Electroweak Measurements at the Tevatron

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Workshop on Monte Carlo Generator Physics

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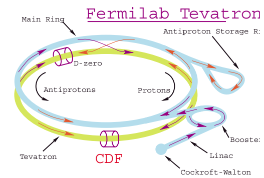
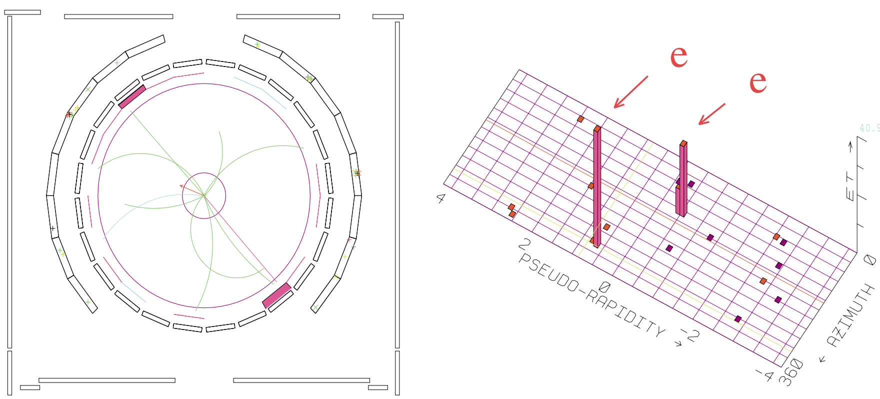
Fermilab

W and Z Events at the Tevatron

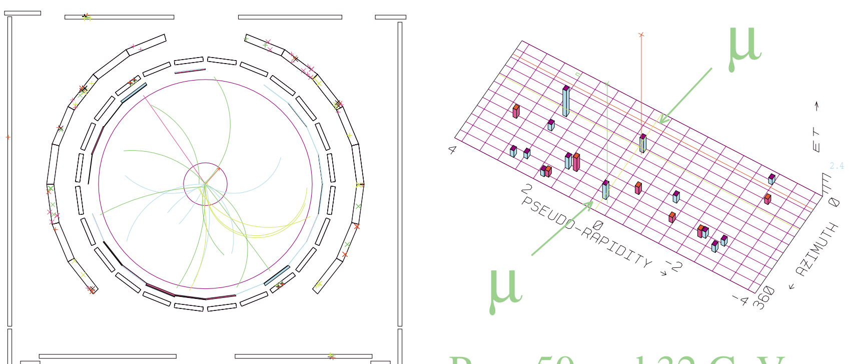


- Easy to find using leptons
- Clear signatures
- Large p_T kick
- Low backgrounds

$Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ Events CDF

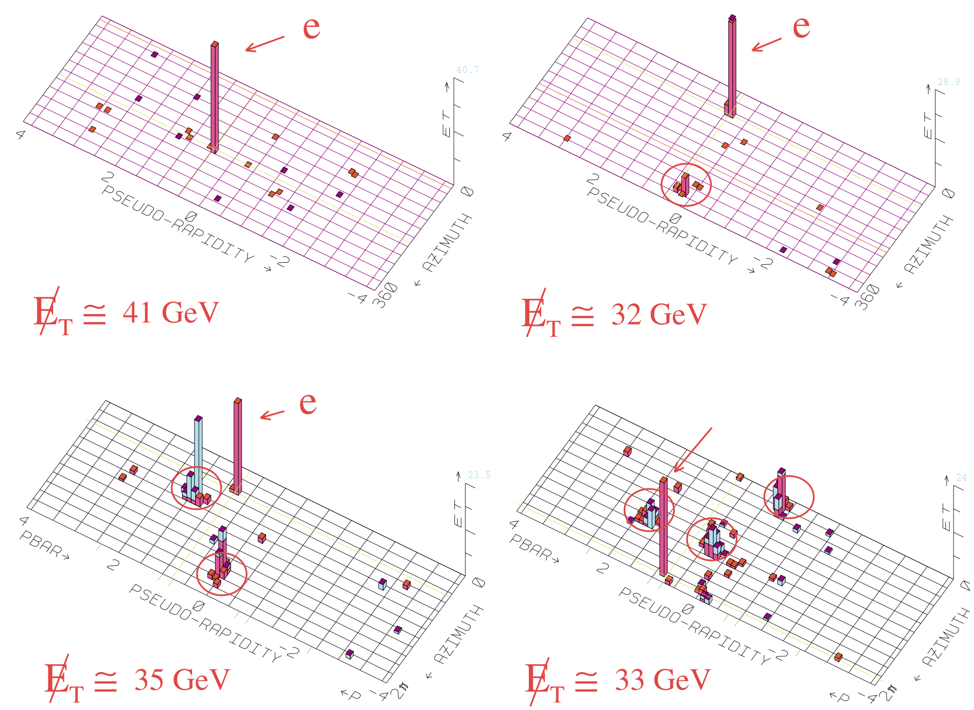


$E_T \cong 44$ and 36 GeV



$P_T \cong 50$ and 32 GeV

W + 0,1,2,3 jet(s) Events CDF



$\not{E}_T \cong 41$ GeV

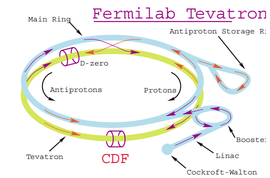
$\not{E}_T \cong 32$ GeV

$\not{E}_T \cong 35$ GeV

$\not{E}_T \cong 33$ GeV

(use missing E_T to find kinematics of neutrino)

Tevatron Electroweak Physics Topics:



(Partial list from Run I...)

- W, Z cross sections
- Drell-Yan cross section, A_{FB}
- W, Z + jet production
- p_T distributions
- W production asymmetry
- W decay angular distribution

- W mass
- W width (direct and indirect)

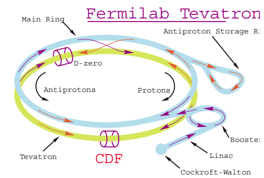
- $W \to \tau \nu$
- $Z \to b\bar{b}$
- Rare decays

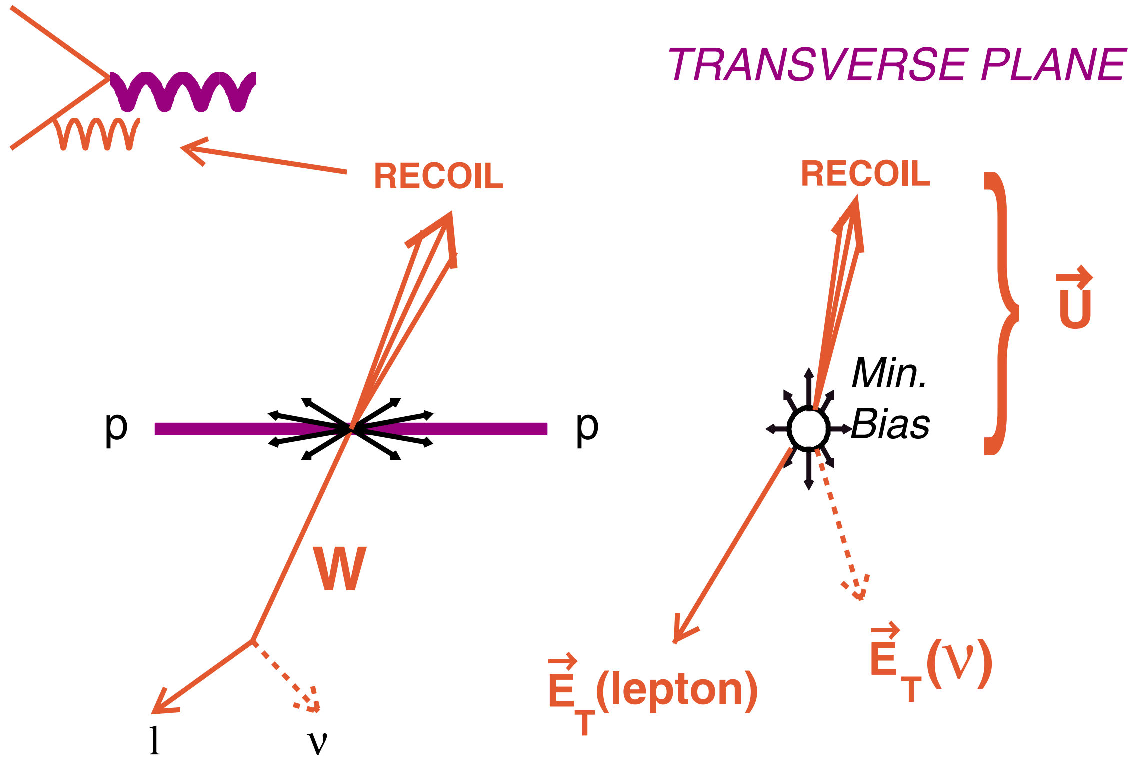
- Diboson physics
- $WW\gamma$ couplings
- WWZ couplings
- $Z\gamma\gamma$ couplings
- $ZZ\gamma$ couplings

(Could be a talk by themselves!! Save for later...)

Concentrate on results that fit this discussion...

Physics of W, Z production in Hadron Collisions



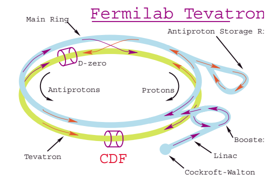


W, Z decay products not produced at rest either along or transverse to the beam in hadron collisions. Need to account for the energy in the underlying event due to spectators, multiple interactions, and recoil... ⇒ Requires model and detailed understanding of response of detector at low energies!!

Lose longitudinal energy down the beam pipe ⇒ measure transverse quantities

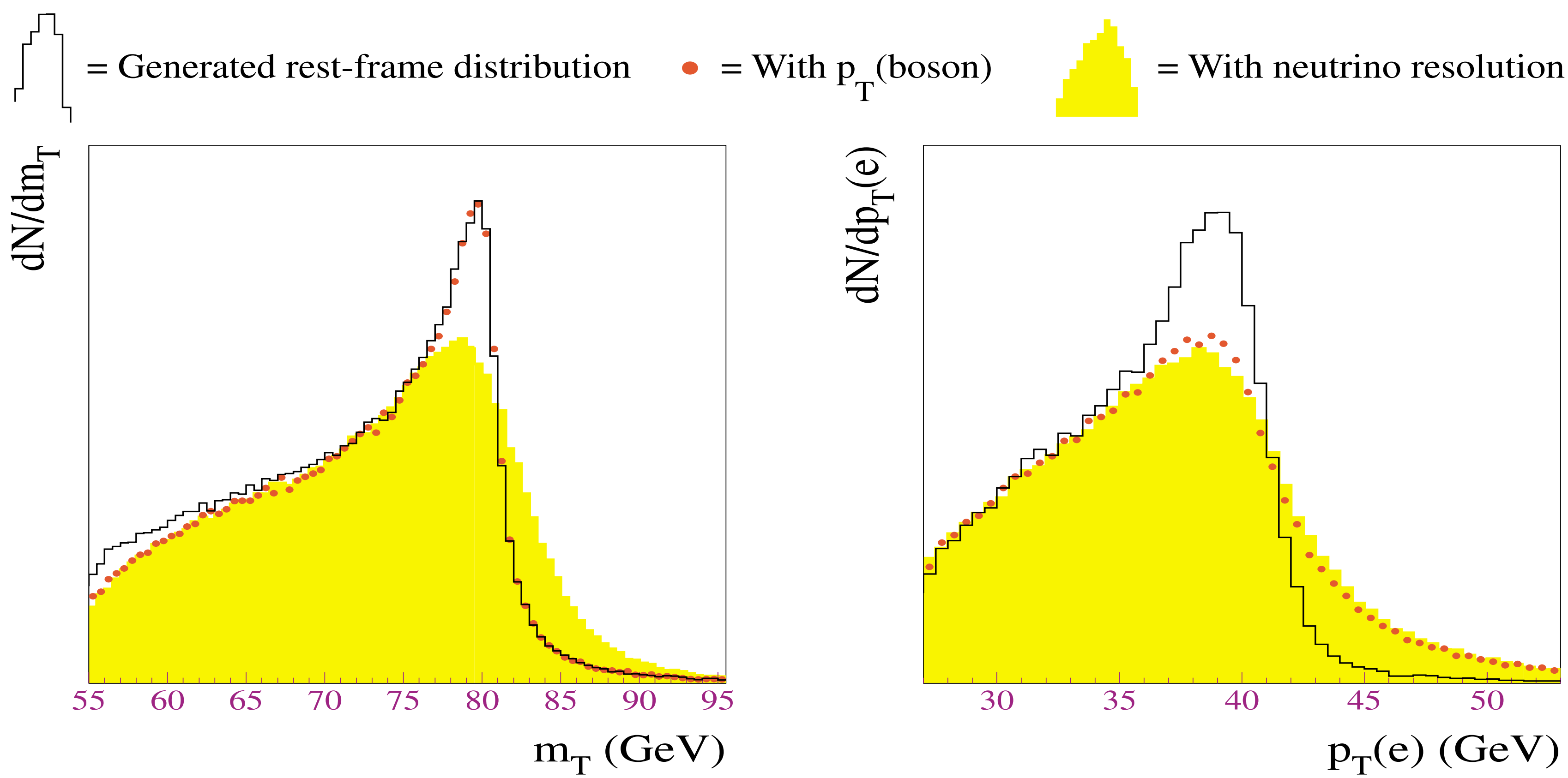
$$(p_T\ ,\ \ M_T = \sqrt{(2E_T^{e}E_T^{\nu}(1\text{-}\cos\phi^{e\nu}))}\ )$$

Measuring W, Z production in Hadron Collisions

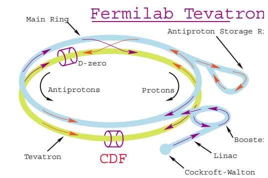


The W or Z of interest acquires a kick during production from recoil. This does not alter the transverse mass distribution appreciably, but affects other distributions, e.g. the p_T of the observed leptons. *Note these effects are very different from each other!!*

Neutrino resolution from detector effects, min. bias resolution, etc. further obscures original boson production properties.



Tevatron Event Yields: Past and Future

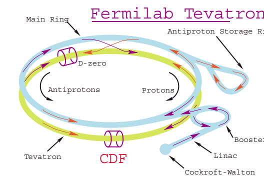


Per Experiment -- CDF and D-Zero

Channel	Run I (100 pb^{-1})	Run IIa (2 fb^{-1})	Run IIb (20 fb^{-1})
$W \to e\nu$	60,000	1,000,000	10,000,000
$W \to \mu\nu$	40,000	600,000	6,000,000
$Z \to ee$	6,000	160,000	1,600,000
$Z \to \mu\mu$	4,000	50,000	500,000
$Z \to b\bar{b}$	90	45,000	450,000

(More later...)

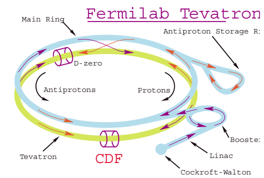
Tevatron Event Yields: Past and Future



Implications:

$W \rightarrow e\nu$	Provides luminosity calibration, cross-checks
$W \rightarrow \mu\nu$	Luminosity cross-check, tracking calibrations
$Z \rightarrow ee$	Enough data for detailed EM calorimeter studies
$Z \rightarrow \mu\mu$	Tracking and EM/Had calorimeter cross-calibration
$Z \rightarrow b\bar{b}$	Finally!! A resonance with a hadronic final state to set jet energy scale, calibrate Had calorimeter, etc. (Requires silicon-based trigger to work…)

Program for Tevatron Electroweak Precision Measurements

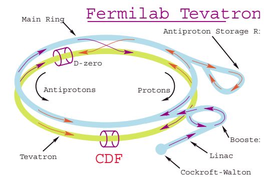


(1) Understand the *physics* of vector boson production and QCD corrections in hadron collider environment.

(2) Understand the response of the *detectors* including backgrounds, calibrations, luminosity, resolution, systematic uncertainties, & possible biases.

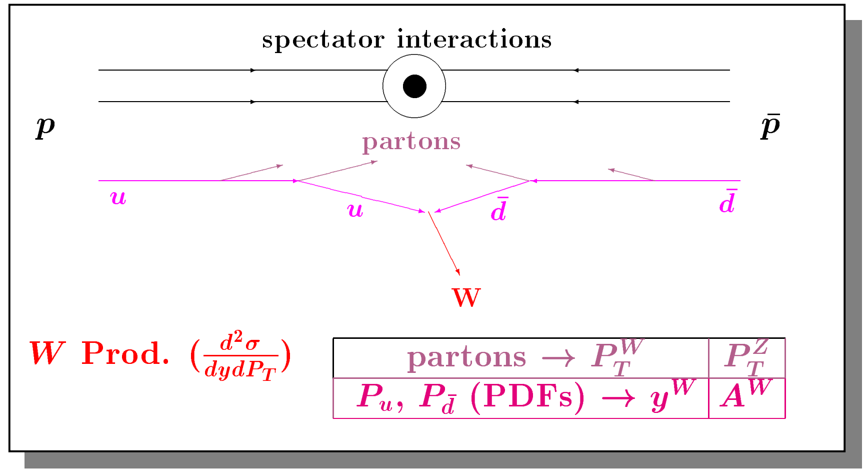
(3) Perform *fits* to MC templates to extract electroweak quantities (W mass, W width, p_T distributions, etc.)

