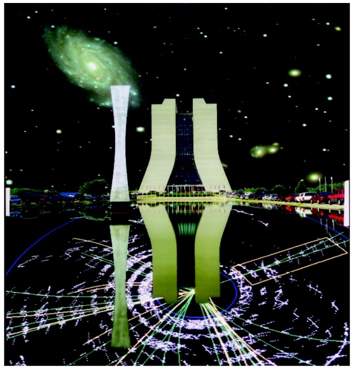


W/Z + jet production at Tevatron

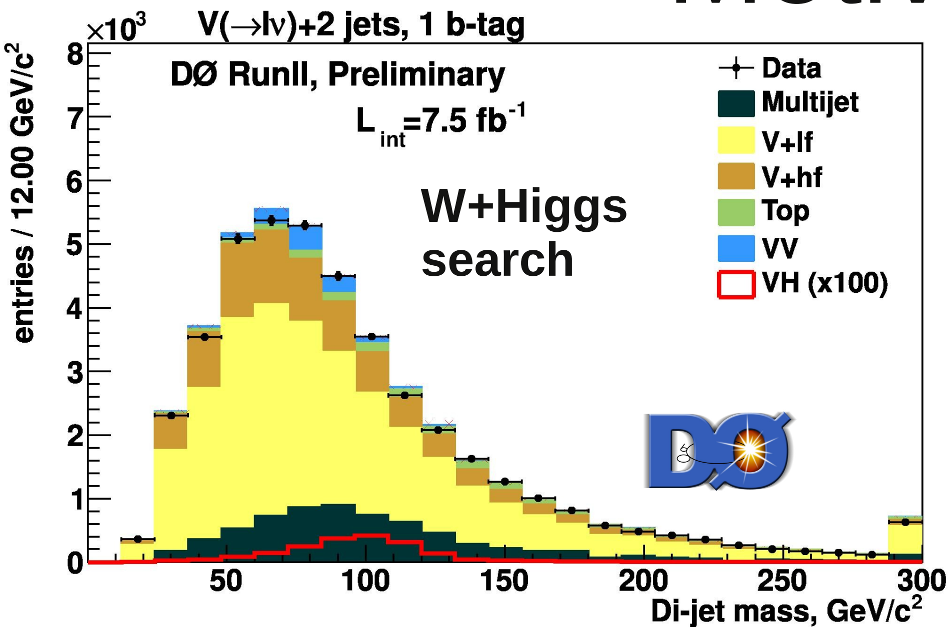
Stefano Camarda

IFAE - Barcelona

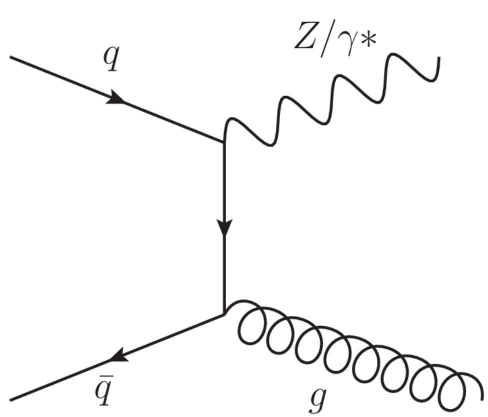
On behalf of the
CDF and DØ Collaborations

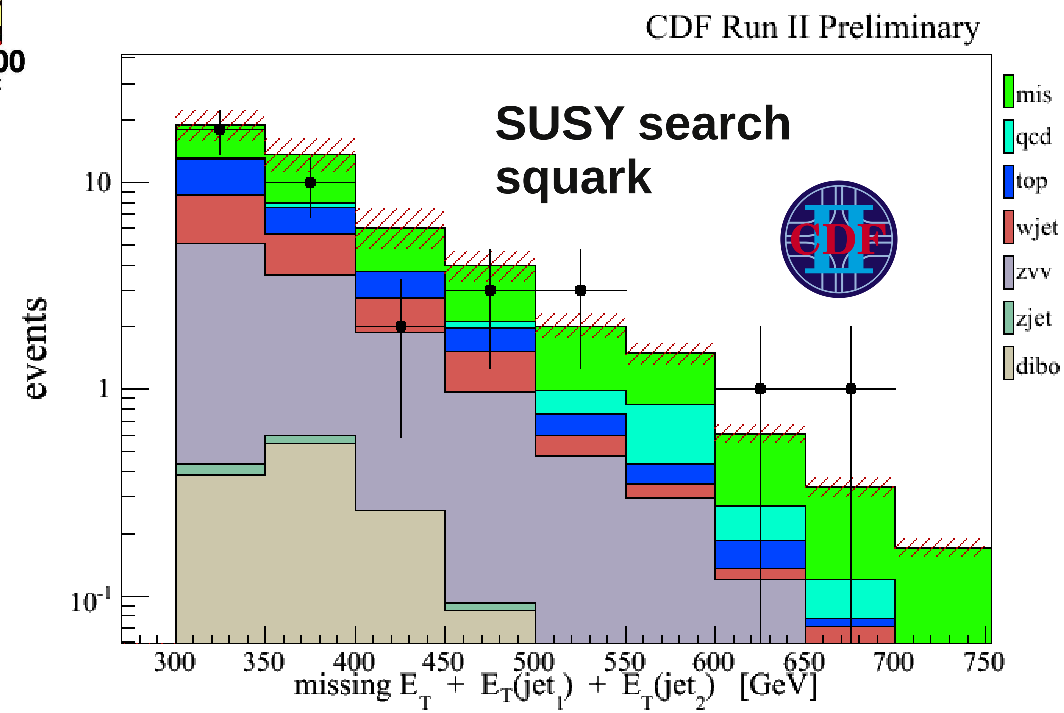
QCD @ LHC
August 22-26, 2011
St Andrews

Motivation



- Test perturbative QCD at high Q^2
- Background for rare SM processes (top, diboson) and new Physics searches
- 30% - 40% uncertainty in some of the processes (boson + HF)





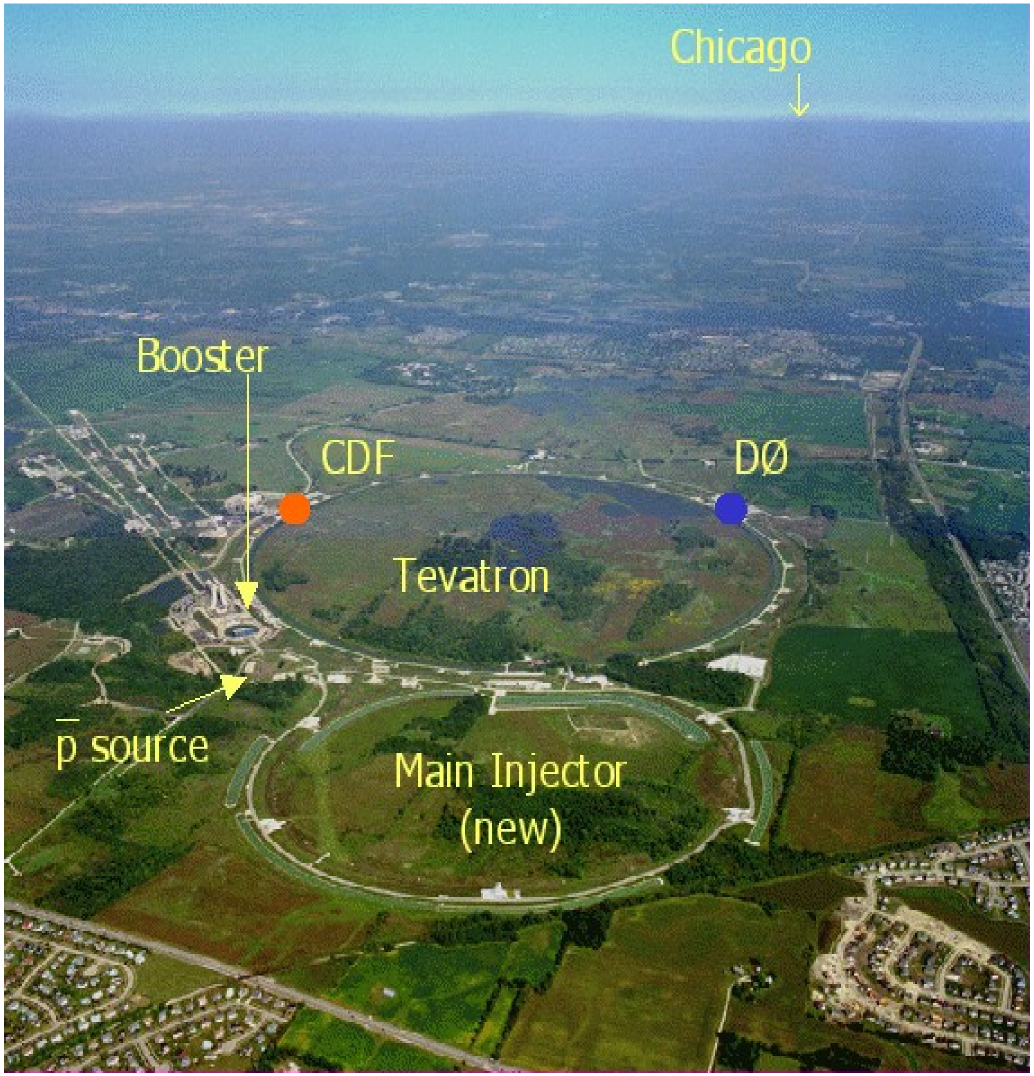
W/Z + Jets results from the Tevatron

Measurements with associated luminosity

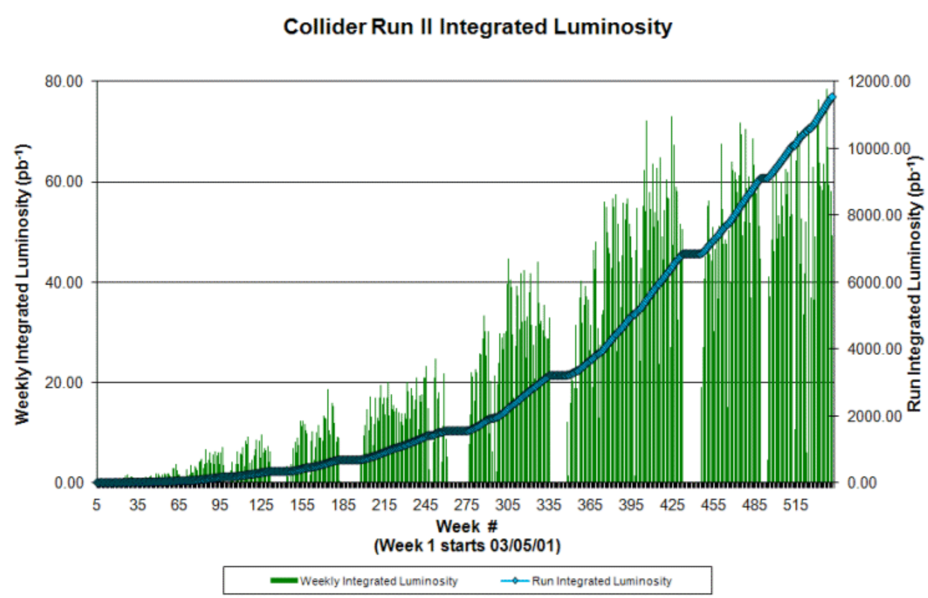
	Final State	DØ	CDF
W/Z + Jets	$Z \rightarrow l^+l^-$ + Jets	1.0 fb^{-1}	8.2 fb^{-1}
	W + Jets	4.2 fb^{-1}	2.8 fb^{-1}
W/Z + HF	Z + b	4.2 fb^{-1}	7.9 fb^{-1}
	W + b	–	1.9 fb^{-1}
	W + c	1.0 fb^{-1}	4.3 fb^{-1}

