W/Z properties and W/Z+jets production at the Tevatron

Hadron Collider Physics Symposium 2011

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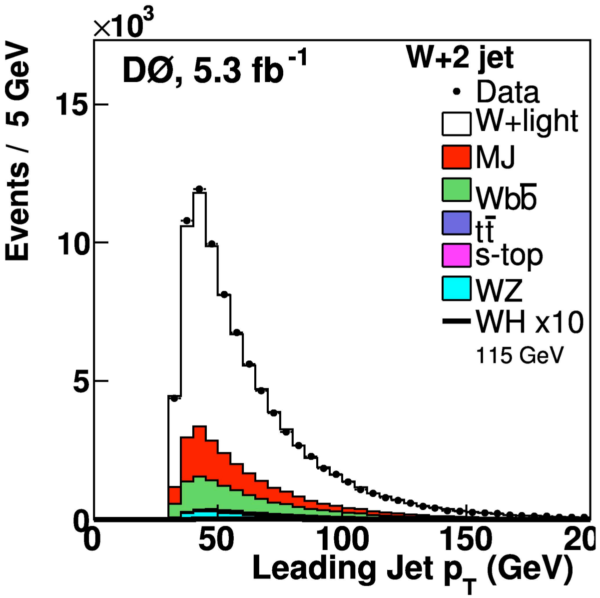
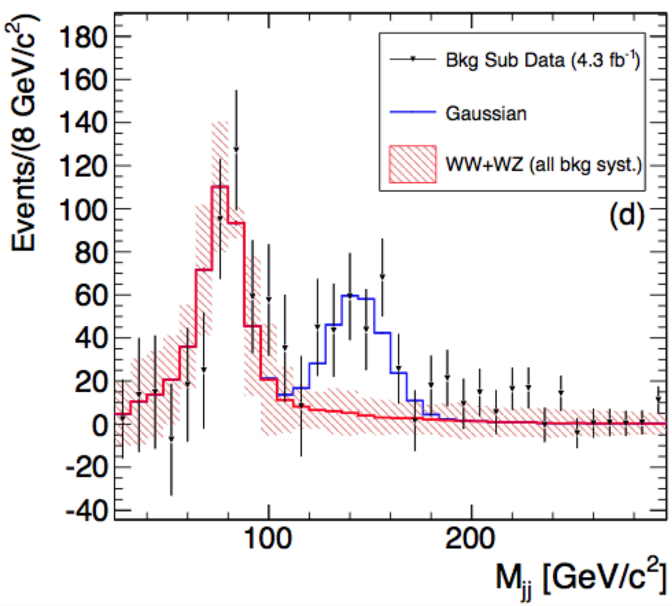
on behalf of the CDF and DØ collaborations



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

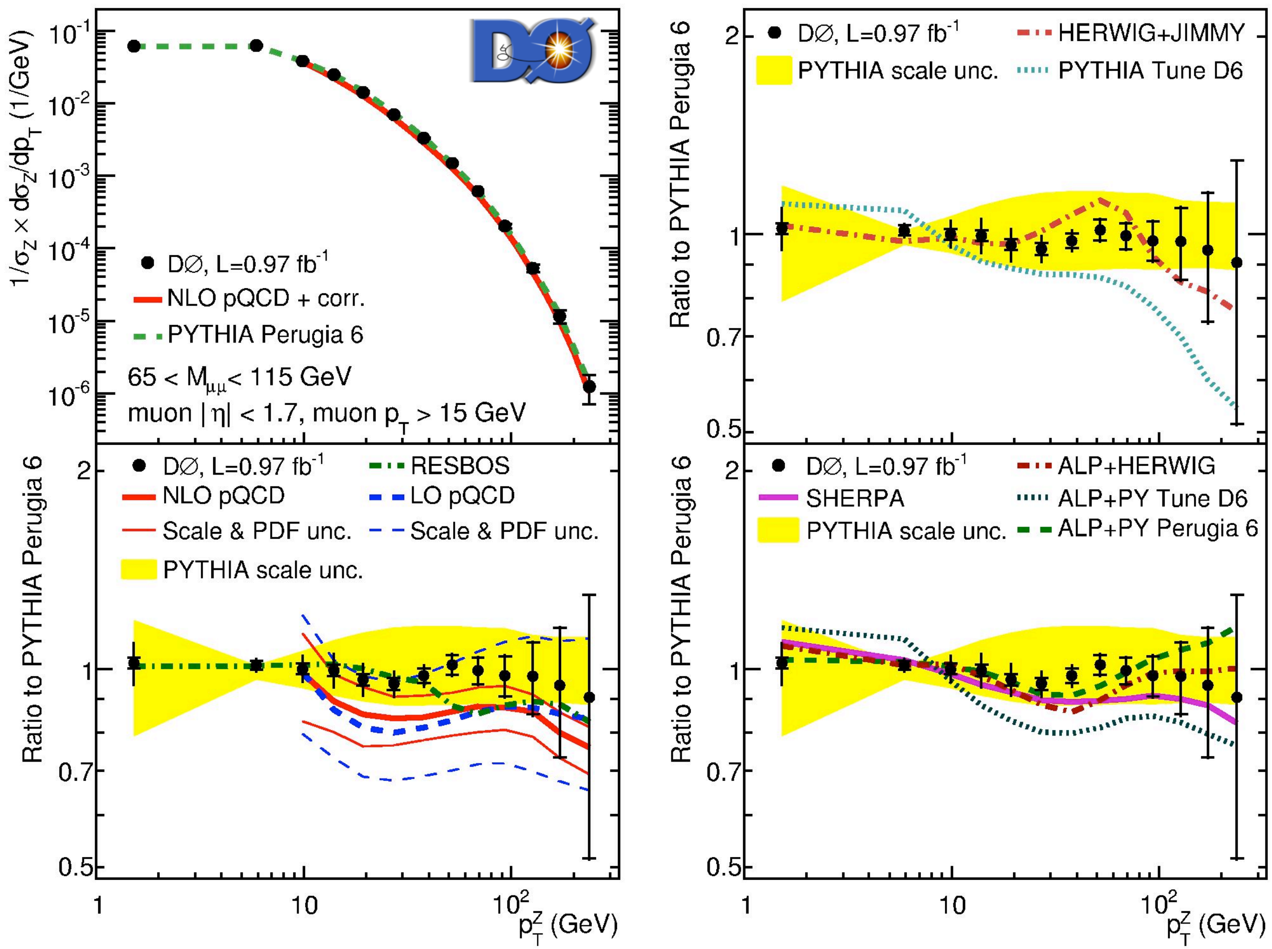
PHYS. LETT. B 693, 522 (2010), ARXIV:1006.0618

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

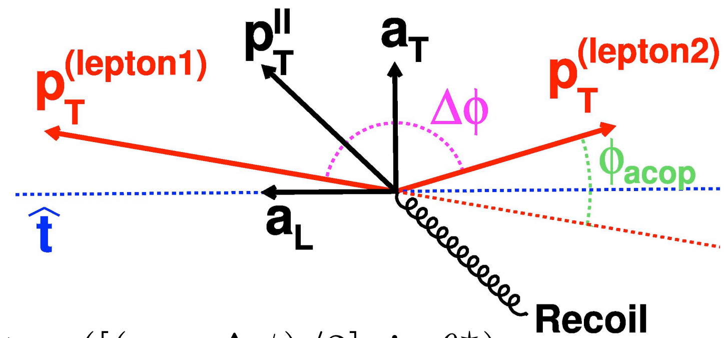


PHYS. REV. LETT. 106, 122001 (2011), ARXIV:1010.0262

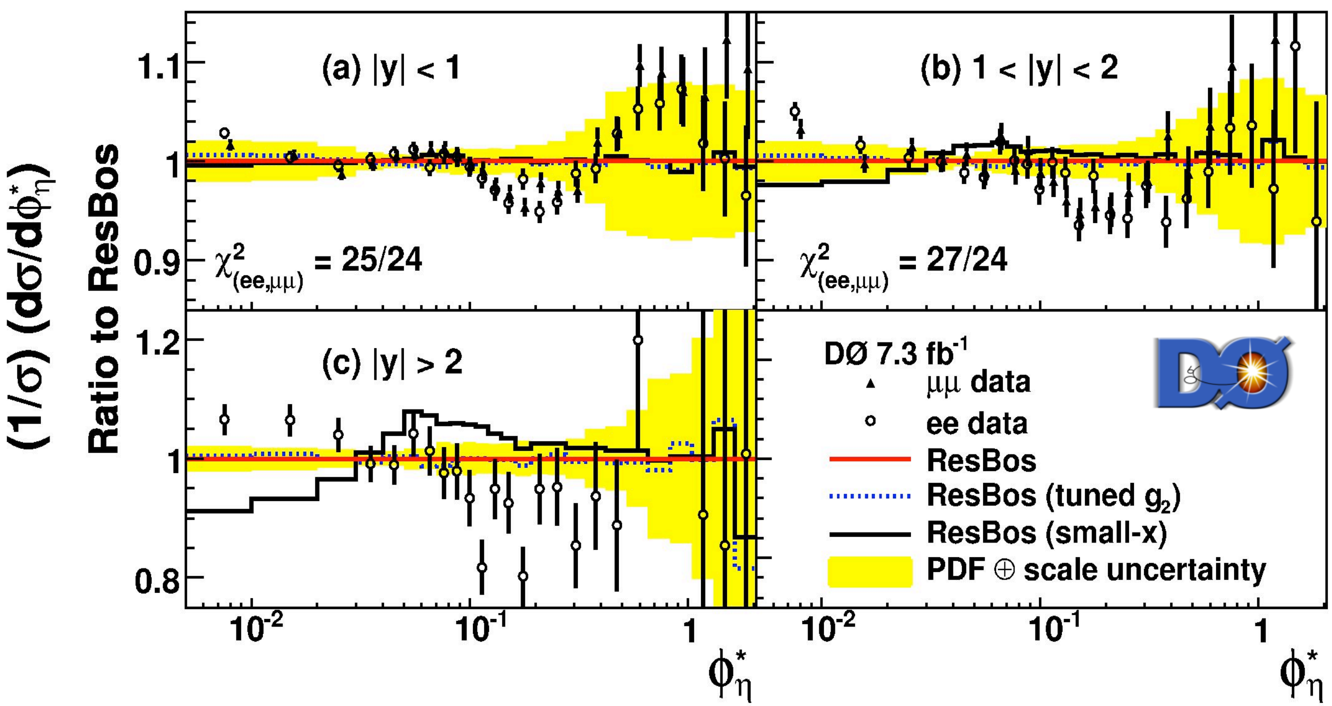
Recent DØ result (7.3 fb^{-1}) uses new variable ϕ^* based on the two lepton directions

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

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



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



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

Small-x broadening strongly disfavoured

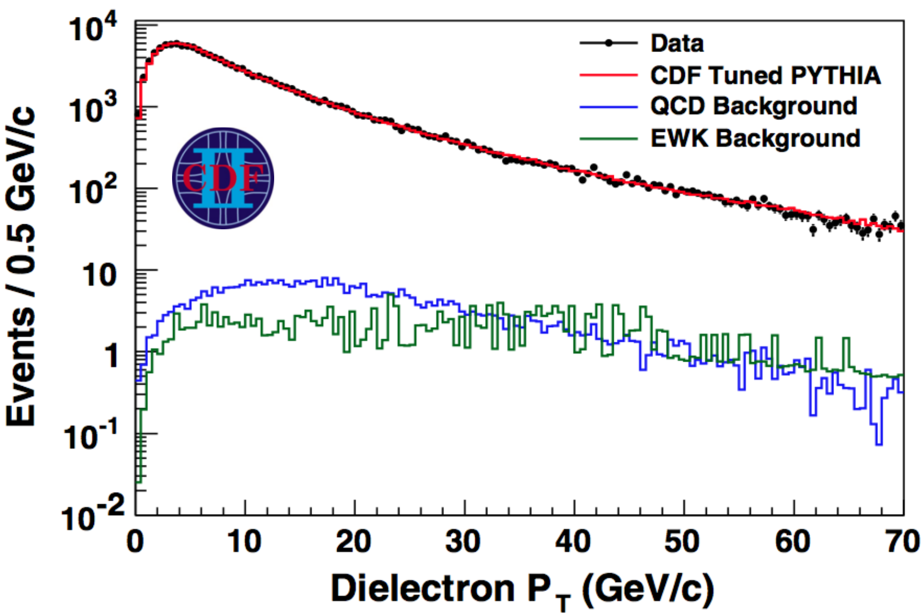
Lepton angular distribution in Z/γ*

Lepton angular distribution in Collins-Soper frame given by:

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

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

PHYS. REV. LETT. 106, 241801 (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

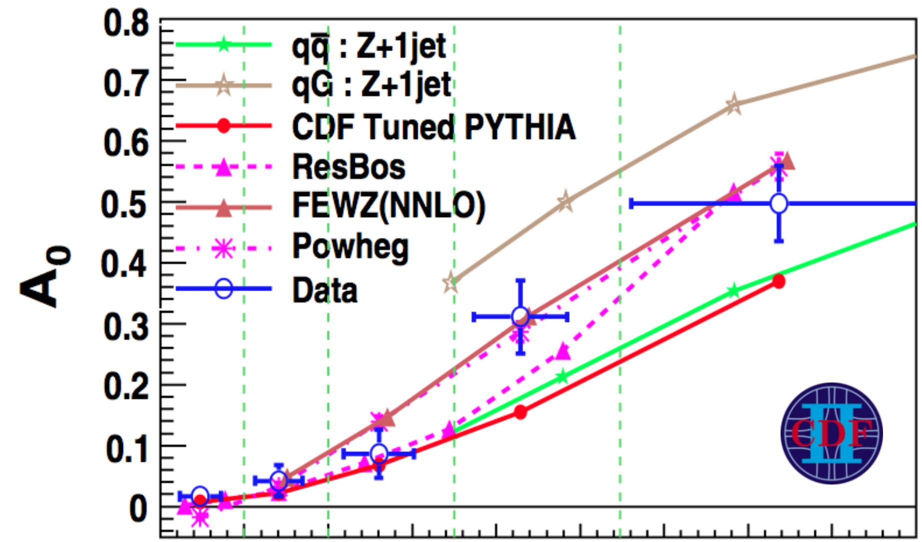
A_3, A_4 expected relatively flat with p_T
A_4 related to A_{FB} and $\sin^2 q_W$

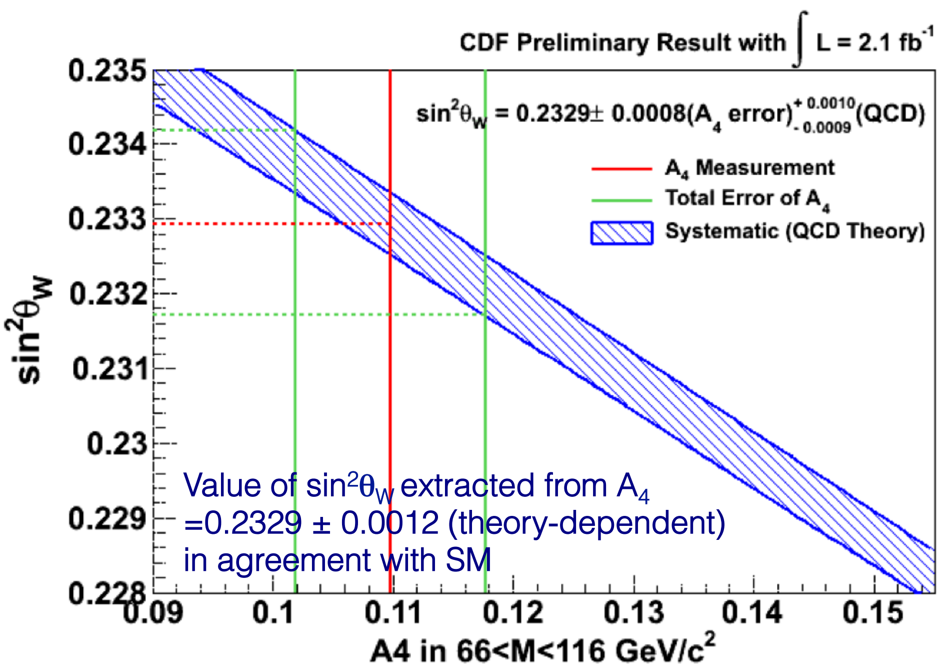
Strong p_T dependence observed in A_0 and A_2

