Electroweak Physics at the Tevatron

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LISHEP Collider Workshop

3 April 2006

Outline

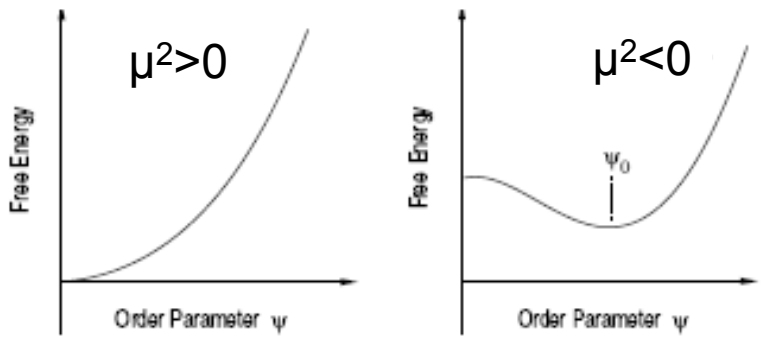
- What do we hope to learn in electroweak physics?
- What can we measure at the Tevatron?
- Results
- Prospects

Electroweak Standard Model

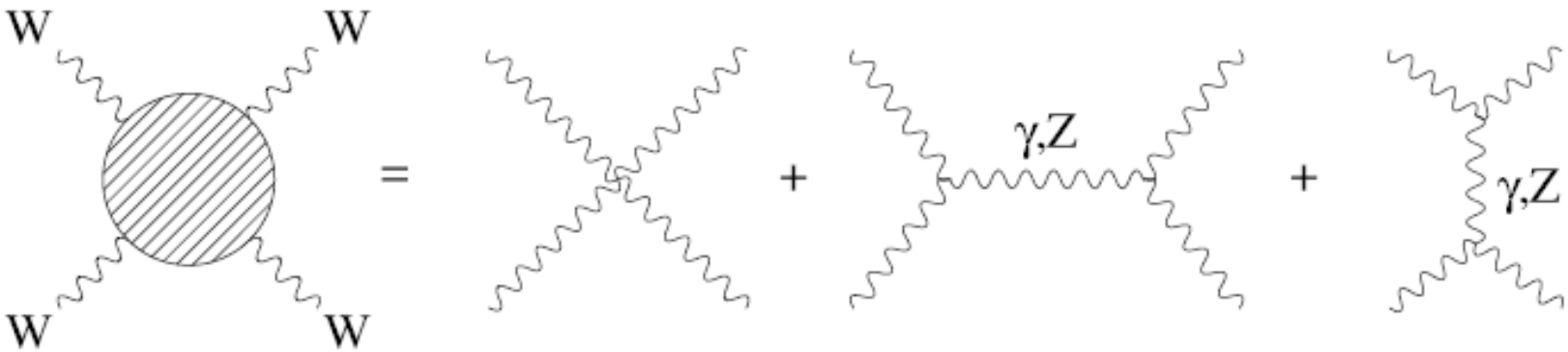
- Electroweak “standard model” occupies an auspicious place in fundamental physics
  - Theoretical unification of forces:
    - Newton’s Law of gravity on earth and solar system
    - Maxwell’s electromagnetic theory
- Key problem is completing and testing the theory of electroweak symmetry breaking
  - why is the photon massless while the weak bosons are heavy, ~100 GeV?

Breaking the EW Symmetry

- Role of the Higgs mechanism is to
  - break the symmetries of the high energy EWK theory $SU(2)_L x U(1)_Y$ while preserving $U(1)_{EM}$
- Realized with a complex doublet of scalar fields with a potential $V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$
- When the minimum of the potential is not at zero:
  - three of the degrees of freedom give the $W^\pm$ and Z^0 mass, while preserving a massless photon
  - the fourth is the Higgs boson, a massive fundamental scalar

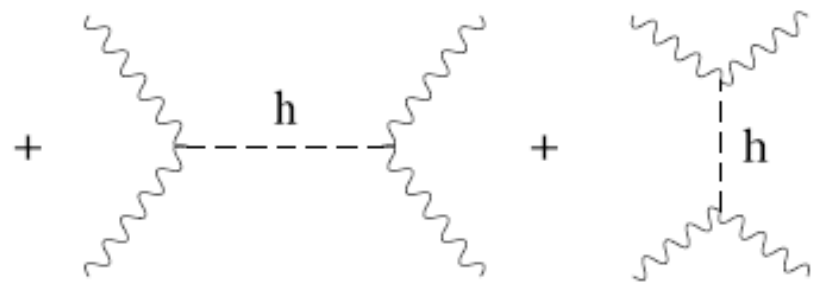


Avoiding Strong WW Scattering



- These diagrams give an amplitude $\propto G_F E^2_{CM}$
- Can be cancelled by…

  … if coupling $\propto M_W$ and $M_{Higgs} \lesssim 1$ TeV

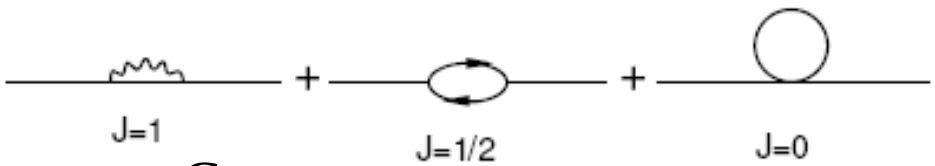


- *Any effective theory replacing the Higgs mechanism has to also reproduce these properties*

Why is the Higgs not the whole story?

- Quantum corrections to the Higgs mass…

$$m_H^2 \rightarrow m_{tree}^2 +$$



$$\delta m_H^2 \approx \frac{G_F}{4\pi^2\sqrt{2}}\Lambda^2\left(6M_W^2 + 3M_Z^2 + M_H^2 - 12m_t^2\right)$$

$$= -\left(\frac{\Lambda}{1\ \mathrm{TeV}} \times 300\ \mathrm{GeV}\right)^2$$

- to keep these corrections small, need physics to cancel these loops at 1 TeV

- Leads to the so-called hierarchy problems

Why is the Higgs not the whole story? (cont'd)

Hierarchy Problem

- new physics should be at a known scale
  - e.g., GUT scale, Planck scale, etc., far from 1 TeV

Hierarchy Problem

- OK, forget the "known scale". What is allowed?
  - much (all?) new physics that could fix this problem is already excluded by frontier colliders and precision experiments
  - up to 5 – 1000 TeV scale, depending on form of new physics

- *Our "standard model" may be an effective theory with the new physics pushed just above our current reach*

What do we look for to gain more understanding?

- Look at the Higgs
  - direct search *(Landsberg)*
  - test properties of Higgs
    - in direct couplings
    - and through loop effects
- Verify EW couplings among bosons
  - search for new interactions to cancel strong dynamics
- Search for new gauge bosons
  - generic prediction of dynamical EWSB theories

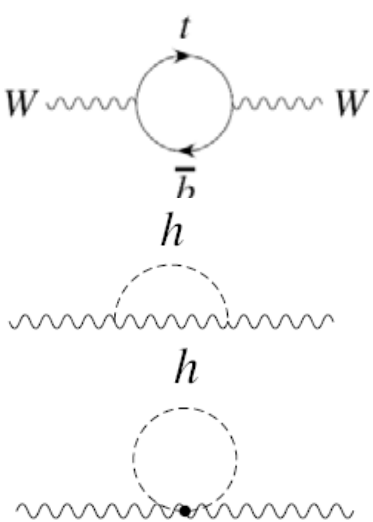
Electroweak Measurements at the Tevatron

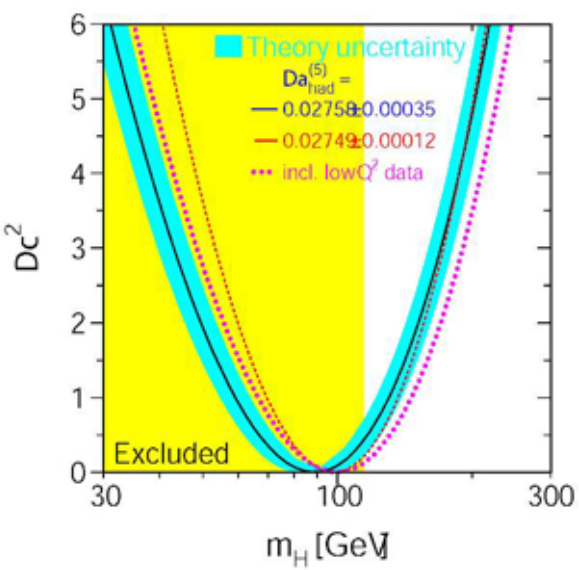
Hadron and Lepton Colliders

- Lepton colliders
  - point-like initial state, $\sqrt{s_{\text{hard scattering}}} = \sqrt{s_{\text{beam}}}$
    - at least up to ISR
  - "clean" final state, e.g., can identify $W \to q\bar{q}$
- Hadron colliders
  - range of energies, charges in initial state
  - higher $\sqrt{s_{\text{hard scattering}}}$
    - leads to overwhelming statistics in single W production, access to Wγ, WZ, etc.

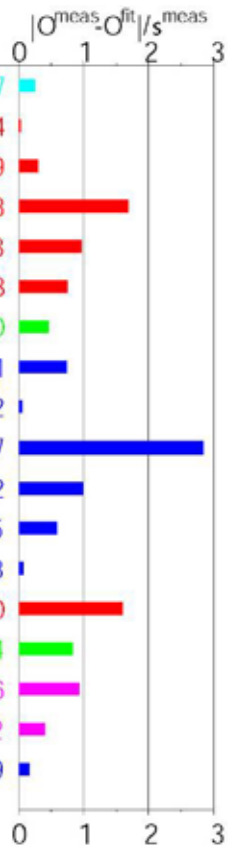
Testing EW Theory with Loops

- Loop corrections to precisely measured parameters
  - verify consistency, and
  - provide Higgs mass estimate





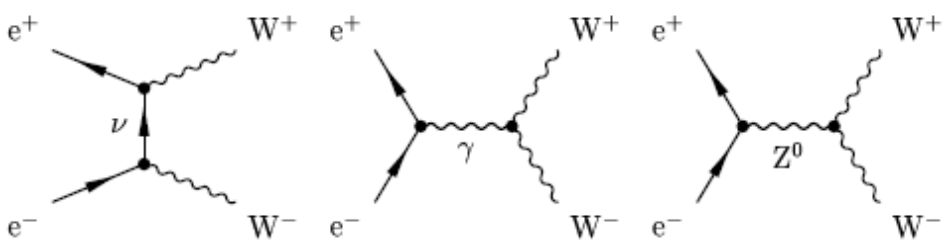
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758± 0.00035	0.02767
m_Z [GeV]	91.1875± 0.0021	91.1874
Γ_Z [GeV]	2.4952± 0.0023	2.4959
σ_{had}^0 [nb]	41.540± 0.037	41.478
R_l	20.767± 0.025	20.743
$A_{fb}^{0,l}$	0.01714± 0.00095	0.01643
$A_l(P_\tau)$	0.1465± 0.0032	0.1480
R_b	0.21629± 0.00066	0.21581
R_c	0.1721± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707± 0.0035	0.0742
A_b	0.923± 0.020	0.935
A_c	0.670± 0.027	0.668
A_l(SLD)	0.1513± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324± 0.0012	0.2314
m_W [GeV]	80.404± 0.030	80.376
Γ_W [GeV]	2.115± 0.058	2.092
m_t [GeV]	172.5± 2.3	172.9



