EW/QCD Results from the Tevatron

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Overview

- Introduction
- Recent Electroweak results
  - Single W or Z boson production
  - Diboson production
- Recent QCD results
  - Inclusive jet production
  - Vector boson + jets
  - Diphoton production
- Conclusion

- Only results after May 2010 are shown here
- CDF electroweak: http://www-cdf.fnal.gov/physics/ewk/
  QCD: http://www-cdf.fnal.gov/physics/new/qcd/
- D0 electroweak: http://www-d0.fnal.gov/Run2Physics/wz/
  QCD: http://www-d0.fnal.gov/Run2Physics/qcd/

Introduction

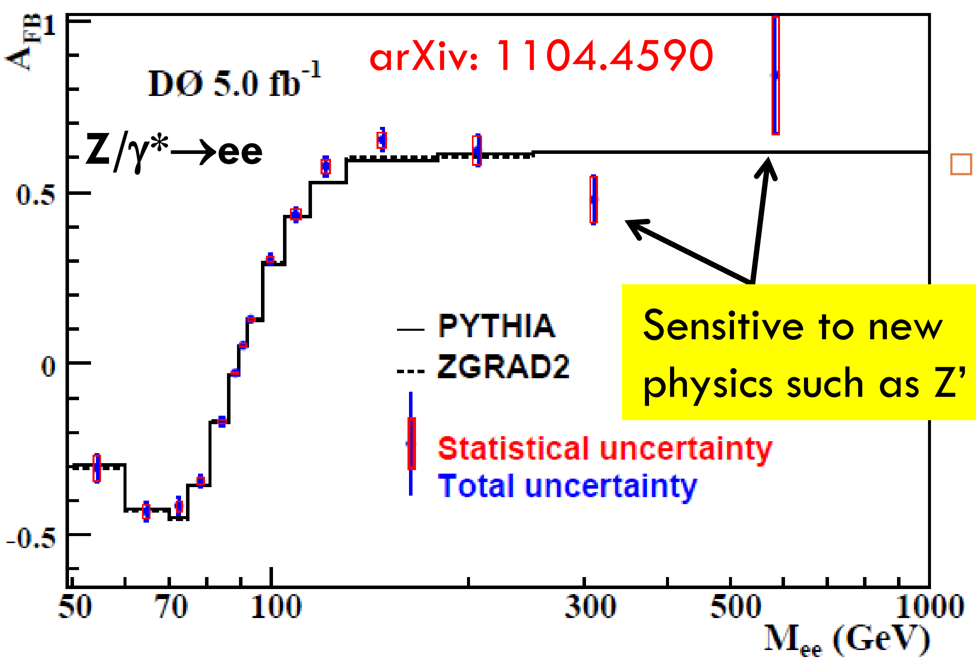
- The LHC has replaced the Tevatron as the highest energy collider
- But Tevatron results will still remain competitive in many selected topics:
  - Large datasets:
    - $>11\ fb^{-1}$ of data delivered so far
    - $\sim 10\ fb^{-1}$ of data recorded per experiment
  - Good understanding of detector performance:
    - Tevatron: $\Delta M_W = 31$ MeV, $\Delta M_{top} = 1.06$ GeV
    - JES uncertainty of <2% for a large p_T range
  - Nature of $p\bar{p}$ collisions:
    - Important for many charge asymmetry measurements such as like-sign dimuon charge asymmetry, top and Z A_{FB}, $W^+(W^-)$ mass measurement etc
    - D0 detector has the feature to switch the solenoidal and toroidal polarities
  - Center-of-mass energy $\sqrt{s} = 1.96$ TeV:
    - Smaller V+jets backgrounds makes WH/ZH search in the $b\bar{b}$ channel feasible

Recent electroweak results

- Analyses with single W or Z boson:
  - Precision test of vector boson production at hadron colliders
  - Precision measurements of fundamental parameters such as M_W and $\sin^2\theta_W$
  - Z/γ^* boson A_{FB} measurement (D0, 5 fb^{-1})
  - Z/γ^* boson transverse momentum (D0, 7.3 fb^{-1})
  - Lepton angular distribution in Z/γ^* events (CDF, 2.1 fb^{-1})
- Analyses with diboson:
  - Better understanding of diboson production at hadron colliders
  - Extraction of anomalous triple gauge couplings (aTGCs)
  - Understanding backgrounds for many new physics searches
  - $W\gamma$ (D0, 4.2 fb^{-1})
  - WW/WZ (CDF, 4.3 fb^{-1})
  - ZZ (D0, 6.4 fb^{-1}) (CDF, 6 fb^{-1})

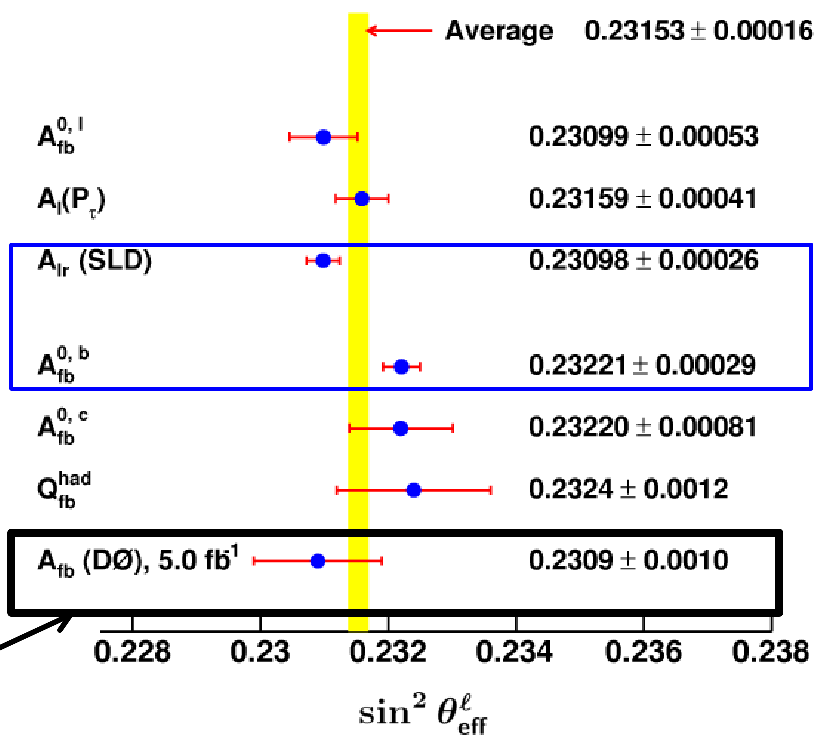
Z/γ^* A_{FB}

Unfolded A_{FB} distribution



Sensitive to new physics such as Z'

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



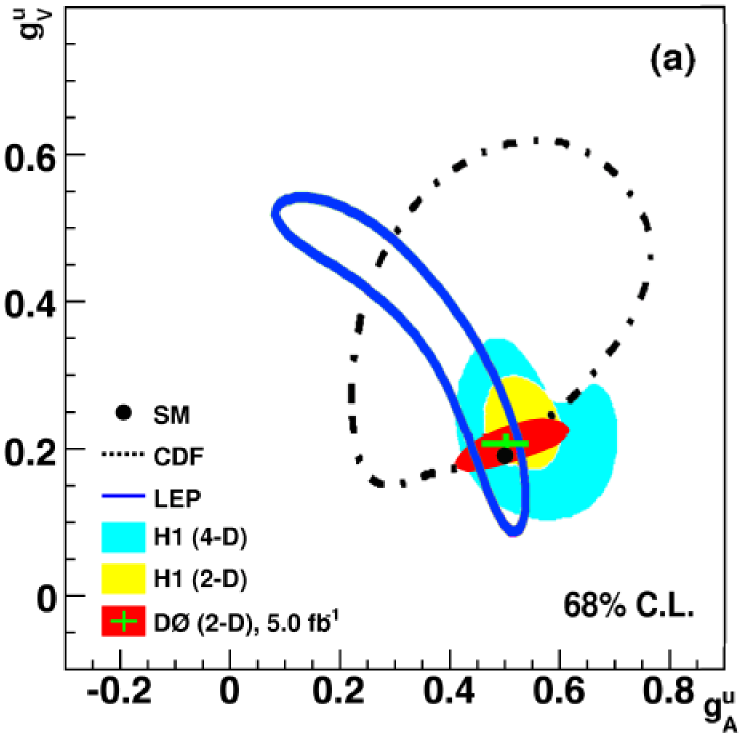
- Similar precision as LEP A_{FB}(b) can be achieved with 10 fb^{-1} by combining CDF and D0 e + μ channels results

$u\bar{u}$($d\bar{d}$) $\to e^+e^-$ at Tevatron compared with $e^+e^- \to q\bar{q}$ at LEP

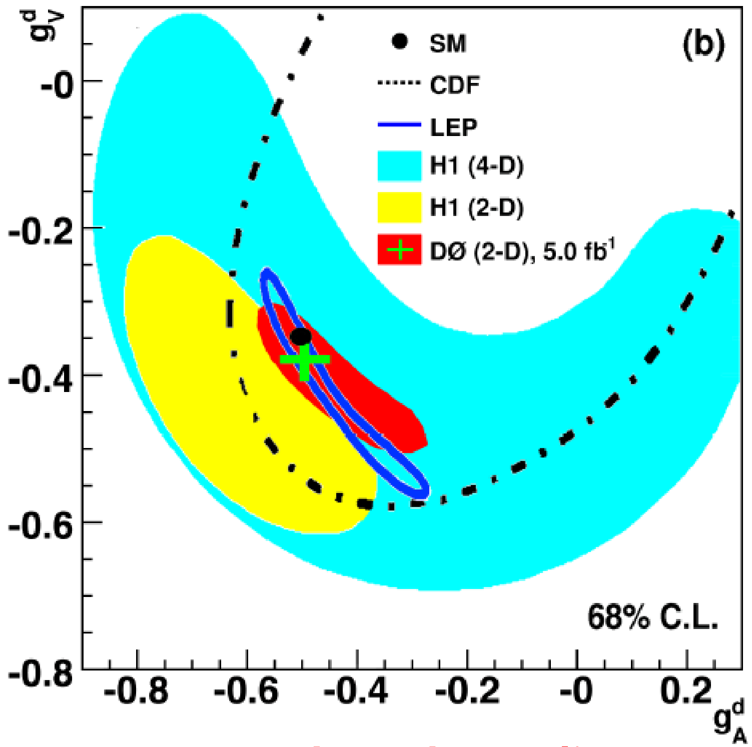
Z-u/Z-d couplings

	g^u_A	g^u_V	g^d_A	g^d_V
D0	0.502± 0.040	0.208± 0.014	-0.495± 0.037	-0.378± 0.027
SM	0.501	0.192	-0.502	-0.347

- Compare unfolded A_{FB} distribution with theoretical predictions with different Z-u and Z-d couplings
- Most precise direct measurement of Z-u and Z-d couplings



Z-u quark couplings



Z-d quark couplings

Z/γ^* boson transverse momentum

- Z/γ^* boson p_T is mainly due to emission of mulitple soft gluons or single parton
- $<p_T^Z>\sim 5$ GeV, while experimental resolution for Z/γ^* p_T is close to 2 - 3 GeV
- Use the well-measured lepton angles to overcome the poor Z/γ^* p_T resolution

$$\phi_\eta^* = \tan(\phi_{acop}/2)\sin\theta_\eta^* \qquad \phi_{acop} = \pi - \Delta\phi^{ll} \qquad \cos\theta_\eta^* = \tanh[(\eta^- - \eta^+)/2]$$