Average A_0-A_2 = 0.02 ± 0.02

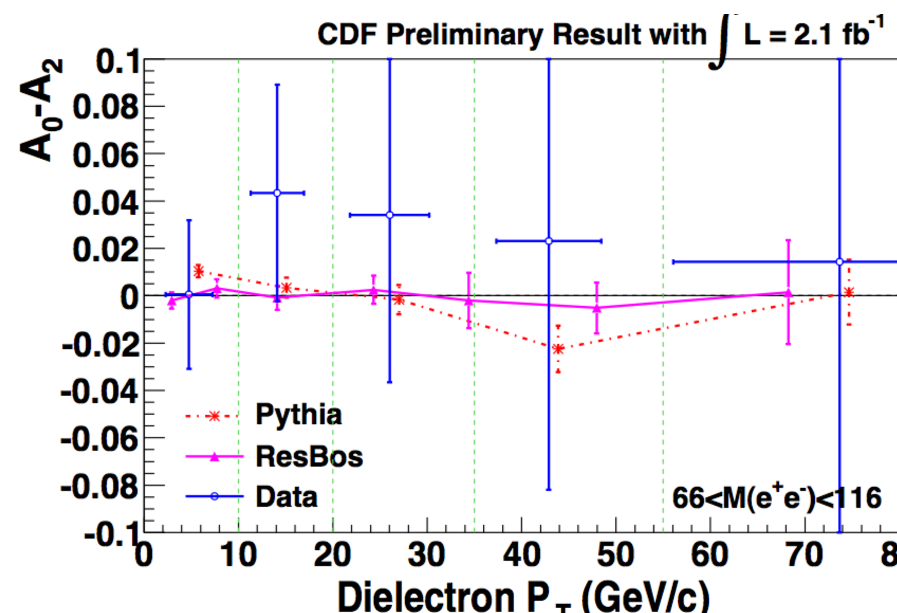
Lam-Tung relation ($A_0 \approx A_2$) implies gluon is spin-1 – validated by data
(Relation badly-broken for scalar gluons)

PHYS. REV. LETT. 106, 241801 (2011)



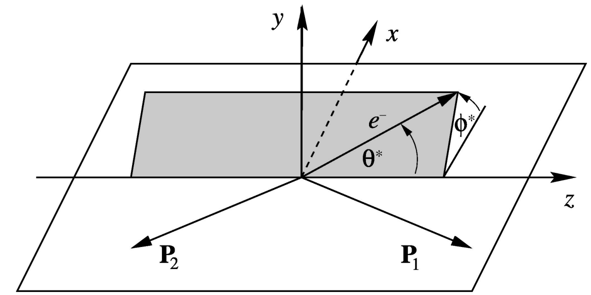


Value of $\sin^2\theta_W$ extracted from A_4 =0.2329 ± 0.0012 (theory-dependent) in agreement with SM

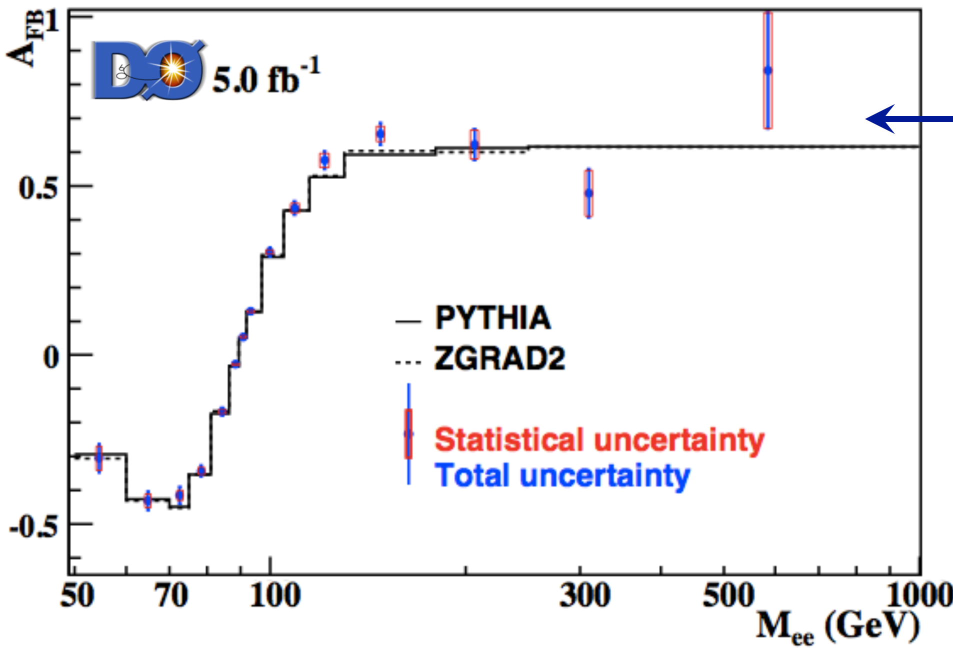


Z/γ* Forward-backward asymmetry

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

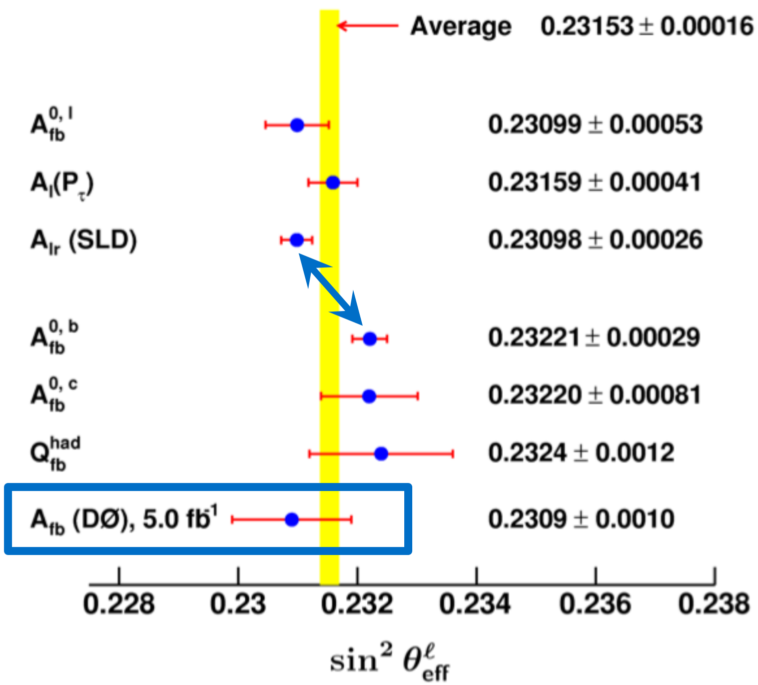


ARXIV:1104.4590, PHYS. REV. D 84 012007 (2011)



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

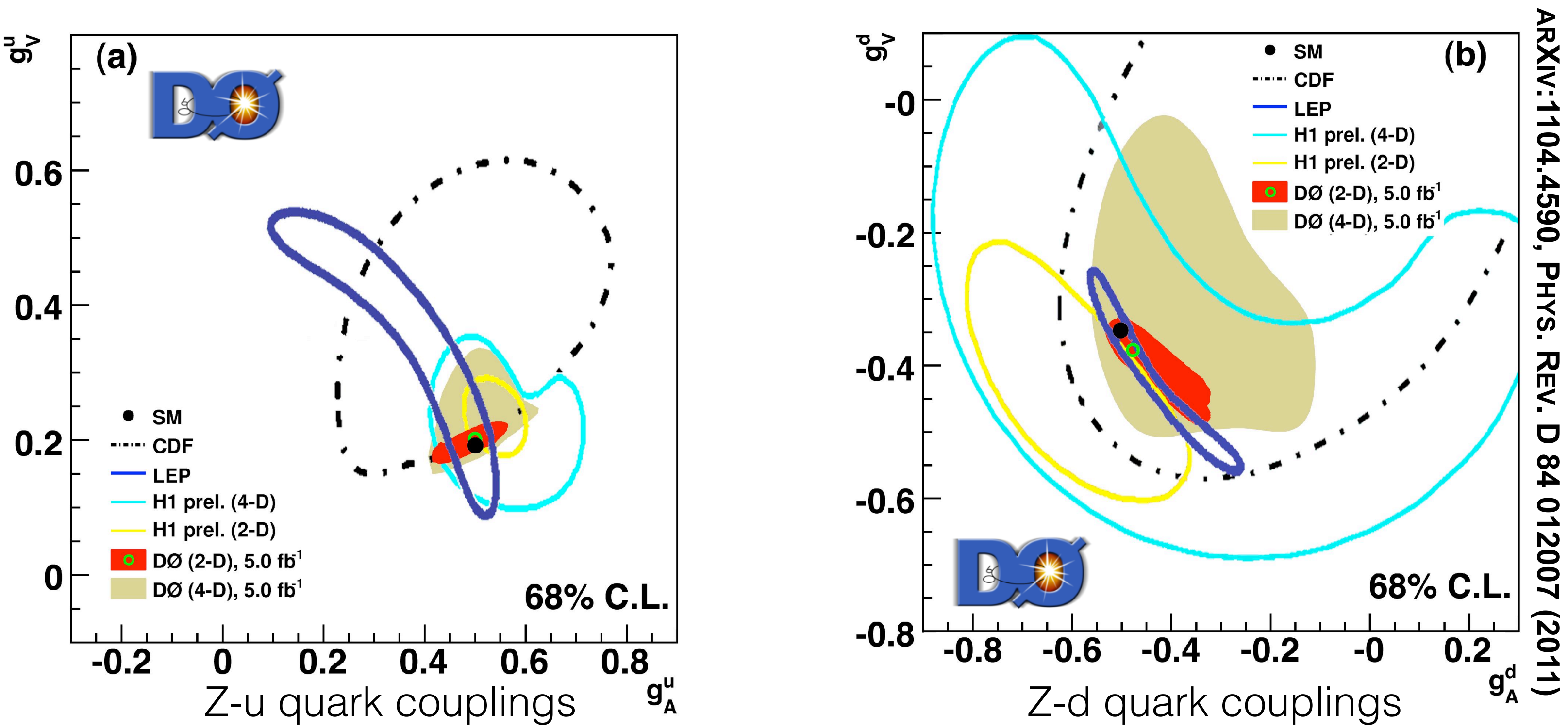
Z-u and Z-d couplings

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

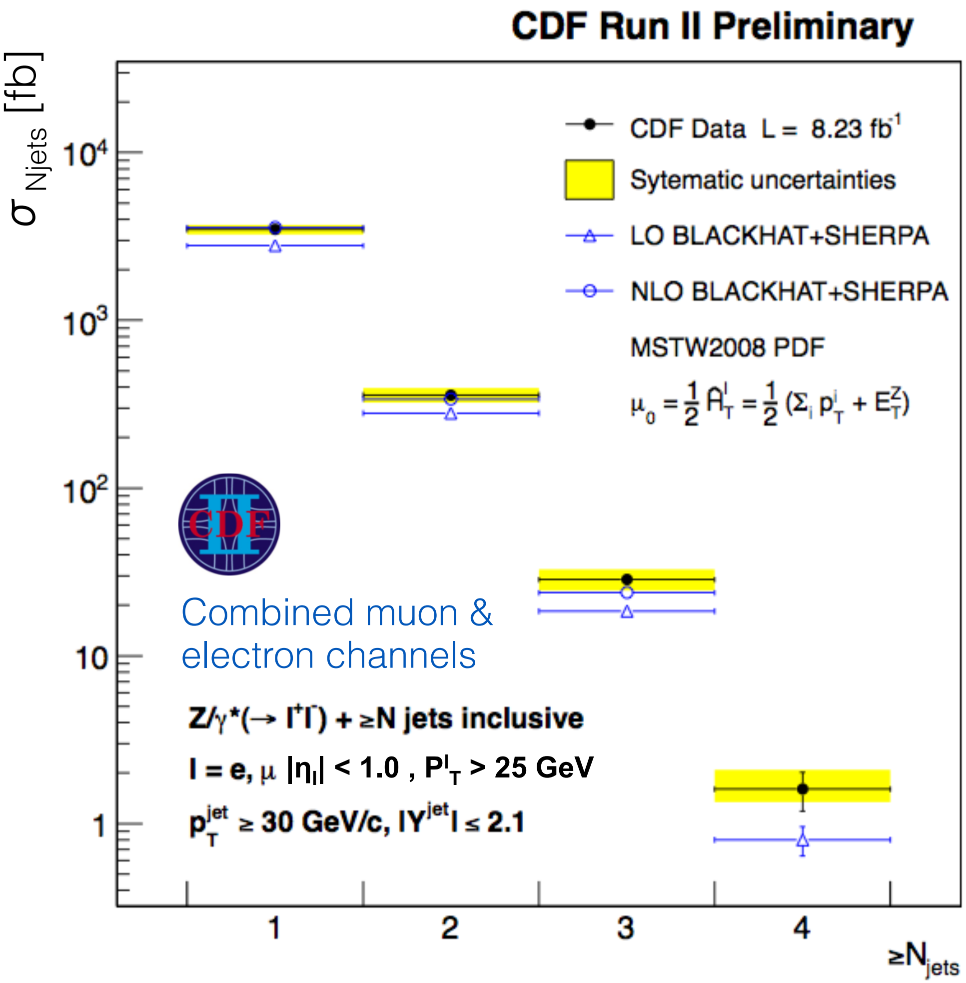
Compare unfolded AFB distribution with theoretical predictions with different Z-u and Z-d couplings

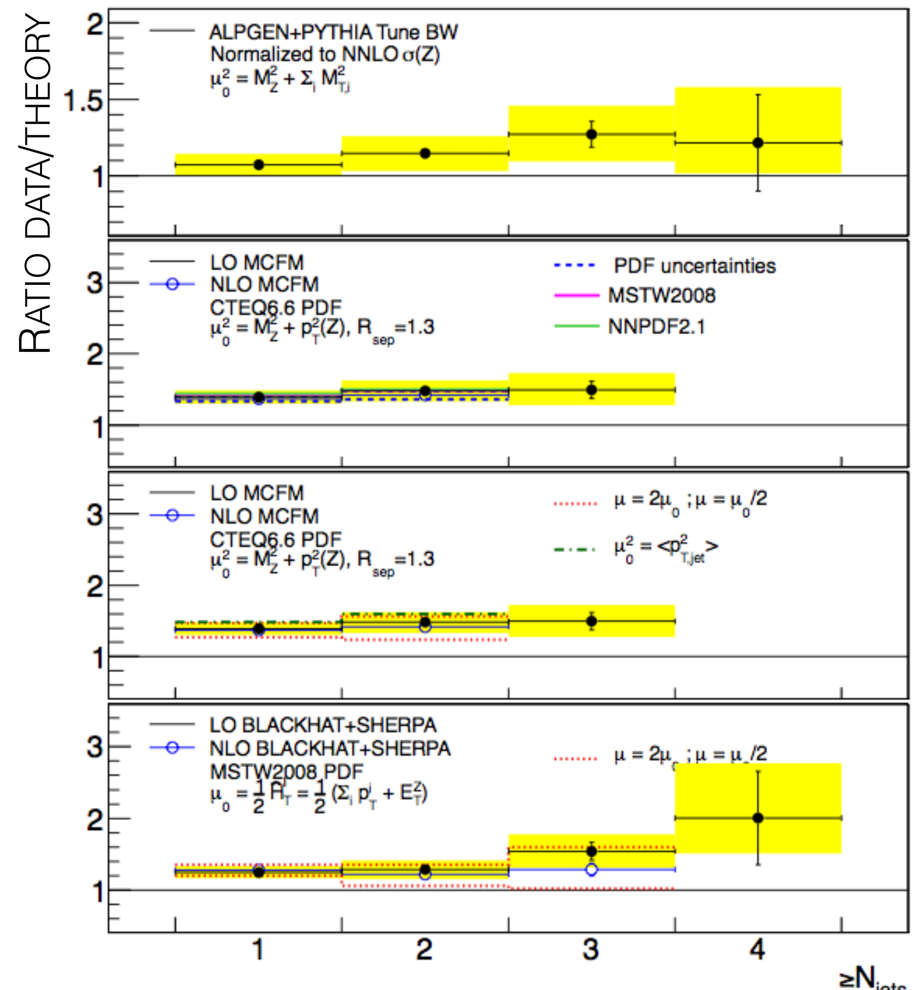
2-D fits are made to u, d vector and axial-vector couplings to Z and compared to other experiments – most precise to date!



