



ATLAS measurements of jets and heavy flavor produced in association with W and Z bosons



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Outline

- + Context of the measurements
- + Measurements details (done with 2010 dataset)
- + Results
 - W+jets,
 - Z+jets,
 - Rjets
 - W+b,
 - Z+b
- + Conclusions

Context of the measurements

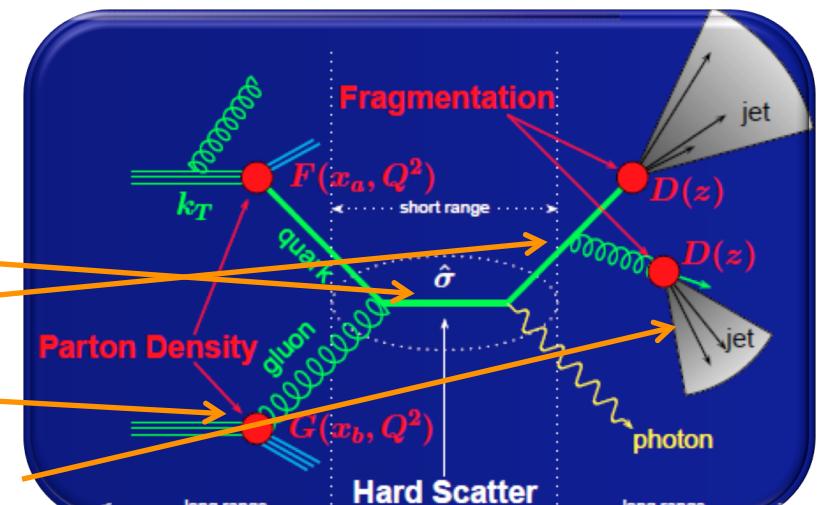
Studying QCD at the LHC (I)

- + Events with jets in final state are copiously produced via the strong interaction at hadron machines
 - Good understanding of soft and perturbative QCD crucial for the LHC physics program (both for measurements and searches)

- + Convolution of short distance physics and non-perturbative effects:

- Hard scatter ($\hat{\sigma}$)
- QCD bremsstrahlung
- Parton density function ($f_{i,j} = F, G$)
- Fragmentation, hadronization ($D(z)$)
- Multiple interaction

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



The focus of this presentation is on short distance cross sections 4

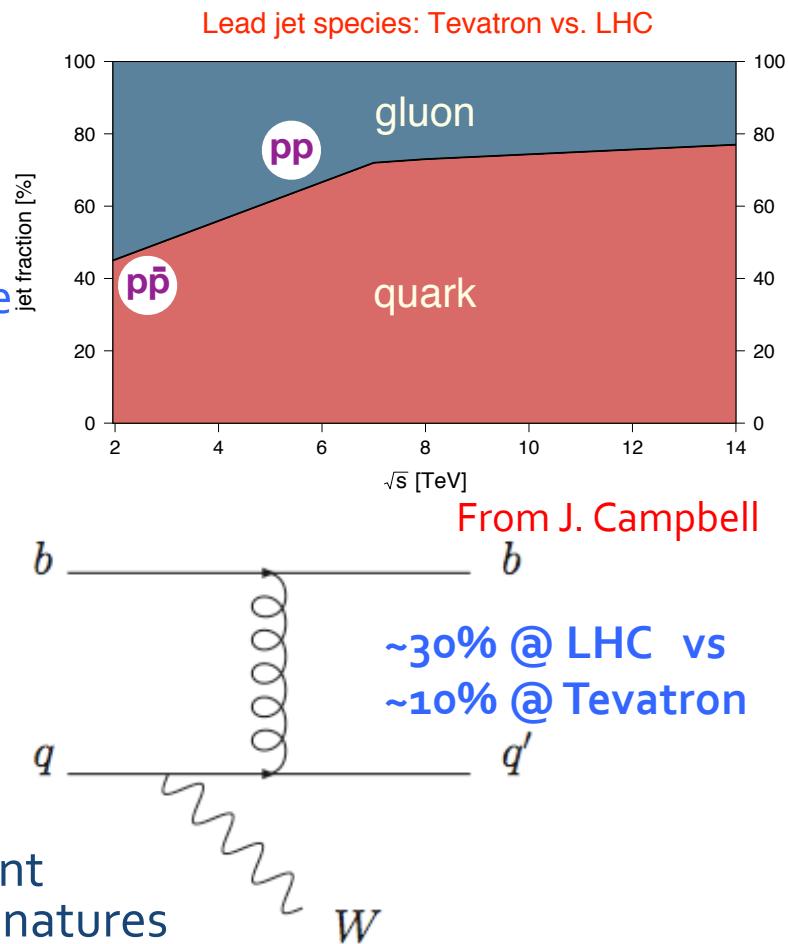
Studying QCD at the LHC (II)

- + Different level of predictions to be tested
 - LO matrix element + Parton Shower + hadronization
 - e.g.: Pythia, Herwig
 - LO matrix element + matching to parton shower
 - Various matching scheme (e.g.: MLM, CKKW)
 - e.g.: Alpgen, Sherpa
 - Full fixed order NLO calculation
 - Method based on Feynman diagram+known integrals
 - e.g.: MCFM
 - Method based on unitarity and on-shell recursion
 - e.g.: Blackhat+Sherpa
 - Full fixed order NLO + parton shower
 - e.g.: Powheg

