Comparison of predictions and experimental measurements for V+jets at the Tevatron and LHC

Pierluigi Catastini
Harvard University

on behalf of the
CDF, D0, ATLAS and CMS Collaborations

Introduction: Why V+jets

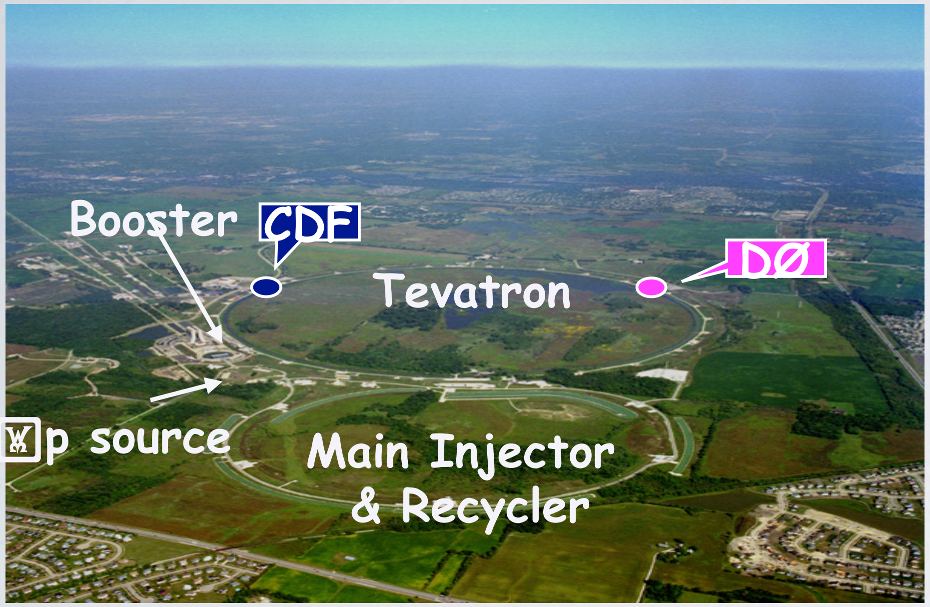
- Test of pQCD predictions.

- W/Z+jets final states are the dominant signatures for the identification of a number of heavy particles produced at high energy, both in the SM and in theories beyond the SM.

- Tevatron crucial to the study of these processes and the development and tuning of MC tools: first extensive comparisons between data and MC.

- At the LHC larger available energy than at Tevatron:
  - More jets; larger kinematic reach
  - Cross sections spanning several orders of magnitude
  - Higher relevance of processes initiated by qg and gg
  - Different contribution to the cross section compared to Tevatron
  - Processes with heavy flavor in the initial state become important

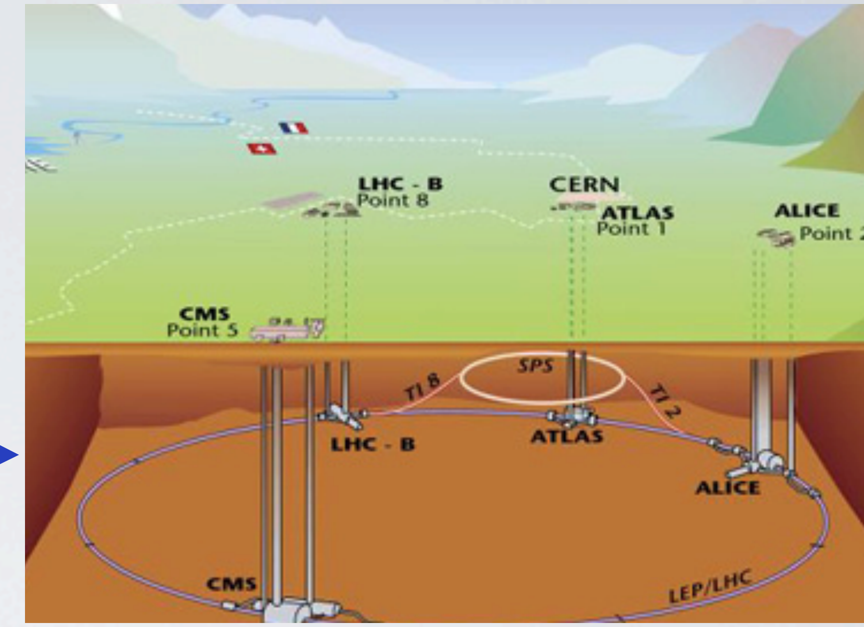
The Machines



Tevatron

$\sqrt{S}$ = 1.96 TeV

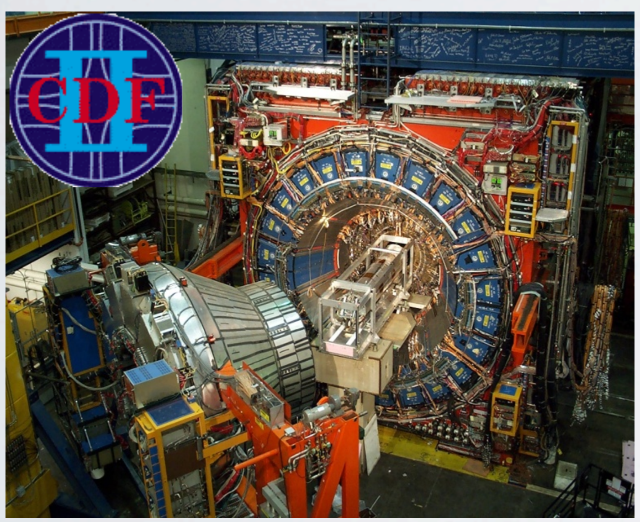
3 decades of Physics !

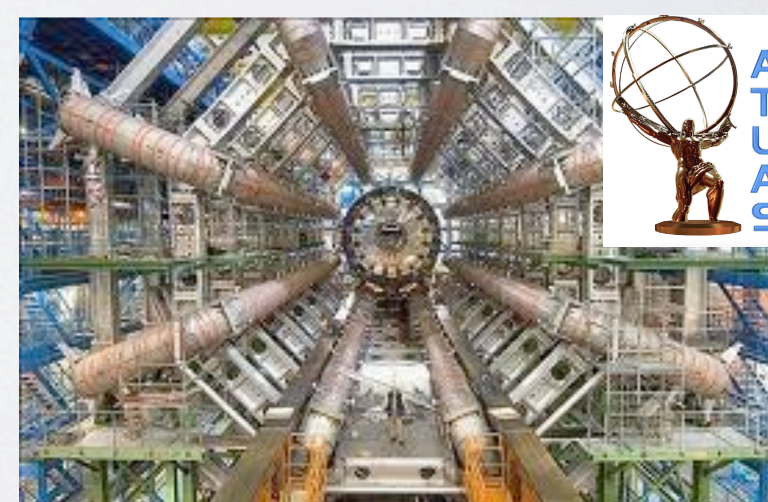


LHC

Currently $\sqrt{S}$ = 7 TeV

The Future !





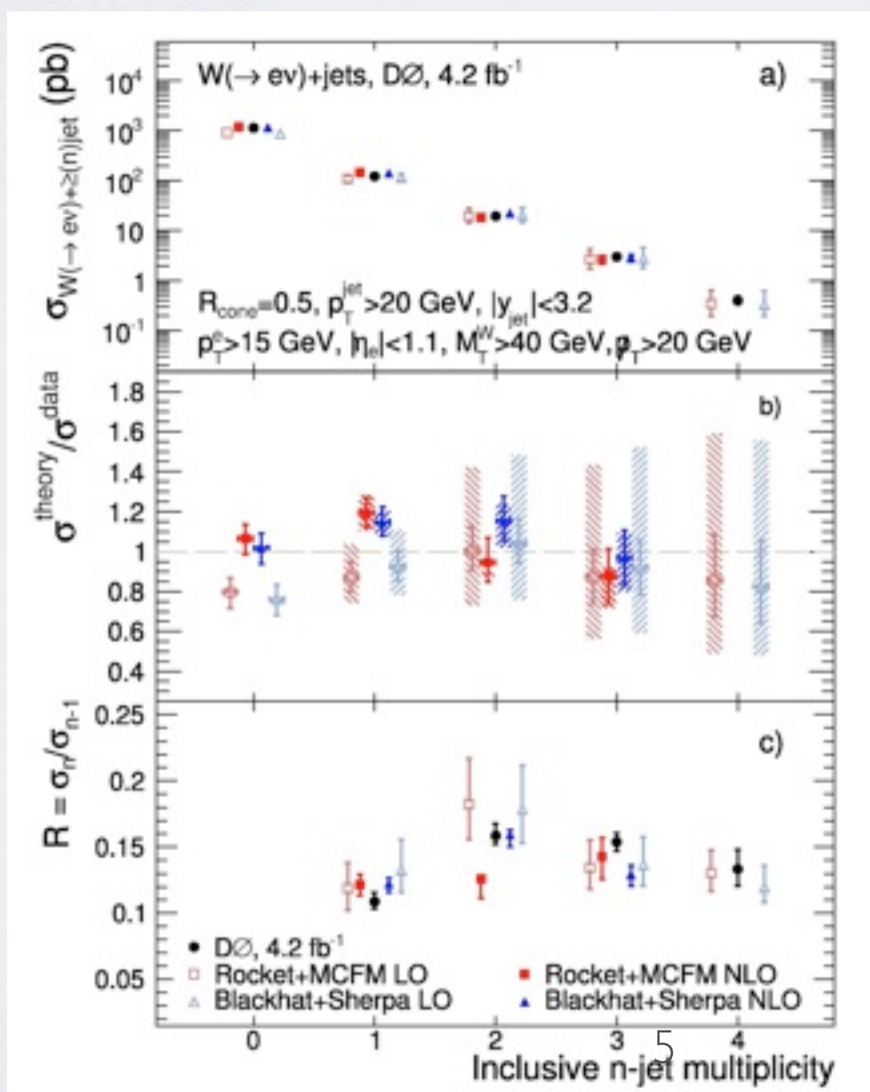
Will discuss results from:

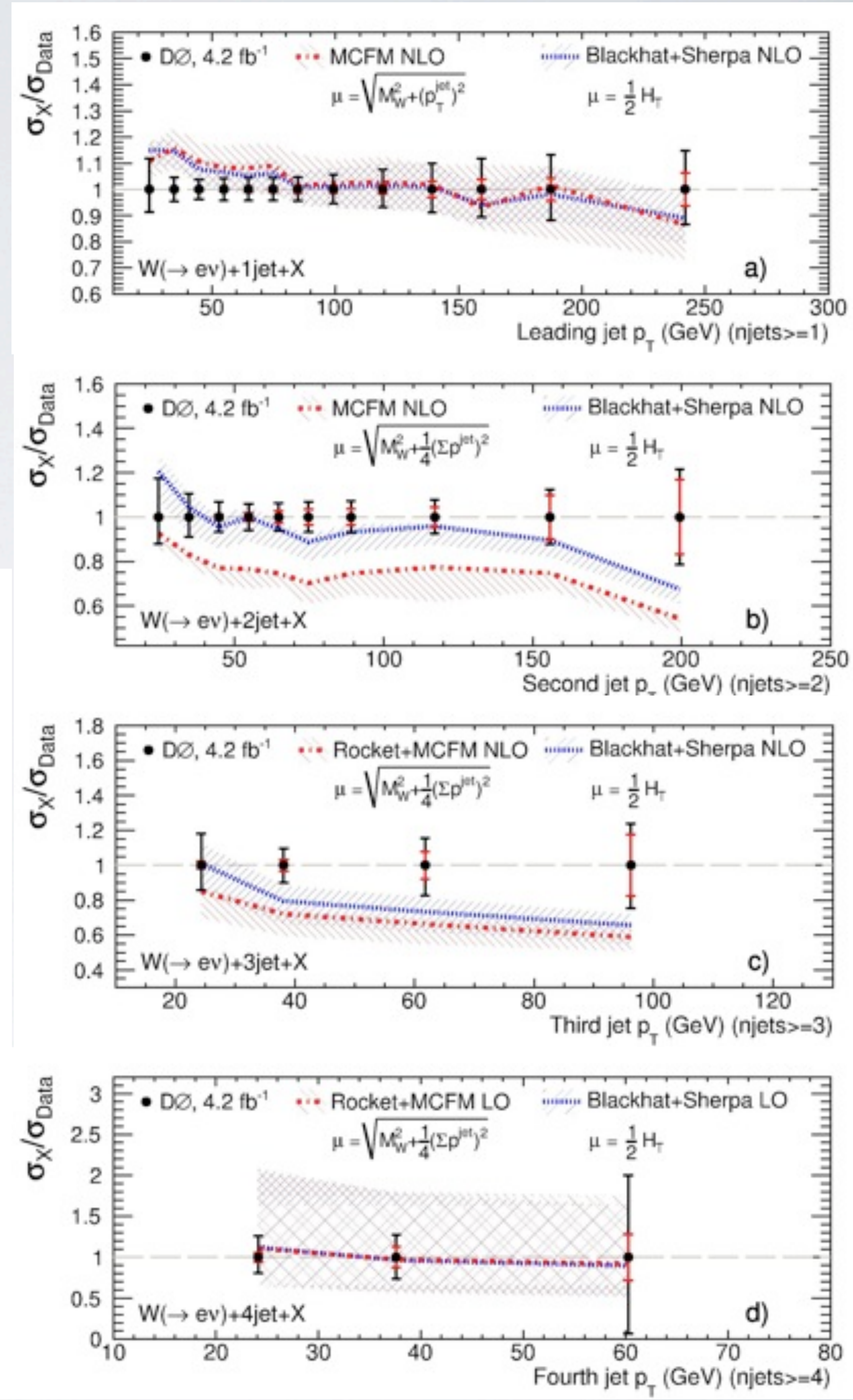
- 2 Colliders
- 4 Experiments

V+Jets

W+jet results

- Inclusive measurement of W(eν)+ njet (n=1-4) as a function of jet transverse momentum
- Jets reconstructed with midpoint algorithm with R=0.5, pT > 20 GeV and |y|< 3.2
- Measurements corrected at particle level
- Compared to NLO pQCD for njet up to 3.
- Compared to LO pQCD in the 4 jets bin





- The measured cross sections are generally found to agree with the NLO calculation.
- Some regions of the phase space might be improved.

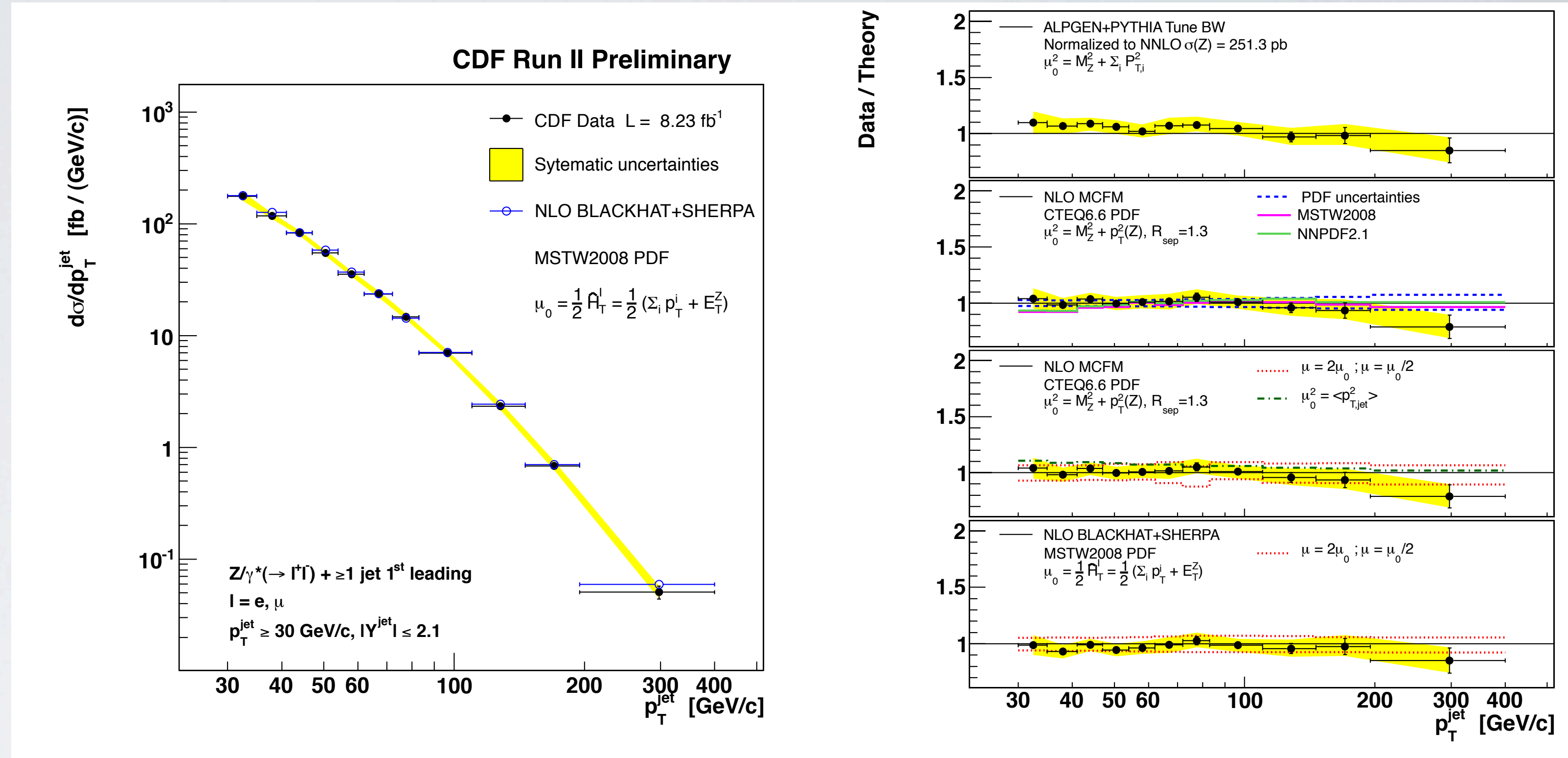
arXiv:1106.1457

Z+jet Results

Muons and electrons Combined.

- MidPoint algorithm with R=0.7
- Hadron level jets with p_T^{jet} > 30 GeV/c and $|y^{jet}|$ < 2.1
- $\Delta R(l,\text{jet})$ > 0.7
- Theory prediction corrected for non-pQCD effects

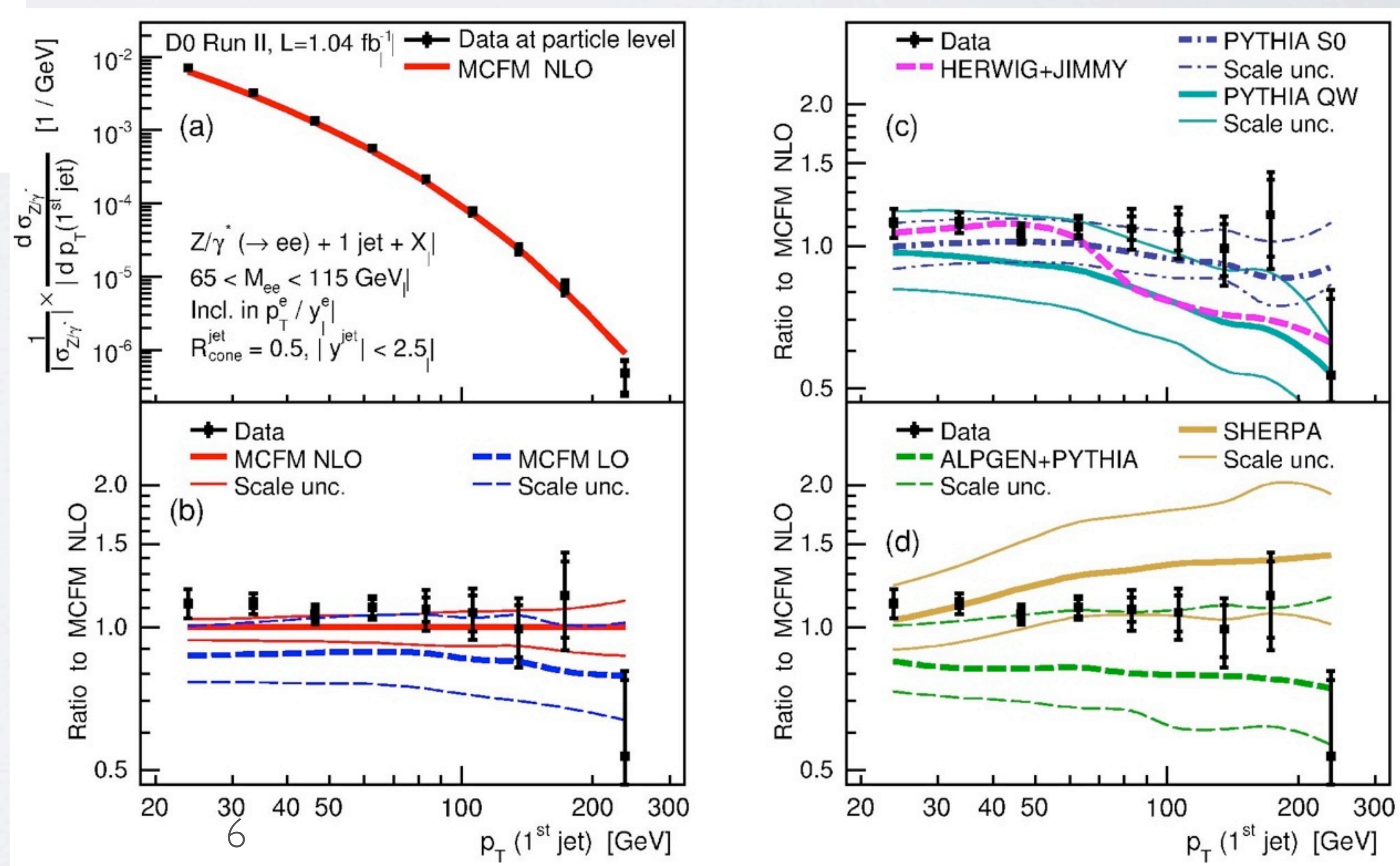
Good agreement with NLO pQCD



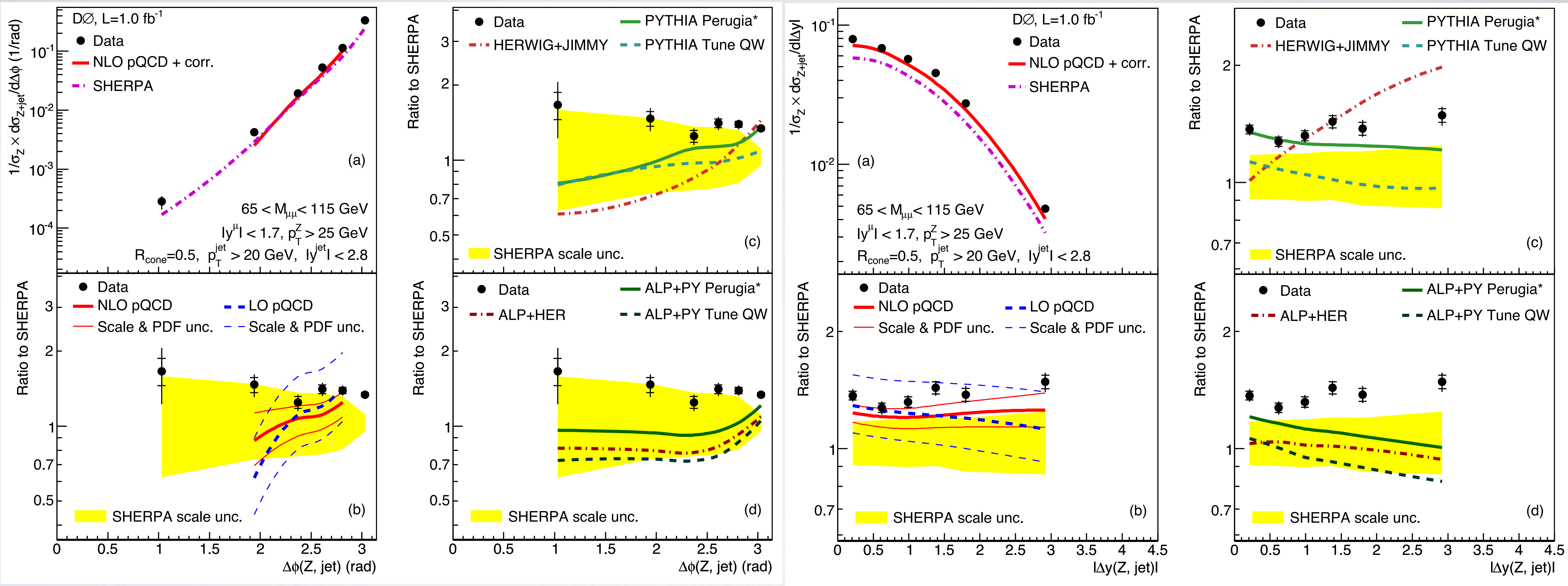
PLB 678, 45 (2009)