New Results

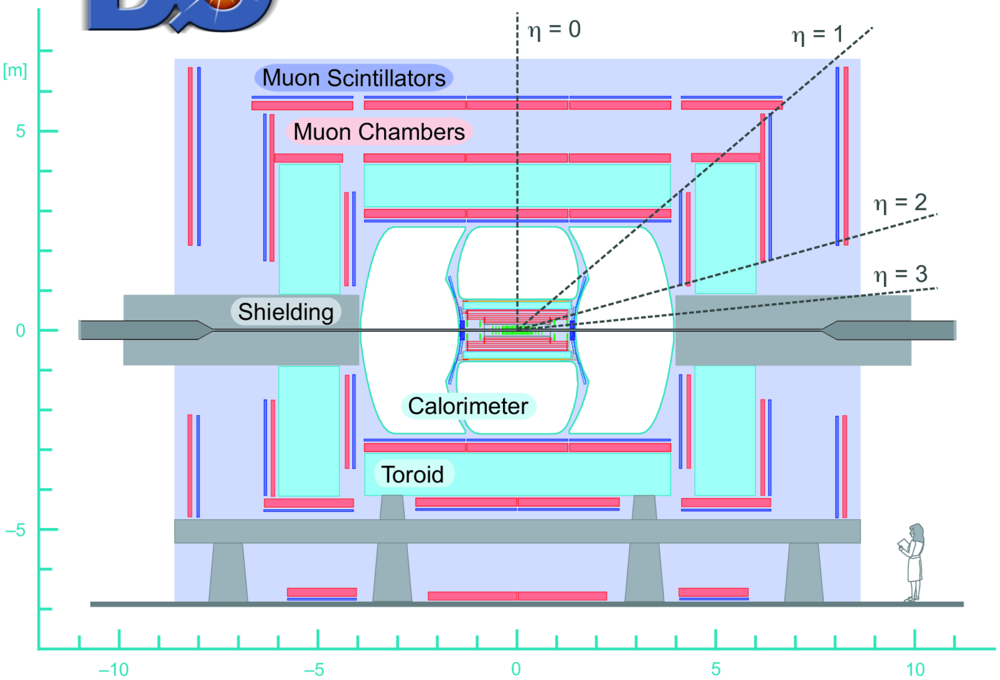
Tevatron



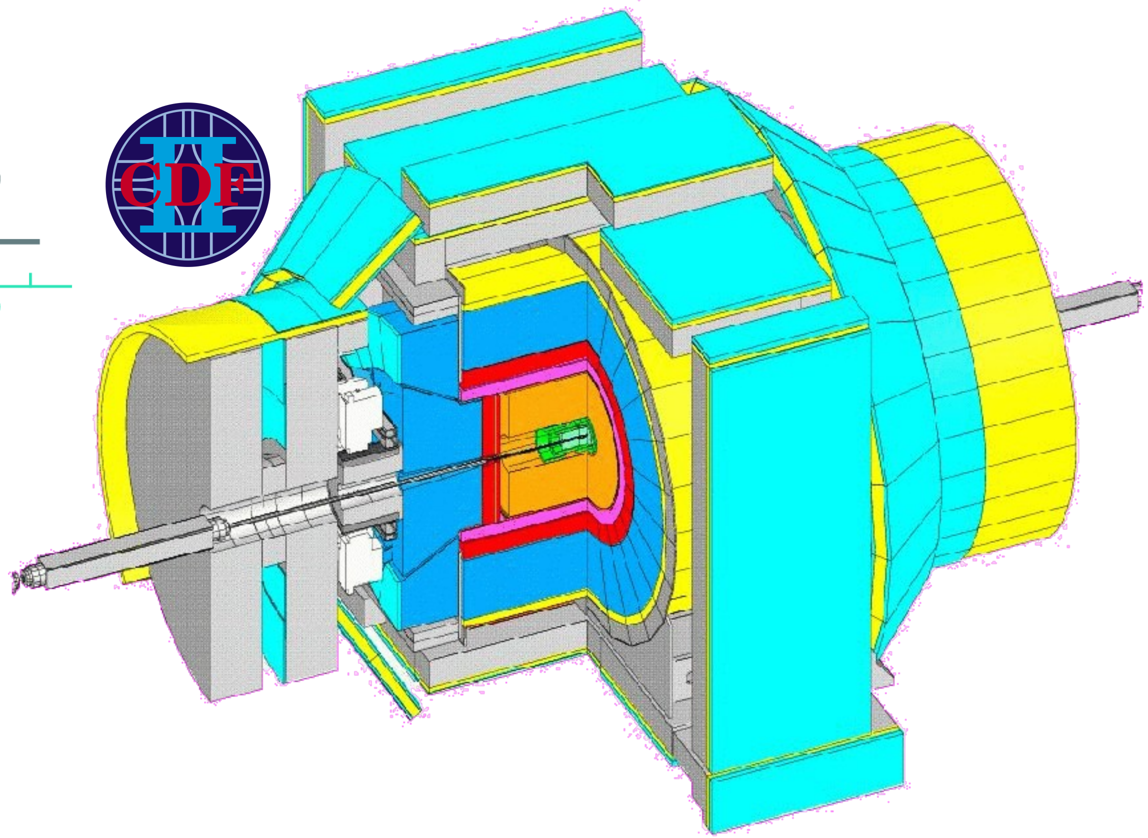
- $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV
- Peak instantaneous luminosity ~ 4 x 10^{32} cm^{-2} s^{-1}
- ~ 12 fb^{-1} of delivered luminosity
- End of Operations → September 30^{th} 2011



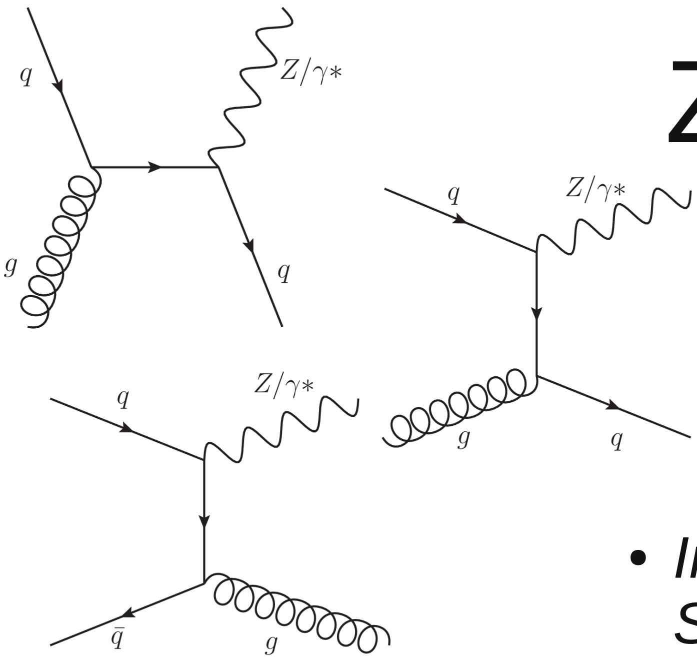
DØ and CDF detectors



Multi purpose detectors



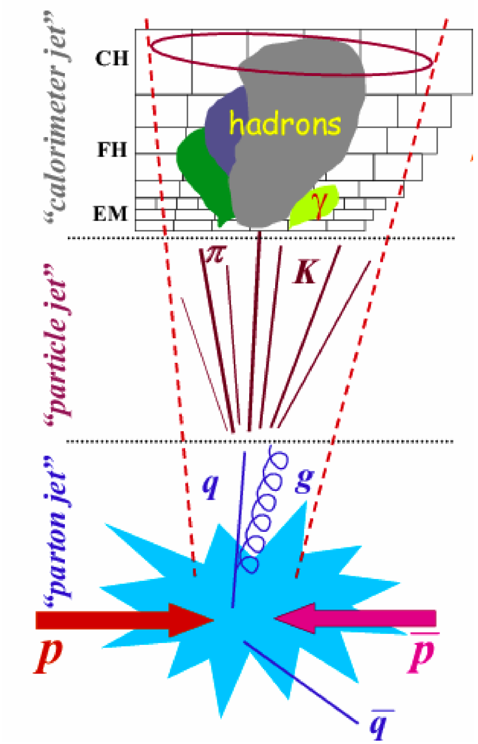
- Central Tracking systems
- Calorimeters
- Muon detectors



$Z/\gamma^* \rightarrow l^+l^- +$ jets

Updated results with $\mathcal{L}$ = 8 fb^{-1}

- *Important background for ZH → ll bb, SUSY MET + jets*
- *Test pQCD NLO predictions*



$Z \rightarrow \mu^+\mu^-$ and $Z \rightarrow e^+e^-$ channels combined accounting for correlation between uncertainties

Measurements are unfolded back to Hadron level

Differential distributions in Z + ≥3 jets final state

Measurement in the $Z \rightarrow e^+e^-$ channel published in PRL 100, 102001 (2008) with 1.7 fb^{-1}

$Z/\gamma^* \rightarrow l^+l^- +$ jets

Data driven backgrounds
- QCD multi-jet
- W + jet

MC backgrounds
- Z + γ
- Top
- Diboson
- Z $\rightarrow \tau\tau$ + jets

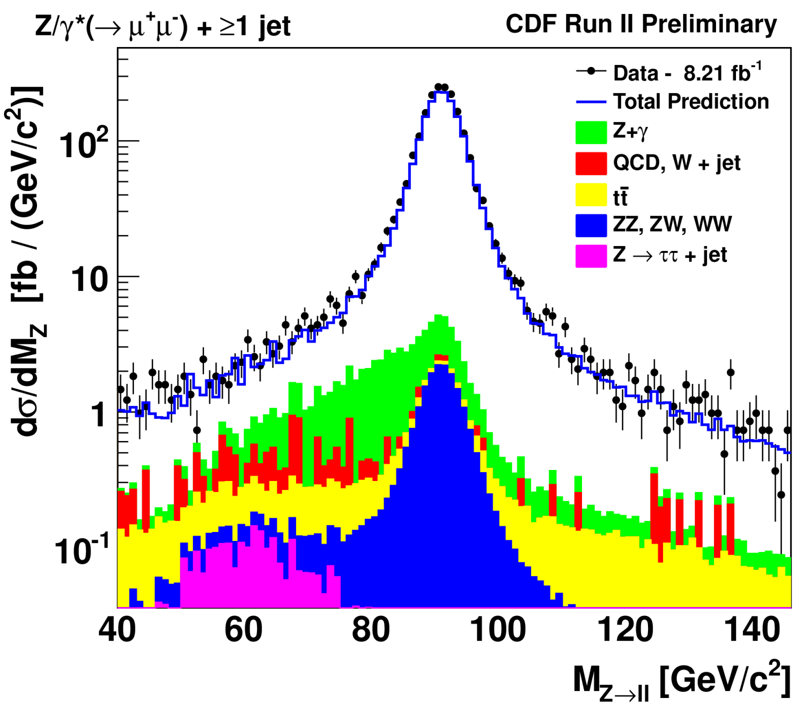
Z Kinematic region

$66 < M_Z < 116$ GeV/c²

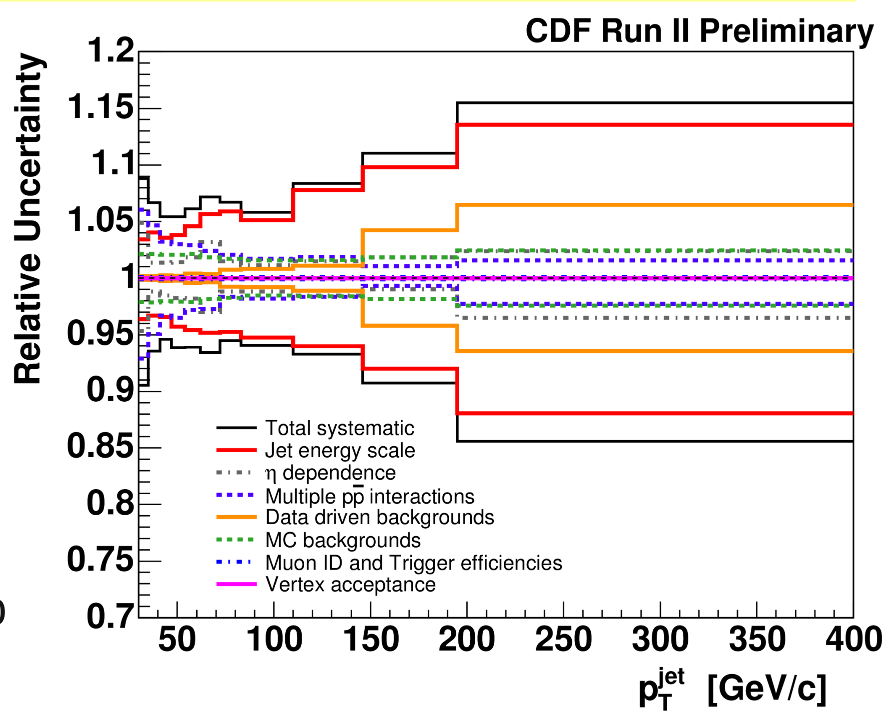
$E_T^l > 25$ GeV/c, $|\eta^l| < 1$

MIDPOINT R=0.7 jet

$p_T > 30$ GeV/c, $|Y| < 2.1$



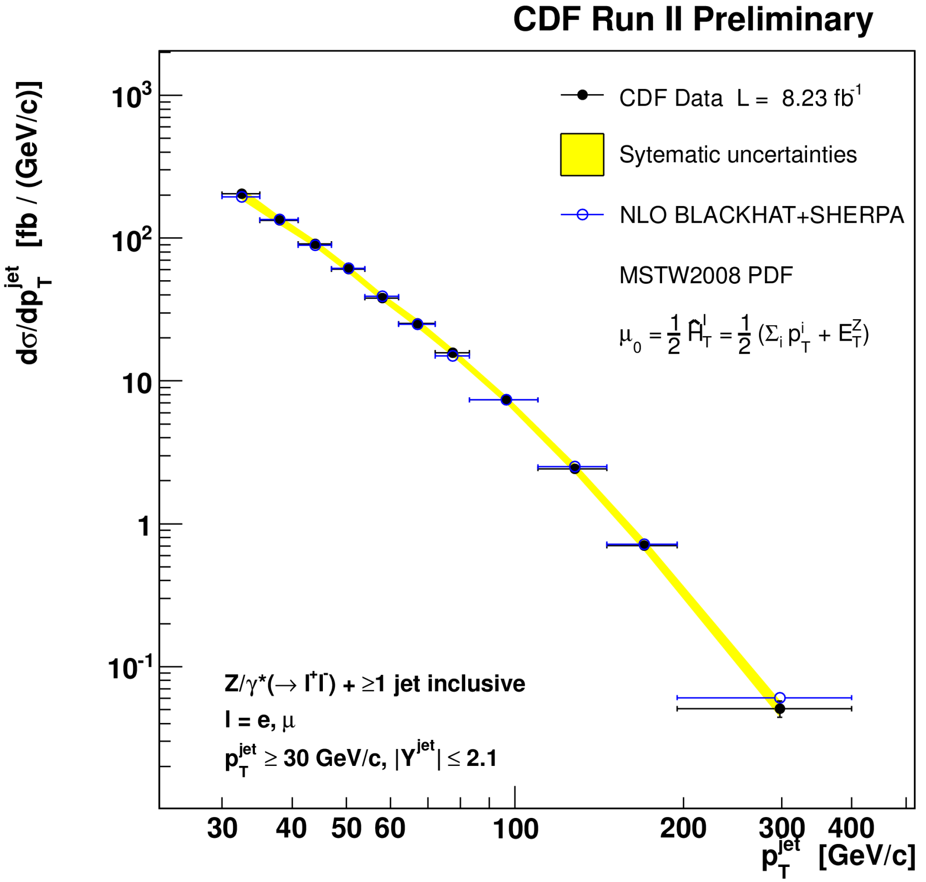
5% to 15% systematic uncertainties
Jet Energy Scale is the dominant

