The W Angular Decay Distribution

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For the DØ Collaboration

Wine & Cheese Seminar Sept. 1, 2000

Outline

Introduction to QCD with W and Z Bosons

Some Measurements:

W/Z Cross Section, W width, Z p_T

W Angular Decay Distribution:

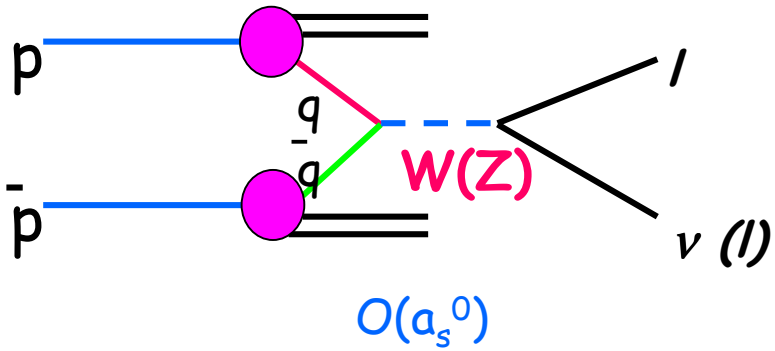
Monte Carlo

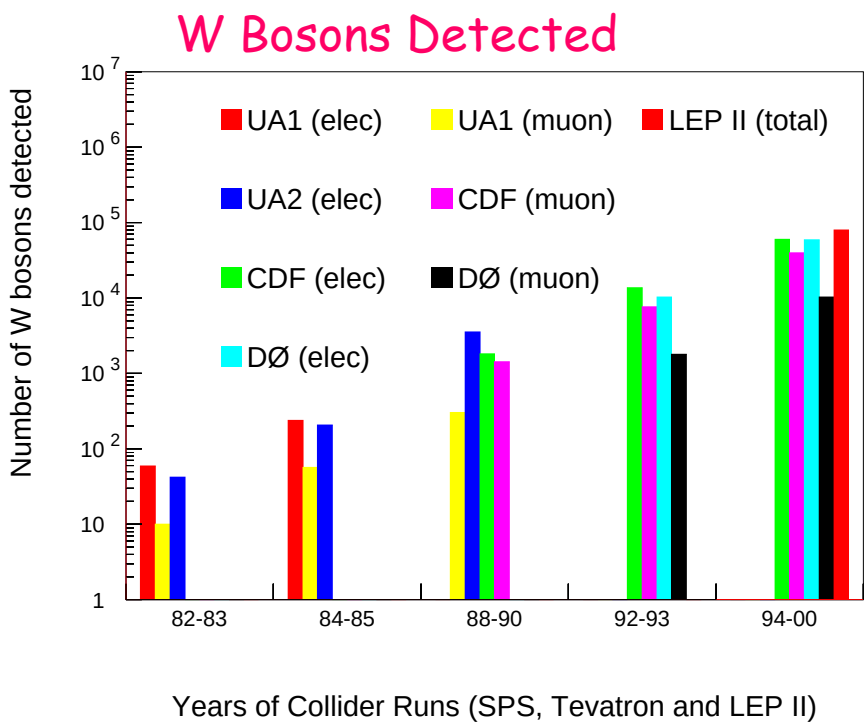
Data Selection

Backgrounds

Results

Introduction to W & Z Production at the Tevatron

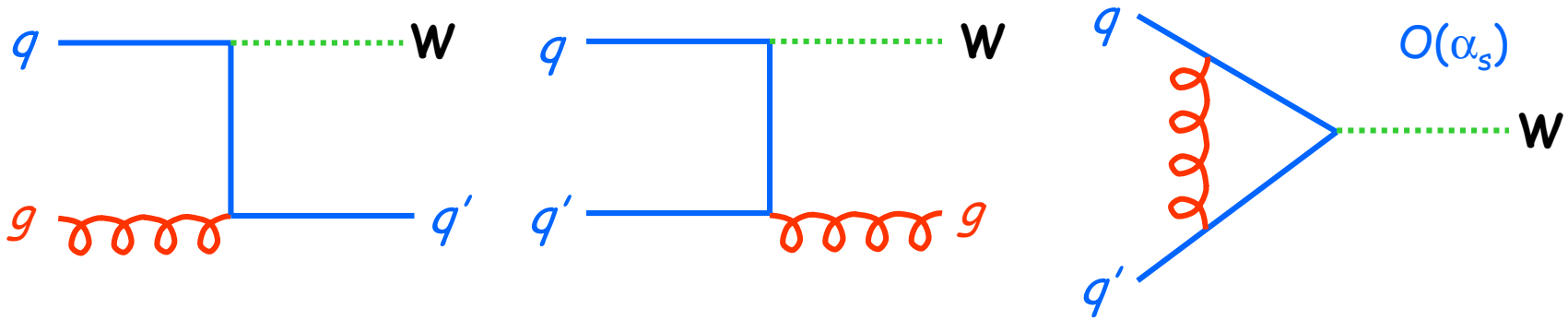




- Production dominated by $q\bar{q}$ annihilation
- Due to very large $p\bar{p} \rightarrow jj$ production, need to use leptonic decays
  - $W \rightarrow l\nu$ (BR ~ 11% per mode)
  - $Z \rightarrow ll$ (BR ~ 3% per mode)
- Distinctive event signatures
  - High P_T isolated leptons (e or μ)
  - One high P_T lepton + Missing E_T (W)
  - Two high P_T leptons (Z)
- Low backgrounds
- Large samples
- Well understood EW vertex

➔ Test QCD

QCD Corrections $O(\alpha_s)$



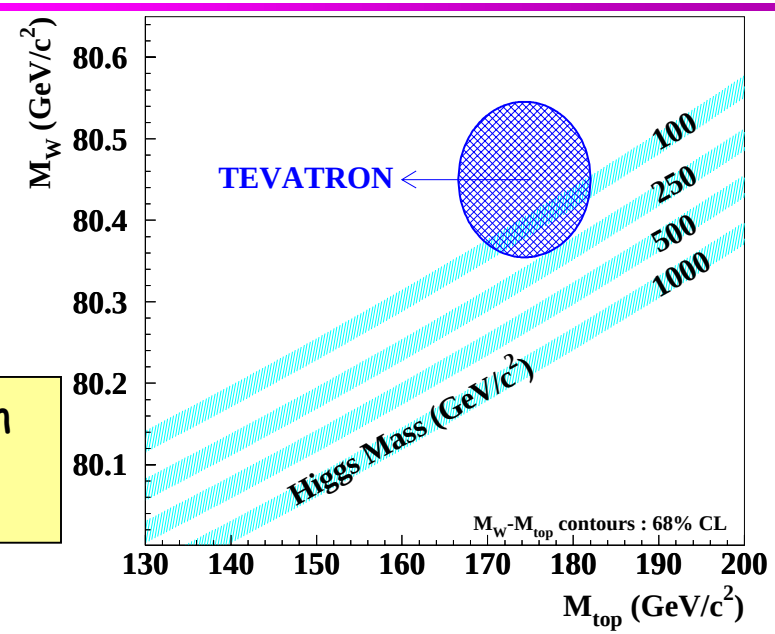
Modifications due to QCD corrections:

- **Boson produced with transverse momentum ($< P_T >$ ~ 10 GeV)**
- **Boson + jet events possible (W + 1 jet ~ 7%, E_T^{jet} > 25 GeV)**
- **Inclusive cross sections larger (K factor ~ 18%)**
- **Boson decay angular distribution modified**

Connections between W,Z Production, QCD and New Physics

W mass + top mass: Constrain Higgs mass

Current DØ $\delta M_W \sim 10$ -25 MeV from P_T^W model
$\delta M_W = 10$ MeV $\Rightarrow \delta M_H/M_H = 14\%$



