W Boson Physics at the Fermilab Tevatron Collider

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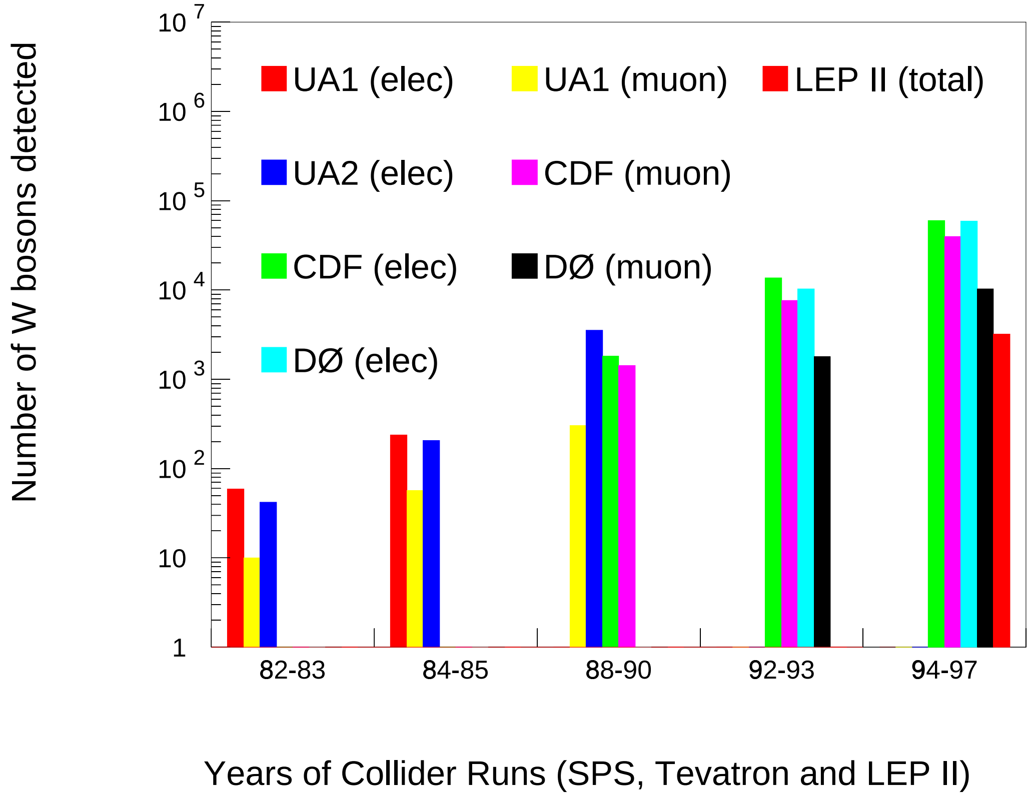
Outline

- W and Z Production Cross Sections
  - e and μ
  - tau
- W Width
  - Indirect measurement
  - Direct measurement
- Rare W Decays
  - $W \rightarrow \pi\gamma$
  - $W \rightarrow D_s\gamma$
- Trilinear Gauge Boson Couplings
  - $W\gamma$, WW/WZ, $Z\gamma$
  - Combined limits
- W Mass
  - $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$
  - Combined results
- Conclusions

W Boson Physics at LEP will be covered in the talk by Monica Pepe Altarelli.

W Bosons Detected



Tevatron Runs:

- Run “0” = 1988-89, $\int Ldt \sim$ 4 pb^{-1} (CDF only)
- Run “1A” = 1992-93, $\int Ldt \sim$20 pb^{-1}
- Run “1B” = 1994-95, $\int Ldt \sim$90 pb^{-1}
- Run “1C” = 1995-96, $\int Ldt \sim$20 pb^{-1}

W and Z Production Cross Sections

$p\bar{p} \rightarrow W + X$ $\qquad$ $p\bar{p} \rightarrow Z + X$

The W and Z bosons are detected via their leptonic decays: $W \rightarrow e\nu, \mu\nu, \tau\nu$ $\quad Z \rightarrow ee, \mu\mu$

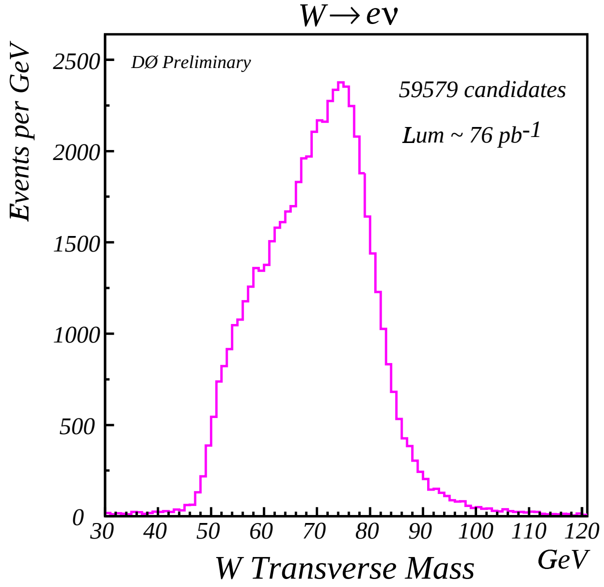
For the e and μ channels, one selects events with:

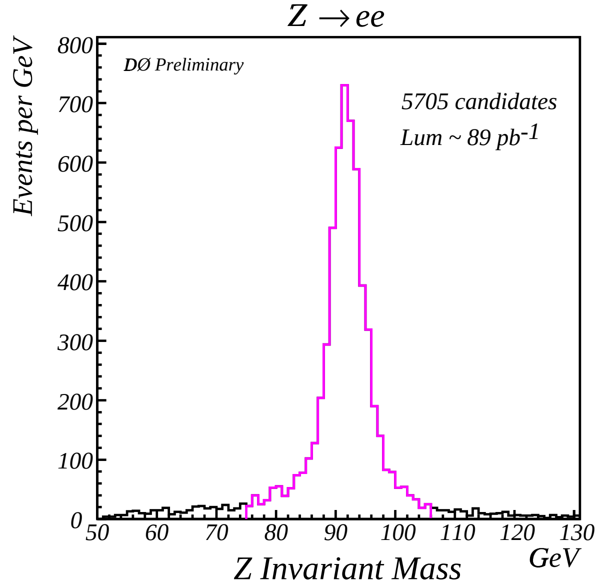
W: one isolated high p_T lepton (>20-25 GeV/c) + large missing E_T (>20-25 GeV)

Z: two isolated high p_T leptons (>20-25 GeV/c)

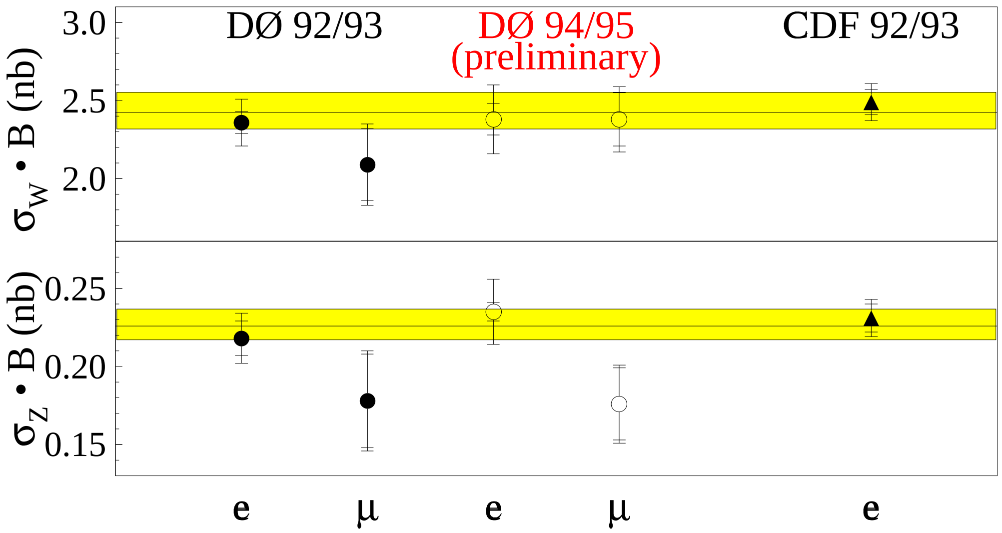
Backgrounds are typically < 15% for W, and < 5% for Z (due to QCD, cosmic rays, etc)

Typical candidate samples are:





W and Z Production Cross Sections (cont.)



Theoretical prediction at $O(\alpha_s^2)$:

- Hamberg, van Neerven & Matsuura, NP B359, 343 ('91); van Neerven & Zijlstra, NP B382, 11 ('92).
- Uses CTEQ2M pdf.
- Error dominated by pdf uncertainties (3-5%).

