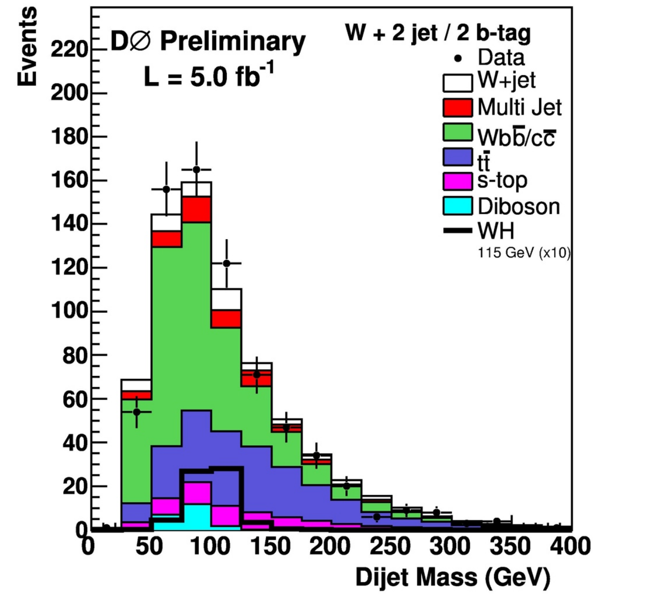
Production of W/Z bosons and of W/Z+jets at the Tevatron

Standard Model Benchmarks at High-Energy Hadron Colliders 2011

Darren Price,
INDIANA UNIVERSITY

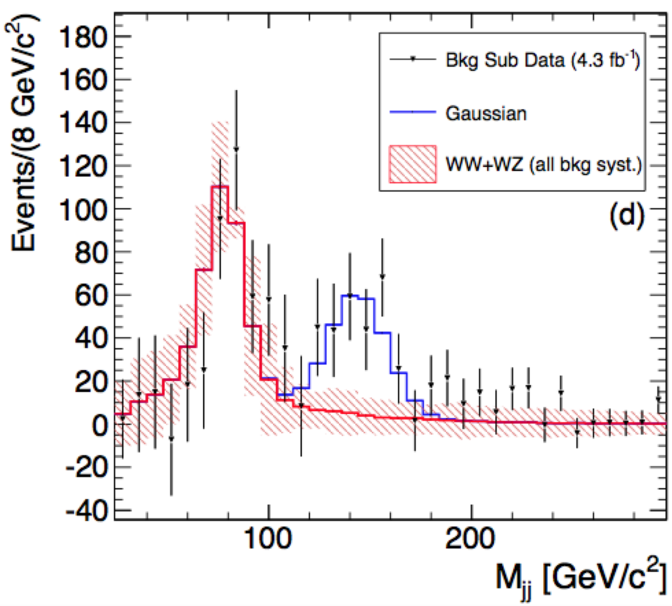
on behalf of the CDF and DØ collaborations



Tevatron results continue to provide rich legacy of precision results for understanding of Standard Model processes.

Will remain competitive with LHC in many selected topics

Good understanding of detector performance: uncertainties are such that CDF/DØ can do precision QCD/EW physics



Improve SM background understanding: particularly those with large jet multiplicities and/or heavy flavour components

Interplay between heavy flavour models, MC tunes, PDFs and scale choices needs to be understood to model SM for future precision measurements and searches.

Z/γ* transverse momentum

PHYS. LETT. B 693, 522 (2010), ARXIV:1006.0618

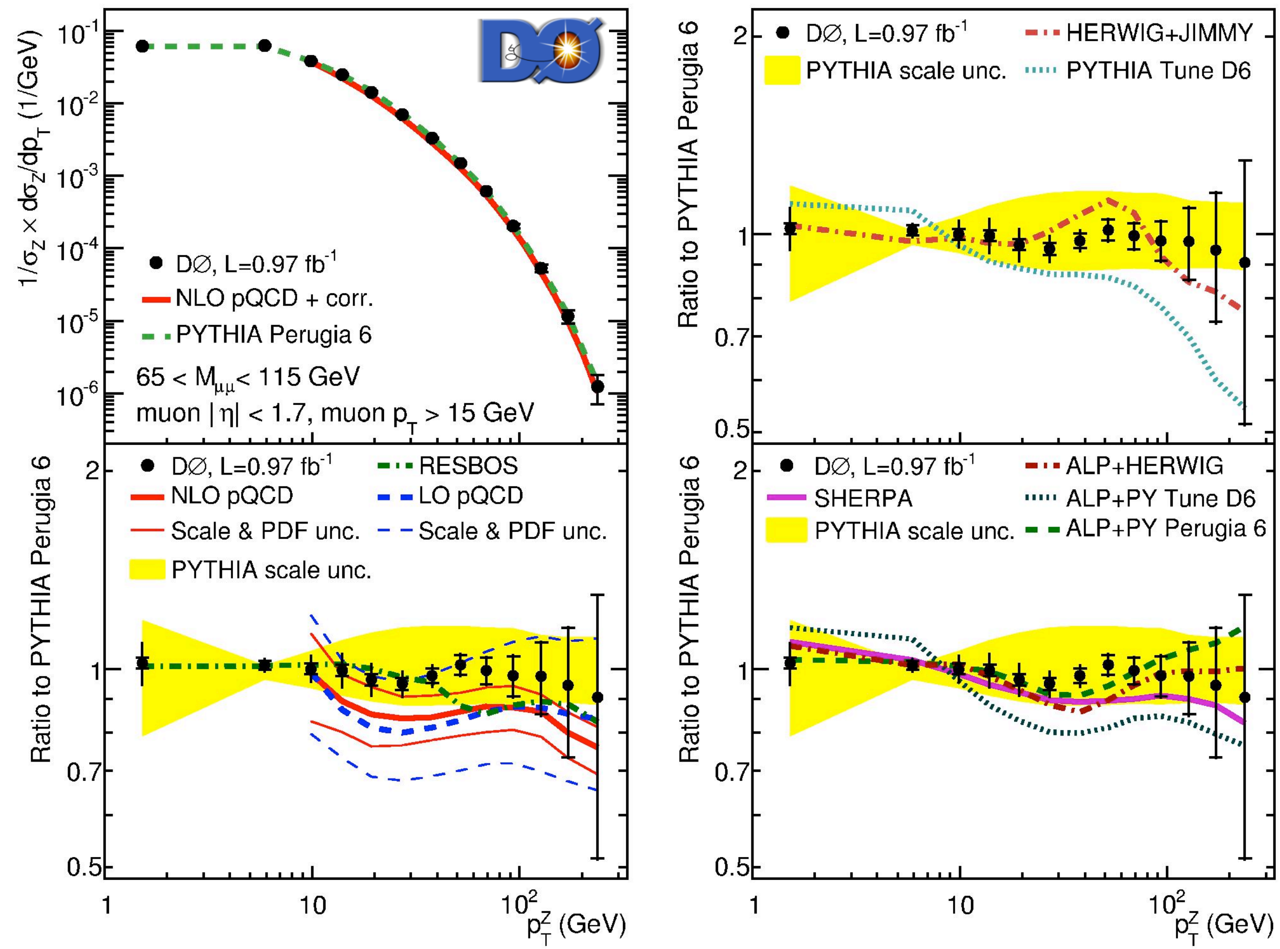
Z/γ* kinematics provides colourless probe of underlying collision process. Results corrected back to particle-level

Vector boson p_T spectrum sensitive to parton initial state radiation

Pythia Perugia6 gives best description of data over entire kinematic range

Low p_T spectrum sensitive to multiple soft gluon emission

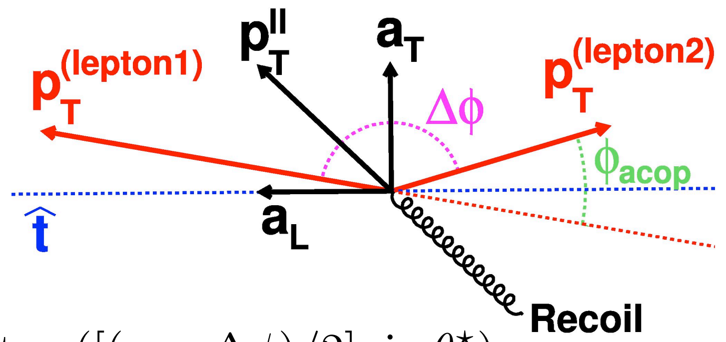
Requires resummation techniques/models



Z/γ* transverse momentum

Phys. Rev. Lett. 106, 122001 (2011), arXiv:1010.0262

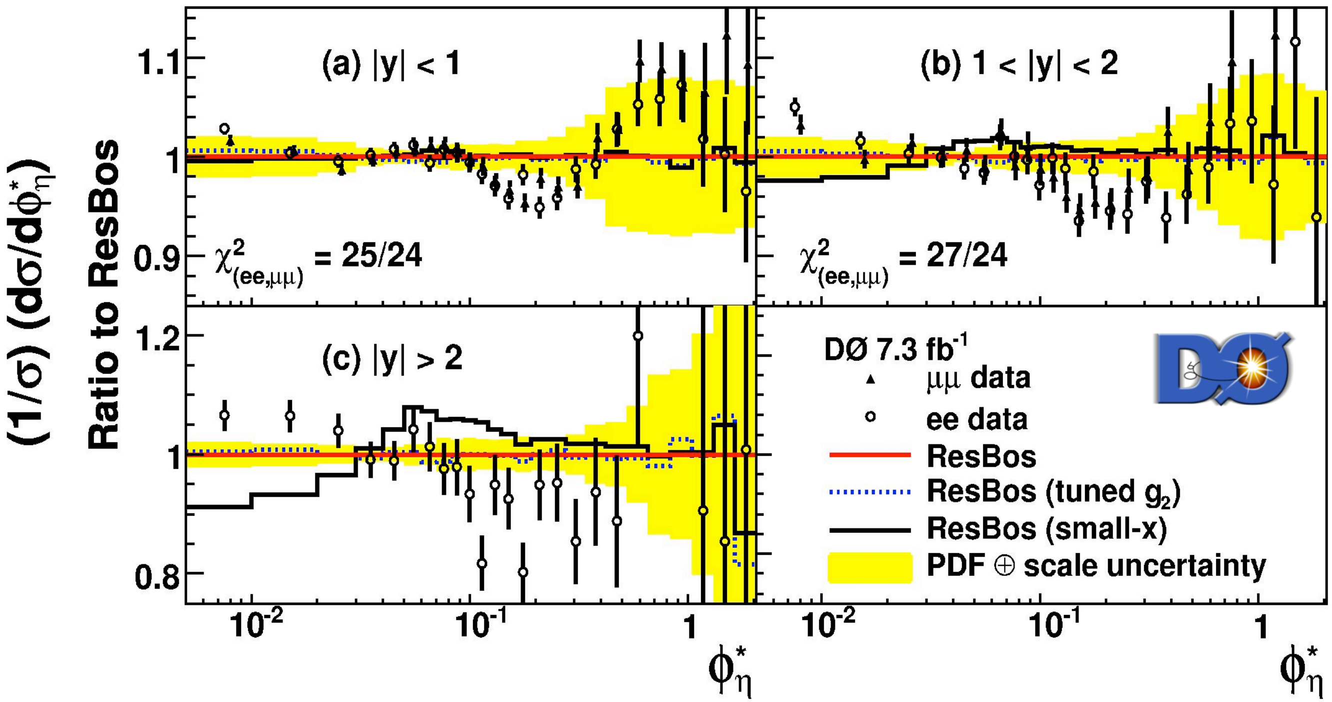
Recent DØ result (7.3 fb^{-1}) uses new variable ϕ^* based on the two lepton directions



Less vulnerable to detector resolution/efficiency limiting precision of $p_T(Z)$ measurement

ϕ^* correlated with Z/γ^* p_T distribution

$$\phi^*_\eta = \tan\left([(\pi - \Delta\phi)/2]\sin\theta^\star\right)$$
$$\cos\theta^\star = \tanh\left([\eta^- - \eta^+]/2\right)$$



Data broadly described by NLO +NLL but detailed shape poorly described by ResBos

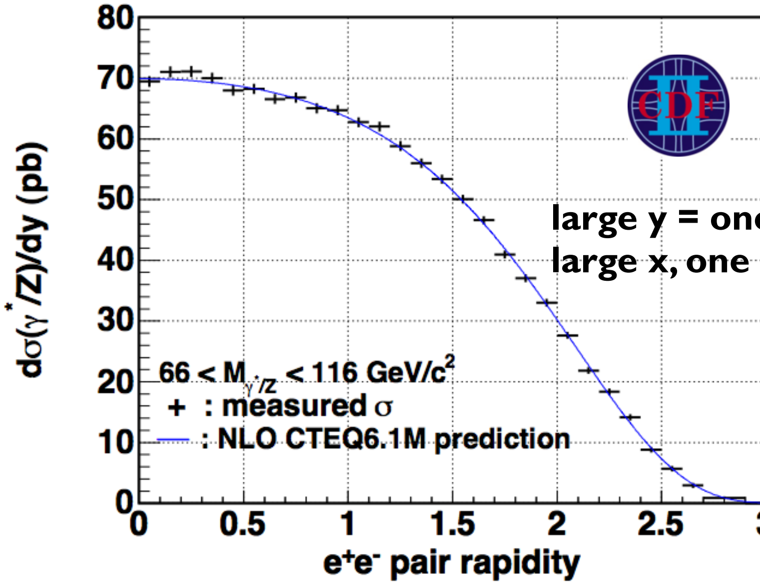
Small-x broadening strongly disfavoured

Z/γ* rapidity related to fraction of momentum carried by two partons

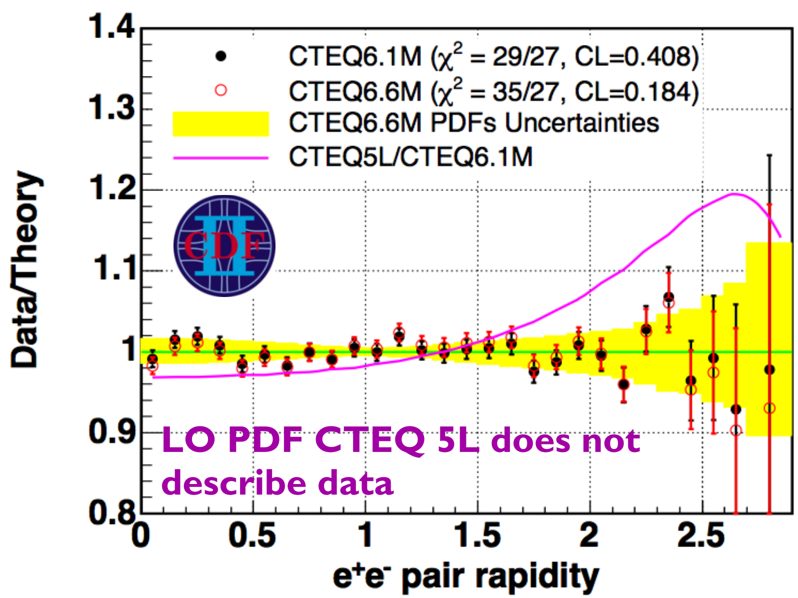
Differential cross section measurement carries information for PDFs complementary to W charge asymmetry