- ϕ_η^* is correlated with the Z/γ^* p_T distribution

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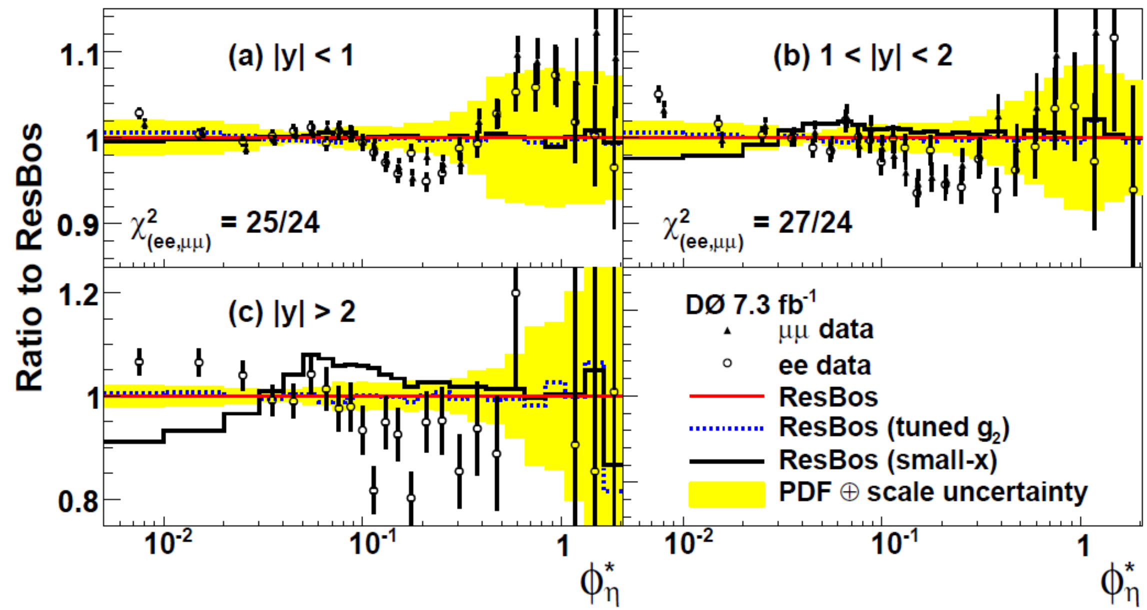
- Consistent results between electron and muon channels
- Predictions of ResBos are unable to describe the detailed data shape
- A prediction that includes the effect of small-x broadening is strongly disfavored



Lepton angular distribution in Z/γ^*

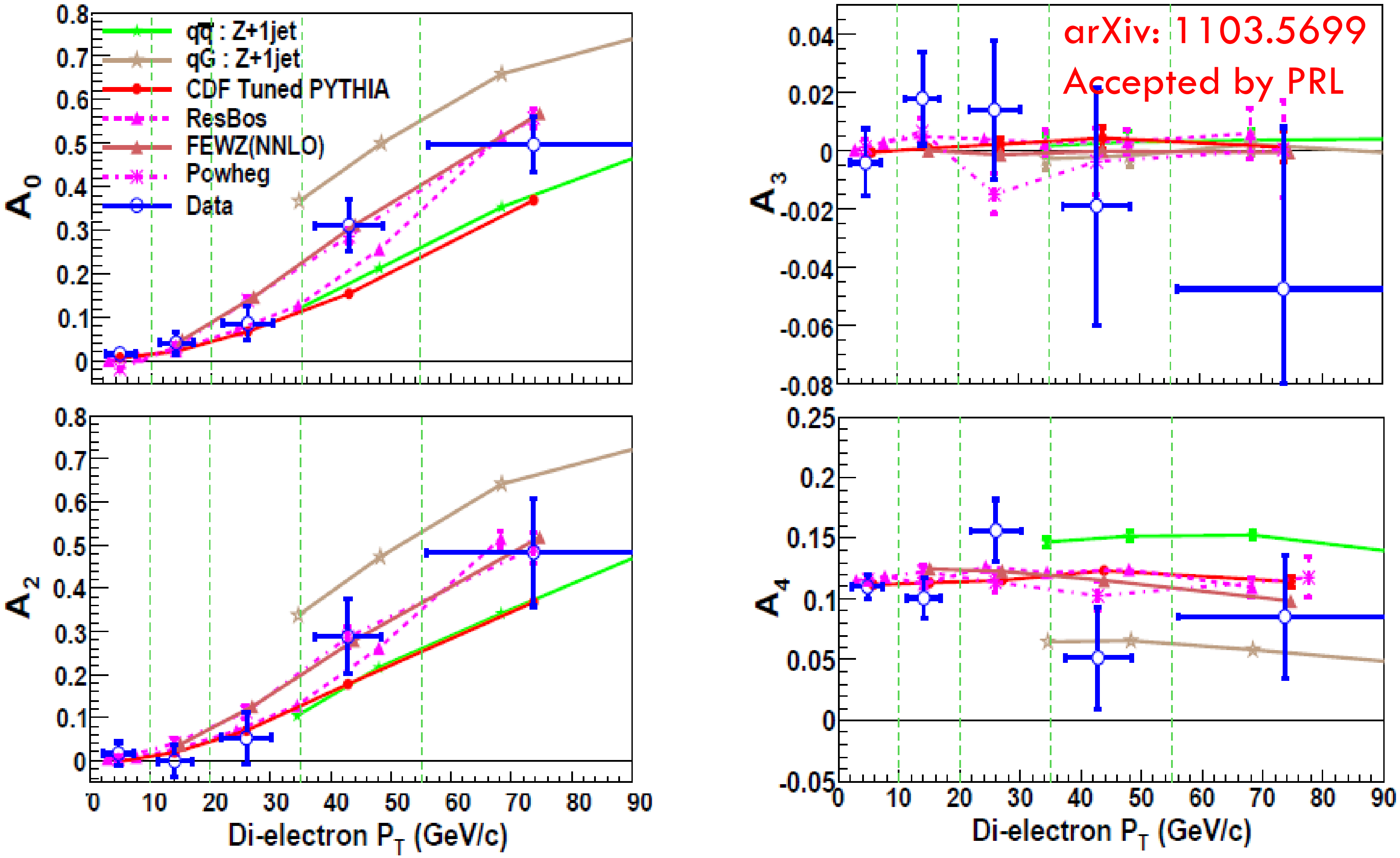
- Lepton angular distribution in the Z/γ^* boson rest frame:

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

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

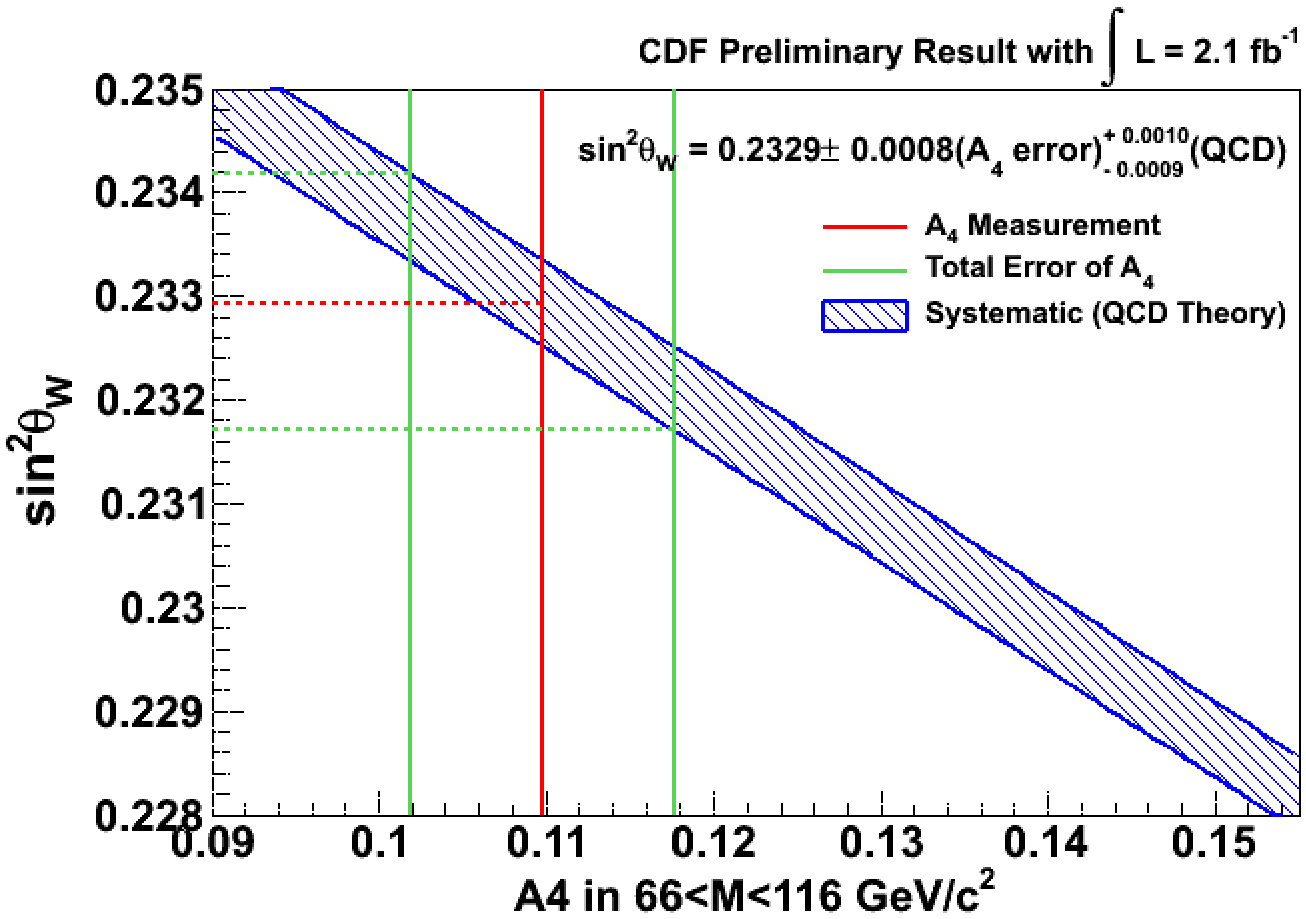
- A_0 and A_2 have different dependences on the Z/γ^* boson mass and p_T, also different for $q\bar{q}$ annihilation and qg Compton scattering processes
- High p_T region: dominated by qg Compton scattering process
- Lam-Tung relation for these angular coefficients: $A_0 \approx A_2$
  - This relation only works for vector gluons (spin 1) and badly broken for scalar gluons (spin 0)
  - Confirmation of the Lam-Tung relation is equivalent to a measurement of the spin of the gluon

Lepton angular distribution in Z/γ^*



Will be an interesting measurement to perform at the LHC due to larger contribution from qg process

