

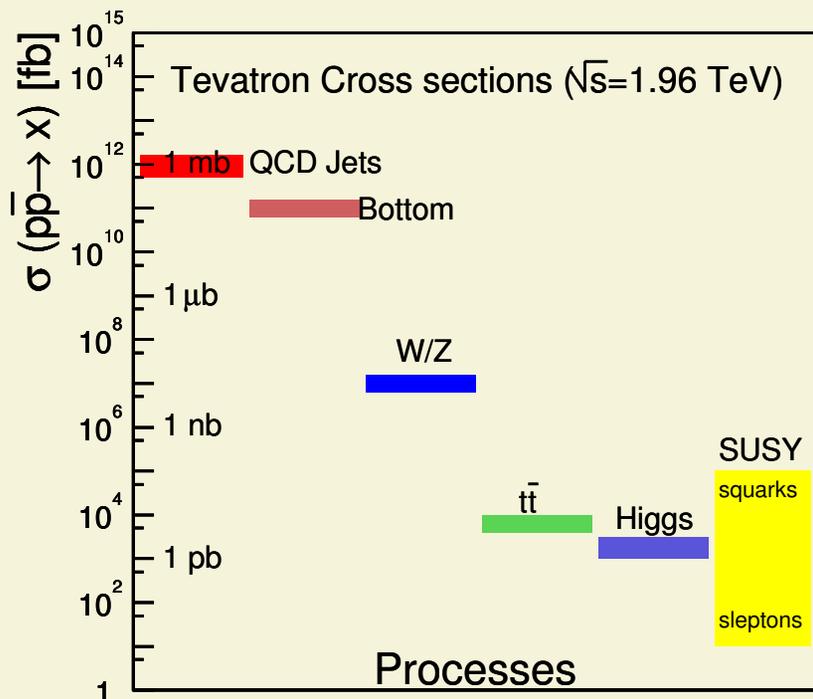
QCD, Electroweak and SM Higgs at the Tevatron Experiments

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On behalf of the CDF and DØ Collaborations

Outline of the talk

Understanding the Standard-Model Interactions and Bosons



- **QCD Physics:**

- **Jet and Photon production**

- **W/Z + Jet production**

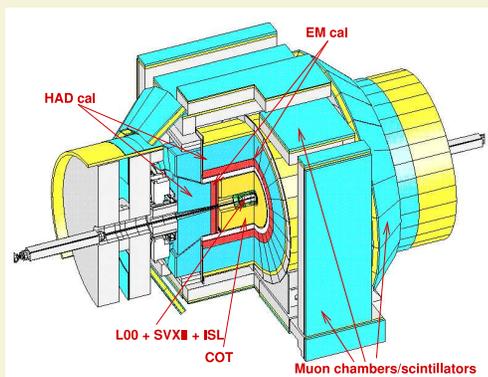
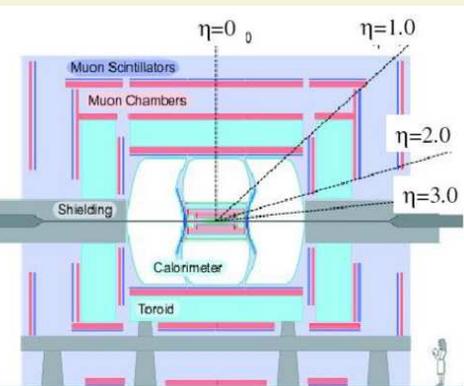
- **EWK Physics:**

- **W mass and width measurement**

- **Z and W Production properties**

- **Diboson production**

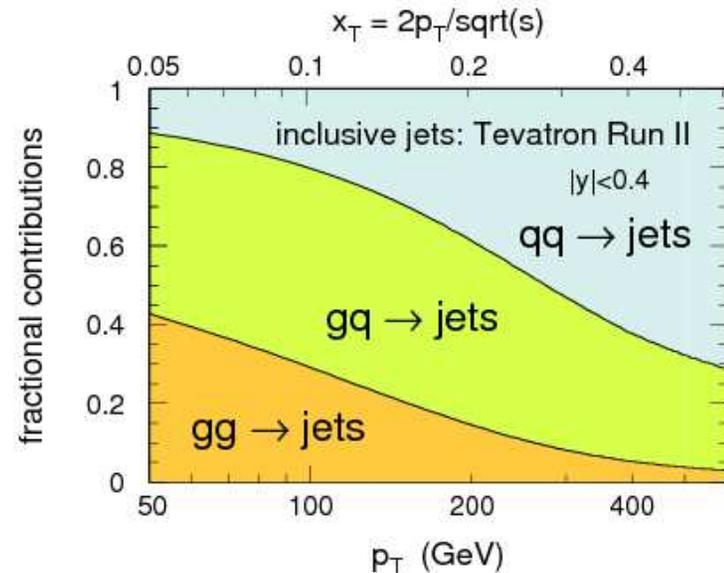
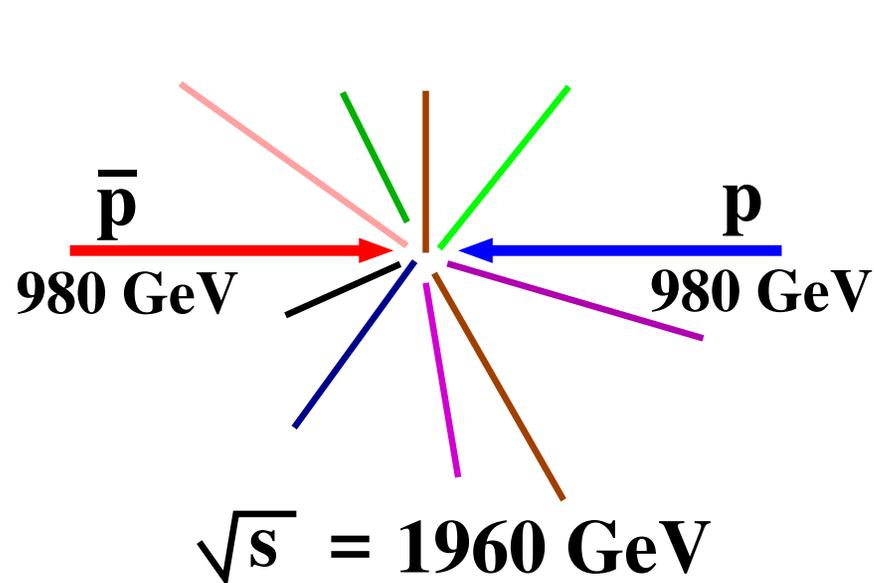
- **The search for the Higgs Boson**



DISCLAIMER: Due to time constraints, for most of the topics I will just show the result from one experiment. Almost always the other has something similar, so do not forget to check the web pages with the result.

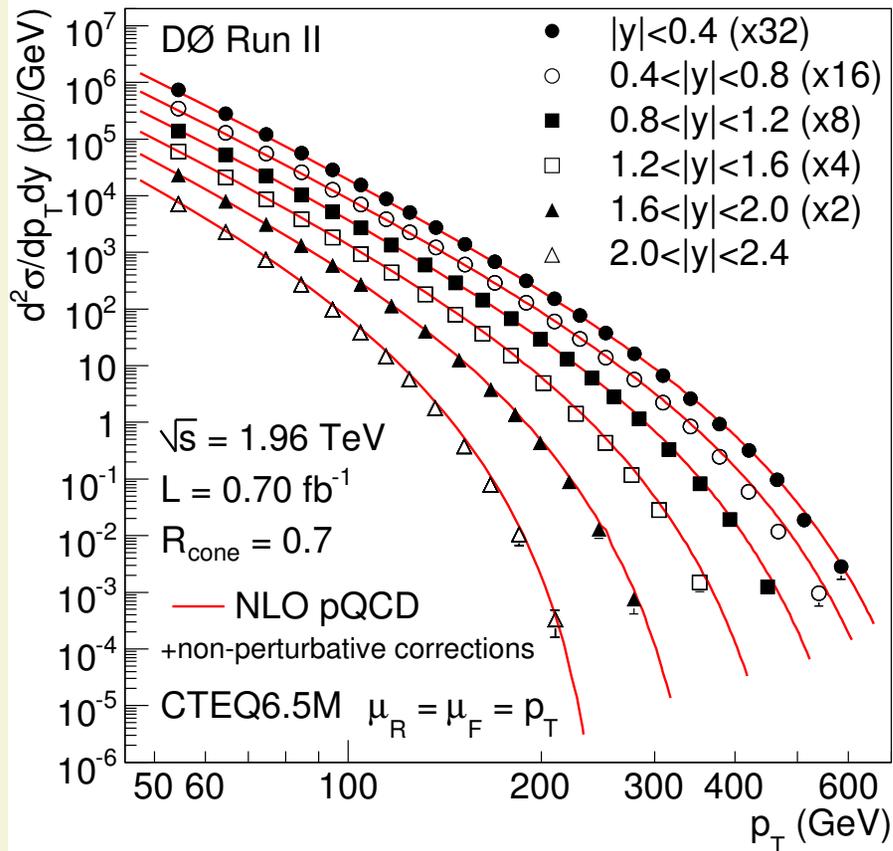
QCD Physics

Jet production and the structure of the proton



Inclusive Jet Production

- Measuring the jet production cross section over 8 orders of magnitude.
- Impressive agreement.

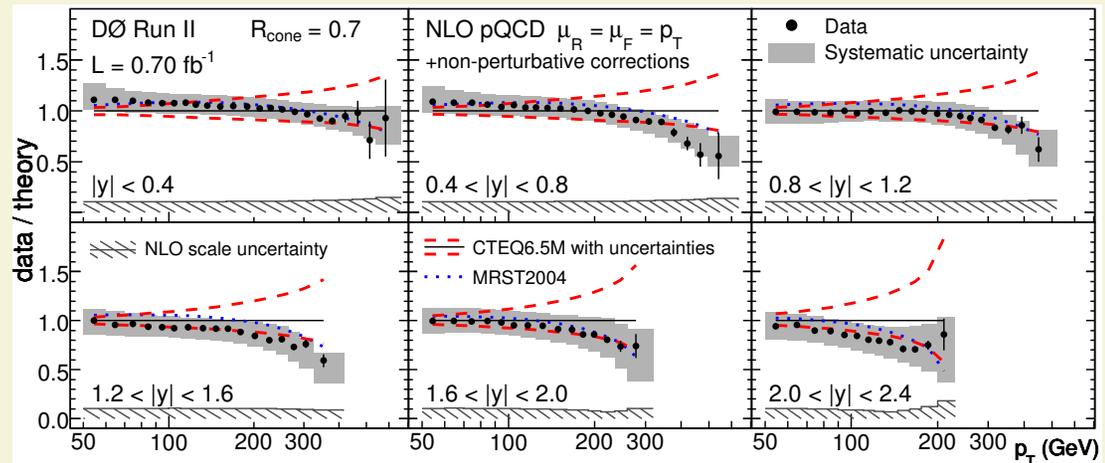


⇒ MidPoint Algorithm ($R=0.7$)

⇒ $p_{T,\text{jet}} > 50 \text{ GeV}$

⇒ $|y| < 2.4$

⇒ Comparison to modern PDFs



- Potential impact to global PDF fits (gluon at high x).
- Full analysis of systematic uncertainties.
- Most precise and with the widest kinematic range to date.

High- p_T $b\bar{b}$ Production

Using the capability of CDF to select heavy-flavour enhanced samples at the trigger level, a high statistics and high purity sample of $b\bar{b}$ was studied.

