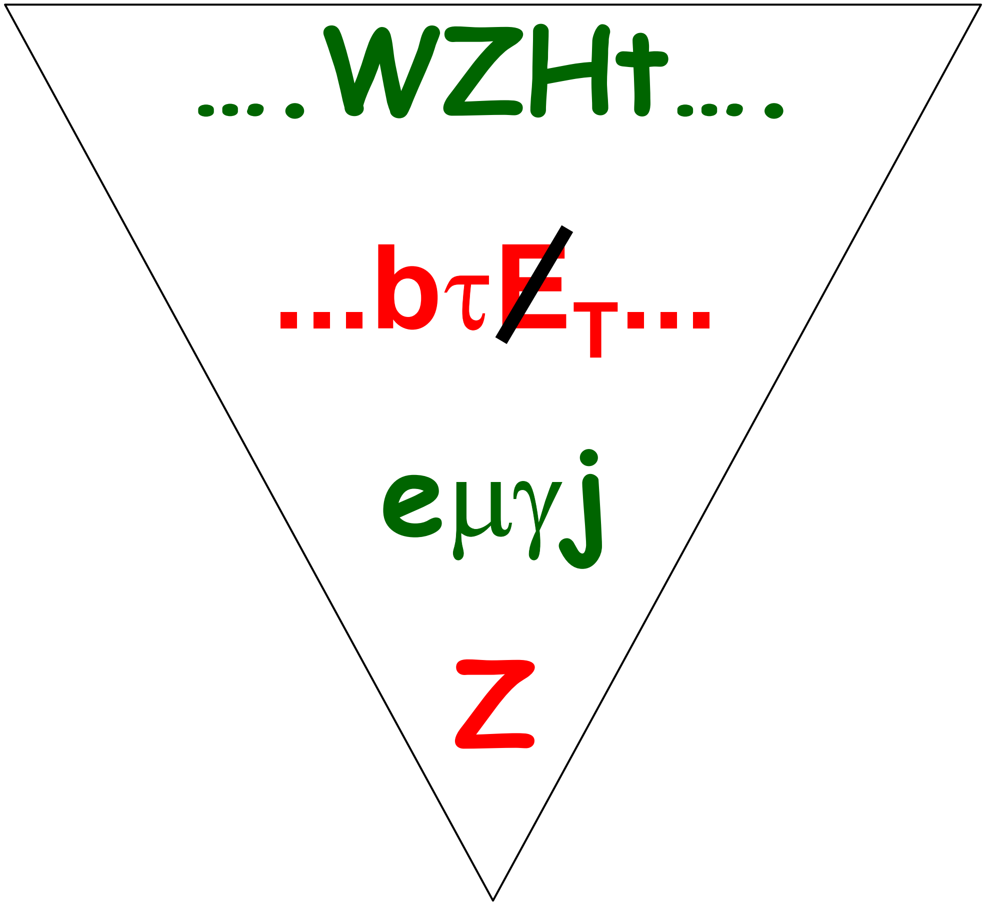
W and Z as probes at the Tevatron

- Probes of the apparatus.
- Probes of the proton.
- Probes of the electroweak force.
- Other probes discussed elsewhere:
  - Top
  - Higgs
  - New physics searches

Apologia

- I define “electroweak physics” as “the physics that the CDF and D0 electroweak physics group do.”
- I will not systematically list here all analyses or all measurements that go with each analysis.
- I will not be systematic here with citations. All missing details and appropriate references are available on the CDF and D0 public web pages.

All Tevatron physics depends on the Z



....WZHt....

$\ldots b\tau\not{E}_T\ldots$

eμγj

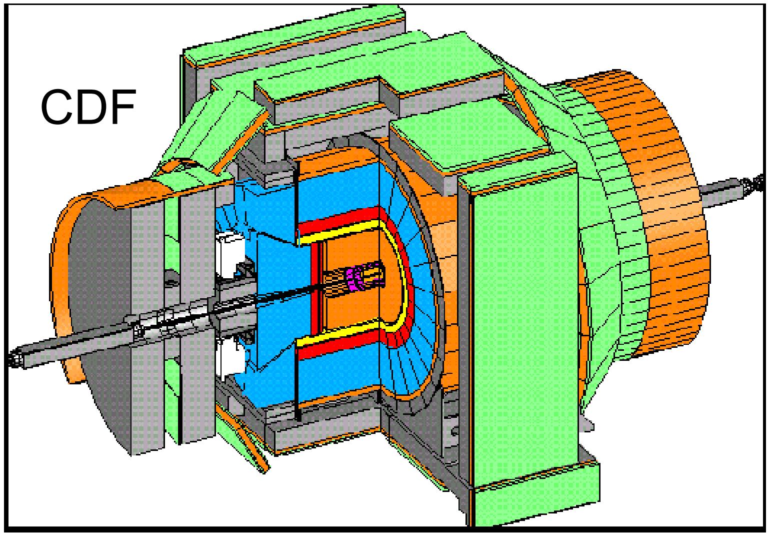
Z

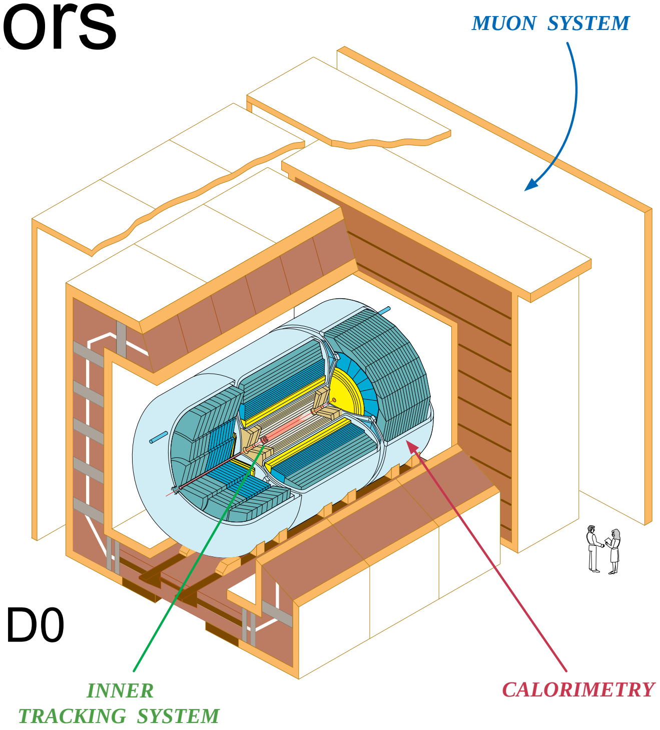
- Calorimeter+tracker energy scale and resolution.
- e,μ,τ ID efficiencies.
- Trigger efficiencies.
- Tracking efficiencies.
- ……..

Example: Tag and Probe

- Z mass constraint allows selection of clean sample of events with one e/μ well measured (the “tag”) and the other required to pass relatively loose requirements (the “probe”).
- The relative efficiency for any tighter single track requirement can then be measured from data via $\varepsilon\sim$ “tight” / “loose”.
- Consequence: **many Tevatron “systematic” errors go as $1/\sqrt{N_Z}$.**

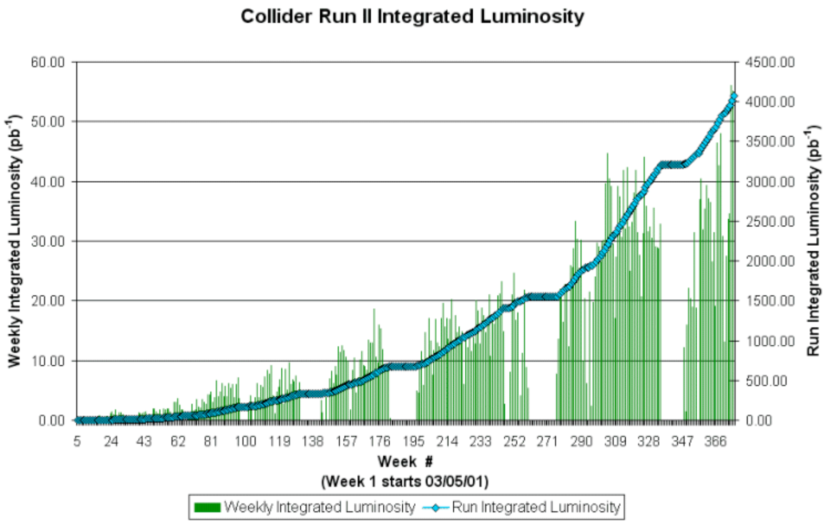
Detectors

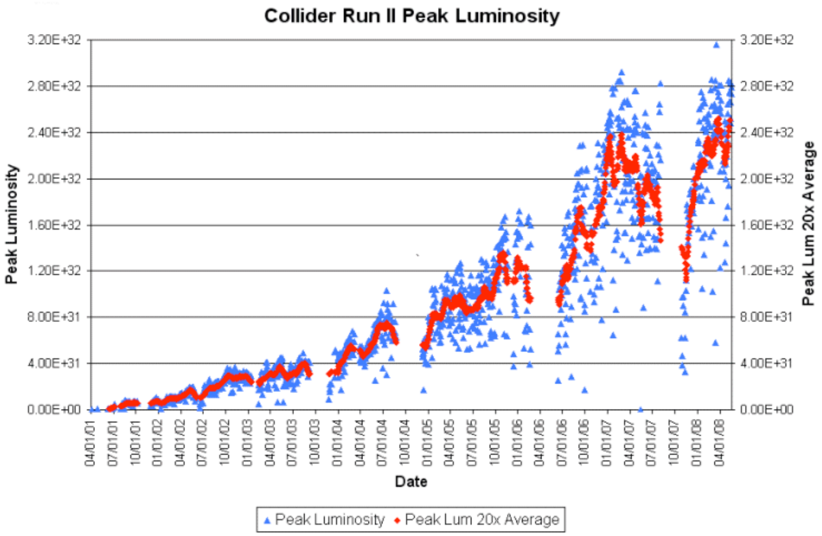


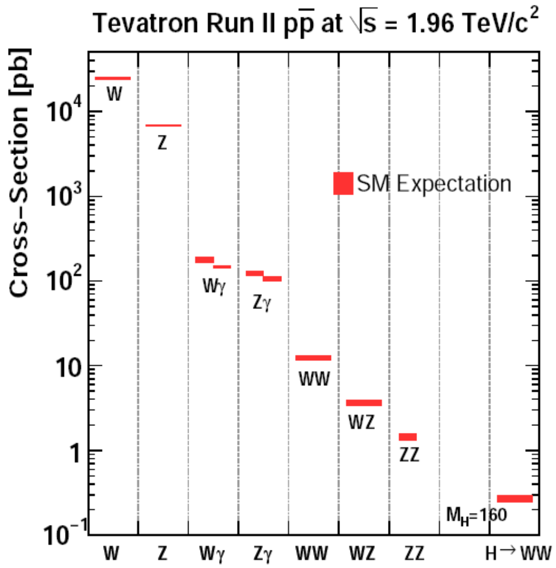


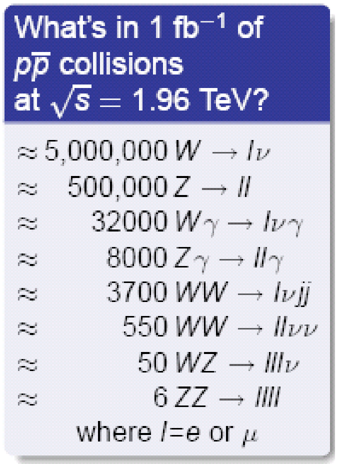
- **Common features**
  - High field magnetic trackers with silicon vertexing
  - electromagnetic and hadronic calorimeters
  - muons systems
- **Competitive Advantages**
  - CDF has much better momentum resolution in the central region and displaced track triggers at Level 1
  - D0 has more calorimeter segmentation, silicon disks, and a far forward muon system.

Rates: $\sigma\times\mathcal{L}\times\varepsilon$








What's in 1 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV?

$\approx$ 5,000,000 $W \to l\nu$

$\approx$ 500,000 $Z \to ll$

$\approx$ 32000 $W\gamma \to l\nu\gamma$

$\approx$ 8000 $Z\gamma \to ll\gamma$

$\approx$ 3700 $WW \to l\nu jj$

$\approx$ 550 $WW \to l l\nu\nu$

$\approx$ 50 $WZ \to lll\nu$

$\approx$ 6 $ZZ \to llll$

where l=e or μ

- Current situation: ~ 1 pb sensitivity after BF, ε factors are incorporated.