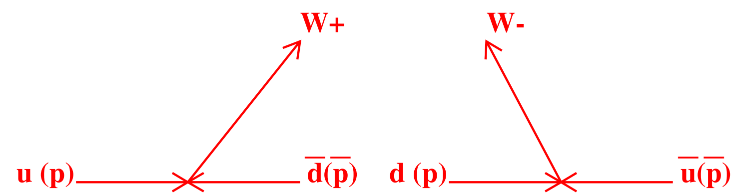
Results



Basic Ingredients (Parton Level)

- W's, Z's primarily produced through $q\bar{q}$ annihilation ($u\bar{d} \rightarrow W^+$, $\bar{u}d \rightarrow W^-$)
- Valence-sea (55 - 60%) interactions dominate over sea-sea (20%) and other contributions
- Parton Distribution Functions (PDFs) control probability for finding quarks at particular kinematics
- Excess of u(x) over d(x) means W^+ preferentially boosted along proton direction (and vice versa for W^-)





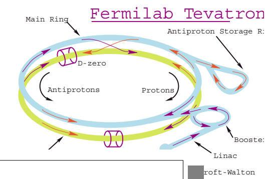
- Basic calculation for lowest-order process ($q\bar{q}' \rightarrow W \rightarrow e\,\nu$) :

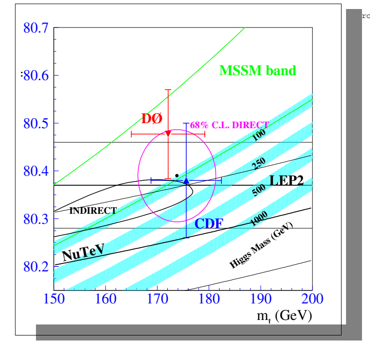
$$\hat{\sigma}_{ij} = \frac{1}{3}\frac{|V_{ij}|^2}{3\pi}\left(\frac{G_F M_W^2}{\sqrt{2}}\right)\frac{\hat{s}}{(\hat{s}-M_W^2)^2 + (\hat{s}\,\Gamma_W / M_W^2)^2}$$

(Breit-Wigner with quadratic dependence in magnitude on boson mass)

- Resummation methods used to provide non-perturbative component to match low-p_T region into parton-level calculation (Ladinsky-Yuan, Ellis).

Connections between W,Z Production, QCD and New Physics





W boson mass + top quark mass: Constrain Higgs mass

Need precise model of W production and decay for Monte Carlos

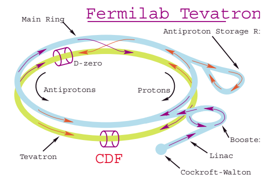
W mass measurements require low P_T^W

NLO QCD

Resummation techniques

Non-perturbative QCD

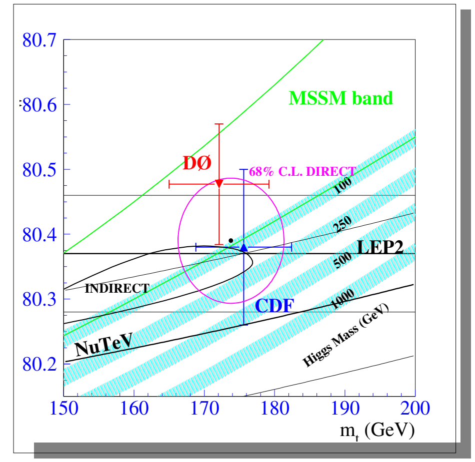
Connections between W,Z Production, QCD and New Physics



W boson mass + top quark mass: Constrain Higgs mass

Current CDF/DØ δM_W ~ 5-9 MeV from P_T^W model

δM_W = 10 MeV => $\delta M_H/M_H$ = 14%



W production Monte Carlos tuned to Z data

NLO QCD

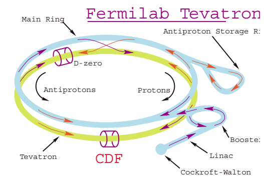
Non-perturbative QCD

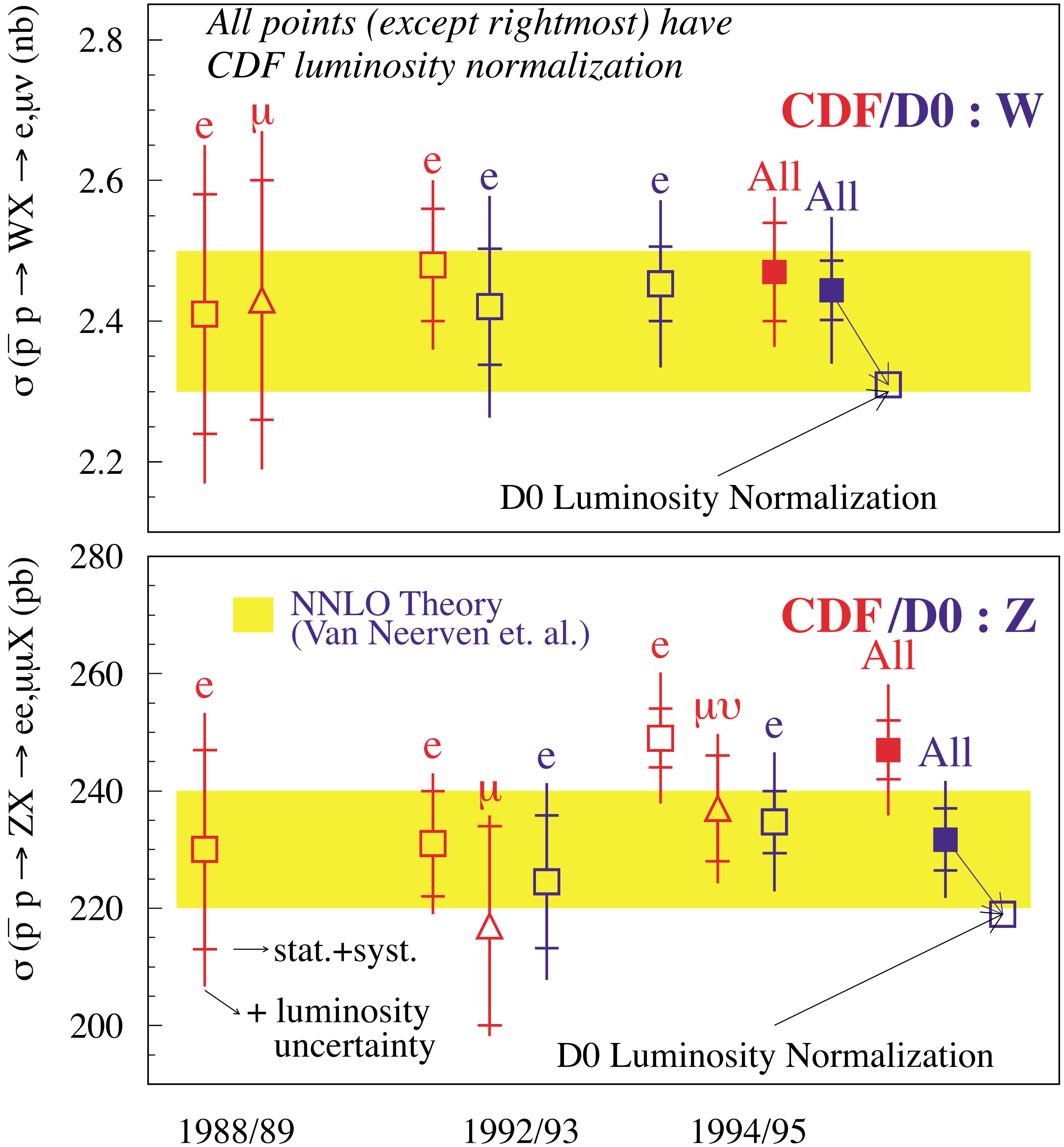
Resummation techniques

W, Z P_T distributions "confirm" formalism(s)

Z P_T distributions constrain non-pert. parameters

Inclusive Cross Sections





NNLO theory

… CDF and D0 Run I luminosity normalization 6.2% different ...

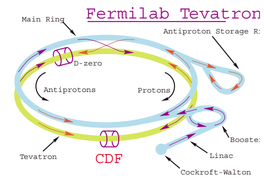
NNLO theory

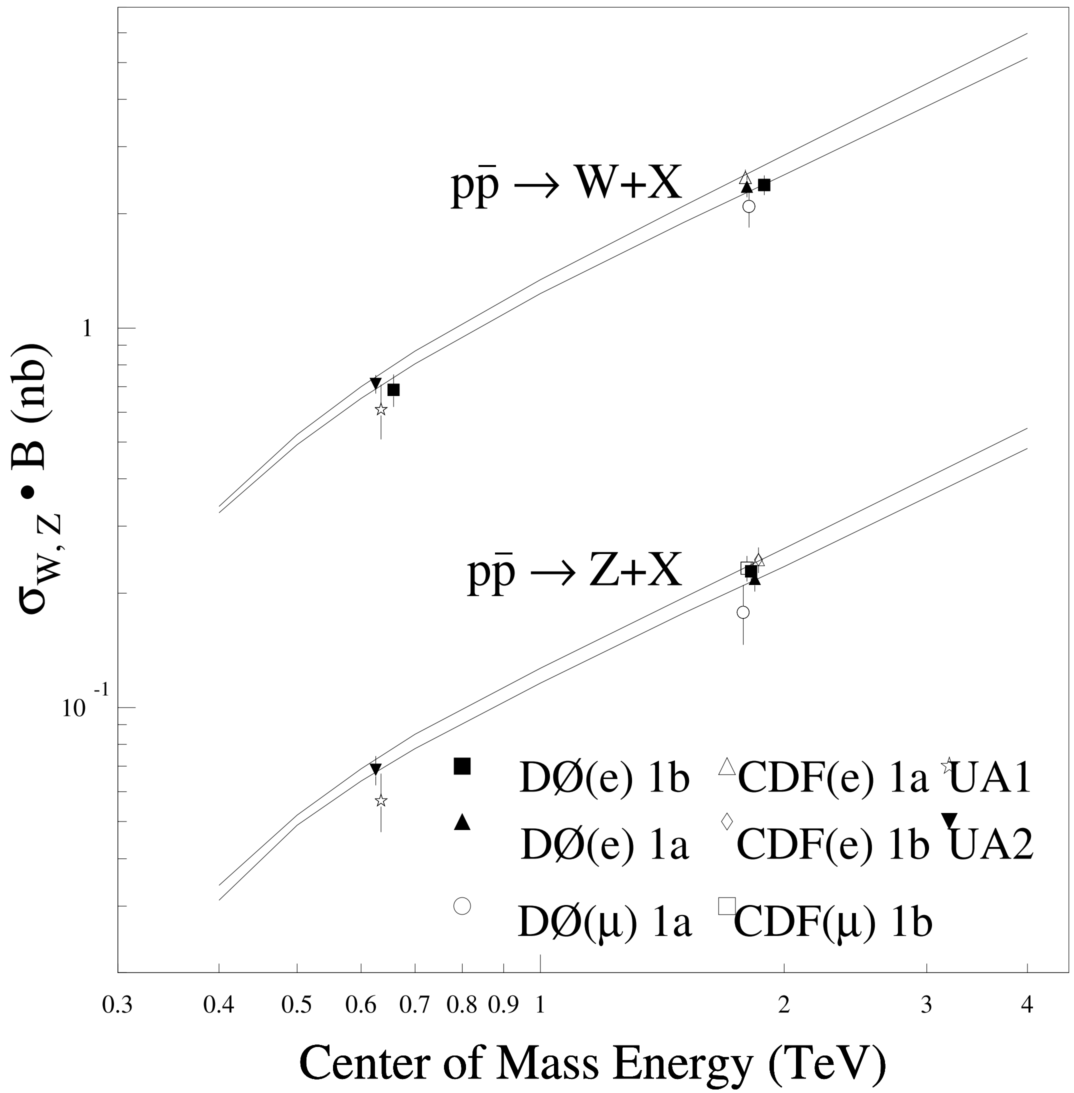
Theory error: ~ 3%, NNLO, $O(\alpha_s^2)$

(Hamberg, van Neerven, Matsuura)

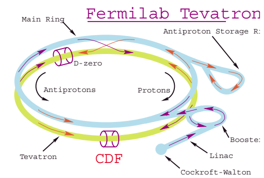
(Dominated by PDF's at NLO -- need NNLO)

Inclusive Cross Sections

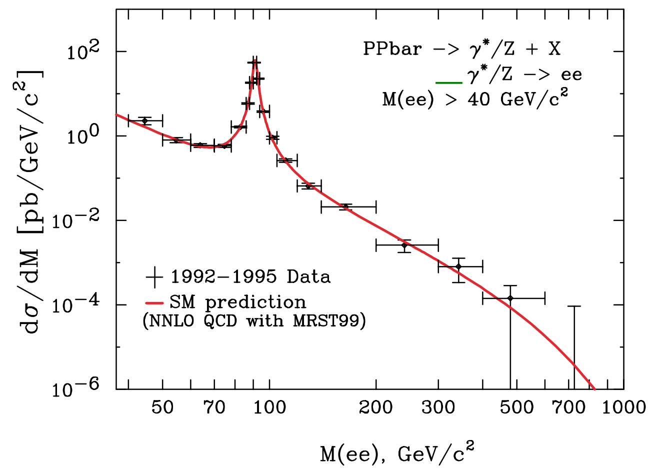


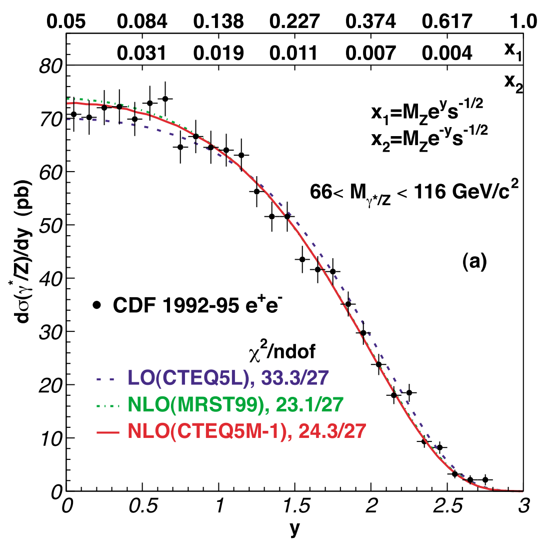


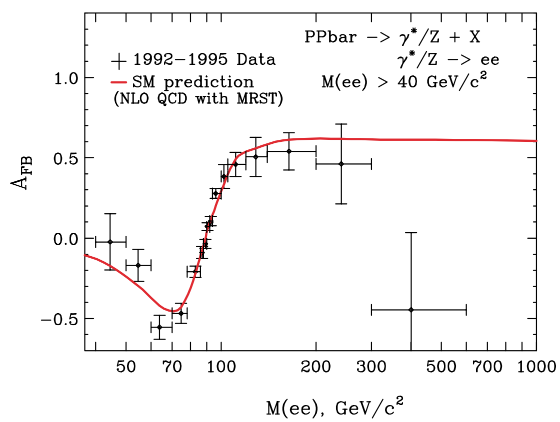
Drell-Yan Z –> e^+e^-



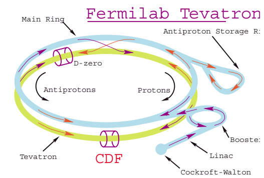
- Red curve is a $\overline{\mathrm{MS}}$ NNLO calculation with MRST99 PDFs.
- Calculated differential cross-section is normalized by the ratio of the measured ee-pair total cross section in the Z-region (66-116 GeV) to the calculated cross section: 253 pb to 227 pb.
- Within present uncertainties, data are well described by existing PDFs.
- LO calculation with LO PDFs do not fit the shape of the high-y data as well as the NLO calculation with NLO PDFs.
- Increase in data in Run II and additional tracking & calorimetry upgrades in forward region will allow better constraints to be placed on PDFs at high rapidity.
- AFB (shown in Colins-Soper frame) agrees w/ SM with slight deficit in highest-mass bin:

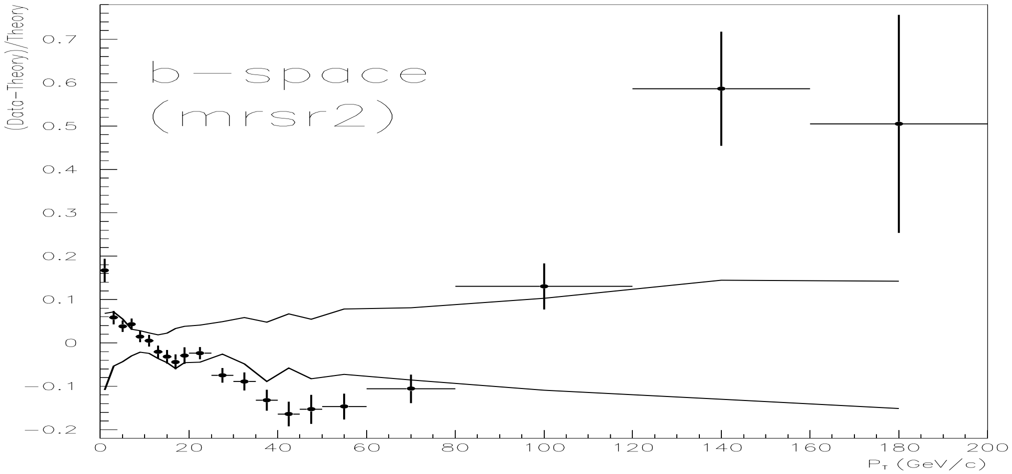


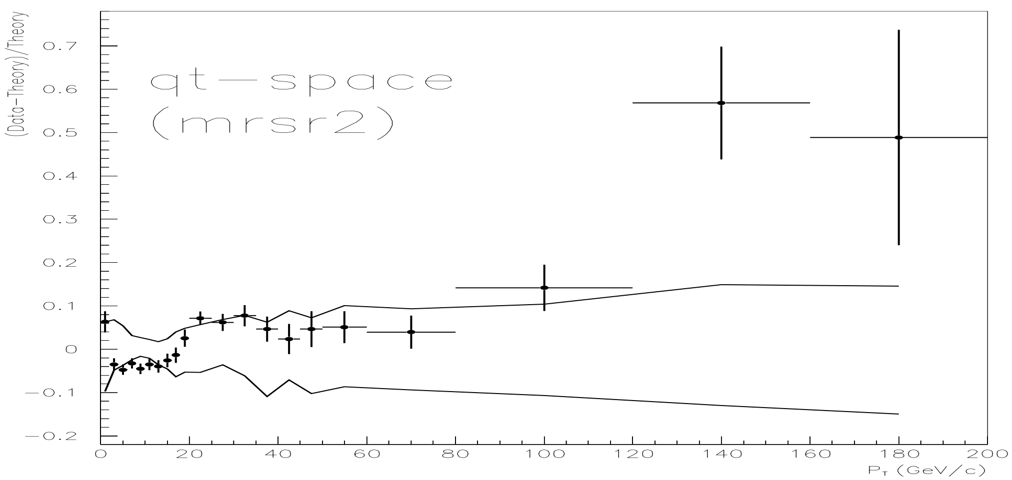




CDF $p_T(W)$ Measurements

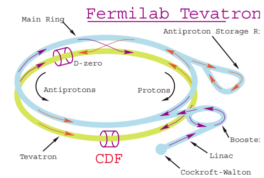




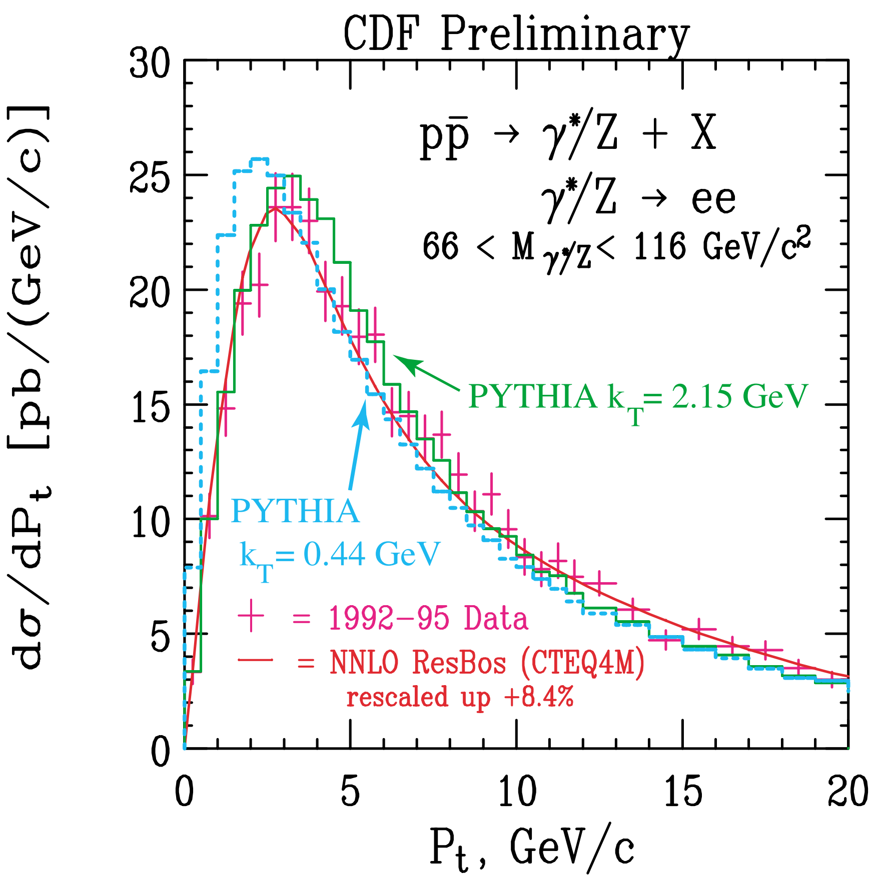


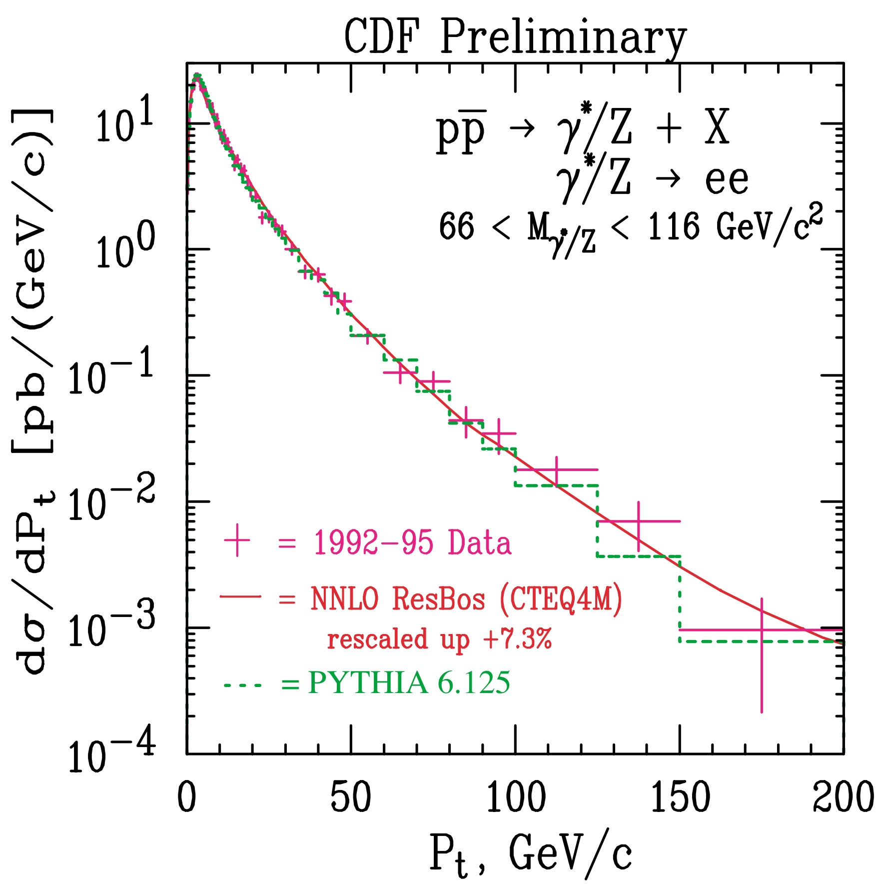
Ellis, Ross, Veseli, NP B503, 309 (97). $O(\alpha_s)$, qt space, after detector simulation.

CDF $p_T(Z)$ Measurements



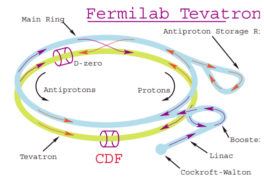
Parton Shower MC's can be made to agree w/ ResBos...



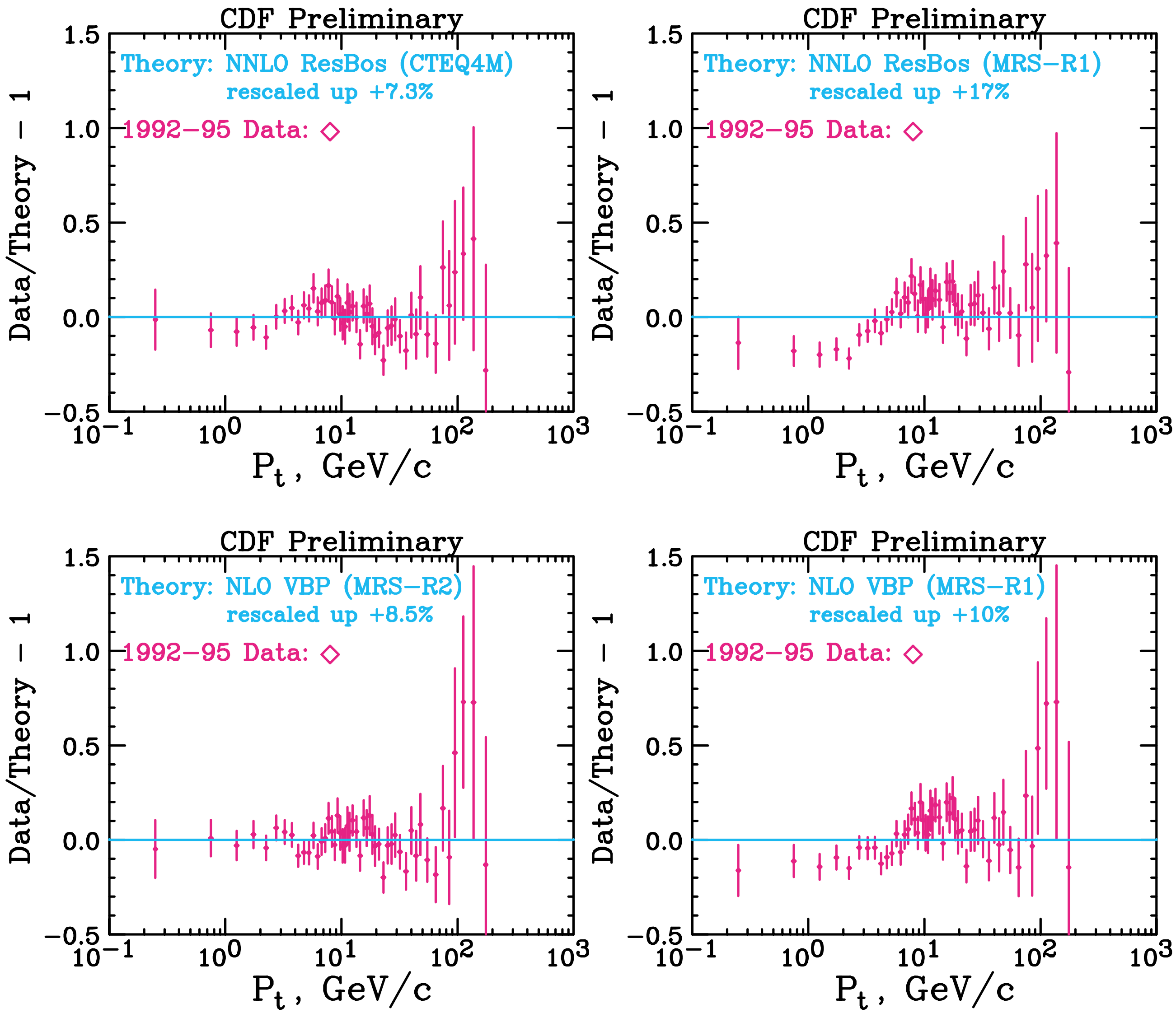


ResBos: Balasz, Yuan, *PRD 56, 5558 (1997)*, $O(\alpha_s^2)$, b-space.
Pythia tuning as described in hep-ph/0002032 (C. Balazs et al.)

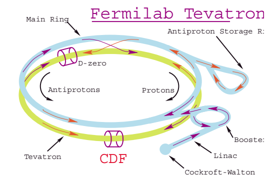
CDF $p_T(Z)$ Measurements



…but uncertainties due to choice of PDFs, etc. still exist:

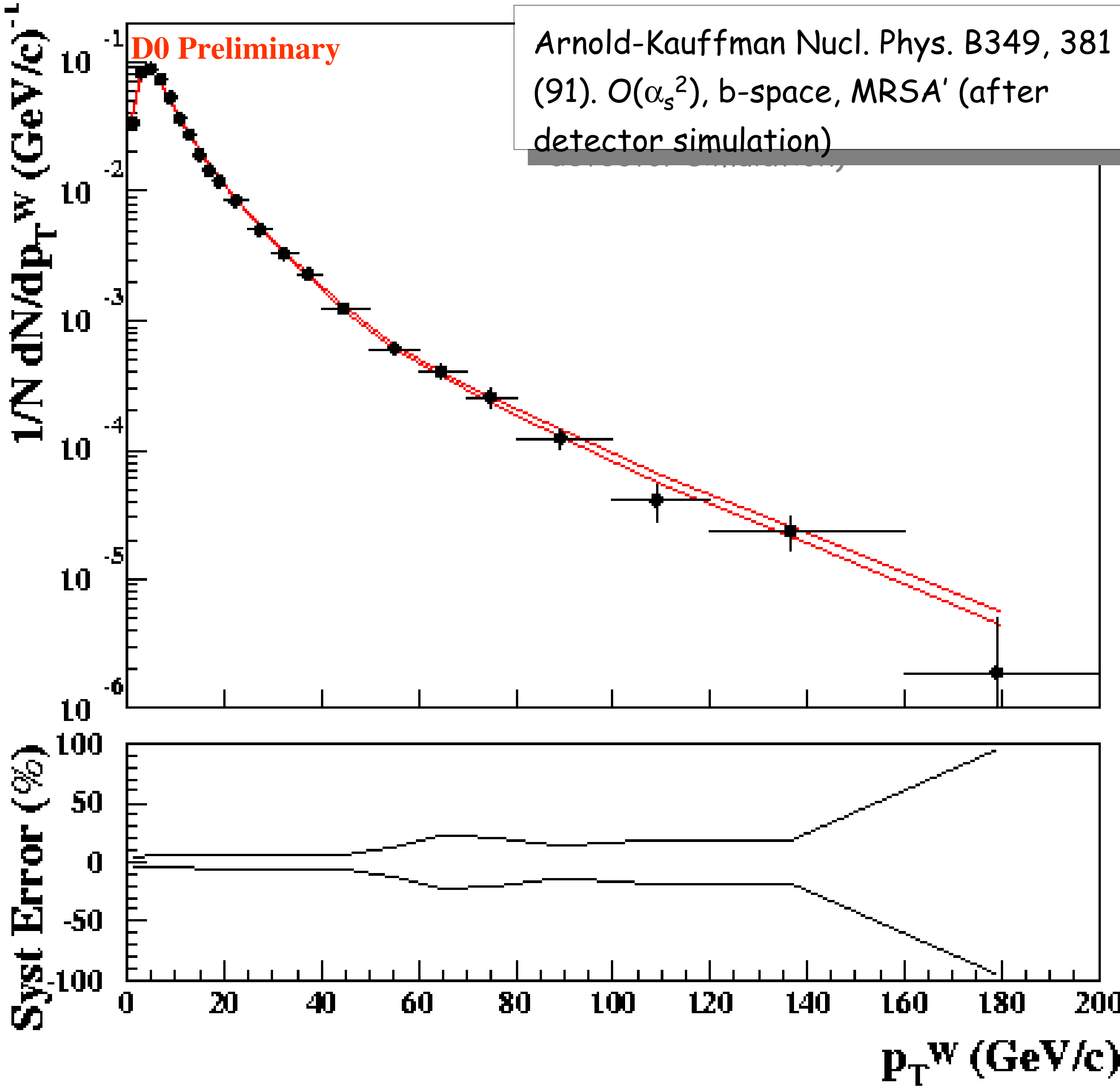


ResBos: Balas, Yuan, PRD 56, 5558 (1997), $O(\alpha_s^2)$, b-space
VBP: Ellis, Veseli, NP B511,649 (1998), $O(\alpha_s)$, qt-space

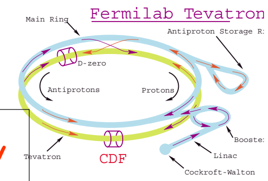


D0 W P_T measurements

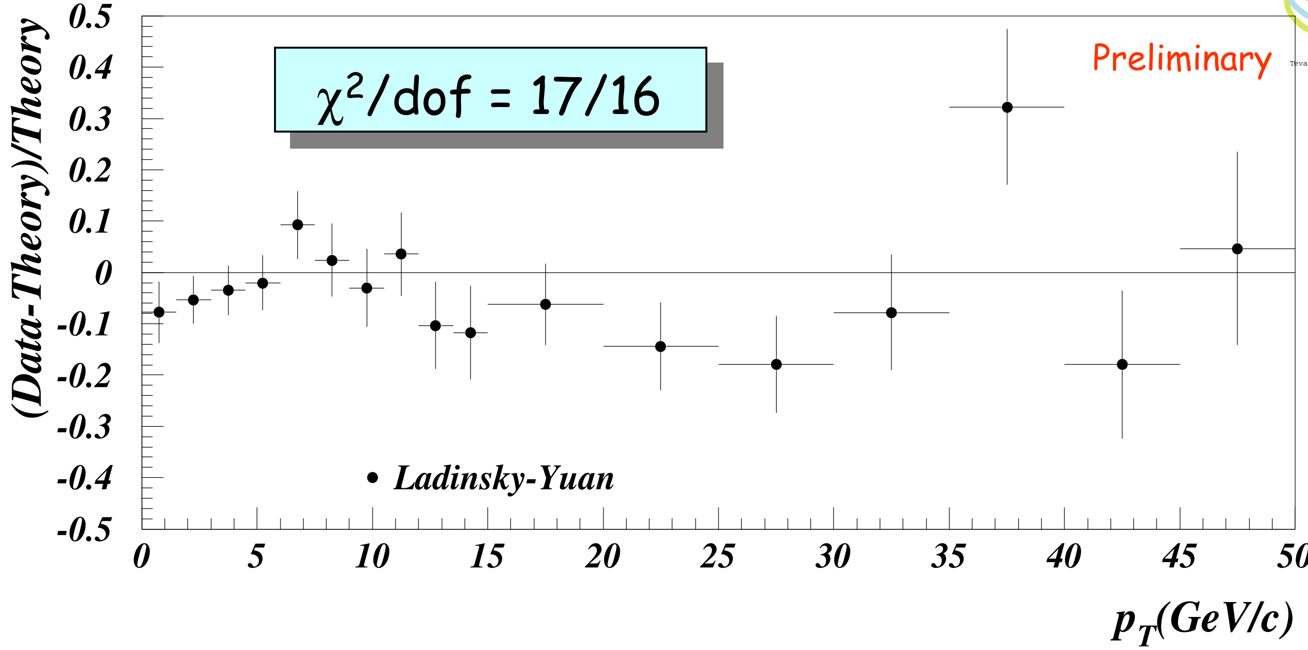
Arnold-Kauffman Nucl. Phys. B349, 381 (91). $O(\alpha_s^2)$, b-space, MRSA' (after detector simulation)