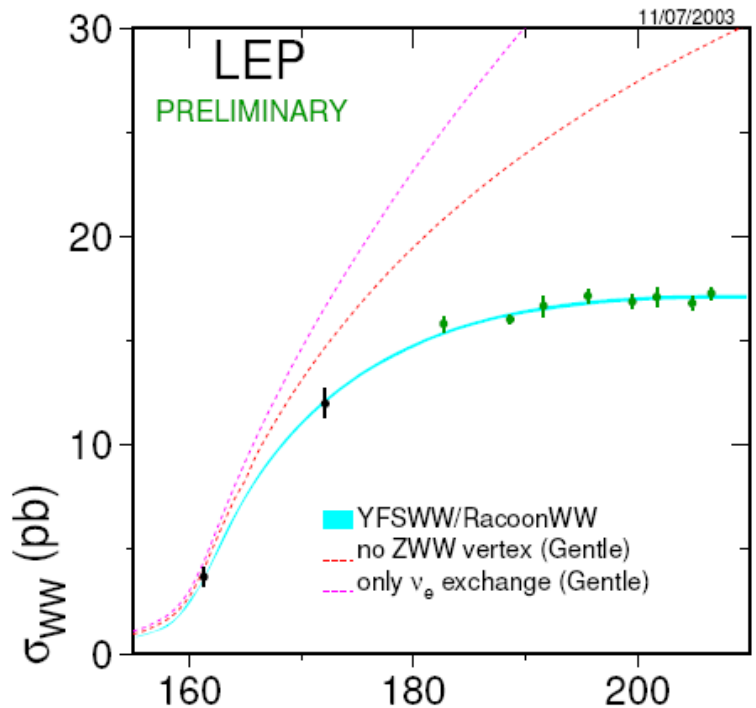
Direct Tests of EW Theory

- An example from LEP2…

$e^+e^- \to W^+W^-$ in $SU(2)_L \otimes U(1)$:

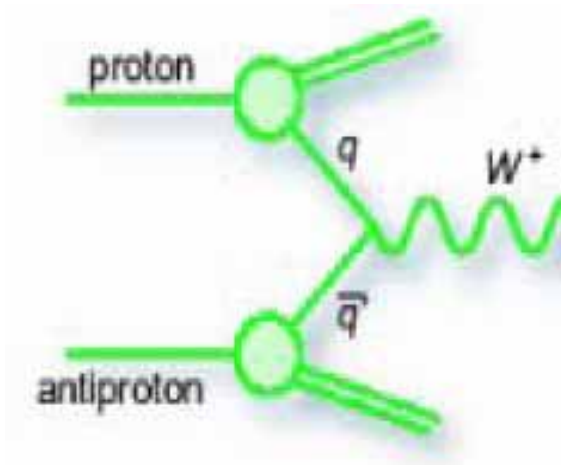


- This test establishes that the theory correctly predicts WWγ and WWZ couplings



Tevatron Electroweak Program

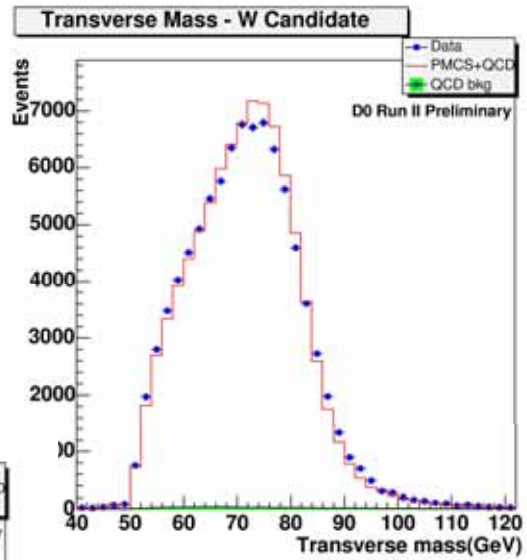
- Single boson production
  - *now testing properties of proton constituents that collide to produce weak bosons!*
- Searches for new gauge bosons, Higgs
- Precision properties
  - top mass, W mass and width
- Multi-boson final states
  - **W/Z+γ**, WW, ZZ and **WZ**
  - new physics in couplings?

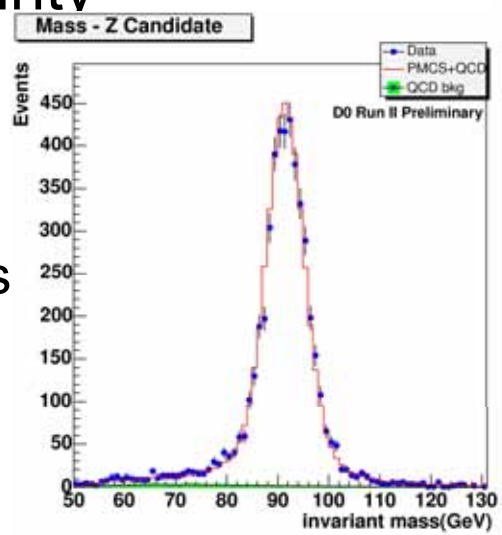


Tevatron Recent Results

Single Boson Cross-sections

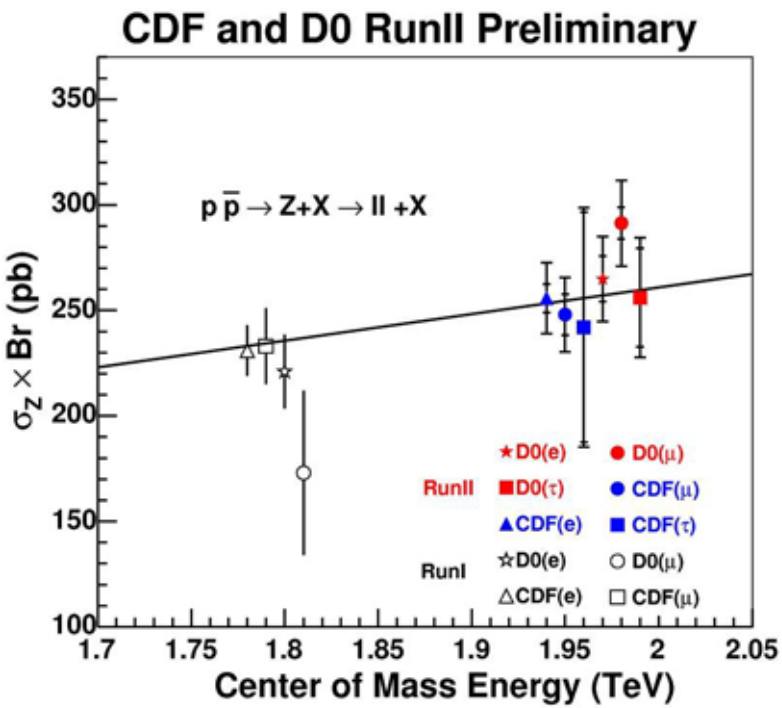
- Theoretically well under control
  - NNLO cross-sections available (~2% unc.)
  - PDFs well constrained (1.5-2% unc.)
- Low backgrounds, signal understood
- But significant uncertainty in luminosity (~6%)
- Cross-sections measured in all leptonic final states, central and forward regions

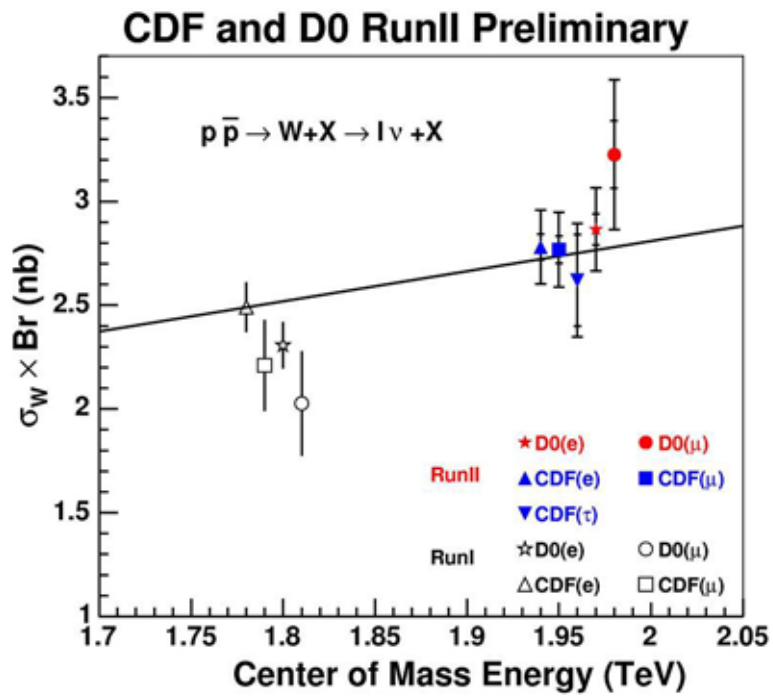




Single boson cross-section summary

- Uncertainties ~few %, except luminosity
- Wide varieties of channels build confidence in results

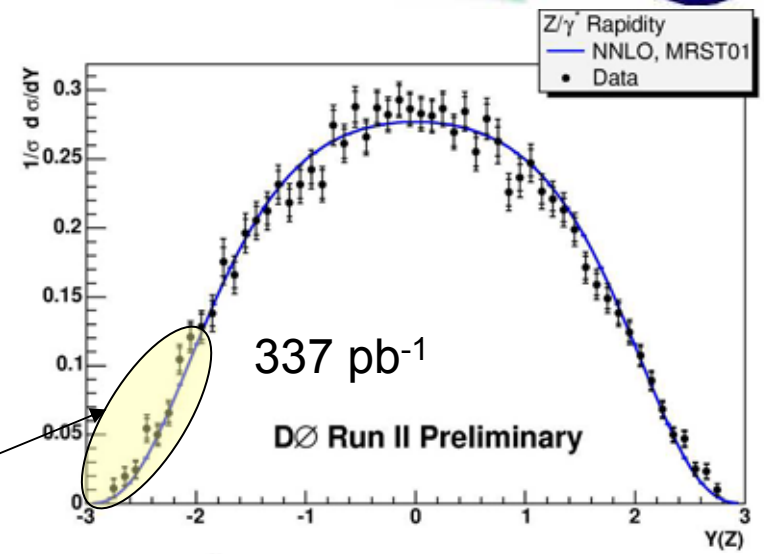


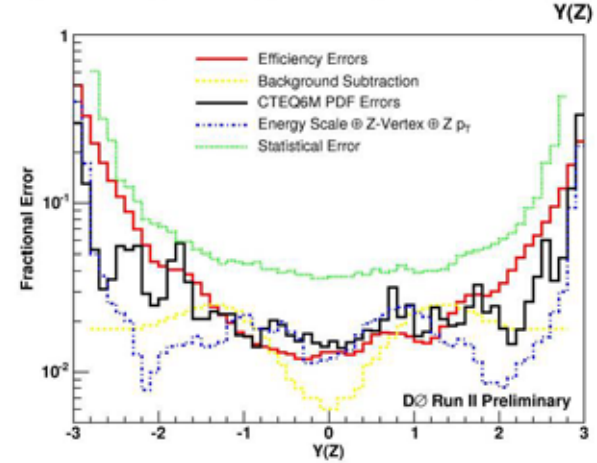


Z Rapidity Distribution

- dσ/dy known to NNLO
- Since theory is so accurate, can use differential distributions to probe PDFs

$$x_{1(2)} = \frac{M_Z}{\sqrt{s}} e^{\pm y}$$

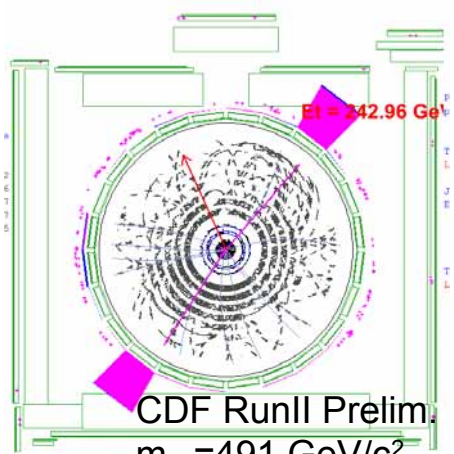




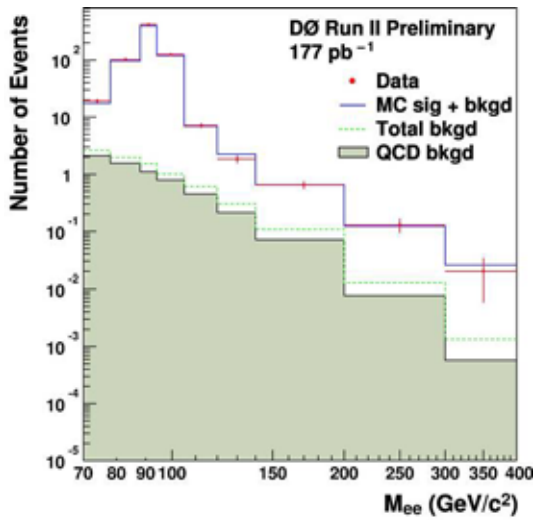
- High rapidity implies one high x parton in the collision
  - sensitive probe of high x quarks