Typical Selection Criteria

- Selection: usually W→$\ell\nu$ or Z→$\ell\ell$, ℓ=e,μ.
- Typical electron criteria:
  - p_T>20 GeV.
  - Shower shape.
  - Isolation.
  - Matching track (central).
- Typical muon criteria:
  - p_T>20 GeV.
  - Muon detector track.
  - Central track match.
  - Isolation.
- Typical missing E_T>20 GeV.
- More leptons→looser cuts.

- Selection efficiencies at all levels are usually measured in data via "tag and probe" methods.
- Most analyses use MC simulation only to correct for signal geometric and kinematic acceptance.
- Detector simulations are highly tuned to match control data samples (often Z→$\ell\ell$).

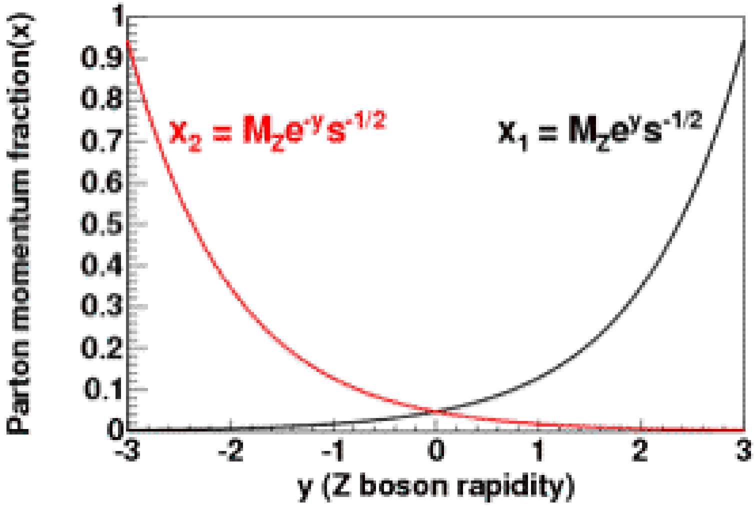
Typical backgrounds

- Electrons: jet/photon mis-ID.
  - ~few % central
  - To ~10% forward
- Muons: jet μ from π/K/c/b
  - ~few % central.
  - to ~10% forward.
- Missing E_T (ν)
  - QCD multi-jets (c,b).
  - Z with missing ℓ.
  - Intrumental.

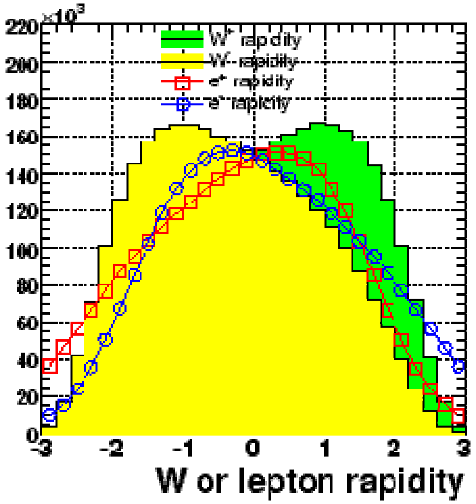
- All backgrounds from jet→lepton and instrumental effects are measured with data.
- Purely leptonic backgrounds are estimated by MC (usually PYTHIA):
  - Example: $Z \rightarrow \tau\tau \rightarrow ee\nu\nu\nu\nu$ background to $Z \rightarrow ee$.
- Small backgrounds from top quarks estimated from combination of MC and data techniques.

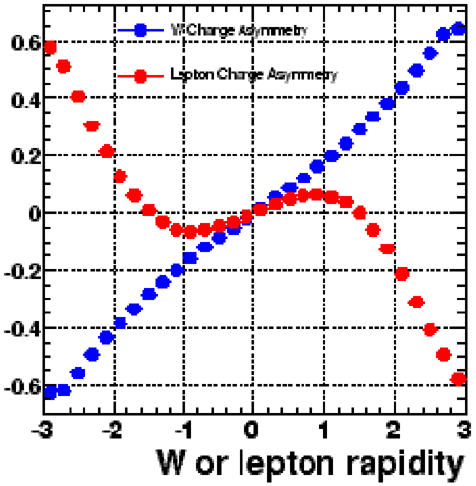
Probing the proton with W/Z

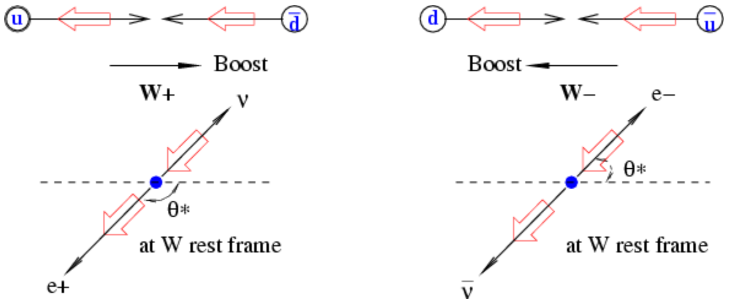
- The $P_{\parallel}$= of the W/Z probe PDF.
  - Z rapidity
  - W charge asymmetry
  - W$\rightarrow\ell\nu$ charge asymmetry
- Kinematics reminders
  - $P_{\parallel}=\surd P_T^2+M^2\times\sinh(y)=\surd s/2(x_1-x_2)$
  - $E=\surd P_T^2+M^2\times\cosh(y)=\surd s/2(x_1+x_2)$
  - High $|y|$←→high$|\eta|$.←→high$|x|$



W→$\ell\nu$ asymmetry



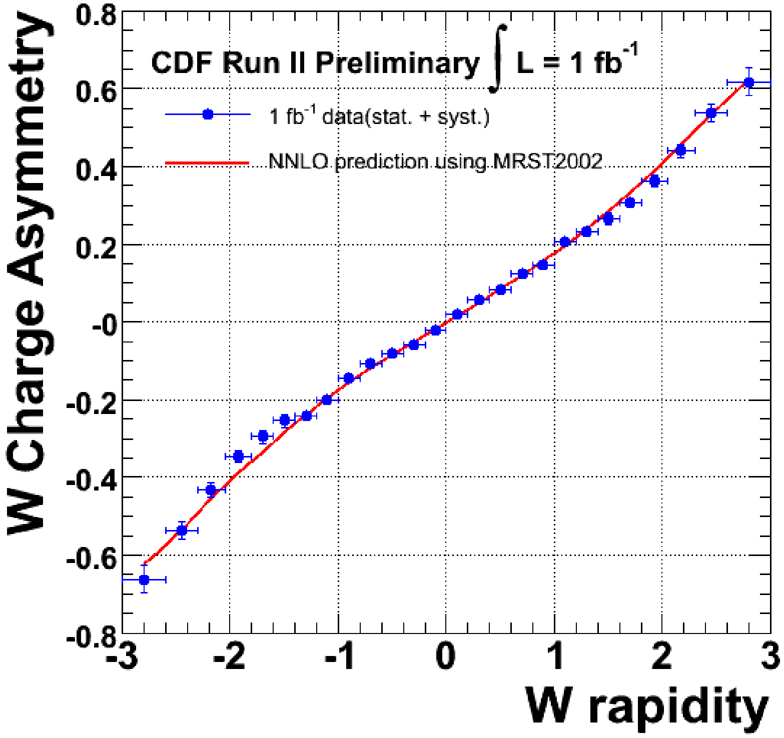




- Basic ideas: W^+ production driven by $\sim u_p(x_1) \otimes d_p(x_2)$. W^+ tend to follow proton. V-A decay cause ℓ^+ to follow antiproton.
- Asymmetry measurements form robust observables, both experimentally (small backgrounds, weak model dependencies) and theoretically (NLO in pQCD).
- CDF measures $A_W(y_W)$.
- D0 measures $A_\mu(\eta_\mu)$.

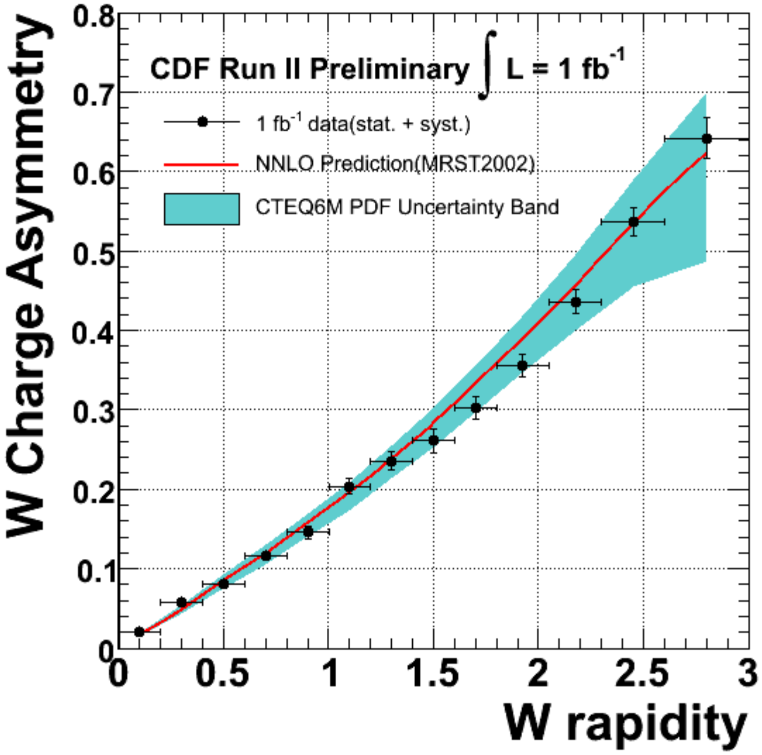
CDF W→eν charge asymmetry

- Missing ν leaves 2-fold ambiguity in y.
- CDF uses known production⊗decay matrix elements to weight hypotheses.
- Result is first direct measurement of W asymmetry.



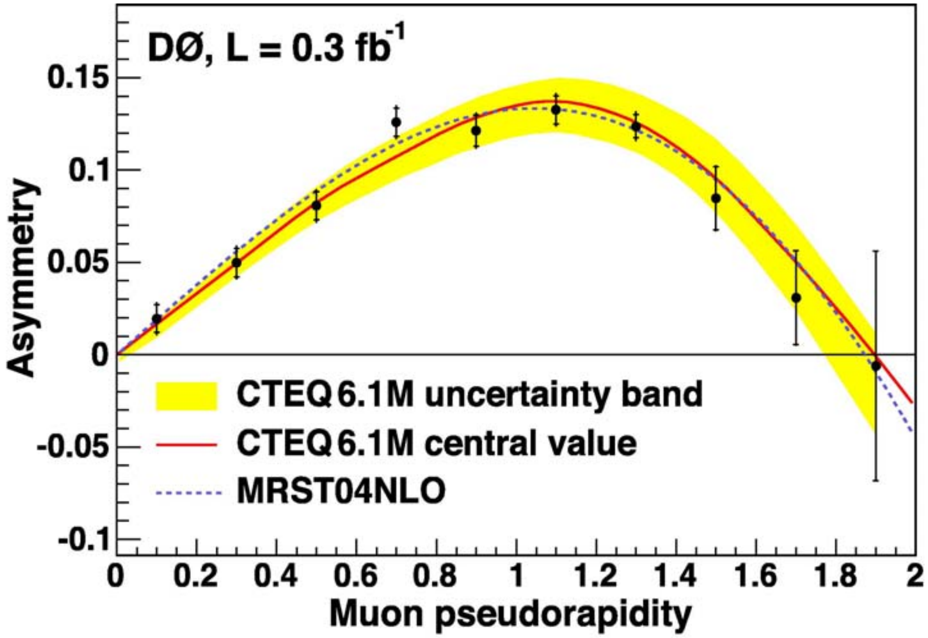
CDF W→eν comparison to theory

- Data are consistent with CP symmetry.
- Combine: A(y) = -A(-y).
- To |y|~2.8, measurements are superior to NNLO predictions with CTEQ6M PDF.
- Implies that data will better constrain PDF.