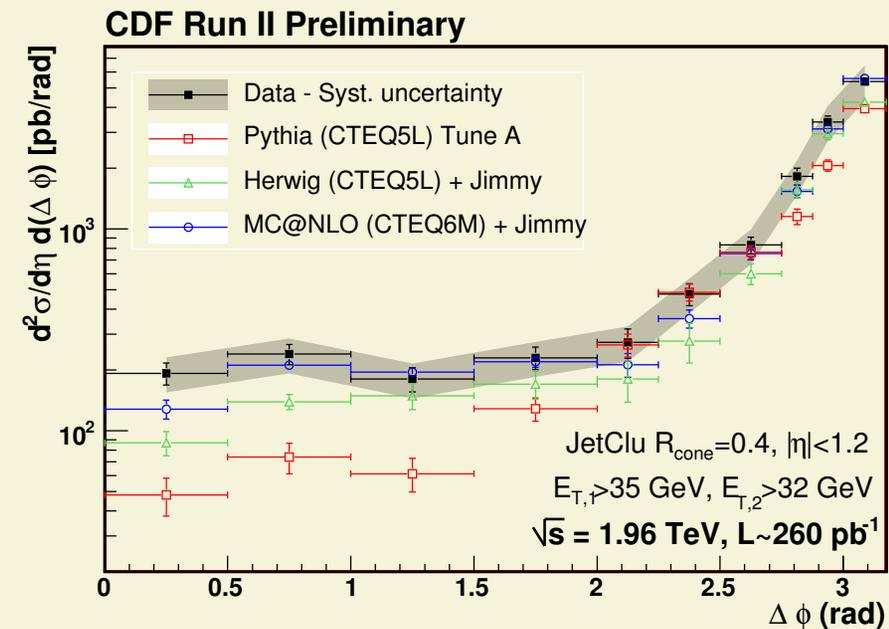
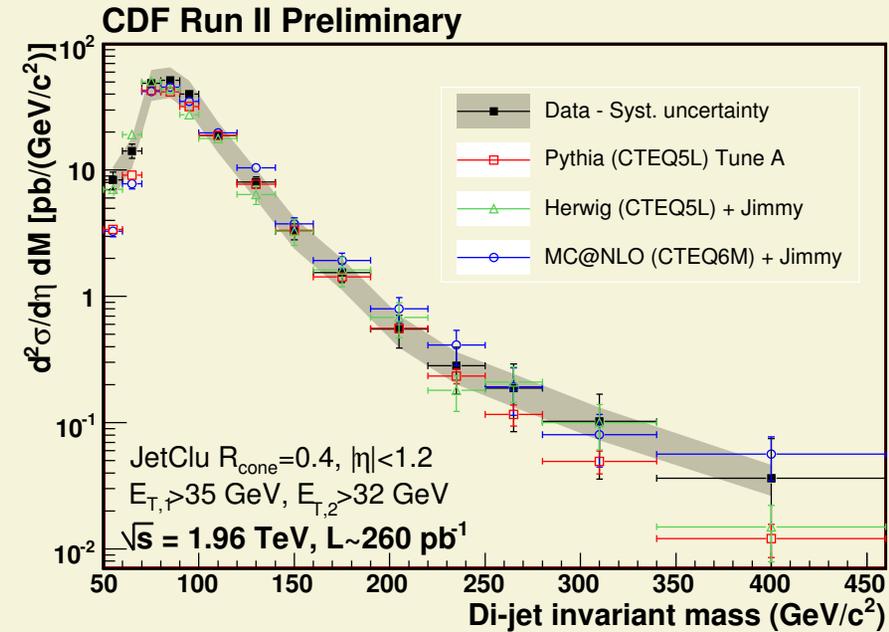
- Template (to vertex mass) analysis to estimate Heavy-flavour content.

CDF Run II Preliminary	σ [pb]
	$ \eta_{1,2} < 1.2, E_{T,1} > 35 \text{ GeV}, E_{T,2} > 32 \text{ GeV}$
Data	$\sigma = 5664 \pm 168 \text{ (stat.)} \pm 1270 \text{ (syst.)}$
Pythia (CTEQ5L) Tune A	$\sigma = 5136 \pm 52 \text{ (stat.)}$
Herwig (CTEQ5L) + Jimmy	$\sigma = 5296 \pm 98 \text{ (stat.)}$
MC@NLO (CTEQ6M) + Jimmy	$\sigma = 5421 \pm 105 \text{ (stat.)}$

- Several differential cross sections were measured.

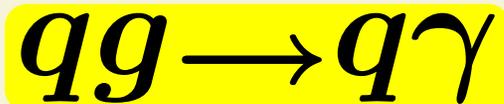
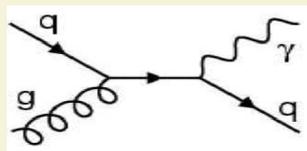
- Agreement with theory improves using **MC@NLO (+Jimmy) predictions.**

(Jimmy is a package care of the Underlying Event)



Photon+Jet production

- For $p_T^\gamma < 120 \text{ GeV}/c$, dominant production is through Compton scattering:



- Probe PDFs in the range:

$$900 < Q^2 < 1.6 \cdot 10^5 \text{ (GeV}^2\text{)}$$

$$0.007 < x < 0.8$$

- Data selection:

$$\Rightarrow |y^\gamma| < 1.0 \text{ (isolated)}$$

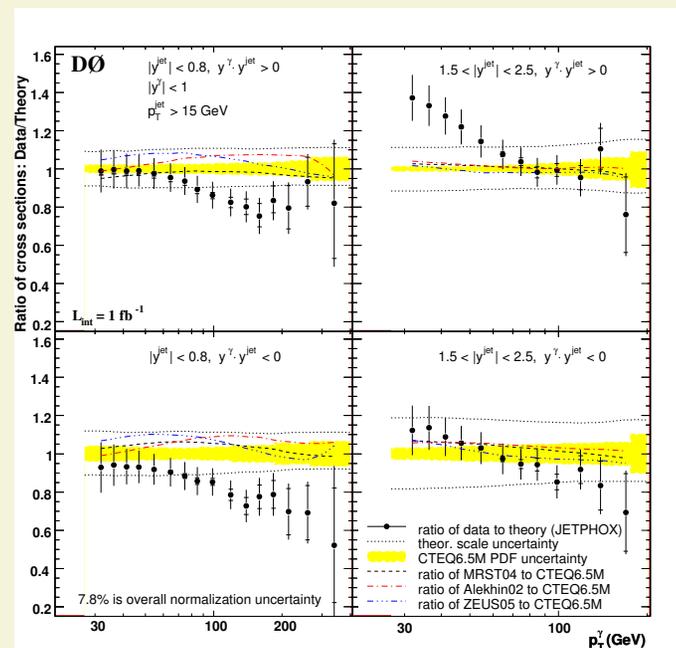
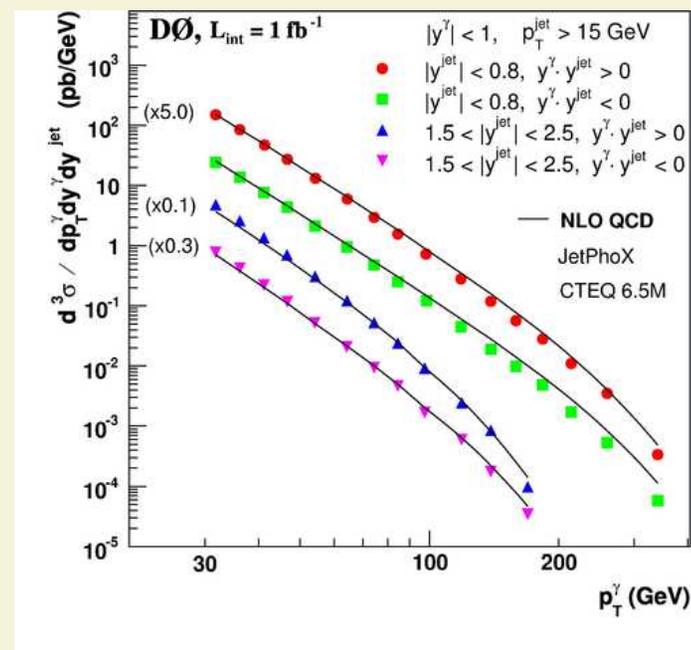
$$\Rightarrow p_T^\gamma > 30 \text{ GeV}/c$$

- Measurements (over 5 orders of magnitude) are not well described by the theory.

- p_T dependence is similar to inclusive photon production in UA2, CDF and DØ.

- All PDFs give similar shape predictions.

- Need improved description for γ +jet in theory.

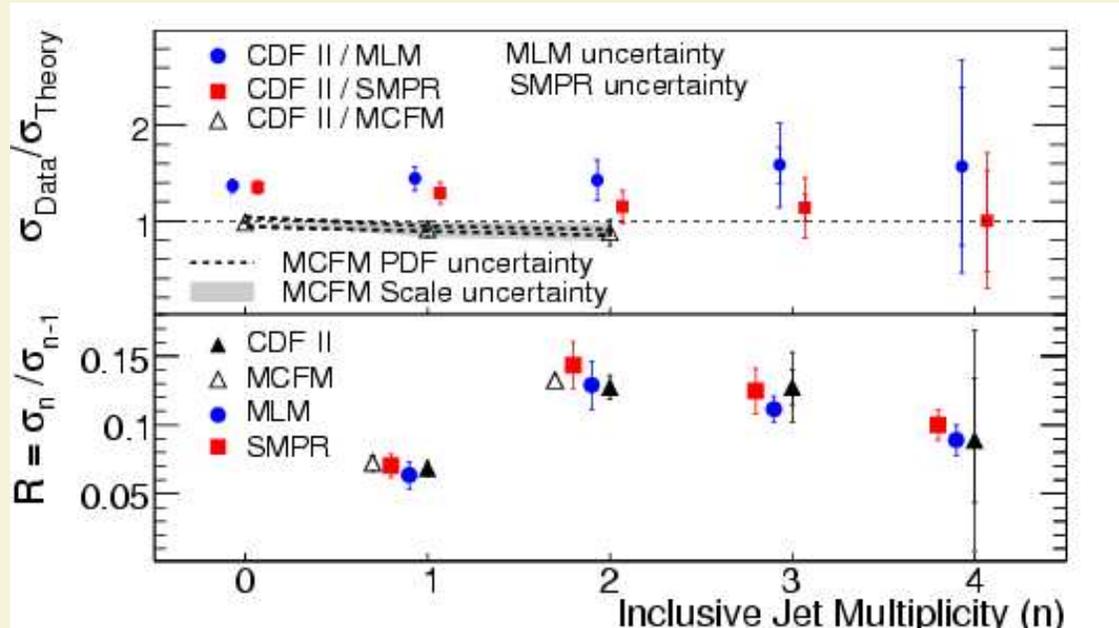


Boson + Jet Production at the Tevatron

- Tevatron experiments are involved in a big effort to test the predictions for W/Z +jets with high accuracy.
- Important tests of Quantum Chromodynamics (QCD):
 - ⇒ Comparison to NLO predictions
 - ⇒ Comparison to LO ME+PS Event Generators
- Recent LO and NLO simulations need experimental verification.
- These processes are important backgrounds to several interesting analysis:
 - ⇒ Background for $t\bar{t}$ production
 - ⇒ Background for searches on Higgs, single top
 - ⇒ Searches on SUSY, Leptoquarks,...
- The importance of these processes will be increased at the LHC.

W + Jet Production

- Selecting $W \rightarrow e\nu$ events with $E_T^e > 30$ GeV



⇒ MCFM (NLO) gives **good and accurate description of the data** (but limited in jet multiplicity)

⇒ MLM (AlpGen+Herwig+MLM-matching) gives **good description of the jet multiplicity**, but fails in absolute normalization (as expected).

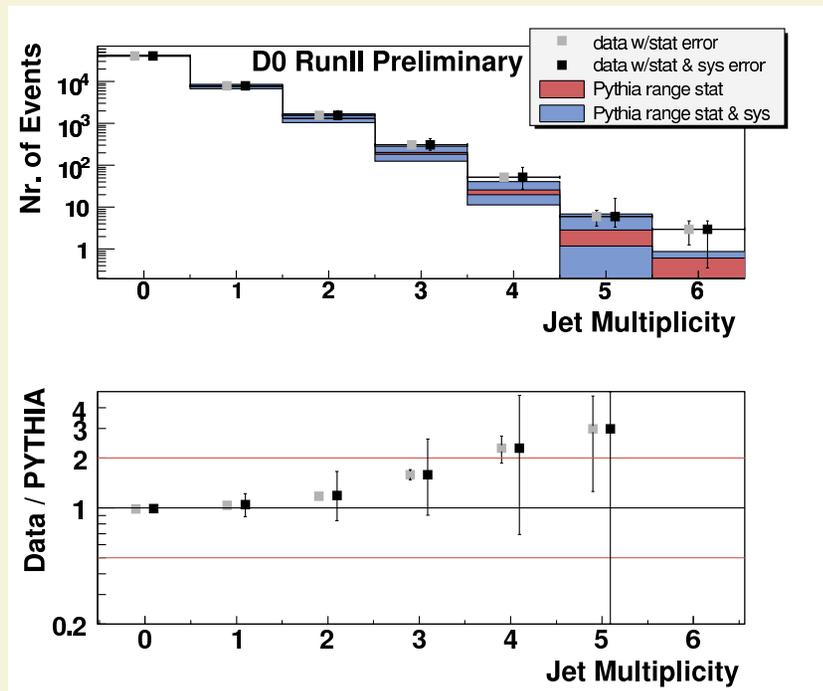
⇒ SMPR (MadGraph+Pythia+CKKW matching) tends to **overestimate the jet multiplicity**.

