Electroweak Results from the Tevatron

presented by:

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representing the

CDF and DØ Collaborations

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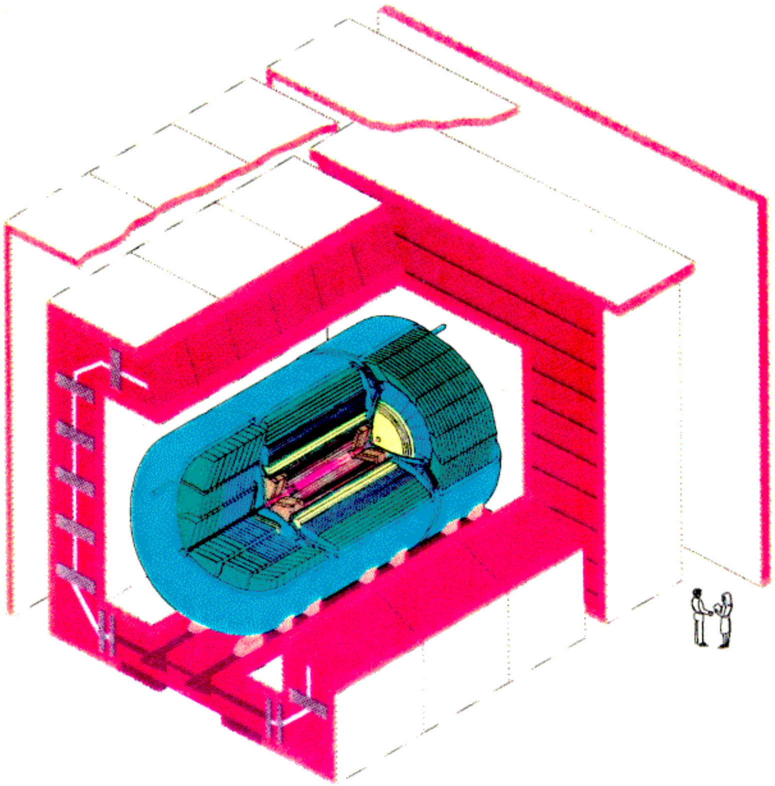
Outline

- W and Z production
  - ▷ $\sigma \cdot B(W, Z \to e,\mu)$
  - ▷ Γ_W – indirect, direct
  - ▷ $\sigma \cdot B(W \to \tau\nu)$
- Rare W decays
  - ▷ $W \to \pi\gamma$
  - ▷ $W \to D_s\gamma$
- Drell-Yan production: quark/lepton substructure
- Latest results for M_W
- Trilinear Gauge Boson Couplings
  - ▷ $W\gamma$, WW/Z, $Z\gamma$
  - ▷ Combined limits
- Conclusions

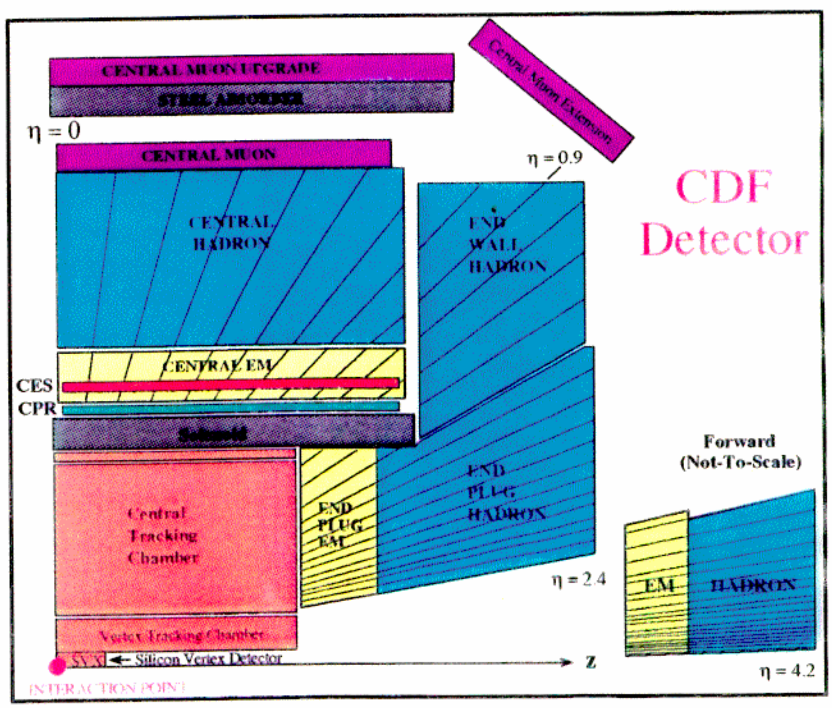
Run I Detectors



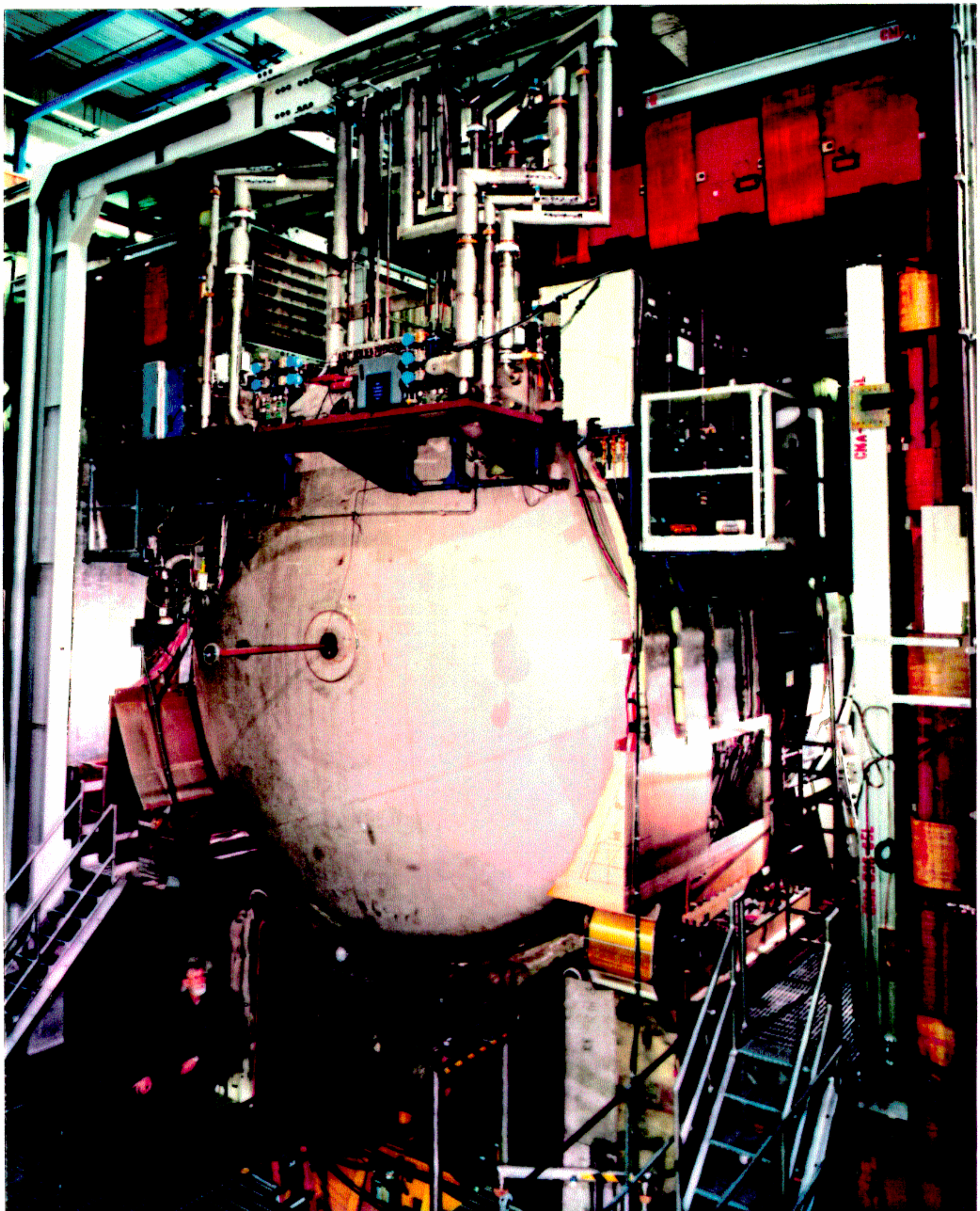
DØ Detector

DØ: Hermetic, high-resolution Ur/LAr calorimetry ($|\eta| < 4.0$)

CDF: Extensive magnetic inner tracking volume (1.4 T)



CDF Detector



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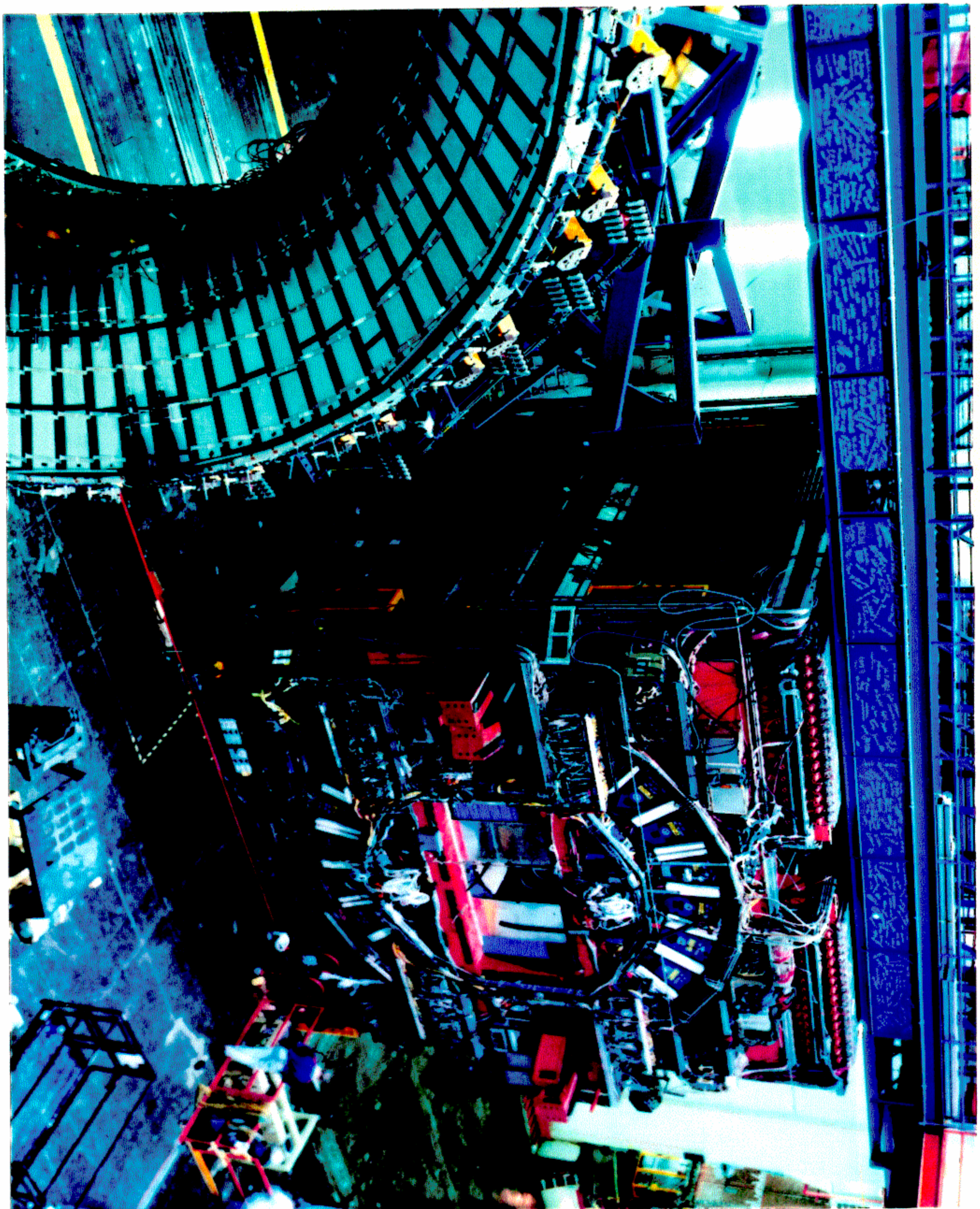
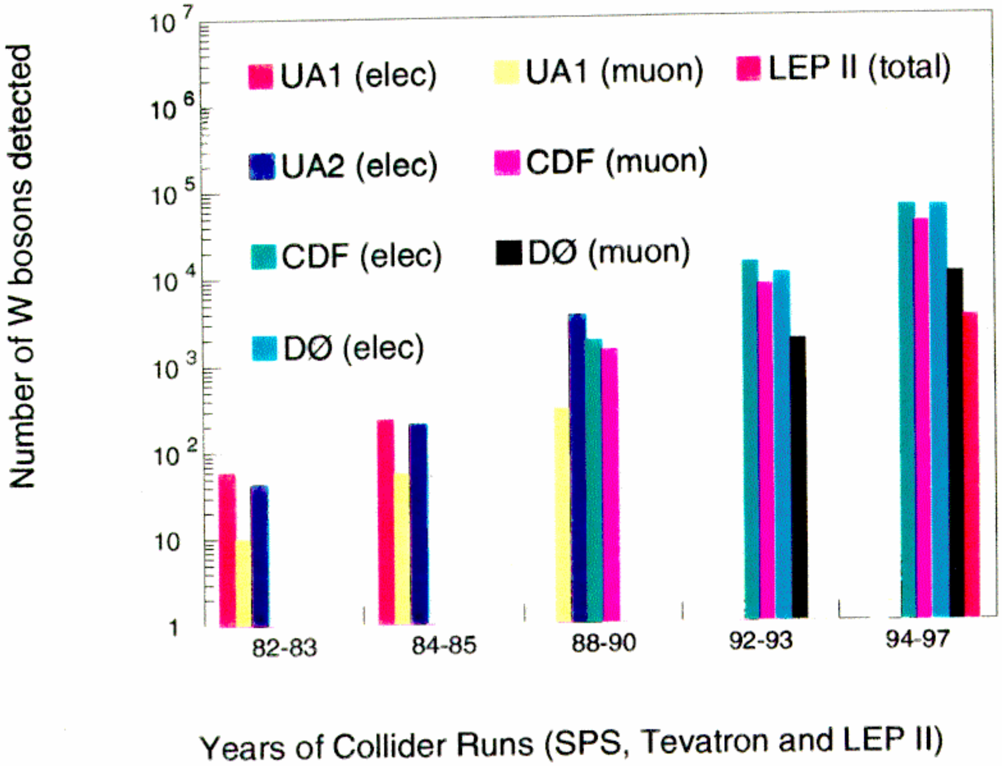


96-419

W Bosons Detected



Tevatron Run	Year	$\int \mathcal{L}dt$ (pb^{-1})
"0"	1988-89	4 (CDF only)
1A	1992-93	20
1B	1994-95	90
1C	1995-96	20
		$\sim$ 130 total
2	begins April, 2000	$> 2\ fb^{-1}$ ($\times 20$)