D0 W->$\mu\nu$ lepton asymmetry

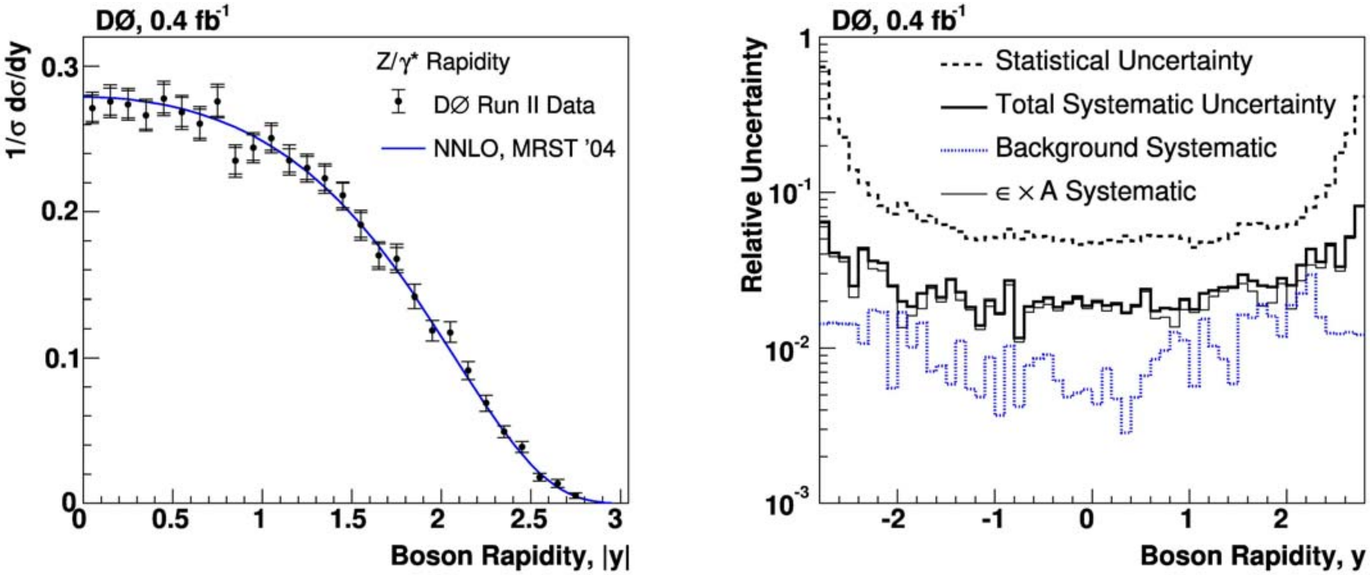
- Similar story in lower statistics complementary mode:
- For much of range, experimental; precision comparable to theory.
- Expect improved PDF constraints.



Z rapidity distribution

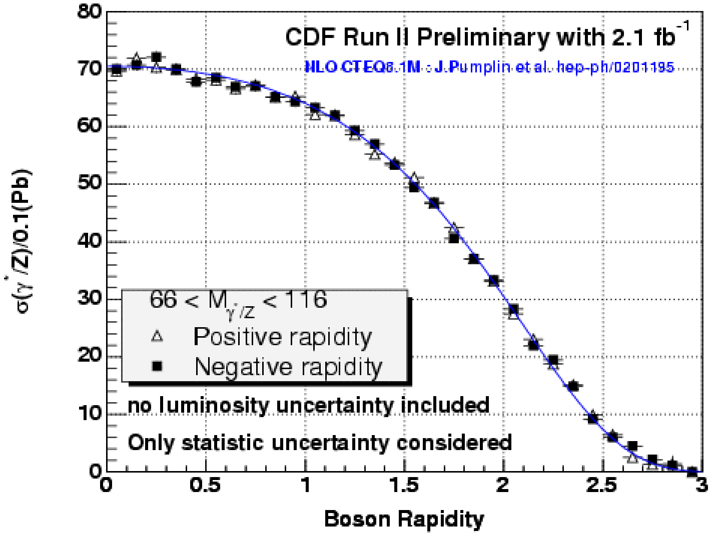
- Basic ideas:
  - Measurement here probes $\sim u_p(x_1) \otimes u_p(x_2) + d_p(x_1) \otimes d_p(x_2)$.
  - No problem reconstructing boson kinematics.
- D0 measures the shape $(1/\sigma)d\sigma/dy$.
- CDF measures measures the shape and level of $d\sigma/dy$, also permitting a total cross section determination.

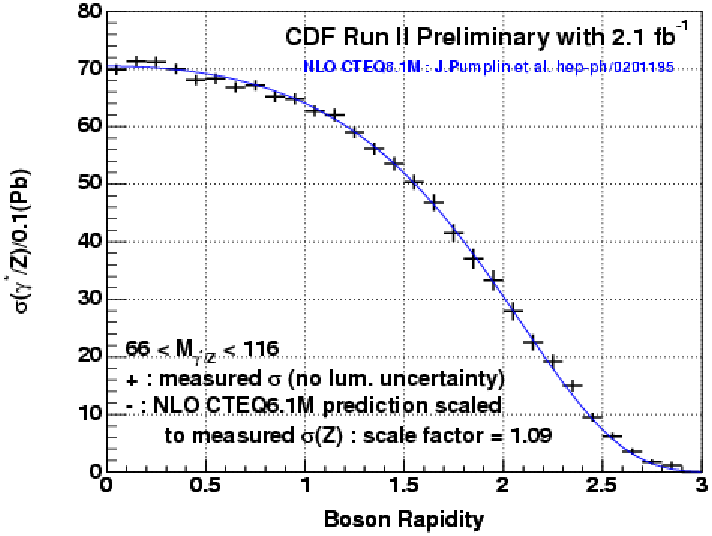
D0 Z rapidity shape measurement



- Statistics dominated measurement over all |y|.
- Good agreement with NNLO QCD+MRST.
- Precision comparable to PDF uncertainties.

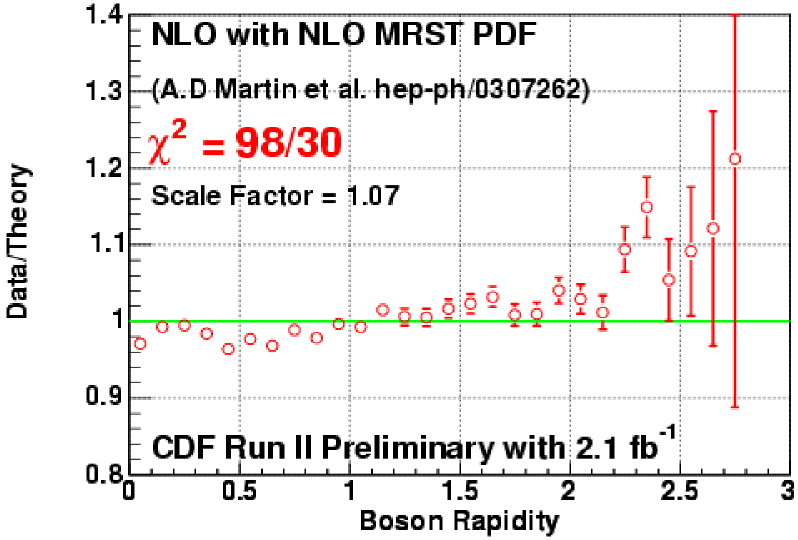
CDF Z rapidity, 5× more data

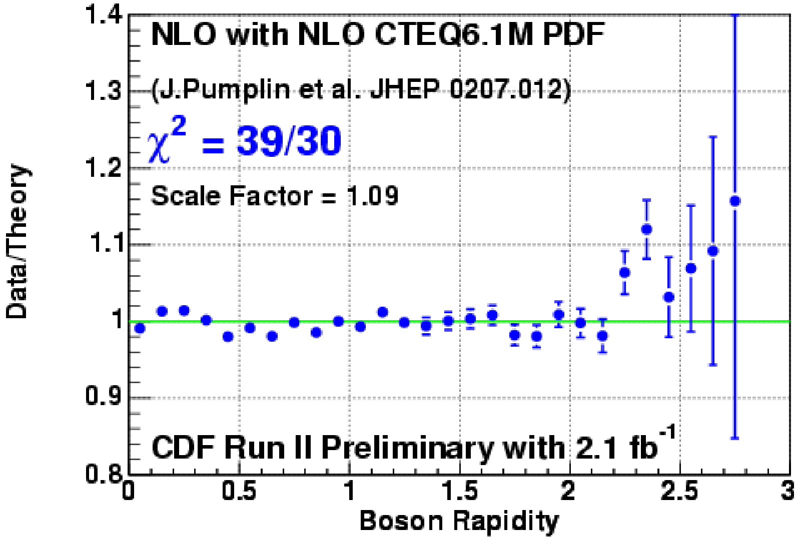




- 0.15M Z, careful systematic control through overlapping detector samples allow high precision to |y|=3.
- Excellent agreement between y<0 and y>0 sample allows CP-folding.

CDF Z-rapidity PDF discrimination



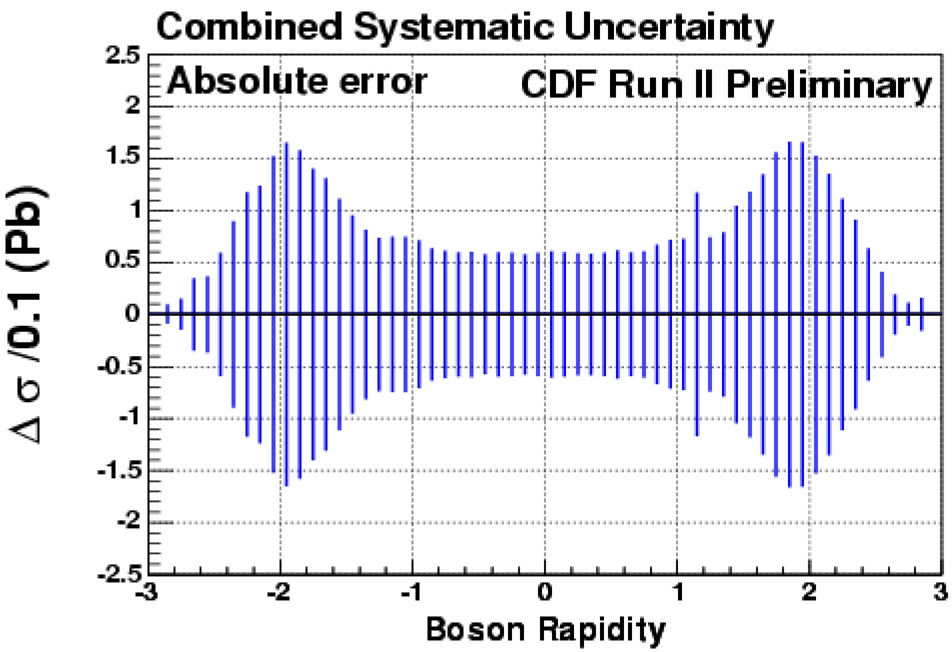


- $d\sigma/dy$ shape significantly favors CTEQ6.1M PDF over MRST using NLO QCD.
- NNLO predictions similar to NLO with CTEQ6.1M.

QCD probes: σ_{TOT} and dσ/dpT

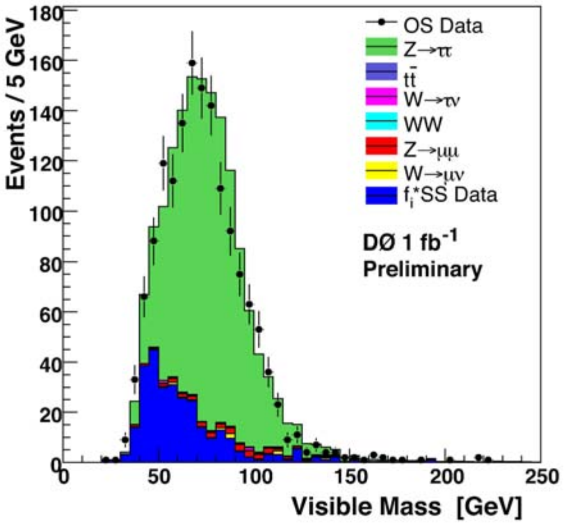
- Total cross section, basic ideas:
  - Following the “more inclusive = better” rule, these should provide high quality QCD tests; the reality of ~6% luminosity uncertainties prevents this.
  - “Flip” point of view:
  - σ_{TOT} measurements provide important “reality checks” on Higgs and other new physics searches, e.g. $\sigma_{TOT}\times BF(Z\rightarrow\tau\tau)$, $\sigma_{TOT}(WW)$,$\sigma_{TOT}(ZZ)$.
  - A better luminosity determination? Both CDF and D0 effectively normalize to the total inelastic proton-antiproton cross section. Why not normalize to $\sigma_{TOT}(Z)$?

