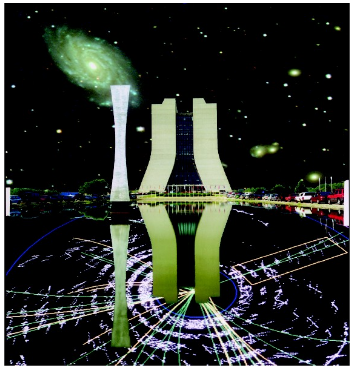
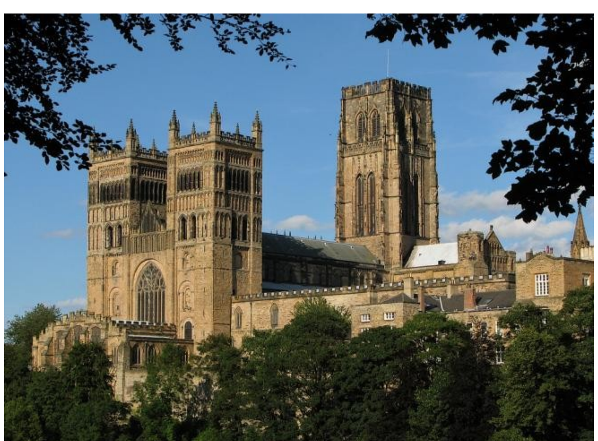


V + Jets at the Tevatron

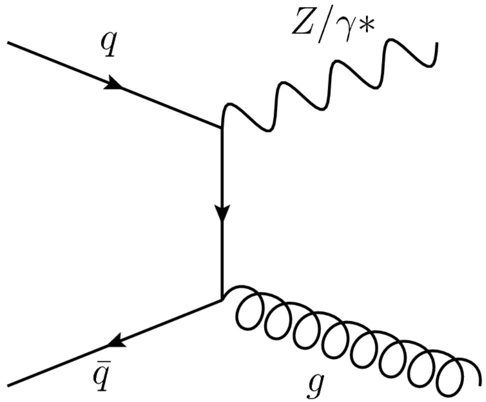
Stefano Camarda

IFAE - Barcelona

On behalf of the
CDF and DØ Collaborations

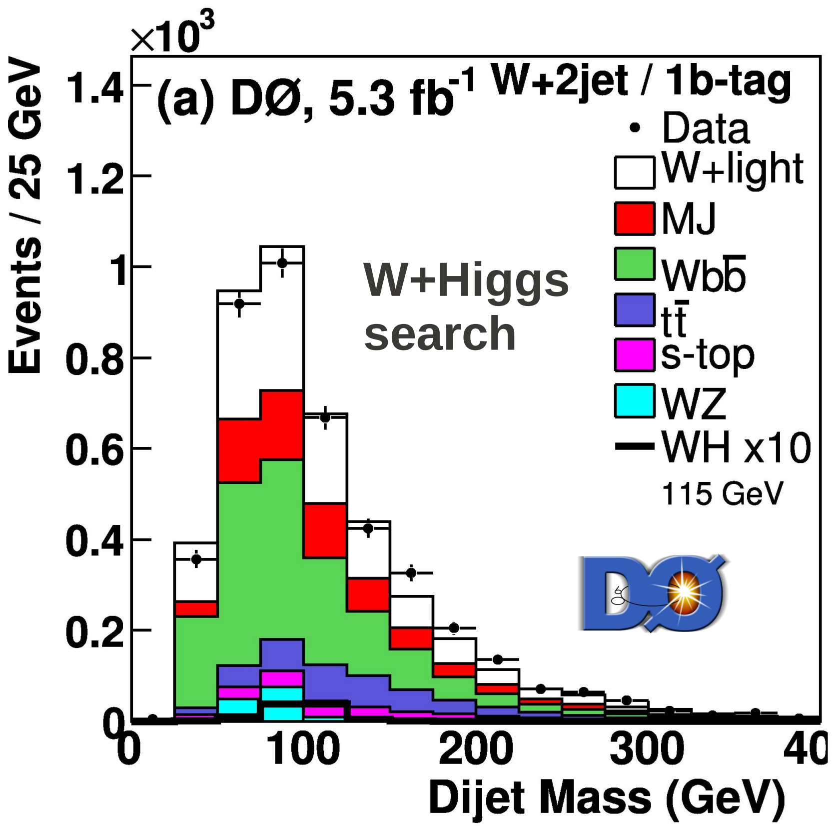


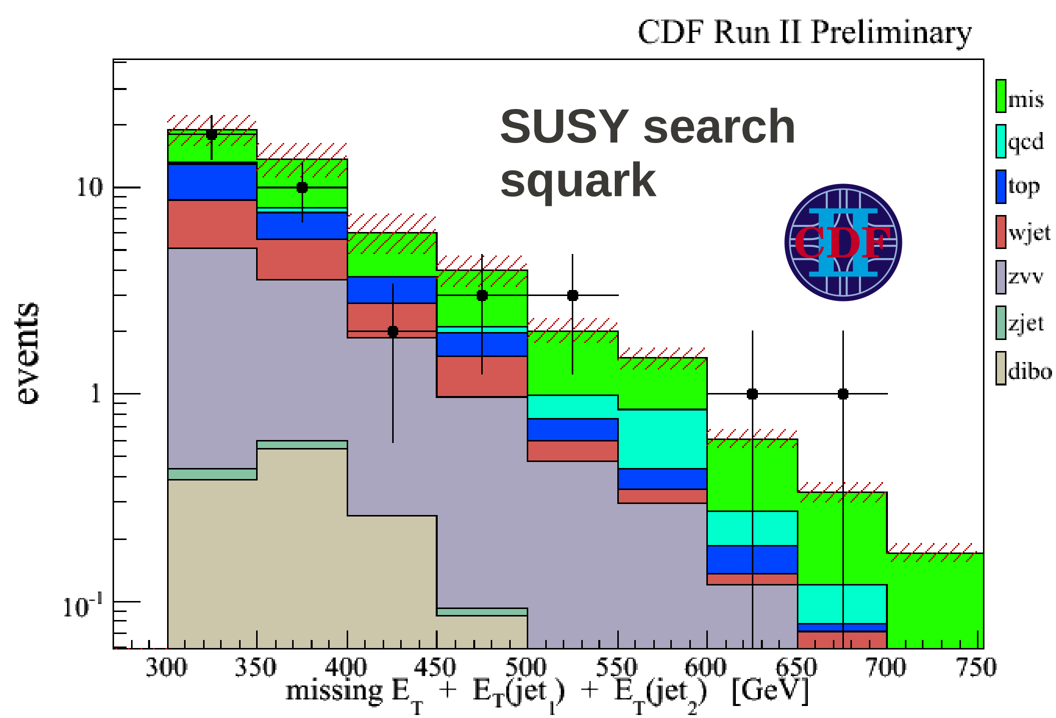
SM @ LHC
April 10-14, 2011
Durham



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

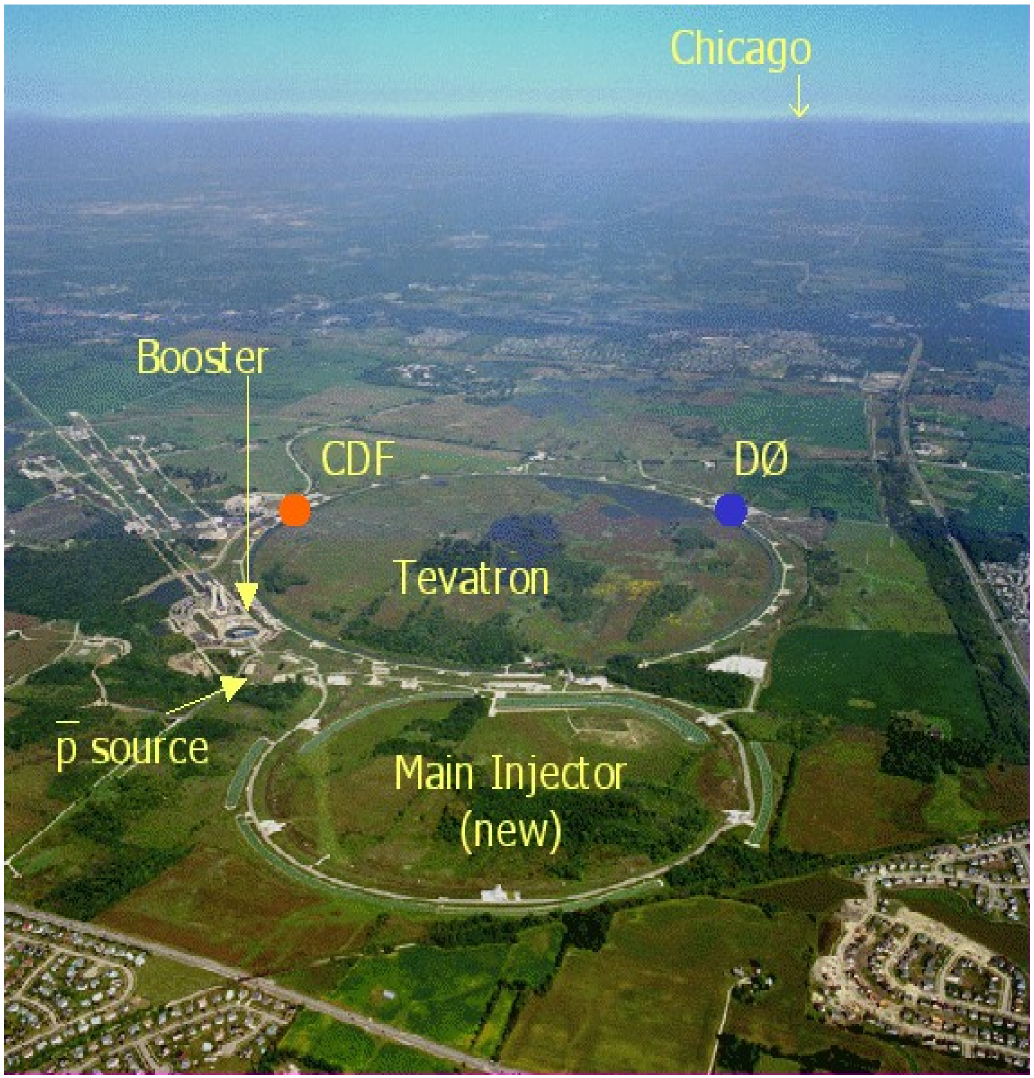
Measurements with associated luminosity

	Final State	DØ	CDF
W/Z + Jets	$Z \rightarrow e^+e^-$ + Jets	1.0 fb^{-1}	6.2 fb^{-1}
	$Z \rightarrow \mu^+\mu^-$ + Jets	1.0 fb^{-1}	6.0 fb^{-1}
	Z + jet P_T balance	–	4.6 fb^{-1}
	W + Jets	–	2.8 fb^{-1}
W/Z + HF	Z + b	4.2 fb^{-1}	2.0 fb^{-1}
	W + b	–	1.9 fb^{-1}
	W + c (μ channel)	1.0 fb^{-1}	1.8 fb^{-1}
	W + c (e channel)	–	4.3 fb^{-1}