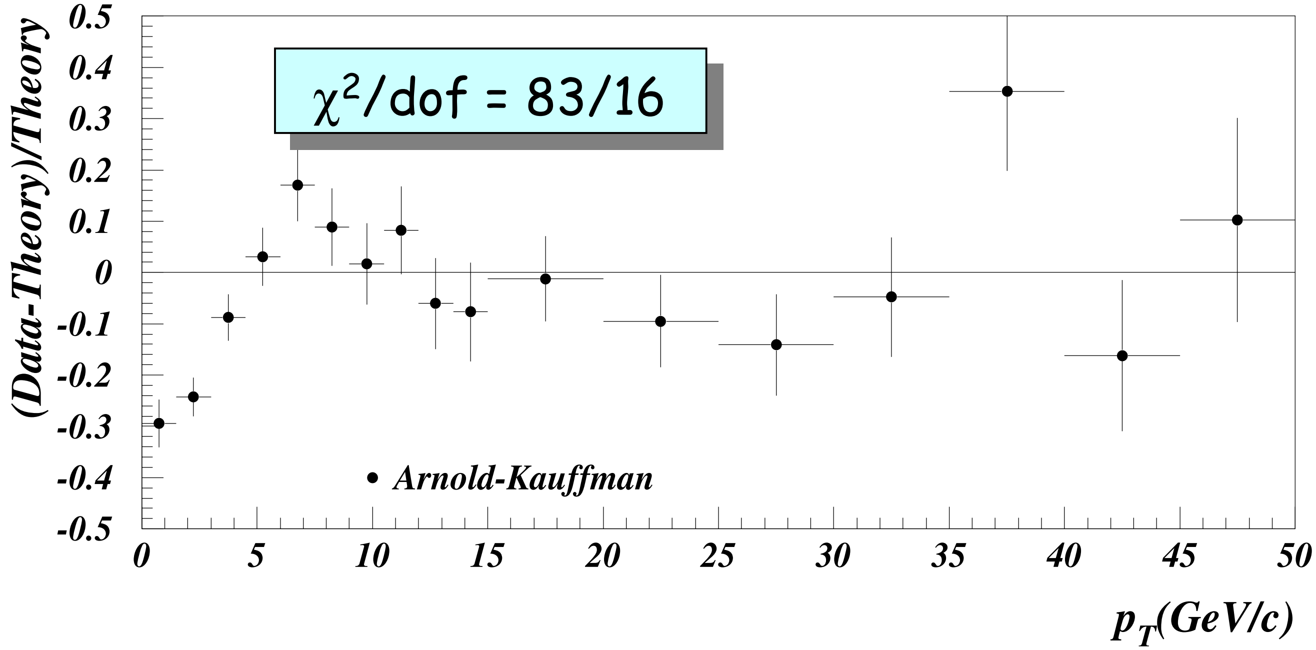
D0 Z P_T measurements



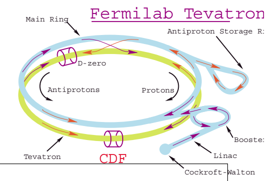
Ladinsky, Yuan, PRD 50, 4239 (94), $O(\alpha_s^2)$, b-space.



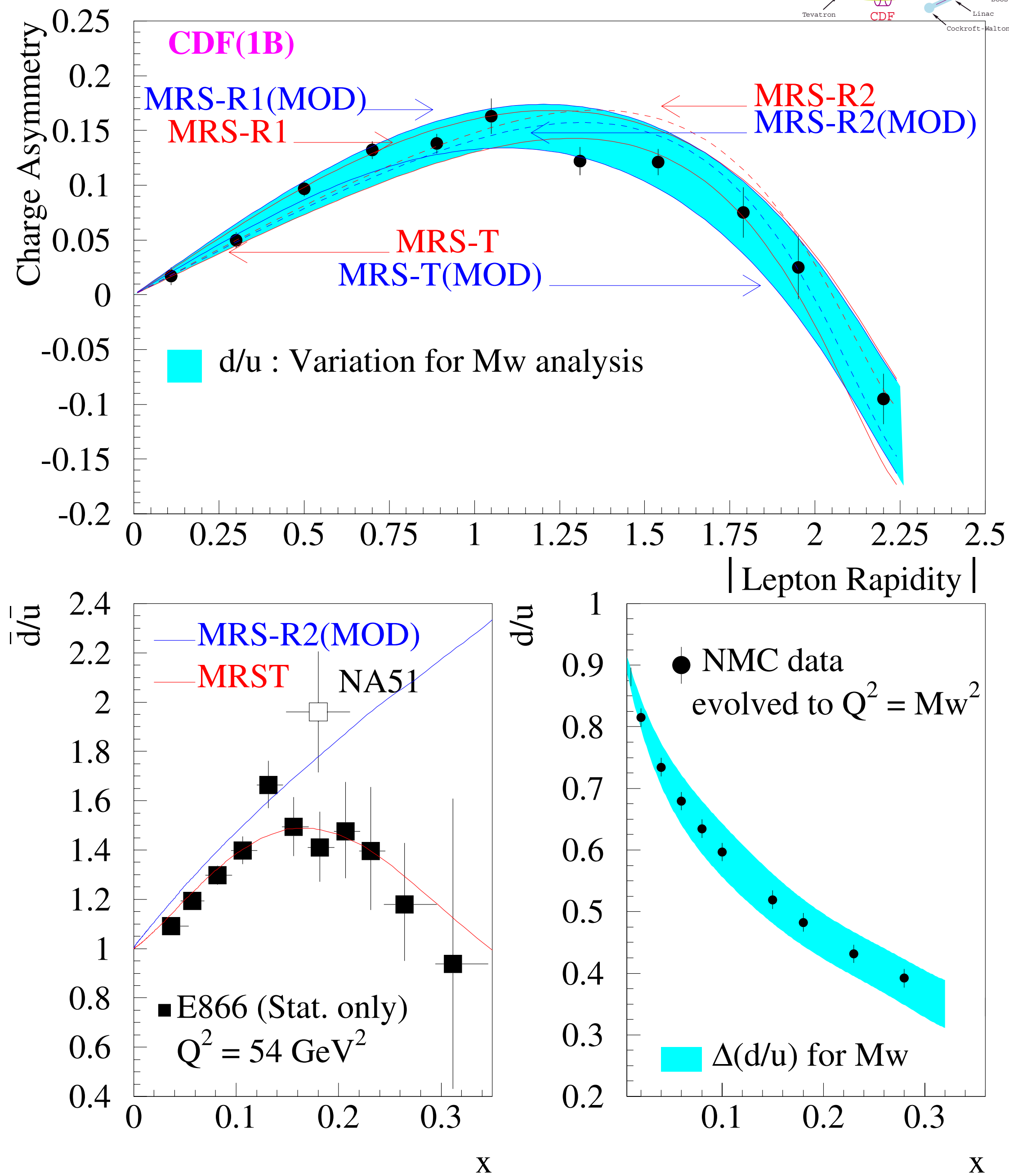
Arnold, Kauffman, NP B349, 381 (91), $O(\alpha_s^2)$, b-space.



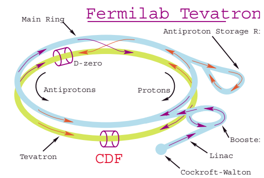
Constraining PDF's: (CDF)



- CDF measures W production asymmetry and uses it to constrain PDF's used in W mass analysis
- In addition to standard PDF's, modified versions that fully span the range of NMC, NA51, E866 and CDF data are used.
- Idea is to more completely allow for variation that might enter into the W mass result
- Resulting d/u variation is used to evaluate the uncertainty in the W mass from this source.



$p_T(W)$ PDF Uncertainties (CDF)



- Constraints on parton distributions from a wide variety of experiments are available - BUT:

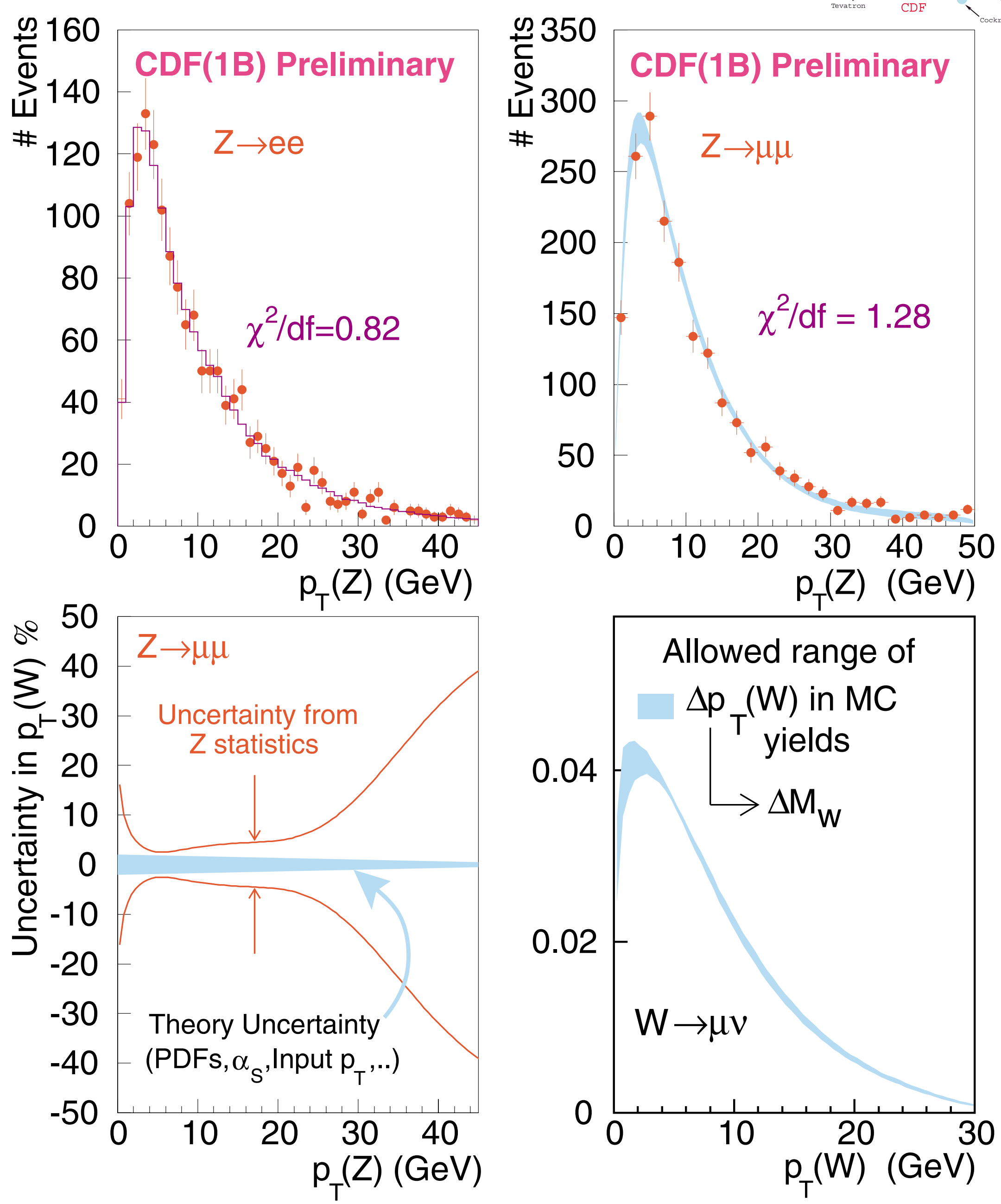
- We need to make certain that these apply to our conditions,

  (a) they fully explore the range of data for Tevartron conditions

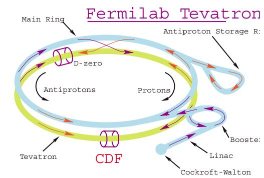
  (b) excessive deviations ruled out by our data are not used

- $p_T(Z)$ uncertainty from $Z\rightarrow\mu\mu$, $Z\rightarrow ee$ combined with theoretical differential cross section ratio $d^2\sigma/dp_T dy$

- This is then used to project allowable range in W p_T distribution using fast Monte Carlo



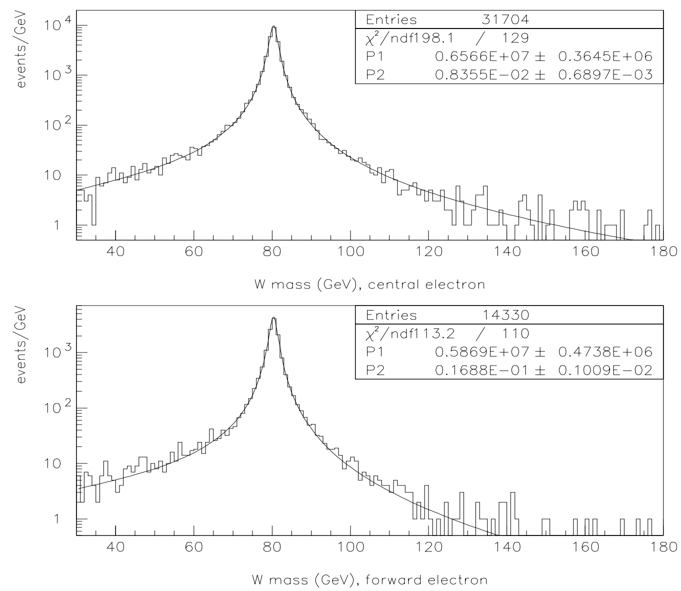
Use of PDF's: (D0)

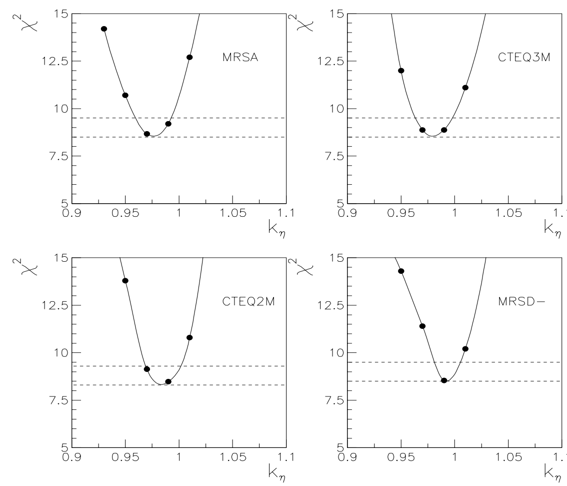


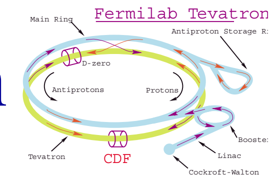
- Basic technique is the same (theoretical differential cross section $d^2\sigma/dp_T dy$ for W, Z production used to transfer parton luminosity uncertainties from Z to W). Similar PDF choices are used.

- Mass-dependent fit done separately for each W and Z topology (central vs. forward, see later).

- Scale $\eta(W)$ in Monte Carlo by factor k_η, then use large rapidity coverage for electrons (80% total containment compared w/ 60% for CDF) to check fits for M_T, $p_T(e)$, and $p_T(\nu)$.