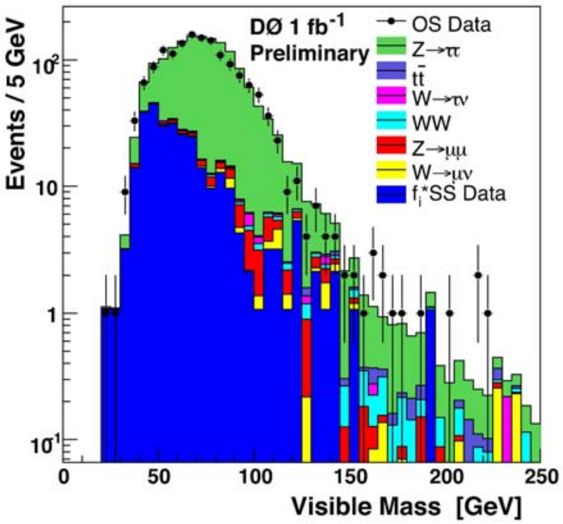
CDF Z→ee total cross section



- σ×BF = 258.2±0.7±4.8 pb (excluding luminosity uncertainty).
- Total experimental error is <1/3 luminosity error.

D0 Z→ττ results

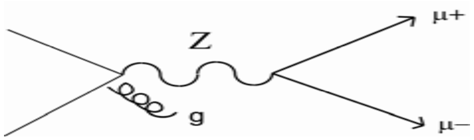


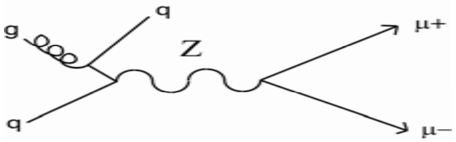


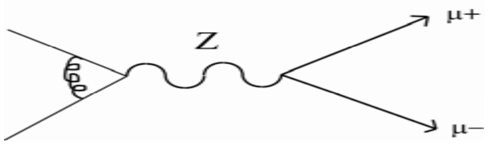
- ττ observed at high statistics in three modes with good S/B.
- Observation is consistent with SM Z→ττ.

☐ $\sigma \times BF = 247 \pm 8_{STAT} \pm 13_{SYS} \pm 15_{LUMI}$ pb. Total experimental uncertainty again comparable to luminosity uncertainty!

Z-boson Z p_T distribution from D0

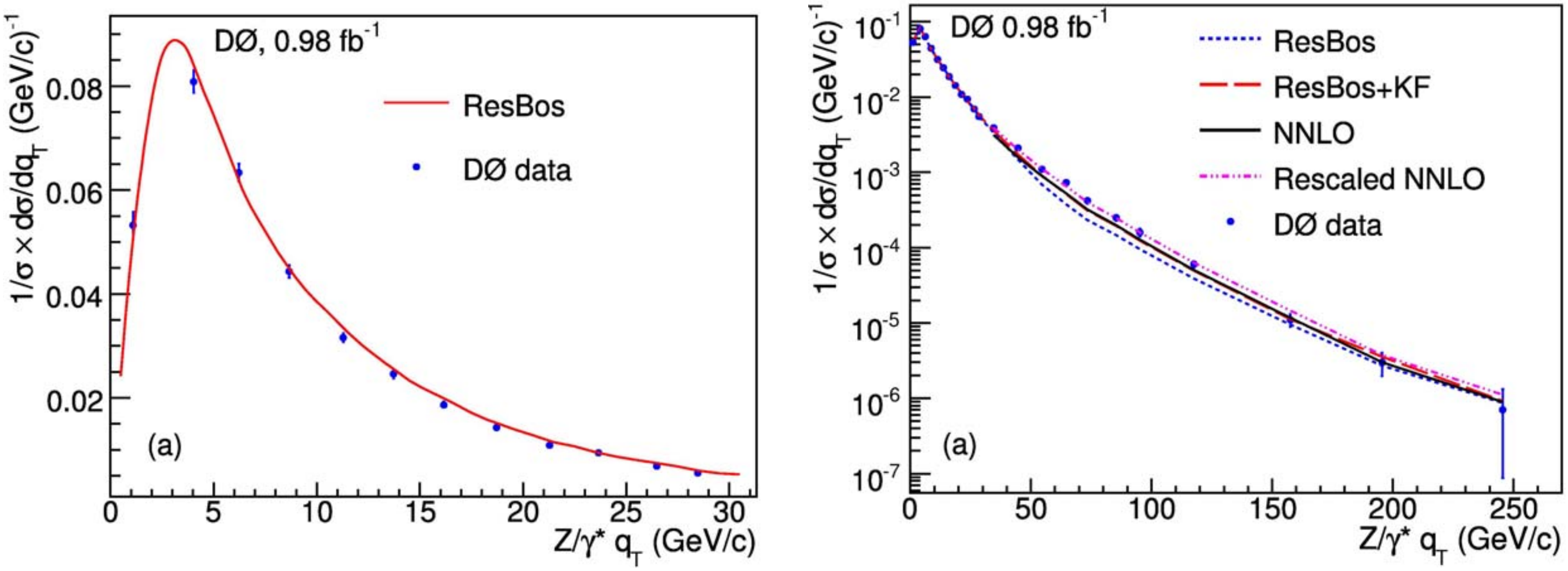






- Basic ideas: $$\frac{d^2\sigma}{dp_T{}^2dy} \propto \frac{\alpha_w\alpha_s}{p_T^2}\ln(\frac{Q^2}{p_T^2}) \to \infty \; as \; p_T^2 \to 0$$
  - Low p_T Z production calculations involve "large logs". Need to re-sum these terms, which requires a model to handle non-perturbative contributions. The model is implemented as the MC event generator **RESBOS**.
  - High p_T Z production should allow a direct test of pQCD. This test can be performed to NNLO.
  - The inclusive Z p_T distribution provides an empirical inclusivity constraint to "V+jet" models like SHERPA and ALPGEN.

$(1/\sigma)d\sigma/dpT$ from D0

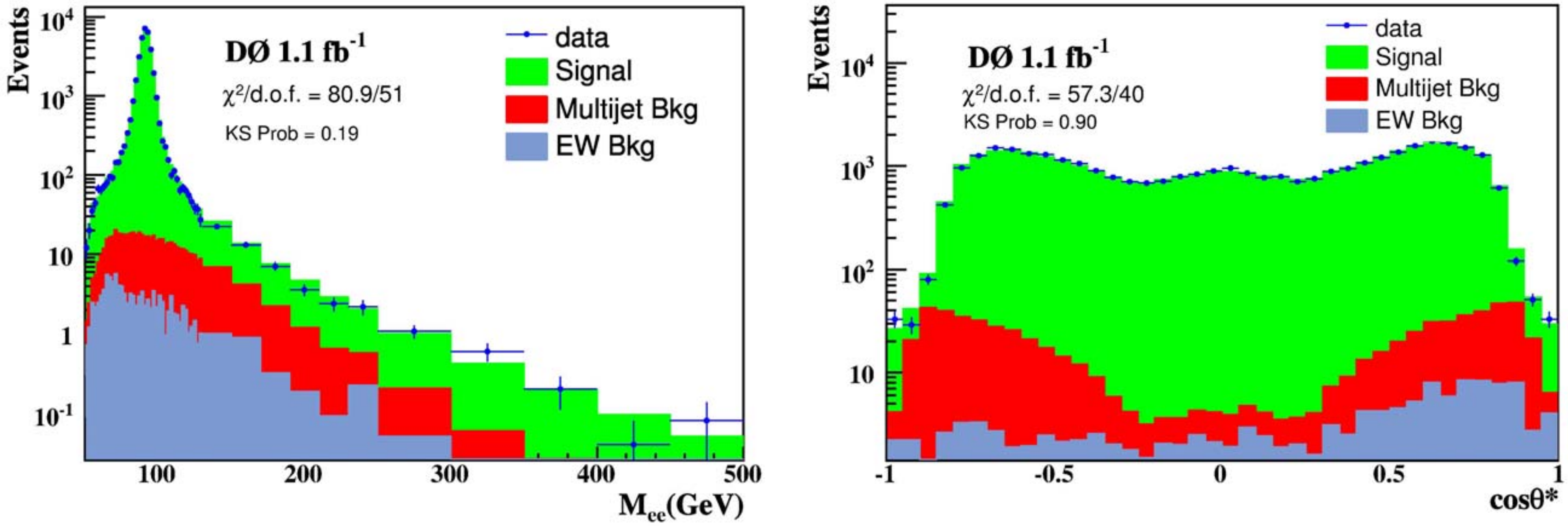


- At low p_T, data are consistent with RESBOS model.
- At high p_T, data are consistent in shape with NNLO QCD, but data are ~1.25× prediction.

Electroweak Probes

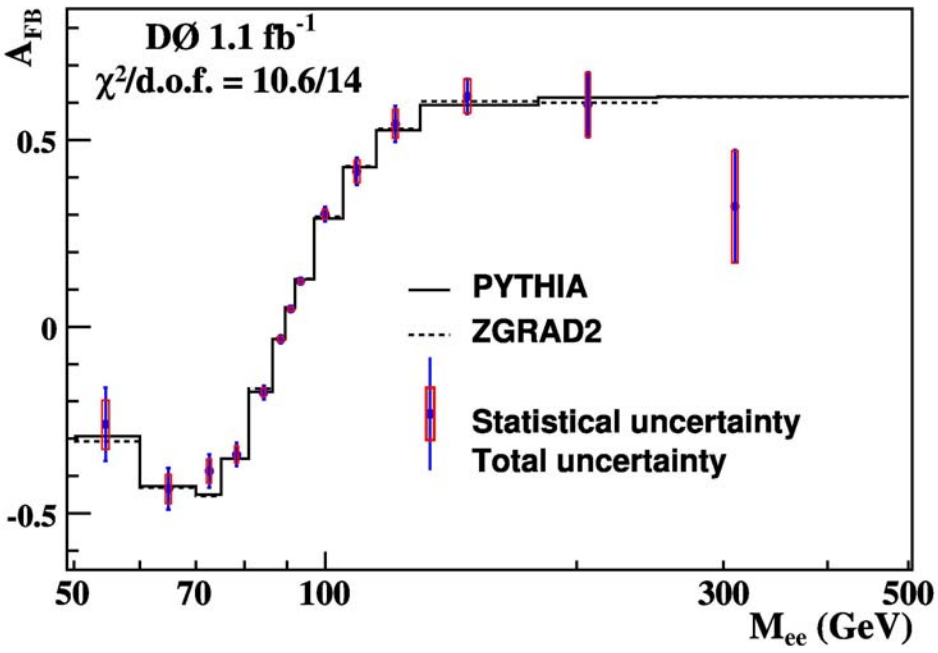
- Z forward-backward asymmetry
- W mass and width
- Di-boson production
- Context:
  - The LEP/SLC precision EW physics program was *very good*.
  - Improving on LEP precision is a daunting task.
- A better view:
  - The Tevatron *tests* LEP-driven prediction.
  - The Tevatron *extends* tests to higher $\sqrt{s}$.
  - The Tevatron *allows* observation CC and NC processes.
- HERA shares many of these complementary features.

Z→ee forward-backward asymmetry at D0



- Basic idea: A_{FB} probes $(u_V,d_V,u_A,d_A)\otimes(e_V,e_A)$; electron terms are essentially known “exactly” at Z-pole.
- (u,d) couplings least-probed at LEP/SLD.
- Some hints of discordance with SM from (u,d) tests in νN scattering at NuTeV.
- Sensitivity to new physics at high mass.