- Jets reconstructed with midpoint algorithm with R=0.5, pT > 20 GeV and |η|< 2.5
- Measurements normalized to inclusive Z XS and MCFM prediction corrected for non-pQCD effects

NLO pQCD well described the data. Compared to event generators, ME+PS show reasonable description of shapes but large scale uncertainties



Z+jet Angular Distributions



Phys. Lett. B 682, 370 (2010)

- 65 < Mll <115 GeV
- pT(Z) > 25 GeV and |y|< 1.7
- Jets reconstructed with midpoint algorithm with R=0.5, pT > 20 GeV and |η|< 2.8
- Measurements normalized to inclusive Z XS and MCFM prediction corrected for non-pQCD effects

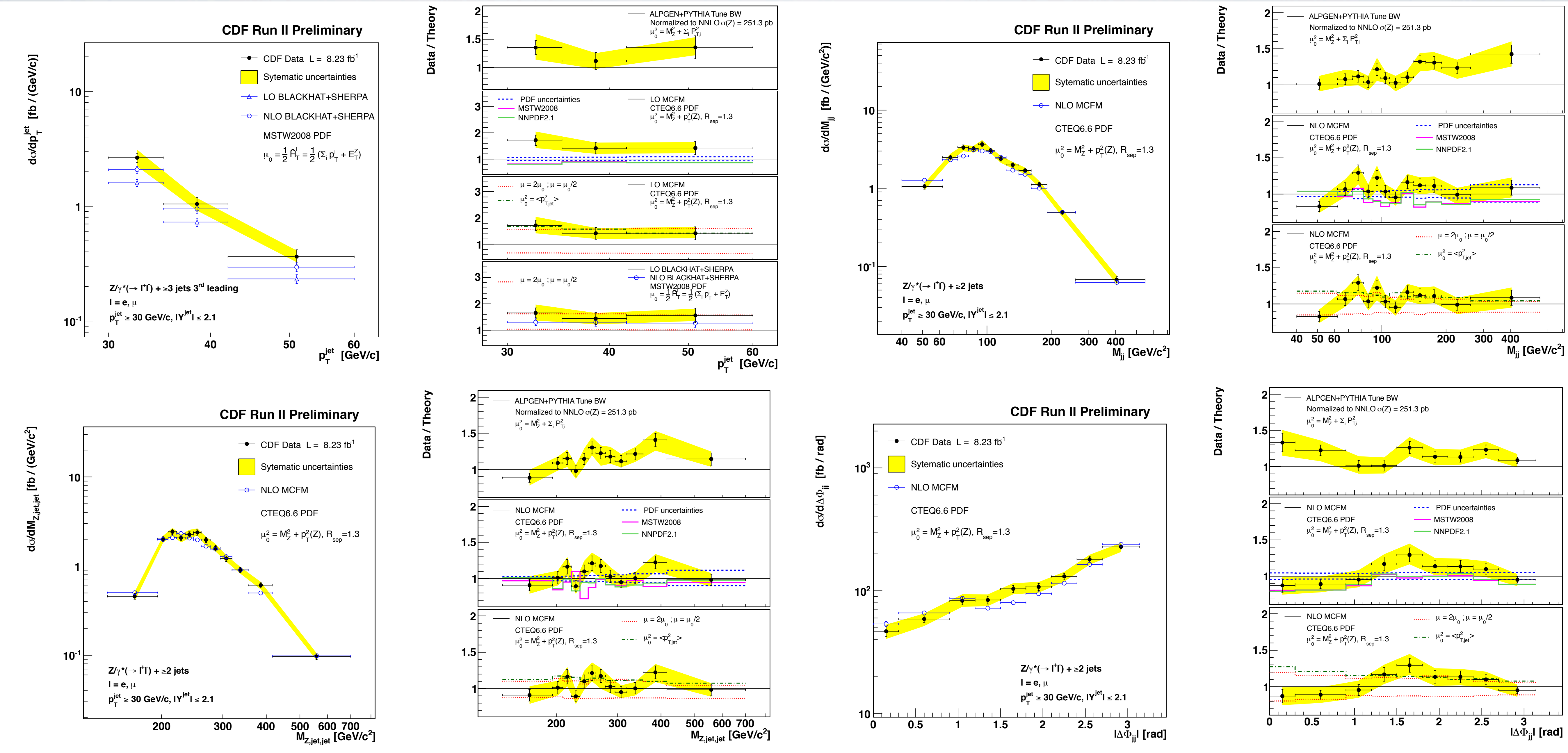
Sensitive to QCD Radiation, excellent for tuning of Monte Carlos

Measurements are normalized to σz to reduce systematic uncertainties

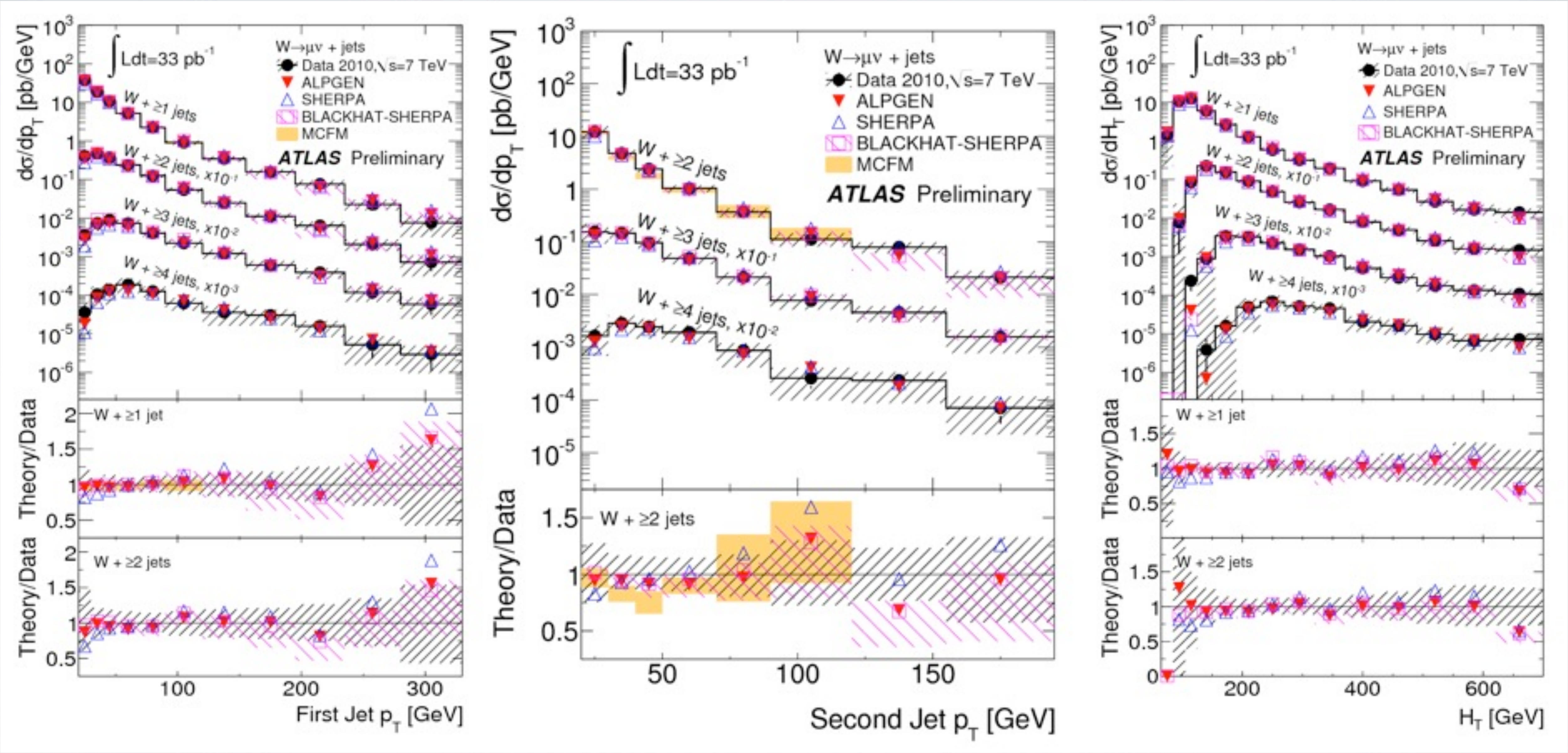
SHERPA MC well describes shapes but not the normalization

Z+jet results

Measured $Z/\gamma^{*}+\geq 2$ jets production as a function of several kinematic distributions at hadron level. Muons and electrons decays are combined.

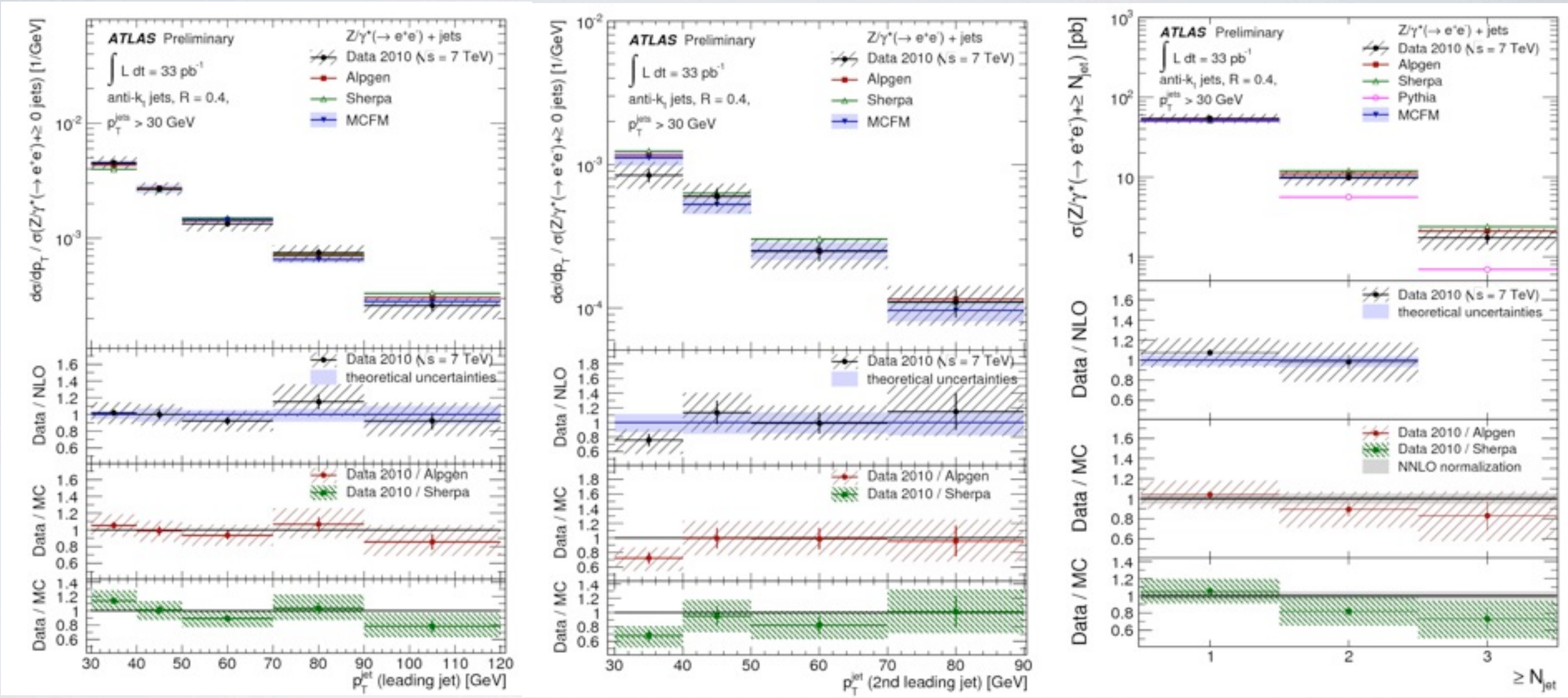


W+jet results



- Anti-k_T algorithm (R=0.4); p_T>20 GeV; |y|<2.8; jets are considered if $\Delta R_{l\text{-}jet}$>0.5
- Detector effects corrected for using bin-by-bin unfolding
- Cross section measured as a function of several kinematic variables