Measurement of inclusive Z(ee/μμ)+(n)jet cross-sections (8.2 fb^{-1})

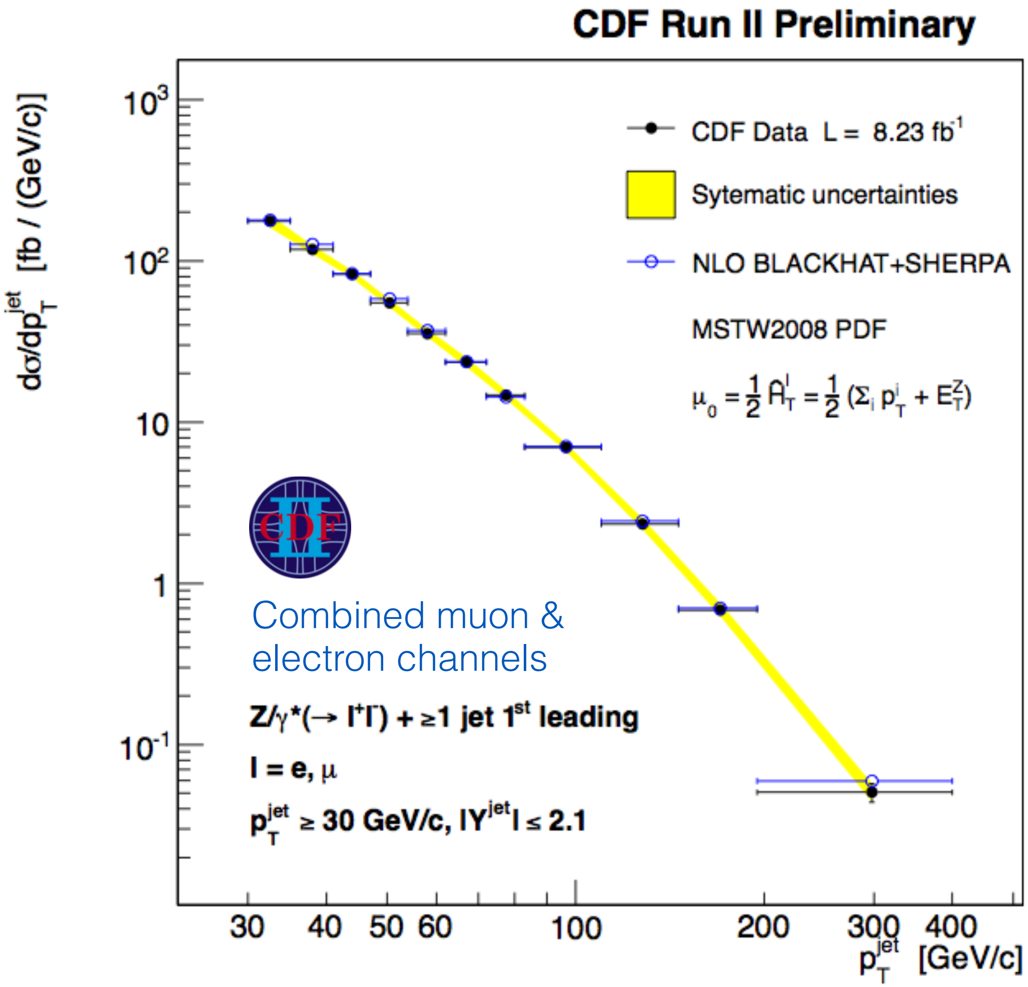
Test of pQCD calculations; dominant background for SM measurements and new physics
Corrected to particle-level, compared to NLO pQCD corrected with parton-to-particle level corrections



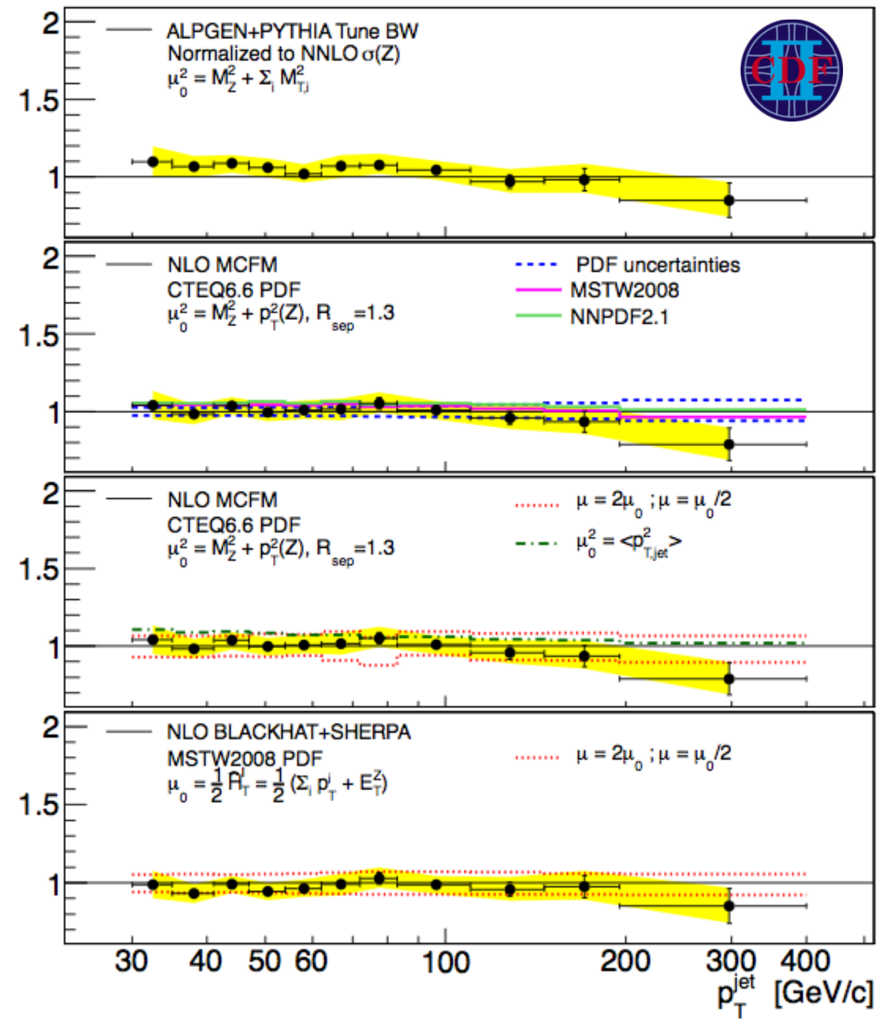


Inclusive jet differential cross-section (combined muon/electron channel): study kinematics of hadronic recoil to Z.

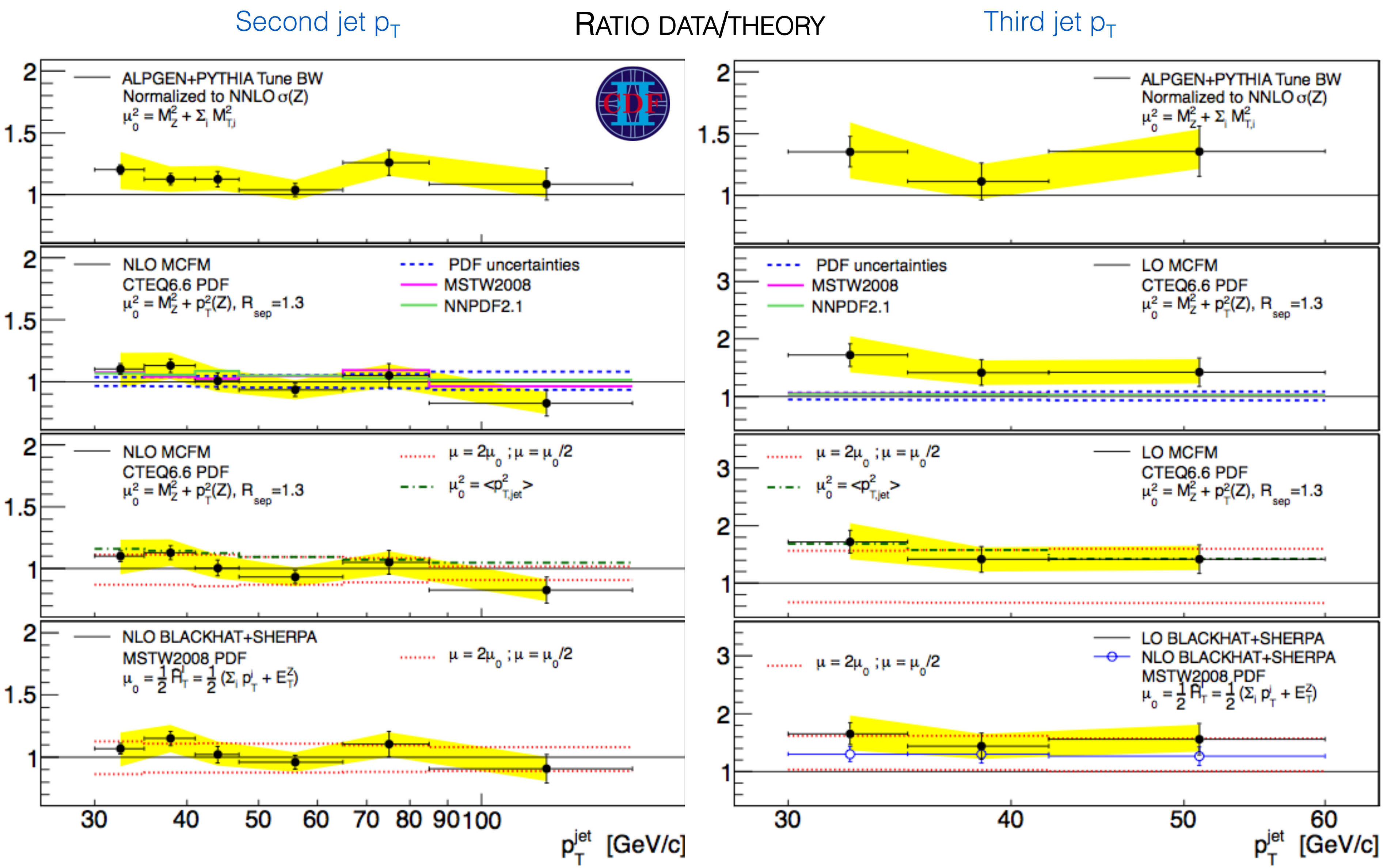
Data well-described by NLO theory



RATIO DATA/THEORY



Z+jets production: second & third jet p_T



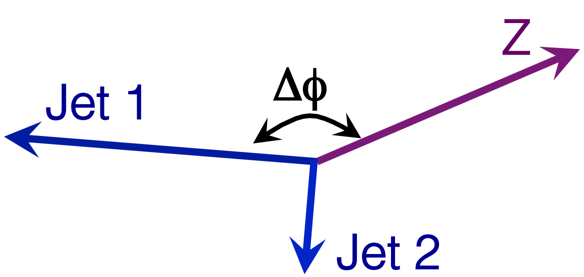
Z+jets angular observables: $\Delta\phi(Z,j)$

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



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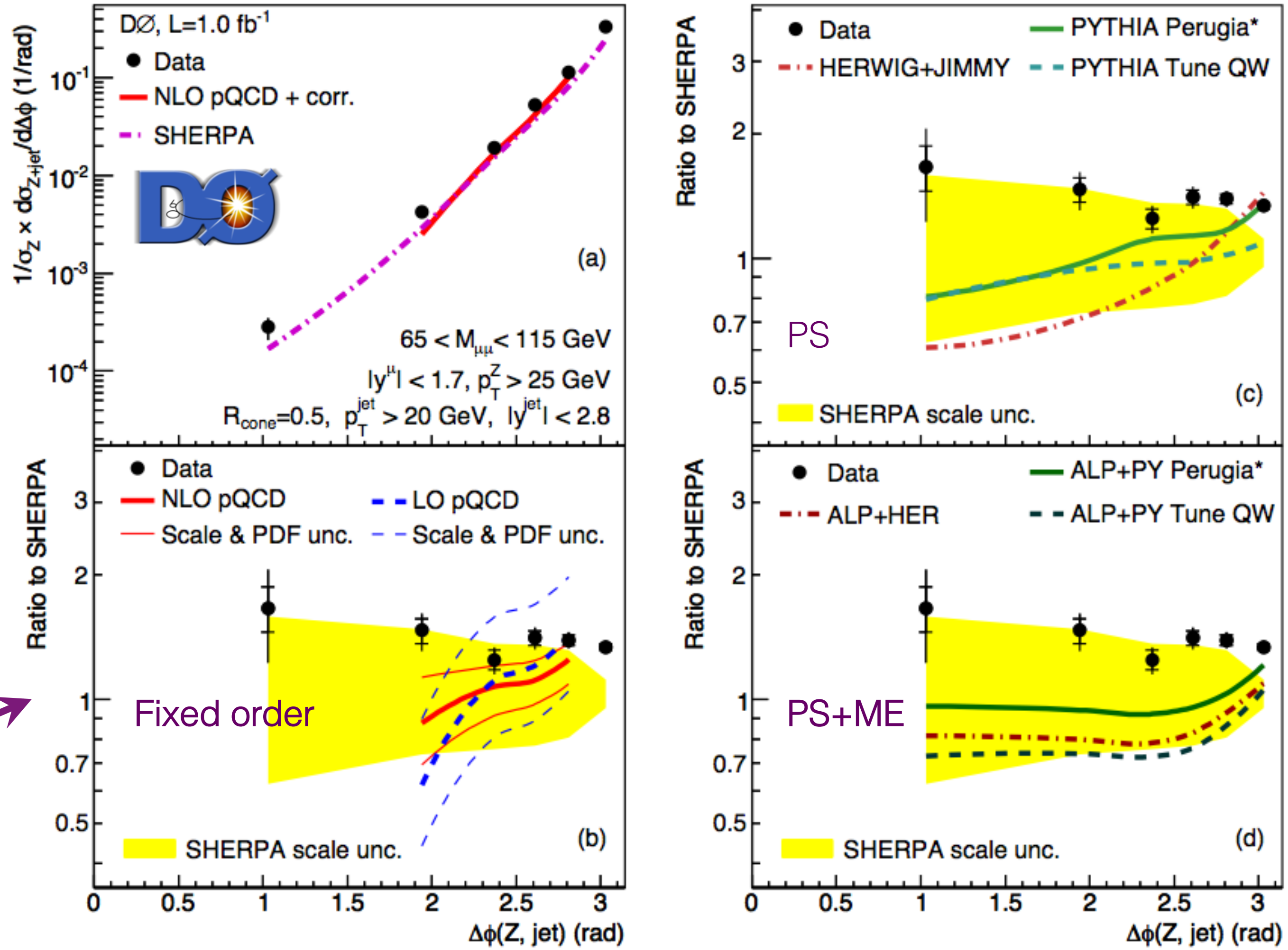