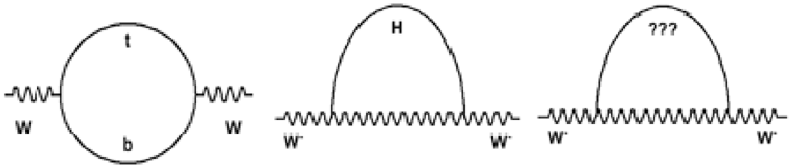
A_{FB} results from D0



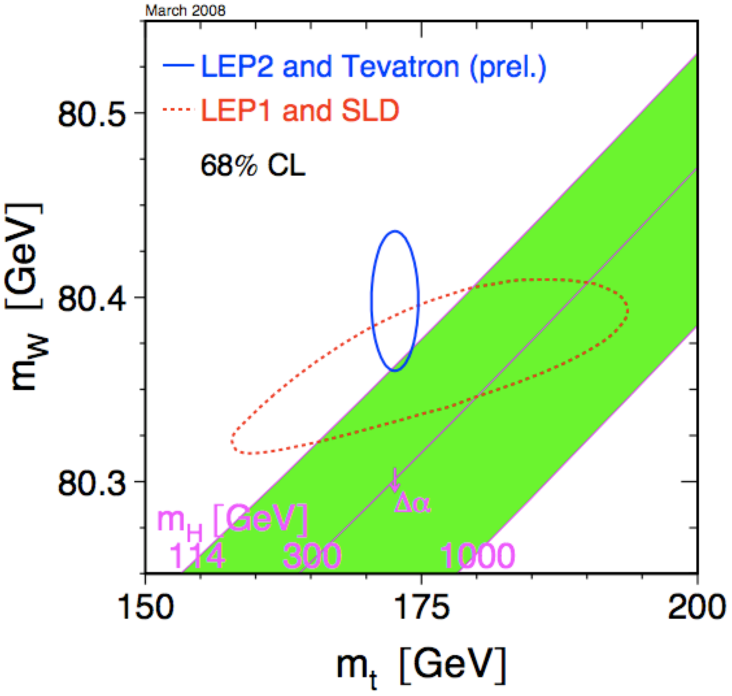
- Good agreement with SM predictions over full range for A_{FB}.
- Effective $\sin^2\theta_W = 0.2327 \pm 0.0018_{STAT} \pm 0.0006_{SYS}$.
  - *Not* competitive with world average.
  - But comparable to other determinations with u,d fermions.
- Measurement is currently statistics-limited.

Precision W mass from CDF

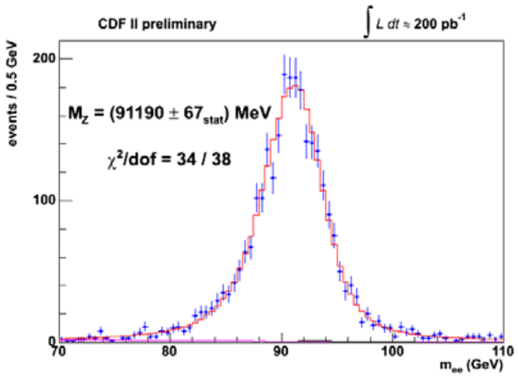
$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}\left(\frac{1}{1-\Delta r}\right)$$

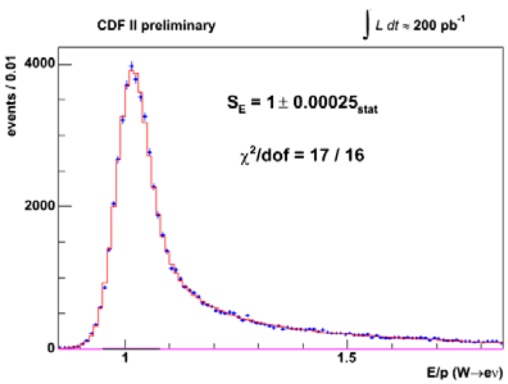


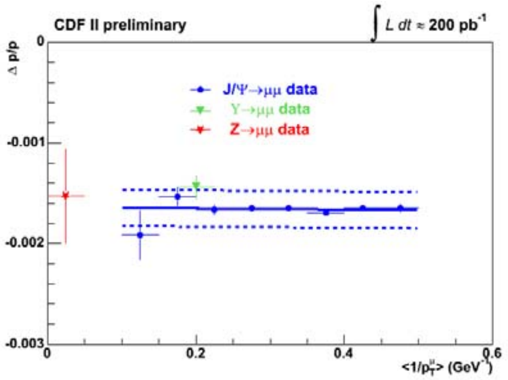
- Basic ideas:
  - $M_W=M_{W0}+A\times M^2_{top}+B\times\ln(M_{Higgs}/M_Z)$
- "High M_W, low M_{top}" drives "low M_{Higgs}".
- M_{Higgs} constraints will be sharpened most by improved M_W.



CDF W-mass, towards a 0.06% measurement

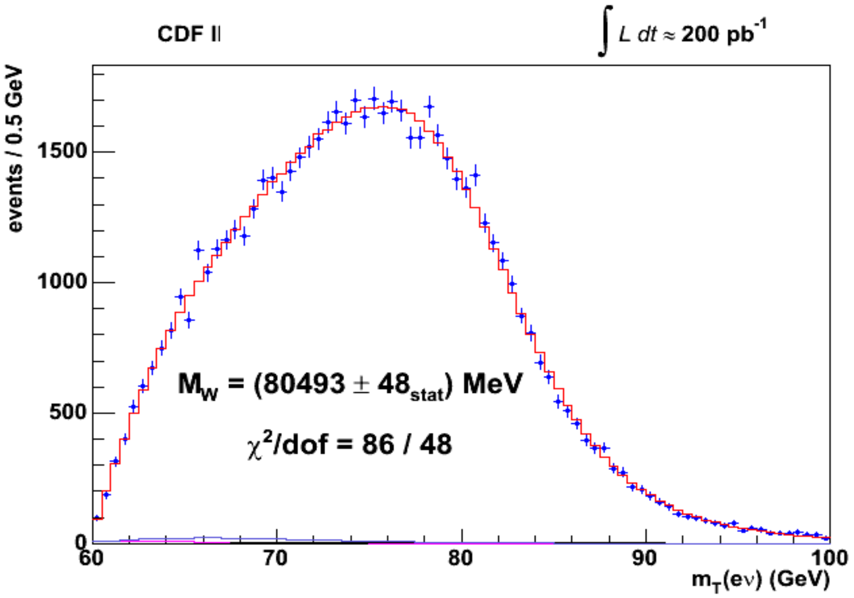


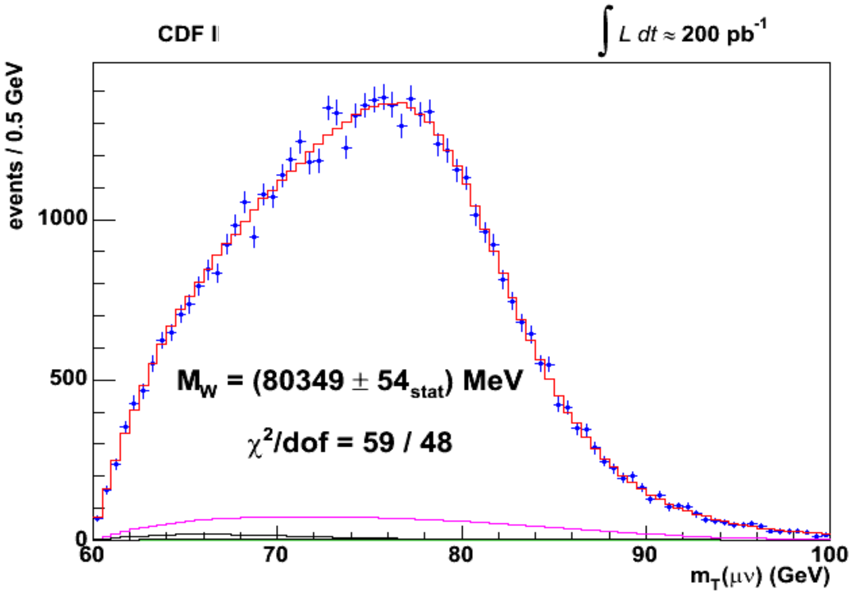




- CDF achieves this with extensive calibrations using Z, J/Ψ, and Υ data with its calorimeter and tracker.
- Calibrations, along with a detailed production model, are used to make templates for $p_{T,\ell}$, transverse mass M_T, and missing E_T distributions that are then compared to data to achieve a best fit.

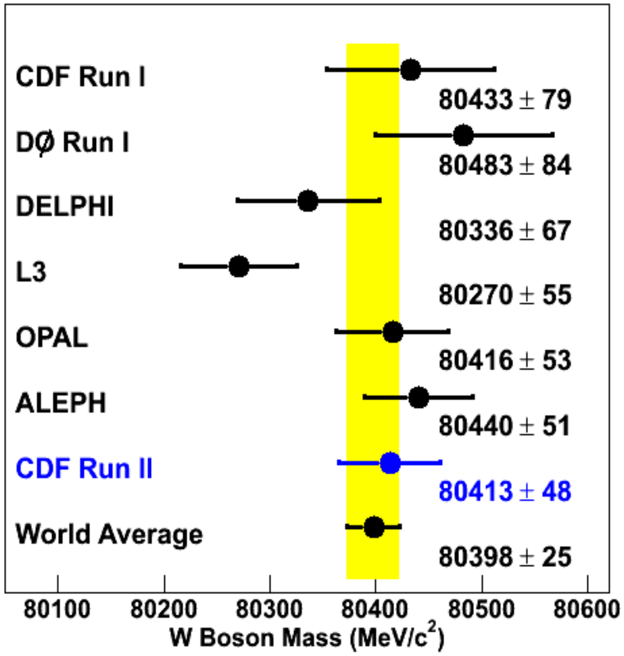
CDF W-mass M_T fits

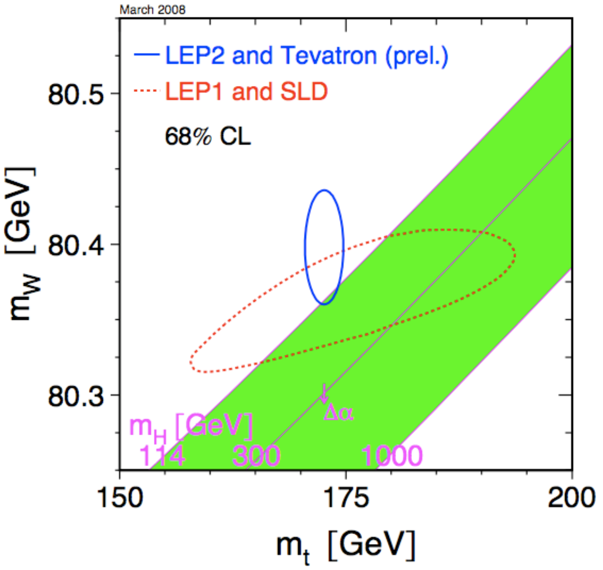




- Good agreement between e and μ modes.
- Also good agreement with $p_{T,\ell}$, missing E_T fits in both modes.

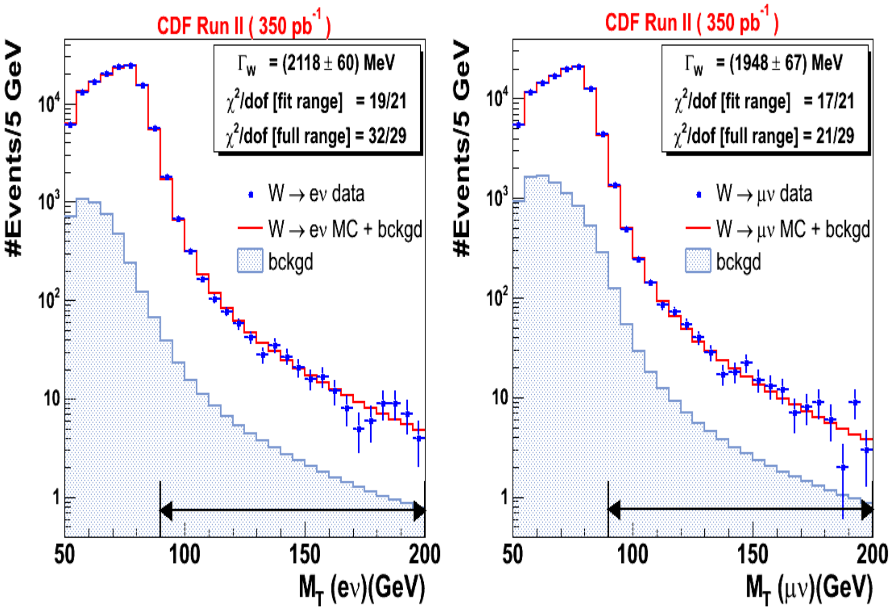
CDF W-mass result

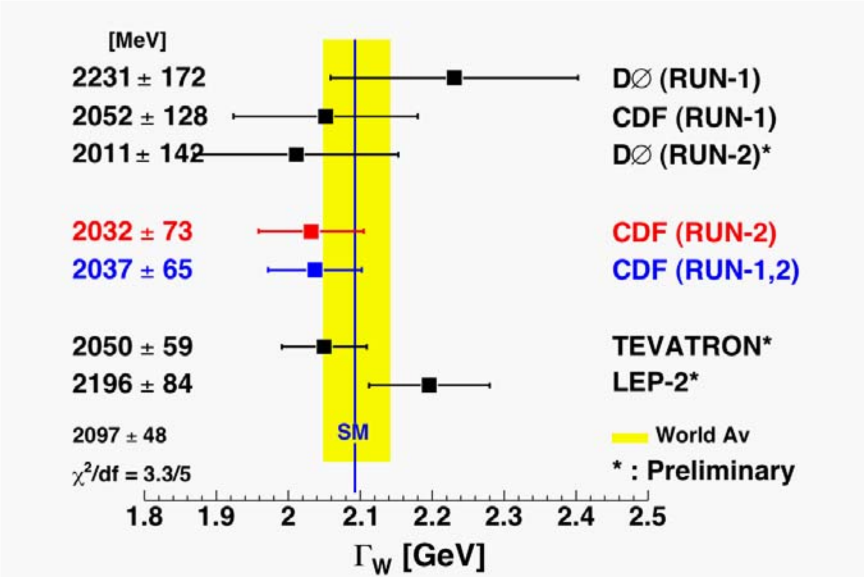




- CDF has performed the single most precise MW measurement.
- CDF confirms the low M_{Higgs} interpretation of precision EW tests.