Need precise model of W production and decay for Monte Carlos

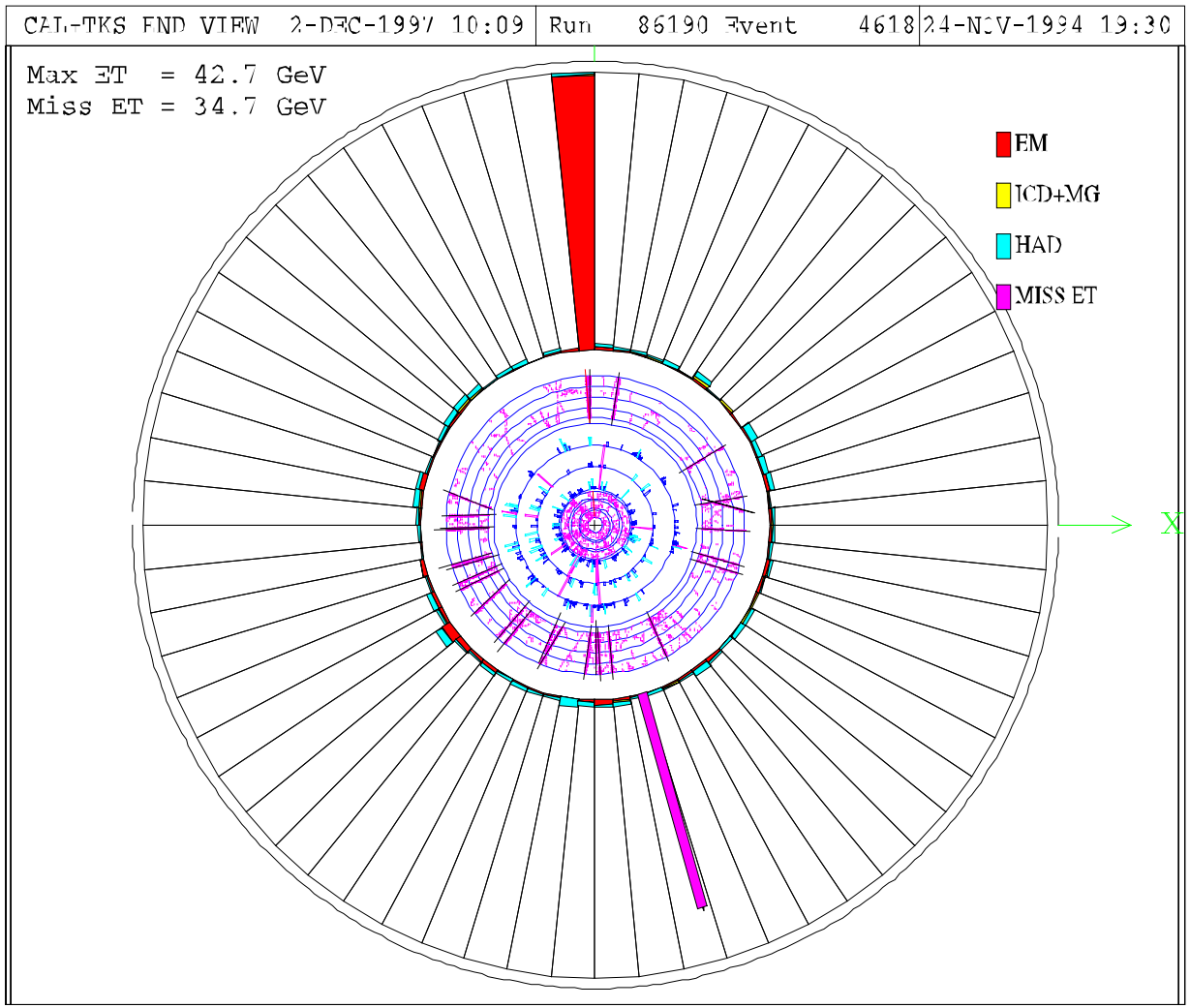
W mass measurements require low P_T^W

NLO QCD

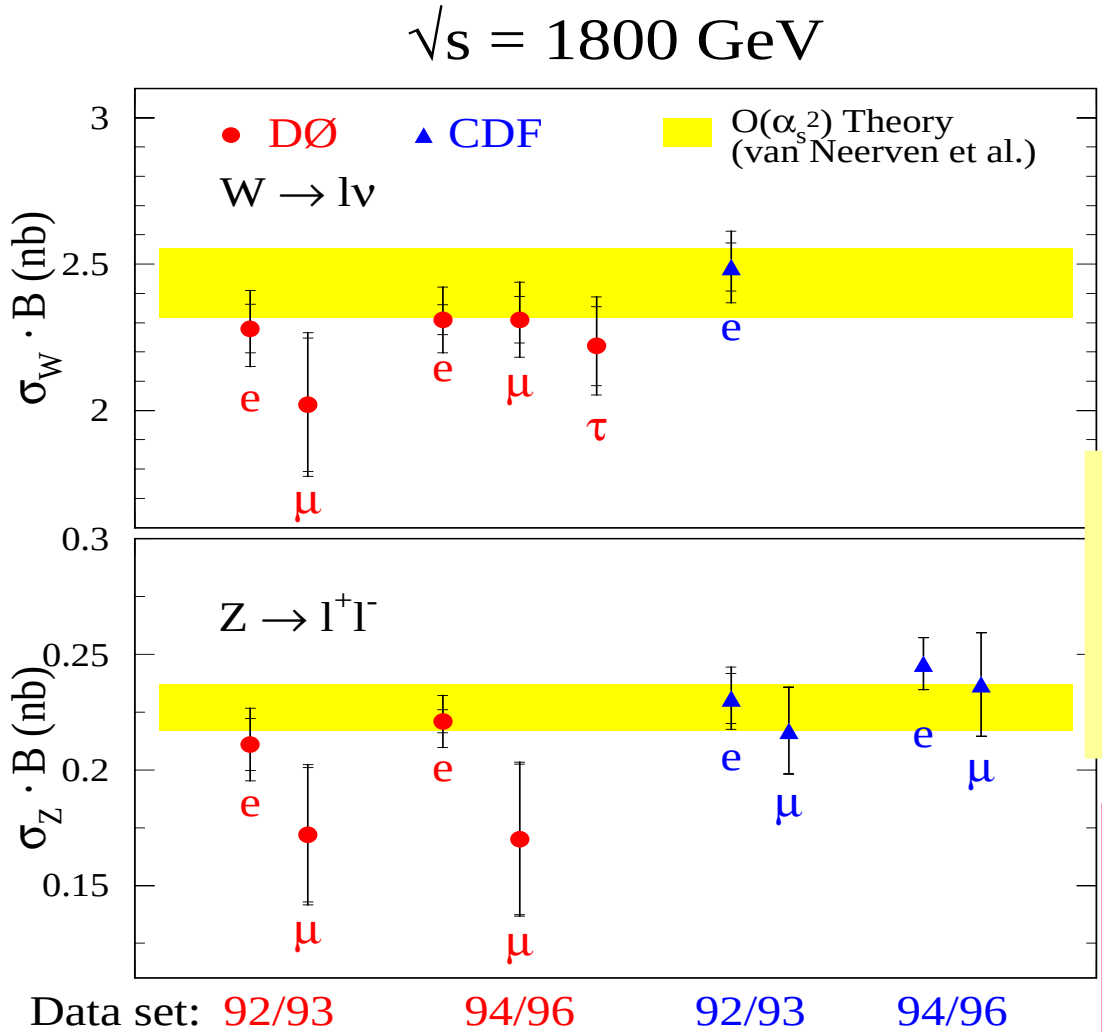
Resummation techniques

Non-perturbative QCD

W Event


CAL-TKS END VIEW 2-DEC-1997 10:09
Run 86190 Event 4618
24-NOV-1994 19:30
Max ET = 42.7 GeV
Miss ET = 34.7 GeV
EM
ICD+MG
HAD
MISS ET
X

Inclusive Cross Section



- **Measurement errors:**
  - Stat ⊕ Sys ~ 2%,
  - Luminosity error ~ 4%

- **Theory error:**

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

  Dominated by PDF's at NLO…

  (need NNLO)

L(D0) = 1.062 x L(CDF)
D0 uses world avg. $\sigma(p\bar{p})_{inel}$, CDF uses CDF measurement

W Width

Form ratio:

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

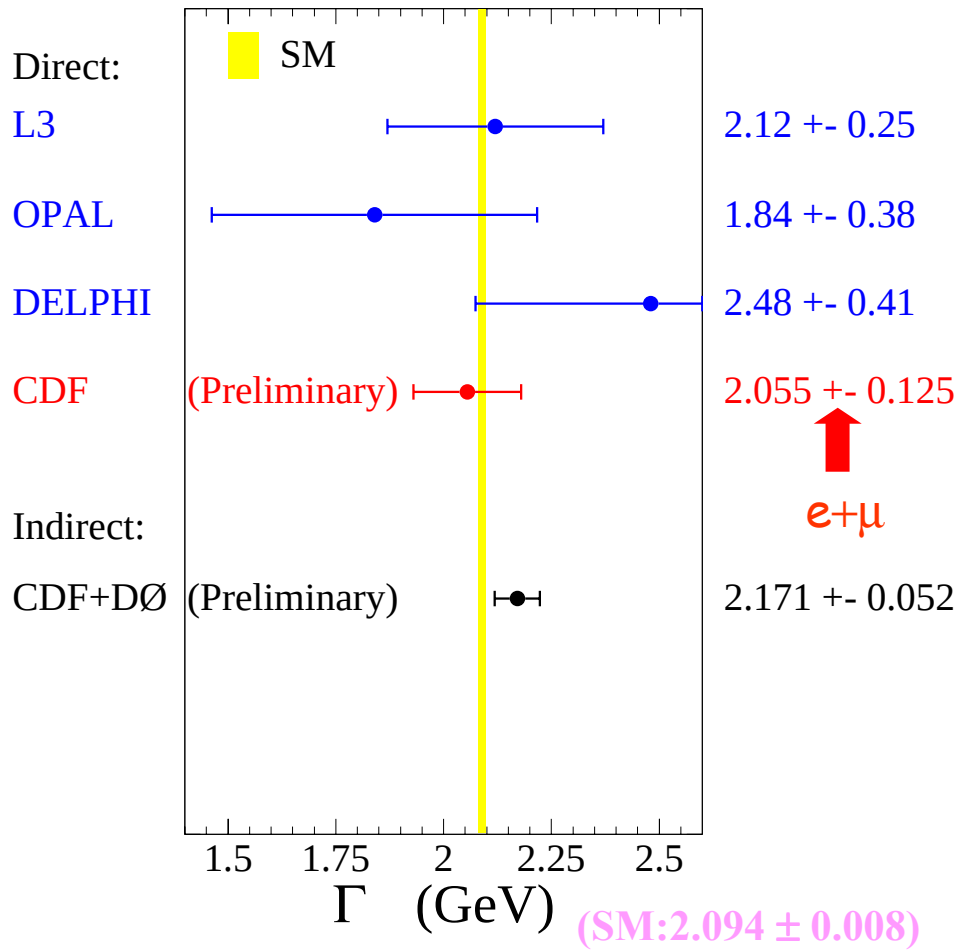
$$= \frac{\sigma(W)}{\sigma(Z)} \times \frac{\Gamma(Z)}{\Gamma(Z \to ll)} \times \frac{\Gamma(W \to l\upsilon)}{\Gamma(W)}$$

SM EW

Perturbative QCD

LEP

W Width



W, Z p_T Theory

$$\frac{d\sigma}{dp_T^2} \sim \frac{\alpha_s}{p_T^2} \ln\left(\frac{Q^2}{p_T^2}\right)\left[\nu_1 + \nu_{21}\alpha_s \ln^2\left(\frac{Q^2}{p_T^2}\right)\right]$$

- **Large P_T region** ($P_T \geq 30$ GeV): Use pQCD, $O(\alpha_s^2)$ calculations exist

  Ellis, Martinelli, Petronzio (83); Arnold & Reno (89);
  Arnold, Ellis, Reno (89); Gonsalves, Pawlowski, Wai (89)

- **Small P_T region** ($\Lambda_{QCD} < P_T < 10$ GeV): Resum large logs

  Altarelli, Ellis, Greco, Martinelli (84); Collins, Soper, Sterman (85)

- **Very low P_T region** ($P_T \sim \Lambda_{QCD}$): Non-perturbative parameters extracted from data

  b-space:

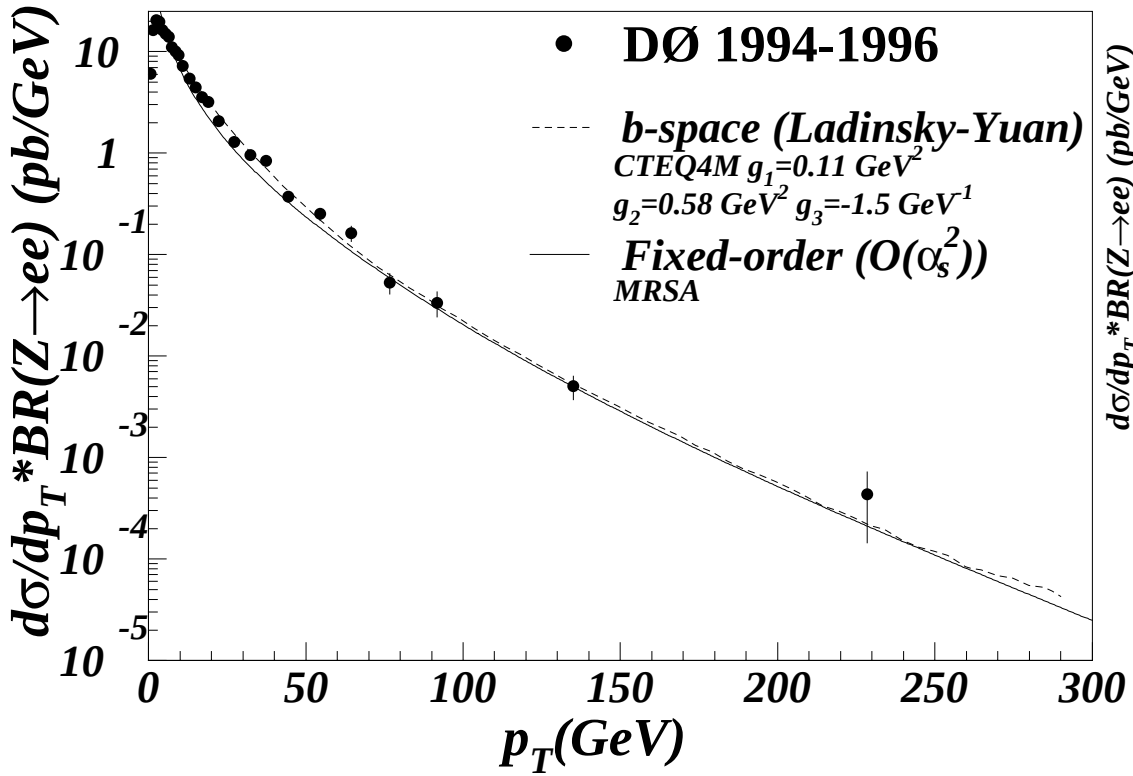
  Parisi-Petronzio (79); Davies-Stirling (84); Collins-Soper-Sterman (85); Davies, Webber, Stirling (85); Arnold- Reno-Ellis (89); **AK**: Arnold-Kauffan (91); **LY**: Ladinsky-Yuan (94)

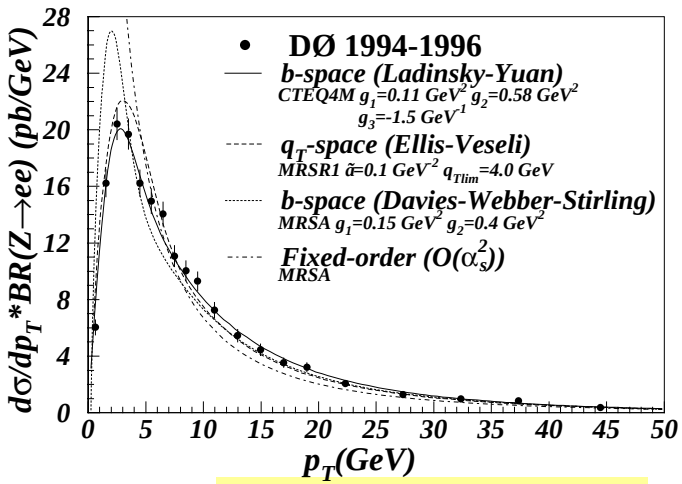
  p_T-space:

  Dokshitser-Diaknov-Troian (80); Ellis-Stirling (81); Altarelli-Ellis-Greco-Martinelli (84); Gonsalves-Pawlowksl-Wai (89); **ERV**: Ellis-Ross-Veseli (97); Ellis-Veseli (98)