Typical Candidate Samples

- Mass of Z measured directly from invariant mass:

$$M_Z = \sqrt{2E_{l_1}E_{l_2}(1 - \cos\theta_{l_1,l_2})}$$

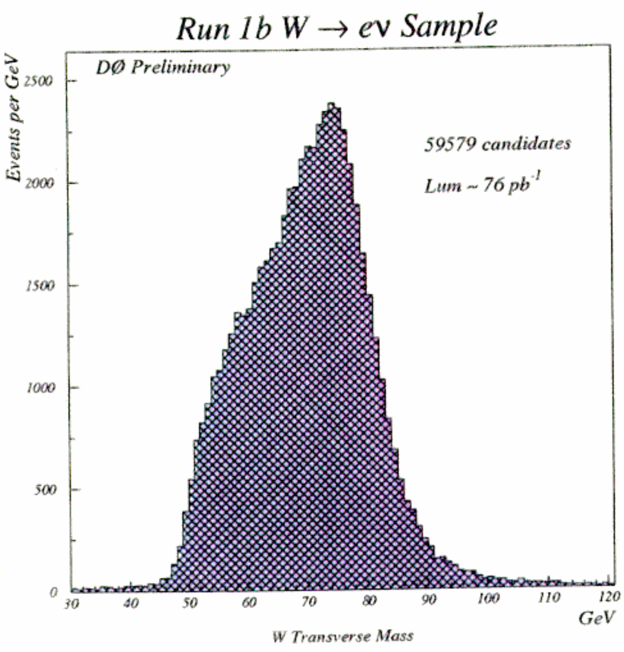
- Mass of W extracted from M_T^W:

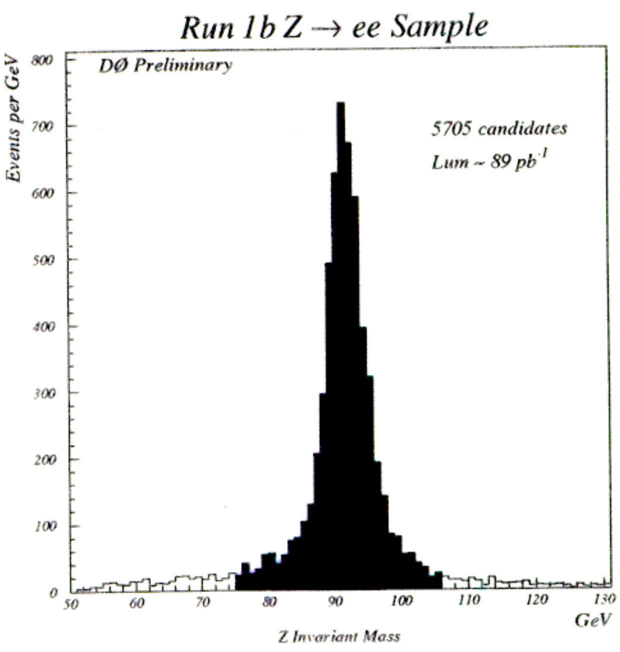
$$M_T^W = \sqrt{2E_T^l E_T^\nu(1 - \cos\Delta\phi^{l,\nu})}$$

- Background contamination:

  $<15\%$ for W, $<5\%$ for Z

  (QCD, cosmic rays, etc.)



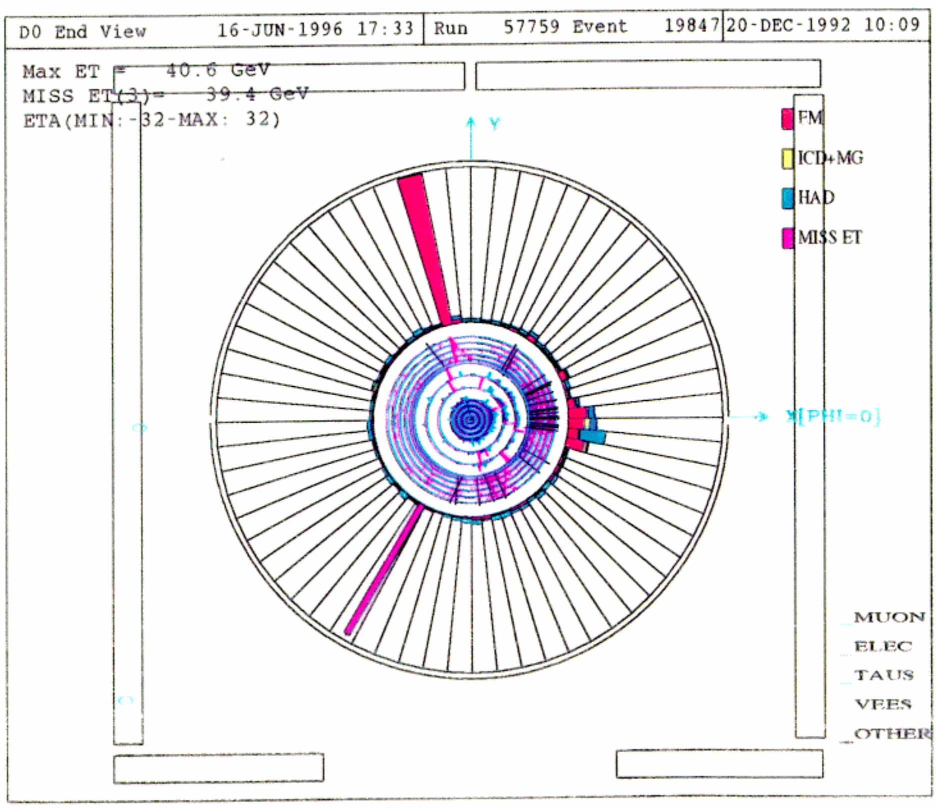


W and Z Production

$$p\bar{p} \to W + X, \quad W \to l\nu \qquad\qquad p\bar{p} \to Z + X, \quad Z \to ll$$

- At $\sqrt{s} = 1.8$ TeV:
  - ⋆ valence-sea contribution $\approx 55\%$
  - ⋆ sea-sea $\approx 20\%$
- W/Z identified via leptonic decays: $l = e, \mu, (\tau)$
  - ⋆ Isolated, high-p_T (>20-25 GeV/c) charged lepton(s)
  - ⋆ Neutrino in W decays "detected" via $\not\!\!E_T$:

$$\not\!\!E_T \equiv -(\text{observed } E_T) = E_T^{\nu} \ (>20\text{-}25 \text{ GeV})$$



W & Z Cross Sections

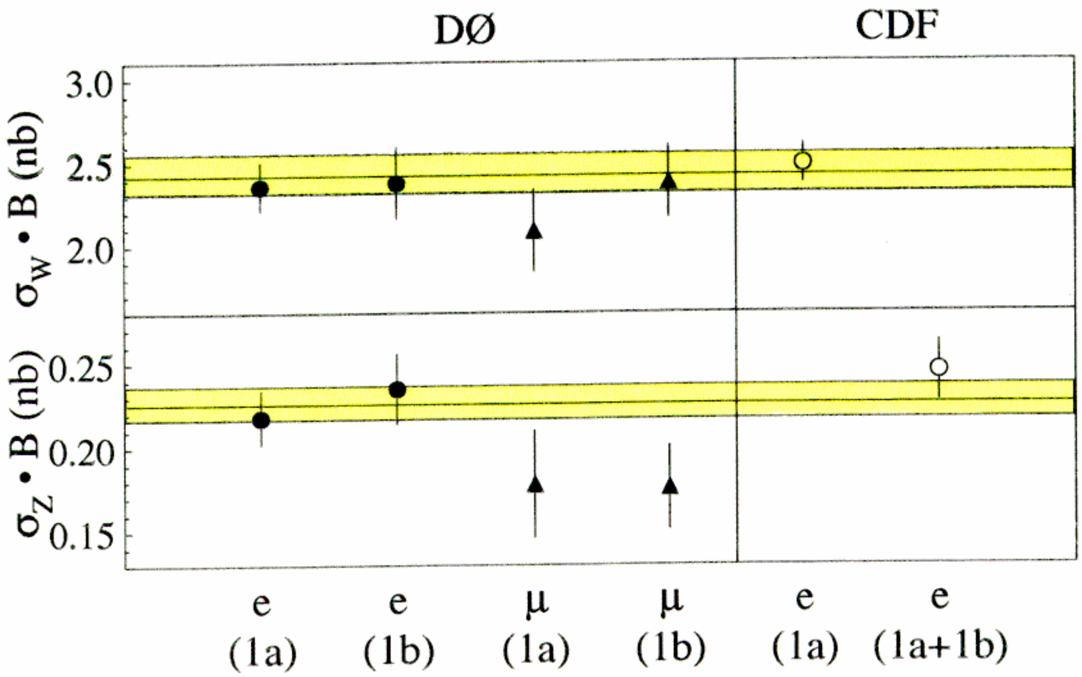
$$\sigma \cdot B = \frac{N_C - N_B}{\mathcal{L}} \cdot \frac{1}{\mathcal{A}\mathcal{E}}$$

N_C = number of candidates
N_B = estimated background
$\mathcal{L}$ = integrated luminosity
$\mathcal{A}$ = acceptance
$\mathcal{E}$ = efficiencies

- **Measurements available from:**
  - **DØ: e, μ channels**
    (Run 1A and Run 1B data samples)
  - **CDF: e channel**
    (Run 1A (W), Run 1A+1B (Z) data samples)
- **Theoretical prediction at $\mathcal{O}(\alpha_s^2)$ (CTEQ2M)**
  - *R. Hamberg et al., Nucl. Phys. B359, 343 (1991)*
  - *van Neerven & Zijlstra, Nucl. Phys. B382, 11 (1992)*

	DØ (e)	CDF (e)
$\int \mathcal{L}dt$ (pb^{-1})	75.9 ± 6.4	19.7 ± 0.7
W candidates	59,579	13,796
$\mathcal{A}_W$ (%)	43.4 ± 1.5	34.2 ± 0.8
$\mathcal{E}_W$ (%)	70.0 ± 1.2	72.0 ± 1.3
Bkg W (%)	8.1 ± 0.9	12.3 ± 1.2

W & Z Cross Sections (cont.)



- **Dominant uncertainties:**
  - ▹ **Theory: pdf's (3-5%)**
  - ▹ **Data: luminosity**

	$\sigma \cdot B(W \to l\nu)$ (nb)	$\sigma \cdot B(Z \to ll)$ (nb)
DØ(e) (Run 1B)	2.38 $\pm 0.01 \pm 0.09 \pm 0.20$	0.235 $\pm 0.003 \pm 0.005 \pm 0.020$
DØ(μ) (Run 1B)	2.38 $\pm 0.03 \pm 0.17 \pm 0.13$	0.176 $\pm 0.011 \pm 0.020 \pm 0.009$
CDF(e)	2.49 $\pm 0.02 \pm 0.08 \pm 0.09$ (Run 1A)	0.245 $\pm 0.004 \pm 0.004 \pm 0.018$ (Run 1A+1B)
Standard Model	2.42 ± 0.12	0.226 ± 0.010

Extracting Γ_W

$$R_\ell = \frac{\sigma \cdot B(W \to \ell\nu)}{\sigma \cdot B(Z \to \ell\ell)} = \frac{\sigma_W}{\sigma_Z} \cdot \underbrace{\frac{\Gamma(Z)}{\Gamma(Z \to \ell\ell)}}_{B^{-1}(Z \to \ell\ell)} \cdot \frac{\Gamma(W \to \ell\nu)}{\Gamma(W)}$$

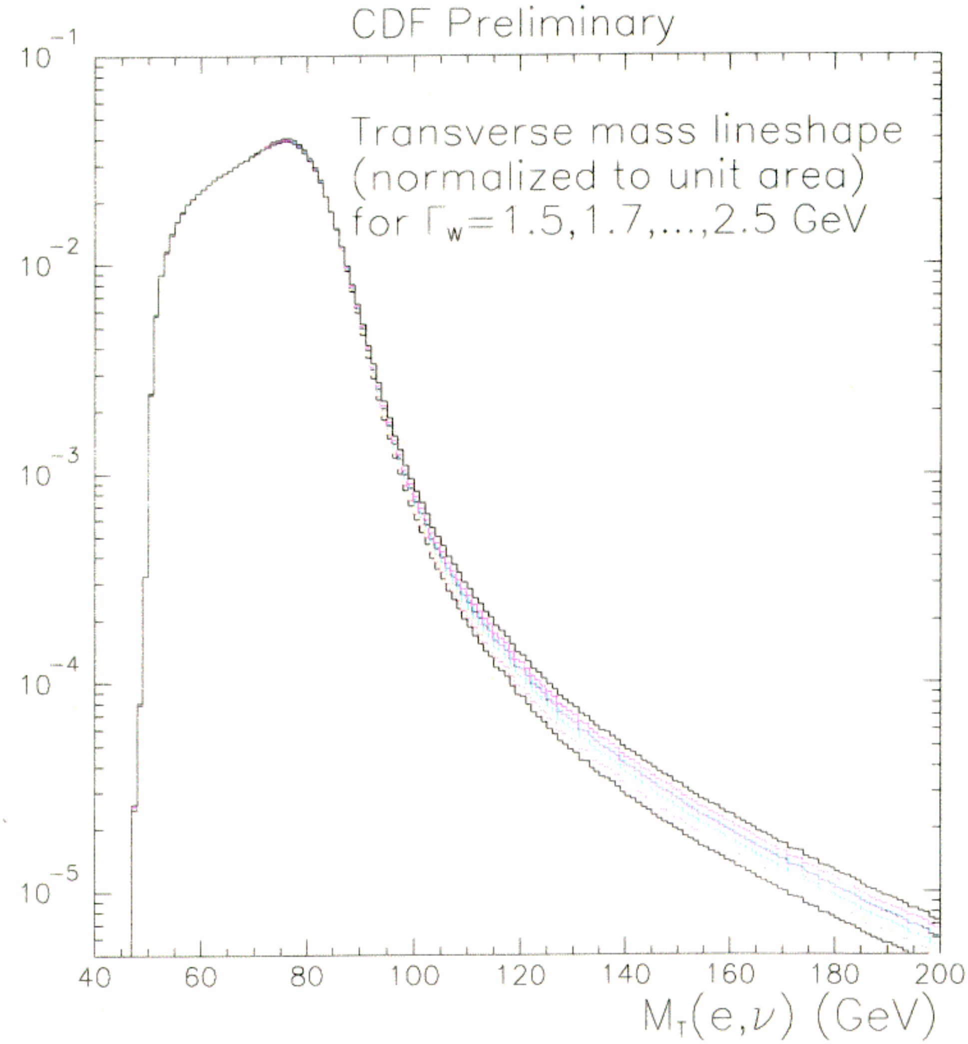
- Measure R_ℓ directly (expt'l errors tend to cancel)
- Obtain remaining quantities on RHS to extract Γ_W:
  - ▹ $\frac{\sigma_W}{\sigma_Z} = 3.33 \pm 0.03$ (theory)
    R. Hamberg et al., Nucl. Phys. B359, 343 (1991)
  - ▹ $B(Z \to \ell\ell) = (3.367 \pm 0.006)\%$ (LEP/SLC)
  - ▹ $\Gamma(W \to \ell\nu) = \frac{G_F}{\sqrt{2}} \frac{M_W^3}{6\pi} (1 + \delta) = 225.2 \pm 1.5$ MeV
    Rosner et al., PRD49, 1363 (1994)

DØ ($e + \mu$) Run 1B Preliminary	
R_ℓ	10.48 ± 0.43
$B(W \to \ell\nu)$ (%)	10.59 ± 0.44
Γ_W (GeV)	2.126 ± 0.092
Standard Model (GeV)	2.077 ± 0.014