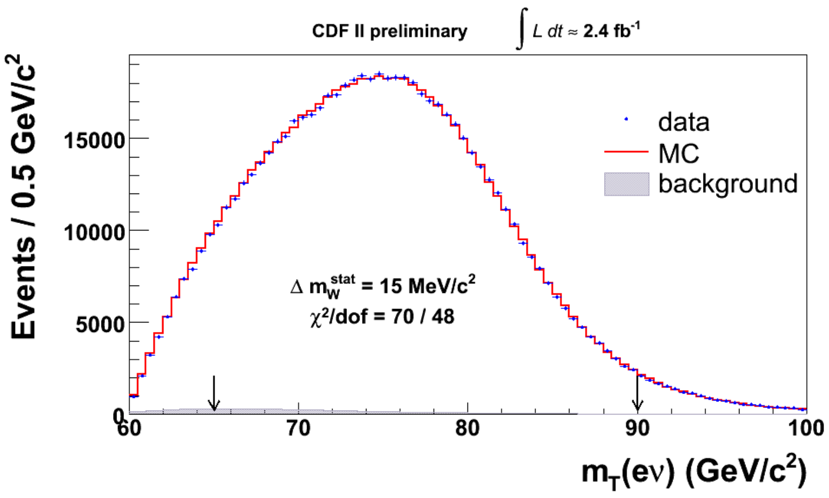
CDF W width

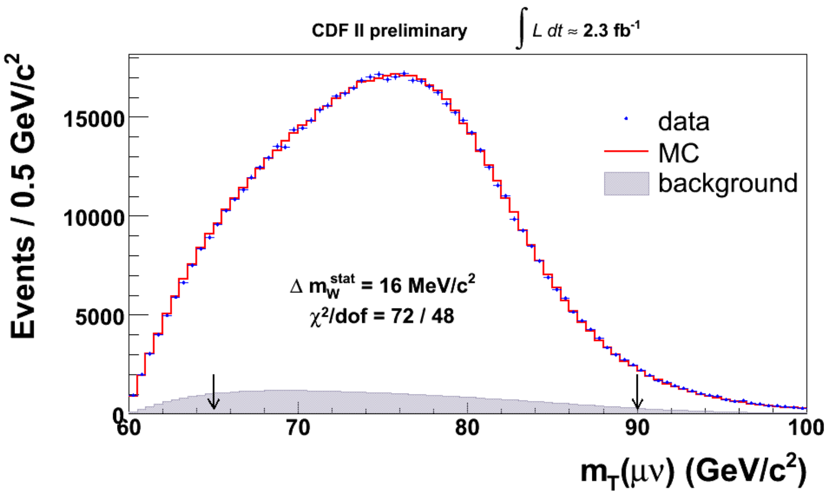




- While M_W is sensitive to the peak of the M_T distribution, Γ_W is sensitive to the tail.
- Using many methods from the W-mass measurement, CDF obtains the best single direct measurement: $\Gamma_W = 2032 \pm 45_{STAT} \pm 57_{SYS}$ MeV, vs. SM prediction of $\Gamma_W = 2091 \pm 2$ MeV.

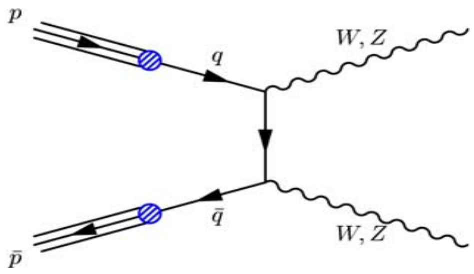
CDF W-mass with 12×more data

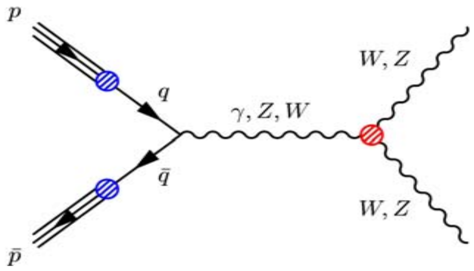




- Calibrations demonstrated to work with higher luminosity running.
- Uncertainties scaling as expected with statistics.
- ΔM_W = 25 MeV soon?

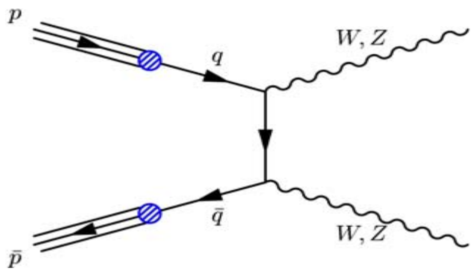
Di-boson production

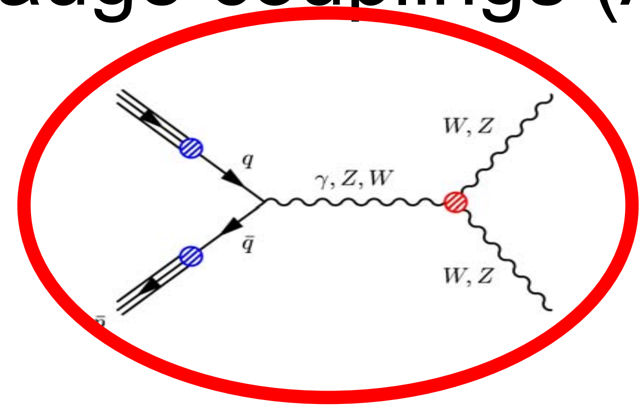




- Basic idea I, cross sections: verify SM predictions to ~10% (γW,γZ), ~25% (WW), ~50% (WZ,ZZ). Demonstrate ability to see Higgs-like signals (WW,ZZ). In situ γ calibration source (γZ).
- Basic idea II, triple gauge couplings (TGC): search for new physics effects. Anomalous TGC generically boost cross sections over SM predictions and harden spectra of final state bosons.

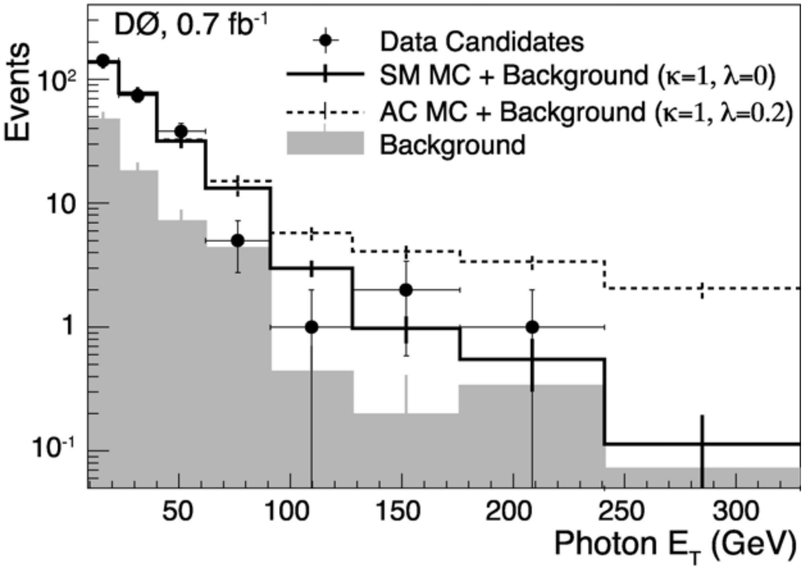
Anomalous triple gauge couplings (ATGC)

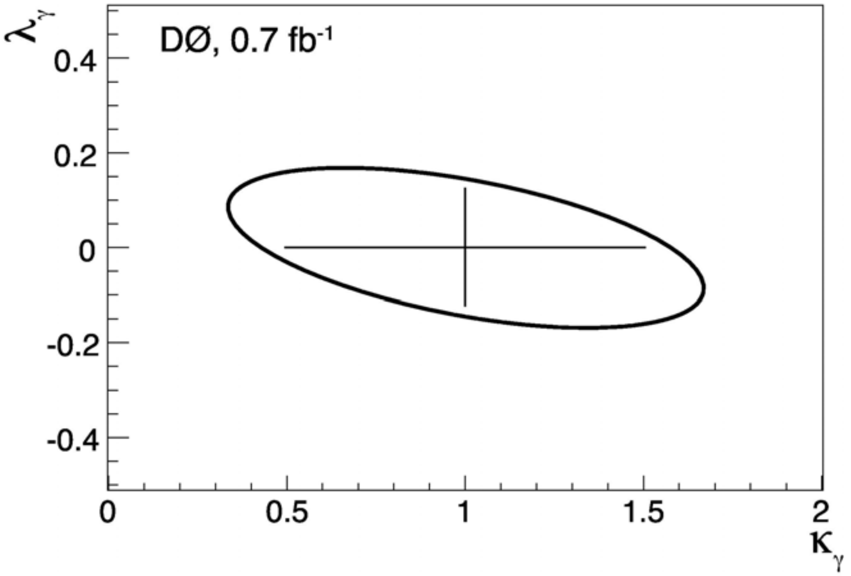




- Basic idea: Generalize SM Lagrangian to include all possible terms consistent with SM symmetries. Will not give detailed exposition here.
- Expansion introduces ATGC parameters $\lambda^{(i)}_{V1,V2,V3}$. These will violate unitarity unless cut off at large parton $\sqrt{s}$. Usual prescription is with dipole form-factor with cut-off parameter $\Lambda \sim$ 1-2 TeV.
- As sensitivity increases, $\lambda^{(i)}_{V1,V2,V3}$ can be probed for larger Λ.
- Typical sensitivites are $|\delta\lambda^{(i)}_{V1,V2,V3}|<0.1$, where 1.0 would be comparable to a SM coupling strength for an allowed channel.
- Several SM couplings are absent, e.g., ZZZ, ZZγ,Z$\gamma\gamma$,

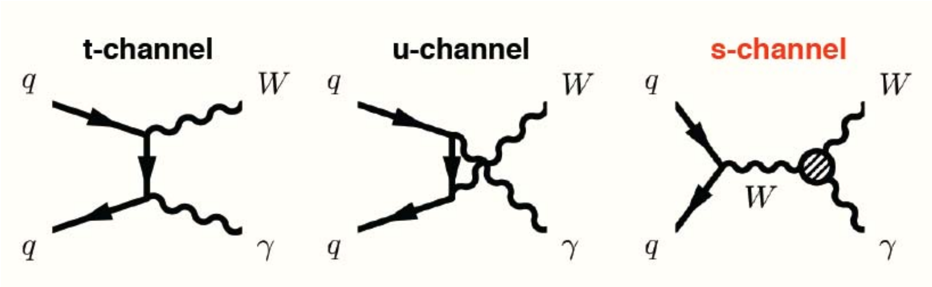
Wγ from D0

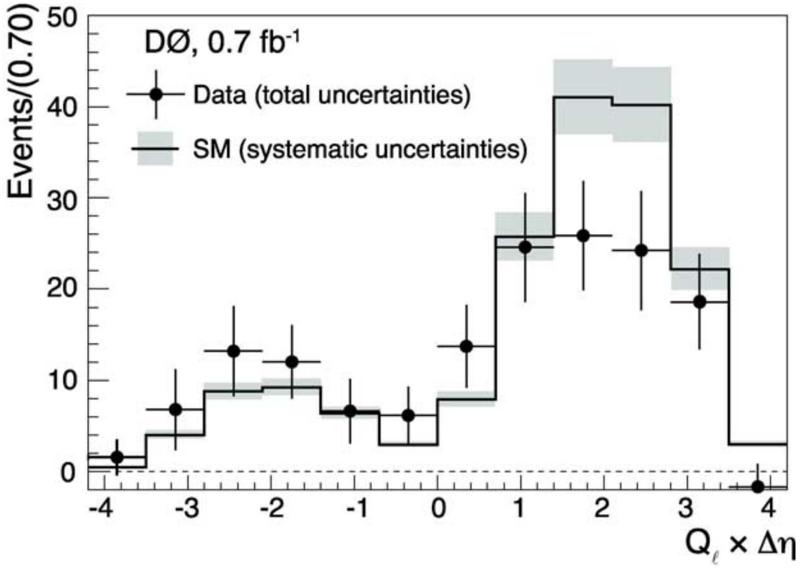




- pT,γ distribution shows effects of ATGC.
- Limits in λ_γ (~ $\lambda^{(1)}_{WW\gamma}$) vs κ_γ (~$\lambda^{(2)}_{WW\gamma}$) plane. Note $\kappa_\gamma=1$ is SM.