Z p_T

Data corrected for resolution effects





Less dominated by detector res. at low p_T

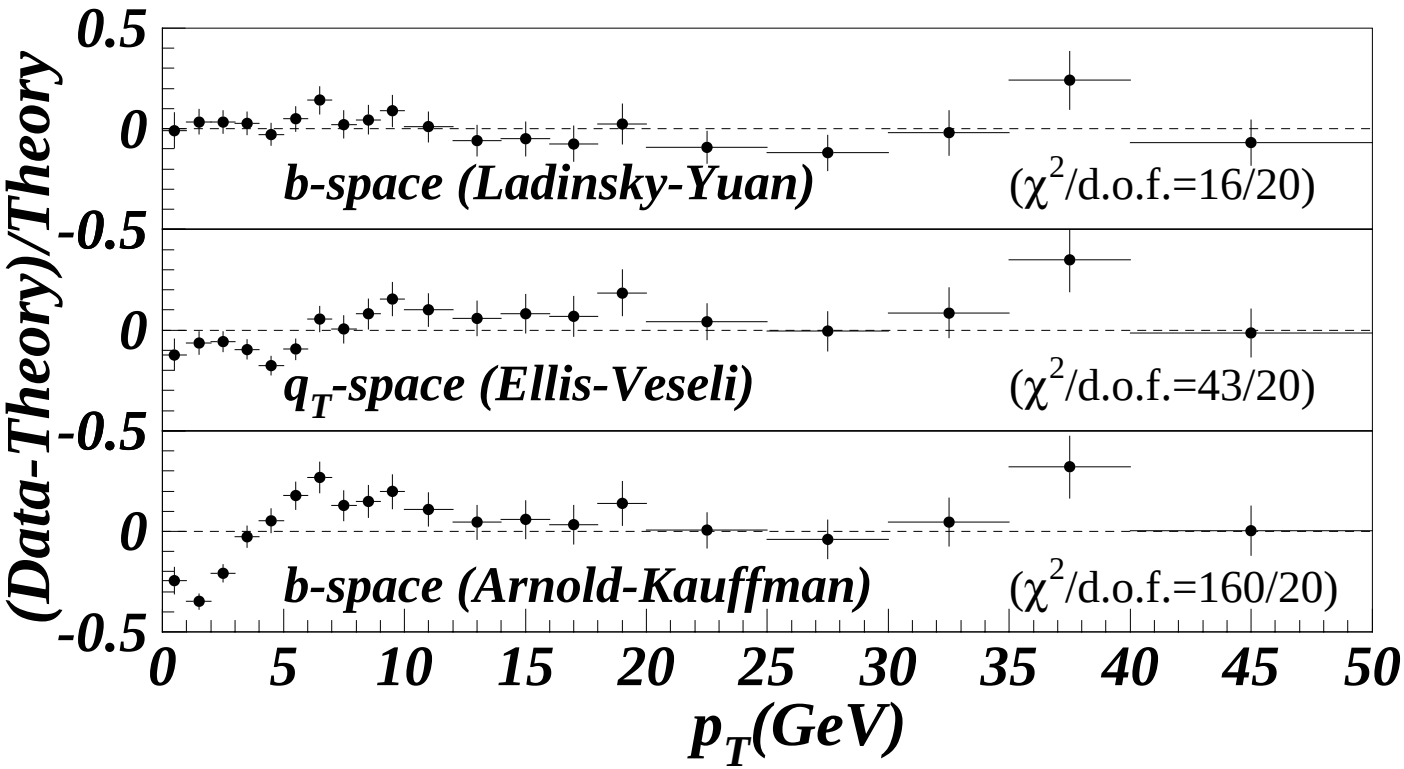
More sensitive to theory than W

PRD 61 (2000) + PRL 84 (2000)

W p_T in progress, results and W&C soon

Z p_T: Data-Theory/Theory

Compared to published parameters, could be refitted



W Angular Decay Distribution

V-A Theory: Angular Distribution in W Rest Frame:

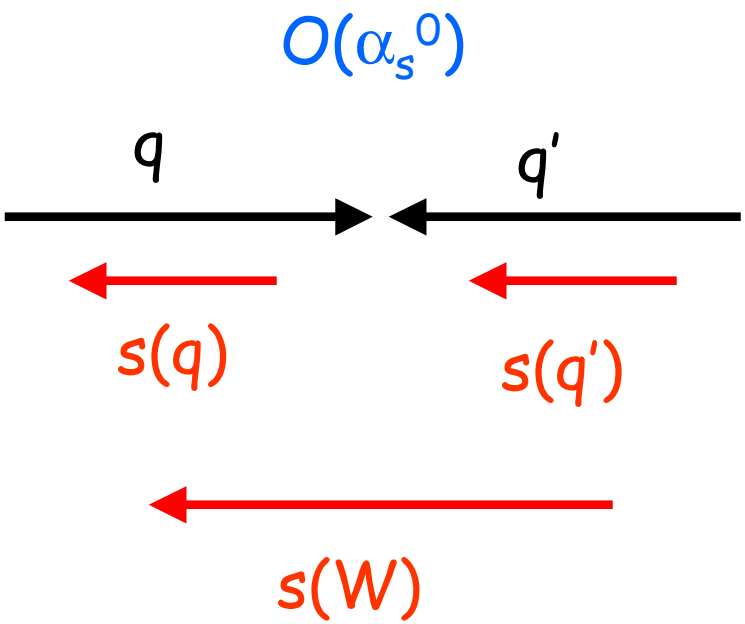
$$\frac{d\sigma}{d\cos\theta^*} \propto (1 \pm \cos\theta^*)^2$$

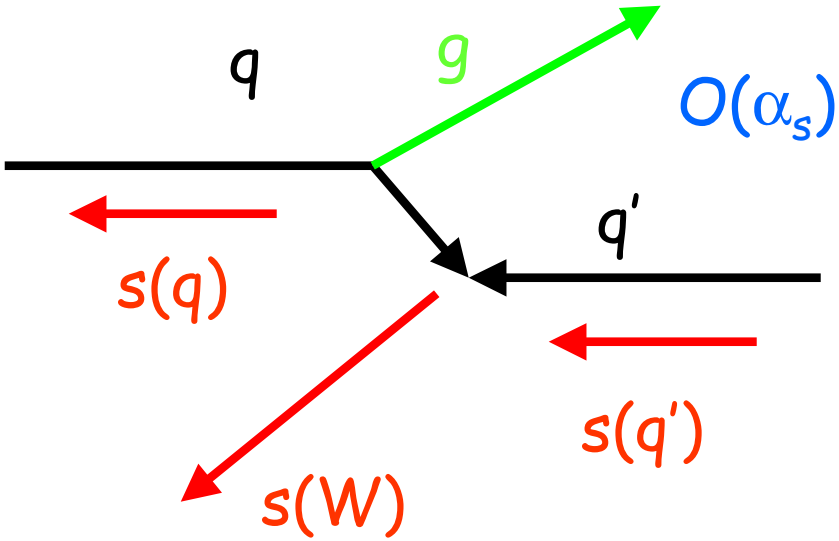
- Sign of Charge of W

QCD effects alter the Angular Distribution.

Calculation now done Collins-Soper-Frame.

W Angular Decay Distribution





Spin orientation altered by additional gluon.

Angular Distribution Theory

general

QCD

$$\frac{d^3\sigma}{dp_T^2 dy d\Omega^*} = \sum_\alpha g_\alpha(\theta,\phi)\frac{3}{16\pi}\frac{d^\alpha\sigma}{dp_T^2 dy}$$

Eight helicity terms

$$d\Omega^* = d\cos\theta^* d\phi^*$$

Integration over ϕ yields:

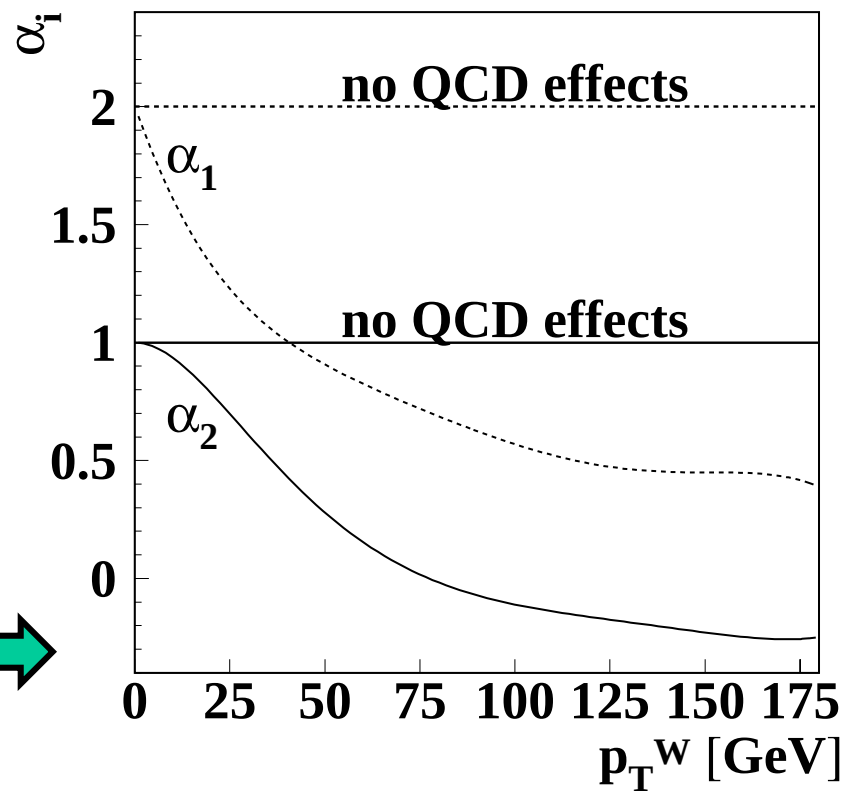
$$\frac{d\sigma}{dp_T d\cos\theta^*} = C(1 \pm \alpha_1(p_T)\cos\theta^* + \alpha_2(p_T)\cos^2\theta^*)$$

W Angular Decay Distribution

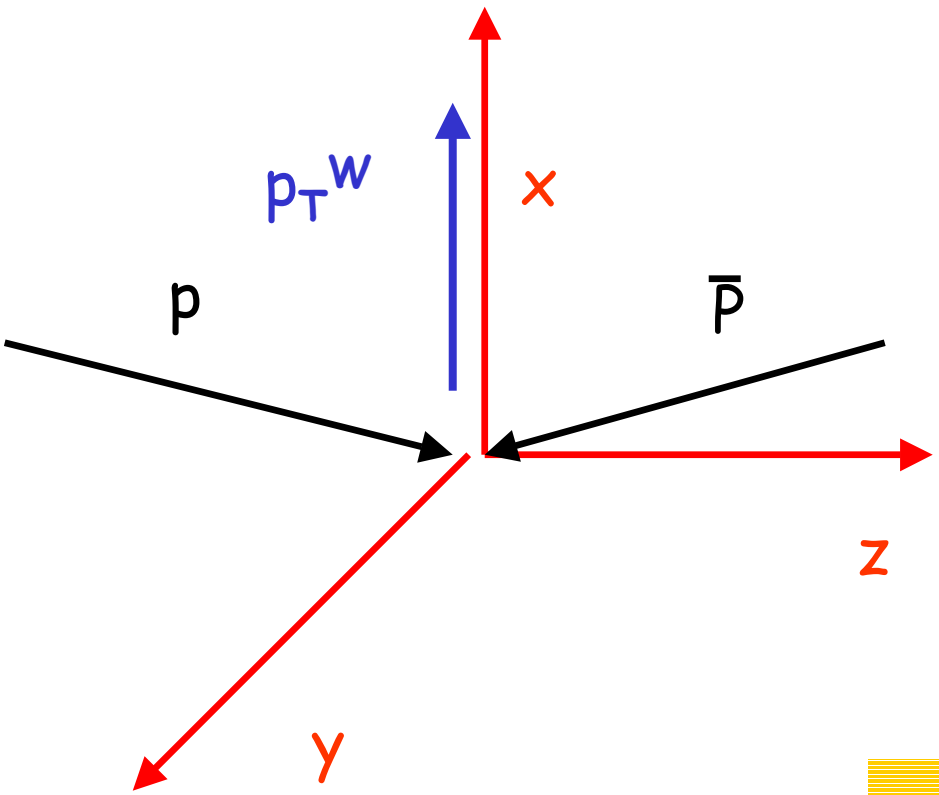
$$\frac{d\sigma}{dp_T d\cos\theta^*} \propto 1 \pm \alpha_1 \cos\theta^* + \alpha_2 \cos^2\theta^*$$

E. Mirkes. Nucl. Phys., **B387** 3 (1992)

$$\alpha_i = \alpha_i(p_T)$$



The Collins-Soper Frame



From Lab Frame to CS Frame:

- Rotation around z, orienting p_T^W along x
- Boost along z so that W is at rest wrt z
- Boost along x' so that W is at rest

Ambiguity in M_W and sign

$$\cos\theta^* = \pm\sqrt{1-\left(\frac{p_{T\,CS}^{E}}{\frac{1}{2}m_W}\right)^2}$$

W Angular Decay Distribution

We measure $\alpha_2(p_T)$

Independent test of QCD corrections

Spin Structure of W Production and Decay

Correction to W Mass Measurement ~40 MeV

Previous Measurement of $\alpha_2(p_T)$ in Run 1a by Manuel Martin, who developed many of the techniques used here.

