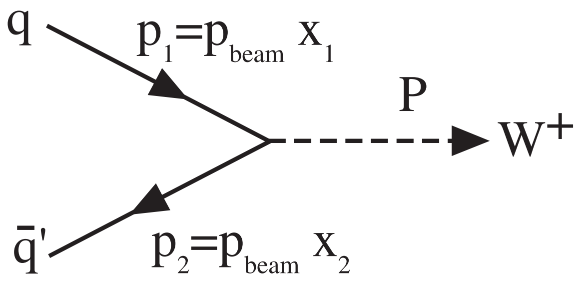
W and Z Boson Production

W's and Z's are produced via Drell-Yan annihilation

- Parton-level cross section is a weak interaction
- Weak matrix element for W case is

$$\mathcal{M} = -iV_{qq'}\frac{g}{\sqrt{2}}\epsilon_\alpha^\lambda(P)\bar{v}(p_1)\frac{1}{2}\gamma^\alpha(1-\gamma_5)u(p_2)$$

where $g^2 = 8M_W^2 G_F/\sqrt{2}$



- sum over W polarisation and average over quark spins
  - Longitudinal W $\epsilon_0^\lambda = (p/M_W, 0, 0, E/M_W)$ (helicity 0)
  - Transverse W $\epsilon_\pm^\lambda = (0, 1/\sqrt{2}, \pm i\sqrt{2}, 0)$ (helicity ± 1)

$$\begin{aligned}\sum|\mathcal{M}|^2 &= |V_{qq'}|^2 g^2 M_W^2 = |V_{qq'}|^2\frac{8G_F M_W^4}{\sqrt{2}} \\ \Rightarrow \hat{\sigma}(qq' \to W^+) &= \left(\frac{1}{2}\right)^2\frac{1}{2\hat{s}}\left(|V_{qq'}|^2\frac{8G_F M_W^4}{\sqrt{2}}\right)2\pi\int d_2(PS)\end{aligned}$$

- 2-body phase space is just $\delta(\hat{s}-M_W^2)$

$\boxed{\text{CKM Matrix}}$

Cabbibo-Kobayashi-Maskawa matrix

- represents mixing of mass eigenstates under weak force
- assumed to be unitary

Latest estimates (from J. Hewett at SSI 95)

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$= \begin{pmatrix} 0.9747-0.9759 & 0.218-0.224 & 0.002-0.006 \\ 0.218-0.224 & 0.9738-0.9752 & 0.032-0.048 \\ 0.004-0.015 & 0.030-0.048 & 0.9988-0.9995 \end{pmatrix}$$

Total cross section for W^+ production given by

$$\sigma = \frac{K}{3}\int_0^1 dx_1 \int_0^1 dx_2 \sum_q f_1(x_1, M_W^2) f_2(x_2, M_W^2)\hat{\sigma}$$

where $K \sim 1 + \frac{8\pi}{9}\alpha_s(M_W^2)$ and $\frac{1}{3}$ for colour

- Use $sx_1x_2 = M_W^2$ and transform to to $\hat{s}$ and W rapidity y

$$dx_1 dx_2 = \frac{d\hat{s}dy}{s}$$

$$\begin{aligned}
\Rightarrow \sigma &= \frac{K}{3}\int_0^s \int_{y_{min}}^{y_{max}} \frac{d\hat{s}dy}{s} \sum_q f_1 f_2 \frac{2\pi G_F M_W^4 |V_{qq'}|^2}{\sqrt{2}\hat{s}} \delta(\hat{s} - M_W^2) \\
&= \frac{K}{3}\frac{2\pi G_F}{\sqrt{2}} \int_{y_{min}}^{y_{max}} dy \sum_q |V_{qq'}|^2 \left(x_1 x_2\right) f_1(x_1, M_W^2) f_2(x_2, M_W^2)
\end{aligned}$$

- In this integration,

$$x_1 = \frac{M_W}{\sqrt{s}} e^{+y} \qquad \text{and} \qquad x_2 = \frac{M_W}{\sqrt{s}} e^{-y}$$

since we transformed to W rapidity

Formula is now almost complete

Can use this expression to get differential cross section

- take into account Cabbibo-mixing

$$\begin{aligned}\frac{d\sigma}{dy}(p\bar{p} \to W^+) &= \frac{2\pi K G_F}{3\sqrt{2}} \sum_q |V_{qq'}|^2 (x_1 x_2) \\ &\Big\{\cos^2\theta_C \big[u(x_1)d(x_2) + \bar{d}(x_1)\bar{u}(x_2)\big] + \\ &\quad \sin^2\theta_C \big[u(x_1)s(x_2) + \bar{s}(x_1)\bar{u}(x_2)\big]\Big\}.\end{aligned}$$

- PDF's evaluated at $Q^2 = M_W^2$

If we assume "valence" dominated proton, then

$$\frac{d\sigma}{dy}(p\bar{p} \to W^+) = \frac{2\pi K G_F}{3\sqrt{2}}(x_1 x_2) u(x_1) d(x_2)$$

- $u(x) > d(x) \Rightarrow W^+$ rapidity correlated with u quark
- Charge asymmetry test of structure functions
- Total cross section comes from integrating over y
  - y_{min} and y_{max} are defined by requiring $x_i \leq 1$
  - Can estimate σ if one knows $u(x)$ and $d(x)$
- Calculation for Z production essentially the same

Observed Cross Section

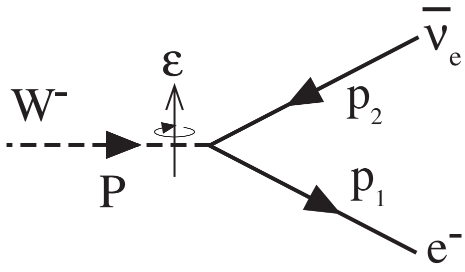
Both UA2 and CDF have measured σ_W

- In excellent agreement with SM prediction
- Predict $\sigma \sim 3$ nb at $\sqrt{s} = 630$ GeV
- Increases with energy due to
  - Larger rapidity region (50% increase going to Tevatron)
  - Structure function growth at low x ($\times 4$)

W Decay

Can calculate $W^- \to e^- \bar{\nu}_e$ using EWK matrix element

$$\mathcal{M} = -i\frac{g}{\sqrt{2}}\epsilon_\alpha^\lambda(P)\bar{v}(p_1)\frac{1}{2}\gamma^\alpha(1-\gamma_5)u(p_2)$$



- Average over W^+ spin and sum over final state spins

$$\begin{aligned}\frac{1}{3}|\mathcal{M}|^2 &= \frac{g^2}{6}\Big(-g^{\alpha\beta} + \frac{P^\alpha P^\beta}{M_W^2}\Big) Tr\Big(l\gamma\alpha k_{\gamma\beta}\Big[\frac{(1-\gamma_5)}{2}\Big]\Big) \\ &= \frac{g^2}{3}\Big(l \bullet k + 2\frac{(P\bullet l)(P\bullet k)}{M_W^2}\Big) = \frac{1}{3}g^2 M_W^2.\end{aligned}$$

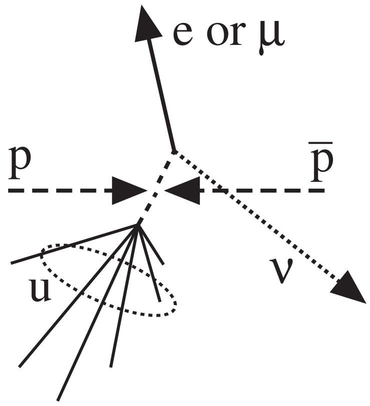
Use Fermi's Golden Rule to calculate decay rate

$$\begin{aligned} d\Gamma(W^- \to e^- \bar{\nu}_e) &= \frac{1}{2M_W}\,\frac{1}{3}g^2 M_W^2\,\frac{1}{4\pi^2}d_2(PS) \\ \Rightarrow \Gamma(W^- \to e^- \bar{\nu}_e) &= \frac{1}{48\pi}\,g^2 M_W \simeq 0.227 \text{ GeV}\end{aligned}$$

- 3 leptonic channels contribute
- $\bar{u}d$ and $\bar{c}s$ contribute with factor $\sim 3|V_{qq'}|^2$
- Gives predicted total width of $\Gamma_W = 2.09$ GeV

Observing W's

Most accessible channel is $W \to l\nu_l$



- Large cross section (~ 2 nb per lepton)
- Have charged lepton with $p_T \gtrsim 20$ GeV/c
- Have neutrino leaving $\not{E}_T \gtrsim 20$ GeV
- Good fraction of W production is "central"
  - Can focus on interval $|\eta| \lesssim 1.1$
  - Region with CDF's best lepton identification
- Higher rapity region important for asymmetry measurement

Select samples requiring

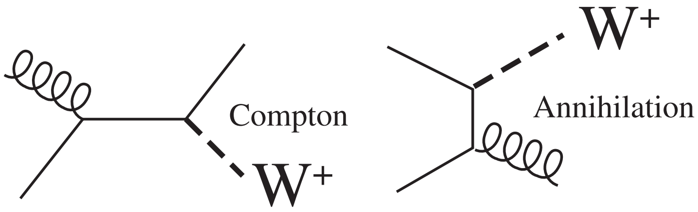
- Well-identified $e^{\pm}$ or $\mu^{\pm}$ candidate with $p_T > 20$ GeV/c
- Require $\not{E}_T > 20$ to tag neutrino
- Require charged lepton "isolated" from nearby energy flow
  - Rejects backgrounds from
    - Dijet backgrounds with one jet faking lepton
    - Heavy quark semileptonic decay $b \to l\nu_l X$

Provides very clean sample of W boson candidates

W Kinematics

In a $W \to l\nu_l$ decay

- Don't know initial state p_z or neutrino p_z
- W often produced with significant p_T
  - About 1/3 of all $W \to l\nu_l$ have jets

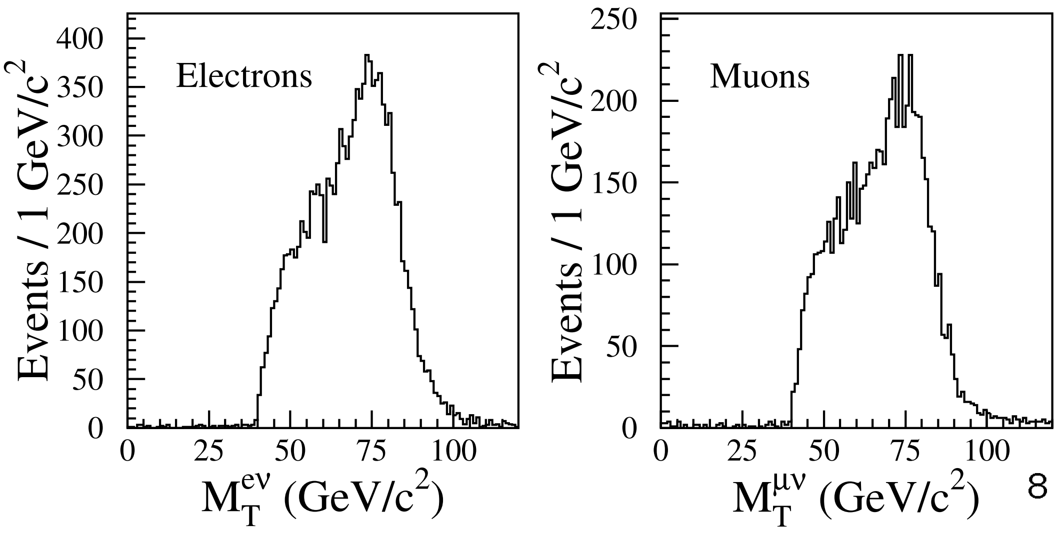


Despite all this "missing" information

- Can see clear signal using transverse mass

$$M_T \equiv \sqrt{2E_T^l \not{E}_T(1 - \cos\phi_{l\nu})}$$

- Requires good background control
  - No other sources of real high p_T leptons
  - Need excellent lepton ID capability



Background Issues

Potential source of backgrounds from jet production

- One jet fragments into either:
  - high p_T $\pi^\pm$
    - charge-exchanges $\pi^\pm N \to \pi^\circ N'$ in calorimeter
    - Decays via $\pi^\pm \to \mu^\pm \nu_\mu$
  - high p_T $\pi^\pm \pi^\circ$ pair
    - "Overlap" in calorimeter fakes $e^\pm$
- Heavy quark decay also possible background
  - Most comes in at low M_T
- Rejected by lepton ID cuts
- Less than 1% of sample is remnant QCD

$W \to \tau\nu\nu$ largest remaining background

- Rejected primarily by kinematics
- About 2% of sample is remnant τ decays

Other backgrounds are relatively small ($\lesssim$ 0.5%)

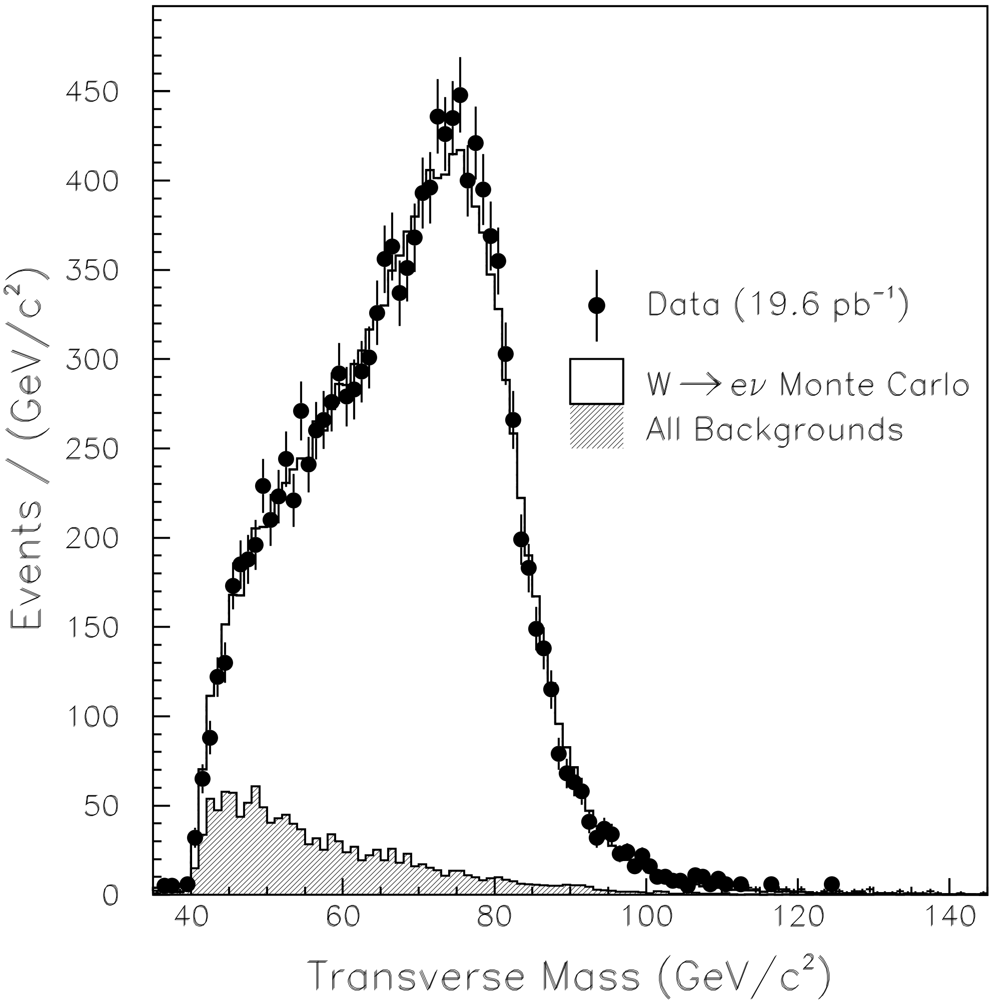
- Conversions $\gamma \to e^+e^-$
- Missed $Z \to l^+l^-$ where one lepton not found

Shape of Backgrounds

Distribution shows size and shape of backgrounds for electrons

- Muon channel similar
- Can further reduce backgrounds with tighter M_T cut

Figure 5.10



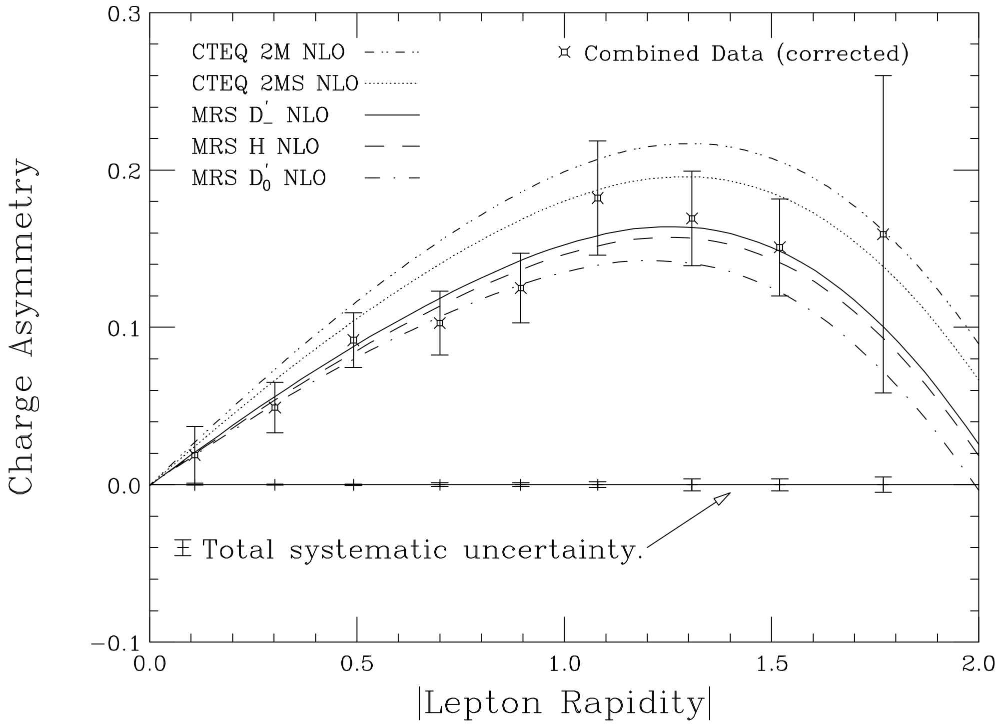
W Asymmetry

Showed that W^+ production aligned with u quark

- W^- production aligned with $\bar{u}$ quark
- Difference in u and d PDF's result in asymmetry
- Not washed out by $V - A$ decay of W

Measure

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



W Boson Width

The width of the W boson can be indirectly measured

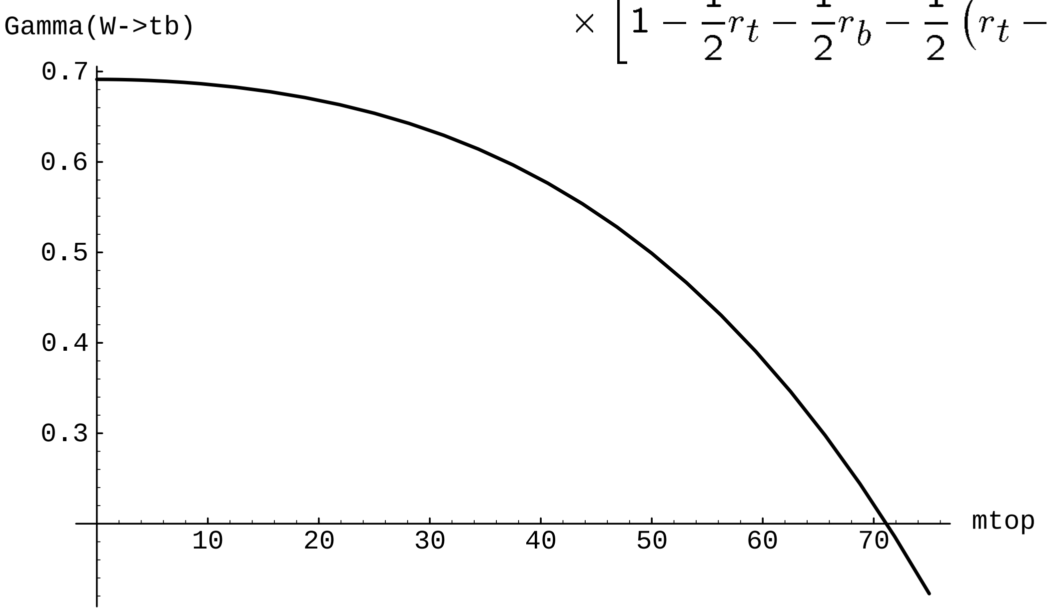
$$R = \frac{\sigma(p\bar{p} \to W \to e\nu_e)}{(\sigma(p\bar{p} \to Z \to e^+e^-)} = \frac{\sigma(p\bar{p} \to W)}{\sigma(p\bar{p} \to Z)} \bullet \frac{\Gamma(W \to e\nu_e)}{\Gamma(Z \to e^+e^-)} \bullet \frac{\Gamma_Z}{\Gamma_W}$$

- Can use SM to calculate total cross sections
- Use LEP data for Γ_Z
- Use SM to calculate $\Gamma(W \to e\nu_e)$

Experiment just needs to measure R

- Sensitive to phase space for heavy quark decay

$$\begin{aligned}\Gamma(W \to t\bar{b}) &= 3|V_{tb}|^2\Gamma(W \to e\nu_e) \\ &\quad \times\sqrt{1 + r_t^2 + r_b^2 - 2r_t - 2r_b - 2r_t r_b} \\ &\quad \times \left[1 - \frac{1}{2}r_t - \frac{1}{2}r_b - \frac{1}{2}\left(r_t - r_b\right)^2\right]\end{aligned}$$

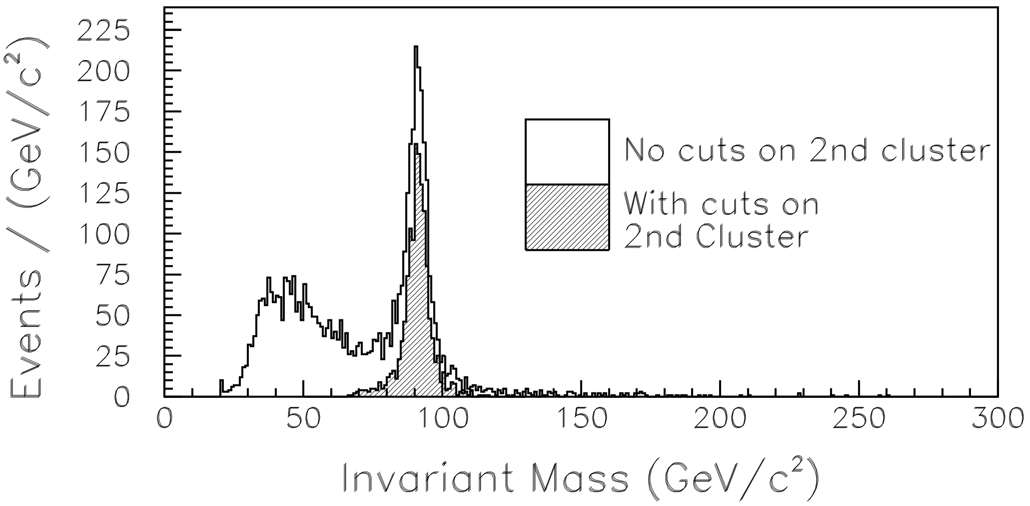


Z Selection for R Measurement

$Z \to e^+e^-$ decays easily identified

- Use W sample before $\not{E}_T$ cut
- Require second electron candidate

Figure 3.2



Results on R

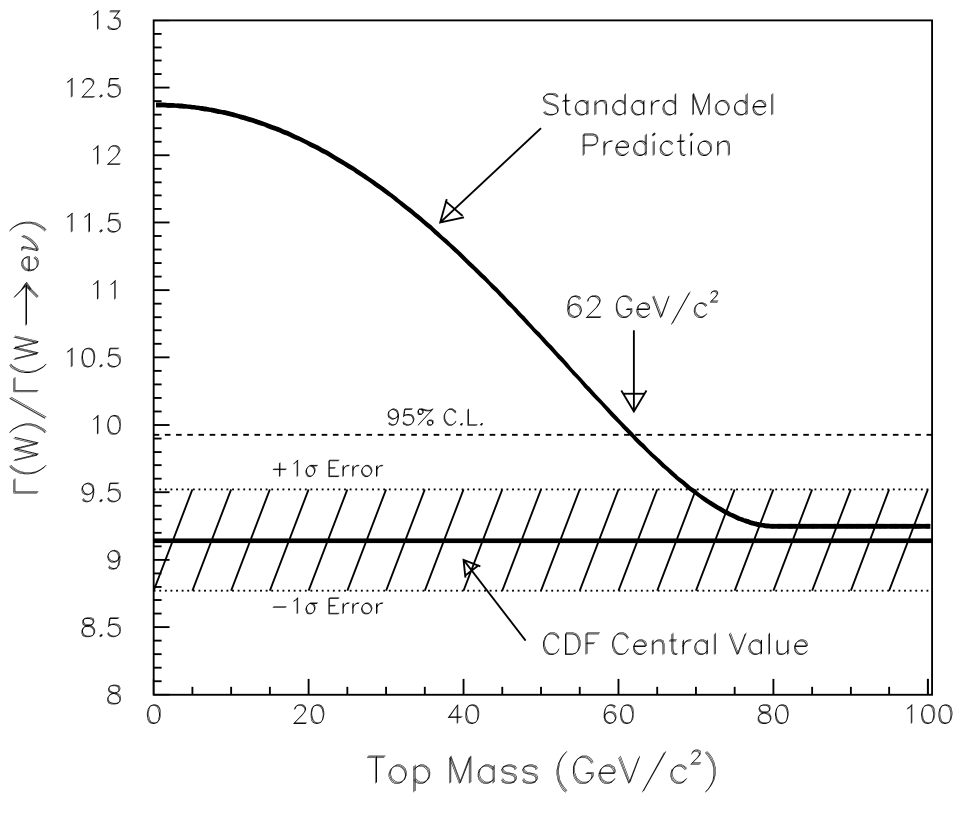
Measured value of R is

$$R = 10.90 \pm 0.32(\text{stat}) \pm 0.29(\text{syst})$$

- Can use it
  - Measure $\Gamma_W = 2.063 \pm 0.061 \pm 0.060$ GeV
  - set a limit on the top quark mass
- Note that it is independent of how t decays

$$M_{\text{top}} > 62 \text{ GeV/c}^2 \text{ at } 95\% \text{ CL}$$

Figure 10.1



Trilinear Gauge Couplings in SM

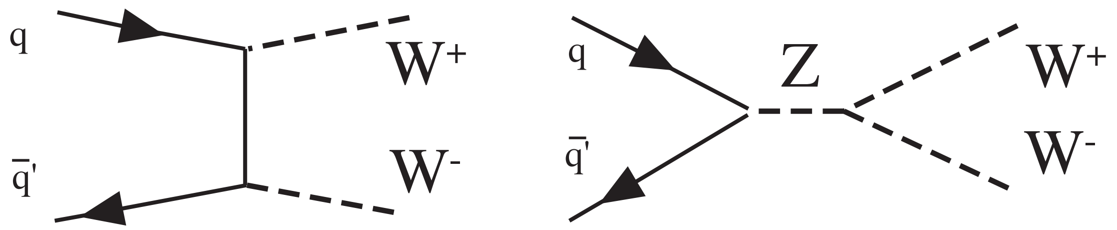
SM predicts self-interactions among bosons

- s-channel and t-channel amplitudes are both large
- Destructive interference neccessary to maintain unitarity

$$\sigma(\mathrm{t-channel}) \propto \frac{G_F^2 s}{3\pi}$$

- Can measure these couplings using

$$\begin{aligned} p\bar{p} &\rightarrow W^{\pm}\gamma \text{ and } Z\gamma \\ p\bar{p} &\rightarrow W^{+}W^{-},\ W^{\pm}Z, \text{ and } ZZ \end{aligned}$$



Total WW cross section estimated to be ~ 9.5 pb

- One can generalise to include "anomolous couplings"
  - can include both CP-conserving and non-conserving
  - In general, there is a large number of parameters
- Initial goal is to verify that σ_{VV} is consistent with SM

$\boxed{\text{SM Production of WW}}$

The matrix element for W^+W^- production is

$$\mathcal{M}(q\bar{q}' \to W^+W^-) = i\bar{v}(q')T^{\mu\nu}u(q)\epsilon^*_\mu(W^+)\epsilon_\nu(W^-)$$

where the tensor current is

$$\begin{aligned} T_{\mu\nu} &= e^2\left(\frac{Q_q}{s} + D_Z\frac{g_V^q - g_A^q\gamma_5}{\sin^2\theta_W}\right) \\ &\times \left[g_{\mu\nu}(W^+ - W^-) + \gamma_\mu(2W^+ + W^-)_\nu - \gamma_\nu(2W^+ + W^-)_\mu\right] \\ &- e^2\frac{(1+\gamma_5)}{4\sin^2\theta_W}\,\frac{\gamma_\nu(q - W^-)\gamma_\mu}{(q - W^-)^2} \end{aligned}$$

- D_Z is Z-propogator

$$D_Z = \frac{1}{\hat{s} - M_Z^2 + iM_Z\Gamma_Z}$$

- g_V^q and g_A^q are vector and axial-vector couplings
- Q_q is charge of incoming quark

Shows the separate s and t-channel contributions

- Individually grow $\propto \hat{s}$
- Both must exist (and cancel) to avoid violating unitarity

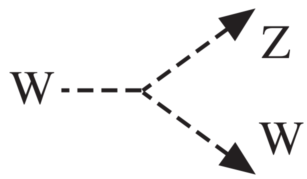
Observation of WZ Production

Anomolous couplings can be interpreted in various ways

- Sensitive to "new" physics
- Non-SM $WW\gamma$ couplings modify W dipole moments

$$
\begin{aligned}
\mu_W &= \frac{e}{2M_W}(2 + \Delta\kappa + \lambda) \\
Q^e_W &= \frac{-e}{2M^2_W}(1 + \Delta\kappa - \lambda)
\end{aligned}
$$

assuming that CP is conserved



Results to date have focused on $WW\gamma$ and $ZZ\gamma$ vertices

- $W\gamma$ and $Z\gamma$ production has been measured
- Limited $|\Delta\kappa| < 3.0$ and $\lambda < 0.95$ at 95% CL

New CDF data starting to be sensitive to WWZ

- Predicted cross section is 9.5 pb for WW
- Predicted cross section is 2.5 pb for WZ
- Can expect to see a few events in sample

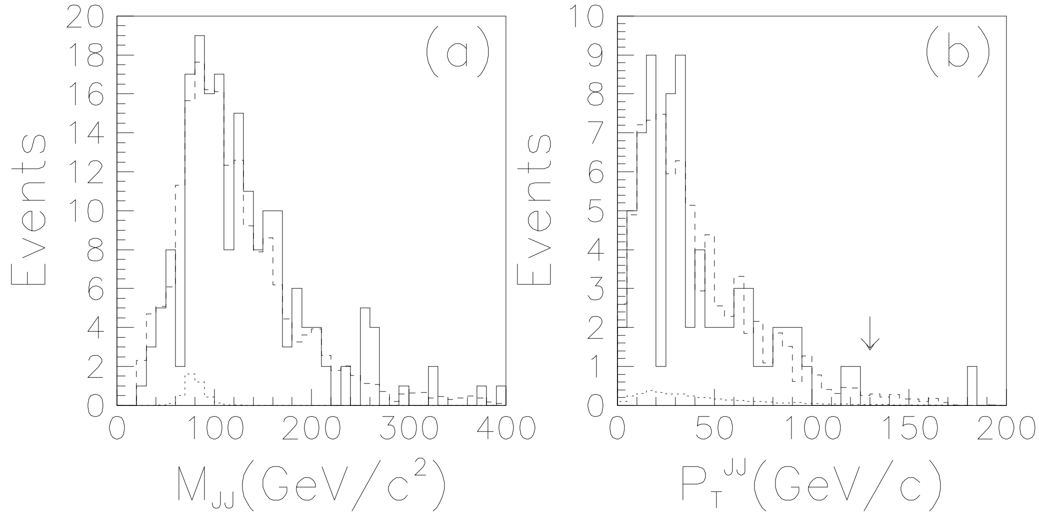
Search for DiVector Boson Events

Search for events where

- One W or Z decays hadronically into two jets
  - Require jet $E_T > 30$ GeV
  - Require dijet mass $60 < M_{jj} < 110$ GeV/c^2
- Other boson decays leptonically
- Sensitive to WW and WZ final states

Large backgrounds from W/Z + jet events

- Require dijet $P_T > 130$ for leptonic W candidates
- Require dijet $P_T > 100$ for leptonic Z candidates



Results of WW/WZ Search

Expect to see virtually no signal with SM couplings

- Expect 0.13 events with leptonic W
- Expect 0.02 events with dileptonic Z
- Observe:
  - one event with leptonic W decay
  - no events with leptonic Z decay

Allows us to exclude anomalously large WWZ couplings

- Note that if WWZ coupling is zero, we would expect of order 15 events!
  - $\Rightarrow WWZ$ coupling is non-zero
- Can set limits on specific choices of κ and λ
- Most sensitive to WWZ couplings

Can set limits making assumptions

- For example, assume SM correct except for WWZ and $WW\gamma$
- Assume WWZ and $WW\gamma$ couplings equal
- Conclude $-0.11 \leq \kappa^Z \leq 2.27$ and $-0.81 \leq \lambda^Z \leq 0.84$