Z+jet results

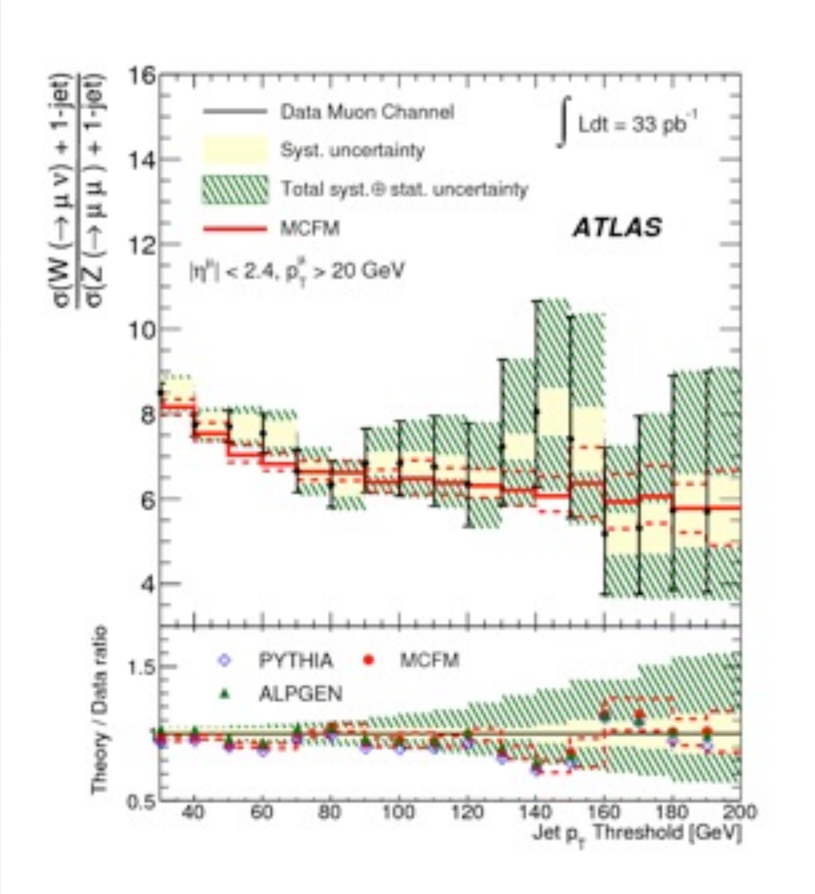


Both for W+jet and Z+jet:

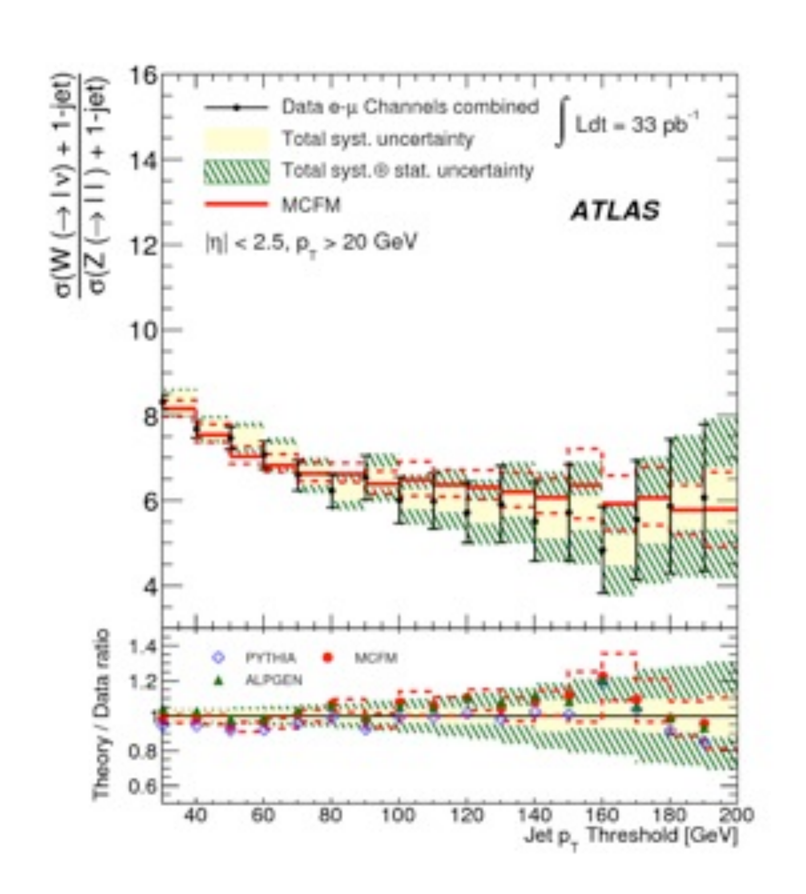
- Very good agreement with NLO (renorm. and fact. scales = Ht/2) predictions from MCFM and Blackhat-Sherpa in the total and differential cross sections
- Good agreement with matched LO prediction from AlpGen and Sherpa once normalized to the NNLO prediction
- Poor agreement with LO PYTHIA in the high jet multiplicity

(Z+1 jet)/(W+1 jet) Rjet ratio

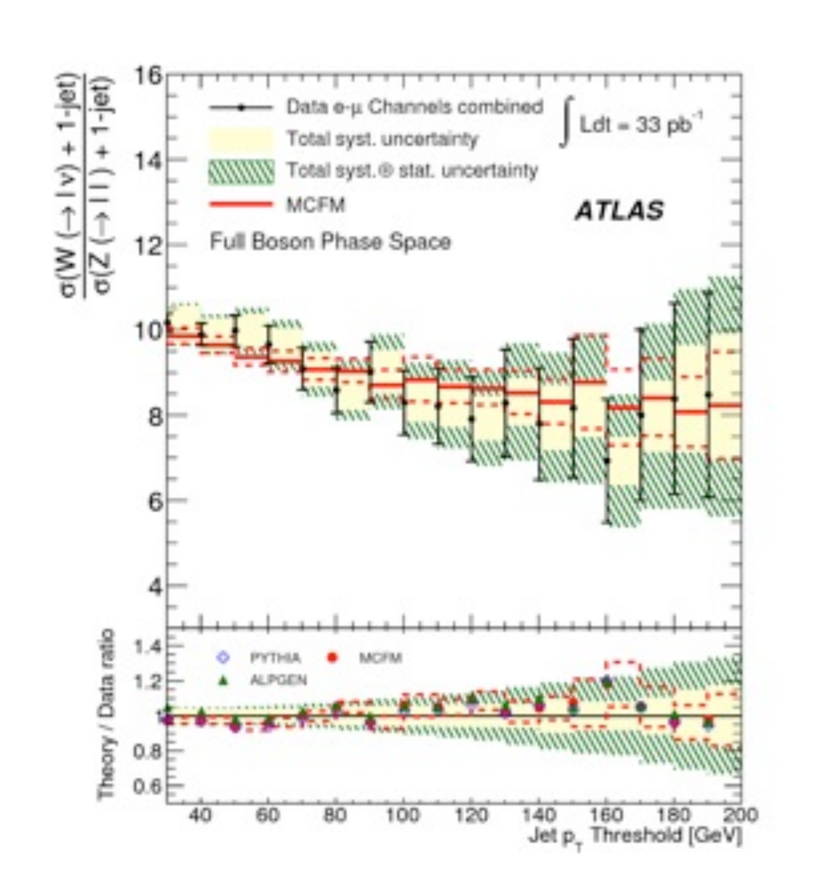
Muon (Fiducial)



Combined (Fiducial)



Combined (Full Phase Space)



- Probe QCD dynamics without QCD uncertainties
- Theory uncertainty is reduced in the Rjet ratio(control on systematics at few precent level): in particular there is significantly reduced dependence on the PDF
- The Rjet is measured for events with only one jet with p_T>30 GeV and |η|<2.8 as a function of the minimum jet p_T
- Results are given for the electron and muon channel separately and also combined, both in the fiducial and total bosons phase space

Very good agreement of NLO prediction from MCFM
Very good agreement with matched LO prediction from AlpGen and PYTHIA (norm. to data)

W + jet results

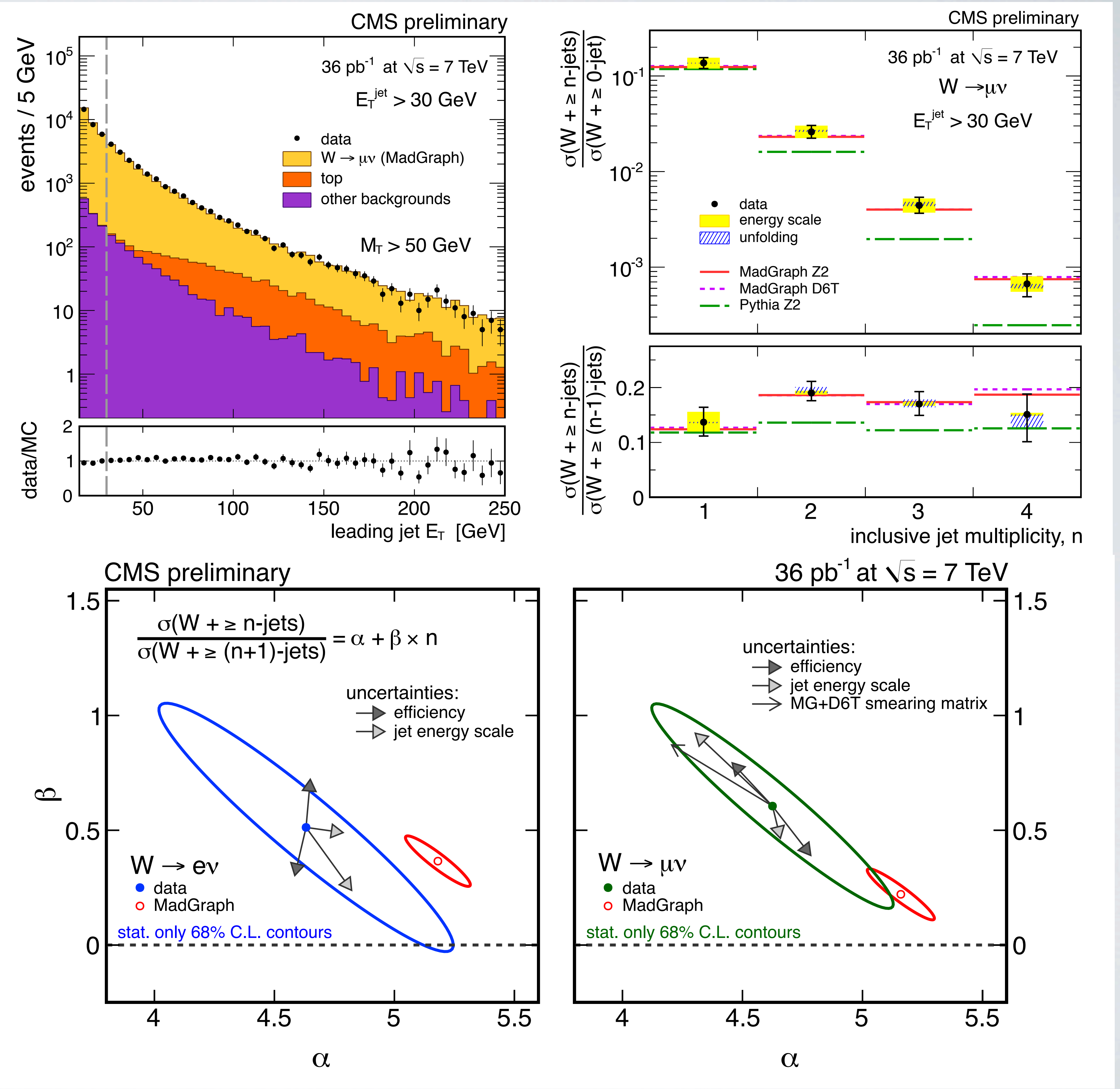
- Jets clustered by the anti-kt algorithm (size parameter = 0.5).
  Particle Flow technique used to reconstruct the jet constituents.
- Count jets with:
  - pT > 30 GeV/c
  - |η|<2.4
- Unfolding procedure applied to correct for migration between Njet bins due to imperfect jet energy resolution and reconstruction efficiency.
- Measurement of:

σ(W + n jets) / σ(W) and **σ(W + n jets) / σ(W + (n-1) jets)**

Test of Berends-Giele scaling behaviour

$$C_n = \sigma(V+n\text{jets})/\sigma(V+(n+1)\text{jets})$$

- $C_n = \alpha + \beta n$: allow for deviations from LO.
- Use measurements of cross section ratios to fit for α and β.
- 68% CL countours on the plots for statistical uncertainty only. Systematic uncertainties shown as arrows.