Z + Jet Production

Very clean (almost background-free) environment.

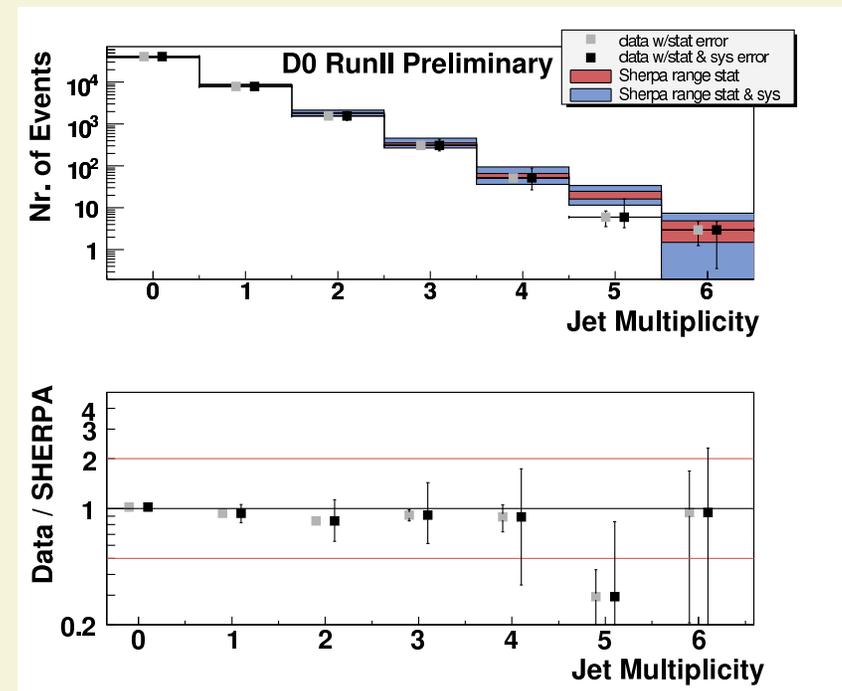
PYTHIA:

- Born Process + Parton-Shower
- Multijet states generated using PS



SHERPA:

- Matrix-Elements for hard parton radiation
- Soft radiation with CKKW matching

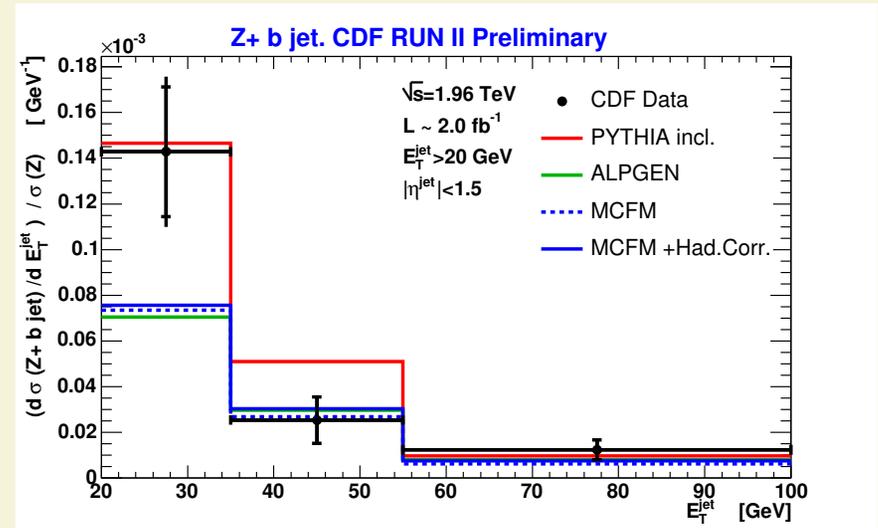
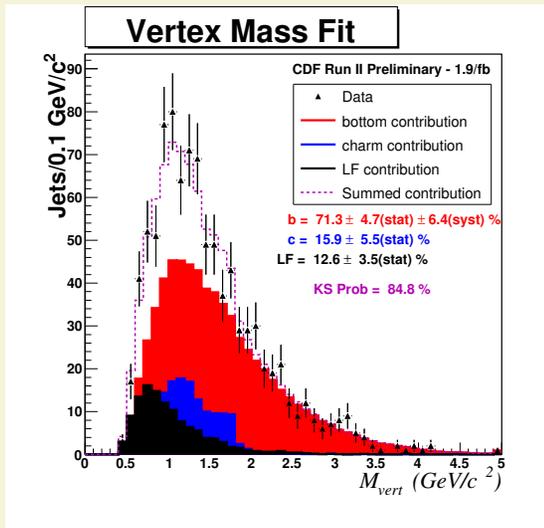


PYTHIA underestimates the production of multijet states.

SHERPA provides better description of the jet multiplicity (and kinematics)

LO Matrix-Elements (AlpGen/MadGraph/Sherpa) generators improve the description of hard multiparton radiation

W/Z + B-Jet(s)



	CDF Data	PYTHIA	ALPGEN	HERWIG	NLO	NLO +U.E+hadr.
$\sigma(Z + b \text{ jet})$	$0.86 \pm 0.14 \pm 0.12 \text{ pb}$	–	–	–	0.51 pb	0.53 pb
$\sigma(Z + b \text{ jet})/\sigma(Z)$	$0.336 \pm 0.053 \pm 0.041\%$	0.35%	0.21%	0.21%	0.21%	0.23%
$\sigma(Z + b \text{ jet})/\sigma(Z + \text{ jet})$	$2.11 \pm 0.33 \pm 0.34\%$	2.18%	1.45%	1.24%	1.88%	1.77%
$\sigma(W + b \text{ jet})$	$2.74 \pm 0.27 \pm 0.42 \text{ pb}$	–	0.78 pb	–	–	–

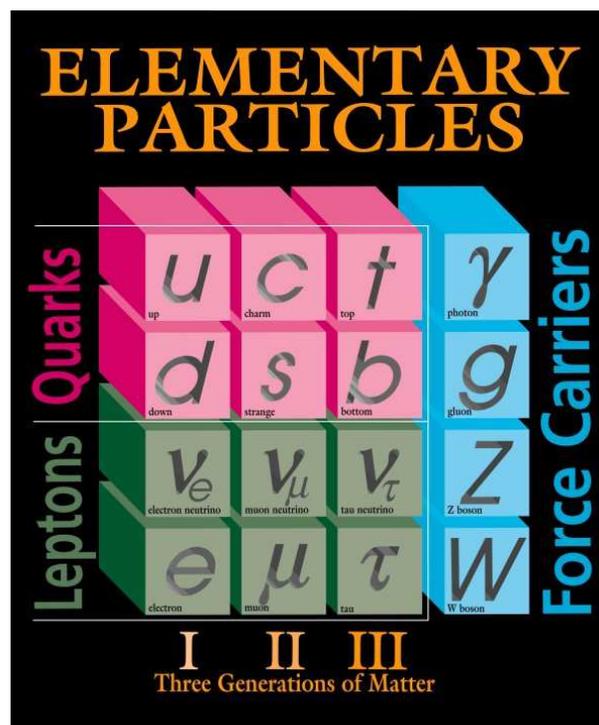
**ALPGEN and NLO Predictions seem to underestimate the data in this case
More predictions are needed, especially to study w+b-jet discrepancy**

More studies are needed in the W/Z + heavy-flavour jets channel to understand the experimental results.

**These final states are basic (and common) backgrounds
in studies and searches at Tevatron and the LHC**

Electroweak Physics

Studying the structure of the Standard Model to the last corner



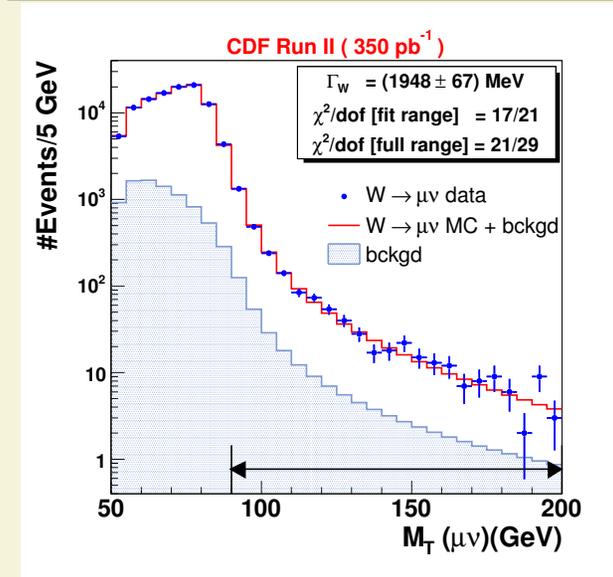
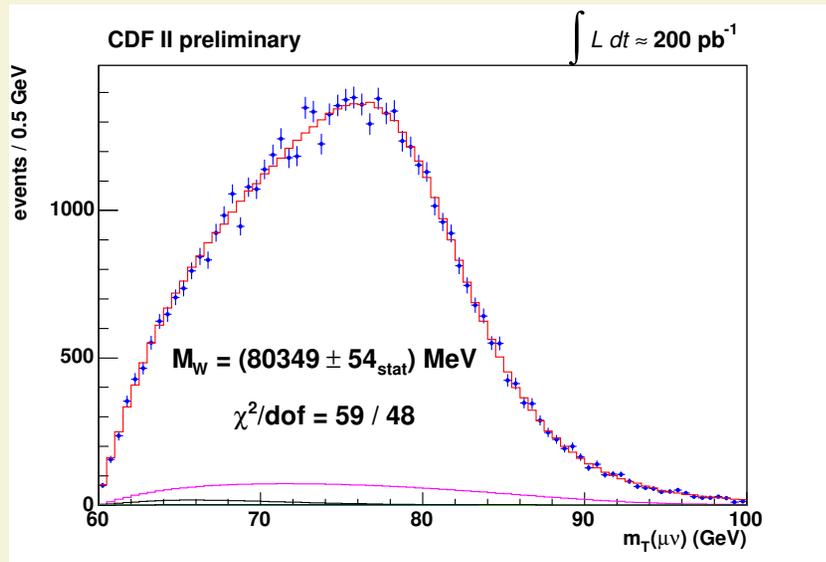
Fermilab 95-759

W Mass and Width Measurements (I)

Tevatron provides the best place to measure the properties of the W boson to the highest precision.

Width of the W tests the very precise SM value (from the PDG)

$$\Gamma_W = 2.091 \pm 0.002 \text{ GeV}/c^2$$



- Lots of effort to understand energy scale (using J/ψ , Υ and Z events) which is the largest systematic.
- Investigation to reduce uncertainty in hadronic recoil using Z events.

- Fit of Γ_W in the tail of the transverse mass.
- Required very accurate and fast detector simulation.

$$m_W = 80.413 \pm 0.048 \text{ GeV}/c^2$$

$$\Gamma_W = 2.032 \pm 0.073 \text{ GeV}/c^2$$

Both are the world's most precise single measurements of these quantities.