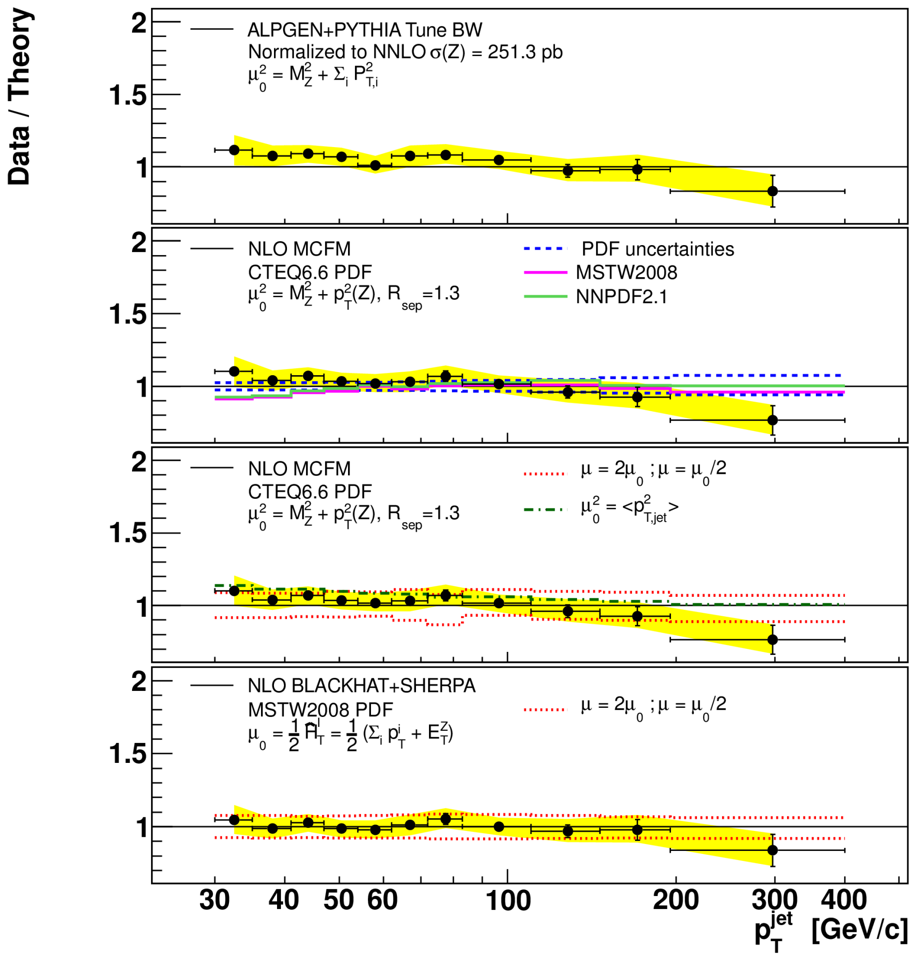


- Total backgrounds between 5%-10%
- Main background is Z+γ

Z + jets

Z + ≥1 jet inclusive P_T^{jet}



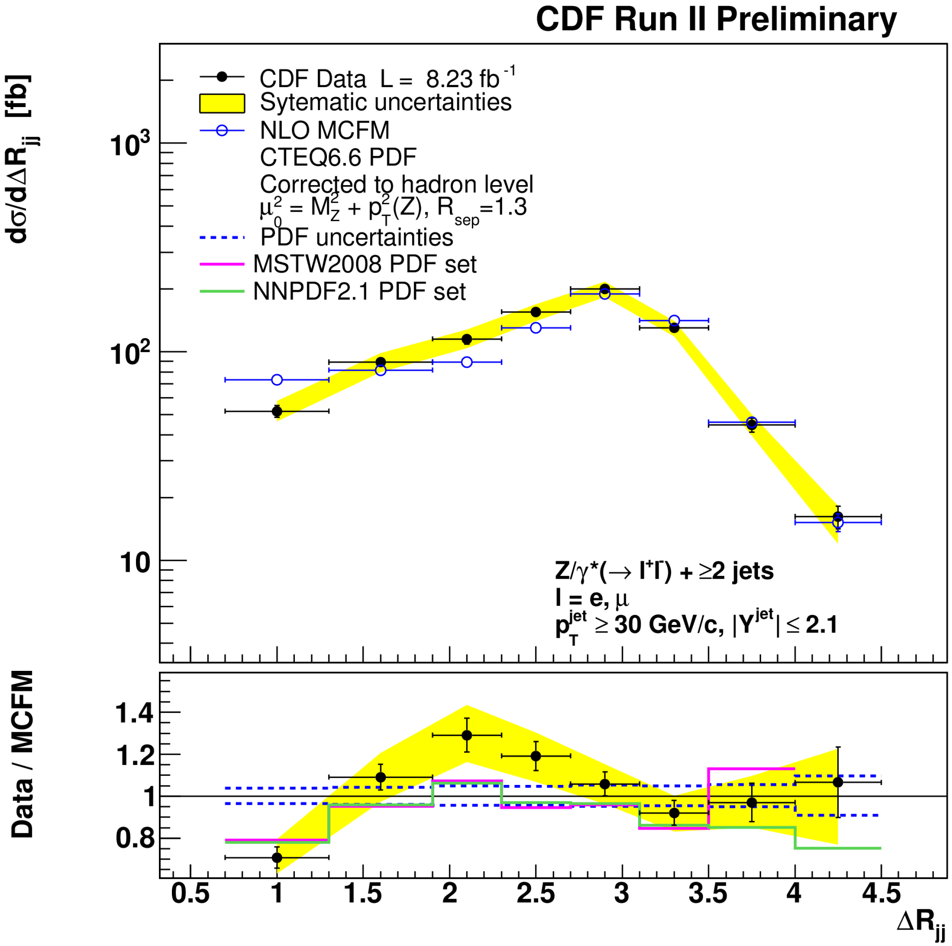


Theory prediction and measured cross sections corrected to Hadron level

Good Agreement between data and NLO pQCD predictions (BLACKHAT and MCFM)

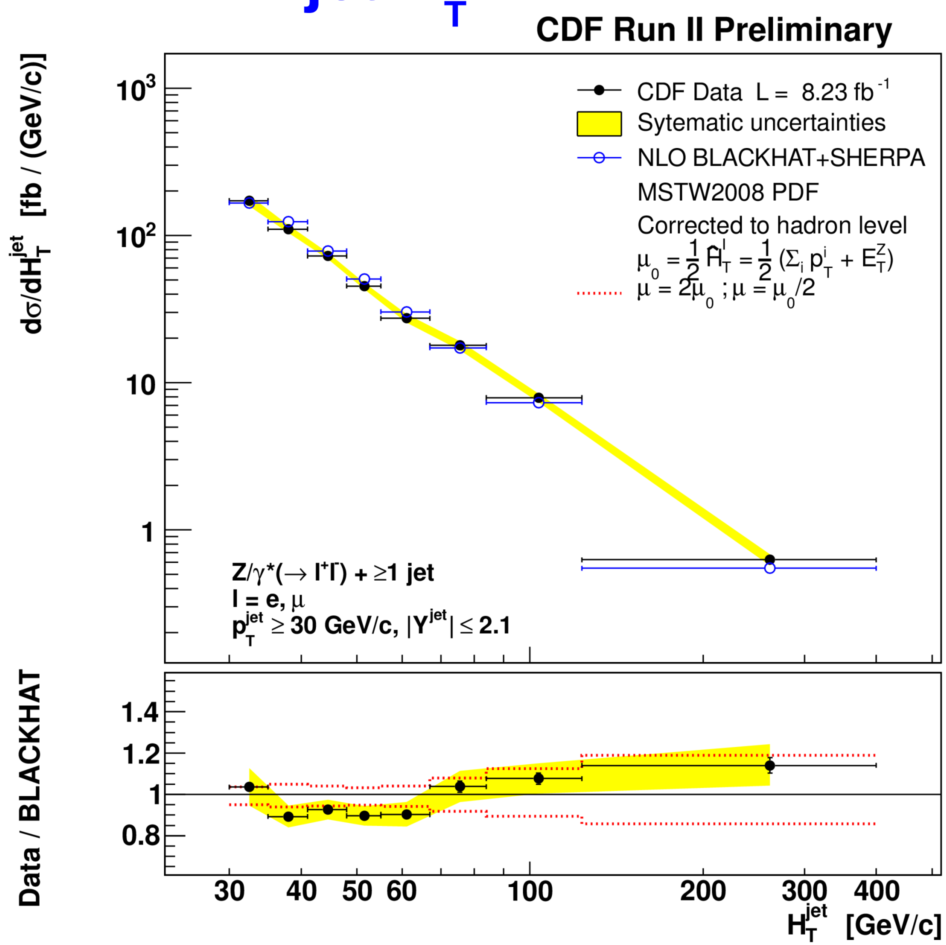
Z + jets

Z + ≥2 jets DR_{jj}



Some observables like H_T^{jet} are expected to have larger contribution at NNLO (Rubin, Salam, Sapeta arXiv:1006.2144)

Z + ≥1 jet H_T^{jet}

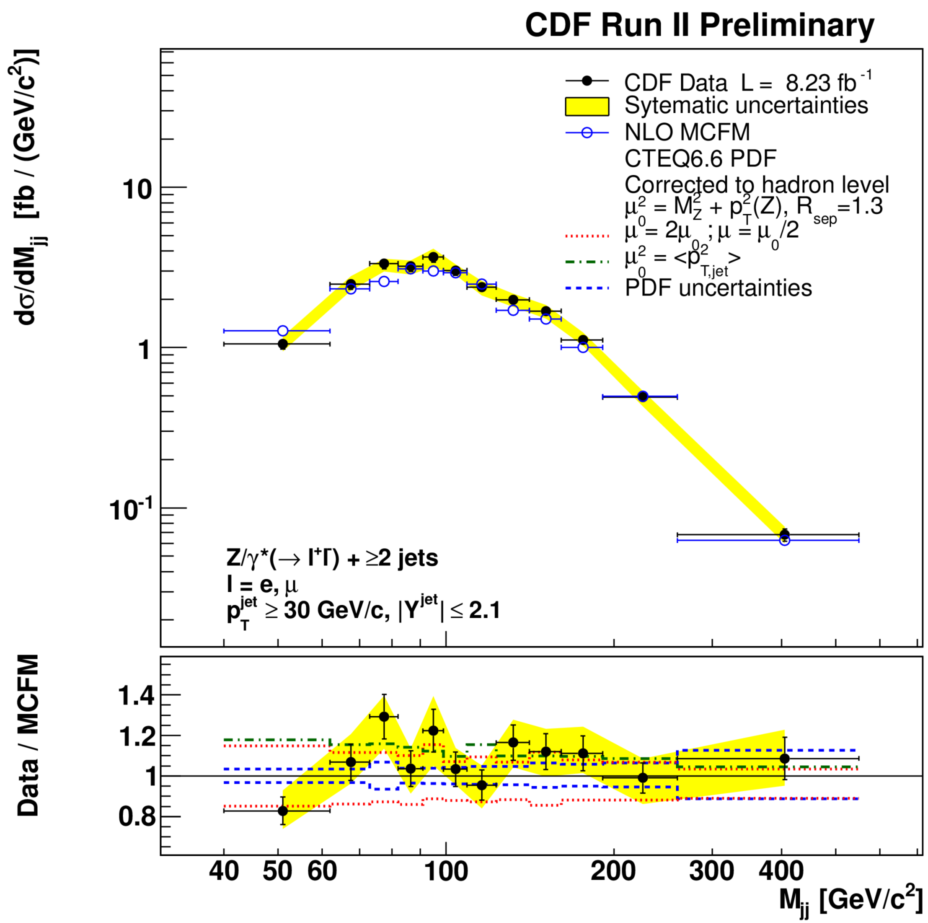


Comparison with different PDF sets

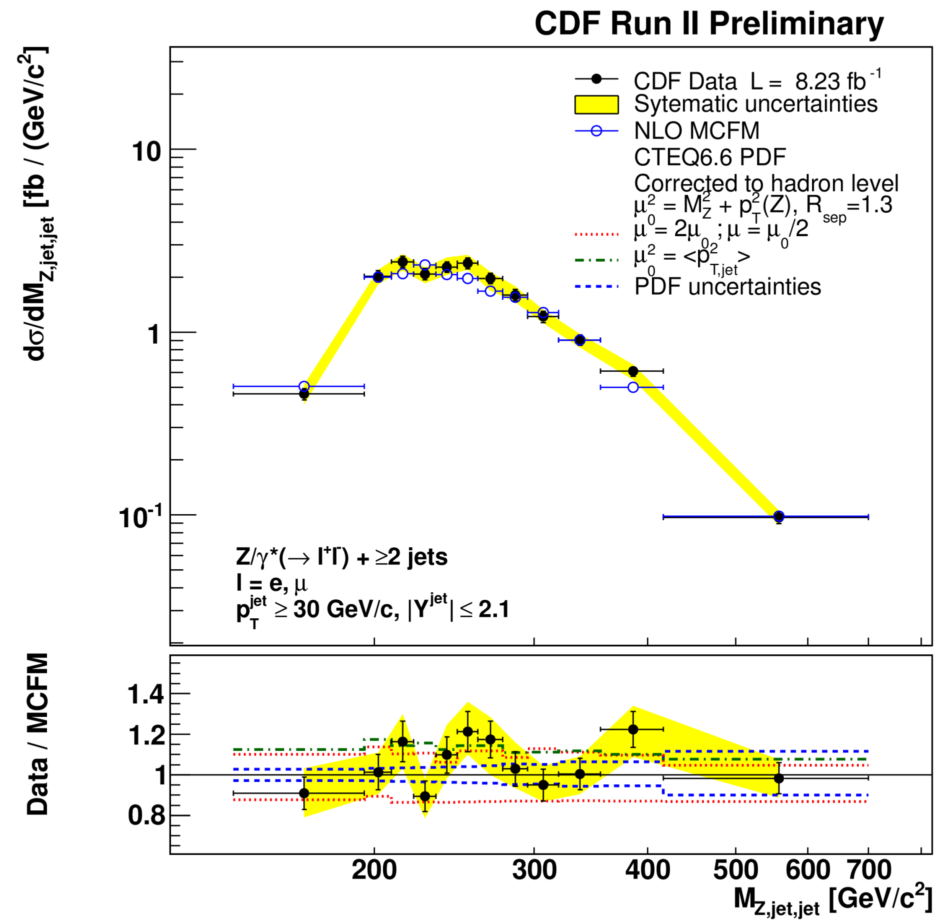
- Dependence on PDF sets is visible only in a few distributions
- MSTW2008 better agrees than CTEQ6.6
- No significant difference between MSTW2008 and NNPDF2.1