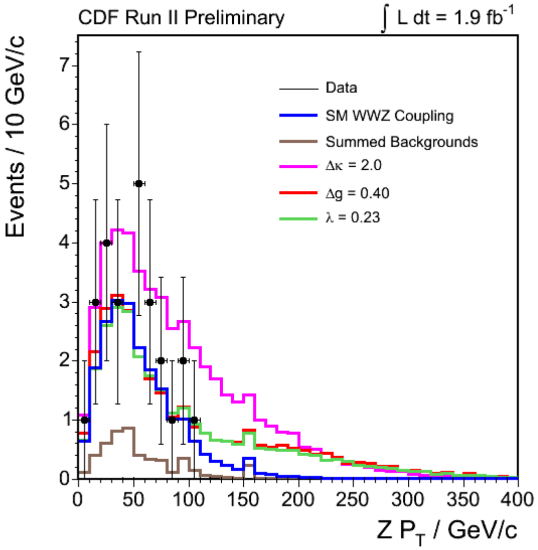
The radiation-zero in Wg production at D0

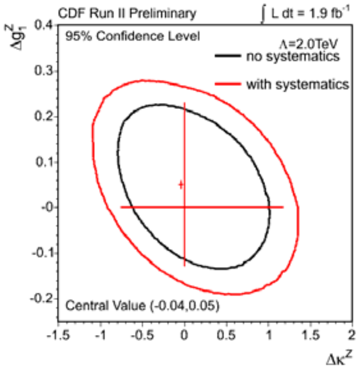


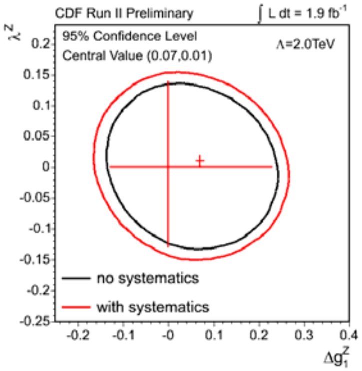


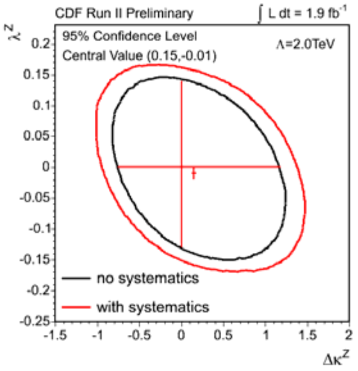
- An interesting QM interference effect produces a distinct dip in the distribution of η_ℓ-η_γ.
- D0 observes this dip with a bit less than 3σ significance.
- ATGC effects would fill in the dip, but they are better probed through the $p_{T\gamma}$ distribution.

WZ production at CDF



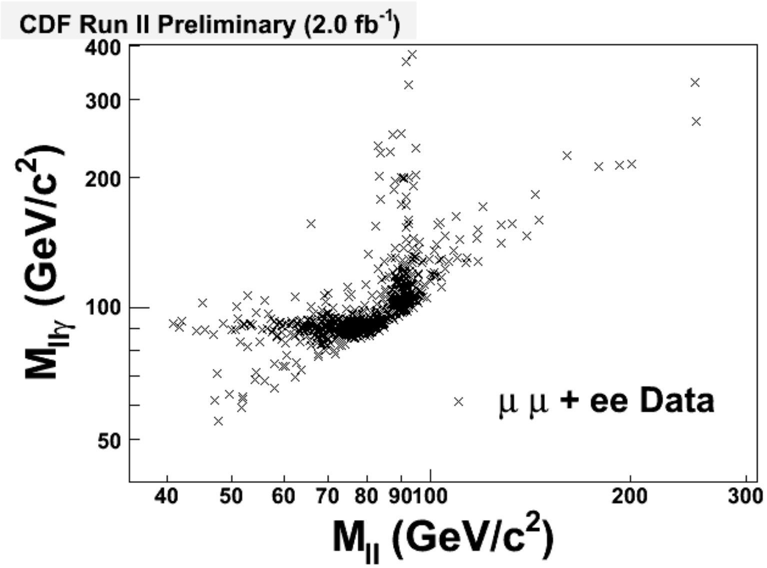


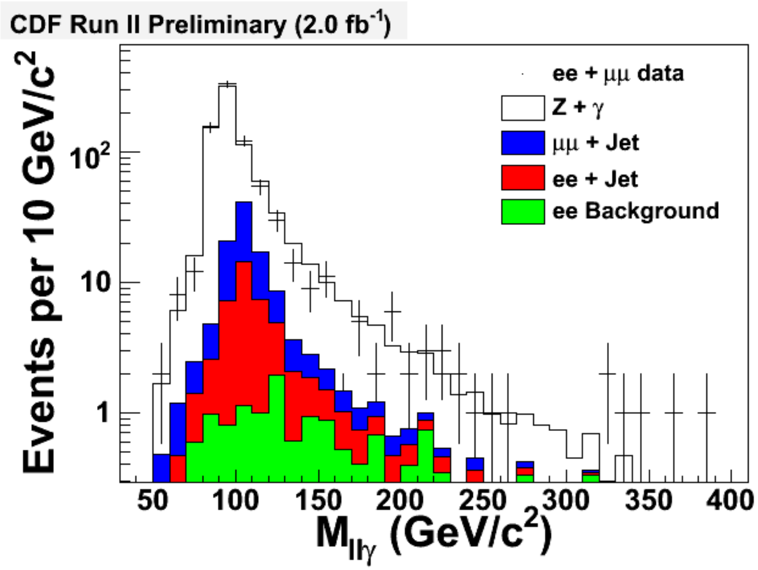




- No evidence for ATGC effects in Z pT distribution.
- Limits on three pairs of ATGC.
- Tevatron complementarity: access to CC couplings differentiates WWγ and WWZ parameters.

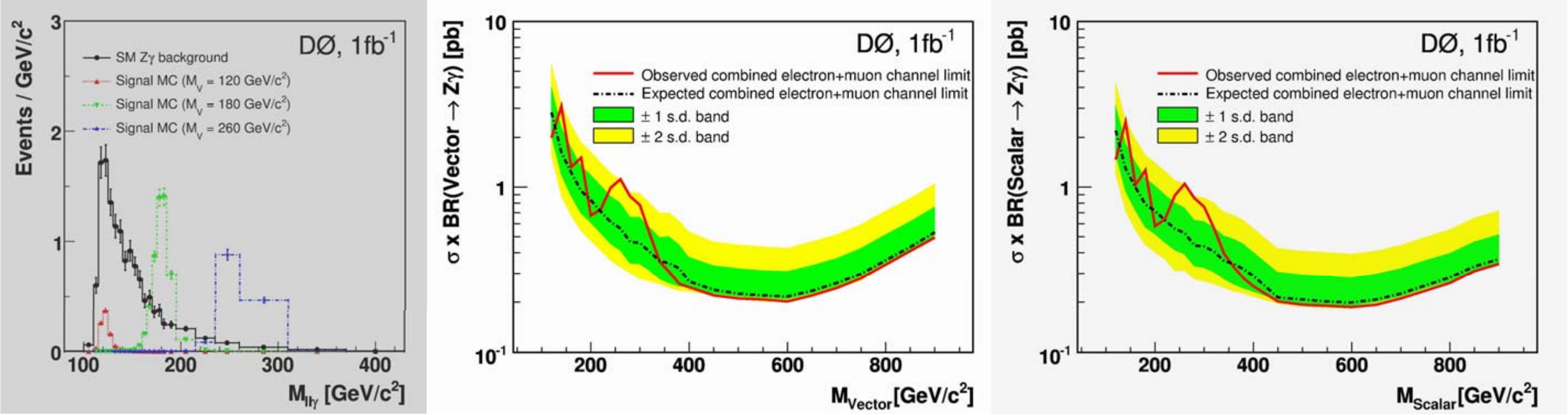
The Zγ final state at CDF





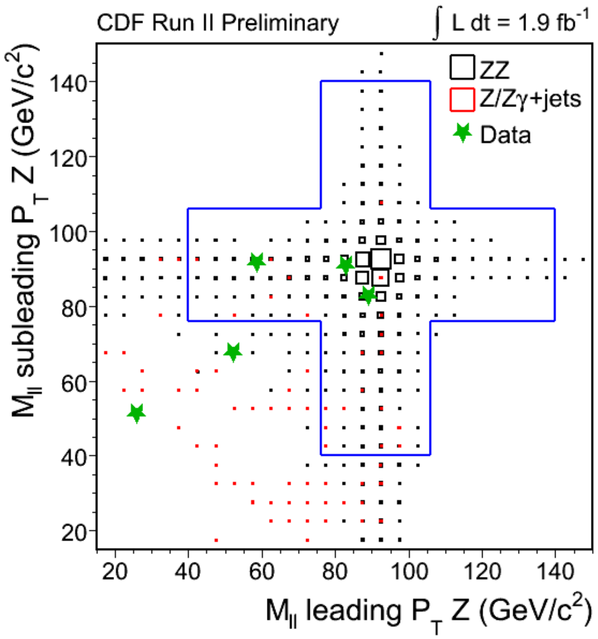
- One can clearly observe “initial state” and “final state” radiation.
- Total rate and kinematics consistent with SM.

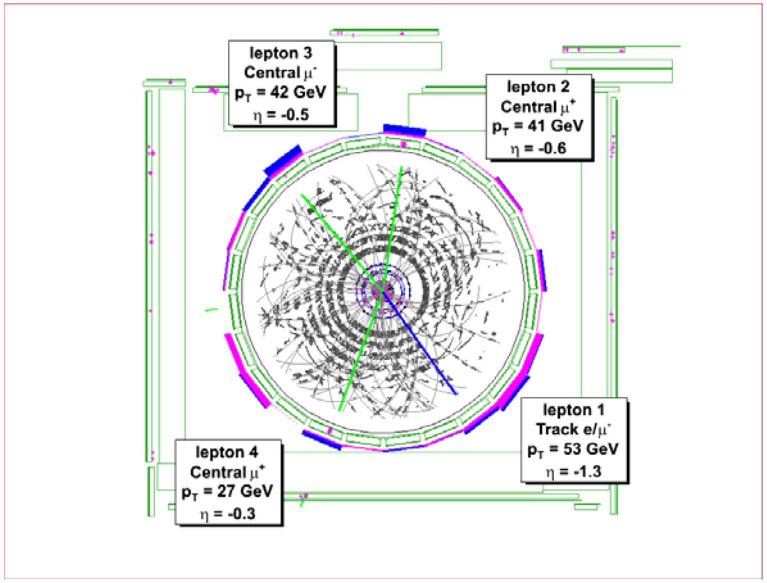
Richness of Zγ final state



- γ p_T distribution→ATGC.
- γZ mass distribution→search for X→γZ resonance.
- ☐ $\gamma\ell\ell$ mass at Z-pole→ calibration photons.
- $\gamma\ell$ mass distribution→excited lepton searches ℓ^*→$\ell\gamma$.

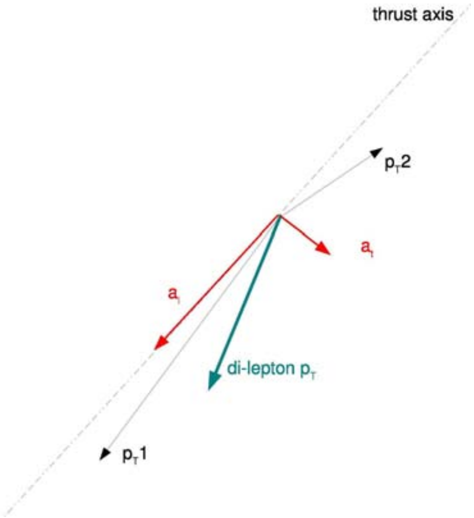
ZZ→all charged leptons at CDF

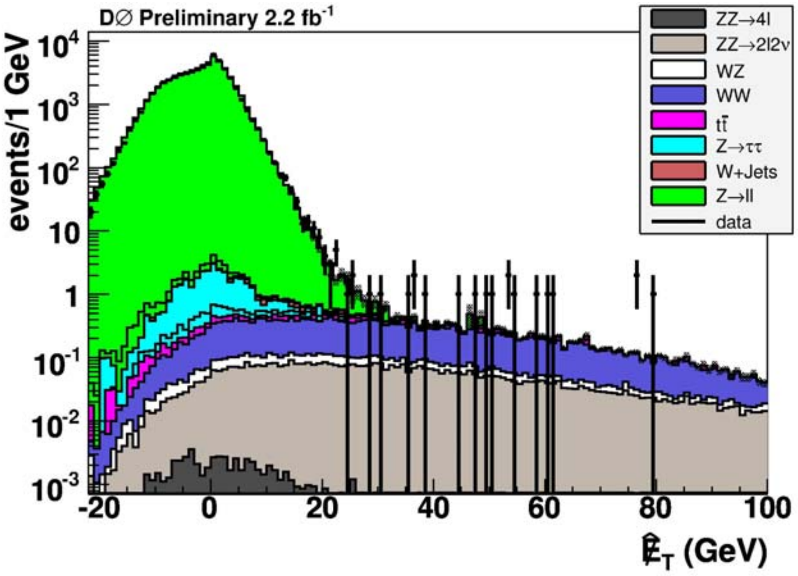




- CDF observes this channel with 4.4σ significance using 4ℓ (3 candidates) and 2ℓ2ν (5 candidates) modes.
- Almost all significance is from nearly background-free 4ℓ mode.

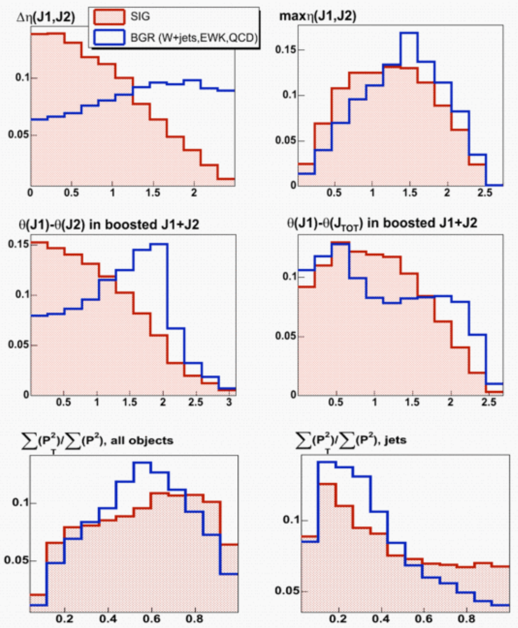
ZZ→$\ell\ell\nu\nu$ at D0

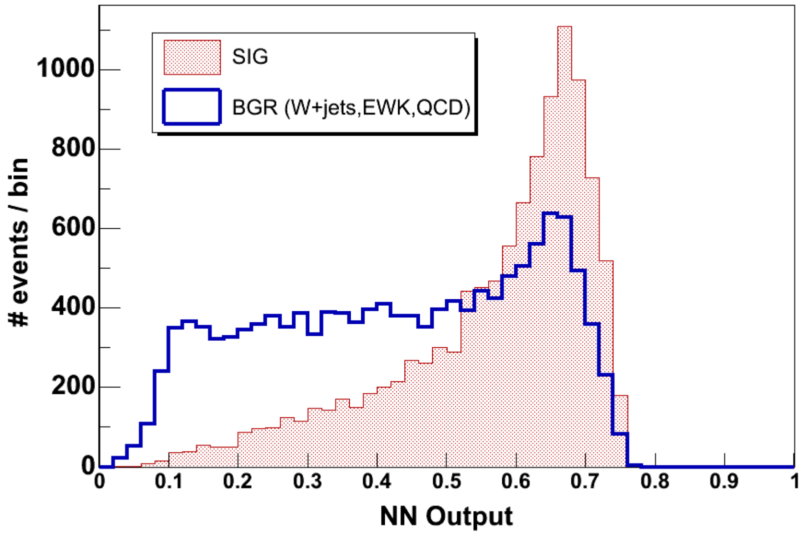




- First challenge is to suppress huge potential background from Z+missing E_T production.
- Use of dilepton transverse momentum perpendicular to thrust axis achieves effective separation
- Neural network used to separate ZZ from WW production.

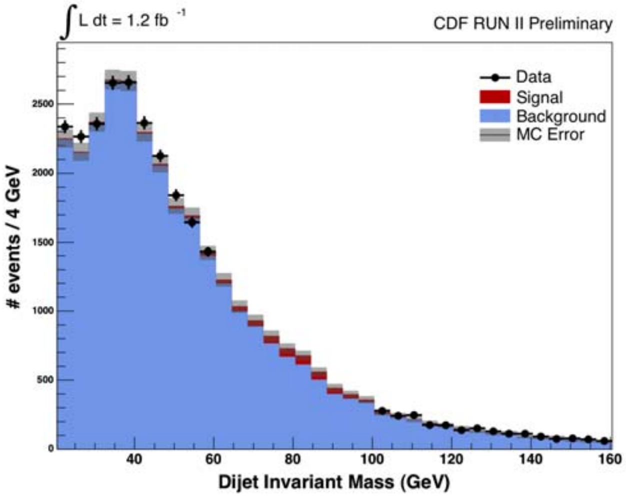
CDF WW+WZ→$\ell\nu$jj

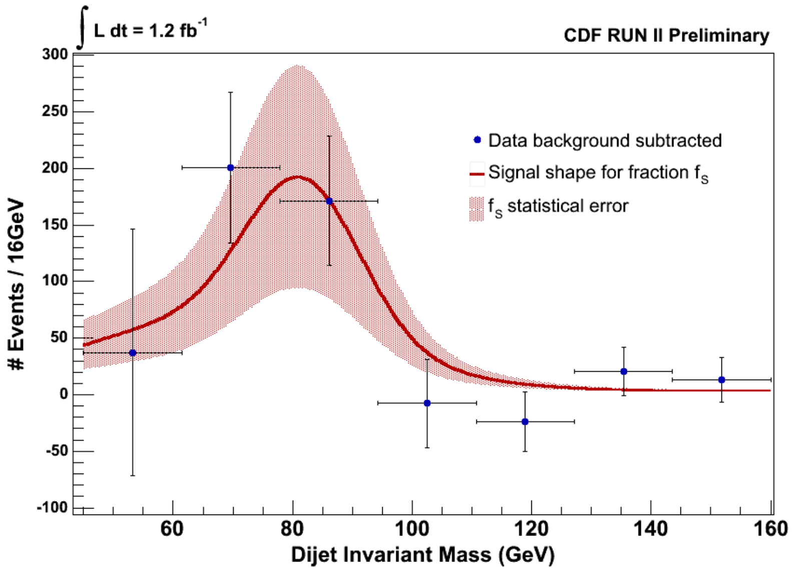




- Very different EW analysis with low S/B.
- "Higgs-style" multivariate analysis applied to a "SM calibration".
- Can in principle probe ATGC as large BF compensate for S/B.

CDF WV→$\ell\nu$jj result



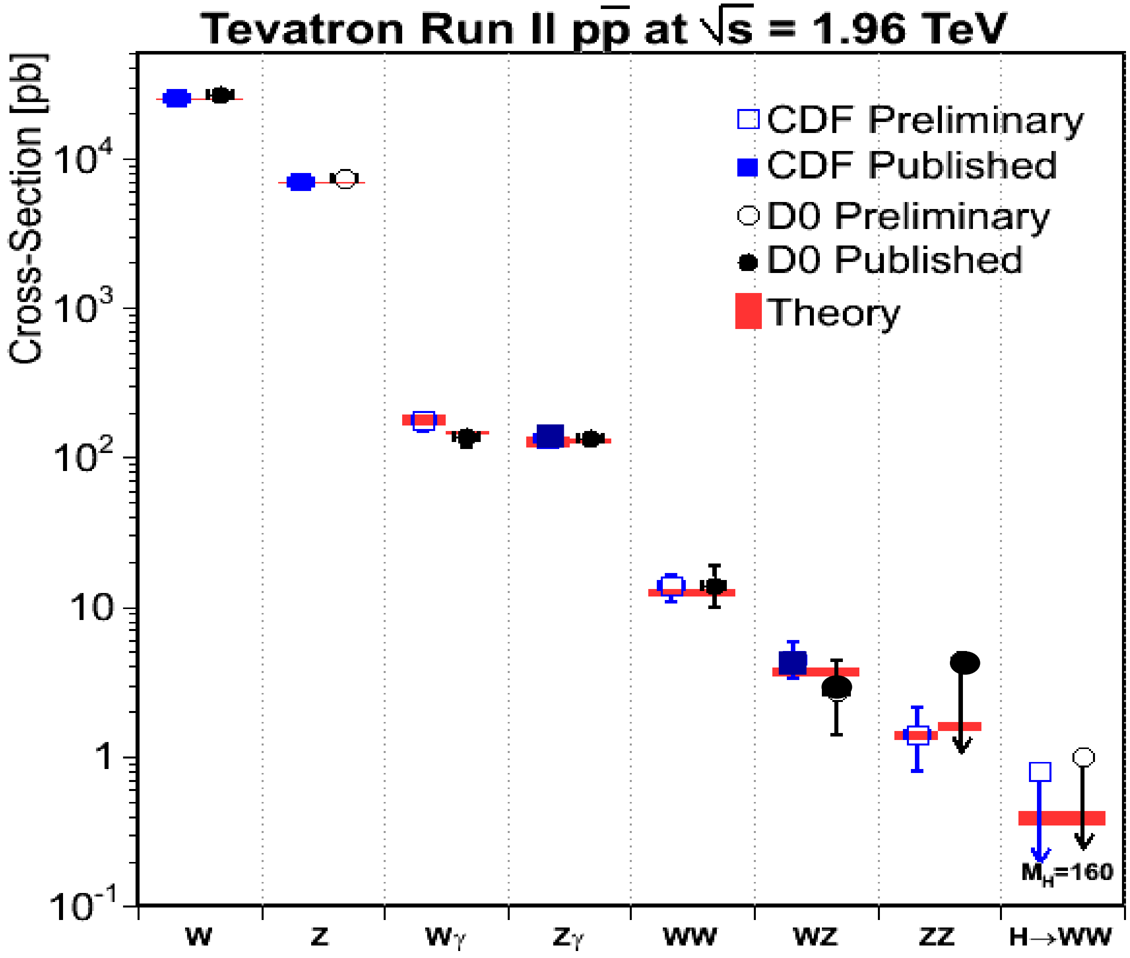


- Encouraging results consistent with SM.
- W/Z→jet jet still a real challenge, but one that must be overcome to get to the Higgs!

Scorecard: W and Z as probes

- Probes of the apparatus.
  - Many systematic errors continue to shrink as Z-bosons are accumulated, keeping much of the Tevatron physics program statistics-limited.
- Probes of the proton.
  - Precision of W-asymmetry and Z rapidity distributions demands updated PDF sets.
- Probes of QCD
  - Precision cross section and p_T distribution measurements push for improved theory.
  - Absolute normalization to Z nearing feasibility.
- Probes of the electroweak force.
  - Best W mass measurements confirm low M_{Higgs} prediction.
  - More SM check marks from A_{FB}, Γ_W, ATGC searches.
  - Observation of all diboson modes demonstrates ability to pull out small cross sections.

Onwards!



Tevatron Run II $p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV
Cross-Section [pb]
10^4
10^3
10^2
10
1
10^{-1}
□ CDF Preliminary
■ CDF Published
○ D0 Preliminary
● D0 Published
🟥 Theory
M_H=160
W
Z
Wγ
Zγ
WW
WZ
ZZ
H→WW