_____ = tested in present analyses

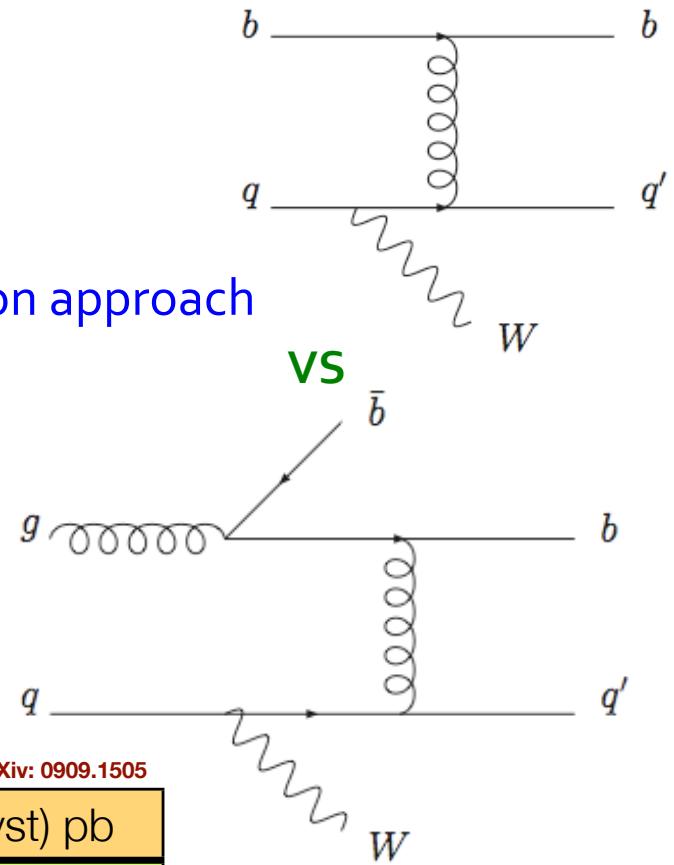
Studying QCD at the LHC (III)

- + Different than at the Tevatron:
 - Higher jet P_T and multiplicity
 - Larger acceptance (e.g.: forward jets)
 - Different mixture of quark and gluons
 - Processes with heavy flavor in initial state
 - + Different than in multijet events:
 - Study quark radiation
 - powerful for jet calibration
 - + Complementary to inclusive W/Z studies
 - sensitive to structure of QCD radiation;
 - Study heavy flavors
 - + Processes involving W/Z+ jets are important backgrounds to numerous new physics signatures
- Essential studies for finding and understanding new physics



Studying QCD at the LHC (IV)

- + Heavy flavor content of the PDF
- + Poorly constrained theoretically
 - Test various flavor schemes and calculation approach
 - Tension between theory and Tevatron
- + Important background to Higgs discovery, BSM searches, and precision measurement of top physics



CDF, arXiv: 0909.1505

CDF	2.74 ± 0.27 (stat) ± 0.42 (syst) pb
ALPGEN	0.78 pb
PYTHIA	1.10 pb
NLO	1.22 ± 0.14 (scale) pb

The measurements

Vector boson plus jets (I)

- + Measured $d\sigma/dO$ for various observables $O: P_T, y, M_{jj}, H_T, \Delta R$, etc.
 - H_T is the (robust) scale used in NLO calculations
 - Test new NLO calculations up to 4-jets
 - Measured ratios with precision in function of jet observables
 - Cancel some experimental and theoretical uncertainties
- + Same lepton triggers and offline selections as in W/Z inclusive measurements
 - See talk of M. Boonekamp and J. Moss
- + Jets are reconstructed using the anti- k_T algorithm with $R = 0.4$
 - Calibration obtained from MC on QCD dijet events
 - Uncertainty improved with in-situ (single hadron, γ +jets, Z+jets) studies
- + The differential cross section for a given jet observable (O):

$$\frac{d\sigma}{dO} = \frac{N_{\text{data}} - N_{\text{bkg}}}{L} U(O)$$

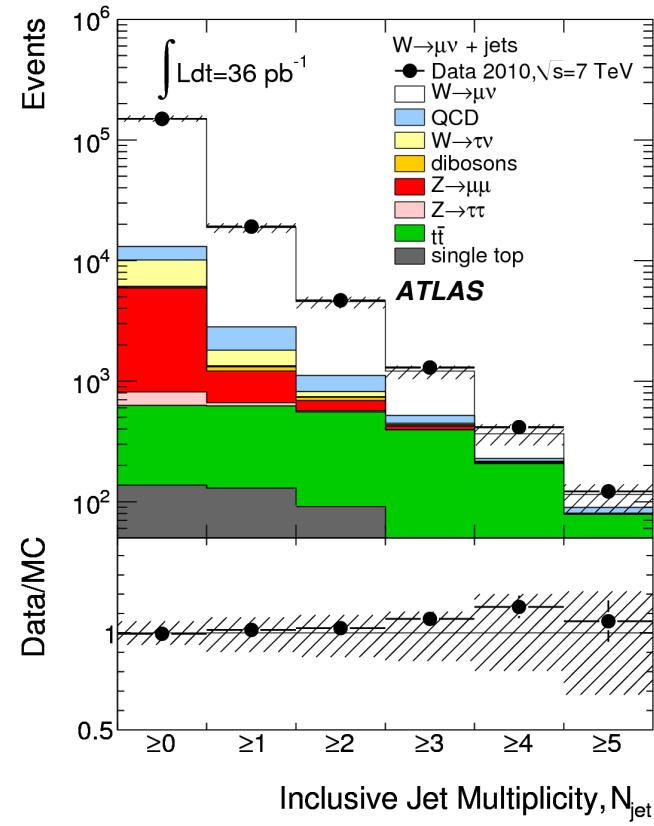
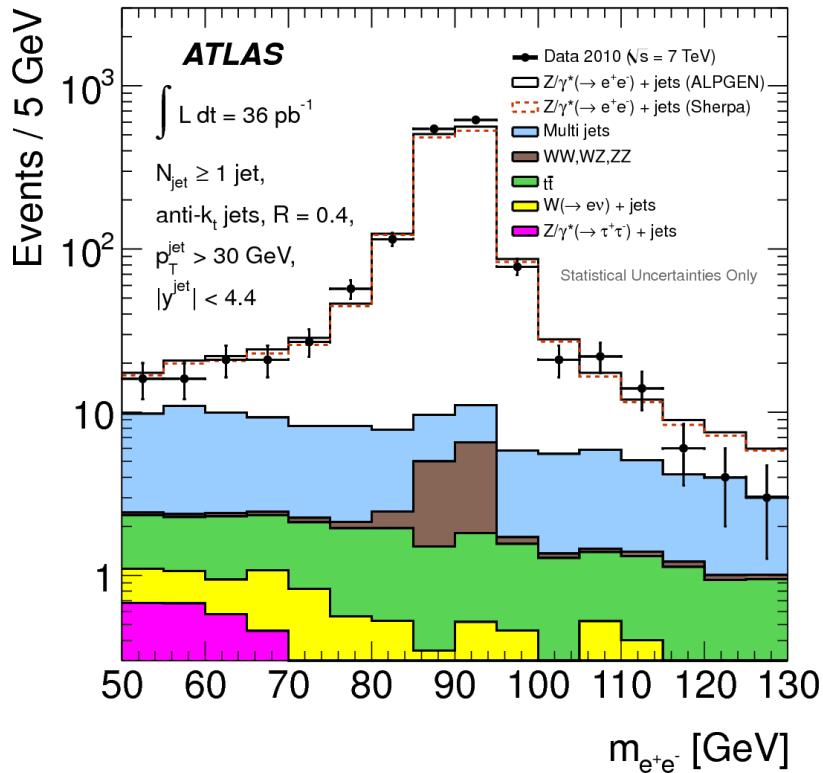
where $U(O)$ is the unfolding factor