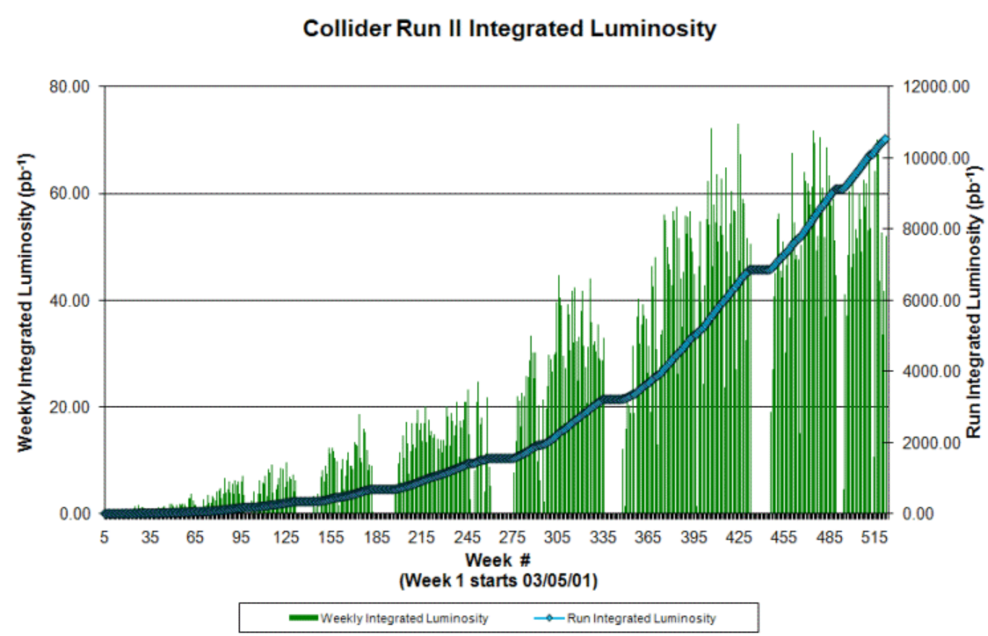
New Results

Dijet Invariant Mass in W + jj with 4.3 fb^{-1} at CDF

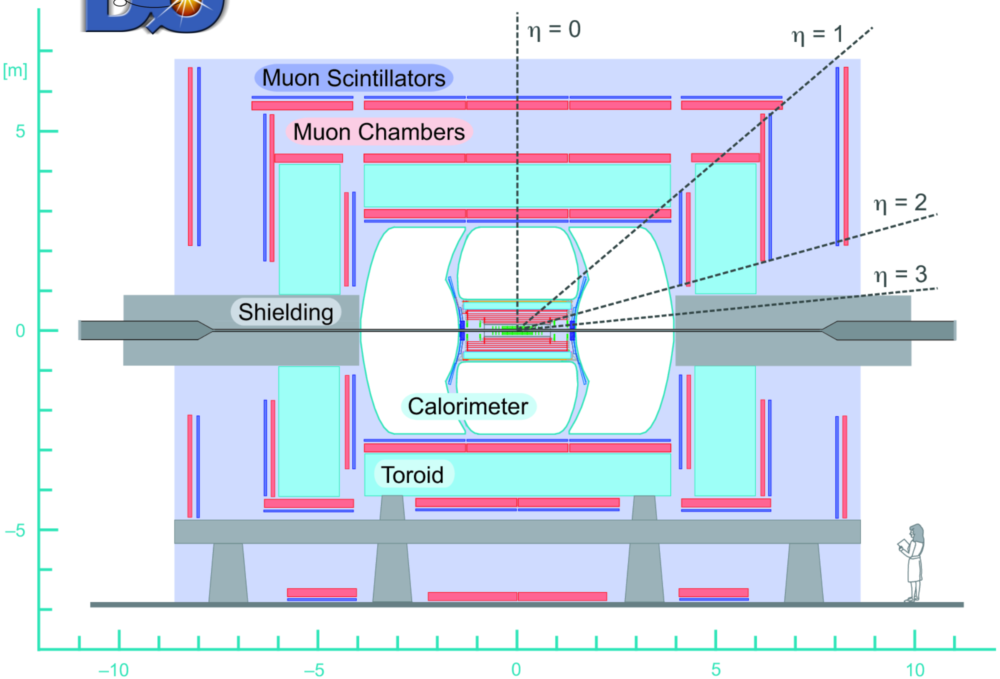
Tevatron



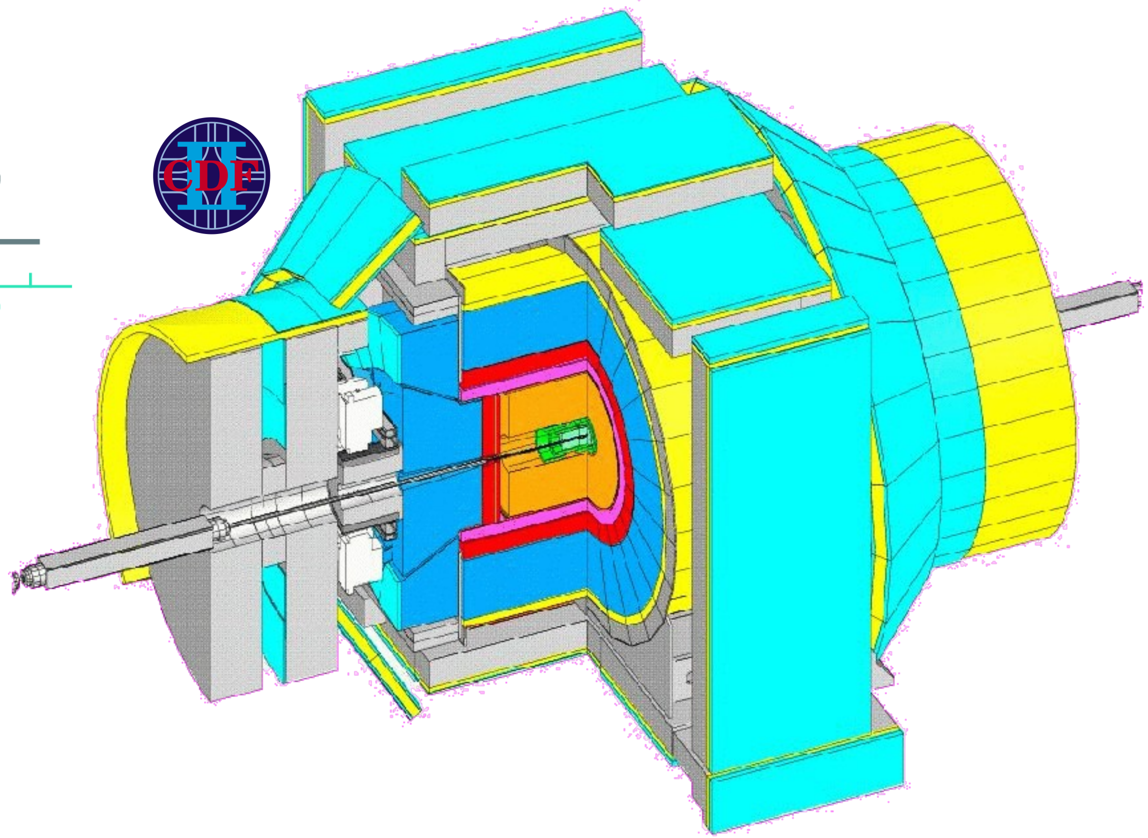
- $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV
- Peak instantaneous luminosity ~ 4 x 10^{32} cm^{-2} s^{-1}
- > 10 fb^{-1} of delivered luminosity



DØ and CDF detectors



Multi purpose detectors



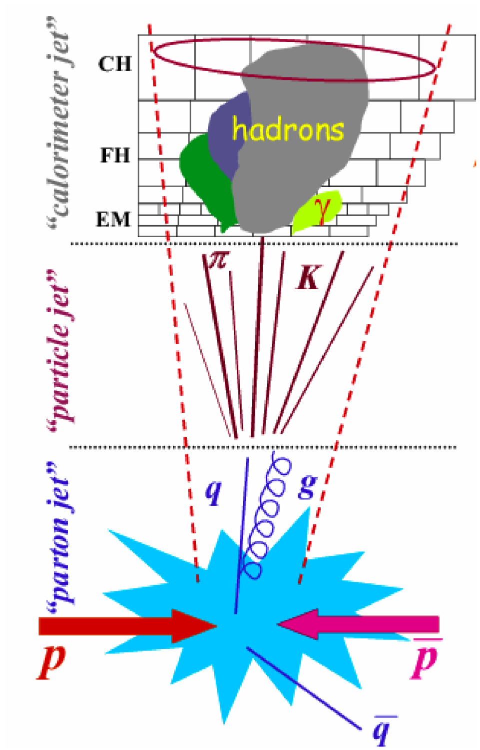
- Central Tracking systems
- Calorimeters
- Muon detectors

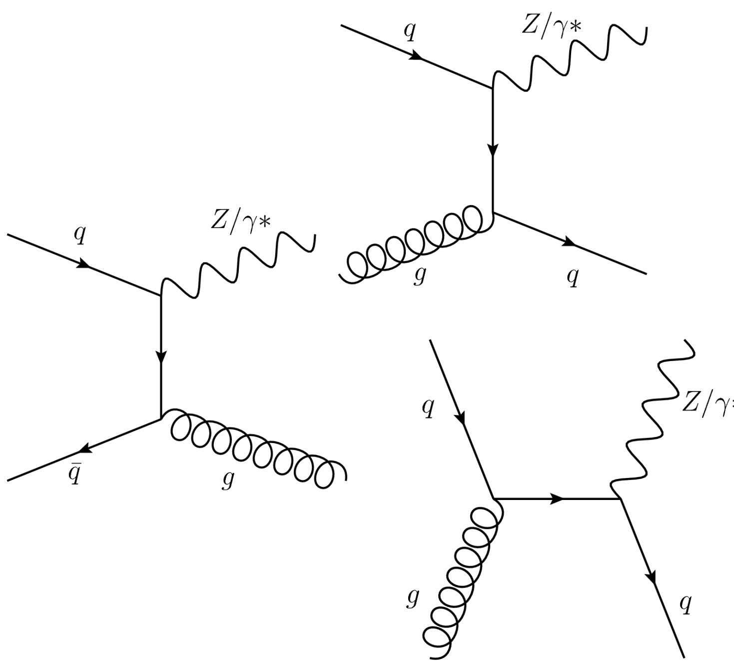
Z/γ* + jets

Angular distributions
with $\mathcal{L}$ = 1 fb^{-1}

Updated results
with $\mathcal{L}$ = 6 fb^{-1}

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





Measurements are unfolded back to Hadron level

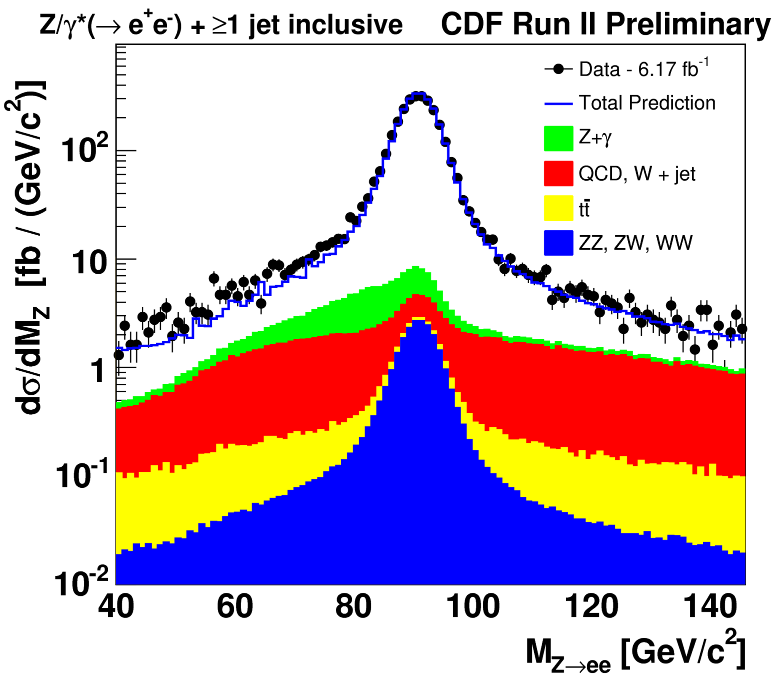
Z/γ* + jets

Data driven backgrounds

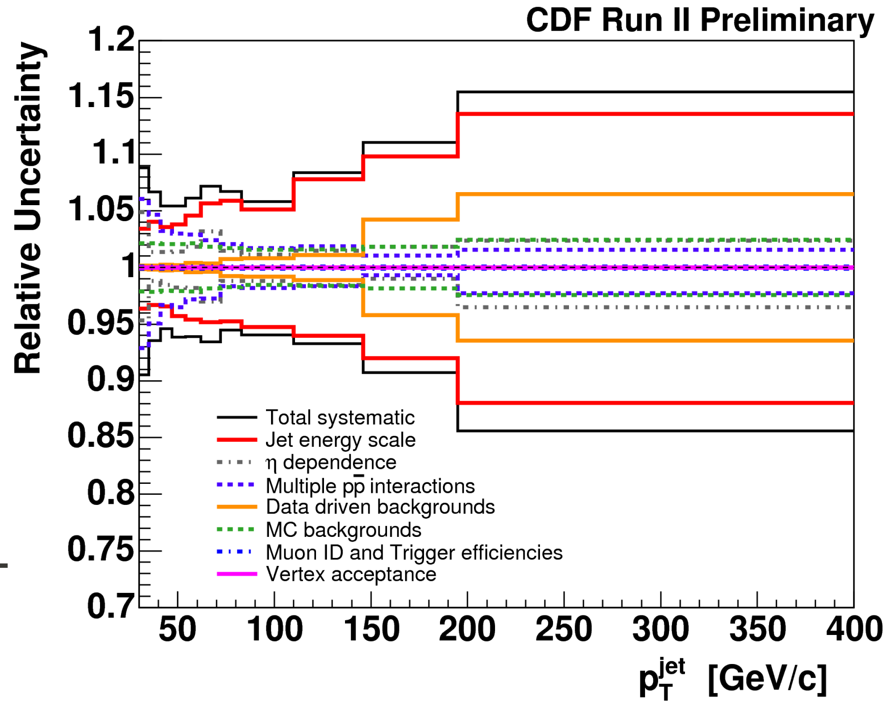
- QCD multi-jet
- W + jet
- μ and e fakes