Z + jets

Z + ≥2 jets M_{jj}



Z + ≥2 jets $M_{Z,jj}$

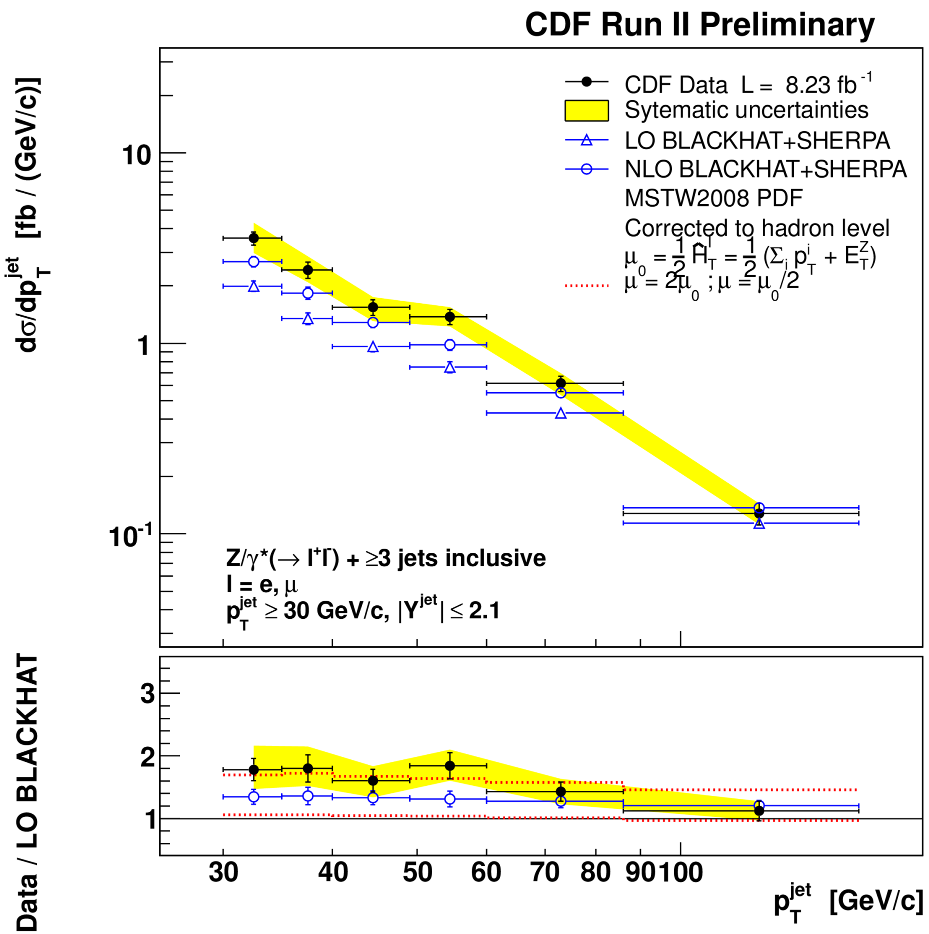


M_{jj} and $M_{Z,jj}$ are sensitive to resonances production

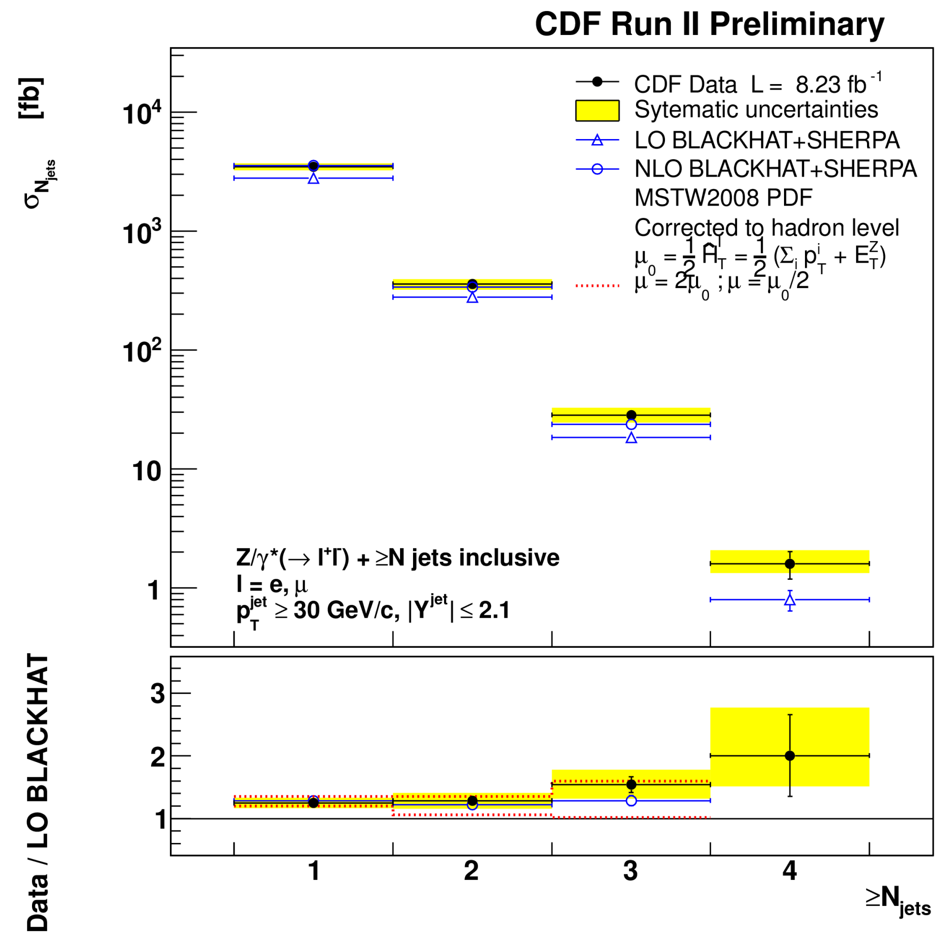
Main uncertainty comes from fixed order calculation

Z + jets

Z + ≥3 jets inclusive P_T^{jet}



Z + ≥n jets



Z + ≥3 jets differential distributions compared to NLO pQCD prediction - BLACKHAT+SHERPA

Many others jets and Z variables measured

$W \rightarrow e\nu$ + jets

W Kinematic region

$M_T^W > 40$ GeV/c²

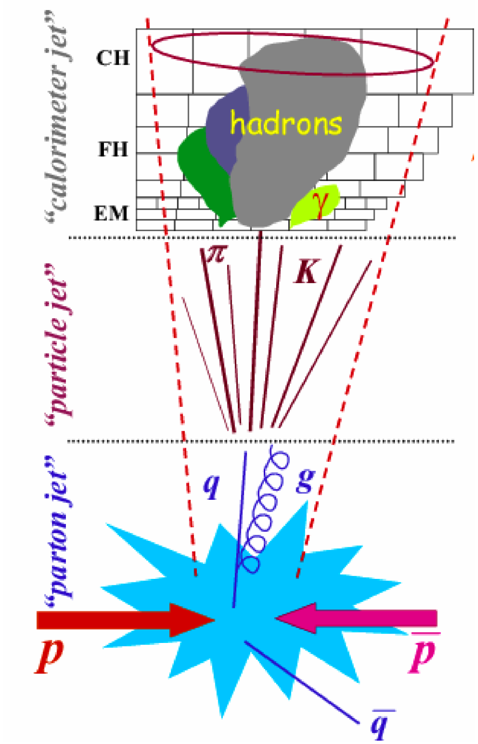
$P_T^e > 15$ GeV, $|\eta^e| < 1.1$

Missing $P_T > 20$ GeV/c

$\mathcal{L} = 4.2\ \mathrm{fb}^{-1}$

MIDPOINT R=0.5 jet
$p_T > 20$ GeV/c, $|Y| < 3.2$

Measured differential cross sections as a function of n^{th} leading jet p_T up to W + ≥4 jets final states



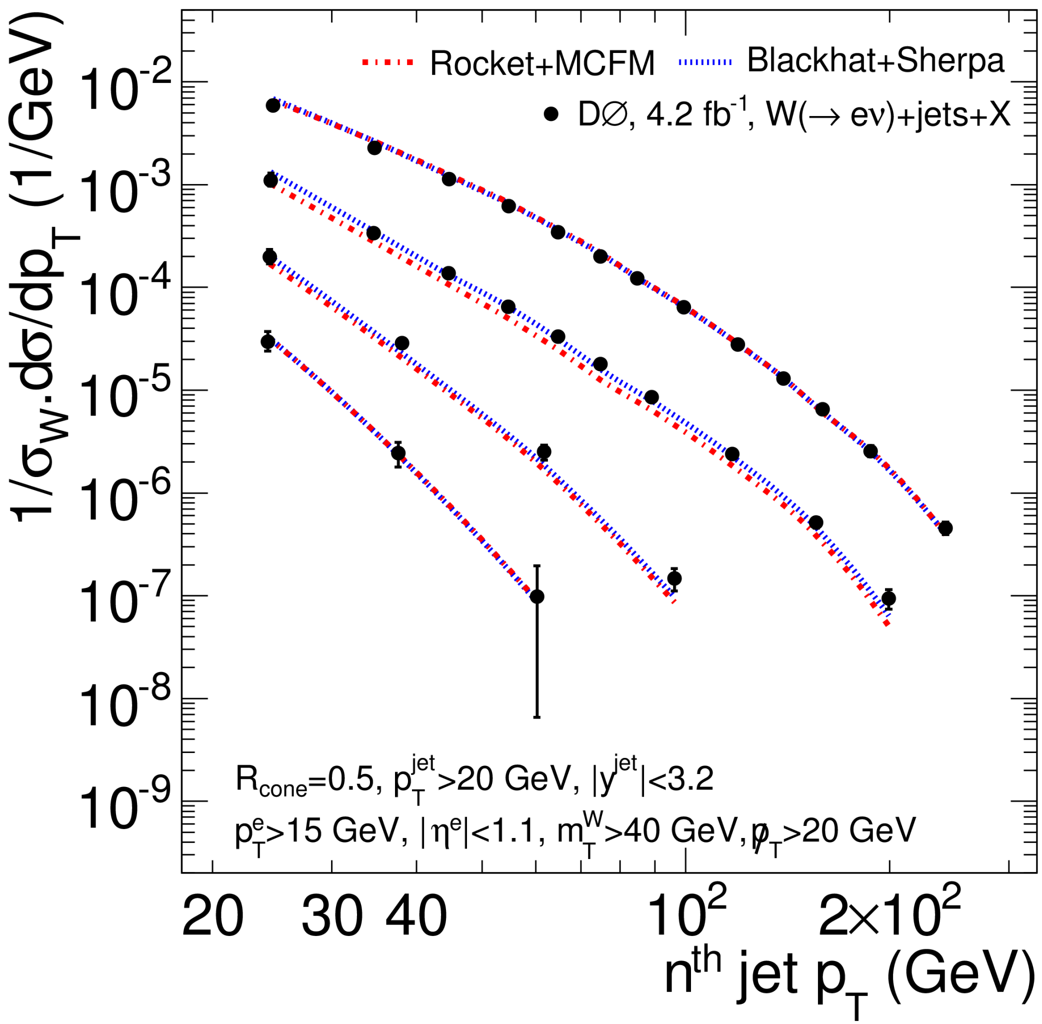
Unfolding to Hadron level

- ALPGEN+PYTHIA MC
- Matrix approach with GURU program

Submitted to Phys. Lett. B, arXiv:1106.1457

W → eν + jets

n^{th} leading jet p_T for W + ≥1,2,3,4 jets

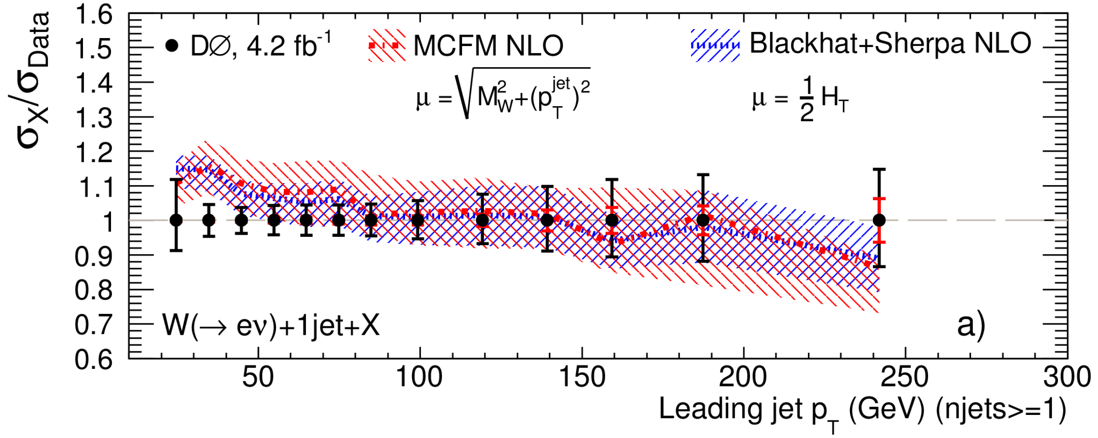


Measurements are normalized to σ_W to reduce systematic uncertainties

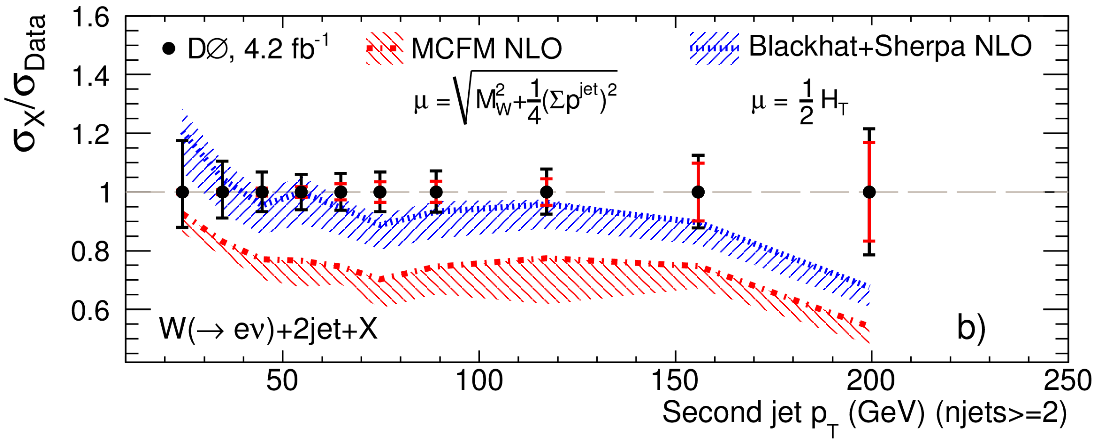
Data are compared to ROCKET+MCFM and BLACKHAT+SHERPA NLO pQCD predictions