Limited by statistics and low p_T^W =>

No distinguishing power

W Mass Monte Carlo: Production

Factorize:

$$\frac{d^5\sigma}{dm\,dp_T\,dy\,d\phi\,d\varepsilon} = \frac{d\sigma}{dm}\cdot\frac{d^2\sigma}{dp_T\,dy}\cdot\frac{d\sigma}{d\phi}\cdot\frac{d\sigma}{d\varepsilon}$$

Polarization

$$\frac{d\sigma}{dm} = PL(m)\cdot\frac{m}{(m^2-M^2)^2+m^4\Gamma^2/M^2}$$

Width

True Mass

Parton Luminosity

$$PL(m) = \frac{e^{-\beta\cdot m}}{m}$$

ß from fits to Herwig + PDFLIB W mass spectrum

W Production cont.

- Sign of W charge is chosen randomly
- For valence quarks, this determines polarization
- For sea-sea interactions (20%), choose polarization randomly

W Transverse Momentum

$$\frac{d^2\sigma}{dp_T dy} \propto \int \frac{d^2 b}{(2\pi)^2} e^{\bar{b}\cdot p_T} W(b_*) e^{-S_{NP}(b)}$$

Perturbative part

$$b_* = \frac{b}{\sqrt{1 + b^2 / b_{\max}^2}}$$

cutoff

Ladinski-Yuan:

$$S_{NP} = g_1 b^2 + g_2 b^2 \ln\left(\frac{Q}{2Q_0}\right) + g_1 g_3 \ln(100 x_A x_B)$$

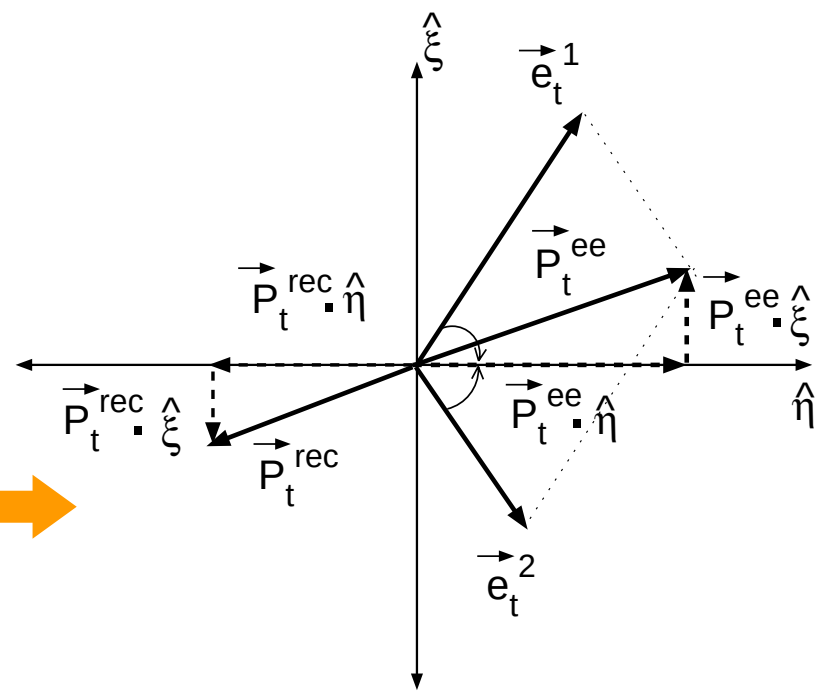
W Decay

- W Bosons are decayed in Collins-Soper Frame, using the QCD prediction for the angular distribution
- Generate Radiative Decays
- Boost to Lab Frame
- Calculate derived quantities
- Apply Detector Smearing

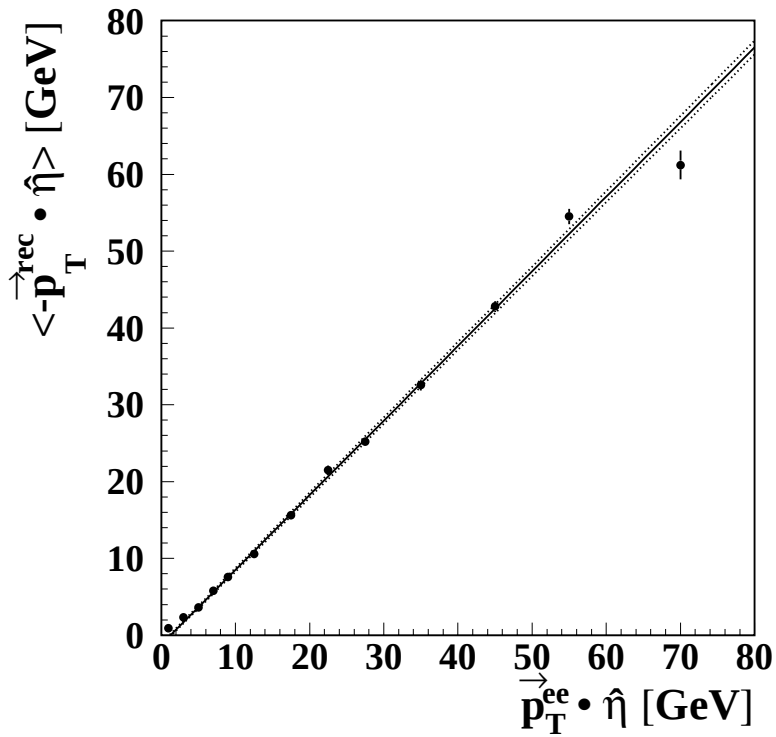
Hadronic Scale

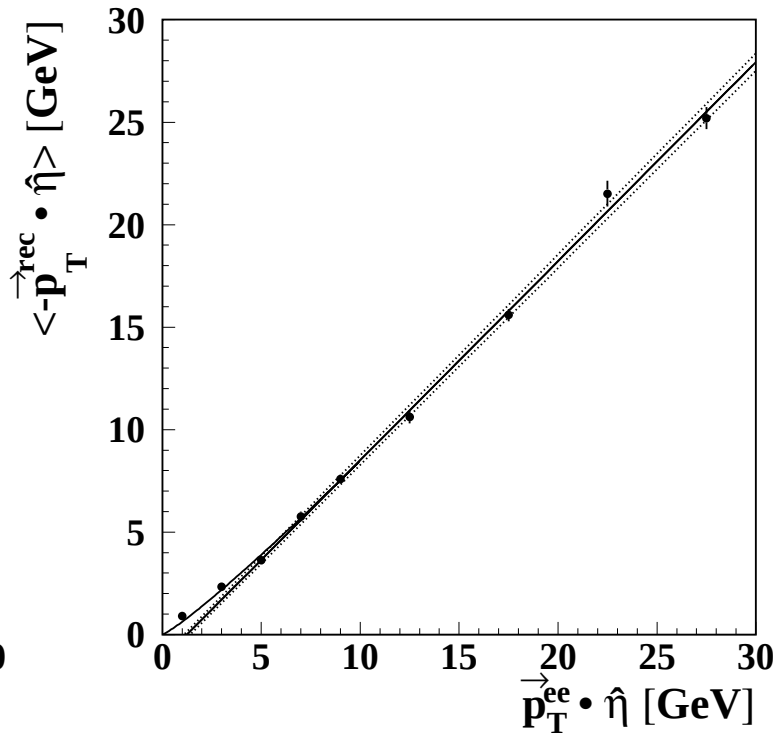
- Scale of hadronic recoil different from EM energy scale: Includes energy from had. Showers, energy loss in uninstrumented regions of calorimeter.

- Determined from $Z \rightarrow ee$ events: Z p_T either from two electron system (p_T^{ee}) or from recoil activity (- p_T^{rec}).
- Project transverse momenta onto η direction.



Hadronic Scale





$$p_{T,\eta}^{rec} = \alpha_{had}\, p_{T,\eta}^{ee} + \beta_{had}$$

$$p_{T,\eta}^{rec} = (\gamma_{had} \ln p_{T,\eta}^{ee} + \delta_{had})\, p_{T,\eta}^{ee}$$

Linear scale for p_T > 10 GeV.

Log scale for p_T < 10 GeV.

Hadronic Resolution

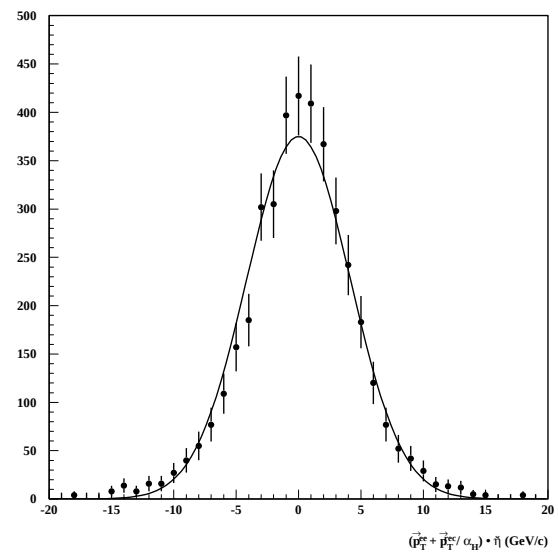
Resolution for hard component of recoil, u_T:

$$\sigma_{rec} = s_{rec}\sqrt{u_T}$$

Soft component of recoil modeled by adding $\not{E}_T$ from Minimum Bias events scaled by tunable factor α_{mb}.

Plot η balance resolution in bins of $p_T^{\eta}(ee)$ and calculate χ^2.

$$(\vec{p}_T^{\,ee} + \vec{p}_T^{\,rec} / \alpha_H) \cdot \hat{\eta}$$

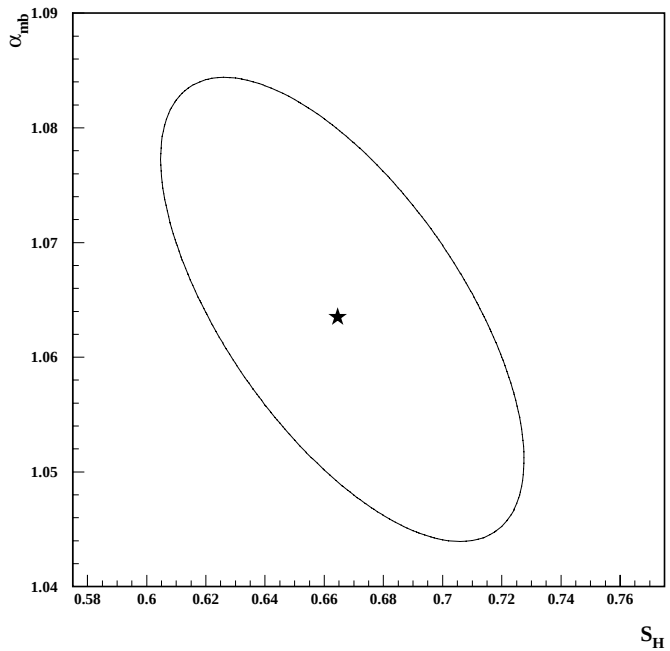


Hadronic Resolution

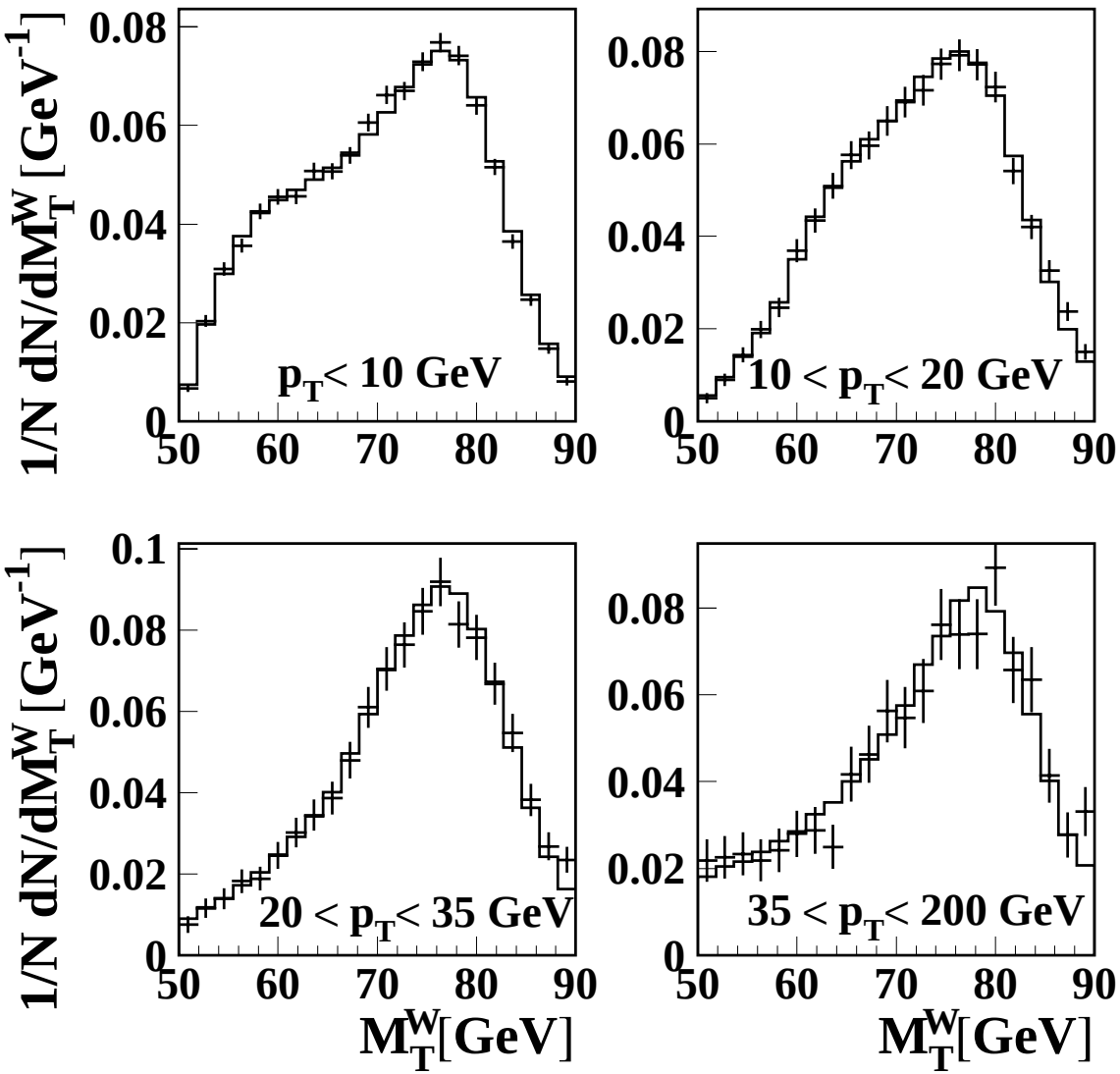
$$\chi^2 = \sum_{p_\eta(ee)bins} \left(\frac{\sigma_{ele} \oplus \sigma_{s_{rec}} \oplus \sigma_{\alpha_{mb}} - \sigma_{data}}{\delta_{data}} \right)^2$$