W Mass and Width Measurements (II)

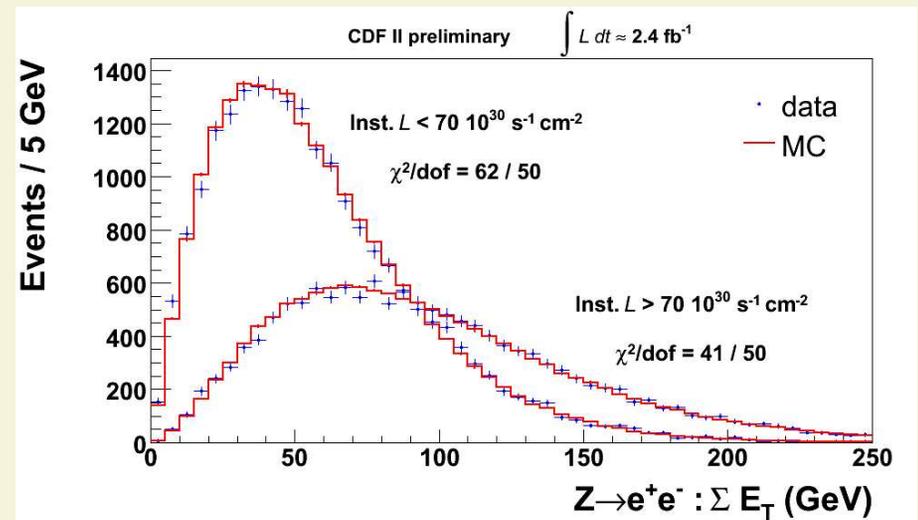
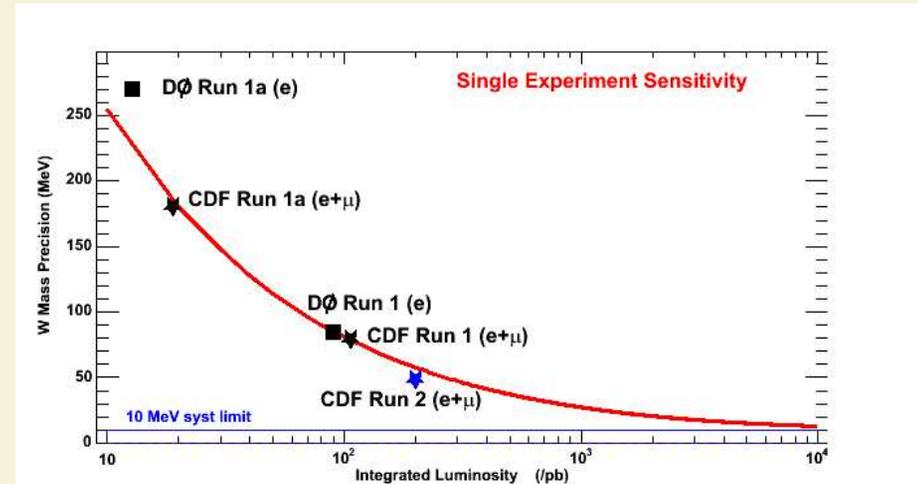
- Currently much more data is available.

With 2 fb^{-1} we may achieve a total error of 25 MeV in m_W .

Provided the following effects are minor (or we keep them under control):

- Aging of the detectors
- Lack of homogeneity in the larger data sample
- Luminosity-dependent (pile-up)

(More information on the back-up slides and the CDF-EWK Group web pages)



Preliminary studies suggest that 25 MeV is achievable with the current data sample

Forward-Backward Z-Production Asymmetry

- The presence of vector and axial-vector couplings in $qq \rightarrow Z/\gamma^* \rightarrow e^+e^-$ gives rise to the following cross section:

$$\frac{d\sigma}{d \cos \theta^*} = A \left[1 + \cos^2 \theta^* \right] + B \cos \theta^*$$

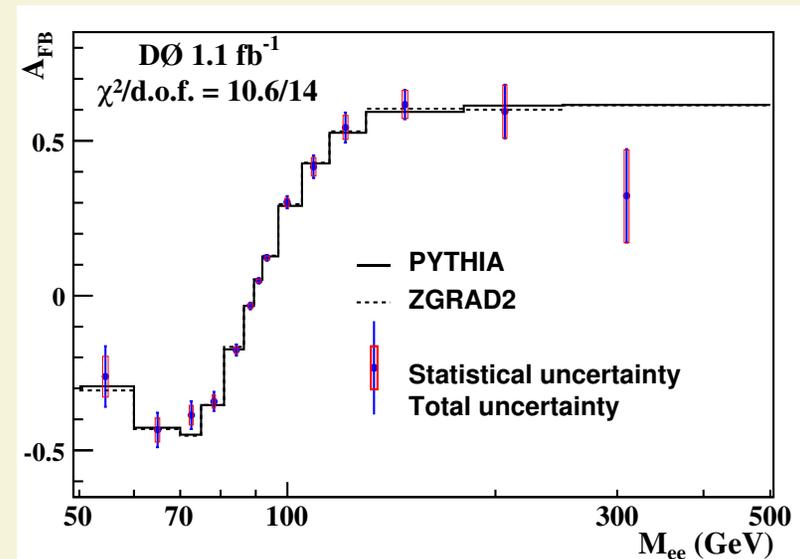
which leads to a Forward-Backward asymmetry which depends on the dilepton mass and it is sensitive to $\sin^2 \theta_W^{\text{eff}}$.

- Asymmetry is defined as the relative difference between the forward and backward cross section (as the rapidity of the produced electron in the Collins-Soper frame).

- Measurement in good agreement with the SM prediction.

- $\sin^2 \theta_W^{\text{eff}} = 0.2327 \pm 0.0019$ (World average is 0.23152 ± 0.00014)

- Large M_{ee} is sensitive to new Z' boson



Radiation Amplitude Zero in $W\gamma$ Events

- $WW\gamma$ vertex is investigated using the production of $W + \gamma$ (s-channel).

- Interference with t-channel gives rise to a RAZ in the angular distribution of the photon.

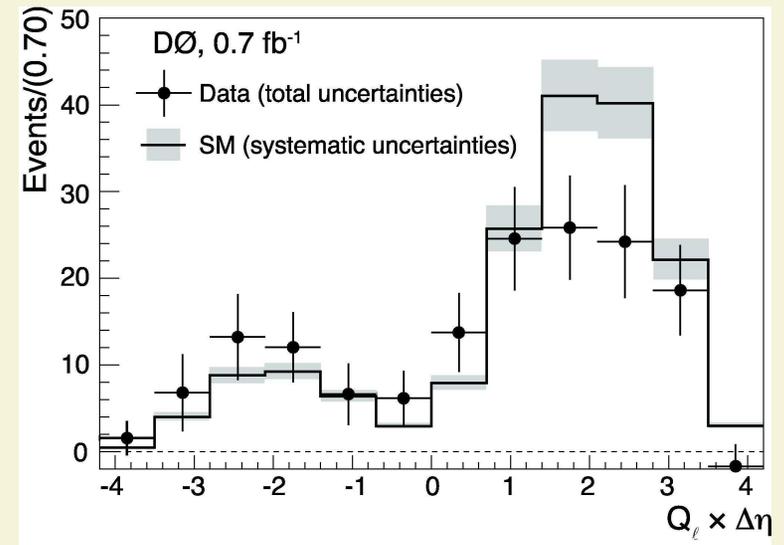
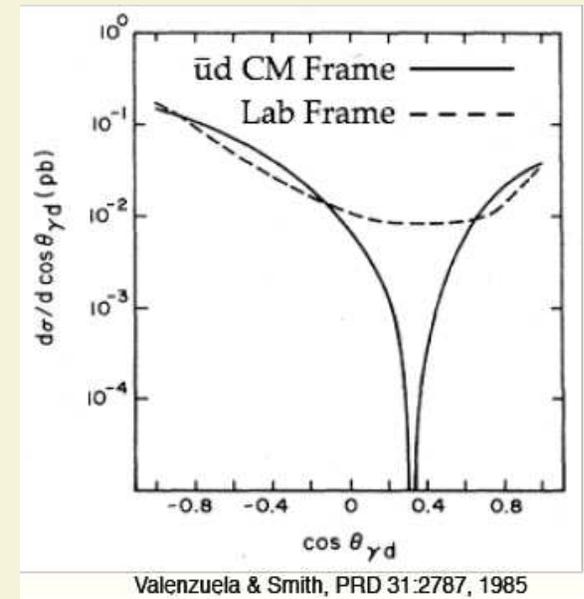
From gauge theory, the dip appears at:

$$\cos \theta_{\gamma d} = \frac{q_u + q_d}{q_u - q_d} = \frac{1}{3}$$

- Dip is diluted by FSR photons off leptons, NLO corrections, backgrounds and anomalous couplings.

- Measured distribution ($Q_l \cdot [\eta_\gamma - \eta_l]$) is sensitive to this property of the Standard Model and is described by the predictions.

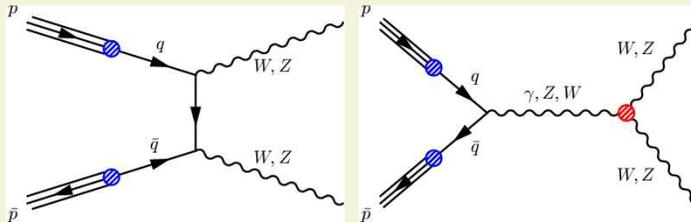
- Tail of $d\sigma/dE_T^\gamma$ distribution was used to set limits on anomalous $WW\gamma$ vertex.



Diboson Production

Diboson production is a very important test of the SM structure

⇒ Sensitive to couplings between EWK bosons.



⇒ Final states are sensitive to new physics (i.e. divergences to the SM predictions) due to the small cross sections.

⇒ Big effort over Run II to measure the production cross sections

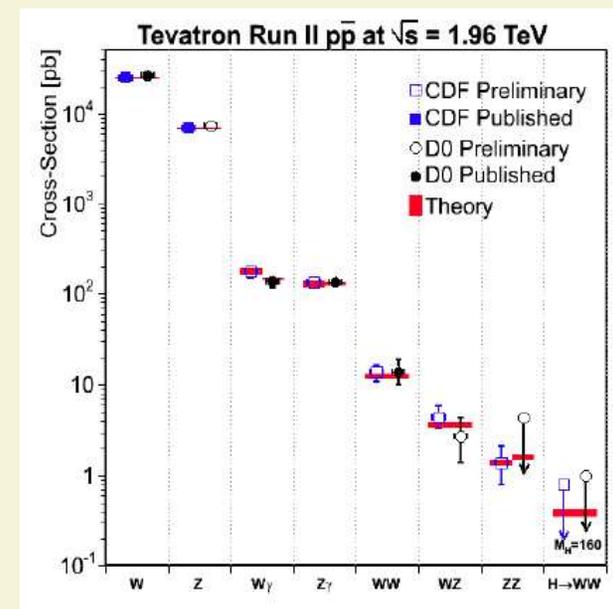
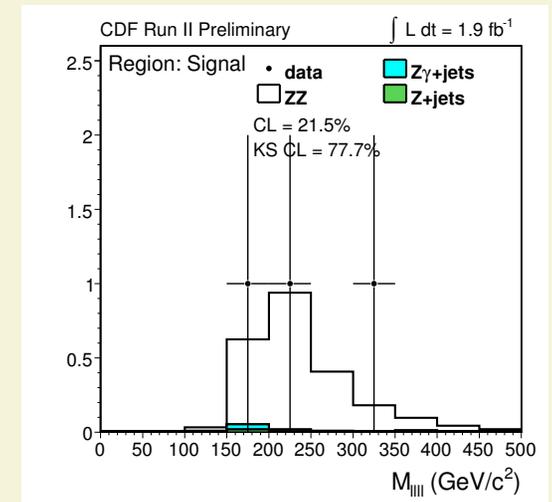
⇒ Last one is ZZ production with large significances:

CDF: 1.4 ± 0.7 (stat) ± 0.6 (sys) pb (4.4σ)

DØ: 2.1 ± 1.1 (stat) ± 0.4 (sys) pb (2.4σ)

Very good agreement with the SM predictions for boson production

⇒ Necessary steps towards the discovery of the Higgs!