MSTW2008 PDF set

W → eν + jets



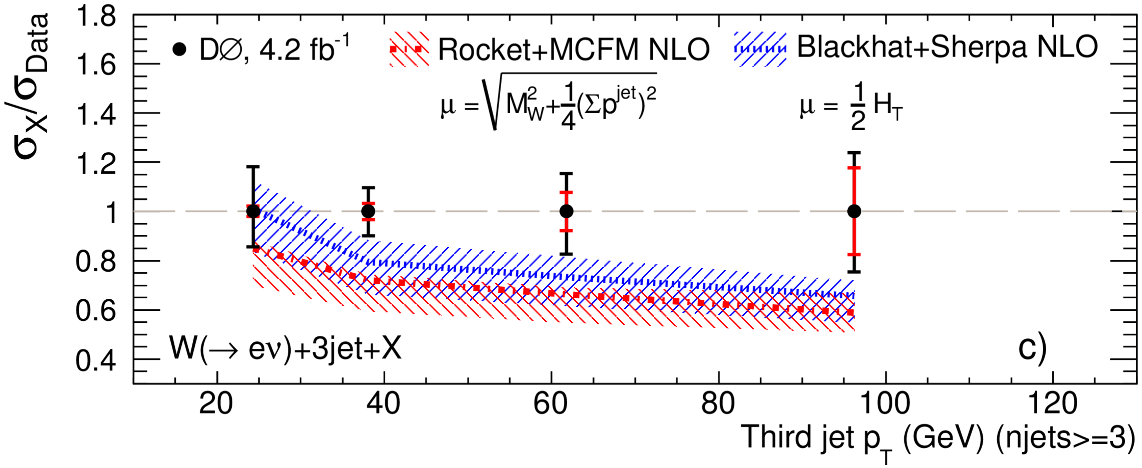
Good Agreement between data and NLO pQCD predictions



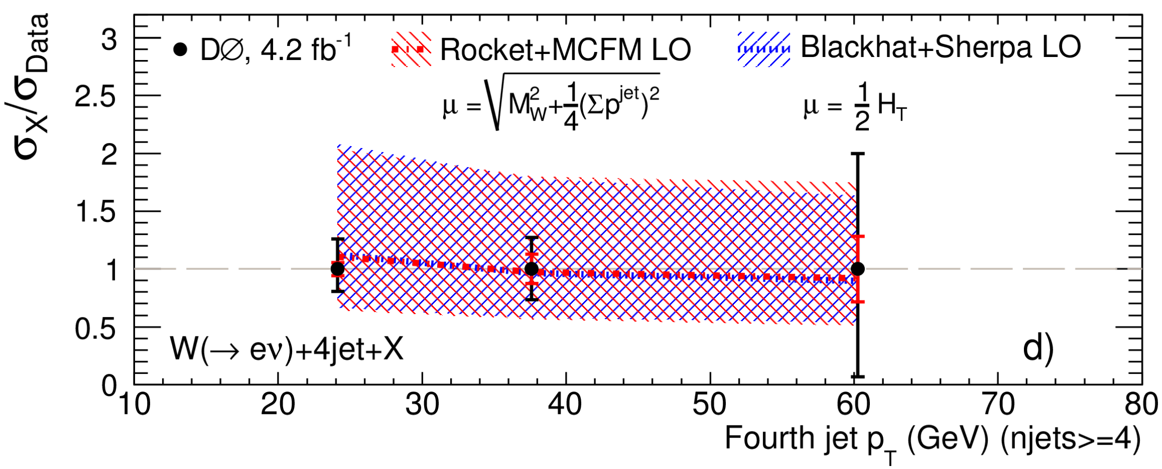
Large uncertainty coming from the functional form of μ scale

Theorists are investigating the discrepancy between calculations

W → eν + jets

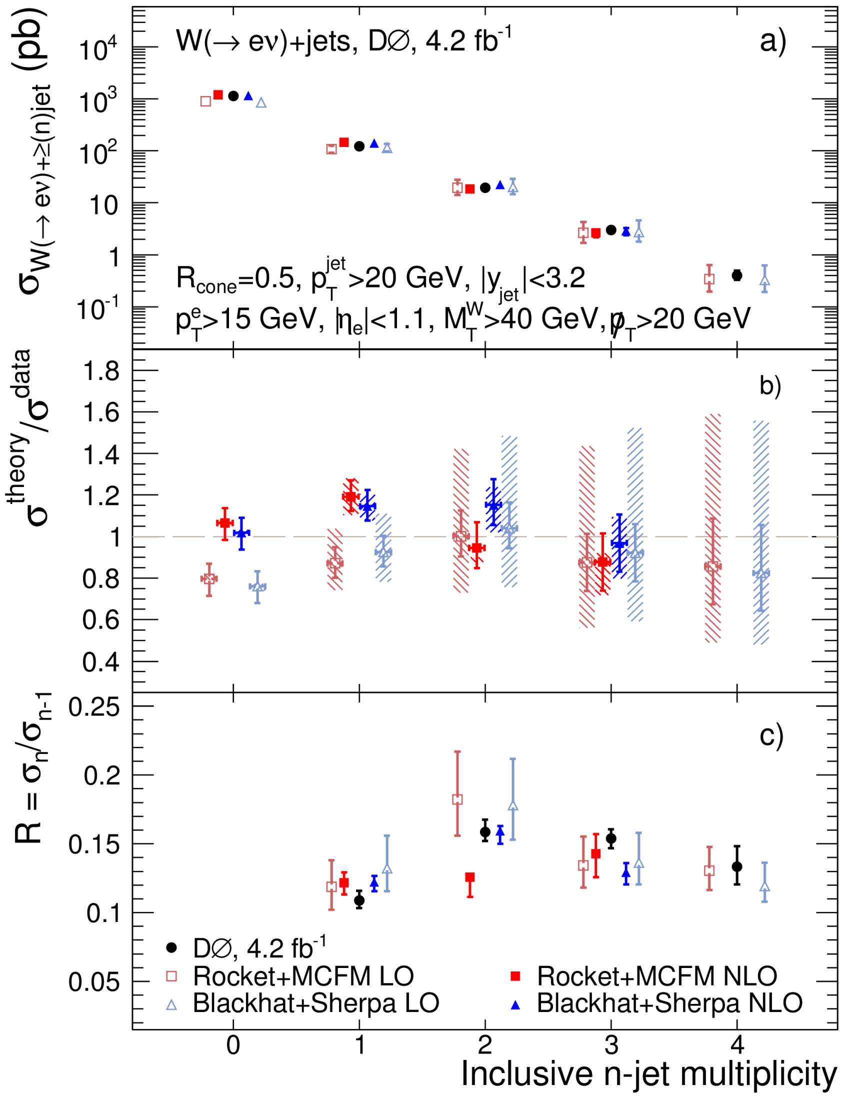


W + ≥3 jets measurement compared to NLO pQCD predictions



W + ≥4 jets final state compared to LO predictions

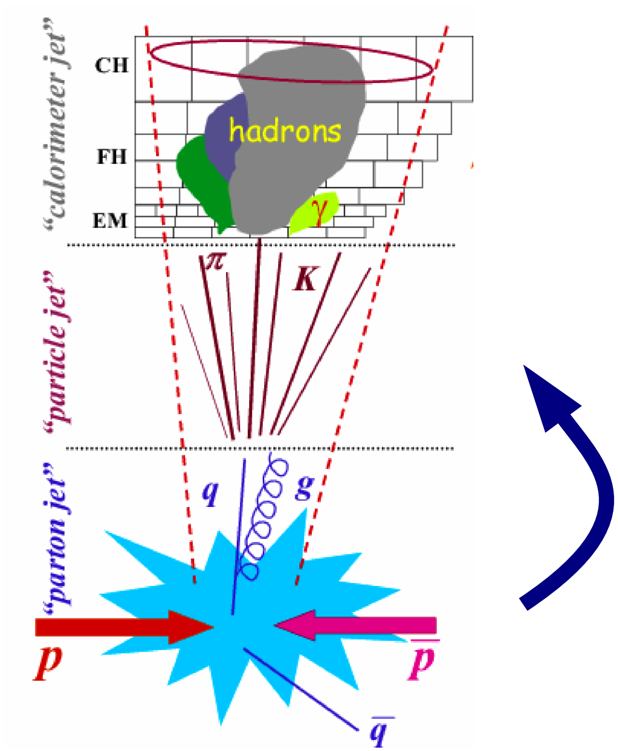
W → eν + jets



Good Agreement between data and NLO pQCD predictions

σ_n/σ_{n-1} ratio reduces scale uncertainty

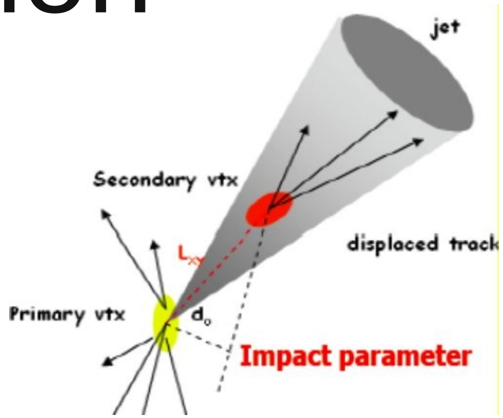
V + jets non pQCD Correction



- Parton to Hadron correction is a delicate point in V + jets measurements:
  - Larger corrections from UE for larger jet cone radius
  - Larger Hadronization correction for smaller cone radius
- In current analysis hadronization correction is evaluated independently with LO-based tools (PYTHIA and SHERPA)
- Theorists suggested an improvement would come from matching pQCD NLO results with NLO shower programs as MC@NLO and POWHEG (Berger, Bern, Dixon, Cordero, … arXiv 1004:1659)
- In W/Z + jets ratio non pQCD effects are expected to cancel out

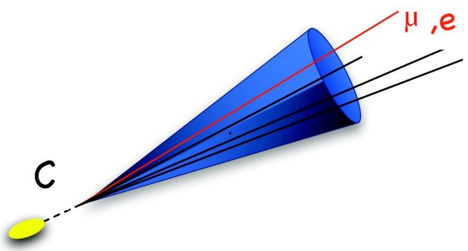
W/Z + HF jets production

Secondary vertex tag
based on large B lifetime

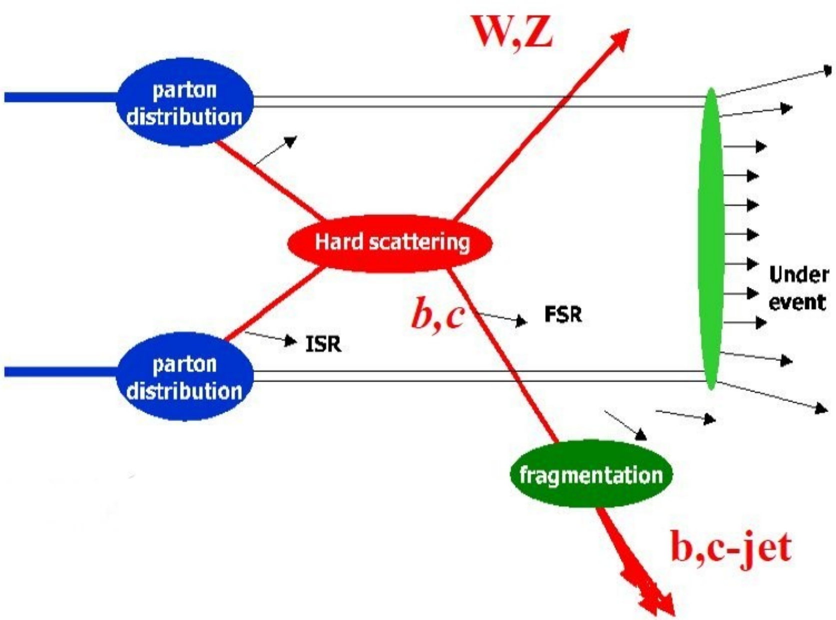


Challenging experimental measurements

- b and c identification
- Low statistics



Soft Lepton tag
(20% Branching ratio)



Challenging theory predictions

- Large variation wrt to scale choice
- PDF uncertainties at high momentum fraction x