Results:

	$\sigma_W \cdot B(W \rightarrow l\nu)$ (nb)	$\sigma_Z \cdot B(Z \rightarrow ll)$ (nb)
D0(e) (Run 1B)	2.38 ± 0.01 ± 0.09 ± 0.20	0.235 ± 0.003 ± 0.005 ± 0.020
D0(μ) (Run 1B)	2.38 ± 0.03 ± 0.17 ± 0.13	0.176 ± 0.011 ± 0.020 ± 0.009
CDF(e) (Run 1A)	2.49 ± 0.02 ± 0.08 ± 0.09	0.229 ± 0.006 ± 0.007 ± 0.008
Theory	2.42 ± 0.12	0.226 ± 0.010

An important verification of QCD and pdf's.

W and Z Production Cross Sections (cont.)

$W \rightarrow \tau\nu$

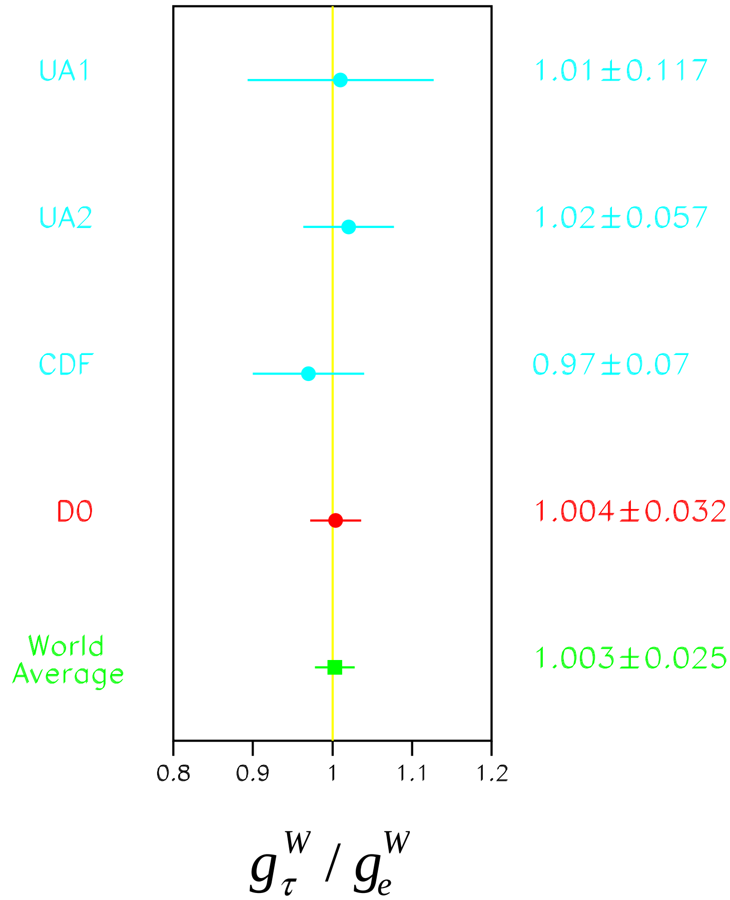
- Event selection (D0):
  - Use hadronic decay of the τ, so require isolated, narrow, high E_T jet with few tracks.
  - E_T(jet) > 25 GeV, missing E_T > 25 GeV.
  - Jet width < 0.25 (RMS width in $\eta-\phi$ space)
  - Profile > 0.55. Profile = (sum of highest two tower E_T's)/(jet E_T).
- QCD background estimated using the Profile distribution.
- Find 1,202 events, with a background of 222 ± 16 events, in 17 pb^{-1}.

➡ $\sigma_W \cdot B(W \rightarrow \tau\nu) = 2.38 \pm 0.09 \pm 0.10$ nb

$$\left(\frac{g_\tau^W}{g_e^W}\right)^2 = \frac{\sigma_W \cdot B(W \rightarrow \tau\nu)}{\sigma_W \cdot B(W \rightarrow e\nu)}$$

➡ $g_\tau^W / g_e^W = 1.004 \pm 0.019 \pm 0.026$

[Using Run 1A published $\sigma_W \cdot B(W \rightarrow e\nu)$]



W Boson Width

Indirect Measurement, from Ratio of W,Z Cross Sections

$$R \equiv \frac{\sigma(W) \cdot B(W \to l\nu)}{\sigma(Z) \cdot B(Z \to ll)} = \left[\frac{\sigma(W)}{\sigma(Z)} \right] \cdot \frac{B(W \to l\nu)}{B(Z \to ll)}$$

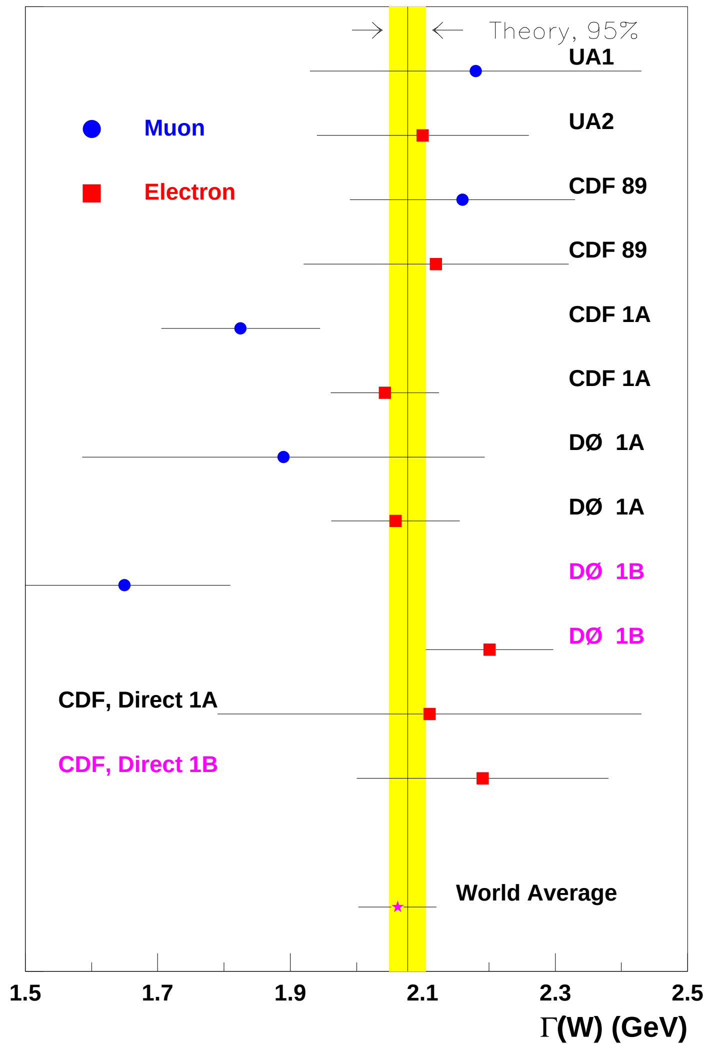
Using: R = 10.48 ± 0.43 (D0 Run 1B preliminary),
$\sigma(W)/\sigma(Z)$ = 3.33 ± 0.03 (theory), and
B(Z → ll) = (3.367 ± 0.006)% (LEP/SLC)
We find: B(W → lν) = (10.59 ± 0.44)%

Using: the above value of B(W → lν), and
Γ(W → lν) = 225.2 ± 1.5 MeV (theory)
We find: Γ_W = 2.126 ± 0.092 GeV

Standard Model value: Γ_W = 2.077 ± 0.014 GeV

Comparing this SM value to the published world average of Γ_W = 2.062 ± 0.059 GeV gives an upper limit (95% CL) on unexpected decays of the W (such as W decays into supersymmetric charginos or neutralinos, or heavy quarks) of:

$\Delta\Gamma_W < 109$ MeV

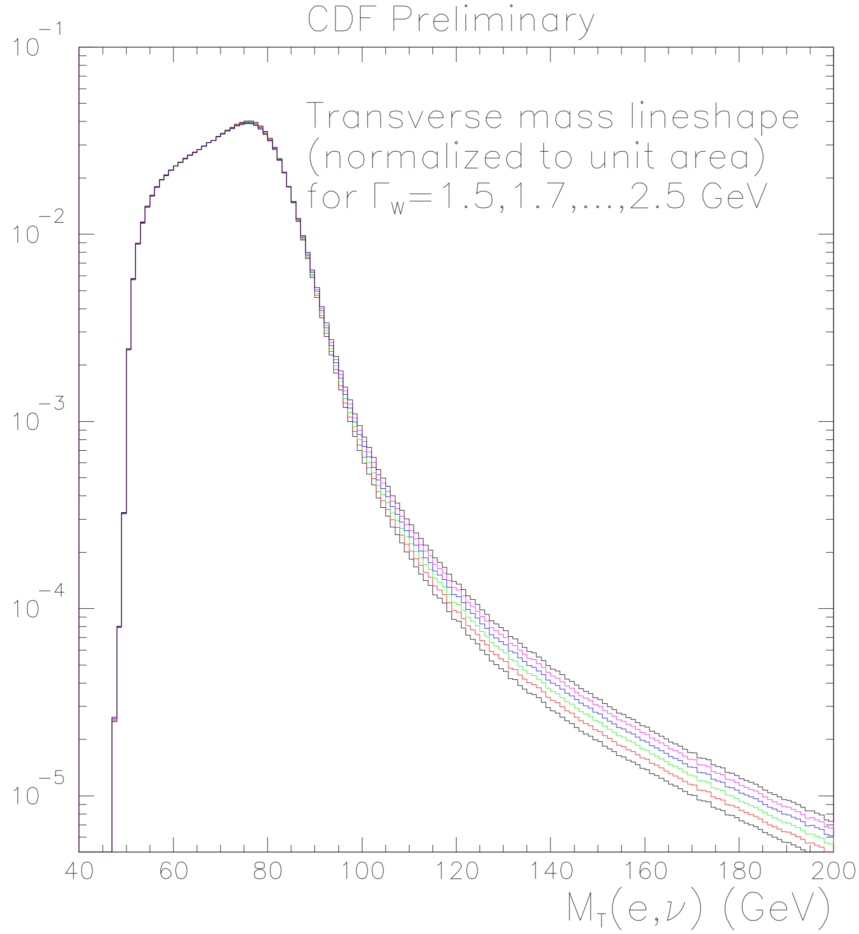


W Boson Width (cont.)