MC backgrounds

- Z + γ
- Top
- Diboson
- Z → ττ



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



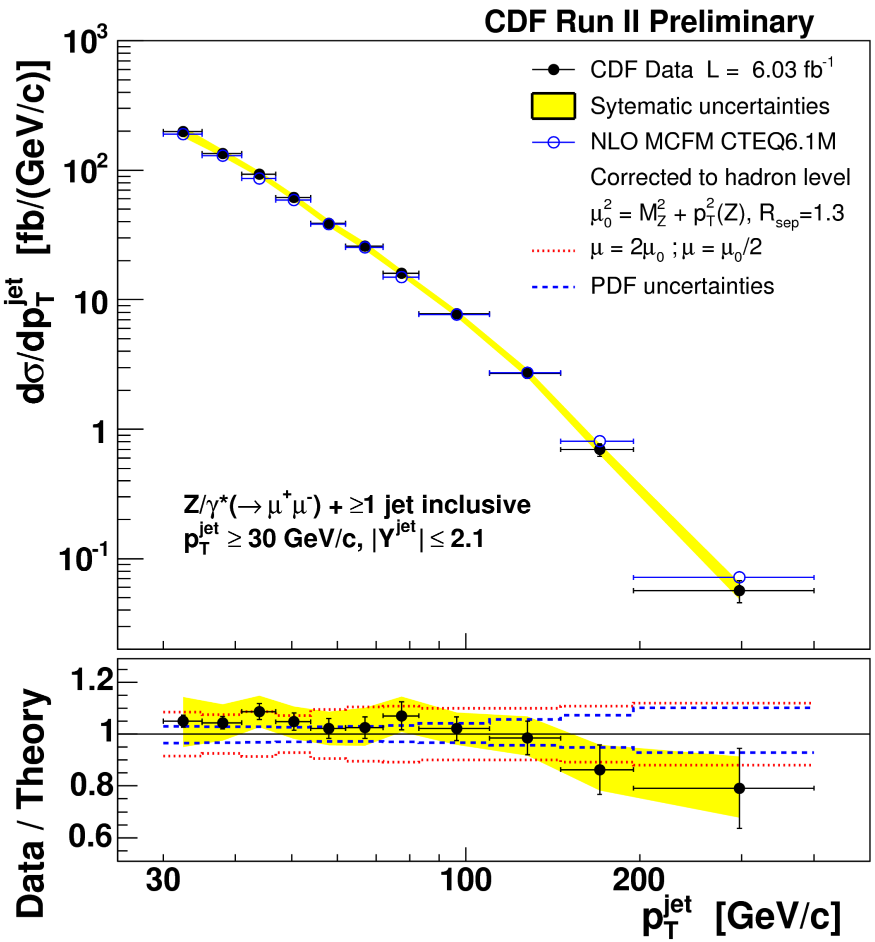
- ~30 x 10^3 Z + ≥1 jet data events in 6 fb-1
- Total backgrounds between 5%-10%
- Main background is Z+γ

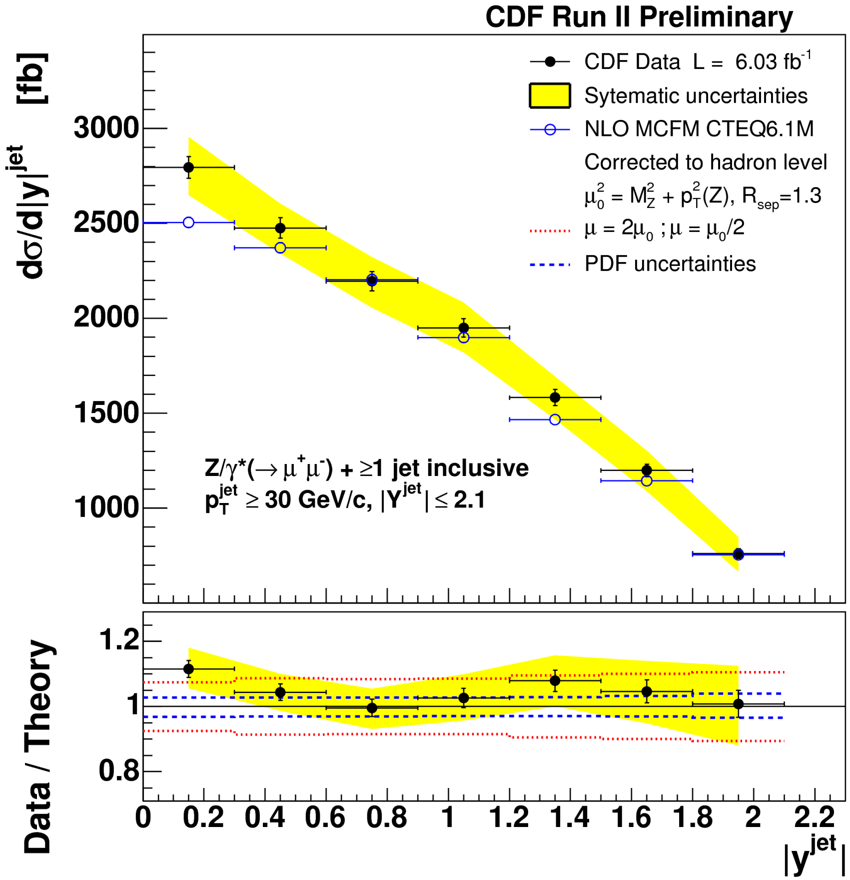
Z Kinematic region
$66 < M_Z < 116$ GeV/c²
$P_T^{\mu} > 25$ GeV, $|\eta^{\mu}| < 1$

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

$\mathcal{L} = 6\ fb^{-1}$

MIDPOINT R=0.7 jet
$p_T > 30$ GeV/c, $|Y| < 2.1$





Theory prediction and measured Xs corrected to Hadron level

Good Agreement between data and NLO prediction (MCFM)