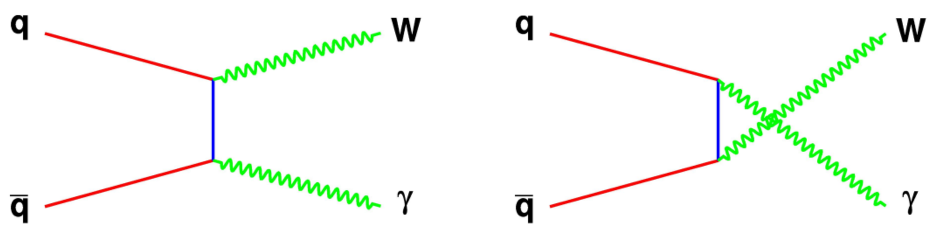
$\sin^2\theta_W$

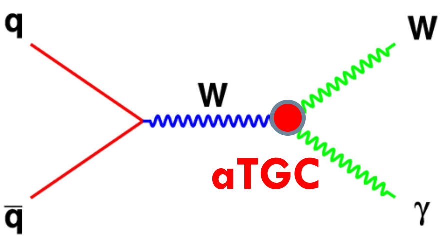


$A_{FB} = 3/8 \times A_4$

$\sin^2\theta_W = 0.2329 \pm 0.0012$

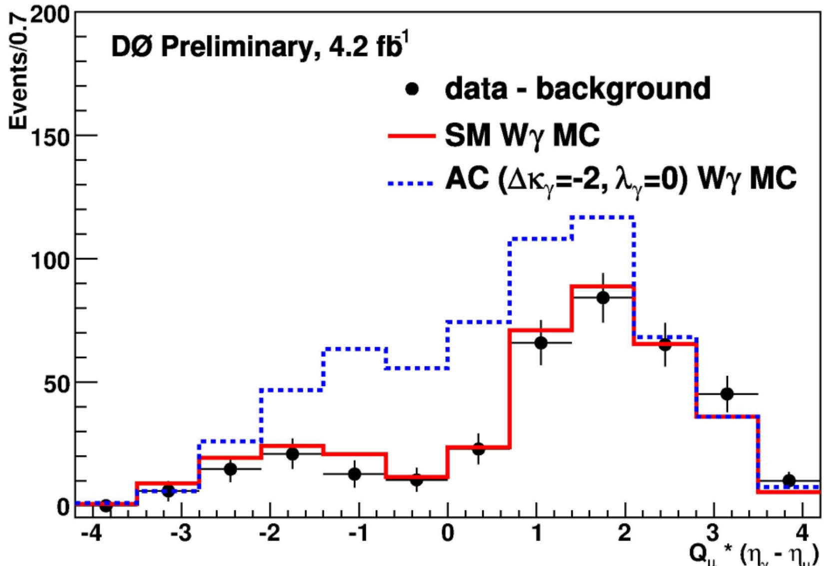
$W\gamma \rightarrow \mu\nu\gamma$



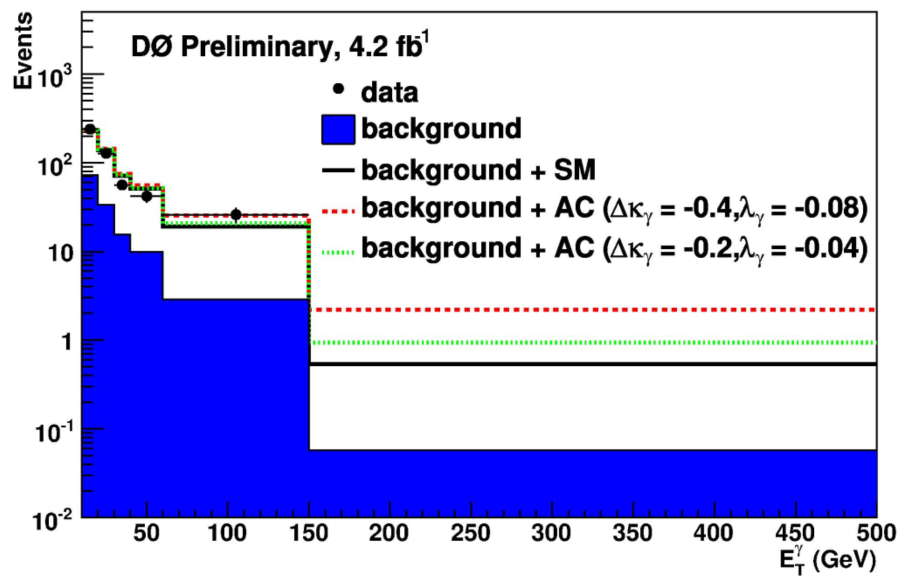


- $\sigma \times Br = 15.2 \pm 0.4$ (stat) ± 1.6 (syst) pb for $E_T(\gamma) > 8$ GeV and $\Delta R(\mu\gamma) > 0.7$
- SM prediction: 16.0 ± 0.4 pb
- Strong indication of radiation amplitude zero
- Use $E_T(\gamma)$ to set 95% C.L. limits on WWγ aTGC parameters:

  $-0.14 < \Delta\kappa_\gamma < 0.15$ and $-0.02 < \lambda_\gamma < 0.02$

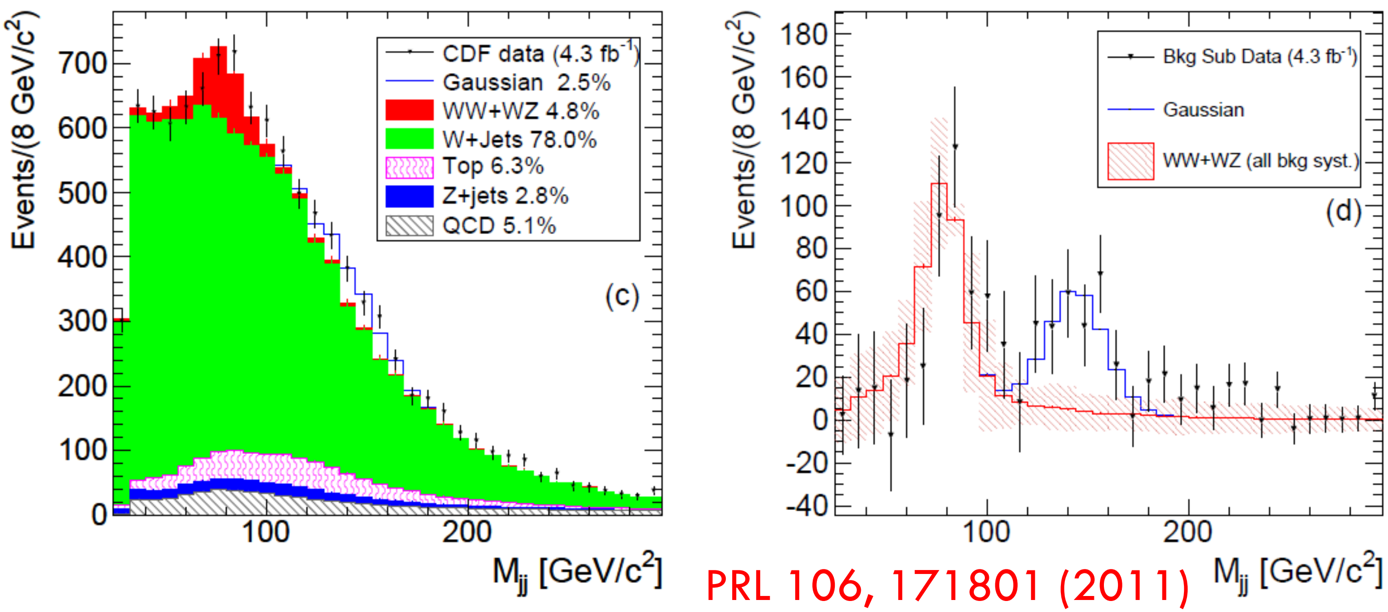


Radiation Amplitude Zero



WW/WZ→ lνjj

- Bkgs: W+jets, Z+jets (Alpgen+Pythia), ttbar/single top (Pythia), QCD multijets (data-driven)
- Binned χ^2 fit to the M_{jj} distribution: $\sigma(X\to jj)$~4pb (300 times higher than $WH\to l\nu+b\bar{b}$), 3.2 σ excess, several new physics models proposed
- Many cross checks performed: various bkg control regions, W+jets modelling, fraction of b-tagged jets, different event selection cuts etc



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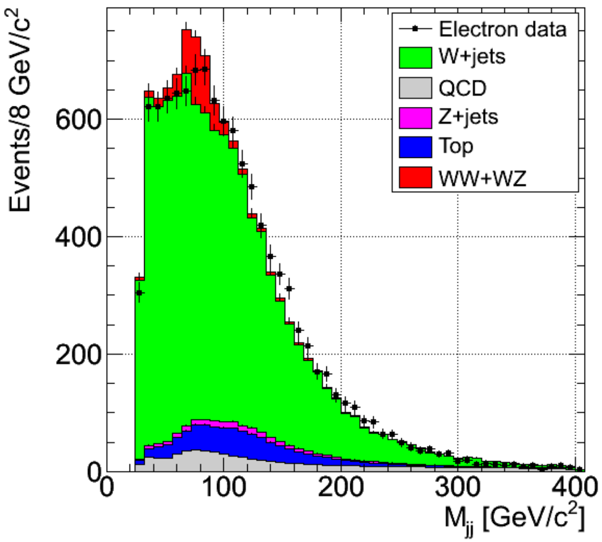
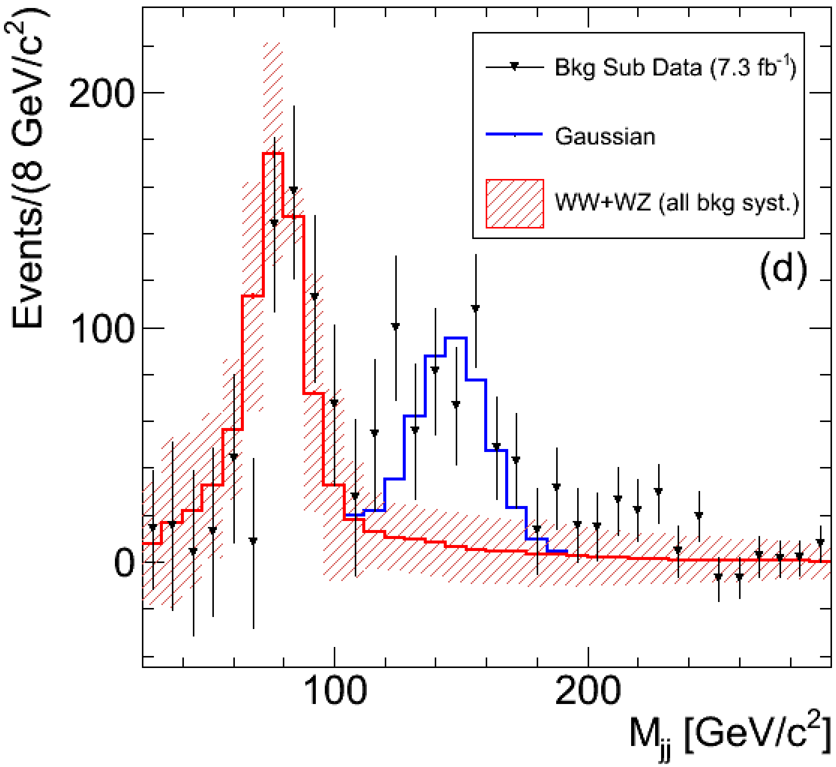
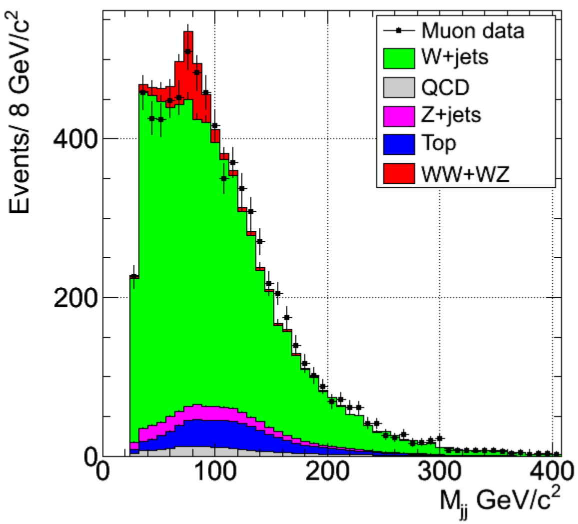
WW/WZ→ lνjj