Z+jet results

- Same technique of W+jet.
- Measurement of:

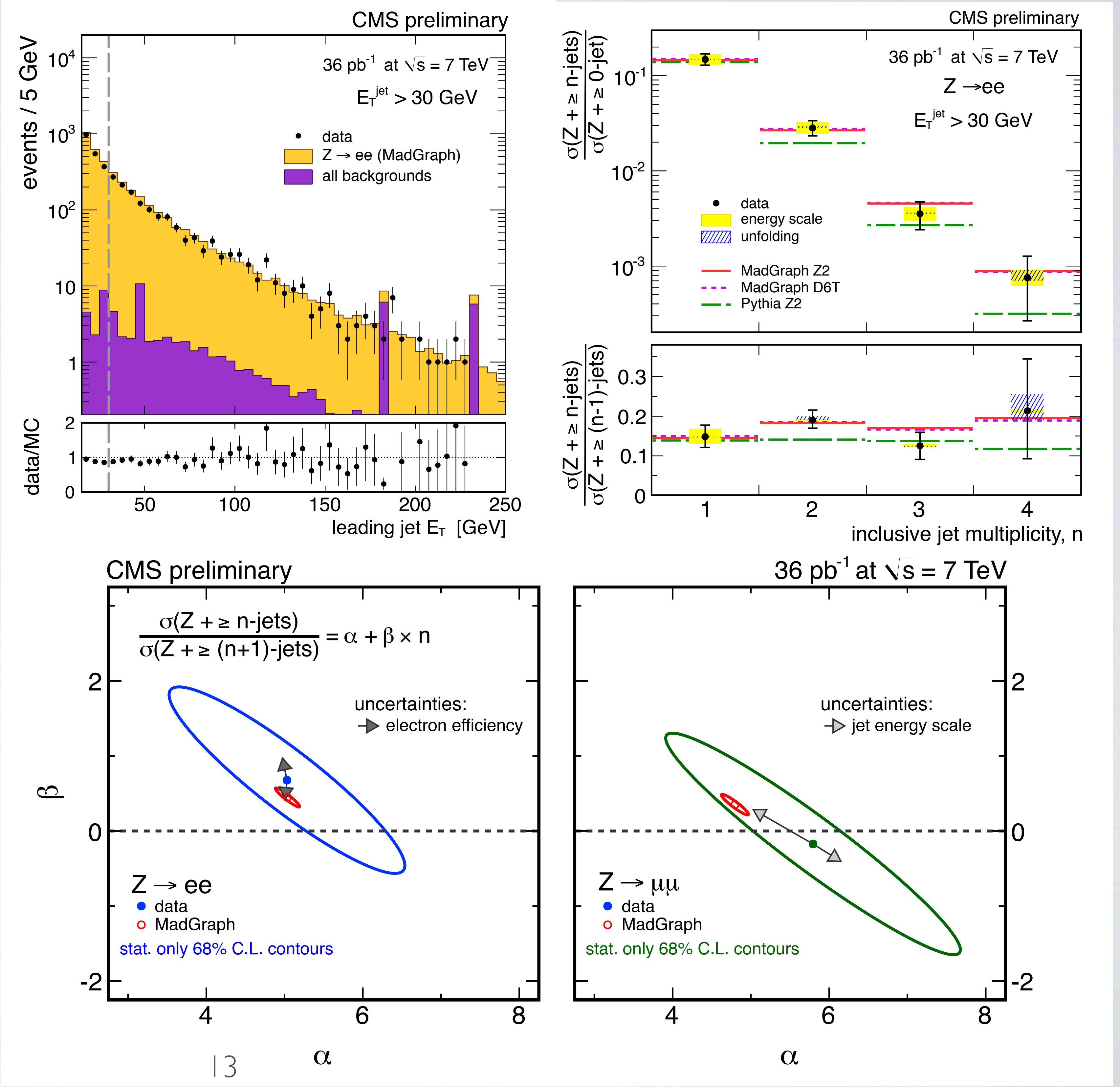
σ(Z + n jets) / σ(Z) and **σ(Z + n jets) / σ(Z + (n-1) jets)**

Both W+jet and Z+jet show:

- Good agreement between data and MadGraph in control plots.

- Good agreement with MadGraph, poor agreement with Pythia at high jet multiplicity as expected.

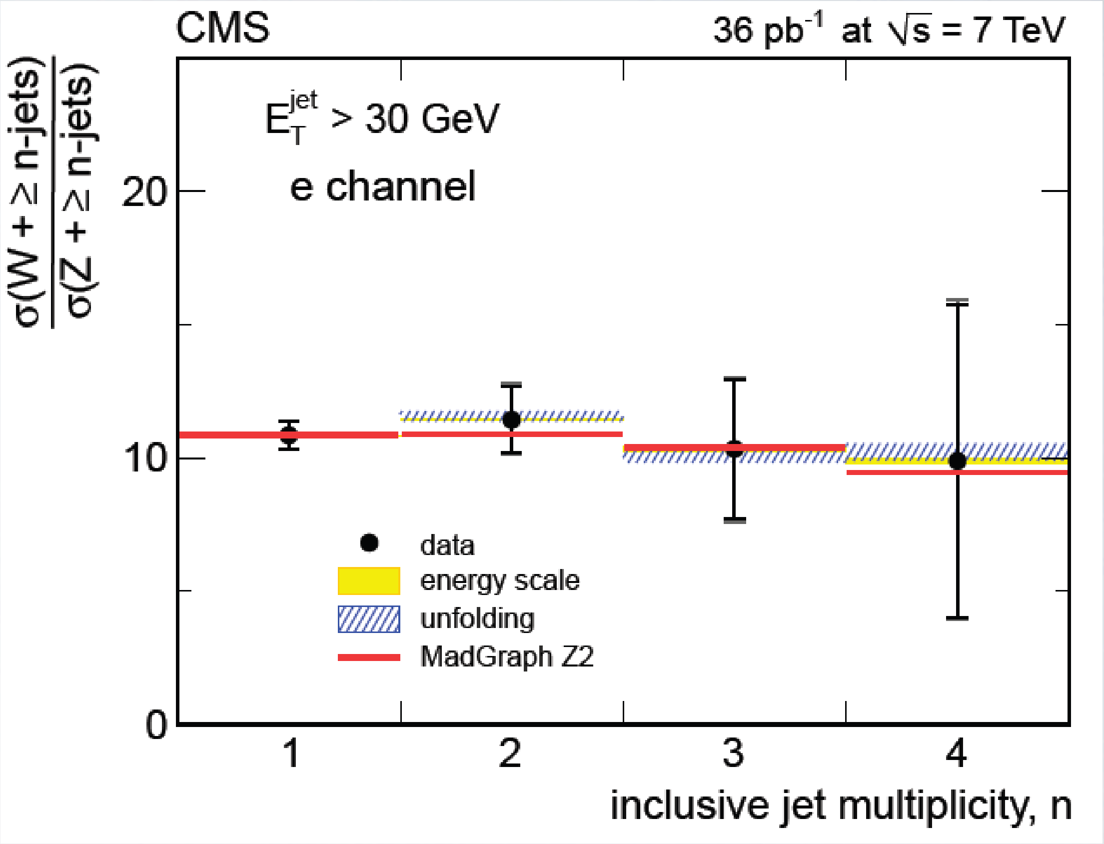
- Berends-Giele scaling behaviour: MadGraph shows reasonable agreement with data.



In addition

W+jets/Z+jets ratios

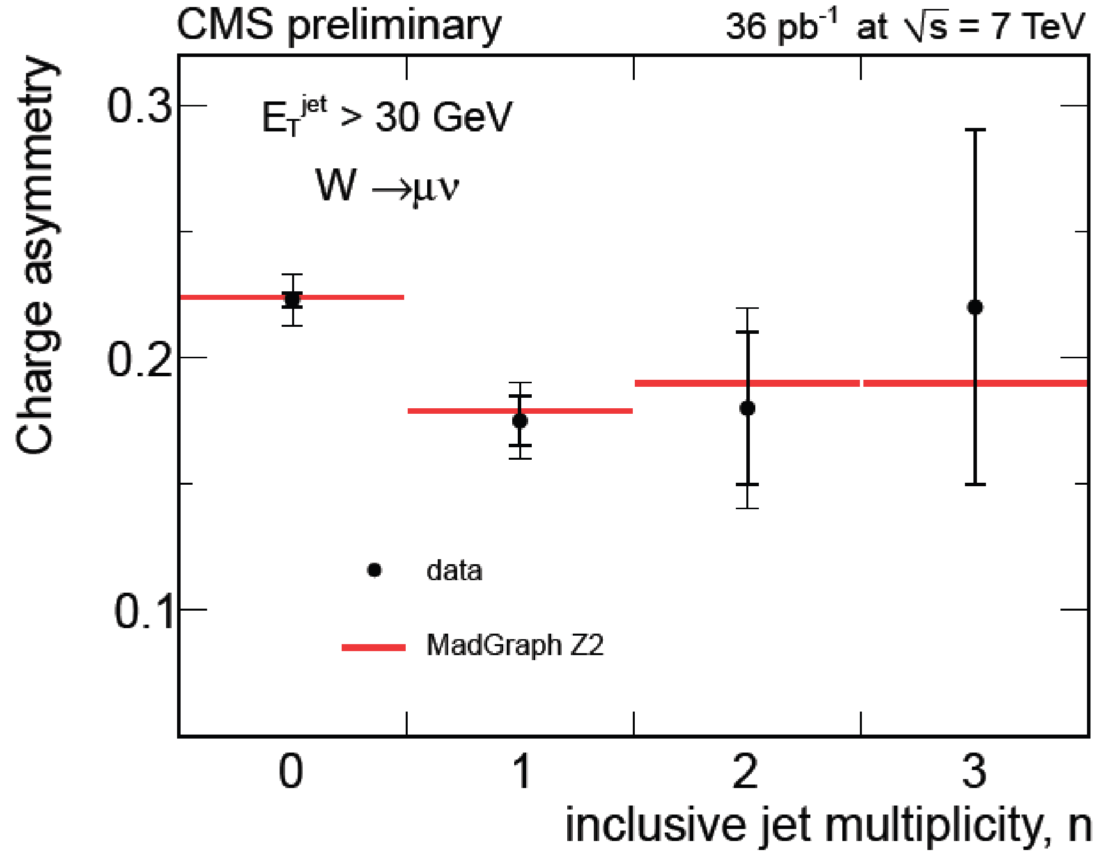
- As a function of jet multiplicity
- Reasonable agreement with MadGraph