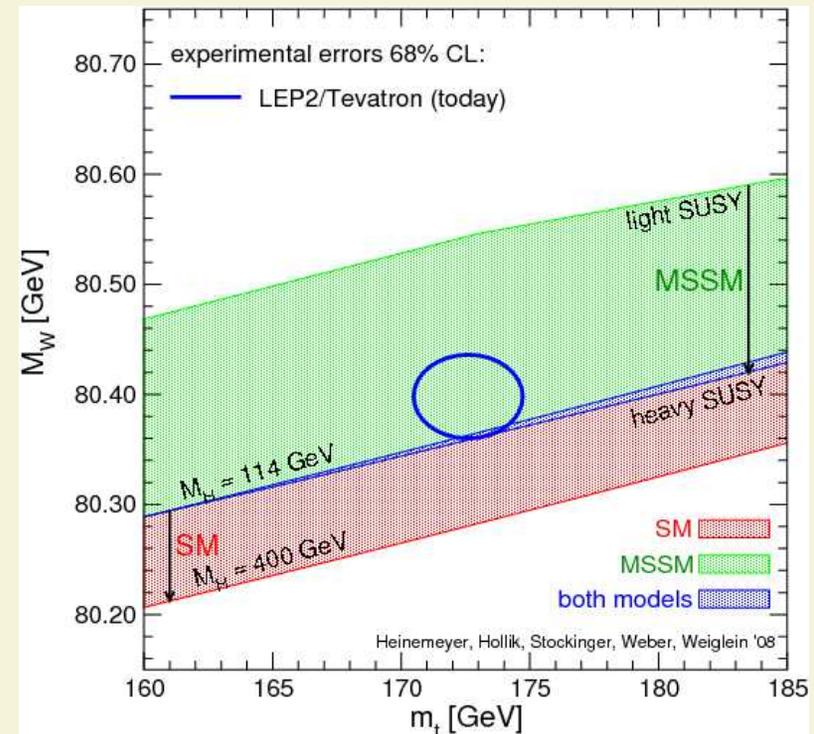
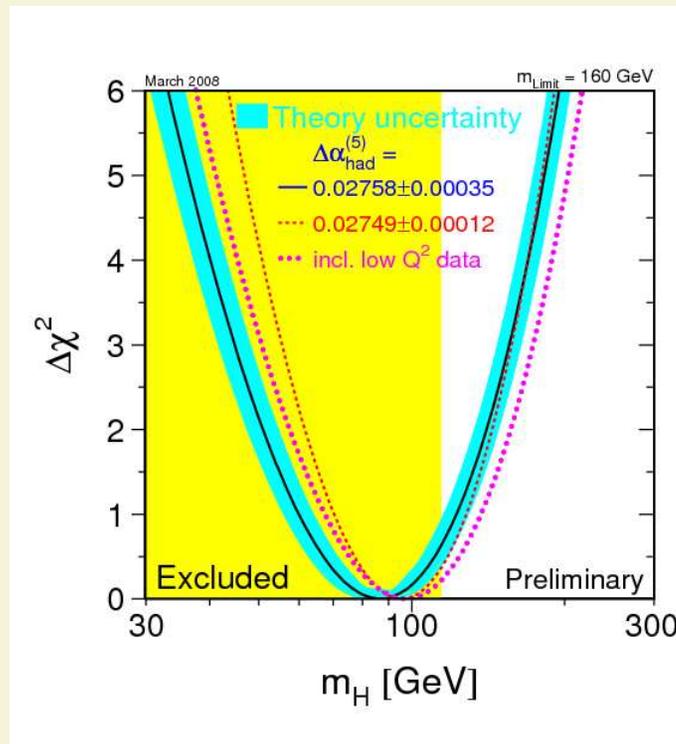
The (still missing) Keystone of the Standard Model

Higgs constraints from indirect measurements

- The Standard Model relies on the Higgs mechanism to explain the structure of the electroweak sector observed in Nature.
- Electroweak (SM) fits constrain the (unknown) Higgs mass to

$$m_H = 87^{+36}_{-27} \text{ GeV}/c^2$$

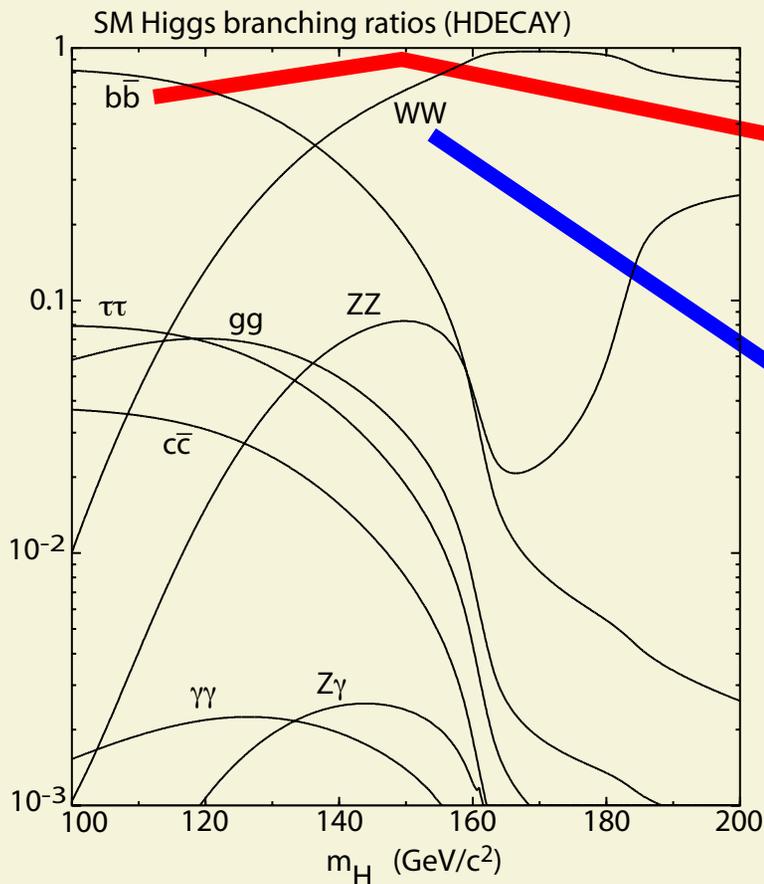
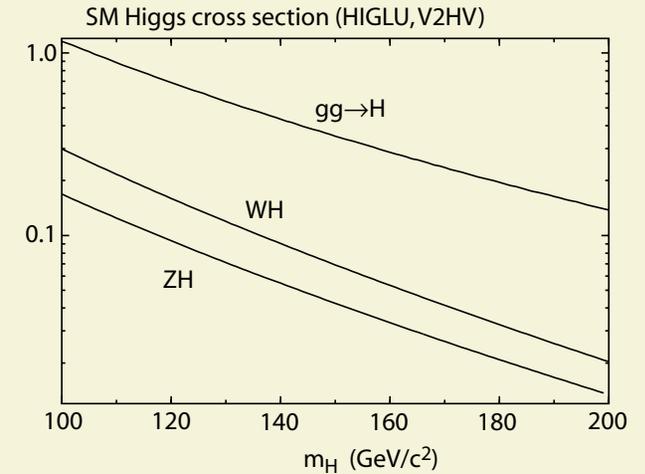
$$m_H < 160 \text{ GeV}/c^2 \text{ at 95\% CL}$$



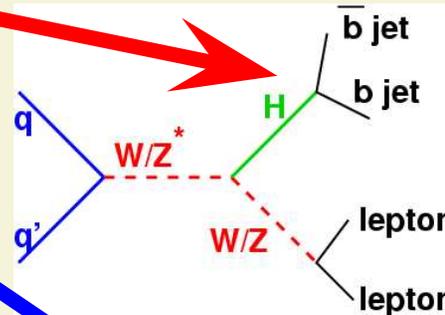
- Direct searches at LEP excluded a Higgs with $m_H < 114.4 \text{ GeV}/c^2$ (at 95% CL)

Higgs at the Tevatron: Strategy

- Small cross section (order of 0.1-1 pb)
- Single Higgs Production via g-g fusion (mostly through top-loop) is the dominant process
- Branching ratios set the basic search strategy (as a function of the Higgs mass)



Channels ordered by sensitivity:

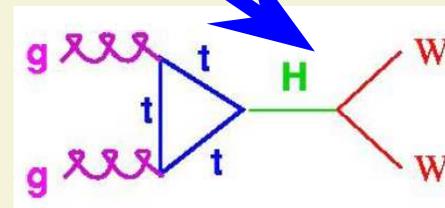


$$ZH \rightarrow \nu\bar{\nu}b\bar{b}$$

$$WH \rightarrow l\nu b\bar{b}$$

$$ZH \rightarrow llb\bar{b}$$

...



$$H \rightarrow WW^* (\rightarrow l\nu l\bar{\nu})$$

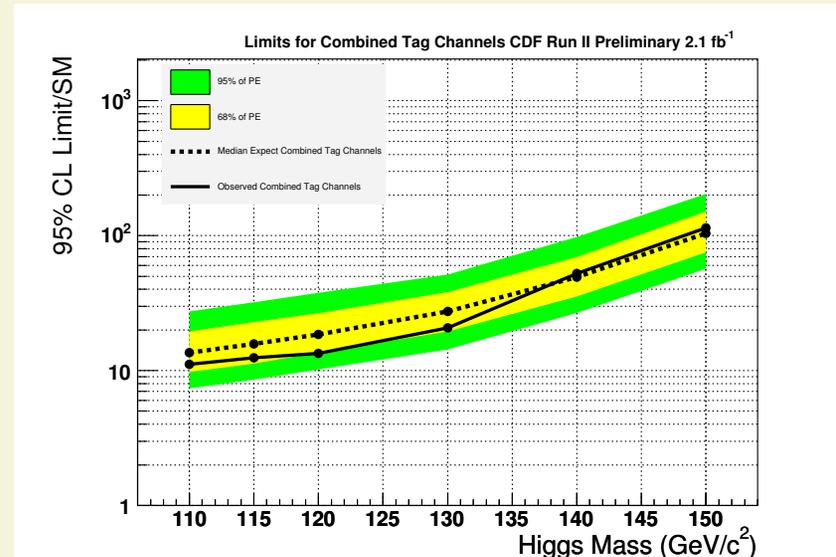
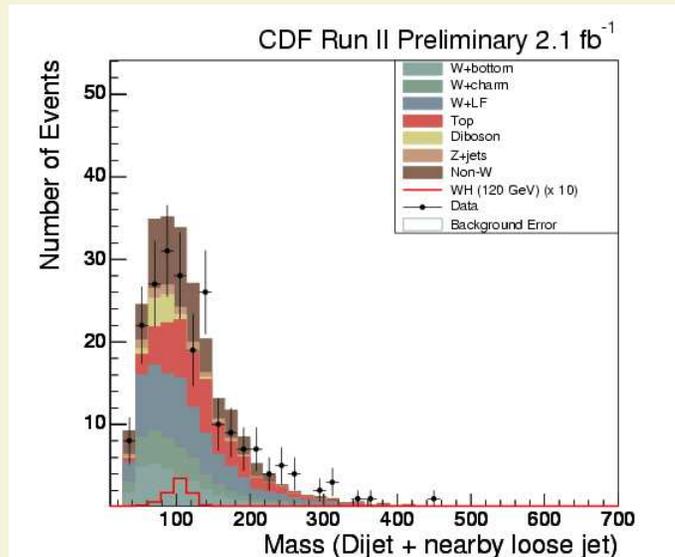
$$WH \rightarrow WWW^*$$

...