Direct Measurement, From Transverse Mass Lineshape

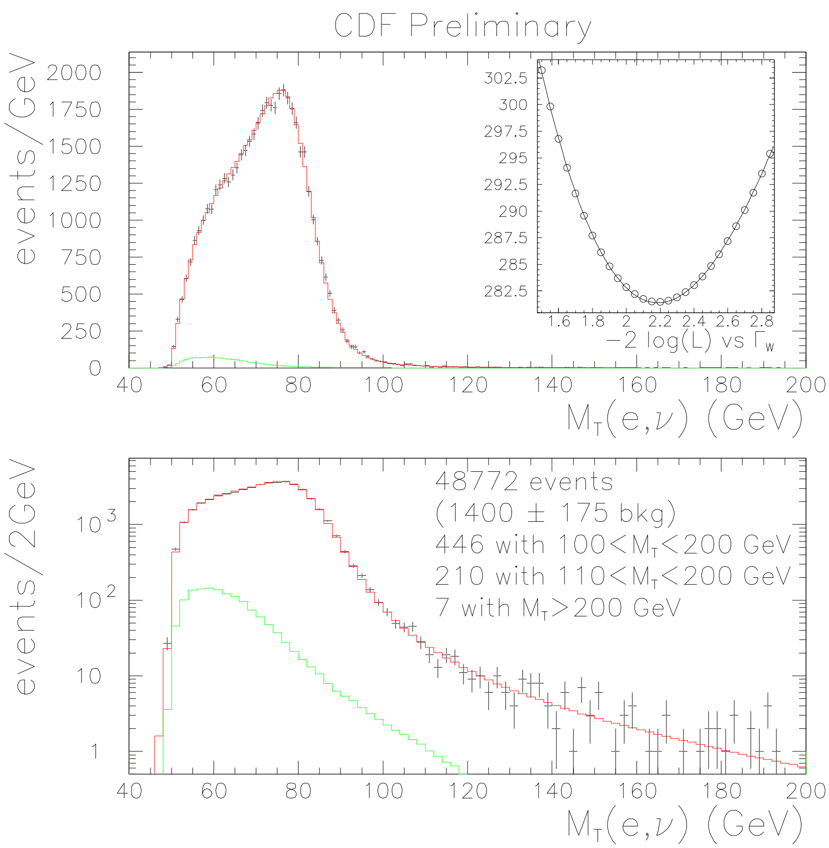
$$M_T^2 = 2E_T^e E_T^\nu (1-\cos\phi^{e\nu})$$

- Tail region of M_T is sensitive to Γ_W.
- Direct measurement avoids using theoretical inputs.
- M_T lineshape modeled with a fast MC that uses the standard CDF W mass measurement detector simulation.
- A fit is done to the CDF M_T data (210 events in a $110 < M_T < 200$ GeV window) to the signal MC + background for various values of Γ_W. Largest systematic uncertainties are due to recoil modeling and electron energy scale.



W Boson Width (cont.)

CDF Direct Measurement, Run 1B



➡ $\Gamma_W = 2.19 \pm 0.17\ (stat) \pm 0.09\ (syst)$ GeV

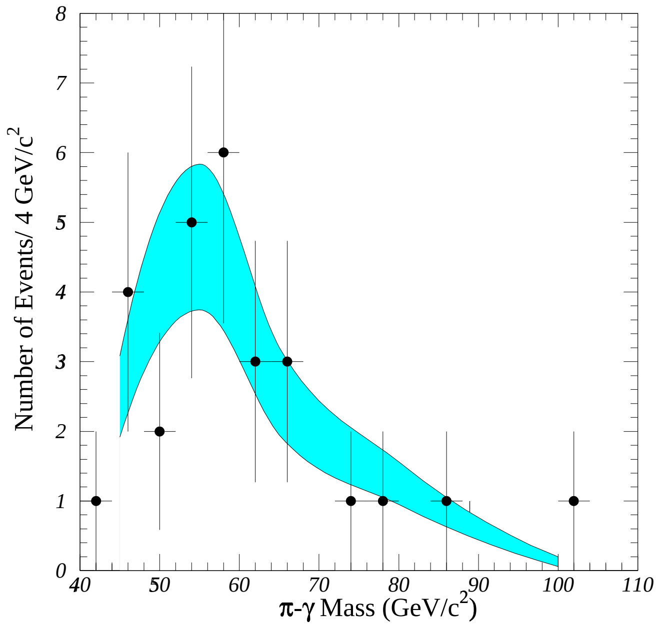
(SM value $\Gamma_W = 2.077 \pm 0.014$ GeV)

Rare W Decays

- At the Fermilab Tevatron, $\sigma(W) \sim 23$ nb $\Rightarrow$ 3 x 10^6 W's produced in 130 pb^{-1}.
- Rare W decays provide precision tests of the Standard Model.

$W \rightarrow \pi\gamma$

- Theory estimate: $\Gamma(W\rightarrow \pi\gamma)/\Gamma(W\rightarrow e\nu) \sim 3\times10^{-8}$
- Previous exp. limits: CDF Run 1A $\leq 2\times10^{-3}$; UA2 $\leq 5\times10^{-3}$
- CDF Run 1B Analysis (accepted for publication in PRD Rapid Communication):
  - Choose events with one isolated high P_t photon (>23 GeV/c) and one jet consistent with a single, isolated charged pion (>15 GeV/c), separated by $\Delta\phi$>1.5 radians, and no other jets with E_t>15 GeV.
  - Find 3 events consistent with signal (π-γ mass within $\pm3\sigma$ of M_W).
  - Background estimate of 5.2 ± 1.5 events (from QCD direct photons).
  - $\varepsilon \bullet A \sim 4\%$, $\int L dt = 83$ pb^{-1}
  - $\rightarrow \sigma_W \bullet B(W \rightarrow \pi\gamma) \leq 1.7$ pb (95% CL)
  - $\rightarrow \Gamma(W \rightarrow \pi\gamma)/\Gamma(W \rightarrow e\nu) \leq 7 \times 10^{-4}$



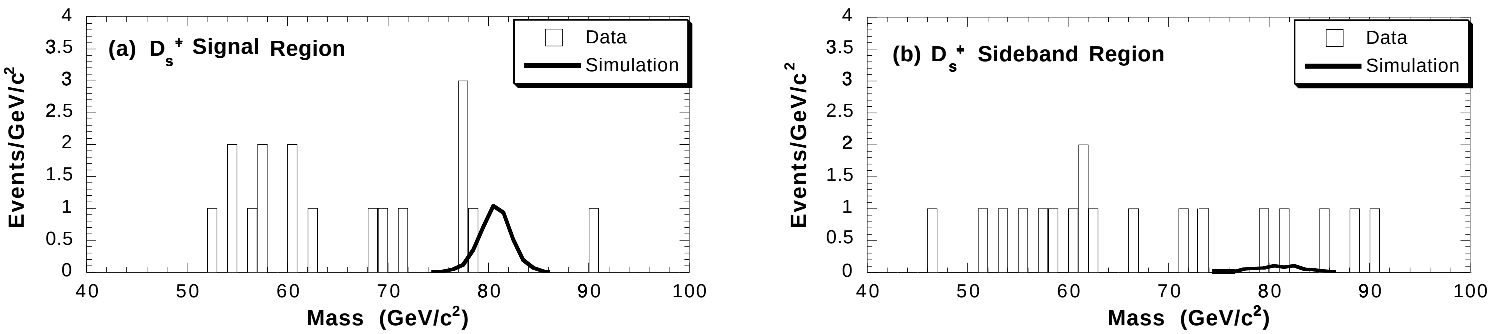
Rare W Decays (cont.)