Vector boson plus jets (II)

Main background:

10-20% in W+jets, dominated by top and QCD (estimated from data)

Z+jets: 1% in muon channel, 5% in electron channel

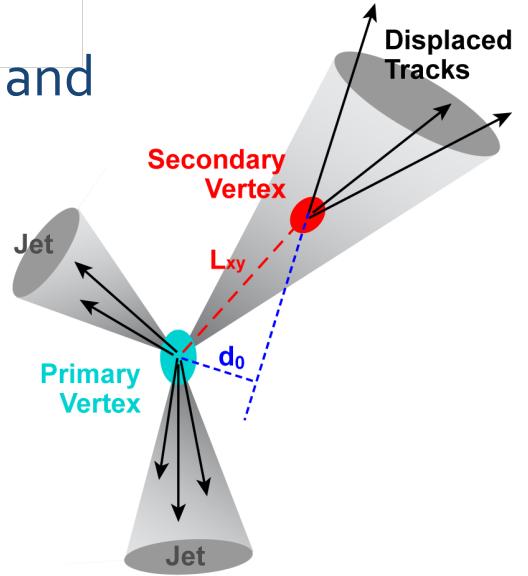


Invariant mass (M_{ee}) in Zee+jets events

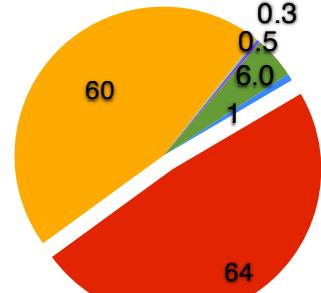
Jet multiplicity (N_{jet}) in $W\mu\nu + \text{jets}$ events 10

W/Z+Heavy flavor (I)

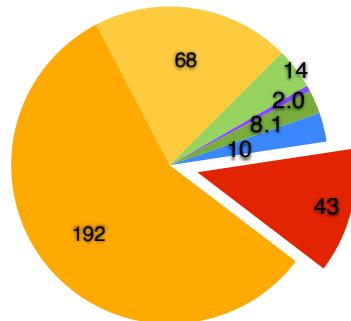
- + Challenging: Small cross section but large background (especially W+b)
- + b-jets are identified by exploiting the long lifetime and large mass of B-hadrons
 - b-tagging require a displaced secondary vertex in a jet with a decay length significance of > 5.85
- + B-tagging affects sample composition



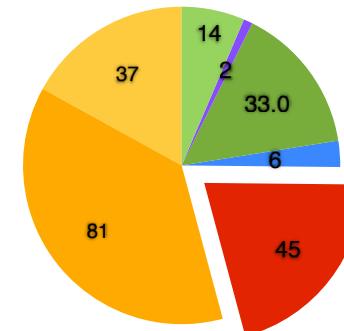
Z+ >1 b-jet Yield



W + 1b-jet Yield



W + 2-jet Yield



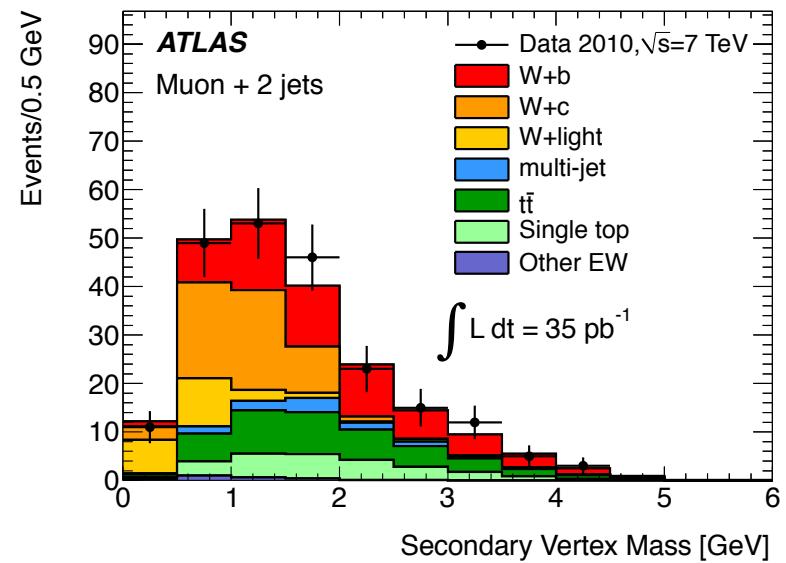
- single top
- diboson
- top
- QCD
- V+b
- V+c
- V+l

W/Z+Heavy flavor (II)

- Fraction of W+b/c/l jets from a fit to the mass distribution of the secondary vertex
- Estimate template shapes from MC

$$\sigma(W + b) = \frac{\mathbf{n}^{\text{tag}} \cdot \mathbf{f}_{W+b}}{\mathbf{L} \cdot \mathbf{U}}$$

- + Cross section at event level
- + First measurement in exclusive jet bins
 - Vetoed on number of jets (<3) to control top background