- Add additional 3 fb^{-1} of data (7.3 fb^{-1} in total)
- Significance of the bump increased to 4.1 σ
- More details at http://www-cdf.fnal.gov/physics/ewk/2011/wjj/7_3.html



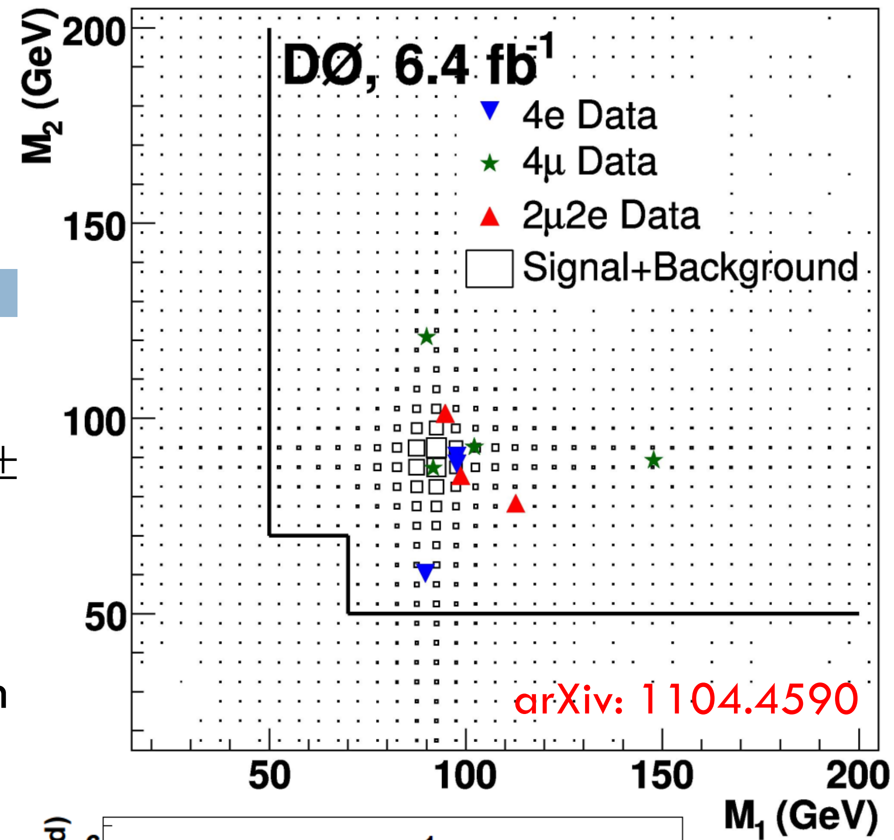


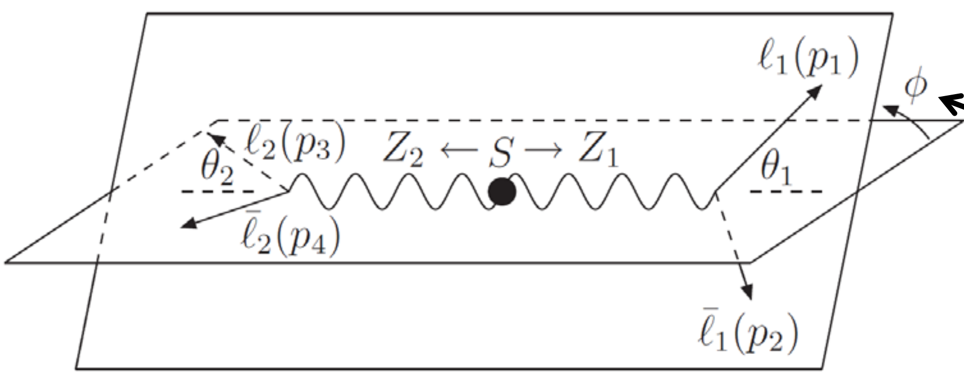


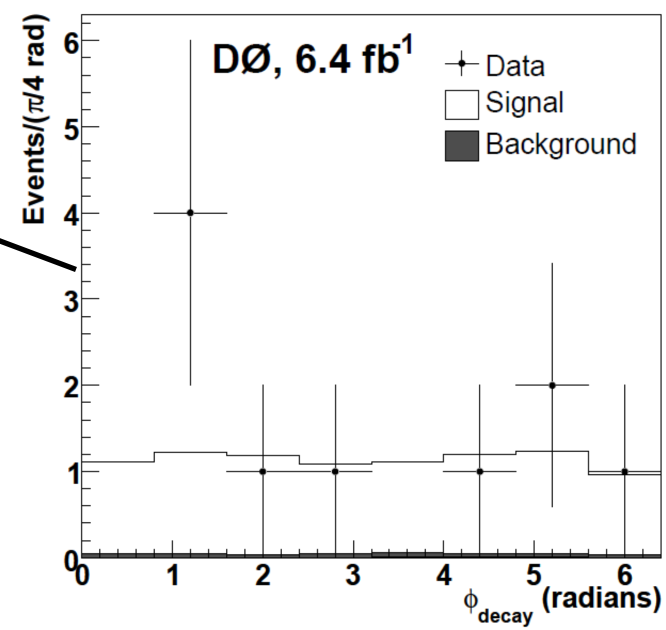
Ongoing similar analysis at D0
Will release an official response soon

ZZ →4l

- 10 candidates with 0.37 bkgs expected
- $\sigma(ZZ)=1.26\ ^{+0.47}_{-0.37}$ (stat) $\pm$ 0.11 (syst) $\pm$ 0.08 (lumi) pb
- SM prediction: 1.3 $\pm$ 0.1 pb
- Kinematic distributions are consistent with the SM predictions



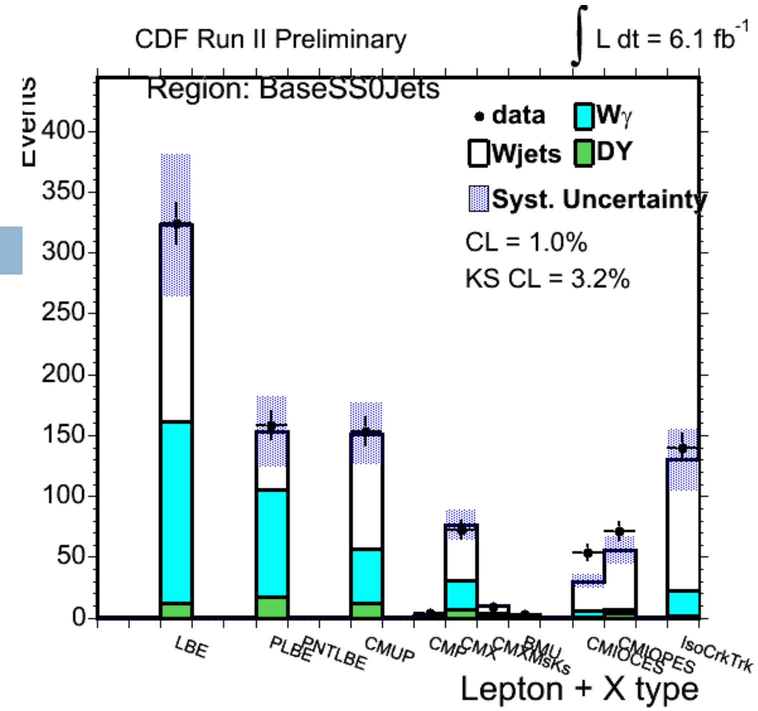




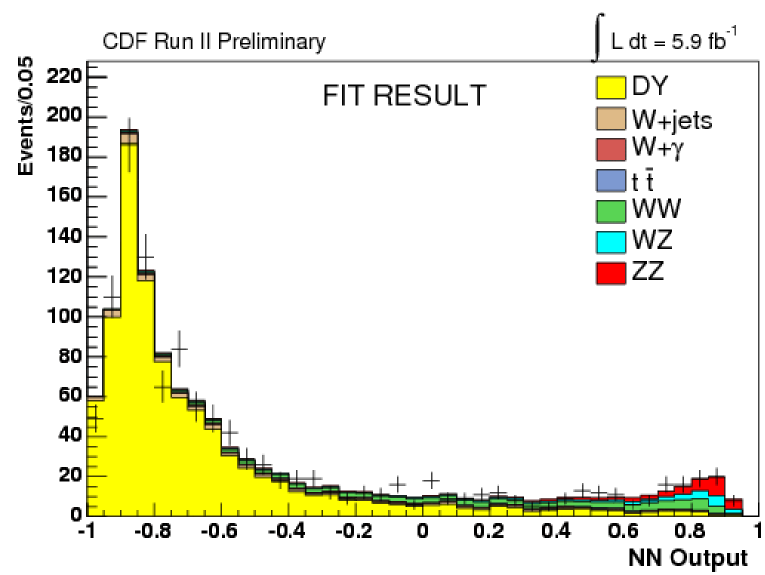
Useful for SM Higgs searches in ZZ

ZZ →4l, llνν

- 14 ZZ→4l candidates with 10.4 ZZ signal expected
- σ(ZZ)=2 ± 0.58 (stat) ± 0.32 (syst) ± 0.12 (lumi) pb
- Include electrons and muons in cracks to increase the overall acceptance



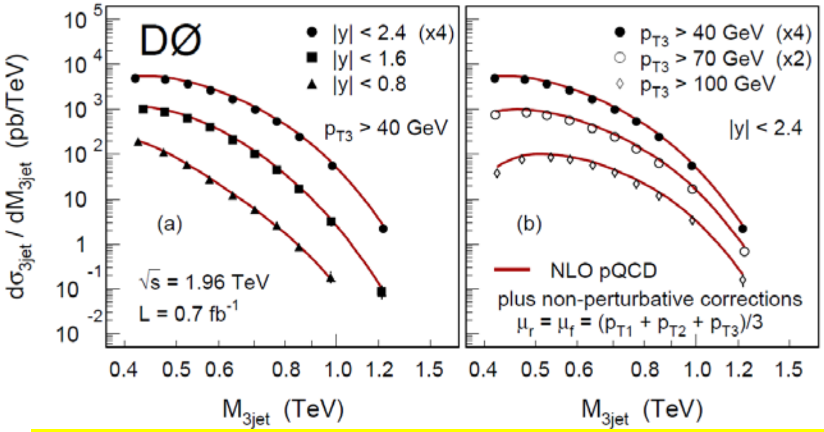
- Large branching ratio for ZZ→llνν, but huge bkgs
- Use Neutral Network discriminant to separate ZZ signal from various bkgs
- σ(ZZ)=$1.45^{+0.45}_{-0.42}$ (stat) $^{+0.41}_{-0.30}$ (syst) pb