⋆ Expect $\sim \times 2$ reduction in error for final result

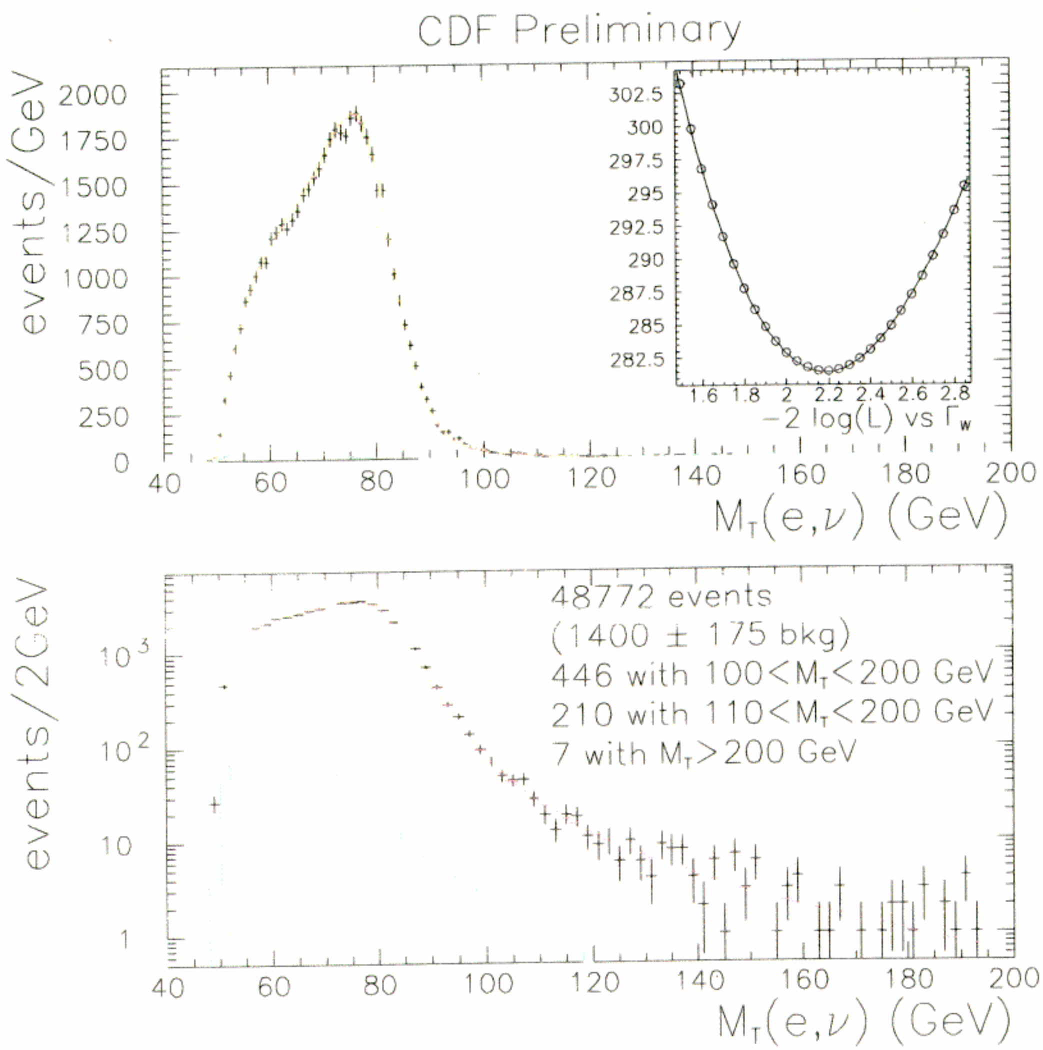
Direct Measurement of Γ_W (CDF)

- High tail region of M_T distribution sensitive to Γ_W
  - ▷ Breit-Wigner shape > calorimeter resolutions
  - ▷ Measurement independent of theoretical input



- Log-likelihood fit to Monte Carlo-generated templates with varying Γ_W
- Fit window: $110 < M_T < 200$ GeV (210 events – Run 1B)
- e channel only

Direct Measurement of Γ_W (cont'd)

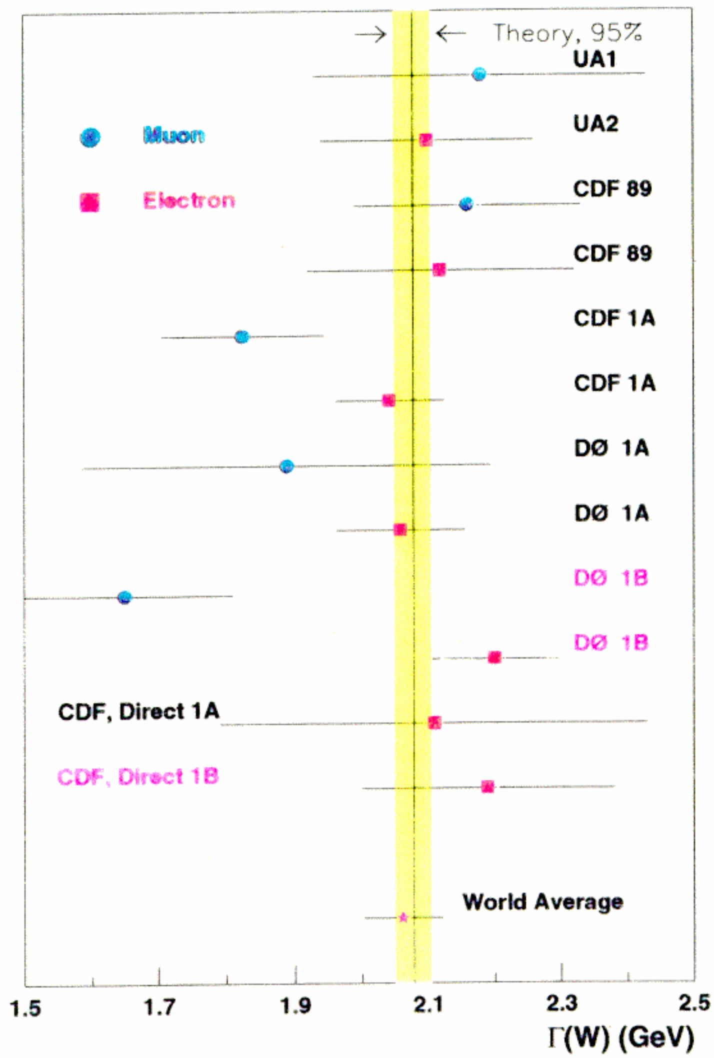


$$\Gamma_W = 2.19 \pm 0.17 \pm 0.09 \text{ GeV}$$

$$(\Gamma_W^{SM} = 2.077 \pm 0.014 \text{ GeV})$$

- Systematic errors dominated by:
  - ▷ W recoil modeling – 55 MeV
  - ▷ electron energy scale – 55 MeV
  - ▷ backgrounds – 40 MeV

Summary of Γ_W



$\Gamma_W = 2.062 \pm 0.059$ World Average

$\Gamma_W = 2.077 \pm 0.014$ SM Prediction

$\Downarrow$

$$\Delta\Gamma_W^{\text{non-SM}} < 109 \text{ MeV } (95\% \text{ CL})$$

Upper limit on unexpected contributions to Γ_W
(supersymmetric charginos or neutralinos, heavy quarks)

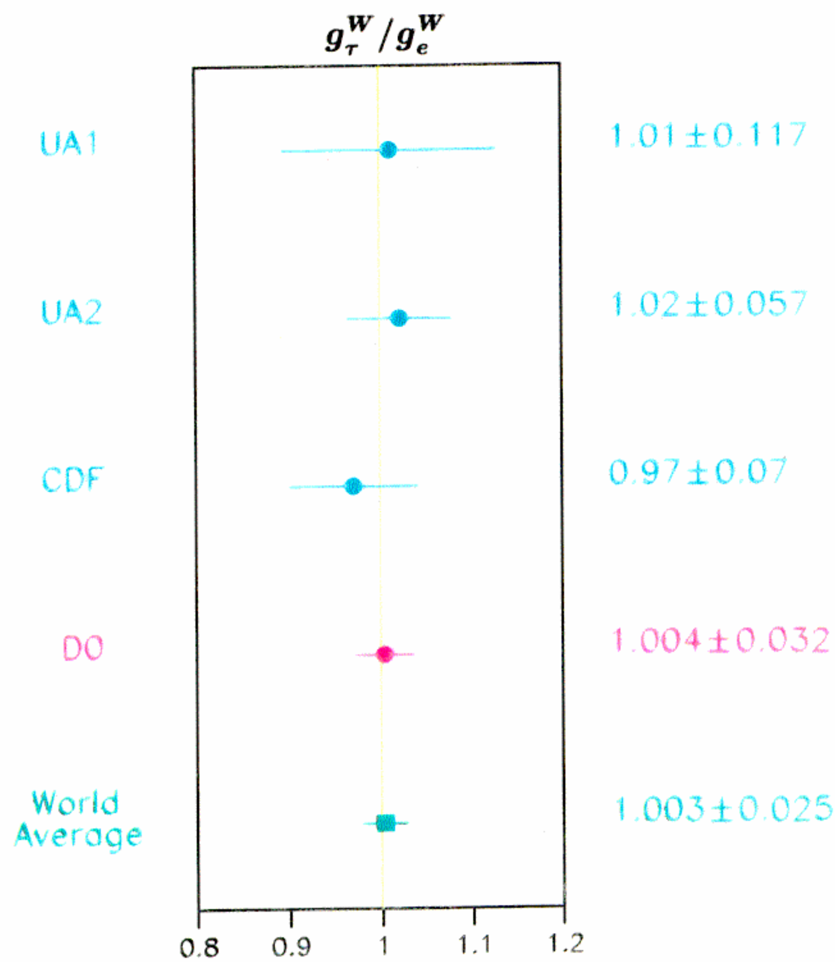
Lepton Universality

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

- **Select hadronic decays of τ:**
  - ▷ Isolated, narrow, high-E_T jet (> 15-25 GeV)
  - ▷ Few associated charged tracks (1,3 prong decays)
  - ▷ Large $\not{E}_T$ (> 20-25 GeV)
  - ▷ No jet opposite in azimuth (QCD background)
- **Recent preliminary DØ result:**
  - ▷ 17 pb^{-1}, 1202 candidates, 222 ± 16 background:

$$\sigma \cdot B(W \to \tau\nu) = 2.38 \pm 0.09 \pm 0.10 \text{ nb}$$

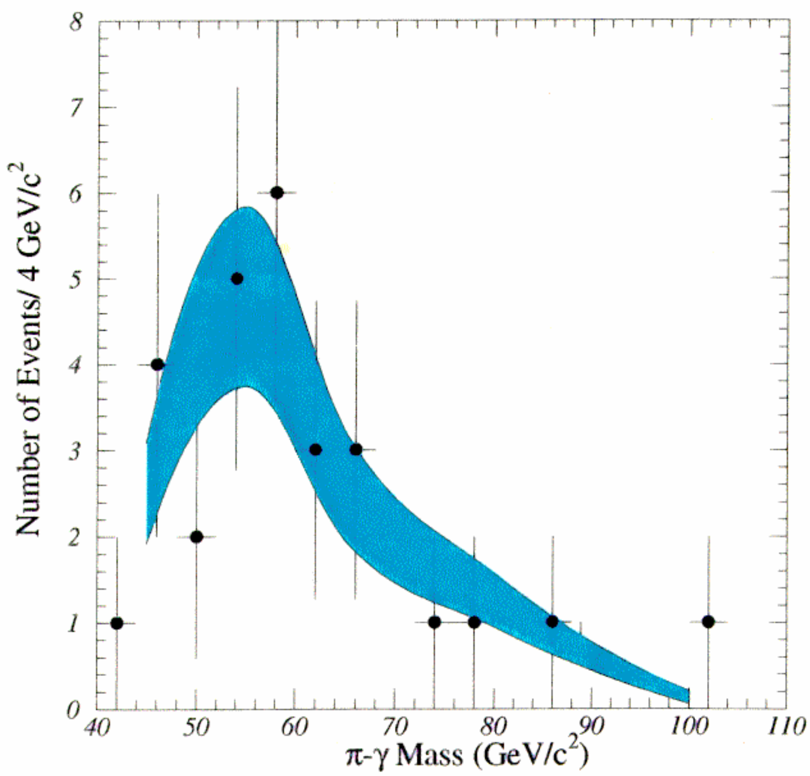
$$\Rightarrow g_\tau^W / g_e^W = 1.004 \pm 0.019 \pm 0.026$$



Rare W Decays

$W^\pm \to \pi^\pm \gamma$

- Theory: $\Gamma(W \to \pi\gamma/\Gamma(W \to e\nu) \sim 3 \times 10^{-8}$
  L. Arnellos et al., Nucl. Phys. B196, 378 (1982)
- Previous experimental limits:
  - ⋆ UA2: $\lesssim 5 \times 10^{-3}$ (1992)
  - ⋆ CDF: $\lesssim 2 \times 10^{-3}$ (Run 1A)
    - ▷ One isolated high-p_T photon (>23 GeV/c)
    - ▷ Jet with isolated high-p_T charged track (>15 GeV/c)
    - ▷ CDF Run 1B: $\epsilon \times \mathcal{A} \sim 4\%$, $\int \mathcal{L}dt = 83\ \text{pb}^{-1}$



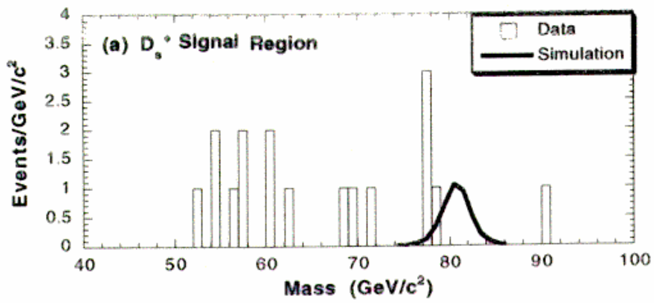
- 3 events in π-γ mass spectrum within $M_W \pm 3\sigma$
- Est. background: (5.2 ± 1.5) events (QCD direct photons)

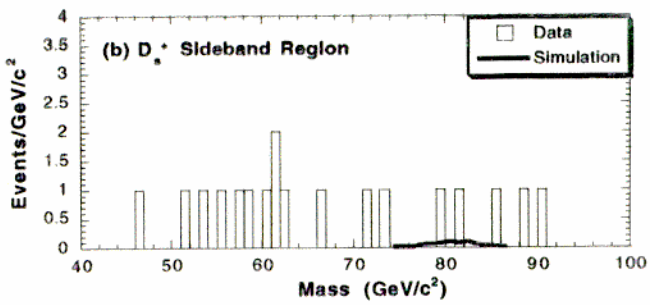
$$\Rightarrow \sigma_W \cdot B(W \to \pi\gamma) \lesssim 1.7\ \text{pb}\ (95\%\ \text{CL})$$
$$\Gamma(W \to \pi\gamma)/\Gamma(W \to e\nu) \lesssim 7 \times 10^{-4}$$

Rare W Decays (cont'd)

$$W^{\pm} \to D_s^{\pm}\gamma$$

- Theory: $\Gamma(W \to D_s\gamma)/\Gamma(W \to e\nu) \sim 1 \times 10^{-8}$
- First experimental limit on this branching fraction
  - ⋆ One isolated high-p_T photon (>22 GeV/c)
  - ⋆ One isolated high-p_T D_s candidate(>22 GeV/c):
    - ▷ $D_s^{\pm} \to \phi\pi^{\pm}$, $\phi \to K^+K^-$
    - ▷ $D_s^{\pm} \to K^{*0}K^{\pm}$, $K^{*0} \to K^{\pm}\pi^{\mp}$
  - ⋆ CDF Run 1B: $\epsilon \times \mathcal{A} \sim 7\%$, $\int \mathcal{L}dt = 82$ pb^{-1}





- 4 candidates in D_s-γ mass spectrum within $M_W \pm 3\sigma$
- Estimated background of 4 events (QCD direct photons)

$$\Rightarrow \sigma_W \cdot B(W \to D_s\gamma) \leq 27.4 \text{ pb (95\% CL)}$$

$$\Gamma(W \to D_s\gamma)/\Gamma(W \to e\nu) \leq 1.1 \times 10^{-2}$$

With 10 fb^{-1}, expect $\leq 10^{-6}$ for these types of processes. Long shot, but Run 2 may reveal something new here...

Drell-Yan Probe of Substructure

$$q\bar{q} \rightarrow (\gamma, Z) \rightarrow l^+ l^-$$

- Broad range of partonic cms energies available in $\bar{p}p$ collisions
  - ▷ Low mass ⇒ low x probe ($x \approx 0.006$)
  - ▷ High mass ⇒ high x, partonic substructure
- Contact interaction:

Eichten at al., PRL 50, 811 (1983)

$$\mathcal{L} = \mathcal{L}_{SM} + \eta_{ij} \frac{g_0^2}{\Lambda_{ij}^2} \left(\bar{\psi}_i \gamma^\mu \psi_i\right) \left(\bar{\psi}_j \gamma_\mu \psi_j\right)$$

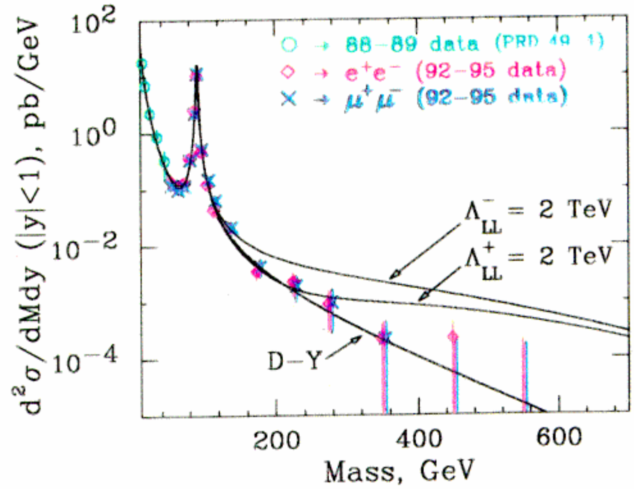
  - ▷ Λ_{ij}^{η} = compositeness scale
  - ▷ $\eta_{ij} = +(-)1$ destructive (constructive) interference
  - ▷ $i, j = L,R$ chirality
- Gives rise to predicted Drell-Yan cross section of form:

$$\frac{d\sigma}{dm} = \left(\frac{d\sigma}{dm}\right)_{DY} + \beta I + \beta^2 C$$

  - ▷ m = dilepton invariant mass
  - ▷ $\beta = 1/(\Lambda_{ij}^{\pm})^2$
  - ▷ I = Drell-Yan/contact term interference
  - ▷ C = pure contact term contribution to xsec
  - ▷ enhancement at high mass
- Measure $M_{ll} \geq 40$ GeV
  - ▷ Isolated ee, $\mu\mu$ pairs, p_T^l >20-25 GeV
  - ▷ Backgrounds: dijets, $Z \rightarrow \tau\tau$, cosmic rays

Drell-Yan (cont'd)

- Normalize predictions to observed cross section for $50 < M_{ll} < 150$ GeV (removes luminosity dependence)
- Binned likelihood fit as function of $\Lambda^{\pm}_{ij}$:



	DØ ($eeqq$) 121 pb^{-1}		CDF ($llqq$) 110 pb^{-1}	
Model (i,j)	Λ^+ (TeV)	Λ^- (TeV)	Λ^+ (TeV)	Λ^- (TeV)
LL	3.3	4.2	3.1	4.3
RR	3.3	4.0	3.0	4.2
LR	3.4	3.6	3.3	3.9
RL	3.3	3.7	3.3	3.7
VV	4.9	6.1	5.0	6.3
AA	4.7	5.5	4.5	5.6

- Other (representative) measurements:
  - ▷ $qqqq \Rightarrow$ 2.4-2.7 TeV (DØ – submitted to PRL)
  - ▷ $eeqq \Rightarrow$ 2.0-4.9 TeV (ZEUS – ICHEP '98)
  - ▷ $eeqq \Rightarrow$ 2.8-6.3 TeV (OPAL – ICHEP '98)
  - ▷ $eell \Rightarrow$ 5.2-11.8 TeV (ALEPH – ICHEP '98)
  - ▷ $\nu\nu qq \Rightarrow$ 4.2-8.3 TeV (CCFR)
  - ▷ $\nu\nu e\mu \Rightarrow$ 3.1 TeV (TRIUMF E185)
- Fundamental composition of matter being probed in variety of reactions; limits from $\sim 2 - 11$ TeV

W Mass

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

- M_Z, α, G_F known to better than 25 ppm
- Δr measure of higher order corrections in SM
  - ▹ γ vacuum polarization (≈ 0.06)
  - ▹ vector boson self-energies (M_{top}^2, $\ln(M_H^2/M_W^2)$ terms)
  - ▹ new physics (?)
  - ▹ $\Delta r \equiv 0$ at tree level (on-shell scheme)

+ Additional corrections in SUSY models
→ $\Delta m_W \propto$ 250 MeV

- Precision measurement of M_W:
  - ▹ measure of radiative corrections in SM
  - ▹ with M_{top}, provides constraint on M_H
  - ▹ tests the SM beyond tree level

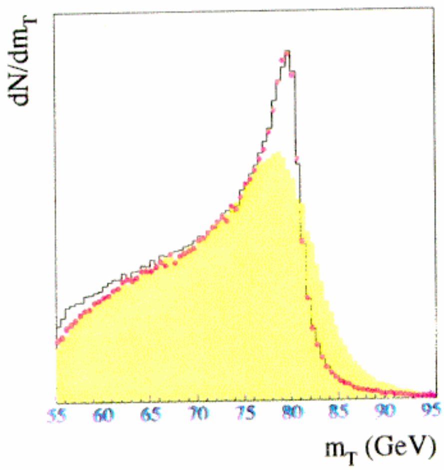
W Mass (cont'd)

- Longitudinal momentum of ν unknown $\Rightarrow$ transverse mass:

$$M_T = \sqrt{2E_T^l E_T^\nu \left(1 - \cos\Delta\phi_{l\nu}\right)}$$

(with E_T^ν inferred from $\not{E}_T$)

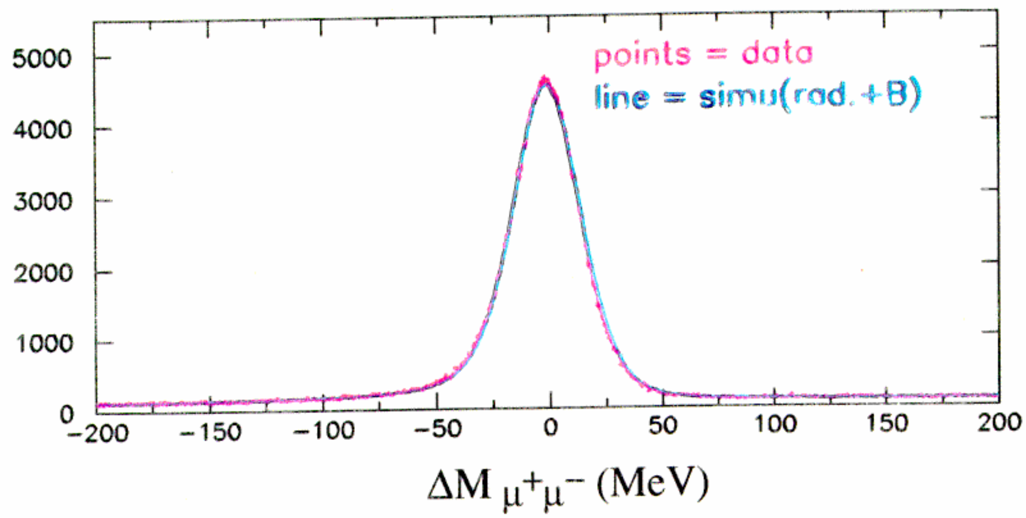
  - ▹ M_T invariant (to 1st order) under transverse Lorentz boosts (less sensitive to p_T^W)
  - ▹ No analytic form for resulting Jacobian $\Rightarrow$ MC



- Extract M_W from fits to observed M_W spectra
  - ▹ Generate M_T lineshapes as function of M_W via fast MC
  - ▹ Perform likelihood fit
- Fast Monte Carlo
  - ▹ Model W production and subsequent decay
  - ▹ Fold in detector response, resolution effects
  - ▹ Generate resulting M_T lineshapes for various input values of M_W
- Energy scale for both experiments anchored to measured invariant masses of known resonances
- Latest Tevatron results: Run 1B ($\approx$ 80-90 pb^{-1})
  - ▹ DØ: $W \to e\nu$, PRL 80 3000 (1998), PRD accepted
  - ▹ CDF: $W \to \mu\nu$, preliminary

W Mass (cont'd)

- **CDF Momentum Scale**
  - ▷ Normalize observed $J/\Psi \to \mu\mu$ peak to world average J/Ψ mass (250,000 events)



$$M_{J/\Psi}^{meas} = 3096.2 \pm 1.5 \text{ MeV}$$

$$M_{J/\Psi}^{PDG} = 3096.88 \pm 0.04 \text{ MeV}$$

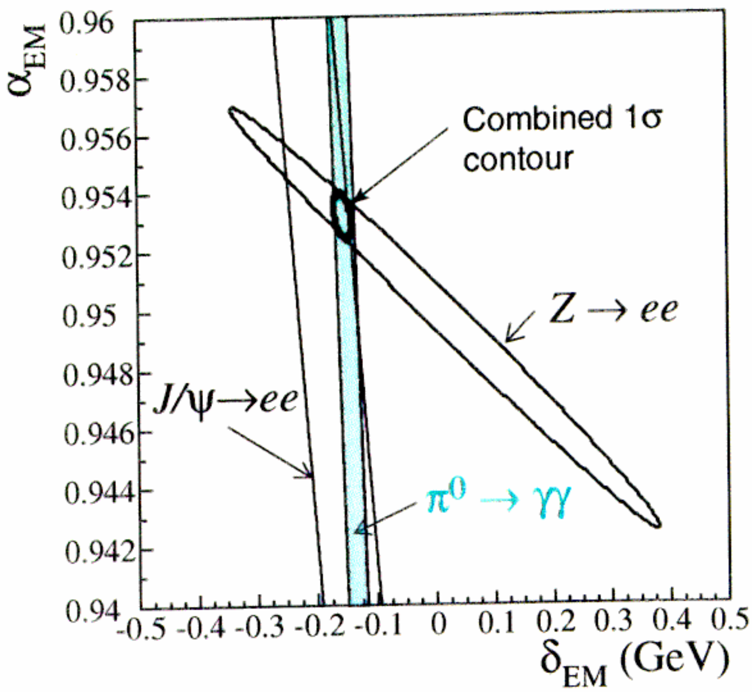
$$M_{J/\Psi}^{meas}/M_{J/\Psi}^{PDG} = 0.99977 \pm 0.00048$$

- Verified using $\Upsilon \to \mu\mu$ and $Z \to \mu\mu$ samples
- Dominant uncertainties are muon upstream energy loss and p_T dependence over relevant 3–40 GeV range ($\Delta M_{J/\Psi} = 1$ MeV, $\Delta M_W = 26$ MeV)

$$\Delta M_W = 40 \text{ MeV}/c^2$$

W Mass (cont'd)

- **DØ Electromagnetic Energy Scale**
  - ▷ Assume energy response of form: $E_{obs} = \alpha E_{true} + \delta$
  - ▷ Implies $M_{meas} \approx \alpha M_{true} + \delta f$ ($f = \frac{2(E_1+E_2)}{m} \sin^2 \gamma/2$)
  - ▷ Compare against MC prediction in (α, δ) grid for resonances reconstructed *in situ*:
    - ⋆ $Z \rightarrow ee$
    - ⋆ $\pi^0 \rightarrow \gamma\gamma \rightarrow eeee$
    - ⋆ $J/\Psi \rightarrow ee$



- J/Ψ and π^0 constrain δ; Z constrains α
- Including systematic errors from underlying event, non-linearities at low E:

$$\alpha = 0.9533 \pm 0.0008$$

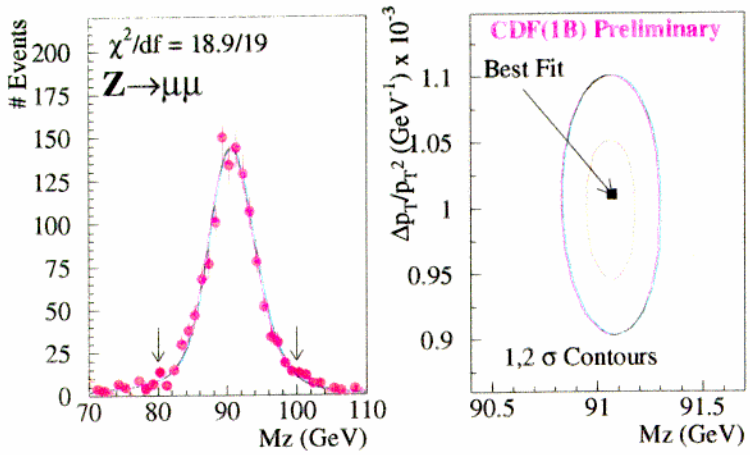
$$\delta = -0.16^{+0.03}_{-0.21} \text{ GeV}$$

$$\Delta M_W = 70 \text{ MeV}/c^2$$

(dominated by Z statistics)

W Mass (cont'd)

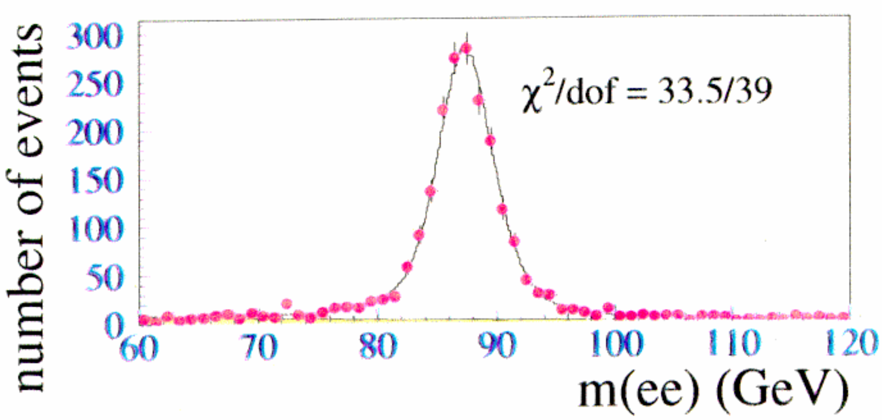
- **CDF Momentum Resolution**
  - ▹ 2-d fit for M_Z and $\sigma(1/p_T)$ in $Z \to \mu\mu$ events



$$\sigma(\tfrac{1}{p_T}) = (1.01 \pm 0.05) \times 10^{-3}$$

$$\Delta M_W = 25 \text{ MeV}/c^2$$

- **DØ EM Energy Resolution**
  - ▹ Use width of $Z \to ee$ to constrain constant term, C, in EM energy resolution: $\frac{\sigma(E)}{E} = \sqrt{C^2 + \frac{S}{\sqrt{E_T}}}$



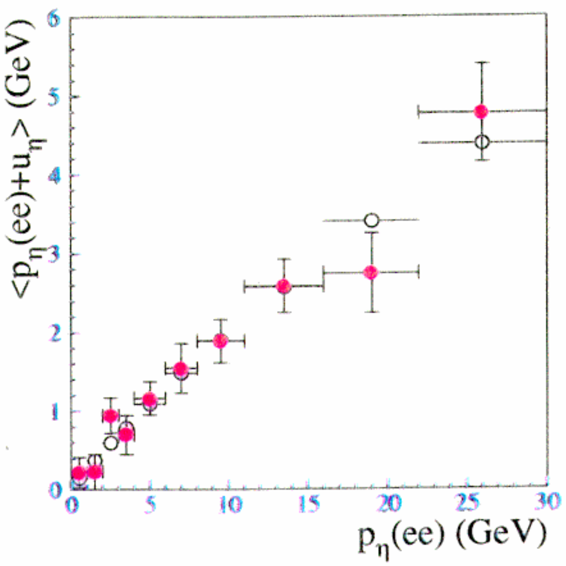
$$C = (1.5^{+0.27}_{-0.35})\%$$

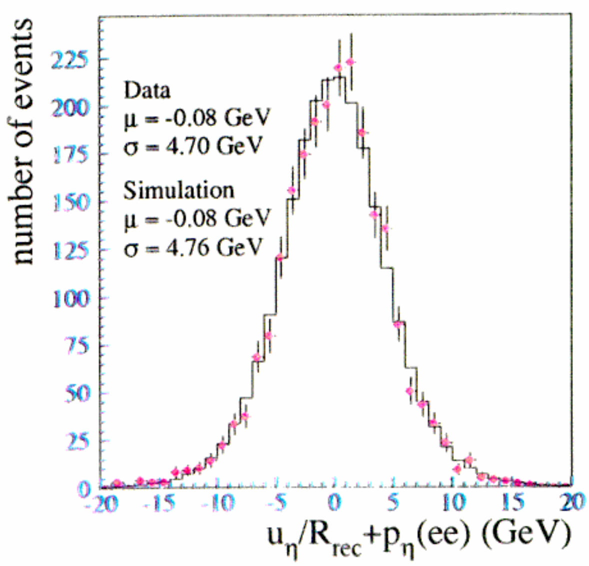
$$\Delta M_W = 20 \text{ MeV}/c^2$$

W Mass (cont'd)

- **Recoil Energy Scale and Resolution**
  - ▷ Hadronic scale and resolution obtained from p_T balance in $Z \to ee, \mu\mu$ decays (constrained)
    - ⋆ For equal EM and hadronic response, $\vec{p}_T^{ee} = \vec{p}_T^{rec}$ (on average)
    - ⋆ Recoil resolution extracted from width of $|\vec{p}_T^{ee} + \vec{p}_T^{rec}|$ distribution

      (Project quantities onto axis defined by inner bisector of $\vec{p}_T^{e_1}$ and $\vec{p}_T^{e_2}$ ("$\vec{\eta}$" axis))
  - ▷ Hadronic scale determined relative to scale for charged leptons

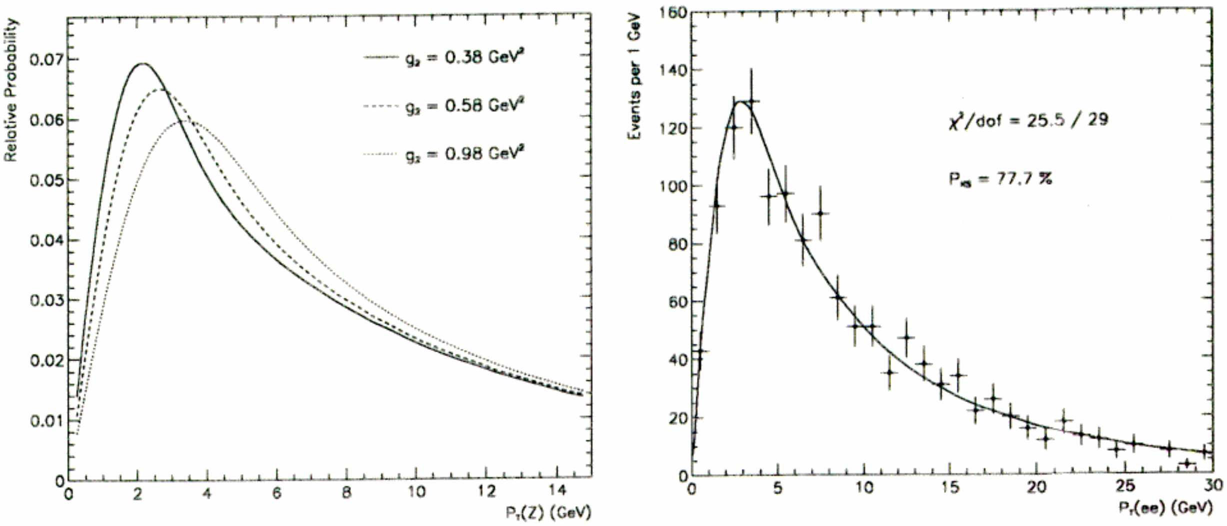




- **DØ:**
  - ▷ $\Delta M_W = 20$ MeV/c^2 (recoil energy scale)
  - ▷ $\Delta M_W = 25$ MeV/c^2 (recoil energy resolution)
- **CDF:**
  - ▷ $\Delta M_W = 90$ MeV/c^2 (recoil energy scale and resolution)
  - ▷ Set conservatively, will improve

W Production Model

p_T^W spectrum constrained by p_T^Z:



- Large p_T region described by pQCD
- Low p_T region: non-perturbative regime
  - ▷ Ladinsky/Yuan: LO QCD matched with resummed calculation (*PRD 50, 4239 (1994)*)
  - ▷ 3 parameters describing non-perturbative effects: g_1, g_2, g_3
  - ▷ g_2 most sensitive to shape effects
- Use p_T^Z spectra to fit for g_2 (and Λ_{QCD}):
  - ⋆ $g_2 = 0.59 \pm 0.095(\text{stat}) \pm 0.052(\text{sys}) \pm 0.013(\text{pdf})\ \text{GeV}^2$
- Used to generate p_T^W spectra

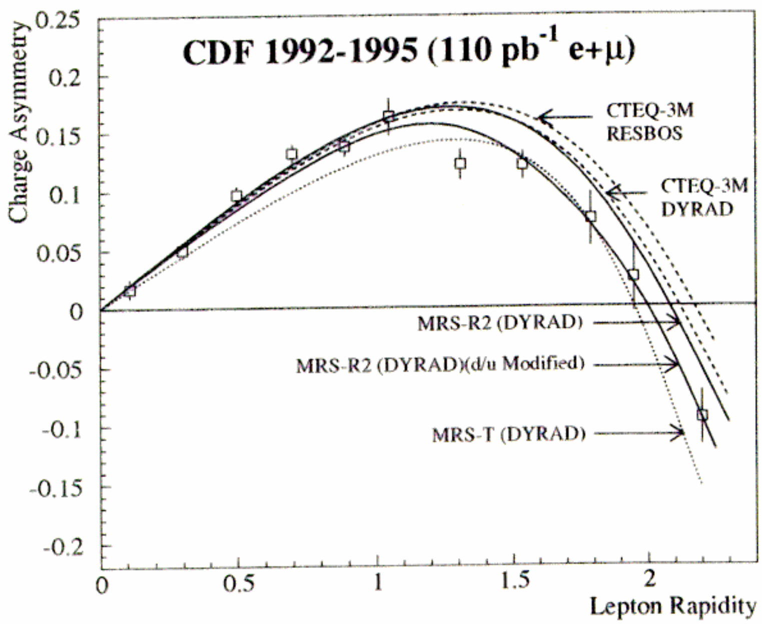
W Charge Asymmetry, PDFs

- ⋆ W production asymmetry
  - → u quarks have larger momentum than d quarks
  - → W^+ boosted along p direction ($u\bar{d} \to W^+$)
  - → W^- boosted along $\bar{p}$ direction ($\bar{u}d \to W^-$)

$$A(y_l) = \frac{d\sigma^+/dy_l - d\sigma^-/dy_l}{d\sigma^+/dy_l + d\sigma^-/dy_l}$$

(Unfold V-A charge asymmetry of decay leptons: $\sim (1 \pm cos\theta)^2$)

- ⋆ Asymmetry measurement provides useful constraints on parton distribution functions in the low x region ($0.007 < x < 0.24$) at $Q^2 \approx M_W^2$



- ⋆ W production and decay modeling (p_T^W, PDFs, radiative decays, Γ_W):

DØ: $\Delta M_W = 30$ MeV/c^2

CDF: $\Delta M_W = 55$ MeV/c^2

W Mass (cont'd)

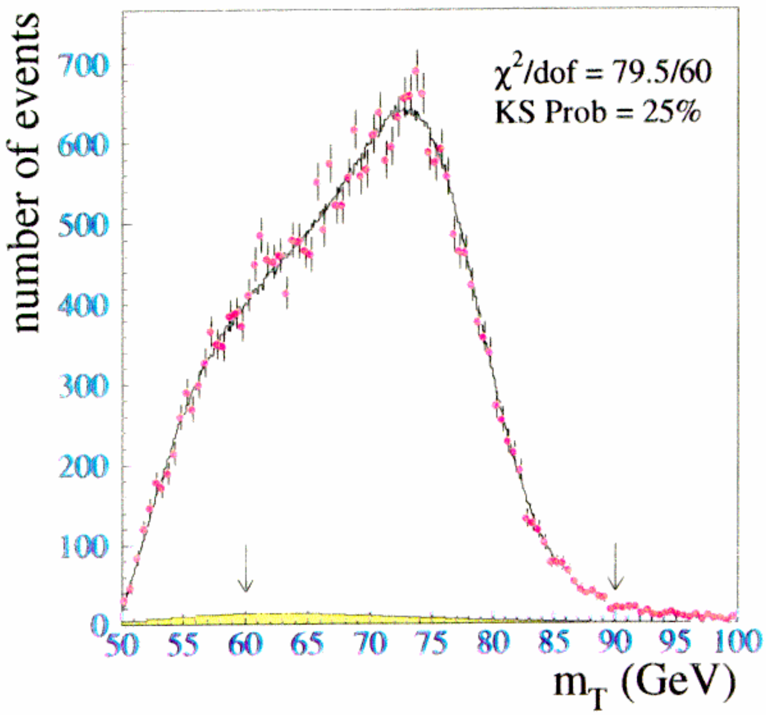
Summary of Errors on M_W (MeV/c^2)

Source	CDF (μ)	DØ (e)
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 Error	155	115

W Mass (cont'd)

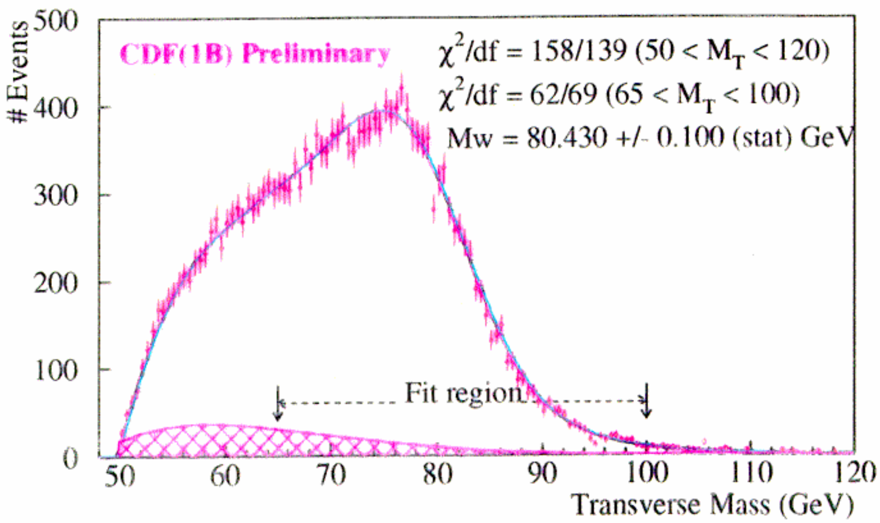
Transverse Mass Fits/Results

DØ($W \to e\nu$)



$$M_W^{DØ} = 80.440 \pm 0.095(\text{stat.}) \pm 0.065(\text{syst.}) \;\; \text{GeV/c}^2$$

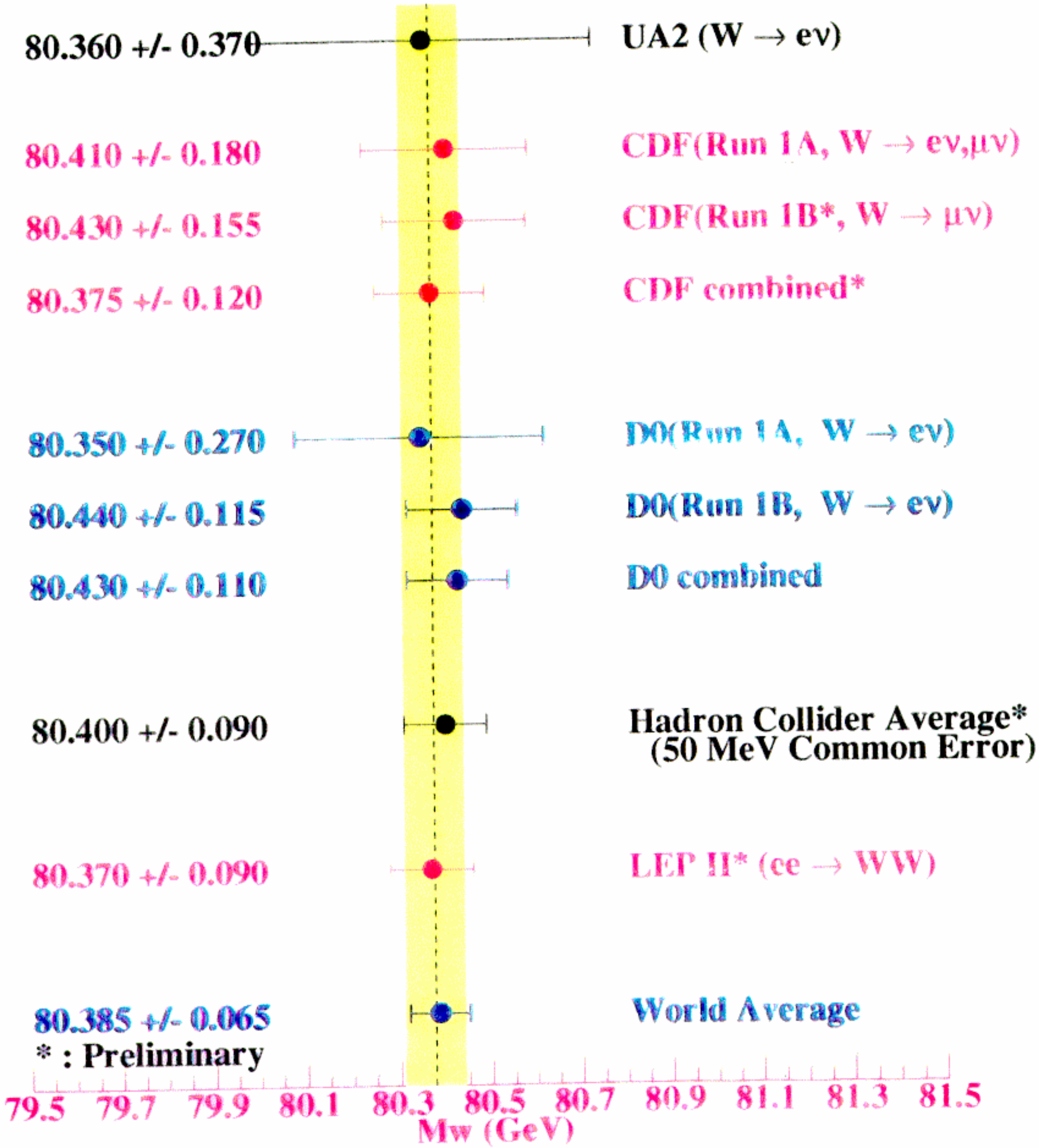
CDF($W \to \mu\nu$)



$$M_W^{CDF} = 80.430 \pm 0.100(\text{stat.}) \pm 0.120(\text{syst.}) \;\; \text{GeV/c}^2$$

W Mass (cont'd)

Direct W Mass Measurements



World Average = UA2+DØ+CDF+LEP2 (Direct)

Including NuTeV ($M_W^{\nu T} = 80.250 \pm 0.110$ GeV/c^2) gives:

$$M_W^{all} = 80.350 \pm 0.055 \text{ GeV/c}^2$$

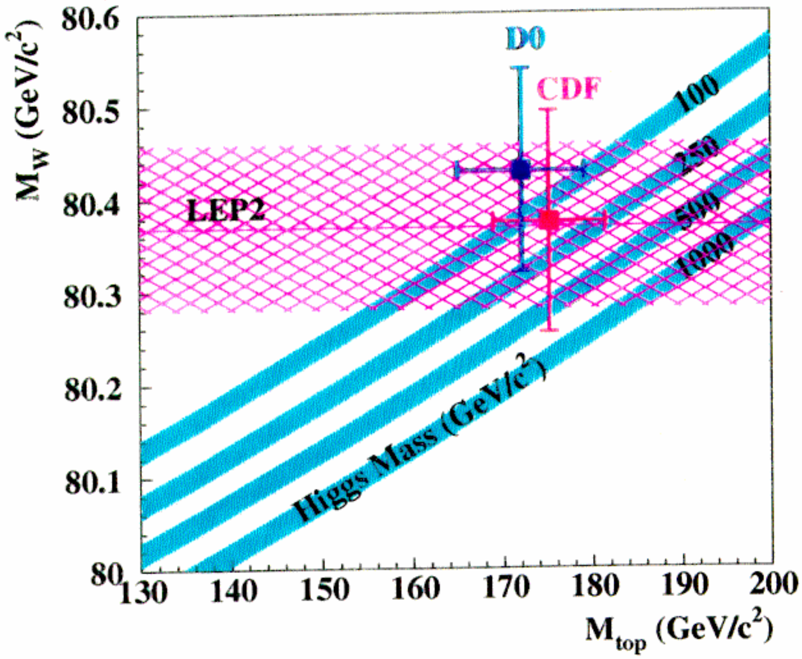
Prospects at the Tevatron

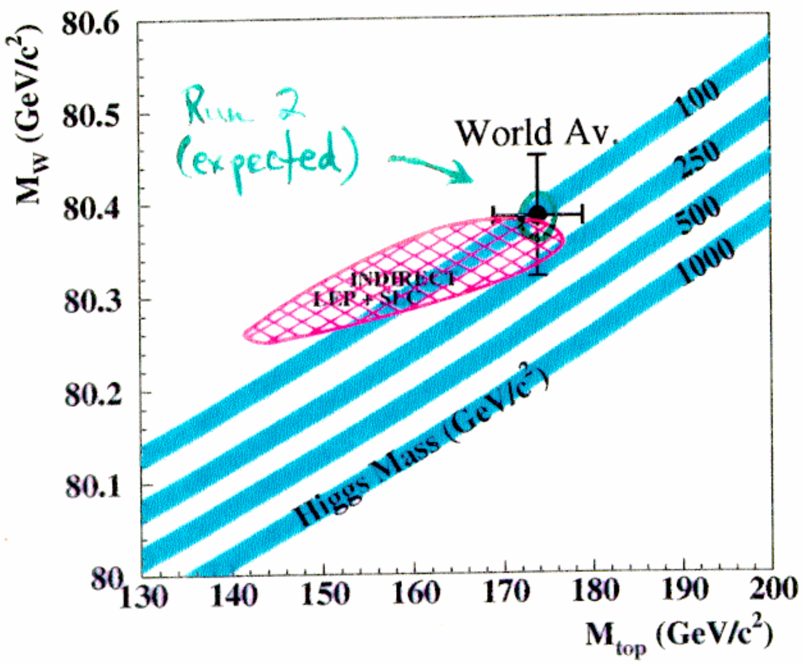
- Most systematic errors in M_W are statistically limited
- Further analysis of Run 1 data:
  - ▷ DØ: use forward electrons
    $\Rightarrow \Delta M_W \sim 100$ MeV/c^2
  - ▷ CDF: Finalize μ result (reduced errors), include e channel
    $\Rightarrow \Delta M_W \sim 90$ MeV/c^2
  - ▷ Final Tevatron Run 1 result:
    $\Rightarrow \Delta M_W \sim 75$ MeV/c^2
- Run 2 with Main Injector – begins April, 2000
  - ▷ $\times 20$ more $\int \mathcal{L}dt$ (> 2 fb^{-1})
  - ▷ $\mathcal{L}_{inst} \approx \times 10$
  - ▷ bunch spacing: 3.5μs $\rightarrow$ 400 (132) nsec
- Extensive detector upgrades now in progress:
  - ▷ DØ:
    - ⋆ new solenoid (precision μ's), new inner tracker (silicon, fiber tracker, preshowers), muon upgrade
  - ▷ CDF:
    - ⋆ new inner tracker (silicon and drift chamber), new scintillator-based forward calorimeter, extended μ coverage

⋆ Each experiment: $\Delta M_W \sim 40$ MeV/c^2

⋆ Combined: $\Delta M_W \sim 25$ MeV/c^2, $\Delta M_{top} \sim 2$ GeV/c^2

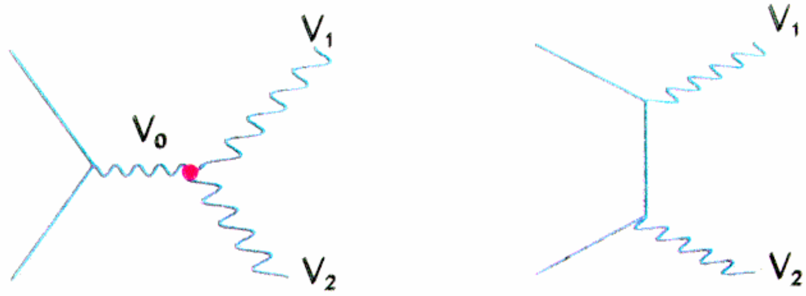
M_W vs. M_{top}





World Avg (Direct) $M_W = 80.385 \pm 0.065$ GeV/c^2
(UA2+DØ+CDF+LEP2)
DØ+CDF Top Mass: $M_{top} = 173.9 \pm 5.0$ GeV/c^2
(see talk by G. Apollinari)

Trilinear Gauge Boson Couplings



- Direct consequence of SU(2)×U(1) gauge symmetry
- Reduced Lagrangian described by four coupling parameters in each of the W and Z sectors (CP conserving/violating):
  - ▷ WWV ($V = \gamma$ or Z): $\kappa, \lambda, \tilde{\kappa}, \tilde{\lambda}$
  - ▷ $ZV\gamma$ ($V = \gamma$ or Z): $h_{30}, h_{40}, h_{10}, h_{20}$
- Gauge invariance of SM constrains boson self-couplings:
  - ▷ $\Delta\kappa \equiv \kappa - 1 = \lambda = 0$
  - ▷ $\tilde{\kappa} = \tilde{\lambda} = 0$
  - ▷ all $h_{i0} = 0$
- WWV parameters related to fundamental properties of the W boson:

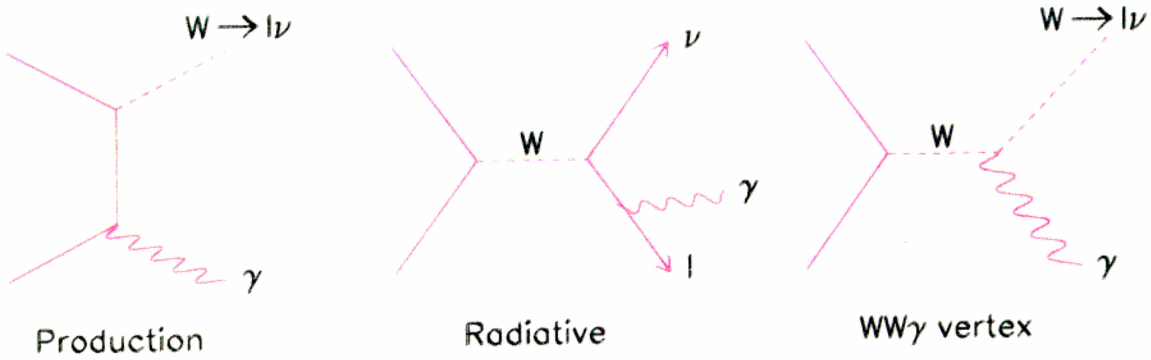
$$\mu_W^m = \frac{e}{2M_W}(1 + \kappa + \lambda) \qquad Q_W^e = \frac{-e}{M_W^2}(\kappa - \lambda)$$

- If couplings anomalous:
  - ▷ Gauge cancellations destroyed
  - ▷ Increase of production cross section at large $\sqrt{\hat{s}}$
  - ▷ Change in differential distributions (*i.e.*, p_T^γ, p_T^W)
  - ▷ Form factor introduced to avoid violation of unitarity:

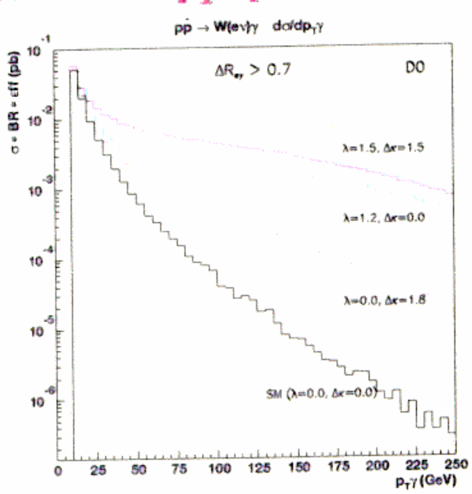
$$ff = \left[1/\left(1 + \hat{s}/\Lambda^2\right)\right]^n, \; n = 2(WWV), \; 3(h_{1,3}), \; 4(h_{2,4})$$

⋆ Investigation of trilinear couplings provides important test of SM – could provide window to new physics

$W\gamma$ Production



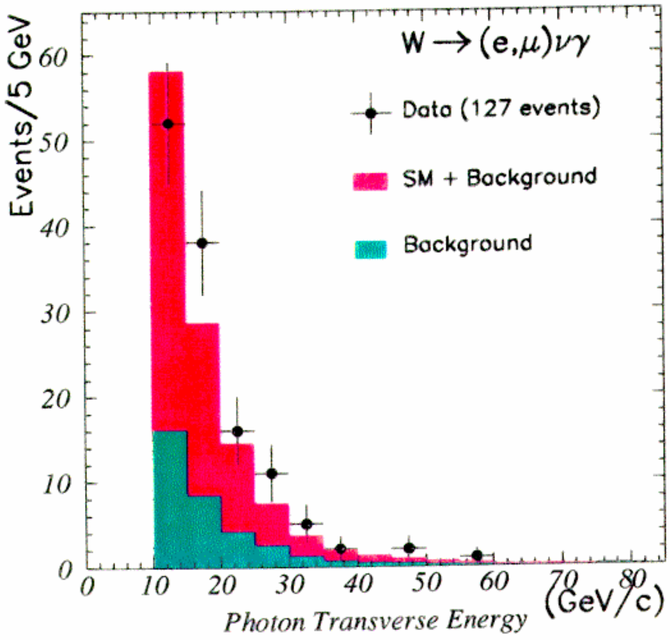
- **Event selection:**
  - ▷ Isolated high p_T muon or electron + large $\not{E}_T$
  - ▷ Isolated photon with $p_T^\gamma > 7$ (CDF) or 10 (DØ) GeV/c
  - ▷ $\Delta R_{l\gamma} > 0.7$ (suppresses contribution from radiative decays)
- **Primary background:** $W+$ jets (with jet $\to \pi^0 \to \gamma\gamma$)
- **Binned likelihood fit to p_T^γ spectrum**

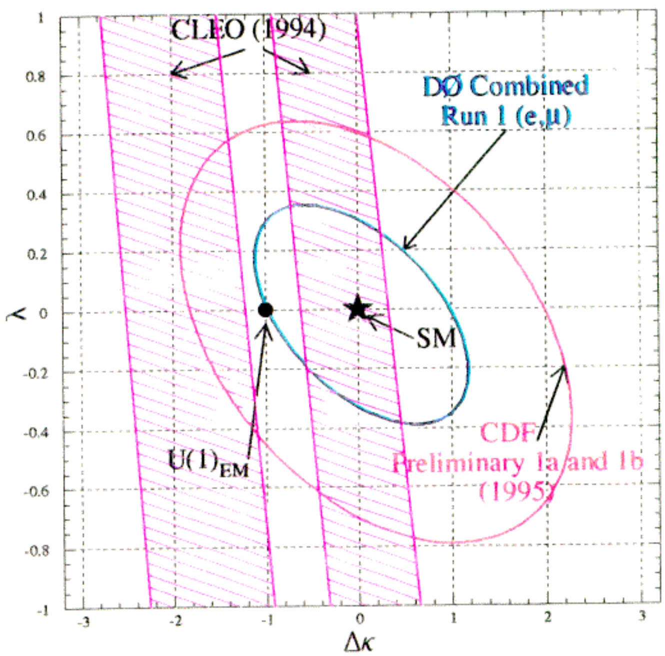


	DØ	CDF
$\int \mathcal{L}dt$ (pb^{-1})	93	67
Number of candidates	127	109
Total background	42.9 ± 5.3	26.4 ± 3.1

$W\gamma$ Production (cont'd)

DØ p_T^γ spectrum





- **DØ limits at 95% CL, $\Lambda = 1.5$ TeV:**

  $-0.93 < \Delta\kappa_\gamma < 0.94$ (for $\lambda_\gamma = 0$)

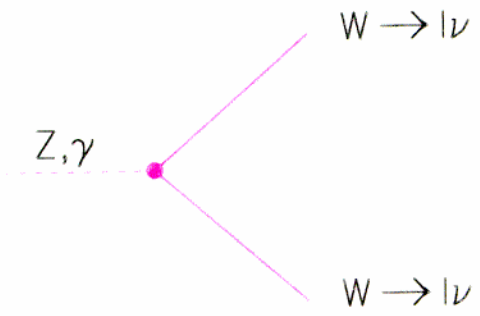
  $-0.31 < \lambda_\gamma < 0.29$ (for $\Delta\kappa_\gamma = 0$)

⋆ **Independent of WWZ vertex (unlike WW production)**

⋆ **First direct evidence that photon couples to more than just electric charge of the W**

  ▹ $U(1)_{EM}$-only coupling ruled out at 96% CL (assuming $\lambda = \tilde{\kappa} = \tilde{\lambda} = 0$)

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



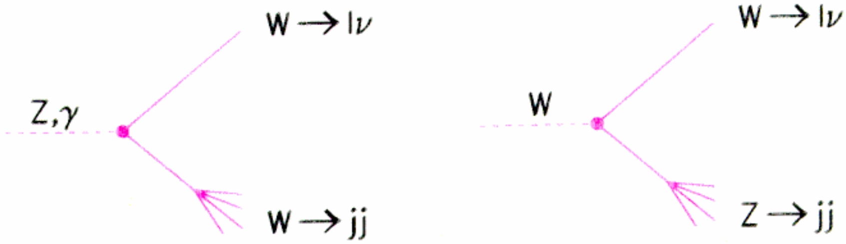
- Event selection:
  - ▷ Two isolated high-p_T leptons ($p_T >$ 15-25 GeV/c)
  - ▷ $\not{E}_T$ > 20-25 GeV
- Backgrounds: $Z \rightarrow \tau\tau$, Drell-Yan, $t\bar{t}$

	DØ	CDF
$\int \mathcal{L}dt$ (pb^{-1})	97	108
Number of candidates	5	5
Total background	3.1 ± 0.4	1.2 ± 0.4
$\mathcal{N}_{SM}$	2.10 ± 0.15	3.5 ± 1.2
σ_{WW}	< 37.1 pb (95% CL)	$= (10.2^{+6.3}_{-5.1} \pm 1.6)$ pb
Standard Model	$\sigma_{WW} = (9.5 \pm 1.0)$ pb	

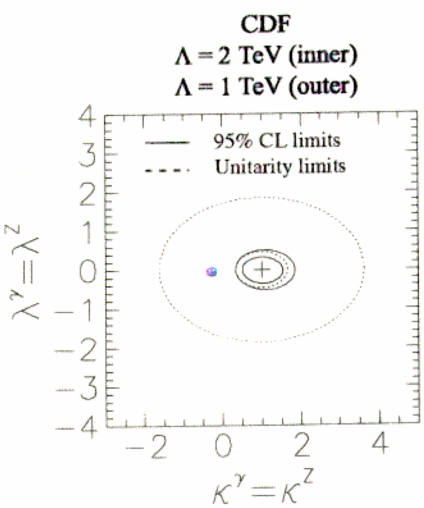
- To obtain limits on anomalous couplings:
  - ▷ CDF fits to total number of events
  - ▷ DØ fits to lepton p_T spectrum (better limits). For $\Lambda = 1.5$ TeV:

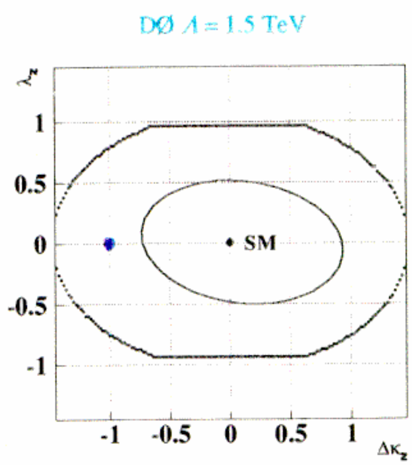
$$-0.62 < \Delta\kappa < 0.77 \text{ (for } \lambda = 0)$$
$$-0.53 < \lambda < 0.56 \text{ (for } \Delta\kappa = 0)$$

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



- **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 jet-jet invariant mass consistent with a W or Z
  - ▷ $\not{E}_T$ > 20–25 GeV, or a second high-p_T lepton (for $lljj$ events)
- **Large backgrounds from $W+$ jets and QCD multi-jets**
- **To obtain limits on anomalous couplings:**
  - ▷ CDF: $p_T(jj) >$ 200 GeV/c (110 pb^{-1})
  - ▷ DØ: binned likelihood fit to $p_T^{e\nu}$ spectrum (96 pb^{-1})



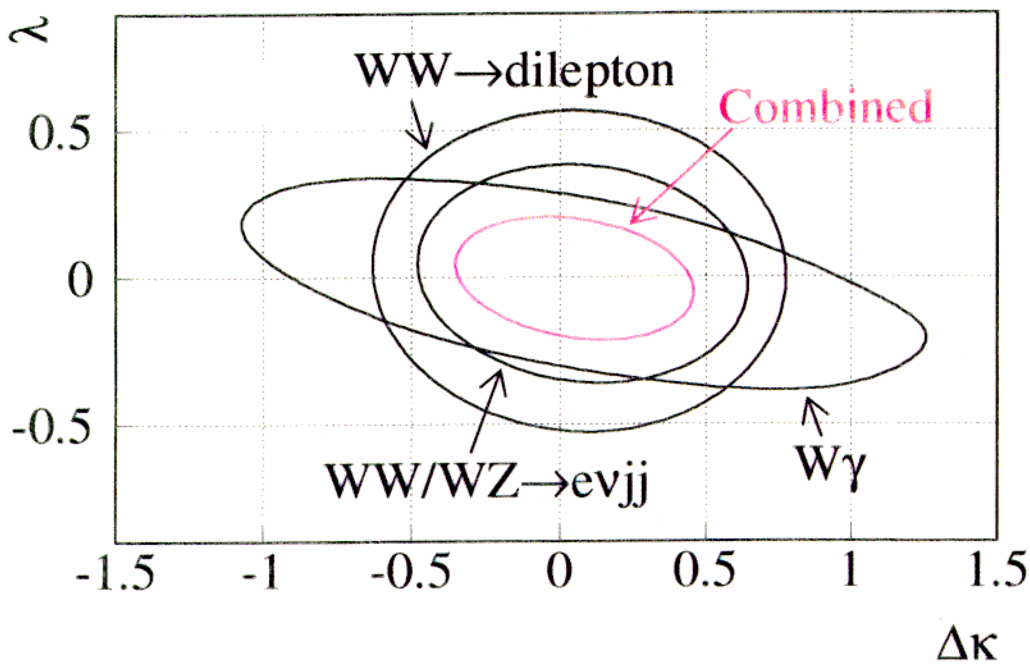


	DØ	CDF
95% CL Limits (Λ = 2 TeV)	$-0.43 < \Delta\kappa < 0.59$ $-0.33 < \lambda < 0.36$	$-0.49 < \Delta\kappa < 0.54$ $-0.35 < \lambda < 0.32$

⋆ Both experiments exclude U(1)$_{EM}$-only point ($\kappa_Z = \lambda_Z = 0$) at 99% CL when SM $WW\gamma$ couplings are assumed
⇒ First direct evidence of WWZ coupling

DØ Combined Analysis of $WW\gamma$ and WWZ Couplings

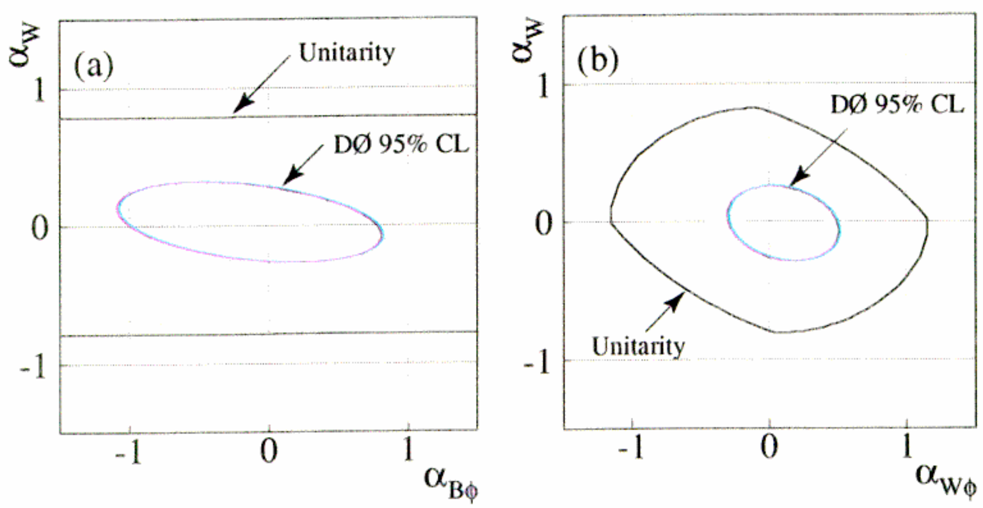
- DØ has performed a simultaneous fit to:
  - ▷ p_T^γ spectrum in $W\gamma$ data
  - ▷ p_T^l distribution in WW dilepton data
  - ▷ p_T^W distribution in $WW, WZ \to e\nu jj$ events
- Limits on coupling parameters extracted from fit, taking into account correlations



- For $\Lambda = 2.0$ TeV, $\lambda_\gamma = \lambda_Z$ and $\Delta\kappa_\gamma = \Delta\kappa_Z$:
  - ⋆ $-0.30 < \Delta\kappa < 0.43$ $(\lambda = 0)$
  - ⋆ $-0.20 < \lambda < 0.20$ $(\Delta\kappa = 0)$

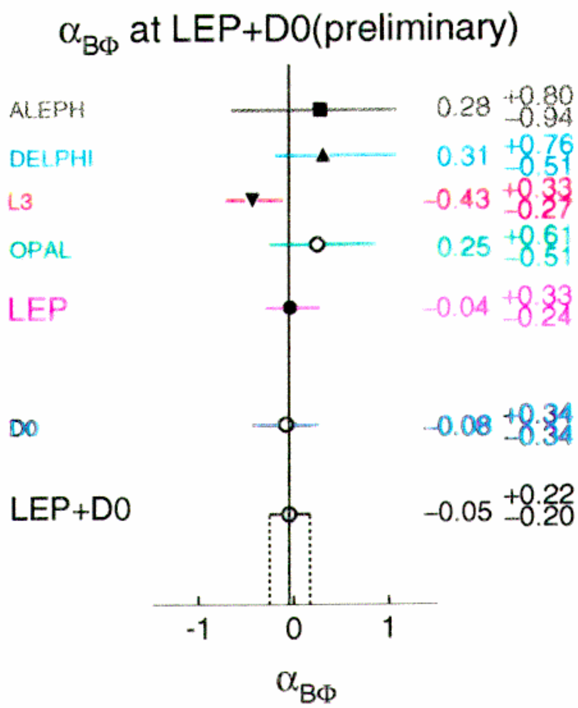
DØ Combined Analysis: $\alpha_{B\phi}$, $\alpha_{W\phi}$, α_W Parameterization

- Allows comparison and combined analysis with LEP2 results. LEP2 parameter set:
  - ▷ $\alpha_{B\phi} \equiv \Delta\kappa_\gamma - \Delta g_1^Z \cos^2\theta_W$
  - ▷ $\alpha_{W\phi} \equiv \Delta g_1^Z \cos^2\theta_W$
  - ▷ $\alpha_W \equiv \lambda_\gamma$
  - ▷ all $\alpha = 0$ in SM
- with constraints:
  - ▷ $\Delta\kappa_Z = -\Delta\kappa_\gamma \tan^2\theta_W + \Delta g_1^Z$
  - ▷ $\lambda_Z = \lambda_\gamma$

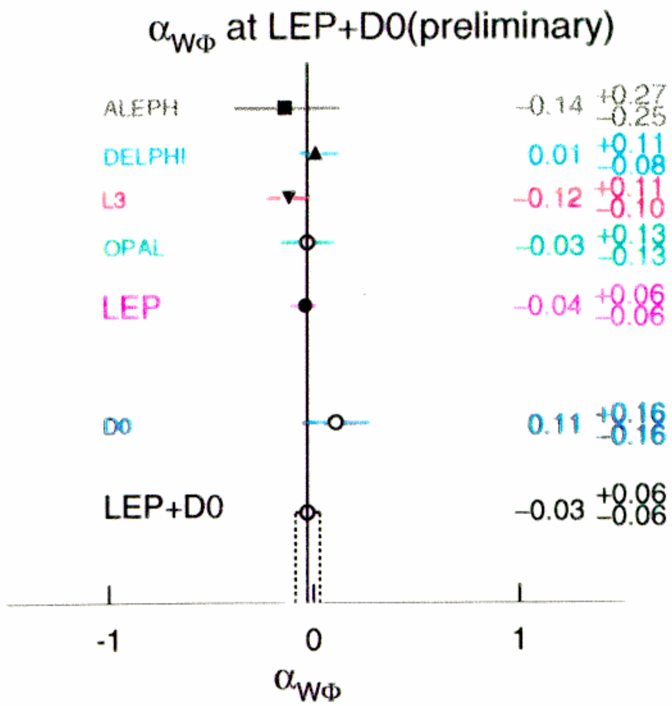


DØ (combined)	LEP2 (combined)
$-0.77 < \alpha_{B\phi} < 0.58$	$-0.44 < \alpha_{B\phi} < 0.95$
$-0.22 < \alpha_{W\phi} < 0.44$	$-0.12 < \alpha_{W\phi} < 0.13$
$-0.20 < \alpha_W < 0.20$	$-0.21 < \alpha_W < 0.27$
95% CL, $\Lambda = 2$ TeV	

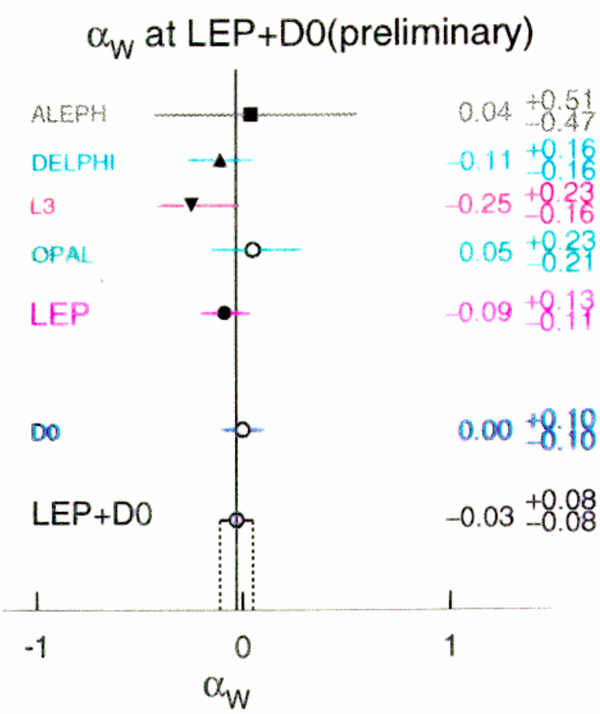
DØ and LEP2 Combined Analysis

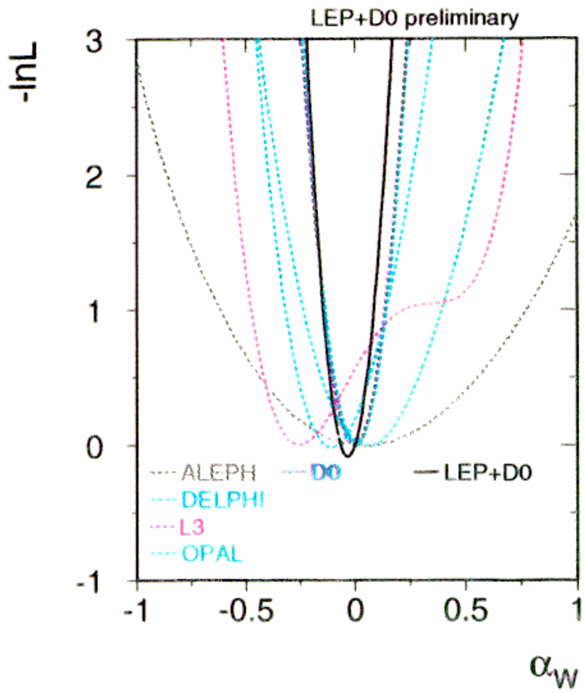


$-0.42 < \alpha_{B\phi} < 0.43$



$-0.14 < \alpha_{W\phi} < 0.10$

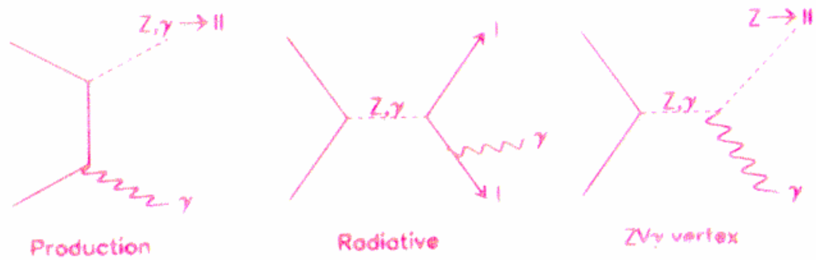




$-0.18 < \alpha_W < 0.13$

(LEPEWWG/TGC/98-01, DØ Internal Note # 3437 (May, 1998))