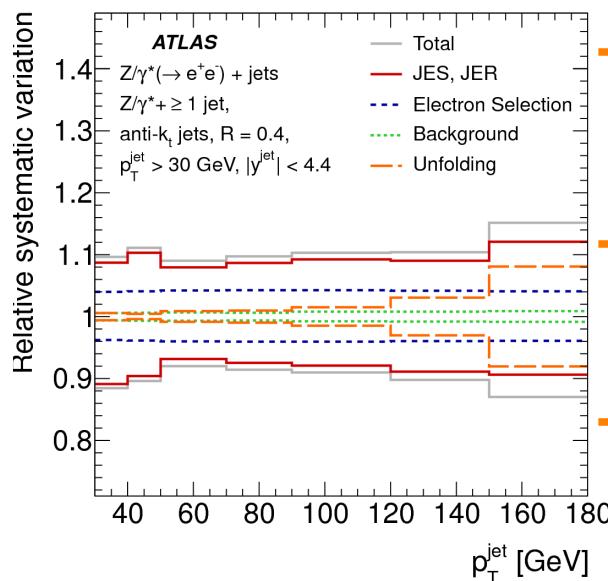
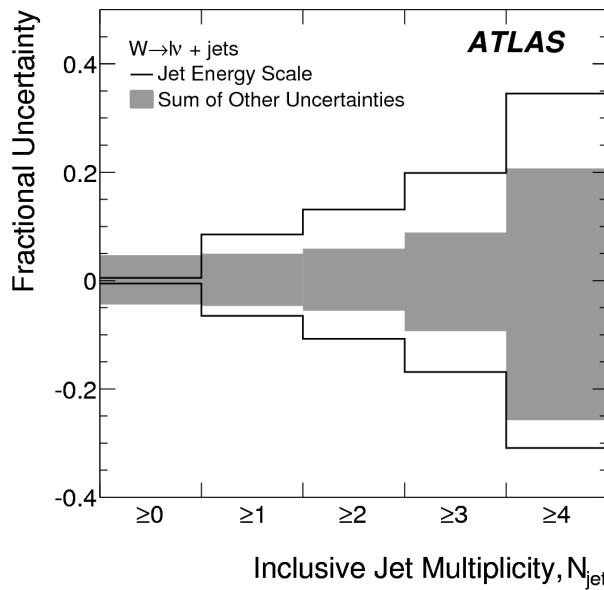


$$\sigma(Z + b) = \frac{N_b}{U_e \times L_e + U_\mu \times L_\mu}$$

- + Inclusive b-jet cross section in association with a Z
- + Electron and muon channels are added to the same template to improve statistics

Systematic uncertainties (I)

- + Systematic uncertainty at same level as the theory uncertainty for W/Z+jets measurements
 - Dominated by Jet energy scale uncertainty (10-20%)
 - Statistical uncertainty important in a large part of the spectrum probed
- + A bit different for W/Z+heavy flavor

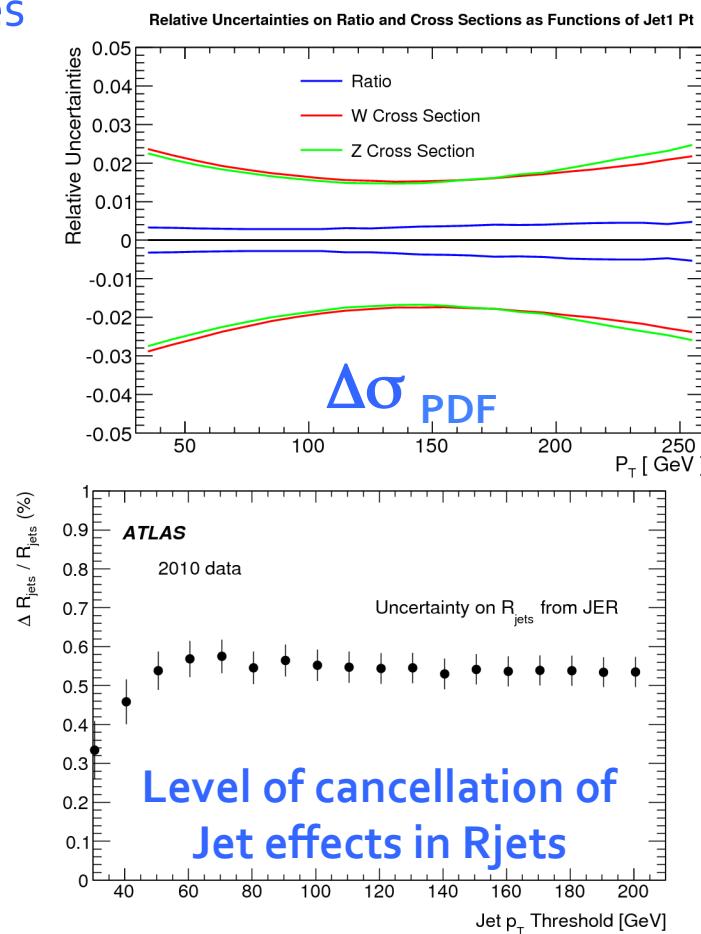
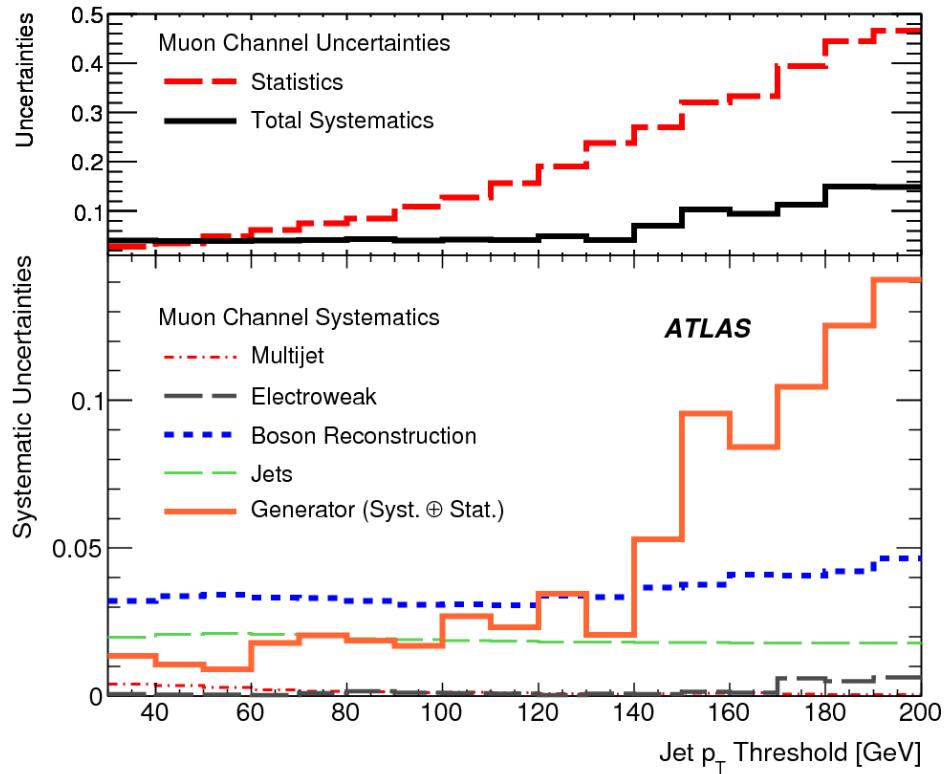