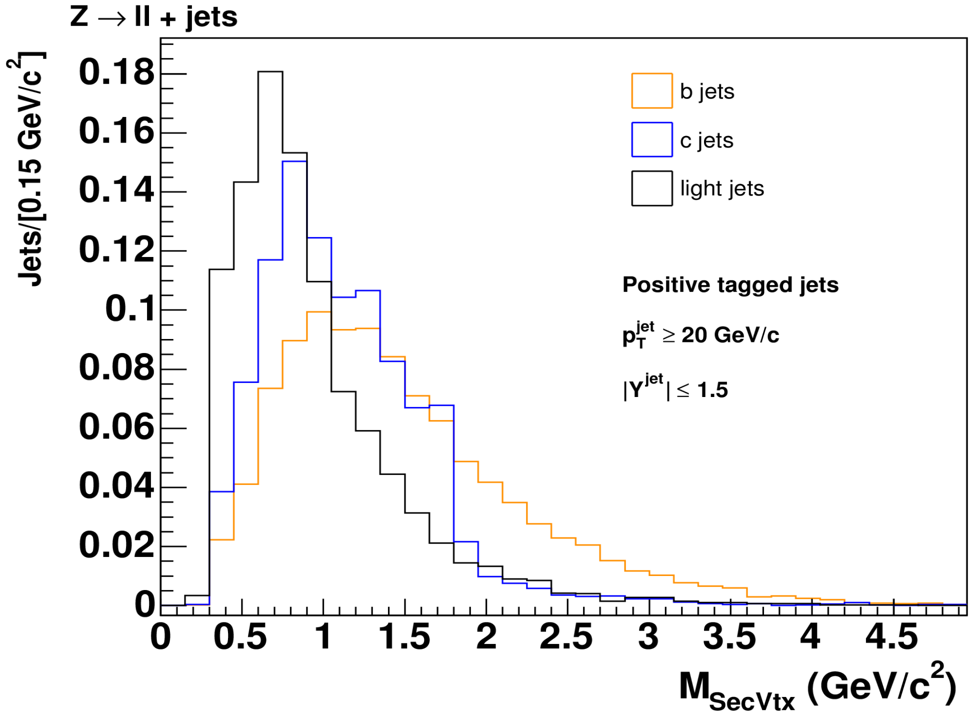
$\mathcal{L}$ = 7.9 fb^{-1}

$Z/\gamma^* \rightarrow l^+l^- +$ b-jet

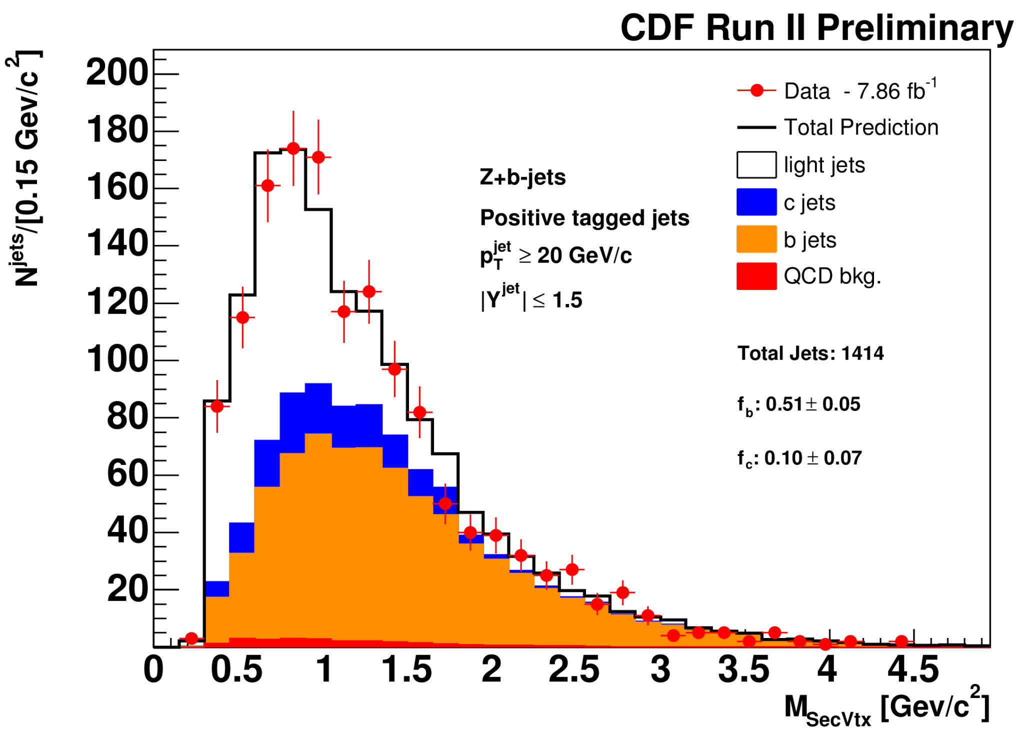
- Measured cross section ratio with respect to Z inclusive and Z+jet cross section to reduce systematic uncertainties
- Z decays leptonically in muons or electrons
- Improved muon identification efficiency with ANN, obtaining a 30% gain in Z acceptance

Jets:
- Midpoint algorithm
- DR = 0.7
- $P_T \geq 20$ GeV/c
- $|Y| \leq 1.5$

B identification:
- Secondary Vertex Tagger
- Extract b-jet composition from a fit to Secondary Vertex Mass



Z + b-jet



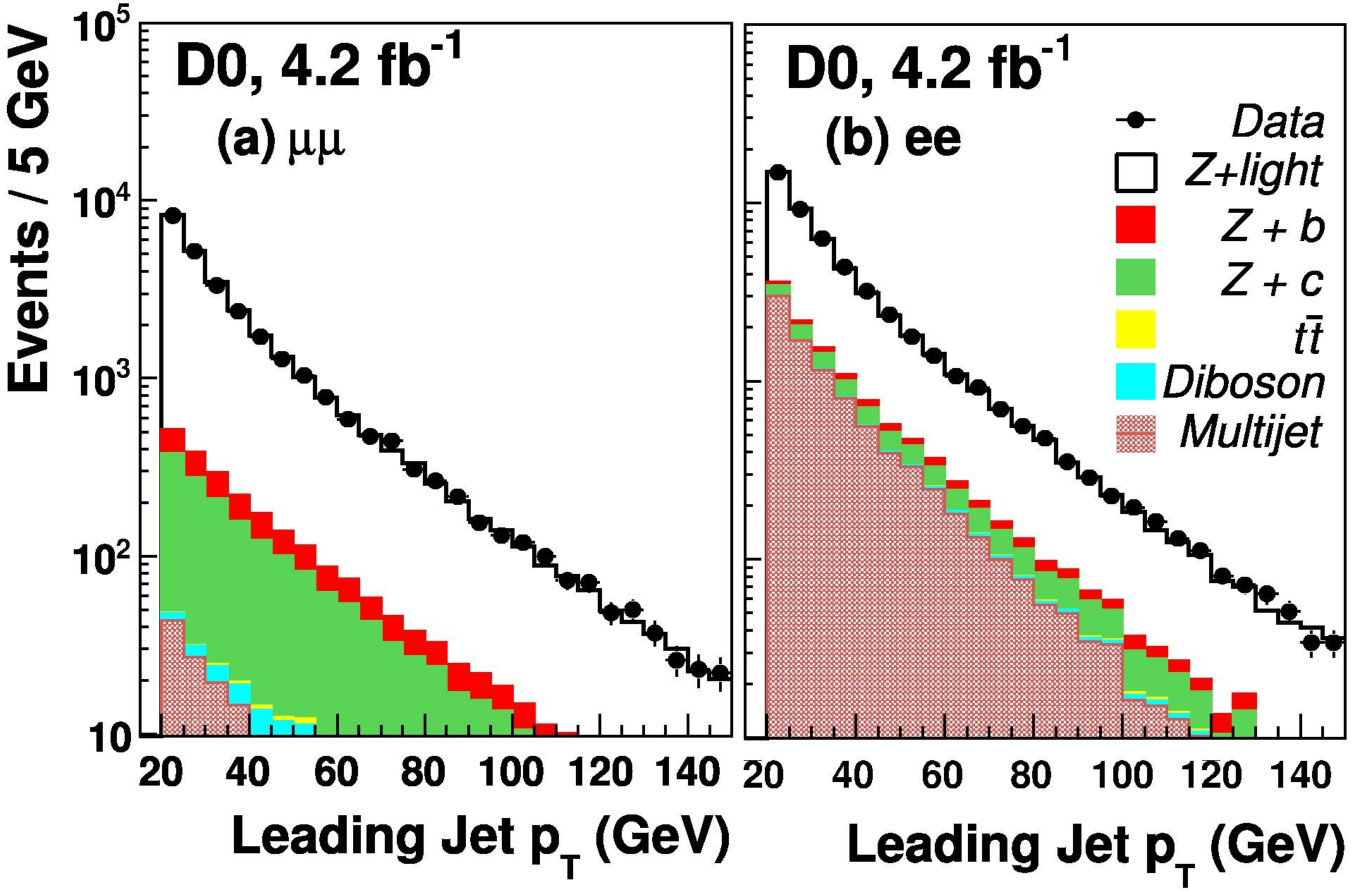
- *Main Systematic uncertainty due to vertex mass template modeling (9 %)*
- *Other systematics come from b-tag efficiency, JES and backgrounds*

Good Agreement with NLO MCFM

	$NLO(Q^2=m_Z{}^2+p_{T,Z}{}^2)$	$NLO(Q^2=<p_{T,jet}^2>)$
$\frac{\sigma_{Z+b-jet}}{\sigma_Z}=2.84\pm0.29\pm0.29\times10^{-3}$	2.3×10^{-3}	2.8×10^{-3}
$\frac{\sigma_{Z+b-jet}}{\sigma_{Z+jet}}=2.24\pm0.24\pm0.26\times10^{-2}$	1.8×10^{-2}	2.2×10^{-2}

$\mathcal{L}$ = 4.2 fb^{-1}

Z + b-jets



MIDPOINT R = 0.5 jet
P_T > 20 GeV/c, |η| < 2.5

NN b tagging based on lifetimes

$$\frac{\sigma_{Z+b-jet}}{\sigma_{Z+jet}} = 0.0193 \pm 0.0022 \pm 0.0015$$

NLO prediction (MCFM)

$$0.0192 \pm 0.0022 (Q^2 = M_Z^2)$$

PRD 83, 031105 (2011)

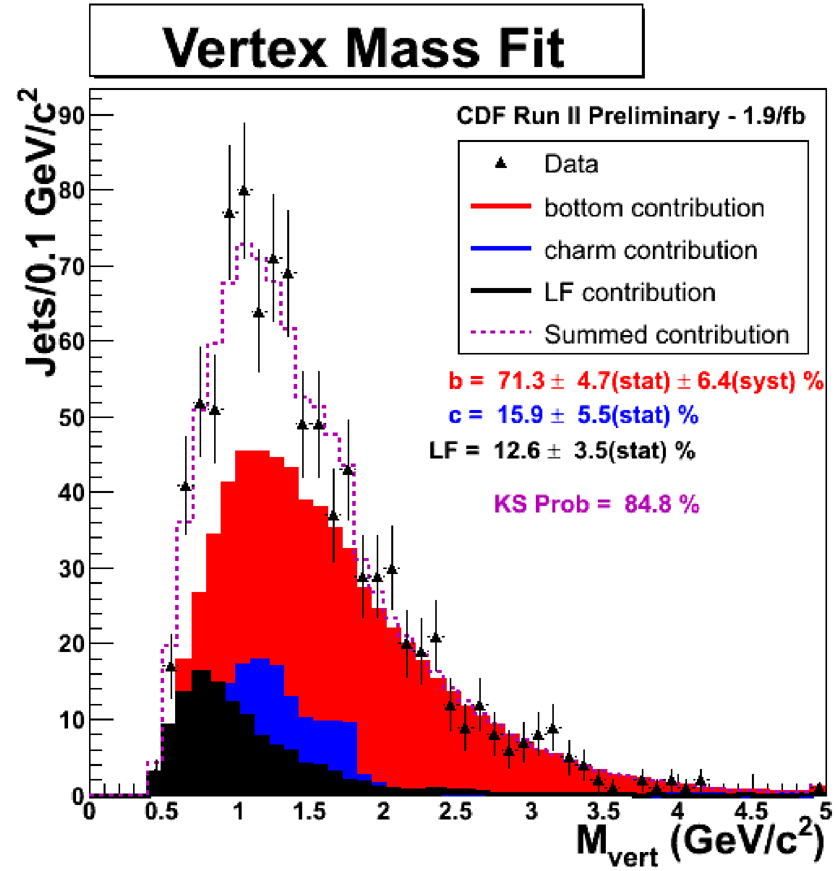
W + b-jets

W Kinematic region
Combined e and μ channels
$P_T^l > 20$ GeV, $|\eta_l^l| < 1.1$
MET > 25 GeV

$\mathcal{L} = 1.9\ fb^{-1}$

JETCLU R=0.4 jet
$E_T > 20$ GeV, $|\eta| < 2.0$

b-quark composition extracted from fit to secondary vertex mass



$$\sigma_{W+b} \times Br(W \to l\nu)$$
$$2.74 \pm 0.27 \pm 0.42\ pb$$

$$ALPGEN = 0.78\ pb$$

$$NLO\ pQCD = 1.22 \pm 0.14\ pb$$

Measured Xs is higher than NLO prediction

PRL 104, 131801 (2010)