Vary α_{mb} and s_{rec} separately

Plot χ^2+1 ellipse for α_{mb} and S_{rec}.

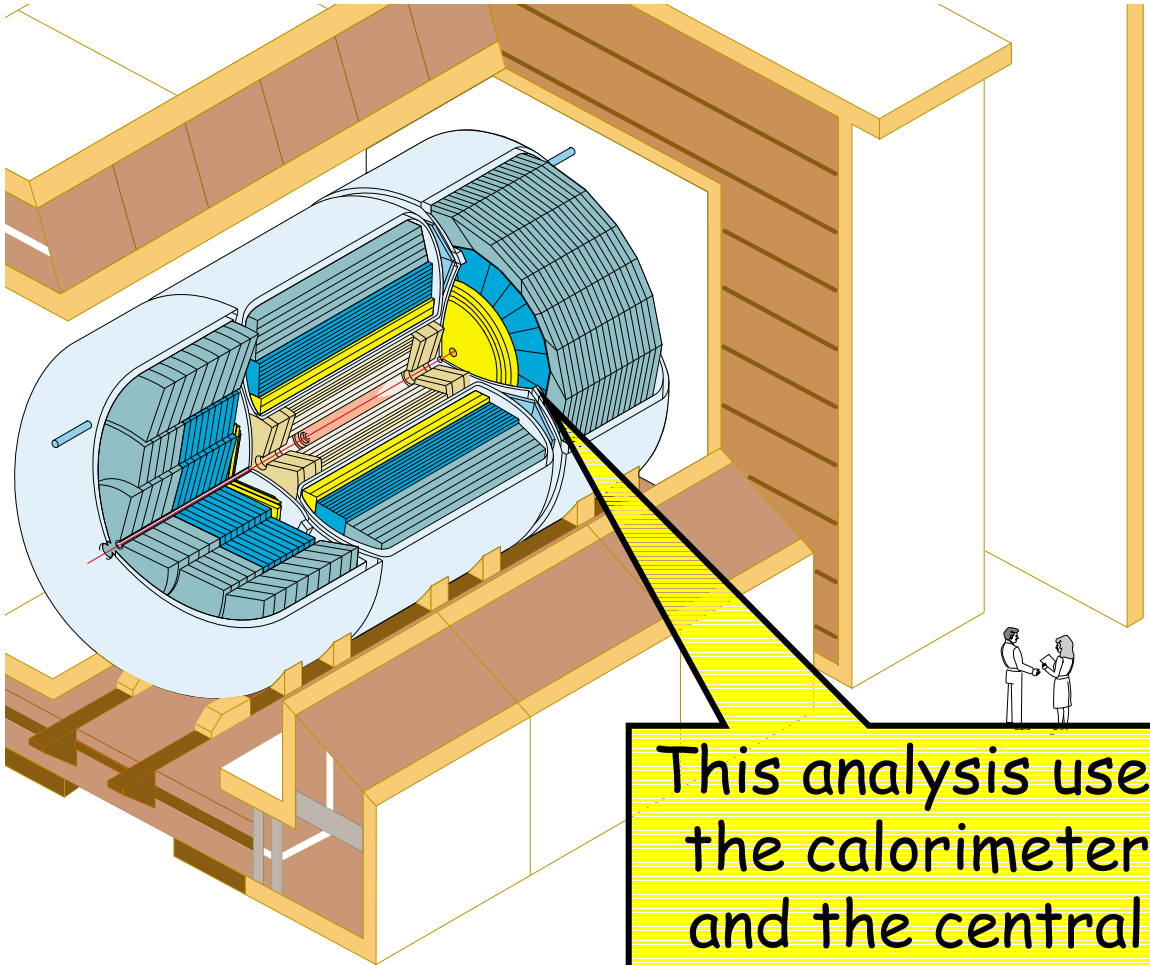


Transverse Mass Distributions



Data and Monte Carlo agree

The DØ detector



DØ Detector

This analysis uses the calorimeter and the central detector

Tracking:

σ(vertex)=6mm

$\sigma(r\phi)$ = 60μm (VTX)

= 180 μm (CDC)

= 200 μm (FDC)

Calorimeter:

$|\eta|<4$

$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

$\sigma(EM) = 15\%/E^{1/2}$

$\sigma(had) = 50\%/E^{1/2}$

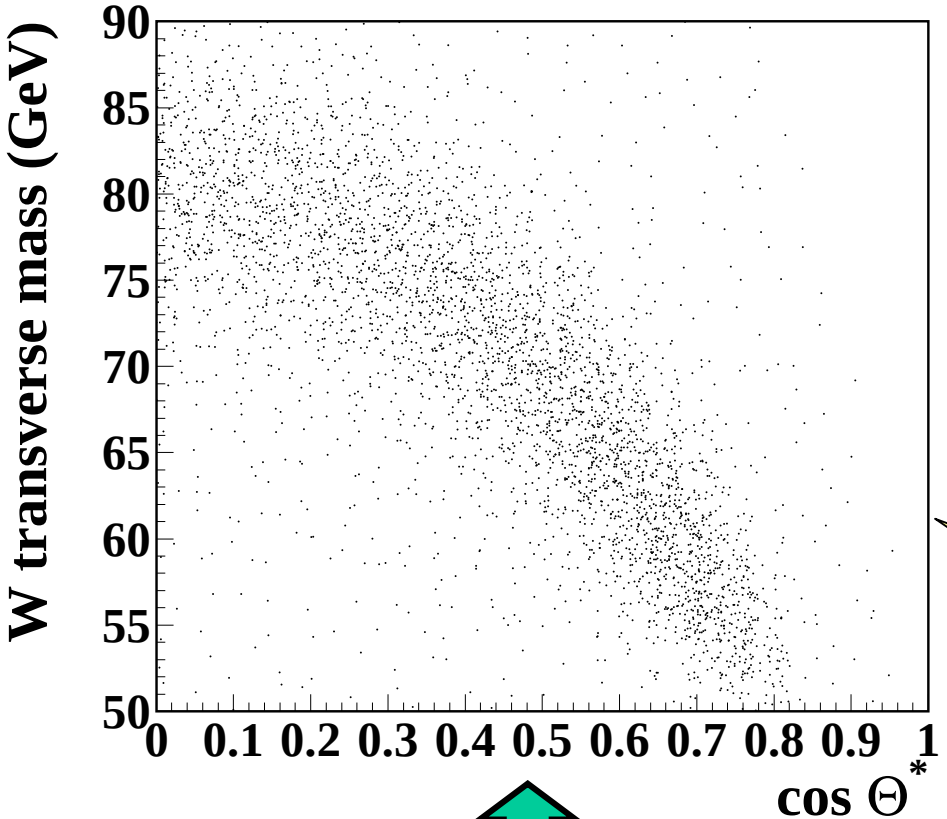
Data Selection

- Electron: E_T>25 GeV, $|\eta|$ <1.1
- Missing E_T>25 GeV
- Reject Events with a second electron and invariant mass close to Z mass: 75 GeV < M_{ee} < 105 GeV.

→41173 events

- This analysis uses 50 GeV <M_T<90 GeV.

W Angular Decay Distribution



angle cannot be measured directly use correlation with transverse mass

M_W sensitive to angular distribution

From Monte Carlo

W Angular Method

Use Bayesian approach:

From Monte Carlo

Prior from V-A theory: $1+\cos^2\theta^*$.

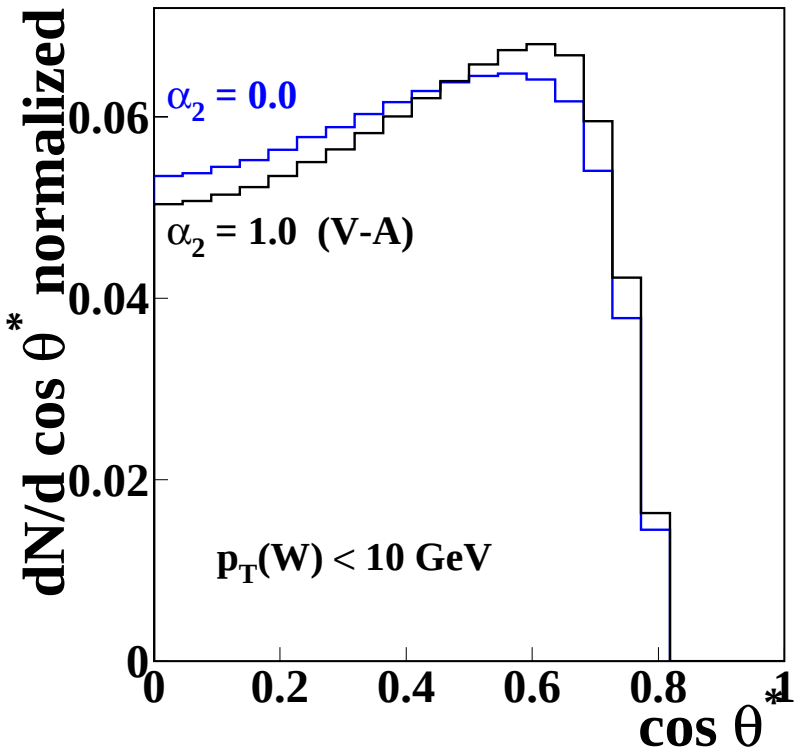
$$p(\cos\theta^* \mid M_T^W, p_T^W) = \frac{p(M_T^W \mid \cos\theta^*, p_T^W)\, p(\cos\theta^*)}{N}$$

Multiply with M_T^W distribution to obtain angular distribution:

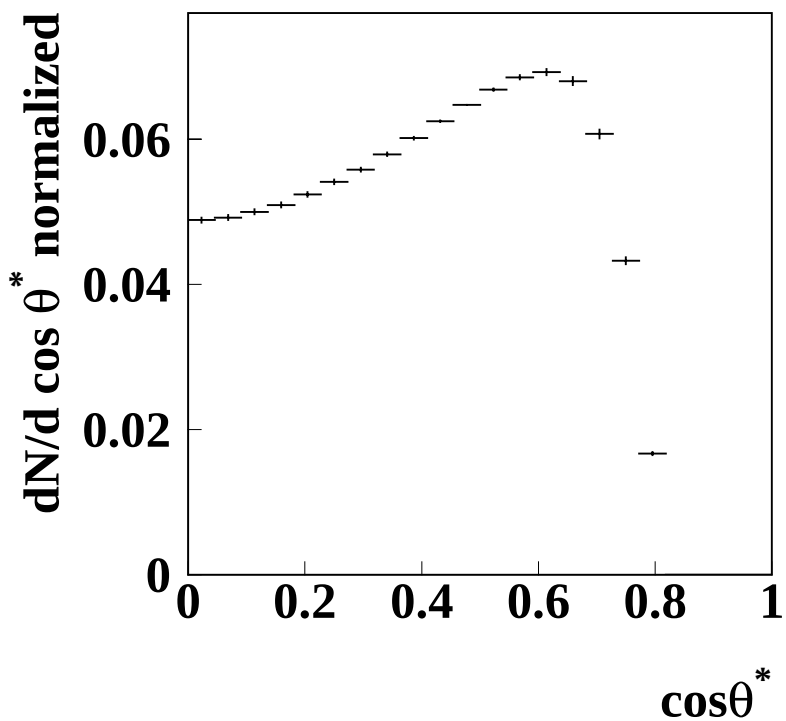
$$f(\cos\theta^*, p_T^W) = \sum_{i=M_T\ bins} N_i p_i(\cos\theta^* \mid M_T^W, p_T^W)$$