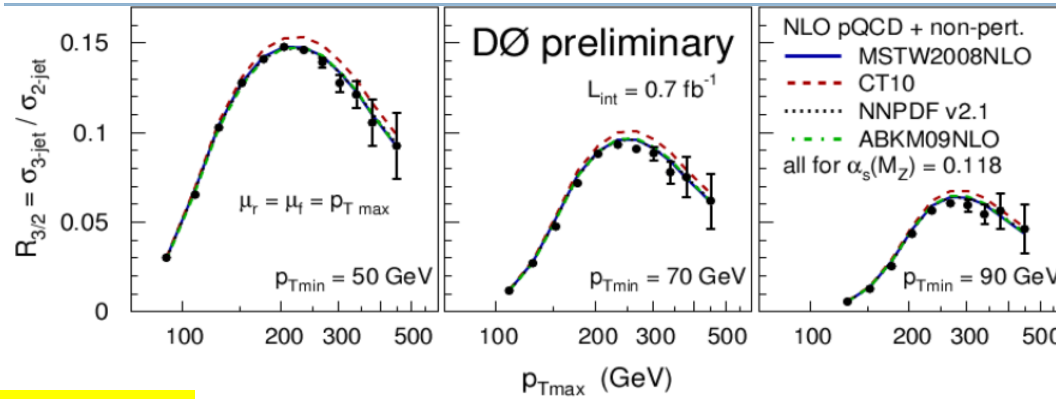


Recent QCD results

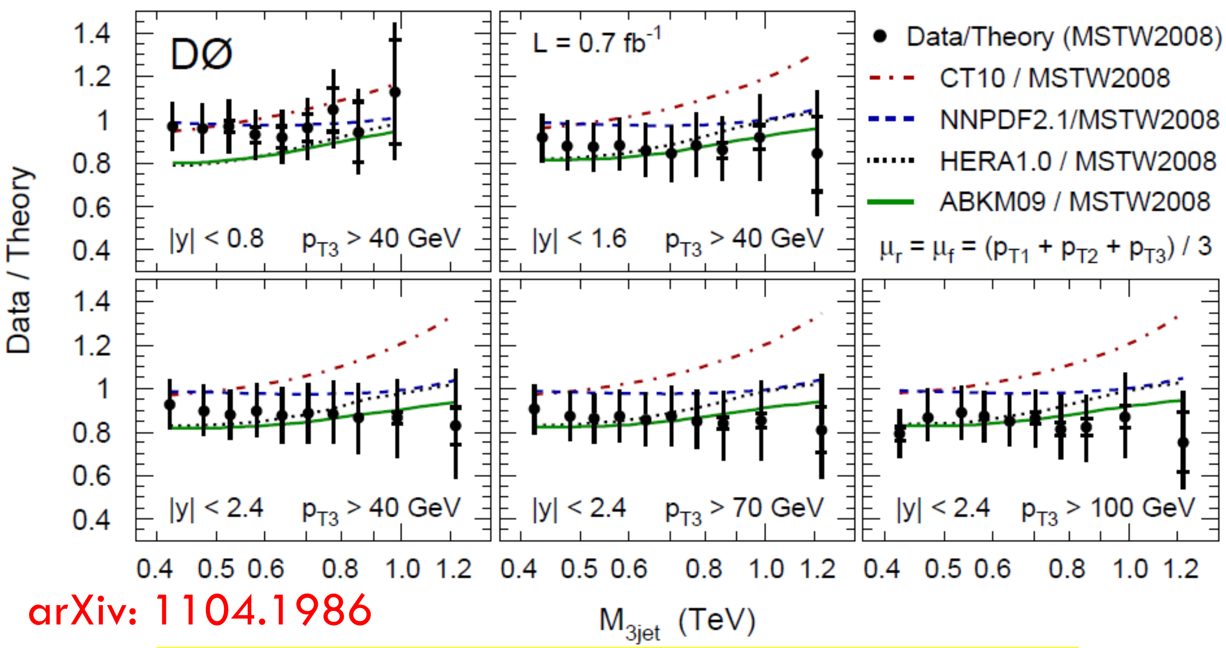
- Analyses with inclusive jet production:
  - Precision test of QCD calculations, determination of α_s, constraints on PDFs
  - Better understanding of jet substructure
  - Three jet mass cross section and $\sigma(3jets)/\sigma(2jets)$ (D0, 0.7 fb^{-1})
  - Substructure of high p_T jets (CDF, 6 fb^{-1})
- Analyses with V(=W, Z)+jets:
  - Better understanding of V+jets production
  - Testing and tuning of phenomenological models
  - V + inclusive jets: Z+jets (CDF, 6 fb^{-1}) W+jets (D0, 4.2 fb^{-1})
  - V + heavy flavor jets: Z+b jets (D0, 4.2 fb^{-1})
- Analyses with diphoton process:
  - Precision test of QCD calculations
  - Major backgrounds for $H\rightarrow\gamma\gamma$ search
  - $\gamma\gamma$ (CDF, 5.4 fb^{-1}) (D0, 4.2 fb^{-1})

Three jet mass and σ(3jets)/σ(2jets)





$d\sigma/dM_{3jets}$ in 3 rapidity and p_T bins on the 3rd jet



- First measurement of σ(3jets)/σ(2jets) which depends on α_s
- Probes running of α_s up to p_T of 500 GeV
- Many systematic uncertainties reduced or cancelled
- Insensitive to PDFs

arXiv: 1104.1986

Best agreement for MSTW2008 with fastNLO

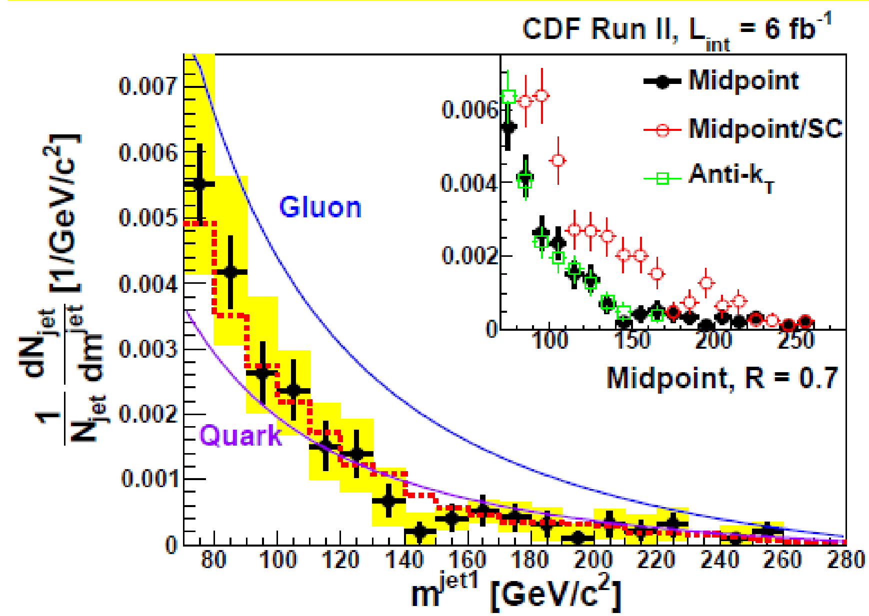
Substructure of high p_T jets

- Test of pQCD calculations and tuning of MC event generators (parton shower)
- Study energy flow within jets
- Search for new physics with massive collimated jets

- Jet mass: each calorimeter tower in a jet is treated as a massless 4-vector and the jet's 4-momentum is the sum of the tower 4-vectors

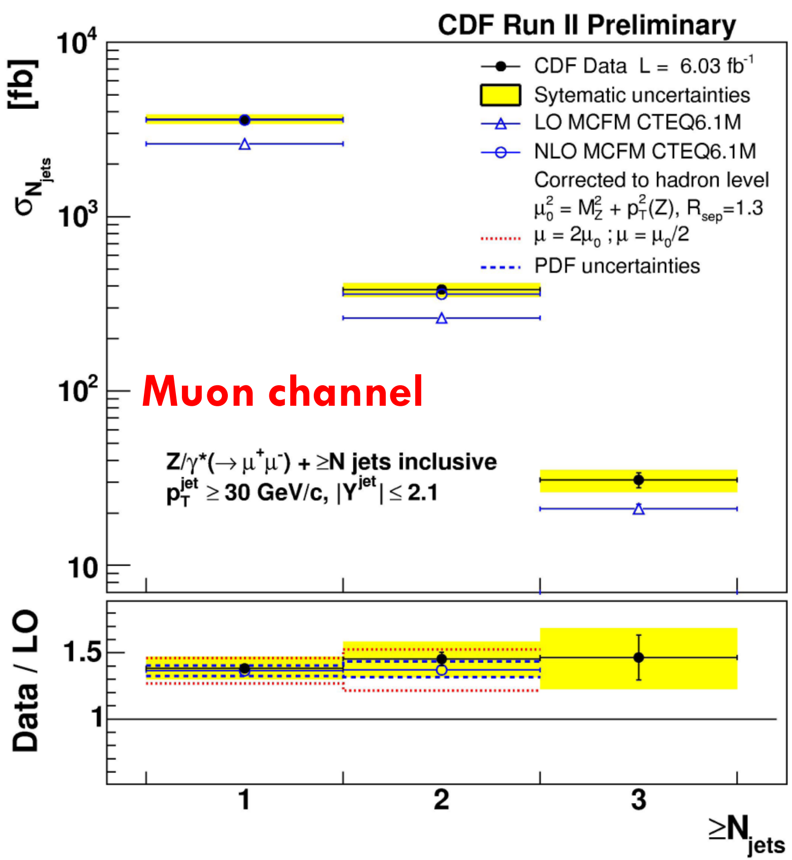
≥1 jet with p_T>400 GeV and 0.1<|y|<0.7

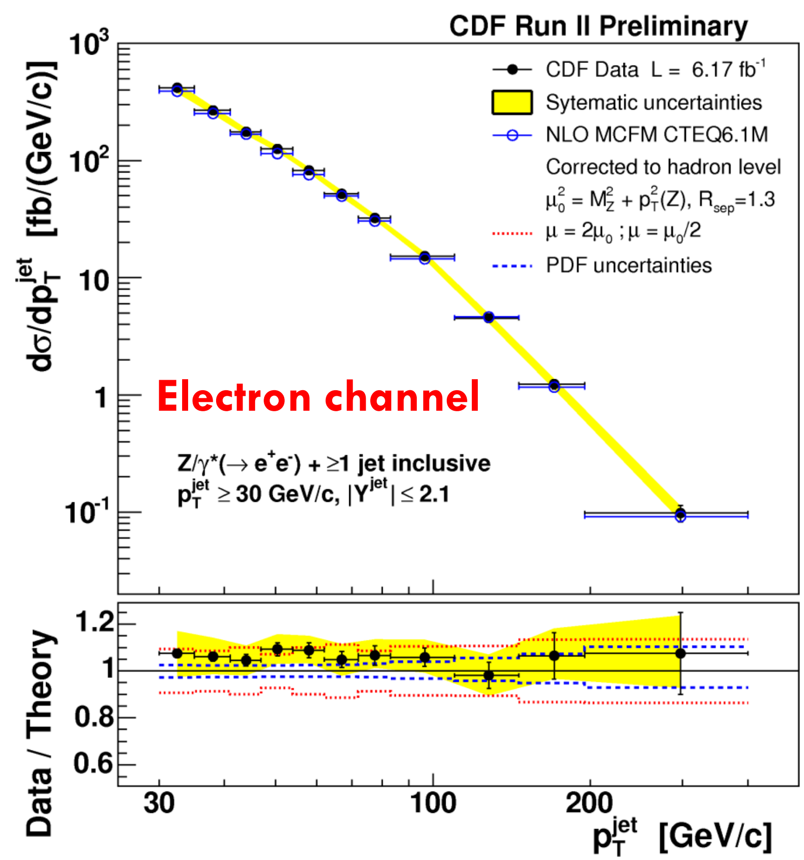
- Good agreement between data and MC for jet mass 70 - 280 GeV and for jet-reconstruction cone sizes of 0.4 and 0.7