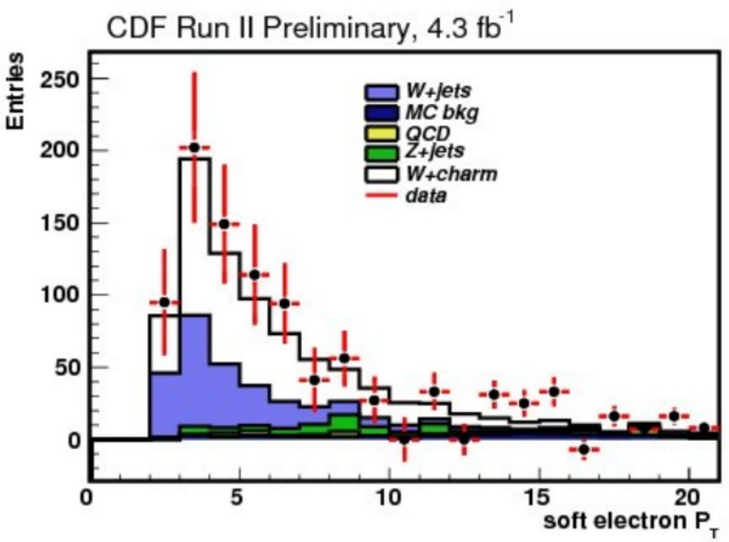
JETCLU R = 0.4 jet
E_T > 20 GeV/c, |η| < 2.0

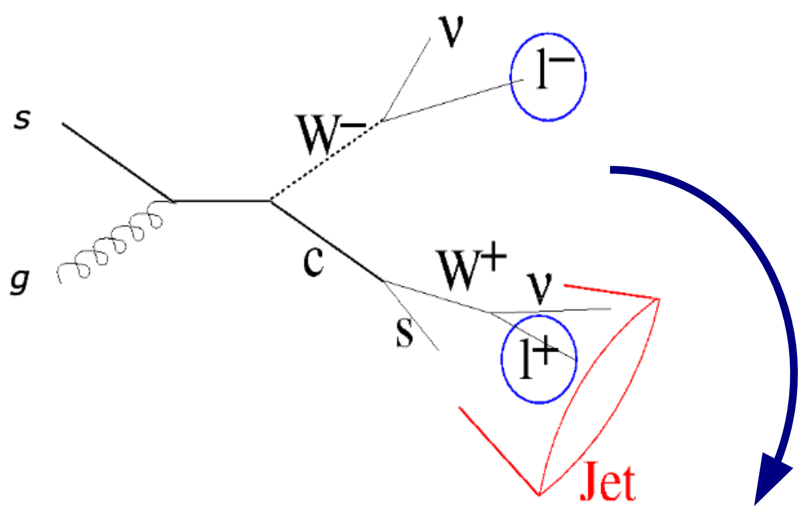
W + c (e channel)

$\mathcal{L}$ = 4.3 fb^{-1}

Probe s-content of proton at high Q²

Charm-jet identified by soft electron tagging (SLT_e) algorithm





Exploit opposite charge correlation between W lepton and SLT electron

$$\sigma_{W+c} \times Br(W \rightarrow l\nu) = 21.1 \pm 7.1\,(stat) \pm 4.6\,(syst)\ pb$$

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

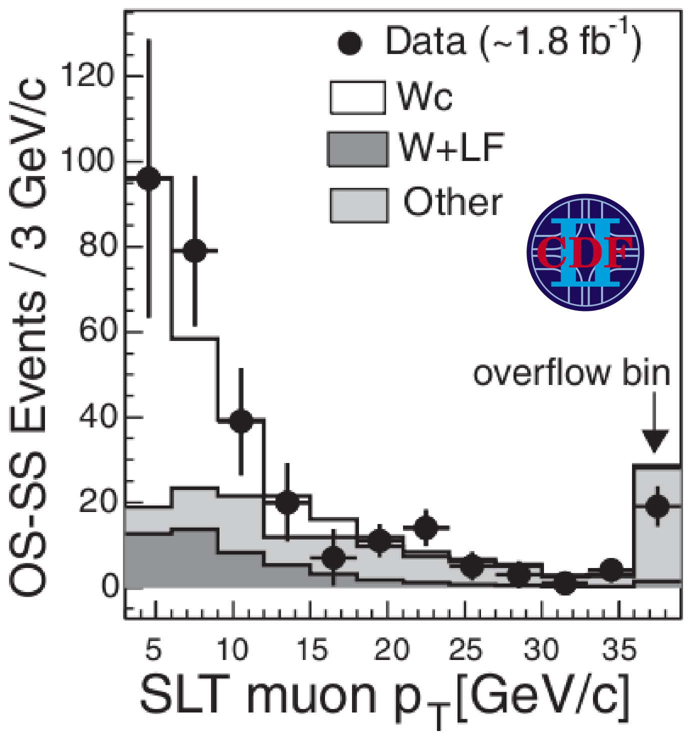
Data and NLO in reasonable agreement

W + c (μ channel)

JETCLU R=0.4 jet

$p_T^C > 20$ GeV/c, $|\eta^C| < 1.5$

$\mathcal{L} = 1.8\ fb^{-1}$



Soft muon tagger

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

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

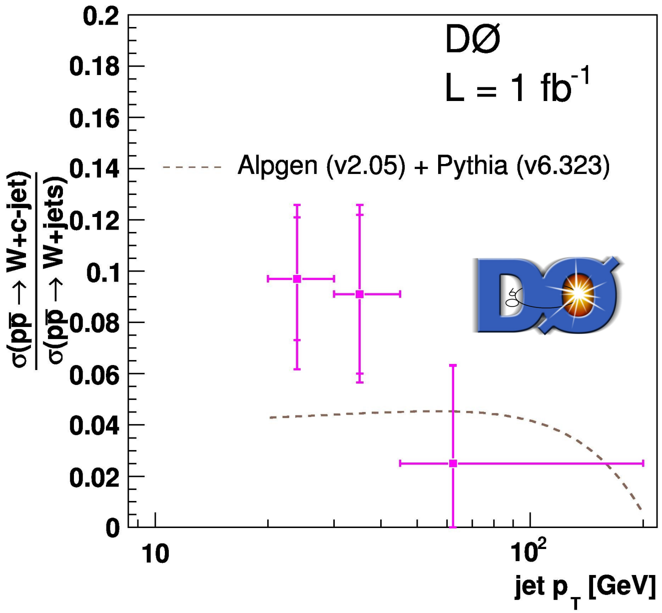
$$NLO(MCFM): 11.0^{+1.4}_{-3.0}\ pb$$

PRL 100, 091893 (2008)

MIDPOINT R=0.5 jet

$p_T^C > 20$ GeV/c, $|\eta^C| < 2.5$

$\mathcal{L} = 1\ fb^{-1}$



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

LO (Alpgen + Pythia) 0.044 ± 0.003

Phys. Lett. B 666, 23 (2008)

Summary

- New precise measurements of Z+jets, Z+b, W+jets
- General good agreement with NLO predictions
- Prospects for Z + ≥1 jet nNLO and W/Z + ≥4 jets NLO comparison
- Ongoing work on Z+b, W+c and W+b updates

More details at:

- http://www-cdf.fnal.gov/internal/physics/qcd/qcd.html
- http://www-d0.fnal.gov/Run2Physics/WWW/results/qcd.htm

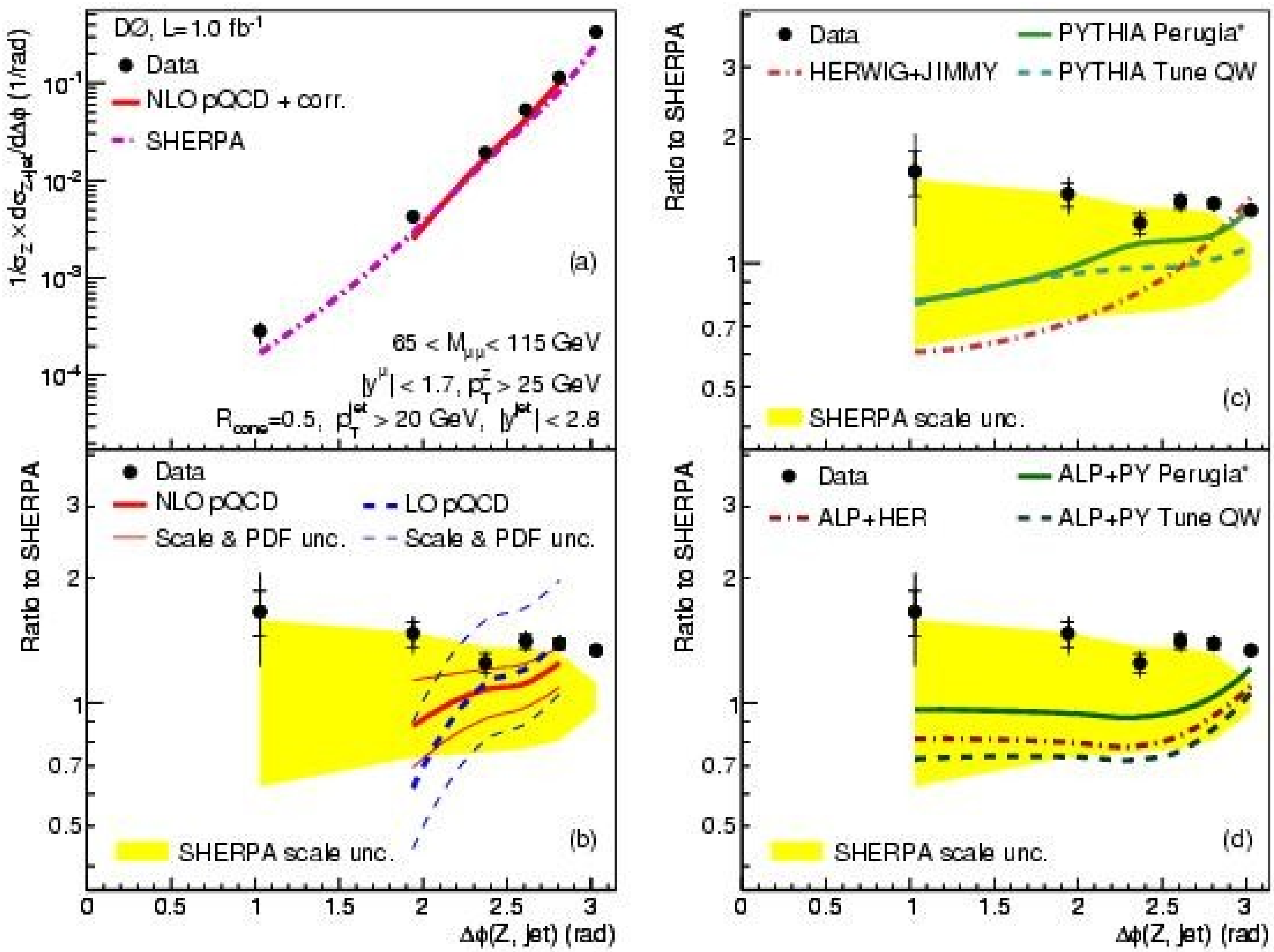
BACKUP

Angular distributions

$Z/\gamma^* \rightarrow \mu^+\mu^- + \text{jets}$

$\mathcal{L}$ = 1 fb^{-1}

MIDPOINT R=0.5 jet
p_T > 20 GeV/c, |Y| < 2.8



Measurements are normalized to σ_Z to reduce systematic uncertainties

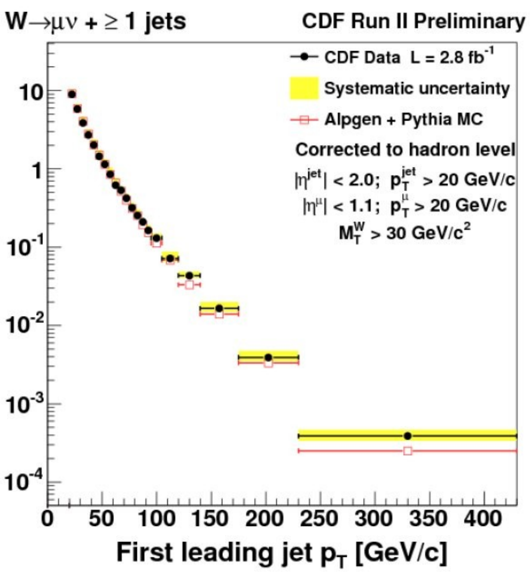
Sherpa MC well describes shape but not normalization

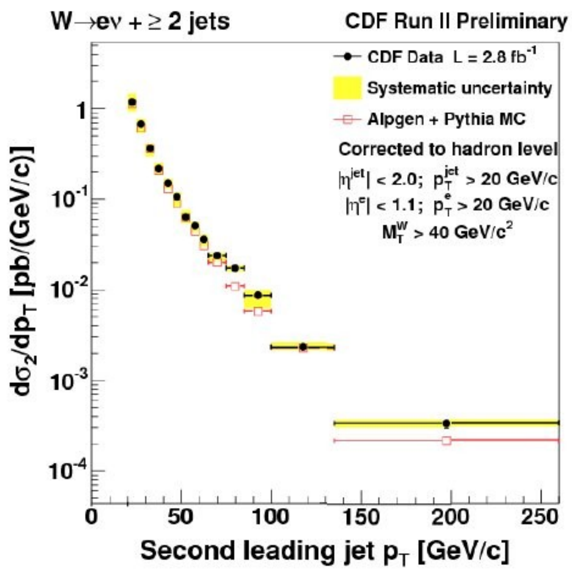
Phys. Lett. B 682, 370 (2010)

W Kinematic region
$M_T^W > 30 / 40\ GeV/c^2\ (\mu/e)$
$P_T^l > 20\ GeV,\ |\eta_1^l| < 1.1$