- + B tagging uncertainty
 - 16% (W) – 10% (Z)
- + Jet +b-jet energy scale
 - 7% (W)-4%(Z)
- + Background in W+b
 - QCD (7%), top (12%)

Systematic uncertainties (II)

- + Systematic substantially reduced in the case of ratios
 - Rjets dominated by lepton rather than jet systematics and prediction almost insensitive to PDF uncertainties

→ A precision observable

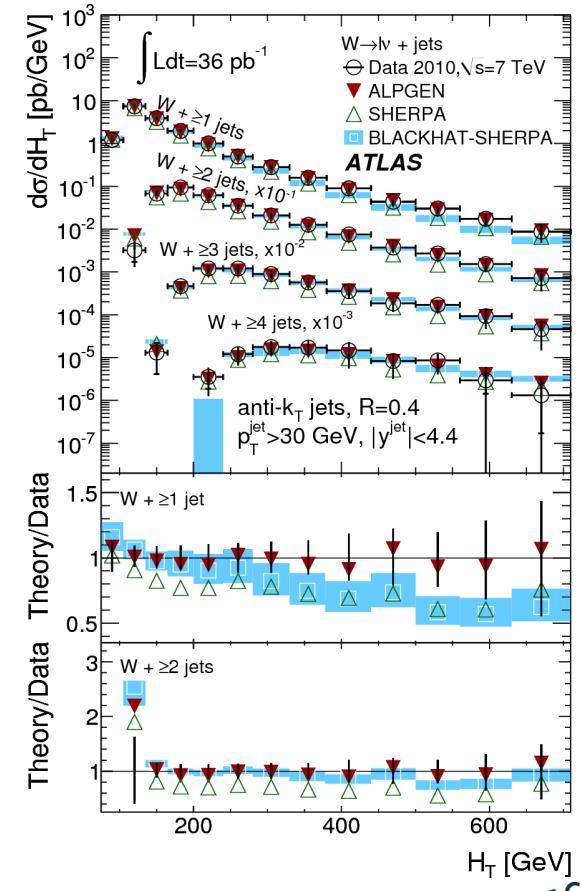
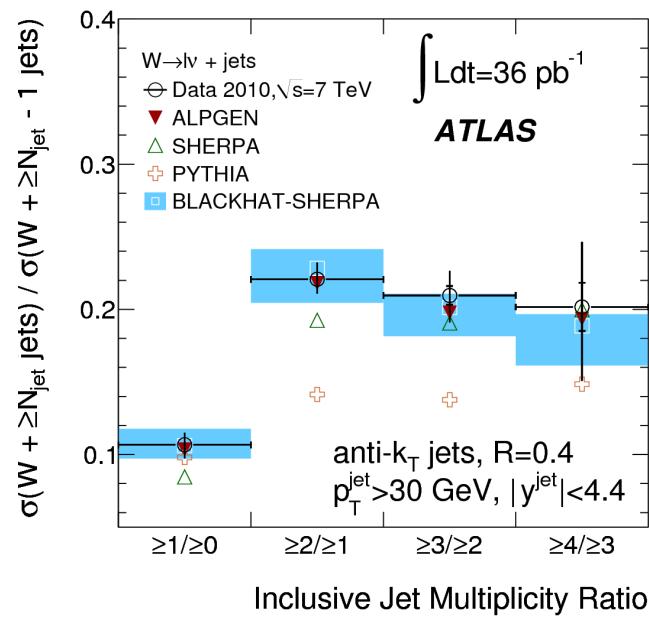
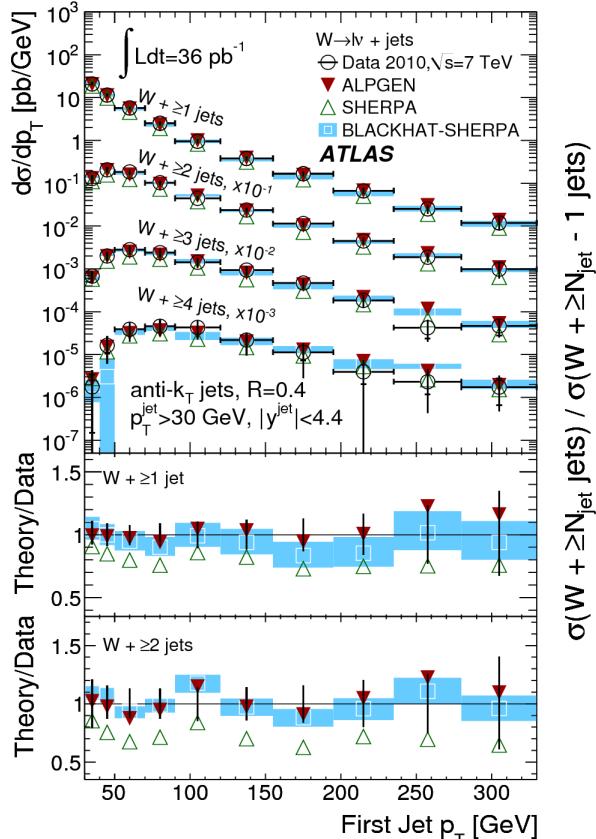


