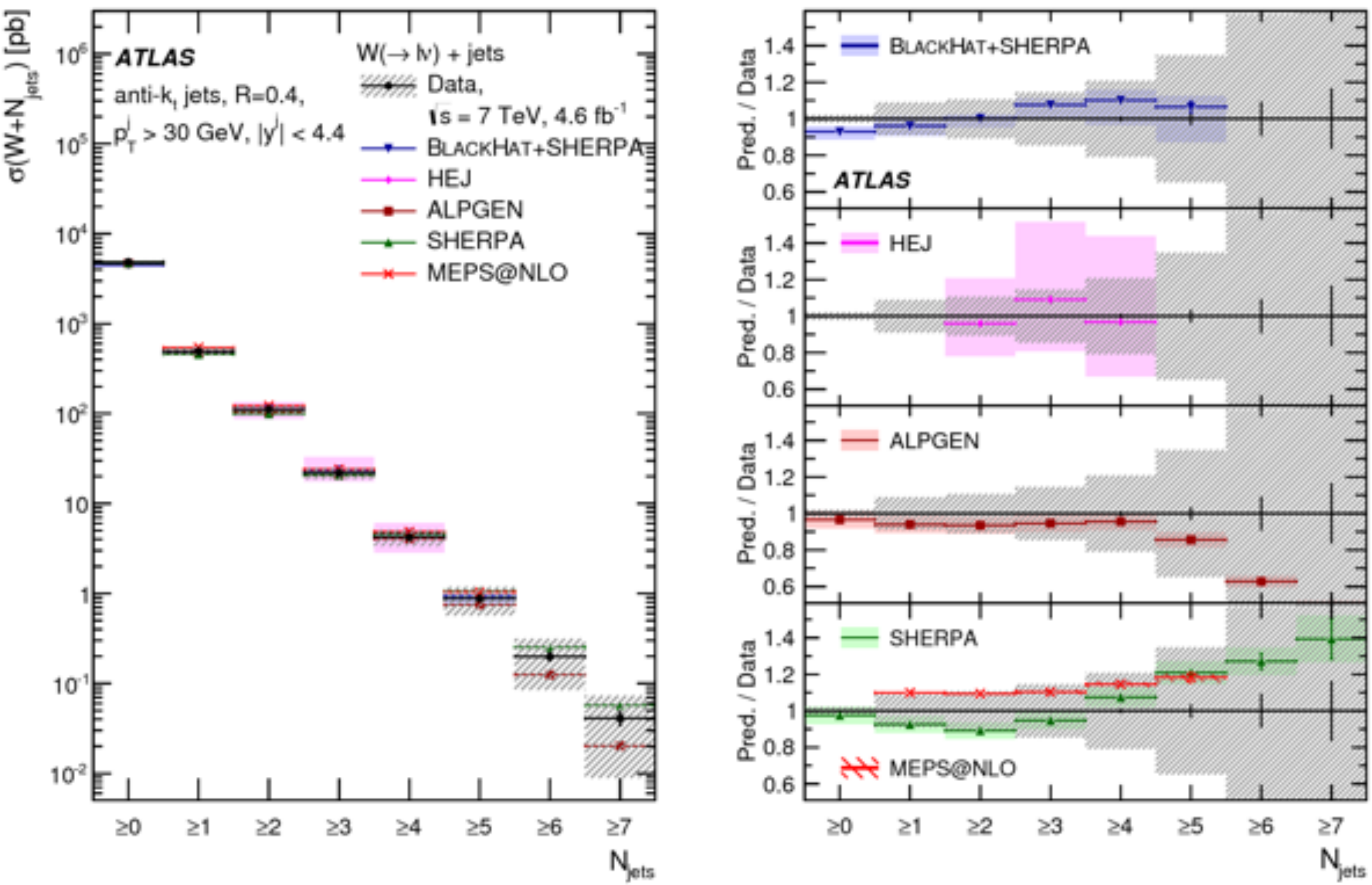
Important test of the Standard Model in a new phase spaces, especially important for searches, where V+jets are major backgrounds

The Theories

- The data are corrected to a well-defined phase space at particle level

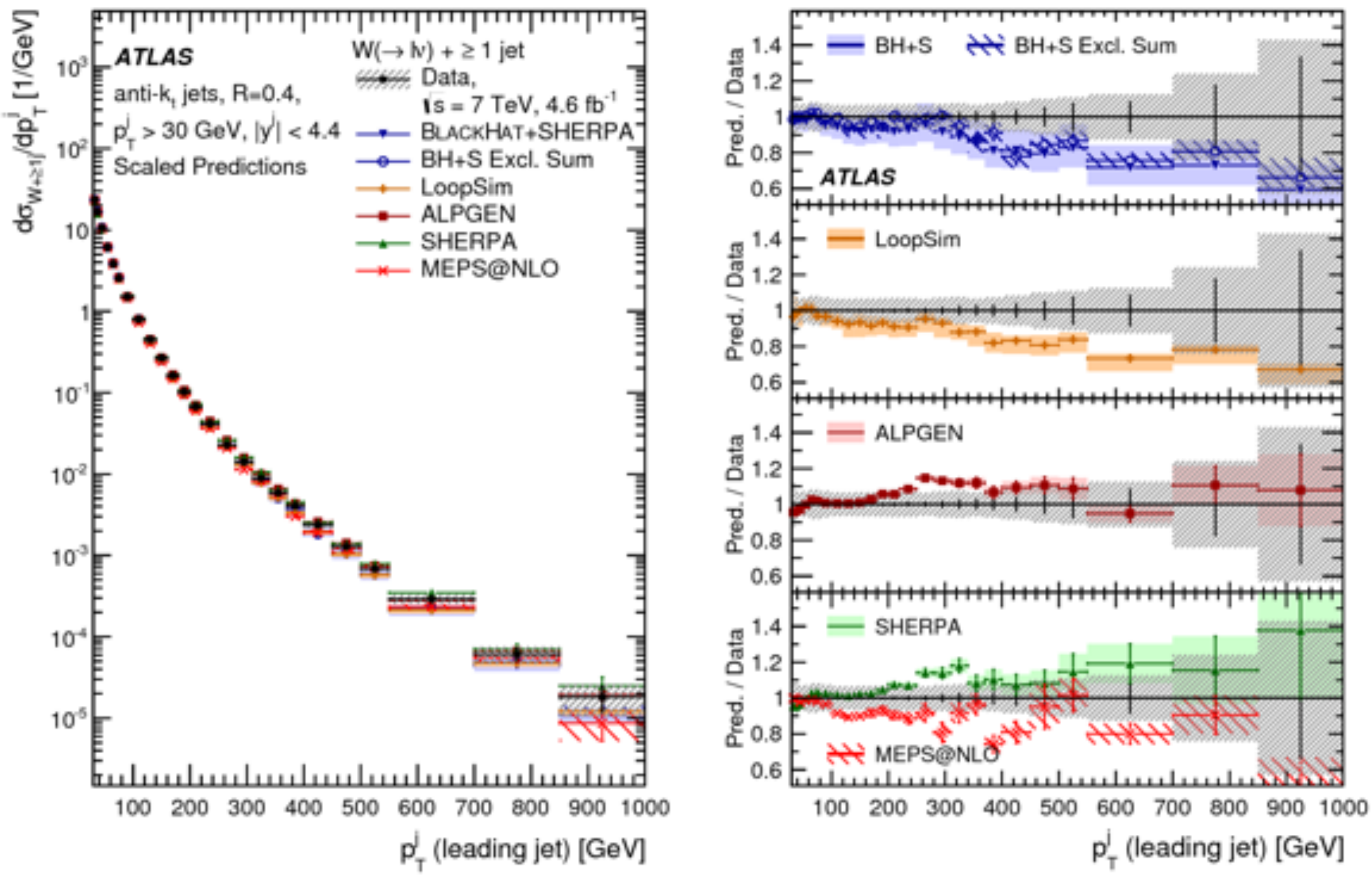
Program	Max. number of partons at approx. NNLO ($\alpha_s^{N_{\rm jets}+2}$)	NLO ($\alpha_s^{N_{\rm jets}+1}$)	LO ($\alpha_s^{N_{\rm jets}}$)	Parton/Particle level
LoopSim	1	2	3	parton level with corrections
BlackHat+SHERPA	–	5	6	parton level with corrections
BlackHat+SHERPA exclusive sums	1	2	3	parton level with corrections
HEJ	all orders, resummation			parton level
MEPS@NLO	–	2	4	particle level
ALPGEN	–	–	5	particle level
SHERPA	–	–	4	particle level