Z Kinematic region

$66 < M_Z < 116$ GeV/c²

$E_T^e > 25$ GeV, $|\eta_1^e| < 1$

$|\eta_2^e| < 1 \,||\, 1.2 < |\eta_2^e| < 2.8$

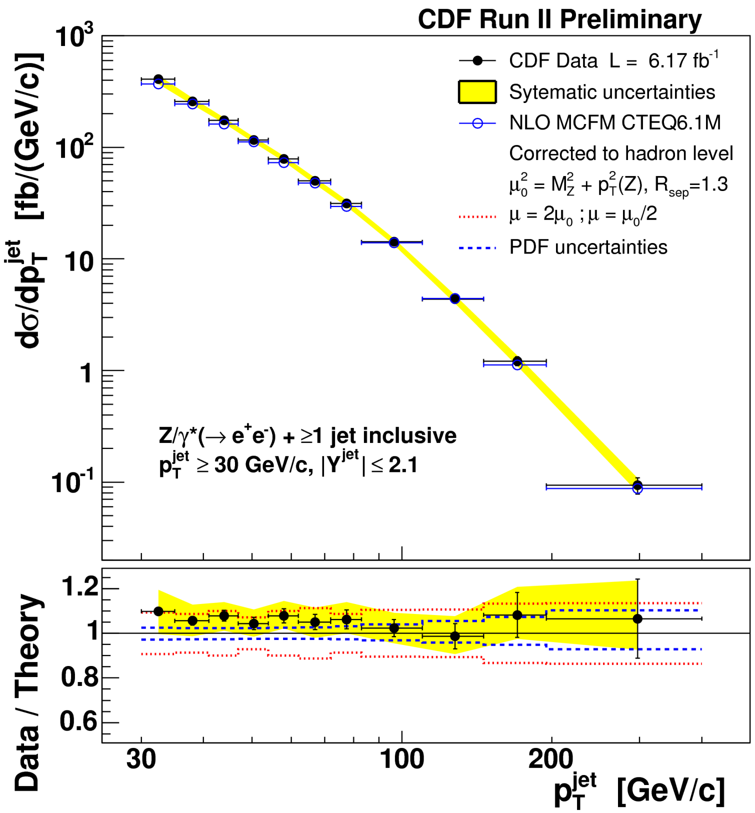
$Z/\gamma^* \rightarrow e^+e^-$ + jets

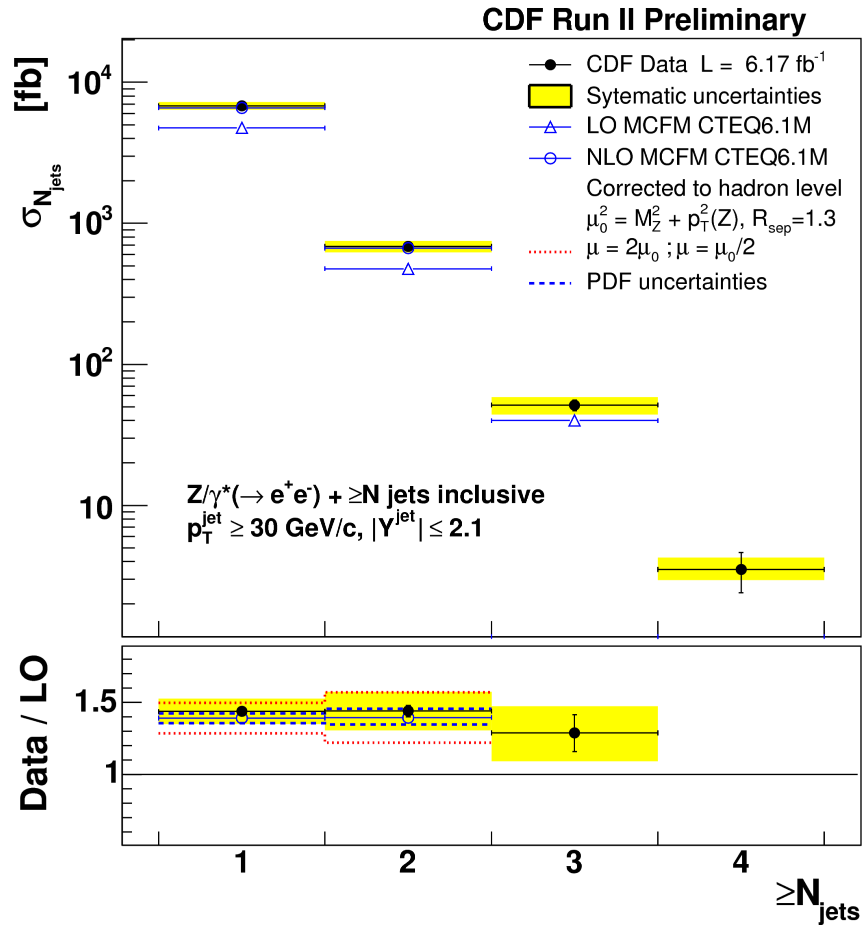
$\mathcal{L} = 6.2\ \mathrm{fb}^{-1}$

MIDPOINT R=0.7 jet

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

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





Same kinematic region of $Z \rightarrow \mu\mu$ + jets to allow combination

First Measurement of Z + ≥4 Jets

Angular distributions

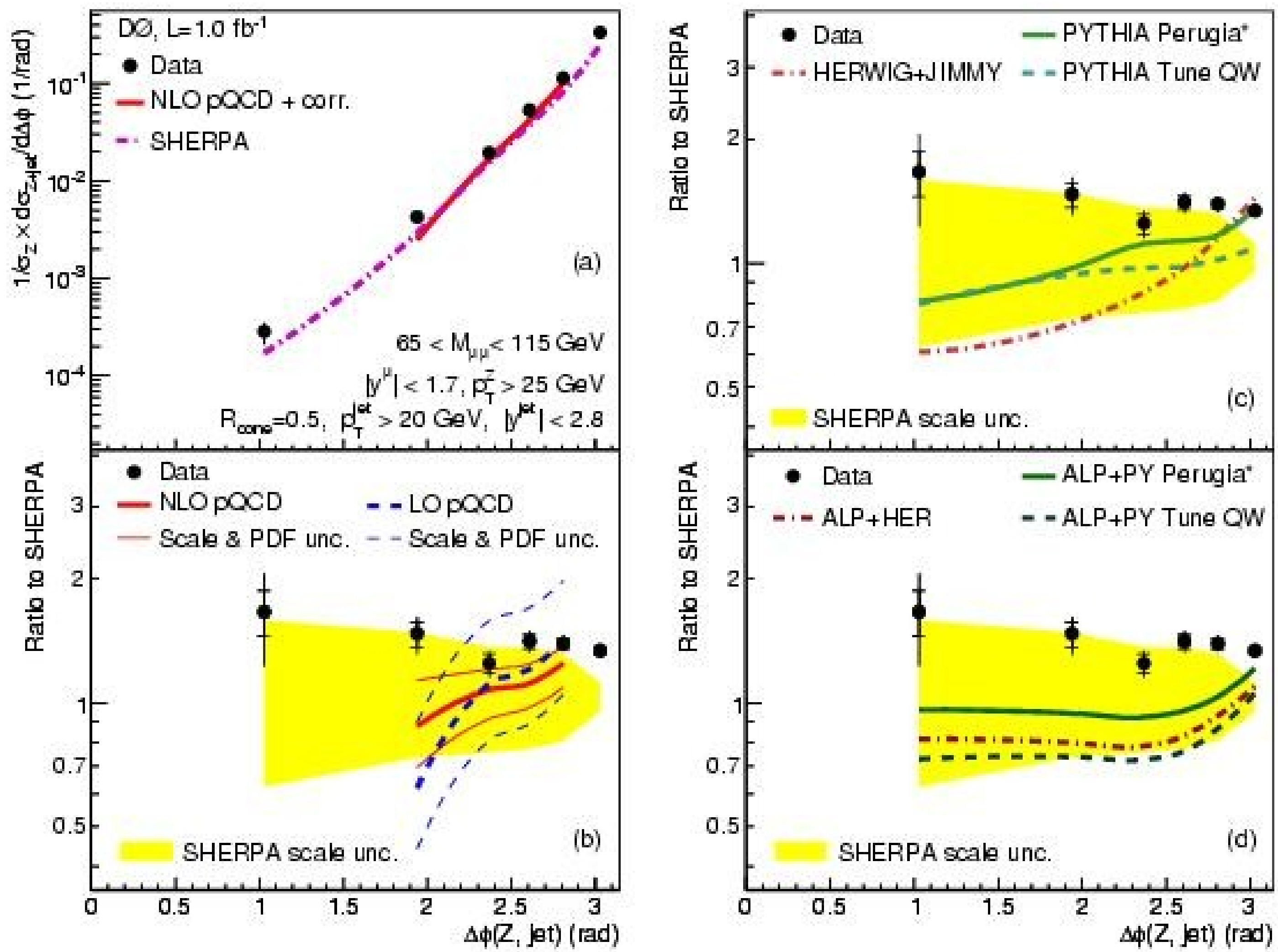
$Z/\gamma^* \rightarrow \mu^+\mu^- + \text{jets}$

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

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



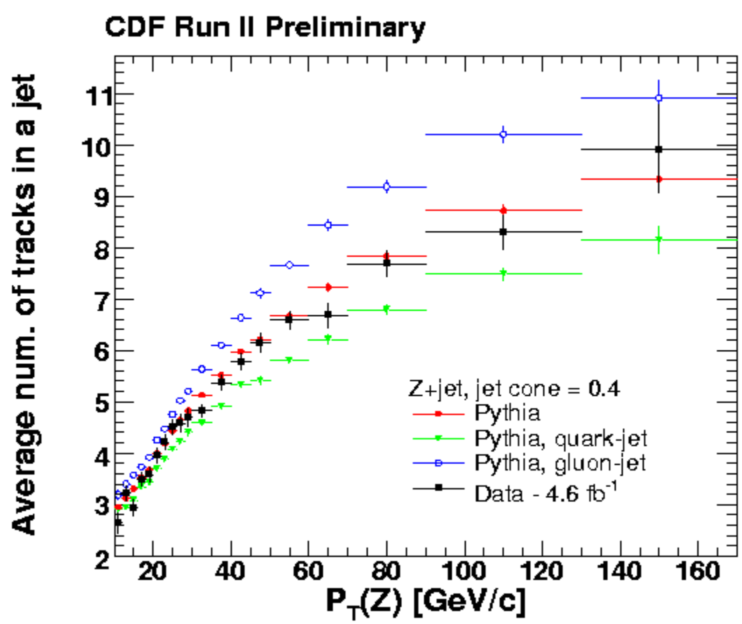
Phys. Lett. B 682, 370 (2010)

Z+jet P_T balance

Large Z + jets sample, can be used for jets studies

$\mathcal{L}$ = 4.6 fb^{-1}

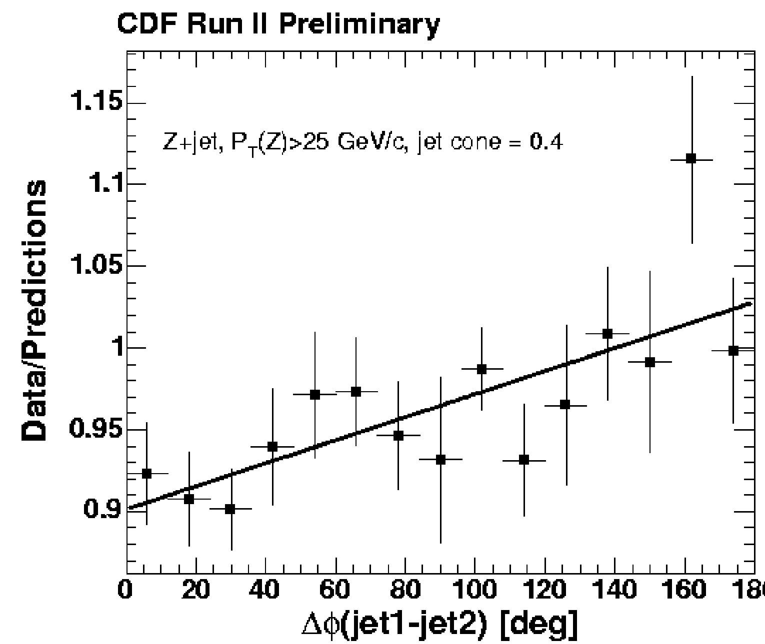
- Reduce uncertainties on measured energy of hadronic jets
- Test QCD jet modeling
- Check quark-gluon composition



Nucl. Instrum. Methods Phys. A 622, 698

P_T-balance definition

$<P_T(jet1)/P_T(Z)>$



Out-of-cone radiation

Mismodeling of large angle FSR in the MC is limiting the uncertainty in hadronic jets energy

W Kinematic region

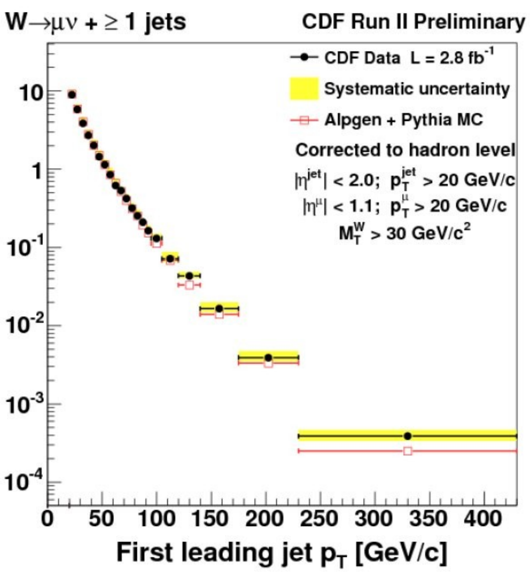
$M_T^W > 30$ / 40 GeV/c² (μ/e)