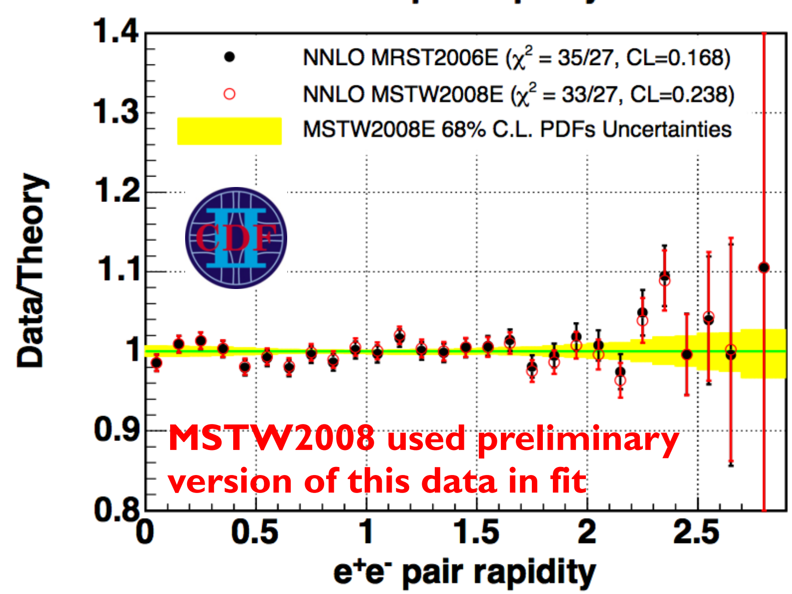
Good agreement between data and theory seen over the entire spectrum

PHYS. LETT. B 692, 232 (2010), ARXIV:0908.3914



large y = one parton large x, one small x



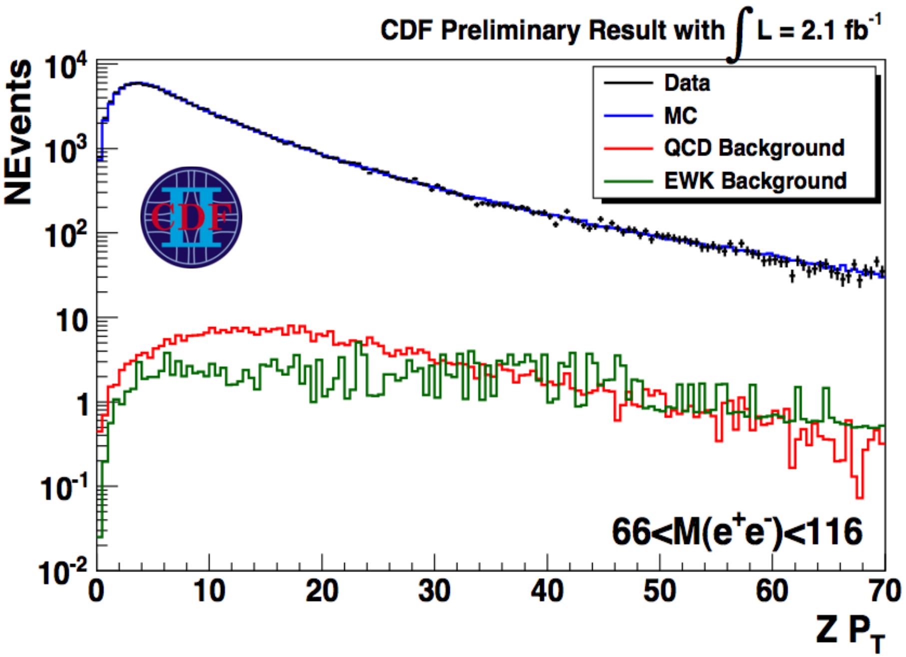


Lepton angular distribution in Collins-Soper frame given by:

$$\frac{d\sigma}{d\cos\theta} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_4\cos\theta$$

$$\frac{d\sigma}{d\phi} \propto 1 + \frac{3\pi A_3}{16}\cos\phi + \frac{A_2}{4}\cos 2\phi$$

CDF PUBLIC NOTE 10312 (2011)



pQCD predicts specific angular distribution and values/behaviour of coefficients:

A_0 & A_2 have specific dependence on Z p_T

Different for quark-antiquark annihilation and Compton scattering processes

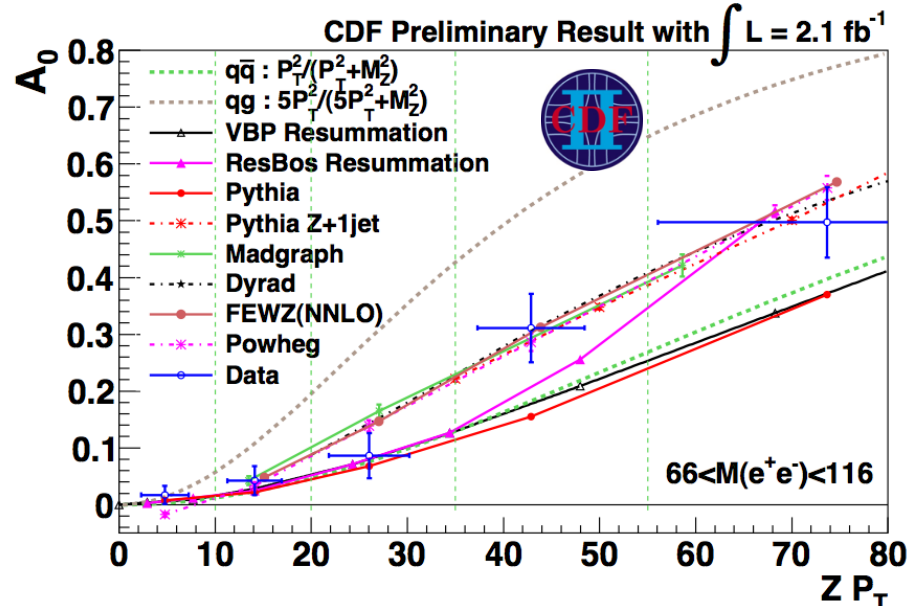
A_3, A_4 expected relatively flat with p_T
A_4 related to A_{FB} and $\sin^2\theta_W$

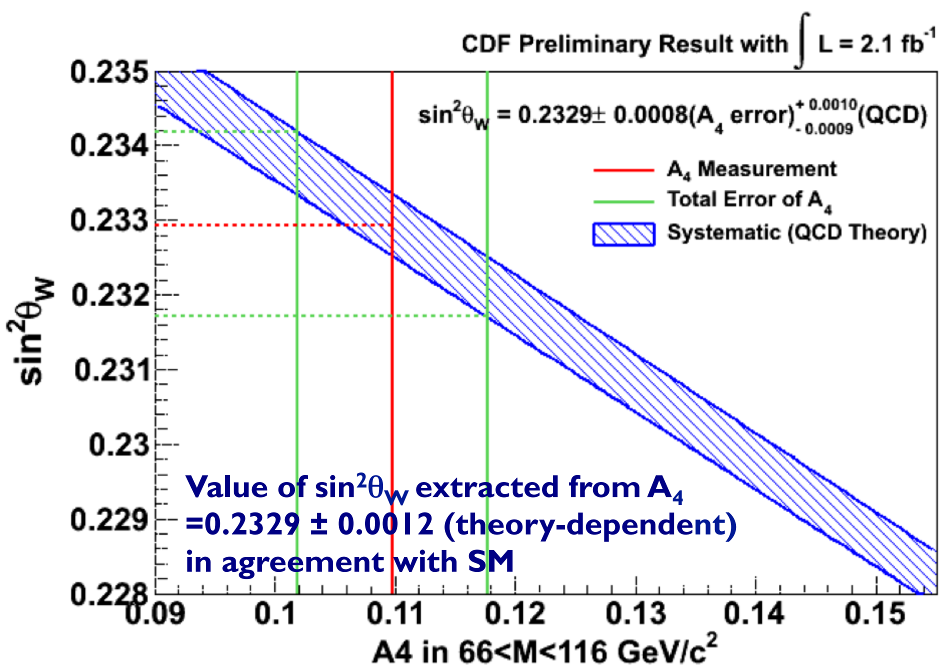
Lepton angular distribution in Z/γ^*

Strong p_T dependence observed in A_0 and A_2

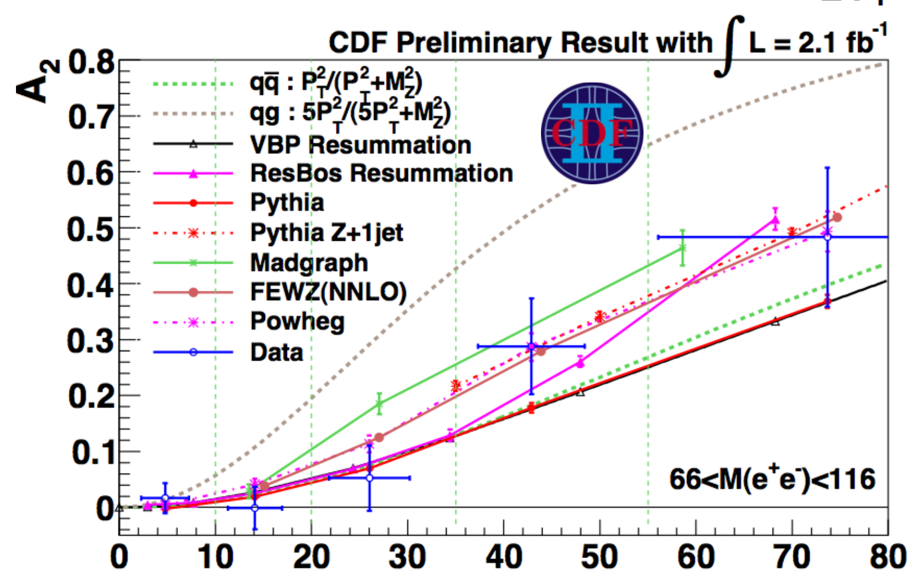
Average A_0-A_2 = 0.017 ± 0.023

Lam-Tung relation ($A_0 \approx A_2$) implies gluon is spin-1 – validated by data
(Relation badly-broken for scalar gluons)





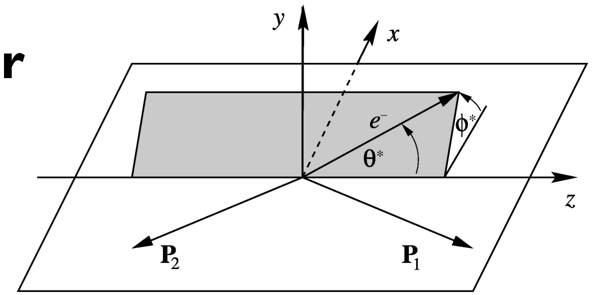
Value of $\sin^2\theta_W$ extracted from A_4 =0.2329 ± 0.0012 (theory-dependent) in agreement with SM



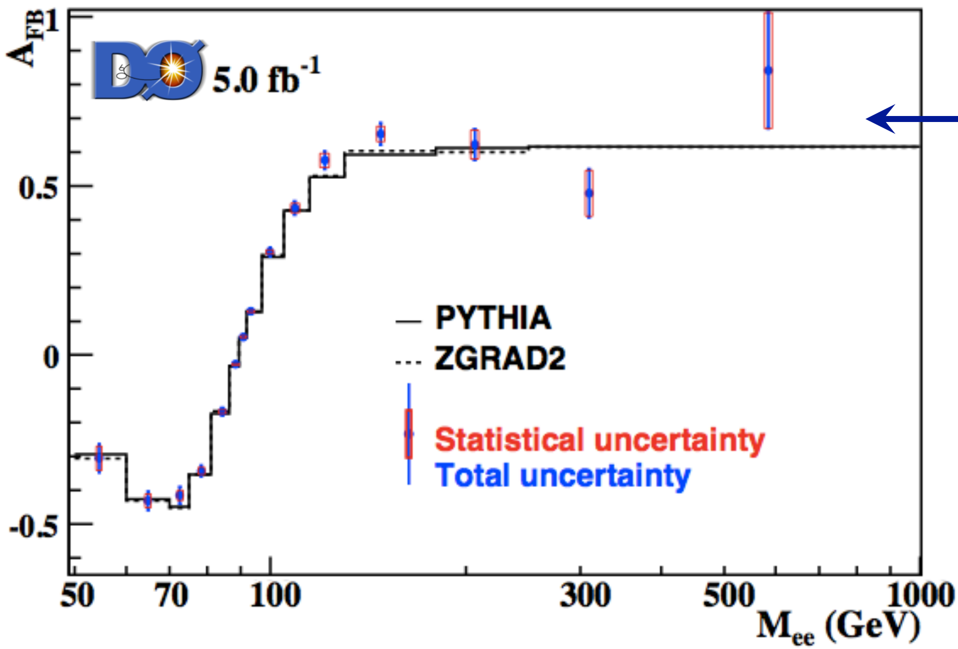
CDF Public Note 10312 (2011)

Z/γ* Forward-backward asymmetry

Presence of vector and axial-vector couplings for fermion-Z causes asymmetric distribution for cosθ* distribution: $A_{FB} = (\sigma_F - \sigma_B)/(\sigma_F + \sigma_B)$

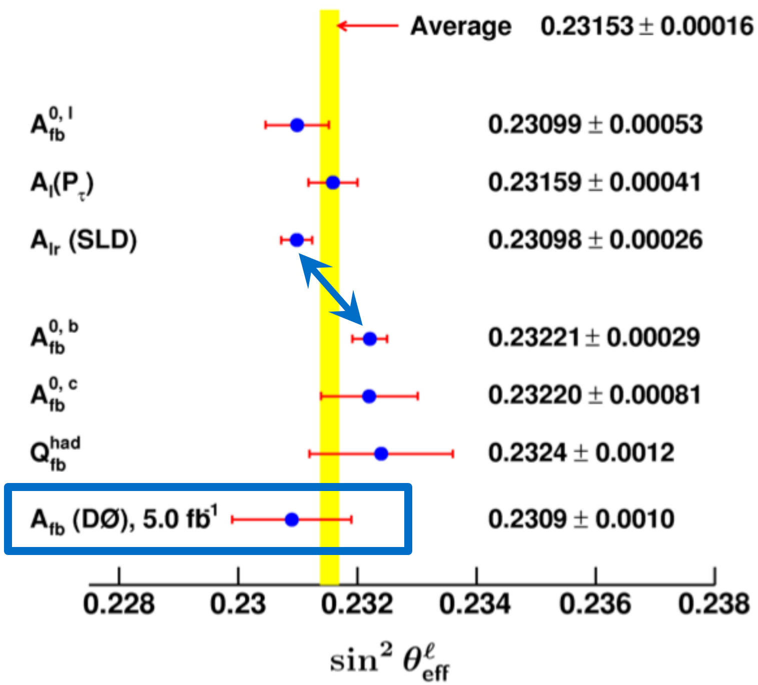


ARXIV:1104.4590, SUBMITTED TO PHYS. REV. D



Unfolded A_{FB} distribution

High mass sensitive to new physics



Extraction of effective weak mixing angle:
$\sin^2\theta_{eff}$ = .2309 ± .0008 (stat) + .0006 (syst)
Agrees well with world average

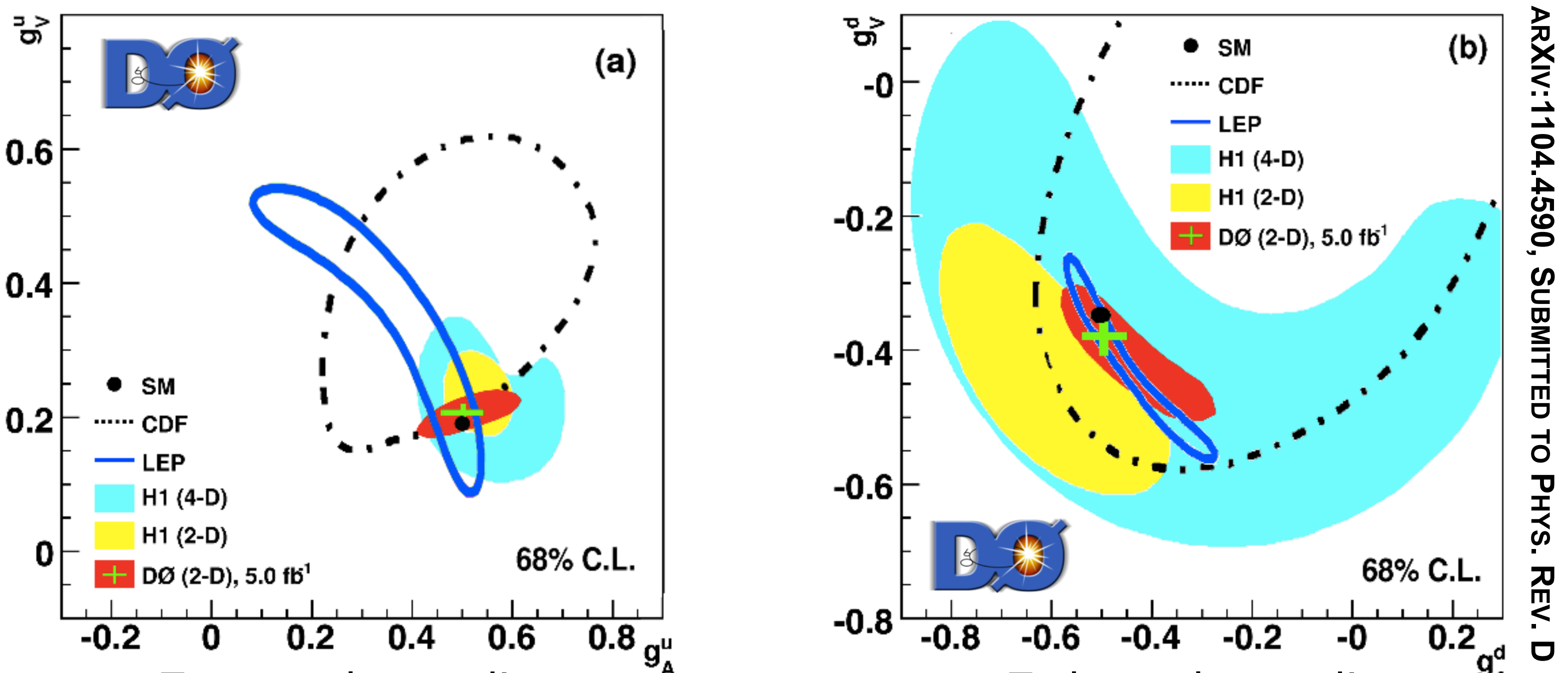
Z-u and Z-d couplings

A_{FB} sensitive to couplings of the light quarks to the Z

New phenomena such as neutral gauge bosons or large extra dimensions can alter AFB

Compare unfolded AFB distribution with theoretical predictions with different Z-u and Z-d couplings

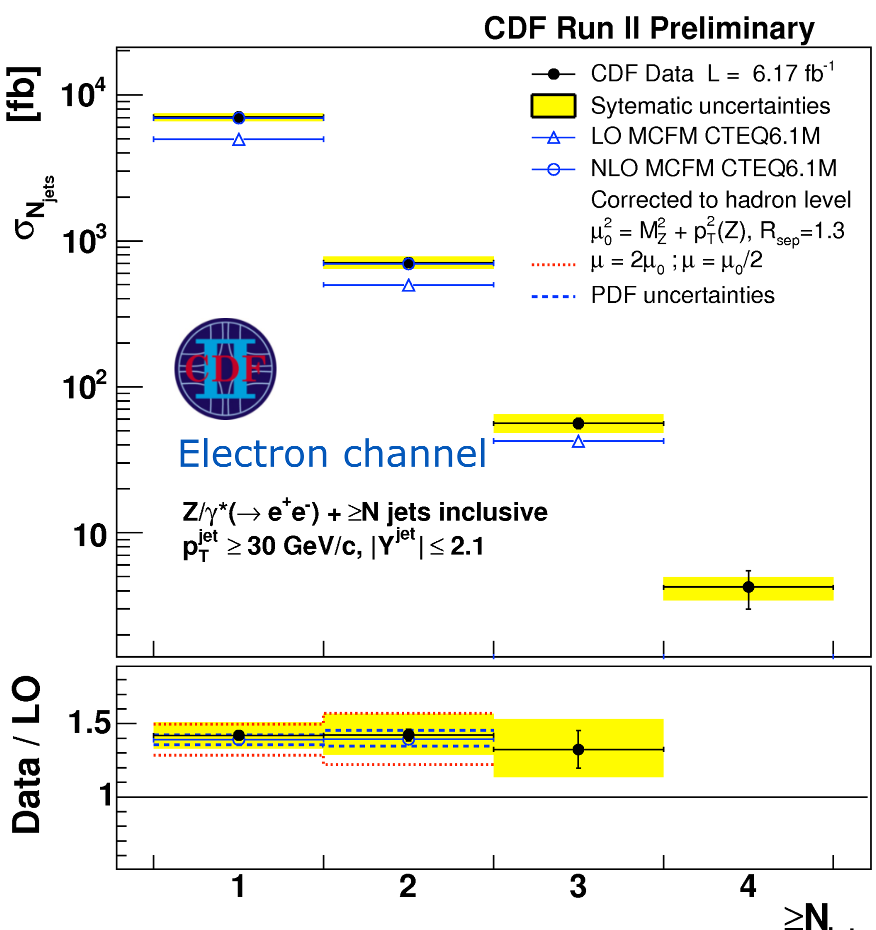
2-D fits are made to u, d vector and axial-vector couplings to Z and compared to other experiments – most precise to date!



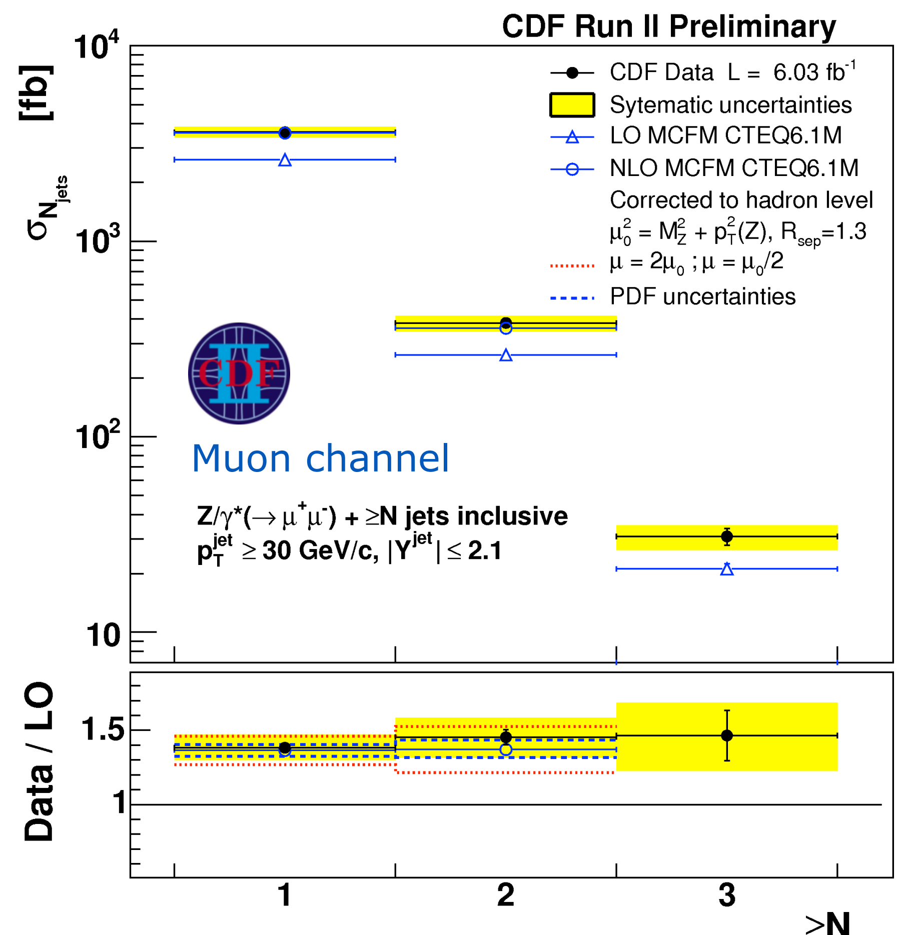
Z-u quark couplings Z-d quark couplings

Measurement of inclusive Z(ee/μμ)+(n)jet cross-sections (6.1 fb^{-1})

Test of pQCD calculations; dominant background for SM measurements and new physics
Corrected to particle-level, compared to NLO pQCD corrected with parton-to-particle level corrections



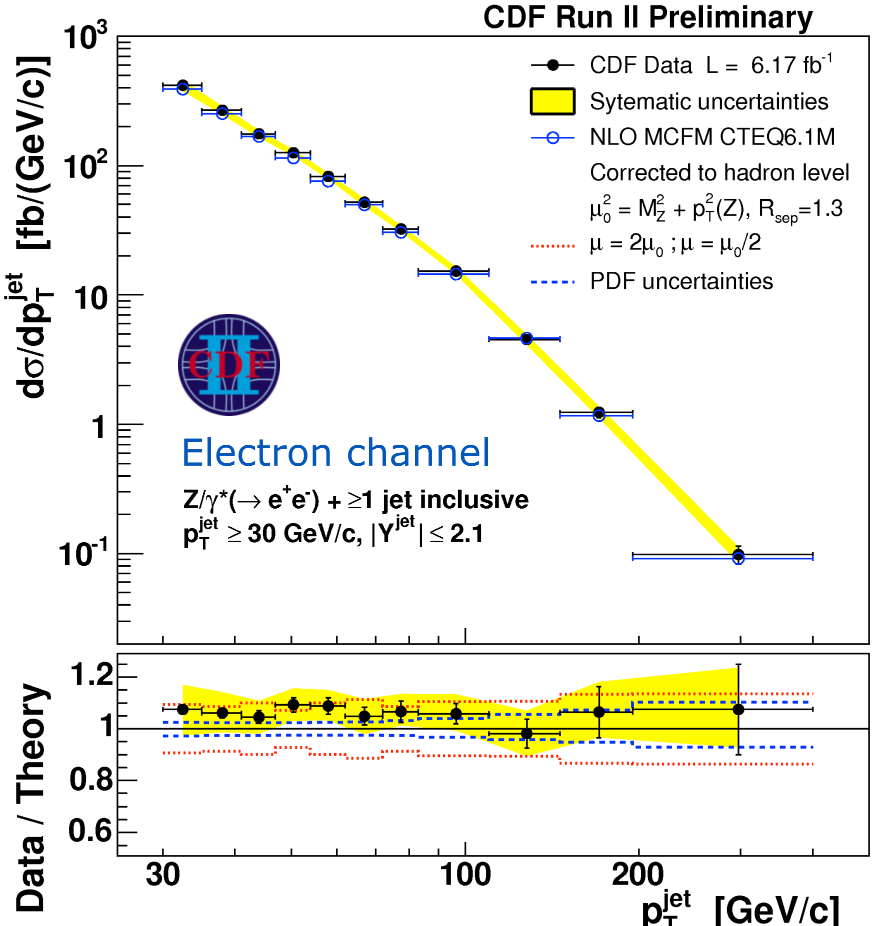
CDF Public Note 10394 (2011)



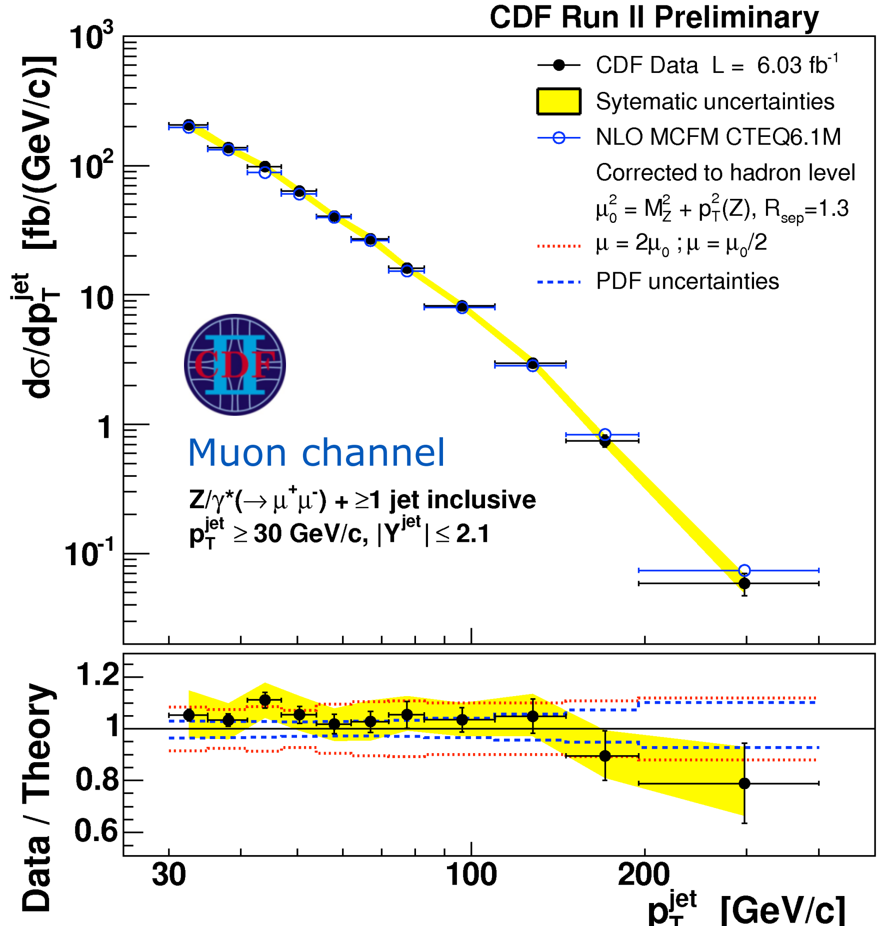
CDF Public Note 10216 (2011)

Inclusive jet differential cross-section (muon/electron channel): study kinematics of hadronic recoil to Z.