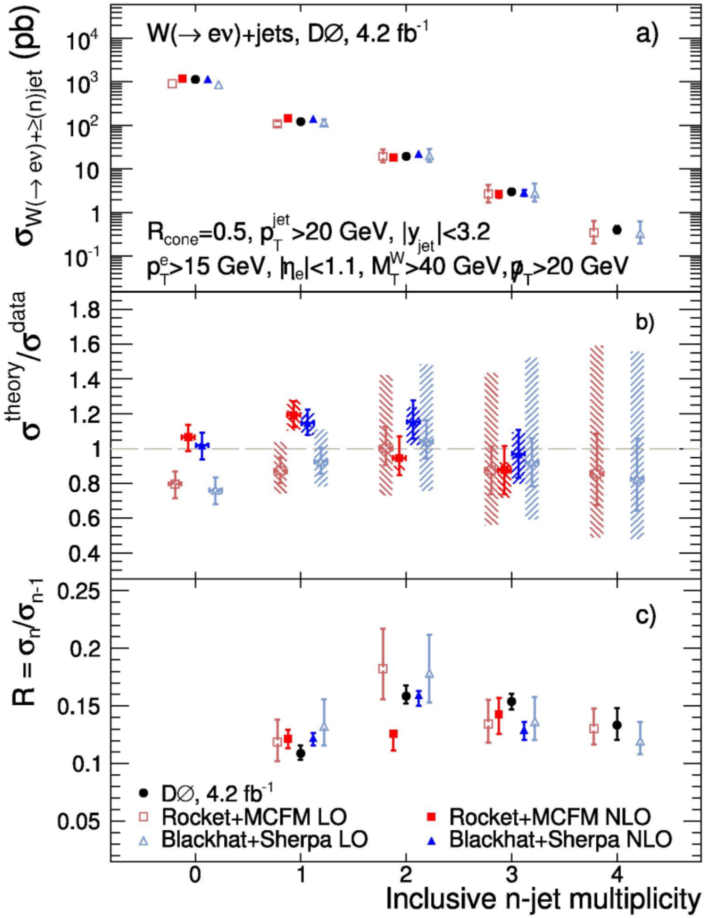
Z+jets

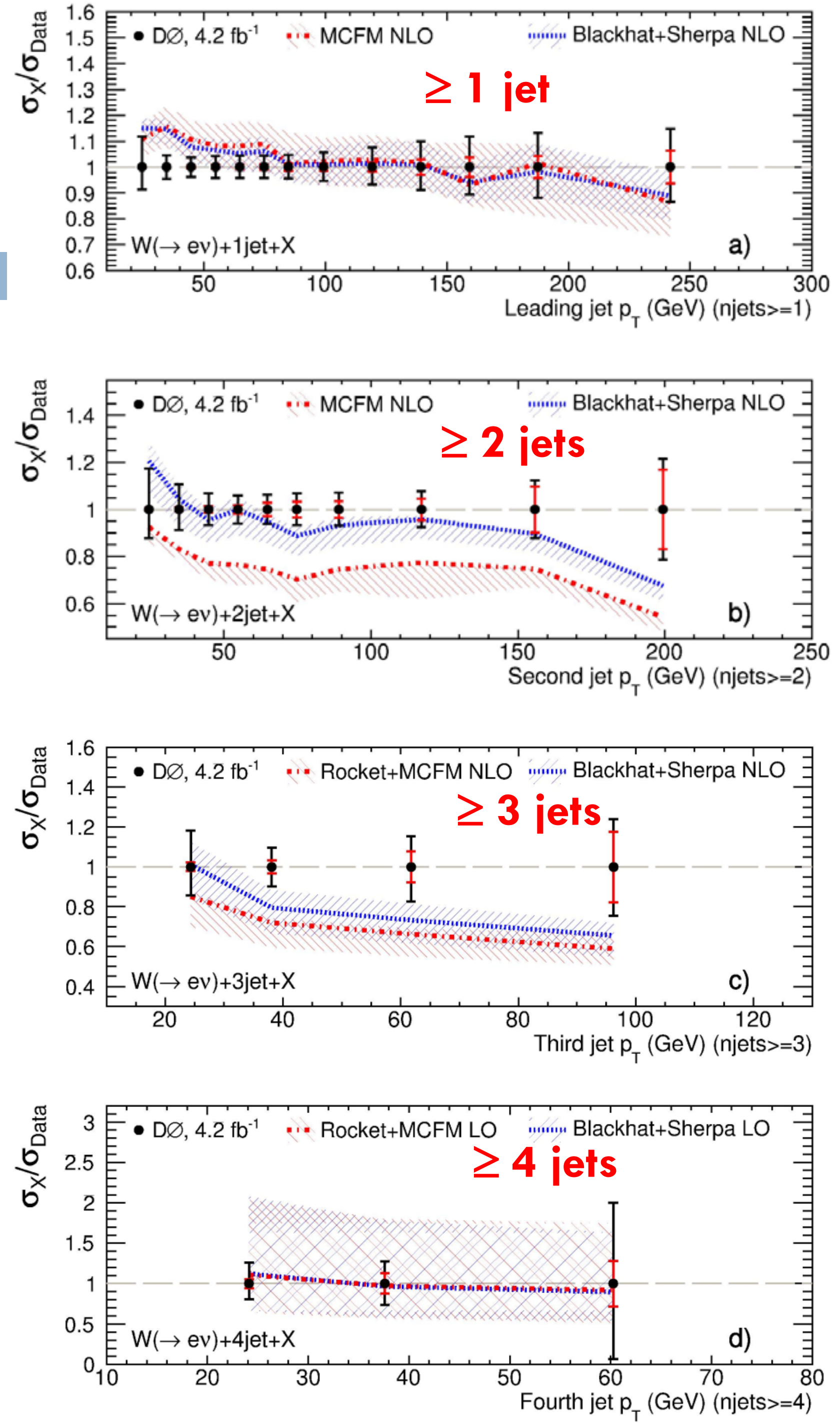
- Z(→ee, μμ) + jets with jet p_T>30 GeV and |y|<2.1
- Good agreement between data and NLO predictions (MCFM) for # of jets and jet p_T distributions





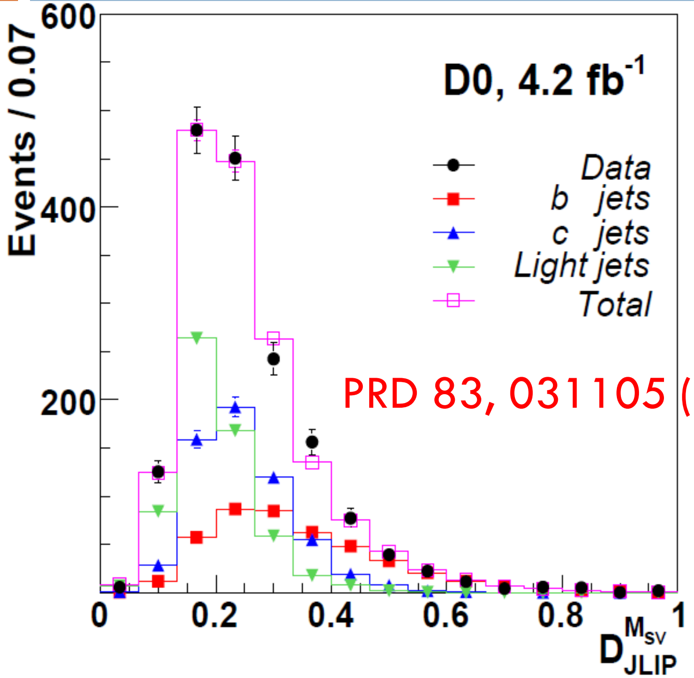
W+jets



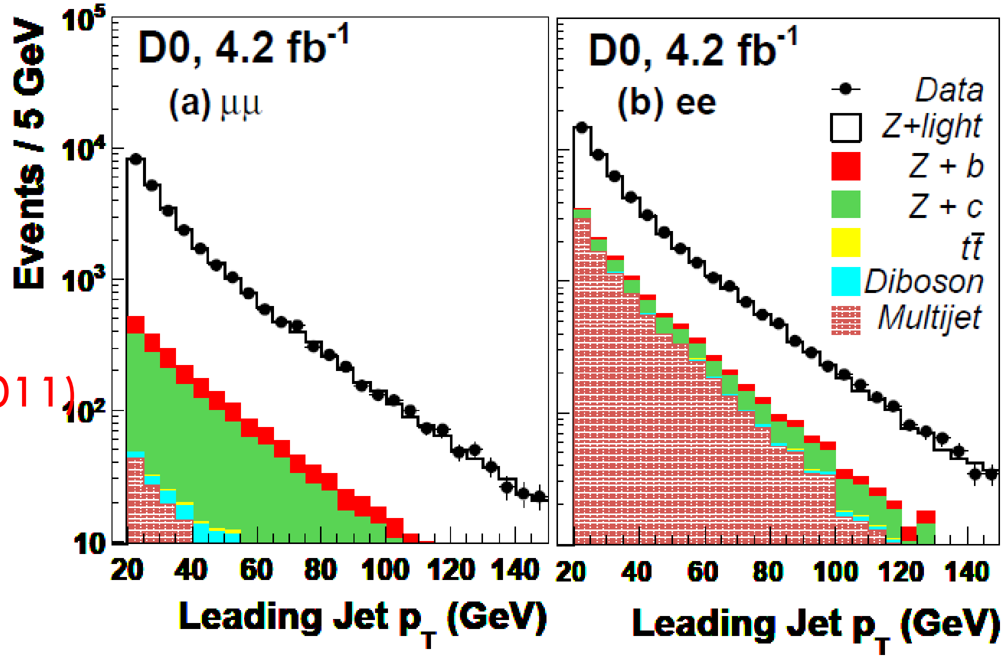


- Measurements of W+n jets inclusive and differential cross sections
- Good agreement for # of jets distribution
- Certain regions of phase space identified where NLO calculations could be improved

Z+b jets



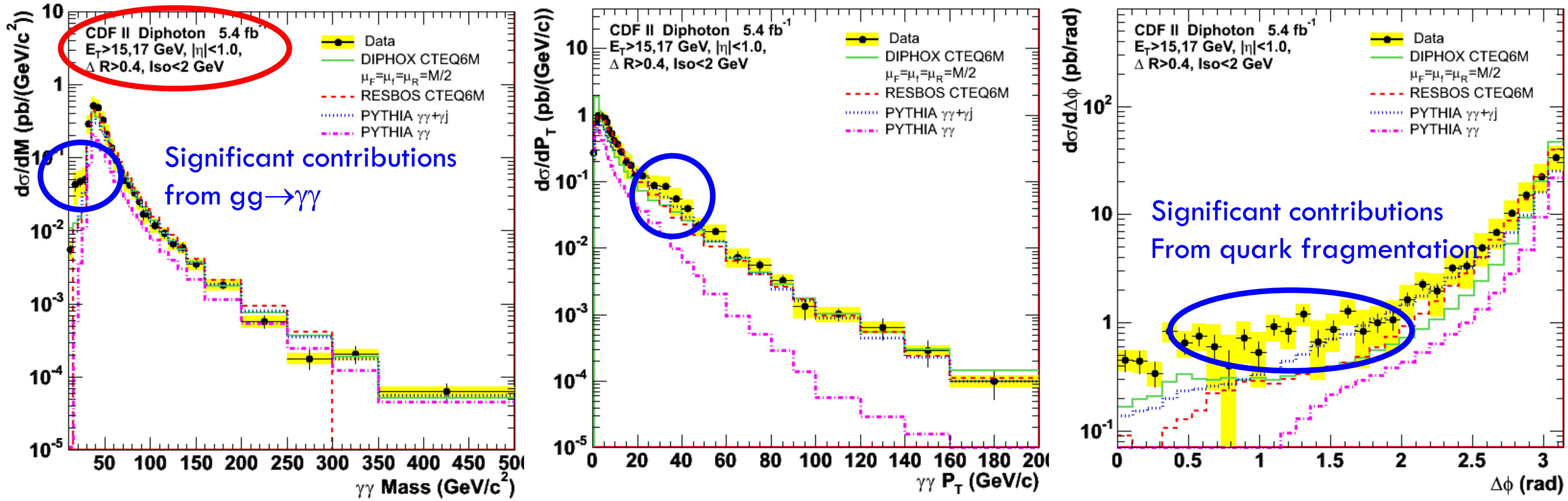
PRD 83, 031105 (2011)