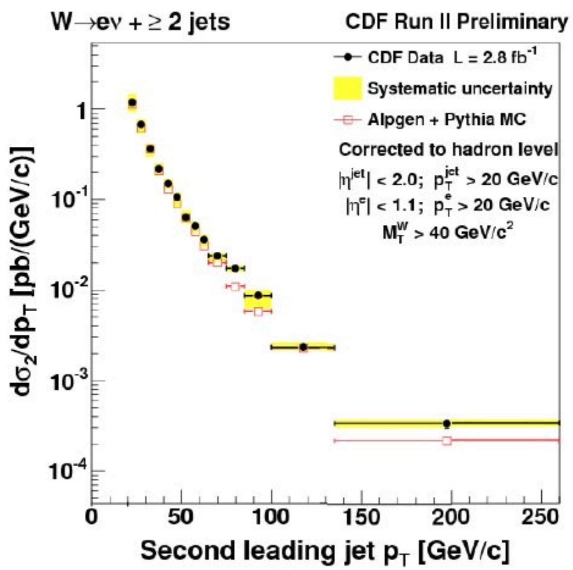
$P_T^l > 20$ GeV, $|\eta_l| < 1.1$

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

W + jets

MIDPOINT R=0.4 jet

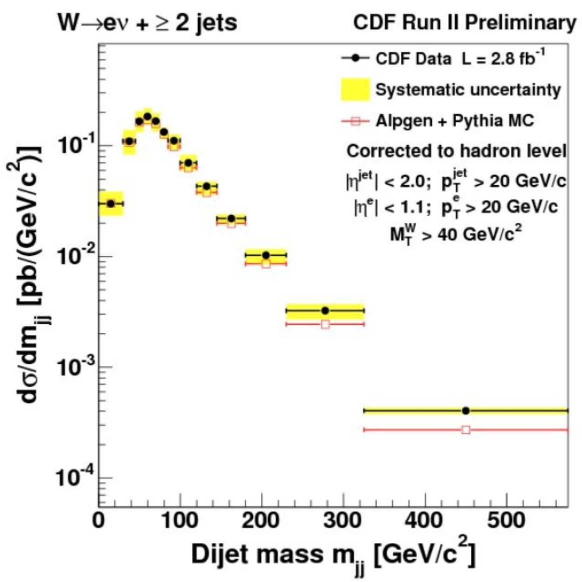


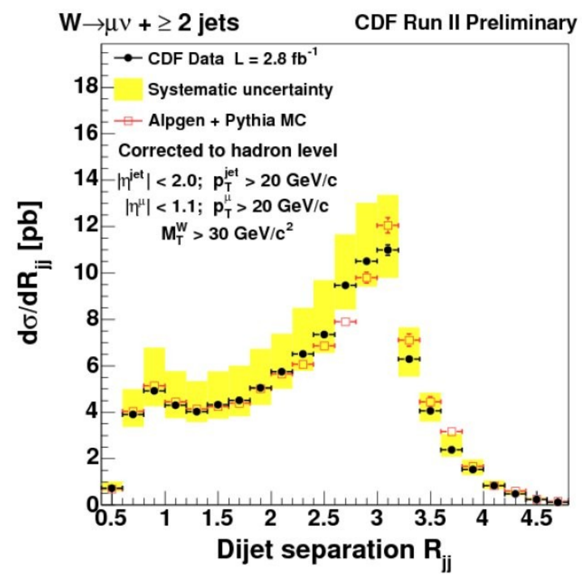


Separate measurements in W → μν and W → eν channels

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

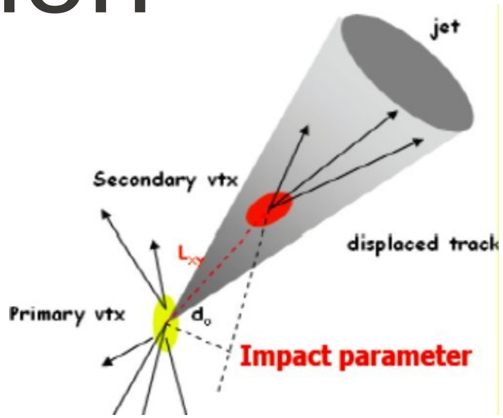




Comparison with NLO prediction will be soon available

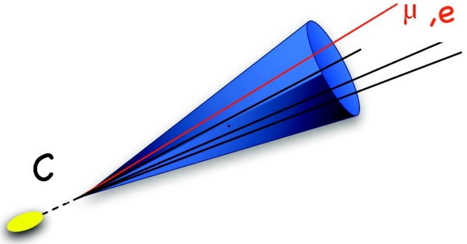
W/Z + HF jets production

Secondary vertex tag
based on large B lifetime

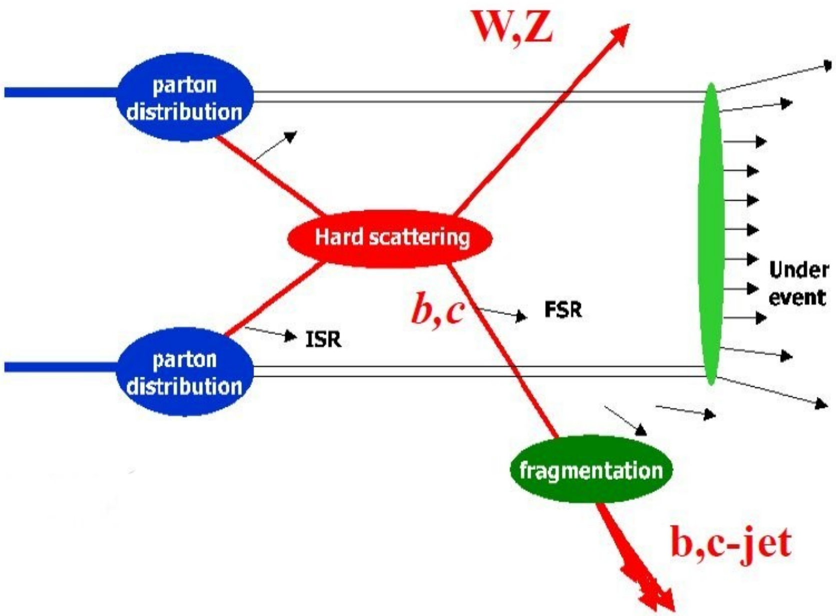


Challenging experimental measurements

- 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

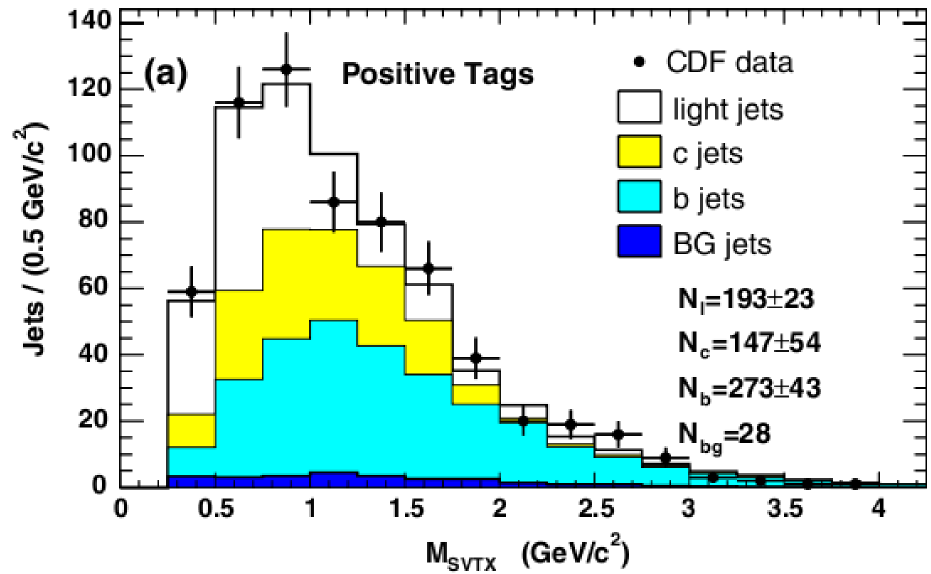
Z + b-jets

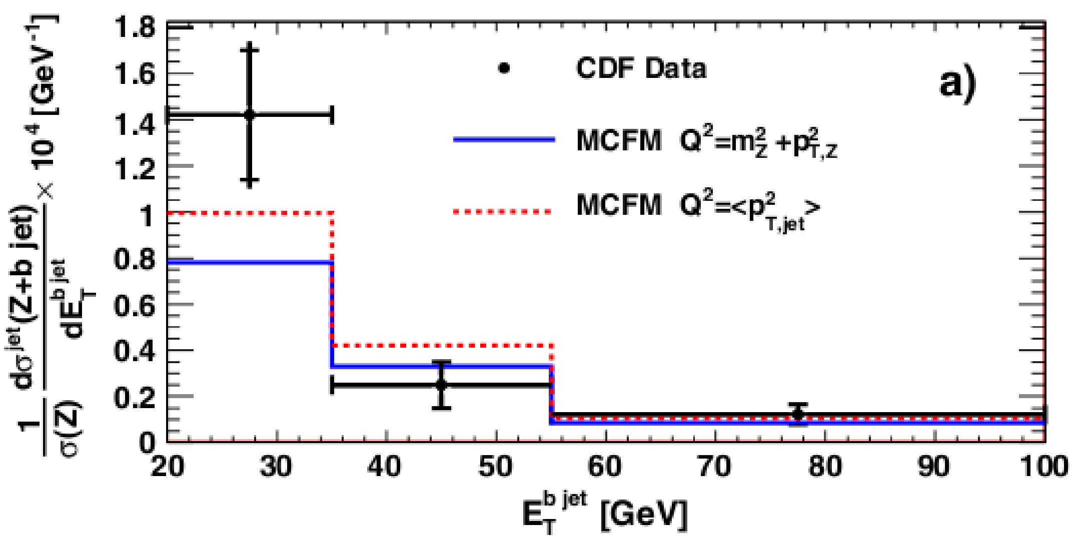
JETCLU R = 0.7 jet
E_T > 20 GeV, $|\eta|$ < 1.5

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

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)

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

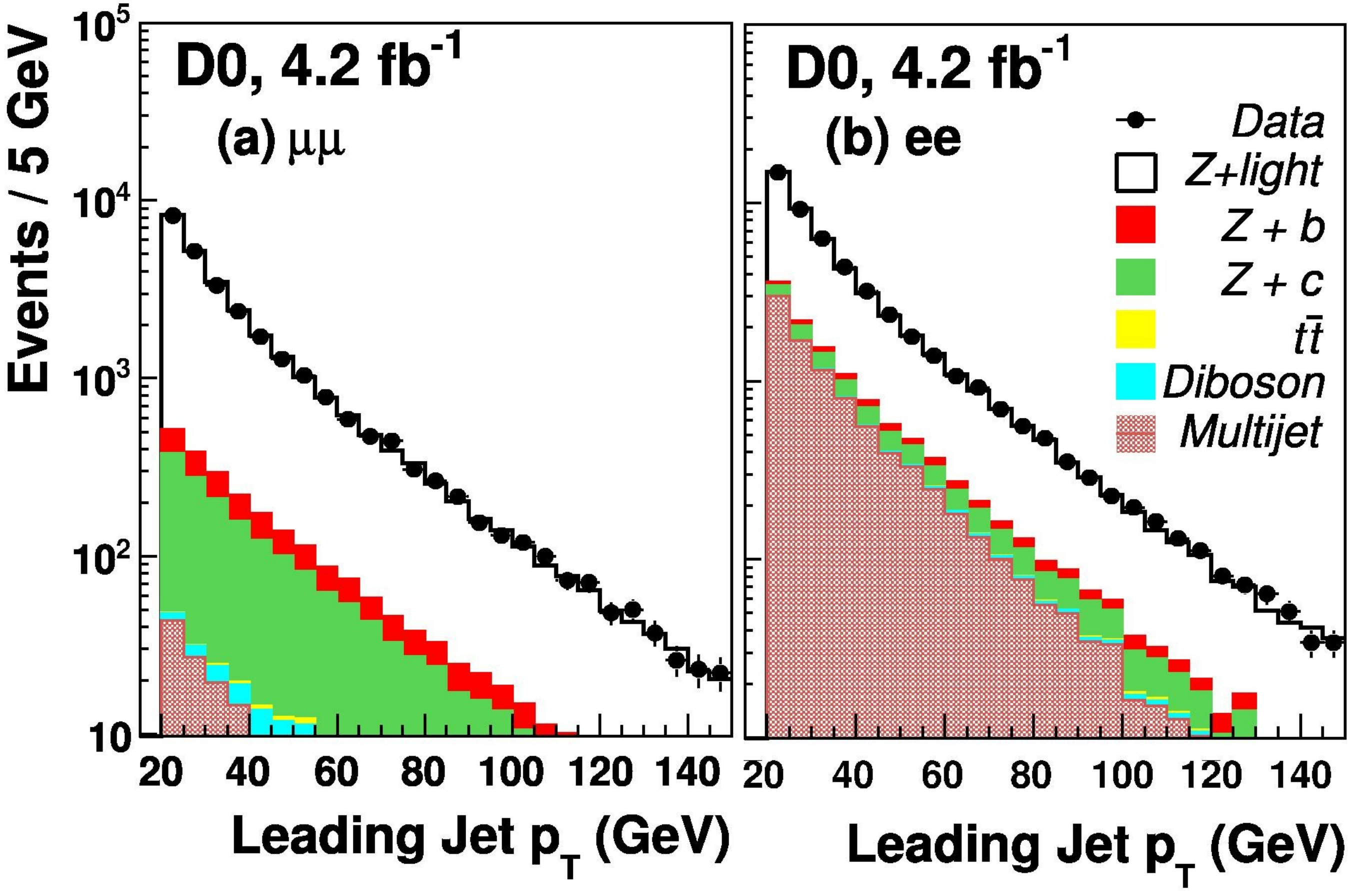
$$2.8 \times 10^{-3} \left(Q^2 = \langle P_{T,Jet}^2 \rangle\right)$$

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

PRD 79, 052008 (2009)

Z + b-jets

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



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)

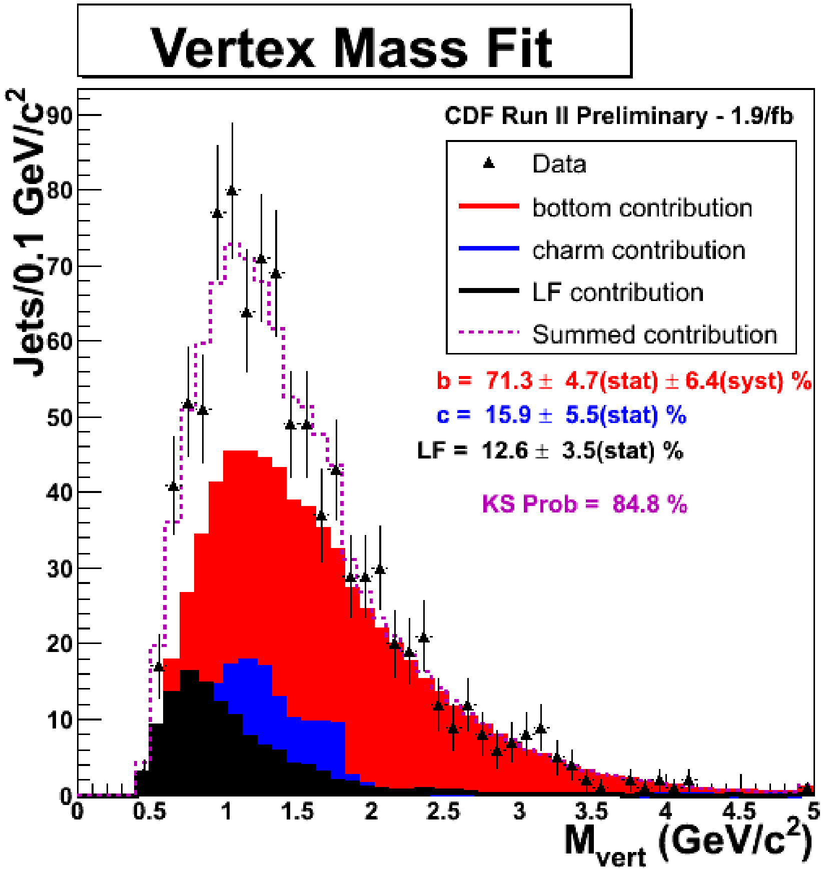
W + b-jets

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

W Kinematic region
Combined e and μ channels
$P_T^l > 20$ GeV, $|\eta_1^l| < 1.1$
MET > 25 GeV

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)

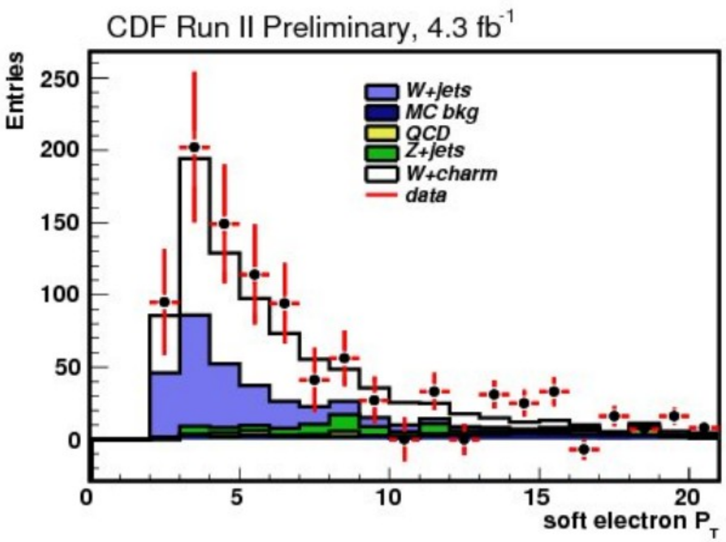
JETCLU R = 0.4 jet
E_T > 20 GeV/c, |η| < 2.0