But first… a classic



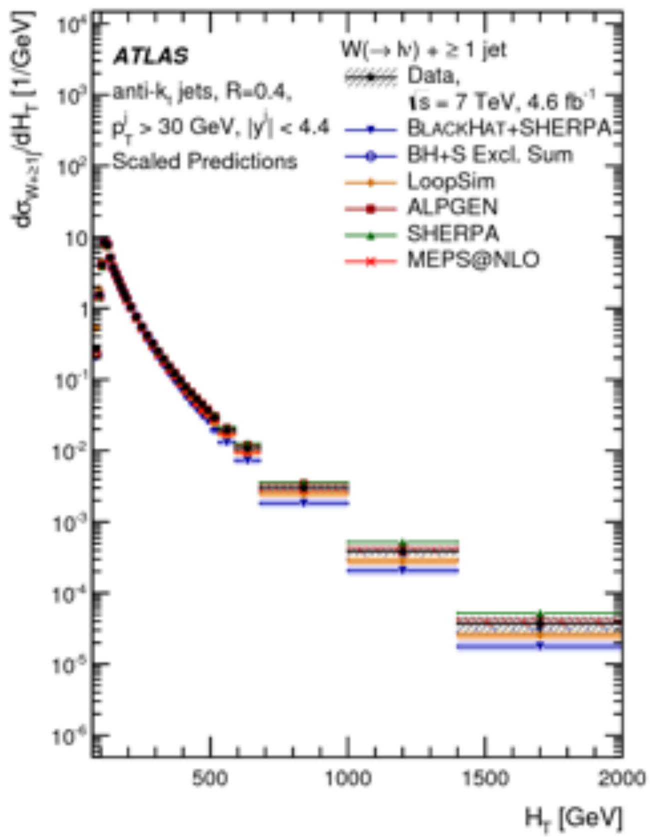
W+jets: Jet p_T

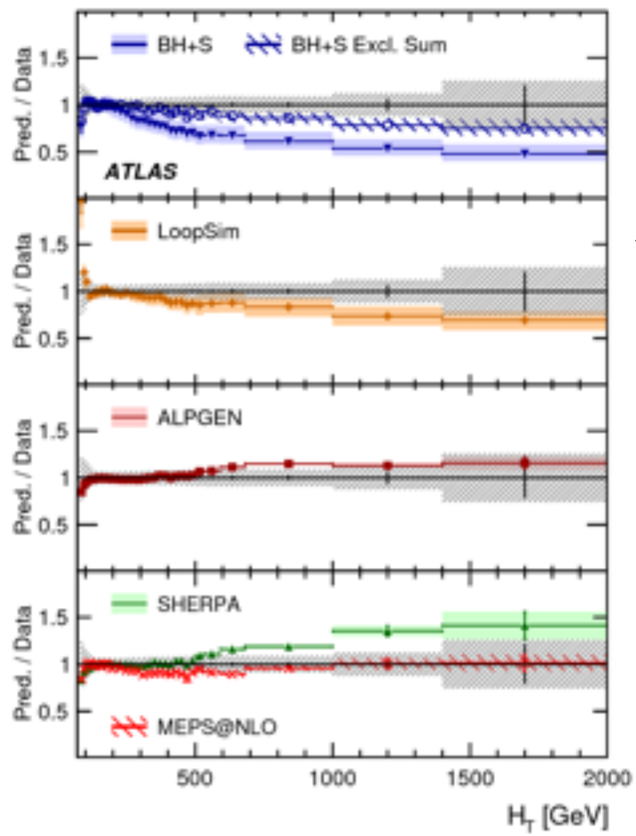
- Can now probe jet energies up to 1 TeV



W+jets: Scale Sums

- Frequently used as
  - The renormalization and factorization scale for fixed-order calc.
  - Searches for new physics