Data well-described by NLO theory



CDF Public Note 10394 (2011)



CDF Public Note 10216 (2011)

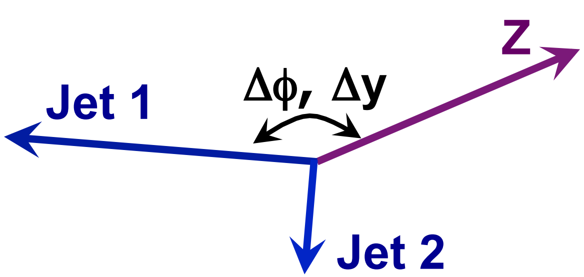
Z+jets angular observables: $\Delta\phi(Z,j)$

First measurement of angular correlations between Z and leading jet

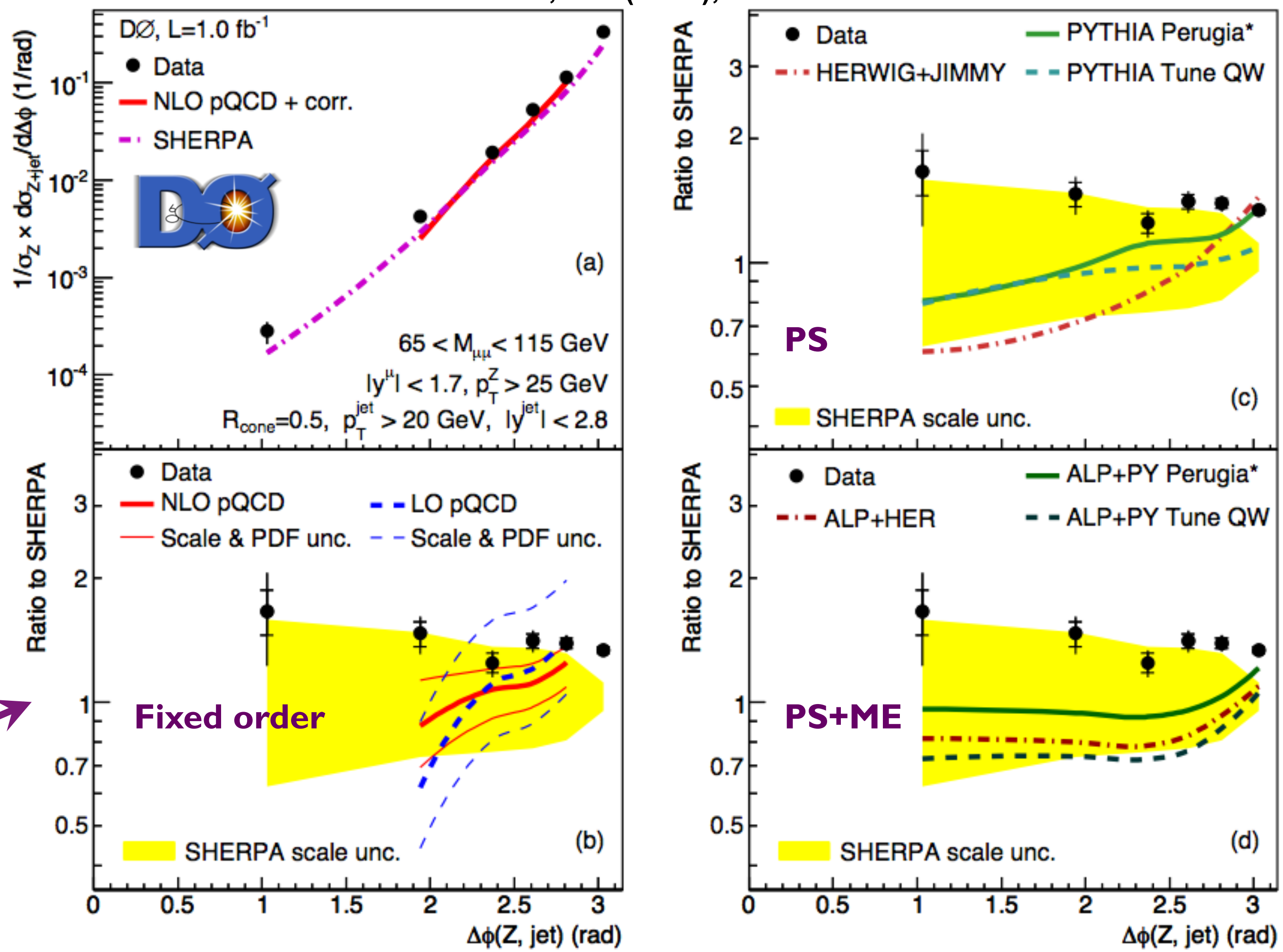
$Z \rightarrow \mu\mu$: $|y^{\mu}|<1.7$, $p_T^{Z}>25$ GeV, jet $p_T>20$ GeV, $|y^{jet}|<2.8$, $R_{cone} = 0.5$

Sensitive to additional QCD radiation:

- **Can probe LO and NLO pQCD corrections without requirement of extra reconstructed jets**
- **Sensitive to jets below reco threshold**



PHYS. LETT. B 682, 370 (2010), ARXIV:0907.4286



W+jets production

W+jets a fundamental test of pQCD and background for many SM and BSM measurements

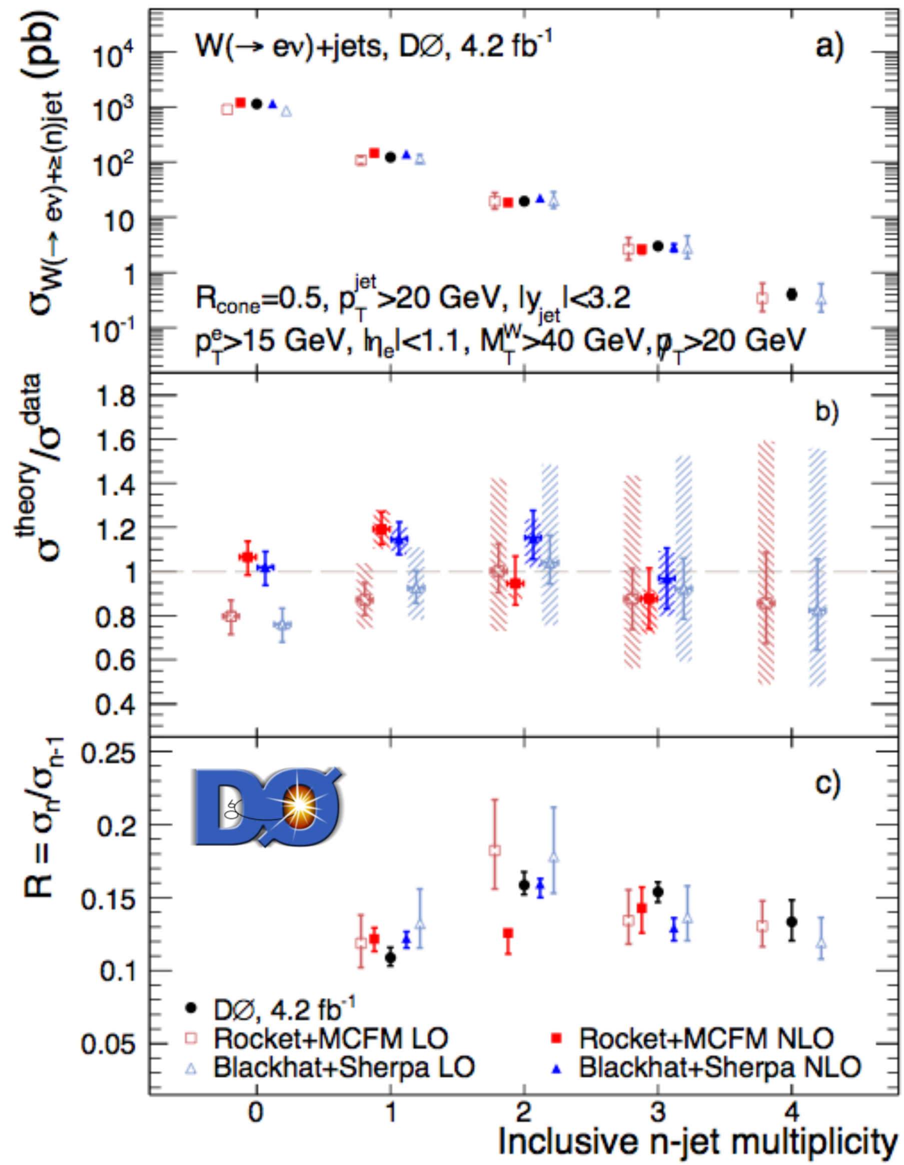
Provide integrated cross-sections and differential cross-sections for W+≤4jets

Unfold to particle-level for NLO/LO comparison using Singular Value Decomposition technique (Guru)

Compare to Rocket+MCFM and Blackhat+Sherpa NLO/LO pQCD calculations

Data precision competitive than best pQCD predictions available (in ratio and absolute measurement)

ARXIV: 1106.1457 SUBMITTED TO PHYSICS LETTERS B



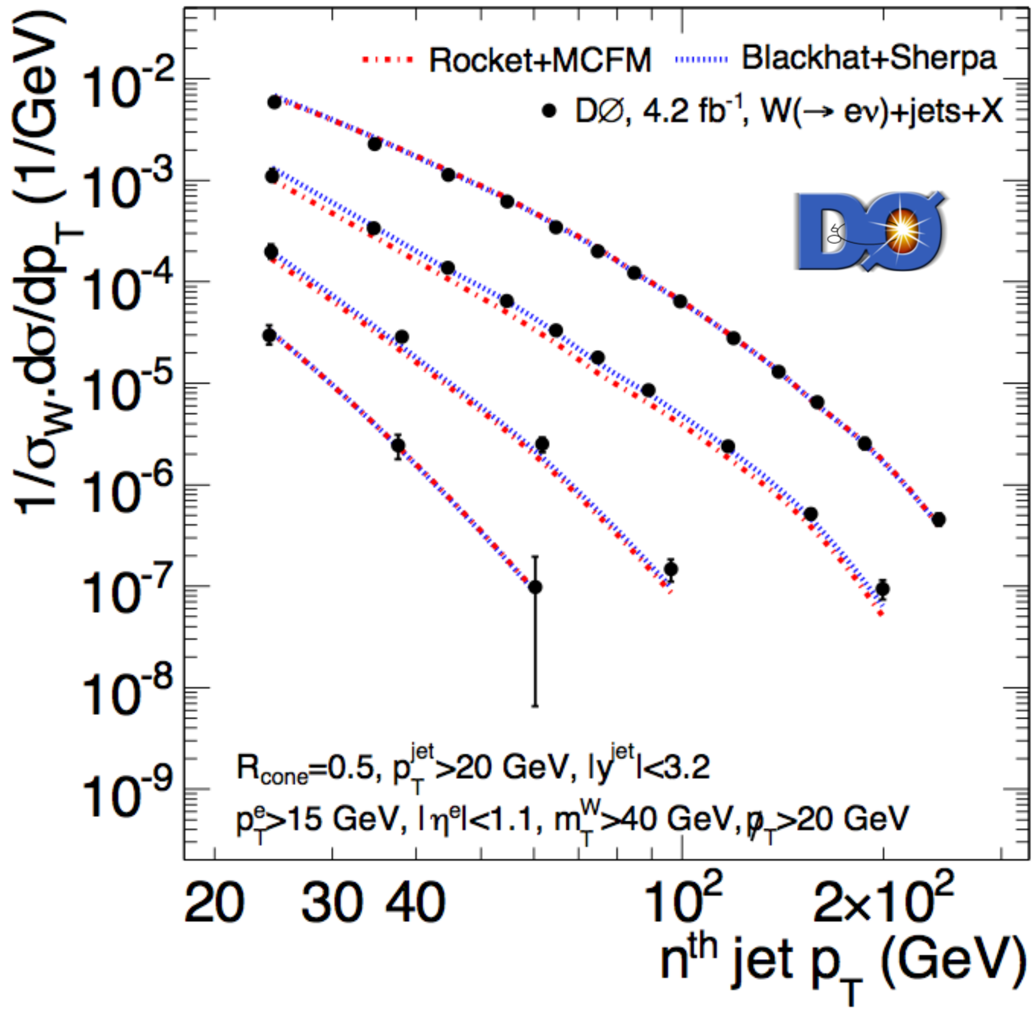
W+jets differential jet spectra normalized to measured inclusive W cross-section

Largest uncertainties:
JES (4-16)%, JER (2-10)%, Vertex confirmation (2-8)%

Many uncertainties cancel in ratio: allows for very precise comparison with theory

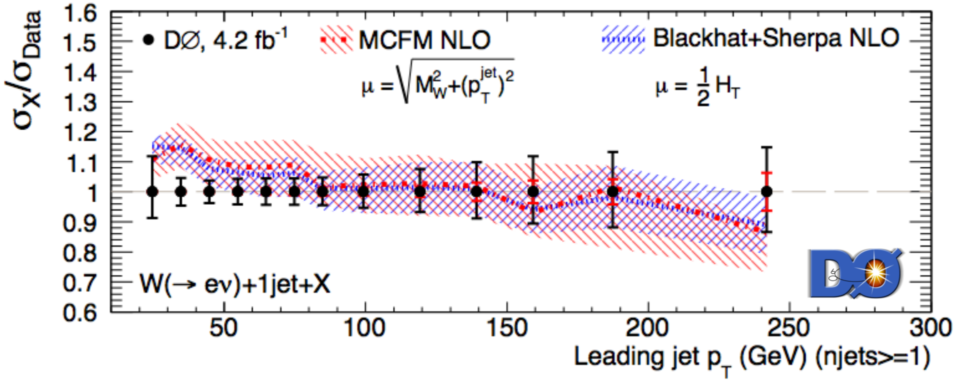
UE+hadronization particle-level corrections to theory derived with Sherpa 1.2.3

ARXIV: 1106.1457 SUBMITTED TO PHYSICS LETTERS B



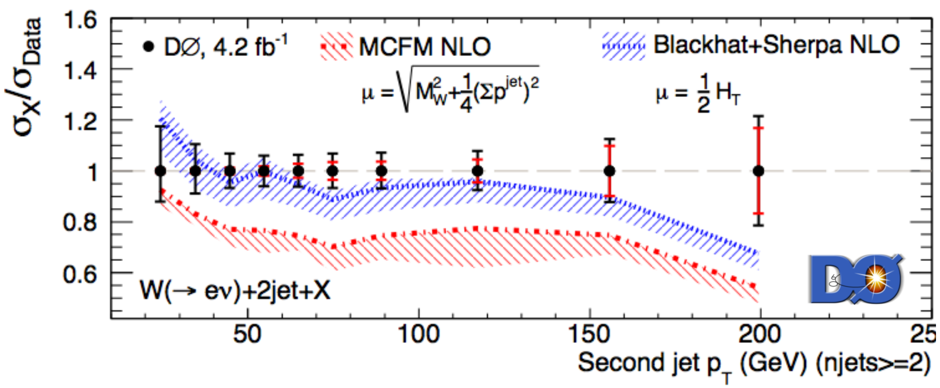
W+jets production: jet p_T

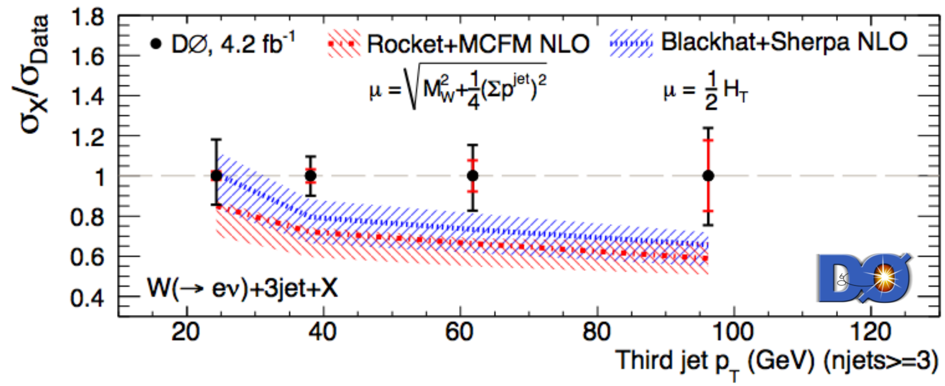
ARXIV: 1106.1457 SUBMITTED TO PHYSICS LETTERS B



NLO performs well: some modelling issues at low p_T?

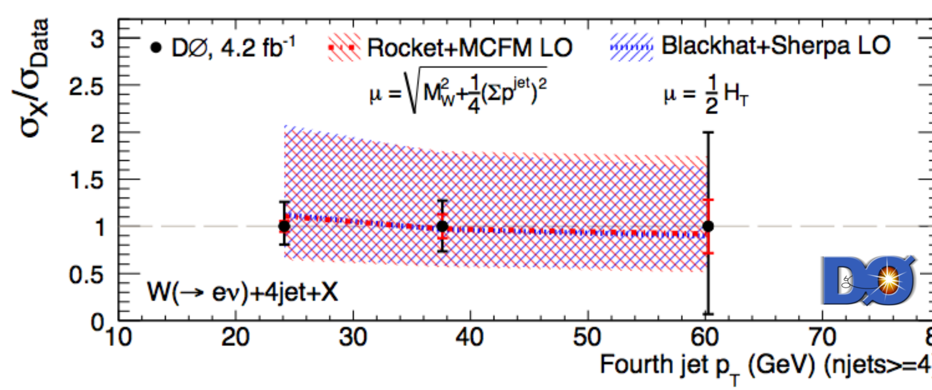
Second jet p_T shows tension between MCFM and Blackhat predictions
Data precise enough to discriminate!