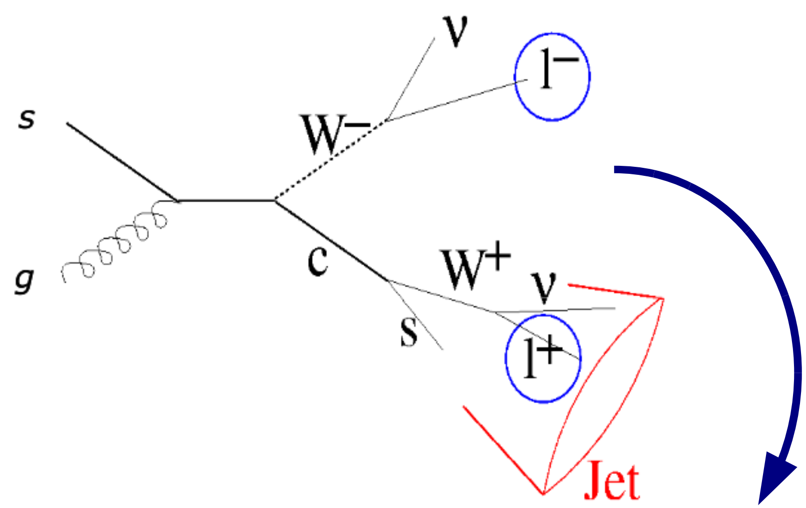
W + c (e channel)

$\mathcal{L}$ = 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

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

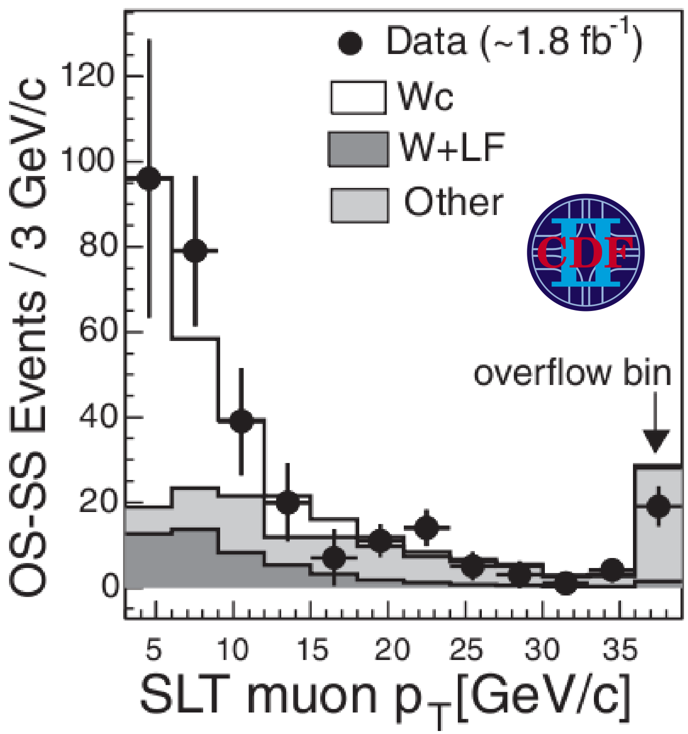
$$NLO\ prediction\ (MCFM): 11.0^{+1.4}_{-3.0}\ pb$$

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

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

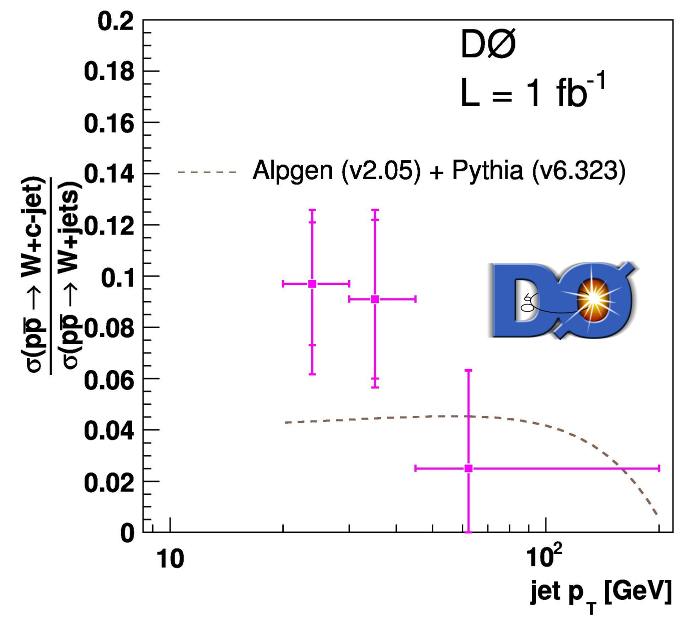
$$9.8 \pm 2.8(stat)^{+1.4}_{-1.6}(syst) \pm 0.6(lum)\,pb$$

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

PRL 100, 091893 (2008)

MIDPOINT R=0.5 jet $\mathcal{L}$ = 1 fb^{-1}

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



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

LO (Alpgen + Pythia) 0.044 ± 0.003

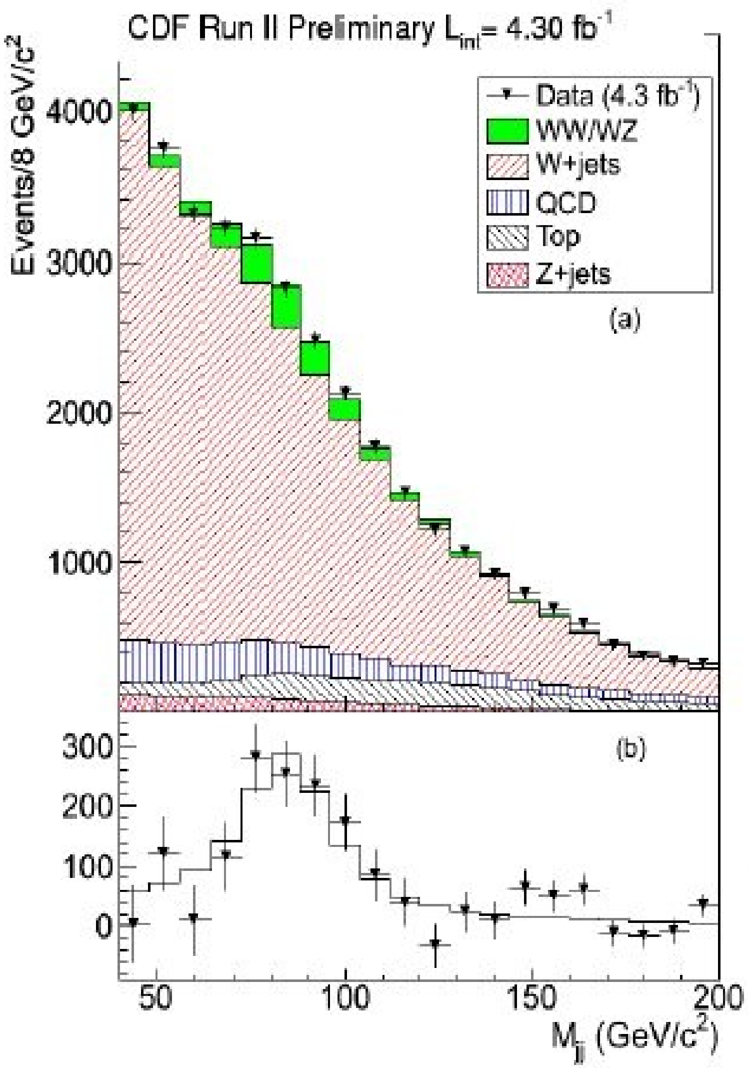
Phys. Lett. B 666, 23 (2008)

V + jets as a background for rare processes

WW/WZ Cross Section in W $\rightarrow l\nu$ + 2 jets final state

Phys. Rev. Lett. 104, 101801 (2010)

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



W + jets as background for rare SM processes

- Fit to the Di-jet invariant mass to measure the WW/WZ production cross section
- Observed 1582 ± 275(stat.)± 107(syst.) events → 5.2σ significance
- Measured cross section is
  σ(WW/WZ) = 18.1 ± 3.3 (stat.) ± 2.5 (syst.) pb
  NLO prediction 15.9 ± 0.9 pb

Some discrepancy in Di-jet Invariant Mass shape

Needed work to understand the nature of the discrepancy:

- Background mismodeling
- Real physics

Invariant Mass Distribution of Jet Pairs Produced in Association with a W boson in pp Collisions at $\sqrt{s}$ = 1.96 TeV

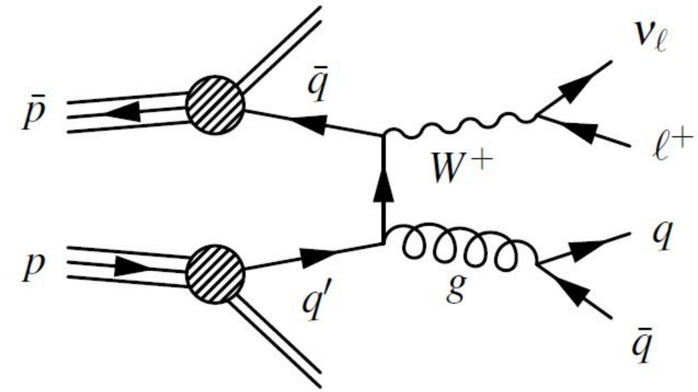
ArXiv:1104.0699
Joint Experimental-Theoretical Seminar at FNAL on April-6

W + 2 Jets - Event Selection

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

W Selection

- Electrons → E_T > 20 GeV, |η| < 1.0
- Muons → P_T > 20 GeV/c, |η| < 1.0
- Missing E_T > 25 GeV
- M_T^W > 30 GeV/c^2



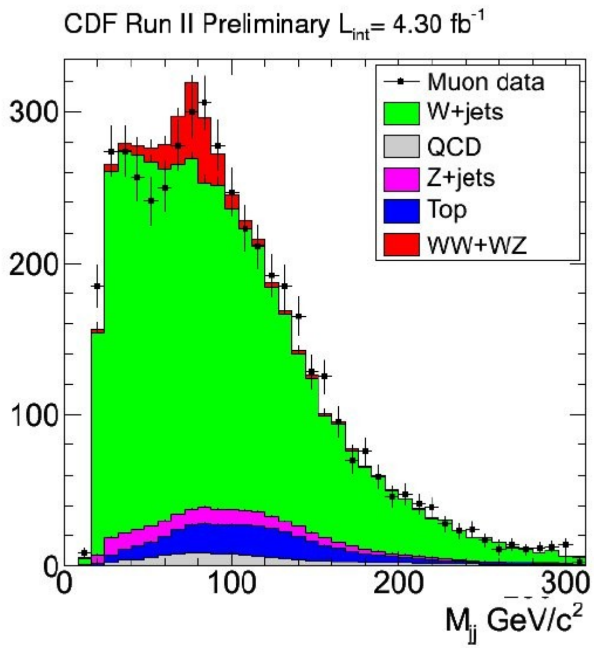
Jets Selection

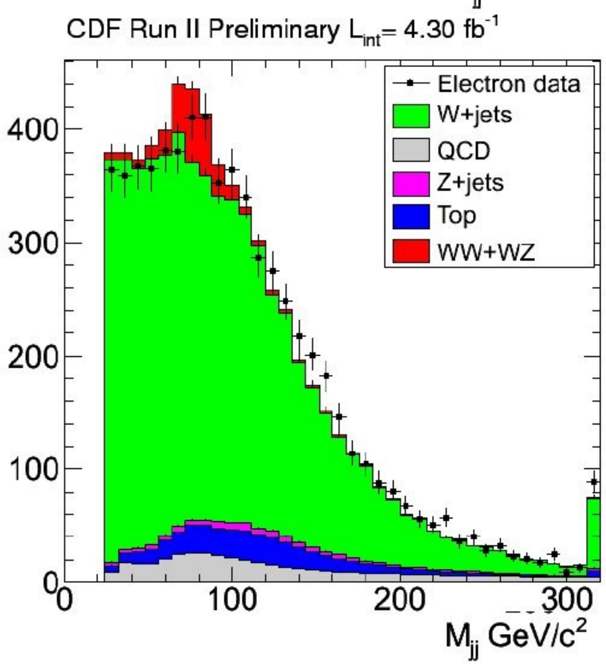
- JETCLU R = 0.4
- E_T > 20 → 30 GeV
- |η| < 2.4
- $|\Delta\eta_{jj}|$ < 2.5
- 2 Jets exclusive
- $P_{T,jj}$ > 40 GeV/c

Similar Event Selection (Except for jet E_T) used to

- *Measure WW/WZ diboson cross section*
- *Study discrepancy in Di-jet Invariant Mass*