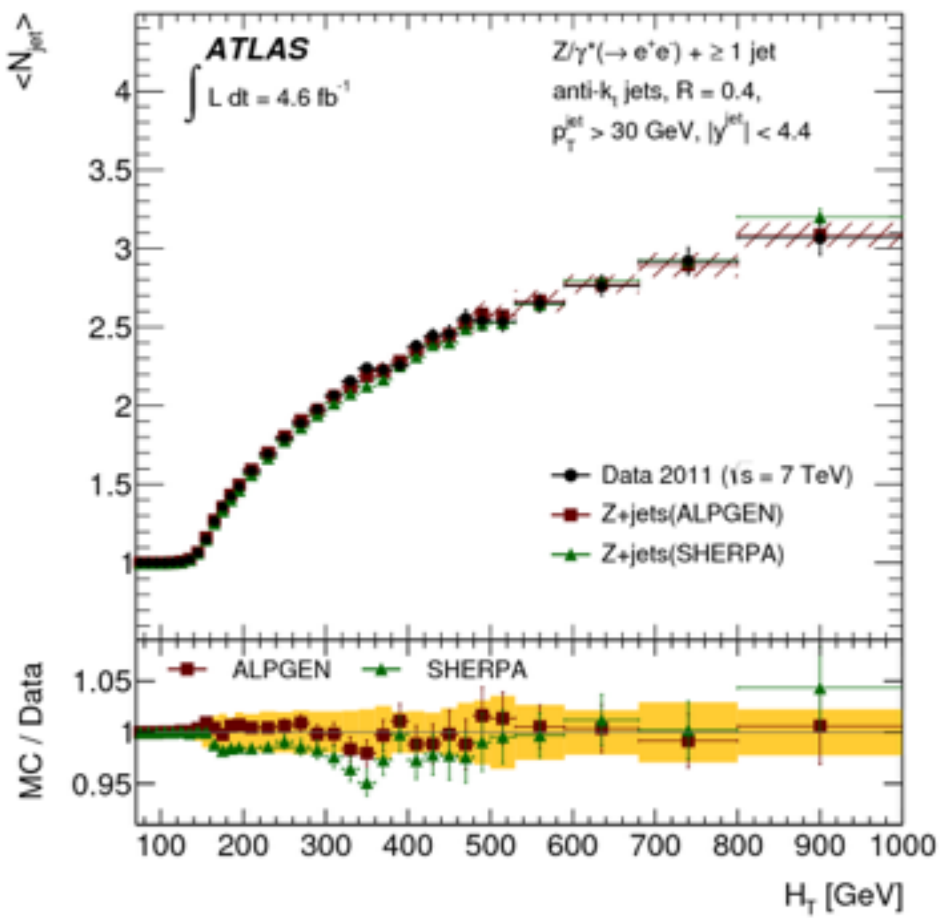


A challenging distribution for NLO calculations

H_T: the scale sum of jets, leptons and missing E_T

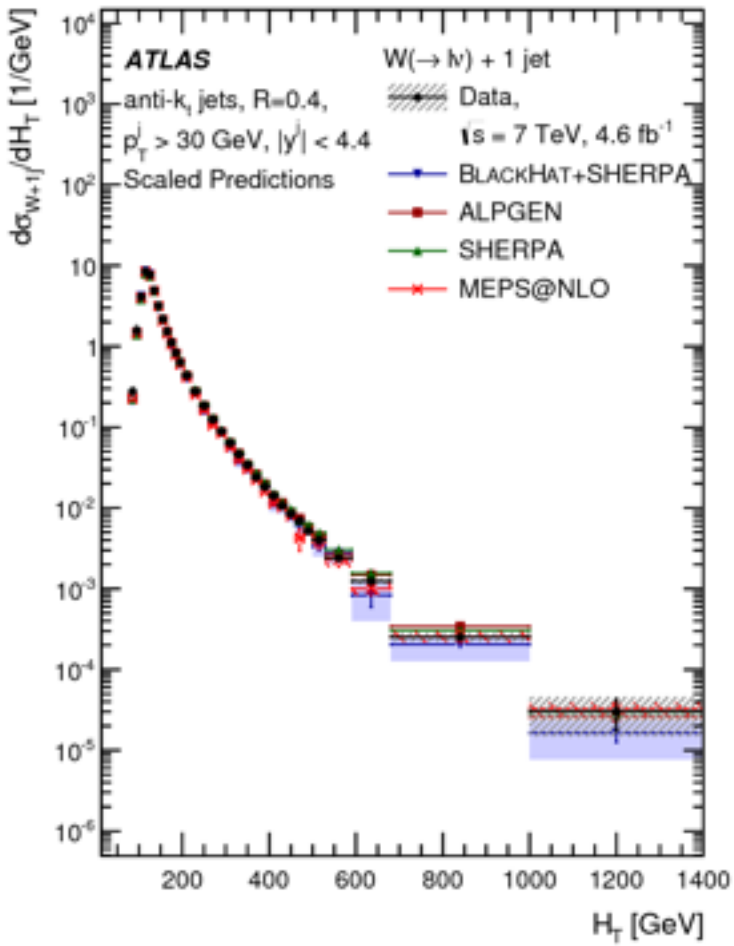
Z+jets: Scalar Sums

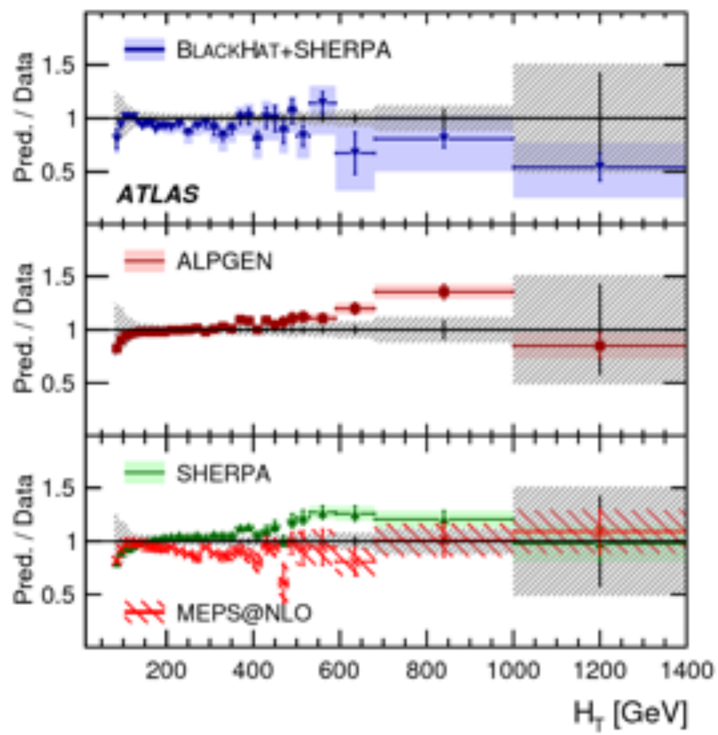
- Average jet multiplicity as a function of H_T
- High H_T implies large jet multiplicities
  - Means missing higher-order terms in MCs are important at high H_T



W+jets: Scalar Sums

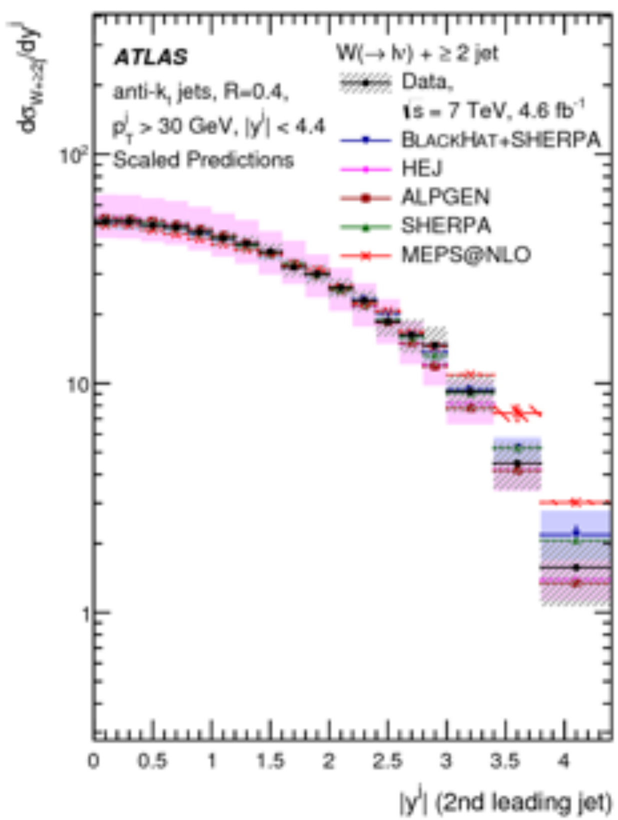
- Requiring an exclusive selection: Njet=1
- Agreement is much improved