Modeling Response Functions and Resolution

Recoil Model: D0

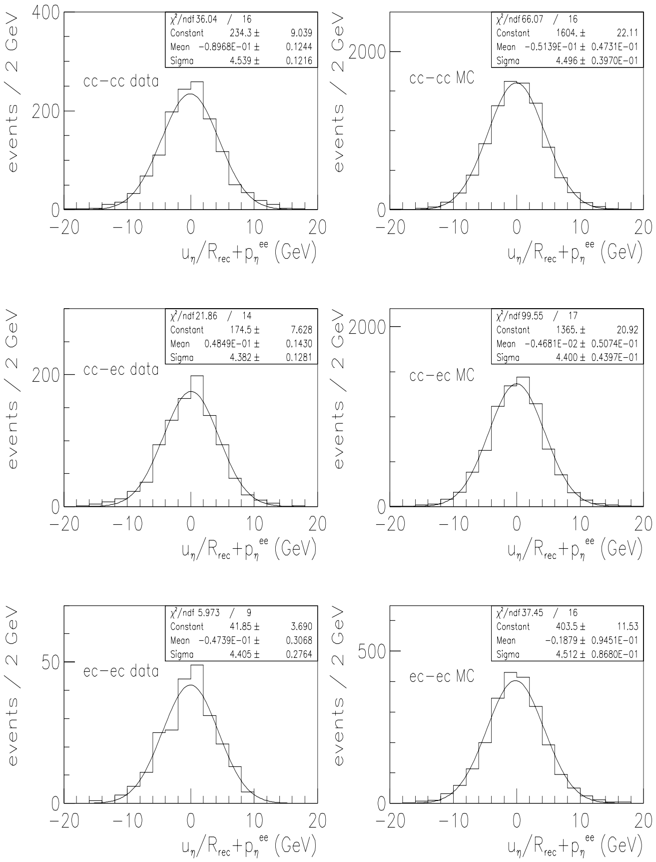
Define response function $p_T^Z = U/R$

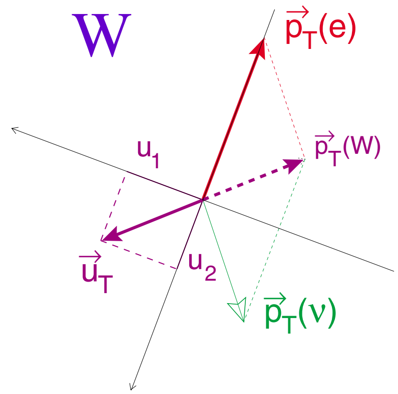
Results show R similar for central vs. EC

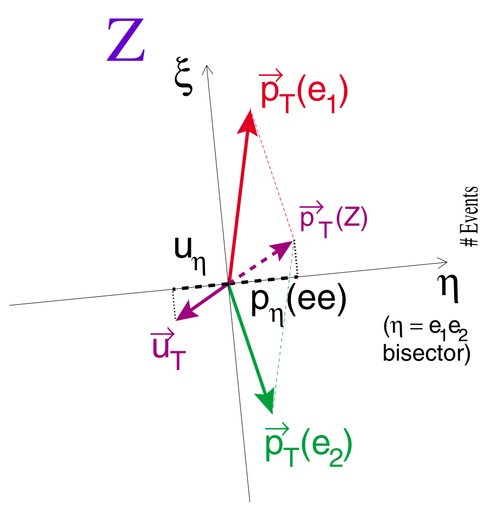
←Axes

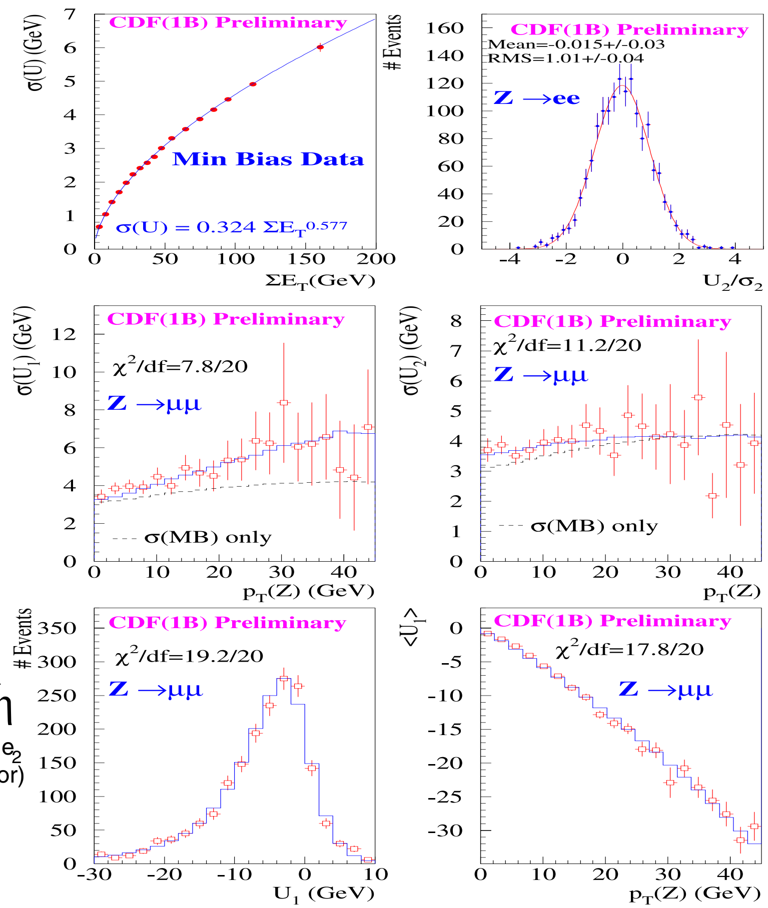
Recoil Model: CDF

Parameters of multivariate model fit to response to underlying event

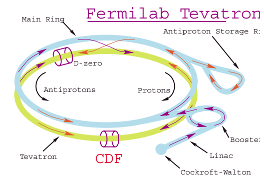




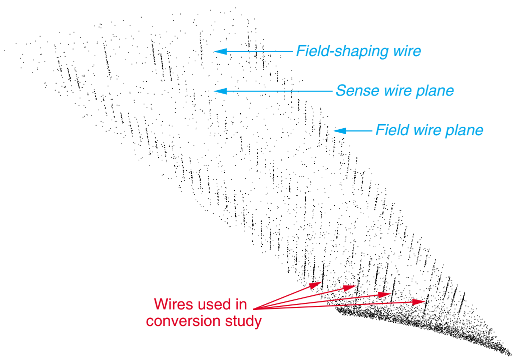


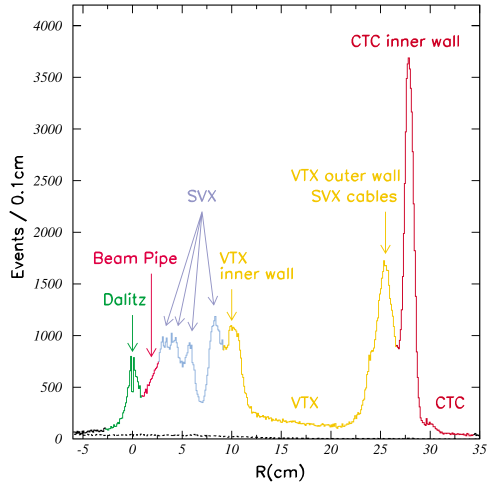


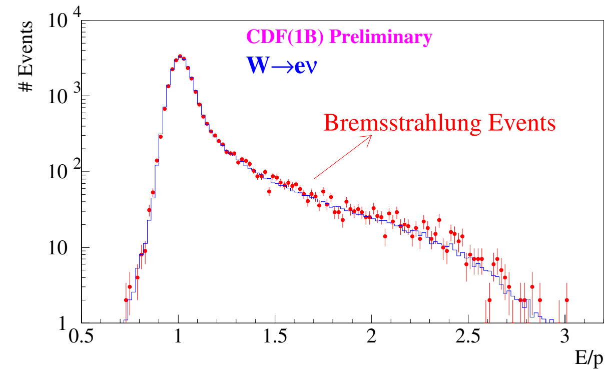
Toy MC Used to Determine Amount of Material Before Calorimeter -- CDF:

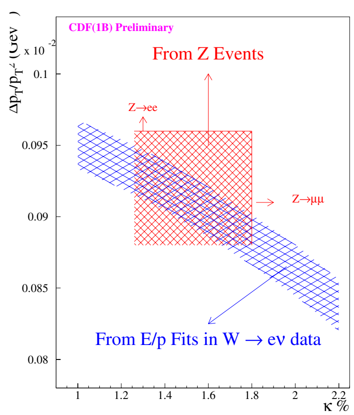


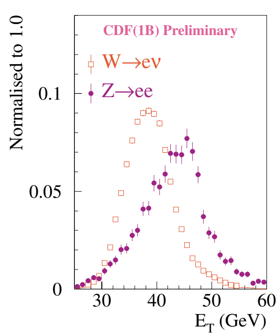
(b) Electrons: check p scale with E/p distribution after calibration of inert material in the tracker:

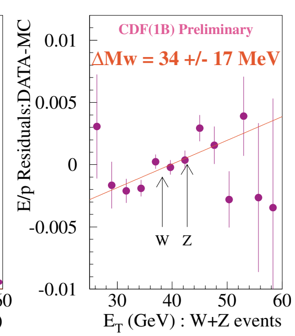


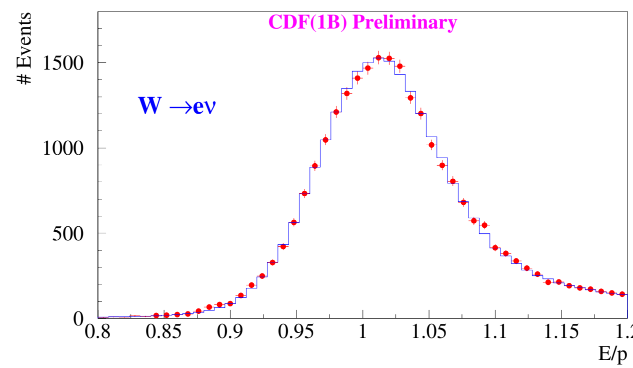






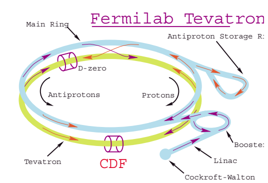




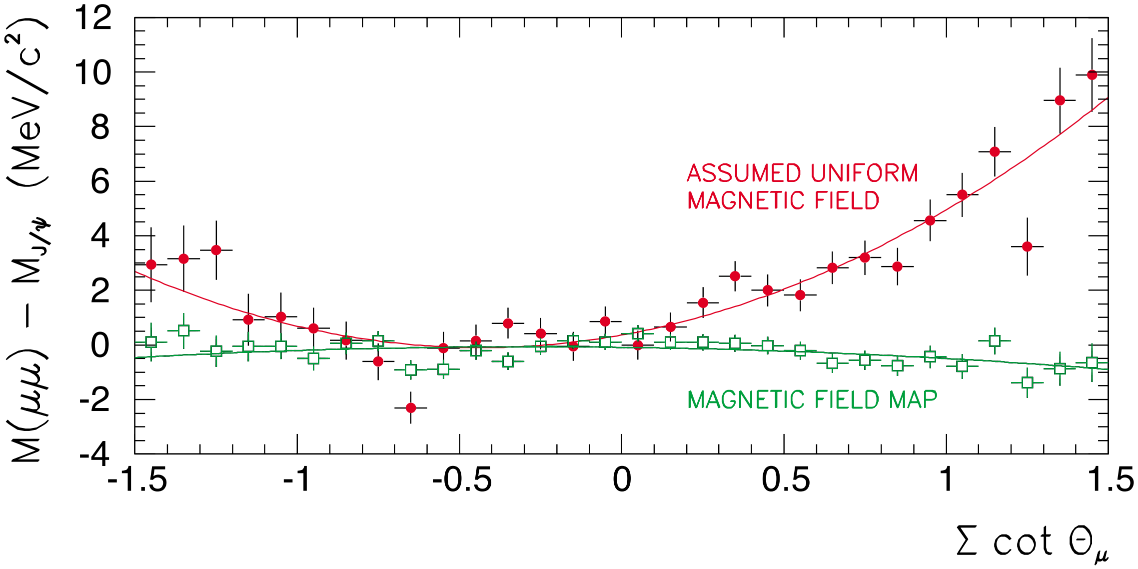


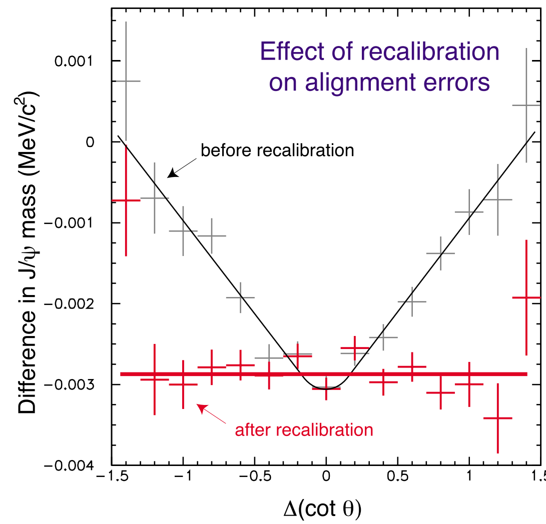
Result: E/p for W→eν tracks agreed in resolution but disagreed in scale with calibrations transferred from the Z. This should not affect the extracted value of M_W, since nonlinearities are small, but is not understood! ⇒ Z scale used!

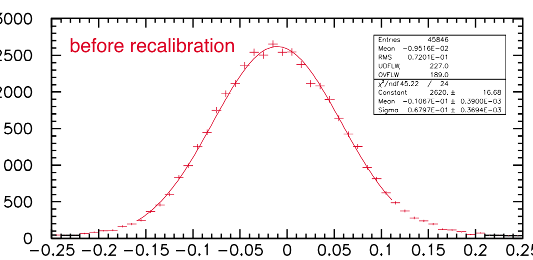
Calibration, Alignment, and Checks of Momentum and Energy Scales -- CDF:

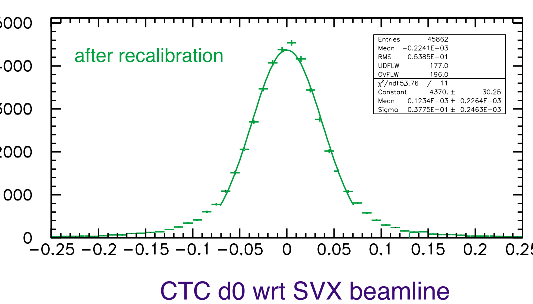


- Many effects:
  - Non-uniform magnetic fields
  - Material distribution
  - CTC calibration and alignment





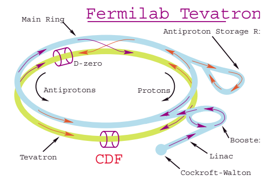




Extensive efforts to calibrate track detectors, remove non-uniform magnetic field effects, map and understand material distribution, etc.

1 MeV /c^2 on J/ψ projects to ~25 MeV/c^2 on M_W.

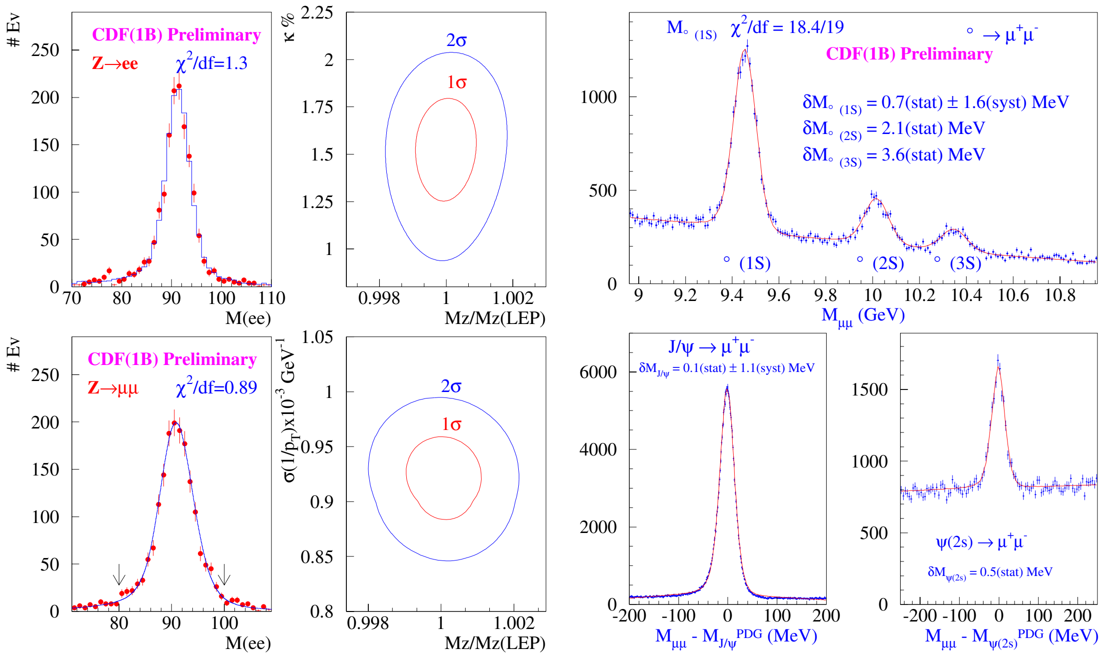
Calibration, Alignment, and Checks of Momentum and Energy Scales -- CDF:

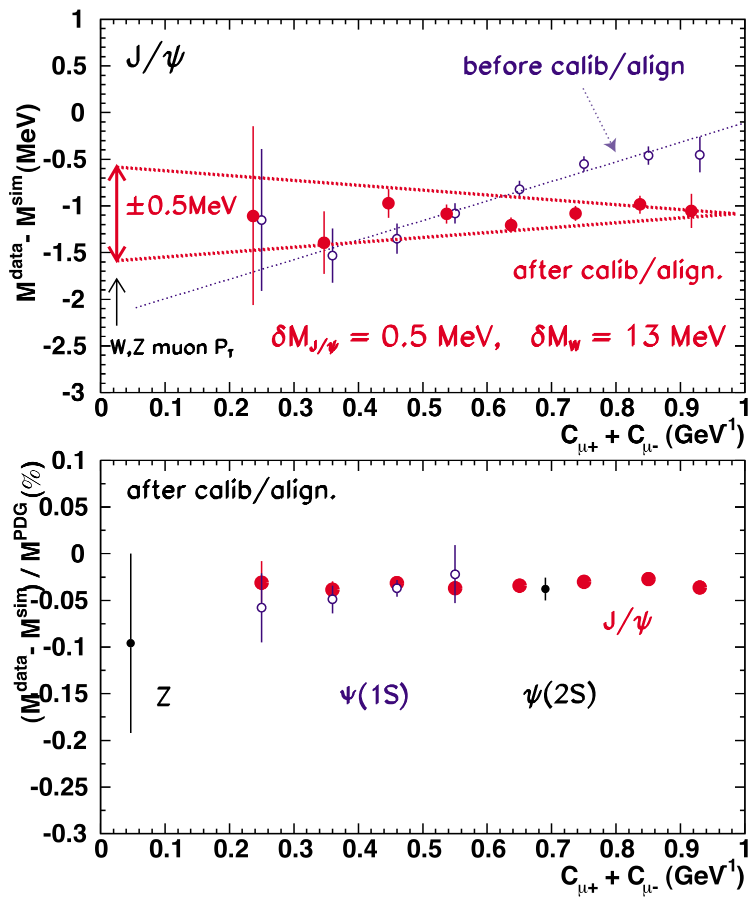


- Calibrate E, p scales on Z

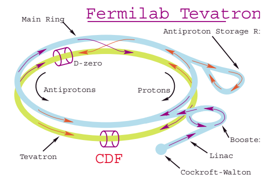
    (a) Muons: check p scale with other resonances