$Z\gamma$ Production

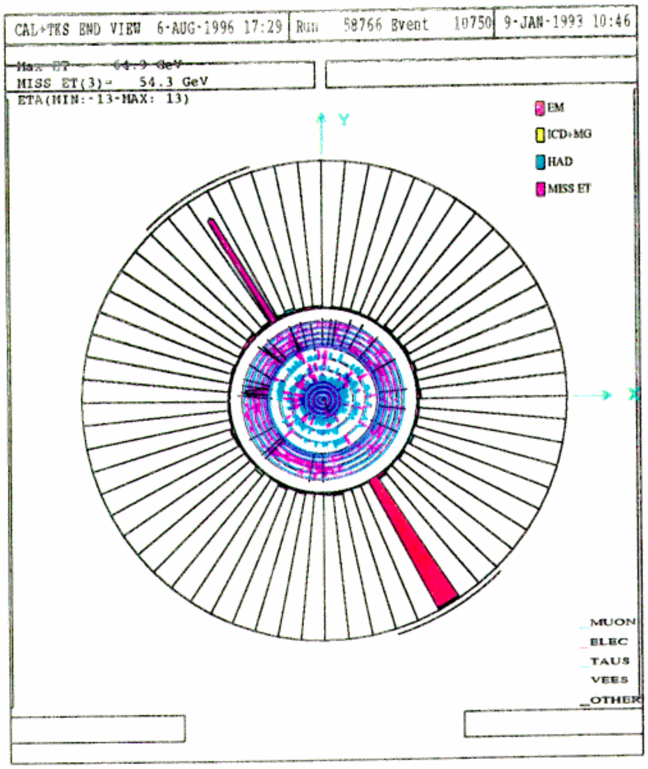


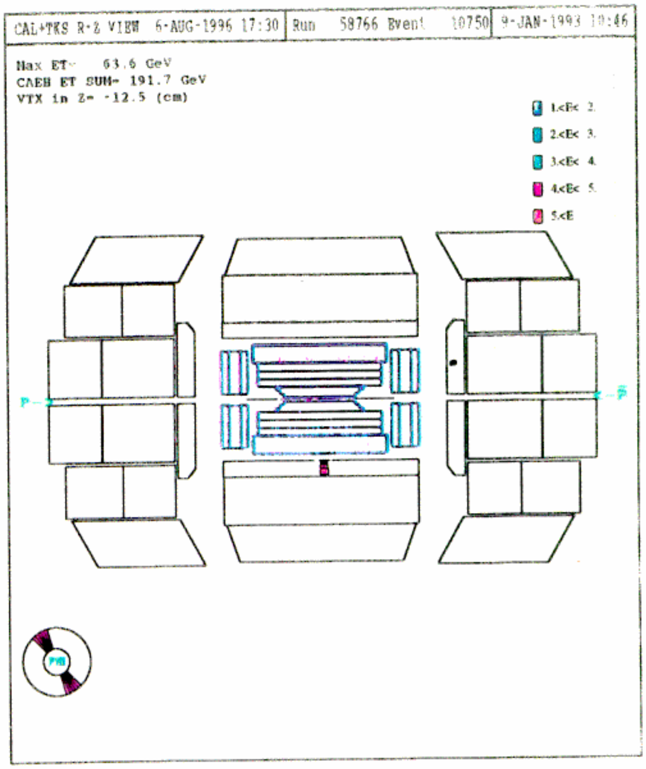
- Both DØ and CDF have performed measurements in the $Z(l^+l^-)\gamma$ mode:
  - ▹ Two high-p_T leptons (ee or $\mu\mu$)
  - ▹ One photon with $E_T^\gamma > 7$–10 GeV
  - ▹ Major background: $Z+$ jet ($\rightarrow$ fake γ)
- DØ (CDF) finds 35 (33) events with a background of 5.9 (1.4) in ~ 105 (67) pb^{-1}.
- Measurements agree with SM expectations. Limits found using binned maximum likelihood fit to E_T^γ spectrum.

⋆ Most sensitive limits come from DØ measurement of $Z(\nu\nu)\gamma$:

- ▹ Larger branching ratio than charged leptonic decay modes
- ▹ No final state radiation from final state l^+l^-
- ▹ High detection efficiency (one final state particle)
- ▹ Backgrounds much higher ($W \rightarrow e\nu$, cosmic ray and beam halo muon bremsstrahlung) $\Rightarrow$ tight selection cuts:
  - ⋆ $E_T^\gamma > 40$ GeV
  - ⋆ $\not{E}_T > 40$ GeV
  - ⋆ no jets with $E_T > 15$ GeV
- ▹ Bremsstraulung background reduced using "photon tracking": "direction" of EM cluster consistent with event vertex
- ▹ $W \rightarrow e\nu$ reduced via "hit counting" in tracking road about photon, and hard cuts on E_T^γ and $\not{E}_T$ (above Jacobian peak)

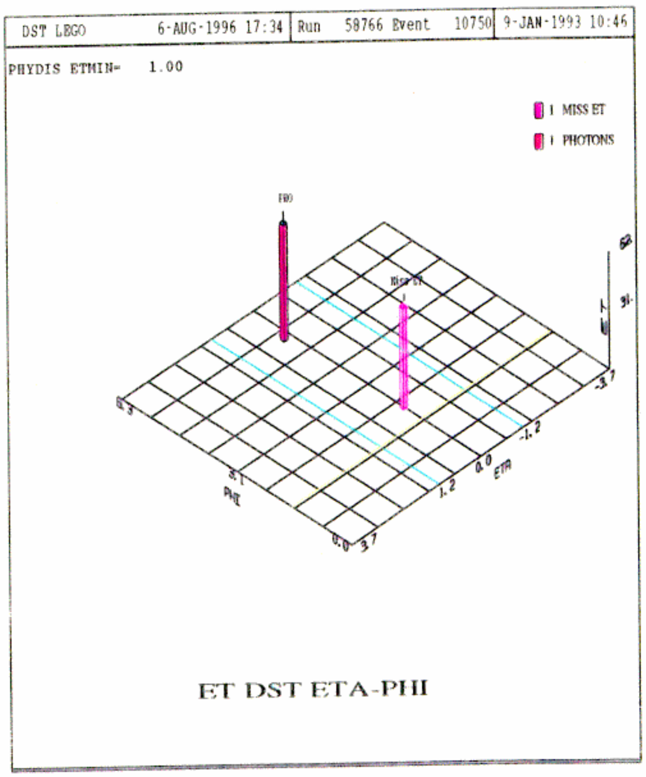
$Z(\nu\nu)\gamma$ Candidate from DØ



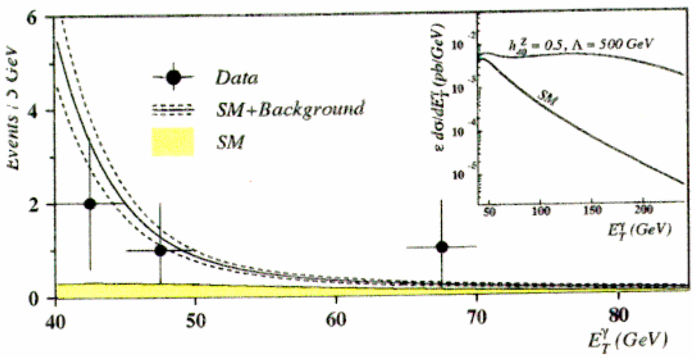


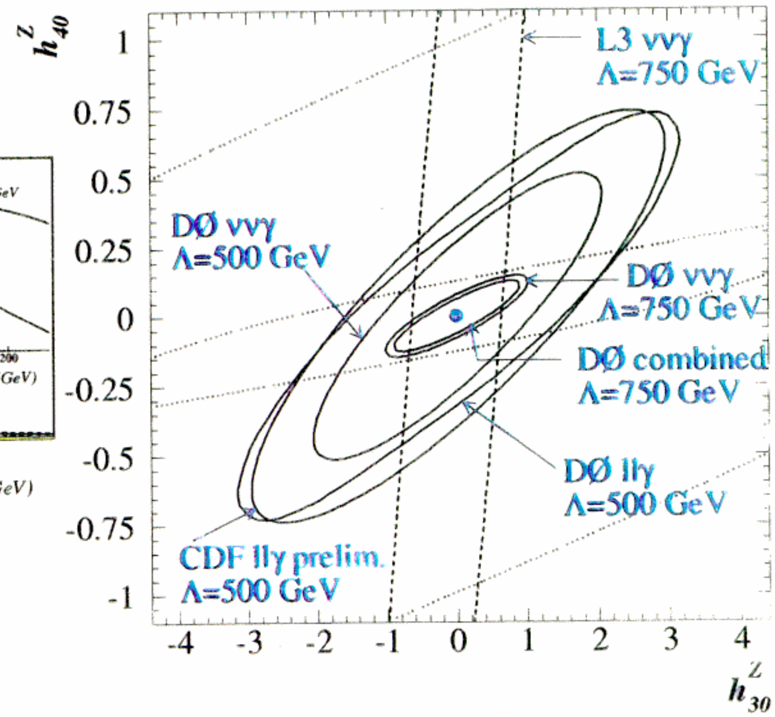
$E_T^\gamma = 67.9$ GeV

$\not{E}_T = 56.6$ GeV



$Z(\nu\nu)\gamma$ (cont'd)





- Find 4 events over background of 5.8 ± 1.0 in 13 pb^{-1}. SM expectation: 1.8 ± 0.2 events.
- Anomalous coupling limits found using binned maximum likelihood fit to E_T^γ spectrum:

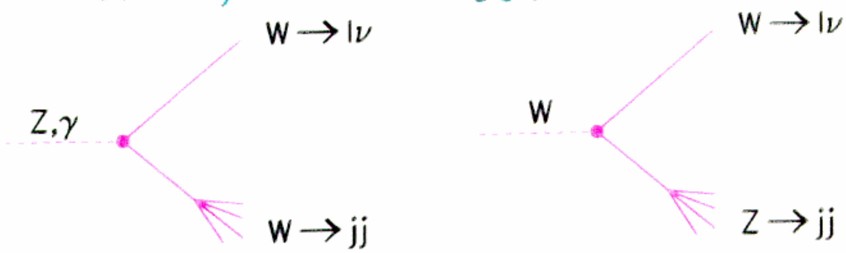
	$Z(\nu\nu)\gamma$ (DØ)	
	h_{i0}^Z	h_{i0}^γ
$\nu\nu$	$\lvert h_{30}^Z\rvert < 0.49$, $\lvert h_{40}^Z\rvert < 0.07$	$\lvert h_{30}^\gamma\rvert < 0.50$, $\lvert h_{40}^\gamma\rvert < 0.07$
$ee,\mu\mu,\nu\nu$	$\lvert h_{30}^Z\rvert < 0.36$, $\lvert h_{40}^Z\rvert < 0.05$	$\lvert h_{30}^\gamma\rvert < 0.37$, $\lvert h_{40}^\gamma\rvert < 0.05$
	95% CL, $\Lambda = 750$ GeV	

Most stringent direct limits on these couplings from any experiment

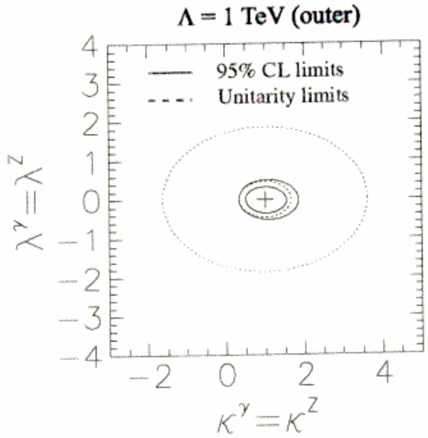
Summary

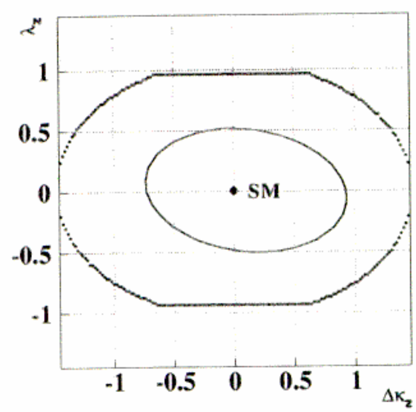
- Production cross section $\sigma \cdot B(W \to l\nu)$ measured for e, μ, and τ
  - ▷ agree with $\mathcal{O}(\alpha_s^2)$ theory
  - ▷ $g_\tau^W / g_e^W = 1.004 \pm 0.032$
- W boson width:
  - ▷ Indirect: $\Gamma_W = 2.126 \pm 0.092$ GeV
  - ▷ Direct: $\Gamma_W = 2.19 \pm 0.19$ GeV
- Rare W decays:
  - ▷ $\Gamma(W \to \pi\gamma)/\Gamma(W \to e\nu) \leq 7 \times 10^{-4}$
  - ▷ $\Gamma(W \to D_s\gamma)/\Gamma(W \to e\nu) \leq 1.1 \times 10^{-2}$
- Limits on compositeness scale Λ from Drell-Yan production range from:
  - ⋆ $eeqq$: $\Lambda_{LL}^{+} \geq 3.3$, $\Lambda_{VV}^{-} \geq 6.1$
  - ⋆ $llqq$: $\Lambda_{RR}^{+} \geq 3.0$, $\Lambda_{AA}^{-} \geq 6.3$
- Trilinear gauge boson couplings:
  - ▷ First direct evidence of WWZ coupling
  - ▷ First direct evidence that the $W\gamma$ coupling is not purely electromagnetic
  - ▷ $WW\gamma$, WWZ:
    - ⋆ $-0.30 < \Delta\kappa < 0.43$, $-0.20 < \lambda < 0.20$
    - ⋆ $-0.77 < \alpha_{B\phi} < 0.58$, $-0.22 < \alpha_{W\phi} < 0.44$, $-0.20 < \alpha_W < 0.20$
  - ▷ $ZZ\gamma$, $Z\gamma\gamma$:
    - ⋆ $|h_{30}^Z| < 0.36$, $|h_{30}^\gamma| < 0.37$, $|h_{40}^{Z,\gamma}| < 0.05$
- W Mass:
  - ▷ Hadron Collider Average: $M_W = 80.400 \pm 0.090$ (UA2+DØ+CDF)
  - ▷ Direct World Average: $M_W = 80.385 \pm 0.065$ (UA2+DØ+CDF+LEP2)

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



- 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 jet-jet invariant mass consistent with a W or Z
  - ▹ $\not{E}_T > 20$–25 GeV, or a second high-p_T lepton (for $lljj$ events)
- Large backgrounds from $W+$ jets and QCD multi-jets
- To obtain limits on anomalous couplings:
  - ▹ CDF: $p_T(jj) > 200$ GeV/c (110 pb^{-1})
  - ▹ DØ: binned likelihood fit to $p_T^{e\nu}$ spectrum (96 pb^{-1})





	DØ	CDF
95% CL Limits ($\Lambda = 2$ TeV)	$-0.43 < \Delta\kappa < 0.59$ $-0.33 < \lambda < 0.36$	$-0.49 < \Delta\kappa < 0.54$ $-0.35 < \lambda < 0.32$

★ Both experiments exclude $U(1)_{EM}$-only point ($\kappa_Z = \lambda_Z = 0$) at 99% CL when SM $WW\gamma$ couplings are assumed
$\Rightarrow$ First direct evidence of WWZ coupling