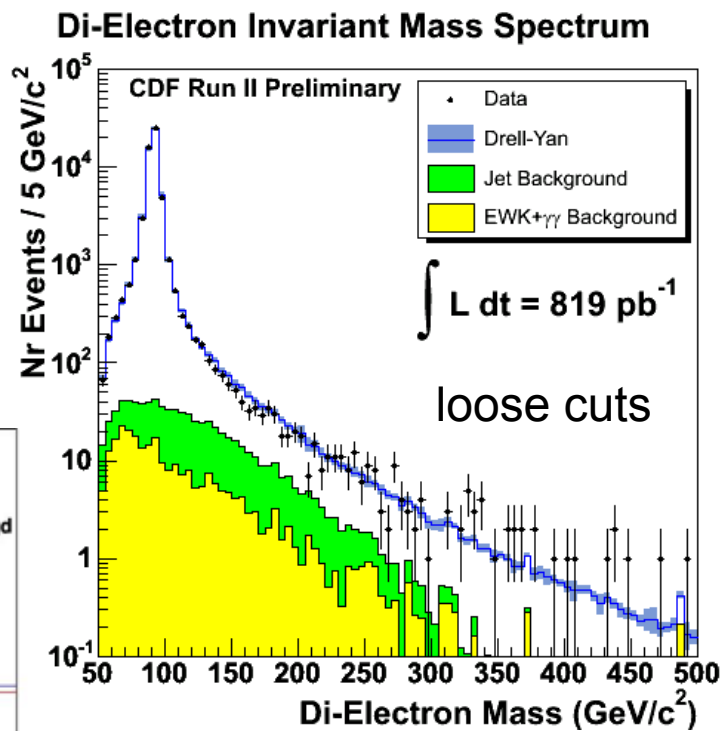
Drell-Yan

- Drell-Yan $p\bar{p} \rightarrow Z^{(*)} / \gamma^* \rightarrow \ell^+\ell^-$
- Z-γ interference an important test of EWK theory
- Also "golden signal" for new gauge bosons



CDF RunII Prelim.
m_{ee}=491 GeV/c²



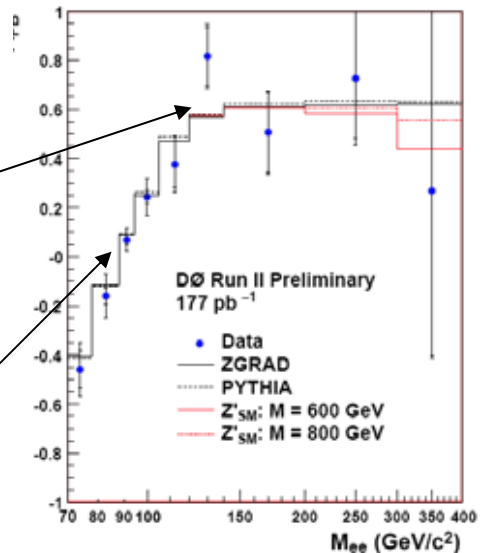


A_{FB} in Drell-Yan

- $p\bar{p} \to Z^{(*)} / \gamma^* \to \ell^+\ell^-$ has a forward-backward asymmetry due to Z exchange contribution

$$\frac{d\sigma}{d\cos\theta} = \frac{4\pi\alpha^2}{3s}[\frac{3}{8}A(1+\cos^2\theta) + B\cos\theta],$$

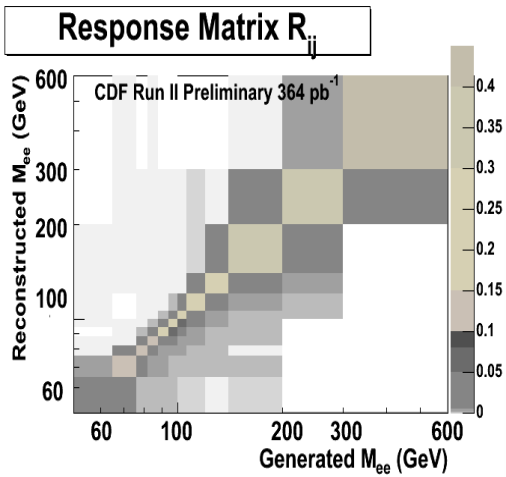
$$\begin{aligned} A &= Q_l^2 Q_q^2 + 2Q_l Q_q g_V^q g_V^l Re(\chi(s)) + {g_V^l}^2({g_V^q}^2 + {g_A^q}^2)|\chi(s)|^2 + {g_A^l}^2({g_V^q}^2 + {g_A^q}^2)|\chi(s)|^2, \\ B &= \frac{3}{2} g_A^q g_A^l (Q_l Q_q Re(\chi(s)) + 2 g_V^q g_V^l |\chi(s)|^2), \\ \chi(s) &= \frac{1}{\cos^2\theta_W \sin^2\theta_W} \frac{s}{s - M_Z^2 + i\Gamma_Z M_Z}, \end{aligned}$$

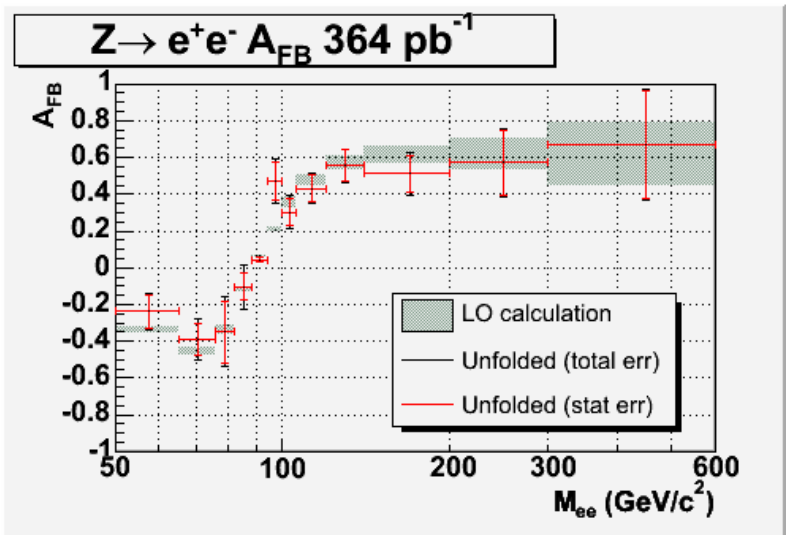


- far from Z pole, $A_{FB} \propto g_A^\ell g_A^q$ with a sign flip at pole
- near pole, $A_{FB} \propto g_V^\ell$ so nearly zero

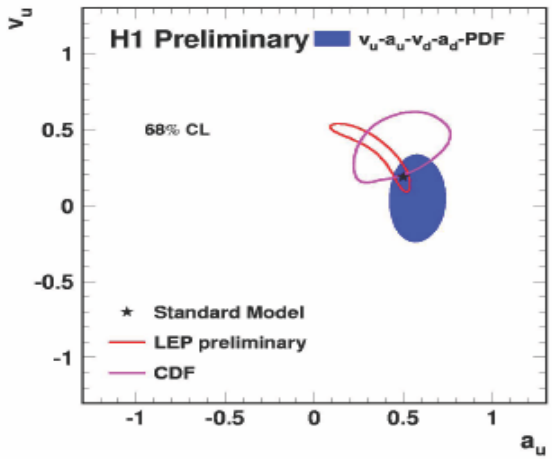
A_{FB} in Drell-Yan

- Most recent update… CDF with 350 pb^{-1} e^+e^-
  - result shown is corrected for smearing, very significant from high rate at pole to nearby bins





- one use: constrain quark-Z couplings



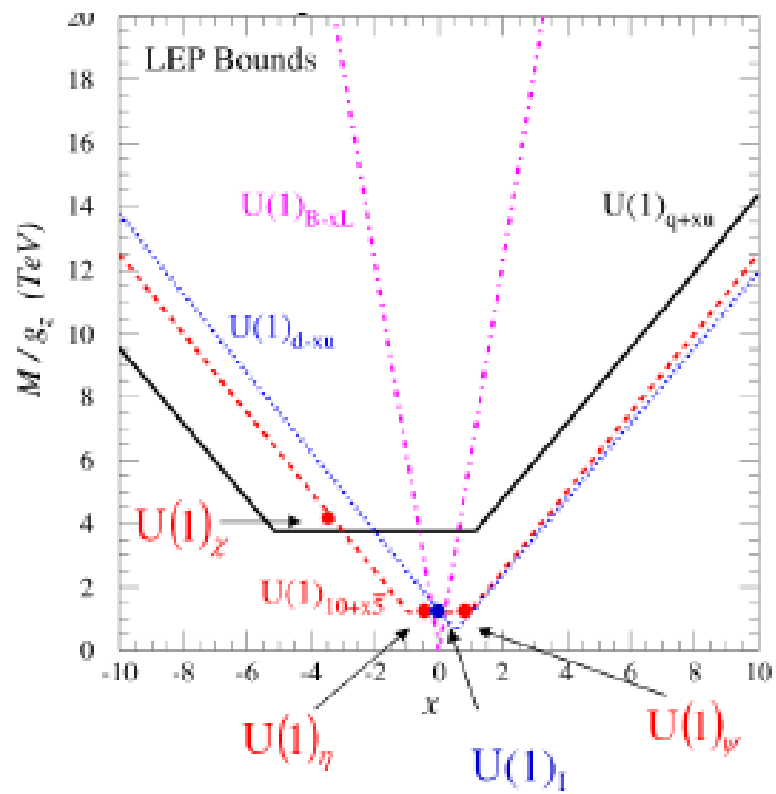
Z' Search in Drell-Yan

- another use for Drell-Yan mass spectrum and A_{FB} is to search for new gauge bosons
  - new CDF result for 448 pb^{-1}
  - no evidence in this data for new Z'
- method: generate 1000s of parameterized Z' models and look at allowed coupling strength in data
  - use generic Z' extensions of Carena, Daleo, Dobrescu Tait PRD70:093003 (2004)
  - use FCNC constraints, no Z'-Z mixing (LEP), anomaly cancellations to reduce to four classes of solutions