Results

W+jets

Phys. Rev. D85 (2012) 092002

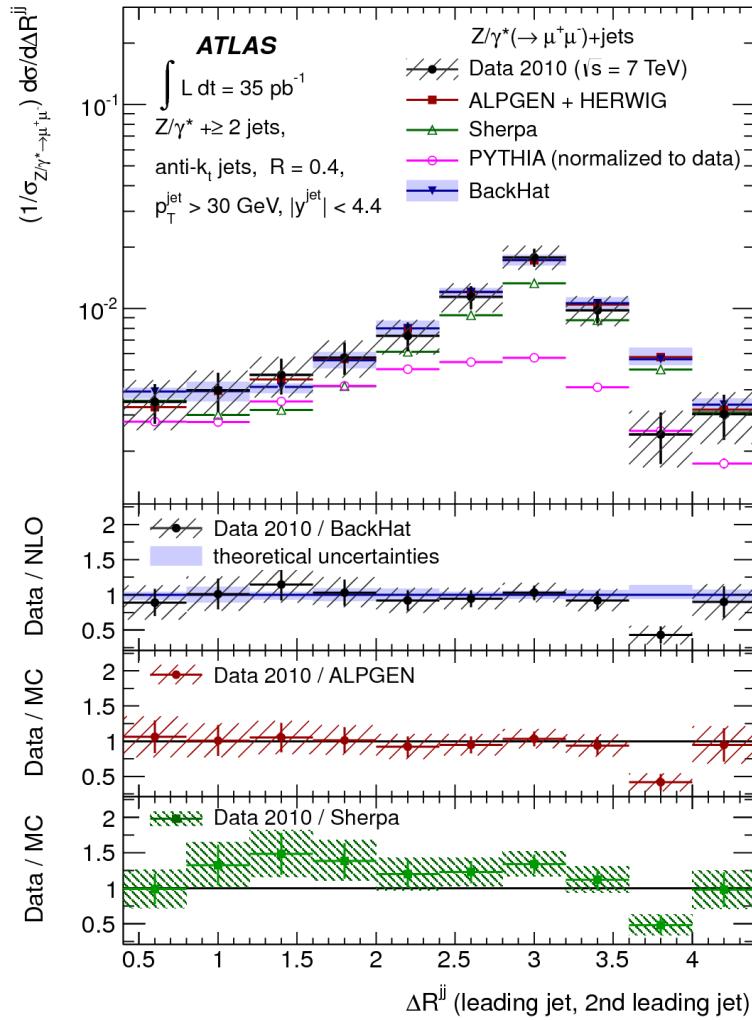
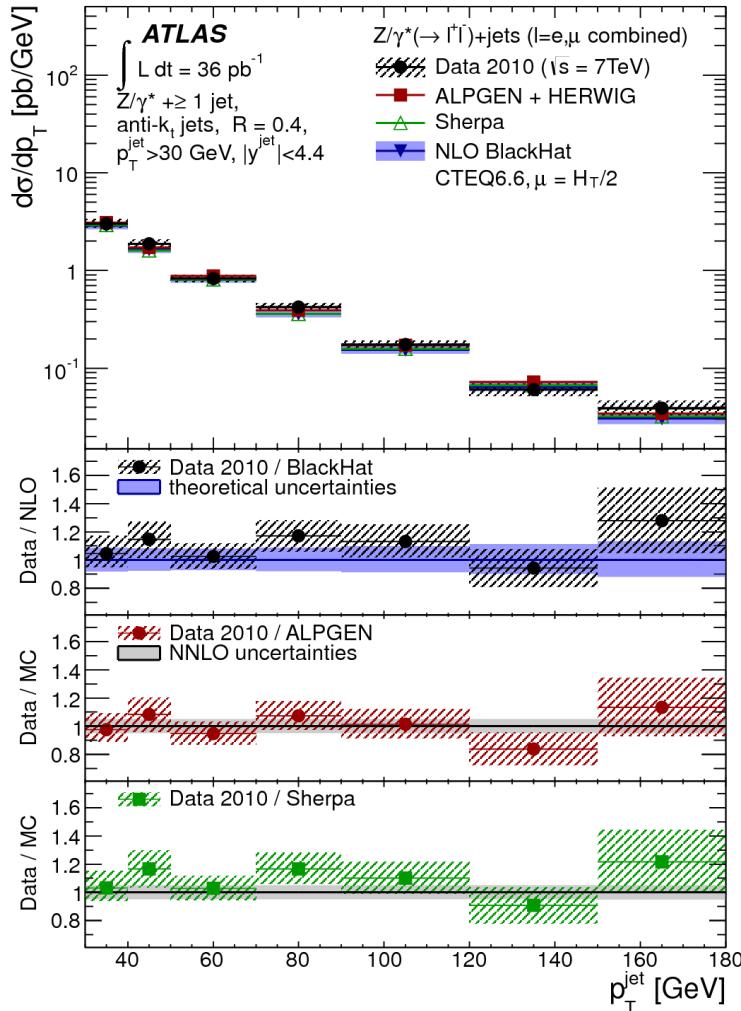
- + Multiplicities generally in good agreement with NLO predictions
 - lack of high-energetic large-angle emissions in PS MC (Pythia)
 - Better modeling of total energy in Alpgen