Sample Composition





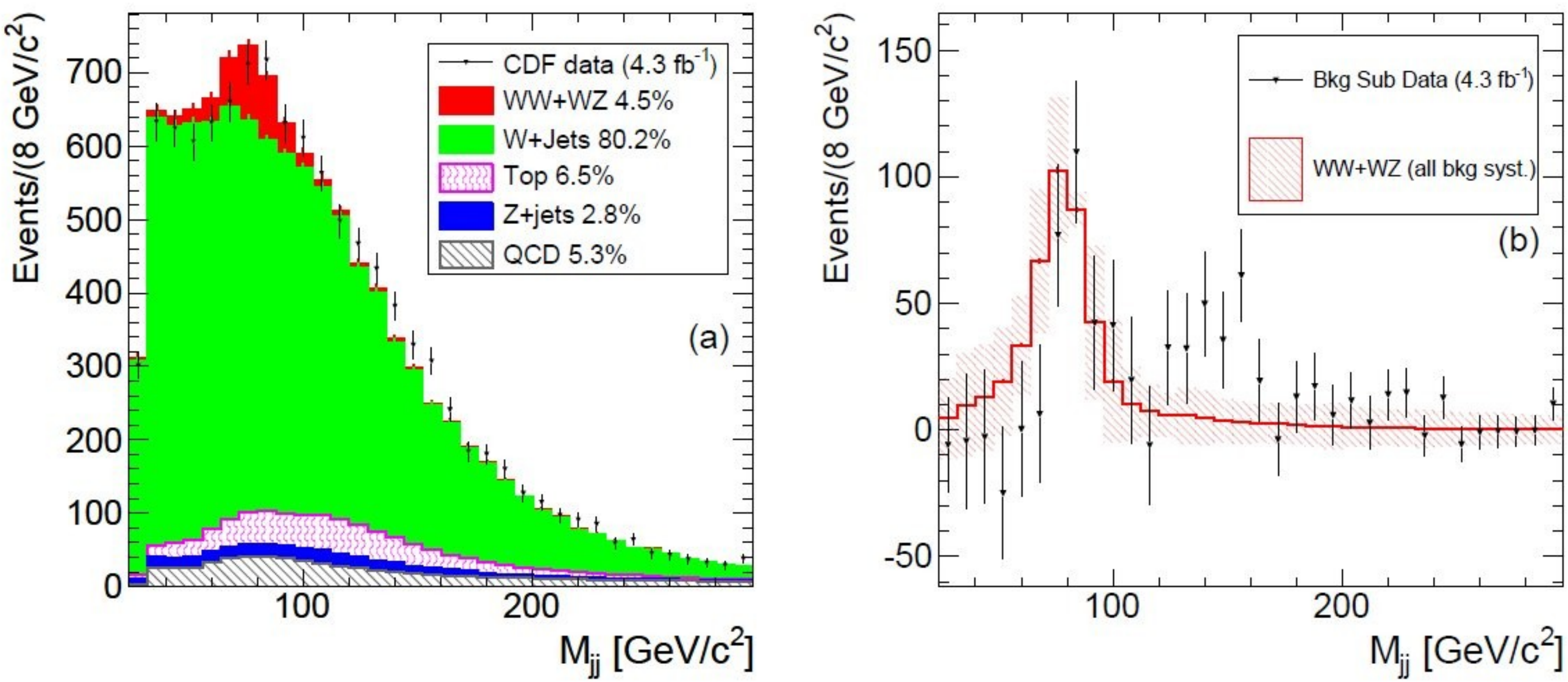
- W $\to l\nu$ + jets
  Main component, simulated with Alpgen + Pythia MC, normalized to data.
- tt + single top
  from MC $\to$ M_t = 172.5 GeV/c^2, σ(tt) = 7.5 pb
  and σ(single top) = 2.9 pb
- Z $\to$ ll + jets
  Modeled with Alpgen + Pythia MC, normalized to measured cross section
- QCD multijet
  Data driven technique: fake lepton templates are normalized to data by fit to the Missing E_T distribution
- WW/WZ
  from MC, normalized to NLO theory prediction 15.9 pb

Fitting procedure

Combined χ^2 fit to the Di-jet mass distribution in electron and muon samples

5 templates:

- W + jets → unconstrained, normalization determined from the fit
- QCD → normalization constrained to its fraction with 25% uncertainty
- Z + jets → normalization constrained to the measured cross section
- top & single top → normalization constrained to the theoretical cross section
- WW+WZ → normalization constrained to the theoretical cross section



Disagreement is observed in 120-160 GeV/c^2 region

Gaussian assumption

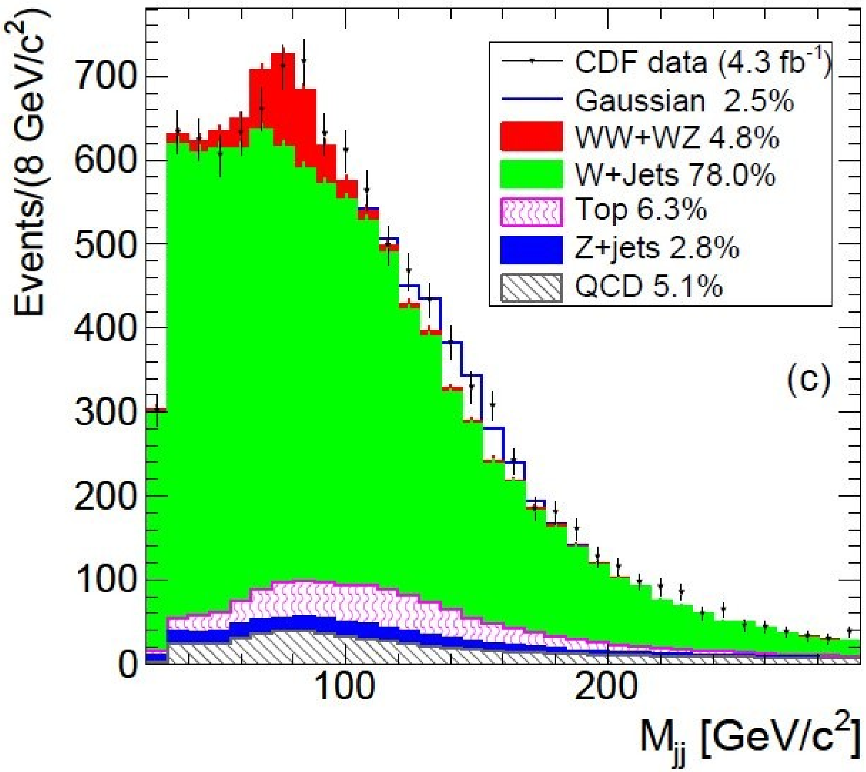
- Try to estimate the significance of the excess assuming an additional gaussian component.
- Since the excess looks narrow with respect to the detector resolution, we search for a peak compatible with the detector resolution for a given dijet mass value.
- Electron and muon channels yields are left separately free

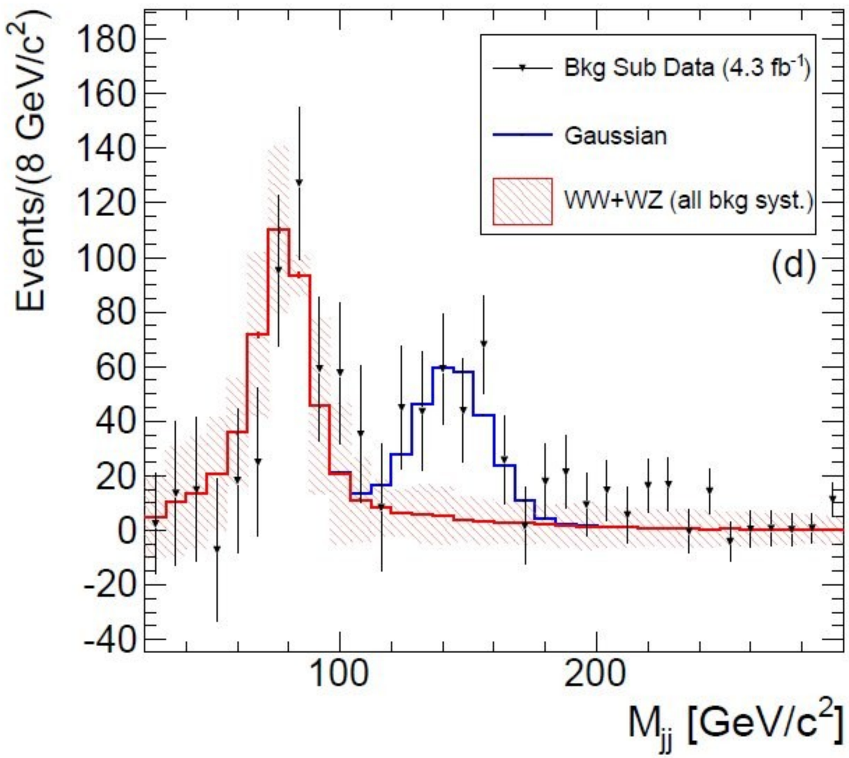
$$\sigma_{gaussian} = \sigma_W \sqrt{\frac{M_{jj}}{M_W}} = 14.3 GeV$$

Procedure to evaluate the significance:

- Fit the data without the gaussian and evaluate χ^2
- Fit the data with the gaussian and evaluate χ^2
- Verify the behavior of the 2 cases with trial factor.

Fit with Gaussian





$\Delta\chi^2$ observed 20.31 that corresponds to a **statistical** significance of 3.7σ

	Electrons	Muons
Excess events	156 ± 42	97 ± 38
Excess events / expected diboson	0.60 ± 0.18	0.44 ± 0.18
Mean of the Gaussian component	144 ± 5 GeV/c^2	

Systematics

- Jet energy scale is moved up and down 1σ in all MC based processes
- QCD shape systematic is evaluated using different Isolation range for fake leptons
- Scale uncertainty on W+jets is evaluated varying the renormalization and factorization scale (Q^2)

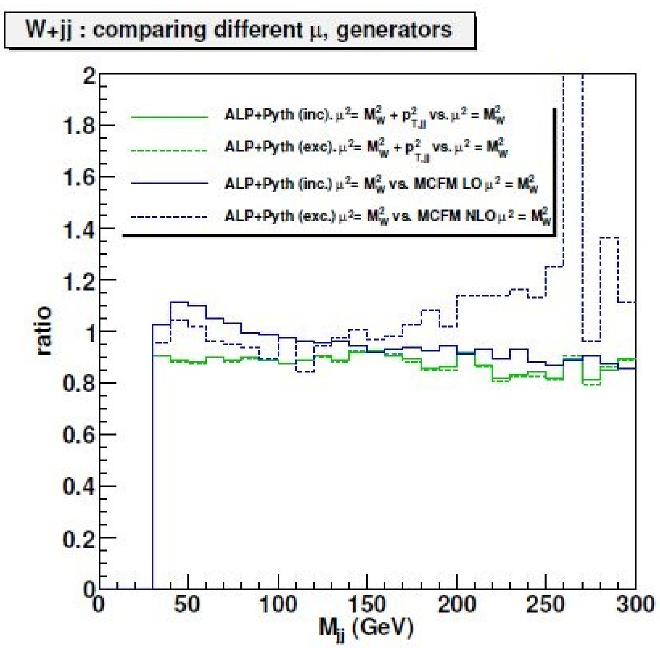
Affected Quantity	Source	Uncertainty (%)
Number of Excess Events	QCD shape	± 1.9
	Q^2	± 6.7
	JES	± 6.1
	Total	$\pm \mathbf{9.3}$

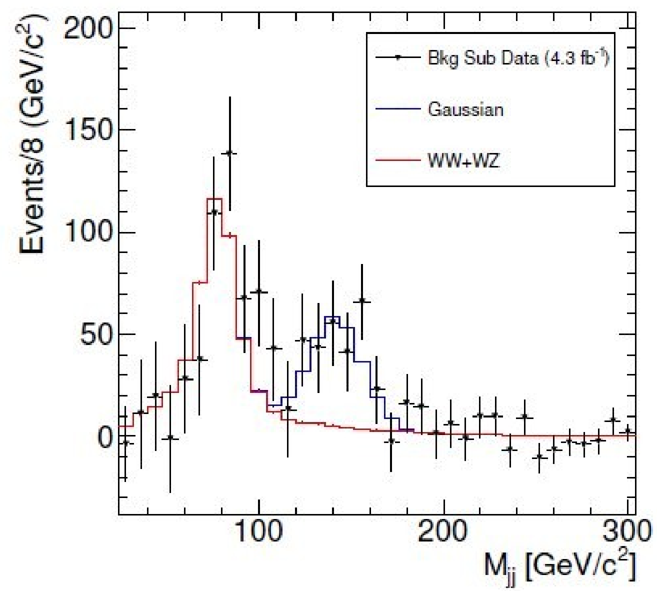
- For each possible combination of systematic effects a different $\Delta\chi^2$ distribution is evaluated
- The distribution that returns the highest p-value (lower significance) is considered → the largest p-value is 7.6 x 10^{-4} corresponding to a significance of **3.2** standard deviations