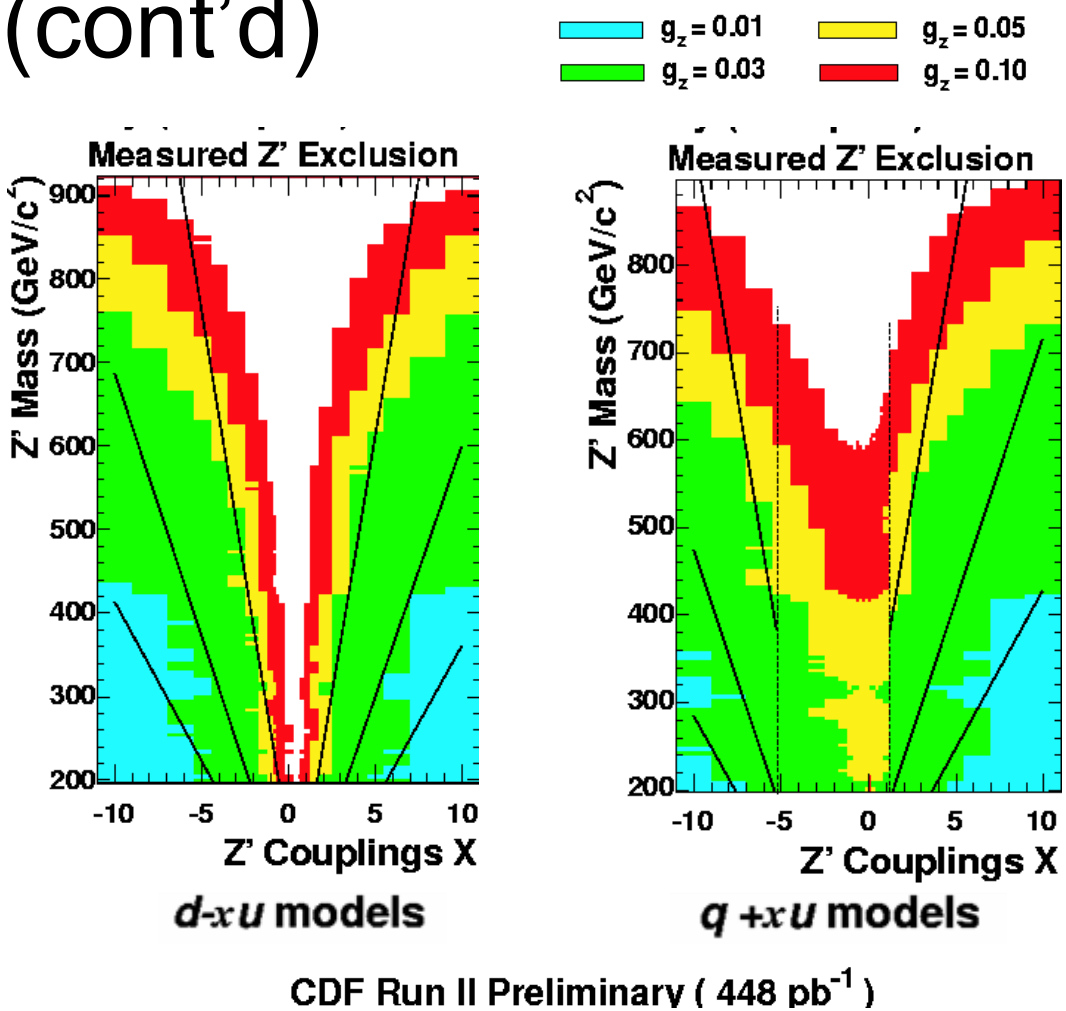
Z' Search in Drell-Yan (cont'd)

- Within each class of solution, remaining free parameters:
  - mass, $M_{Z'}$
  - one mixing, x
  - one overall coupling $g_{Z'}$

	B-xL	q+xu	10+$x\bar{5}$	d-xu
$q_L=(u_L,d_L)$	+1/3	+1/3	+1/3	0
u_R	+1/3	+x/3	-1/3	-x/3
d_R	+1/3	(2-x)/3	-x/3	+1/3
$l_L=(e_L,\nu_L)$	-x	-1	+x/3	(x-1)/3
e_R	-x	-(2+x)/3	-1/3	+x/3



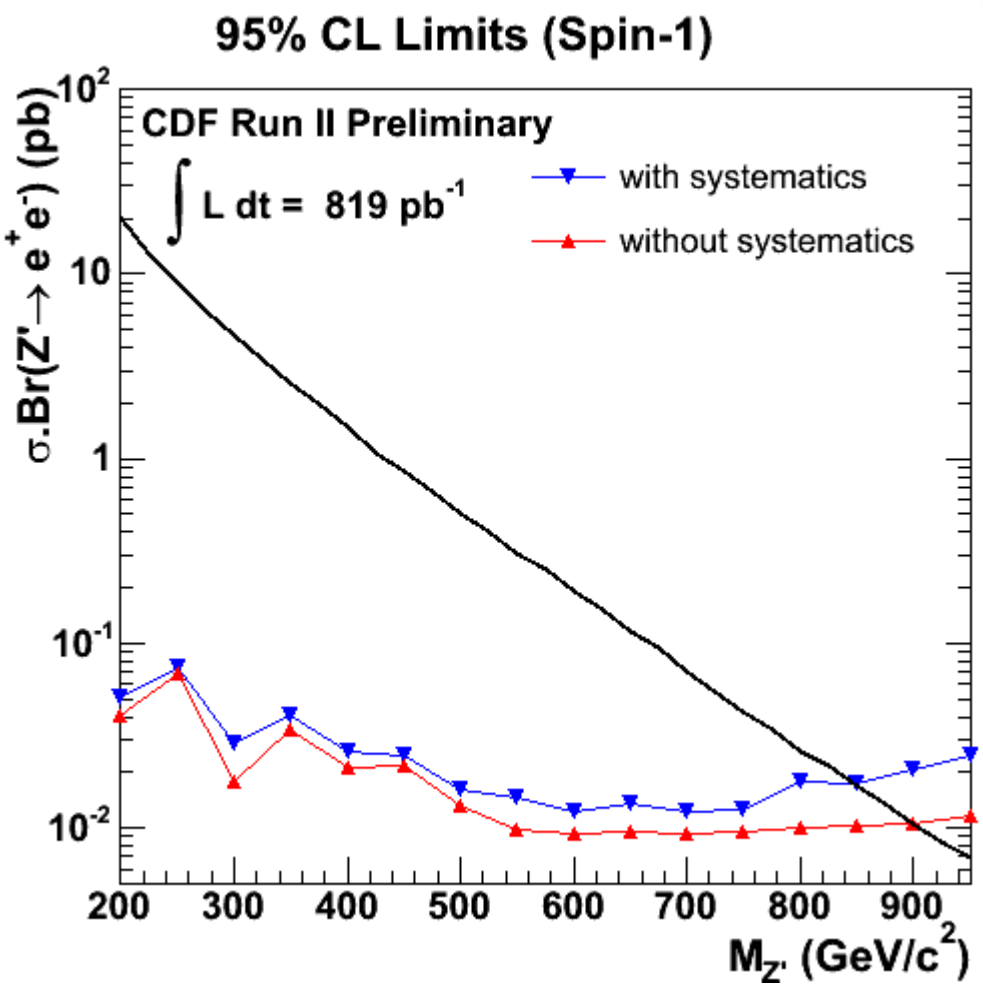
Z' Search in Drell-Yan (cont'd)



- limits shown for two model classes
- LEP2 limits for same $g_{Z'}$ shown as lines
- systematic framework for future results allows tests of new gauge bosons as models are created

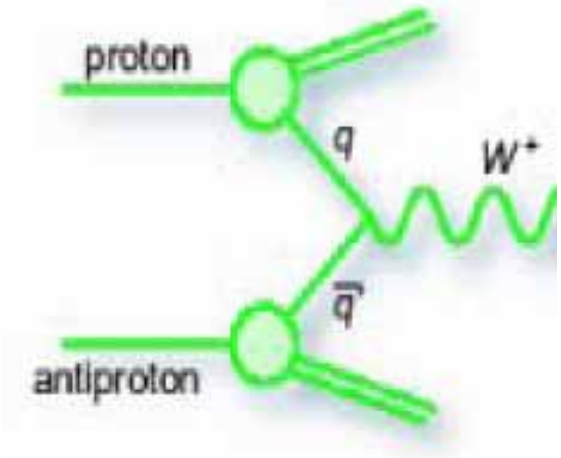
Z' Exclusion at ~1fb^{-1}

- First CDF Z' result with 819 pb^{-1}
- Only limits on Z' with same couplings as Z



W Charge Asymmetry

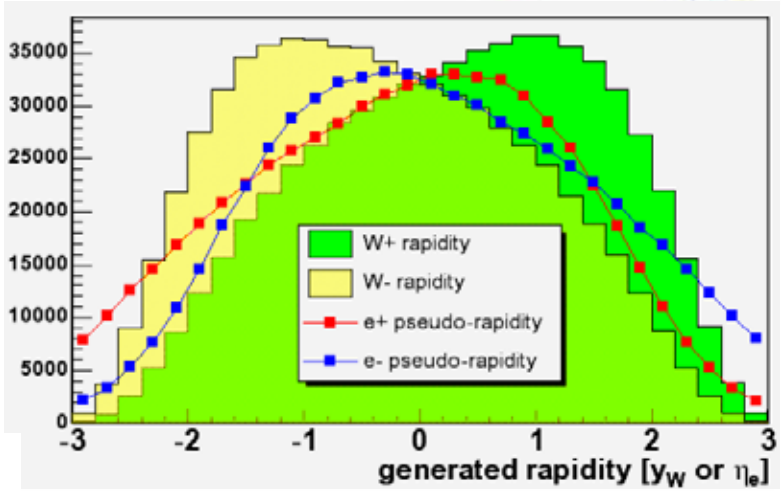
- $W^{+(-)}$ produced from
  - u(d) quark from proton
  - d(u) anti-quark from antiproton
- Since each u quark carries proton momentum than each d quark
  - forward (backward) $W^{+(-)}$ are more copious than $W^{-(+)}$

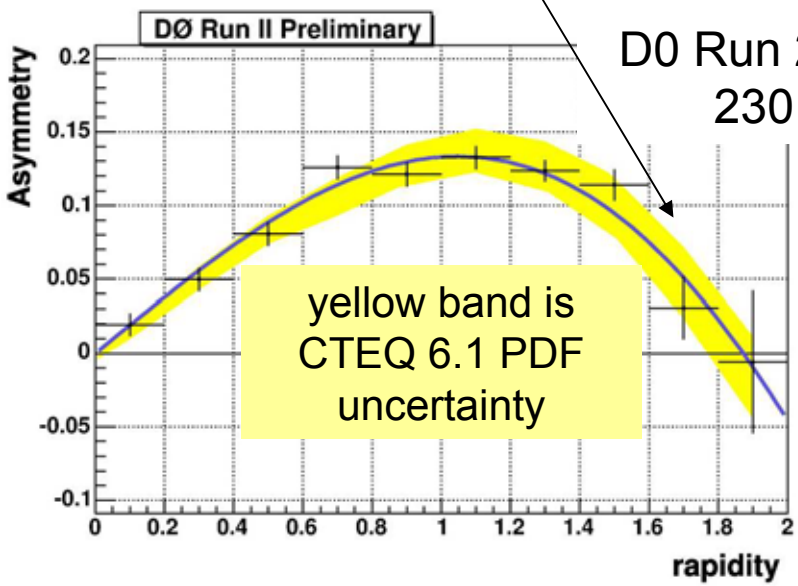


$$\frac{\frac{d\sigma_+}{dy}-\frac{d\sigma_-}{dy}}{\frac{d\sigma_+}{dy}+\frac{d\sigma_-}{dy}} \approx \frac{u\left(\frac{M_W}{\sqrt{s}}e^{+y}\right)d\left(\frac{M_W}{\sqrt{s}}e^{-y}\right)-d\left(\frac{M_W}{\sqrt{s}}e^{+y}\right)u\left(\frac{M_W}{\sqrt{s}}e^{-y}\right)}{u\left(\frac{M_W}{\sqrt{s}}e^{+y}\right)d\left(\frac{M_W}{\sqrt{s}}e^{-y}\right)+d\left(\frac{M_W}{\sqrt{s}}e^{+y}\right)u\left(\frac{M_W}{\sqrt{s}}e^{-y}\right)} \approx F\left(\frac{d\left(\frac{M_W}{\sqrt{s}}e^{|y|}\right)}{u\left(\frac{M_W}{\sqrt{s}}e^{|y|}\right)}\right)$$