Low-Mass Higgs: WH with isolated tracks

Recent analysis in the “getting all the Higgses” approach

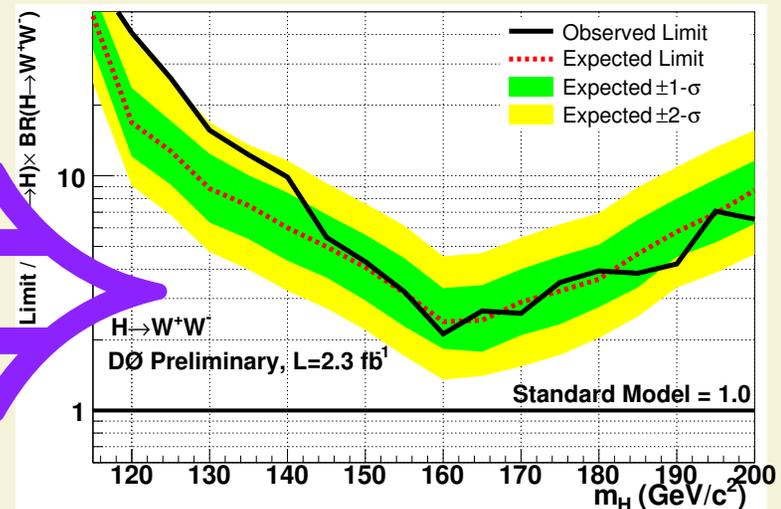
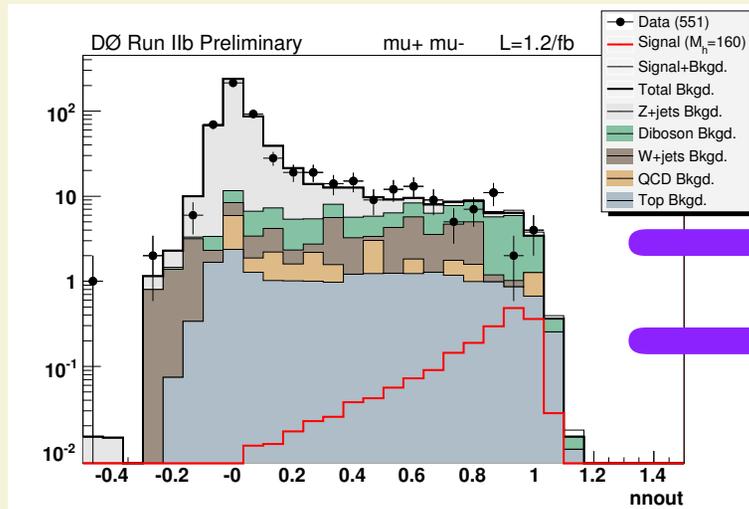
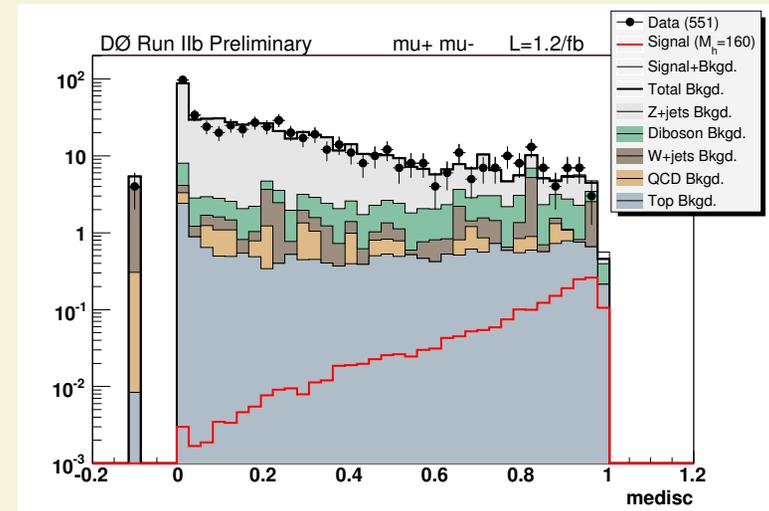
- Increase in 25% acceptance selecting muons with loose requirements (isolated tracks in the detector).
- Events are collected using the MET + 2-jet trigger



- Also a good example of the “achieving the maximum sensitivity” approach: signal separated from background using a Neural-Network output
- Search performed in the single and double b-tagged jet samples.
- Limit still to be added to the combination.
- Recent global $H \rightarrow \tau\tau$ search added 10% in the low-mass range.

High-Mass Higgs: $H \rightarrow WW^*$

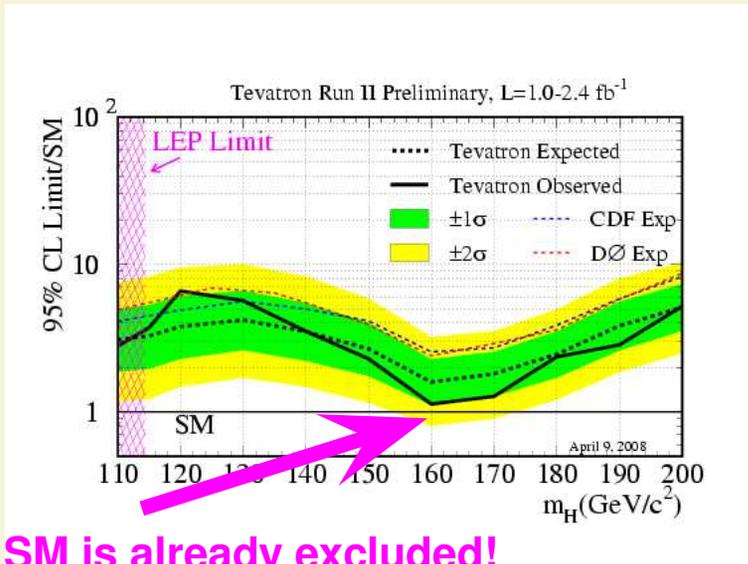
- The WW^* channel is currently the one producing the best limit (for the values $m_H \sim 160 \text{ GeV}/c^2$).
- Recent analysis using a Neural-Network which includes a **Matrix-Element-based discriminant**.
- NN Trained separately for ee , $\mu\mu$ and $e\mu$
- Good agreement in observed output with respect to the background expectation.



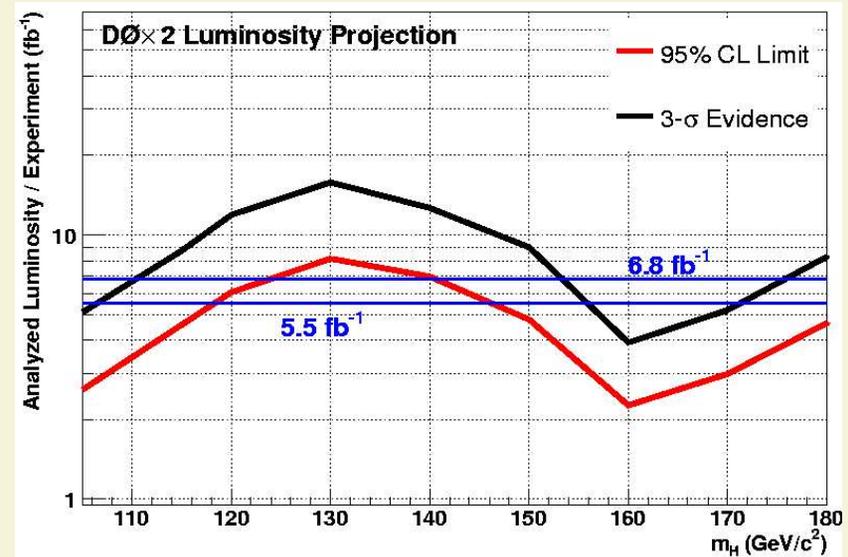
- 95%-CL exclusion limit **approaching the Standard-Model expectation** for $m_H \sim 160 \text{ GeV}/c^2$

Search for the Higgs

- Current 95%-CL limit is above the expected cross sections in the Standard Model for values of the Higgs not excluded (at LEP).
- Limit getting close in the range of $m_H \sim 160 \text{ GeV}/c^2$: **Expect news soon!**



$1.1 \times \text{SM}$ is already excluded!



- Some remarks about expectations:

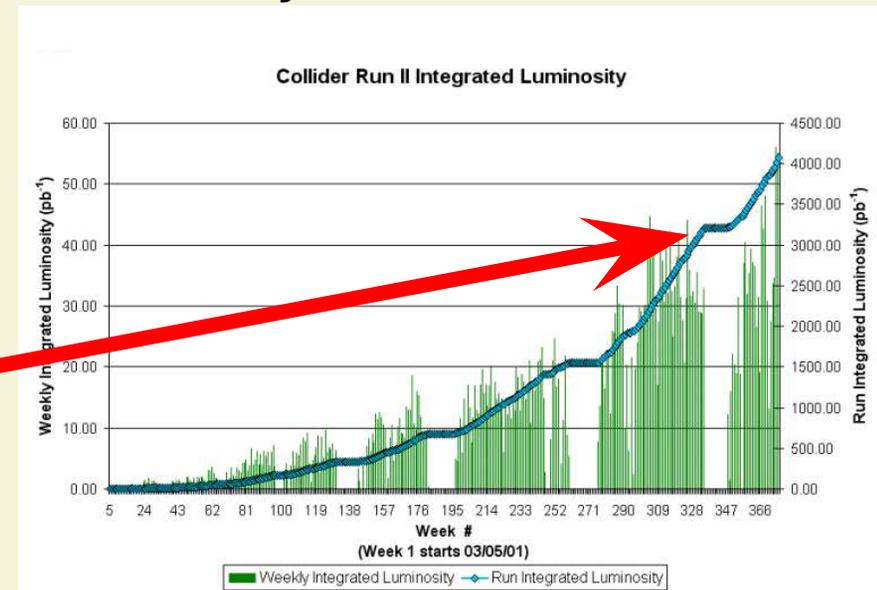
⇒ Exclusion limit has improved more than what expected from luminosity increase (quantified in a 1.7 factor).

⇒ We expect another increase in sensitivity not due to luminosity of **a factor of 2.0 for the low-mass region due to further improvements** in b-tagging, lepton acceptance and dijet mass resolution (among others).

- We expect to exclude (or begin to see hints of) the Higgs in the low-mass end before LHC experiments are ready to make similar statements about this region.

Summary and Outlook

- Results on QCD are giving insights on the most common final states at Hadron colliders.
- Results on EWK achieving highest precision to test SM predictions.
- Chase of the Higgs rapidly progressing: sensitivity improving much more than expectation from increase in integrated luminosity
- Nothing of this would happen without the effort of the FNAL Accelerator Division. **Thanks a lot for the data!**
- Note that most of the analysis only use data up to Aug 2007 shutdown (or less)
- More data to be added soon: **Improved results for ICHEP 2008.**



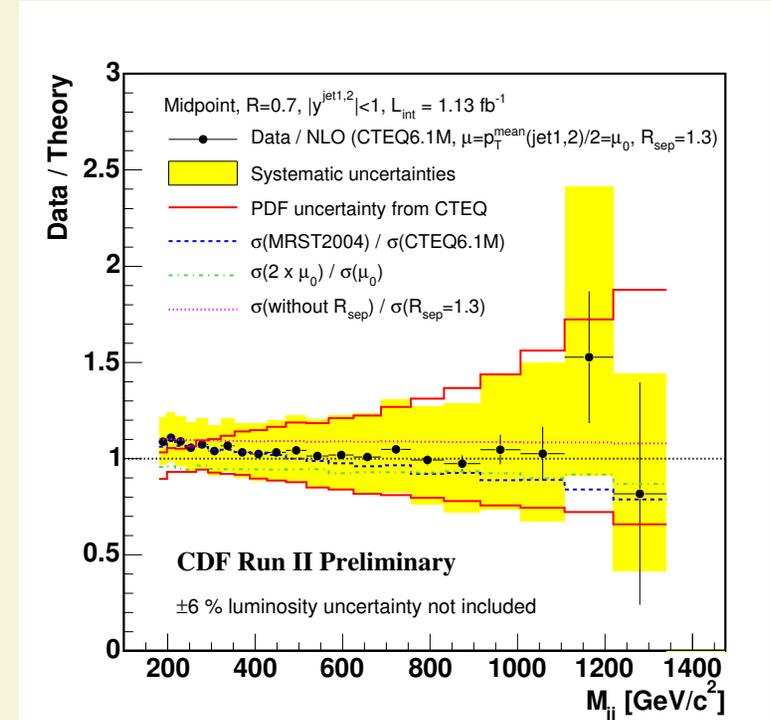
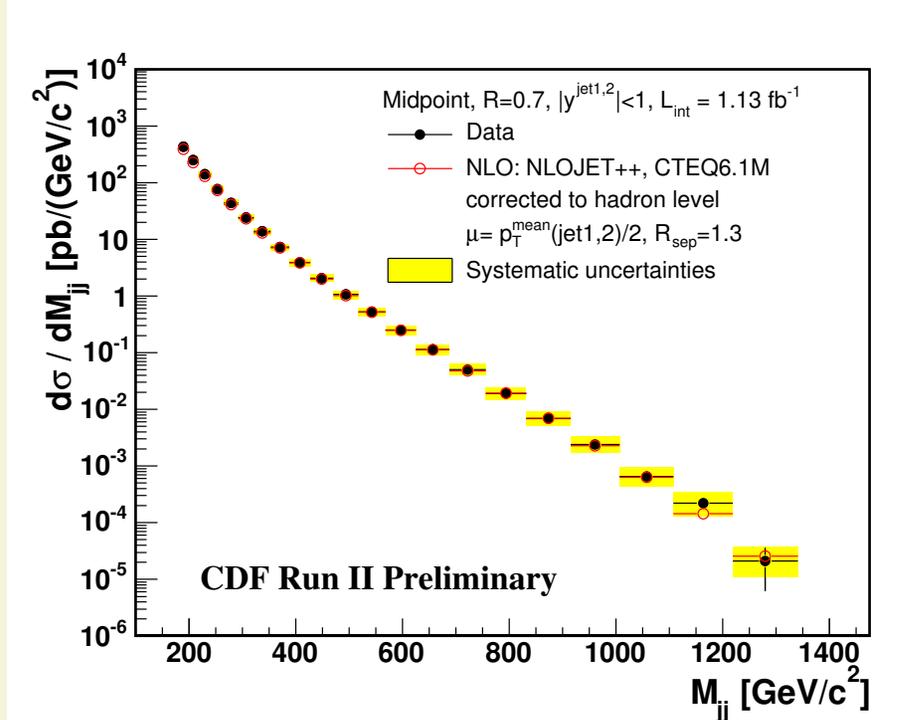
Please check our web pages with more public results: they are open 24/7!!!