- Background for ZH($\rightarrow b\bar{b}$) search, probe b quark PDF and test b-quark fragmentation
- Measurement of σ(Z+b jets)/σ(Z+jets) benefits from cancellation of many systematics
- A NN discriminant based on tracks and b-tagging information

- σ(Z+b jets)/σ(Z+jets)=0.0193 ± 0.0022 (stat) ± 0.0015 (syst)
- Consistent with theory: 0.0192 ± 0.0022 (MCFM, renorm. and factor. scales at M_Z)

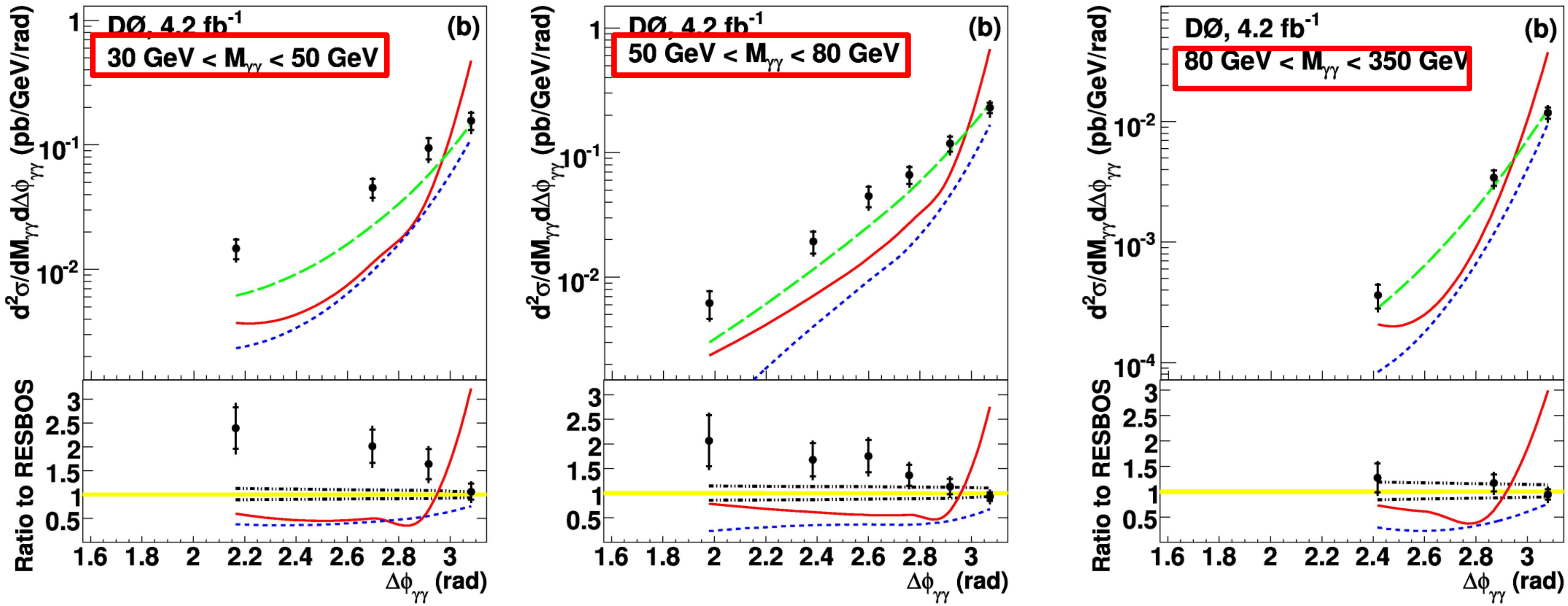
Prompt diphoton



- Differential cross sections vs $M_{\gamma\gamma}$, $p_T^{\gamma\gamma}$ and $\Delta\phi$
- None of the models (Pythia, ResBos and DiPhoX) could describe the data well in all kinematical regions, in particular at low mass $M_{\gamma\gamma}$(<60 GeV), intermediate $p_T^{\gamma\gamma}$ (20 – 50 GeV) and low $\Delta\phi$ (<1.7 rad) regions
- Similar conclusions to those from the published D0 results (PLB 690, 108 (2010))

Prompt diphoton

PLB 690, 108 (2010)



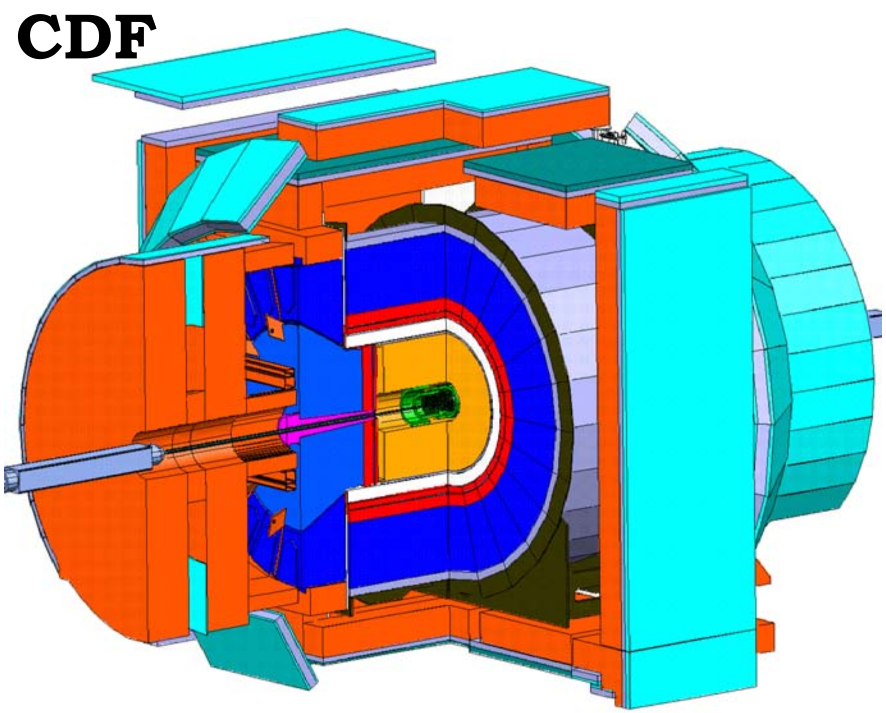
- Differential cross sections vs $M_{\gamma\gamma}$, $p_T^{\gamma\gamma}$, $\Delta\phi$ and $\cos\theta^*$
- Also measured double differential cross sections $d\sigma/dp_T^{\gamma\gamma}$, $d\sigma/d\Delta\phi$ and $d\sigma/d\cos\theta^*$ in three $M_{\gamma\gamma}$ bins

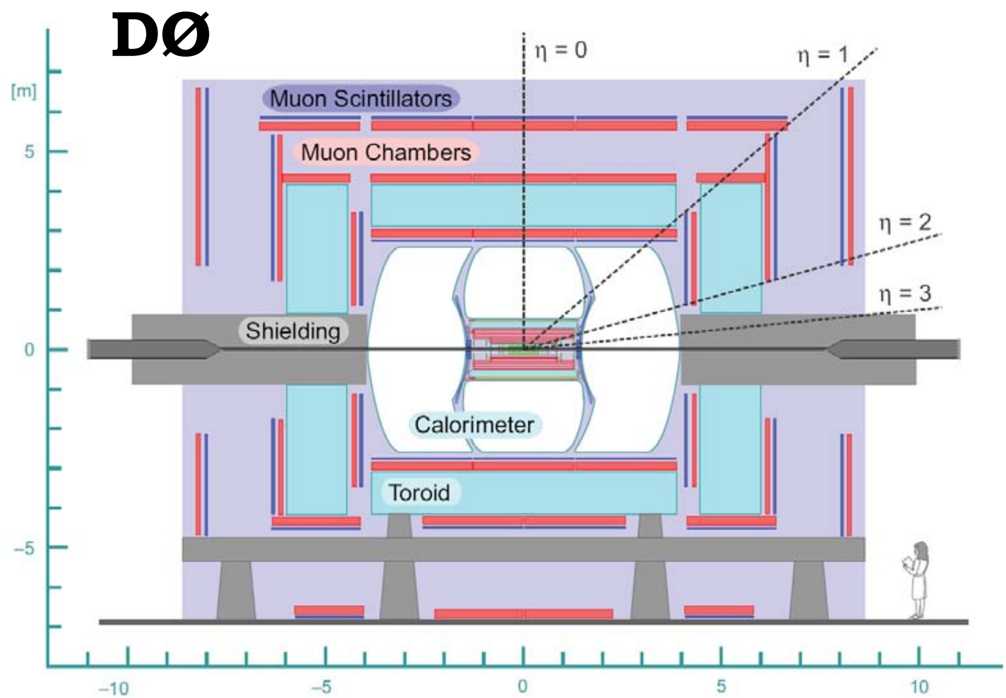
Conclusion

- Legacy EW and QCD measurements from the Tevatron
  - High precision tests of EW and QCD theories: experimental uncertainties similar or smaller than theoretical uncertainties in many cases
  - Determination of fundamental constants
  - Useful inputs to PDFs
  - Testing and tuning phenomenological models
  - Crucial for understanding backgrounds for new physics and SM Higgs searches
  - Constraints on new physics through aTGC measurements
- Hints of possible new physics
- Only 1 ~ 6 fb^{-1} of data analyzed, more exciting results to come!

Backup

CDF and D0 detectors





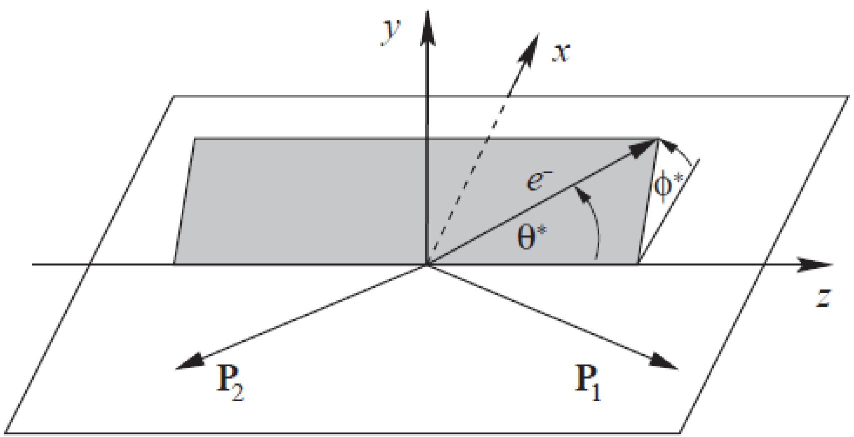
- Silicon and drift chamber
- Pb/Fe scintillator calorimeters
- Muon detectors