W Angular Method

Use this method to generate cos θ* templates (from MC):



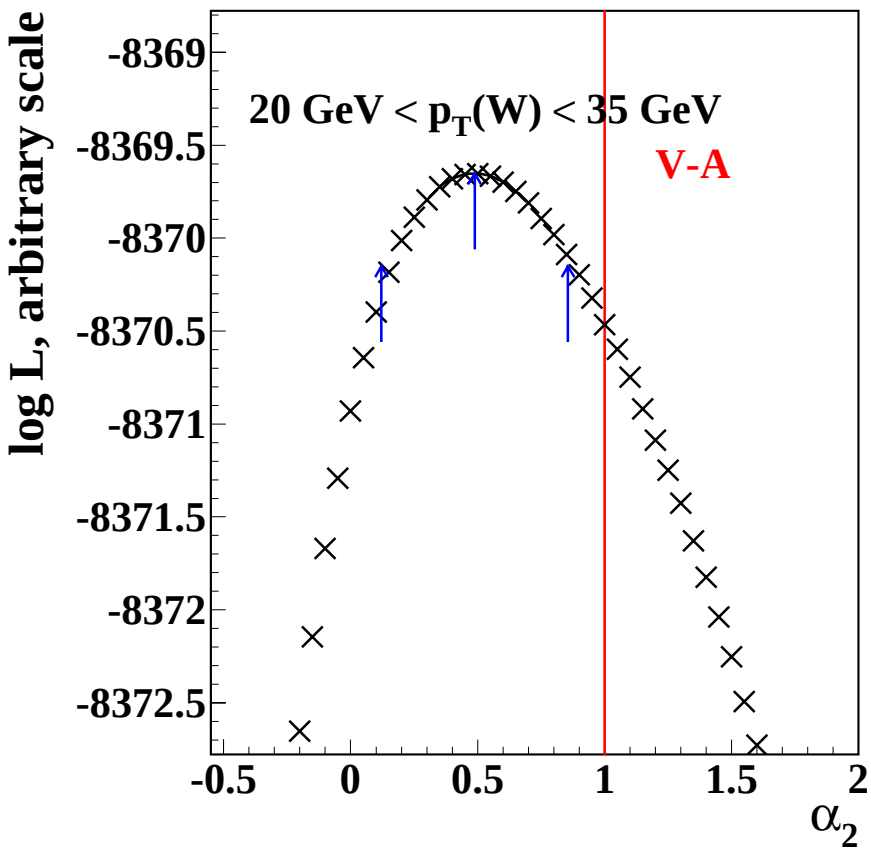
Use same method to obtain cos θ* distribution from data:



W Angular Method

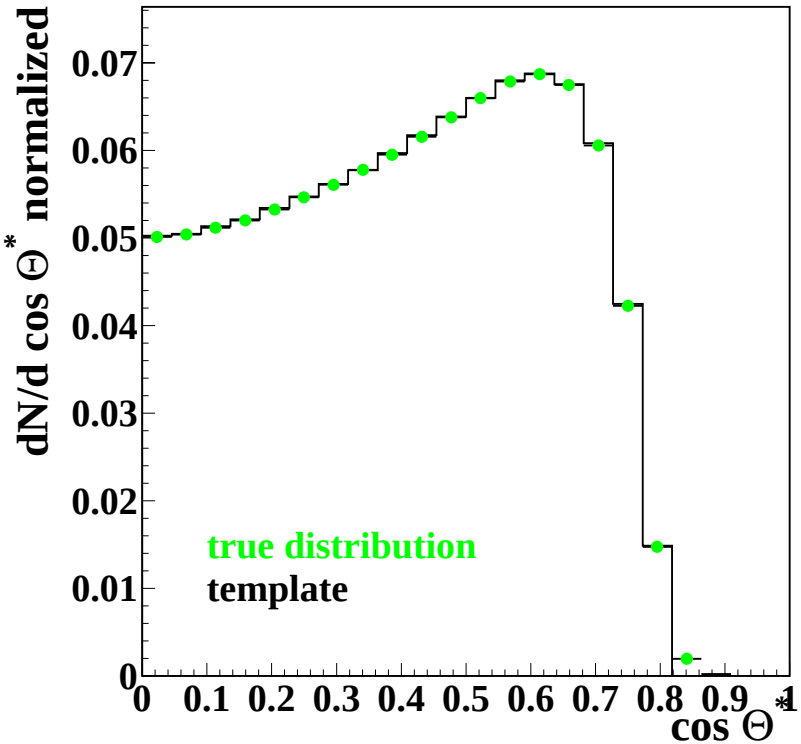
Compare measured angular distribution to templates using Log L method:

$$\log L = \sum_{\cos\theta^* bins} n_i \log P_i$$

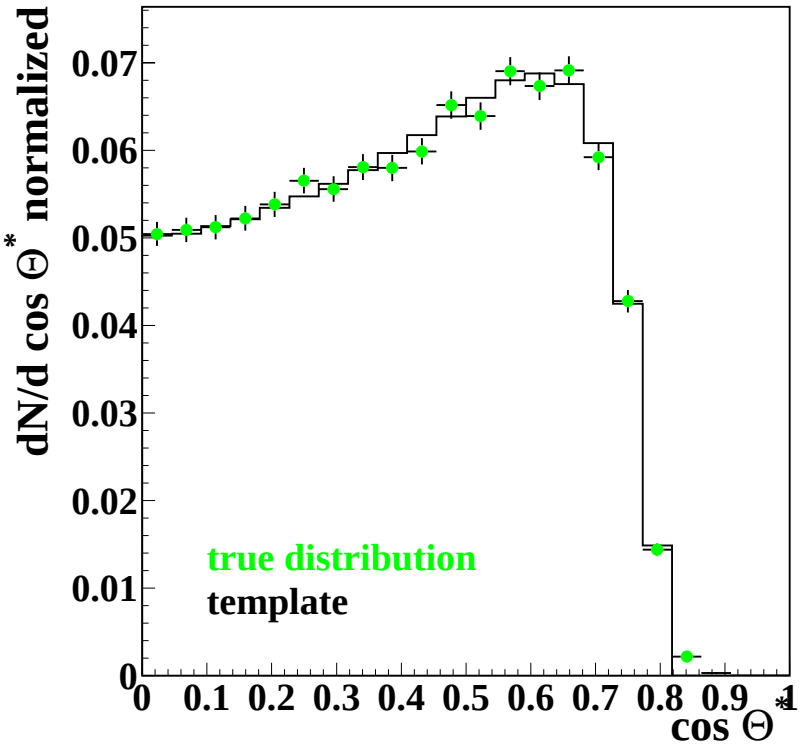


Monte Carlo Closure Test

Large Statistics



Statistics Scaled to Data



Method works!

Backgrounds

QCD multijet: One jet looks like an electron + energy mismeasured → missing E_T.

Determined from data. Rate ~1%

$Z \rightarrow ee$, one electron lost in uninstrumented or underinstrumented region of the calorimeter. Determined from Herwig Monte Carlo. Rate ~1%.

ttbar → WWbb, WW → evjj from Herwig Monte Carlo. Rate ~0.2%.

$W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$: Included in Monte Carlo. Rate ~2%.

QCD Multijet Background

Matrix Method: Divide W sample M with looser cuts in P (pass) and F (fail). Can also divide in B (background) and R (real W's):

$$\begin{pmatrix} P \\ F \end{pmatrix} = \begin{pmatrix} \varepsilon_e & \varepsilon_j \\ 1-\varepsilon_e & 1-\varepsilon_j \end{pmatrix} \begin{pmatrix} R \\ B \end{pmatrix}$$

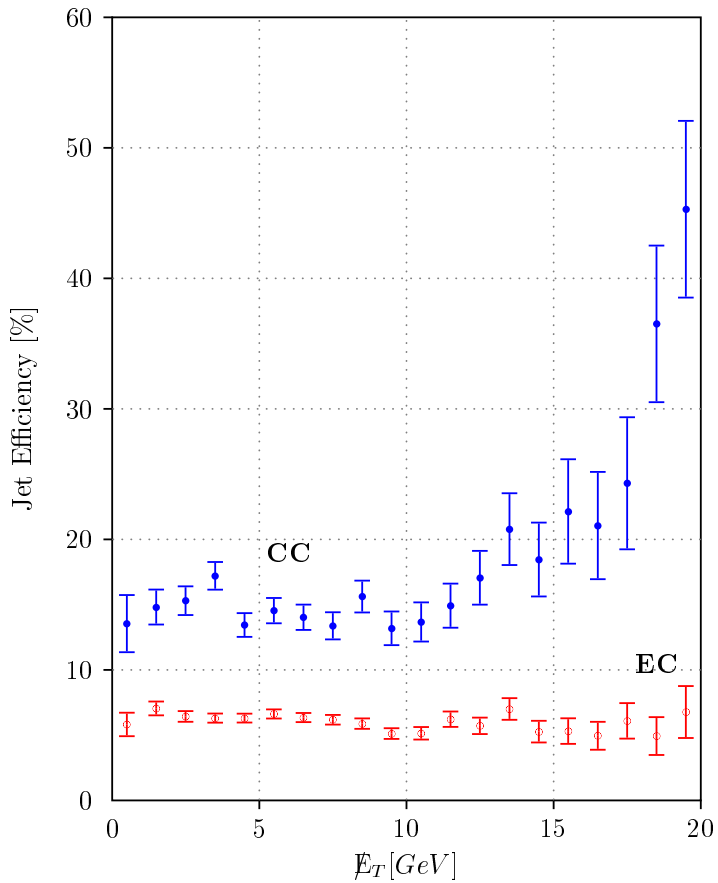
From Z → ee events

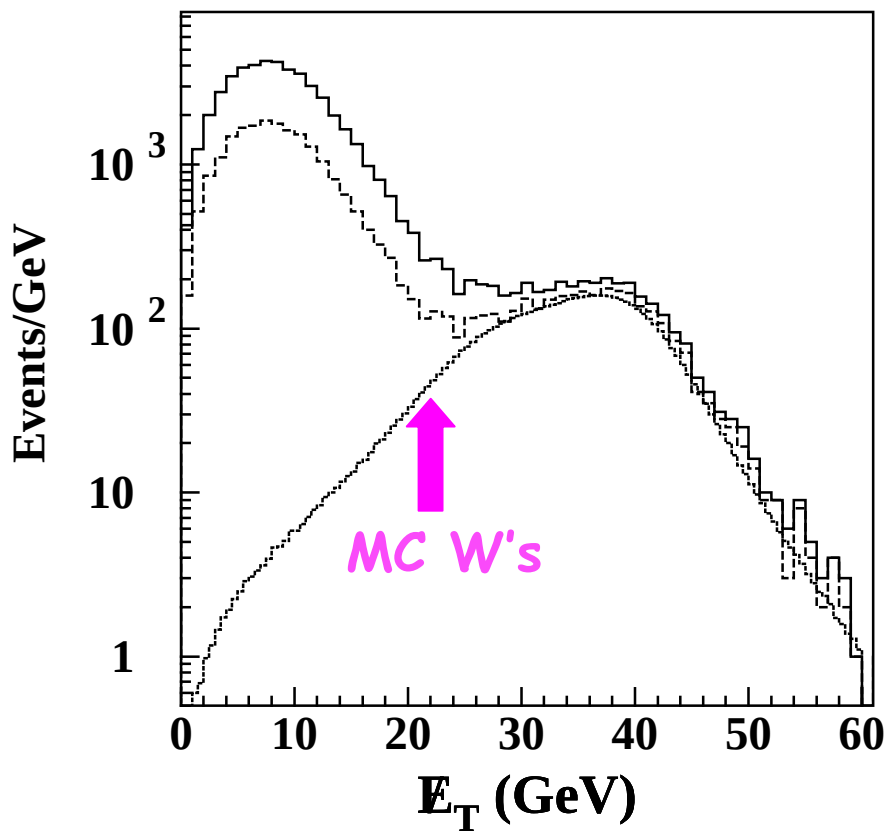
$$f_{QCD} = \frac{\varepsilon_j B}{P} = \frac{\varepsilon_j}{P} \cdot \frac{\varepsilon_e M - P}{\varepsilon_e - \varepsilon_j}$$