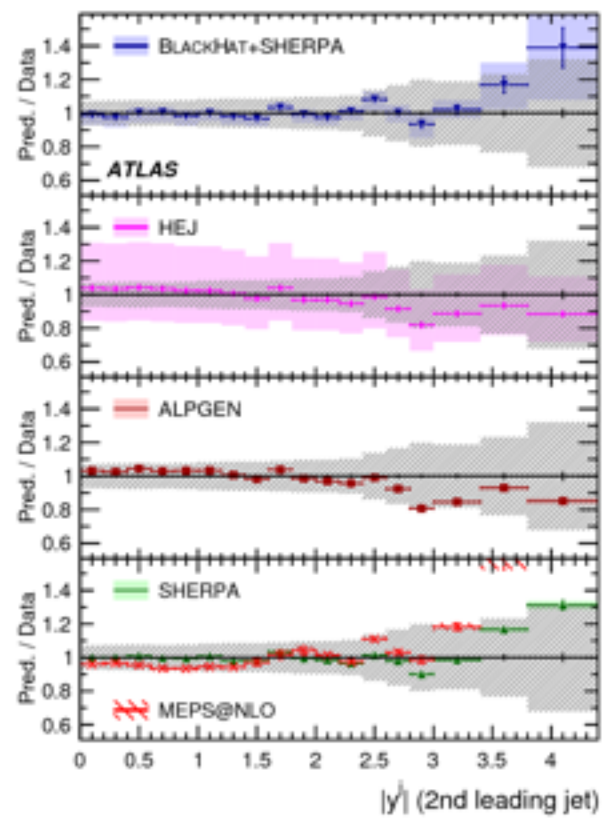




W+jets: Large Rapidities

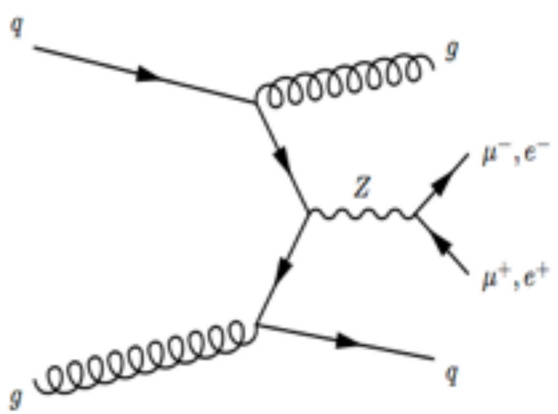
- Measurements of jets at large rapidities is a new region for the LHC
- MC tends to yield different tends



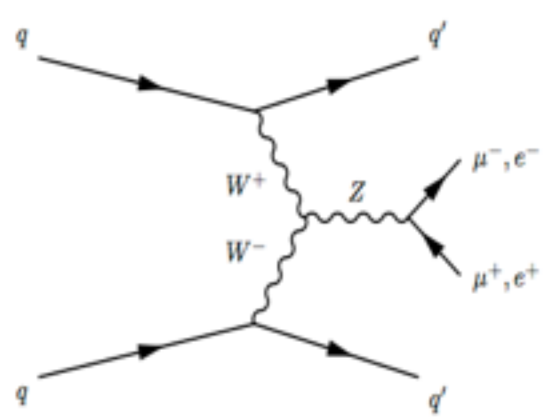


Z+jets in VBF Like Places

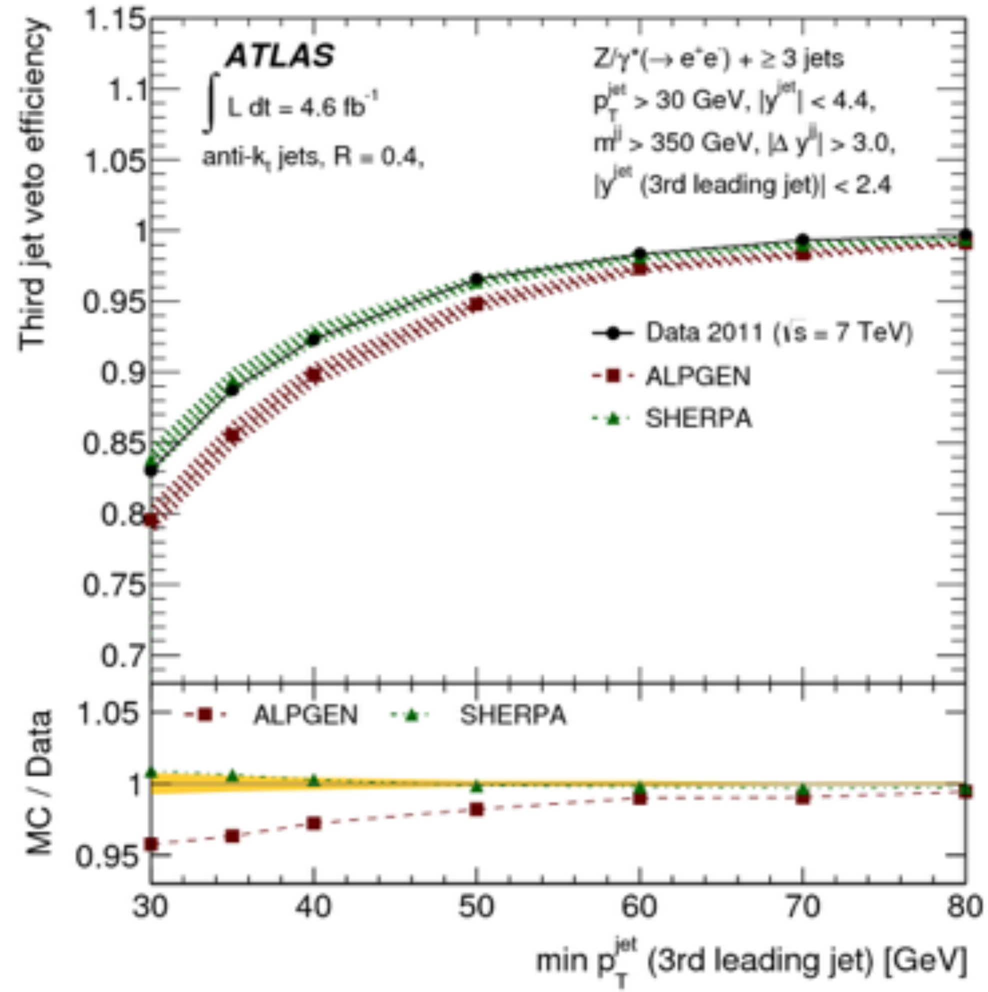
- Measuring 3rd jet probabilities for VBF topologies