    (reconstruct a variety of states with different kinematics)



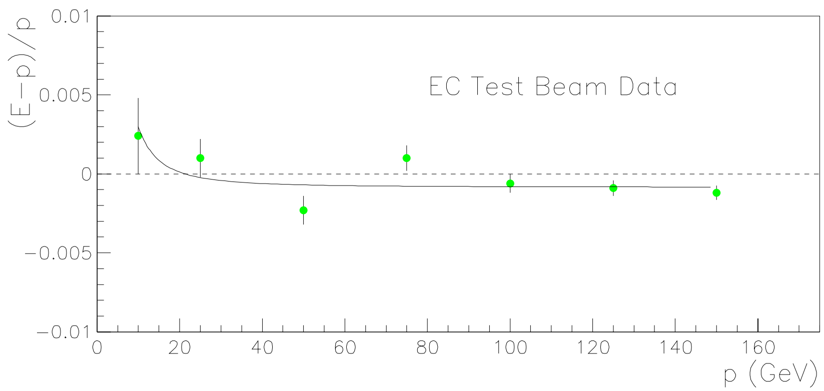


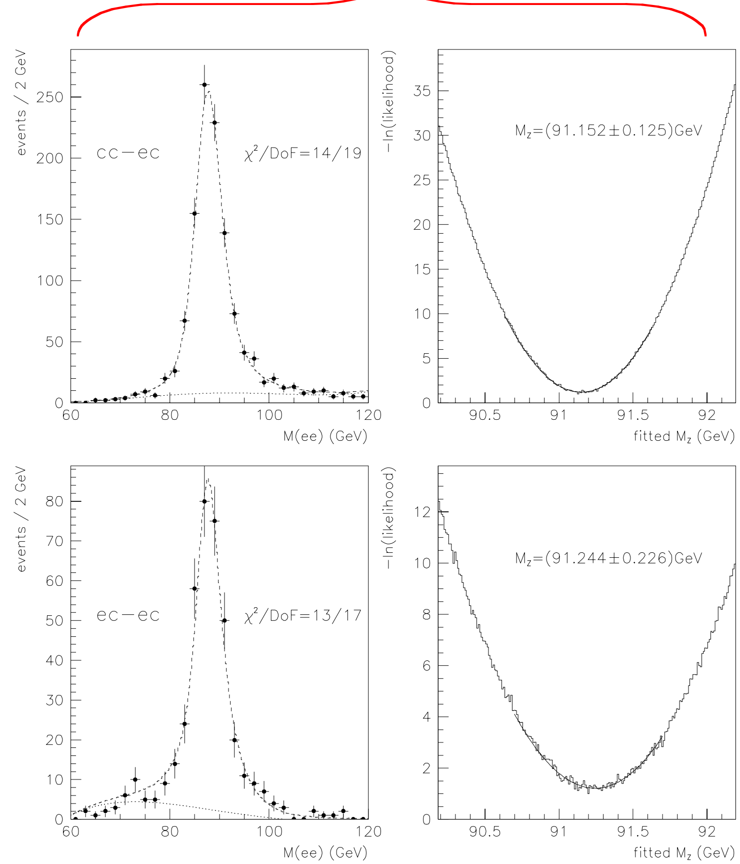
Result: Track momentum scale agreed across the full range very well!



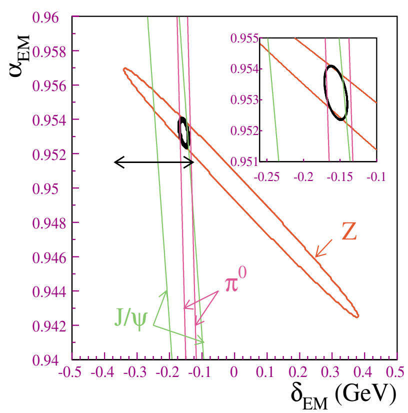
Calibration, Alignment, and Checks of Momentum and Energy Scales -- D0:

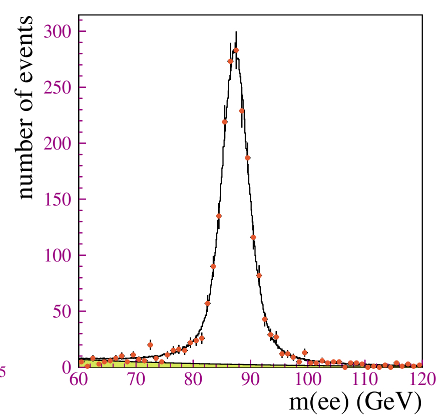
- D0: Use Z mass and low-mass resonances to determine constants in formula $E_{meas} = \alpha E_{true} + \delta$ in central region, then Z to transfer α:





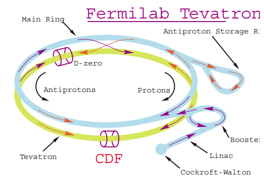
$\Rightarrow \alpha_{EC}$





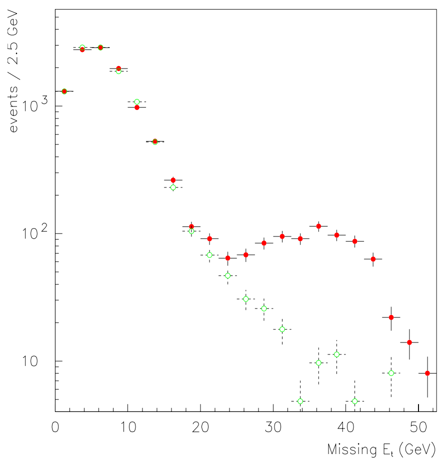
Backgrounds for M_W analyses

(Very small in each case)



D0:

Jet fakes: shape of background distribution extracted from W data, normalization measured using monitor trigger data, with no $\not\!\!E_t$ requirement.



$f_{jet} = (3.6 \pm 0.8)$ %

Using EM energy fraction, shower shape, track-cluster matching and track dE/dx information in combined likelihood ratio gains x2.2 in jet background rejection for 95% efficiency.

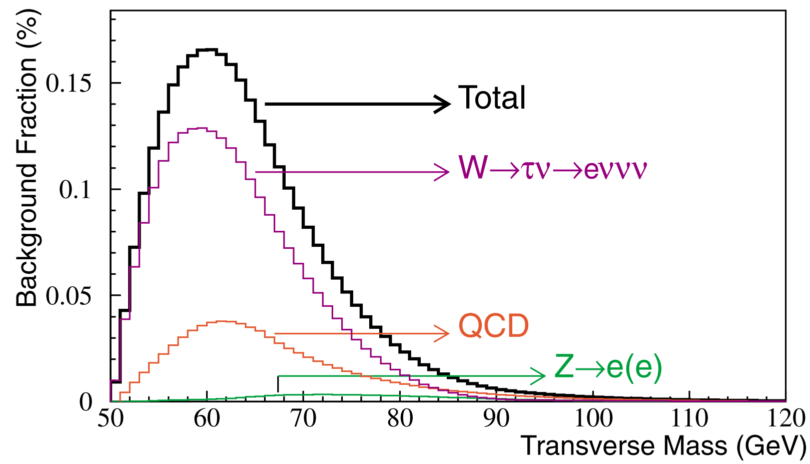
$Z \to e\not{e}$: estimated using GEANT simulation

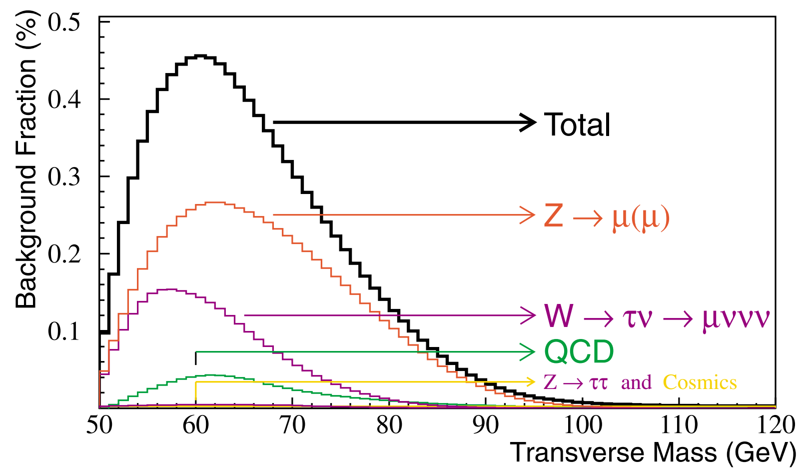
$f_Z = (0.3 \pm 0.02)$ %

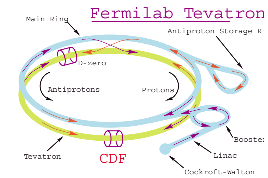
$W \to \tau\nu \to e\nu\bar{\nu}\nu$: Included in Monte Carlo simulation.

$\Delta M_W = 20$ MeV (M_t fit)
$\Delta M_W = 27$ MeV (p_t(e) fit)

CDF:



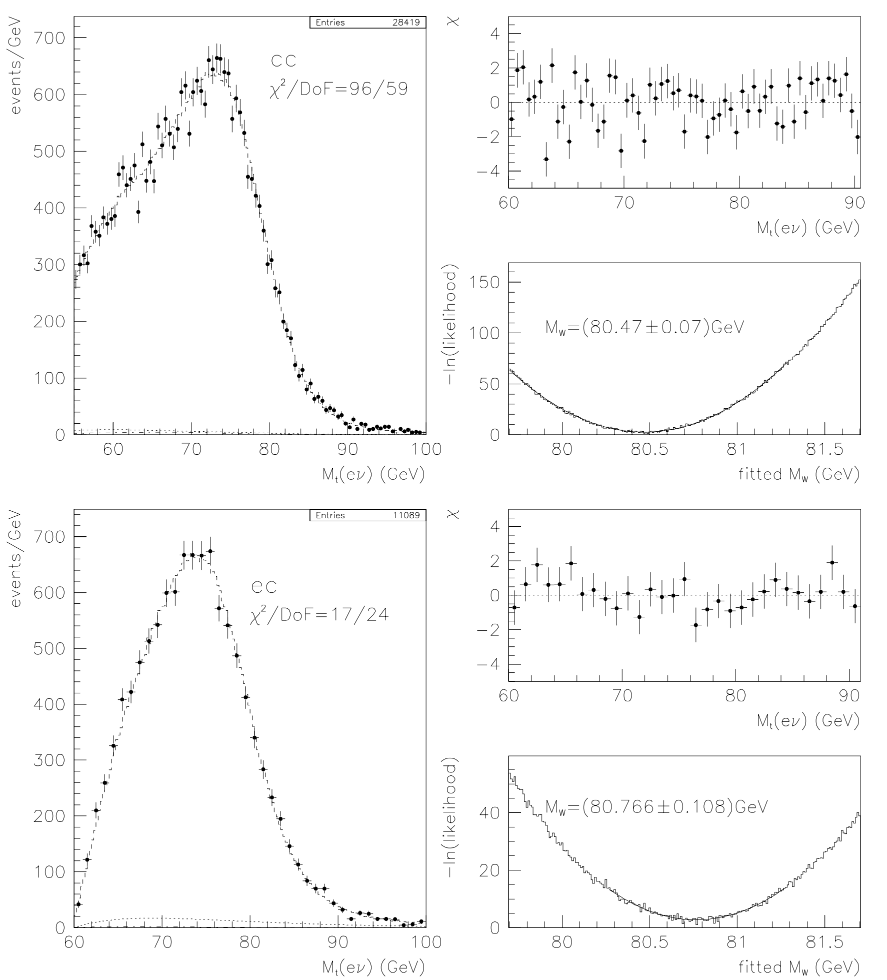




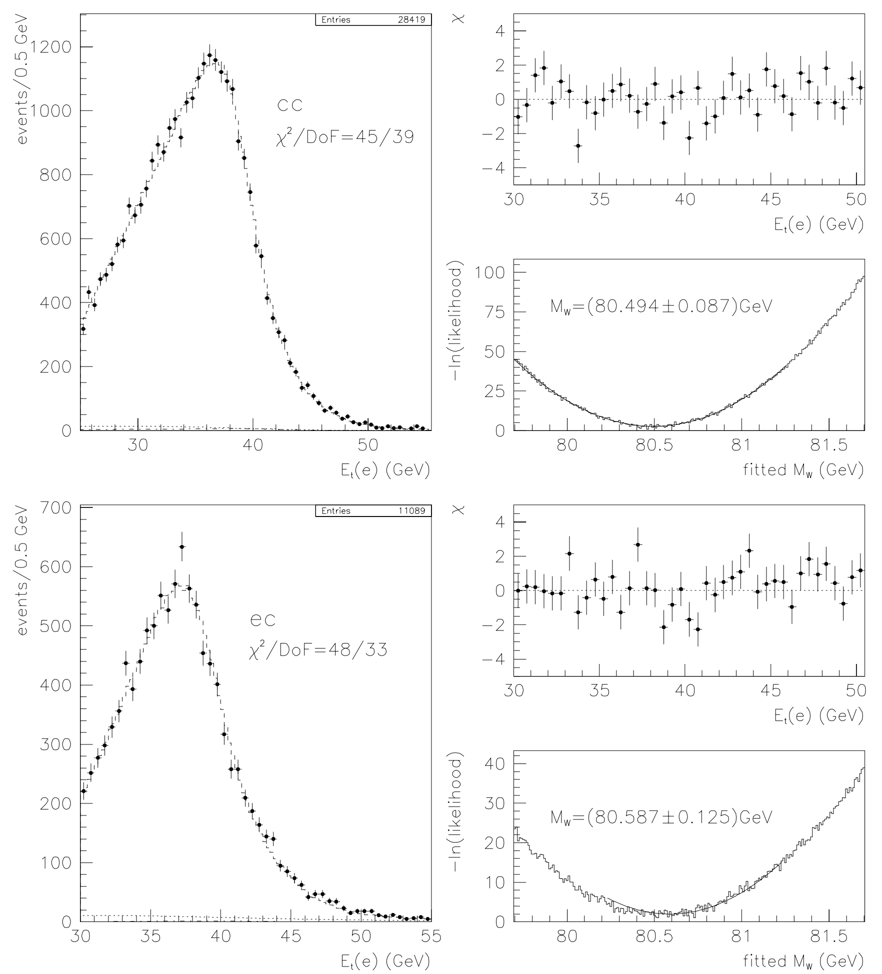
Run I Fits: D0 (Transverse mass and p_T)

D-zero fits separately the $M_T(W)$, $p_T(e)$, and $p_T(\nu)$ spectra, accounting for correlations between the fit parameters with a derivative matrix. Results:

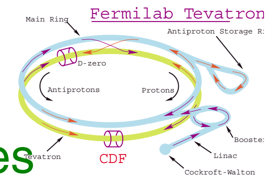
$M_T(e\nu)$



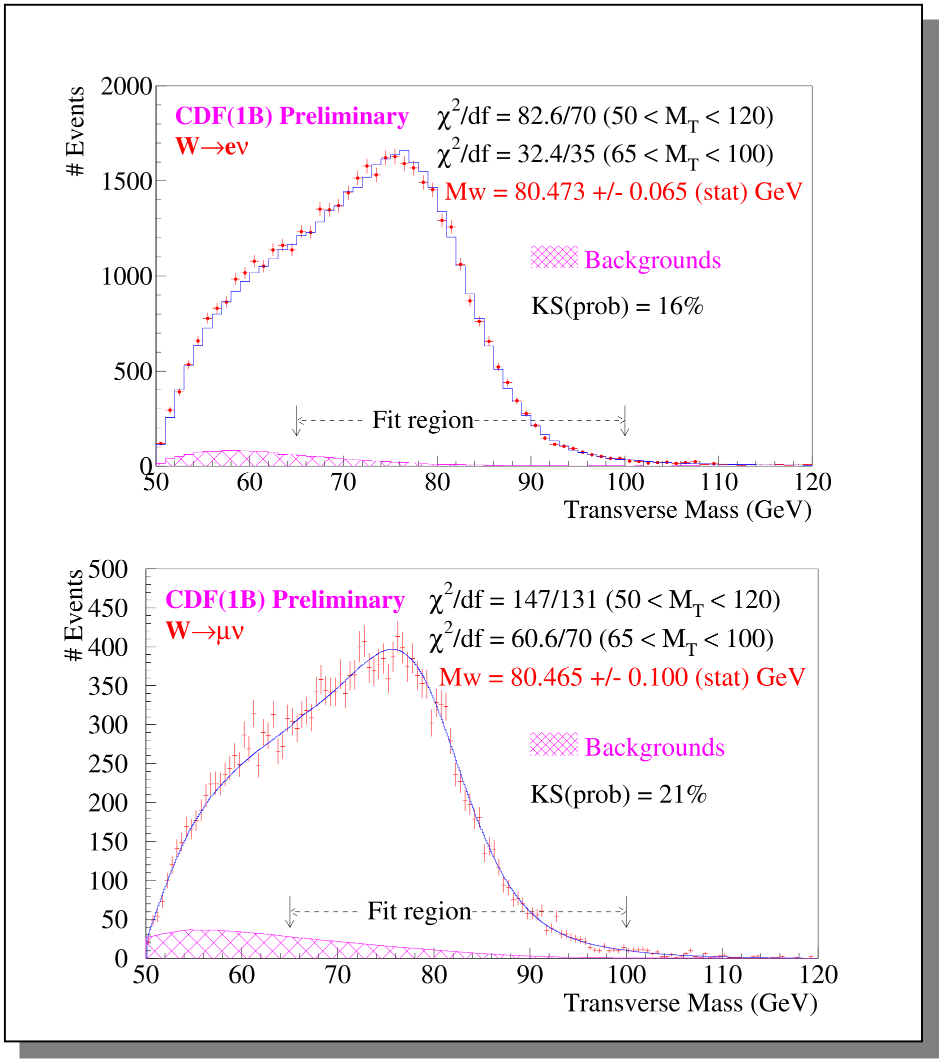
$p_T(e)$

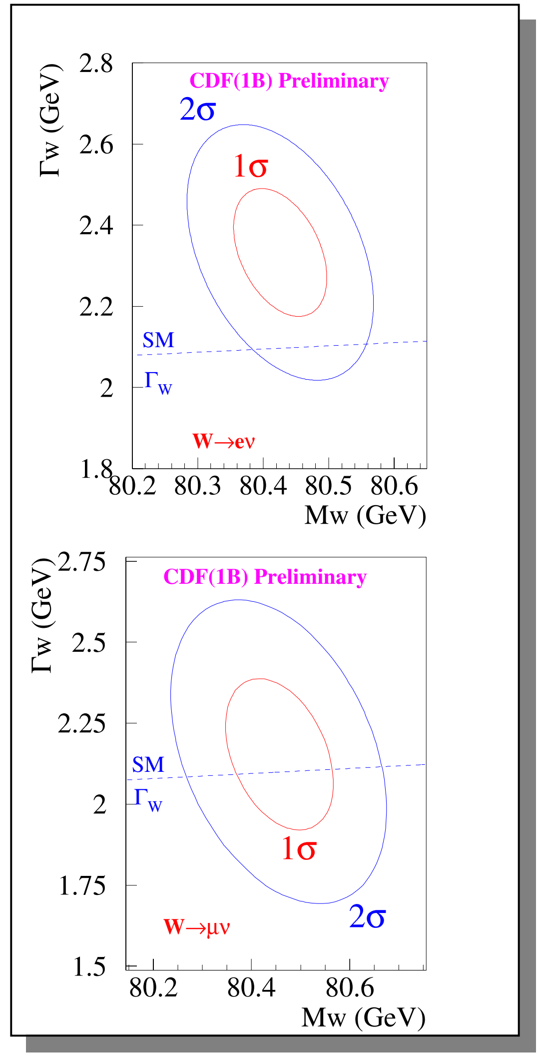


Run I Mass and Mass+Width Fits: CDF

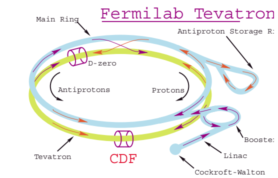


- CDF fits M_T between 65 and 100 GeV for muon and electron samples with W width fixed at 2.093 GeV to derive its primary results.
- As a cross-check, both experiments allow W width to float in separate 2-parameter fits, and find consistency w/ SM:

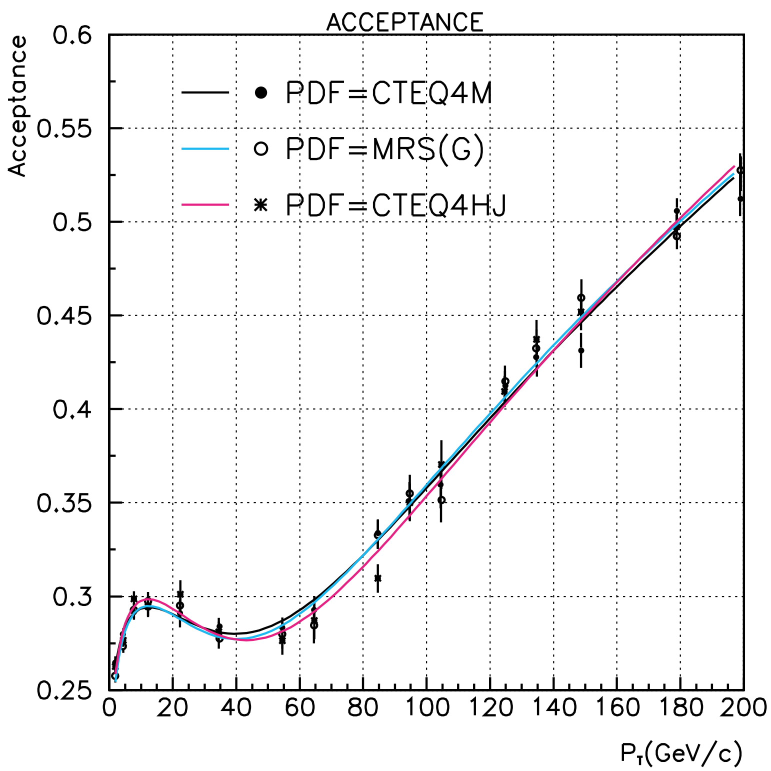


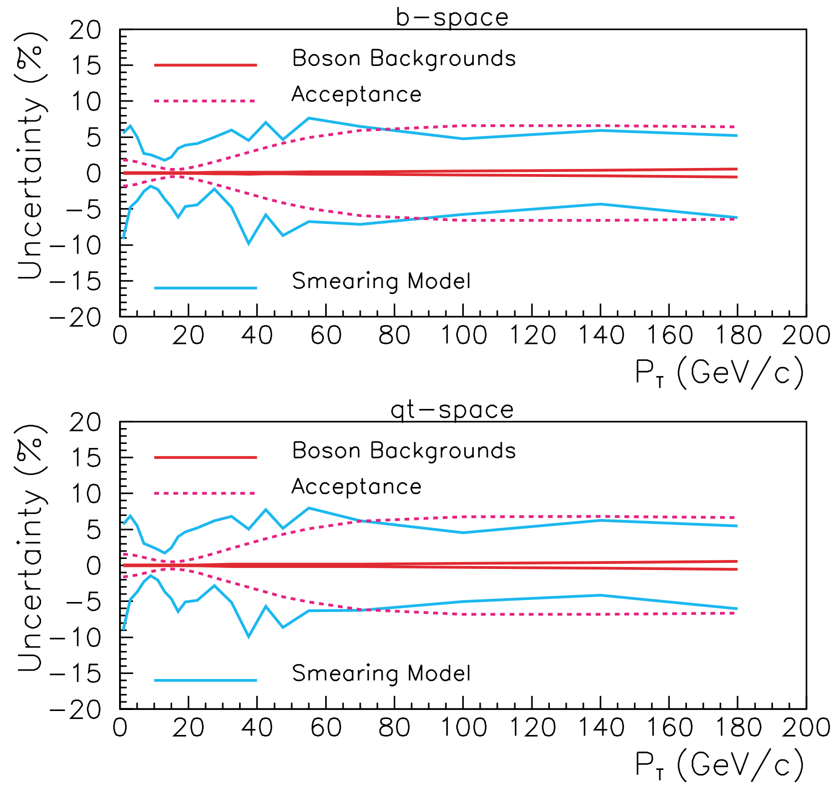


What Are Limitations?

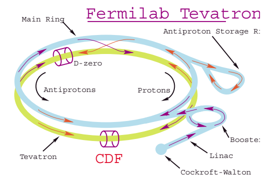


- Backgrounds are low, but not zero.
- Limited ability to explore $p_T(W,Z)$ directly (greater backgrounds especially at high p_T, sensitivity to neutrino smearing and modeling of acceptance).
- E.g. $p_T(W)$ analysis of CDF: ($p_T(Z)$ has similar considerations)

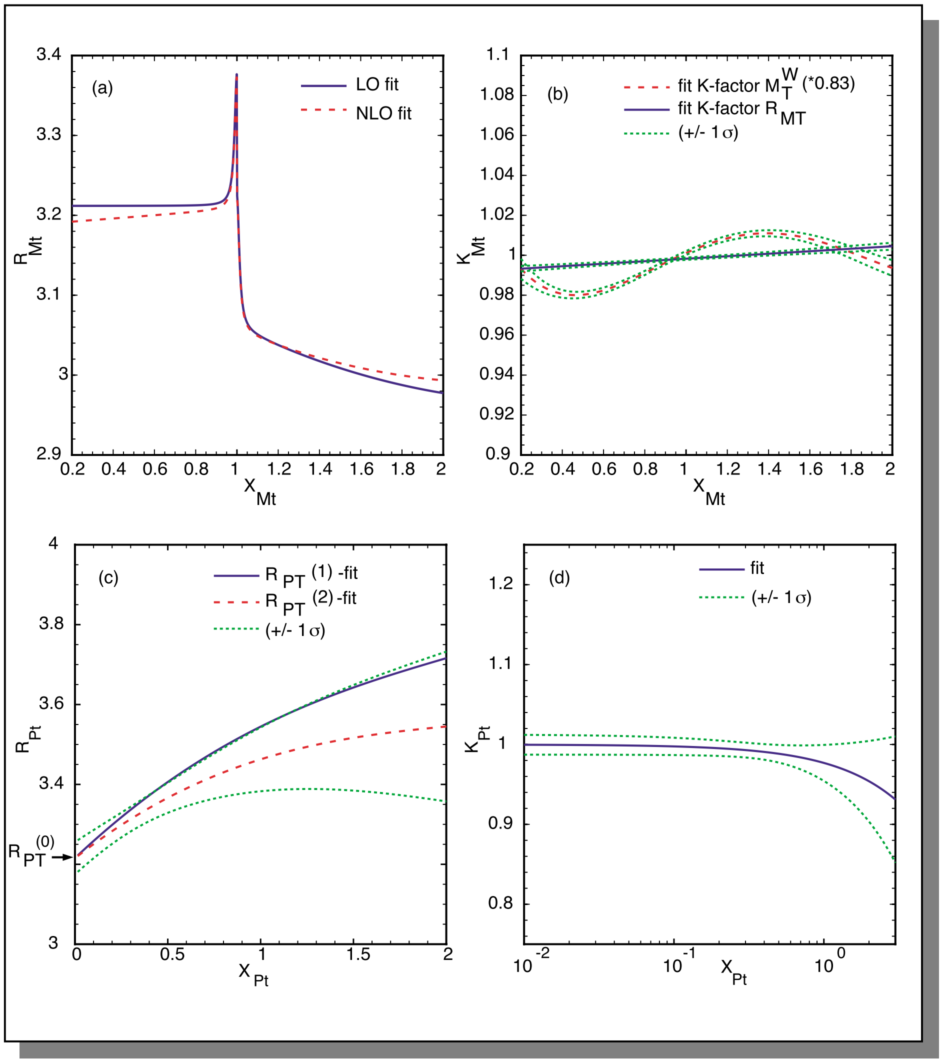




How To Do Better?

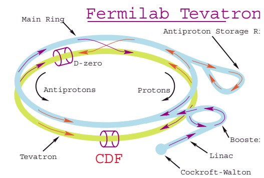


- Many common uncertainties, both with theory and experiment, cancel in ratios of kinematic distributions between W and Z.
- This method is also less sensitive to multiple interactions per crossing and uncertainties in the underlying event modeling.

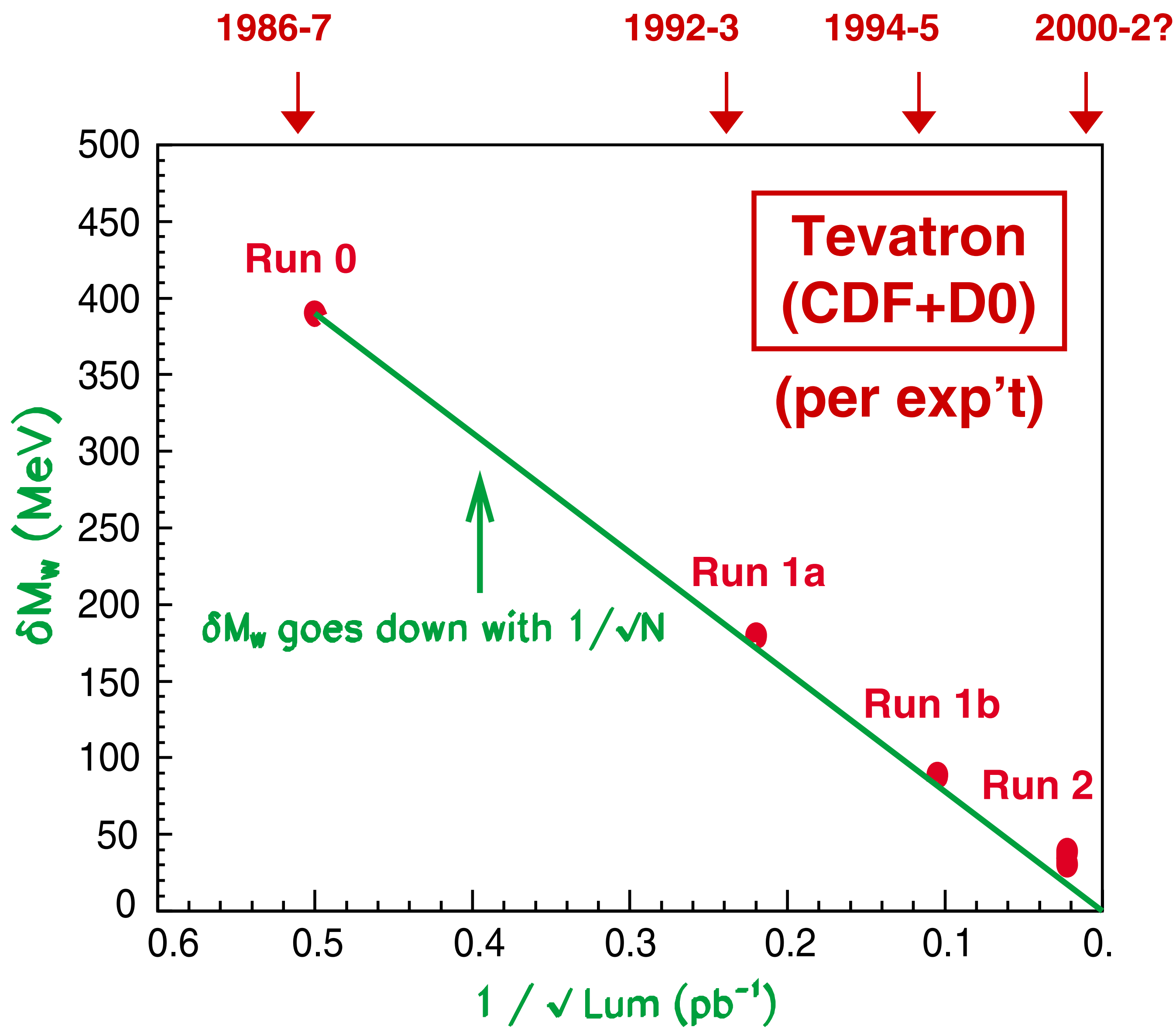


- Form ratios of W, Z kinematic distributions scaled by the mass of each vector boson, e.g. M_T, p_T, etc. (cf. W. Giele, S. Keller, PRD57:4433-4440,1998)
- Z statistics were too limited in Run I to do a good job with this method. Will be different in Run II. (In fact, due to multiple interactions at high luminosity, this may prove to be the only way to do it!)
- Fit to MC templates for these ratios at different values of M_W.

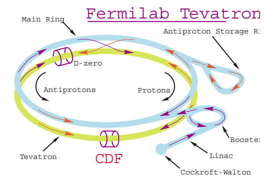
Looking Toward the Future



- Measure and constrain most systematic uncertainties using data (PDF's, energy scale, etc.), plus new methods.
- Thus many (but not all) of the contributions will go down like 1/√(∫ Ldt).
- Projection is hard to do: even in Run I, we encountered difficulties pushing the limit of some analyses. To do better, need all of the techniques described here.