<http://www-cdf.fnal.gov/physics/physics.html>

<http://www-d0.fnal.gov/Run2Physics/WWW/results.htm>

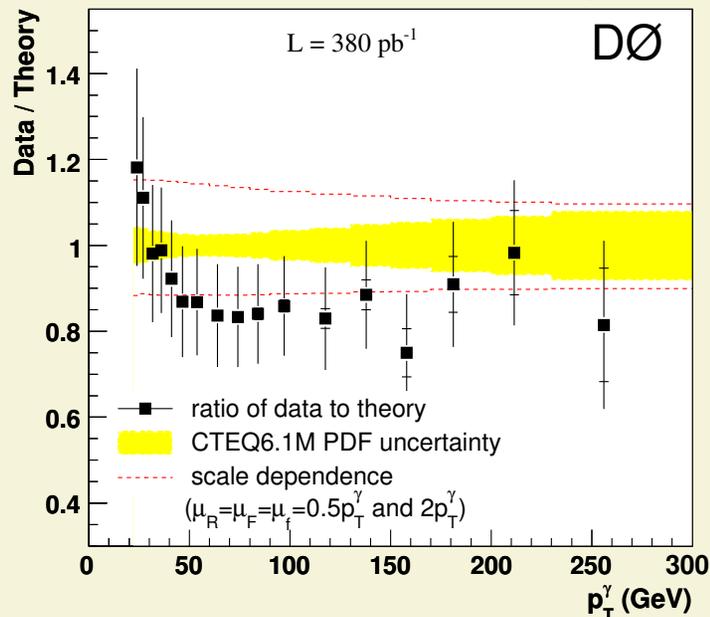
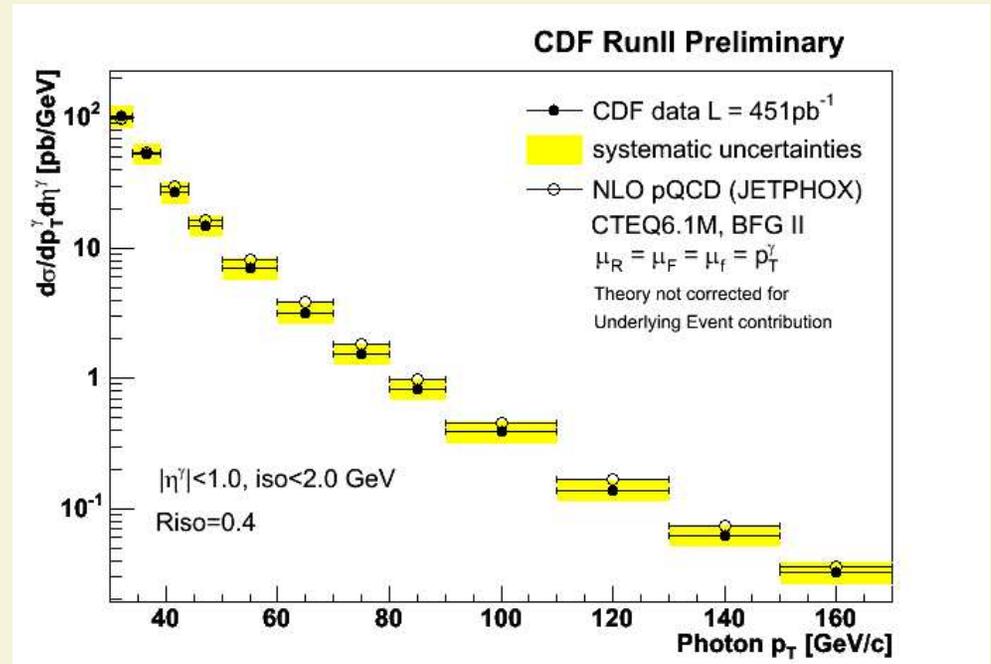
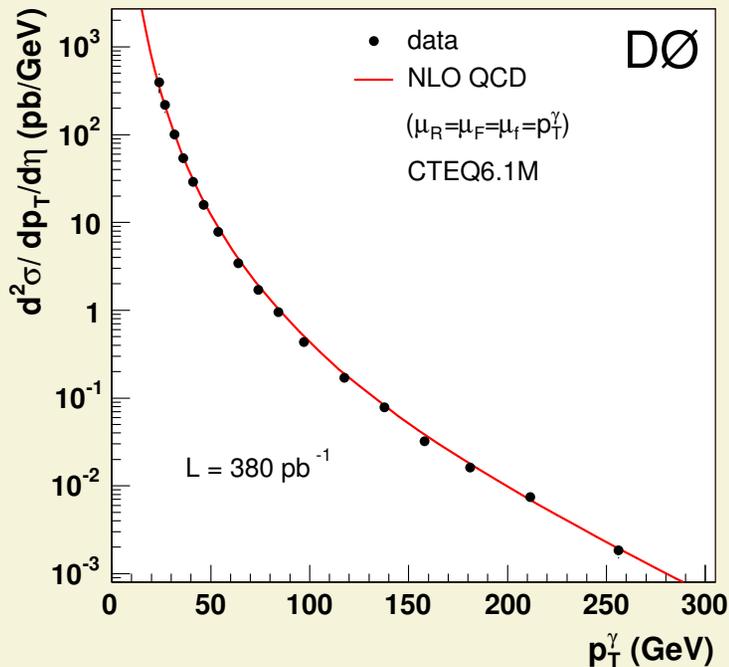
Exclusive Dijet Production: Dijet mass

- Central dijet production is sensitive to new physics.
- Especially sensitive to new resonances.



- NLO predictions describe data well within uncertainties.
- Cross section measured over 7 orders of magnitude.
- PDF Uncertainties pretty large for very hard jets.
- Limits set for excited quarks, massive gluon and Z'/W' scenarios.

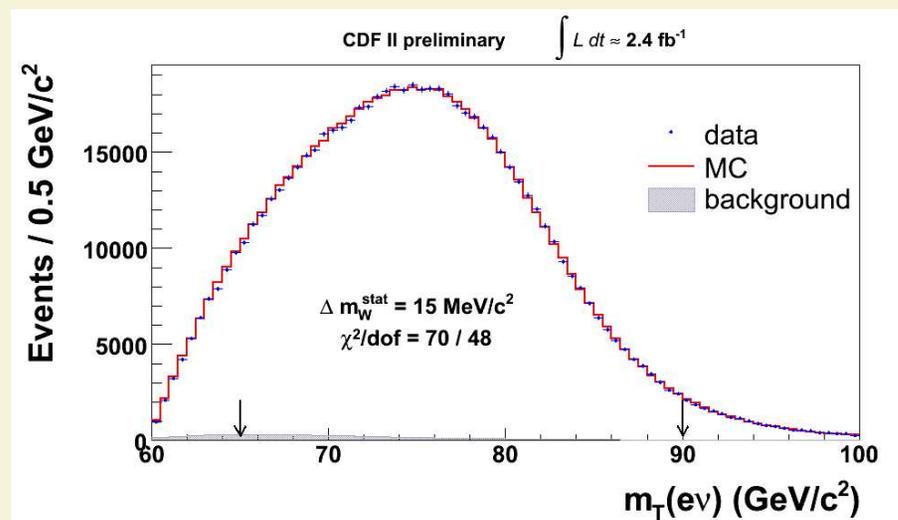
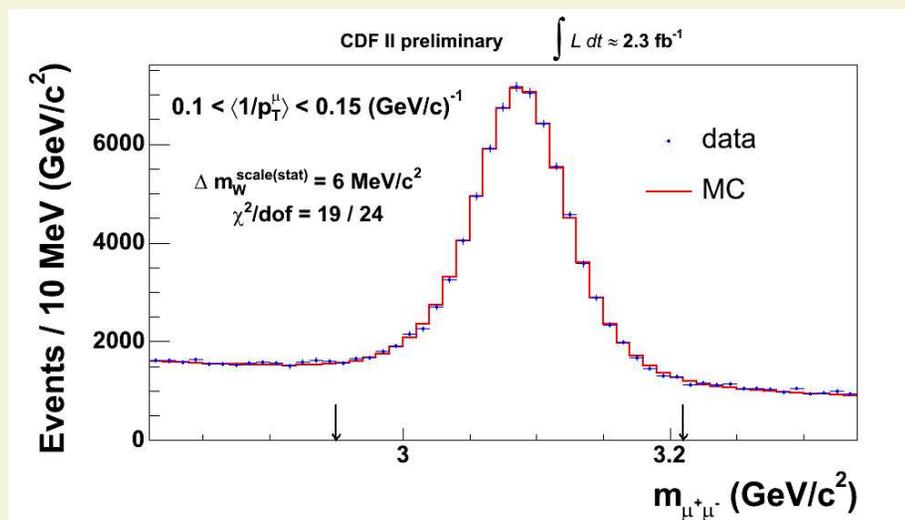
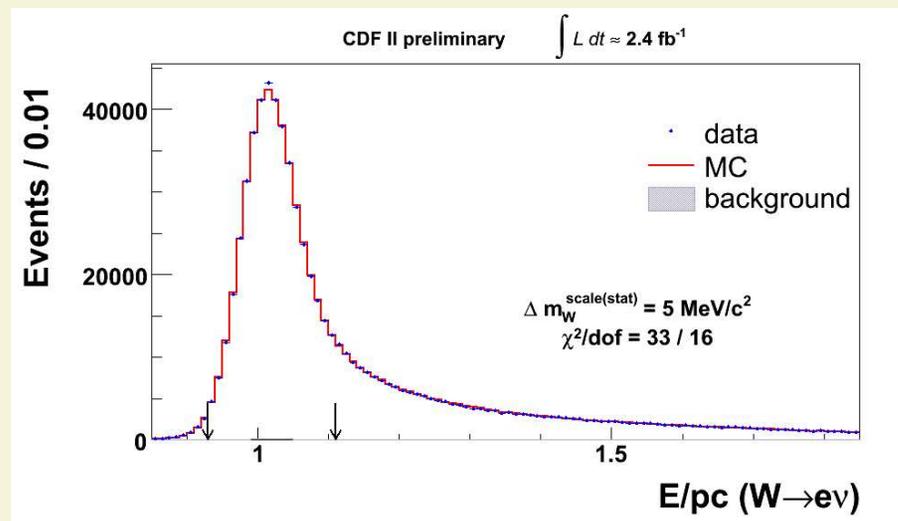
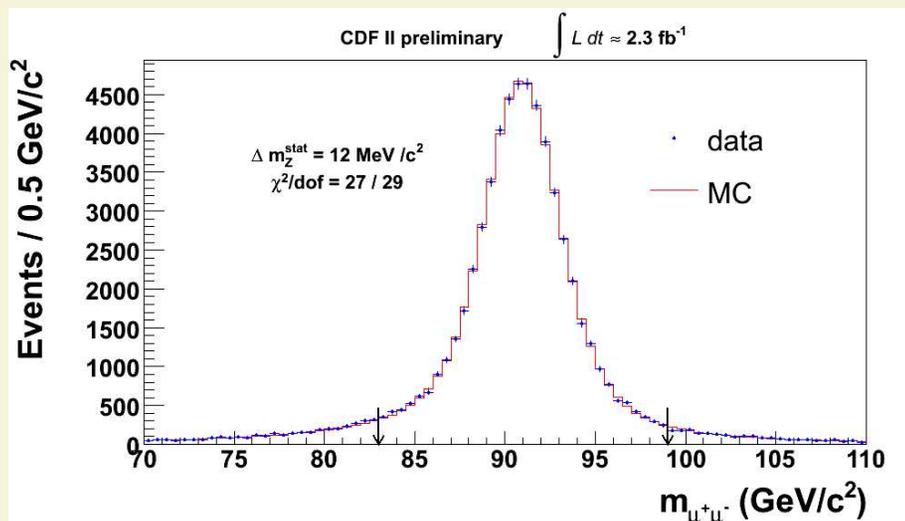
Inclusive Photon Production



- Measurements from both experiments are above the NLO predictions.
- Agreement within 20%.
- p_T dependence similar to former observations (UA2).
- Measurements based on larger datasets coming soon.
- Expecting to reach $300 \text{ GeV}/c$.