$W \to D_s\gamma$

Theory estimate: $\Gamma(W \to D_s\gamma)/\Gamma(W \to e\nu) \sim 1 \times 10^{-7}$

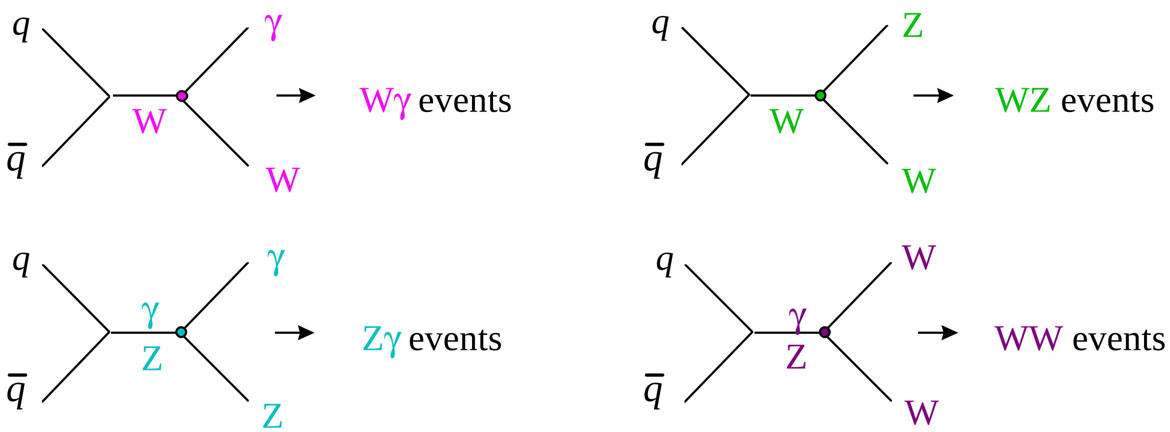
CDF (Run 1B) Analysis

- Event selection:
  - One isolated high P_t photon (>22 GeV/c).
  - One isolated high P_t D_s candidate (>22 GeV/c).
    - » $D_s \to \phi\pi$, $\phi \to KK$
    - » $D_s \to K^{*0}K$, $K^{*0} \to Kp$
  - Find 4 events consistent with signal (D_s-γ mass within $\pm 3\sigma$ of M_W).
- Background of 4 events using D_s sidebands (from QCD direct photons).
- $\varepsilon \cdot A \sim 7\%$, $\int L dt = 82\ pb^{-1}$
- $\to \sigma_W \cdot B(W \to D_s\gamma) \leq 27.4$ pb (95% CL)
- $\to \Gamma(W \to D_s\gamma)/\Gamma(W \to e\nu) \leq 1.1 \times 10^{-2}$ First limit on this branching fraction!



Trilinear Gauge Boson Couplings

- Standard Model (SM) predicts the existence of gauge boson self-interactions, and makes unique predictions for the strength of these trilinear gauge boson couplings.
- Measurements of these couplings test the SM, and any significant deviation from SM predictions would be compelling evidence for new physics.
- The direct measurement of these trilinear couplings (WWγ, WWZ, ZZγ, Zγγ) is possible by measuring diboson production at the Tevatron:

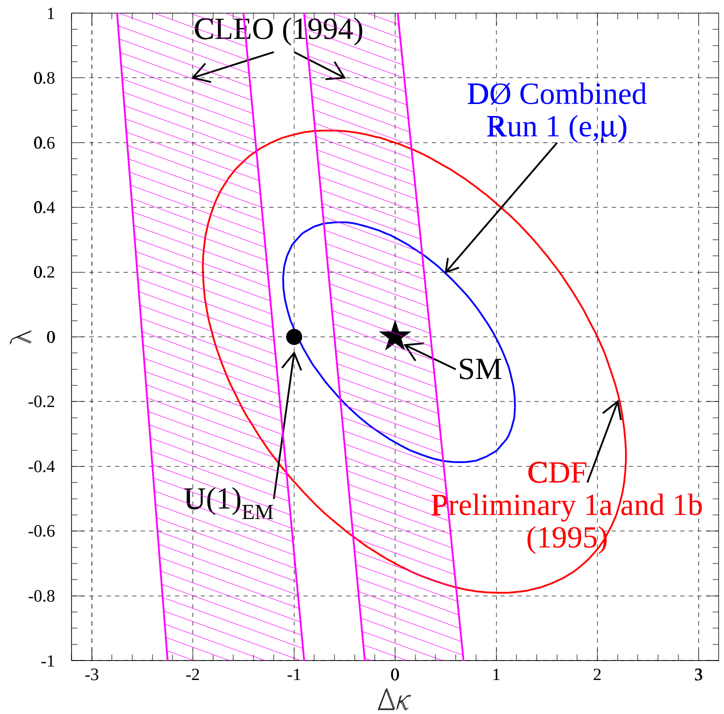


- WWV (V=γ or Z) couplings characterized with the parameters λ_V, $\Delta\kappa_V$ ($\equiv\kappa_V$-1), and Δg_1^V ($\equiv g_1^V$-1), which all equal 0 in the SM.
- ZVγ (V=γ or Z) couplings characterized by h_{30}^V and h_{40}^V, which also equal 0 in the SM.
- To obey unitarity, all couplings multiplied by a form factor $(1+s/\Lambda^2)^n$,n=2(WWV), 3(h_{30}^V) or 4(h_{40}^V), s is the square of the sub process CM energy, and Λ is a form factor scale.
- Anomalous (i.e. non-SM) values of the coupling parameters increase the production cross section and enhance the p_T spectrum of the gauge boson for large p_T.

Trilinear Gauge Boson Couplings (cont.)

Wγ Production

- Event selection:
  - Isolated high p_T muon or electron, plus missing E_T
  - Isolated photon with E_T > 10 GeV (D0) or > 7 GeV (CDF)
- Main background is W+jets, where jet fragments into a π^0, and $\pi^0 \rightarrow \gamma\gamma$.
- Number of candidate events = 127 with 93 pb^{-1} (109 with 67 pb^{-1}) for D0 (CDF)
- Binned likelihood fit to $p_T(\gamma)$ spectrum.



- D0 limits at 95% CL (Λ=1.5 TeV):
  - $-0.93 < \Delta\kappa_\gamma < 0.94$ (for λ_γ=0)
  - $-0.31 < \lambda_\gamma < 0.29$ (for $\Delta\kappa_\gamma$=0)
- Independent of WWZ vertex (unlike WW production).
- First direct evidence that the photon couples to more than just the electric charge of the W boson. ($U(1)_{EM}$-only coupling ruled at 95% CL)

Trilinear Gauge Boson Couplings (cont.)

$WW \rightarrow l\nu\ l\nu\ \ (l = e,\mu)$

- Event selection:
  - Two isolated high p_T leptons (p_T>15-25 GeV/c).
  - Missing E_T > 20-25 GeV.
- Backgrounds due to $Z \rightarrow \tau\tau$, Drell-Yan and t-tbar
- Results:
-

	$\int Ldt$	Events	Background		
D0	97 pb^{-1}	5	3.1 ± 0.4	⇒	σ_{WW} < 37.1 pb (95% CL)
CDF	108 pb^{-1}	5	1.2 ± 0.3	⇒	σ_{WW} = 10.2 +6.3/-5.1 ± 1.6 pb
		Standard model prediction			σ_{WW} = 9.5 ± 1.0 pb

- Limits on anomalous couplings:

  CDF fits to the total number of events
  D0 fits to the lepton p_T spectrum, which gives better limits (Λ=1.5 TeV):

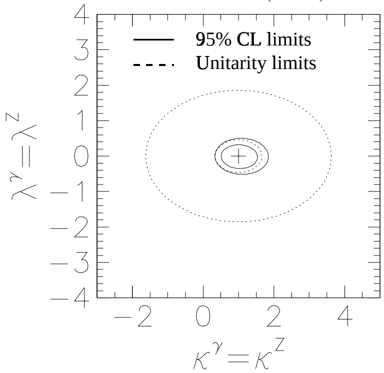
  $-0.62 < \Delta\kappa < 0.77$ (for λ=0)
  $-0.53 < \lambda < 0.56$ (for $\Delta\kappa$=0)

Trilinear Gauge Boson Couplings (cont.)

WW, WZ $\rightarrow$ $l\nu jj$, $lljj$ ($l = e,\mu$)

- Event selection:
  - One isolated high p_T lepton ($p_T > 20$-25 GeV/c).
  - Two or more jets with $E_T > 20$-30 GeV, and invariant mass consistent with a W or Z.
  - Missing $E_T > 20$-25 GeV, or a second high p_T lepton for lljj events.
- Large background from W+jets.
- CDF uses events with $p_T(jj) > 200$ GeV/c to get anomalous coupling limits (110 pb^{-1}).
- D0 uses a binned likelihood fit to the $p_T(W)$ spectrum to get the coupling limits (96 pb^{-1}).

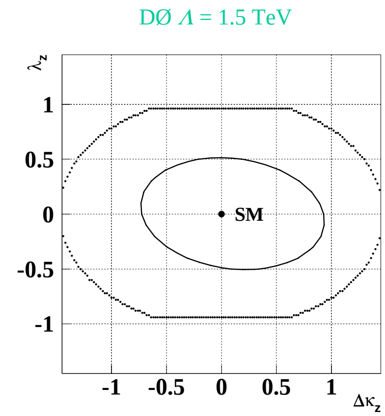
Limits assuming $\kappa_Z = \kappa_\gamma$ and $\lambda_Z = \lambda_\gamma$



D0 limits (Λ= 2 TeV) $-0.43 < \Delta\kappa < 0.59$
$-0.33 < \lambda < 0.36$

CDF limits (Λ= 2 TeV) $-0.49 < \Delta\kappa < 0.54$
$-0.35 < \lambda < 0.32$

Limits assuming SM $WW\gamma$ couplings



$U(1)_{EM}$-only coupling ($\kappa_Z=\lambda_Z=0$ point) excluded at > 99% CL by both experiments, thus providing first direct evidence for WWZ coupling.