Efficiency for "fake" loose electrons to pass tight cuts

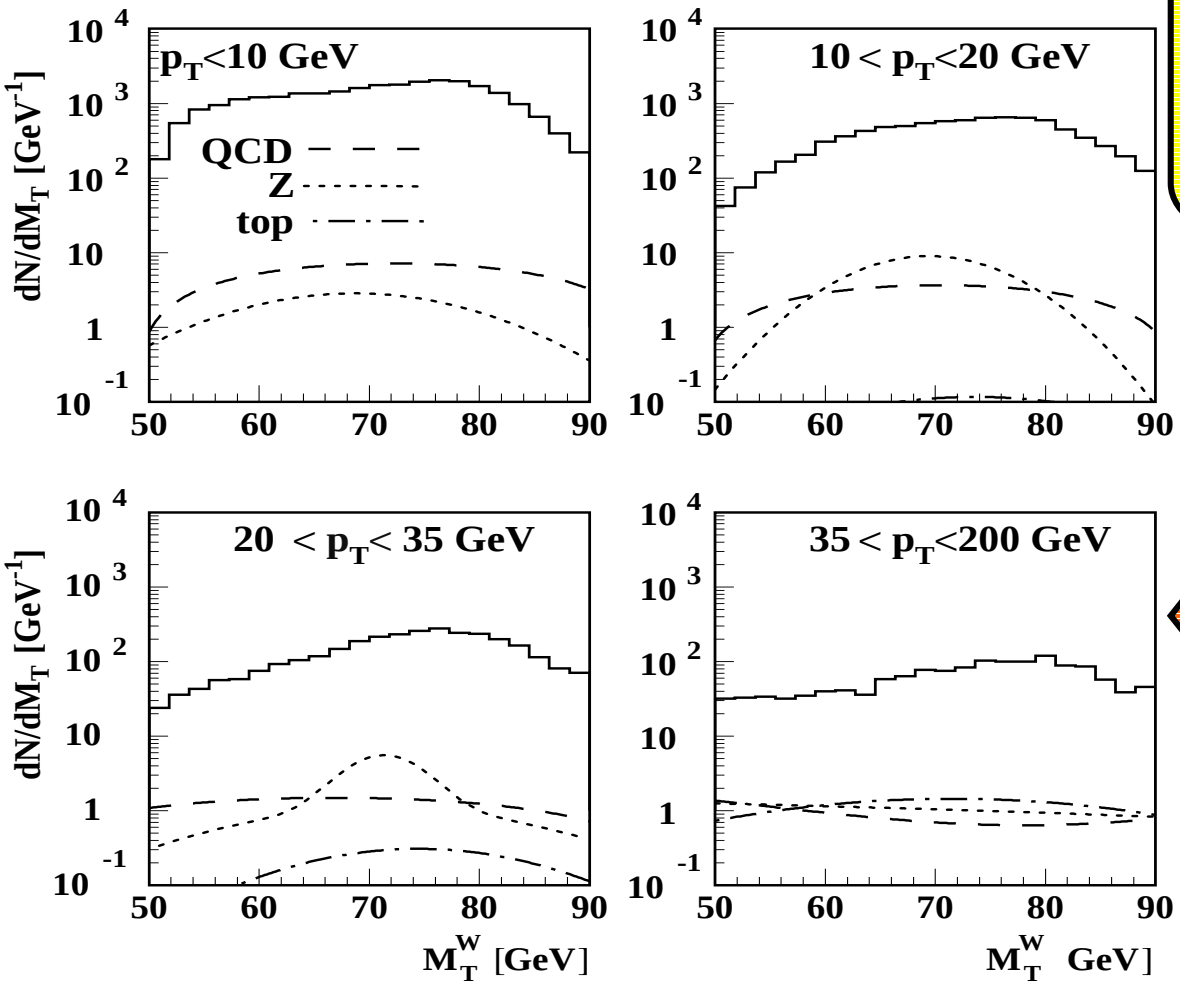
QCD Multijet Background

Jet efficiency ε_j calculated from data sample with anti-W cut: $\not{E}_T < 15$ GeV.





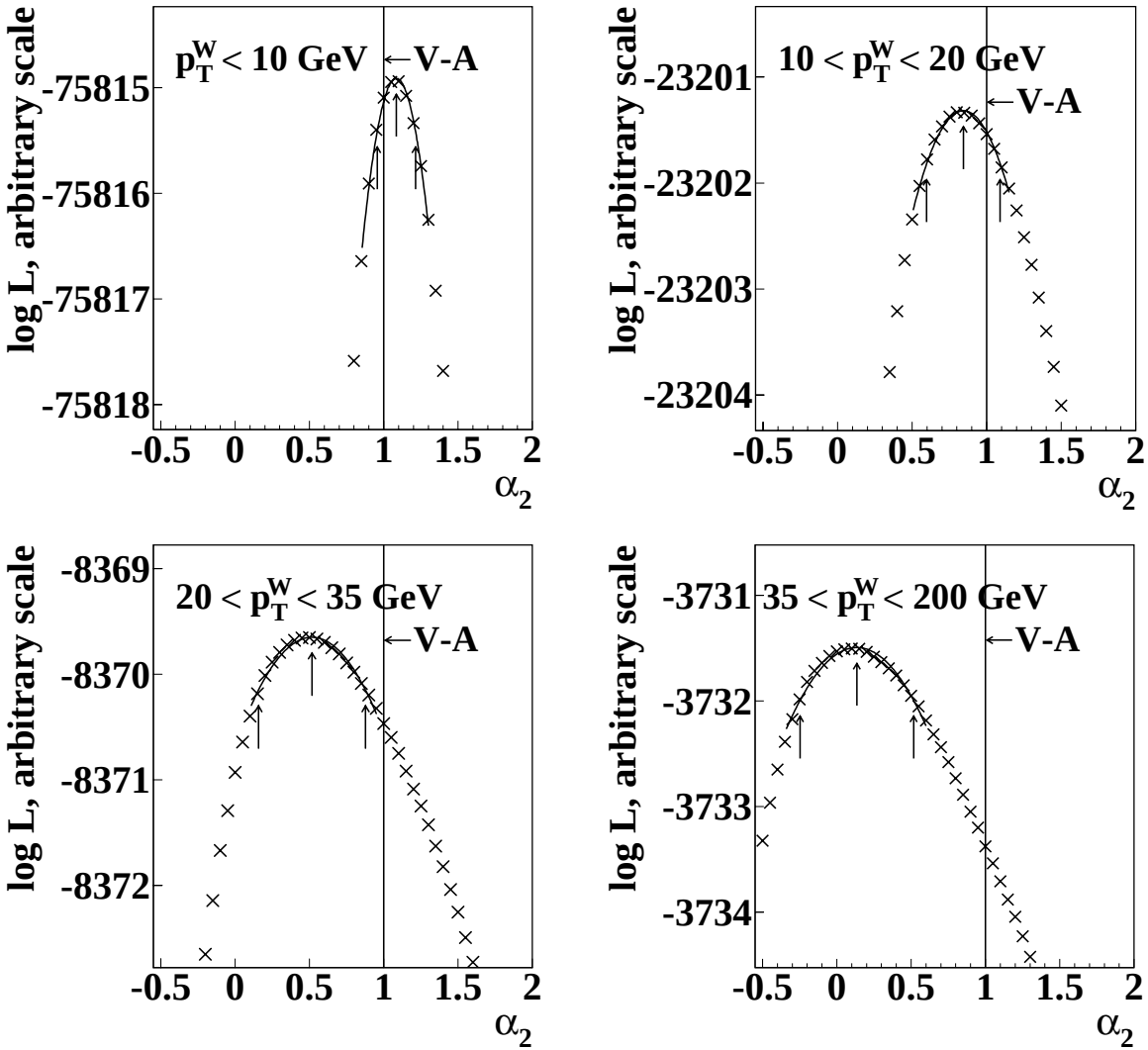
Backgrounds



Backgrounds small due to tight electron quality cuts

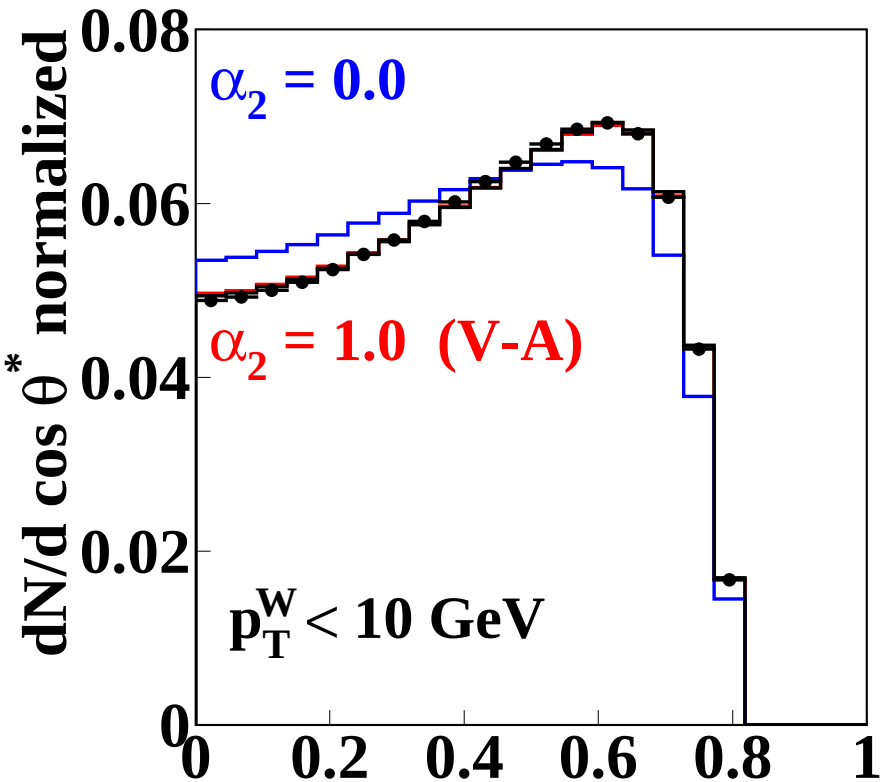
Analysis done in 4 p_T^W bins.

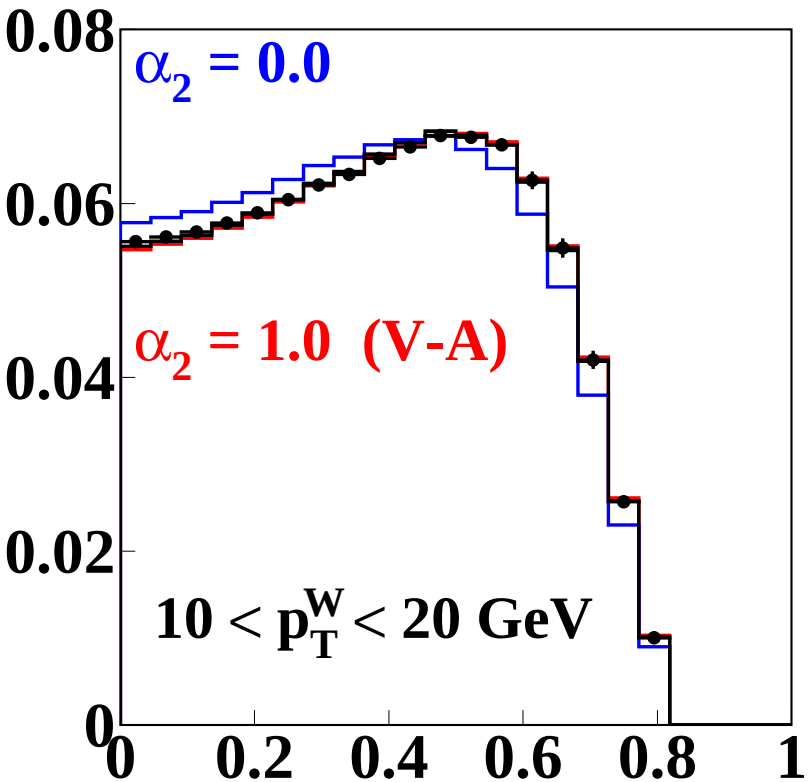
Log L Distributions



Note that α_2 gets smaller for larger p_T.