Charge Asymmetry

$A_W = [\sigma(W^+) - \sigma(W^-)] / [\sigma(W^+) + \sigma(W^-)]$

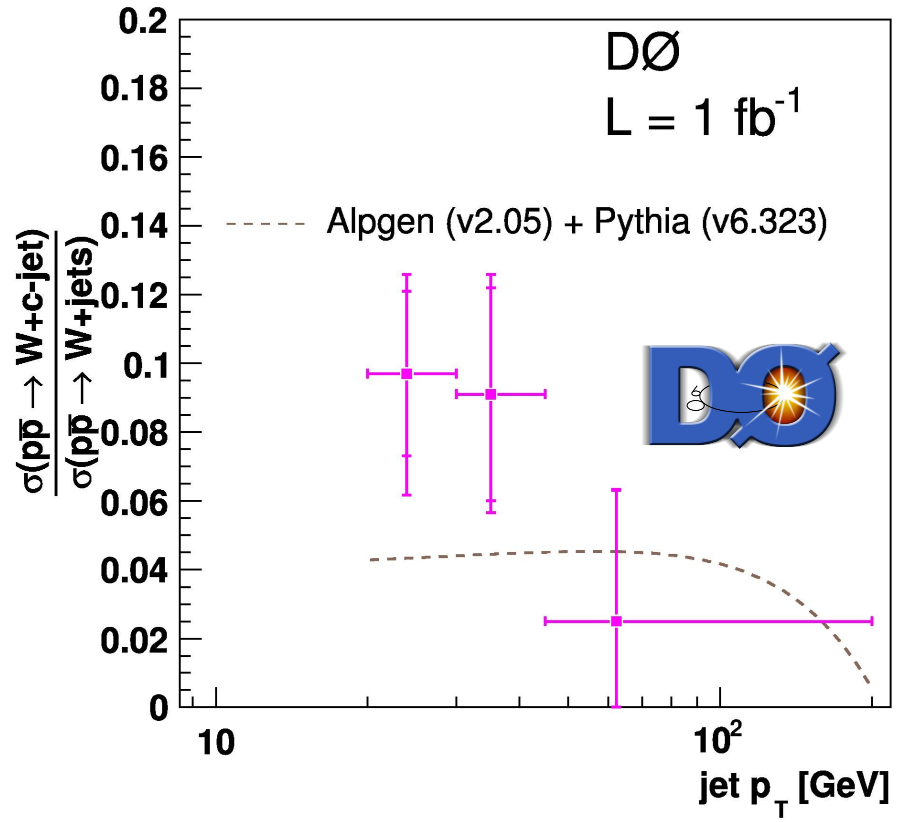
- W charge asymmetry as a function of jet multiplicity in good agreement with MadGraph.
- Asymmetry is smaller in W+jets events as expected.
- Charge misidentification uncertainty and positive vs. negative lepton efficiency uncertainties are small and accounted for.



V+Heavy Flavor

W+c Tevatron

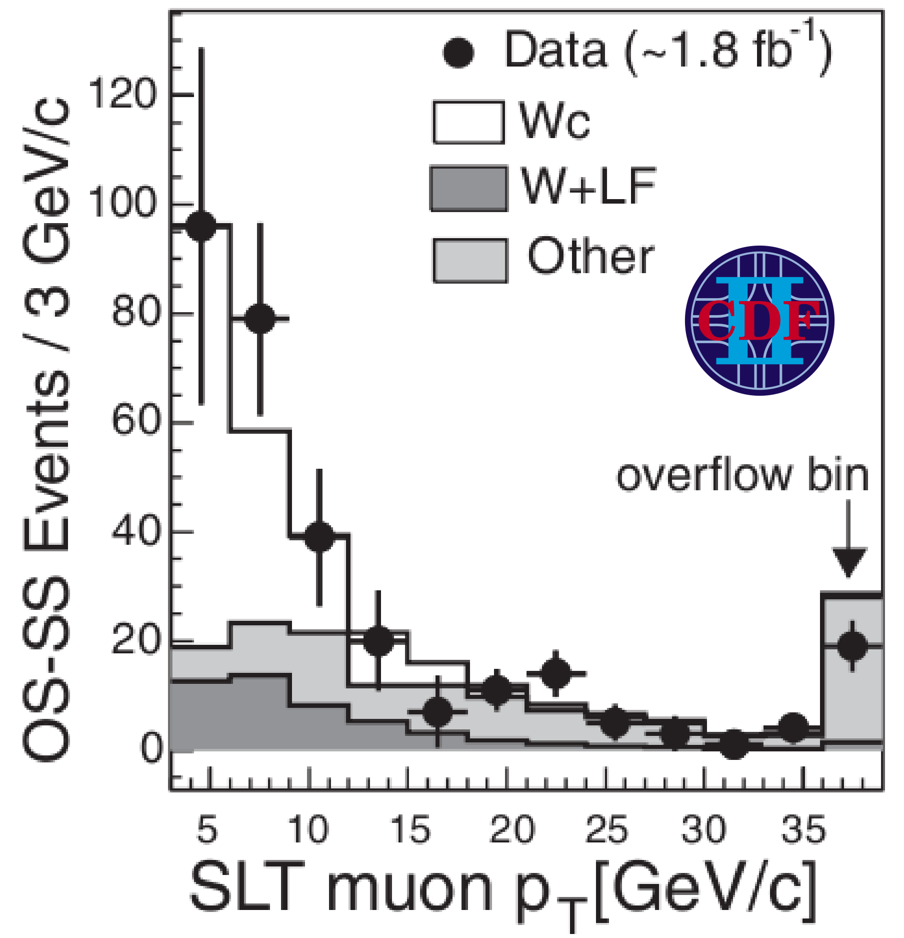
Rate of W+c production sensitive to s quark content of the proton.
Charm jet identified by soft lepton tagging (SLT) algorithm (electron or muon).



$$\frac{\sigma_{W+c}}{\sigma_{W+jets}} = 0.074 \pm 0.019(stat)^{+0.012}_{-0.014}(syst)$$

LO (Alpgen + Pythia) 0.044 ± 0.003

Phys. Lett. B 666, 23 (2008)



$$\sigma_{W+c} \times Br(W \rightarrow l\nu)$$

$$9.8 \pm 2.8(stat)^{+1.4}_{-1.6}(syst) \pm 0.6(lum)\ pb$$

$$NLO\ prediction\ (MCFM): 11.0^{+1.4}_{-3.0}\ pb$$

PRL 100, 091893 (2008)

New result with SLTe ready by next month: still of interest because of different pdf x region at the Tevatron with respect to LHC

W+c CMS

- Select events with muon pT >25GeV/c,η<2.1and at least one jet pT >20GeV/c,η<2.1.
- Require at least one jet tagged with SSVHE algorithm.
- Extract W+c yield by fitting to the SSVHE discriminator with MC templates.
  - Fit extends to negative tags (where SV is in "wrong direction"); helps to constrain the W+l component.
  - tt component checked in control region in data with inverted jet multiplicity cut.

Measure the ratios:

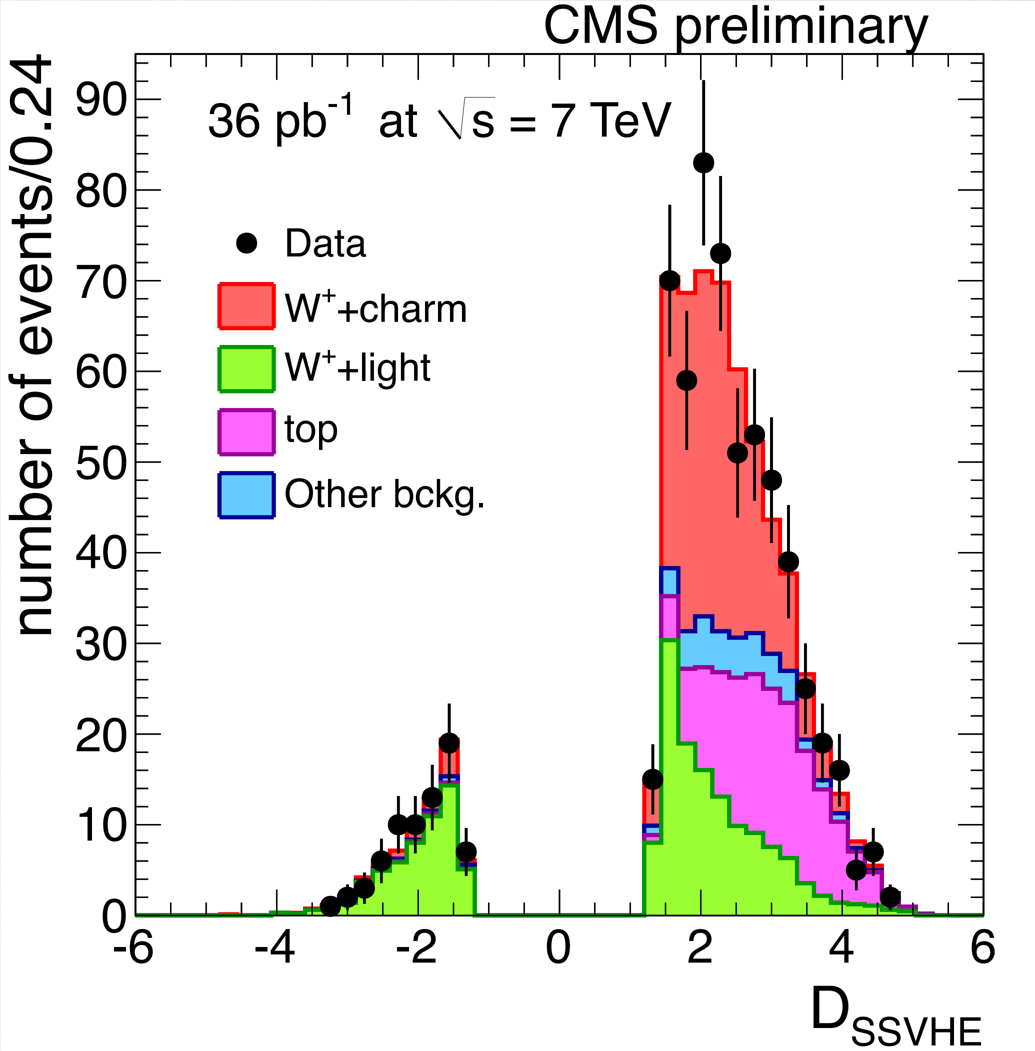
$$R_c^{\pm} = \sigma(W^+c) / \sigma(W^-c)$$
$$R_c = \sigma(W + c) / \sigma(W + j)$$

Results:

$$R_c^{\pm} = 0.92 \pm 0.19\,(stat.) \pm 0.04\,(syst.)$$
$$R_c = 0.143 \pm 0.015\,(stat.) \pm 0.024\,(syst.)$$

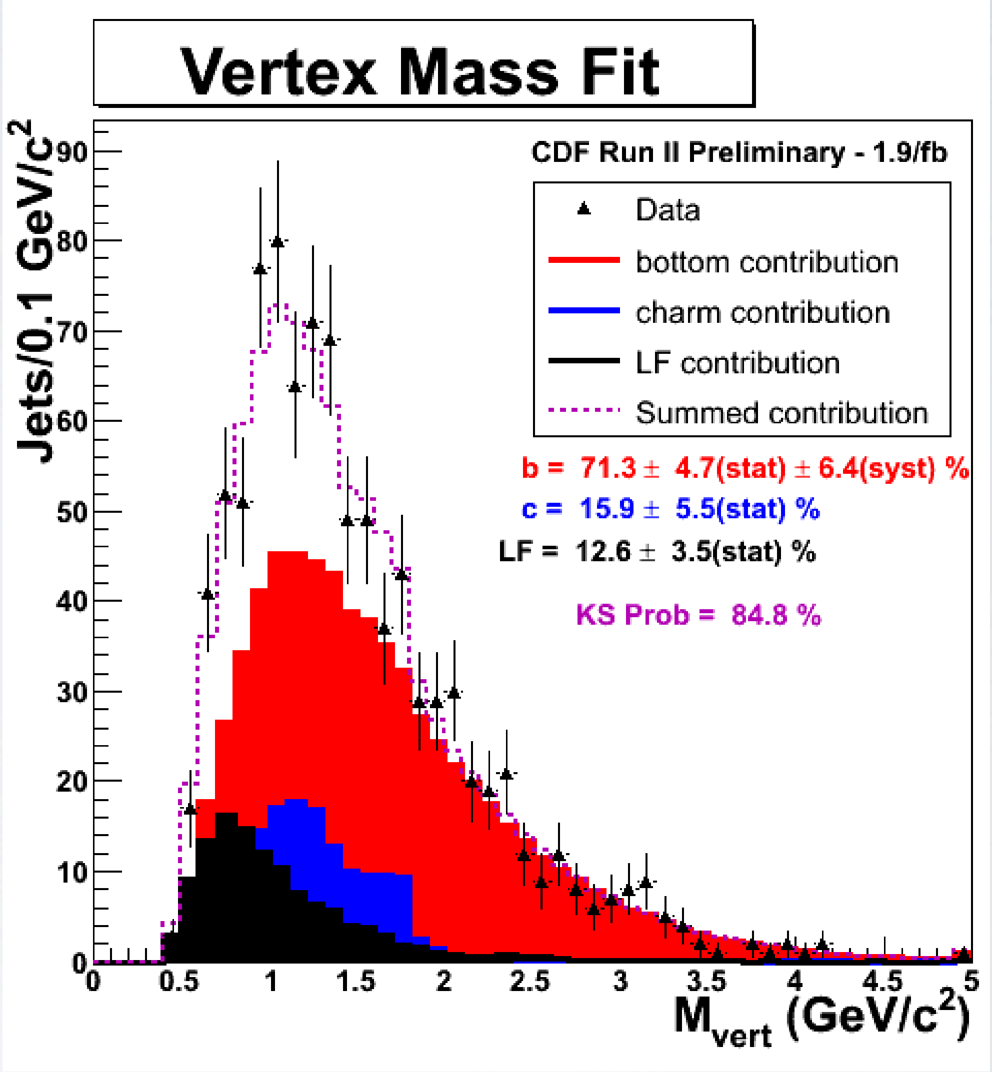
In agreement with MCFM predictions at NLO.