Z+jets

Phys. Rev. D85 (2012) 032009

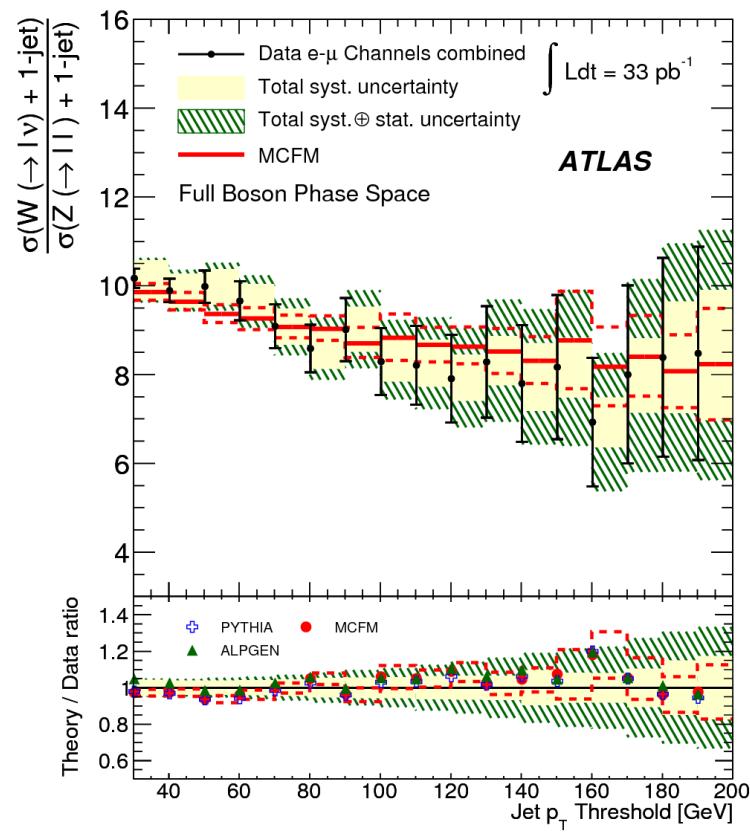
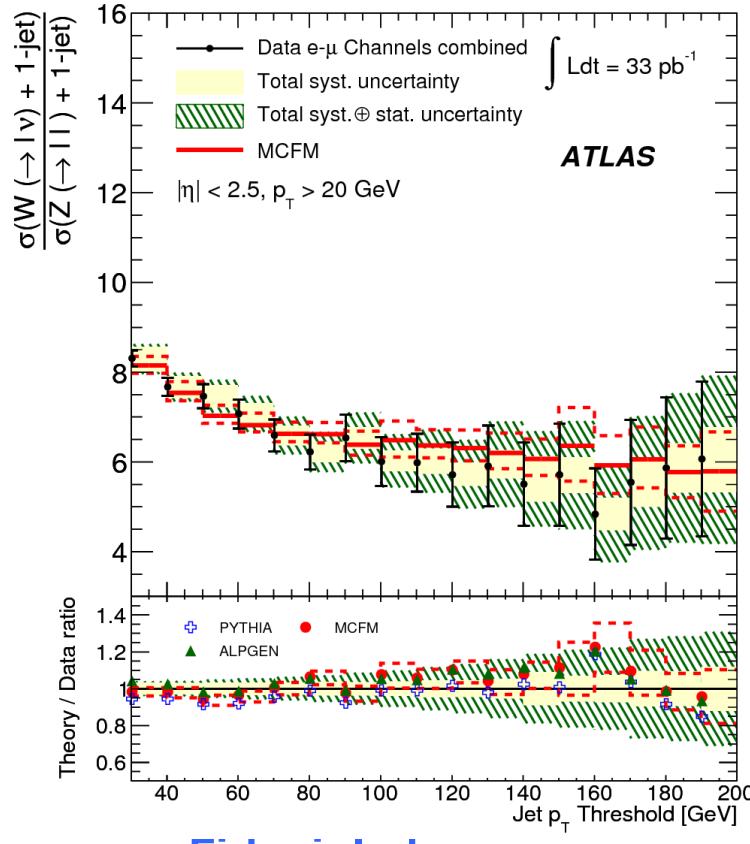
+ Similar conclusion as in W+jets measurements



Rjets

Phys. Lett. B708 (2012) 221-240

- + Similar performance of W+jets and Z+jets is confirmed by precise measurement of Rjets
 - Differential measurement done in 1 exclusive jet bin



Fiducial phase space

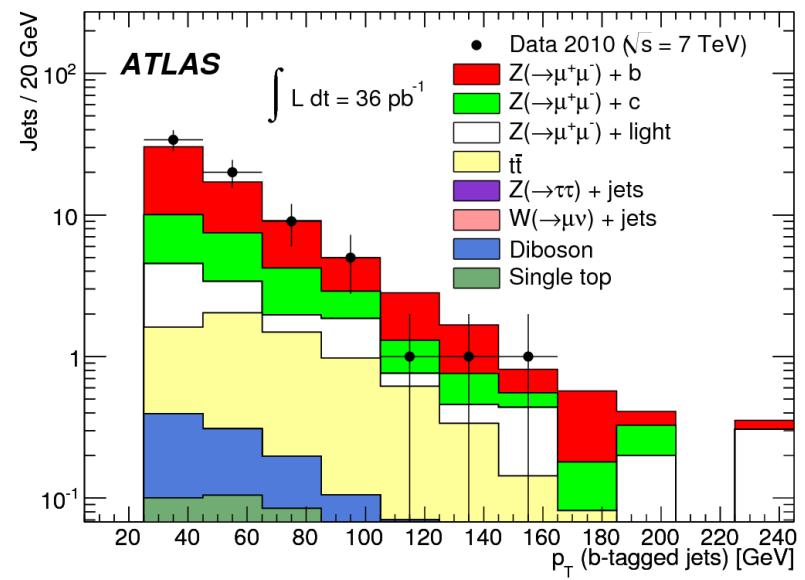
Extrapolation to full phase space

Z+b-jets

Phys.Lett. B706 (2012) 295-313

- + Good agreement with NLO MCFM and SHERPA, but 1.2σ deviation with ALPGEN
 - Seems to favor scheme where b-quark is taken from PDF
- + Good description of b-jet p_T shape
 - Not yet a differential measurement

Experiment	$3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi}) \text{ pb}$
MCFM	$3.88 \pm 0.58 \text{ pb}$
ALPGEN	$2.23 \pm 0.01 \text{ (stat only) pb}$
SHERPA	$3.29 \pm 0.04 \text{ (stat only) pb}$

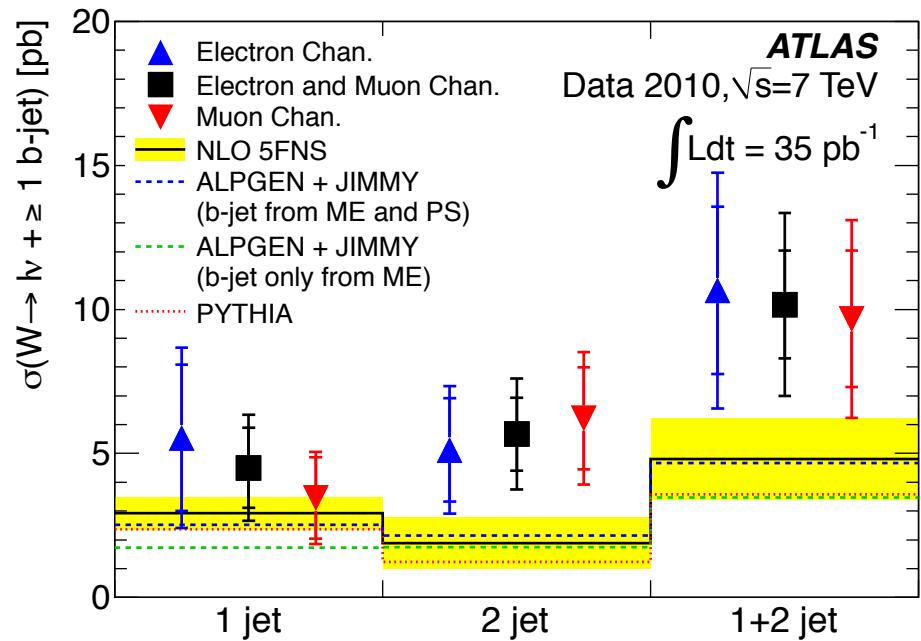


W+b-jets

Phys.Lett. B707 (2012) 418-437

- + While Z+b-jets cross section measurement agrees well with NLO predictions, a small tensions is again observed between W+b-jets measurements and theory predictions
 - Larger in the 2-jet bin
 - Only a 1.5 sigma deviation
- ➔ Not yet significant

Need more data to conclude...



	σ_{vis} [pb]			
1 jet	$2.9^{+0.40}_{-0.36}$ (scale)	$^{+0.18}_{-0.02}$ (PDF)	$^{+0.19}_{-0.10}$ (m_b)	± 0.20 (non-pert.)
2 jet	$1.9^{+0.81}_{-0.37}$ (scale)	$^{+0.14}_{-0.02}$ (PDF)	$^{+0.06}_{-0.05}$ (m_b)	± 0.13 (non-pert.)
1+2 jet	$4.8^{+1.20}_{-0.73}$ (scale)	$^{+0.32}_{-0.03}$ (PDF)	$^{+0.25}_{-0.15}$ (m_b)	± 0.34 (non-pert.)

Conclusions

Conclusion

- + With first 35 pb⁻¹ of data, ATLAS provided serious test of pQCD from an extensive set of measurements
 - Differential cross section for various observable in W/Z+jets
 - Ratio in function of jet observable
 - W/Z+b-jet cross section measurements
- + Measurements challenging NLO predictions
 - Control systematic uncertainties
 - Well-defined quantity
 - set a very high standard for further analyses
- + More differential measurements are coming with 2011 data

Set the stage for discovery!!!

Back-up slides

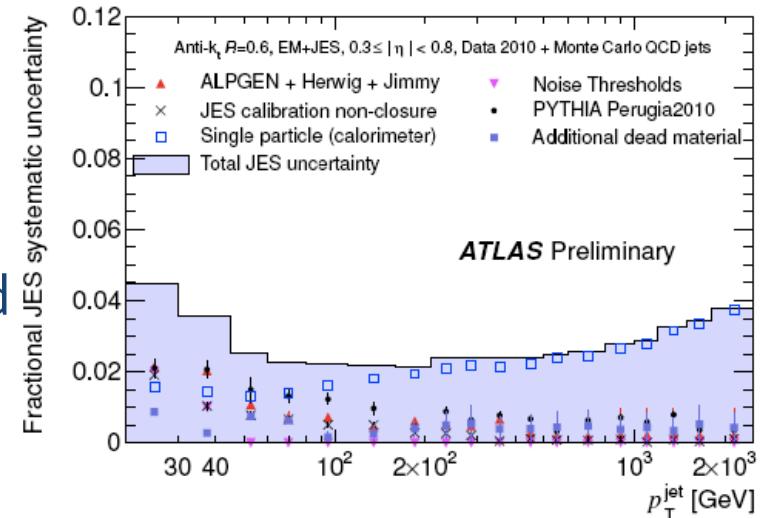
Generators used

Generator	v.	Interfaces	Comments
ALPGEN	2.13	HERWIG, JIMMY, PHOTOS, CTEQ6L1, ATLAS MC09 tune	MLM matching pQCD normalized
SHERPA	1.13	CTEQ6L1, Default UE tune	CKKW matching pQCD normalized
PYTHIA	6.4.21	PHOTOS, MRST 2007 LO	LO Matrix Element + ISR, PS corrections pQCD normalized
MCFM	5.8	CTEQ6.6/CTEQ6L1	PYTHIA UE, fragmentation
SHERPA + BLACKHAT		CTEQ6.6M	PYTHIA UE, fragmentation

Correction for hadronization and underlying events applied to parton-level MC

Jets in the measurements

- + Jets are reconstructed using the anti- k_T algorithm with $R = 0.4$
 - Infrared and collinear safe
 - simple cone-like geometrical shape
 - Used both on predictions and data
- + Calibration from numerical inversion method
 - Obtained from MC on QCD dijet events
 - Dominant systematic uncertainty (10-20%)
 - Improve with in-situ (2011+) studies
 - single hadron, γ -jets and Z -jets events



$JVF = \sum p_T \text{ (tracks) in a jet pointing towards the primary vertex} / \sum p_T \text{ (tracks) in a jet}$

Selection	W+jets	Z+jets	Rjets	W/Z+b-jets
Jet $p_T \geq$	20	30	30	25
Jet $ \eta \leq$	4.4	4.4	2.8	2.1
$\Delta R_{\text{jet-lep}} \leq 0.5$	Jet ignored	Event rejected if $\epsilon [0.2, 0.5]$		As W+jets
$JVF > 0.75$		Applied to all to reject fake pile-up jets		25

Well defined measurements

- + The objective of such SM measurements is precision:
 - Measurement designed to minimize experimental errors
 - Minimal dependence of measurement results on theory input
 - Well defined quantities and final states
- ➔ Fiducial measurement:
 - Unfold to phase space as close as possible to observable phase space
 - Lepton $p_T > 20 \text{ GeV}$, lepton $|\eta| < 2.4$, neutrino $p_T > 25 \text{ GeV}$
 - $M_T(W) > 40 \text{ GeV}$, $66 (\gamma_1) < M_{\gamma\gamma} < 116 (106)$ for Z+jet (Z+b)
- ➔ QED treatment:
 - Unfolded lepton definition includes sum of all photons in a 0.1 cone
- ➔ Particle level b-jets defined as jets containing a B hadron

Unfolding

- + Measurement-theory comparison done at particle level:
 - Raw observation corrected for detector effects
 - Theory predictions corrected for hadronization, underlying events, etc.

→ Allow for direct comparison to calculation and tune the theory

→ Correct for flavor effects in calibration
- + Compare two different methods:
 - Iterative Bayesian unfolding method
 - Lower MC dependence and better stat. treatment
 - Bin-by-bin unfolding
 - Simpler and better understood for ratios
- + Dependence on prior tested by comparing results from different generators (ALPGEN vs SHERPA).