Z+jets



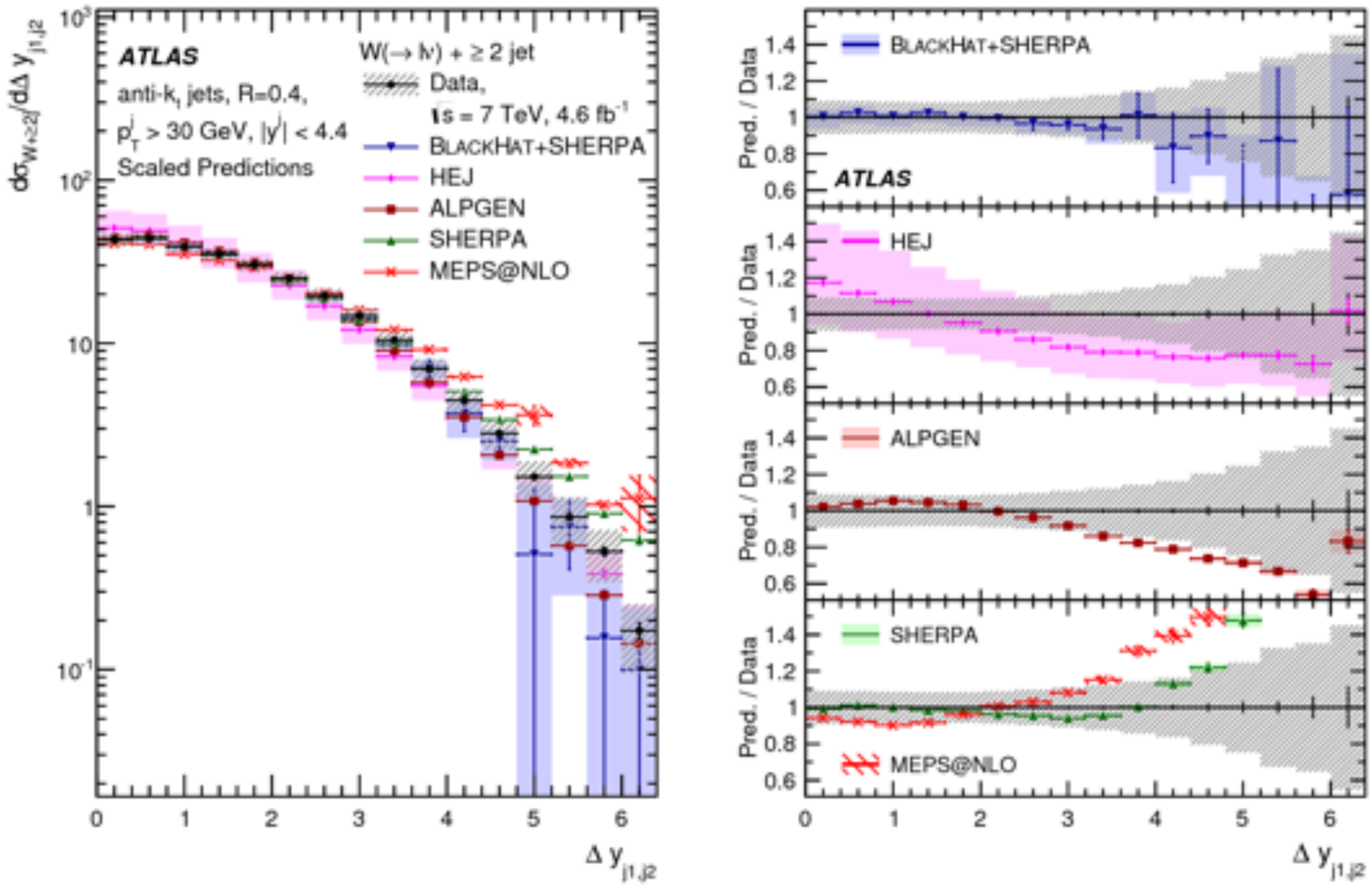
VBF Z+jets



Z VBF Measurement: http://arxiv.org/abs/1401.7610

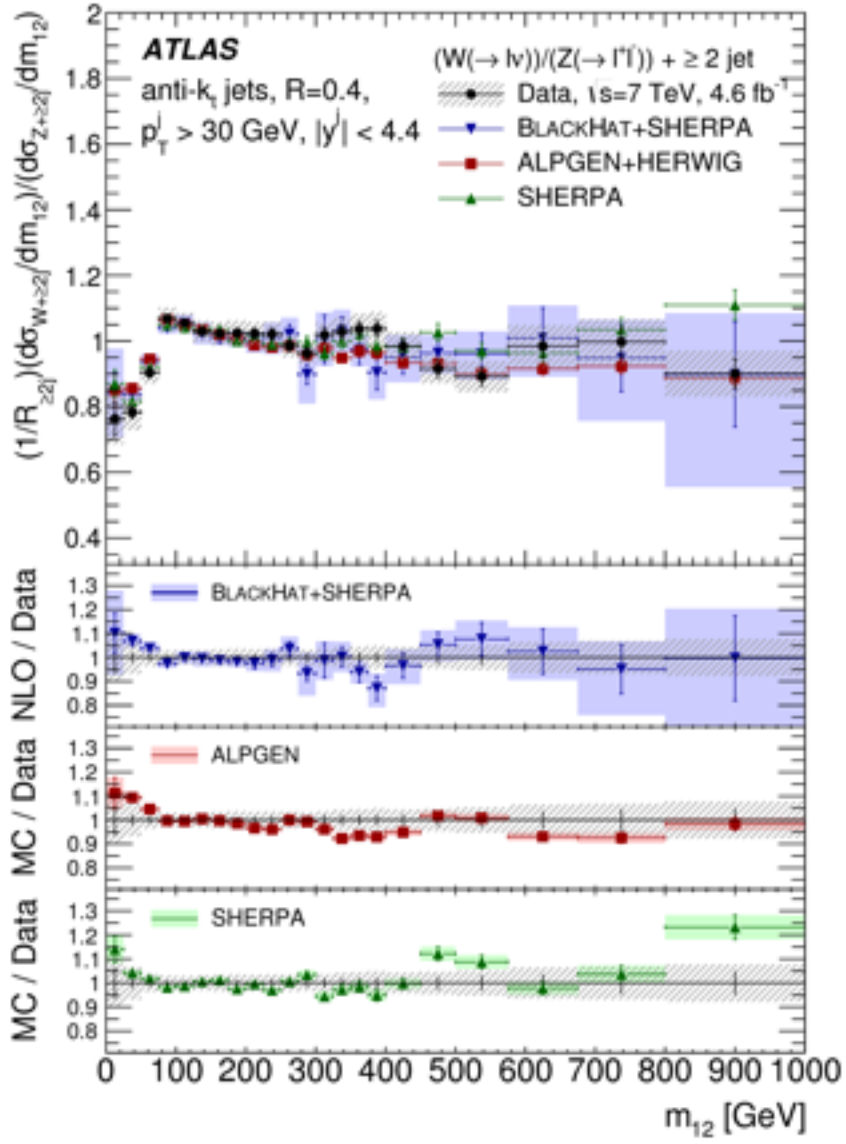
W+jets: Angular Distribution

- Jets with large angular separation are interesting for vector boson fusion topologies



The ratio of W/Z

- Measuring the ratio cancels many of the uncertainties
- Possible sensitive test of new physics



Future Prospects

- ATLAS has recently published extensive cross section measurements using the 7 TeV data set
  - No theory prediction models well all distributions
- Currently, we don't plan to repeat the inclusive phase space measurements at higher energies
- Future measurements will focus more on
  - Ratios i.e. first and second jet p_T, W^+/W^-
  - phase spaces with high i.e. H_T, jet p_T, Z p_T
  - production with heavy flavor

Conclusions

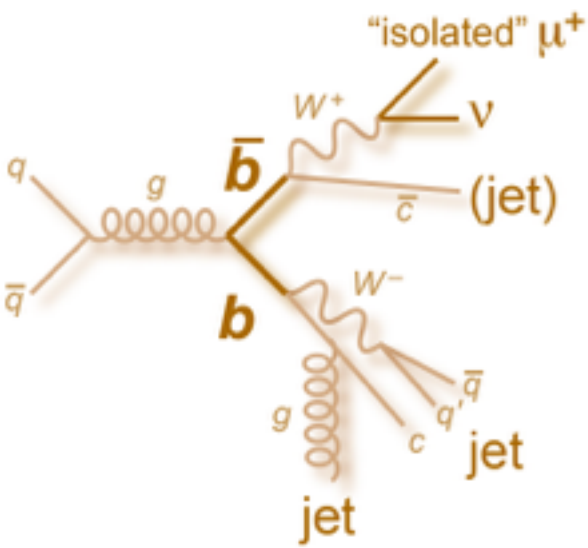
- Even with 'early' LHC data, we have been able to perform precision measurements of V+jets
- With much more data from the LHC, the focus is now on
  - Measurements in new phase spaces
    - Such as boosted Z p_T, high jet p_T
  - Measurements for more observables
    - Such as forward jet rapidities
  - Differential measurements in processes with lower cross sections
    - Such as differential cross sections for Z+bb

ATLAS

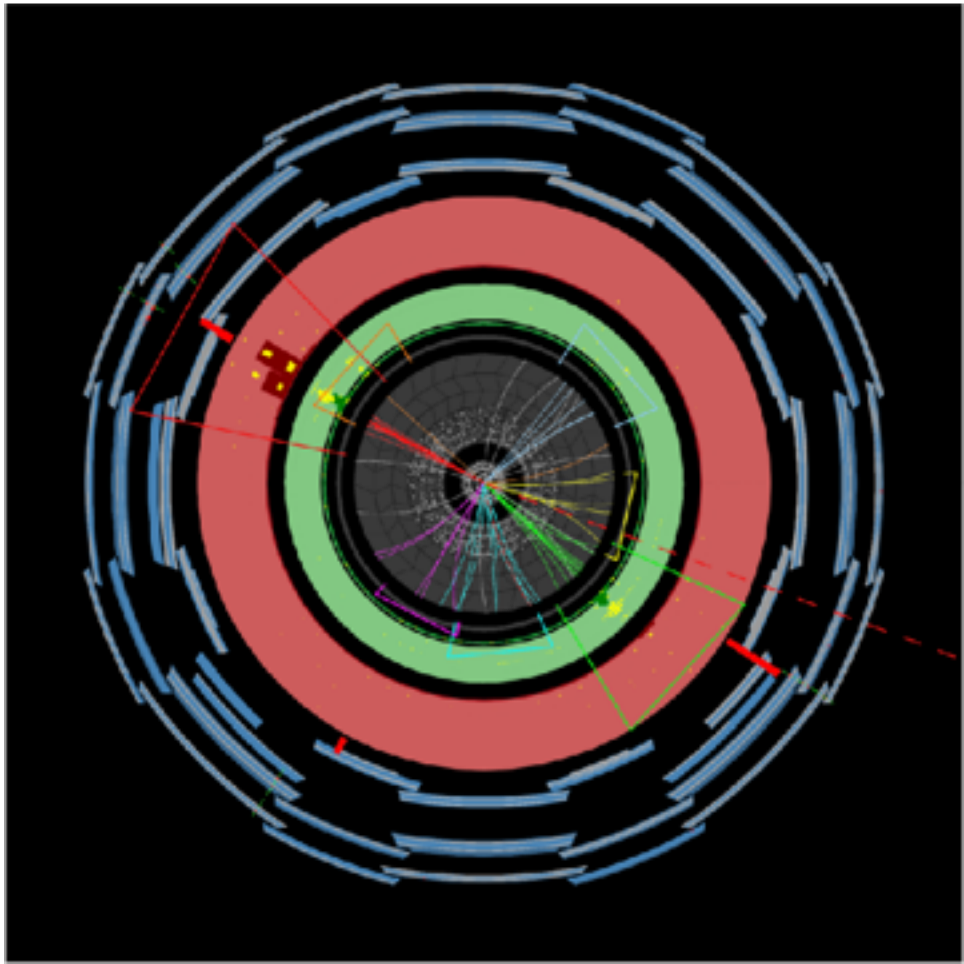
The Multijet Background

- Two types of Multijet backgrounds

A lepton from a b-quark decay

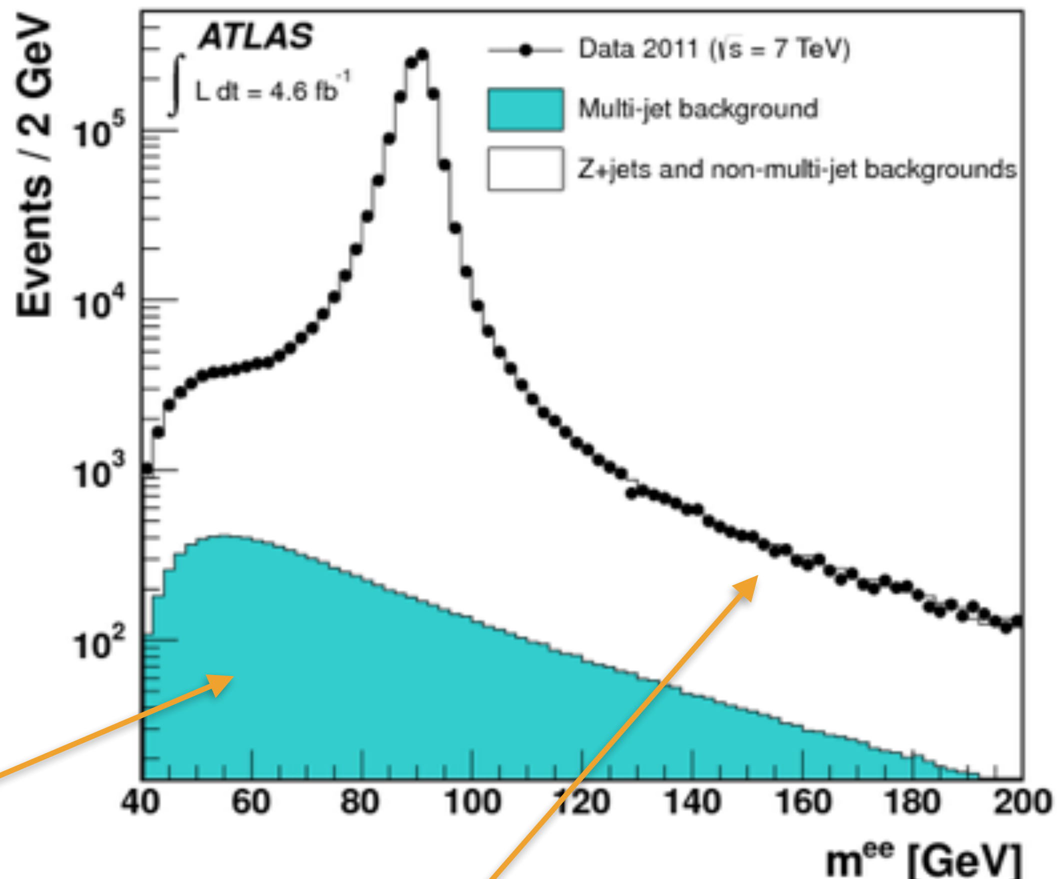


Our electron reconstr. not prefect



Z+jets: Multijets

- Electrons
  - Two ‘loose’ but not ‘medium’ electrons
- Muons
  - Two non-isolated muons

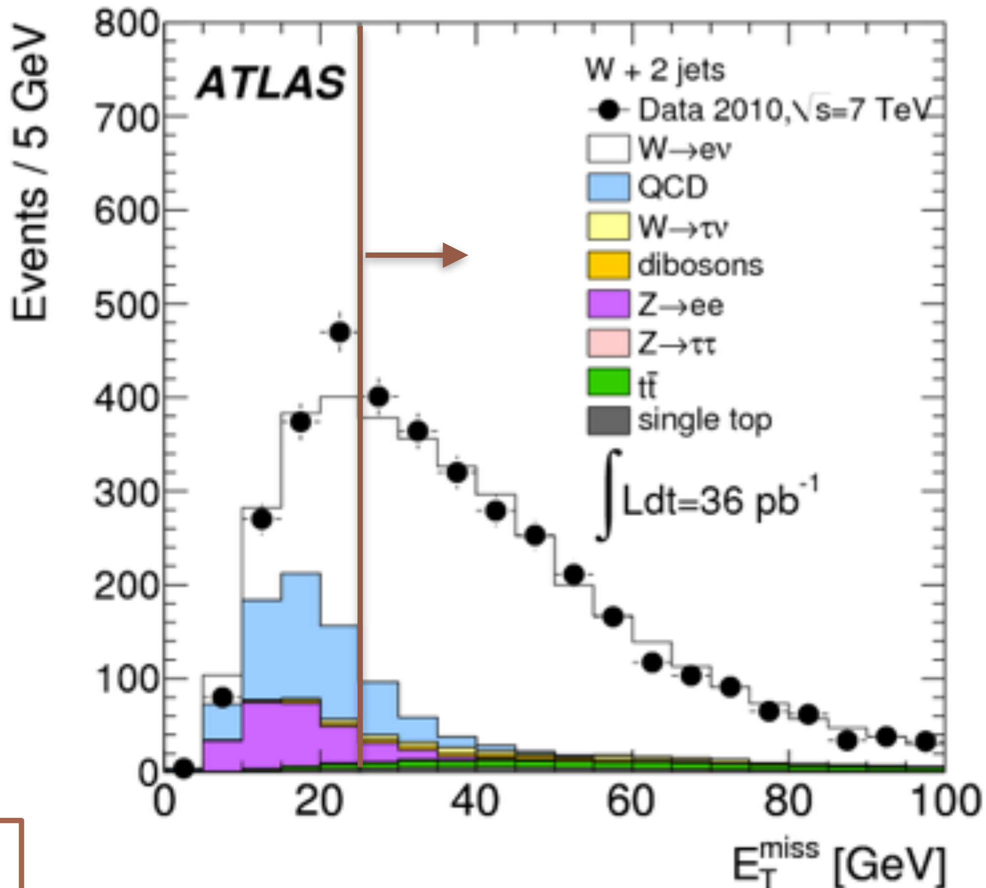


Control region determines the shape

Side-band fit determines the number

W+jets: Multijet

- Electrons: mixture of light quark 'faking' electron and leptonic b-decay
  - One 'loose' but not 'tight' electron
- Muons: leptonic b-decays
  - One non-isolated muon



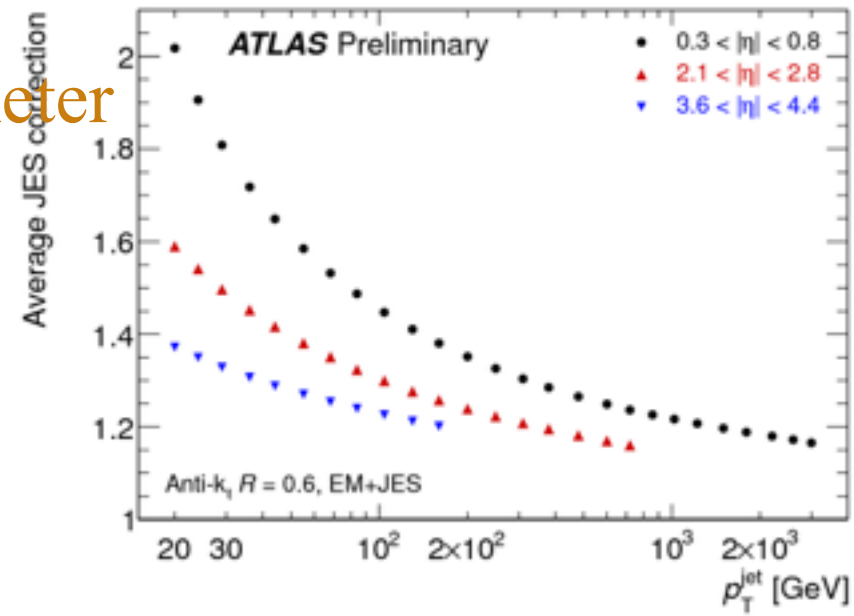
Fit in a low Missing ET region to determined normalization

For all other backgrounds, use MC

Jet reconstruction

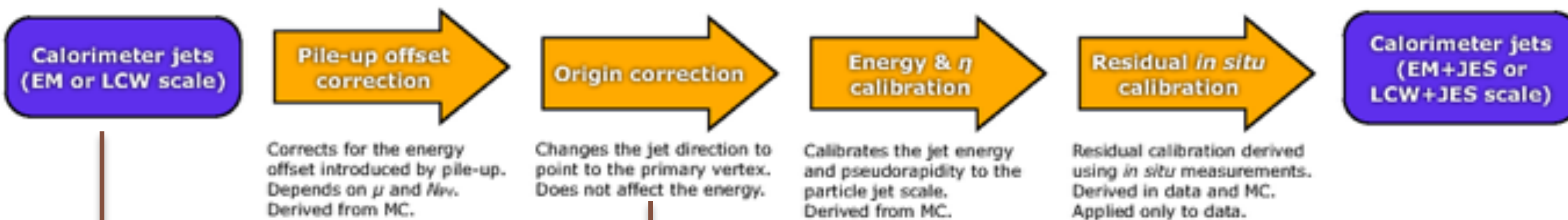
- Jet inputs are clustered with an anti-k_T algorithm
  - Infrared safe, collinear safe
  - Distance parameters 0.4, 0.6 (different sensitivity to non-perturbative QCD effects)
- Jet response corrected for
  - Non-compensating calorimeter
  - Inactive material
  - Out-of-cone effects
- Data and MC-based η, p_t dependent calibration

http://cdsweb.cern.ch/record/1337782



Measuring Jets

- Jet require multiple calibration steps
- No ideal calibration source for the absolute energy scale



Correct jets to 'Hadronic' scale

'Remove' energy from pile-up particles

Adjust jet to the origin

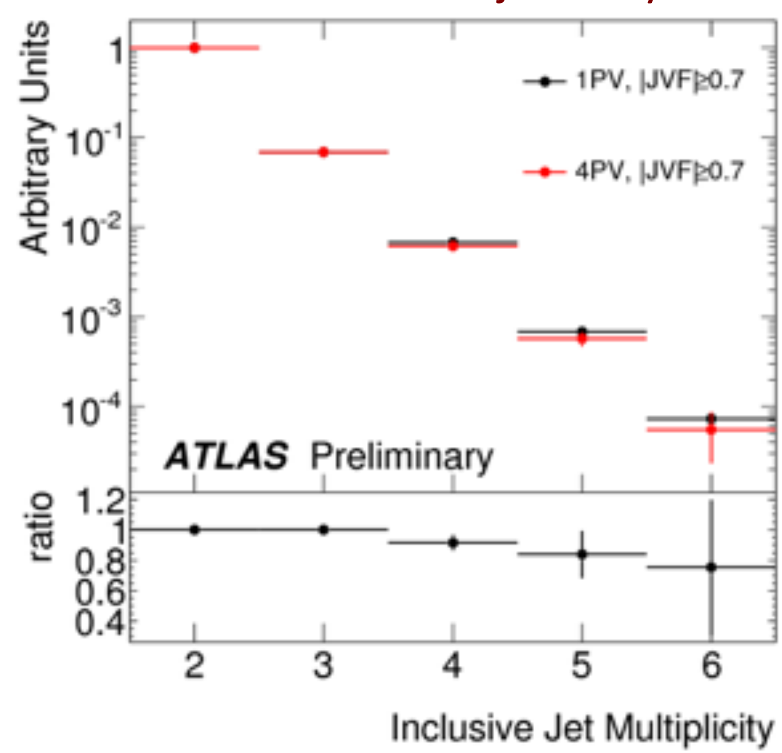
Correct jet to the 'absolute' energy scale. Uses MC