Ratio	MCFM (CT10)	MCFM (MSTW08)	MCFM (NNPDF21)
$R_c^{\pm}$	$0.915^{+0.006}_{-0.006}$	$0.881^{+0.022}_{-0.032}$	0.902 ± 0.008
R_c	$0.125^{+0.013}_{-0.007}$	$0.118^{+0.002}_{-0.002}$	0.103 ± 0.005



W+b CDF

- One or two jets, reconstructed with a cone algorithm with R=0.4
- jet ET > 20 GeV and |η|< 2.0
- Events with at least one b-tagged (ultra- tight secondary vertex requirements)
- Use vertex mass to discriminate between b, c and light jets.
- Templates obtained from MC (Alpgen+Pythia)
- Backgrounds from data (multijets) and MC



$$\sigma_{W+b} \times Br(W \rightarrow l\nu)$$

$$2.74 \pm 0.27 \pm 0.42\ pb$$

$$ALPGEN = 0.78\ pb$$

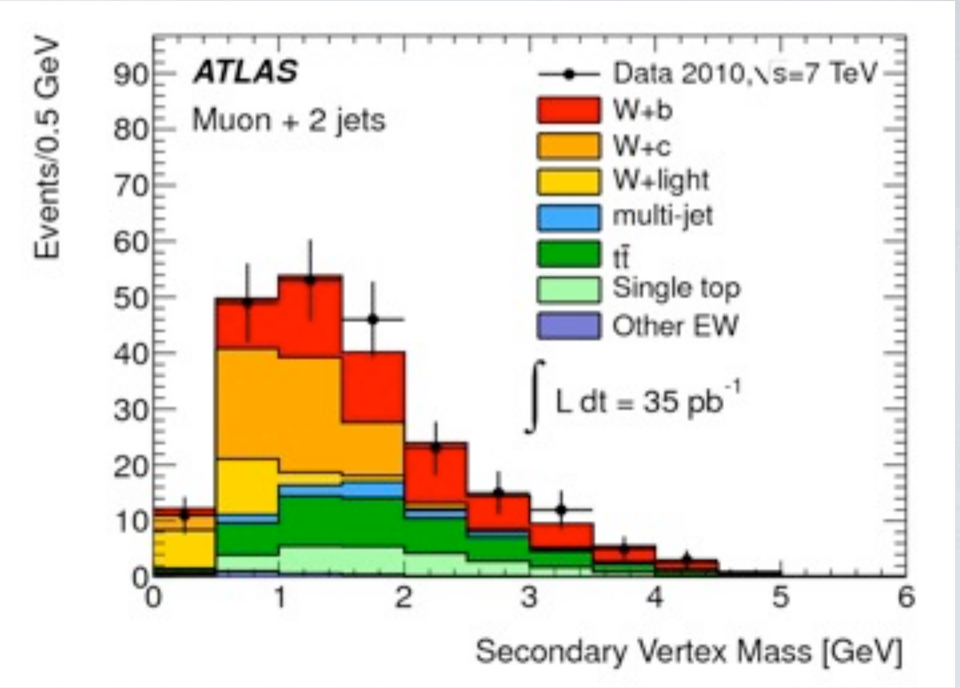
(MCFM) $$NLO\ pQCD = 1.22 \pm 0.14\ pb$$

PRL 104, 131801 (2010)

Higher than NLO

W+b ATLAS

A maximum likelihood fit to the SV0 mass distribution is used to separate b-jets from c- and light-jets, and extract the flavor fraction on a statistical basis.

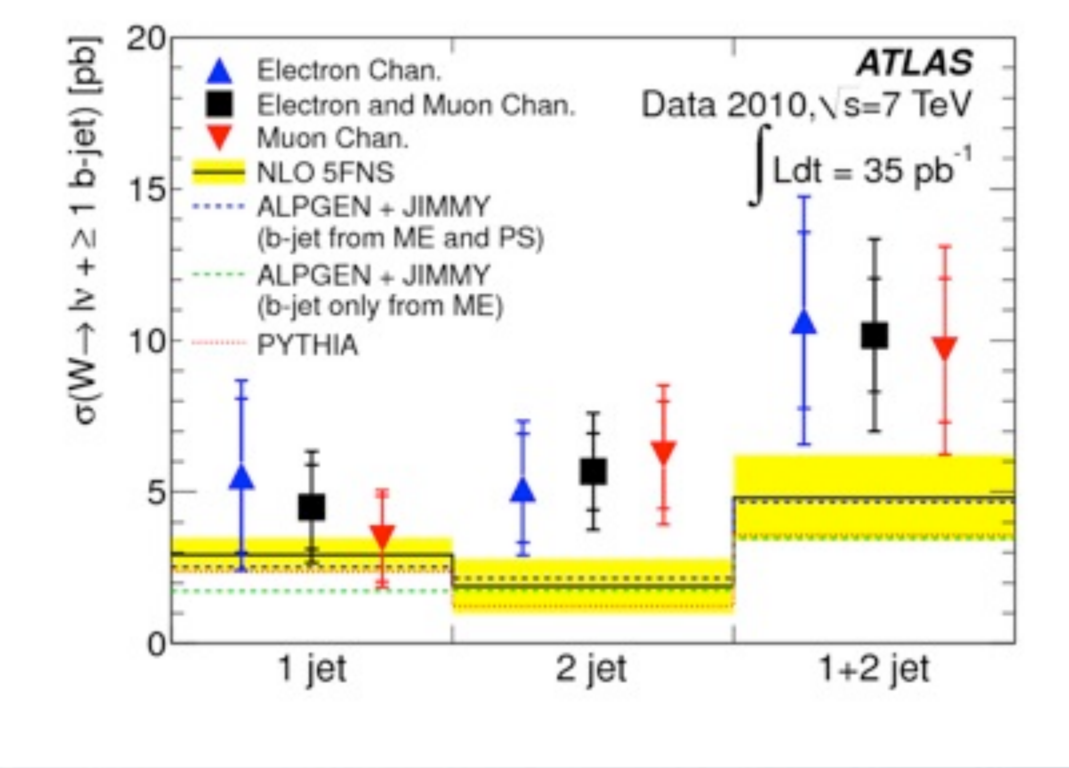


The SV0 b-tagging algorithm is based on requiring a displaced secondary vertex reconstructed within a jet with a decay length significance > 5.85

- SV0 mass template are modeled with MC
- Template systematics: data vs. MC in multi-jet events enriched in light-, c-, and b-jets.
- Event fitted yield is corrected for all detector effects with MC LO matched prediction for Wjet (including heavy flavour) from ALPGEN
  - 1 b-tagged jet
  - 1 or 2 jet
  - Fit each jet bin separately for e and μ

NLO prediction obtained in the 5 flavor number scheme [F. Caola *et al.* arXiv:1107.3714]

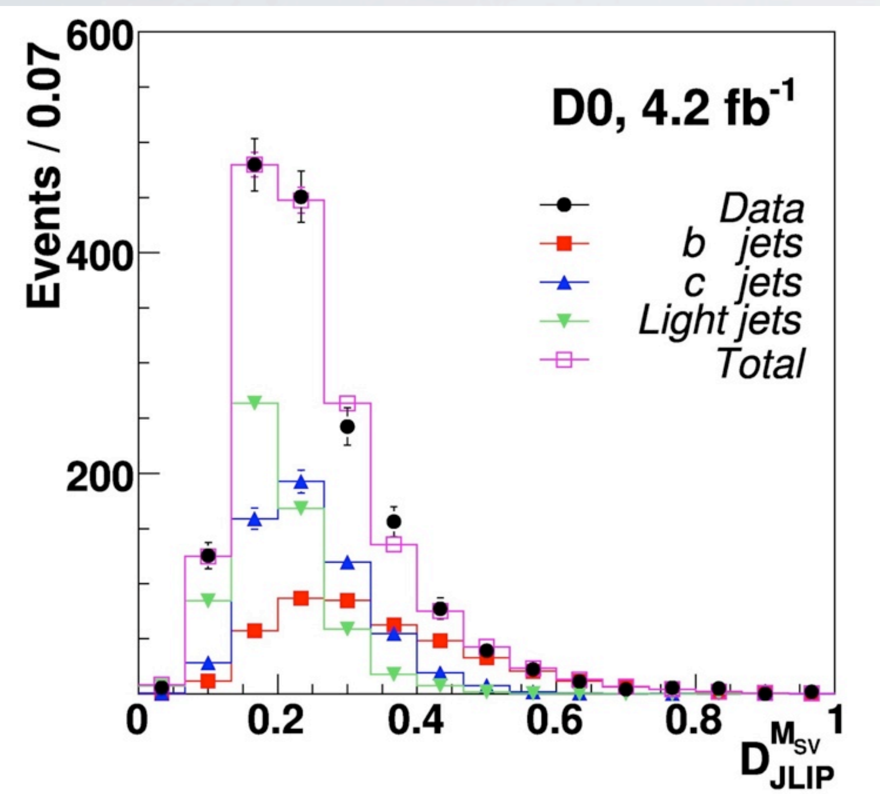
NLO agrees within 1.5 sigma with the measurements



Z+b Tevatron

D0 fit a discriminant built using vertex mass and track probability to originate from primary vertex

Jets reconstructed with midpoint algorithm with R=0.5, pT > 20 GeV and |η|< 2.5



σ(Z + b jet) / σ(Z + jet) = 0.0193 ± 0.0022 (stat) ± 0.0015 (syst)

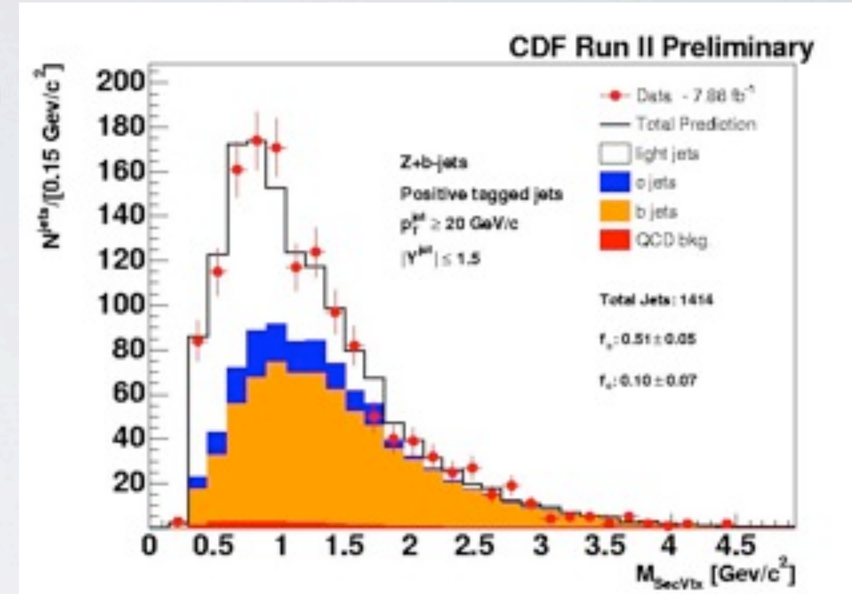
In agreement with

MCFM prediction

$Q^2 = m^2_Z$ 0.0192 ± 0.0022

CDF fits vertex mass to extract the flavor content

Jets reconstructed with cone algorithm with R=0.7, ET > 20 GeV and |η|< 1.5



Good agreement with NLO prediction

$$\frac{\sigma_{Z\_bjet}}{\sigma_Z} = 0.284 \pm 0.029^{stat} \pm 0.029^{syst}\%$$