W+jets production

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

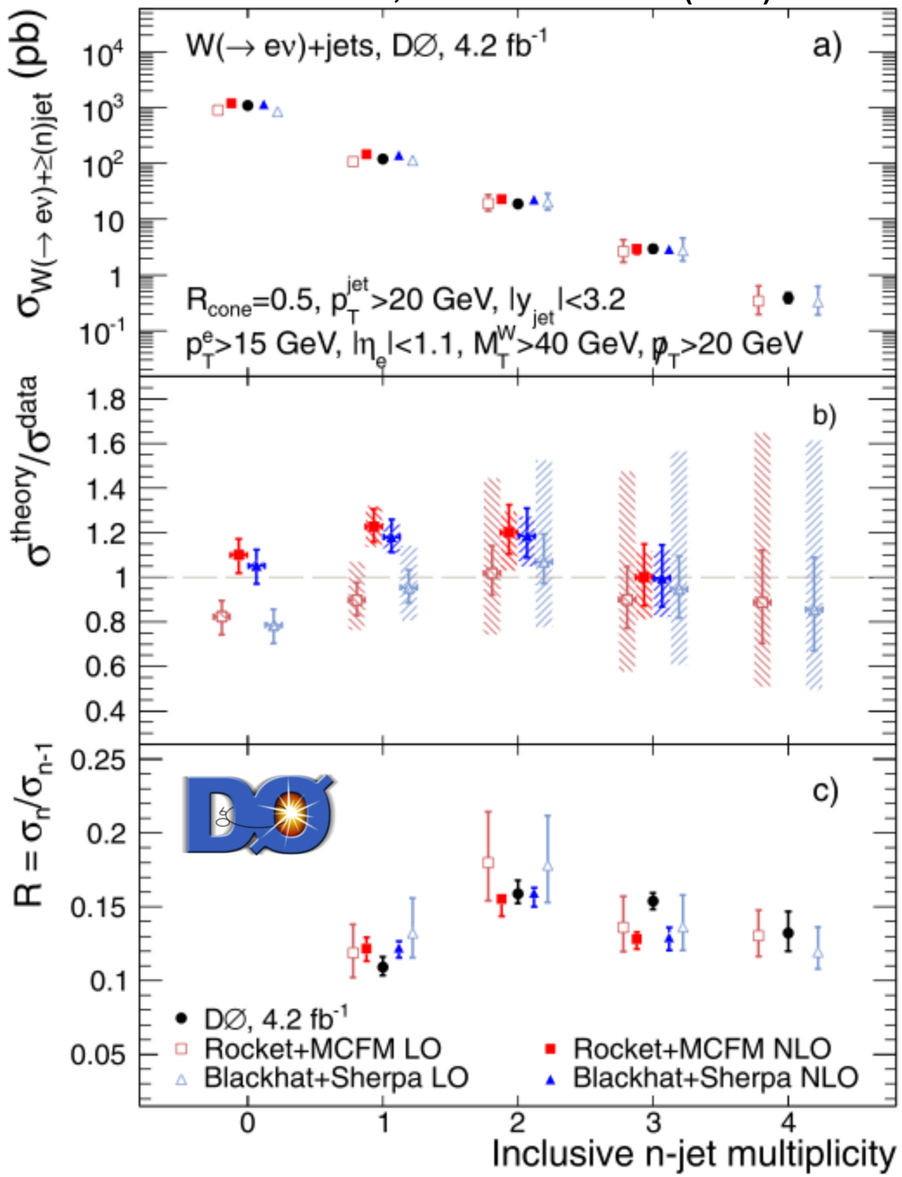
Provide integrated cross-sections and differential cross-sections for W+≤4jets

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 uncertainties competitive with best pQCD predictions available
(in both ratio and absolute measurement)

ARXIV: 1106.1457, PHYS. LETT. B 705 (2011) 200-207



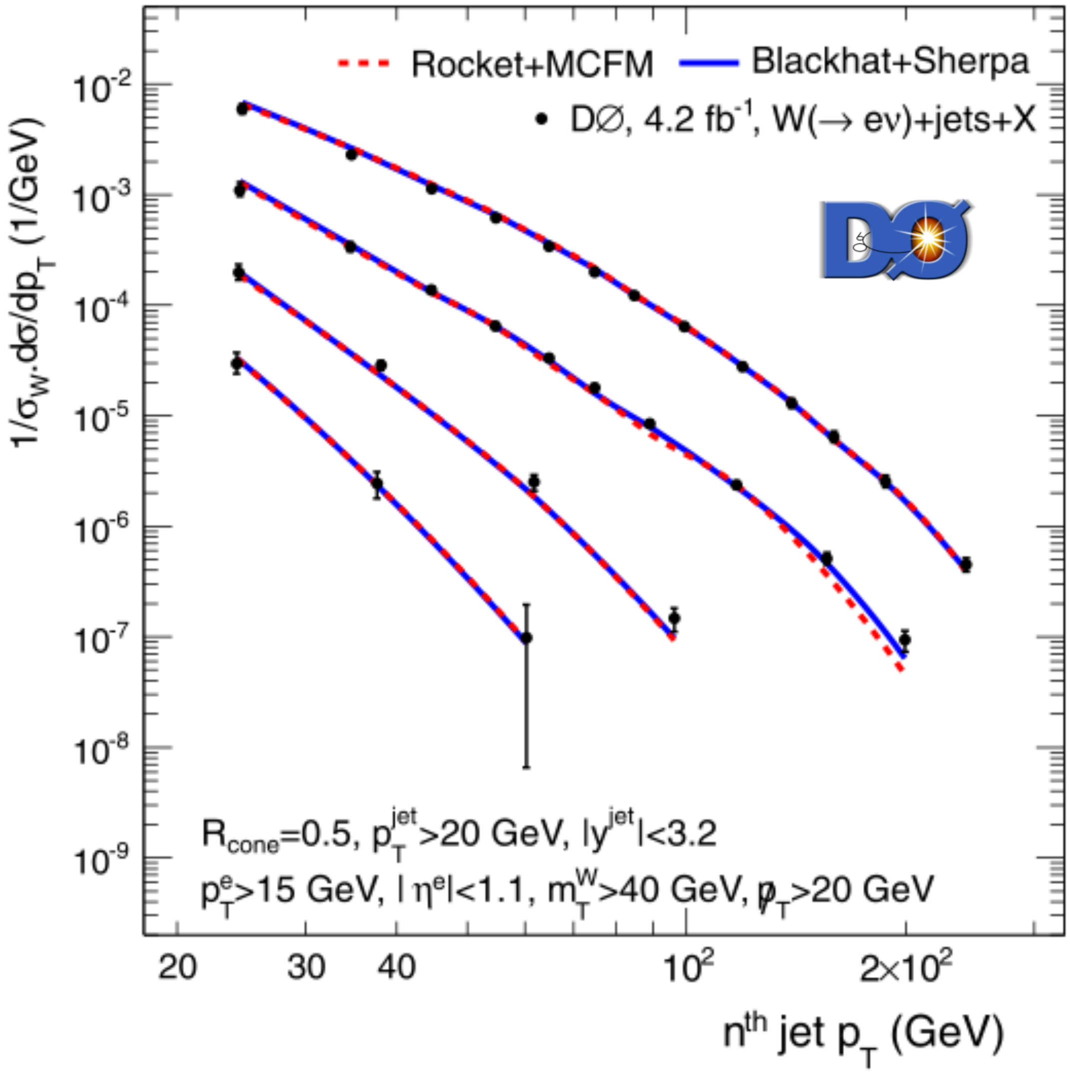
W+jets differential jet spectra normalized to measured inclusive W cross-section

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

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

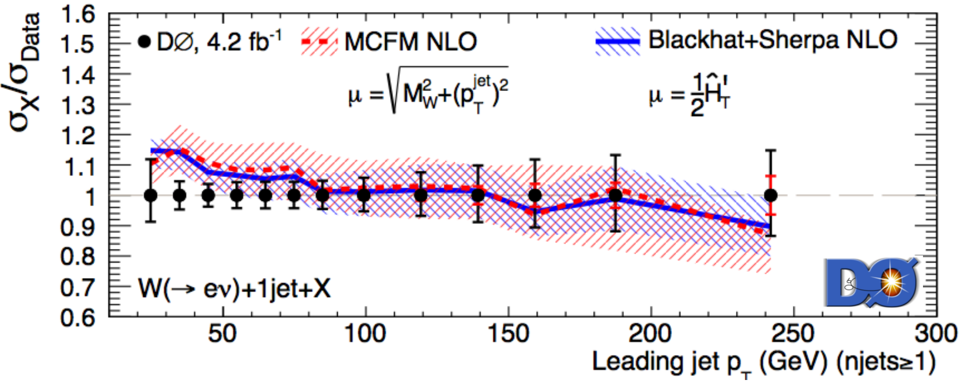
UE+hadronization particle-level corrections to theory derived with Sherpa 1.2.3

ARXIV: 1106.1457, PHYS. LETT. B 705 (2011) 200-207



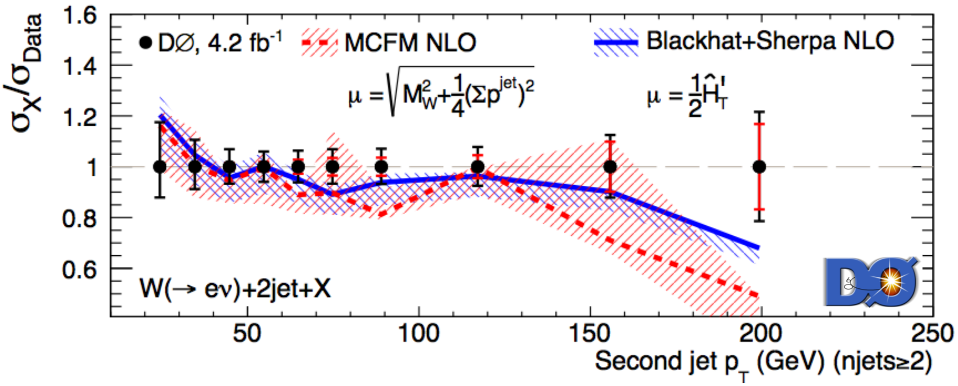
W+jets production: jet p_T

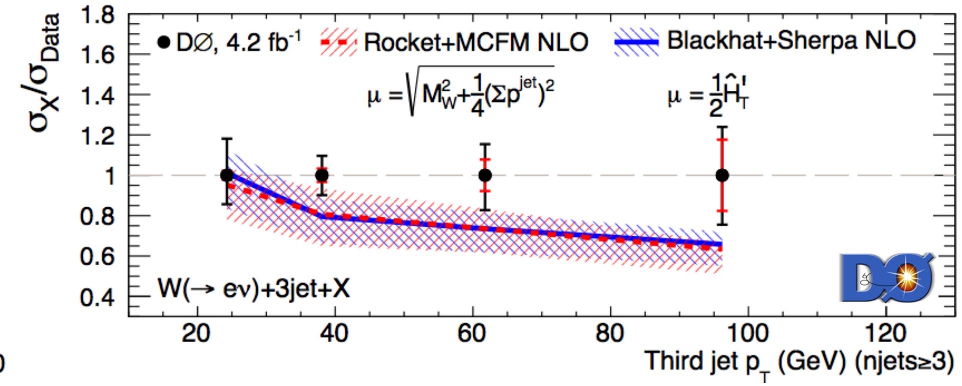
ARXIV: 1106.1457, PHYS. LETT. B 705 (2011) 200-207



NLO performs well: possible modelling issues at low p_T?

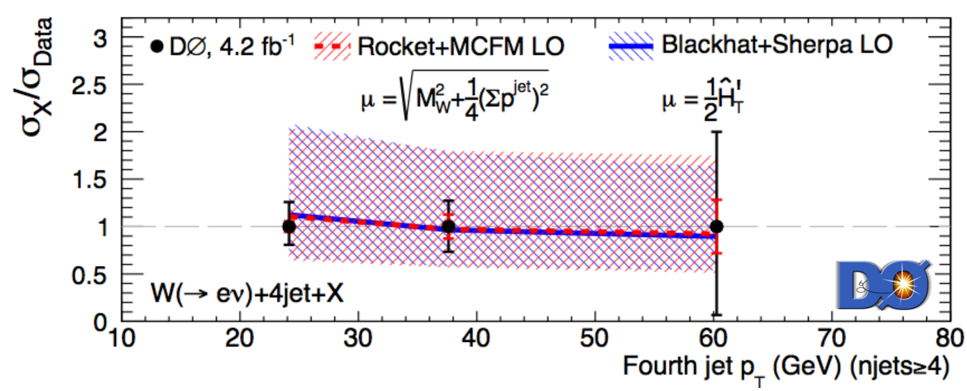
Third jet shows some disagreement in shape & normalization with NLO





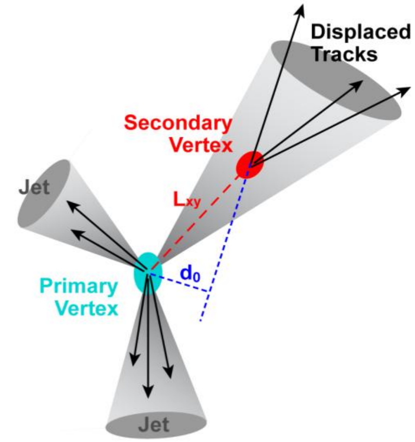
Data uncertainties comparable to theoretical uncertainties over bulk of distributions

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



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

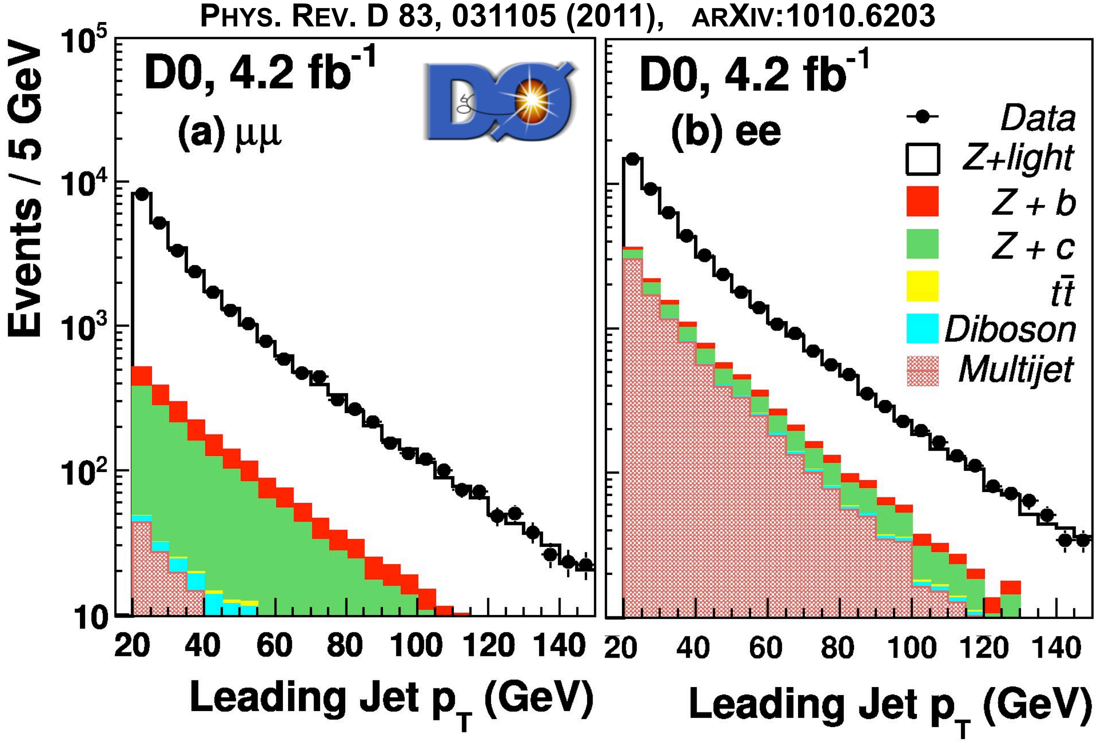


Study both di-electron and di-muon channels:
Lepton p_T>15 GeV, jet p_T>20{15} GeV, jet $|\eta|$<2.5