Third jet shows some disagreement in shape & normalization with NLO

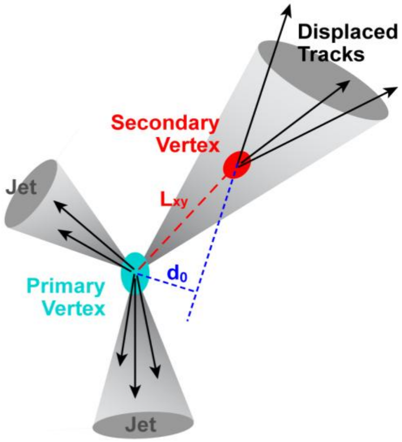
Only LO predictions available for W+4j at Tevatron right now. Good agreement (albeit within large scale uncertainties)



σ(Z+b)/σ(Z+jets) measurement

Ratio of inclusive Z+b to Z+jets cross-sections

Test of pQCD calculations and b-quark fragmentation, b-quark PDF
Z+b important background to single-top, ZH, new phenomena
Ratio cancels many systematics: precise comparison with theory predictions



Study both di-electron and di-muon channels:

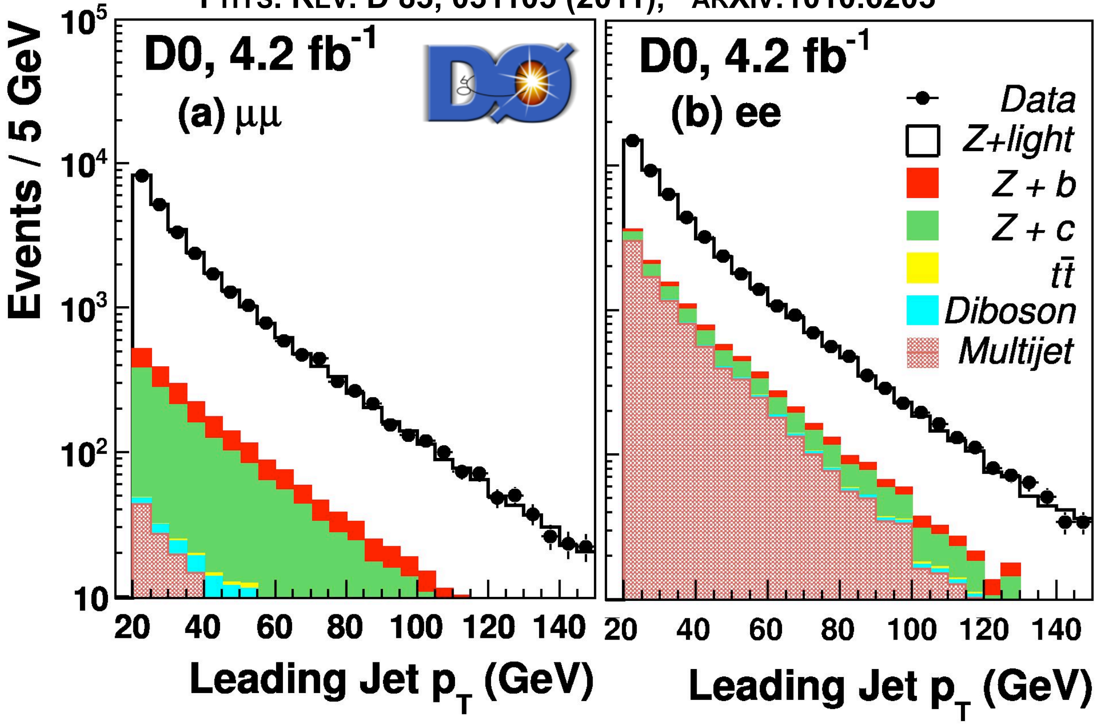
Lepton p_T>15 GeV, jet p_T>20{15} GeV, jet $|\eta|$<2.5

Measurement uses neural network based b-tagging algorithm.

Inputs include: B-lifetime, secondary vertices, vertex mass, & decay length significance…

Tag efficiency: 58%,
mis-tag rate: 2%

PHYS. REV. D 83, 031105 (2011), ARXIV:1010.6203



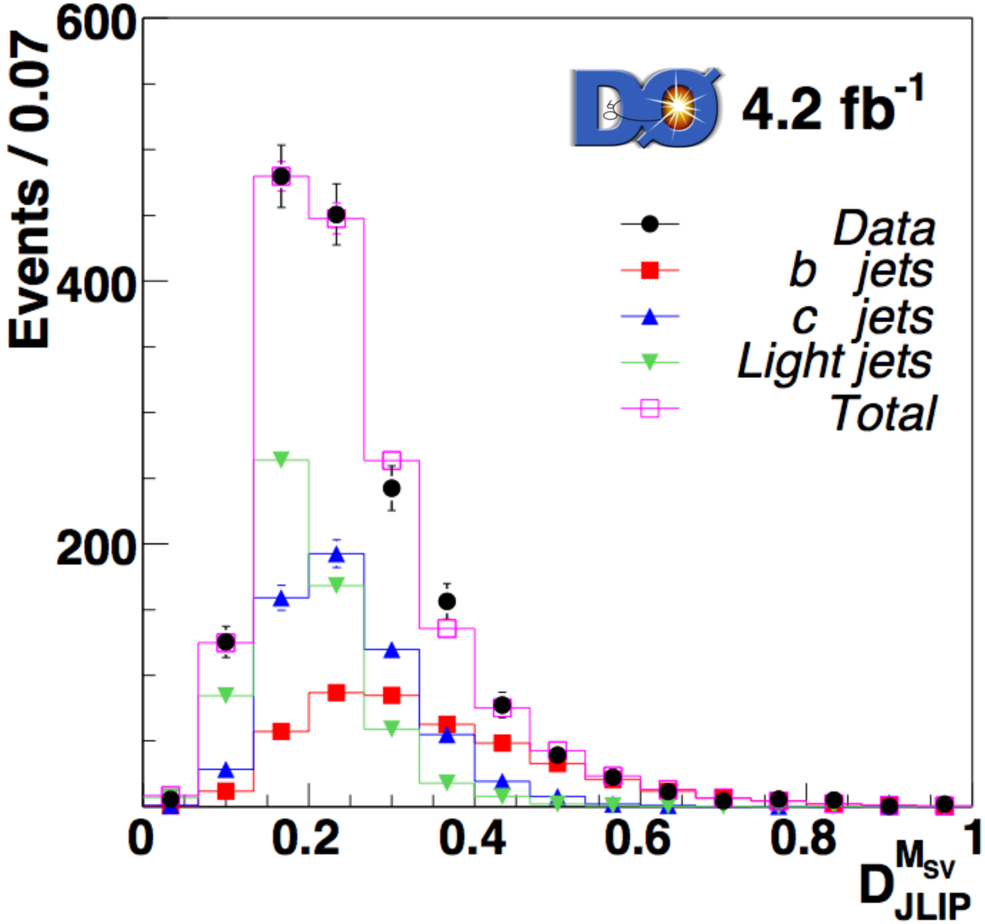
σ(Z+b)/σ(Z+jets) measurement

Jet flavour fractions measured in both di-electron and di-muon channels

Consistent results in both channels, so combine and re-measure with independent fit

Light/charm discrimination not significant, but b-jet fraction insensitive to light/charm correlations

PHYS. REV. D 83, 031105 (2011), ARXIV:1010.6203



Largest systematics come from discriminant template shape (4.2%) and efficiency uncertainties (3.7%)

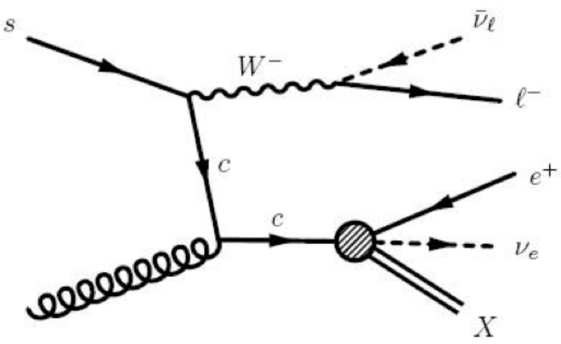
Measured (Z+b)/(Z+jet) =
0.0192±0.0022(stat)±0.0015(syst)

Most precise to-date

Consistent with NLO theory (MCFM) = 0.0185±0.0022

Measurement of W+c production: sensitive to s-quark PDF

Select events with semi-leptonic W, and one jet
Use soft electron tagging to identify heavy-flavour jet
Study charge-correlation between leptons

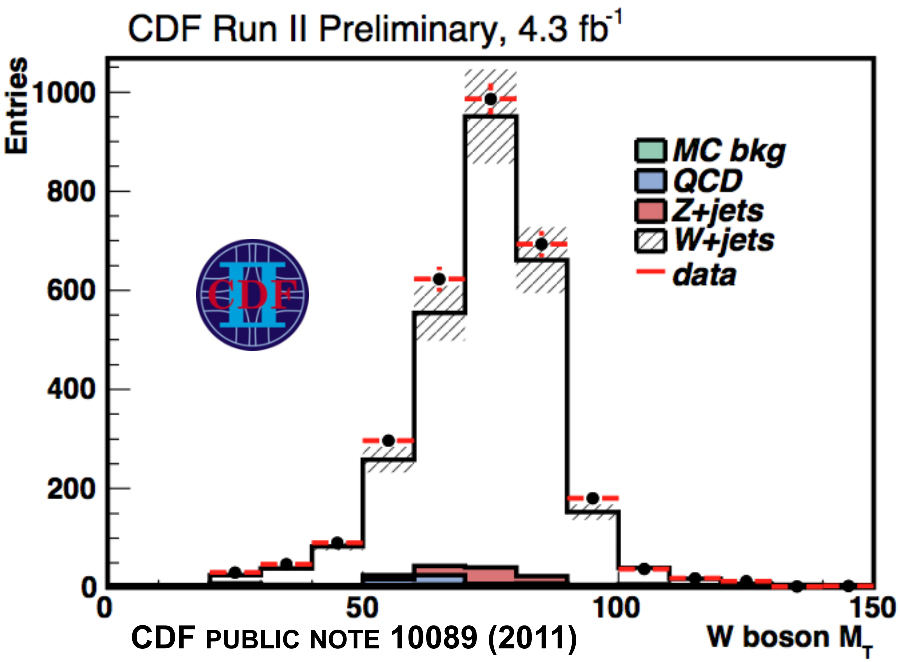


$$\sigma_{Wc} \times \mathrm{BR}(W \to \ell\nu) = \frac{N_{\mathrm{tot}}^{OS-SS} - N_{\mathrm{bkg}}^{OS-SS}}{Acc \cdot \int L \, \mathrm{dt}}$$

Lepton p_T > 20 GeV, jet p_T>20 GeV, $|\eta_j|$<2.0, MET>30 GeV, $m_T(W)$>20 GeV

Extract W+c cross-section
= 33.7 ±11.4 (stat) ±4.7 (syst)

Consistent with NLO prediction
= 16.5 ±4.7



CDF PUBLIC NOTE 10089 (2011)

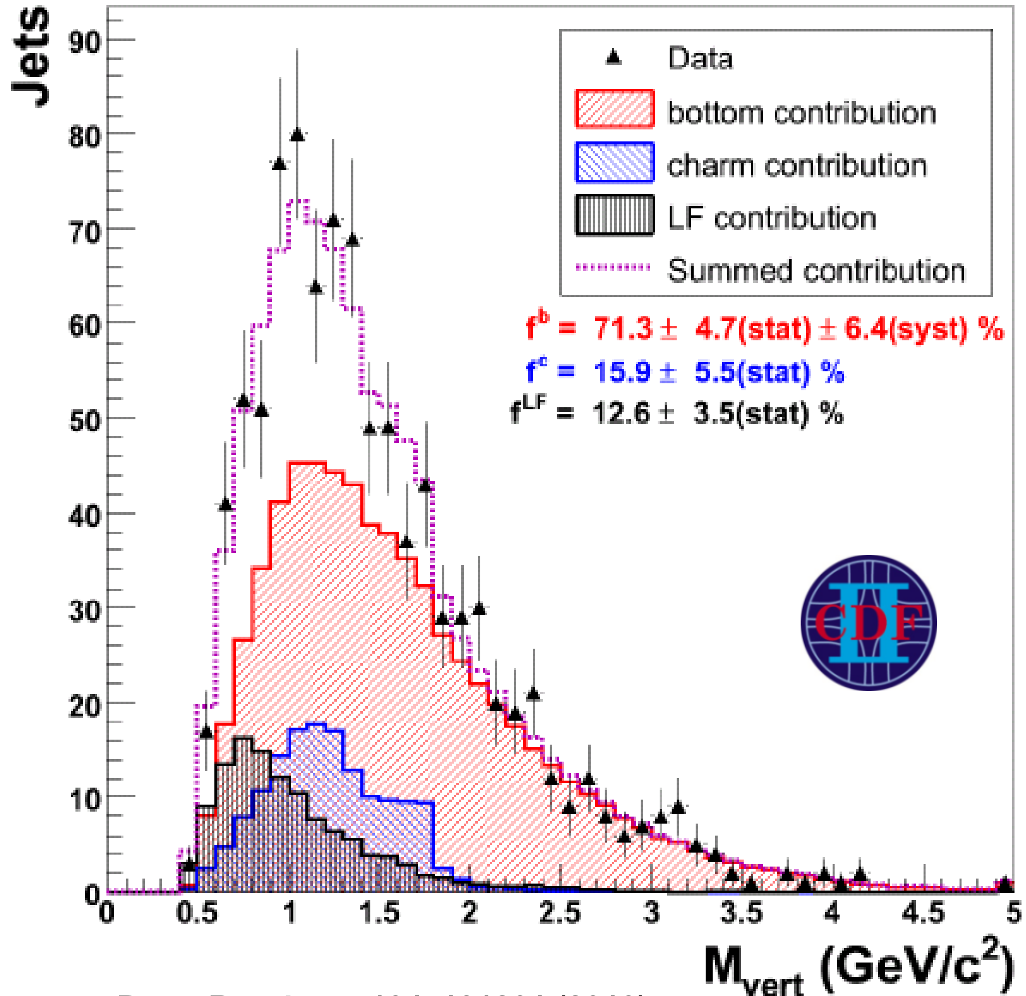
W+bb is a dominant background in low-mass Higgs search

CDF has discrepancy with NLO in this measurement…
DØ expects to publish an equivalent measurement this year

b-fraction determined from likelihood fit to vertex mass

Measured σxBR
= 2.74 ± 0.27 (stat) ± 0.42 (syst) pb

Predictions:
σxBR = 0.78 pb (Alpgen)
σxBR = 1.1 pb (Pythia)
σxBR = 1.22 ±0.14 pb (MCFM)



PHYS. REV. LETT. 104, 131801 (2010)

Diboson production

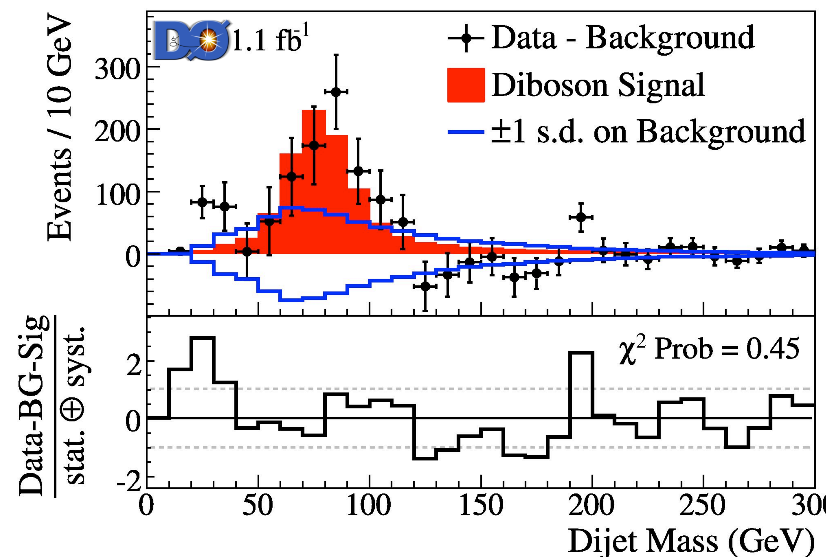
WW, WZ, ZZ, Wγ, Zγ production all studied by CDF and DØ

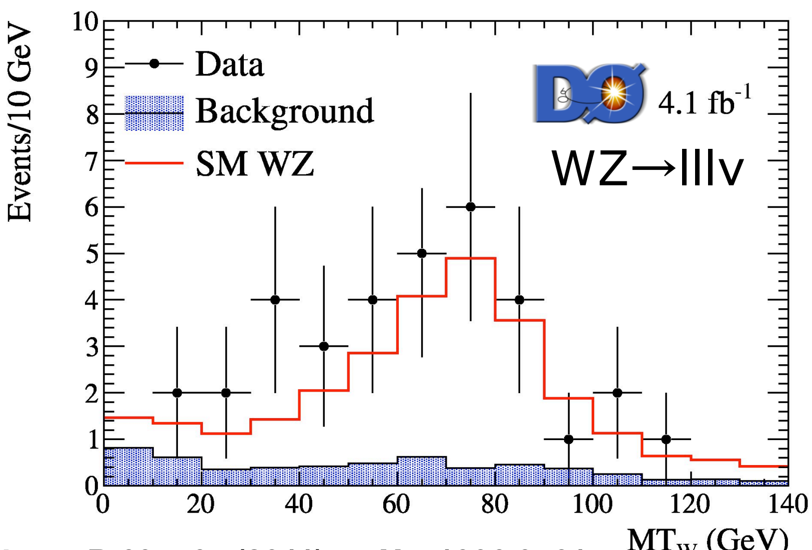
Important backgrounds for high mass Higgs searches; validation of VH search techniques

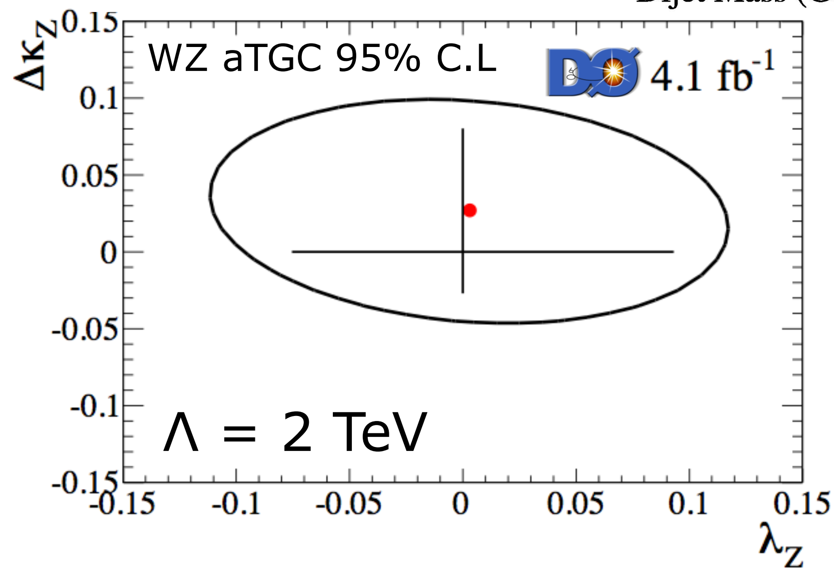
Place limits on anomalous trilinear gauge couplings – several of best limits at hadron colliders to-date

PHYS. REV. LETT. 102 , 161801 (2009)

WW+WZ production with lepton+jets



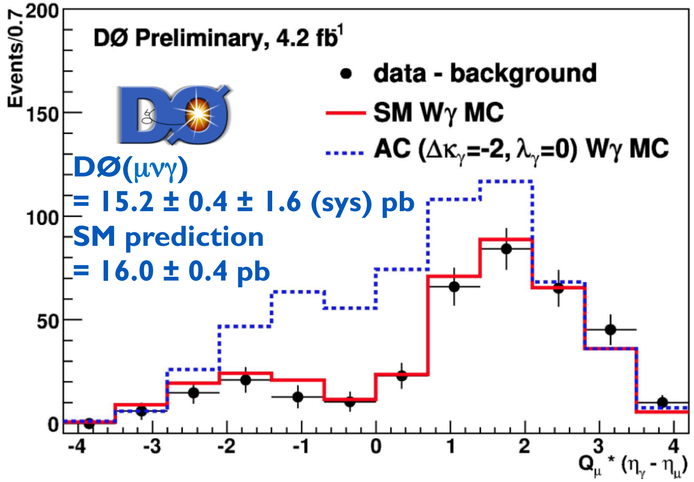


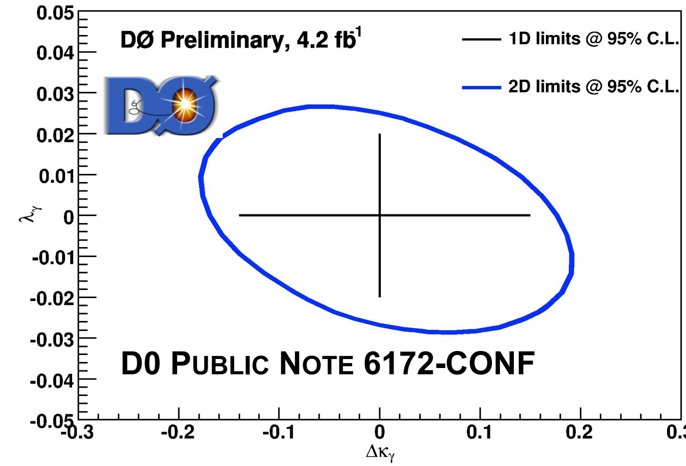


PHYS. LETT. B 695, 67 (2011), ARXIV:1006.0761

Cross-section Wγ measured in good agreement with Standard Model

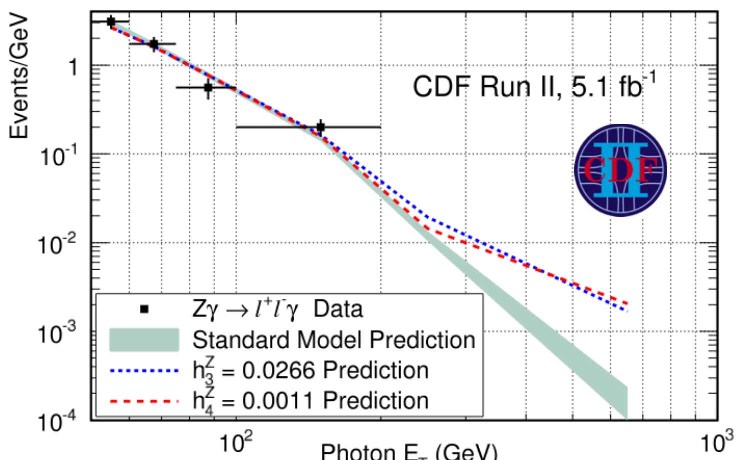
Use $E_T(\gamma)$ to set 95% C.L. limits on WWγ aTGC parameters

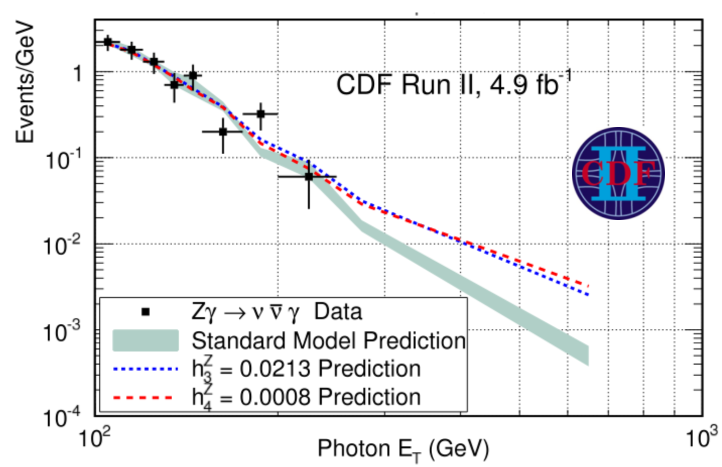




Similar sensitivity to LEP

From measurement of $Z\gamma \rightarrow l^+l^-(\nu\nu)\gamma$ can also set limits on aTGC



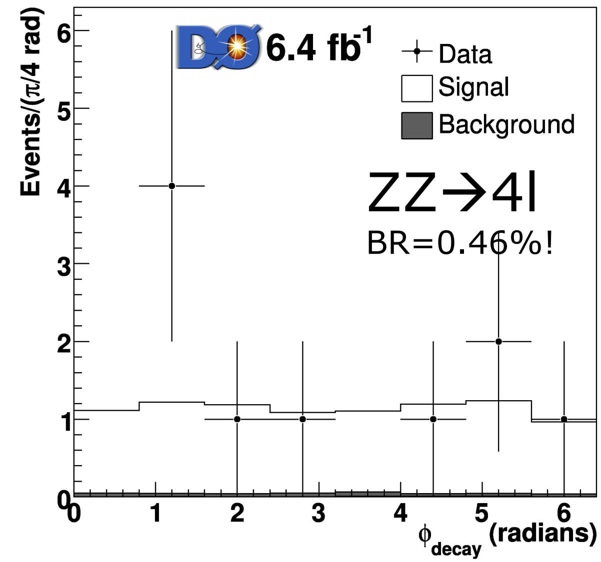


ARXIV:1103.2990, SUBMITTED TO PHYS. REV. LETT

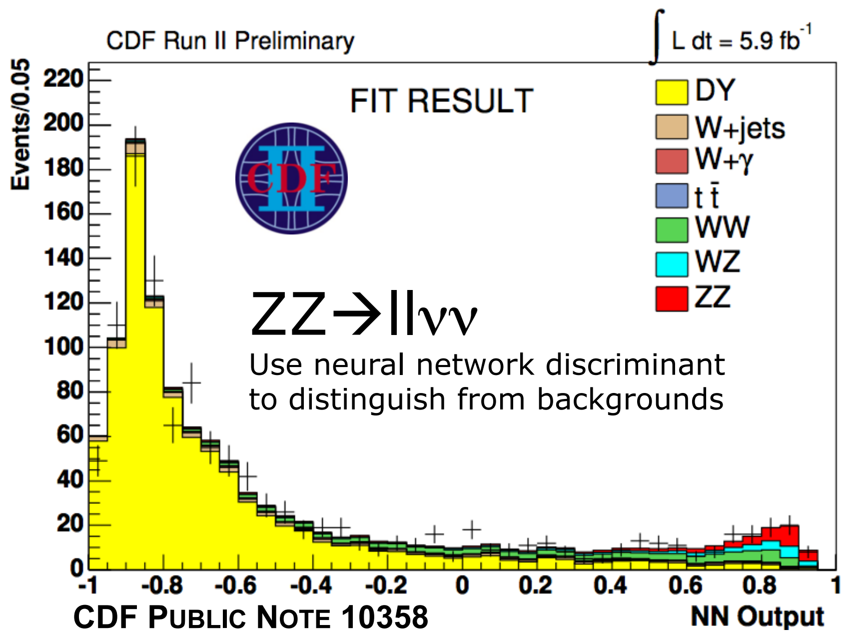
Large dataset allows us to measure processes with cross-sections of order ~1 pb

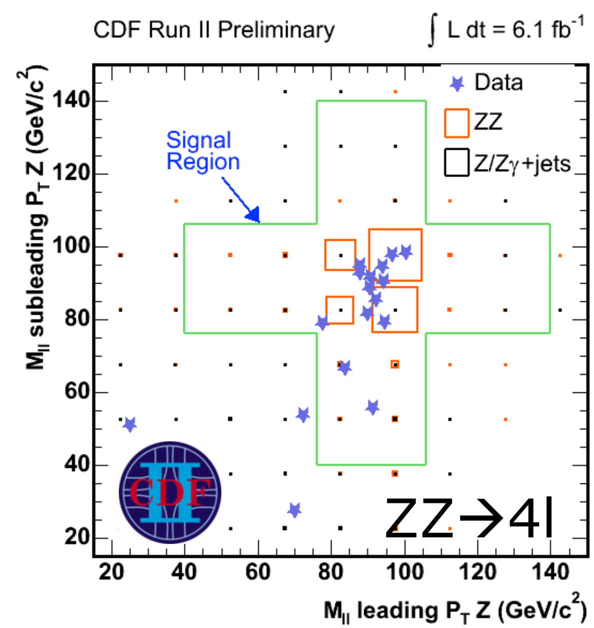
ZZ production, smallest of all diboson processes except VH, measured by CDF/DØ

DØ (4l): 1.26 +0.47-0.37 (stat) ± 0.11 (syst) ±0.08 (lumi) pb
CDF(4l): 2.0 ± 0.58 (stat) ± 0.32 (syst) ± 0.12 (lumi) pb
CDF(llνν): 1.45+0.45–0.42 (stat) +0.41–0.30 (syst) pb
Standard Model prediction: 1.3 ± 0.1 pb

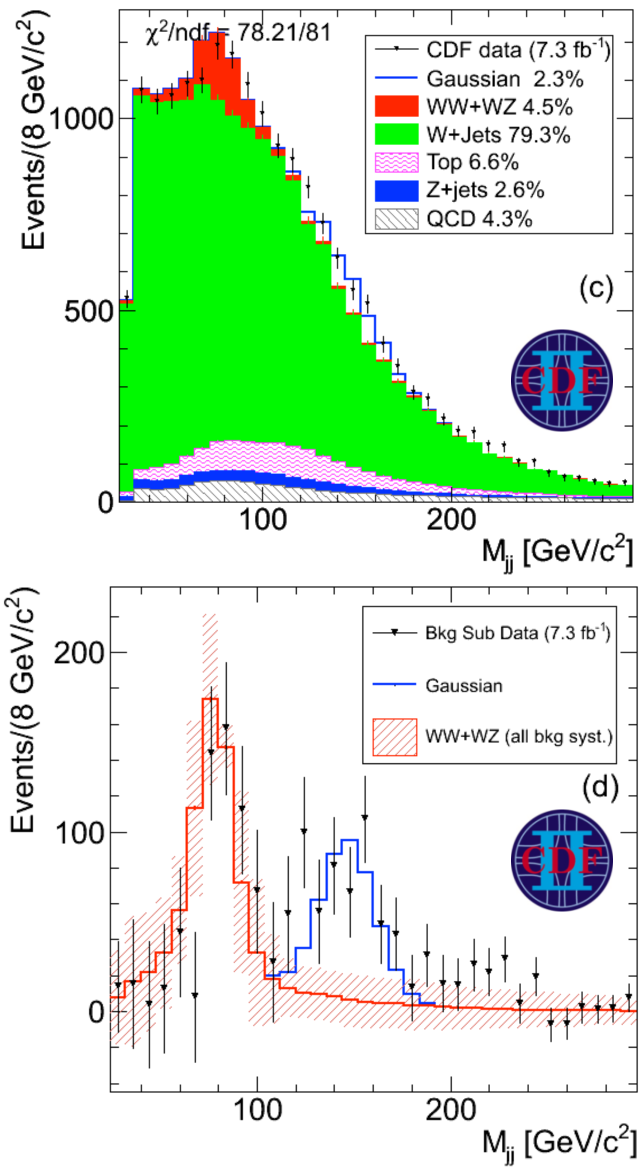


ARXIV:1104.307, ACC. BY PHYS. REV. D





CDF W+jj anomalous production



4.1σ excess seen in dijet mass spectrum of W+2jet (exclusive) sample

Main backgrounds: W+jets, Z+jets (Alpgen+Pythia), ttbar/single top (Pythia), QCD multijets (data-driven)

Binned χ^2 fit to M_{jj} distribution consistent with $\sigma(X\rightarrow jj)\sim$ 4pb (300 times higher than WH→lνbb)

Strong response from theory community
Reason for excess not yet clear
No significant HF tagged component

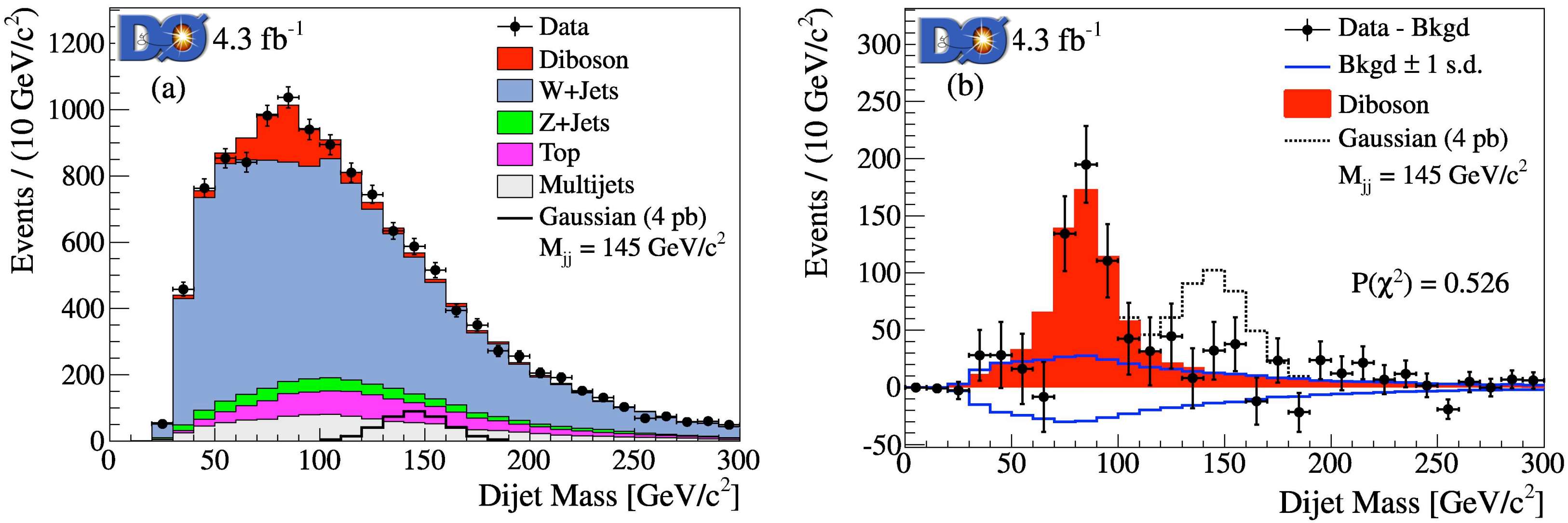
Many cross checks performed: various bkg control regions, W+jets modelling, fraction of b-tagged jets, different event selection cuts etc.

PHYS. REV. LETT. 106, 171801 (2011), ARXIV:1104.0699
AND http://www-cdf.fnal.gov/physics/ewk/2011/wjj/7_3.html

DØ study of W+jj production

DØ repeated CDF's analysis within same phase space, using diboson analysis as starting point; same assumptions on modelling any excess

Dijet mass distributions after fitting SM process to data (4.3 fb^{-1}):



ARXIV:1106.1921, SUBMITTED TO PHYS. REV. LETT.

DØ data consistent with SM prediction!

What if we fit to a resonance like the excess seen by CDF?...

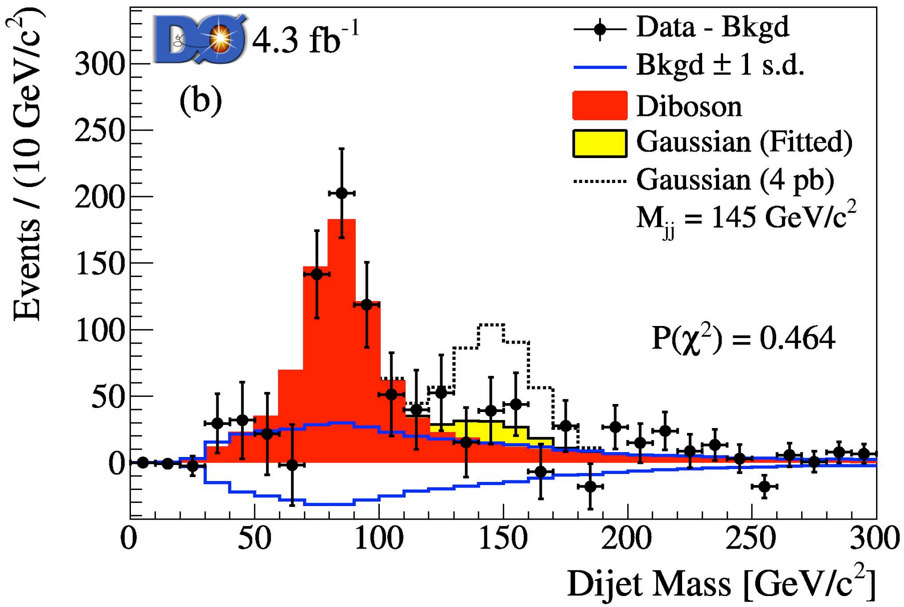
DØ study of W+jj production

Fit $WX \rightarrow l\nu jj$ template (derived from diboson width and $WH \rightarrow Wbb$ efficiency studies) to data along with SM processes

Fitted signal consistent with no excess… How large an excess can be accommodated by DØ data?

Use limit setting and frequentist approach:

If the experiment is repeated many times, what fraction would find a more extreme result?



Construct test statistic:

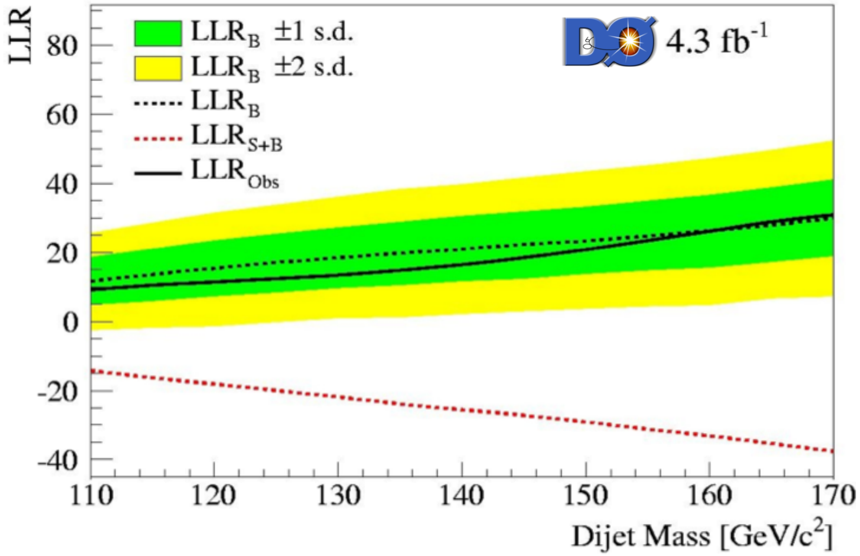
$$LLR = -2\log\left(\frac{P(D;S+B)}{P(D;B)}\right) = \chi^2(D|S+B) - \chi^2(D|B)$$

D = observed number of events
S = predicted number of signal events
B = predicted number of background events

FOR MUCH MORE DETAIL, PLEASE SEE:
http://www-d0.fnal.gov/Run2Physics/WWW/results/final/HIGGS/H11B/JoeHaley_WineCheese10June2011.pdf

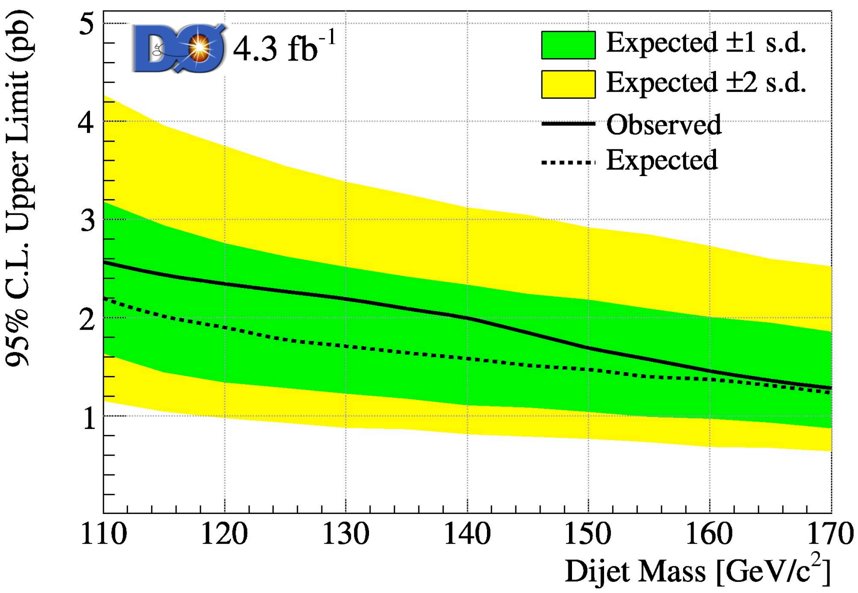
DØ study of W+jj production

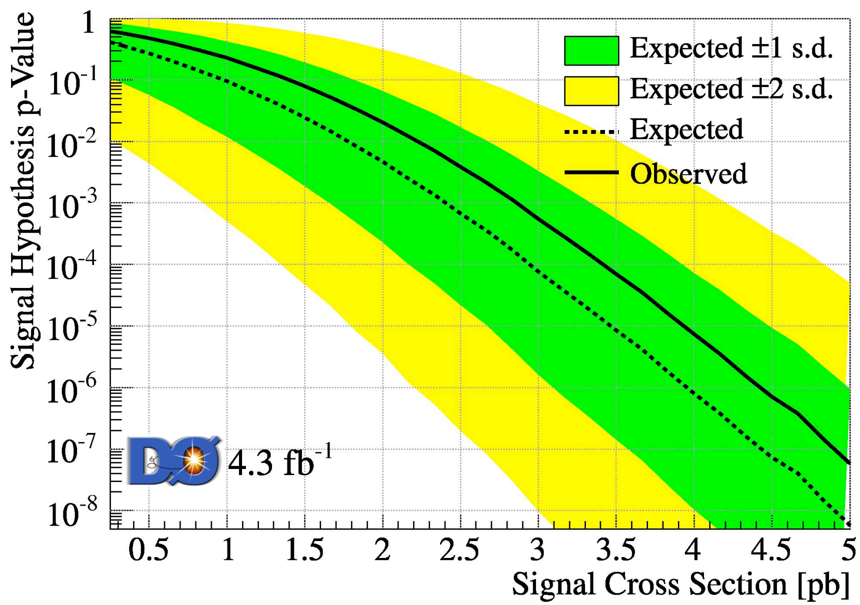
Compare observed LLR to the predicted LLR distributions over the range of dijet mass



95% CL upper limits on WX→lνjj as a function of reconstructed M_{jj}

For Mjj = 145 GeV: 95% CL exclusion for cross-sections greater than 1.9 pb





For a cross-section of 4 pb as reported by CDF Exclude at 99.999% CL – 4 standard deviations

Have presented just a subset of recent W/Z(+jets) results from the Tevatron on ~1—7 fb^{-1} of data:

We have >10 fb^{-1} on tape from each experiment, and plenty more exciting results to come!

Legacy measurements of W/Z and W/Z+jets are being made at the Tevatron now:

- **High precision tests of QCD/EW theory:**
  Precise knowledge of CDF/DØ object ID, energy scales and systematics lead to experimental uncertainties comparable or lower than theoretical uncertainties
- **World class inputs to PDFs**
- **Testing and tuning of phenomenological models**
- **W/Z measurements crucial for understanding backgrounds to new phenomena and SM Higgs searches**