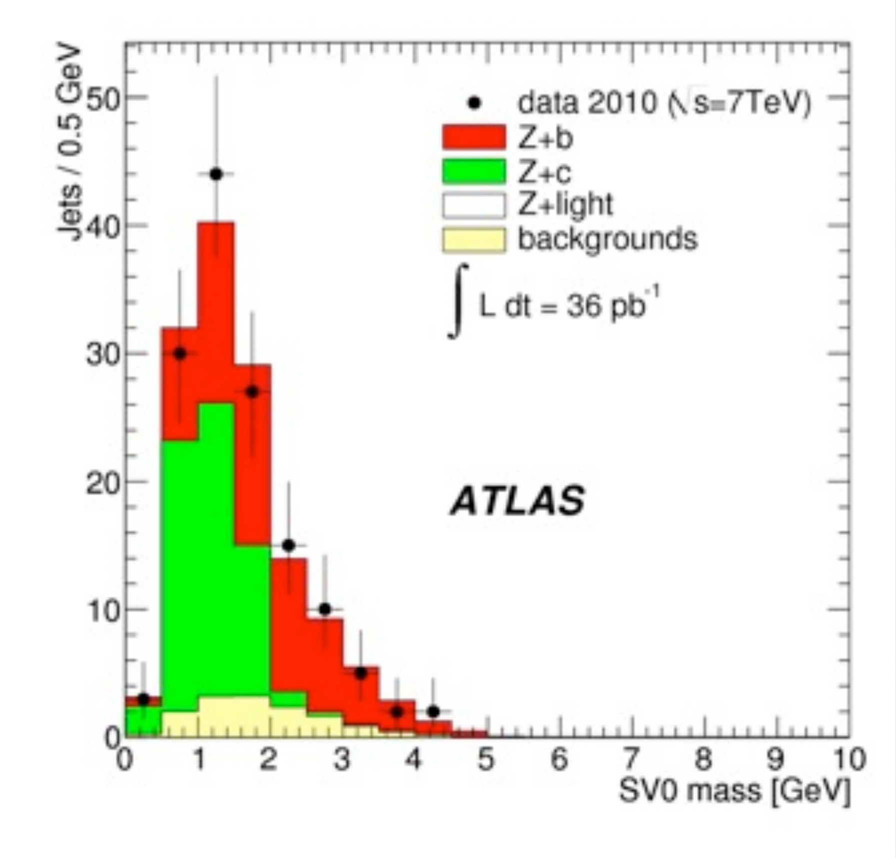
$$\frac{\sigma_{Z\_bjet}}{\sigma_{Zjet}} = 2.24 \pm 0.24^{stat} \pm 0.27^{syst}\%$$

To compare with NLO prediction with MCFM:

	$Q^2 = m_Z^2 + p_{T,Z}^2$	$Q^2 = < p_{T,jet}^2 >$
$\frac{\sigma_{Z\_bjet}}{\sigma_Z}$	0.23 %	0.28 %
$\frac{\sigma_{Z\_bjet}}{\sigma_{Zjet}}$	1.8 %	2.2%

Z+b ATLAS

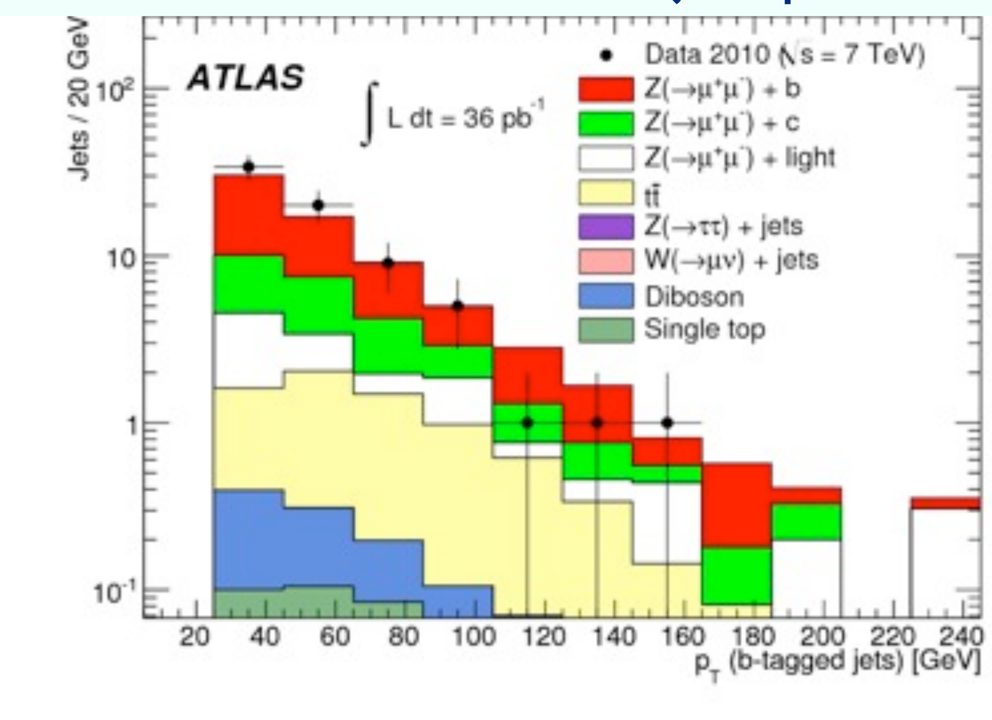
- Inclusive b-jet production cross section in association with a Z boson
- Jet fitted yield is corrected for all detector effects with MC LO matched prediction for Zjet (including heavy flavour) from ALPGEN and SHERPA
- A maximum likelihood fit to the SV0 mass distribution is used also for Z+b to separate b-jets from c- and light-jets.
- Fit the combined e and μ samples and each b-tagged jet in the event
- At least 1 b-tagged jet



MCFM in good agreement with data within uncertainty

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

Z+b uncorrected b-jet spectrum



Z+b CMS

H+b NLO prediction has large uncertainties

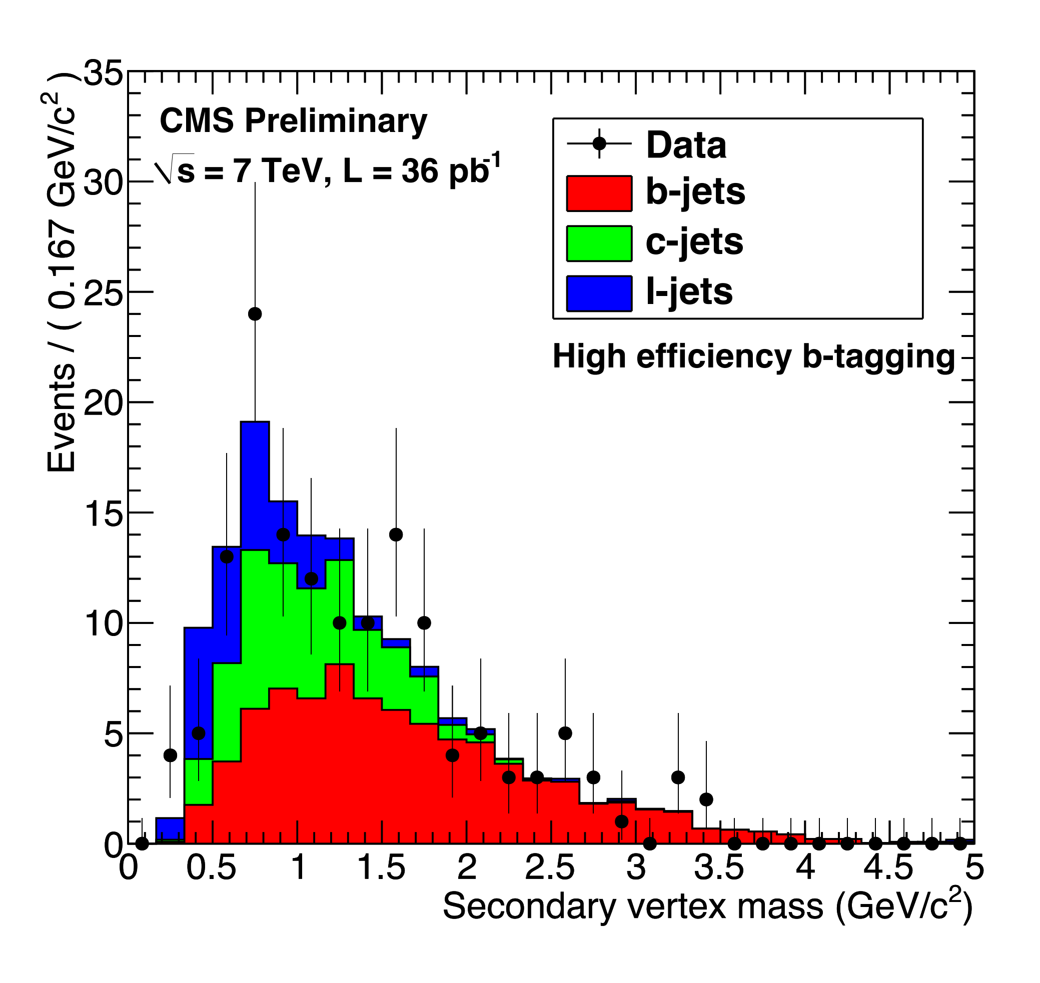
- 30% scheme dependence (variable vs fixed flavor schemes)
- Z+b data should help to clarify

B-tagging descriminant variable built from flight distance between PV and SV

- SSVHE: high efficiency selection with ≥2 tracks attached to SV
- SSVHP: high purity selection with ≥3 tracks attached to SV

Determine Z+b purity in selected sample from binned ML fit:

- SV mass or B-tag discriminant shape
- MC templates for b, c, ligh-jet components



Measure: $\mathcal{R} = \frac{\sigma(pp \to Z+b+X)}{\sigma(pp \to Z+j+X)}$

Results compatible with MadGraph (scaled to NLO) & MCFM

Sample	$\mathcal{R}(Z \to ee)$ (%), $p_T^e > 25$ GeV, $\lvert\eta^e\rvert < 2.5$	$\mathcal{R}(Z \to \mu\mu)$ (%), $p_T^\mu > 20$ GeV, $\lvert\eta^\mu\rvert < 2.1$
Data HE	$4.3 \pm 0.6(stat) \pm 1.1(syst)$	$5.1 \pm 0.6(stat) \pm 1.3(syst)$
Data HP	$5.4 \pm 1.0(stat) \pm 1.2(syst)$	$4.6 \pm 0.8(stat) \pm 1.1(syst)$
MADGRAPH	$5.1 \pm 0.2(stat) \pm 0.2(syst) \pm 0.6(theory)$	$5.3 \pm 0.1(stat) \pm 0.2(syst) \pm 0.6(theory)$
MCFM	$4.3 \pm 0.5(theory)$	$4.7 \pm 0.5(theory)$

Limited statistics: scheme dependence cannot be resolved yet

Conclusions

- Presented results on V+jet measurements from 4 experiments using collisions produced by 2 accelerators with different energies and colliding beams.

- NLO predictions in overall good agreement with the measurements. The event kinematics is also well modeled by the matched LO event generators.

- These measurements are a crucial input to searches for heavy particles

- Tevatron will end its data-taking this Friday: ~10 fb-1 of data.

- At the LHC, analyses are currently being updated with 2011 data: will allow more detailed study of W/Z+jets production with higher statistics and improved systematics uncertainties.

For more information:

- CDF : http://www-cdf.fnal.gov/physics/new/qcd/QCD.html
- D0 : http://www-d0.fnal.gov/Run2Physics/WWW/results.htm
- ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults#W_Z_Physics
- CMS : https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK