Electroweak Physics Results From Hadron Colliders

Marcel Demarteau
Fermilab

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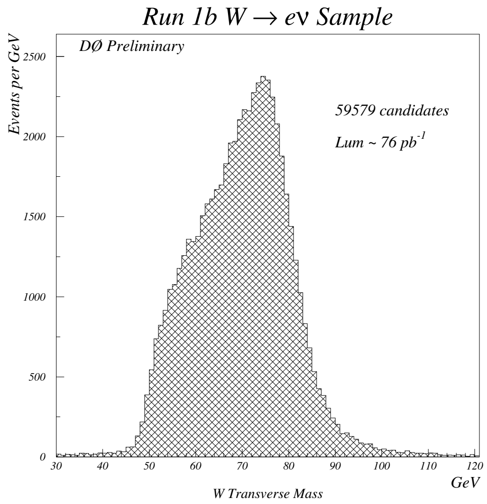
Outline

- **Inclusive W/Z Production**
  - Cross section
  - $\Gamma(W)$
- **Differential Z Production**
  - Drell-Yan
  - Asymmetry
- **W Mass**
- **Comparison SM**
- **Gauge Boson Pair Production**
  - Anomalous couplings
  - WW and WZ production
  - $W\gamma$ production
  - $Z\gamma$ production
- **Conclusions and Outlook**

Inclusive W and Z production cross sections

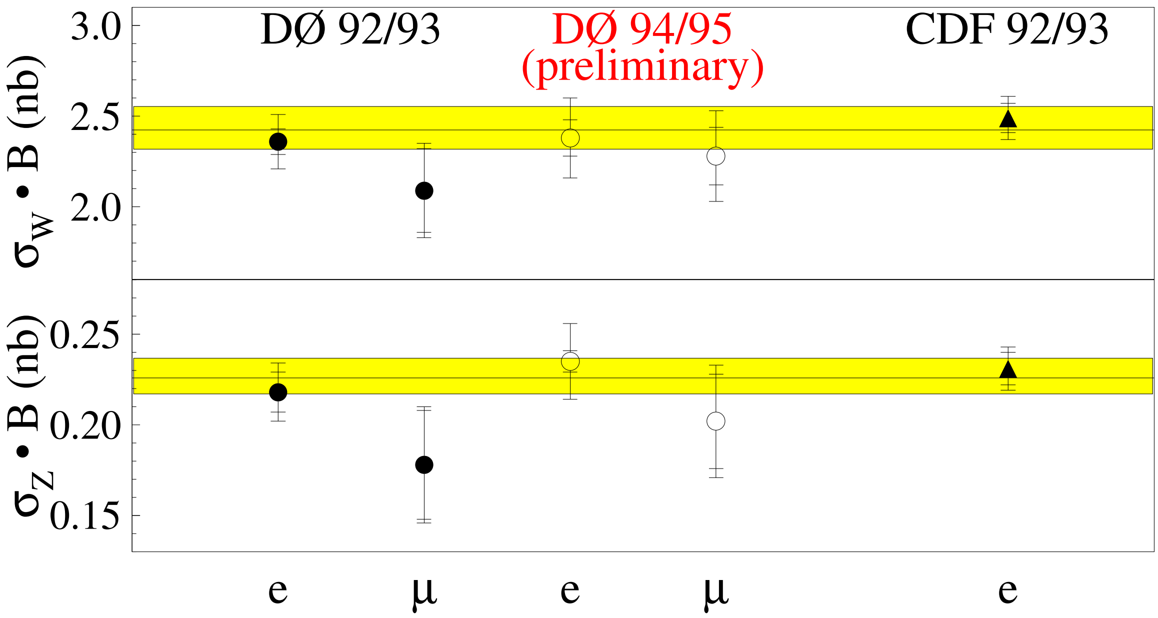
At $\sqrt{s} = 1.8$ TeV:
Valence-sea contribution $\approx 55\%$
sea-sea contribution $\approx 20\%$
Cross sections calculated to
$\mathcal{O}(\alpha_s^2)$ (van Neerven *et al.*)



Event Characteristics

Ws: high p_T lepton, large $\not\!\!E_T$ — $E_T > 25$ GeV, $\not\!\!E_T > 25$ GeV
Zs: two high p_T leptons — $p_T^1 > 25$ GeV, 2^{nd} "loose"

	DØ		CDF	
	e	μ	e	μ
$\int \mathcal{L}$ (pb^{-1})	89.1 ± 7.5	32.0 ± 2.7	19.7 ± 0.7	18.0 ± 0.7
W Candidates	59579	4472	13796	6222
A_W (%)	43.4 ± 1.5	20.1 ± 0.7	34.2 ± 0.8	16.3 ± 0.4
ϵ_W (%)	70.0 ± 1.2	24.7 ± 1.5	75.4 ± 1.1	72.9 ± 1.6
Bkg W (%)	8.1 ± 0.9	18.6 ± 2.1	14.1 ± 1.3	15.1 ± 2.2
Z Candidates	5702	173	1312	423
A_Z (%)	34.2 ± 0.5	5.7 ± 0.5	40.9 ± 0.5	15.9 ± 0.3
ϵ_Z (%)	75.9 ± 1.2	43.2 ± 3.0	69.6 ± 1.7	74.7 ± 2.7
Bkg Z (%)	4.8 ± 0.5	8.0 ± 2.1	1.6 ± 0.7	0.4 ± 0.2



- Prediction at $\mathcal{O}(\alpha_s^2)$, NP B359, 313
- Dominant uncertainties:
  - ◇ Theory: parton distribution functions (brick wall?)
  - ◇ Data: luminosity (brick wall!), pdfs
- Expect to reduce errors by factor 2 for final results

	$\sigma_W \cdot B(W \to \ell\nu)$ (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)	$2.28 \pm 0.04 \pm 0.25$	$0.202 \pm 0.016 \pm 0.026$
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	$2.42\ ^{+0.13}_{-0.11}$	$0.226\ ^{+0.011}_{-0.009}$

$\boxed{\text{Extraction of } \Gamma_W}$

Measure

$$R = \frac{\sigma_W \cdot B(W \to \ell\nu)}{\sigma_Z \cdot B(Z \to \ell\ell)}$$

Extract

$$B^{-1}(W \to \ell\nu) = \frac{\sigma_W}{\sigma_Z} \cdot \frac{1}{B(Z \to \ell\ell)} \cdot \frac{1}{R}$$

or using $\Gamma(W \to \ell\nu)$,

$$\Gamma(W) = \frac{\sigma_W}{\sigma_Z} \cdot \frac{\Gamma(W \to \ell\nu)}{B(Z \to \ell\ell)} \cdot \frac{1}{R}$$

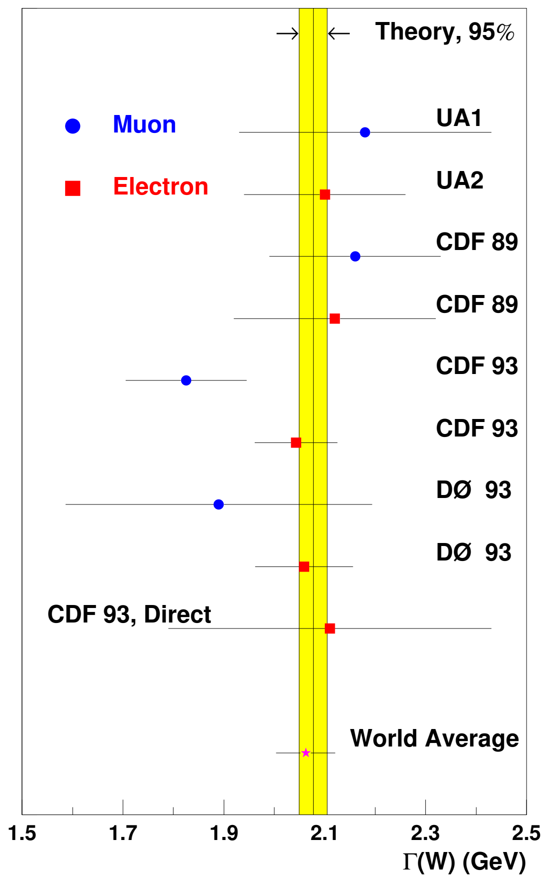
Inputs

$\frac{\sigma_W}{\sigma_Z}$	$= 3.33 \pm 0.03$	(error dominated by pdf's)
$B(Z \to \ell\ell)$	$= (3.367 \pm 0.006)\%$	(LEP)
$\Gamma(W \to \ell\nu)$	$= \frac{G_F}{\sqrt{2}} \frac{M_W^3}{6\pi}(1+\delta)$	Rosner et al, PRD49 (1994) 1363
	$= 225.2 \pm 1.5$ MeV	

$$\boxed{\Gamma(W) = 2.159 \pm 0.092 \text{ GeV (DØ)}}$$

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

For final result expect reduction in uncertainty by factor of two.



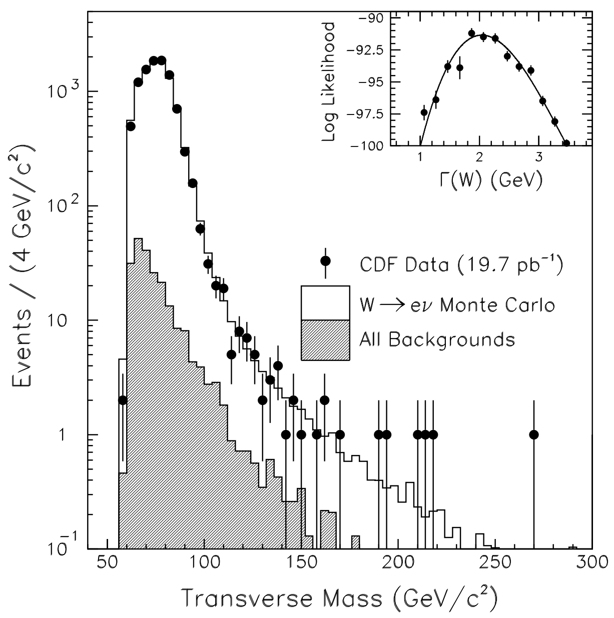
$$\Gamma(W) = 2.062 \pm 0.059 \text{ GeV} \qquad \text{World Average}$$
$$\Gamma(W) = 2.077 \pm 0.014 \text{ GeV} \qquad \text{SM prediction}$$

$$\boxed{\Delta\Gamma_W^{\mathrm{non-SM}} < 109 \text{ MeV} \quad 95\% \text{ C.L.}}$$

Limit on Contributions to $\Delta\Gamma$ from supersymmetry

Direct Γ_W Measurement (CDF)

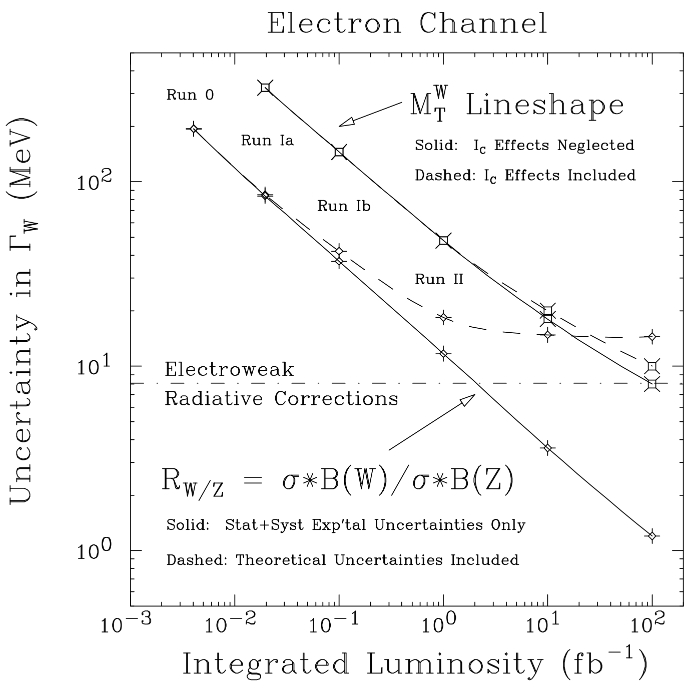
M_W lineshape sensitive to Γ_W
Measurement independent of Standard Model assumptions



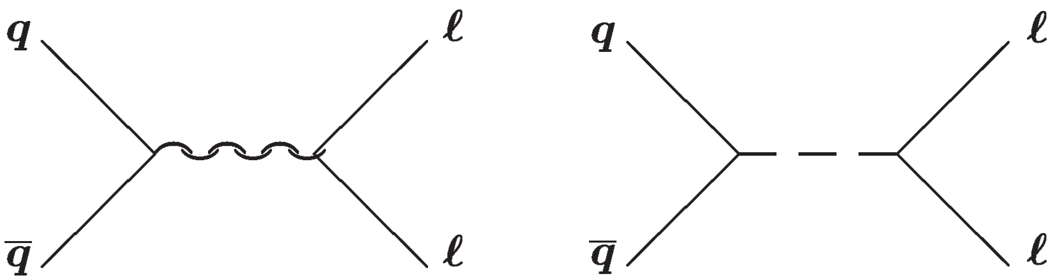
Fit to high M_t region
$M_t > 110$ GeV/c^2

$\Gamma_W = 2.11 \pm 0.28 \pm 0.16$ GeV

May be better suited to measure $\Gamma(W)$ at high $\mathcal{L}$



Drell – Yan Production

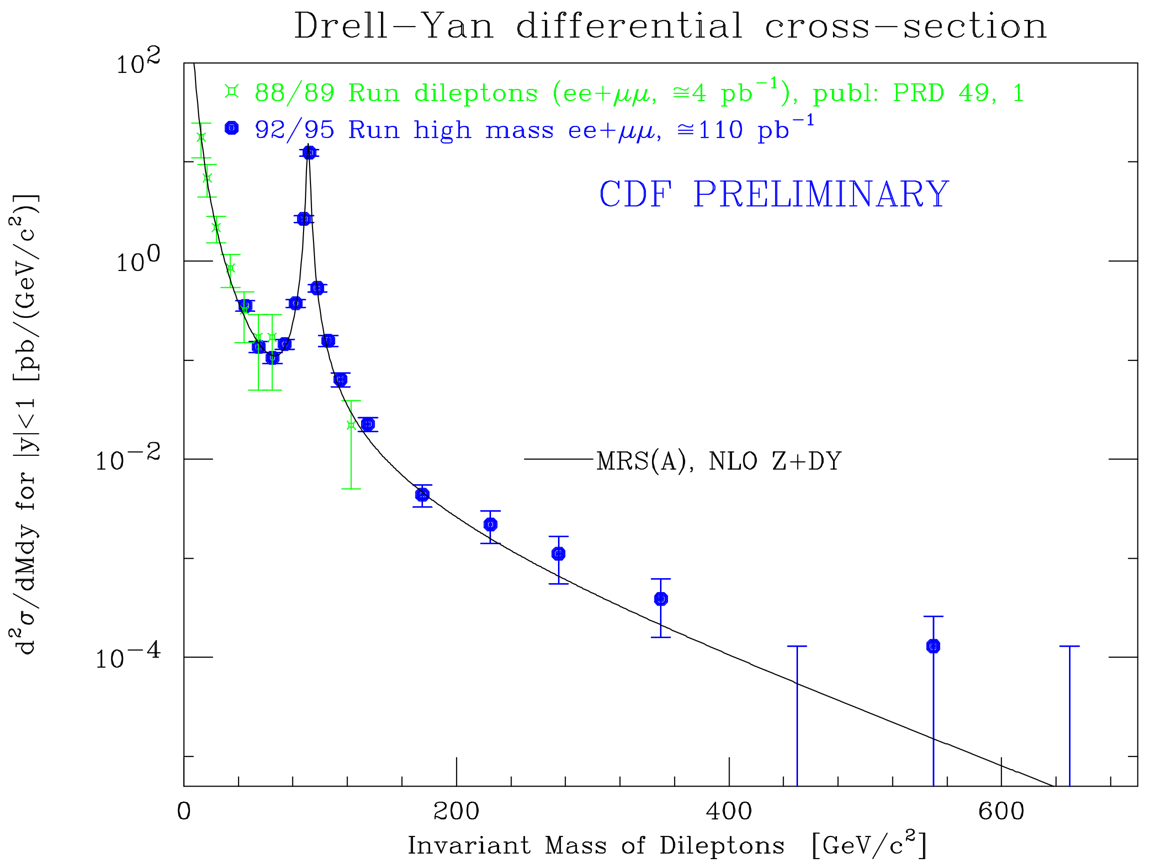


Unique advantage of $\overline{p}p$ collisions:
Wide range of partonic cms energies available

Measure $\dfrac{d\sigma}{dm}$ for $|\eta_\ell| < 1$ and $M_{\ell\ell} > 40$ GeV/c^2

Select: **Isolated $e^+e^-/\mu^+\mu^-$ pairs, $p_T^\ell > 20$ GeV/c**

Background: **QCD di-jet events (estimate from same sign events)**
$Z \to \tau\tau$ (Monte Carlo) and Cosmic rays



Probe of Substructure

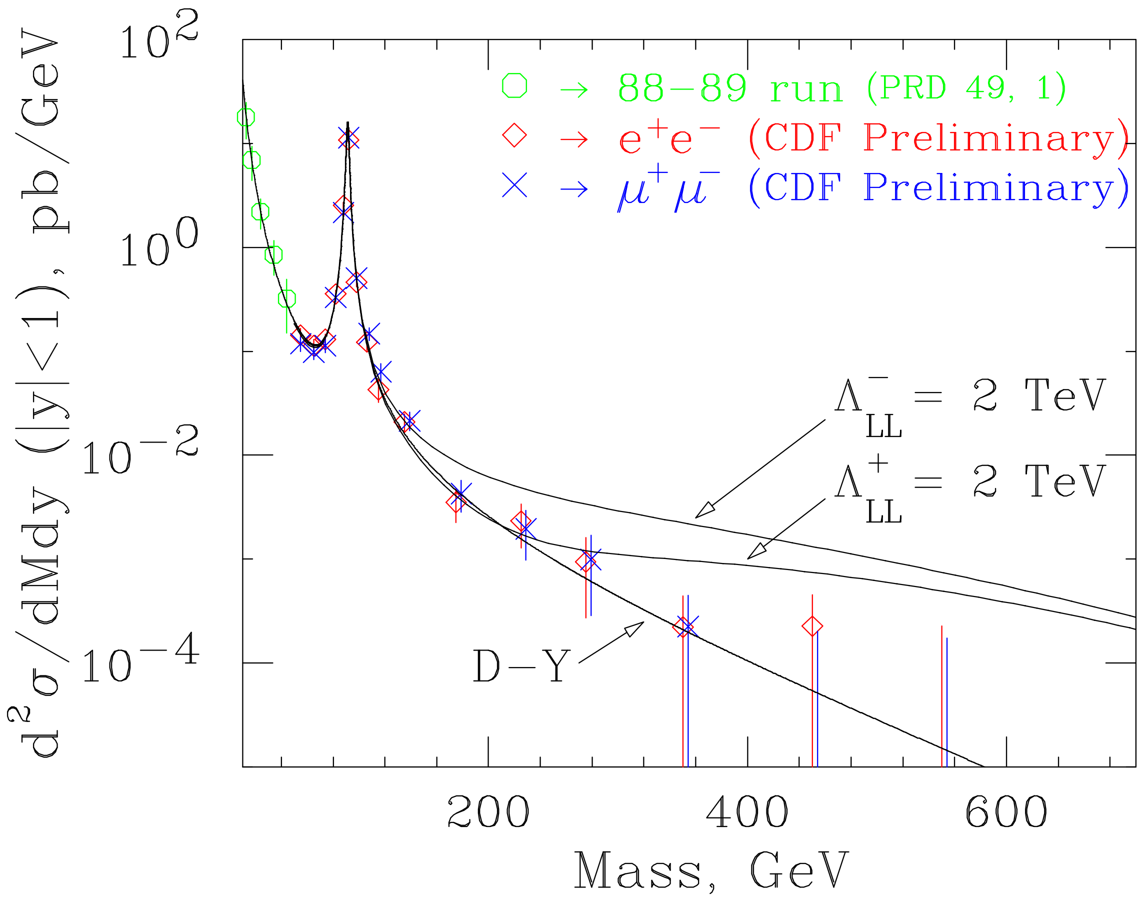
Contact Interaction (Eichten et al., PRL 50 (1983) 811)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \eta\,\frac{g_0^2}{\Lambda^2}\,(\overline{\psi}_i\gamma^\mu\psi_i)\,(\overline{\psi}_j\gamma^\mu\psi_j) \qquad i,j = \mathrm{L,\,H}$$

Λ_{ij}^{η} : **Compositeness Scale**

η : **-1 (+1) constructive (destr.) interference**

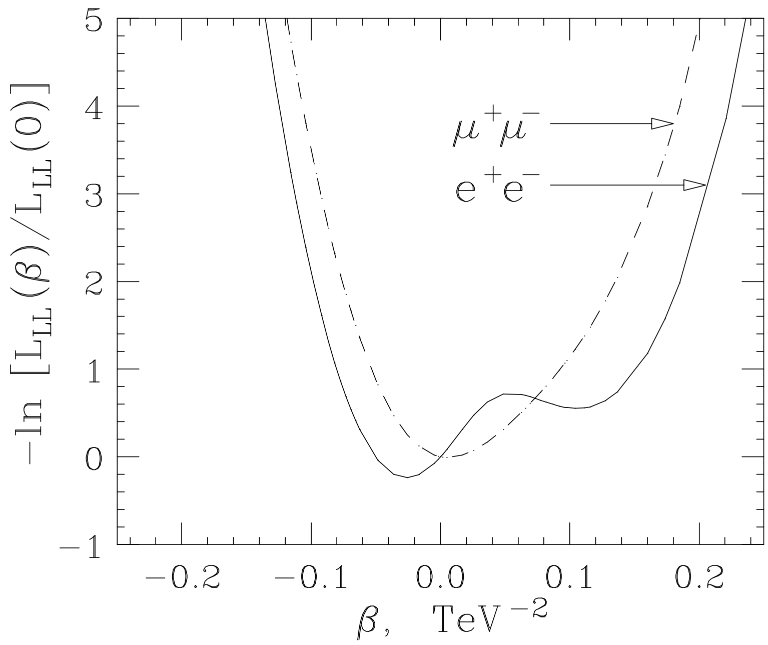
Effect mainly through interference $\sim \dfrac{q^2}{\Lambda^2}$



Normalize predictions to observed cross section for 50 $< M_{\ell\ell} <$ 150 GeV; Removes luminosity dependence

Perform binned Likelihood fit to number of observed and expected events as function of $\Lambda_{ij}^{\pm}$

Set limit on $\beta = \pm 1/(\Lambda_{ij}^{\pm})^2$ for e, μ channels and e, μ combined



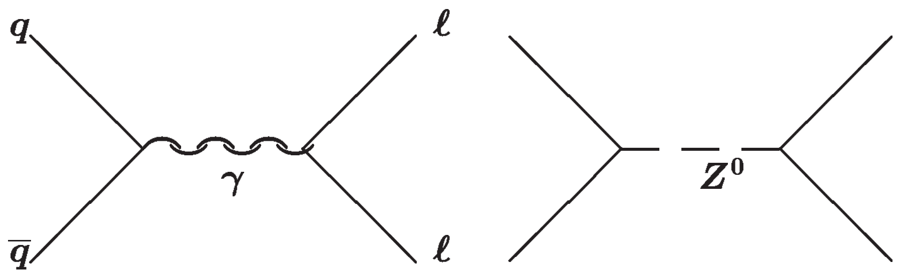
Model ij	Λ^+ TeV	Λ^- TeV
LL	3.1	4.3
LR	3.3	3.9
RL	3.3	3.7
RR	3.0	4.2
VV	5.0	6.3
AA	4.5	5.6
SC	3.3	3.3

Stringent limits on quark-lepton compositeness scale. Compare to:

LEP:	$q\ell$	1.6 - 2.5 TeV	PL B387, 432 (1996) (Opal)
HERA:	$q\ell$	1.0 - 2.5 TeV	PL B353, 578 (1995) (H1)
TeV:	qq	1.6 - 1.8 TeV	PRL 77, 5336 (1996) (CDF)
		2.1 - 2.4 TeV	Prelim. (DØ)
TeV:	$q\nu$	1.3 - 5.2 TeV	Fermilab-97/001 (CCFR)

Probes distances $\approx 10^{-17}$ cm !

Forward – Backward Asymmetry in Z Production



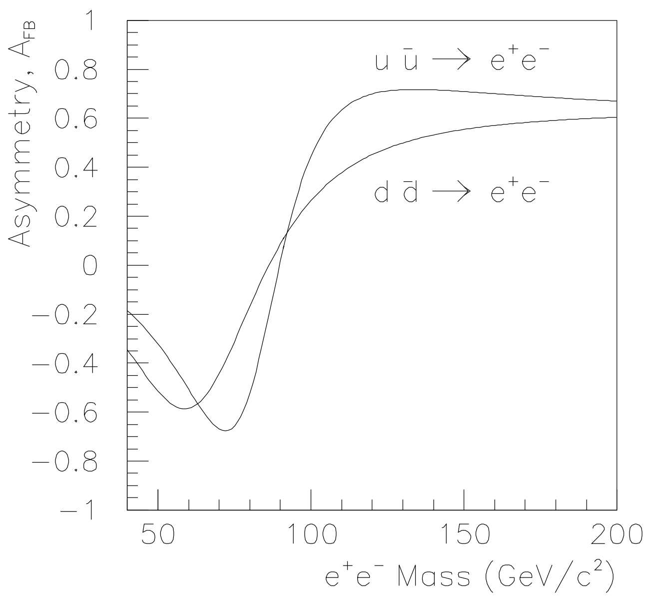
Coupling $\sim (g_V + g_A \gamma_5)$
$g_V = I_3 - 2Q_f \sin^2\vartheta_W$
$g_A = I_3$

$$\frac{1}{\sigma}\frac{d\sigma(s)}{d\cos\vartheta^*} = \frac{3}{8}(1+\cos^2\vartheta^*) + A_{FB}(s)\cos\vartheta$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

Asymmetry direct measurement of Z couplings

Note: Initial state mix of u and d: different asymmetries
Z's have different polarization compared to LEP
at LEP: $(g_V + g_A)^2 \approx (g_V - g_A)^2 \approx g_A^2$

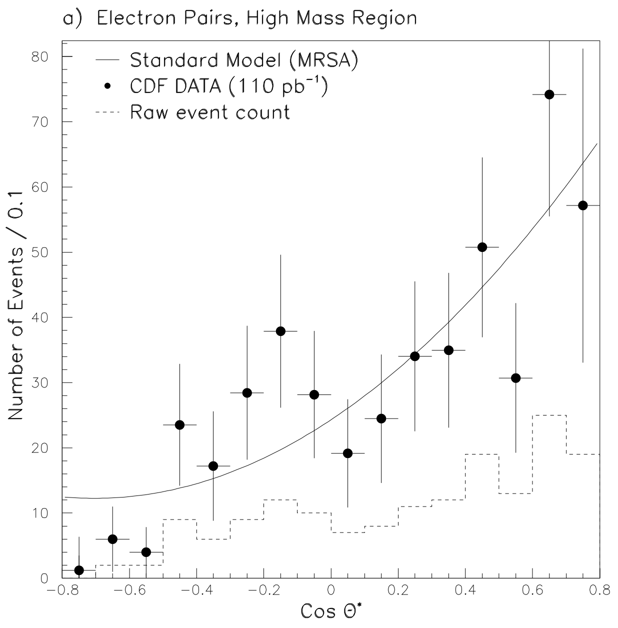


Tevatron: light quark asymmetries free from fragmentation uncertainties

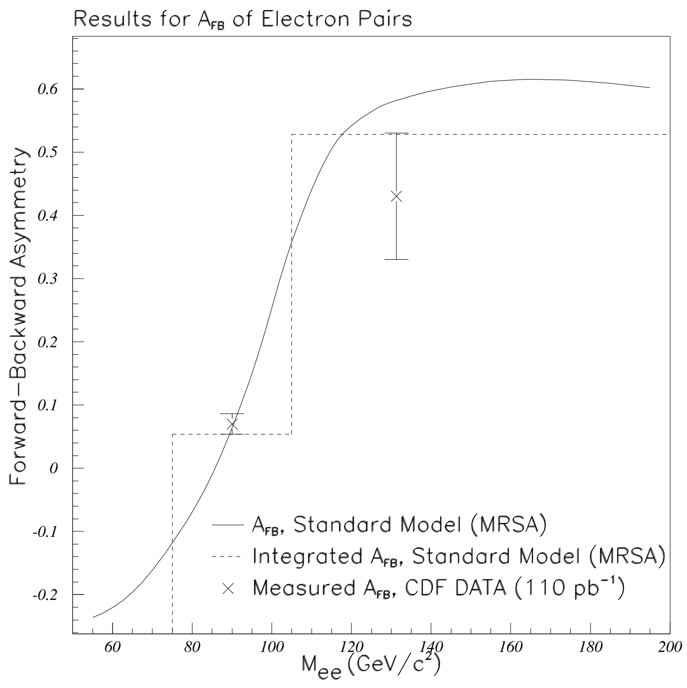
LEP/SLC: asymmetries free from pdf uncert.

Data: electrons only $|\eta_{\ell_1}| < 1.1$ and $|\eta_{\ell_2}| < 2.4$

Pole Region: $75 < Mee < 105$ GeV/c^2 5463 events
High Mass: $Mee > 105$ GeV/c^2 183 events



Correct for backgrounds
Mass deconvolution
and acceptance



Pole:
$A_{FB} = 0.07 \pm 0.016$
$A_{FB} = 0.054 \pm 0.001$ (SM)

High Mass:
$A_{FB} = 0.43 \pm 0.10$
$A_{FB} = 0.528 \pm 0.006$ (SM)

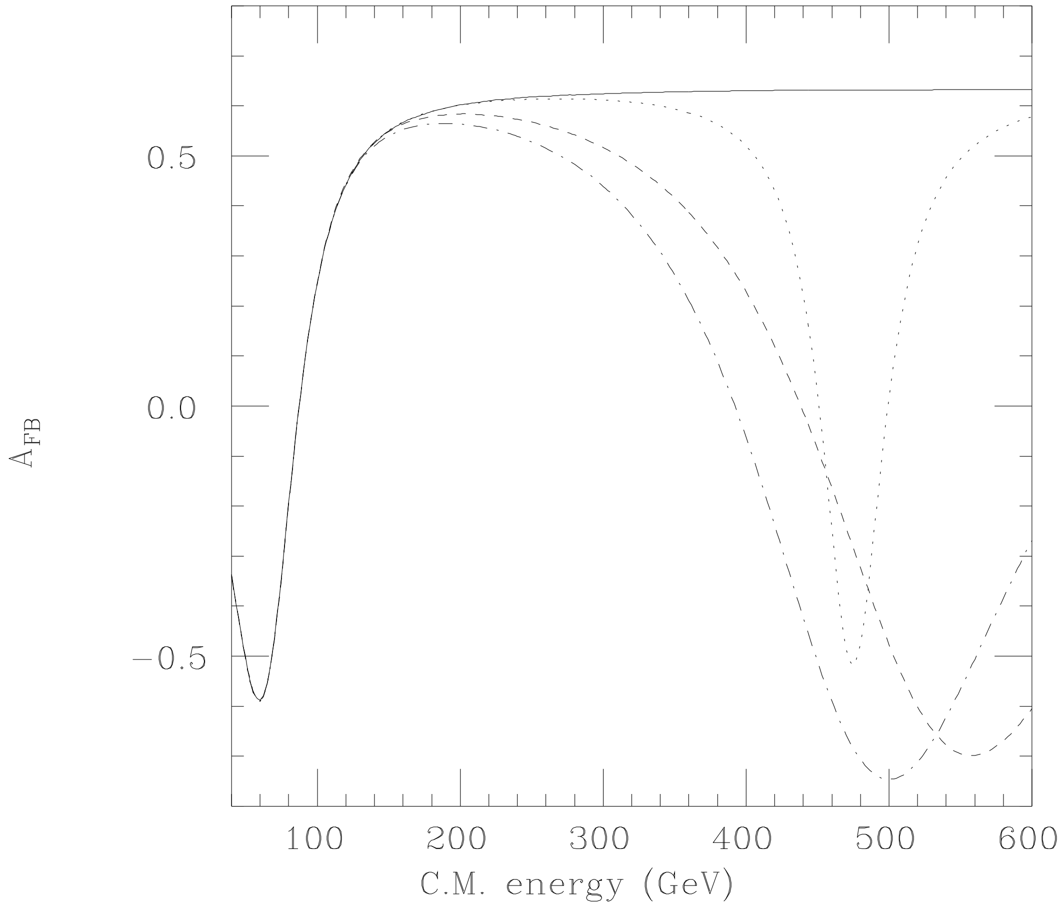
Phys. Rev. Lett. 77, 2616 (1996)

A_{FB}: Extended Gauge Sector

Extended gauge sector, additional gauge bosons:

$$\begin{array}{llll} \mathrm{SO(10)} & \rightarrow \mathrm{SU(5)} \times \mathrm{U(1)} & \rightarrow Z_\chi \\ \mathrm{E6} & \rightarrow \mathrm{SO(10)} \times \mathrm{U(1)} & \rightarrow Z_\psi \end{array}$$

$$Z' = Z_\psi \cos\vartheta + Z_\chi \sin\vartheta \qquad \begin{array}{ll} Z_\eta & \vartheta = \arctan(\sqrt{\tfrac{3}{5}}) \\ Z_I & \vartheta = \arctan(-\sqrt{\tfrac{3}{5}}) \end{array}$$



Because of the large A_{FB} asymmetries predicted, modest event samples probe gauge structure. Measurement has about same reach as direct searches.

J. Rosner, Phys.Rev. D54, 1078 (1996)

W-Mass

Fundamental parameters in the SM

$$\alpha_{\rm em} = 1/137.035989 \qquad \delta\alpha/\alpha = 0.045 \text{ ppm}$$
$$G_F = 1.16639\ 10^{-5}\ \text{GeV}^{-2} \qquad \delta G_F/G_F = 20 \text{ ppm}$$
$$M_Z = 91.1884\ \text{GeV}/\text{c}^2 \qquad \delta M_Z/M_Z = 24 \text{ ppm}$$

As such, M_W predicted (on-shell scheme):

$$M_W^2 = \frac{1}{2}M_Z^2\left(1 + \sqrt{1 - \frac{4\pi\alpha}{\sqrt{2}G_\mu M_Z^2}\frac{1}{1-\Delta r}}\right)$$

Δr measure (in on-shell scheme) of the higher order corrections in the SM. At tree level $\Delta r \equiv 0$.
Contributions to Δr are large and are from

- γ vacuum polarization, ≈ 0.06
- Vector Boson self energies
  $m_t^2, log(m_H^2/m_W^2)$ terms
- $\cdots$ new physics

Thus, direct measurement of M_W (and M_T),

- measure of radiative corrections in the SM
- constraint on m_H
- check of consistency of SM

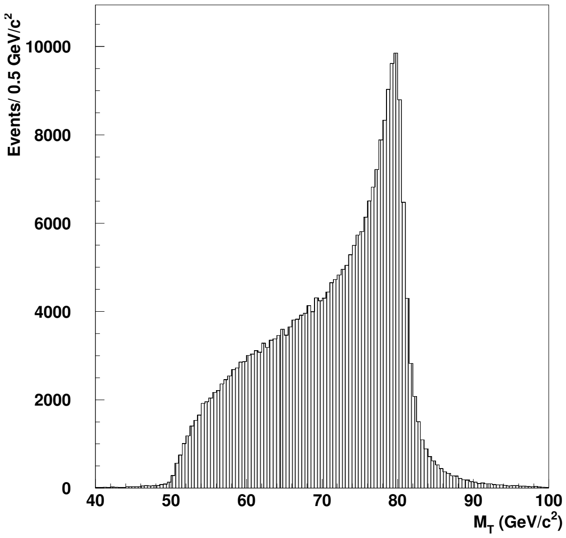
Measurement Technique

Longitudinal momentum of ν unknown; cannot reconstruct invariant mass. Instead study M_T and p_T distributions

$$m_T^2 \quad = \quad 2\, E_T^e\, E_T^\nu\, (1 \;-\; \cos\varphi^{e\nu})$$

E_T^ν inferred from $\not{E}_T$ measurement.

The mass distribution exhibits a Jacobian peak which contains the mass information.



Both M_T and p_T^e invariant under longitudinal Lorentz boosts.

M_T to first order also invariant under transverse boost.

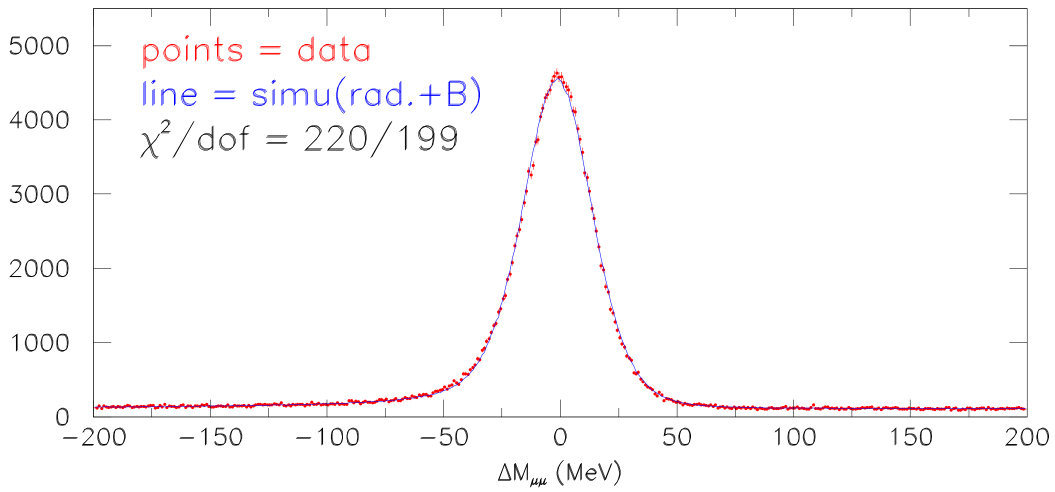
CDF: measurement in muon channel, $\int \mathcal{L}dt = 90\ pb^{-1}$
DØ: measurement in electron channel, $\int \mathcal{L}dt = 80\ pb^{-1}$

M_W obtained from likelihood fit in transverse mass of data to a Monte Carlo simulation.

Both experiments anchor their W mass measurement to the measurement of the invariant mass of known resonances.

Momentum Scale, CDF

Set the momentum scale by normalizing the observed $J/\psi \to \mu\mu$ peak, based on $\sim 250,000$ J/ψ events, to the world average mass.



$$
\begin{aligned}
M_{J/\psi}\big|_{\text{meas}} &= 3096.2 \pm 1.5 \text{ Mev/c}^2 \\
M_{J/\psi}^{\text{meas}}/M_{J/\psi}^{\text{world}} &= 0.99977 \pm 0.00048 \text{ Mev/c}^2 \\
\text{Scale factor} &= 1.00023 \pm 0.00048
\end{aligned}
$$

Major sources of uncertainty:

	in $M_{J/\psi}$	in M_W
QED, B-decay effects	0.3 MeV	7 MeV
Muon energy loss before tracking $(7.4 \pm 0.6)\%$ X_0	1.0 MeV	26 MeV
Residual Field non-unif.	0.2 MeV	6 MeV
p_T dependence from $J/\psi \to W$	1.0 MeV	26 MeV

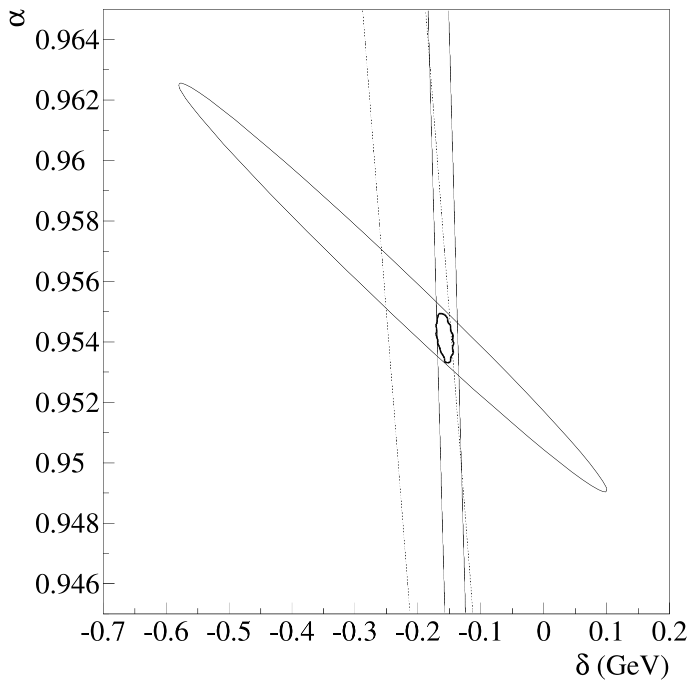
Electromagnetic Energy Scale, DØ

Determine EM energy scale using $J/\psi, \pi^0$ and Z's
Essentially anchor measurement to LEP Z mass

$$
\begin{aligned}
E_{\text{meas}} &= \alpha\, E_{\text{true}} + \delta \\
m_{\text{meas}} &\approx \alpha\, m_{\text{true}} + \delta\, f \\
f_W &\approx f_Z = \frac{2(E_1+E_2)}{m} \sin^2 \gamma/2
\end{aligned}
$$

Energy Scale set by
$Z \to e^+e^-$
$\pi^0 \to \gamma\gamma$
$J/\psi \to e^+e^-$

$$
\left(\frac{\tilde{M}_W}{\tilde{M}_Z}\right) = \left(\frac{M_W}{M_Z}\right)_{\text{true}} \left[1 + \frac{f\,\delta}{\alpha} \cdot \frac{(M_Z - M_W)}{M_Z \cdot M_W}\right]
$$



π^0 and J/ψ constrain δ
Z constrains α

$\alpha = 0.95329 \pm 0.00077$
$\delta = -0.160 \pm 0.016 \ {}^{+0.060}_{-0.210}$ GeV

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

Error dominated by Z statistics

Note: $\frac{\partial M_W}{\partial \alpha} \approx 0$ if $\delta = 0$

$$\frac{\partial M_W}{\partial \delta} \approx -\frac{f}{\alpha}\frac{(M_Z - M_W)}{M_Z} \approx -0.25$$

Modeling W Production and Detector Response

Since there is no analytic description of the M_T distribution, rely on Monte Carlo modelling

◇ **Production Model**
Event Generation

$$\frac{d^3\sigma}{dp_T\,dy\,dm} = \frac{d^2\sigma}{dp_T\,dy} \times \frac{d\sigma}{dm}$$

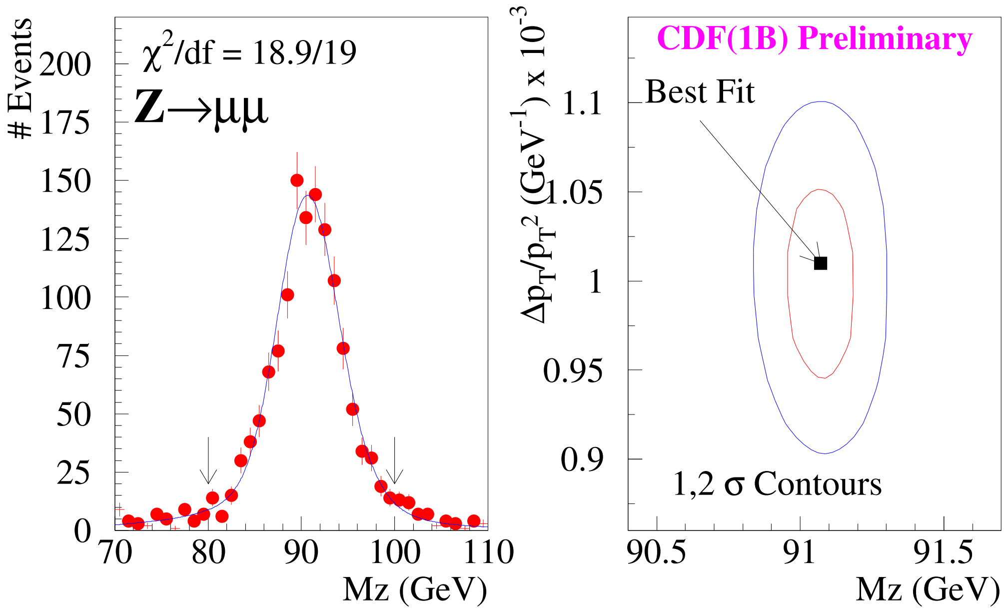
- Double differential cross section:
  Ladinsky-Yuan, PRD 50, 4239 (1994)
  pdf: MRSA (DØ); MRS R2 (CDF)
- Relativistic Breit Wigner
- Decay respects polarization of W:
  E. Mirkes, Nucl. Phys. B387, 3 (1992)

◇ **Detector Model**
Parameters determined/constrained by data

- Resolution, Efficiencies
- Underlying Event and Resolution

Perform event by event maximum likelihood fit of data to transverse mass distribution.

Momentum and Energy Resolution



Use $Z \rightarrow \mu\mu$ (ee) events:

★ **width of M_Z constrains momentum/energy resolution:**

Perform 2-d fit in M_Z and

- $\sigma(1/p_T)$
- **Constant term C:** $\frac{\sigma(E)}{E} = \sqrt{C^2 + \left(\frac{S}{\sqrt{E_T}}\right)^2}$

$\sigma(\frac{1}{p_T}) = (1.01 \pm 0.05)10^{-3}$ $\boxed{\delta M_W = 25 \text{ MeV/c}^2}$

$C = 1.15^{+0.27}_{-0.36}$ % $\boxed{\delta M_W = 23 \text{ MeV/c}^2}$

Underlying Event and Recoil Model

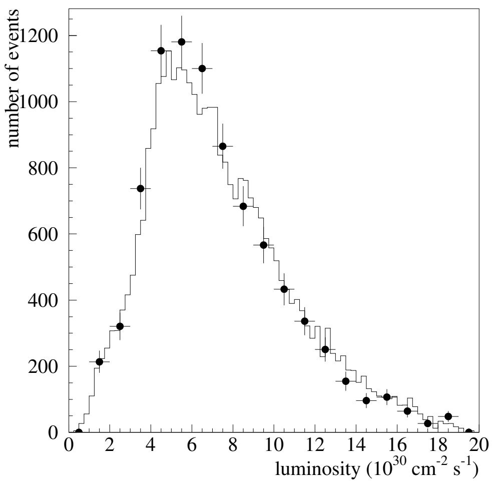
Asymmetric component: W Recoil; $\vec{p}_T^{\,rec} = -\vec{p}_T^{\,W}$

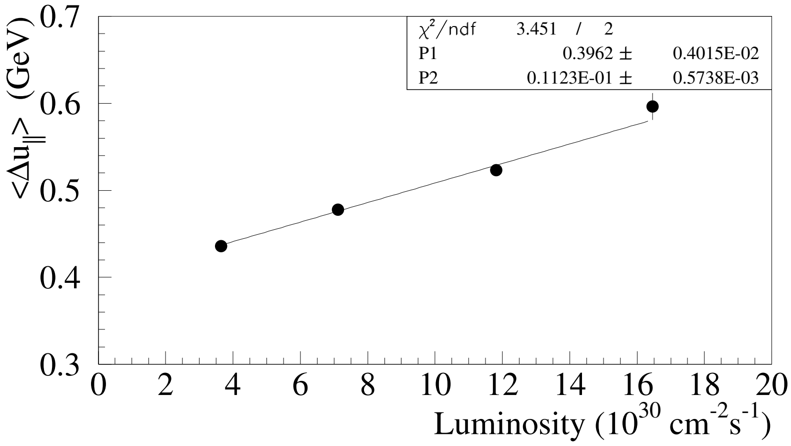
Symmetric component: Underlying event from spectator quarks and multiple interactions; $\mathcal{L}$ dependent!

Affects: Resolution

Energy flow under the electron

p_T^{ν} momentum scale

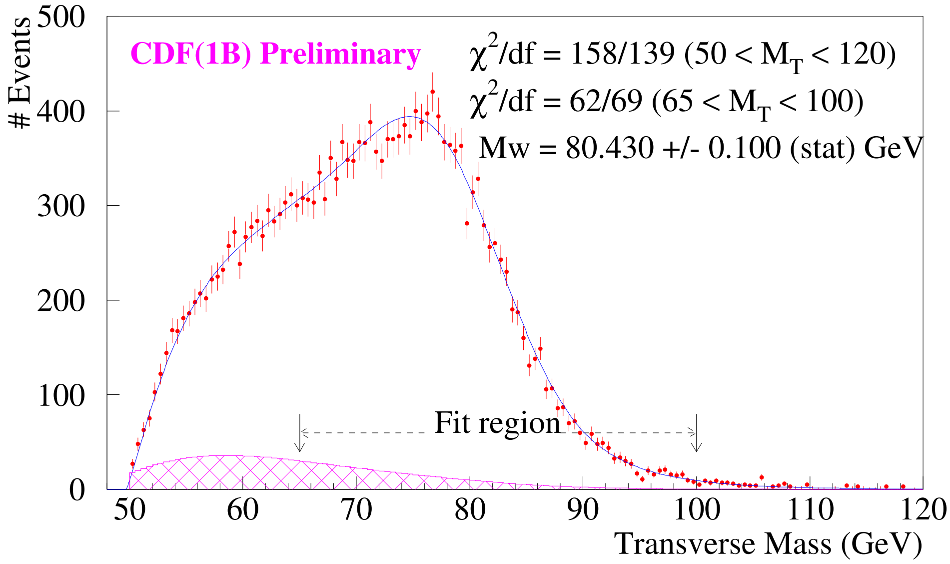


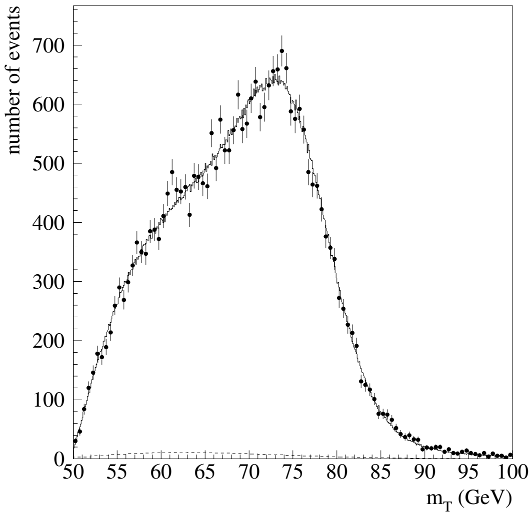


DØ: Use minimum bias data events to model UE

CDF: Use $\sigma(\not{E}_{T\ x,y})$ as function of ΣE_T

Transverse Mass Fit





Preliminary M_W Measurements (Run Ib)

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

$$M_W(e\nu) \;=\; 80.450 \pm 0.070 \text{ (stat.) GeV/c}^2 \text{ (DØ)}$$

Summary M_W Uncertainties in MeV

Source	CDF μ	DØ e
Statistical	100	70
Energy/Momentum scale	40	65
Calorimeter Linearity	—	20
Lepton Angle	—	30
e or μ resolution	25	25
Recoil Model	90	40
p_T^W Model, pdf's	50	25
Radiative Decays	20	20
QCD/QED corr's	20	—
W-width	—	10
Backgrounds/bias	25	10
Fitting procedure	10	—
Total Systematic	115	70
Total	155	120

World Average $\overline{p}p$

$$\boxed{M_W = 80.41 \pm 0.090 \text{ GeV/c}^2}$$

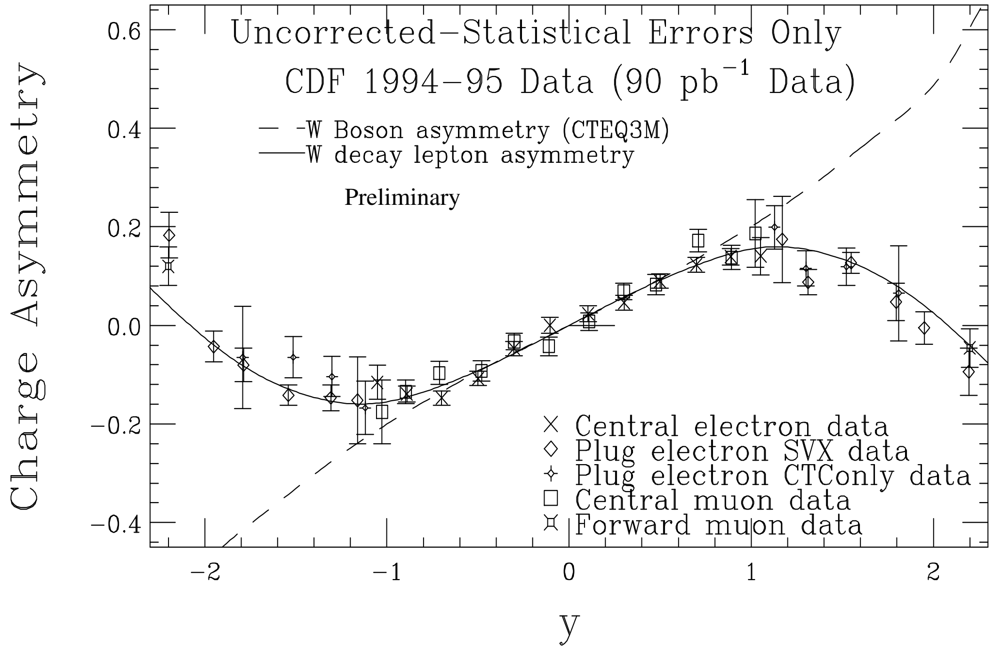
Assuming 50 MeV correlated error due to input p_T^W spectrum and pdf's.

Correlated Uncertainty in M_W: pdf

Dominated by pdf uncertainty and uncertainty on theoretical model. Uncertainty in parton distribution functions constrained by W-charge asymmetry.

Production	**Decay**
u-quark carries more momentum than d-quark More W^+ in direction of p	W almost fully polarized Lepton decay angular distr. $\propto (1 - \cos\vartheta^*)^2$

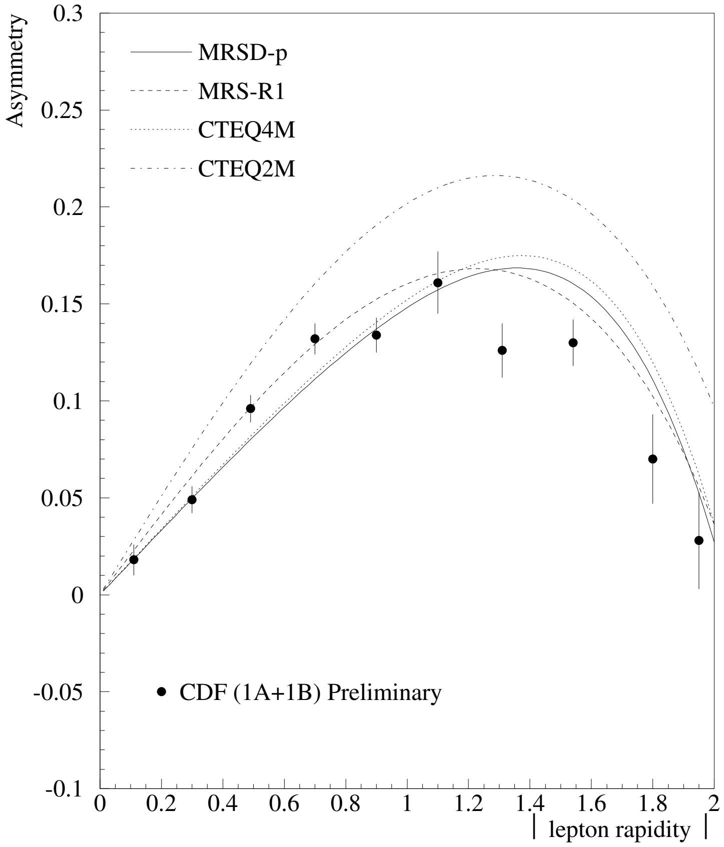
Measure $$A(y_\ell) = \frac{dN^+(y)/dy - dN^-(y)/dy}{dN^+(y)/dy + dN^-(y)/dy}$$

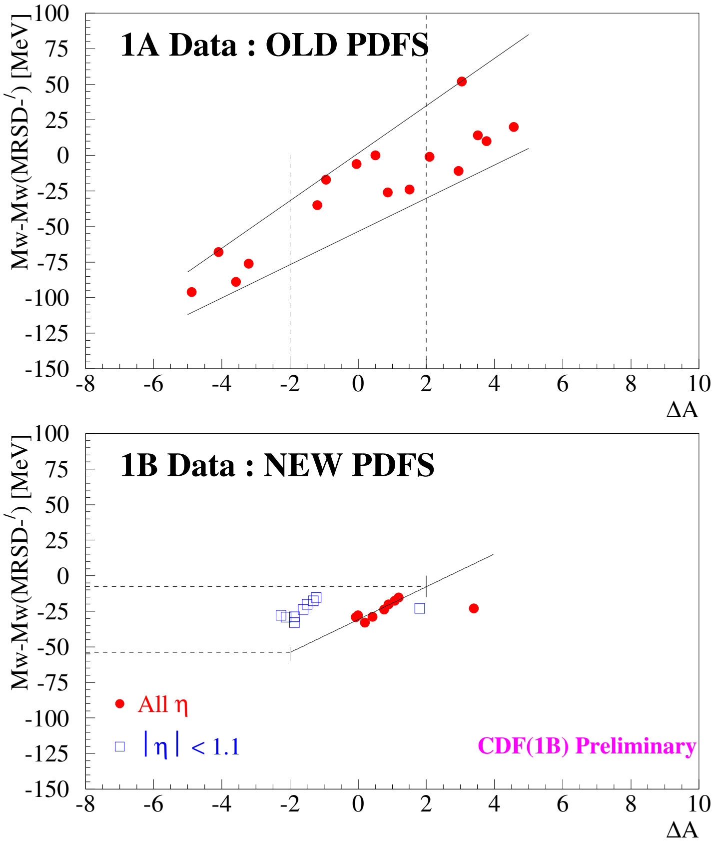


Fold spectrum: $\mathcal{CP}$ symmetry: $A(+y) = -A(-y)$

Constraint from W-Charge Asymmetry

Probe pdf's in range $0.006 < x < 0.3$ at $Q^2 = M_W^2$





$$\Delta A = \frac{\langle A \rangle_{pdf} - \langle A \rangle_{data}}{\sigma(A_{data})}$$

- ⋆ **Spread in M_W is decreasing (< 25 MeV)**
- ⋆ **Need inclusion of asymmetry data in global fit**
- ⋆ **MRS R1 (R3): $\alpha_s(M_Z^2)$=0.113 ($\lambda_{sea} = \lambda_{glue}$ at Q_0)**
  MRS R2 (R4): $\alpha_s(M_Z^2)$=0.120 ($\lambda_{sea} = \lambda_{glue}$ at Q_0)

Correlated Uncertainty in M_W: p_T^W spectrum

Input p_T^W spectrum based on $\mathcal{O}(\alpha_s^2)$ perturbative result at large p_T with soft gluon resummation at low p_T (Arnold, Kauffman)

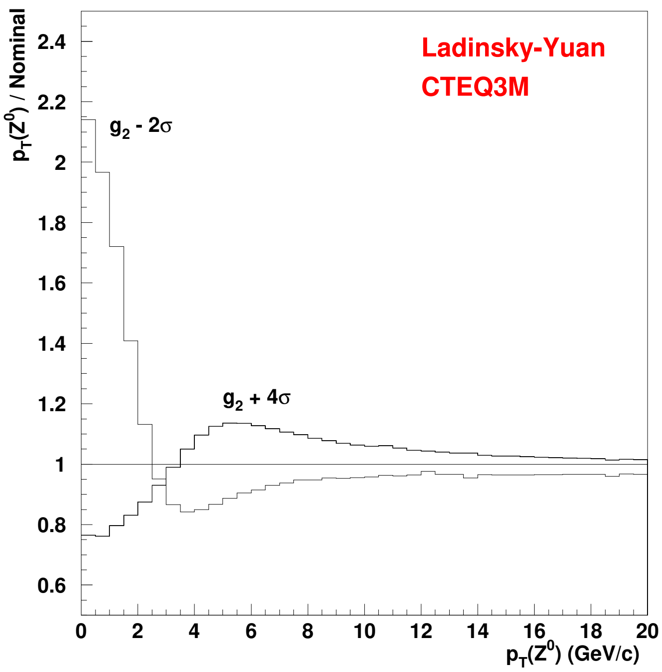
Parametrization of non-perturbative effects extended: (Ladinsky, Yuan)

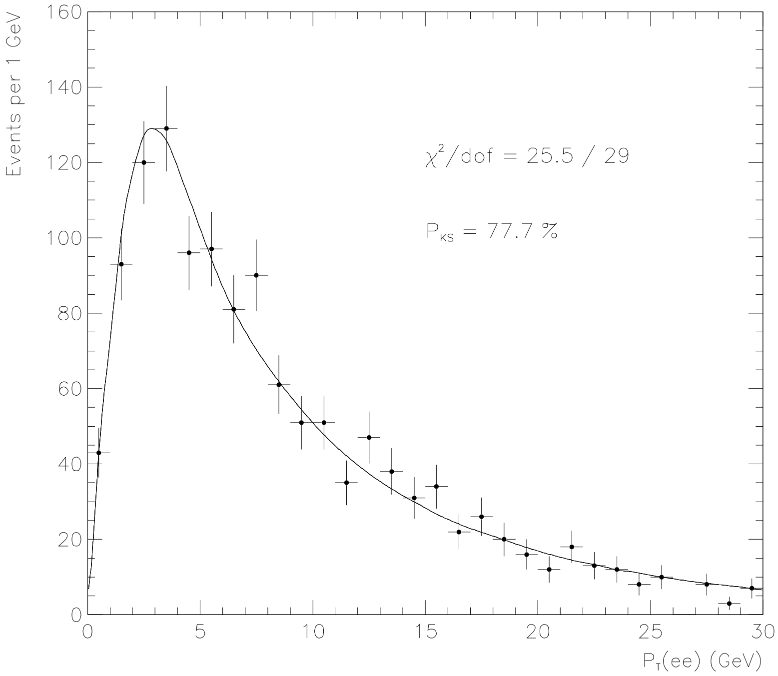
$$\frac{d^2\sigma}{dy\,dp_T} \propto \int d^2b\, e^{i\vec{b}\cdot\vec{p}_T}\; W(b)\; e^{-S_{NP}(b)}$$

$$S_{NP}(b) = b^2\left(g_1 + g_2\,\ln\frac{Q}{2Q_0}\right) \;+\; b\,g_1 g_3 \ln(100 x_1 x_2)$$

S_{NP} parametrizes non perturbative effects.

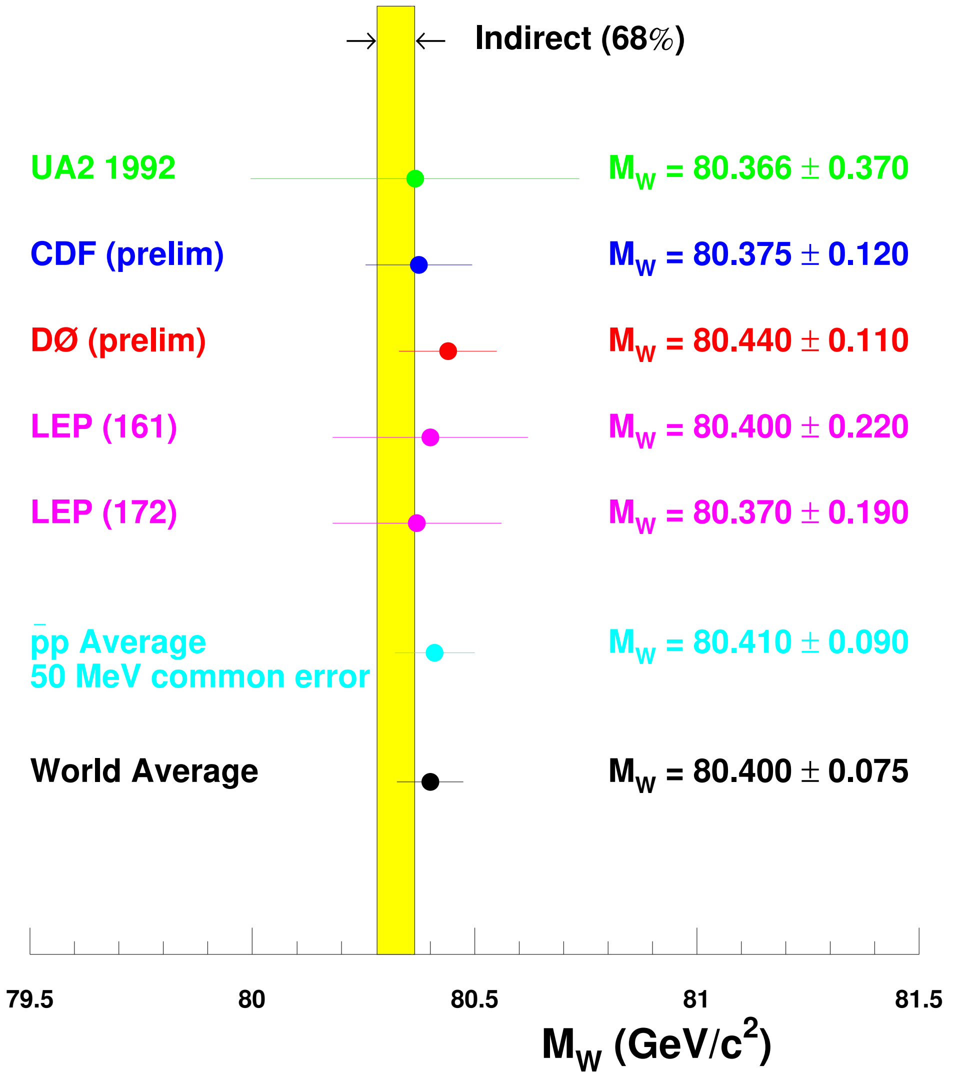
Constraint using measured p_T^Z spectrum.





- ⋆ CDF: $\Delta M_W = 40$ MeV; Taken as fully correlated
- ⋆ More study needed on interplay α_s, pdf's and p_T spectra

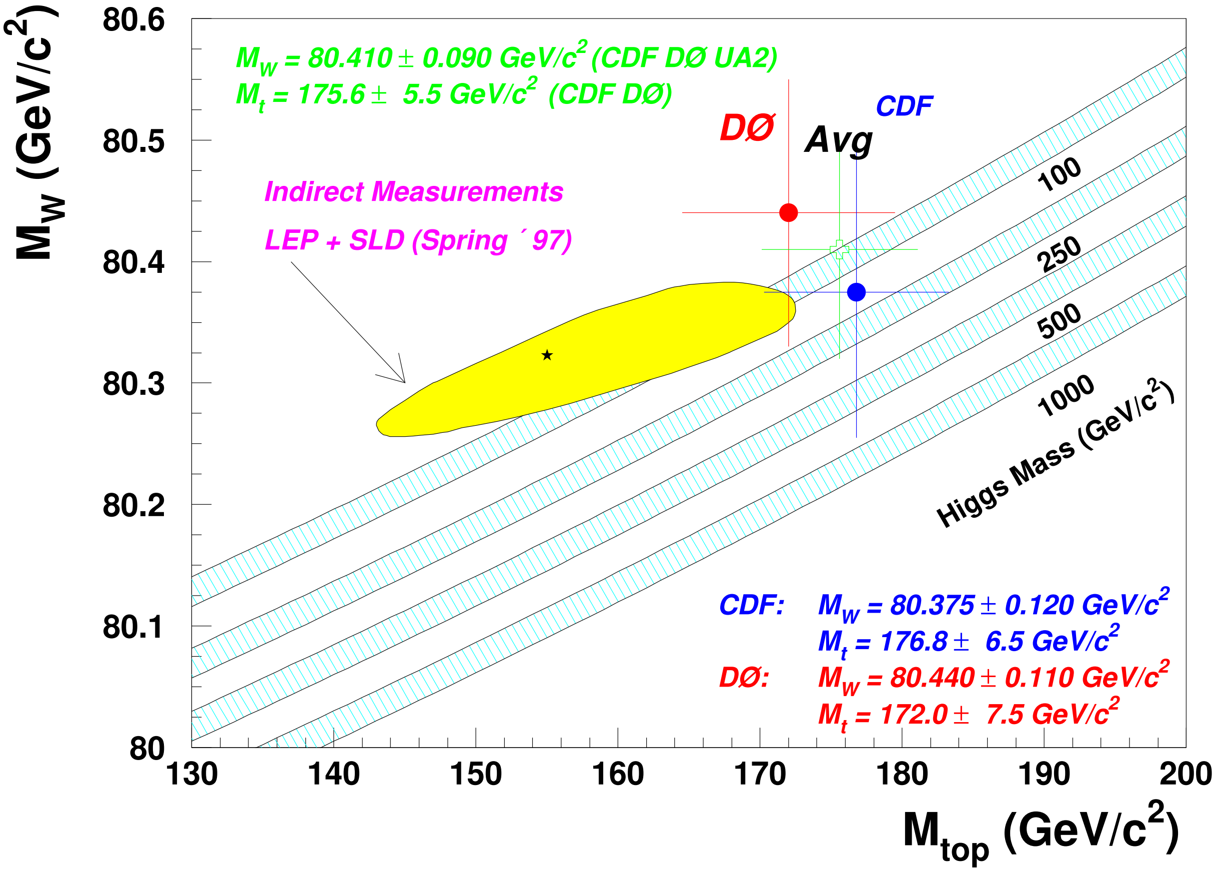
W-Mass Measurements



$$\boxed{\bar{p}p: \quad M_W = 80.410 \pm 0.090 \ \mathrm{GeV/c^2}}$$

$$\boxed{\mathrm{World:} \quad M_W = 80.400 \pm 0.075 \ \mathrm{GeV/c^2}}$$

SM Comparison



$M_t = 175.6 \pm 5.5$ GeV (based on ℓ+jets only)

Anticipated Tevatron $\delta M_W < 75$ MeV/c^2

$$\frac{\partial M_W}{\partial \ln(M_H)} \approx -75 \text{ MeV per unit in } \ln(M_H)$$
$$\frac{\partial M_t}{\partial \ln(M_H)} \approx 12 \text{ GeV per unit in } \ln(M_H)$$

Given current measurements, reducing $\sigma(M_W)$ by a factor of 2 has about twice the power of equivalent $\sigma(M_t)$ reduction.

What can we say?

Δr is a measurable quantity:

$$\Delta r = 1 - \frac{\pi\alpha}{\sqrt{2}G_\mu M_W^2(1 - \frac{M_W^2}{M_Z^2})}$$

Based on $\bar{p}p$ measurement alone of M_W:

$$\Delta r = 0.0335 \pm 0.0054$$

Significance from tree level prediction is: 6.2 σ

But, Δr dominated by QED corrections.
Following Gambino, Sirlin, PRD 49, 1160 (1994):
separate out real electroweak bosonic corrections:

$$\frac{\alpha}{1 - \Delta r} = \frac{\alpha(M_Z^2)}{1 - \Delta r_{res}}$$

$$\Delta r_{res} = -0.0276 \pm 0.0059$$

Significance from tree level prediction is: 4.8 σ !!!

So, from $\bar{p}p$ M_W alone, real demonstration of weak bosonic corrections in the Standard Model. With LEP M_W included, significance increases to 5.5σ.

MSSM Implications

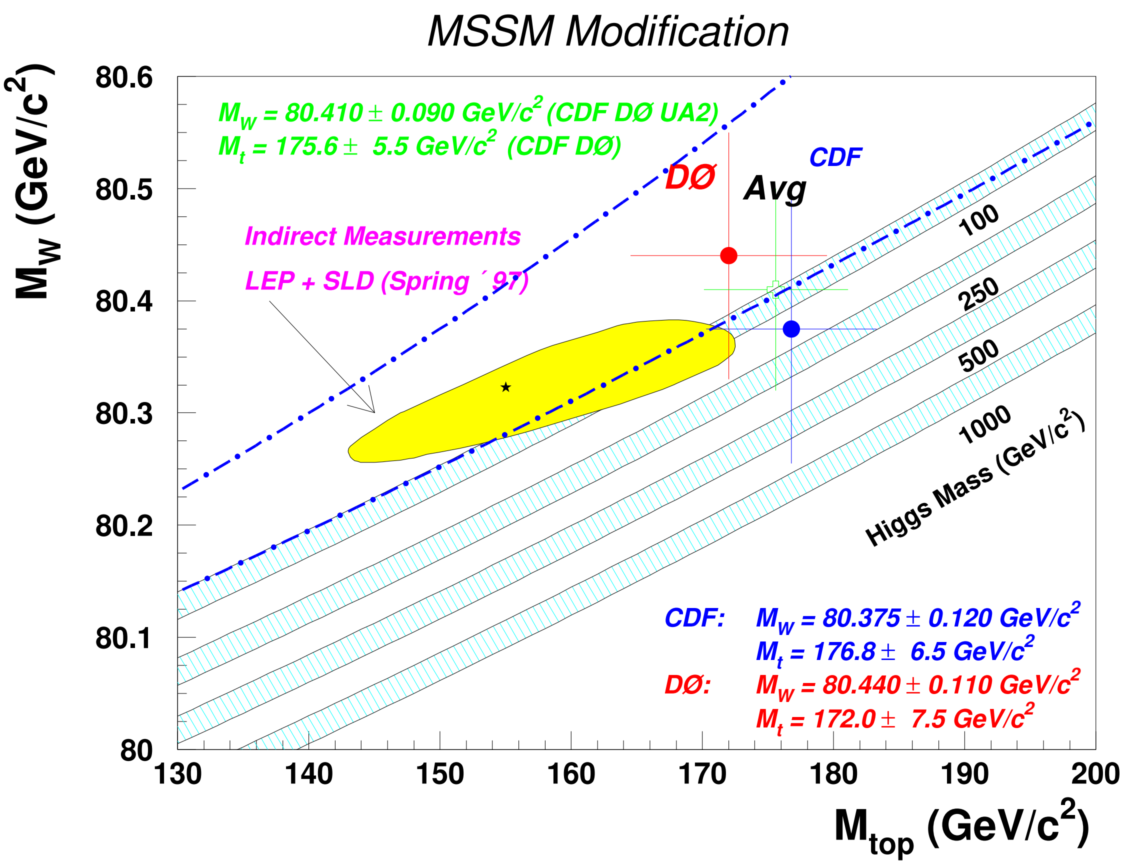
MSSM prediction on M_W alters relation between M_W and M_t

Assumptions here: Variation of $90 < M_H < 1000$ GeV/c^2 and "no SUSY particles at LEP2"

P. Chankowski, *et al.* Nucl. Phys. B417 (1994) 101.

A. Dabelstein, W. Hollik, W. Mösle, Karslruhe KA-TP-5-1995

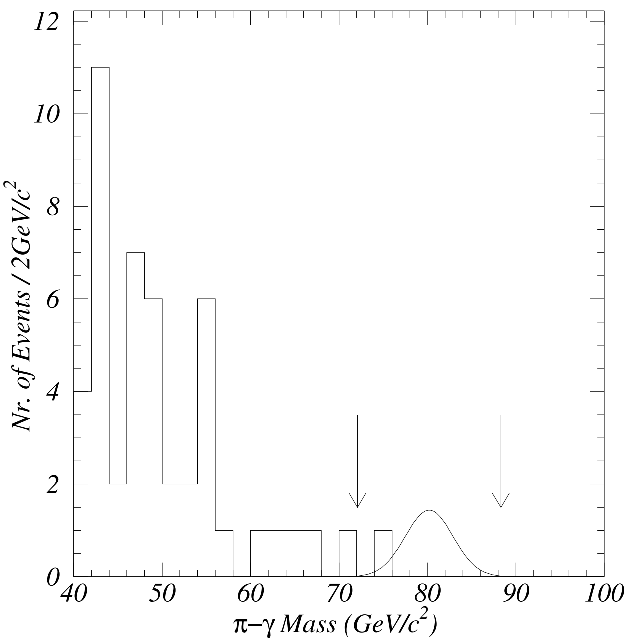
W. de Boer, parallel session



Current run I data from Tevatron (and LEP) should constrain MSSM

Rare W Decays

Mode	BR
$W \to \pi\gamma$	$3.3 \cdot 10^{-9}$
$W \to K\gamma$	$2.4 \cdot 10^{-10}$
$W \to D_s\gamma$	$1.0 \cdot 10^{-8}$
$W \to \pi\pi$	$2.2 \cdot 10^{-10}$
$W \to K\pi$	$2.0 \cdot 10^{-11}$
$W \to DK$	$4.1 \cdot 10^{-9}$



Select γ + 1 jet w/ 1 assoc. track

Effic.: $W \to e\nu$ and MC events

Background: QCD events versus jet track multiplicity

candidate events: 1

background evts: $2.6 \pm 1.0 \pm 1.3$

$$\frac{\Gamma(W \to \pi^{\pm}\gamma)}{\Gamma(W \to e\nu)} < 2 \cdot 10^{-3} \qquad \text{at } 95\% \text{ CL}$$

For $\mathcal{L} = 10\ \text{fb}^{-1}$ still short by 10^{-2}

A long shot, but ......

$\boxed{\text{Triple Gauge Boson Couplings}}$

Triple gauge boson couplings consequence of non-Abelian gauge structure

- Test of SM
- Sensitive to New Physics

What form does the new interaction take ?
Use effective Lagrangian: $\mathcal{L}_{eff}$
Most general Lorentz invariant $\mathcal{L}_{eff}$: 2×7 free params

$$g_1^V,\ \kappa_V,\ \lambda_V,\ g_4^V,\ g_5^V,\ \tilde{\kappa}_V,\ \tilde{\lambda}_V \quad (V = \gamma, Z)$$

$g_4^V,\ g_5^V,\ \tilde{\kappa}_V,\ \tilde{\lambda}_V$ — $\mathcal{C}/\mathcal{P}$ and $\mathcal{CP}$ violating

SM: $g_1^V = 1,\ \kappa_V = 1$, others 0

$$\Delta\kappa_V = \kappa_V - 1$$
$$\Delta g_1^V = g_1^V - 1$$

Too many parameters !

Especially given the small cross sections for di-boson production, try to reduce parameter space.

Approach I:

Use most general $\mathcal{L}_{eff}$

Set all but 2 parameters to their SM values
and/or assume coupling γ = coupling Z

Concentrate on $\Delta\kappa_V$, λ_V, direct physical connection

$\mu_W = \frac{e}{2m_W}(1 + \kappa_\gamma + \lambda_\gamma)$ Magnetic Dipole Moment

$Q^e_W = \frac{-e}{m^2_W}(\kappa_\gamma - \lambda_\gamma)$ Electric Quadrupole Moment

Note: Lagrangian in general does not respect any symmetry and is non-renormalizable.

Approach II:

Construct gauge invariant $\mathcal{L}_{eff}$ with operators of higher dimension. Example: Fermi Theory:

$$\frac{1}{q^2 + M_W^2} = \frac{-1}{M_W^2}\left[1 + \frac{q^2}{M_W^2} + \cdots\right]$$

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \mathcal{L}_{NR}$$

$$\mathcal{L}_{NR} = \frac{1}{\Lambda^{n-4}} \sum_{n=6,8,\ldots} \alpha_n \mathcal{O}_n$$

- Retain only lowest dimension operators (low energy approximation); respect $\mathcal{C}, \mathcal{P}, \mathcal{CP}$ invariance
- Impose symmetry and content on $\mathcal{L}_{NR}$:
  $SU(2) \times U(1)$ invariance plus Higgs doublet
  $\Rightarrow$ three free parameters:
  - ◇ $\Delta g_1^Z = \frac{1}{\cos^2 \vartheta_W}\, \alpha_{W\varphi}$
  - ◇ $\Delta\kappa_\gamma = -\cot^2 \vartheta_W\, (\Delta\kappa_Z - \Delta g_1^Z) = \alpha_{W\varphi} + \alpha_{B\varphi}$
  - ◇ $\lambda_\gamma = \lambda_Z = \alpha_W$
- More "ad hoc" assumptions:
  coupling $SU(2)$ = coupling $U(1)$ ($f_B = f_W$)
  $\Rightarrow$ two free parameters (HISZ):
  - ◇ $\Delta g_1^Z = \frac{1}{2\cos^2 \vartheta_W}\, \Delta\kappa_\gamma$
  - ◇ $\Delta\kappa_Z = \frac{1}{2}(1 - \tan^2 \vartheta_W)\, \Delta\kappa_\gamma$
  - ◇ $\lambda_Z = \lambda_\gamma$

Consequences of anomalous TGC

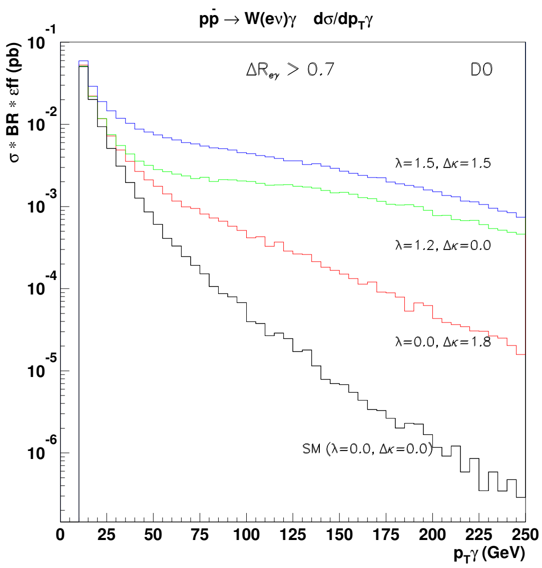
In SM very subtle, strong gauge cancellations. Coupling of W uniquely prescribed. For example, WW production, cross section for t-channel alone violates unitarity

If couplings are anomalous:

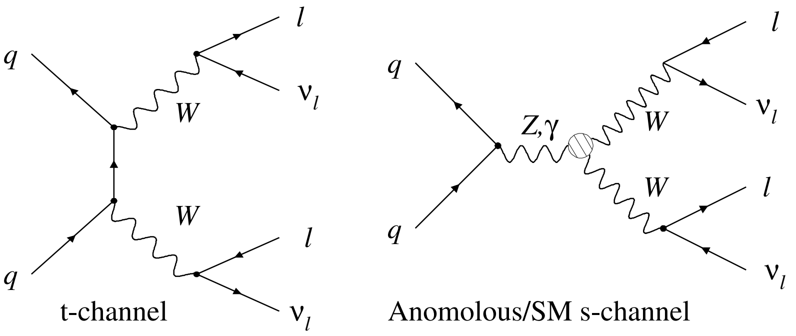
- Destroys gauge cancellations
- Increase in cross section at large $\sqrt{\hat{s}}$
- Change in differential distributions (p_T^γ, p_T^W)
- Need Form Factors not to violate unitarity

$$\lambda(\hat{s}) = \frac{\lambda}{(1+\hat{s}/\Lambda^2)^2} \qquad \Delta\kappa(\hat{s}) = \frac{\Delta\kappa}{(1+\hat{s}/\Lambda^2)^2}$$

- WW
- WZ
- $W\gamma$
- $Z\gamma$



WW Production: di-lepton channel



Sensitive to $WW\gamma$ and WWZ coupling
Channels considered:
ee, $e\mu$, $\mu\mu$

	DØ ($\int \mathcal{L}dt = 96.6\ \mathrm{pb}^{-1}$)	CDF ($\int \mathcal{L}dt = 108\ \mathrm{pb}^{-1}$)
N_{data}	5	5
N_{BG}	3.3 ± 0.4	1.2 ± 0.3
N_{SM}	2.10 ± 0.15	3.5 ± 1.2

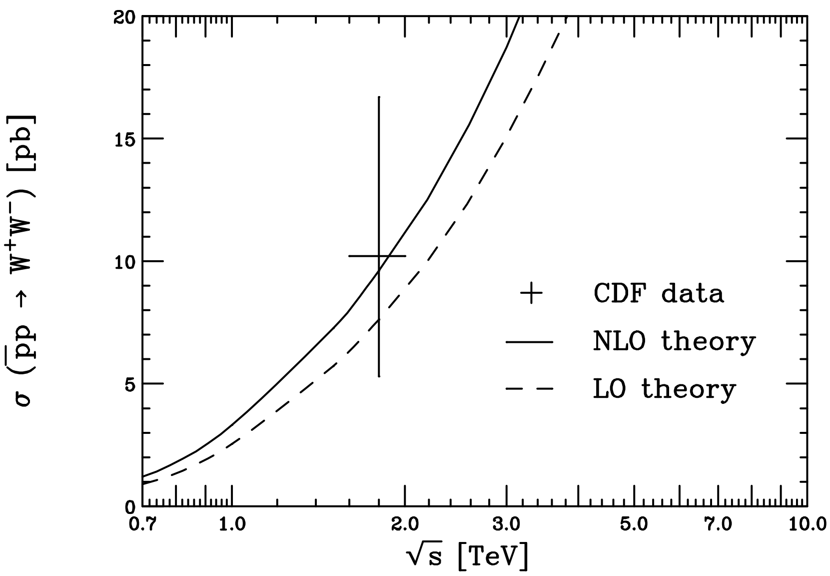
Background dominated by Drell-Yan and fakes.
$t\bar{t}$ background suppressed: jet veto (CDF), hadronic veto (DØ)

CDF:

$$\boxed{\sigma = 10.2^{+6.3}_{-5.1} \pm 1.6\ \text{pb}}$$

$\sigma_{SM} = 9.5 \pm 2.9$ pb
PRL 78, 4536 (1997)

DØ
$\sigma < 43$ pb (95% CL)

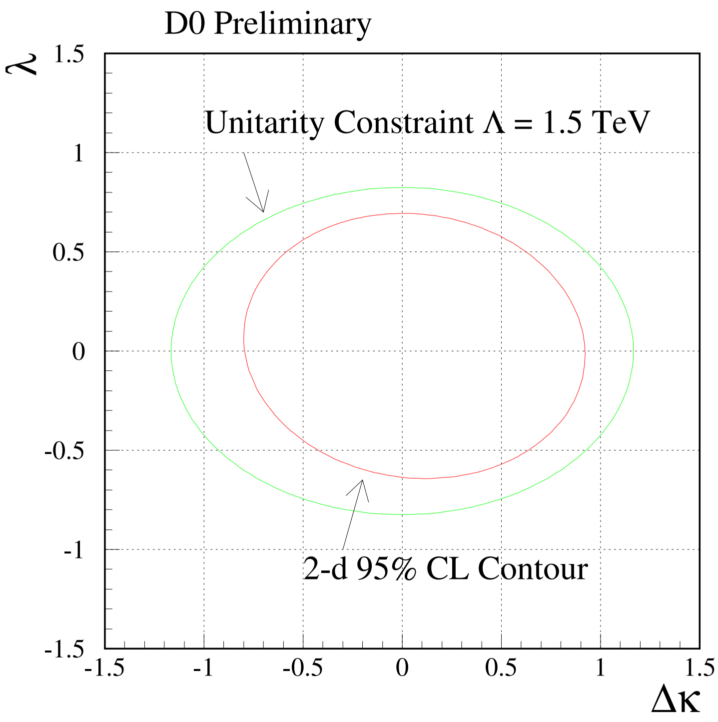


Limits on $WW\gamma$ and WWZ couplings

- From Event Rate
- Maximum Likelihood fit to differential distribution

CDF set limits using evet rate

DØ set limits using 2D fit to lepton E_T spectra

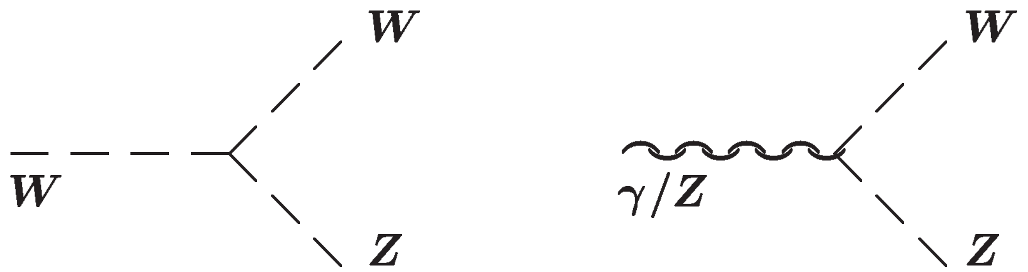


DØ: $\Lambda = 1.5$ TeV
$-0.62 < \Delta\kappa < 0.75 \quad (\lambda = 0)$
$-0.50 < \lambda < 0.56 \quad (\Delta\kappa = 0)$

CDF $\Lambda = 1.0$ TeV
$-1.1 < \Delta\kappa < 1.3 \quad (\lambda = 0)$
$-0.8 < \lambda < 0.9 \quad (\Delta\kappa = 0)$

assuming $\Delta\kappa \equiv \Delta\kappa_\gamma = \Delta\kappa_Z$ and $\lambda \equiv \lambda_\gamma = \lambda_Z$.

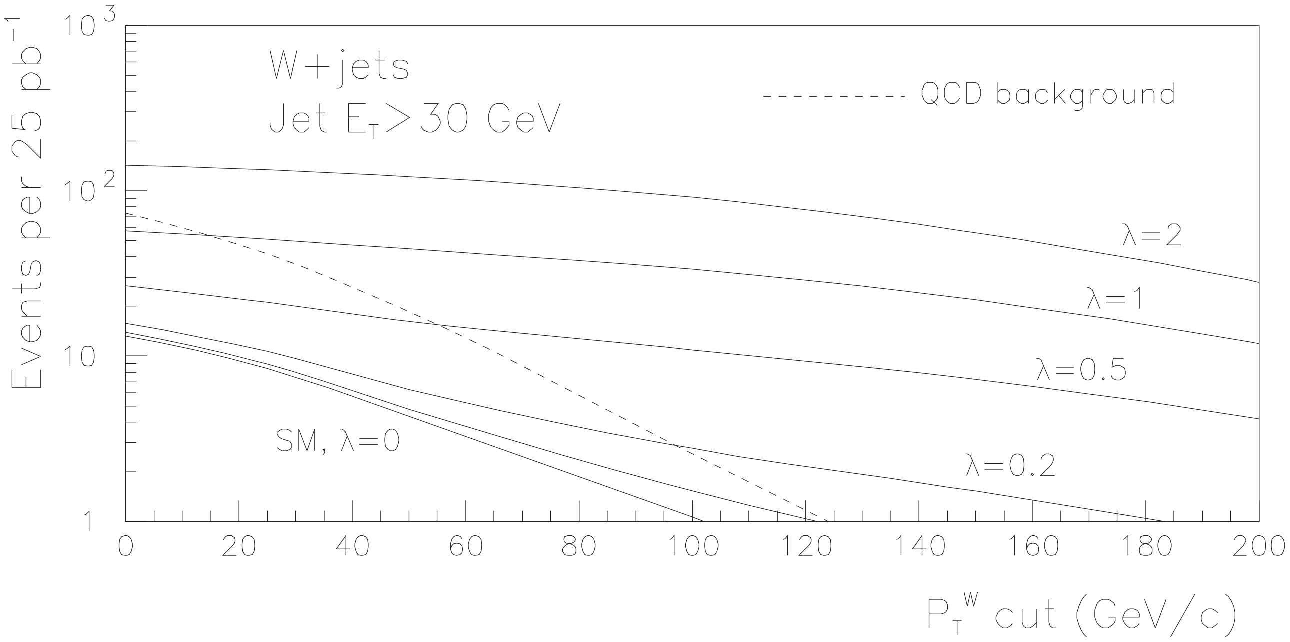
WW / WZ Production: lepton+jets channel



CDF: leptonic decays of W and Z ($\int \mathcal{L}dt = 110$ pb^{-1})
DØ: leptonic decays of W only ($\int \mathcal{L}dt = 96$ pb^{-1})

Signal: p_T^ℓ, $\not{E}_T > 20/25$ GeV/c (leptonic W or Z)
$M_T > 40$ GeV/c^2 or $70 < m_{\ell\ell} < 110$ GeV/c^2
2 jets, $E_T > 30$ GeV, $50/60 < m_{jj} < 110$ GeV/c^2

Background: W/Z+jet production; $S/N \approx 1/30$

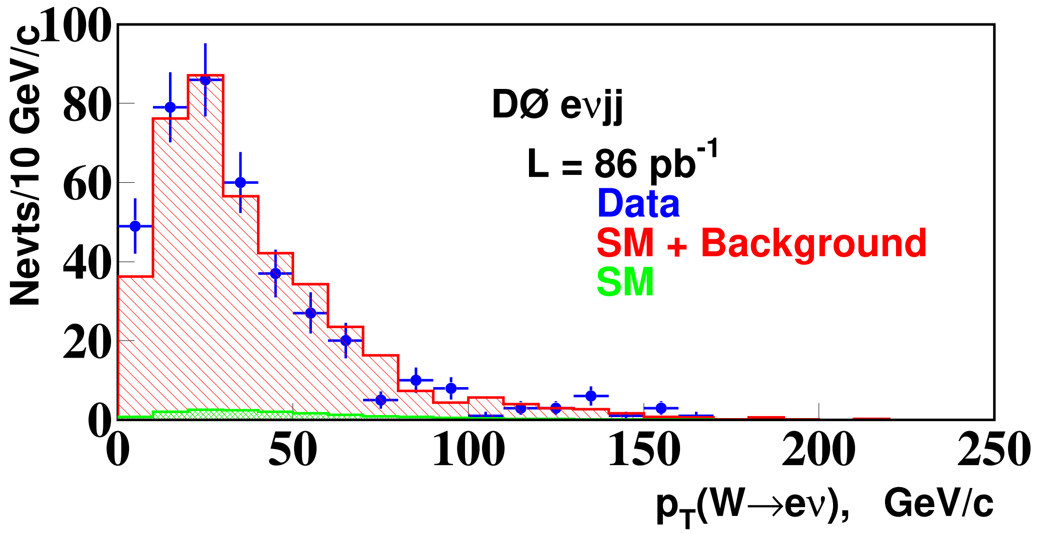


Require high p_T di-jet system
$\Delta R_{jet} = 0.4$ (0.5) to minimize jet merging, CDF (DØ)

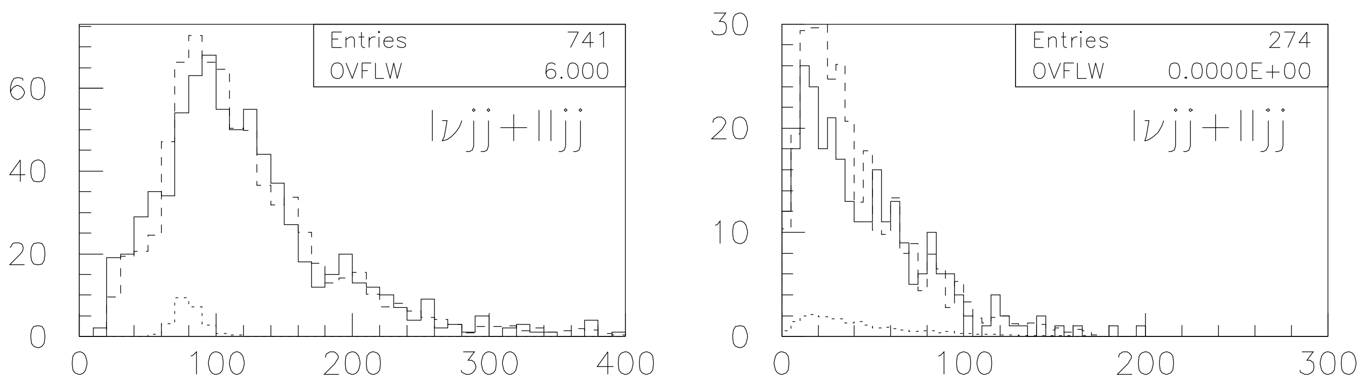
Sensitive to anomalous couplings, not SM WW-production

Method to set limits on anomalous couplings

- DØ: Binned maximum likelihood fit to $p_T^{e\nu}$ spectrum

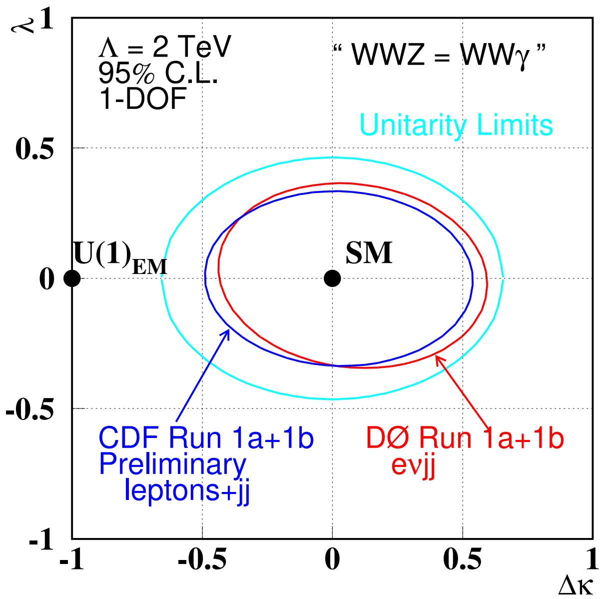


- CDF: Limits from event rate at high p_T^{jj} cut with no events observed



		observed	expected
CDF	$\ell\nu jj$	694 events	21 events
	$\ell\ell jj$	47 events	3 events
DØ	$\ell\nu jj$	483 events	20.7 ± 3.1 events
	Backgrounds		
	QCD $W+\geq 2j$	341.7 ± 38.3	
	QCD multijet	116.5 ± 12.6	
	$t\bar{t}$	4.6 ± 1.3	

Limits from $WW/WZ \to \ell\nu jj/jj\ell\ell$



95% CL limits ($\Lambda = 2$ **TeV**)

$-0.43 < \Delta\kappa < 0.59 \quad (\lambda = 0)$ (DØ)
$-0.33 < \lambda < 0.36 \quad (\Delta\kappa = 0)$ (DØ)

$-0.49 < \Delta\kappa < 0.54 \quad (\lambda = 0)$ (CDF)
$-0.35 < \lambda < 0.32 \quad (\Delta\kappa = 0)$ (CDF)

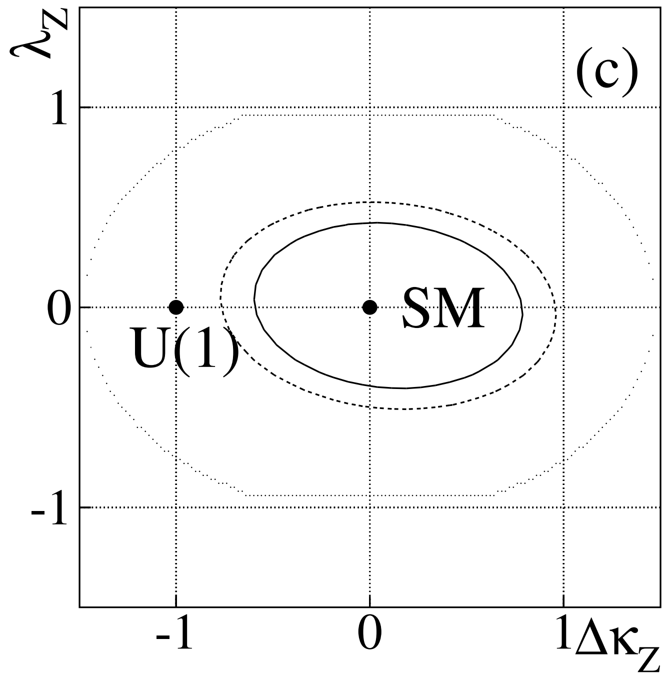
$\lambda_\gamma = \lambda_Z$ **and** $\Delta\kappa_\gamma = \Delta\kappa_Z$ **assumed**

Small cross section (destructive interference) confirms existence of WWZ-coupling.

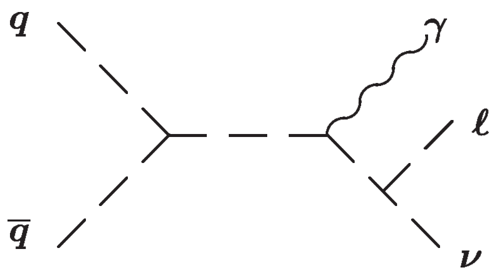
Sensitivity $WW\gamma$ versus WWZ vertex

Set $WW\gamma$-vertex to SM value, then

Vanishing WWZ-vertex excluded at $> 99\%$ CL !!



$W - \gamma$ Production



In $\bar{p}p$ collisions, also probe $W\gamma$ vertex directly without Z interference

Event Characteristics:

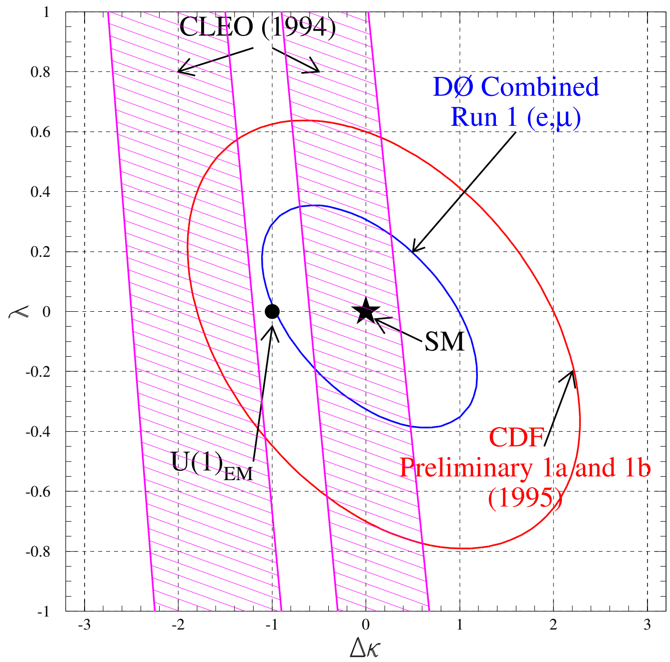
- **Background from Radiative Decays; suppressed using $\Delta R(\ell\gamma) > 0.7$**
- **Major background from W+jets with jet$\rightarrow \gamma$**

Limits set by binned likelihood fit to lepton p_T spectrum

95% CL limits ($\Lambda = 1.5$ TeV)

$-0.93 < \Delta\kappa < 0.94 \quad (\lambda = 0)$ (DØ)
$-0.31 < \lambda < 0.29 \quad (\Delta\kappa = 0)$ (DØ)

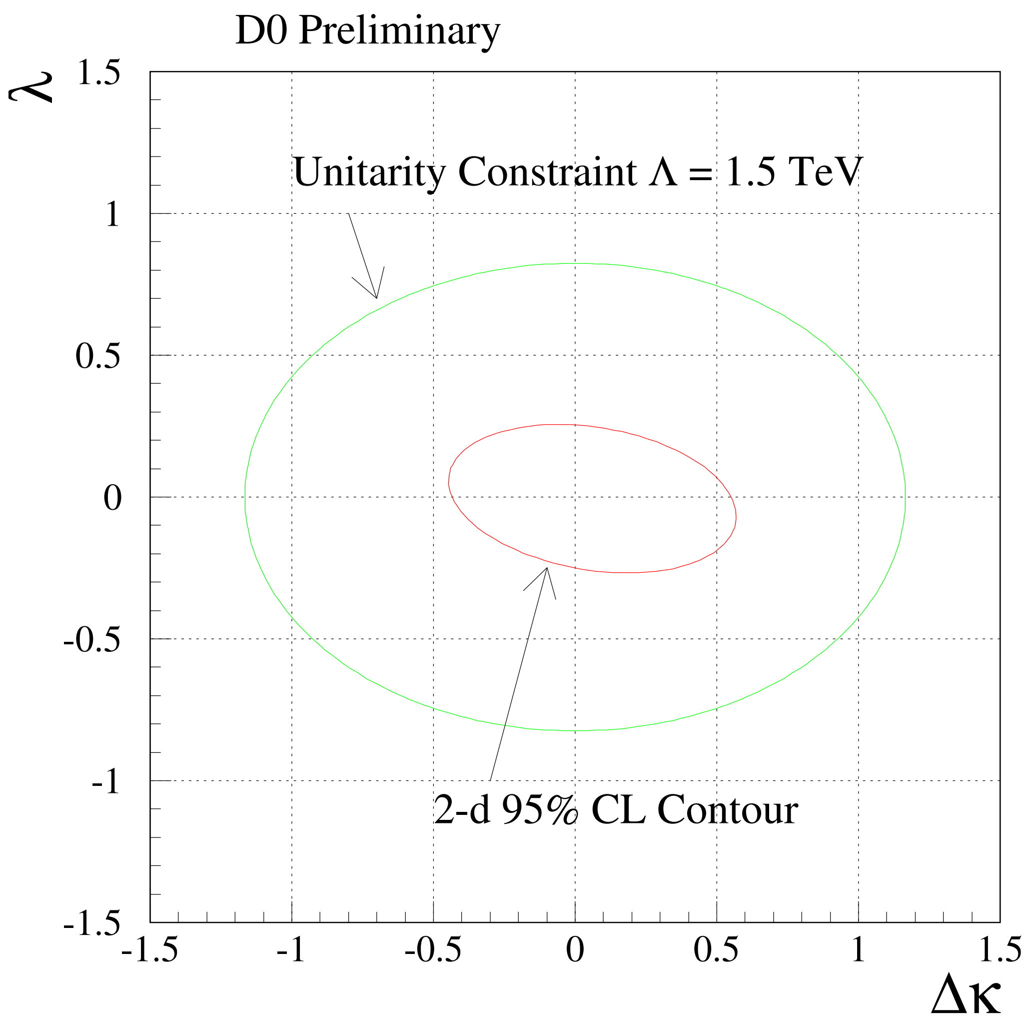
$-1.8 < \Delta\kappa < 2.0 \quad (\lambda = 0)$ (CDF)
$-0.7 < \lambda < 0.6 \quad (\Delta\kappa = 0)$ (CDF)



Bands set by CLEO (PRL 74, 2885 (1995))
$B(b \rightarrow s\gamma) = (2.32 \pm 0.57 \pm 0.35)10^{-4}$

Combining $W\gamma$, WW and WZ channel

Combine likelihood of different processes, including correlations; DØ from full Run I data set



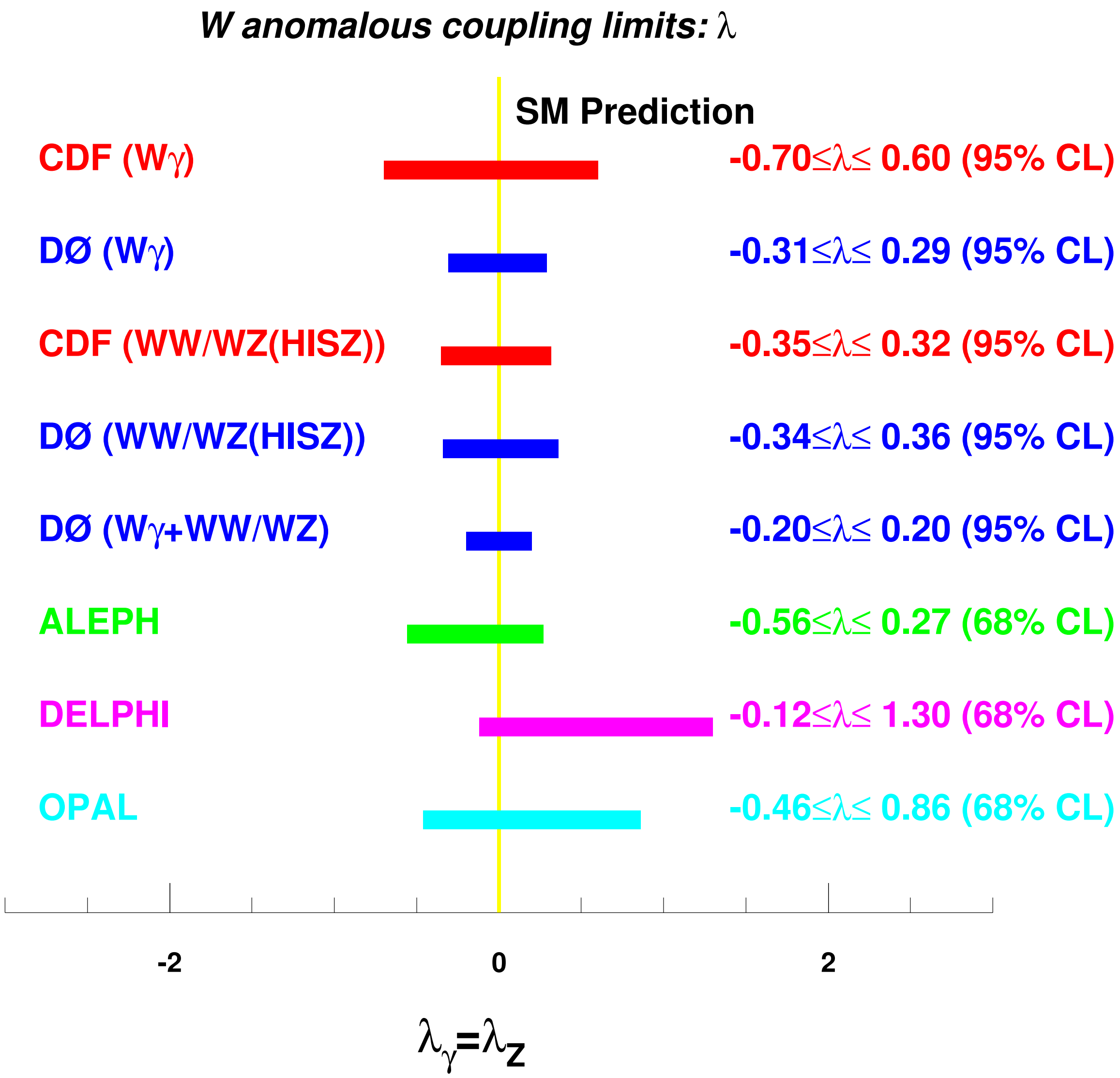
Combined limits at 95% CL for $\Lambda = 1.5$ TeV

$$-0.33 < \Delta\kappa < 0.45 \quad (\lambda = 0)$$
$$-0.20 < \lambda < 0.20 (\Delta\kappa = 0)$$

assuming $\Delta\kappa \equiv \Delta\kappa_\gamma = \Delta\kappa_Z$ and $\lambda \equiv \lambda_\gamma = \lambda_Z$.

Strong constraints anticipated for full Run 1 data sample, combined channels and DØ and CDF combined

Summary Limits on λ



Although different underlying models, 1d-limits on λ can be compared.

What can we say?

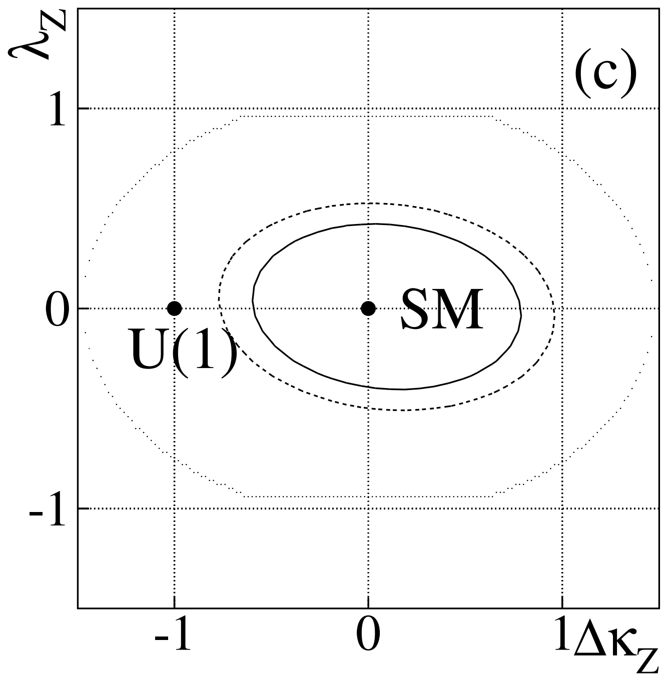
No anomalous trilinear gauge boson couplings observed (Also, not expected, since most models predict anomalous couplings of order $\mathcal{O}(M_W^2/\Lambda^2)$)

But, ... W boson is more than "an electrically charged boson"

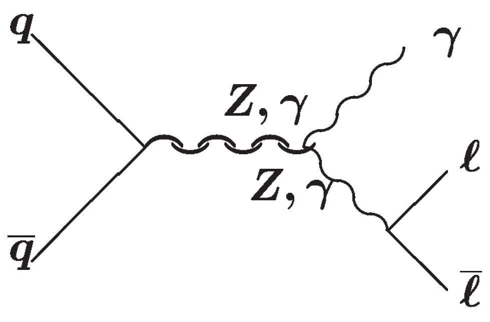
Established at 99% CL that it is a gauge boson, the gauge boson predicted by SM

Vanishing electric quadrupole moment excluded

Bohr magnetic moment ($\frac{e}{2M_W}$) excluded



Probing the $ZZ\gamma$ and $Z\gamma\gamma$ Vertex



The two couplings, $ZZ\gamma$ and $Z\gamma\gamma$ absent in SM

Analysis along same lines as $W\gamma$, WW/WZ analyses in lepton channel

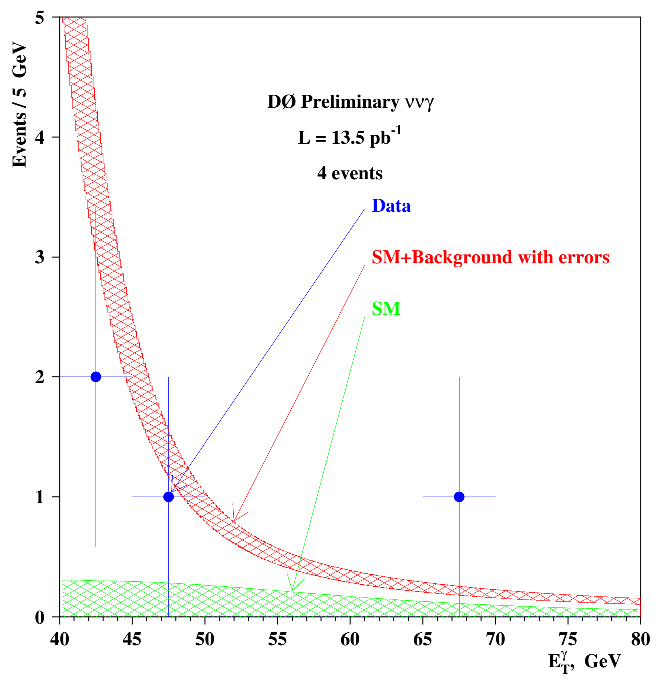
But here additional unique channel: $Z \to \nu\nu$
Signal is single photon detected. Advantages:

- Higher branching ratio
- No radiative contributions
- Need hermetic calorimeter coverage

Select events with single γ with large $\not{E}_T$ (high p_T^Z)

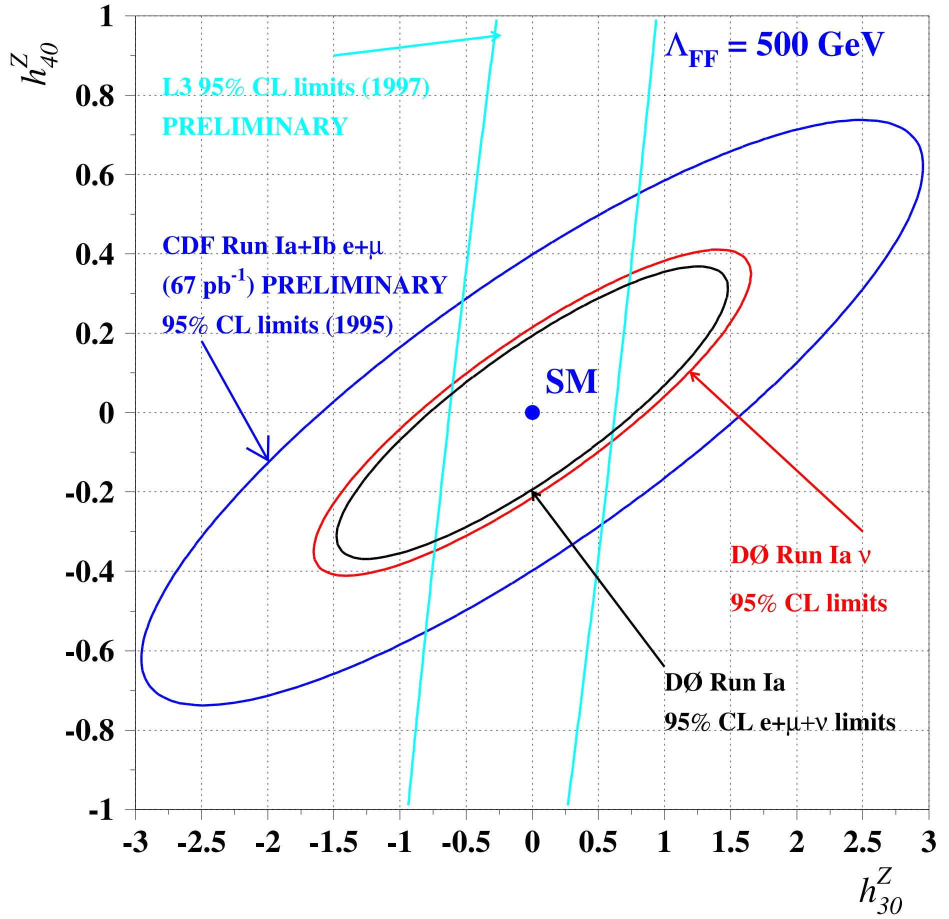
Backgrounds:
cosmics and beam halo
$W \to e\nu,\ e = "\gamma"$

N_{obs}	5
N_{SM}	1.8 ± 0.2
$W \to e\nu$	4.0 ± 0.8
cosmic/halo	1.8 ± 0.6



$ZZ\gamma$, $Z\gamma\gamma$ anomalous coupling limits: $\overline{p}p$ and e^+e^-

$$M \sim (\sqrt{\hat{s}}/M_Z^2)^3 \text{ for } h_{1,3}$$
$$M \sim (\sqrt{\hat{s}}/M_Z^2)^5 \text{ for } h_{2,4}$$



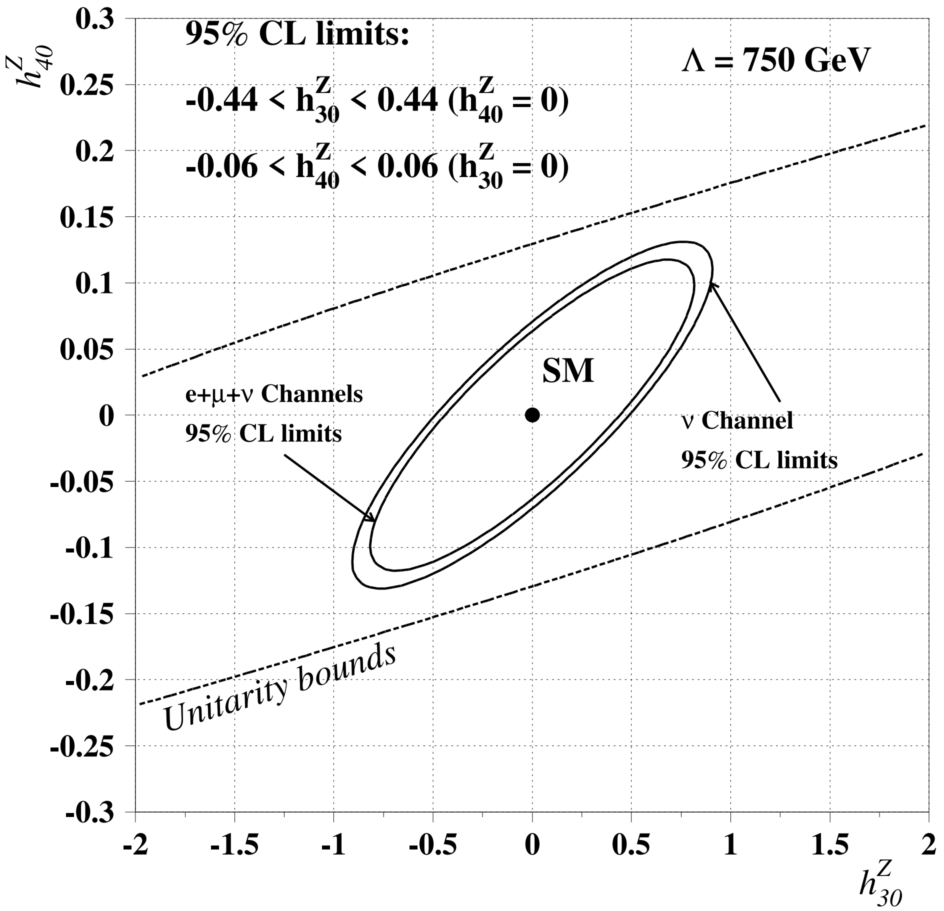
95% CL limits

DØ	$-0.44 < h^Z_{30} < 0.44$	$(h^Z_{40} = 0)$
$\Lambda = 0.75$ TeV	$-0.06 < h^Z_{30} < 0.06$	$(h^Z_{40} = 0)$
CDF	$-1.6 < h^Z_{40} < 1.6$	$(h^Z_{30} = 0)$
$\Lambda = 0.5$ TeV	$-0.4 < h^Z_{40} < 0.4$	$(h^Z_{30} = 0)$

$ZZ\gamma$, $Z\gamma\gamma$ anomalous coupling limits: $\overline{p}p$ and e^+e^-

$M \sim (\sqrt{\hat{s}}/M_Z^2)^3$ for $h_{1,3}$

$M \sim (\sqrt{\hat{s}}/M_Z^2)^5$ for $h_{2,4}$



95% CL limits

DØ	$-0.44 < h^Z_{30} < 0.44$	$(h^Z_{40} = 0)$
$\Lambda = 0.75$ TeV	$-0.06 < h^Z_{30} < 0.06$	$(h^Z_{40} = 0)$
CDF	$-1.6 < h^Z_{40} < 1.6$	$(h^Z_{30} = 0)$
$\Lambda = 0.5$ TeV	$-0.4 < h^Z_{40} < 0.4$	$(h^Z_{30} = 0)$

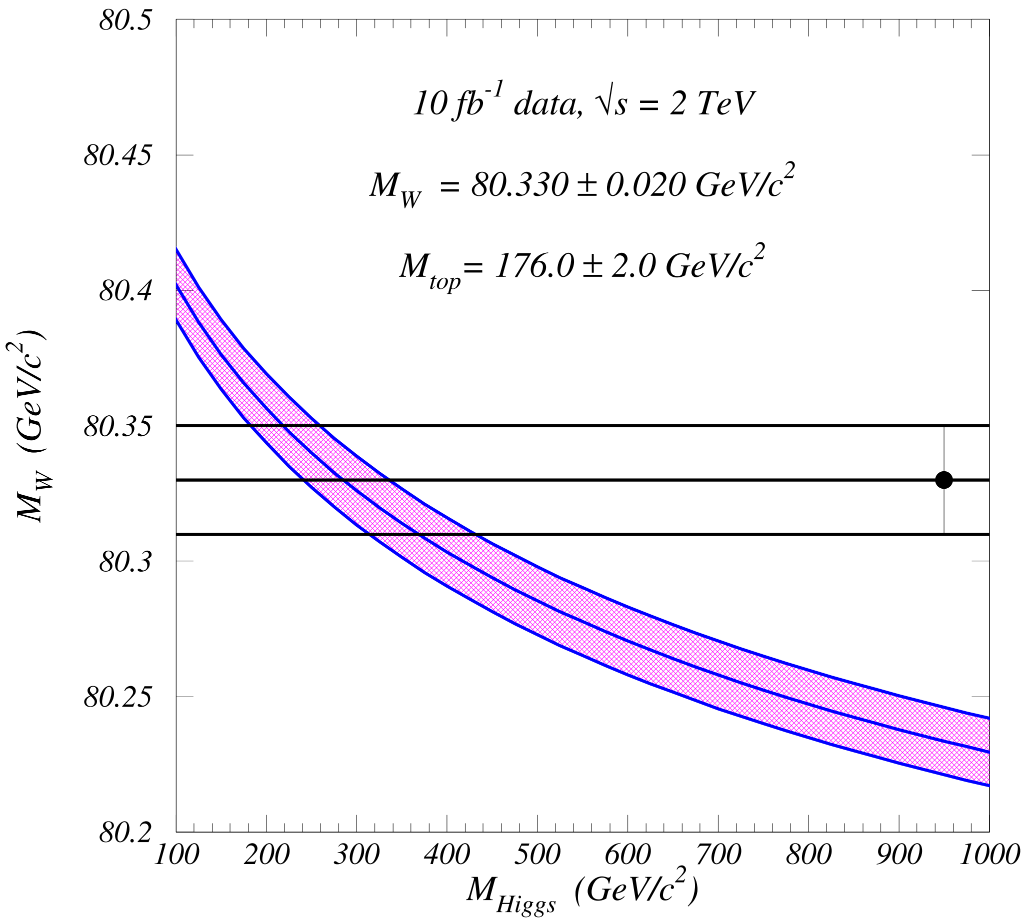
Conclusions ......

- ♣ W mass measured to precision of 90 MeV
- ♣ Expect measurement of W Width to 30-40 MeV in very near future
- ♣ Established that W and Z are truly gauge bosons
- ♣ From electroweak processes, like Drell-Yan production and gauge boson pair production, no sign of anything beyond the SM; Limits on Λ of 5 TeV

Outlook ......

Year 2000-2001:

LEP:	$\delta M_W \sim 45$ MeV/c^2 (35 MeV/c^2 if no I-connct. eff.)
Tevatron Run I:	$\delta M_W \leq 75$ MeV/c^2
Tevatron Run II:	$\delta M_W \sim 40$ MeV/c^2
Tevatron Run II:	$\delta M_t \sim 3$ GeV/c^2



Many other high precision measurements will be available

Results should be internally consistent

A lot of room for excellent physics and interesting times $\cdots$!!

Left Overs !!!

The rest of the slides are spare ones etc. except for the last one: momentum extrapolation CDF muons.

Down side of using M_T:
– must measure neutrino momentum.

$$p_T^\nu = \not{E}_T = \sum_i \vec{p}_{T_i} = -\vec{p}_T^{\,e} - \vec{p}_T(R) - \vec{u}(\mathcal{L})$$

$$\boxed{\begin{array}{ll} \not{E}_T = p_T^\nu + \frac{1}{4}\frac{u^2}{p_T^\nu} & |\vec{u}| \sim \sqrt{n} \\ M_T \Longrightarrow M_T + \frac{3}{16}\frac{u^2}{M_T} & n \ \frac{\#\text{interactions}}{\text{crossing}} \end{array}}$$

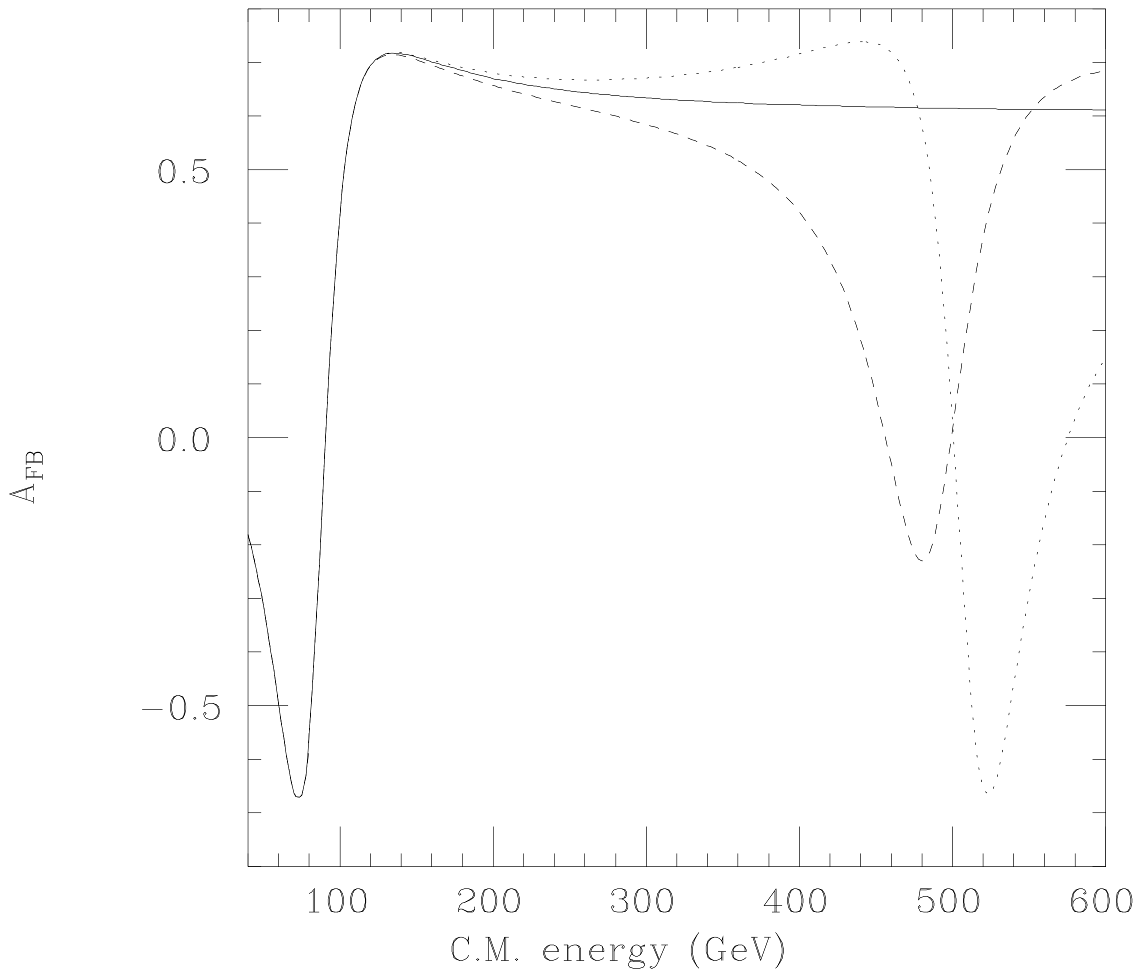
Run Ia	$\mathcal{L} = 3.5 \times 10^{30}\ \mathrm{cm^{-2}s^{-1}}$	$M_T \Rightarrow M_T + 70$ MeV	(6×6)
Run Ib	$\mathcal{L} = 8.0 \times 10^{30}\ \mathrm{cm^{-2}s^{-1}}$	$M_T \Rightarrow M_T + 160$ MeV	(6×6)
Run II	$\mathcal{L} = 8 \times 10^{31}\ \mathrm{cm^{-2}s^{-1}}$	$M_T \Rightarrow M_T + 270$ MeV	(36×36)

At high luminosity:

- determining M_W from p_T^e or ratio M_T^W/M_T^Z might be a better choice (high statistics Z sample)
- measure p_T^W directly from $p_T^Z \to ee$.

A_{FB}: Extended Gauge Sector . . .

A_{FB}: $u\overline{u} \rightarrow e^+e^-$
Z_I does not couple to u quarks



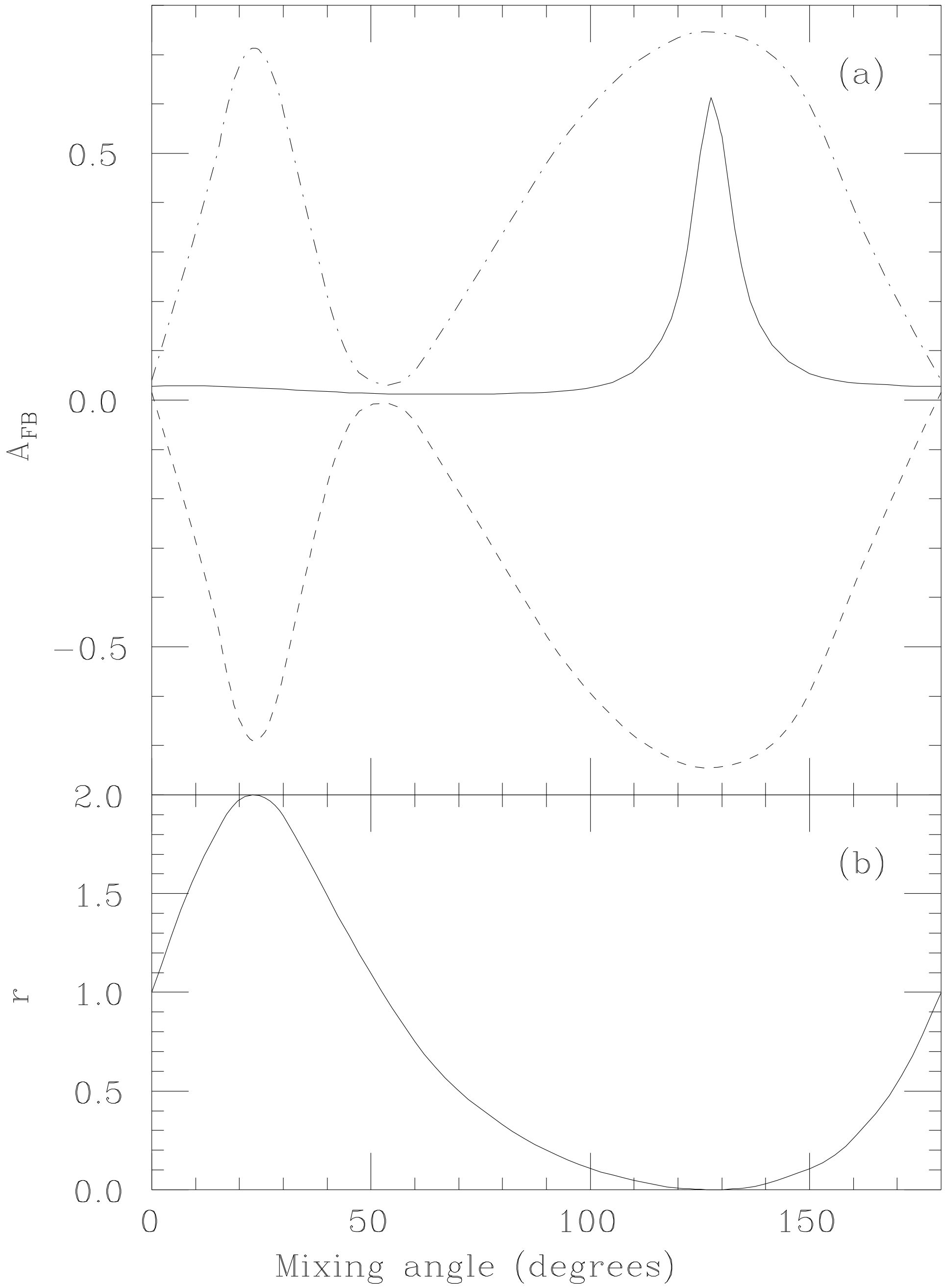
J. Rosner, Phys.Rev. D54, 1078 (1996)

A_{FB} at the pole

$$Z' = Z_\psi \cos\vartheta + Z_\chi \sin\vartheta$$

$Z_\eta \quad \vartheta = \arctan(\sqrt{\tfrac{3}{5}})$

$Z_I \quad \vartheta = \arctan(-\sqrt{\tfrac{3}{5}})$



Gauge Boson Pair Production

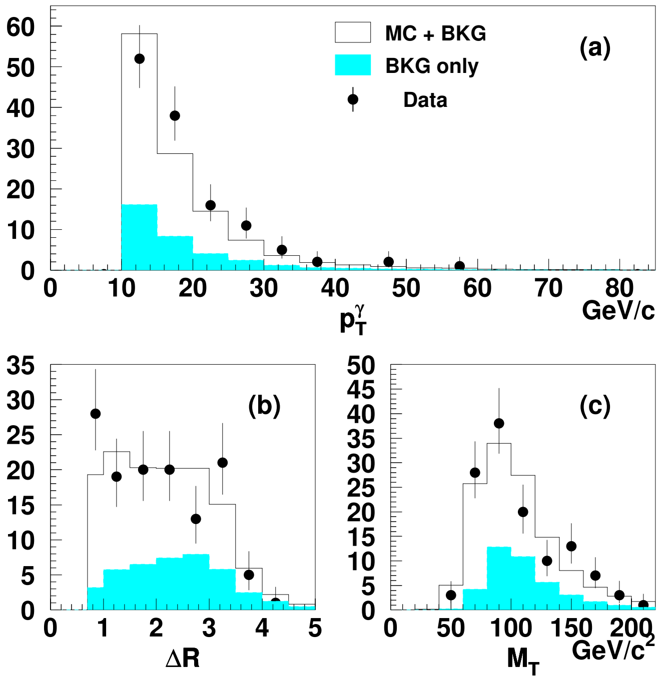
- **Gauge boson self-interactions** are the direct consequence of the non-Abelian $SU(2) \times U(1)$ gauge symmetry
- Measurement of the self-interactions crucial test of the Standard Model.
- Deviations from SM predictions signal new physics

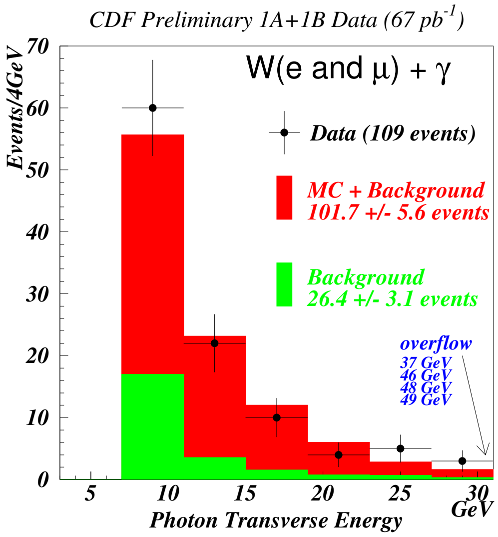
But ... cross sections are small

Production	σ (pb) ($\sqrt{s}$=1.8 TeV)
$W\gamma \rightarrow \ell\nu\gamma$	25
$Z\gamma \rightarrow \ell\ell\gamma$	4.1
$WW \rightarrow \ell\nu jj$	2.8
$WW \rightarrow \ell\nu\ell\nu$	0.47
$WZ \rightarrow \ell\nu jj$	0.38
$WZ \rightarrow jj\ell\ell$	0.11
$WZ \rightarrow \ell\nu\ell\ell$	0.035
$ZZ \rightarrow \ell\ell jj$	0.13
$ZZ \rightarrow \ell\ell\ell\ell$	0.006

No acceptance, efficiency included;
Sum of $\ell = e$ or μ

$W\gamma$ Event distributions





	$(\lambda = 0)$	$(\Delta\kappa = 0)$	$\mathcal{L}$
DØ	$-0.93 < \Delta\kappa < 0.94$	$-0.31 < \lambda < 0.29$	89 pb^{-1}
CDF plim.	$-1.8 < \Delta\kappa < 2.0$	$-0.7 < \lambda < 0.6$	67 pb^{-1}

95% CL limits on anomalous couplings for $\Lambda = 1.5$ TeV

$W - \gamma$ Radiation Zero (CDF)

$W^{\mp}\gamma$ vanishing amplitude at $\cos\theta^*_\gamma = \pm\frac{1}{3}$
θ^*_γ is the angle between photon and incoming quark in the $W\gamma$ rest frame.

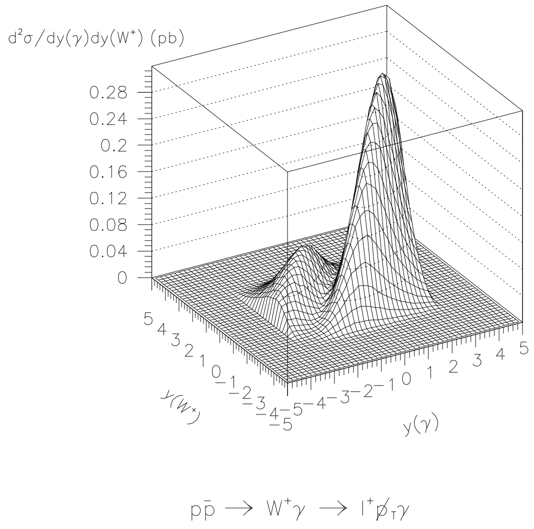


Figure 1

- **Determination $W - \gamma$ rest frame**

  1) Mass constraint $M_{\ell\nu} = M_W \Rightarrow 2\ P_z^\nu$ solutions

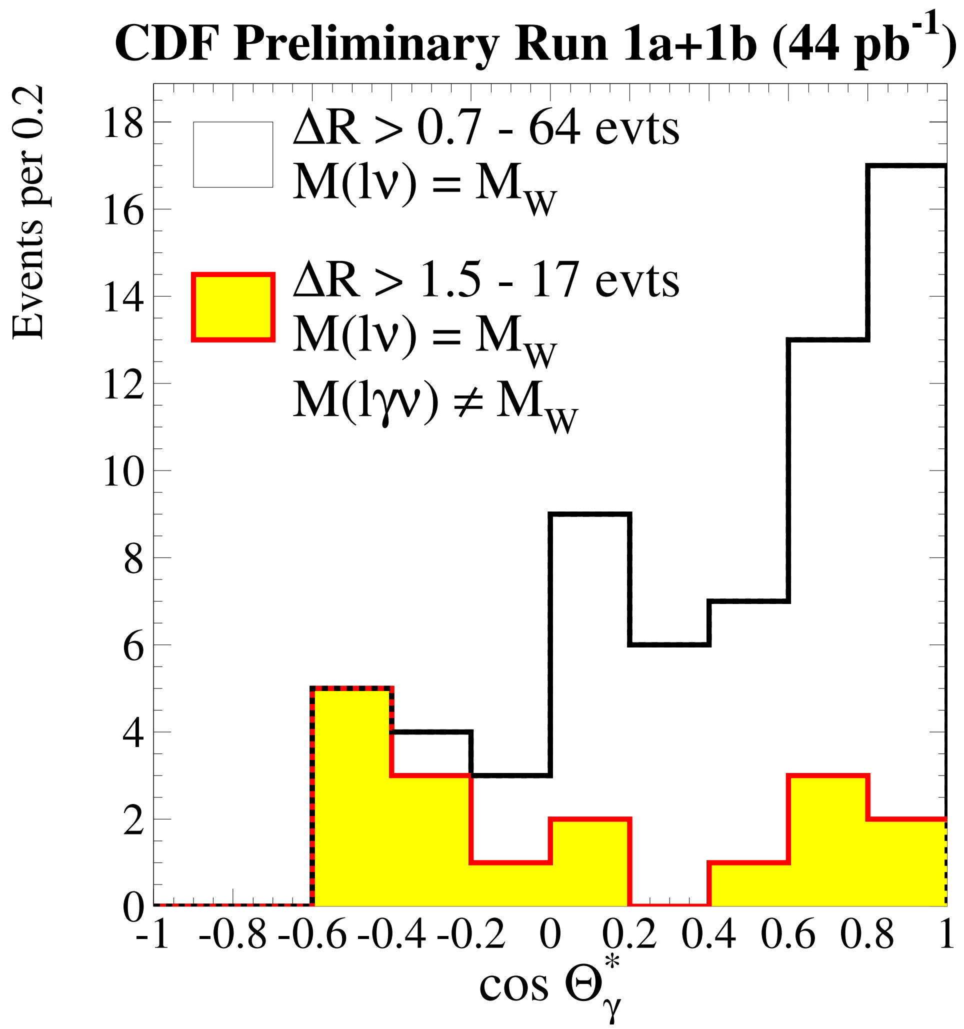
  2) $P_z^\nu = \min(p_{z_1}, p_{z_2})$ for $W^-\gamma$
  $P_z^\nu = \max(p_{z_1}, p_{z_2})$ for $W^+\gamma$
  $\approx 73\%$ correct solution

- **Reduce contribution from decay diagrams**

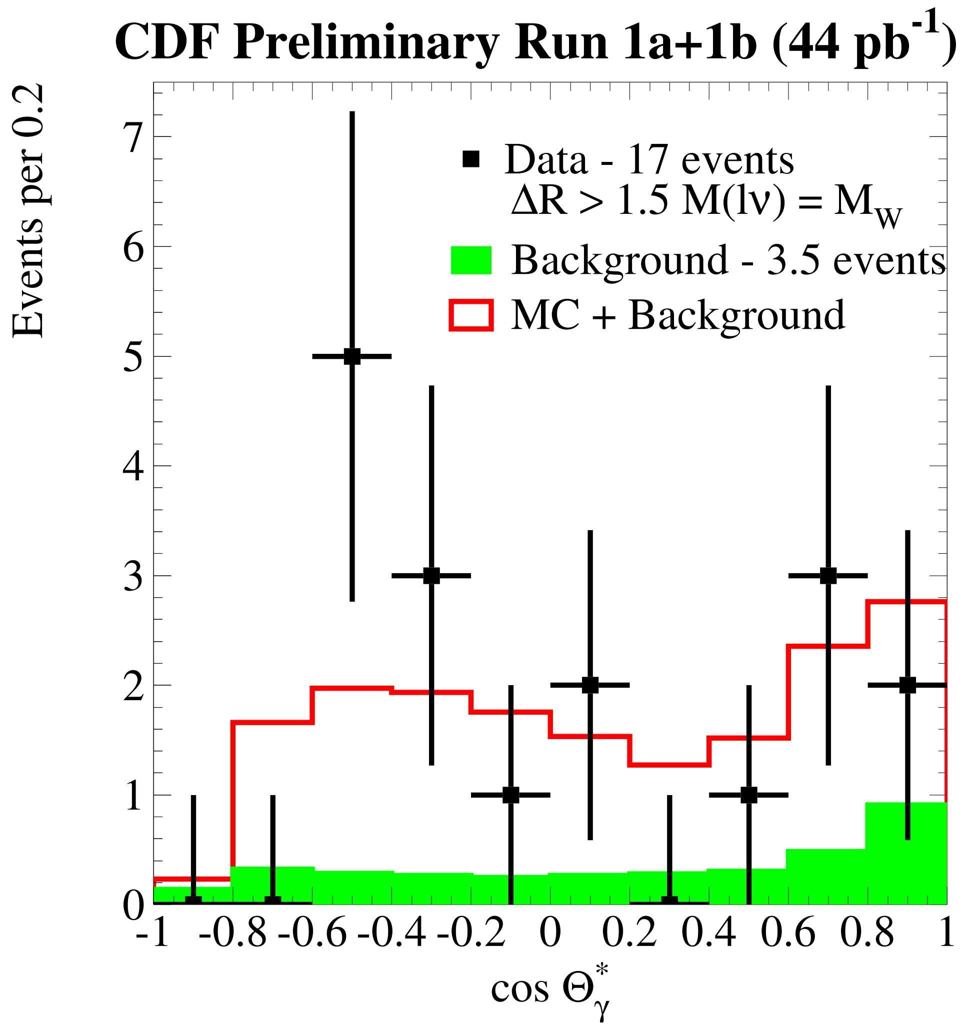
  1) Stringent ΔR cut, $\Delta R > 1.5$

  2) $M(\ell\gamma\nu) \neq M_W$ and $M(\ell\nu) = M_W$

$M(\ell,\nu) = M_W$	$0.7 < \Delta R < 1.5$	$\Delta R > 1.5$
$M(\ell,\nu,\gamma) = M_W W\gamma$	25	13
$M(\ell,\nu,\gamma) \neq M_W W\gamma$	9	17



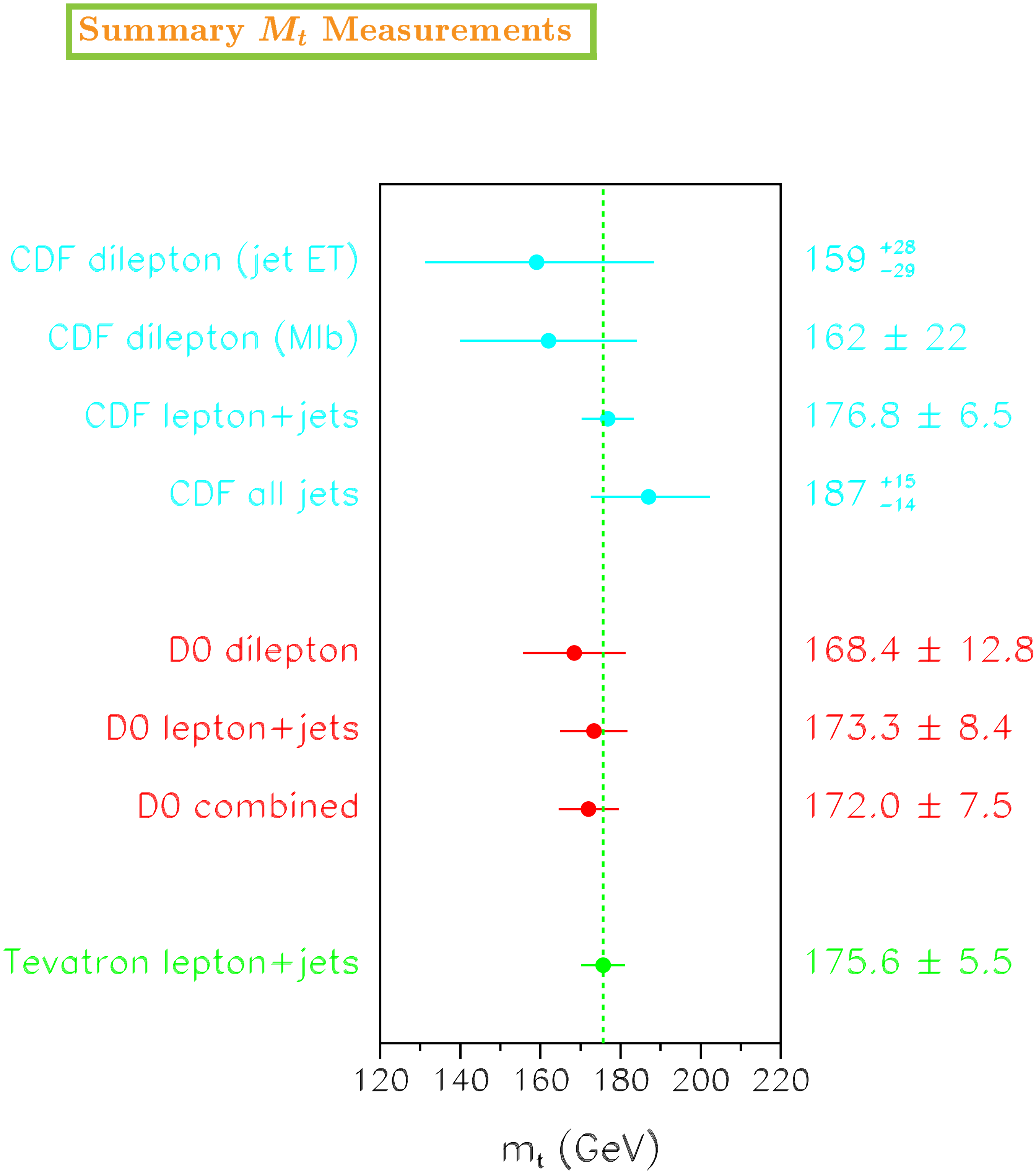
Radiation Zero



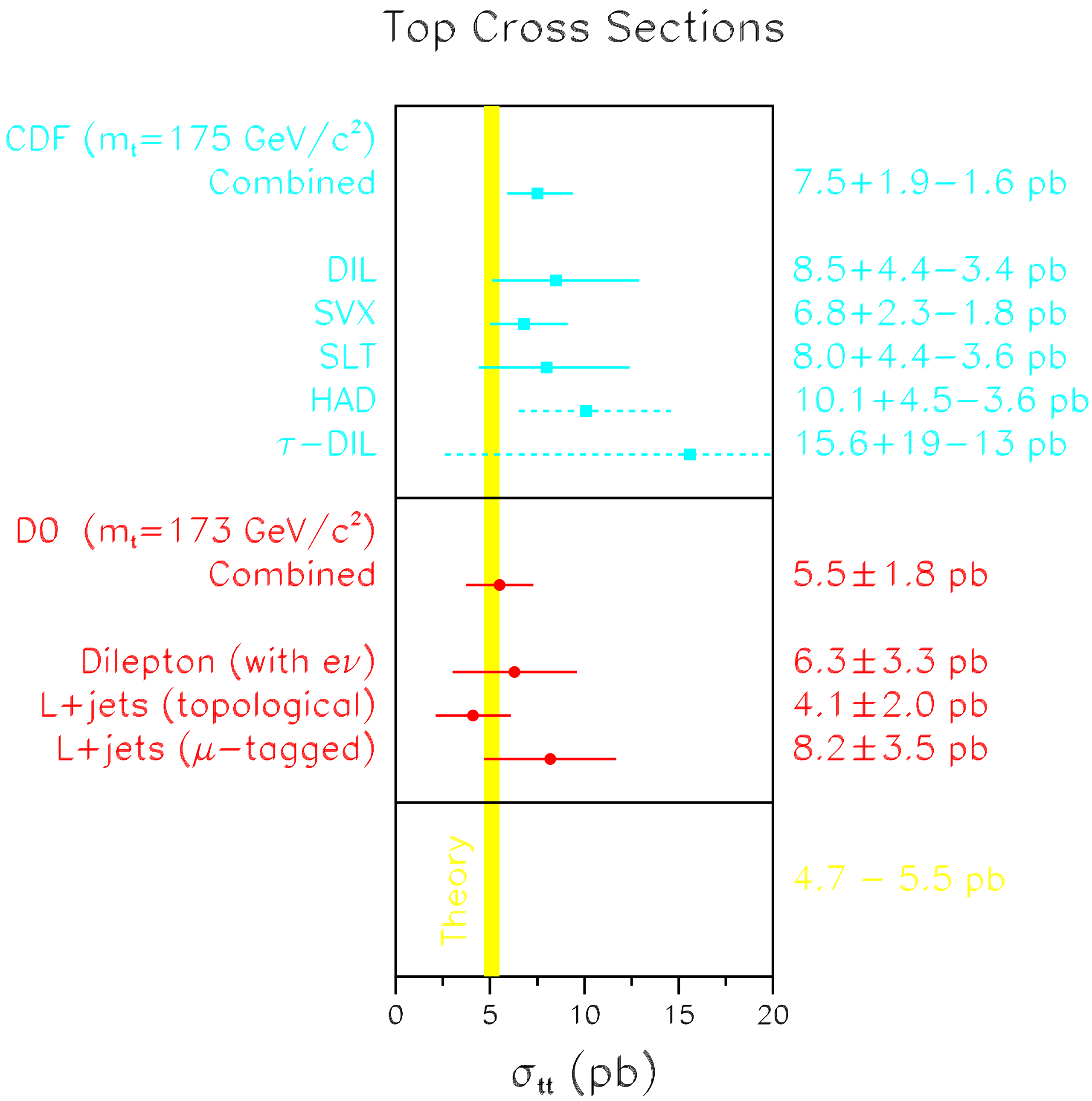
Summary of $WW\gamma/WWZ$ Couplings Measurements

		DØ		CDF	
	Processes	Limits	Λ(TeV)	Limits	Λ(TeV)
$\Delta\kappa_\gamma$	$W\gamma$	-0.98, 1.01	1.5	-1.8, 2.0	1.5
λ_γ		-0.33, 0.31	1.5	-0.7, 0.6	1.5
Δg_1^Z $^{(a)}$	WW/WZ	-0.60, 0.81	2.0	-0.61, 0.68	2.0
$\Delta\kappa_Z$ $^{(a)}$	semileptonic	-0.54, 0.70	2.0	-0.58, 0.68	2.0
λ_Z $^{(a)}$		-0.37, 0.40	2.0	-0.37, 0.40	2.0
$\Delta\kappa_\gamma = \Delta\kappa_Z$	WW/WZ	-0.43, 0.59	2.0	-0.49, 0.54	2.0
$\lambda_\gamma = \lambda_Z$	semileptonic	-0.33, 0.36	2.0	-0.35, 0.32	2.0
$\Delta\kappa_\gamma = \Delta\kappa_Z$	$WW \rightarrow$	-0.62, 0.75	1.5		
$\lambda_\gamma = \lambda_Z$	dileptons	-0.50, 0.56	1.5		
$\Delta\kappa_\gamma = \Delta\kappa_Z$	Combined	-0.33, 0.45	1.5		
$\lambda_\gamma = \lambda_Z$	fit	-0.20, 0.20	1.5		
$\Delta\kappa_\gamma$ (HISZ)	WW/WZ	-0.53, 0.78	2.0	-0.61, 0.67	2.0
λ_γ (HISZ)	semileptonic	-0.34, 0.36	2.0	-0.34, 0.33	2.0

(a) SM $WW\gamma$ couplings assumed

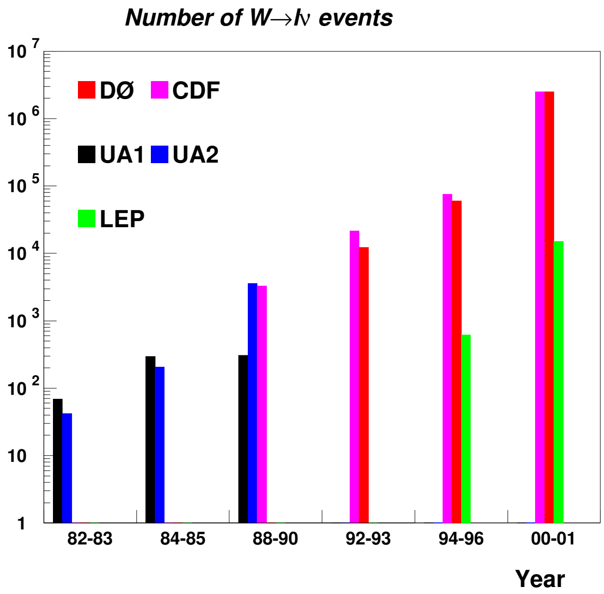

Summary M_t Measurements
CDF dilepton (jet ET)
159 $^{+28}_{-29}$
CDF dilepton (Mlb)
162 ± 22
CDF lepton+jets
176.8 ± 6.5
CDF all jets
187 $^{+15}_{-14}$
D0 dilepton
168.4 ± 12.8
D0 lepton+jets
173.3 ± 8.4
D0 combined
172.0 ± 7.5
Tevatron lepton+jets
175.6 ± 5.5
120 140 160 180 200 220
m_t (GeV)

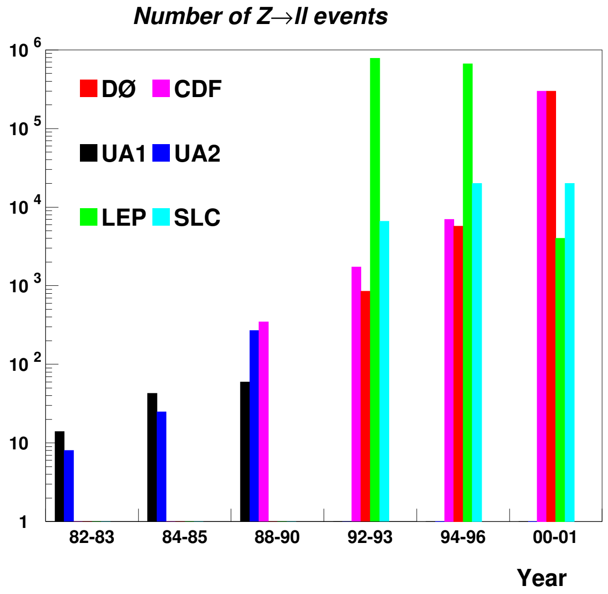
Summary $\sigma_{t\bar{t}}$ Measurements



Outlook . . . . . .

Rather than speculate, what's the event yield at the turn of the century with 2 fb^{-1} collected at the Tevatron





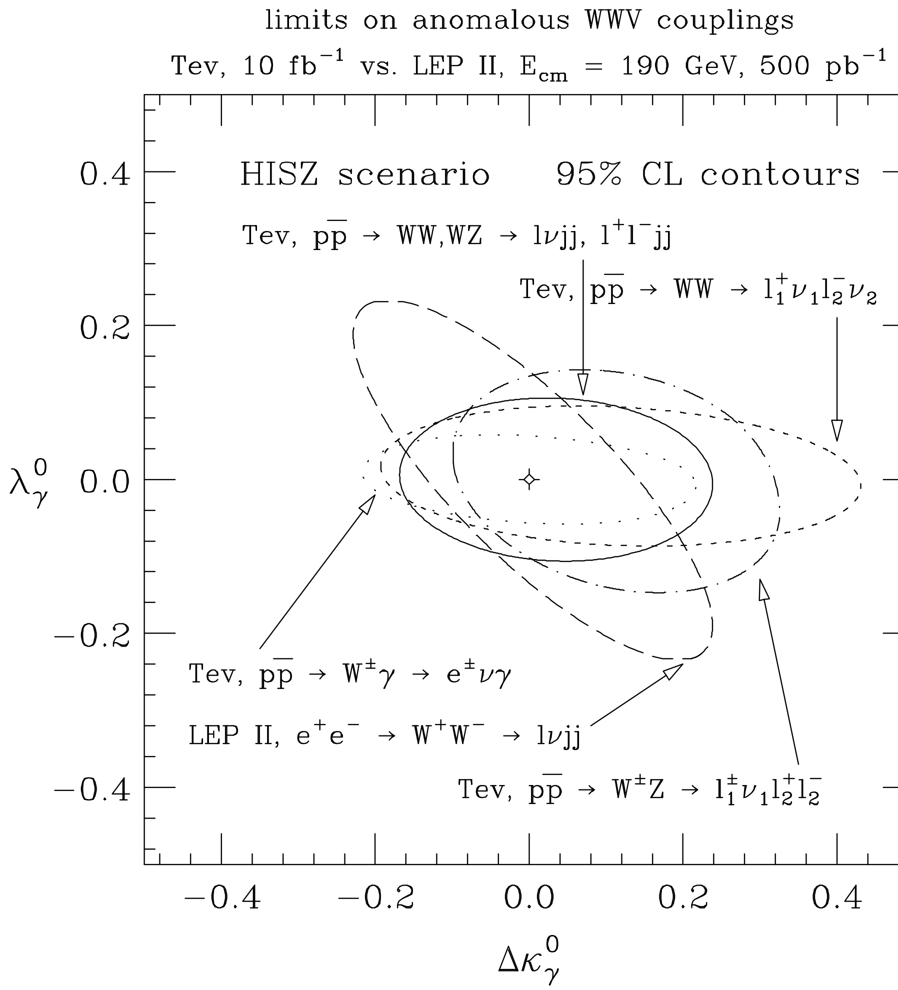
W's abundant at the Tevatron

Total LEP $Z \rightarrow \ell\ell$ (e, μ) statistics $\sim$ 1.2 M.

Tevatron will have accumulated about 0.6 M $Z \rightarrow \ell\ell$ (e, μ) events.

A lot of room for excellent physics

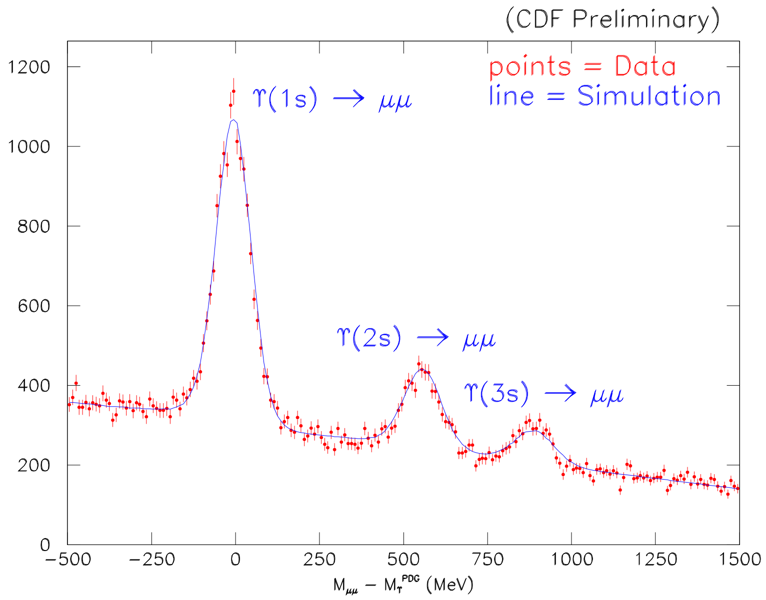
Outlook ......

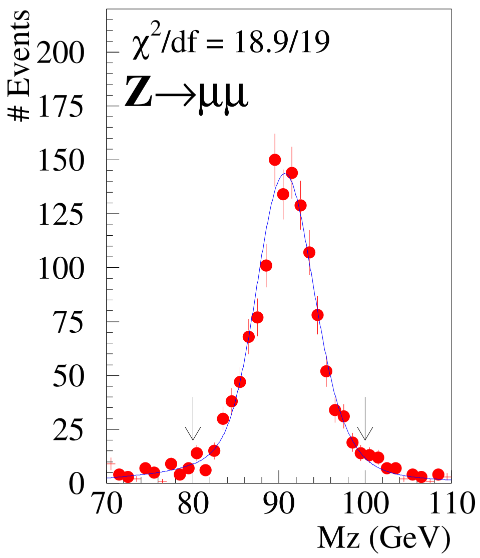


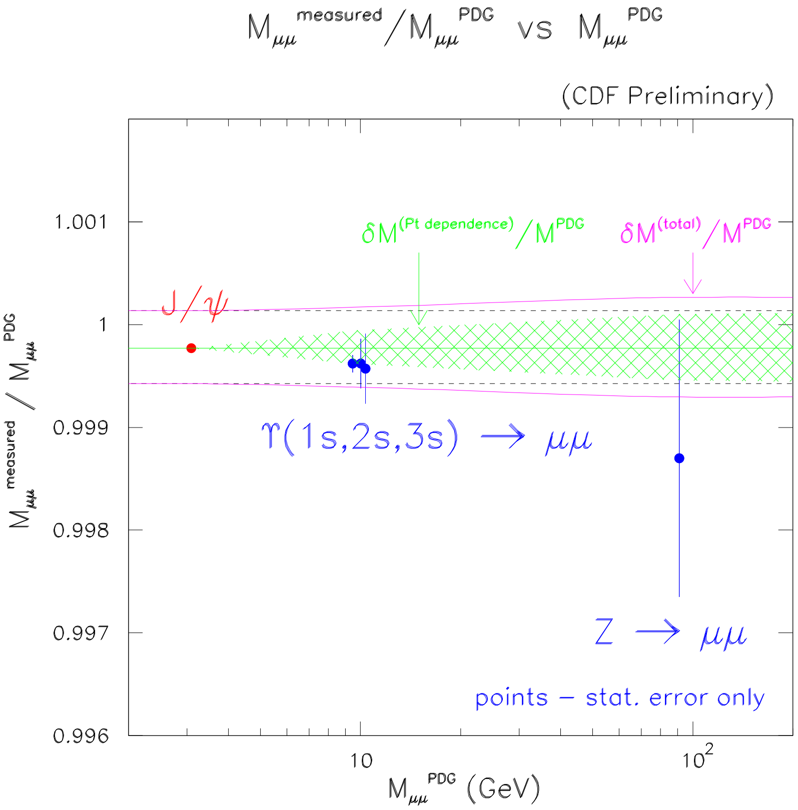
Tevatron $\sqrt{s} = 1.8$ TeV $\int \mathcal{L}dt = 1$ fb^{-1}	LEP II $\sqrt{s} = 176$ GeV $\int \mathcal{L}dt = 500$ pb^{-1}	LHC $\sqrt{s} = 14$ TeV $\int \mathcal{L}dt = 100$ fb^{-1}
$-0.23 < \Delta\kappa < 0.29$ $-0.15 < \lambda < 0.15$ $-0.11 < h_{30}^Z < 0.11$ $-0.006 < h_{40}^Z < 0.006$	$-0.19 < \Delta\kappa < 0.21$ $-0.18 < \lambda < 0.18$ $-0.50 < h_{30}^Z < 0.50$ $-0.45 < h_{40}^Z < 0.45$	$-0.006 < \Delta\kappa < 0.010$ $-0.005 < \lambda < 0.007$ $-0.005 < h_{30}^Z < 0.005$ $-9 \times 10^{-5} < h_{40}^Z < 9 \times 10^{-5}$

Extrapolation to p_T range for W muons

Extrapolation to p_T range for W muons







$$\boxed{\delta M_W = 40 \text{ MeV}}$$