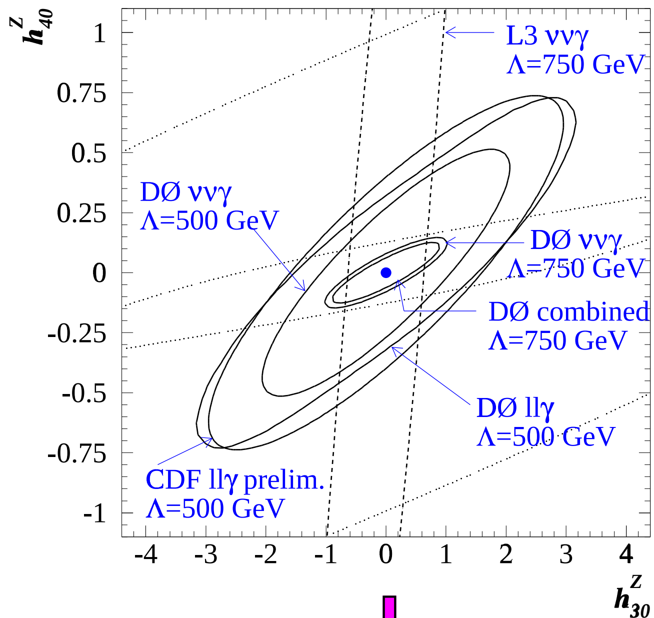
Trilinear Gauge Boson Couplings (cont.)

Zγ Production

- D0 and CDF have each measured Z(ee)γ and Z(μμ)γ production. D0 (CDF) finds 35 (33) events in ~105 (67) pb^{-1}, with a background of 5.9 (1.4) events. The measurements agree with SM expectations. Limits on the anomalous coupling parameters are found using a binned maximum likelihood fit to the photon E_T spectra.

Z(νν)γ

- D0 has measured Z(νν)γ production, and this provides the most sensitive limits.
- Advantages are a larger branching ratio, no contributions from radiative processes of final state leptons, and higher detection efficiency (only one final state particle). But the backgrounds are much higher.
- Tight selection cuts: $E_T^\gamma > 40$ GeV, missing $E_T > 40$ GeV, no jets with $E_T > 15$ GeV.
- Reduce $W \rightarrow e\nu$ background with "hit counting" in the tracking chambers.
- Reduce cosmic ray muon bremsstrahlung and beam halo background with "photon tracking" (to see if the γ came from the interaction vertex) and "muon detection" in the finely segmented calorimeter.
- Find 4 events, with a background of 5.8 ± 1.0 events, in 13 pb^{-1}. Expect 1.8 ± 0.2 events from the SM.
- Anomalous coupling limits found using a binned maximum likelihood fit to the E_T^γ spectrum.



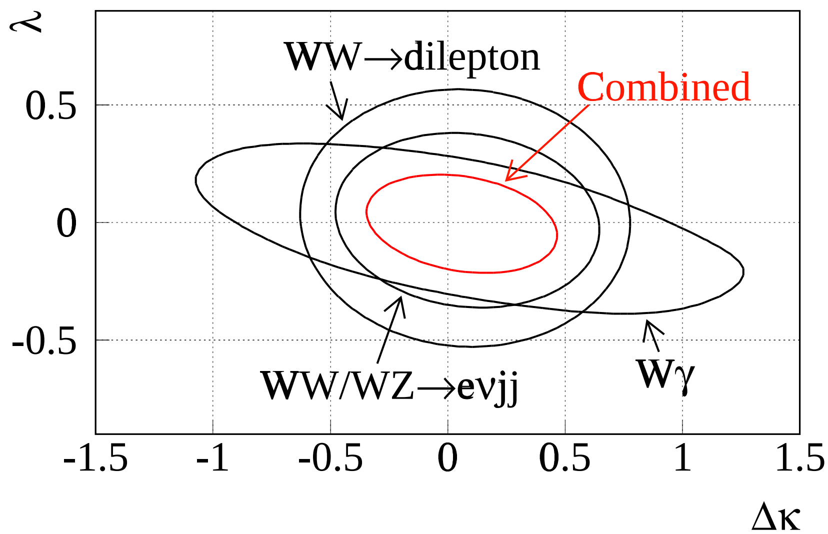
D0 combined limits (Λ=750 GeV):

$|h_{30}^{Z,\gamma}| < 0.37 \quad |h_{40}^{Z,\gamma}| < 0.05$

These are the most stringent direct limits on anomalous couplings from any experiment.

D0 Combined Analysis of WWγ and WWZ Couplings

- D0 has performed a simultaneous fit to:
  - Photon p_T spectrum in the Wγ data
  - Lepton p_T distribution in the WW dilepton data
  - $p_T(W)$ distribution in the WW/WZ $\rightarrow$ eνjj data
- Limits on the WWγ and WWZ anomalous coupling parameters are extracted from the fit, taking into account proper correlations.



Limits for Λ=2.0 TeV: $-0.30 < \Delta\kappa < 0.43$

$-0.20 < \lambda < 0.20$

D0 Combined Analysis: $\alpha_{B\phi}$, $\alpha_{W\phi}$, α_W Parameterization

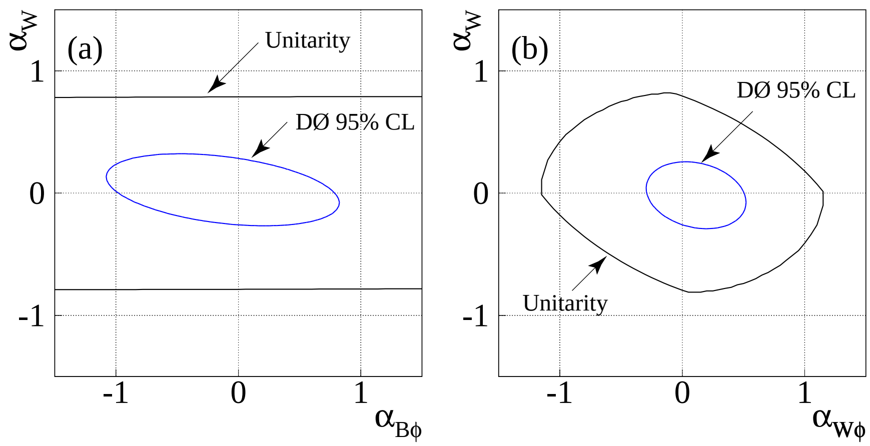
LEP 2 anomalous coupling results use a different set of parameters:

$$\alpha_{B\phi} \equiv \Delta\kappa_\gamma - \Delta g_1^Z \cos^2\theta_W$$
$$\alpha_{W\phi} \equiv \Delta g_1^Z \cos^2\theta_W$$
$$\alpha_W \equiv \lambda_\gamma$$

with the constraints:

$$\Delta\kappa_Z = -\Delta\kappa_\gamma \tan^2\theta_W + \Delta g_1^Z$$
$$\lambda_Z = \lambda_\gamma$$

New D0 limits on $\alpha_{B\phi}$, $\alpha_{W\phi}$, α_W from the D0 combined analysis:



D0 95% CL (Λ=2.0 TeV):

