Electroweak Physics

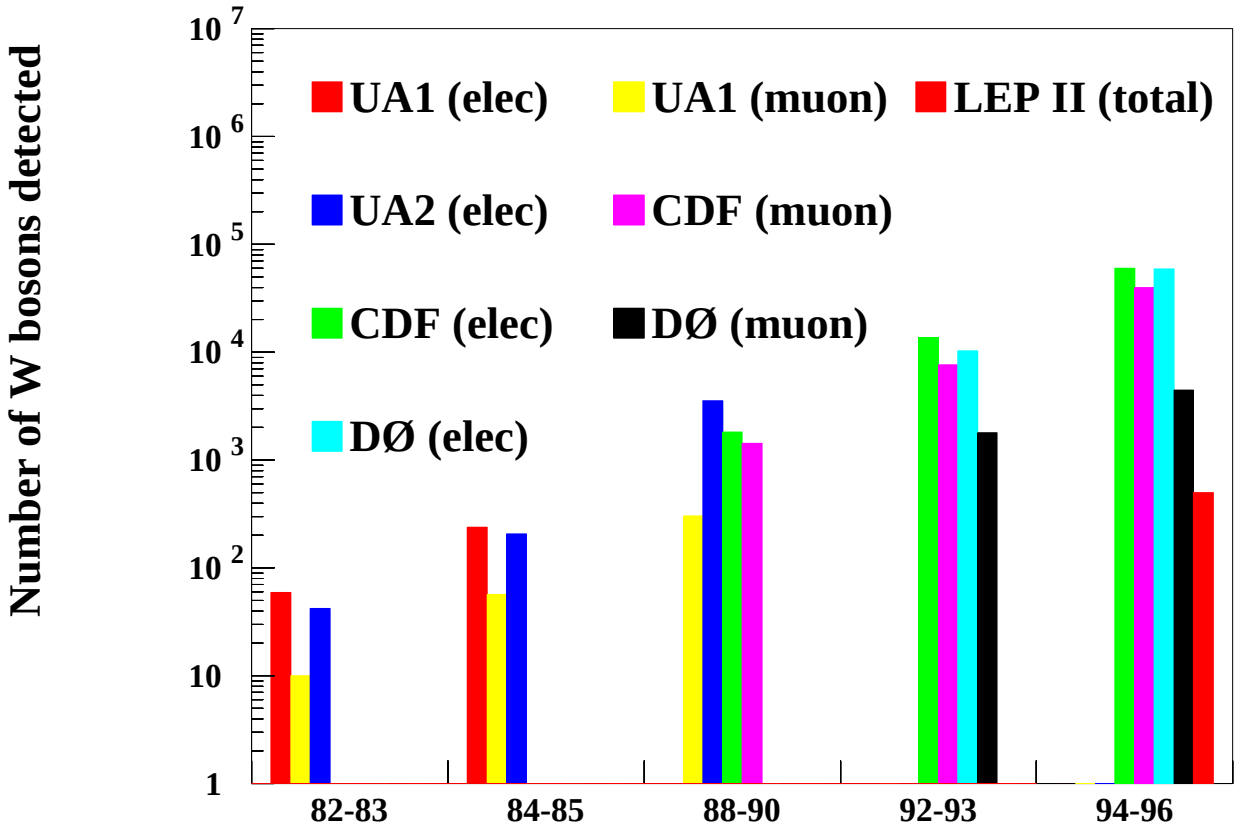
Qizhong Li
Fermi National Accelerator Laboratory

Fermilab Users Meeting, 1997
July 14, 1997

Outline

- *W/Z* production (CDF & D0)
  - Cross section
  - *W* width $\Gamma(W)$
  - $W \rightarrow \tau\nu$
- Diboson production and trilinear couplings (CDF & D0)
  - $W\gamma$
  - *WW, WZ*
  - $Z\gamma$
- ν_τ observation experiment (E 872)
- $\sin^2\theta_W$ (E 815)
- *W* mass (CDF & D0)
- Summary and prospects

W boson detected



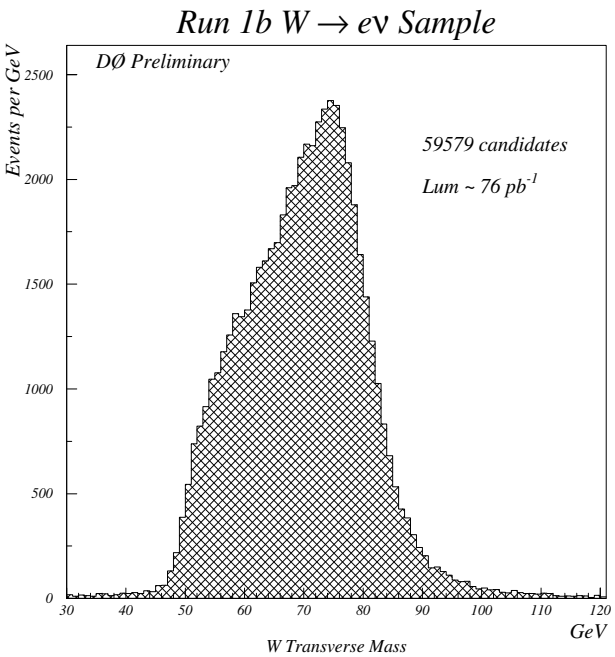
- Tevatron "Run Ia" = 1992-93 $\int Ldt \sim 13 pb^{-1}$
- Tevatron "Run Ib" = 1994-95 $\int Ldt \sim 80 pb^{-1}$
- LEP2 161 GeV, $\int Ldt \sim 10 pb^{-1}$
- LEP2 172 GeV, $\int Ldt \sim 10 pb^{-1}$

W and Z inclusive samples

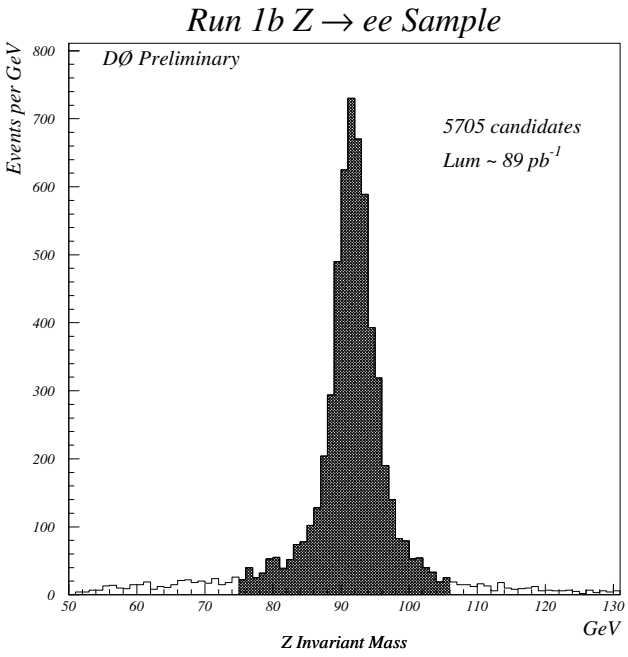
- Event selection:
  - detect W and Z through leptonic decay

    $W \rightarrow \ell + \nu$ $\quad$ $Z \rightarrow 2\ell$
  - require isolated e or μ with high p_T (> 20 or 25 GeV/c)
  - for select W's:

    require large $\not\!\!E_T$ (> 20 or 25 GeV/c)

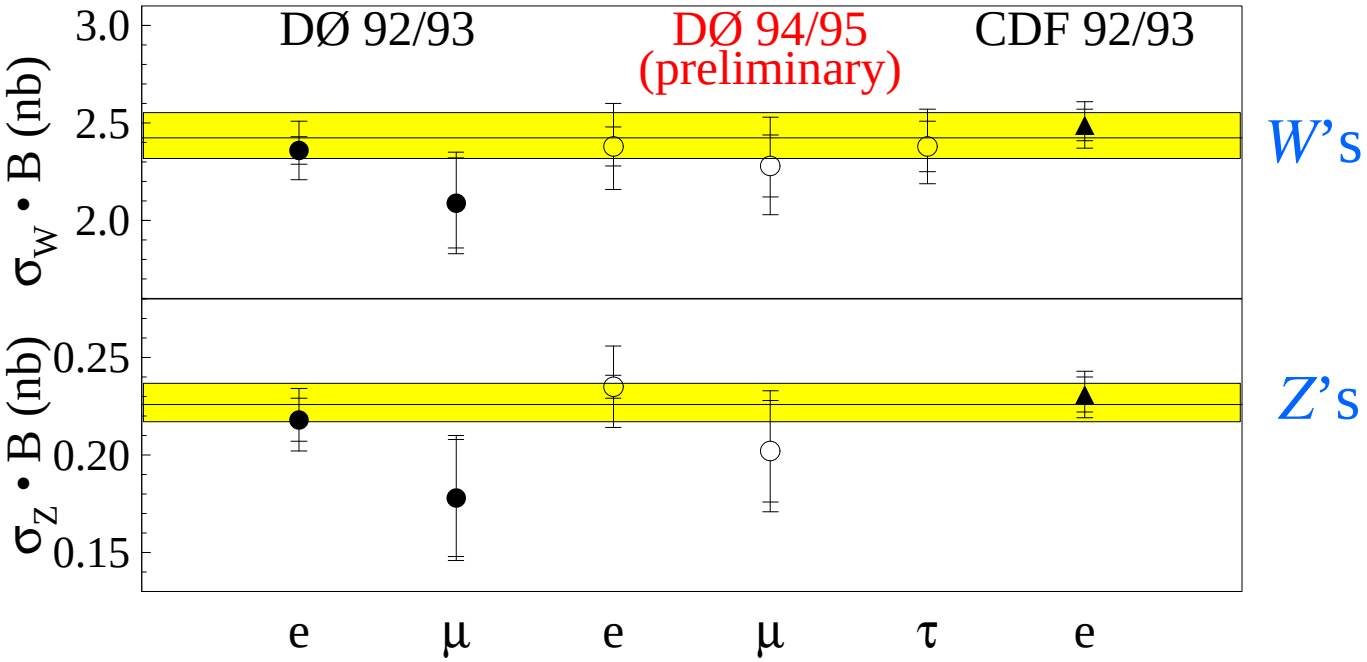


Transverse mass ($W \rightarrow e\nu$)



Z invariant mass ($Z \rightarrow ee$)

W and *Z* cross sections



- Theoretical prediction at $O(\alpha_s^2)$:
  Hamberg, van Neerven & Matsuura, NP B359, 313;
  van Neerven & Zijlstra, NP B382, 11.
- Dominant uncertainties:
  - data: luminosity
  - theory: parton distribution functions

	$\sigma_W \cdot B(W \to \ell\nu)$ (nb)	$\sigma_Z \cdot B(Z \to \ell\ell)$ (nb)
DØ (e) (Run 1B)	$2.38 \pm 0.01 \pm 0.22$	$0.235 \pm 0.003 \pm 0.021$
DØ (μ) (Run 1B)	$2.28 \pm 0.04 \pm 0.25$	$0.202 \pm 0.016 \pm 0.026$
DØ (τ) (Run 1B)	$2.38 \pm 0.09 \pm 0.16$	
CDF (e) (Run 1A)	$2.49 \pm 0.02 \pm 0.12$	$0.231 \pm 0.006 \pm 0.011$
CDF (μ) (Run 1A)	$2.48 \pm 0.031 \pm 0.16$	$0.203 \pm 0.010 \pm 0.012$
Standard Model	$2.42\ ^{+0.13}_{-0.11}$	$0.226\ ^{+0.011}_{-0.009}$

W Width $\Gamma(W)$

- Indirect measurement:
  - Take cross section ratio: many errors cancel

$$R = \frac{\sigma(W)}{\sigma(Z)} \bullet \frac{B(W \to \ell\nu)}{B(Z \to \ell\ell)}$$

  - Use theoretical calculation of $\sigma(W)/\sigma(Z)$
  - Use LEP measurement of $B(Z \to \ell\ell)$
  - Obtain:

$$\boldsymbol{B}(W \to \ell\nu)$$

  - Use theoretical calculation of $\Gamma(W \to \ell\nu)$
  - Obtain:

$$\Gamma(W) = \frac{\sigma(W)}{\sigma(Z)} \bullet \frac{\Gamma(W \to \ell\nu)}{B(Z \to \ell\ell)} \bullet \frac{1}{R}$$

$= 2.062 \pm 0.059$ GeV (CDF, D0 combined, Ia)

- Direct measurement: (CDF)

  from tail of M_T^W distribution (binned likelihood fit for $M_T^W > 110$ GeV)

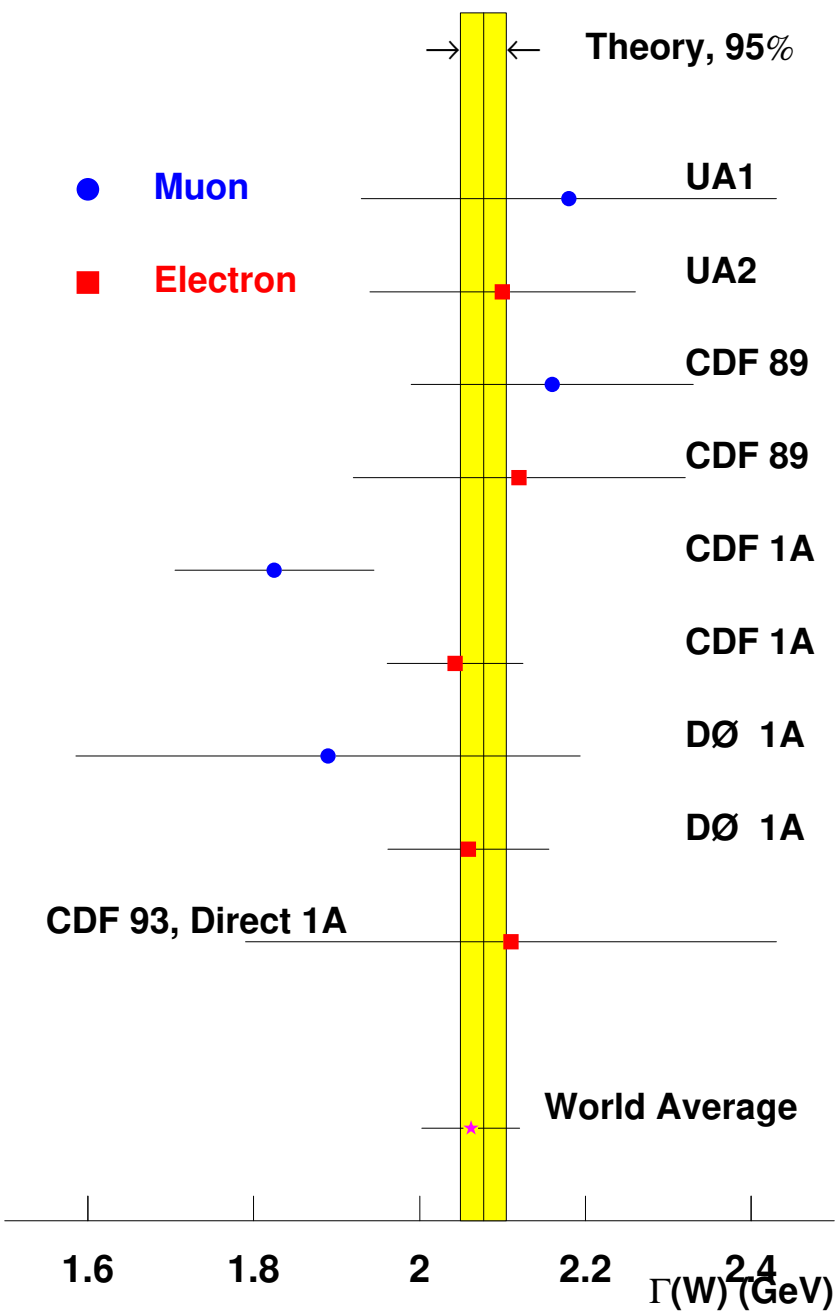
  require fewer SM assumptions

$$\Gamma(W) = 2.11 \pm 0.28 \pm 0.16 \text{ GeV}$$

- Standard Model:

$$\Gamma(W) = 2.077 \pm 0.014 \text{ GeV}$$

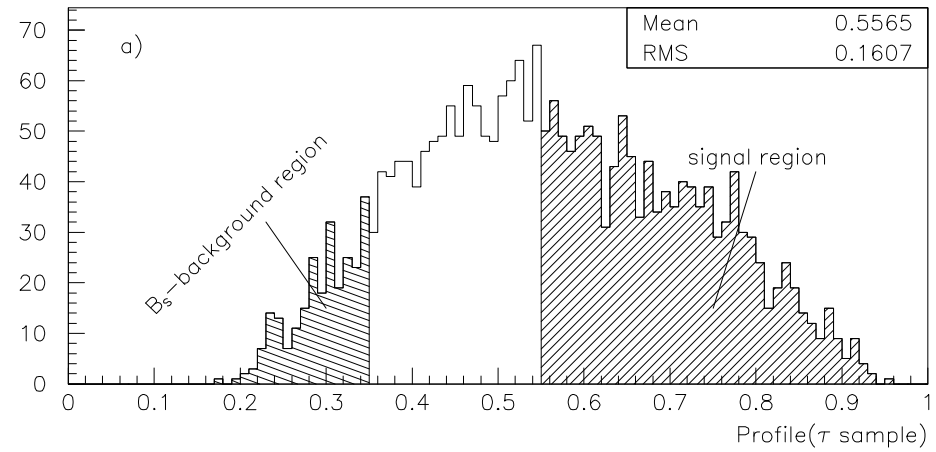
$\Gamma(W)$

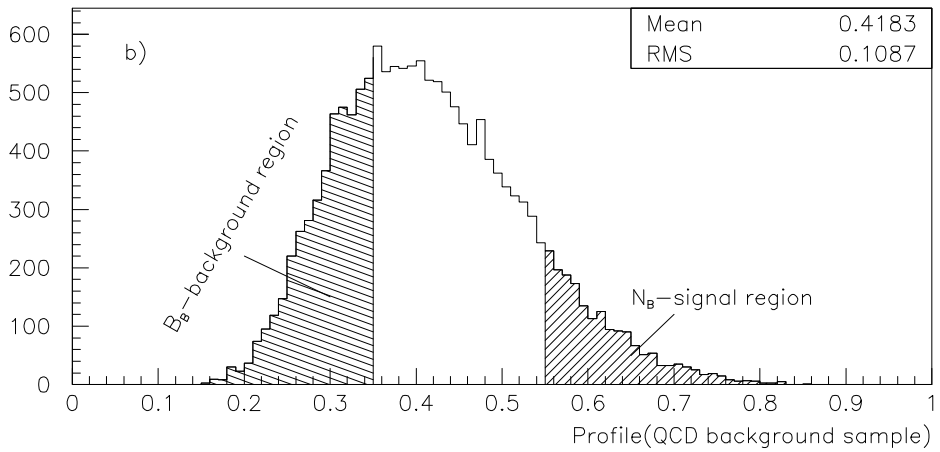

Theory, 95%
Muon
Electron
UA1
UA2
CDF 89
CDF 89
CDF 1A
CDF 1A
DØ 1A
DØ 1A
CDF 93, Direct 1A
World Average
1.6
1.8
2
2.2
2.4
Γ(W) (GeV)

$W \rightarrow \tau\nu$ (D0)

- Event selection:
  - use hadronic decay of the tau:
    τ signature:
    isolated, narrow jet with few tracks
  - distinguish τ by calorimeter energy pattern
    Profile = (sum of highest two towers E_T)/(jet E_T)
    (Profile > 0.55 for τ's)
  - require a high E_T τ-jet and large $\not\!\!E_T$

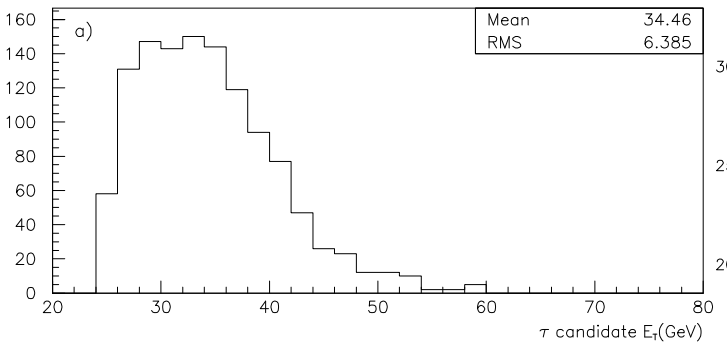
- Estimate QCD background from Profile distribution

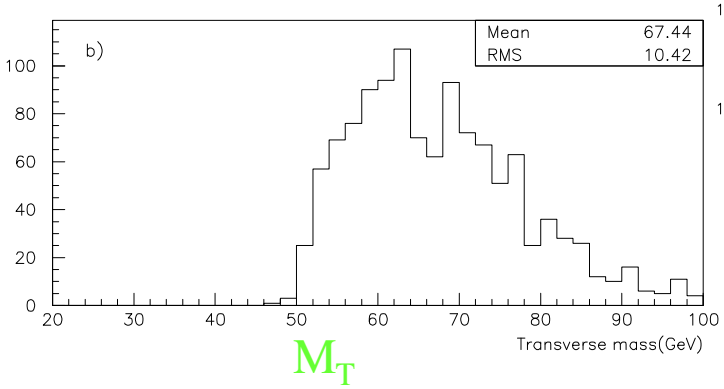




$W \to \tau\nu$

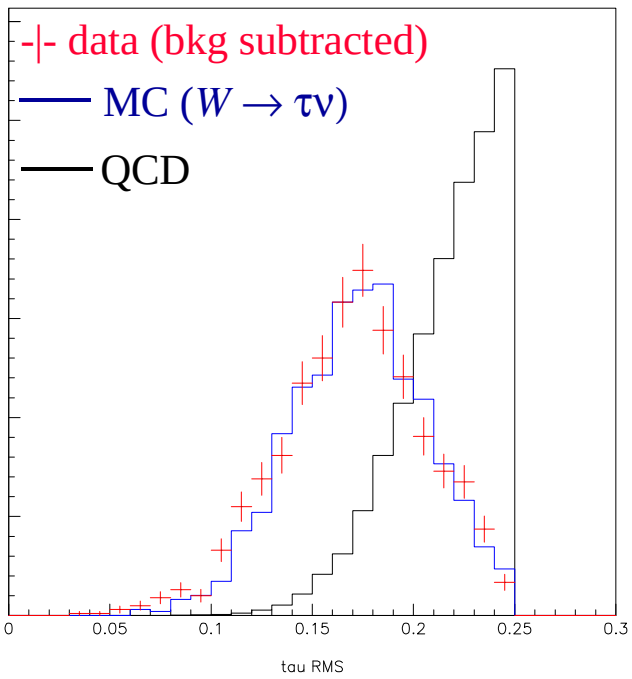
E_T





M_T

Jet width



$W \to \tau\nu$ results

	Number of Events
Final Data Sample	1202
QCD Background	$106 \pm 7 \pm 5$
Noise Events	81 ± 14
$Z \to \tau\tau$	32 ± 5
$W \to e\nu$	3 ± 1

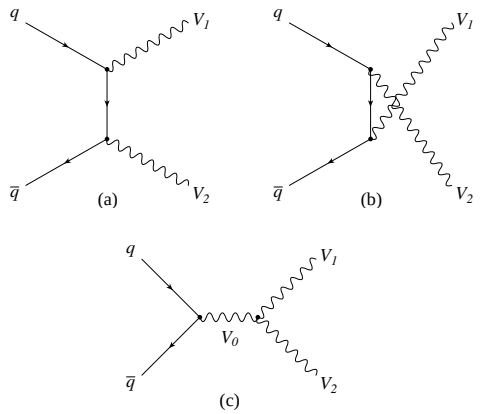
Luminosity: $16.8 \pm 0.9 \text{pb}^{-1}$

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

(luminosity error is not included)

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

Diboson production and trilinear gauge couplings



- Standard Model $SU(2)_L \times U(1)_Y$ predicts existence of gauge boson self-interactions
- Non-SM *WWZ*/*WW*γ interaction can be characterized by parameters: λ, $\Delta\kappa = \kappa - 1$

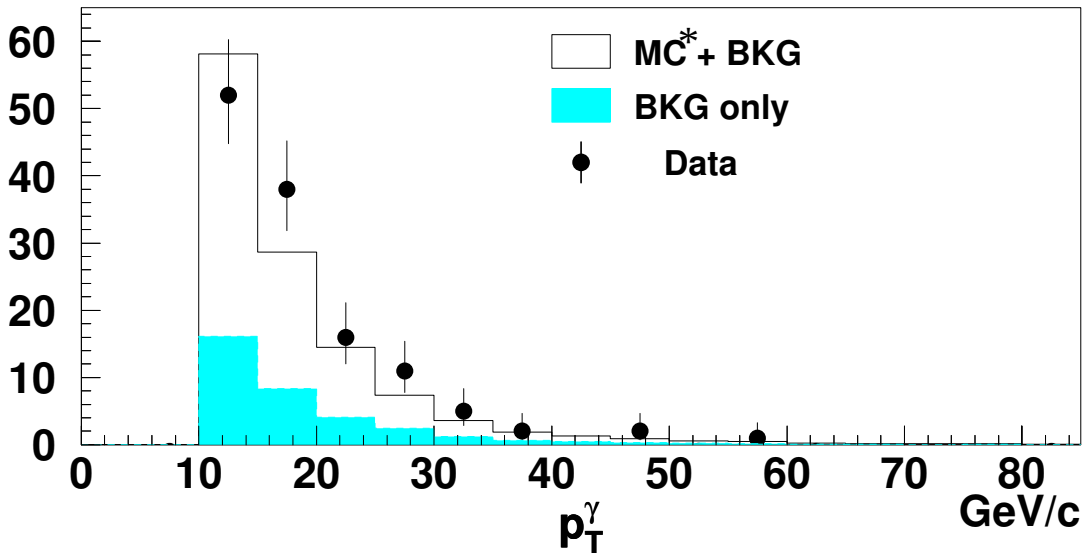
$$\mu_W = \frac{e}{m_W}(1 + \kappa + \lambda)$$

- Signature of anomalous trilinear gauge boson coupling:
  - increased cross sections at large $\hat{s}$ (an advantage for Tevatron over LEP 2)
  - increased cross sections for high $\boldsymbol{p_T}$ gauge bosons
- At Tevatron,
  - we study: *W*γ, *WW*, *WZ*, *ZZ*, *Z*γ,
  - measure production rates and $\boldsymbol{p_T}$ spectrum
- Importance:
  - test of SM
  - sensitive to new physics

$W\gamma$ production

- D0: $\int Ldt = 89.1$ pb^{-1} $E_T^\gamma > 10$ GeV, $|\eta_\gamma| < 2.5$

  $\sigma \bullet BR = 11.3\ ^{+1.7}_{-1.5} \pm 1.4 \pm 0.6$ pb (SM: 12.5±1.0 pb)



- CDF:

$\int Ldt \sim 67$ pb^{-1}

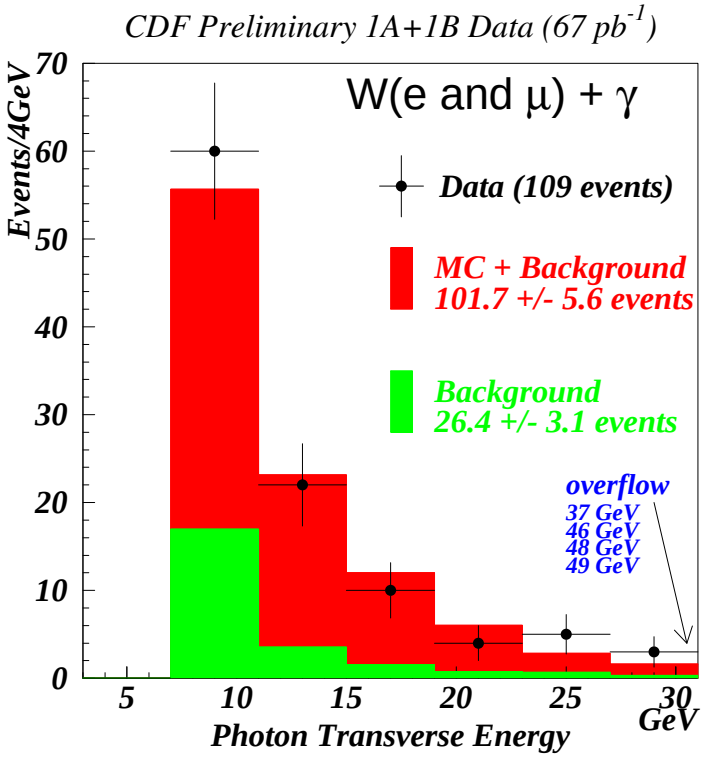
$E_T^\gamma > 7$ GeV

$|\eta_\gamma| < 1.1$

$\sigma \bullet BR =$

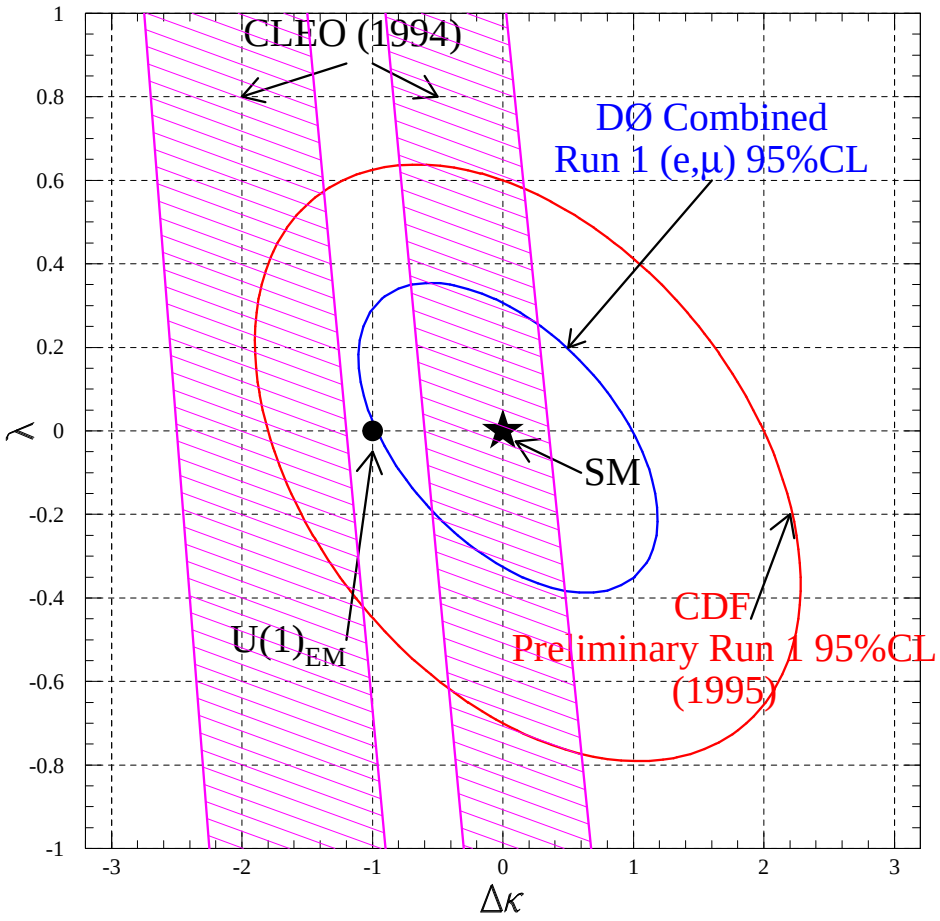
$20.7 \pm 2.9 \pm 0.7$ pb

(SM: 18.6±2.9 pb)



* MC: U. Baur and D. Zeppenfeld

$WW\gamma$ limits



limits set by binned likelihood fit to p_T^{γ} spectrum

	$\lambda_\gamma = 0$	$\Delta\kappa_\gamma = 0$
D0	$-0.93 < \Delta\kappa_\gamma < 0.94$	$-0.31 < \lambda_\gamma < 0.29$
CDF preliminary	$-1.8 < \Delta\kappa_\gamma < 2.0$	$-0.7 < \lambda_\gamma < 0.6$

- D0 limit on λ_γ is the tightest single channel limit to date
- $U(1)_{EM}$ only point is excluded at 96% CL.

$WW \rightarrow$ dileptons

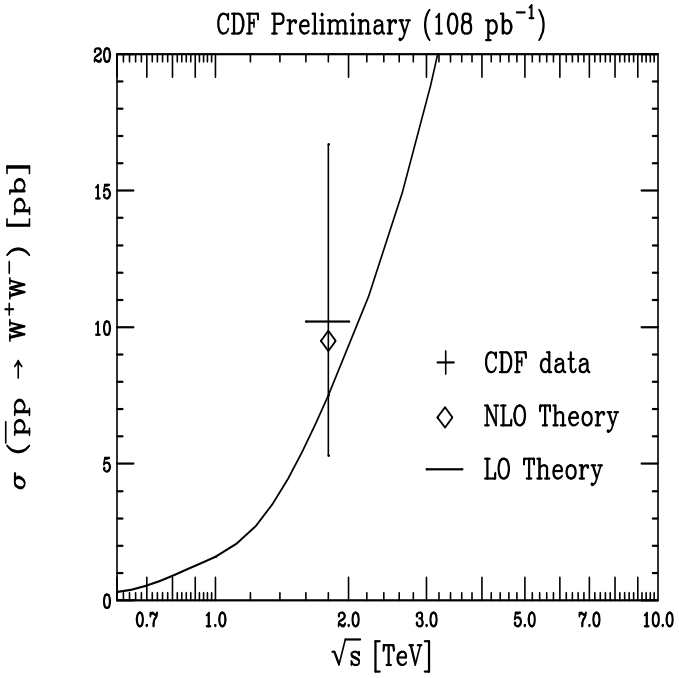
- Channels considered: ee, $e\mu$, $\mu\mu$
- Major backgrounds:
  Drell-Yan, $t\bar{t}$, $Z \rightarrow \tau\tau$, misidentified e or μ,
- Results:
  - CDF sees WW
  - D0 set limit using 2D fit to lepton E_T spectrum

	D0	CDF
$\int Ldt$	89.1pb^{-1}	108pb^{-1}
N_{data}	5	5
N_{bkg}	3.3±0.4	1.2±0.3
N_{SM}	2.10±0.15	3.5±1.2

D0:
Λ = 1.5 TeV
$-0.62 < \Delta\kappa < 0.75$ (λ=0)
$-0.5 < \lambda < 0.56$ ($\Delta\kappa$ = 0)

CDF:
Λ = 1.0 TeV
$-1.1 < \Delta\kappa < 1.3$ (λ=0)
$-0.8 < \lambda < 0.9$ ($\Delta\kappa$ = 0)
(assuming $\Delta\kappa \equiv \Delta\kappa_\gamma = \Delta\kappa_Z$
and $\lambda \equiv \lambda_\gamma = \lambda_Z$)

$\sigma(\bar{p}p \rightarrow W^+W^-)$:
CDF: $10.2\ ^{+6.3}_{-5.1} \pm 1.6$ pb
SM: 9.5 pb



$WW/WZ \rightarrow \ell\nu jj,\ \ell\ell jj$

- CDF : $W \rightarrow \ell\nu$, $W \rightarrow jj$ $\int Ldt = 110\ \text{pb}^{-1}$
- D0: $W \rightarrow e\nu$, $W \rightarrow jj$ $\int Ldt = 96\ \text{pb}^{-1}$
- Dominant background:
  W/Z+jets production , S/N = 1/30
- Results:

MC: Hagiwara, Woodside and Zeppenfeld

D0:

Λ = 2.0 TeV (D0)

$-0.43 < \Delta\kappa < 0.59$ (λ=0)

$-0.33 < \lambda < 0.36$ ($\Delta\kappa$ = 0)

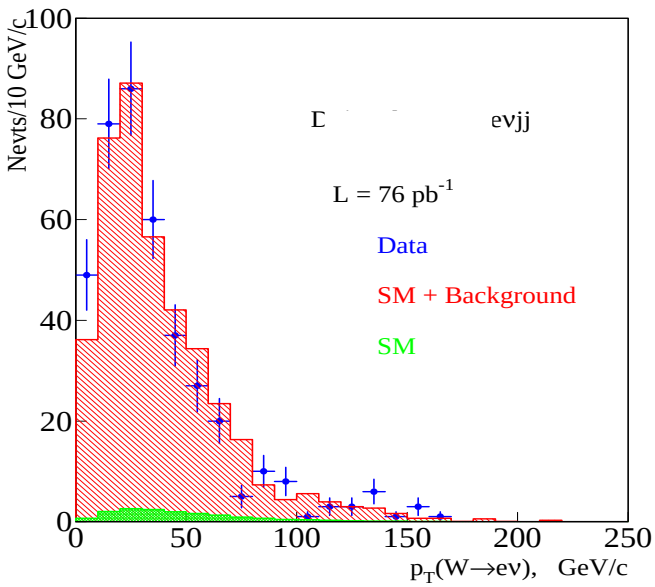
CDF:

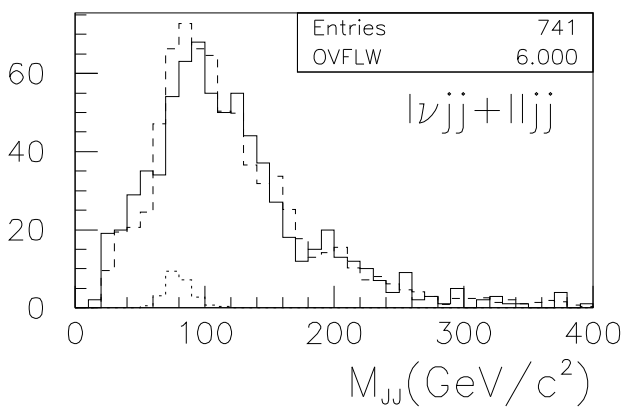
after $p_T^{JJ} > 200$ GeV/c cut, 0 events.

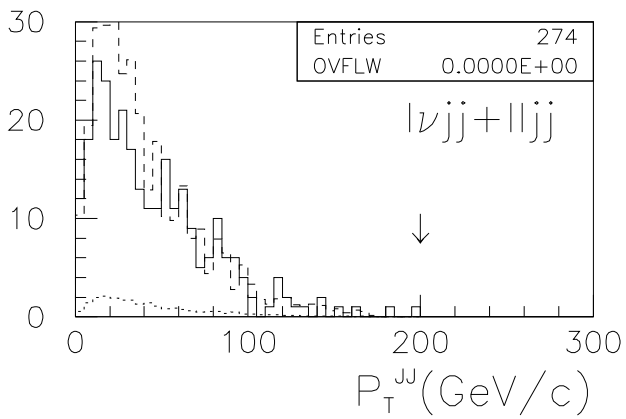
Λ = 2.0 TeV (CDF)

$-0.49 < \Delta\kappa < 0.54$ (λ=0)

$-0.35 < \lambda < 0.32$ ($\Delta\kappa$ = 0)





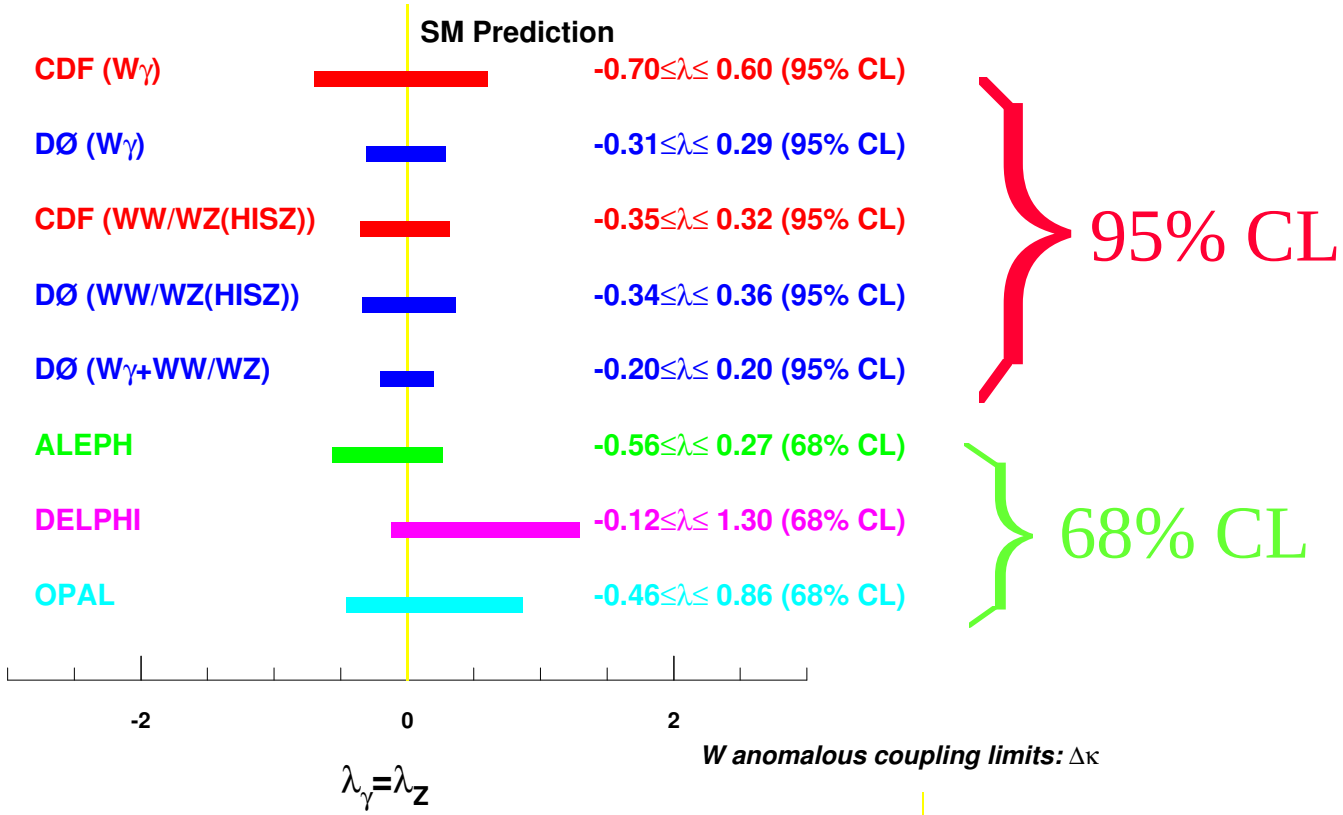


U(1)-only coupling rules out for WW production at 99% CL

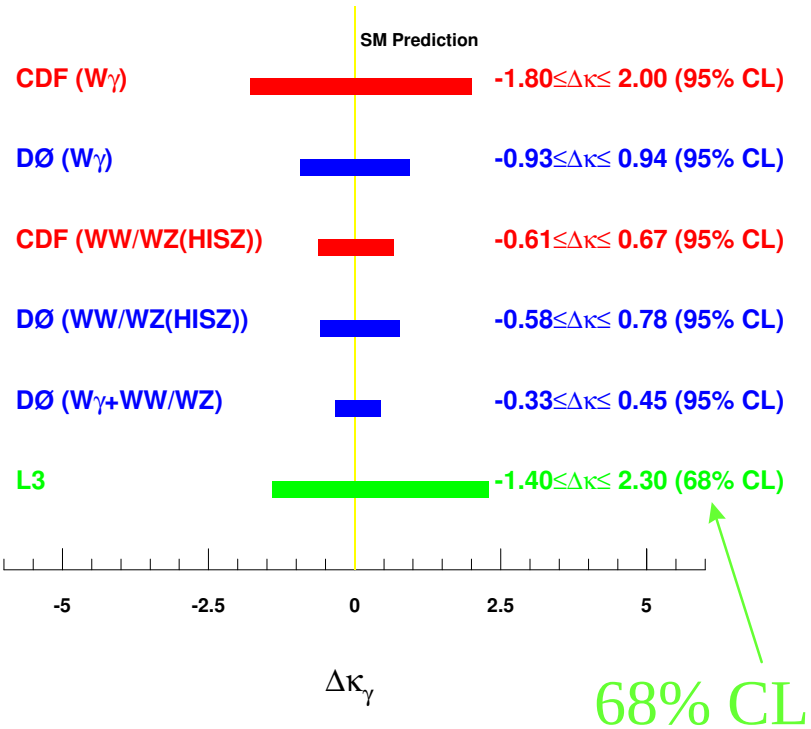
($\Rightarrow$ existence of WWZ coupling)

WWγ and *WWZ* couplings

W anomalous coupling limits: λ

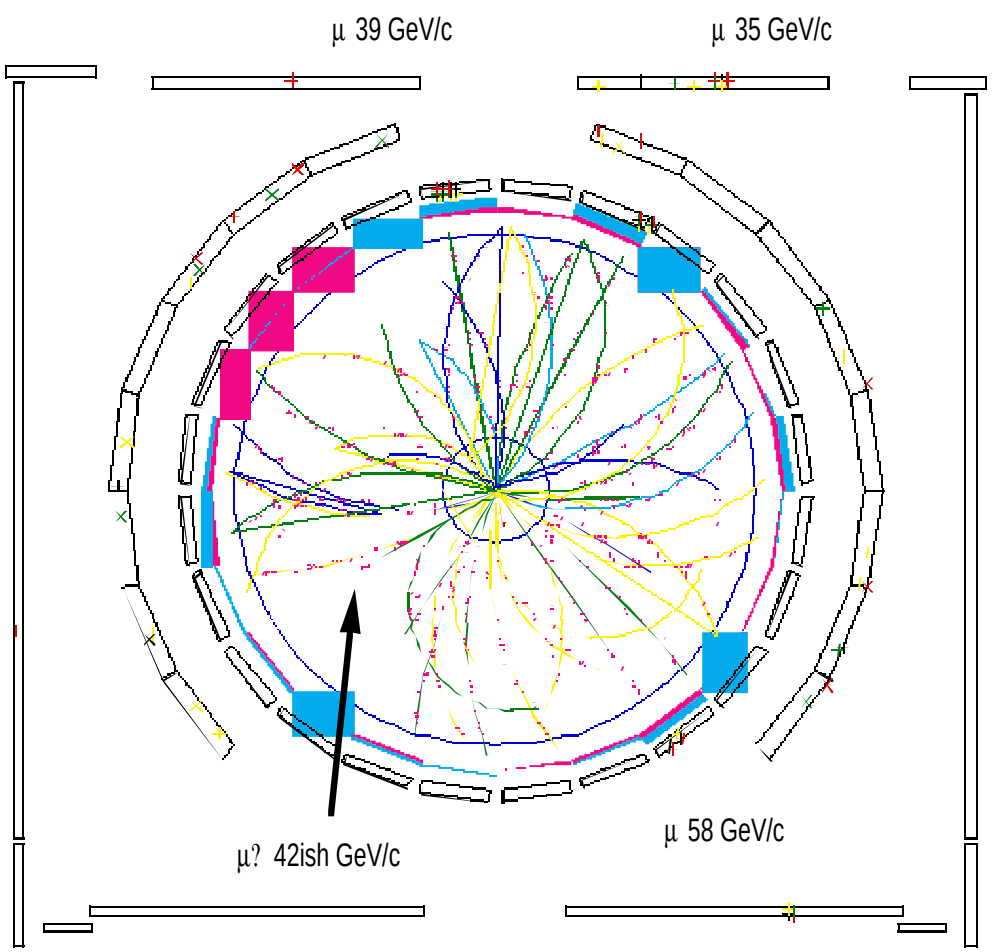


W anomalous coupling limits: Δκ



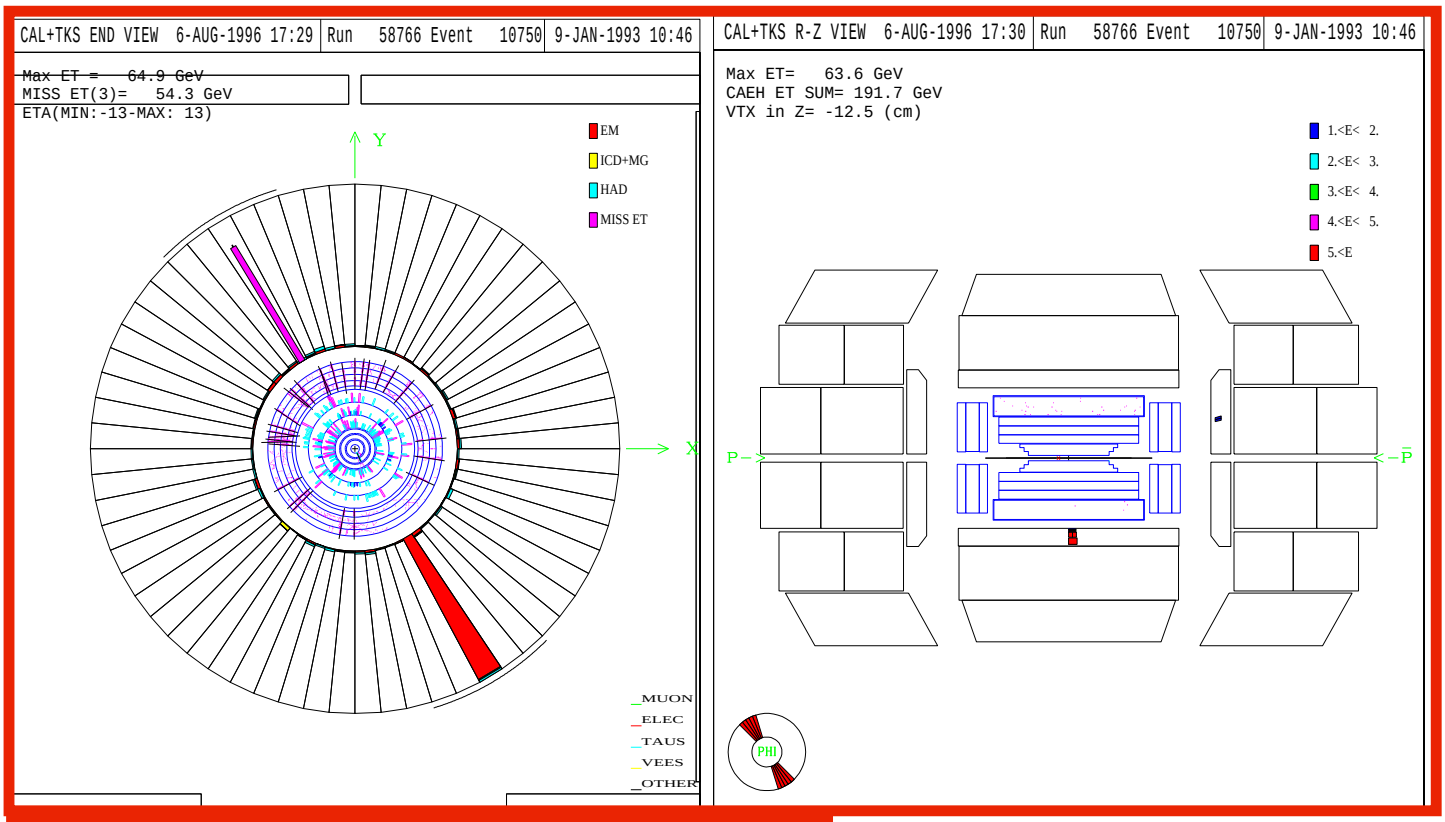
Caution:
- different C.L.
- different notations
- different model assumptions

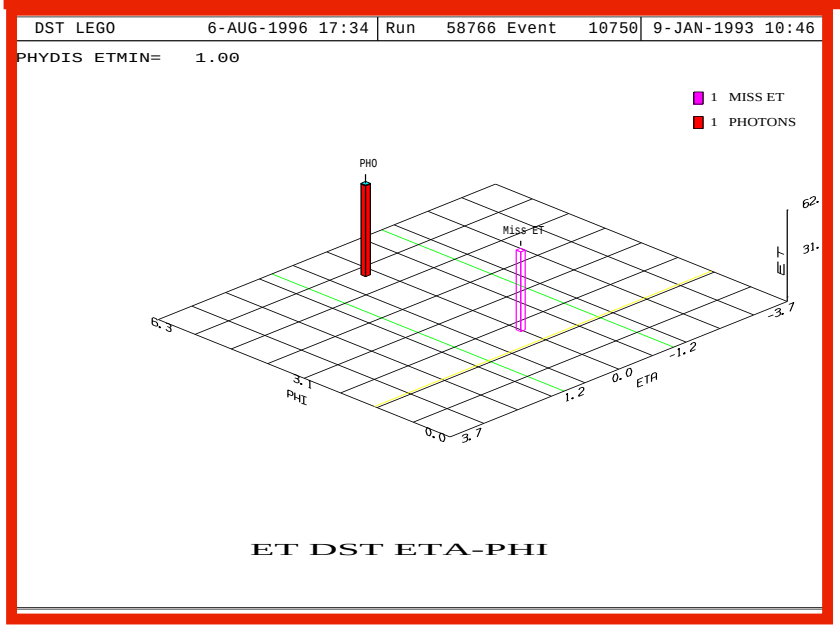
ZZ Candidate from CDF



- Three Central Muons. One muon inferred from a high-P_T track.
- Expected 0.1 event.
- Backgrounds “should be small”

$Z(\nu\nu)\gamma$ Candidate from D0





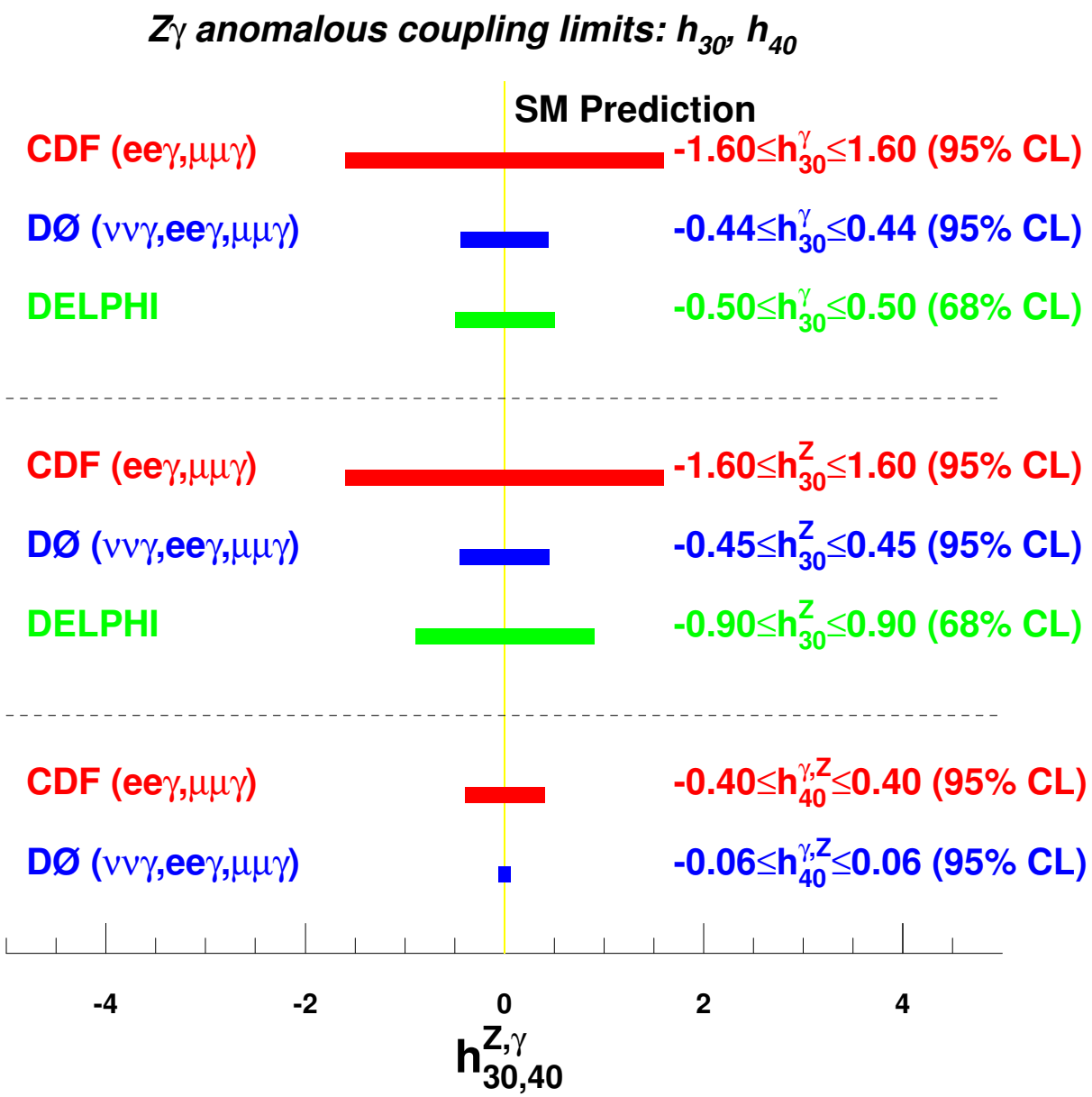
Run: 58766
Event: 10750
Recorded: 01/09/93

$E_T^{\gamma} = 67.9$ GeV

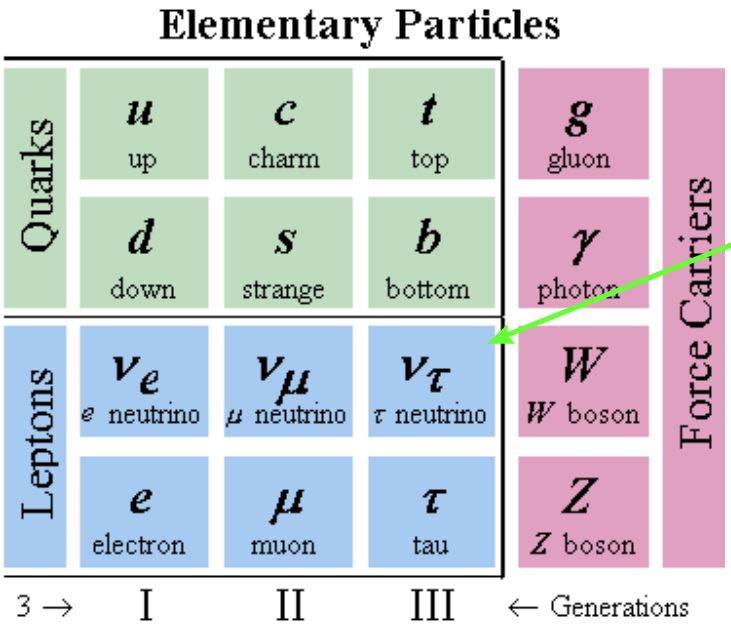
$\not{E}_T = 56.6$ GeV

$\eta_{\gamma} = 0.02$

$ZZ\gamma$ and $Z\gamma\gamma$ couplings

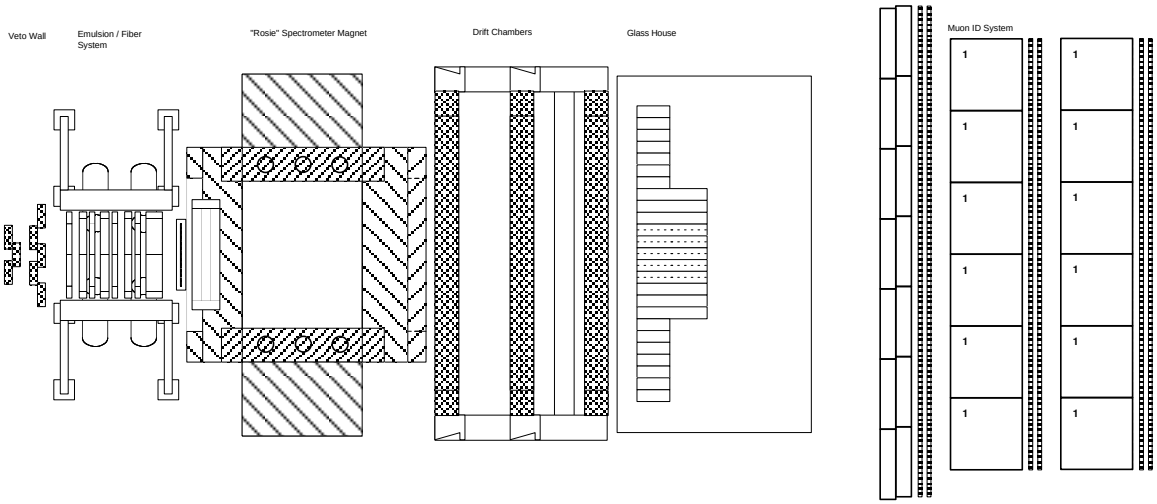


ν_τ observation experiment (E872)



The only one has not been seen yet

Planned direct observation of ν_τ



- ν created from a beam dump (5% ν_τ)
- Emulsion target: to detect τ (decay length=2.5mm)

ν_τ observation experiment (E872)

τ lepton yield:

- experimental efficiencies
  - fiducial and τ finding: 75%
  - trigger: 95% efficient
  - total live-time : ~90%
- Physics uncertainties
  - $\sigma(D_S) = 15.4 \pm 2.9$ μb
  - $BR(D_S \rightarrow \tau\nu) = 4.1 \pm 1.0$ %
  - $\sigma_{cc}(\nu_\tau) = (0.42 \pm 0.08) \times 10^{-37}$ cm^2

⇨ 61 ± 22 τ's should be observed for 5×10^{17} protons on target

- Next steps:
  - present run established the method and first interactions
  - A fixed-target run in 1998 is likely
  - first module will be analyzed in August

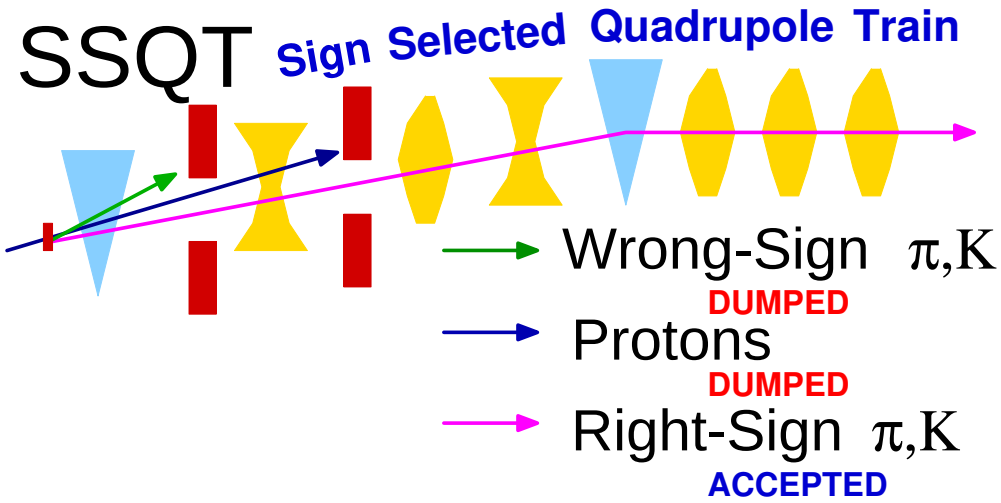
Measurement of $\sin^2\theta_W$ (E815)

- νN DIS to measure $\sin^2\theta_W$

  Using the ratio of neutral current (Z exchange) to charged current (W exchange) cross sections

  ⇨ precision measurement of $\sin^2\theta_W$.

- NuTeV improves CCFR measurement on $\sin^2\theta_W$



SSQT reduces systematics by:

– separating ν and $\bar{\nu}$

reduce charm effect $\dfrac{\sigma^{\nu}_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar{\nu}}_{CC}} = \rho^2\left(\dfrac{1}{2} - \sin^2\theta_W\right)$

– Removing K_L's from the beam

$K_L \to \pi\, e\nu$ contributes the most uncertainty in CCFR

continuous in-situ detector calibration

reduce calibration error to be 0.3% (~factor of 3 better)

Measurement of $\sin^2\theta_W$ (E815)

- CCFR results:

$$\sin^2\theta_W = 0.2236 \pm 0.0041 \quad \text{(combined)}$$

gives indirect measurement: $M_W = 80.35 \pm 0.21$ GeV/c^2

(for m_{top} = 175 GeV/c^2, m_{Higgs} = 150 GeV/c^2)

- NuTeV:
  $\sin^2\theta_W$ analysis improvements over CCFR

Source of uncertainty	CCFR $\Delta\sin^2\theta_W$	NuTeV
statistics	0.0019	~ 0.0013
ν_e flux	0.0015	improved (no K_L)
hadron shower length	0.0007	factor 2 or better (Test beam)
model m_c=1.31±0.24 (GeV/c^2)	0.0027	factor of 3 better (ν/ν method, major contribution canceled)
…		
Total uncertainty	0.0041 (ΔM_W=210MeV)	Goal: 0.0020 (ΔM_W~100MeV)

The expected W mass uncertainty is comparable and complementary to the direct measurement of W mass

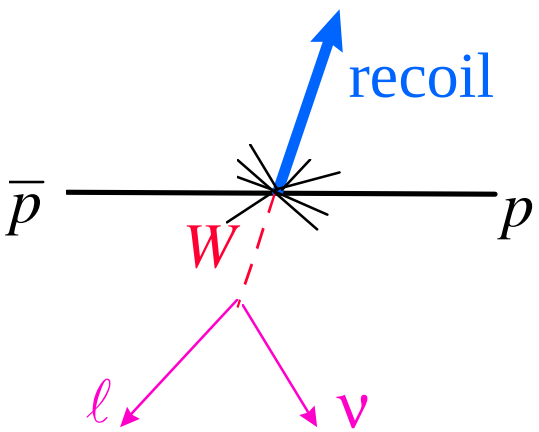
NuTeV integrated protons on target

W mass measurement (CDF&D0)

- Direct measurement of M_W
  - measure of radiative corrections in the SM
  - constraint on M_H
  - check of consistency of SM
- Method:
  - longitudinal momentum of ν unknown, cannot reconstruct invariant mass. Instead study M_T and p_T distributions

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

  - likelihood fit of $M_T(W)$ spectrum to Monte Carlo simulation



- use M_T to measure M_W
  less sensitive to $p_T(W)$
  more sensitive to $\not{E}_T$

- alternative use $p_T(\ell)$
  less sensitive to $\not{E}_T$
  more sensitive to $p_T(W)$

- Measurement strategy
  - Monte Carlo model
  - true lepton energy response/resolution
  - true recoil response/resolution
  - likelihood fit to M_T or $p_T(\ell)$
  - systematic uncertainties, cross check

W mass event sample

- Run Ib measurement - preliminary -
  - CDF: $W \rightarrow \mu\nu$
  - D0: $W \rightarrow e\nu$

  Run Ia *W* mass results published
    - CDF PRL 75 (1995) 11
    - D0 PRL 77 (1996) 3309
- Event selection:
  - isolated lepton in the central region
  - $p_T^{\ell} > 25$ GeV
  - $\not\!\!E_T > 25$ GeV
  - $p_T(W) < 15$ GeV (D0); $p_T(W) < 20$ GeV (CDF)
- Total events:

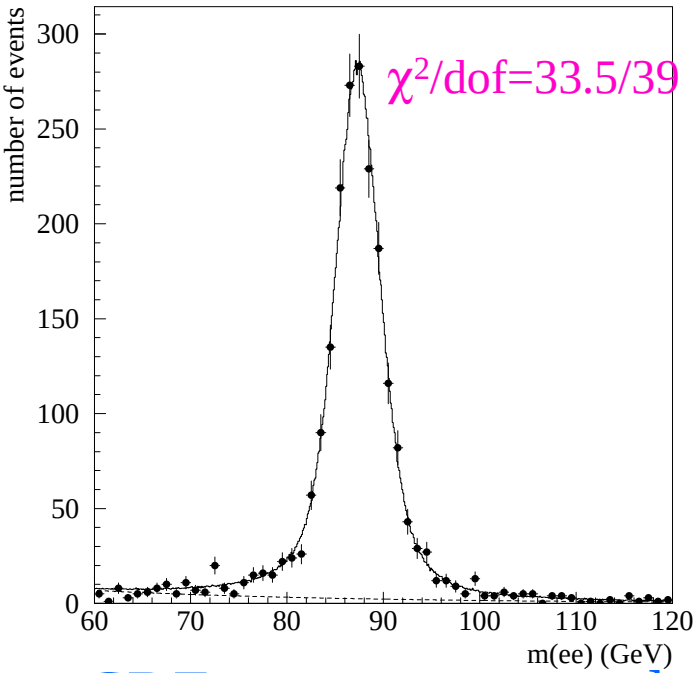
  D0: ~28K (~23K in M_T^W fit) CDF: ~21K (~15K in M_T^W fit)
- Background:
  - $Z \rightarrow ee$ (D0), $\mu\mu$ (CDF)
  - QCD
  - $W \rightarrow \tau\nu$

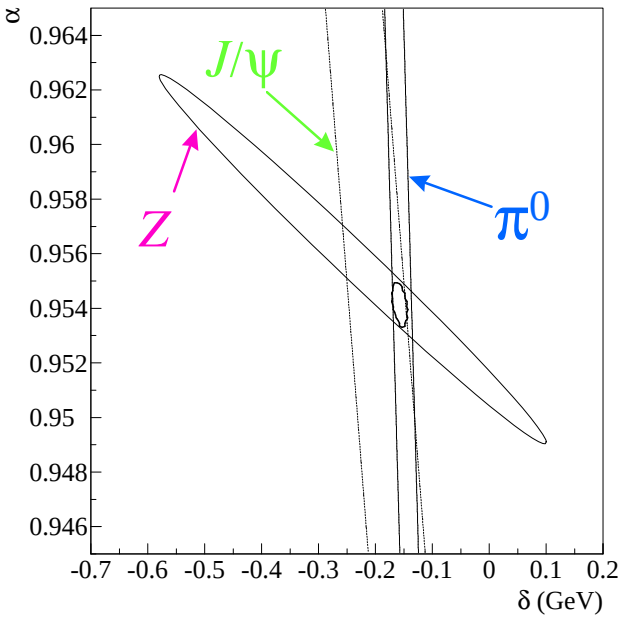
background	D0	CDF
uncertainty in ΔM_W	12 MeV	20 MeV

Lepton scale calibration

- D0: EM energy response $E^{meas} = \alpha E^{true} + \delta$

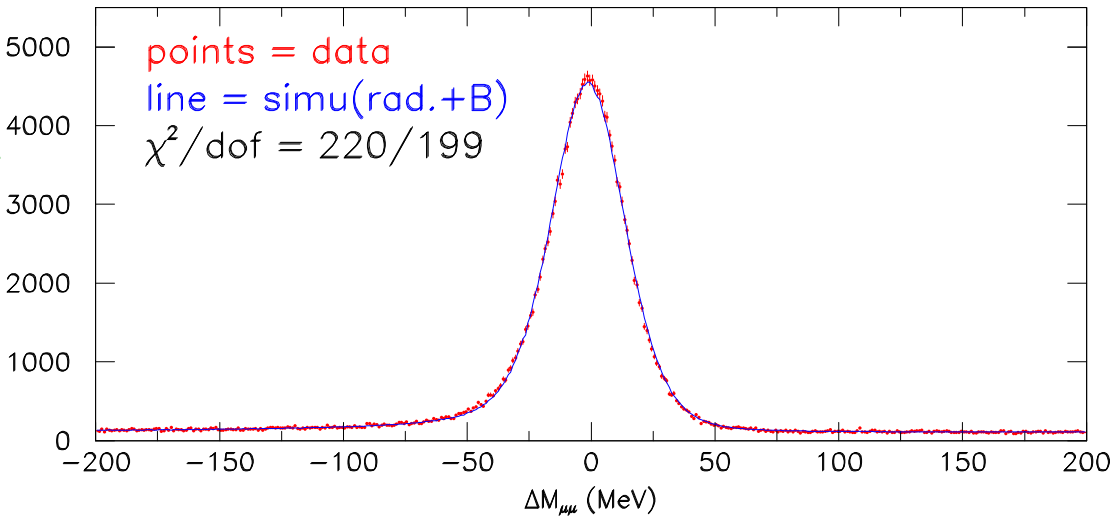
  Z data determine α, π^0 and *J*/ψ events determine δ





- CDF: momentum scale

determined by $J/\psi \rightarrow \mu^+\mu^-$ (250k J/ψ events)

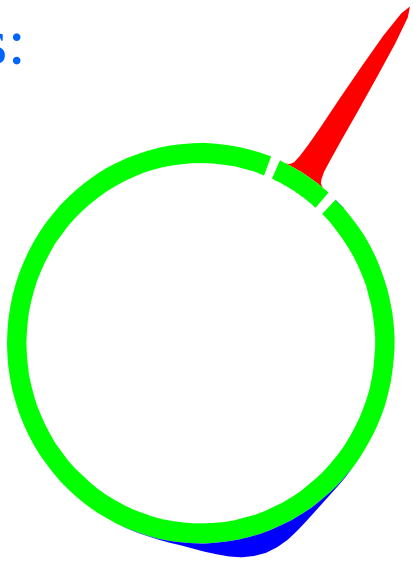


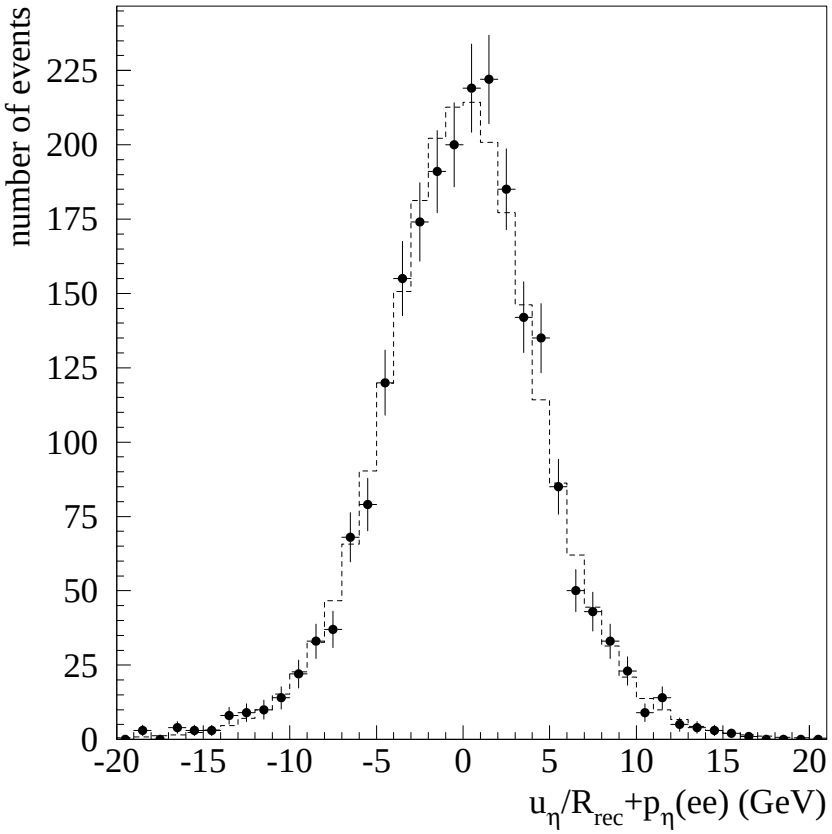
lepton energy scale	D0	CDF
uncertainty in ΔM_W	65 MeV	40 MeV

Recoil response and resolution

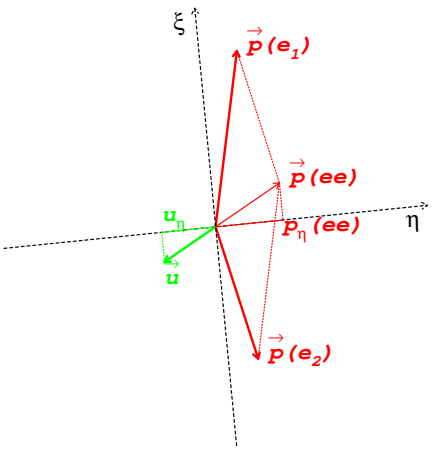
- Recoil has two components:
  - due to $p_T(W)$
  - due to underlying event

Using $Z \rightarrow ee$ data



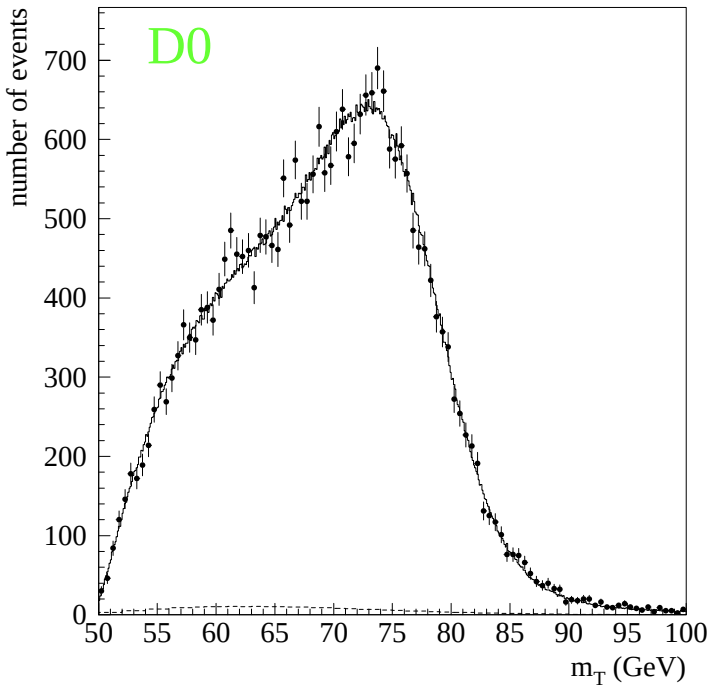


χ^2/dof =25/40

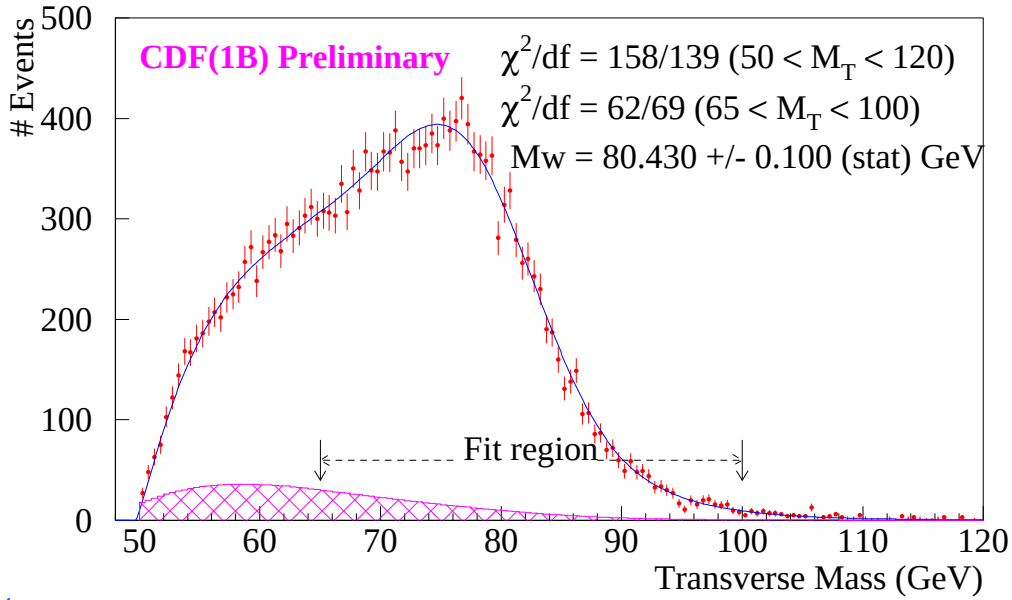


Recoil model	D0	CDF
uncertainty in ΔM_W	40 MeV	90 MeV

M_W: transverse mass fit



χ^2/dof = 77/59
(60<M_T<90)

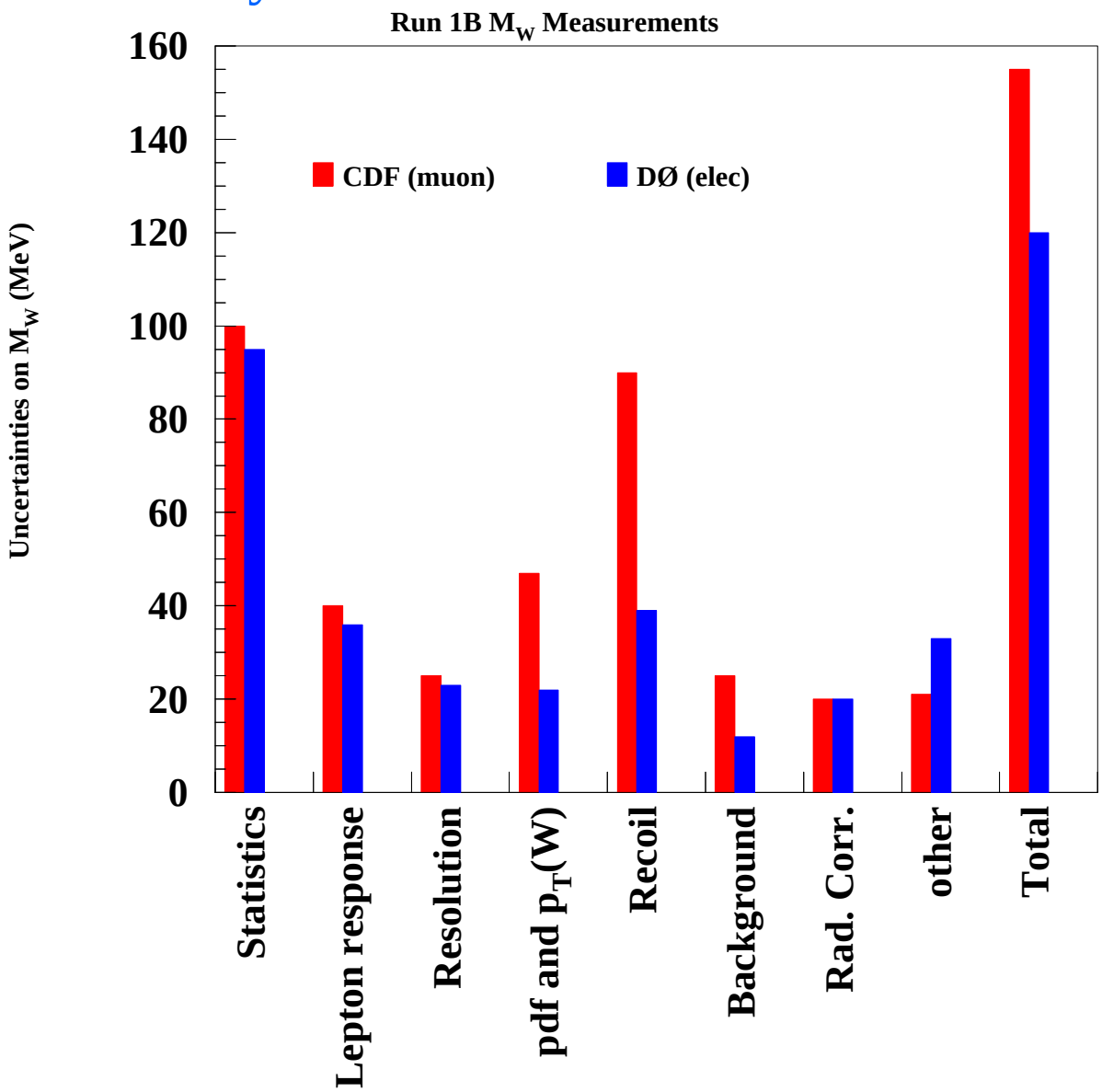


Results:

	M_W (run Ib) (GeV/c^2)
D0	80.45 ± 0.07 (fit stat.)
CDF	80.43 ± 0.10 (fit stat.)

M_W results and summary of errors

- Summary of errors:



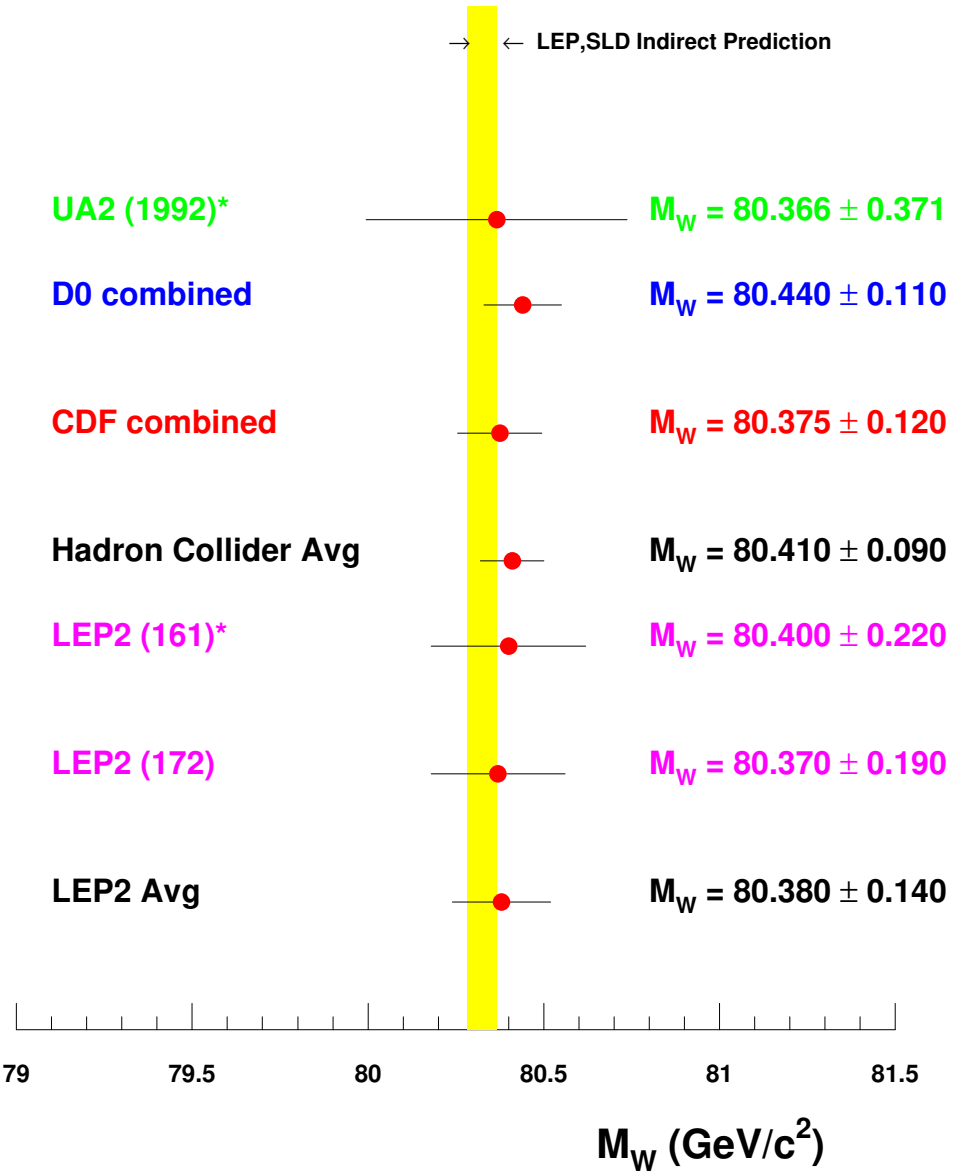
- *W* mass results (Run Ib preliminary)

CDF: $M_W = 80.43 \pm 0.10 \pm 0.12 (\text{GeV}/c^2)$

D0: $M_W = 80.45 \pm 0.10 \pm 0.07 (\text{GeV}/c^2)$

not syst. dominated

World Average *W* mass

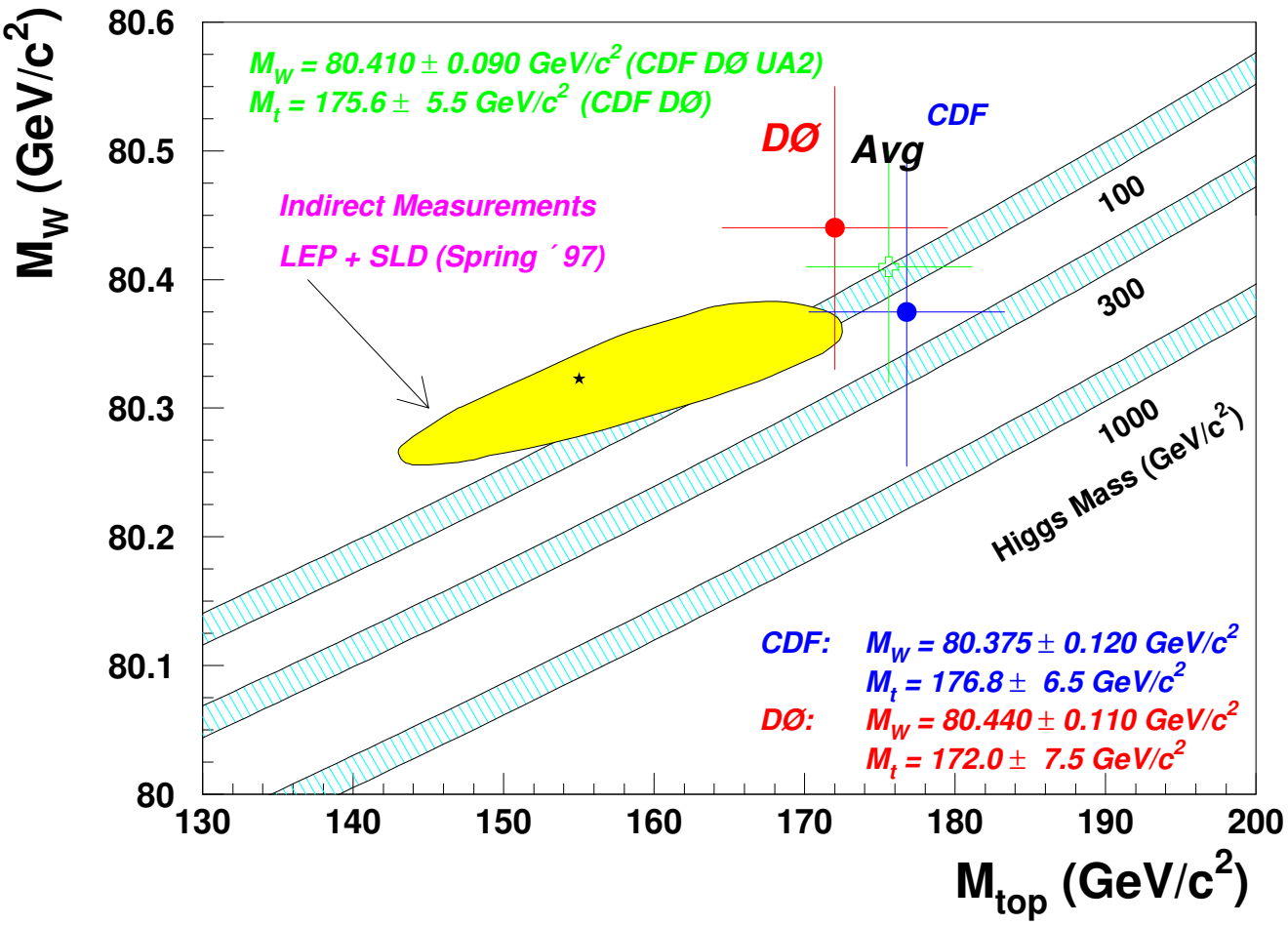


Tevatron combined (CDF+D0):

$$M_W = 80.41 \pm 0.09 \ (\mathrm{GeV}/c^2)$$

World average: $M_W = 80.40 \pm 0.08 \ (\mathrm{GeV}/c^2)$

Constraints on Higgs mass



Summary and prospects

- CDF & D0:
  - from diboson production studies obtained best limits on $WW\gamma$, WWZ, $ZZ\gamma$ couplings
  - direct measurement of W mass gives most precise result
  - D0 measured $\sigma \cdot BR(W\rightarrow\tau\nu)$ and g_τ^W/g_e^W , consistent with e-τ universality
- E872 expects to observe 61 ± 22 ν_τ interactions
- NuTeV will improve the error on the $\sin^2\theta_W$ measurement by factor of 2
- Tevatron Run I analysis prospects:
  - final cross section $W\rightarrow e\nu$, $W\rightarrow\mu\nu$ from Run Ib data expected soon
  - CDF Run Ib W mass measurement expected from electron channel with improvements on errors
  - D0 adding forward region to W mass measurement, expect to further reduce error
  - CDF W/Z gamma Run Ib results expected this summer
  - D0 $Z(\nu\nu)\gamma$ Run Ib result still to come

Prospects

Tevatron Run II:

- Tevatron and detector upgrades provide 2 fb^{-1} data samples.
- Quantitative expectations on trilinear gauge couplings:
  - Factor of 20 in luminosity provides

    ~ factor of 2.5 improvement in anomalous couplings limit (at fixed form factor scale and not including improvements in detector and technique).
- Expect the error on the *W* mass measurement to be ~ 40 MeV per experiment in Run II.