W Charge Asymmetry

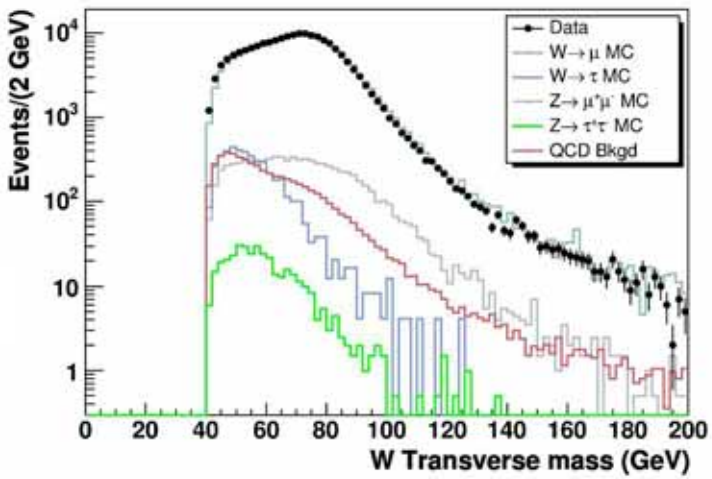
- Current method: look at lepton pseudorapidity
  - positive (negative) lepton boosted backward (forward) by V-A structure of W decay





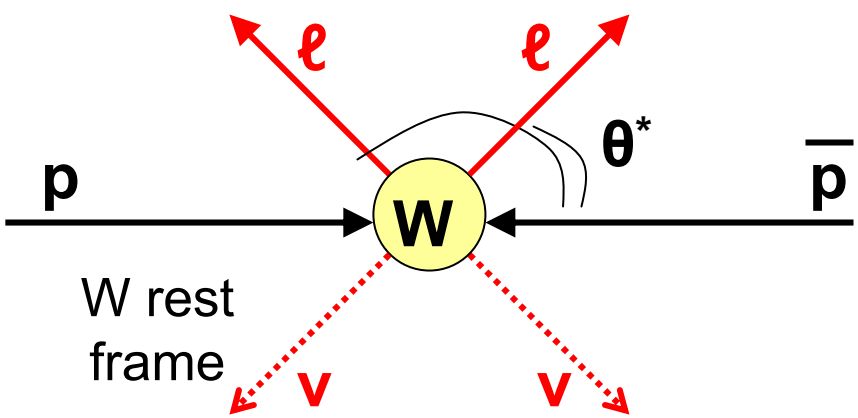
D0 Run 2 Prelim.
230 pb^{-1}

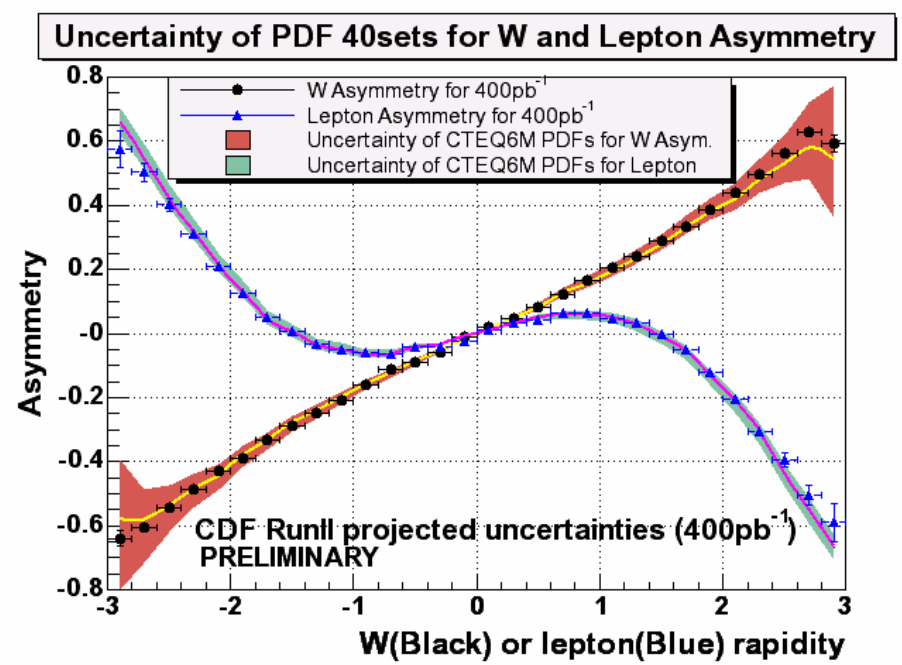
W→μν



W Charge Asymmetry (New Technique)

- Alternatively, can reconstruct W rapidity directly
  - unknown neutrino momentum along beam
    → 2 solutions for y_W, one favored by decay θ^*

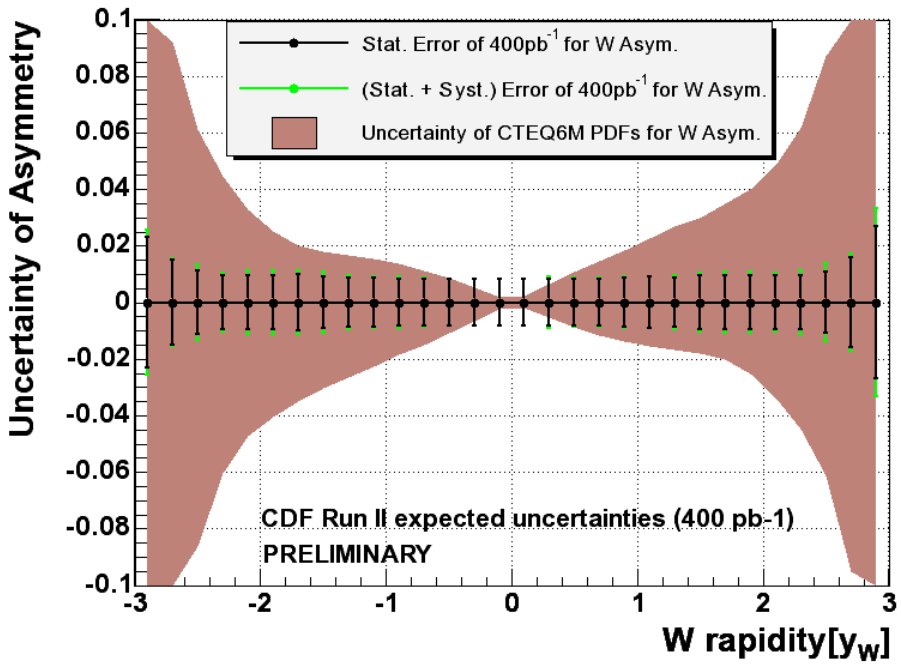




- Better sensitivity to d/u
- But smearing from two solutions, neutrino E_T res.

W Charge Asymmetry (New Technique, cont'd)

- Even with smearing, expected sensitivity is limited by statistical uncertainties (400 pb^{-1})
  - first result (CDF) expected by summer

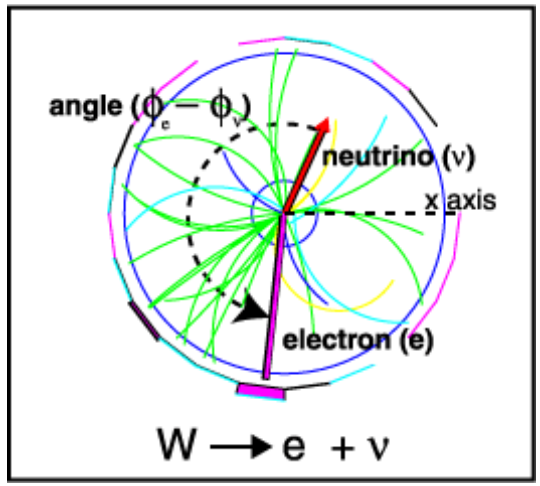


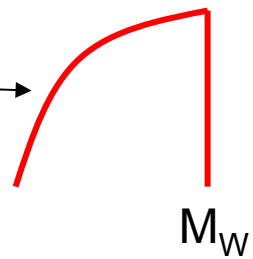
W Boson Width

- What does the W boson width measure?
  - $\Gamma(W \to \ell\nu)$ is one of the "input" to SM fits (G_F from τ_μ)
  - but if $\Gamma(W \to qq)$ is different, it would affect Γ_W
- No W resonance to be observed in $W \to \ell\nu$
  - and $W \to jj$ cannot be isolated
- Reconstruct transverse mass
  - E_T of electron or muon
  - missing E_T from neutrino (unknown p_z^ν)

$$M_T^{\,2} = 2E_T^{\ell}E_T^{\nu}\left(1-\cos\left(\phi_e-\phi_\nu\right)\right)$$

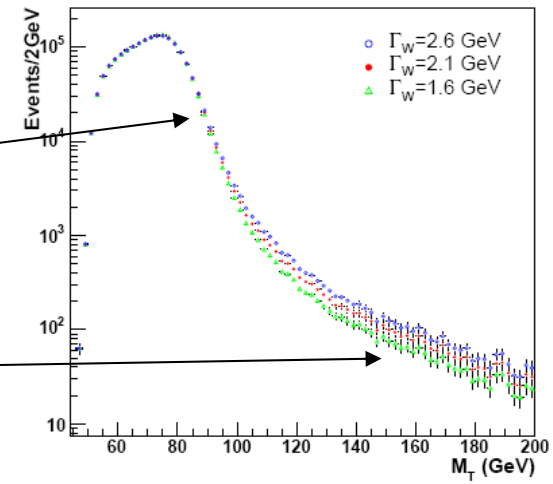
  - with perfect reconstruction, get Jacobian edge at M_W