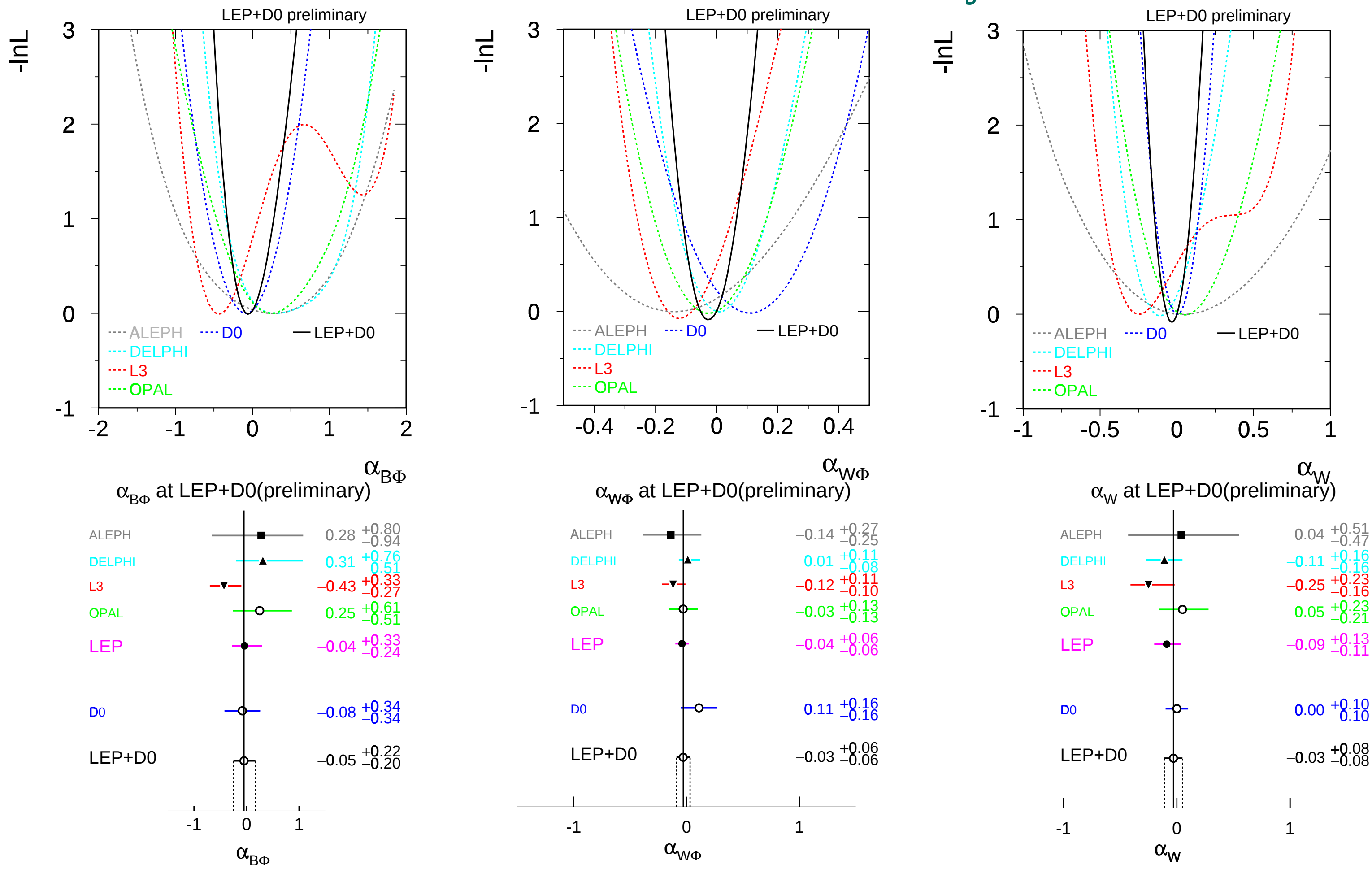
$-0.77 < \alpha_{B\phi} < 0.58$
$-0.22 < \alpha_{W\phi} < 0.44$
$-0.20 < \alpha_W < 0.20$

LEP2 95% CL (Λ=2.0 TeV):

$-0.44 < \alpha_{B\phi} < 0.95$
$-0.12 < \alpha_{W\phi} < 0.13$
$-0.21 < \alpha_W < 0.27$

Trilinear Gauge Boson Couplings (cont.)

D0 and LEP2 Combined Analysis



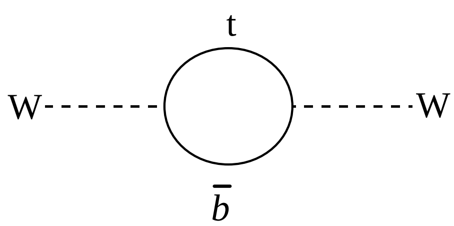
$-0.42 < \alpha_{B\phi} < 0.43$ $-0.14 < \alpha_{W\phi} < 0.10$ $-0.18 < \alpha_{W} < 0.13$

W Boson Mass

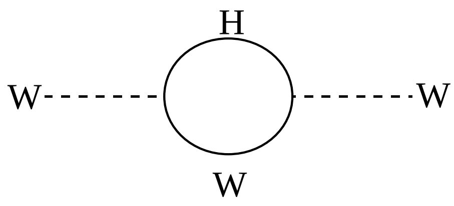
The W boson mass is a fundamental parameter of the Standard model, and is sensitive to top quark and Higgs boson radiative corrections:

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

$\Delta r \sim M_t^2$



$\Delta r \sim \ln M_H$



Fermilab Tevatron Measurements

- Run 1A (1992-93) data set:
  - D0 $W \rightarrow e\nu$ published
  - CDF $W \rightarrow e\nu, \mu\nu$ published
- Run 1B (1994-95) data set:
  - D0 $W \rightarrow e\nu$ published in PRL, accepted by PRD
  - CDF $W \rightarrow \mu\nu$ preliminary

W Boson Mass (cont.)

W Mass Measurement Method at D0 and CDF

$$p\bar{p} \rightarrow W + \text{jets}$$
$$\Downarrow$$
$$\text{lepton} + \nu$$

- Measure the lepton momentum and p_T of recoil system.
- Measure E_T^{ν} from the transverse energy balance.
- Calculate the transverse mass, $M_T^2 = 2E_T^{e}E_T^{\nu}(1\text{-}\cos\phi^{e\nu})$, which shows a sharp Jacobian peak at the W mass.
- Use a fast Monte Carlo to model $W \rightarrow l\nu$ events.
- Add backgrounds and model the detector. Since the E_T^{ν} measurement depends on the momentum of both the lepton and the recoil hadrons, it is critical to understand the leptonic and hadronic energy scale and resolutions. Use Z events for calibrations.
- Generate M_T spectra for various M_T values.
- Fit the Monte Carlo M_T spectra to the the data to obtain the best fit M_T value using the maximum likelihood method.

Event Selection Criteria

Isolated, high quality, high p_T (>25 GeV/c) lepton in the central region.

Missing E_T > 25 GeV.

Hadronic recoil < 15-20 GeV.

Resulting sample of 28K $W \rightarrow e\nu$ events for D0, and 21K $W \rightarrow \mu\nu$ events for CDF.

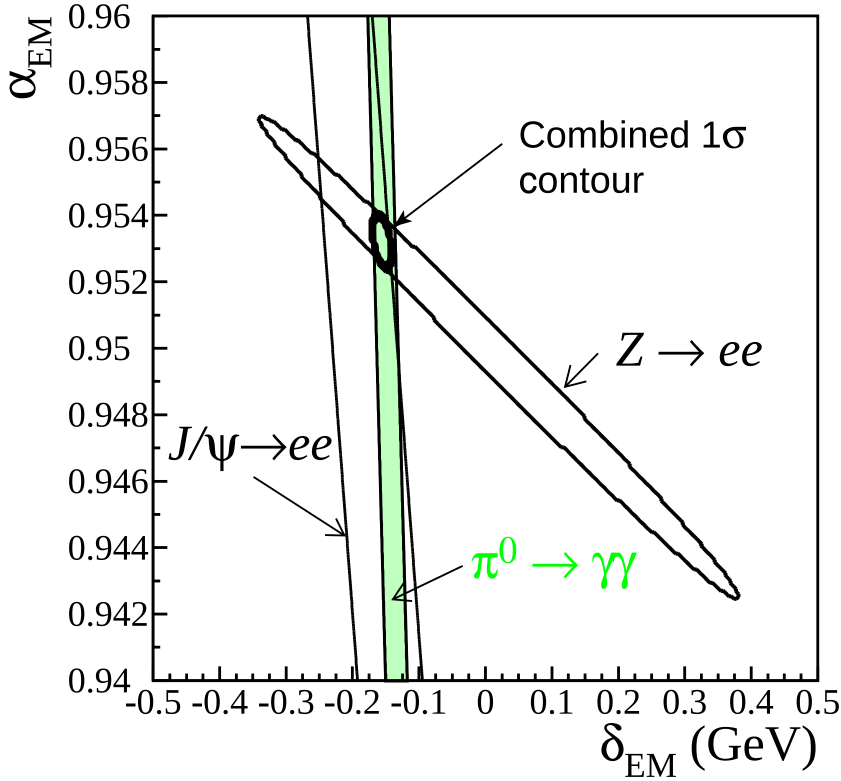
D0 Energy Scale

- Test beam measurements show that the calorimeter energy response is linear to <0.5% for E_T^e> 10 GeV.
- The final normalization and offset of the energy scale were measured with $Z \to ee$, $\pi^0 \to \gamma\gamma$, and $J/\psi \to ee$ collider data. Parameterize $E_{obs} = \alpha E_{true} - \delta$. See plot at right.
- Including systematic errors from underlying event corrections and non-linearity at low E_T^e results in:

$$\alpha = 0.9533 \pm 0.0008$$

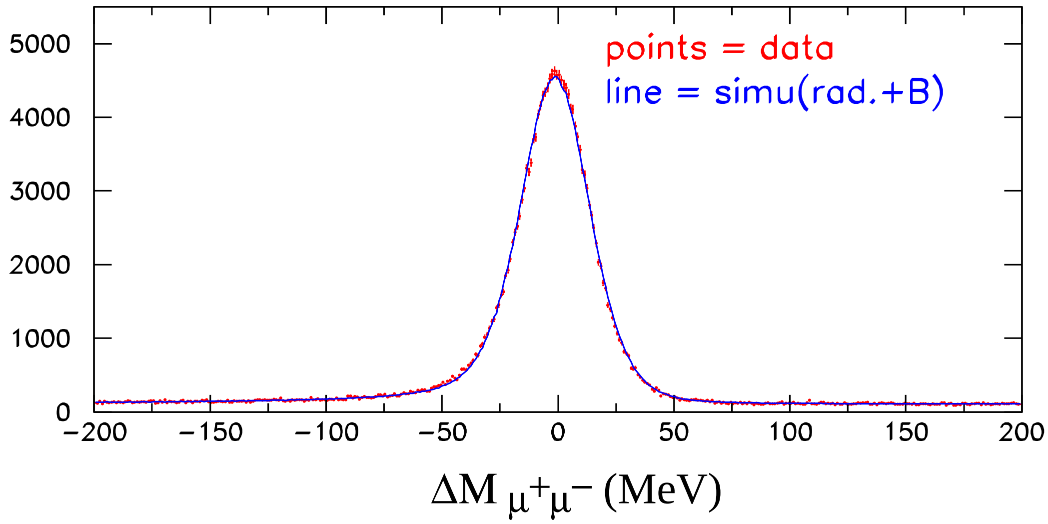
$$\delta = -0.16^{+0.03}_{-0.21} GeV$$

$\Delta M_W(\Delta\alpha)$ = 65 MeV, $\Delta M_W(\Delta\delta)$ = 20 MeV



CDF Momentum Scale

- The momentum scale of the central tracker is set by normalizing the measured $J/\psi \rightarrow \mu\mu$ peak to the world-average mass. Used 250,000 $J/\psi \rightarrow \mu\mu$ events!



Measured $M^{J/\psi} = 3096.2 \pm 1.5$ MeV

PDG avg. $M^{J/\psi} = 3096.88 \pm 0.04$ MeV

$\Delta M^{J/\psi} = 0.7 \pm 1.5$ MeV $\longrightarrow$ $\Delta M_W = 40$ MeV

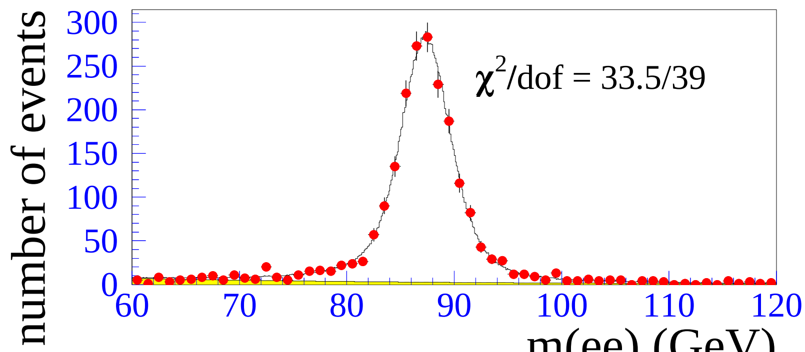
W Boson Mass (cont.)

D0 Energy Resolution

- Use the $Z \rightarrow ee$ sample to constrain the constant term, C_{em}, in the energy resolution.

$$C_{em} = (1.15^{+0.27}_{-0.35})\%$$

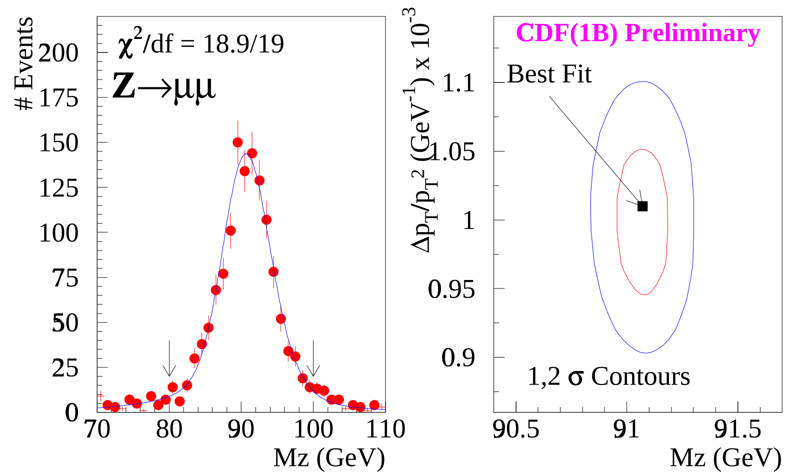
$\Delta M_W = 20$ MeV



CDF Momentum Resolution

- Use the $Z \rightarrow \mu\mu$ sample and fit for M_Z and $\sigma(1/p_T)$.

$\Delta M_W = 25$ MeV



Recoil Energy Scale and Resolution

- Use transverse energy balance of the Z and the hadronic recoil products in Z + X collider events to determine the hadronic recoil energy scale and resolution.
- $Z \rightarrow ee$ (D0) or $Z \rightarrow \mu\mu$ (CDF) events. Thus the hadronic recoil scale is measured relative to the lepton energy scale.

⇒ D0: $\Delta M_W = 20$ MeV due to recoil energy scale
$\Delta M_W = 25$ MeV due to recoil energy resolution

⇒ CDF: $\Delta M_W = 90$ MeV due to recoil energy scale & resolution (set conservatively, and will improve).

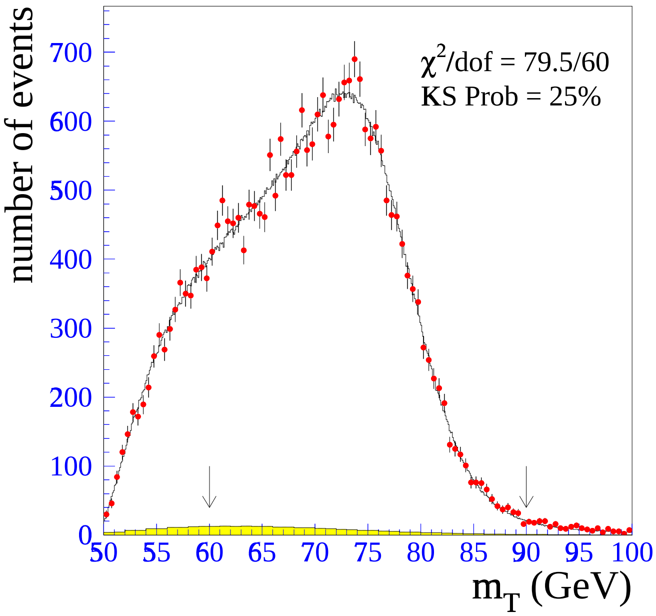
W Boson Mass (cont.)

Summary of Errors on M_W (in MeV/c^2)

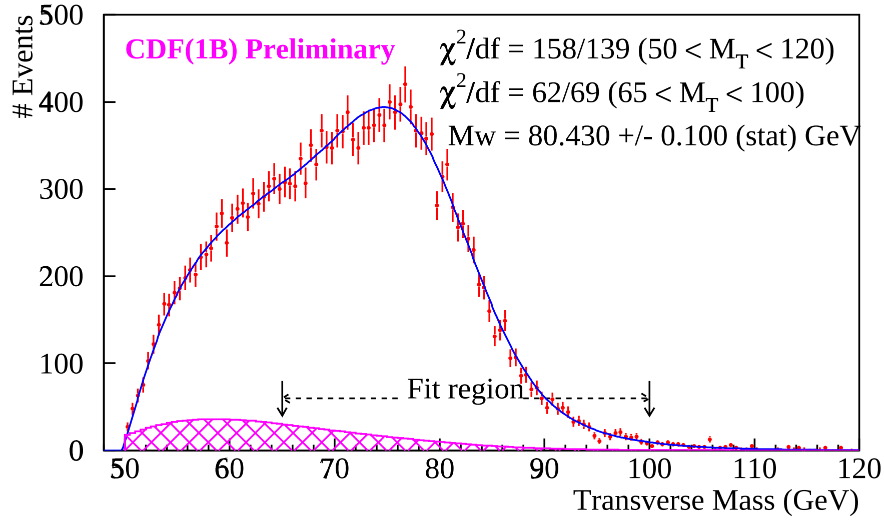
	CDF	D0
Statistical		
W sample	100	70
Z sample (e energy scale)	-	65
	---	---
Total Statistical	100	95
Systematic		
Muon momentum scale	40	-
Lepton energy resolution	25	20
Calorimeter linearity	-	20
Recoil modeling	90	35
W production model	55	30
Backgrounds	25	10
Lepton angle calibration	-	30
Fitting	10	-
Miscellaneous	15	10
	---	---
Total Systematic	120	65
	===	===
Total Uncertainty	155	115