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

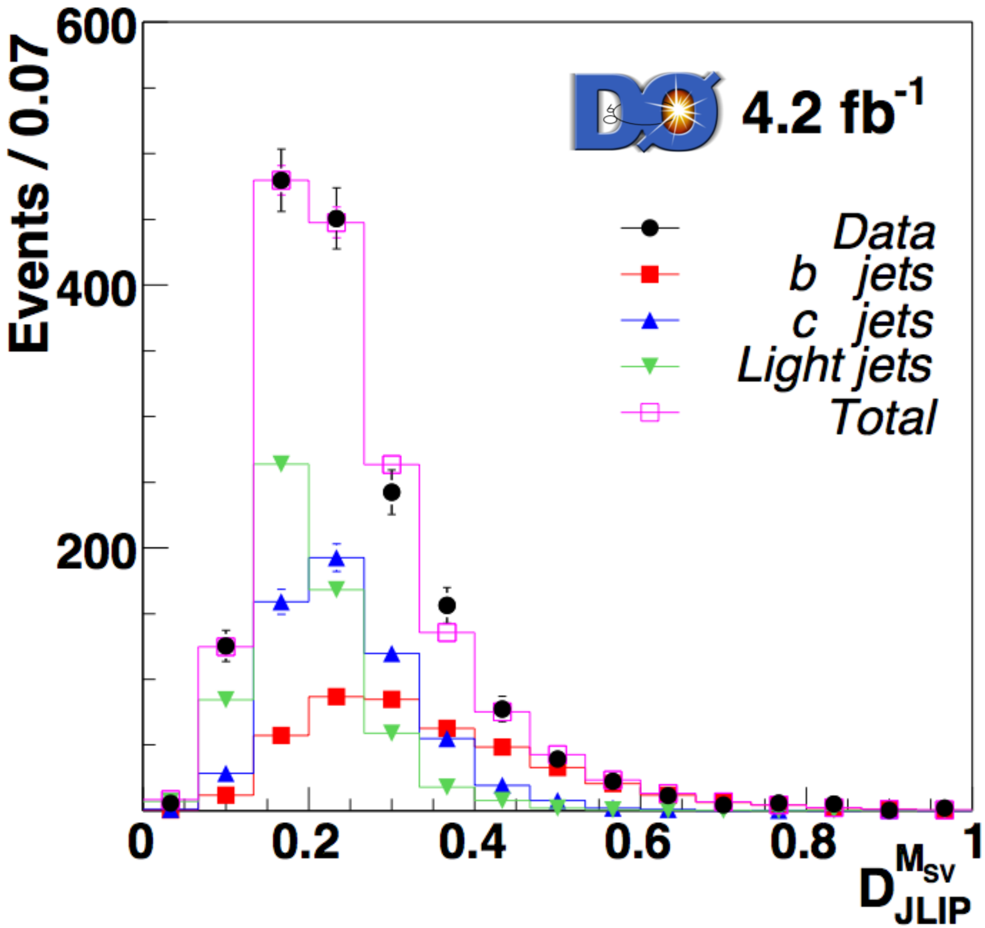


Jet flavour fractions measured in both di-electron and di-muon channels

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

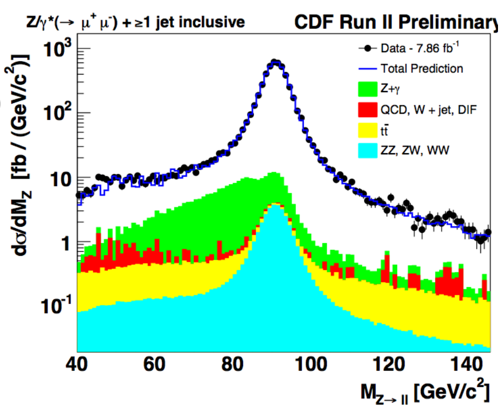
Consistent with NLO theory (MCFM) = 0.0185±0.0022

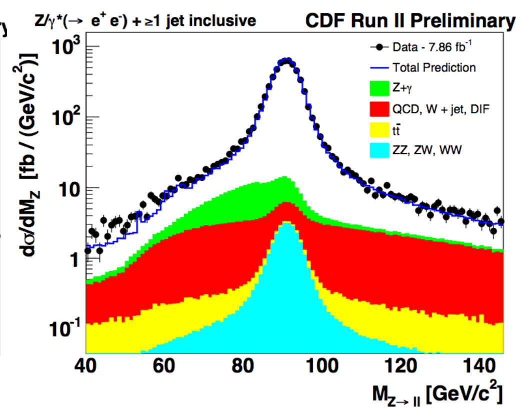
σ(Z+b)/σ(Z+jet) and σ(Z+b)/σ(Z) CDF measurement with 7.86 fb^{-1}

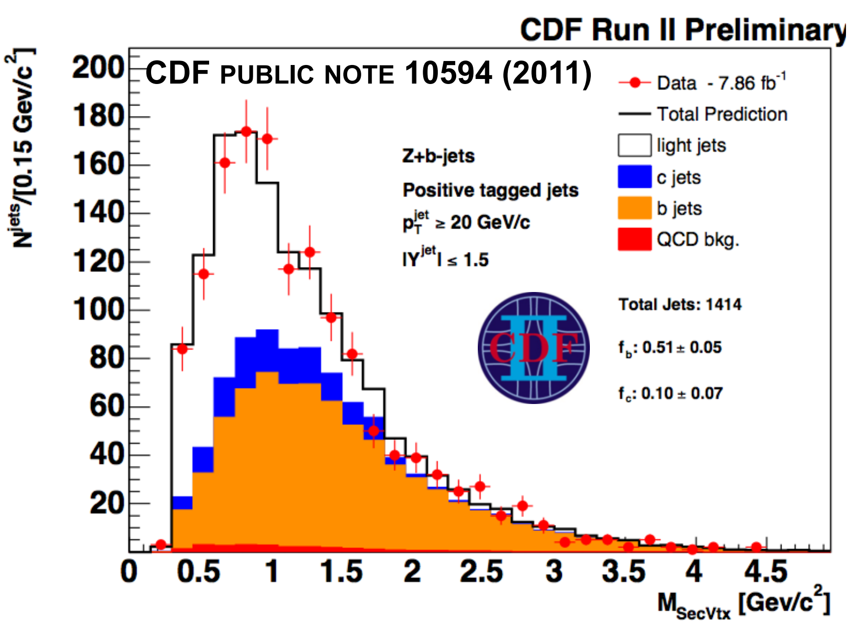
Similar template fit method as used in DØ analysis
Combine analysis from di-electron and di-muon channels:

Require high p_T central b-tagged jets, (|y|<1.5, R=0.7 midpoint cone, p_T>20 GeV)

Largest systematics from JES, template modelling, b-tag efficiency.







Results:

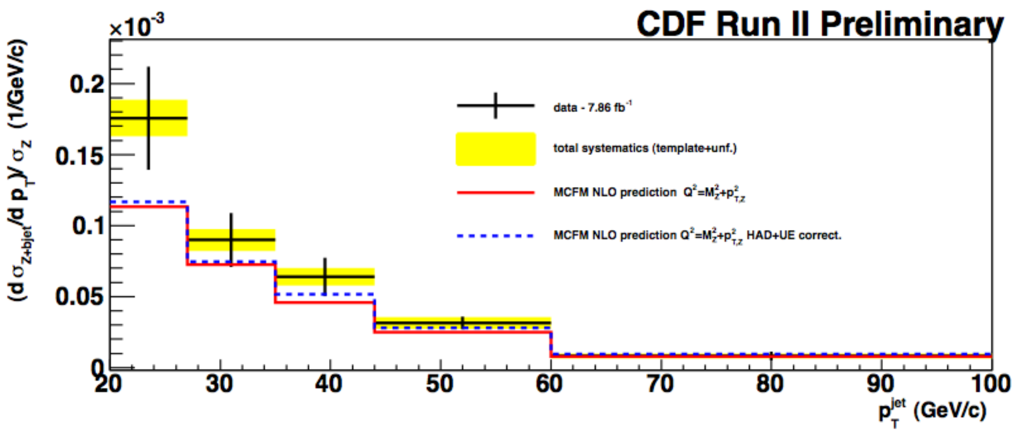
σ(Z+b)/σ(Z)= $0.284\pm0.029^{stat}\pm0.029^{syst}$%
σ(Z+b)/σ(Z+jet)= $2.24\pm0.24^{stat}\pm0.27^{syst}$%

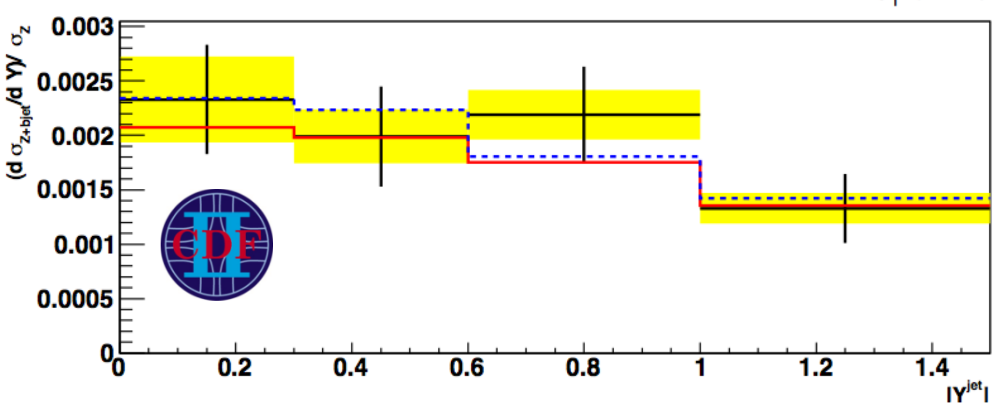
NLO: (range from different scale choice)
σ(Z+b)/σ(Z)= 0.23—0.28%
σ(Z+b)/σ(Z+jet)= 1.8—2.2%

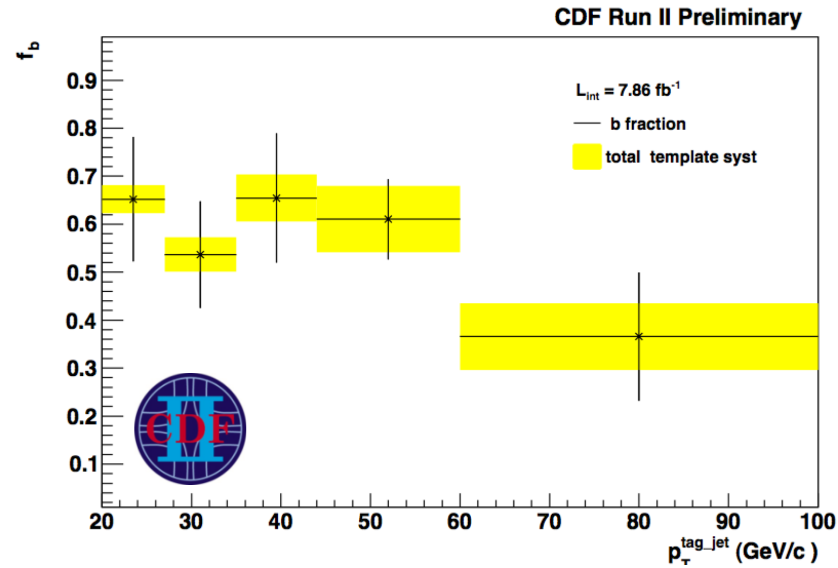
Data above Alpgen predictions by ~ factor 1.6

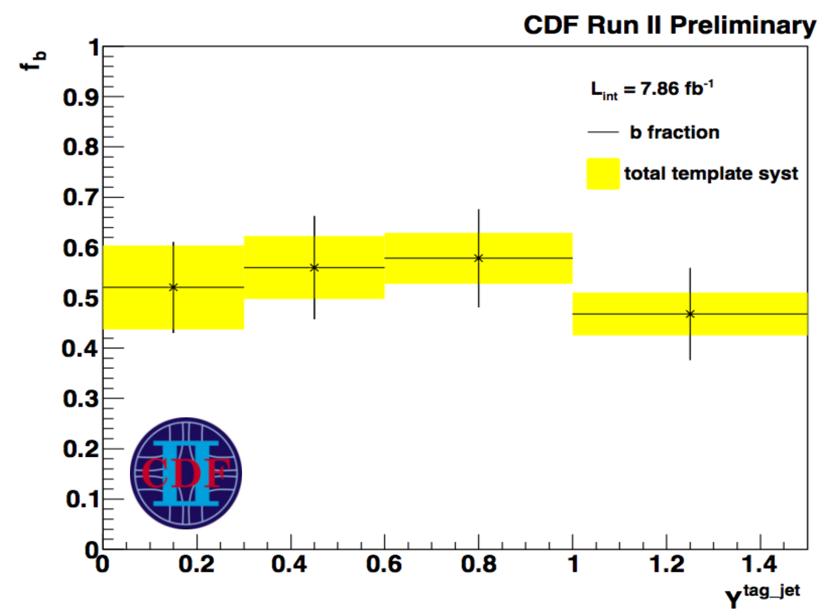
Following from Z+b total cross-section measurements, extract:
fitted b-fractions and normalised differential cross-sections as function of jet p_T/y

Comparisons made to MCFM NLO predictions





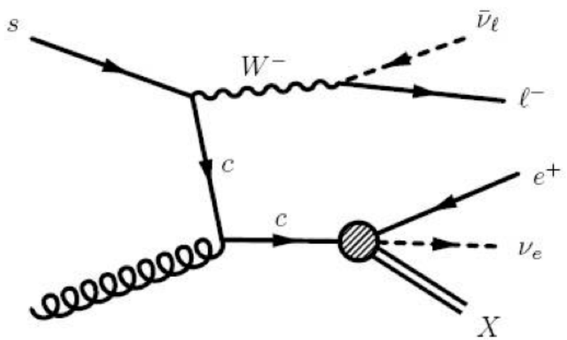




Measurement of W+c production: sensitive to s-quark PDF

Background to single-top and associated WH production

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



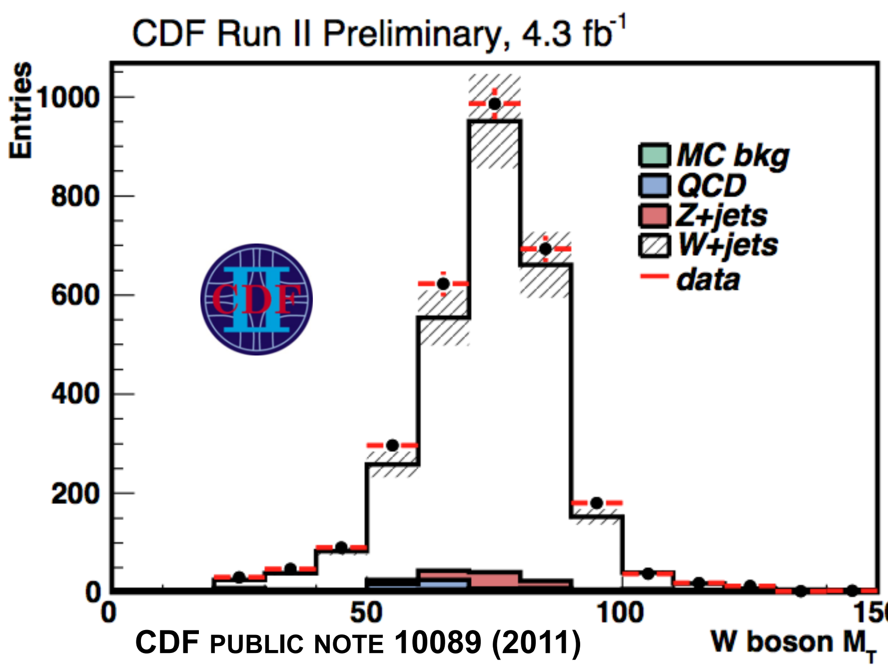
$$\sigma_{Wc} \times \mathrm{BR}(W \to \ell\nu) = \frac{N^{OS-SS}_{\mathrm{tot}} - N^{OS-SS}_{\mathrm{bkg}}}{Acc \cdot \int L \, \mathrm{d}t}$$

Lepton p_T > 20 GeV, jet p_T>15 GeV, $|\eta_j|$<2.0, MET>25 GeV, $m_T(W)$>20 GeV

Extract W+c cross-section:

SLT_e = 13.4 ±2.3 (stat) ±2.4 (syst) ±1.1 (lumi)
SLT_μ = 14.2 ±6.5 (stat) ±3.4 (syst) ±1.2 (lumi)
Combination:
= $13.3^{+3.3}_{-2.9}$ (stat+syst)