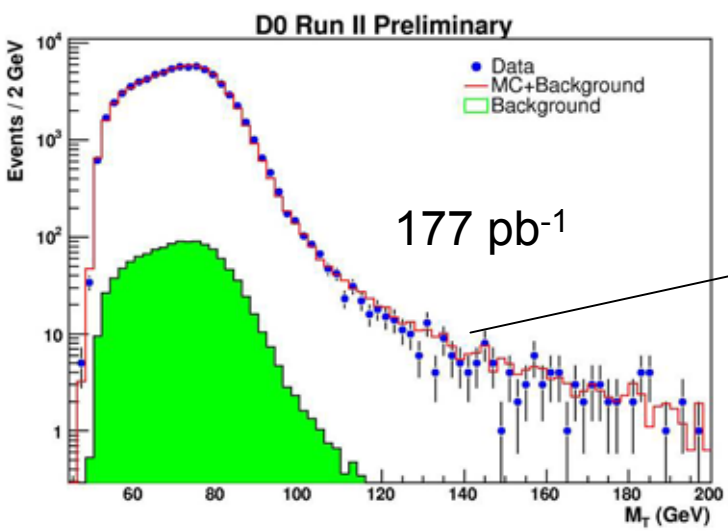


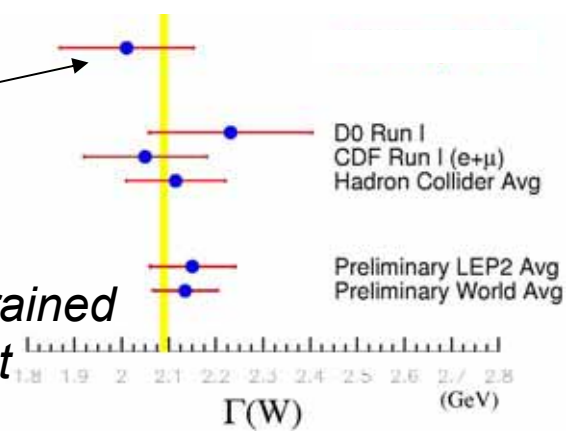


W Boson Direct Width

- High side tail of transverse mass results from
  - detector resolution
  - inherent W width which dominates the largest M_T



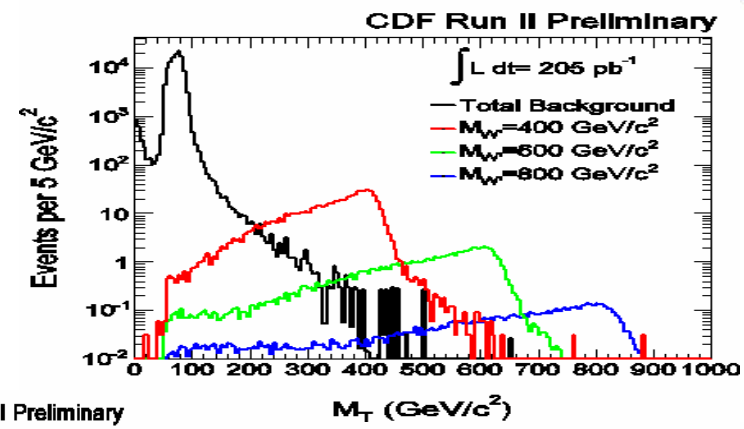




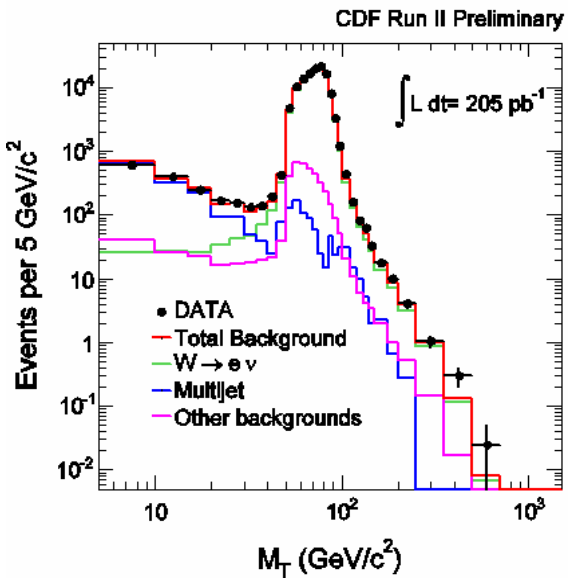
largest systematic uncertainties are constrained by Z→ℓℓ data, so expect improvements to come!

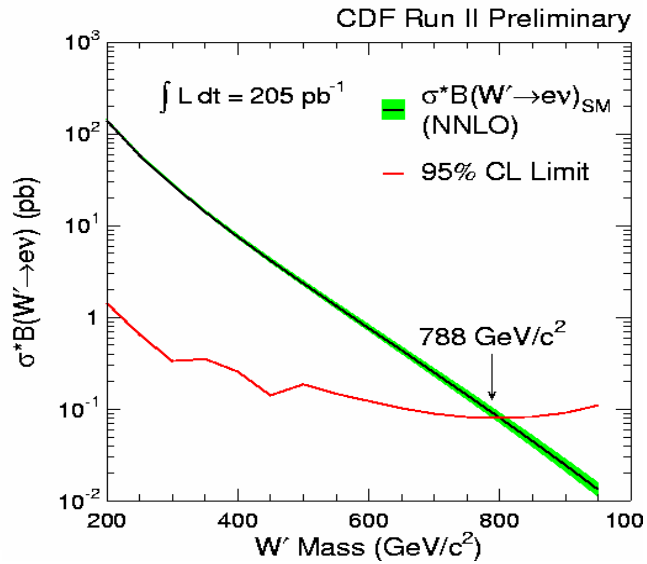
W' Search

- Same M_T measurement gives access to $W' \rightarrow \ell\nu$
- No evidence for W', can set limits on σxBR in range of 0.1-1.0pb from 205pb^{-1}



Boson Wu, under 14 table tennis champion





W Indirect Width

- Can also get at W width *indirectly*

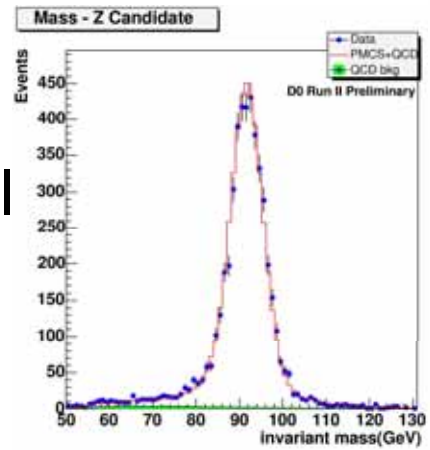
$$R = \frac{\sigma_W \times BR(W \to \ell\nu)}{\sigma_Z \times BR(Z \to \ell\ell)} = \frac{\sigma_W}{\sigma_Z}\,\frac{\Gamma_Z}{\Gamma_{Z\to\ell\ell}}\,\frac{\Gamma_{W\to\ell\nu}}{\Gamma_W}$$

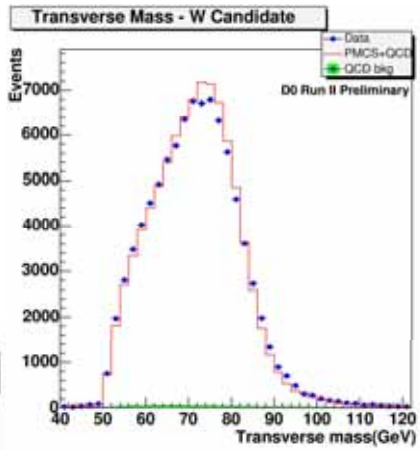
from "G_F" SM input 226.4±0.3 MeV

NNLO calculation 3.361±0.024

LEP R_ℓ gives 29.71±0.02

- Luminosity cancels in ratio
- Some common efficiencies and acceptances also cancel





D0 W→ev, Z→ee, 177pb^{-1}

W Indirect Width

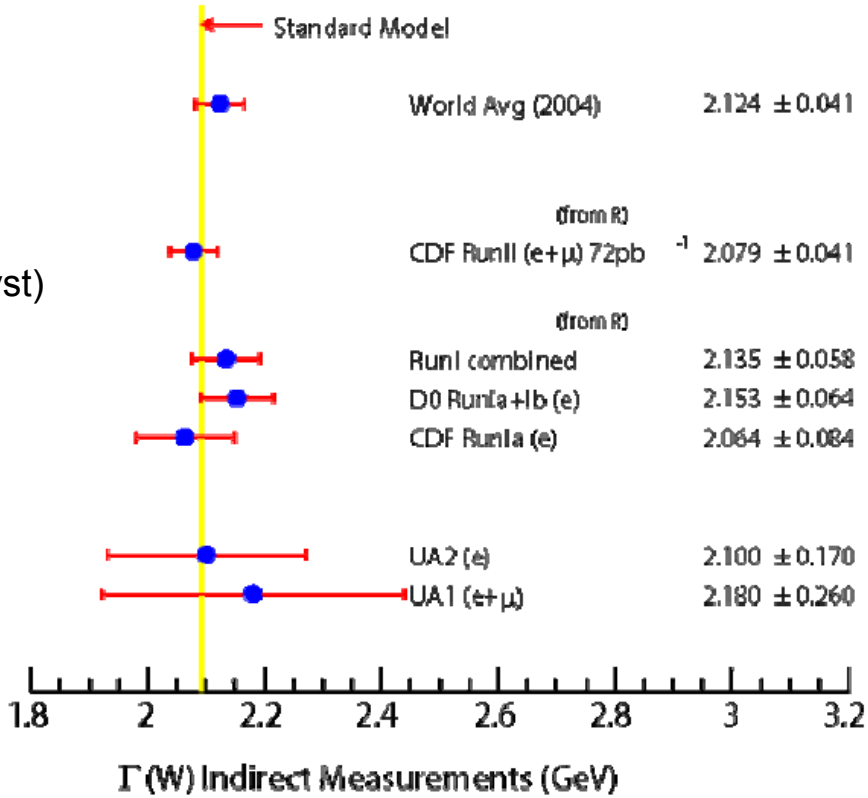
D0 Preliminary:

R(e)=10.82 ±0.16(stat)
±0.25(syst) ±0.13 (PDF)

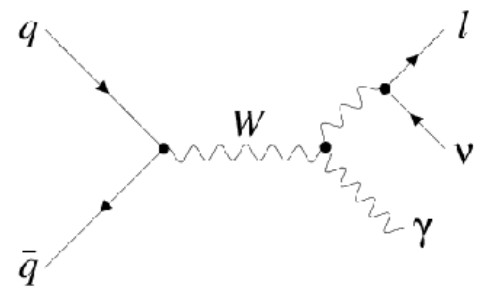
CDF PRL 94 091803 (2005)

R(e/μ)=10.92 ±0.15(stat) ±0.14(syst)

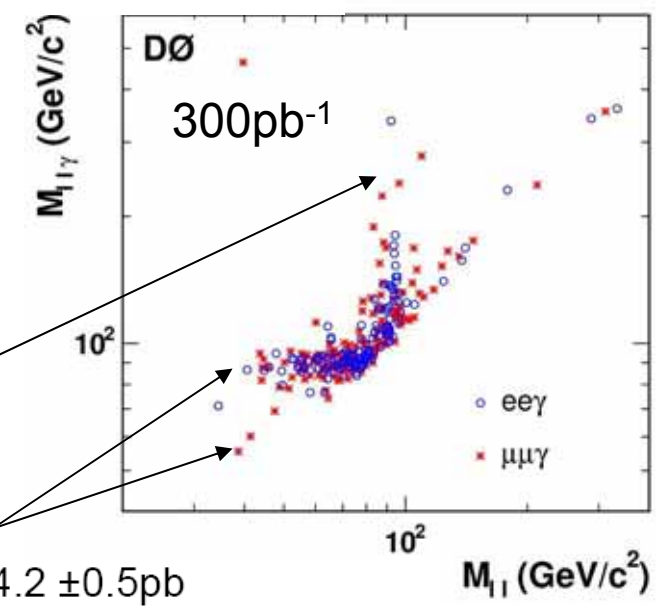
- Beginning to be a very interesting test… 2%
- Future:
  - New CDF method to reduce systematics, identify only one lepton and use missing E_T to separate W/Z



Diboson (W/Z+γ)



- Wγ and Zγ final states have large contributions from WWγ, ZZγ and Zγγ vertices
- Deviations from expectation could be a sign of new physics in boson couplings…
- Also have contributions from
  - *quark initial state radiation*
  - *final state radiation in boson decay*



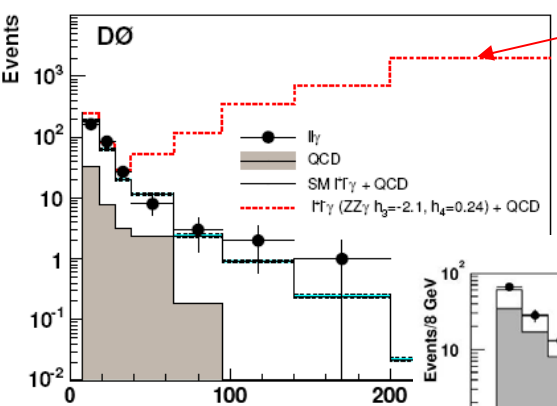
$\sigma(ll\gamma) = 4.2 \pm 0.5$pb

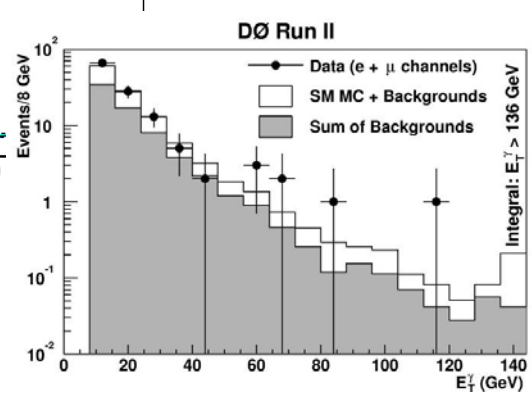
SM Prediction: 3.9 ±0.2 pb

$E_T(\gamma) > 8$ GeV, $\Delta R_{l\gamma} > 0.7$, $M_{ll} > 40$ GeV

Diboson (W/Z+γ) (cont'd)

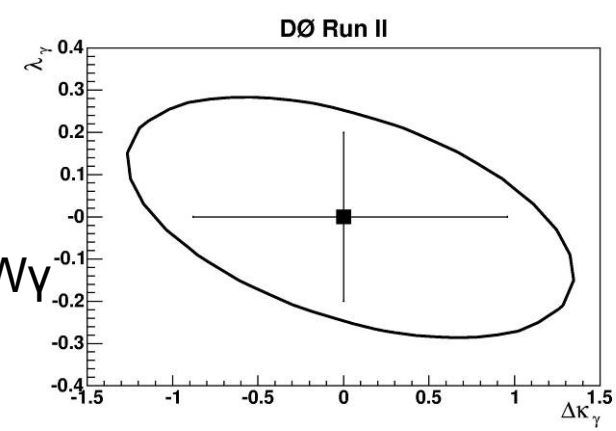
- Analysis postulates anomalous couplings in the WWγ, ZZγ and Zγγ vertices
  - Look for allowed new terms in Lagrangian (classified by CP)
  - These new interactions are taken as effective theories which are cut off at scale Λ~1-2 TeV (above the sensitivity of the data)





Wγ data

limits on CP conserving WWγ couplings

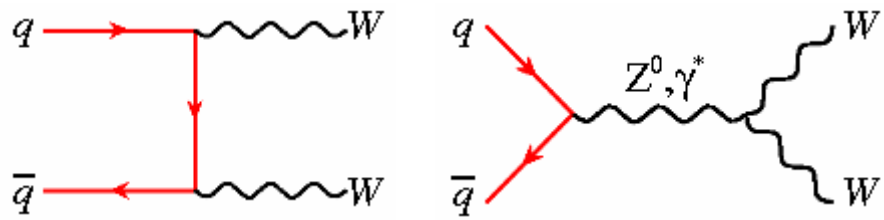


$\sigma(W\gamma) = 14.8 \pm 1.6_{(stat)} \pm 1.0_{(sys)} \pm 1.0_{(lum)}$

SM Prediction: 16.0 ±0.4 pb

Diboson (WW)

- Study WWZ and WWγ couplings w/ WW, WZ final states
- WW: expect t-channel to dominate (90%)
  - two leptons, missing E_T
  - backgrounds from Drell-Yan, W+fakes, other diboson states

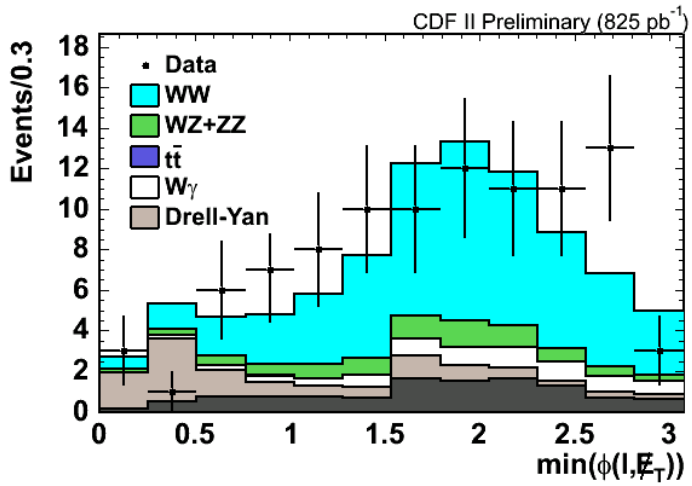


Mode	ll
WW	$52.4 \pm 0.1 \pm 4.3$
Drell-Yan	$11.8 \pm 0.8 \pm 3.1$
$t\bar{t}$	$0.2 \pm 0.0 \pm 0.0$
$WZ + ZZ$	$7.9 \pm 0.0 \pm 0.8$
$W\gamma$	$6.8 \pm 0.2 \pm 1.4$
W+jets	$11.0 \pm 0.5 \pm 3.2$
Sum Bkg	$37.8 \pm 0.9 \pm 4.7$
Expected	$90.2 \pm 0.9 \pm 6.4$
Data	95

CDF 825pb^{-1}:

σ(WW)=
13.6 pb ±2.3(stat)
±1.6(syst) ±1.2(lum)

(expect 12.4 ±0.8)



Diboson (WZ)

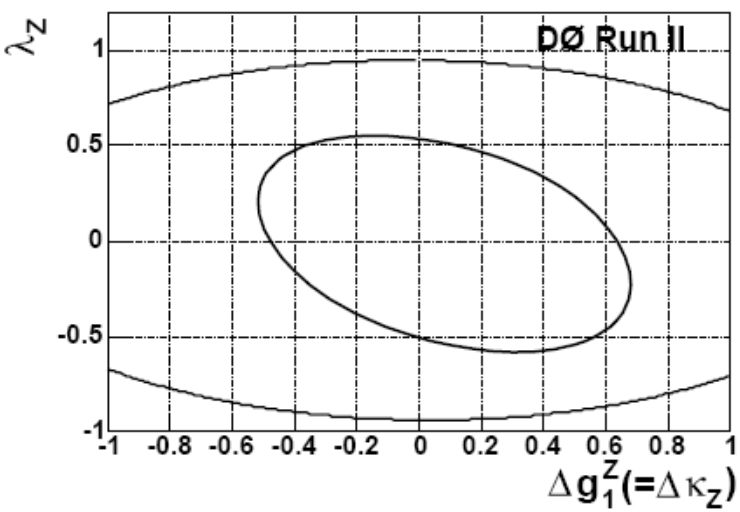
- WZ:
  - three leptons, missing E_T
  - backgrounds from Z+fakes, other diboson

Signal:

WZ:	3.72 ± 0.02 (stat.) ± 0.15 (syst.)

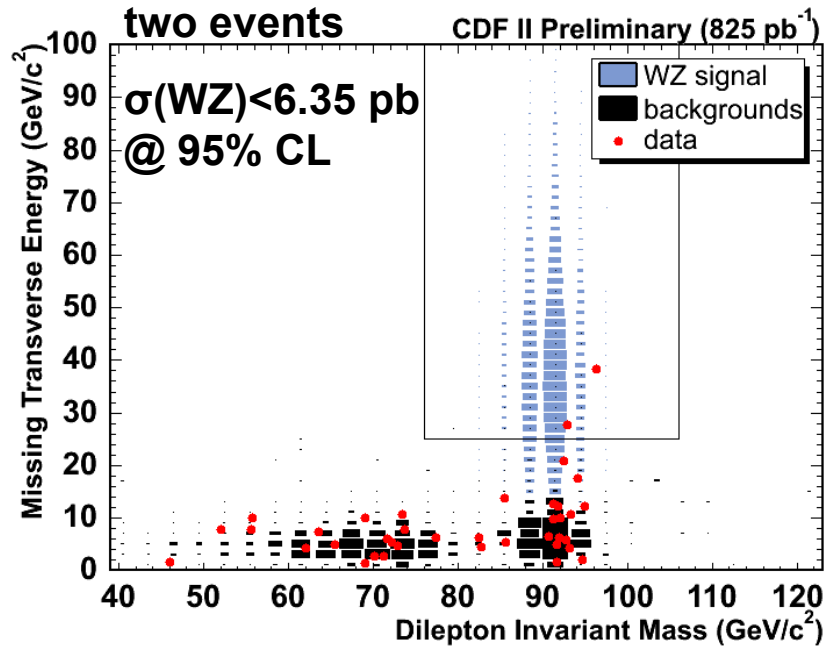
Backgrounds:

ZZ:	0.50 ± 0.01 (stat.) ± 0.05 (syst.)
$Z\gamma$:	0.03 ± 0.01 (stat.) ± 0.01 (syst.)
$t\bar{t}$:	0.05 ± 0.01 (stat.) ± 0.01 (syst.)
Z+jets:	0.34 ± 0.07 (stat.) $^{+0.15}_{-0.09}$ (syst.)
Total:	0.92 ± 0.07 (stat.) $^{+0.16}_{-0.10}$ (syst.)