NLO correction

Investigate Next to Leading Order contributions to the W+2 partons prediction

- ALPGEN + PYTHIA is compared to the NLO prediction evaluated with MCFM (private communication with J.Campbell, E. Eichten, K.Lane, A.Martin)
- A correction as a function of M_{jj} is applied to the ALPGEN + PYTHIA sample used in our background model.
- The statistical significance with the reweighted MC is 3.4σ





Flavour Composition

- The cross section times branching ratio into di-jets of a real process behind this excess would be 4 pb → not compatible with Standard Model Higgs: WH x BR(bb) = 12 fb

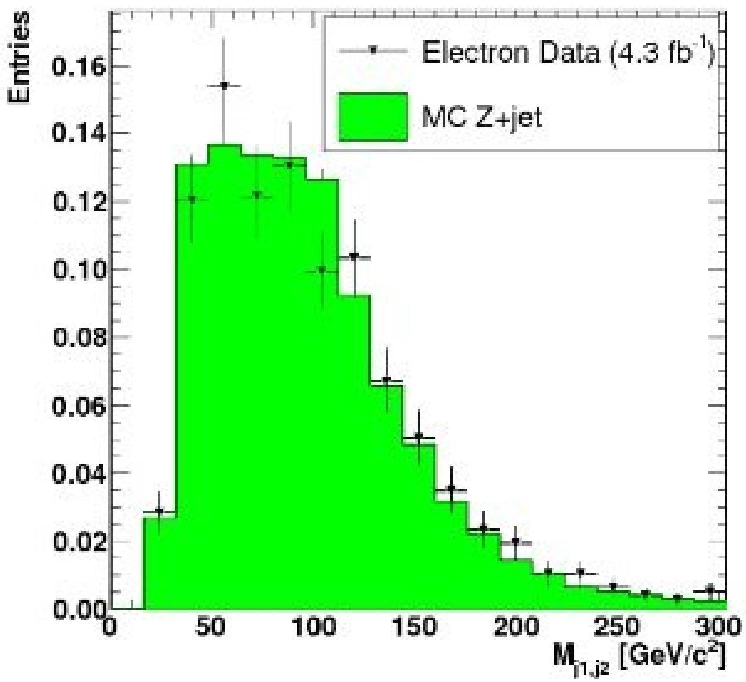
- Compared the fraction of events with b-jets in the sidebands to that in the excess region (120> M_{jj} >160 GeV/c^2)

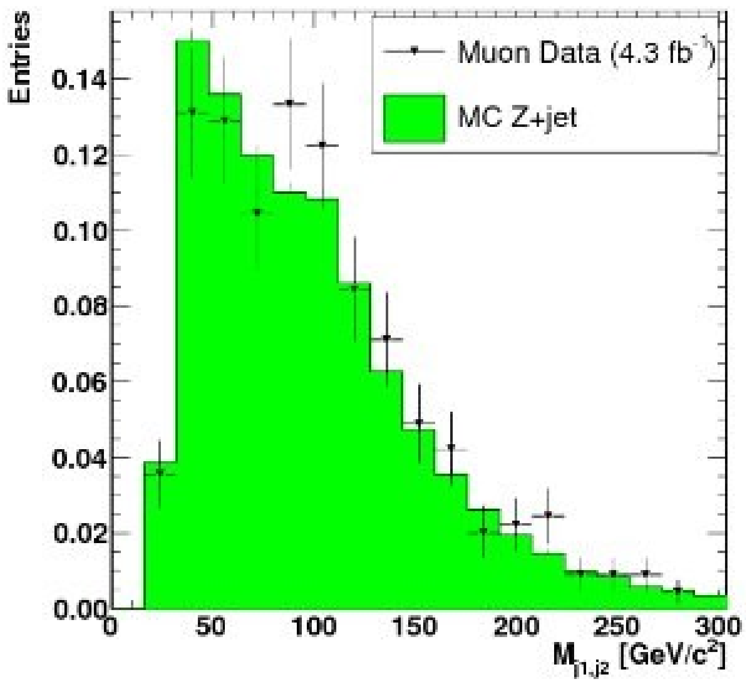
Tag requirement	Excess region	Sideband region
Muons		
1 tag	0.1027 ± 0.0112	0.0813 ± 0.0096
2 tag	0.0078 ± 0.0030	0.0084 ± 0.0030
Electrons		
1 tag	0.0897 ± 0.0088	0.0945 ± 0.0087
2 tag	0.0110 ± 0.0030	0.0095 ± 0.0026

Z + 2 Jets

Check MC modeling in Z + 2 Jets final state

- Same Jets selection as in W + 2 Jets study
- Z $\rightarrow$ ll reconstructed in muons and electrons channels
- ~10 times less statistics

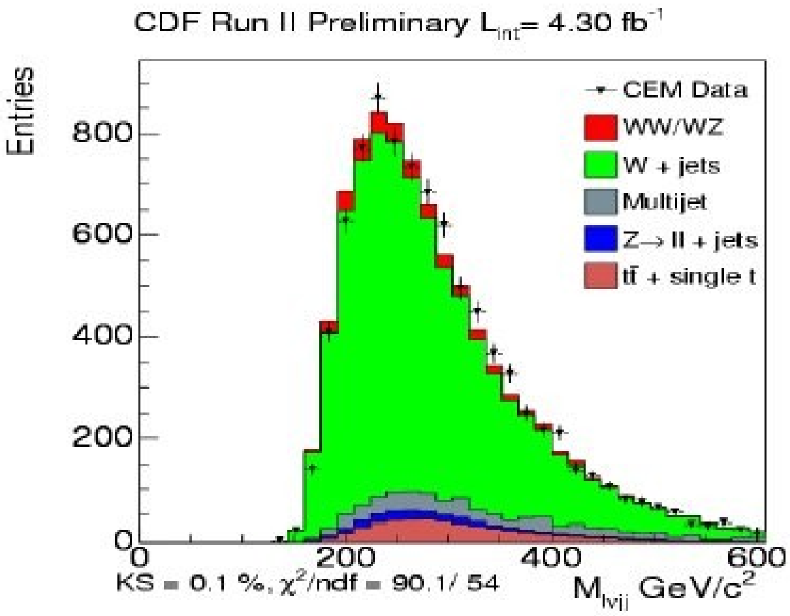


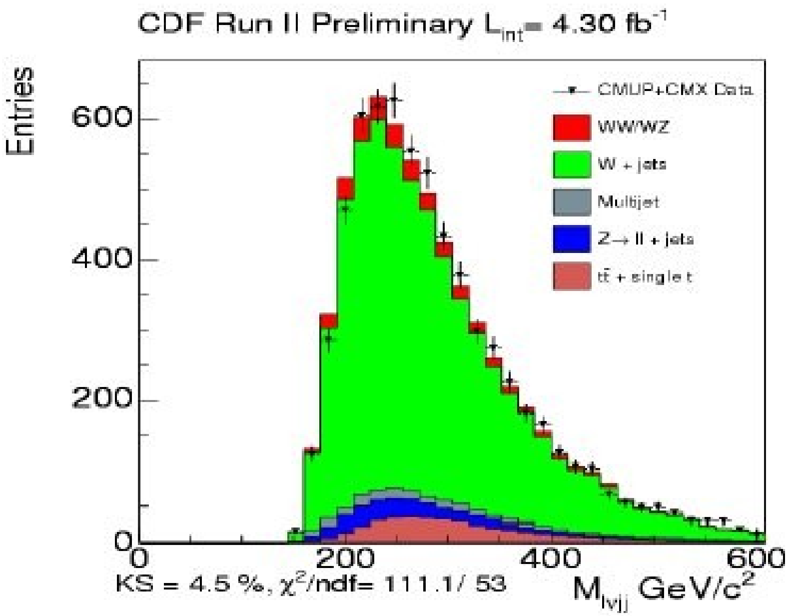


No significant discrepancy observed

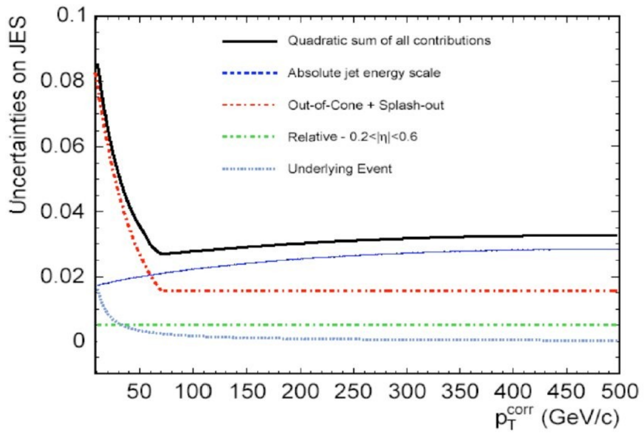
lνjj Invariant Mass

- Invariant Mass of the (l ν j j) system for events with Mjj in the range 120-160 GeV/c^2 for electron and muon channels
- The distributions are compatible in shape with the background-only hypothesis

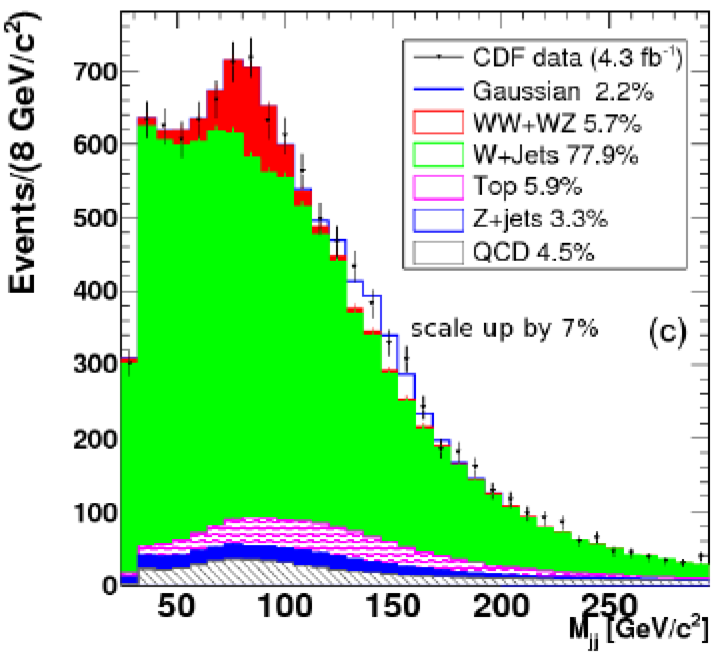


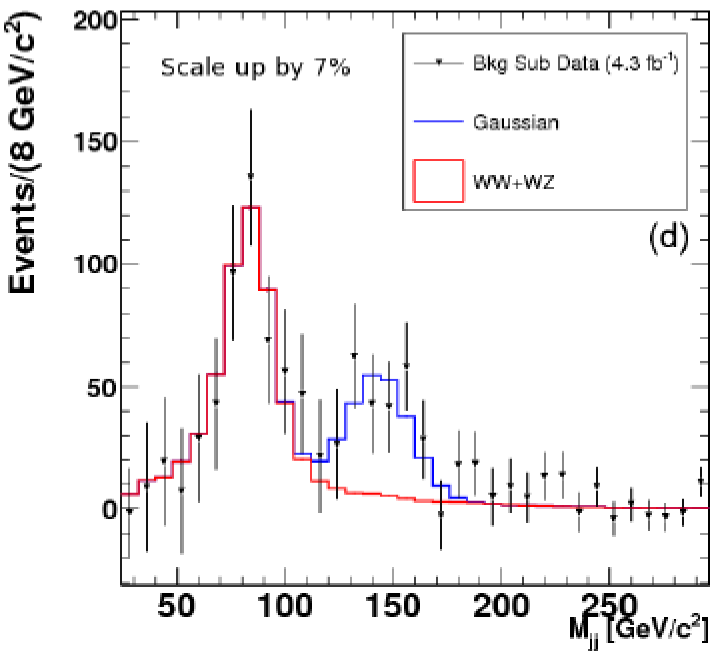


Scale JES of 7%



Scale the Jet Energy Scale up of 7% in the MC





Significance is always above 3σ

W + 2 Jets - Conclusions

- Significant disagreement with MC modeling in Di-jet Invariant Mass
- Challenging theory → need to understand the accuracy of MC modeling
- Compare with other experiments
- Need more work to understand if the excess is real new physics or mismodeling

Summary

- New results on Z+jets, Z+b, W + jets
- General good agreement with NLO predictions
- Interesting discrepancy in W + 2 Jets final state
- Prospects for more precise W/Z + HF measurements, Z + jets e-μ combination and W + c combination

More details at:

- http://www-cdf.fnal.gov/internal/physics/qcd/qcd.html
- http://www-d0.fnal.gov/Run2Physics/WWW/results/qcd.htm
- http://www-cdf.fnal.gov/physics/ewk/2011/wjj

BACKUP

Diboson in W + 2Jets