NLO prediction = 16.5 ±4.7



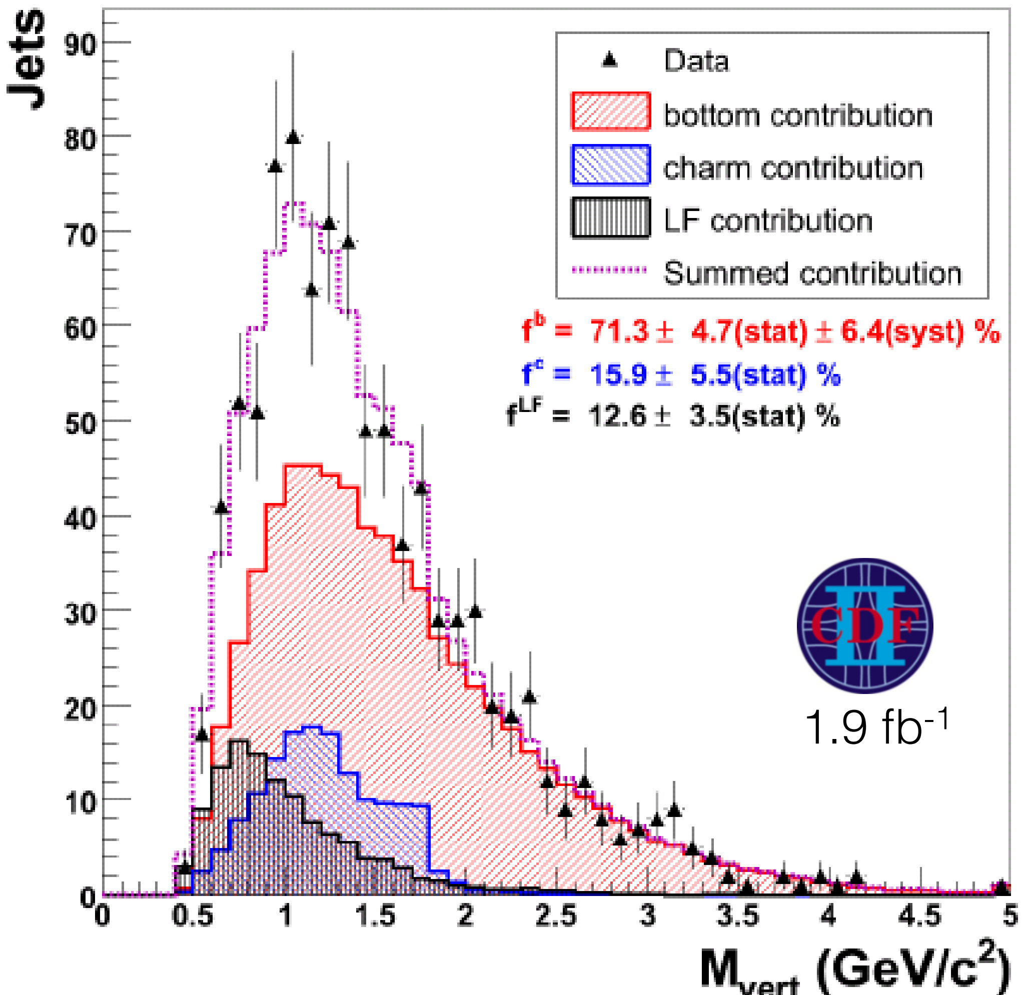
W+bb is a dominant background in low-mass Higgs search

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

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)



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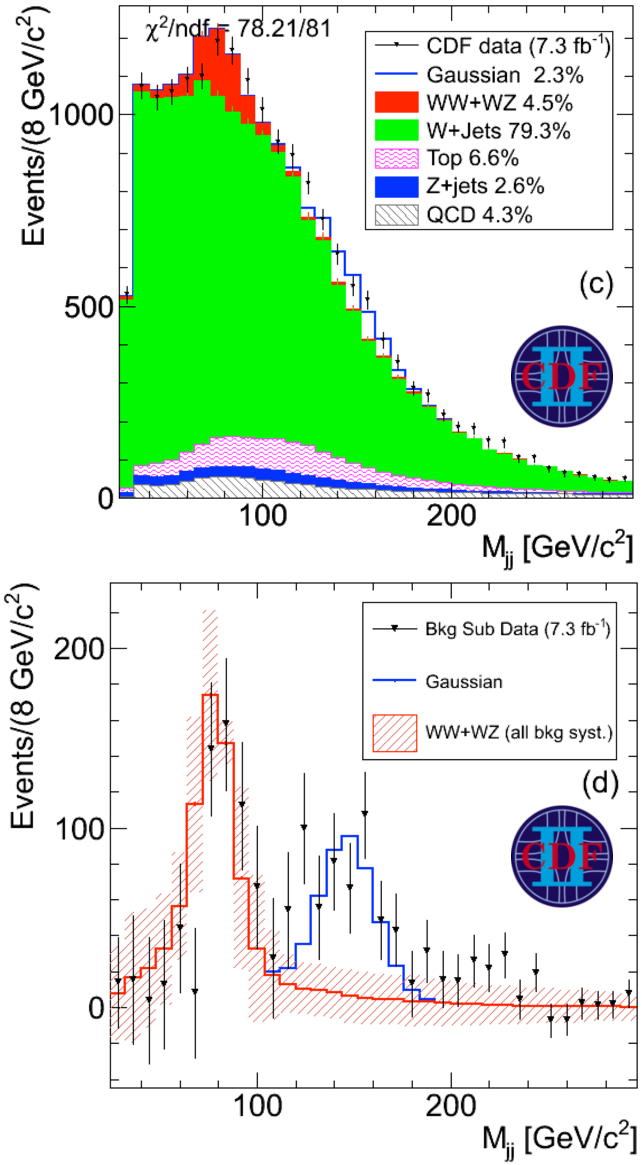


4.1σ excess seen in dijet mass spectrum of W+2jet (exclusive) sample

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 σ(X→jj)~ 4pb (300 times higher than WH→lvbb)

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.

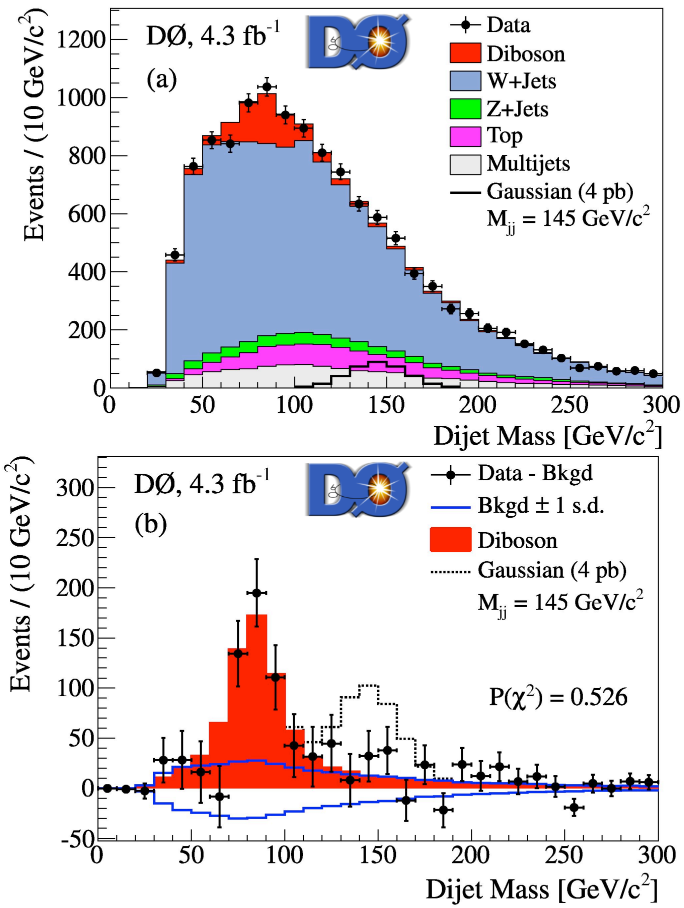
PHYS. REV. LETT. 106, 171801 (2011), ARXIV:1104.0699
AND http://www-cdf.fnal.gov/physics/ewk/2011/wjj/7_3.html

DØ study of W+jj anomalous production

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

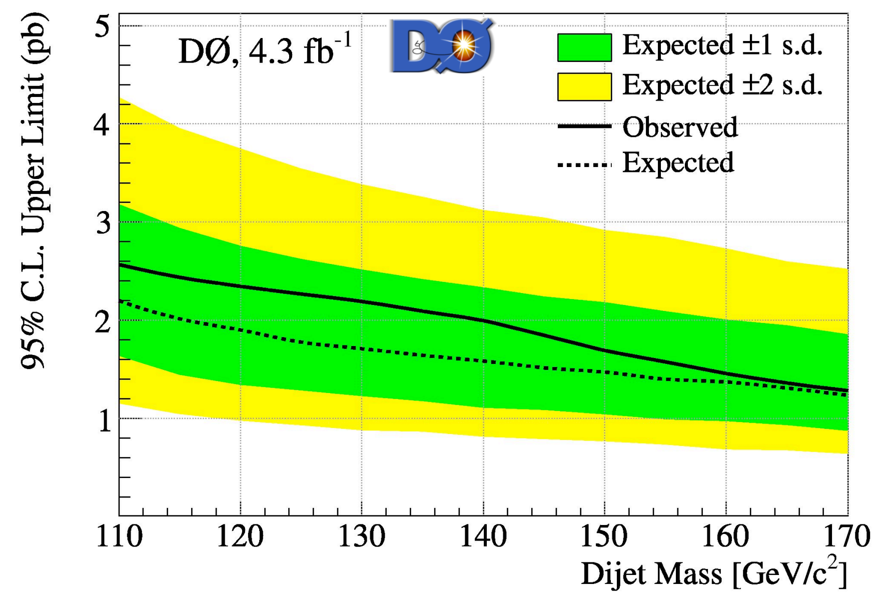
Dijet mass distributions after fitting SM processes to data (4.3 fb^{-1}):

ARXIV:1106.1921,
PHYS. REV. LETT. 107 (2011) 011804



DØ data consistent with SM prediction!

Set 95% CL upper limits on WX→lνjj



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

Summary

Have presented just a subset of recent W/Z(+jets) results from the Tevatron on ~1—8 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

Additional slides

Theoretical response to DØ Φ* study

Theoretical study of the ϕ^* distribution by Banfi, Dasgupta, Marzani and Tomlinson (arXiv:1102.3594 and 1110.4009)

State-of-the-art result which includes
- fixed order (NLO) calculation, valid at large ϕ^* (with MCFM)
- resummation of large logarithms (next-to-next-to-leading logs) at small ϕ^*

Purely perturbative prediction, without non-perturbative (NP) form factors

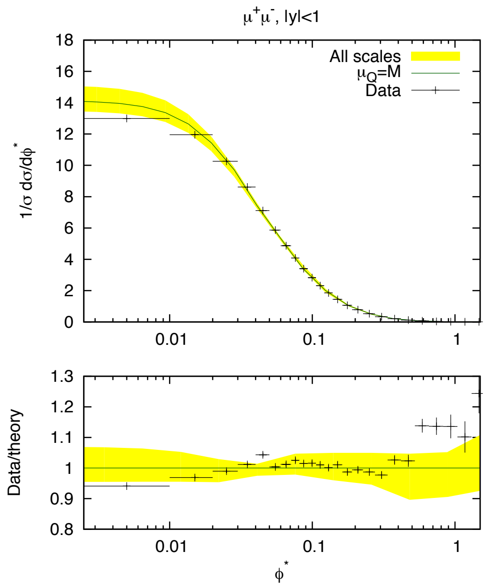
The theoretical calculation is exclusive in the leptons' momenta, so it takes fully into account the experimental cuts

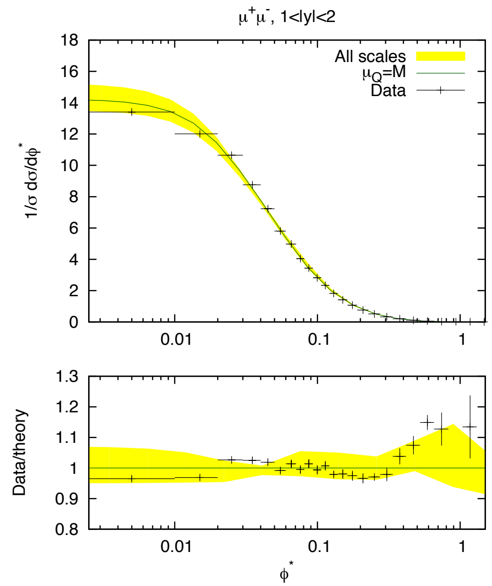
Theoretical uncertainties are faithfully estimated by varying the perturbative scales (renormalisation, factorisation and resummation scales) around the dilepton invariant mass

PDFs uncertainties are found to be small (percent level) in the low ϕ^* region

Predictions for LHC (for both ϕ^* and more traditional Q_T) are work in progress

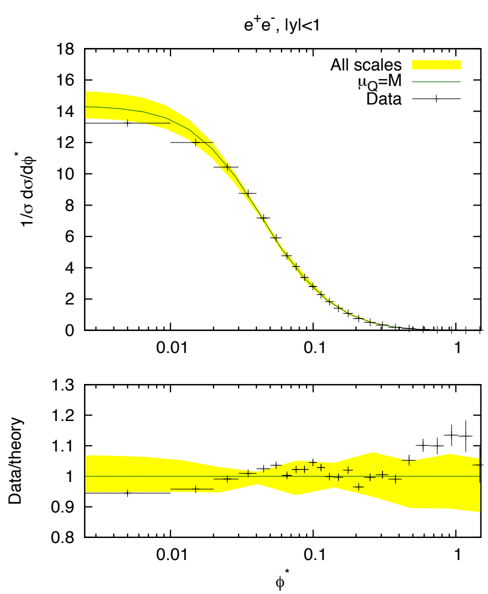
Theoretical response to DØ Φ* study

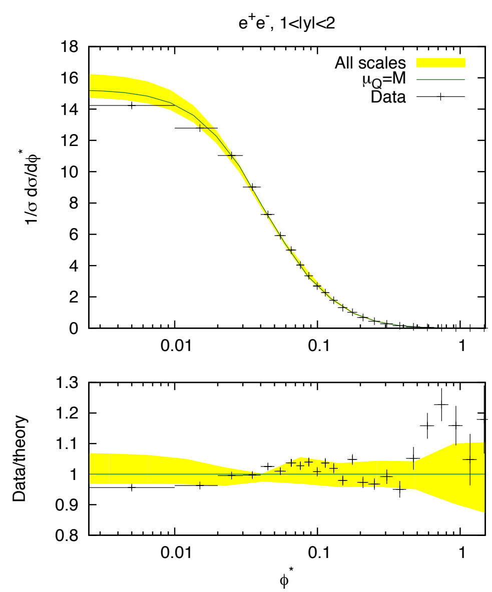


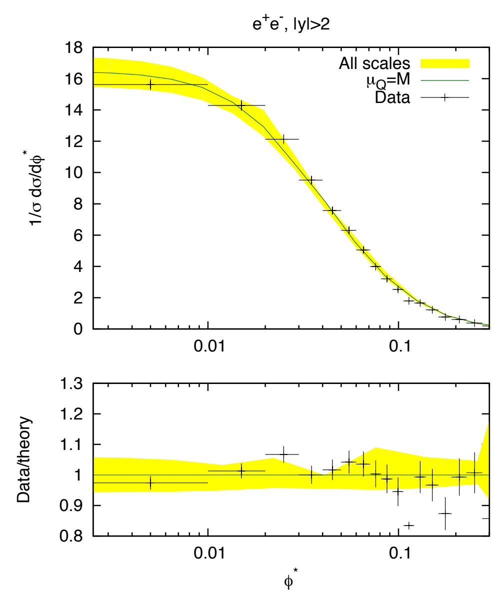


Good agreement, within uncertainties, for all rapidity bins

NP effects seem small and NP form factors are not necessary to describe the data at low ϕ^*