More on the 2.3 fb^{-1} Measurement of the W Mass

- Work is already in a very advanced state.
- All basic tools are ready and looking fine.

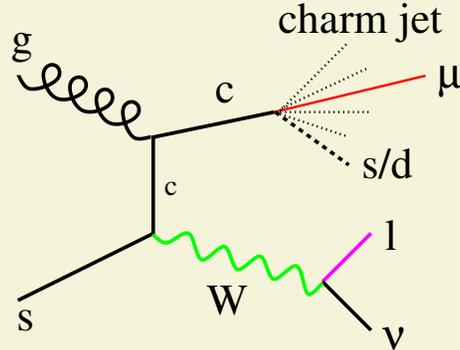


W + Charm Jet

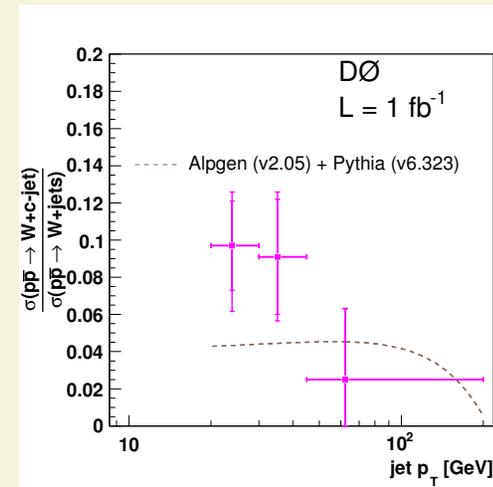
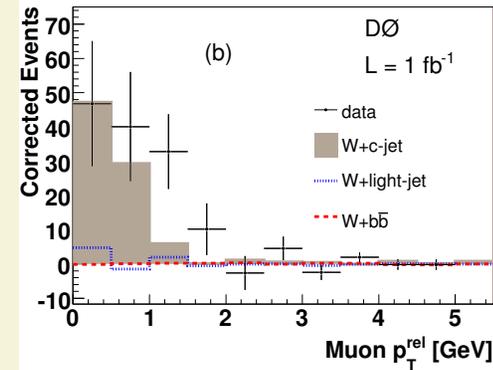
Production of Heavy-Flavour jets with vector boson is very important being an important background for analyses based on b-tagging.

- Selection based on muon-based tagger allows studies of the interesting W +charm:

⇒ Opposite charge of muon in jet and (isolated) lepton from W :



⇒ Gives information on the PDF for strange quark, and it is sensitive to the $|V_{cs}|$ element of the CKM matrix.



The probability that background fluctuations could produce the observed fraction of W + c events is estimated to be $2.5 \cdot 10^{-4}$, which corresponds to a 3.5σ statistical significance.

Cross section at CDF for $p_T^c > 20$ GeV, $|\eta^c| < 1.5$ is 9.8 ± 2.8 (stat) $_{-1.6}^{+1.4}$ (syst) ± 0.6 (lumi) pb in good agreement with the NLO (MCFM) prediction of $11.0_{-3.0}^{+1.4}$ pb

W + Bottom Jet

- With a tight b-tagger, it is possible to investigate the production of W +b-jets with high precision.

- Here using the tagging algorithm based on secondary-vertex reconstruction, **with a very tight selection to reduce contamination from mistagged jets.**

⇒ Very clean selection (70% b-jets): background is dominated by $t\bar{t}$

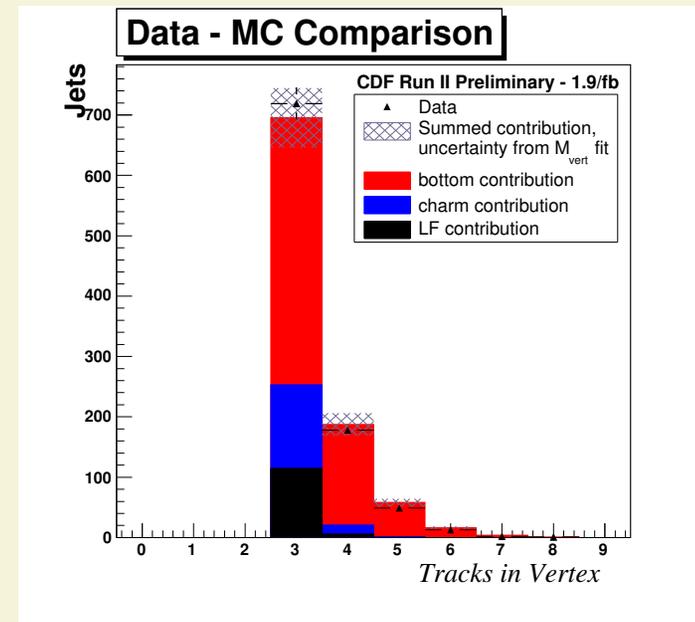
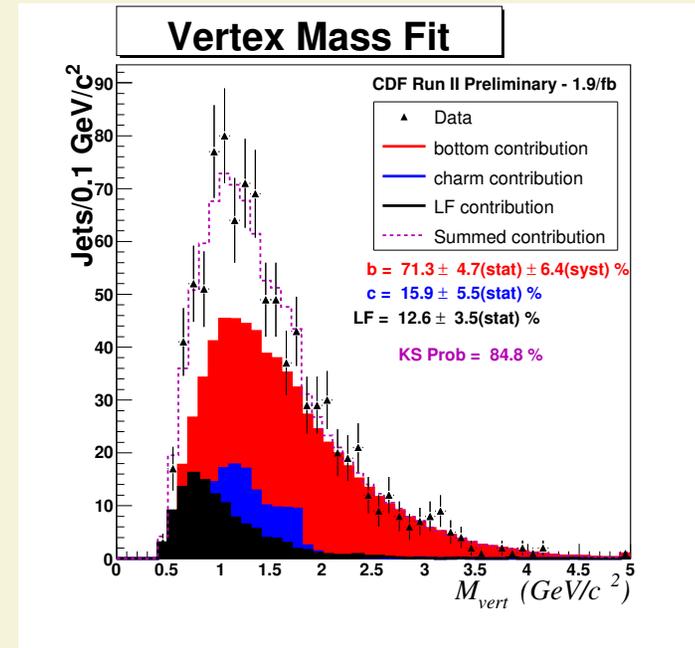
⇒ Vertex properties are well reproduced by the simulation.

- Cross section of Wb production was measured:

$$\sigma = 2.74 \pm 0.27 \text{ (stat)} \pm 0.42 \text{ (syst) pb}$$

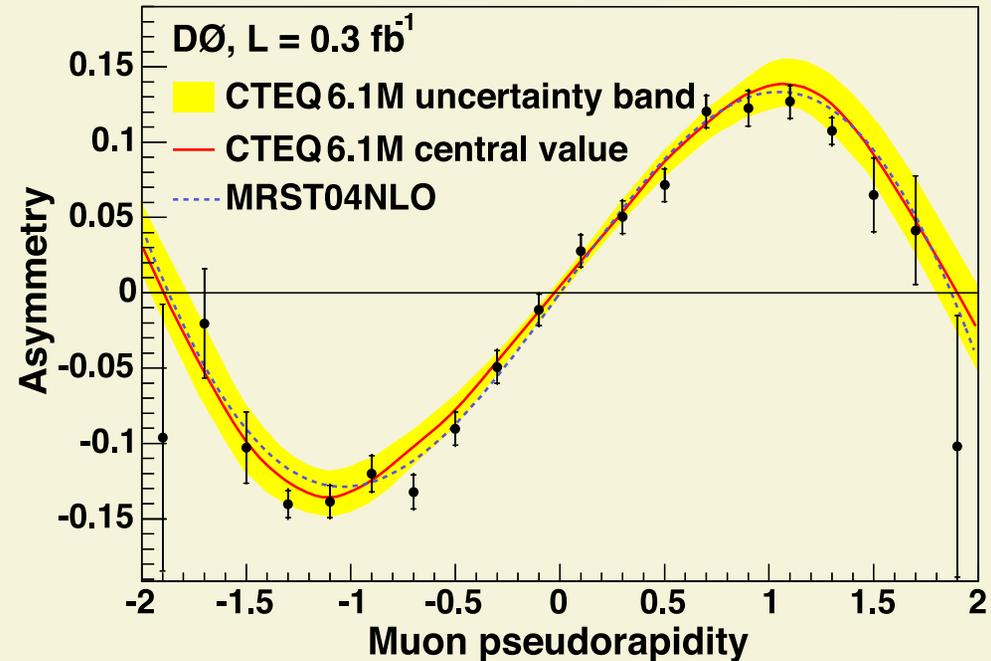
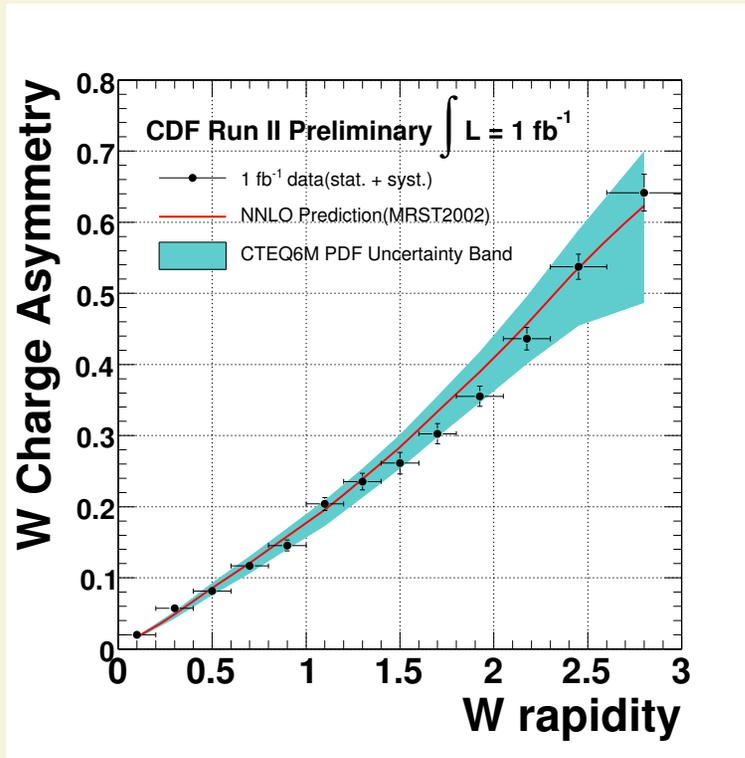
which is underestimated by ALPGEN (0.78 pb).

- Work to get alternative predictions in progress.



Measuring the W -Production Charge Asymmetry

Due to the asymmetry in charge of the initial state, W production is charge-asymmetric in rapidity.



It should be noted that the V-A structure of the W decays favors an asymmetry for the charged leptons opposite to that of the W production.

CDF corrects for this by reconstructing the kinematics of the W (using a mass constrain and weighting the relative contribution of each solution).

Observed asymmetry is in good agreement with the SM expectations

Z Rapidity

- Measurement of the Z rapidity is sensitive to the fraction of the (anti)proton momentum carried by the initial partons:

$$x_p = M_Z e^y \sqrt{s}$$

$$x_{\bar{p}} = M_Z e^{-y} \sqrt{s}$$

being $y = \frac{1}{2} \ln \frac{E_Z + p_L^Z}{E_Z - p_L^Z}$ the rapidity of the Z boson.

- Measuring $d\sigma/dy$ constrains the proton PDFs.
- Measurement is compared to modern PDFs (statistical error only).