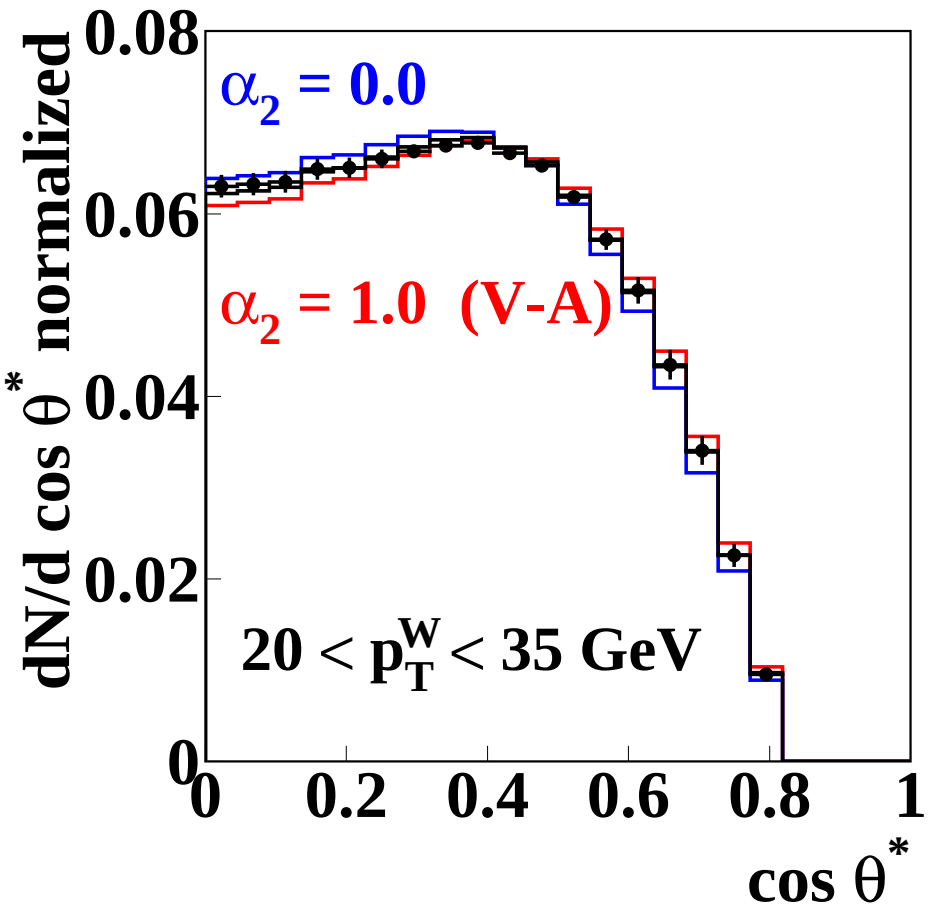
Angular Distributions

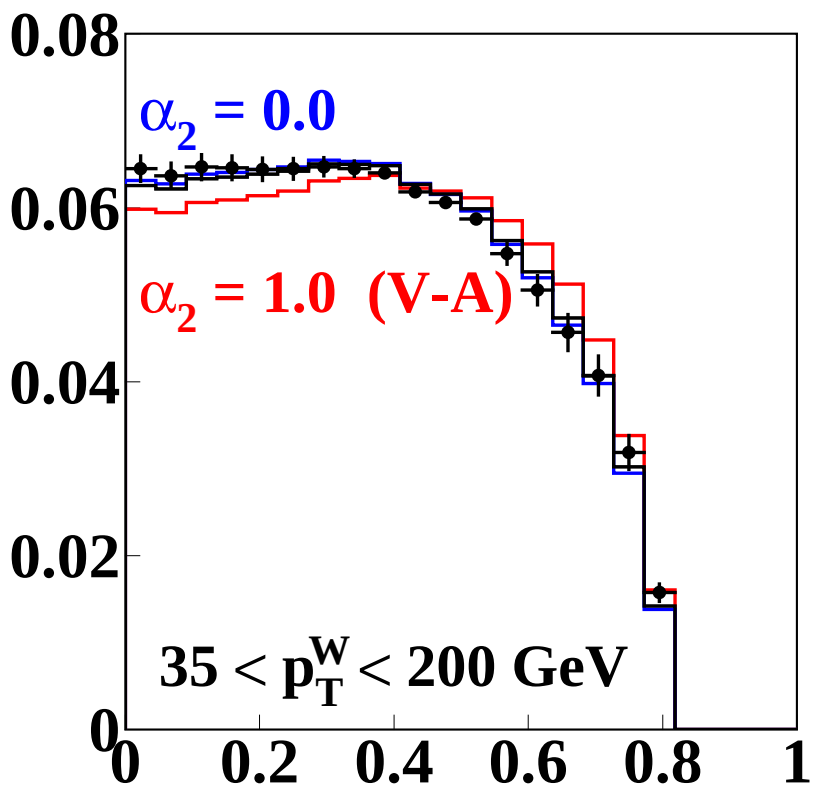




Lower p_T^W

Angular Distributions





Higher p_T^W

Result

p_T (GeV)	0-10	10-20	20-35	35-200
α_2,measured	1.09	0.84	0.52	0.13
Stat. Errors	±0.13	±0.25	±0.36	±0.38
α_2,predicted	0.98	0.89	0.68	0.24
Mean p_T^W	5.3	13.3	25.7	52.9
Combined Syst.	±0.08	±0.09	±0.12	±0.12

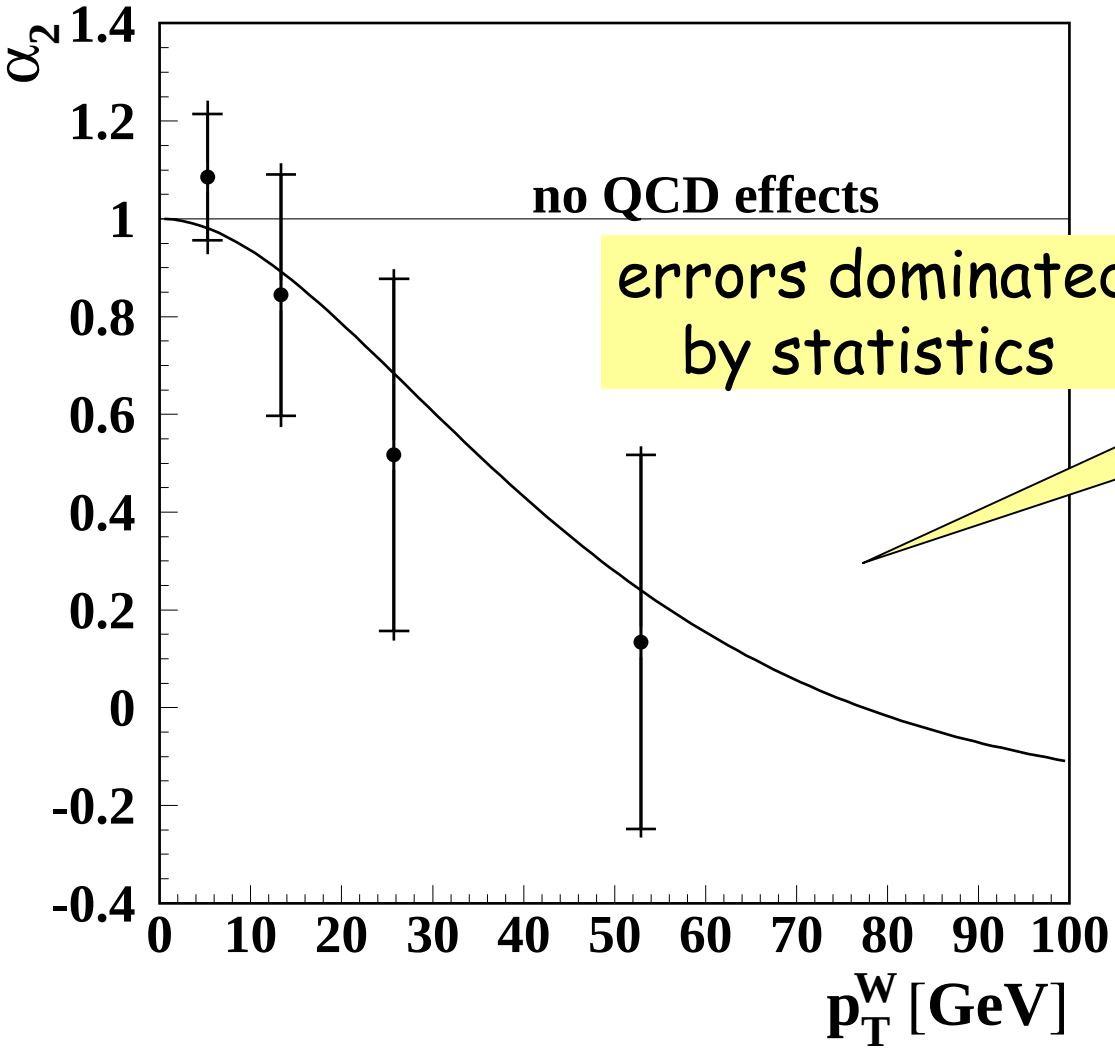
Dominated by Statistical Errors

Systematic Errors

p_T (GeV)	0-10	10-20	20-35	35-200
QCD	±0.04	±0.05	±0.09	±0.07
$Z \rightarrow ee$	±0.01	±0.01	±0.02	±0.04
ttbar	±0.00	±0.00	±0.00	±0.02
EM scale	±0.06	±0.05	±0.03	±0.04
Had Scale	±0.03	±0.01	±0.04	±0.04
Had Resol	±0.02	±0.02	±0.05	±0.06
fixed α_1	±0.01	±0.05	±0.03	±0.03
Combined syst.	±0.08	±0.09	±0.12	±0.12

Estimated by generating cos θ^* templates with varied parameters.

W Angular Result



errors dominated by statistics

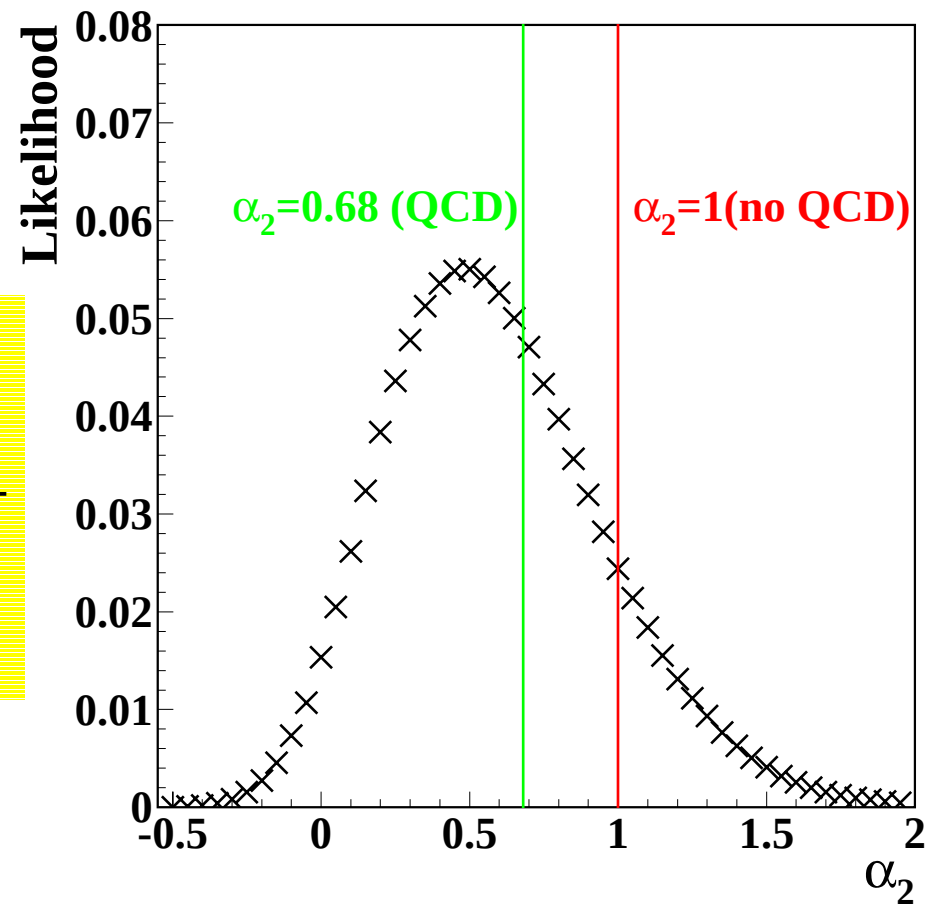
QCD preferred: 2.3 σ effect

To be submitted to PRD very soon

Significance Calculation

Odds-Ratio Method

$$R = \frac{\prod_i p_i(\alpha_2(QCD))}{\prod_i p_i(\alpha_2(no\ QCD))}$$



Log R = 0.5 → 1 σ

We get 2.3σ

Summary

- Measured the Angular Distribution in W Decays
- Angular Distribution Modified by QCD Corrections
- Important Effect in W mass measurement
- NLO QCD Calculation preferred by 2.3 σ

- Other Measurements probing QCD with W and Z Bosons include:
- Inclusive W and Z Cross Sections and W Width
- The Z p_T Distribution
- Coming soon: W p_T paper and W&C