Some interesting discrepancies arising…

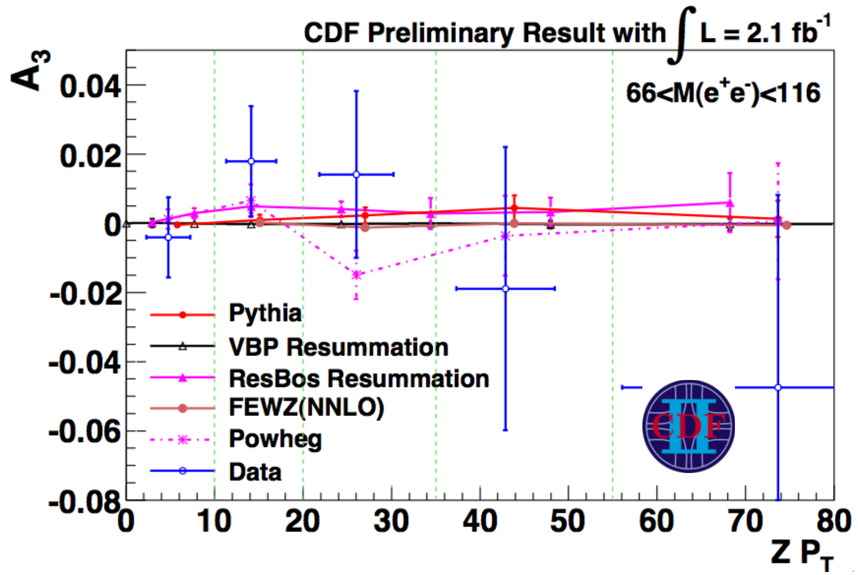
Additional slides

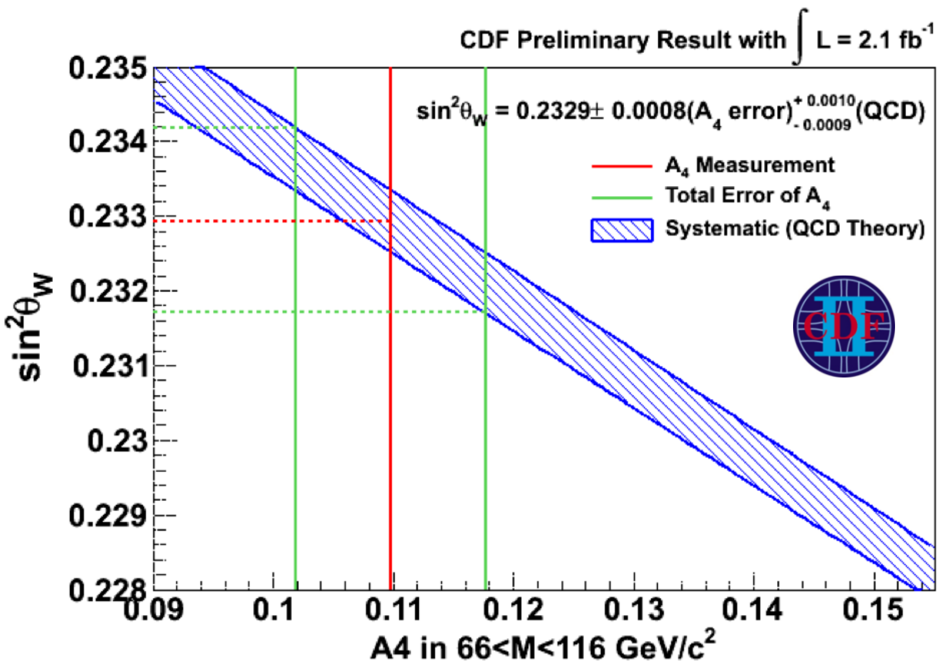
Lepton angular distribution in Z/γ^*

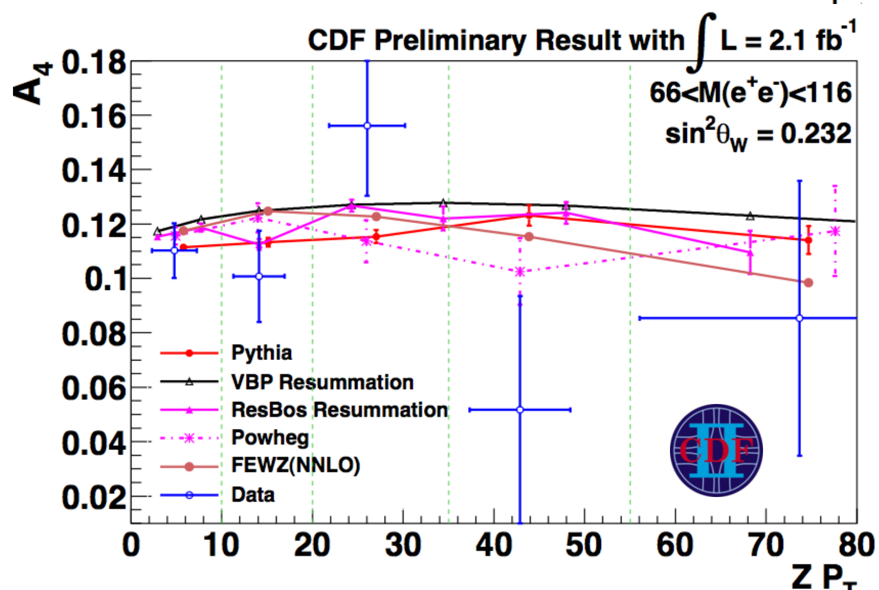
A3, A4 relatively flat in p_T

A4 related to forward-backward asymmetry ($=3/8 \times A_{FB}$) and strongly (anti-)correlated to $\sin^2\theta_W$

Value of $\sin^2\theta_W$ extracted $=0.2329 \pm 0.0012$ (theory-dependent) in agreement with SM







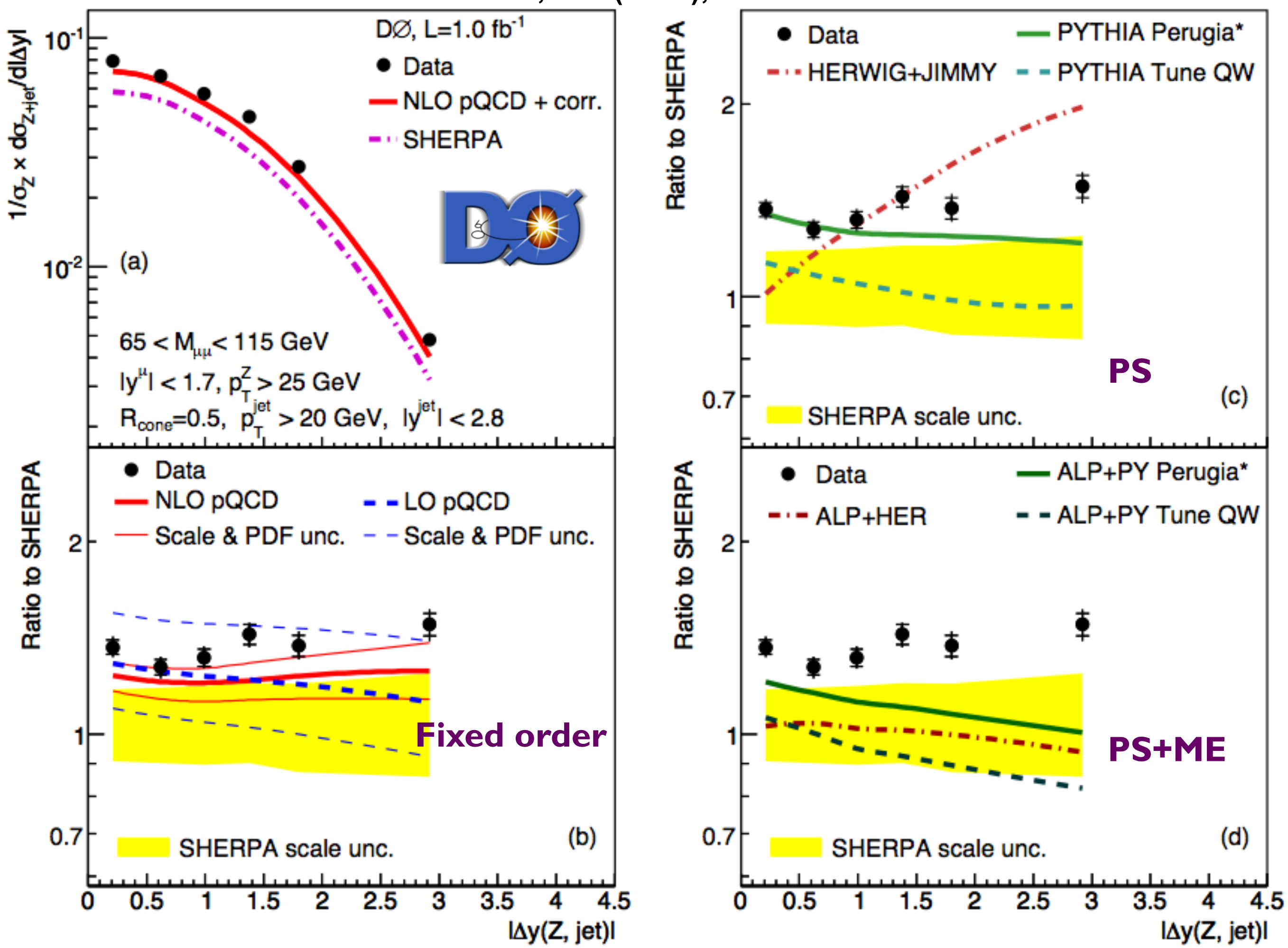
CDF Public Note 10312 (2011)

Z+jets angular observables: Δy(Z,j)

NLO pQCD and Sherpa do good job of describing shape of Δy(Z,j)

Pythia also does a reasonable job, unlike in Δϕ(Z,j)

PHYS. LETT. B 682, 370 (2010), ARXIV:0907.4286



Pythia p_T ordered
Perugia* tune
MRST07 LO* pdf

Pythia Q^2 ordered
Herwig+Jimmy

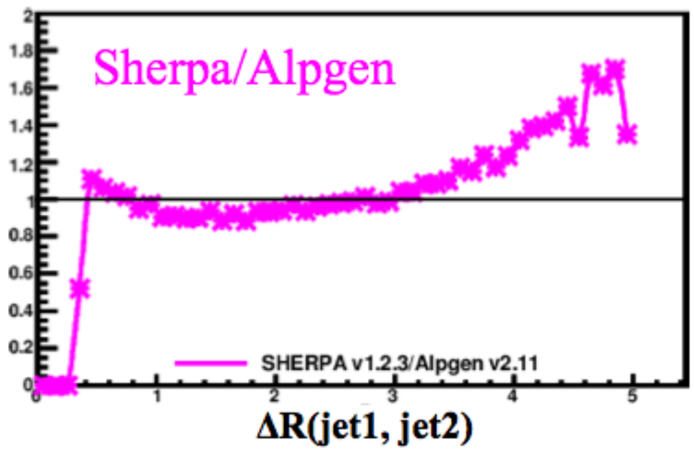
Alpgen+Pythia p_T
Alpgen+Herwig
Alpgen+Pythia Q^2

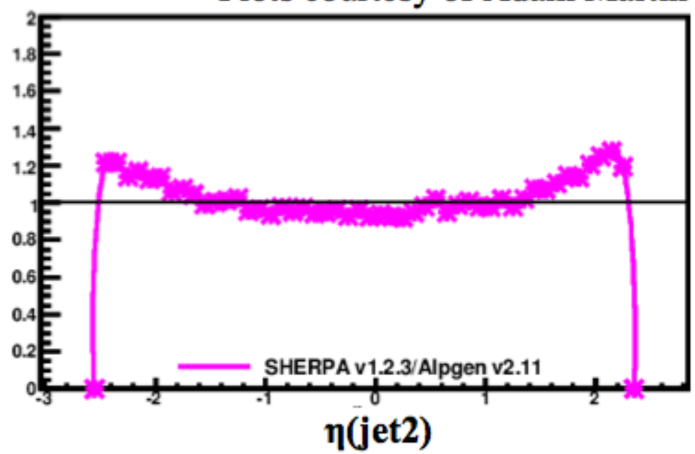
DØ study of W+jj anomalous production

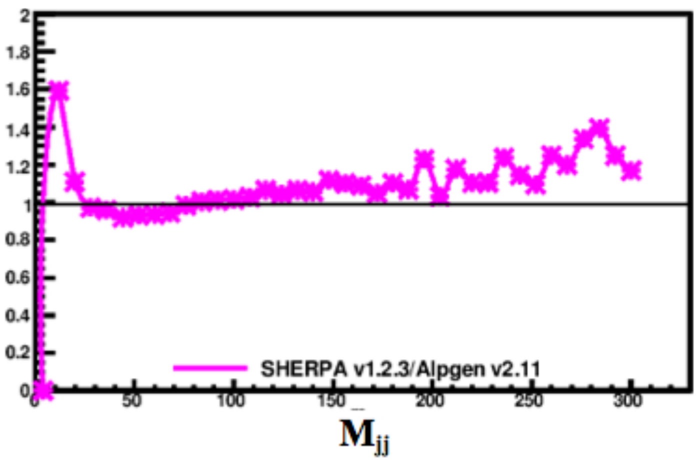
Alpgen modelling effects

- We know that Alpgen is not the final answer in modeling W+jets
  - Different generators have different predictions

Plots courtesy of Adam Martin





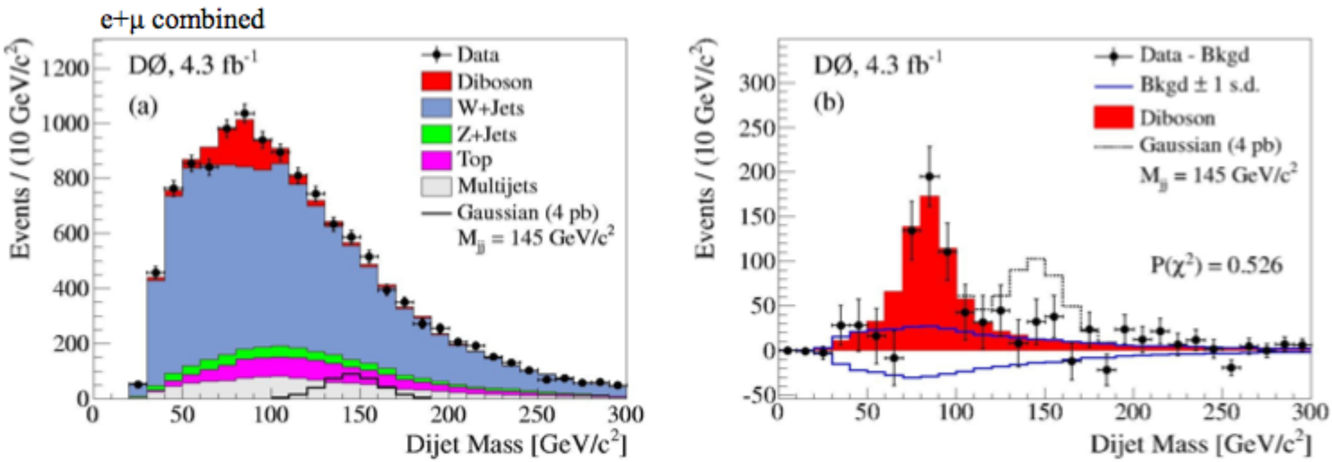


- In analyses with looser cuts (*e.g.*, WH→lνbb) we see clear discrepancies of exactly this type

Slide taken from Wine & Cheese seminar by Joe Haley; June 10 2011
http://www-d0.fnal.gov/Run2Physics/WWW/results/final/HIGGS/H11B/JoeHaley_WineCheese10June2011.pdf

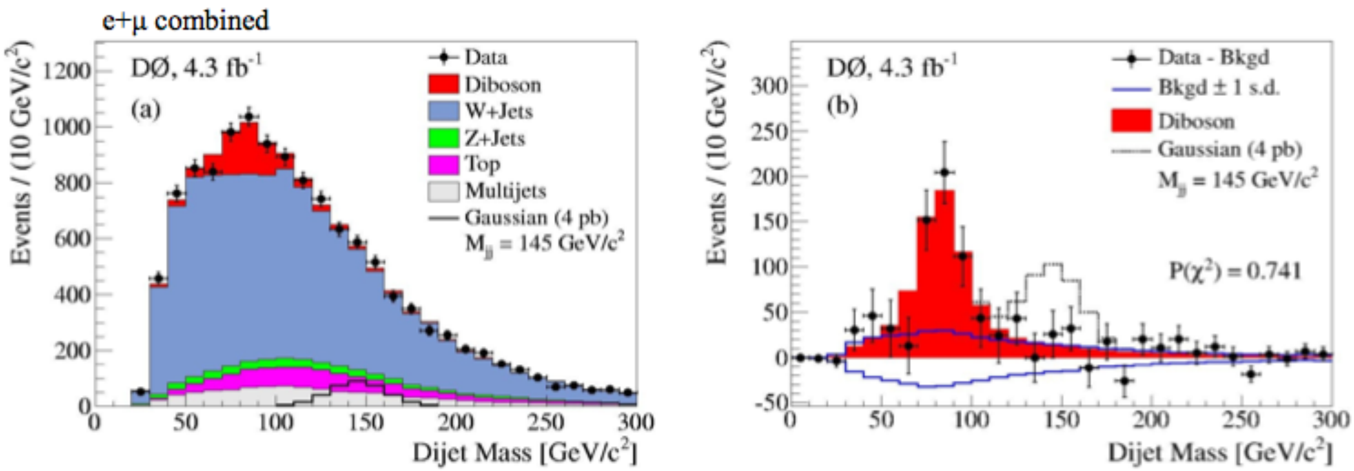
The dijet mass distributions after fitting SM processes to data

Without Alpgen modeling corrections applied:



→ 95% CL exclusion for cross sections greater than 1.9 pb @ m_{jj} = 145 GeV

With Alpgen modeling corrections applied:



→ 95% CL exclusion for cross sections greater than 1.5 pb @ m_{jj} = 145 GeV