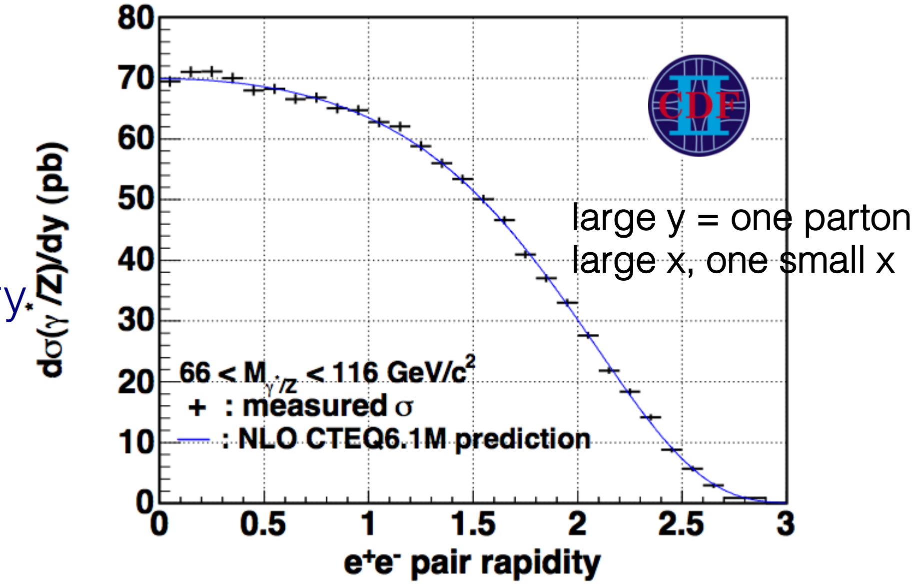
Z/γ* rapidity

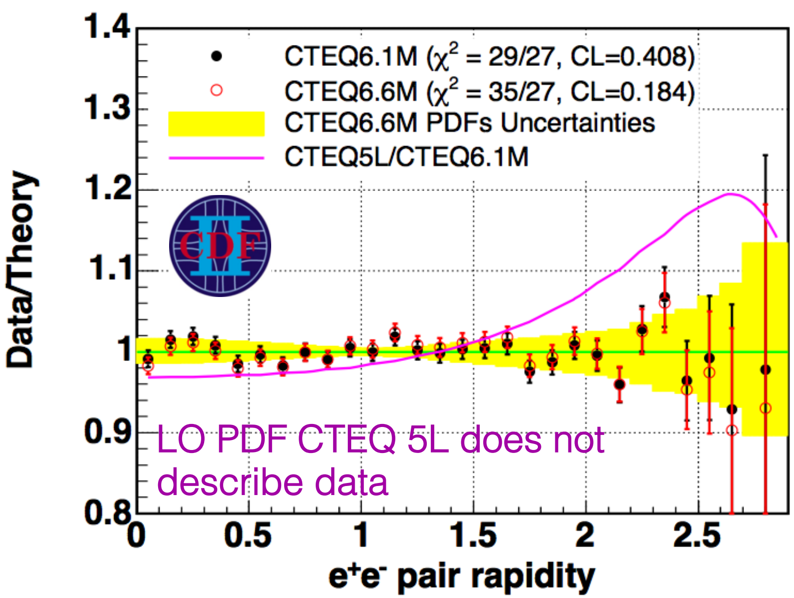
Z/γ* rapidity related to fraction of momentum carried by two partons

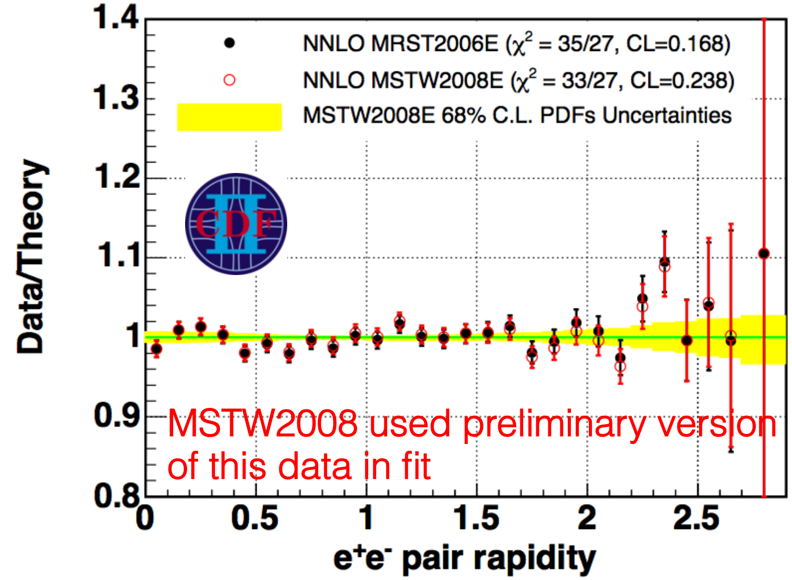
Differential cross section measurement carries information for PDFs complementary to W charge asymmetry

Good agreement between data and theory seen over the entire spectrum

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





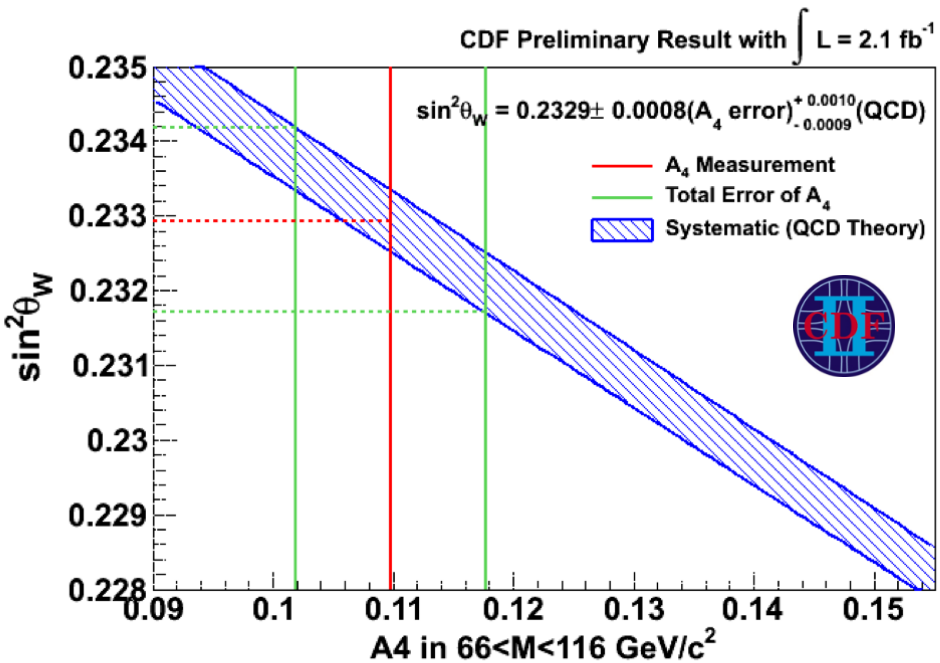


Lepton angular distribution in Z/γ^*

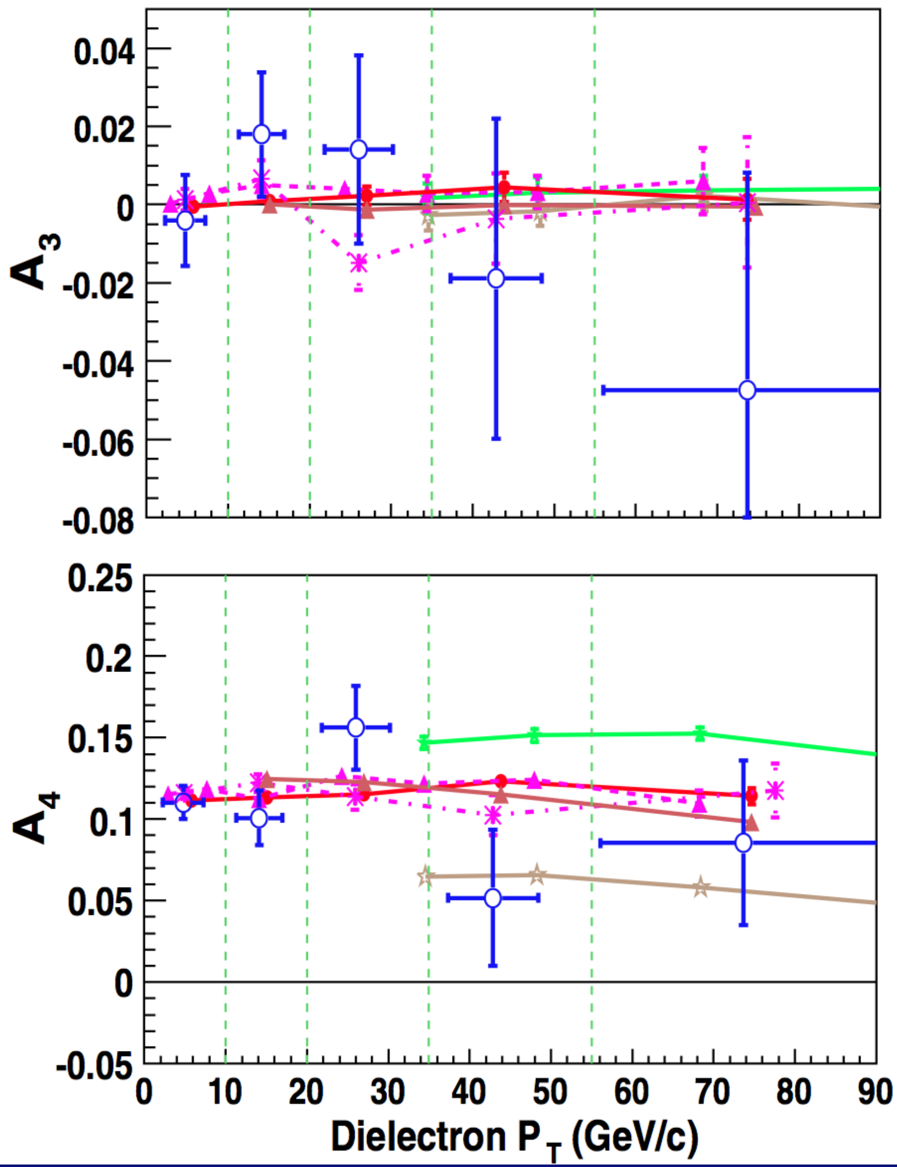
A3, A4 relatively flat in p_T

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

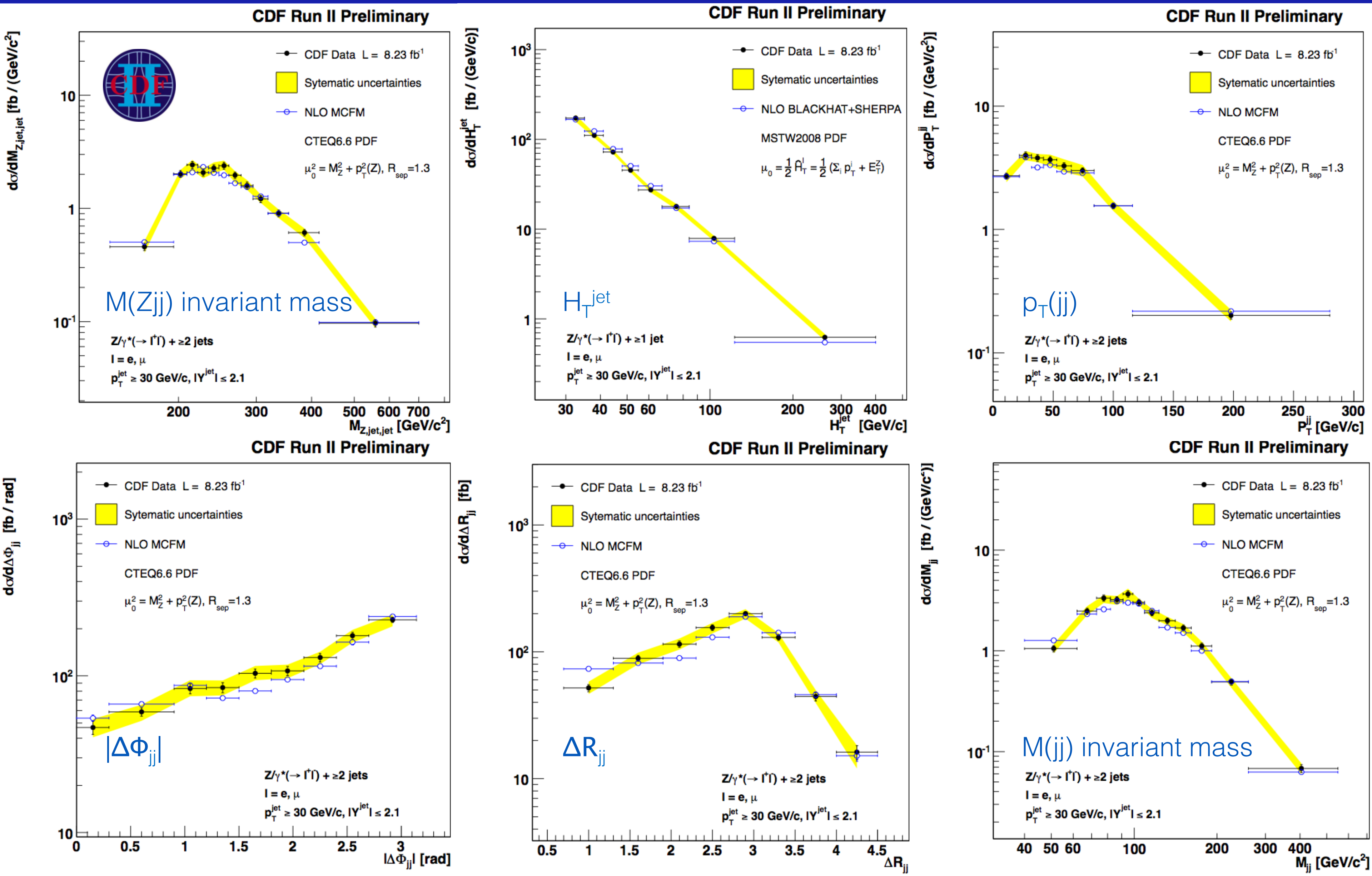
Value of $\sin^2 q_W$ extracted =0.2329 ± 0.0012 (theory-dependent) in agreement with SM



PHYS. REV. LETT. 106, 241801 (2011)