Connections between W,Z Production, QCD and New Physics



Inclusive Cross Sections

Measure:

$$\sigma(p\bar{p} \to W + X) \times BR(W \to l\upsilon)$$

$$\sigma(p\bar{p} \to Z + X) \times BR(Z \to ll)$$

Form ratio:

$$R \equiv \frac{\sigma(p\bar{p} \to W + X) \times BR(W \to l\upsilon)}{\sigma(p\bar{p} \to Z + X) \times BR(Z \to ll)}$$

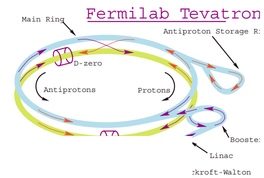
$$= \frac{\sigma(W)}{\sigma(Z)} \times \frac{\Gamma(Z)}{\Gamma(Z \to ll)} \times \frac{\Gamma(W \to l\upsilon)}{\Gamma(W)}$$

SM EW

Perturbative QCD

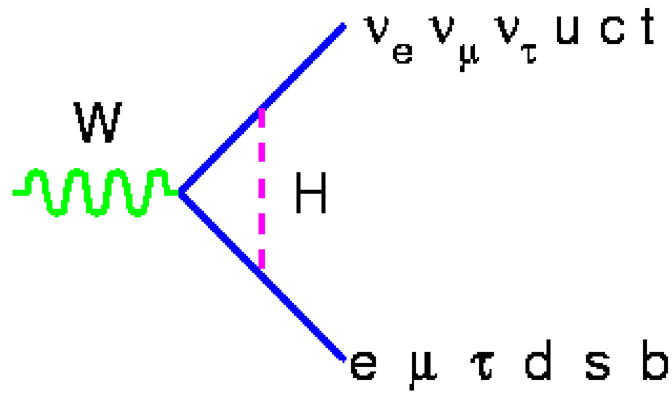
LEP measurement

W Width



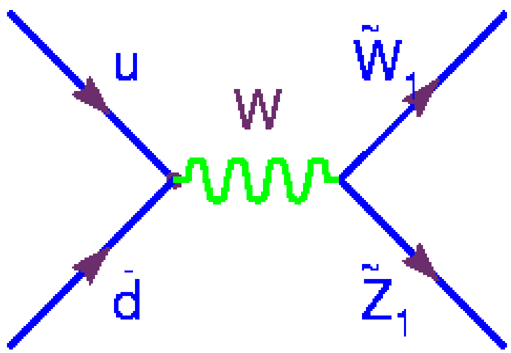
Indirect vs Direct W Width Measurements

Vertex Corrections: same for quarks and leptons, so cancel in BR($W \to l\nu$)



Rosner, Worah, Takeuchi, hep-ph/9309307

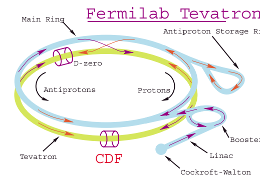
W decays:

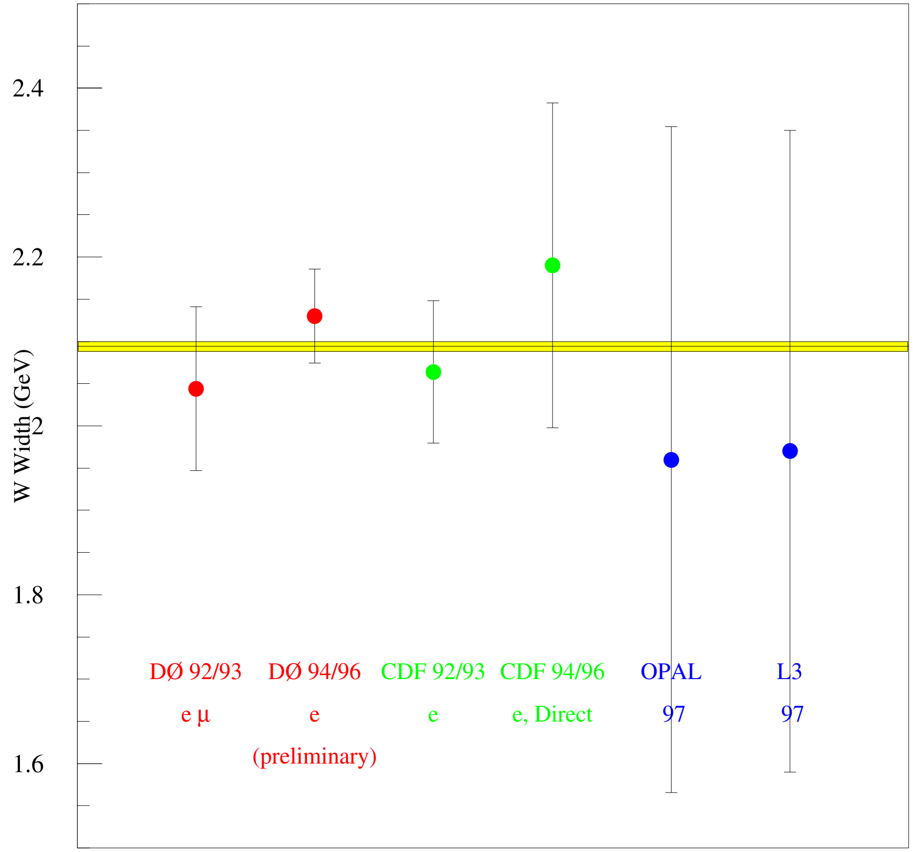


Kalinowski and Zerwas hep-ph/9702386

Indirect has no sensitivity to corrections to the coupling of the W to fermions, but is sensitive to possible non-standard model decay modes of the W.

W Width

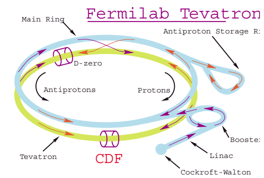




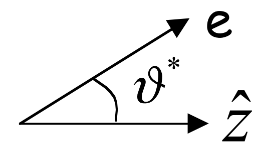
D0 (e + μ), 1b	2.130 ± 0.030 ± 0.052 GeV
D0 (e + μ), 1a	2.044 ± 0.097 GeV
CDF (e), 1a	2.064 ± 0.060 ± 0.059 GeV
CDF (e, direct), 1b	2.19 ± 0.17 ± 0.09 GeV
OPAL (1997)	1.96 ± 0.34 ± 0.20 GeV
L3 (1997)	1.97 ± 0.38 GeV

(Preliminary)

W Decay Distribution



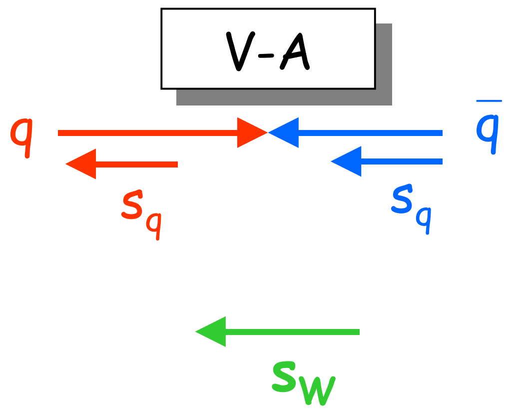
Angular distribution of electron in W rest frame:

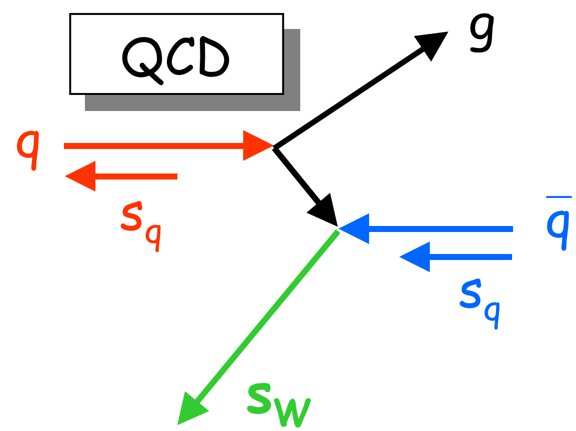


Collins-Soper frame

$$\text{Pure V-A:} \quad \frac{d\sigma}{d\cos\vartheta^*} \propto (1 + P(W)\cos\vartheta^*)^2$$

NLO QCD corrections to production modify this distribution:

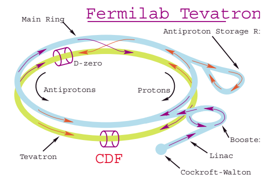




$$\text{V-A + QCD:} \quad \frac{d\sigma}{d\cos\vartheta^*} \propto 1 + P(W)\alpha_1\cos\vartheta^* + \alpha_2\cos^2\vartheta^*$$

Mirkes, NP B387, 3 (1992) - $O(\alpha_s^2)$.

D0 method to measure α_2



- Infer cosθ* on a statistical basis from probability function:
  - Define

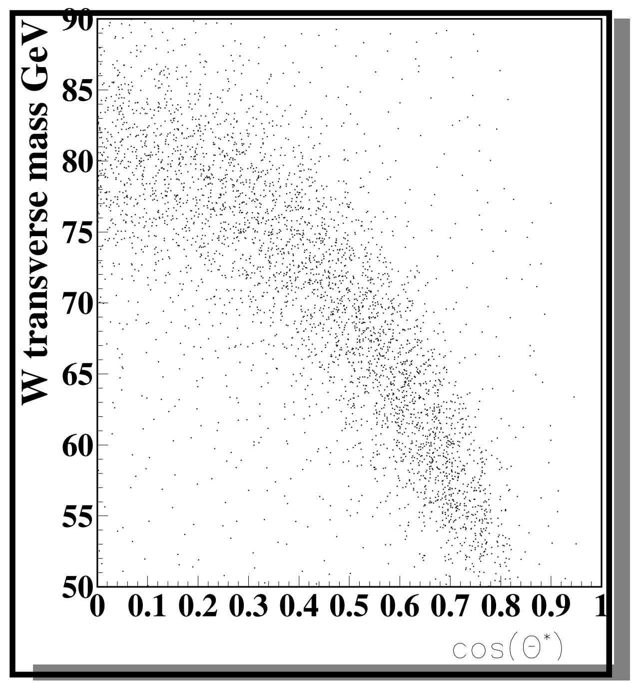
$$f(m_T, \cos\vartheta^*) = \frac{1}{N} g(m_T / \cos\vartheta^*) h(\cos\vartheta^*)$$

Bayesian method:
(statistical correlation between kinematic variables)

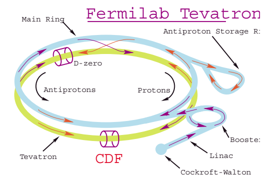
- For each $P_T(W)$ bin, plot background subtracted $m_T(W)$ and get

$$n_i = \sum_{m_{T_j}} N_{m_{T_j}} f(m_{T_j}, \cos\vartheta^*_i)$$

- Compare to n_i templates from MC
- Use log-likelihood to determine best value of $\alpha_2(P_T(W))$

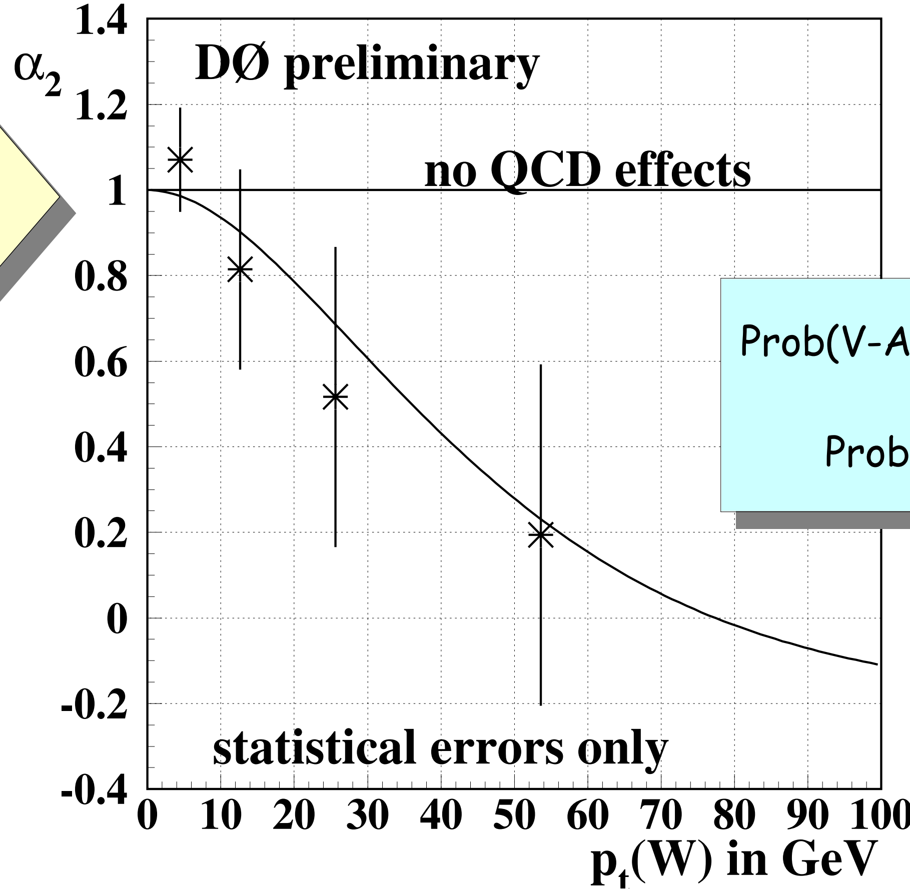


W Decay Distribution - α_2



$$\frac{d\sigma}{d\cos\vartheta^*} \propto 1 + P(W)\alpha_1 \cos\vartheta^* + \alpha_2 \cos^2\vartheta^*$$

V-A: $\alpha_2 = 1$



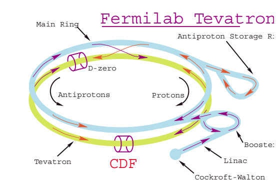
Prob(V-A + NLO QCD) = 87%

Prob(V-A only) = 7%

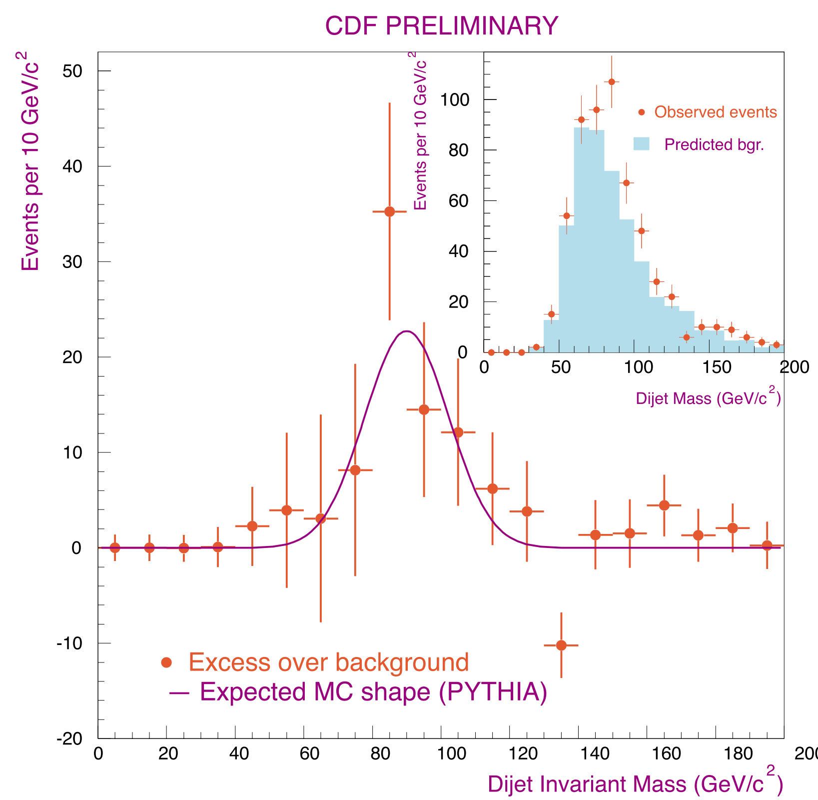
Connections between W,Z Production, QCD and New Physics:

Including this effect in W mass Monte Carlo: $\Delta M_W \sim 40$ MeV/c^2

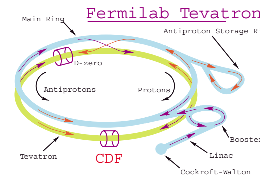
Observation of Z -> b $\bar{b}$



- Calibration signals for hadronic calorimetry and jet energy corrections are hard to come by, making searches that depend on good resolution difficult.
- The results shown here are thus significant in what they mean for precision EW measurements *as well as* for new particle searches (such as H->Wb$\bar{b}$).
- Study based on separate jets plus tracks w/ significant impact parameters
- **Z mass known** + low contamination from other flavors (MC study) => well constrained jet kinematics.
- This analysis has already been used by CDF to study jet energy corrections.
- Requires silicon-based trigger. Both CDF & D0 plan such triggers in Run II.



Tevatron Electroweak Physics: Summary



- **W, Z inclusive cross sections & W width** are in good agreement with SM.

  X-sect: Stat ⊕ Sys ~ 2%, Luminosity error ~ 4%, Theory error: ~ 3%

  -> (Can be used to *determine* luminosity in Run II.)

  W width measurements (direct and indirect) agree with SM

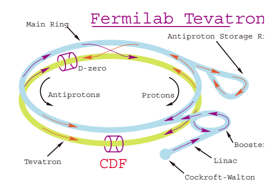
  -> Indirect measurement error ~ 3%

- **Drell-Yan cross-section, A_{FB}** measured in detail over broad kinematic range.
  - Provide comparisons with LO and NLO QCD, independent check of acceptance, etc.

- **W, Z p_T distributions** and **asymmetries** measured w/ good precision.
  - CDF & D0 data span wide range of p_T with uncertainties ~ 10 - 20%
  - Significantly constrain PDF's -> important for W mass and other analyses
  - Tests NLO QCD + resummation technique + non-perturbative models

- QCD NLO correction to **W decay distribution** confirmed w/ low statistics.
  - D0 measurement of α_2 vs P_T^W
  - Provides example of direct checking of NLOQCD terms
  - Will improve in Run II with improved statistics

Tevatron Electroweak Physics Summary



- **W mass** and other precision analyses may hit intrinsic limits in Run II, require new techniques.
  - W mass already ~ 0.05% measurement. Theory, experimental errors may cancel in ratio method, but this method needs more statistics.
  - Better understanding of detector, recoil modeling, and understanding of underlying event needed to make progress.

- **Higgs physics** and **beyond SM processes** can be constrained (or found!) through EW precision analyses, and must be approached through EW context.
  - M_W, M_Z, m_{top}, etc. form critical inputs into multivariate fitting and BSM physics limits.
  - Diboson radiation zero and triboson couplings provide other more direct probes
  - Need to do the best possible job with improving models, detector simulation, and basic measurements to provide confidence in our understanding of cross section,W, Z + jet production, kinematics etc. New physics *must* be studied in this context!

- **Z -> $b\bar{b}$ calibration signal** observed, strong implications for the future.
  - Will be an important method for reducing uncertainties on M_{top} and M_W from jet energy scales and for testing production models in Run II.