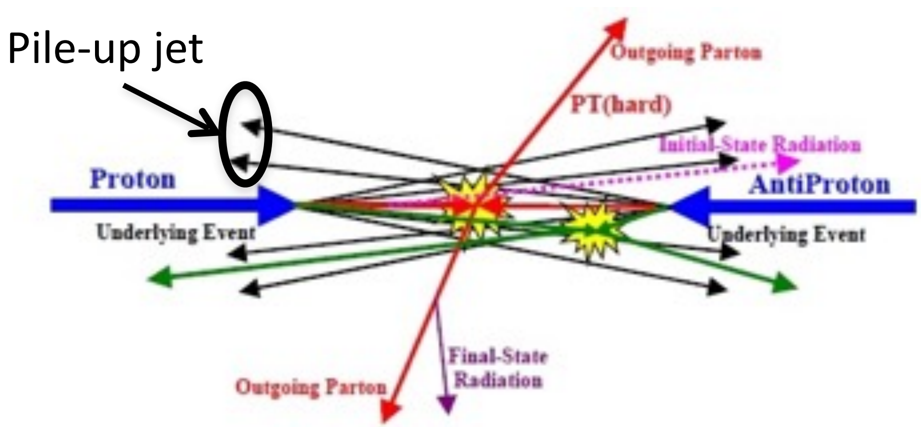
Use data like Z+jets for final corrections and uncertainties

Considering Pile-up

- Additional interactions result in additional jets from pile-up, leading to miscounting of jet multiplicity
  - Also affects Missing E_t

From multijet analysis





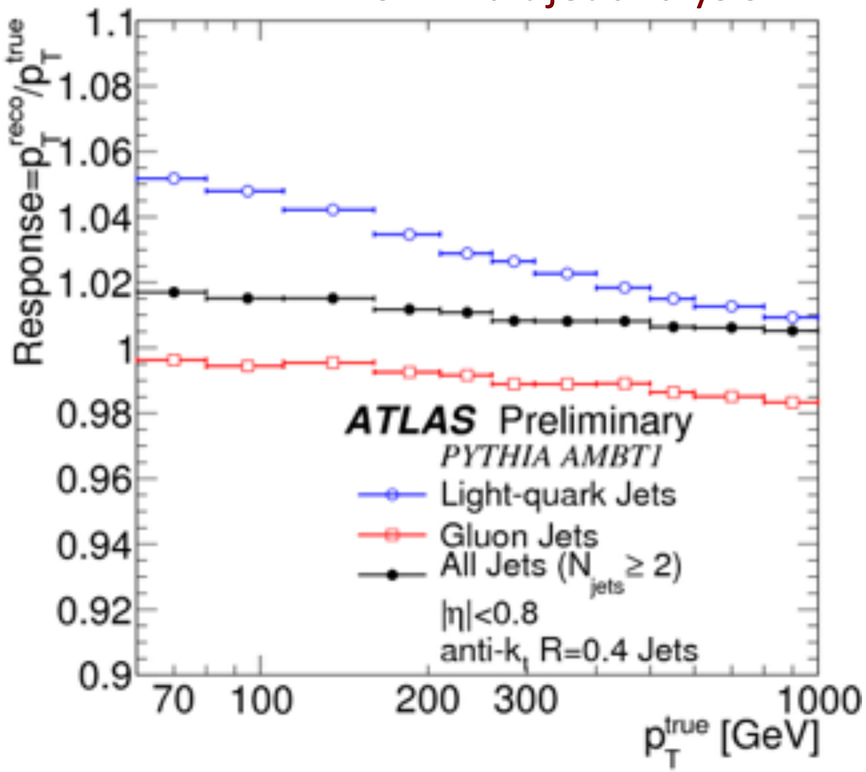
→Jets from pile-up is 7% for jet with p_T = 20 GeV

Calibration vs. Signal

- Important to consider difference between the calibration sample and measurement
  - Jet calibration is derived using QCD di-jets (mainly gluon-initiated jets)
  - W+jets are mainly quark-initiated jets

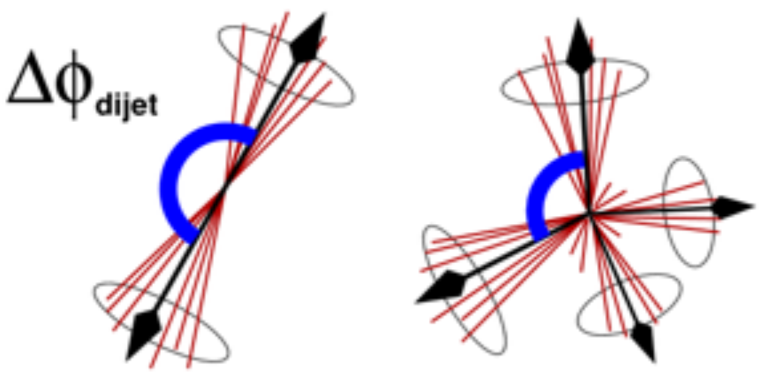
→Uncertainties in quark/gluon fraction up to 3% additional uncertainty

From multijet analysis

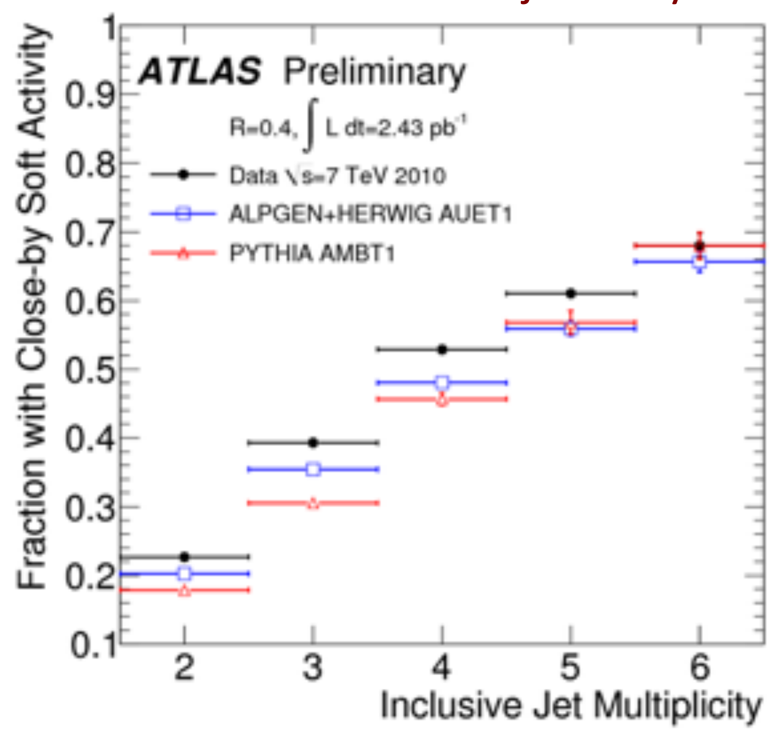


The Multijet Environment

- Multi-jet environment is more 'crowded' therefore additional jet energy scale uncertainties are required
  - Jet calibration is derived mainly with two jet events



From multijet analysis



→Uncertainty due to close-by jets up to 1.5%