- Silicon and fiber tracker
- Uranium/liquid Argon calorimeters
- Muon detectors

Z/γ^* A_{FB} measurement

- $\bar{q}q \rightarrow l^+l^-$: mediated by γ^*, Z boson or γ^*/Z interference
- Vector coupling for Fermion-γ, vector & axial-vector coupling for Fermion-Z

$$g_V^f = I_3^f - 2q_f \cdot \sin^2\theta_W$$
$$g_A^f = I_3^f ,$$



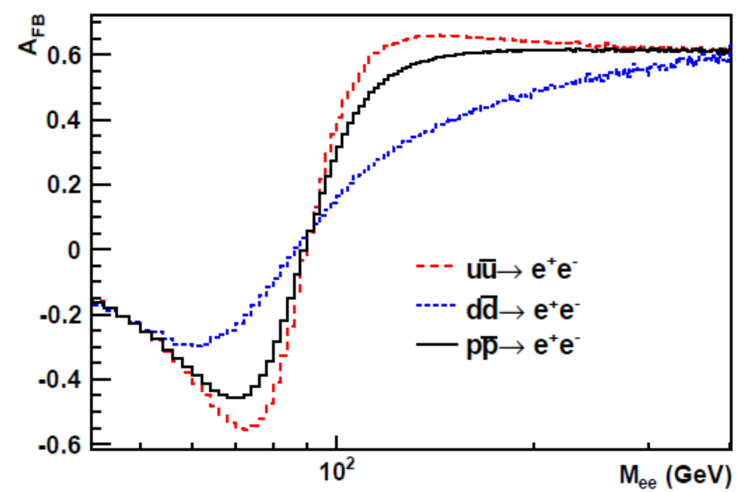
Z/γ^* rest frame

Asymmetric distribution for $\cos\theta^*$ distribution

Forward events: $\cos\theta^* > 0$

Backward events: $\cos\theta^* < 0$

$A_{FB}=(\sigma_F - \sigma_B)/(\sigma_F+\sigma_B)$ as a function of M_Z



- extract $\sin^2\theta_W$
- measure Z-light quark couplings
- make constraints on PDFs
- constrain new physics that interfere with Zs

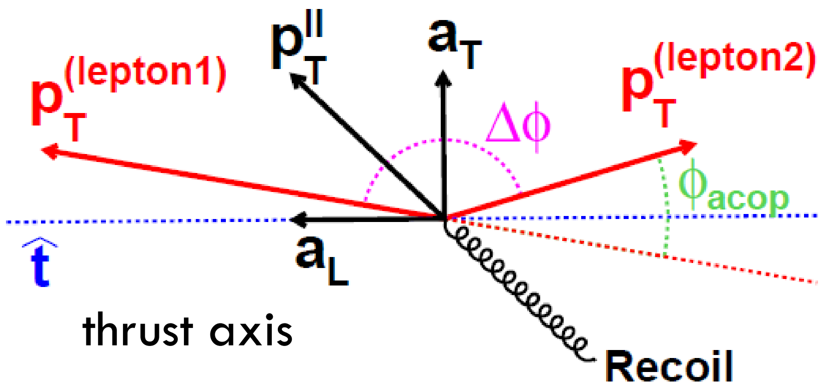
Z/γ^* boson transverse momentum

- Emission of a single hard p_T parton (p_T^Z>~30 GeV): pQCD
- Emission of multiple soft gluons (p_T^Z<~30 GeV): gluon resummation
- $<p_T^Z>$~5 GeV, while experimental resolution for Z/γ^* p_T is close to 2.5 - 3 GeV
- Use the well-measured lepton angles to overcome the poor p_T resolution

$$\phi_\eta^* = \tan(\phi_{acop}/2)\sin\theta_\eta^*$$

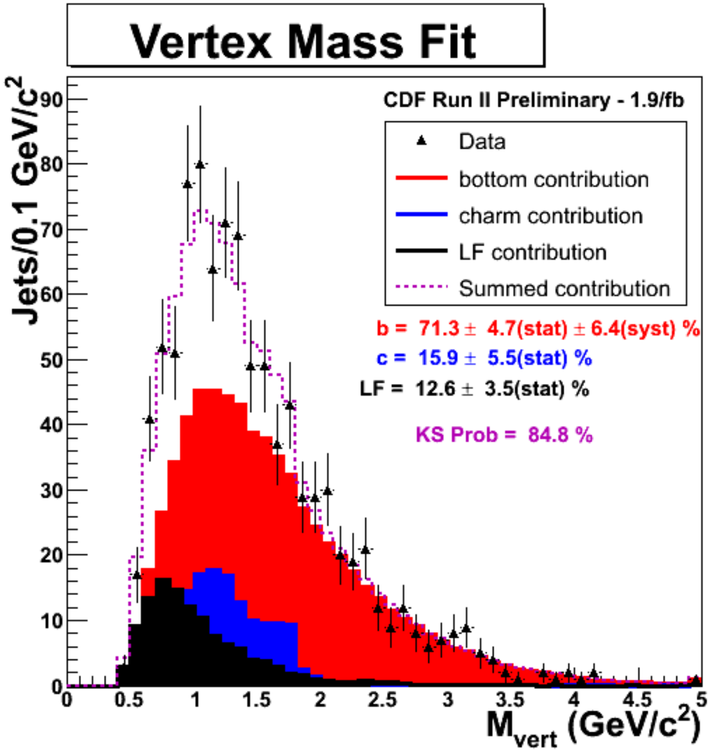
$$\phi_{acop} = \pi - \Delta\phi^{ll} \qquad \cos\theta_\eta^* = \tanh[(\eta^- - \eta^+)/2]$$

- ϕ_η^* is highly correlated with the quantity a_T/m_{ll} which reflects the Z/γ^* p_T distribution

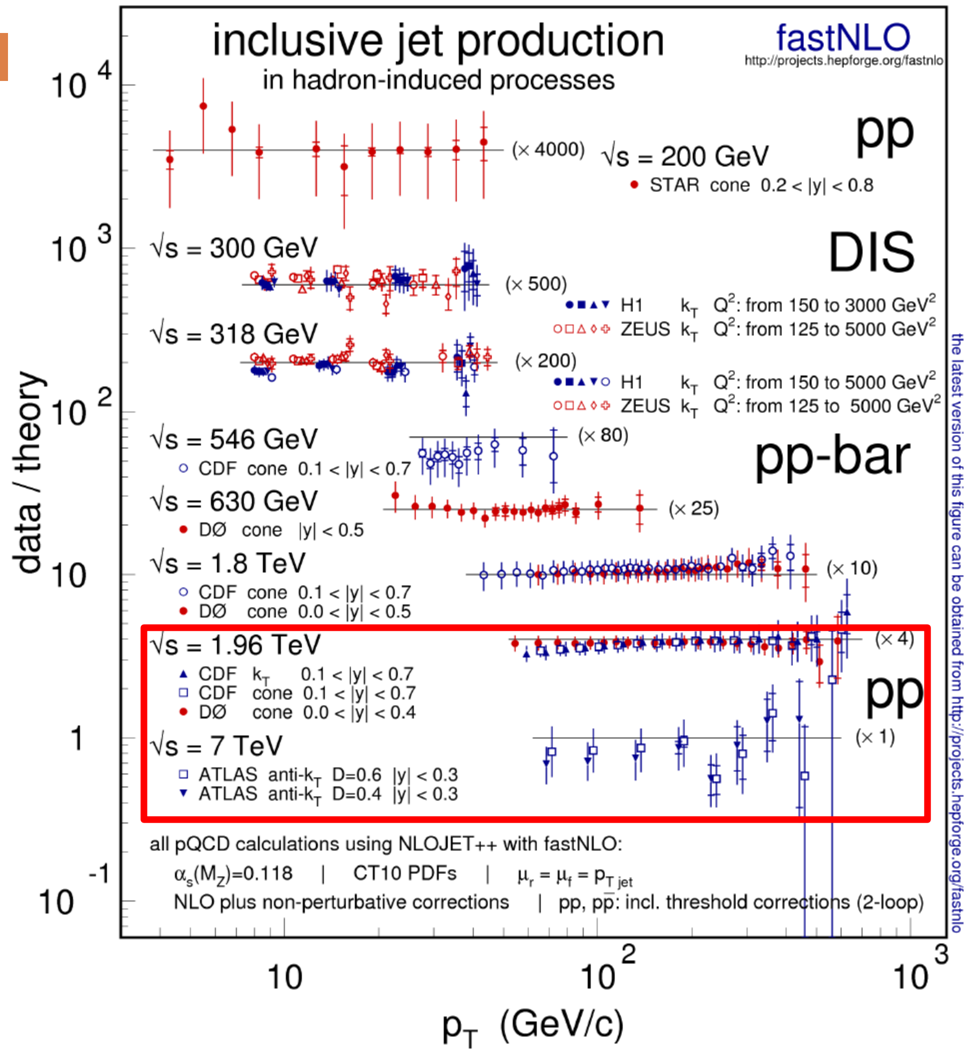


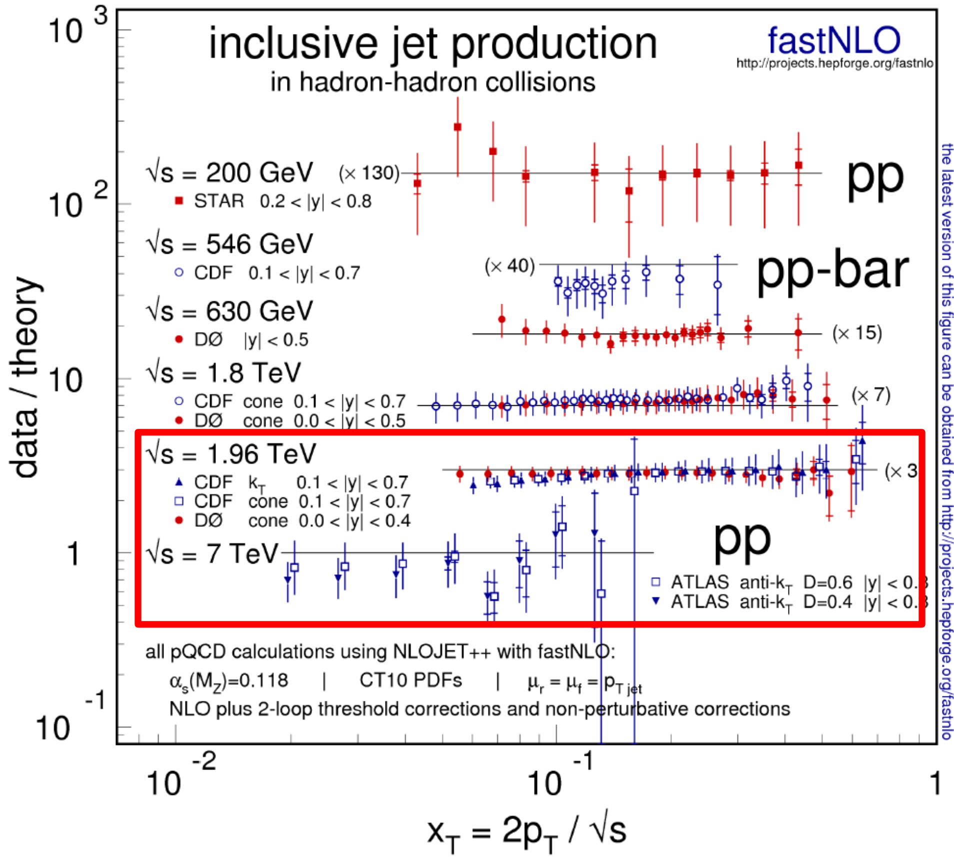
W+b jets

- CDF has discrepancy with NLO calculation in this measurement
- b-fraction determined from likelihood fit to Mvert
- $\sigma(W+b\ \text{jets}) \times Br(W \rightarrow l\nu) = 2.74 \pm 0.27\ (\text{stat}) \pm 0.42\ (\text{syst})$ pb
- NLO prediction 1.22 ± 0.14 pb



Inclusive jet production





- pT plot: the Tevatron pT reach is still about as good as the published LHC results
- xT plot: the Tevatron data have far better high-x sensitivity