W + jets

$\mathcal{L} = 2.8\ fb^{-1}$



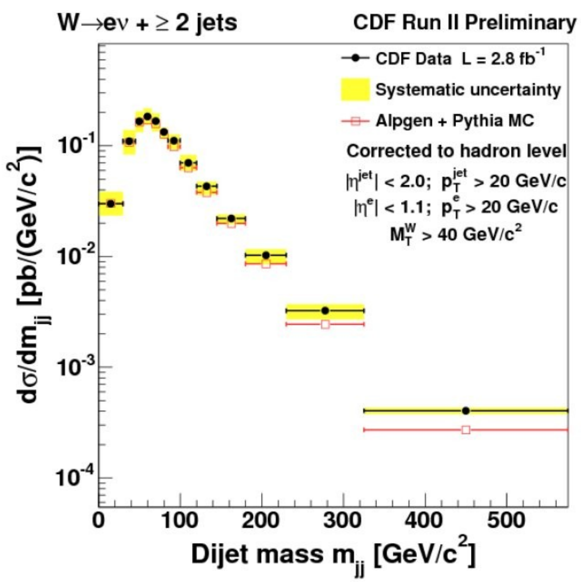


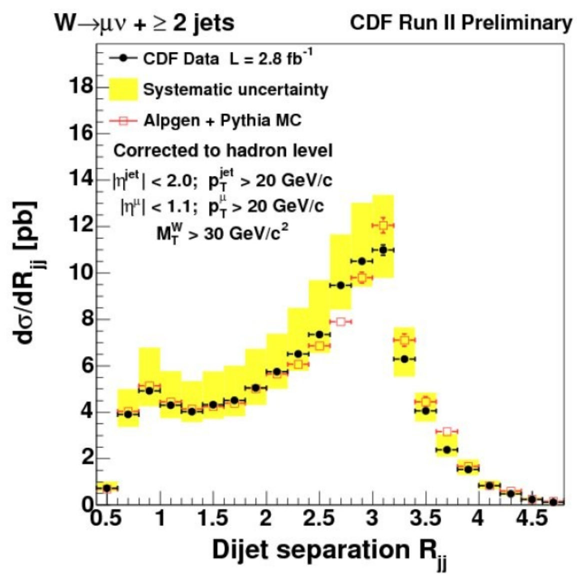
MIDPOINT R=0.4 jet

Separate measurements in
W → μν and W → eν channels

Measured differential cross sections
in several kinematic variables

Alpgen+Pythia MC normalized
to data for each Njet bin in
control region M_T>20 GeV





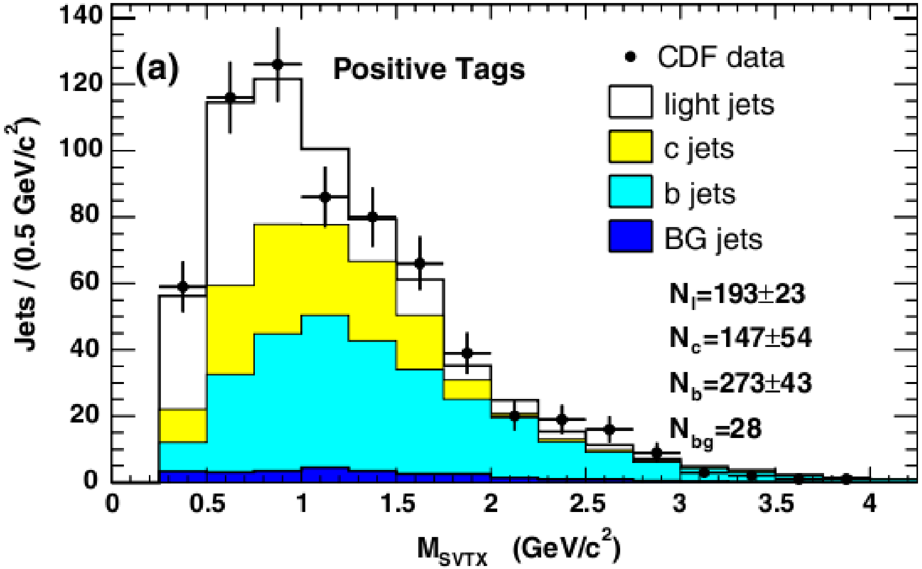
Z + b-jets

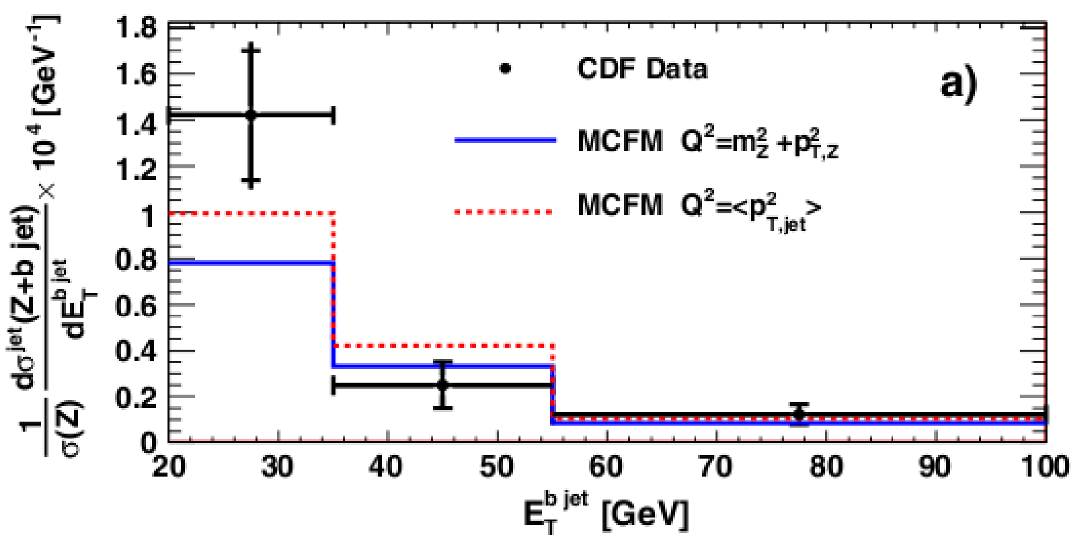
$\mathcal{L} = 2\ \text{fb}^{-1}$

JETCLU R = 0.7 jet
$E_T > 20$ GeV, $|\eta| < 1.5$

e and μ channel combination

b-quark composition extracted from fit to secondary vertex mass





$$\frac{\sigma_{Z+b-jet}}{\sigma_Z} = 3.32 \pm 0.53 \pm 0.42 \times 10^{-3}$$

NLO (MCFM)

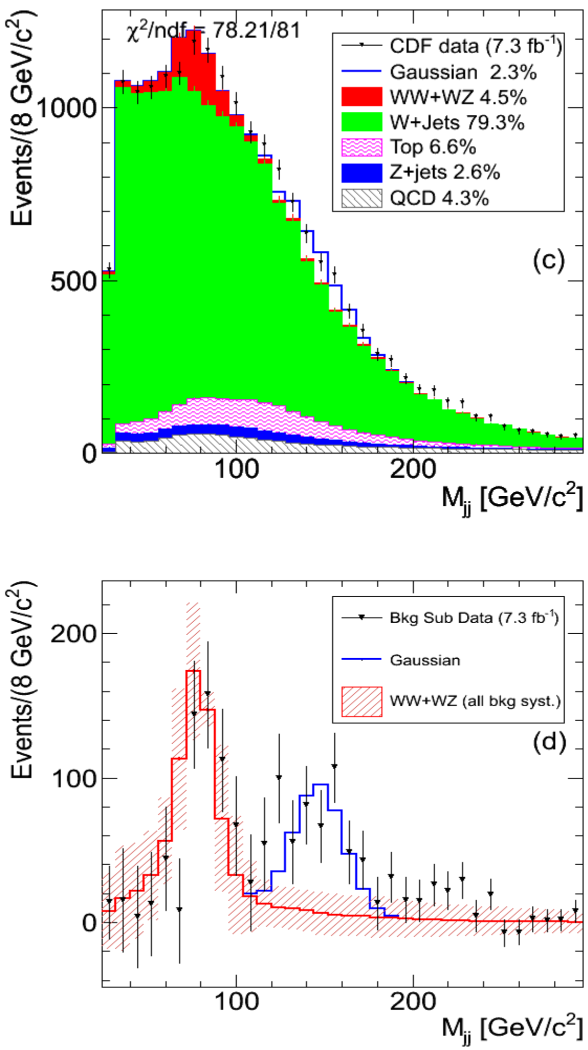
$$2.3 \times 10^{-3} \left(Q^2 = M_Z^2 + P_{T,Z}^2\right)$$

$$2.8 \times 10^{-3} \left(Q^2 = \langle P_{T,Jet}^2 \rangle\right)$$

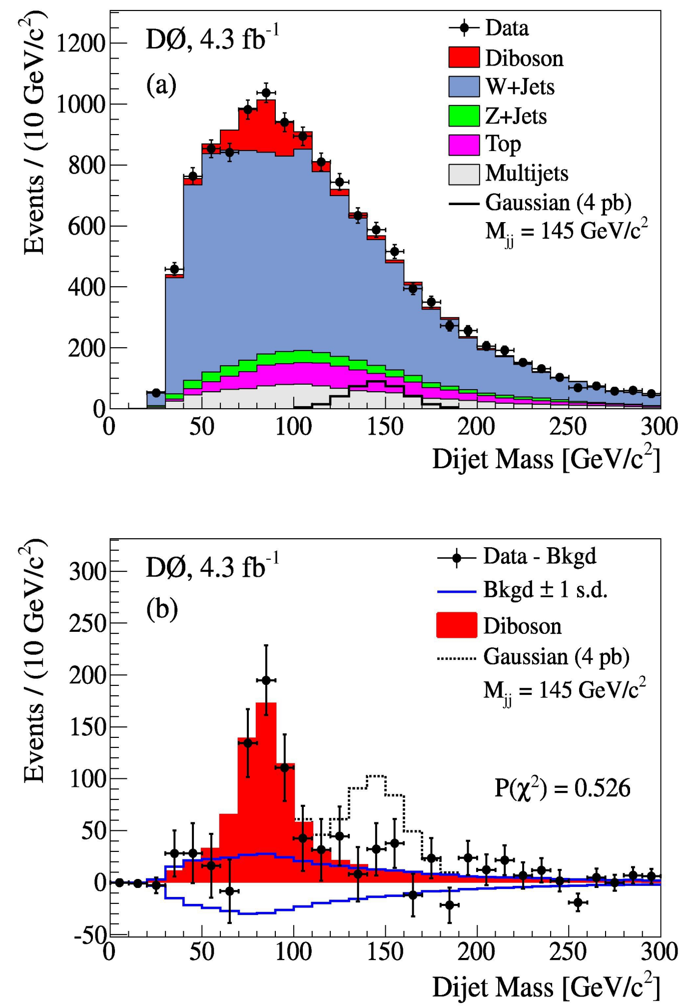
Measurement in agreement with NLO prediction (large uncertainties in both data and theory)

PRD 79, 052008 (2009)

W + 2 jets M_{jj}

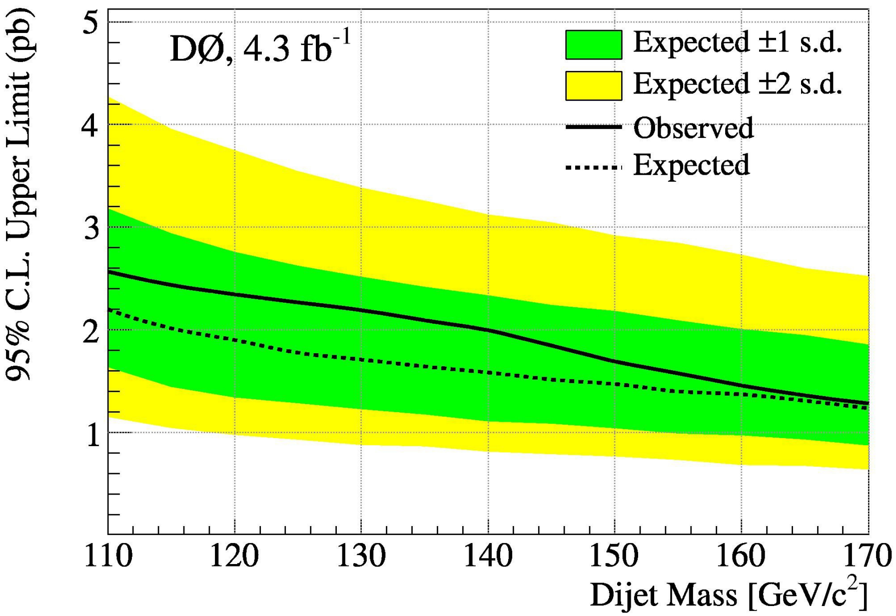


χ^2/ndf = 78.21/81
CDF data (7.3 fb^{-1})
Gaussian 2.3%
WW+WZ 4.5%
W+Jets 79.3%
Top 6.6%
Z+jets 2.6%
QCD 4.3%
(c)
Events/(8 GeV/c^2)
M_{jj} [GeV/c^2]
Bkg Sub Data (7.3 fb^{-1})
Gaussian
WW+WZ (all bkg syst.)
(d)



DØ, 4.3 fb^{-1}
(a)
Data
Diboson
W+Jets
Z+Jets
Top
Multijets
Gaussian (4 pb)
M_{jj} = 145 GeV/c^2
Events / (10 GeV/c^2)
Dijet Mass [GeV/c^2]
DØ, 4.3 fb^{-1}
(b)
Data - Bkgd
Bkgd ± 1 s.d.
Diboson
Gaussian (4 pb)
M_{jj} = 145 GeV/c^2
P(χ^2) = 0.526

W + 2 jets M_{jj}



CDF evaluated cross section
- 3.1 ± 0.8 pb (with 4.3 fb^{-1})
- 3.0 ± 0.7 pb (with 7.3 fb^{-1})

D0 Result
- 0.82 ± 0.83 pb

D0 favors the null hyptotesis
Two experiments are ~2σ apart

Identified differences in D0 analysis:
- D0 jets corrected for out-of-cone: effective jet threshold lower
- Double QCD contamination from low purity electrons
- Fit procedure morphs M_{jj} To correct for systematics

Ongoing task force at FNAL to understand CDF-D0 different results