Transverse Mass Fits and Results

D0 $W \to e\nu$



CDF $W \to \mu\nu$

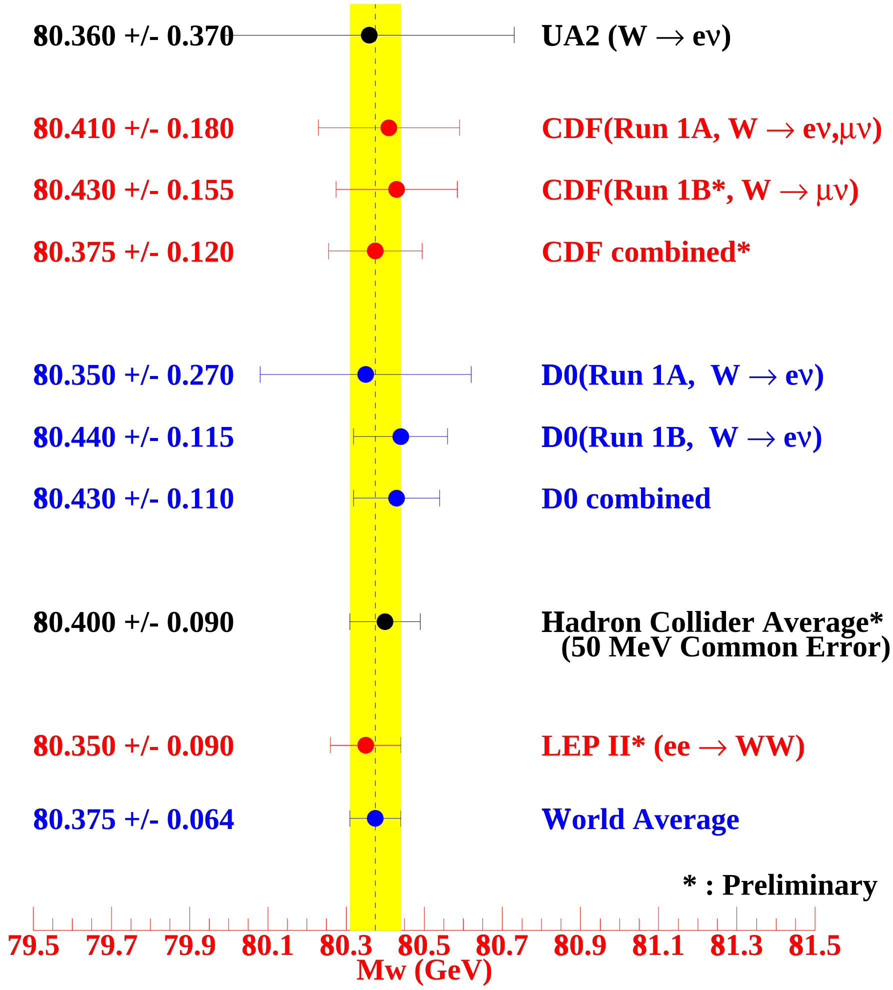


D0: $M_W = 80.440 \pm 0.095$ (stat.) ± 0.065 (syst.) GeV/c^2

CDF: $M_W = 80.430 \pm 0.100$ (stat.) ± 0.120 (syst.) GeV/c^2

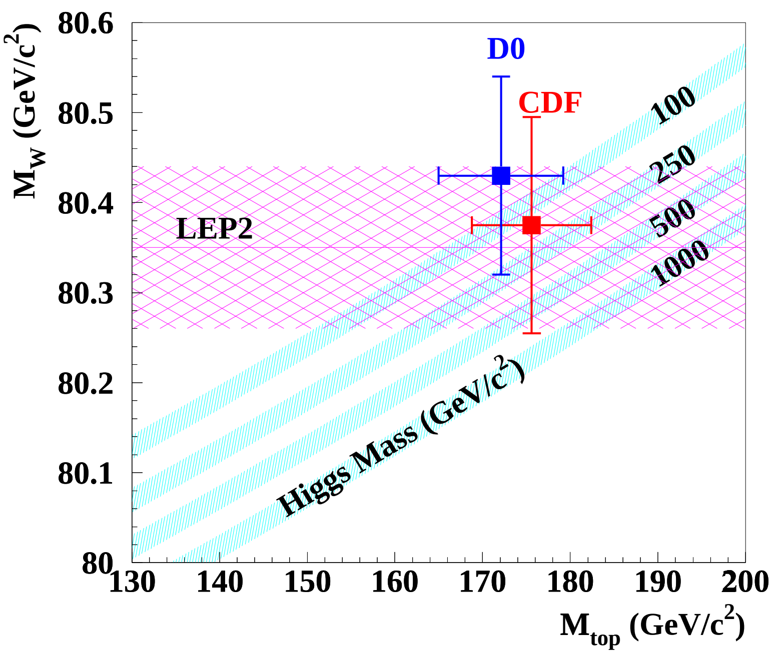
W Boson Mass (cont.)

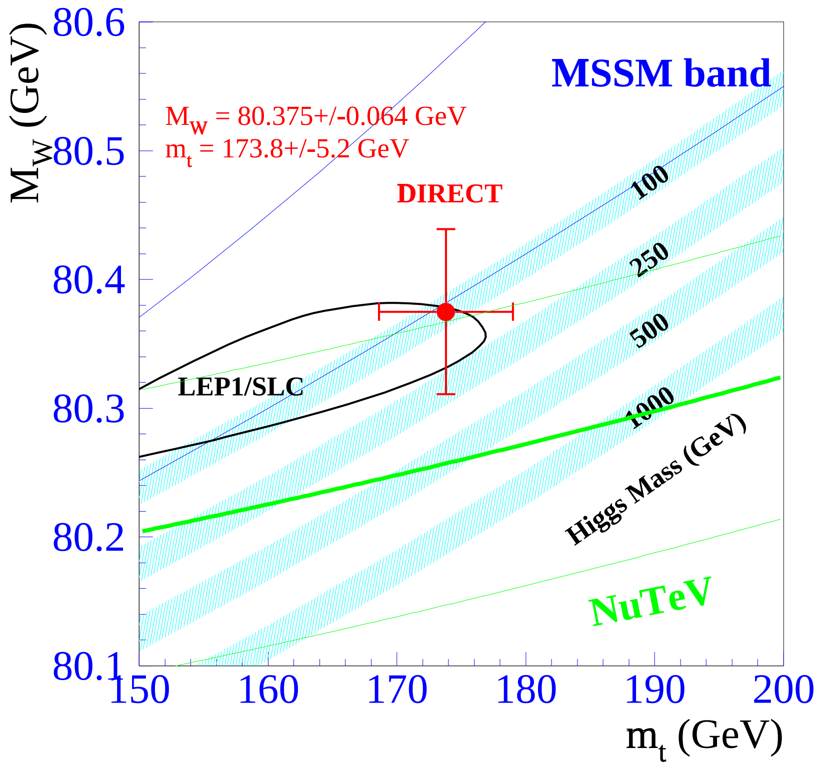
Direct W Mass Measurements



W Boson Mass (cont.)

M_W vs. M_{top}





DIRECT: M_W: UA2 + D0 + CDF + LEP2
M_{top}: D0 + CDF

Prospects from the Tevatron Collider

- Most systematic errors are still statistics limited.
- Run 1 Data:
  - D0: Use forward electrons; final ΔM_W ~ 100 MeV ?
  - CDF: Finalize μ results with smaller errors, and use Run 1B electrons; final ΔM_W ~ 90 MeV ?
  - Tevatron: final ΔM_W ~ 75 MeV ?
- Run 2 (beginning Spring, 2000):
  - 20 times more luminosity
  - D0: new solenoid (use μ's), new tracking chambers, new preshower detectors
  - CDF: new tracking chambers, new forward calorimeter, extended μ coverage
  - Each experiment: ΔM_W ~ 40 MeV ?

Conclusions

- Production Cross Sections:
  - $\sigma_W \bullet B(W \rightarrow l\nu)$ measured for l=e, μ and τ, and all agree with $\mathcal{O}(\alpha_s^2)$ theory.
  - $g_\tau^W/g_e^W = 1.004 \pm 0.032$
- W Boson Width:
  - Indirect: $\Gamma_W = 2.126 \pm 0.092$ GeV (SM $\Gamma_W = 2.077$ GeV)
  - Direct: $\Gamma_W = 2.19 \pm 0.19$ GeV
- Rare W Decays:
  - $\Gamma(W \rightarrow \pi\gamma)/\Gamma(W \rightarrow e\nu) \leq 7 \times 10^{-4}$
  - $\Gamma(W \rightarrow D_s\gamma)/\Gamma(W \rightarrow e\nu) \leq 1.1 \times 10^{-2}$
- Trilinear Gauge Boson Couplings:
  - First direct evidence that the photon couples to the weak isospin of the W boson.
  - First direct evidence for WWZ coupling.
  - $\sigma_{WW} = 10.2 + 6.3/-5.1 \pm 1.6$ pb
  - $ZZ\gamma/Z\gamma\gamma$: $|h_{30}^{Z,\gamma}| < 0.37$, $|h_{40}^{Z,\gamma}| < 0.05$
  - $WW\gamma/WWZ$: $-0.30 < \Delta\kappa < 0.43$, $-0.20 < \lambda < 0.20$, or
    $-0.77 < \alpha_{B\phi} < 0.58$, $-0.22 < \alpha_{W\phi} < 0.44$, $-0.20 < \alpha_W < 0.20$
- W Boson Mass:
  - $M_W = 80.400 \pm 0.090$ GeV Hadron Collider Average (UA2 + CDF + D0)
  - $M_W = 80.375 \pm 0.064$ GeV Direct World Average (UA2 + CDF + D0 + LEP2)