Z+jets production kinematics

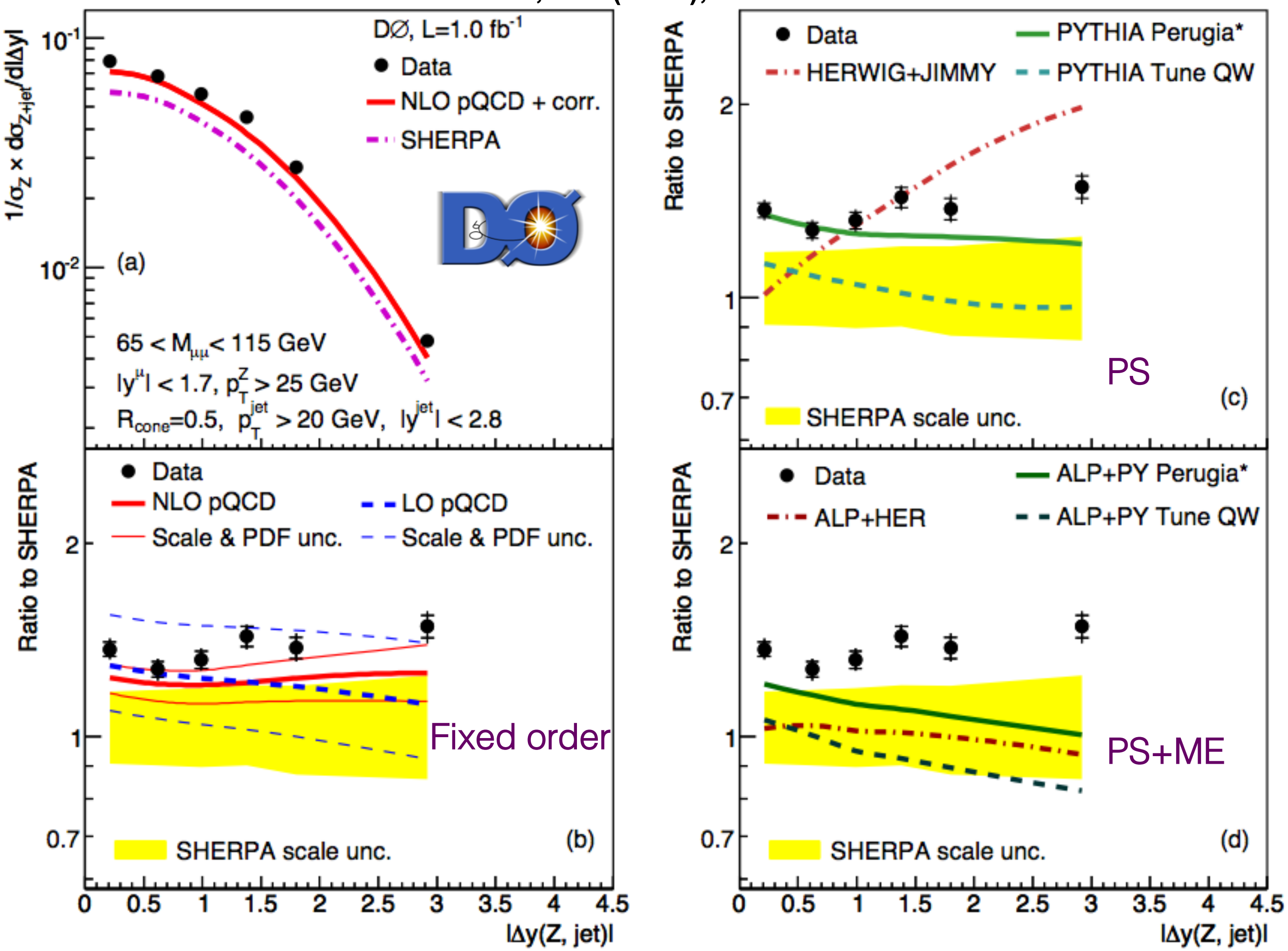


Z+jets angular observables: $\Delta y(Z,j)$

NLO pQCD and Sherpa do good job of describing shape of $\Delta\psi(Z,j)$

Pythia also does a reasonable job, unlike in $\Delta\phi(Z,j)$

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

pp→Z/γ*(ee)+X differential Z p_T cross-section with 2.1 fb^{-1} data

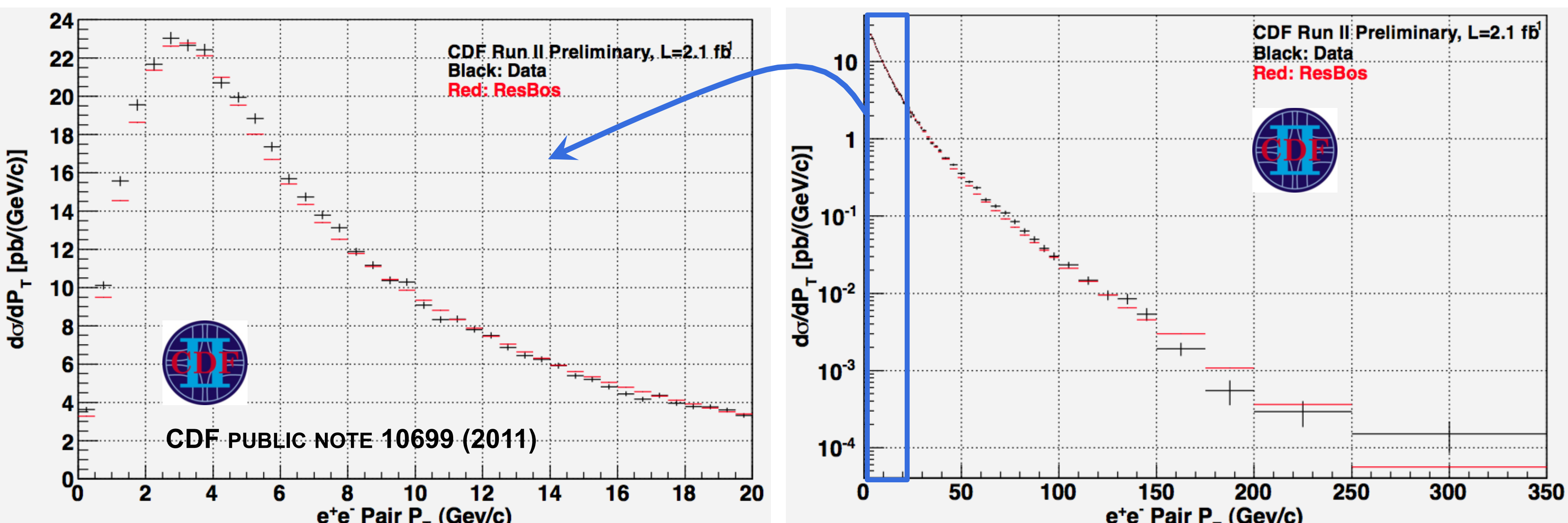
Fully-corrected cross-section measurement, uses acceptance corrections from Pythia+PHOTOS with iterative tuning to match reconstructed data

QCD backgrounds 0.3%, EWK backgrounds 0.2% of selection

Low p_T region shape a test of QCD gluon-resummation

Comparison to RESBOS with CTEQ 6.6 (cross-section 254 pb)

Total measured cross section: 257.1 ±0.7 (stat) ±2.6 (syst) ±14.9 (lumi) pb,

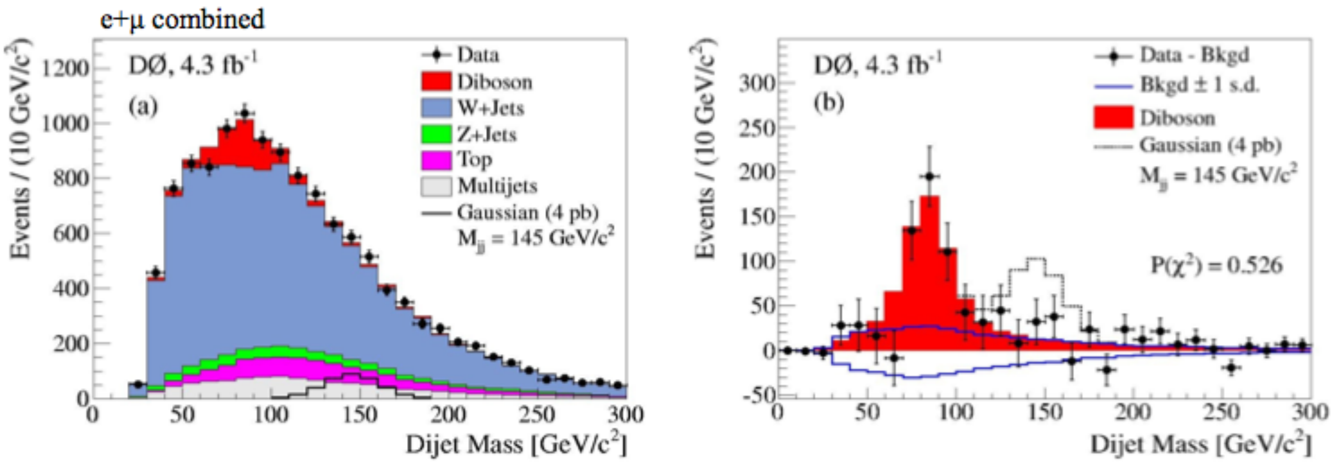


DØ study of W+jj anomalous production

Alpgen modelling effects

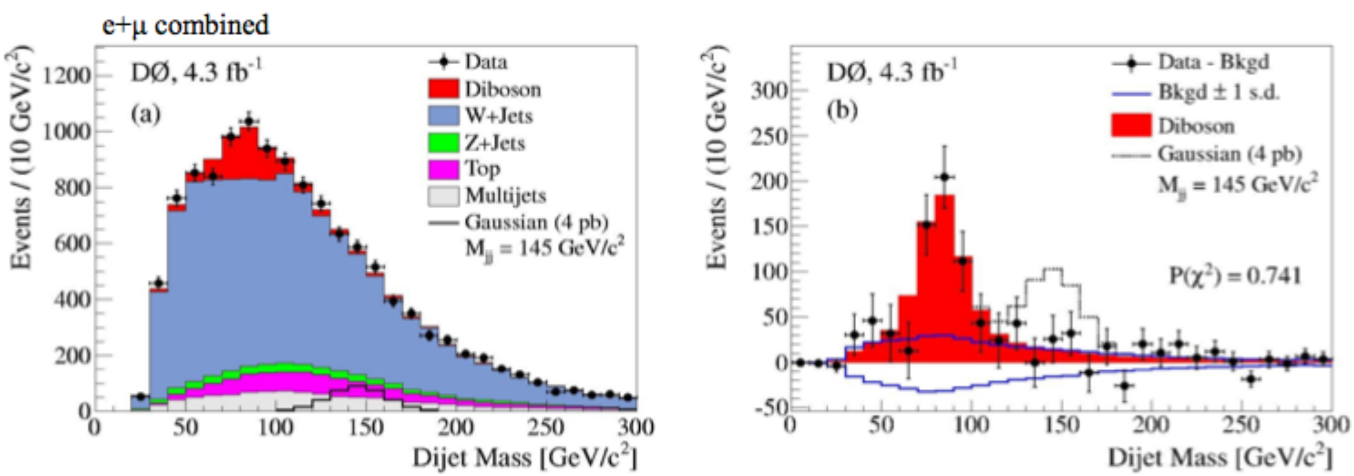
The dijet mass distributions after fitting SM processes to data

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:

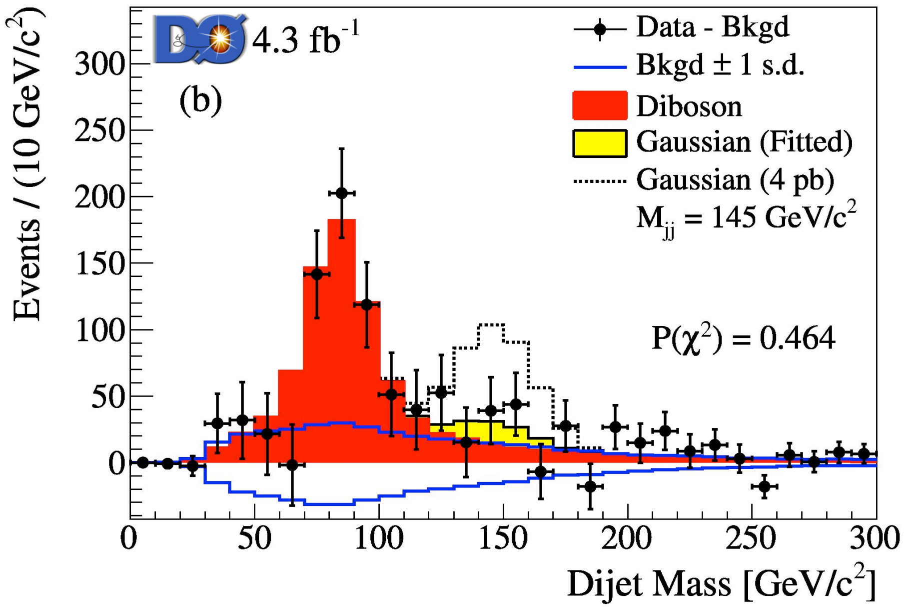


→ 95% CL exclusion for cross sections greater than 1.5 pb @ m_{jj} = 145 GeV

Fit WX→lνjj template (derived from diboson width and WH→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?



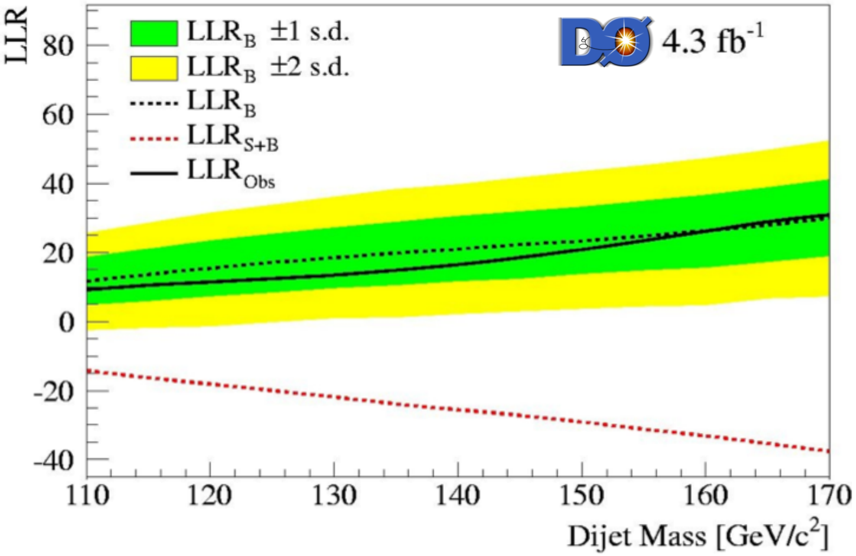
Construct test statistic:

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

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

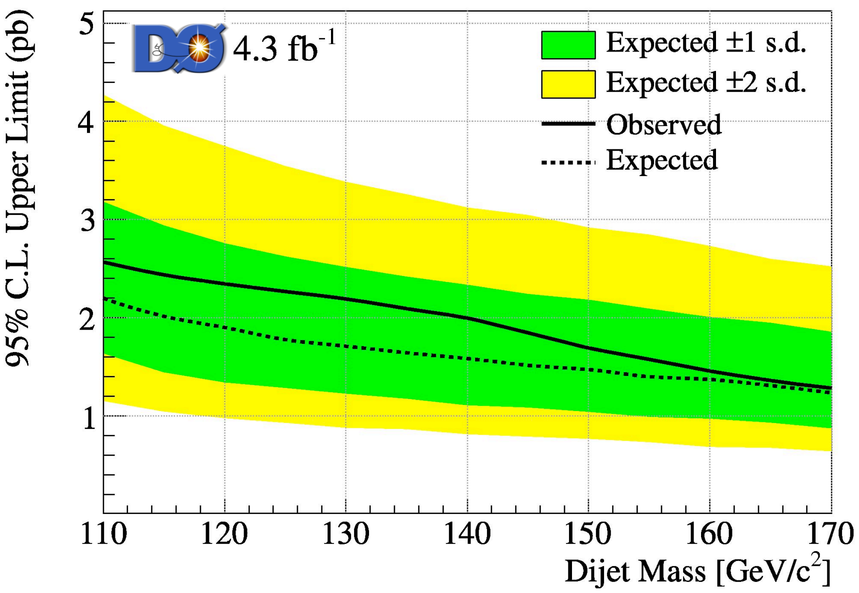
FOR MUCH MORE DETAIL, PLEASE SEE:
http://www-d0.fnal.gov/Run2Physics/WWW/results/final/HIGGS/H11B/JoeHaley_WineCheese10June2011.pdf

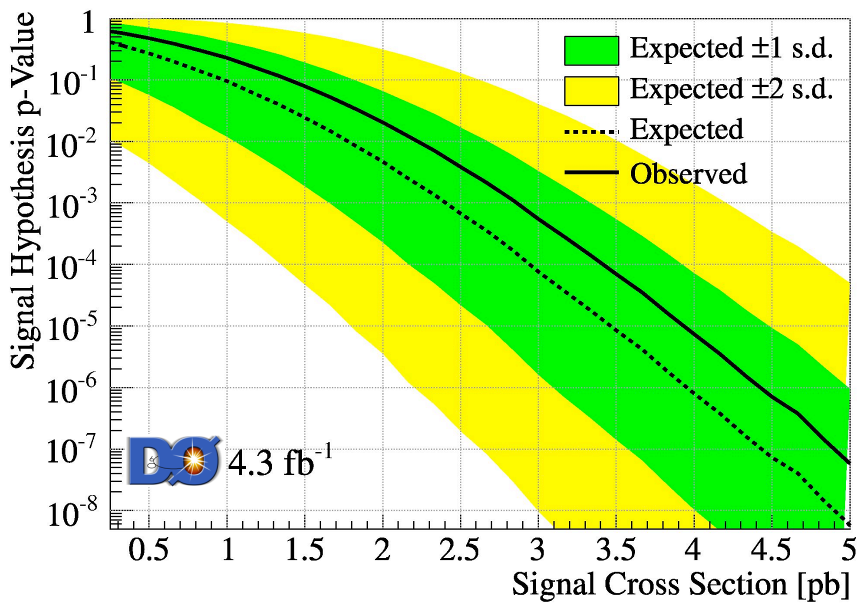
Compare observed LLR to the predicted LLR distributions over the range of dijet mass



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