D0 300pb^{-1}, coupling limits

CDF 825pb^{-1}
two events

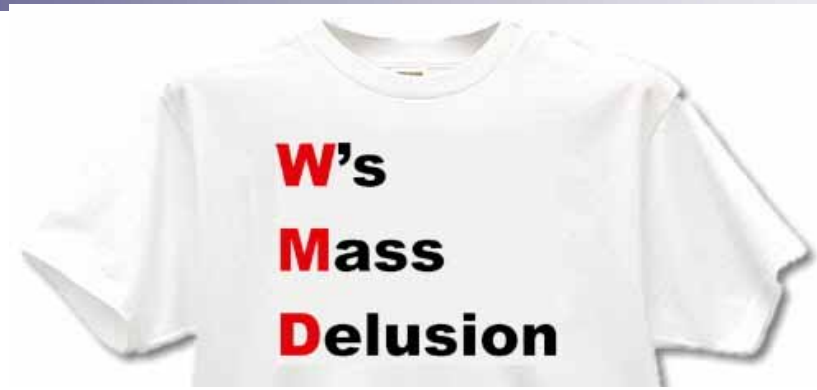


Tevatron Prospects

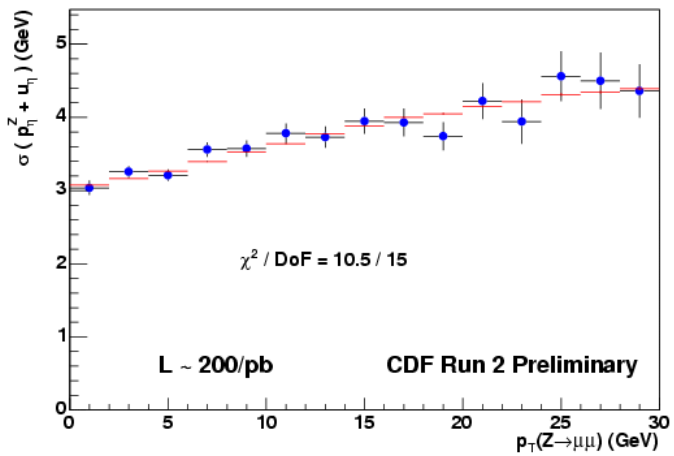
Improvements with luminosity

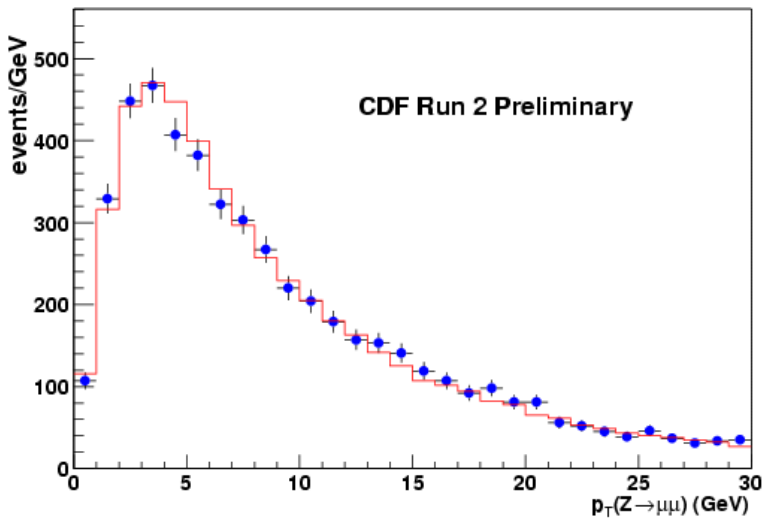
- WW, WZ, ZZ studies will continue to improve linearly with luminosity
- Single boson cross-sections unlikely to improve in precision
  - but ratio analyses (e.g., $R_{e/\mu}$ or asymmetries) will continue to improve

W Mass



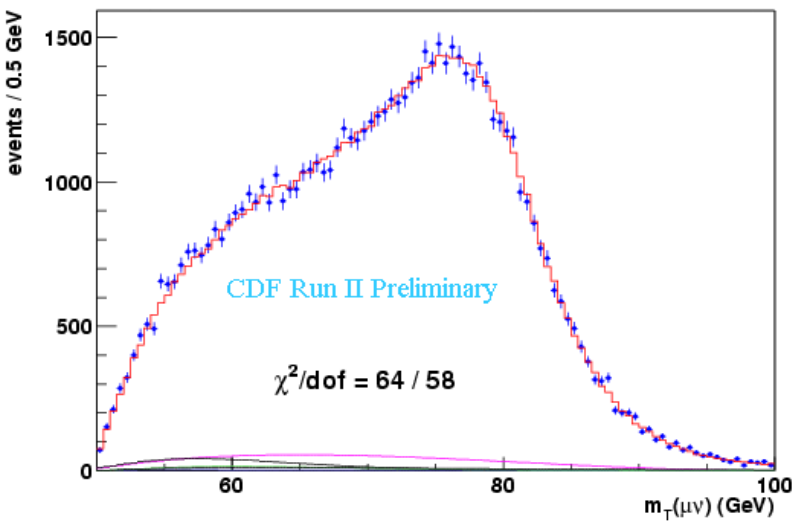
- The challenge of the W mass at the Tevatron is that analysis is difficult, not a lack of luminosity
- In fact, many systematic uncertainties reduced with luminosity
  - example: Z p_T distribution to test recoil

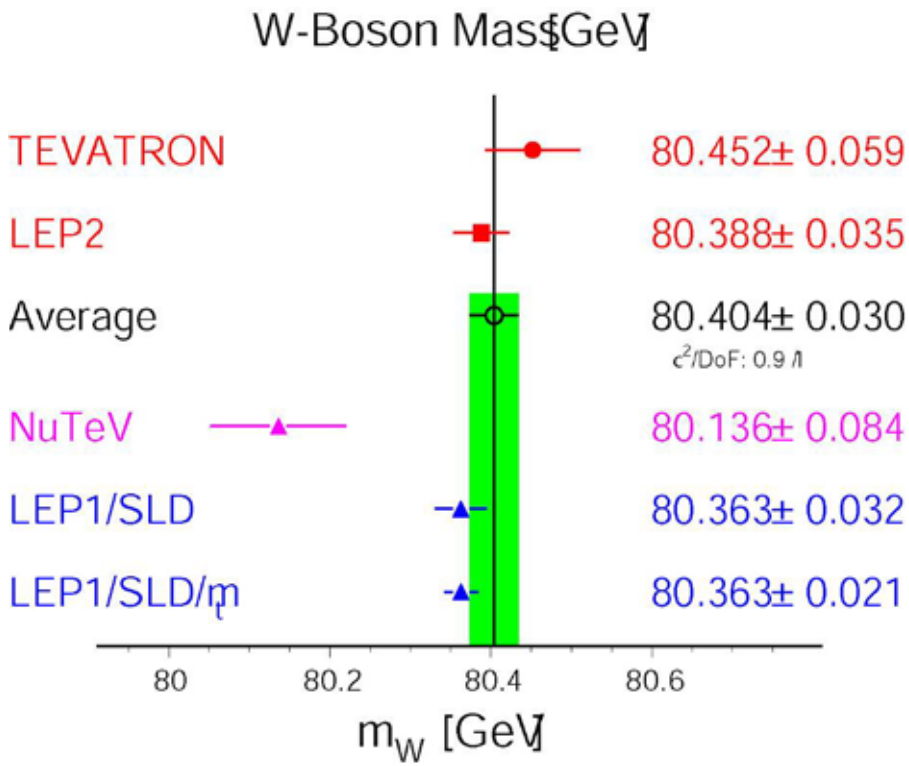




W Mass

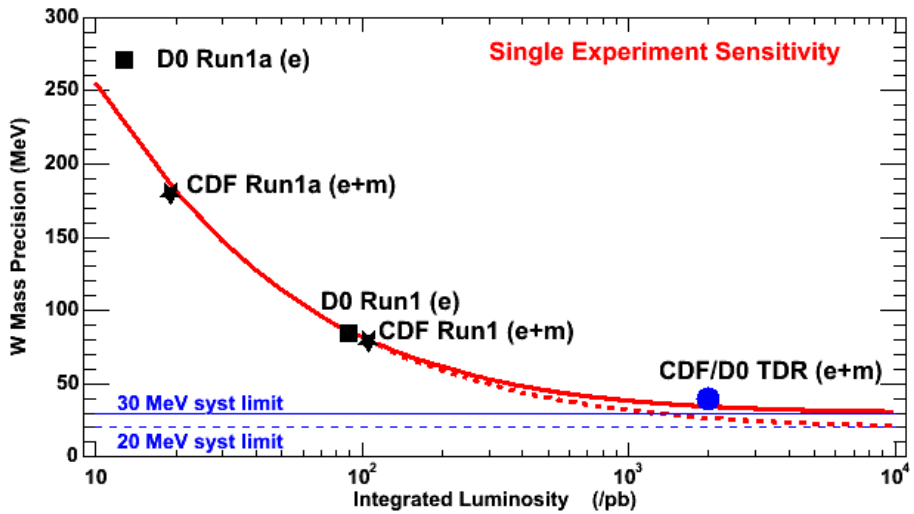
- Large data samples are in hand with statistical errors low enough to
  improve over LEP2





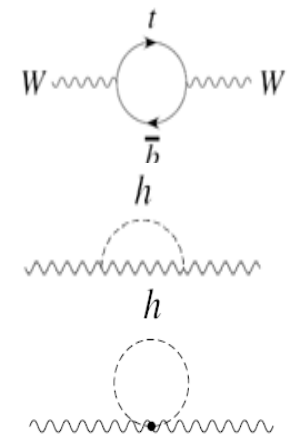
Run 2 Projected Uncertainties

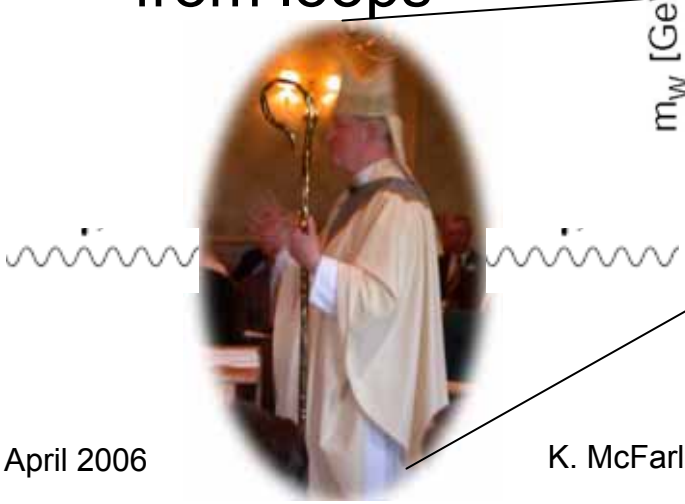
- Extrapolated from Run Ib measurement
- Uncertainties likely to scale with luminosity:
  - Statistical uncertainties
  - Energy and momentum scale, Hadron Recoil against W
- Uncertainties which may not be reduced with increased luminosity:
  - W production and decay: PDFs, d(sigma_W)/d(Pt), higher order QCD/QED
  - Expected these between 20-30 MeV

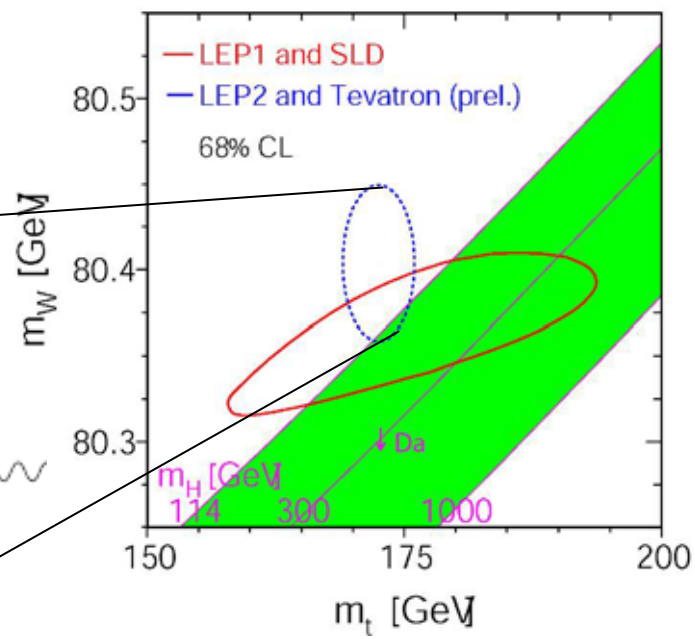


Higgs: Loops vs. Physical Mass

- Ultimate goal:
  - find Higgs at Tevatron if we are lucky
  - if not, discovery at LHC
  - compare mass to prediction from loops







Conclusions

- *Tevatron making important contributions to studies of electroweak unification*
  - single boson asymmetries and differential distributions to study components of proton
    - new studies and new techniques
  - new gauge boson searches and tests of gauge boson couplings
    - will benefit from increased luminosity
  - data to significantly improve W mass is in hand
- *in next several years, except these analyses to be updated with 4-20x more data than shown!*