Production of Gauge Bosons at the Tevatron

Recent Results

Harry Melanson

Fermilab

A shopping list of W, Z Tevatron topics:

- W cross section
- Z cross section
- Drell-Yan cross section
- P_T distributions
- W production asymmetry
- W + jet production

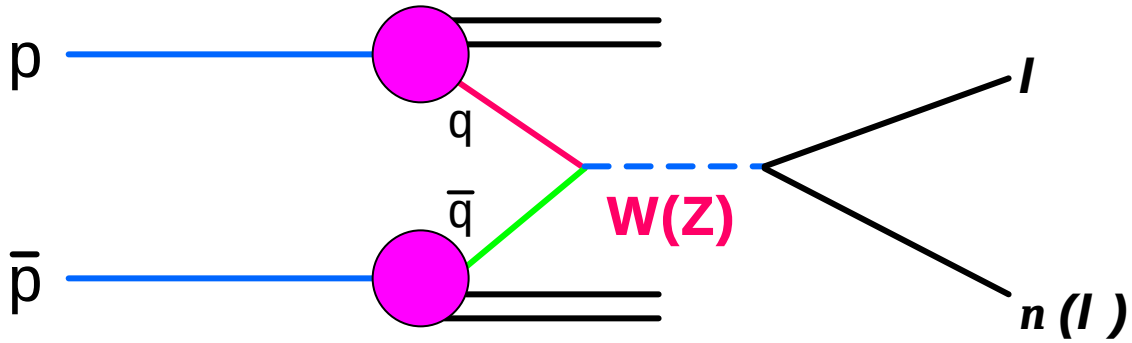
- W mass
- W width

- W decay distribution
- $W \to \tau \nu$
- $Z \to b\bar{b}$

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

Pick recent results
with a QCD flavor

Introduction to W, Z Production at the Tevatron



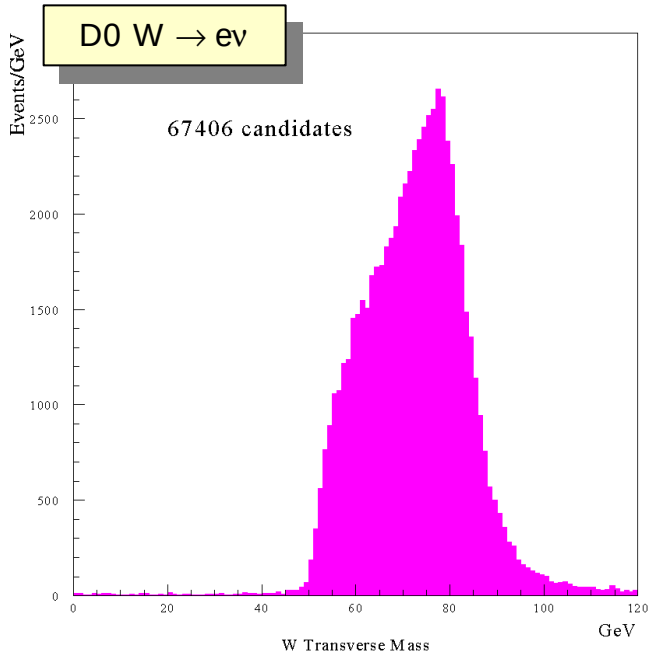
$O(\alpha_s^0)$

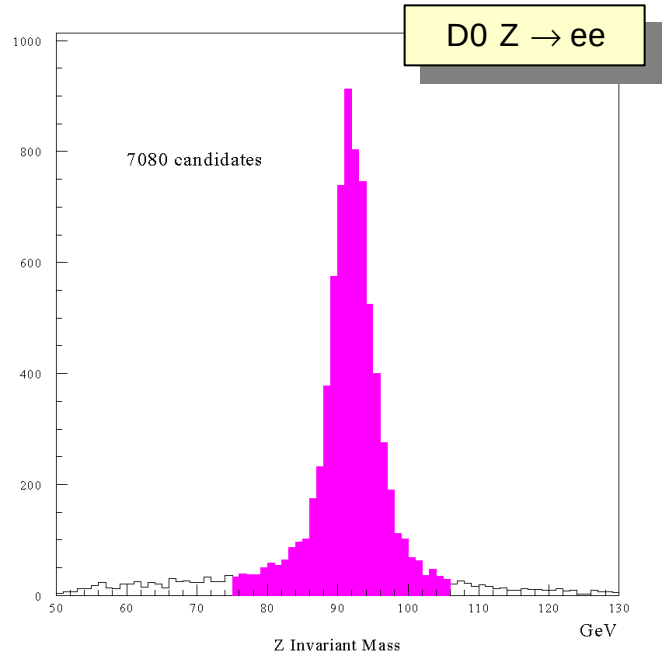
- Production dominated by $q\bar{q}$ annihilation (~60% valence-sea, ~20% sea-sea)
- Due to very large $p\bar{p} \rightarrow jj$ production, need to use leptonic decays
  - $W \rightarrow e\nu$, $W \rightarrow \mu\nu$, $W \rightarrow \tau\nu$ (BR ~ 11% per mode)
  - $Z \rightarrow ee$, $Z \rightarrow \mu\mu$ (BR ~ 3% per mode)
- Leptonic decay features:
  - W: High P_T isolated lepton, Large missing transverse energy
  - Z: Two high P_T isolated leptons

CDF has $Z \rightarrow b\bar{b}$

"Easy"

Introduction to W, Z Production at the Tevatron



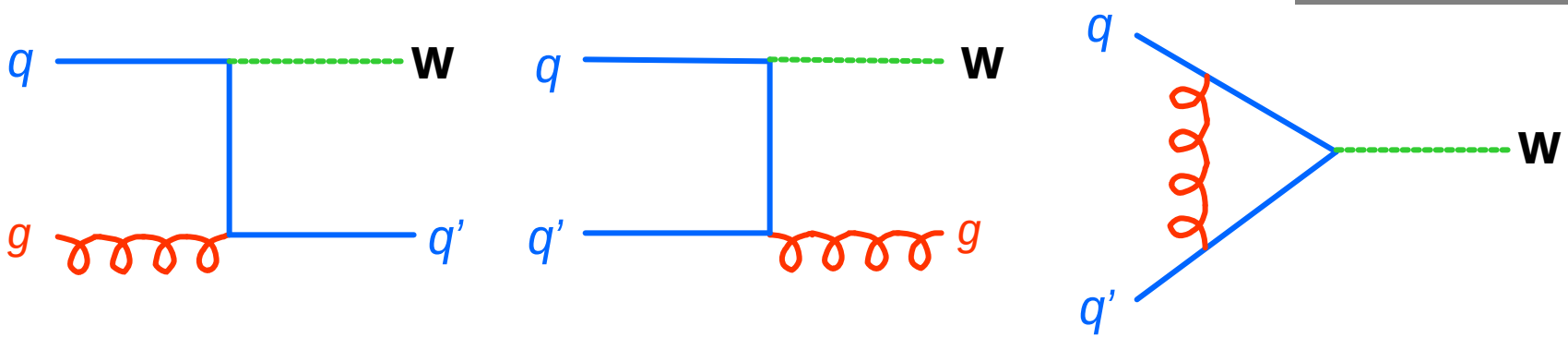


Benefits of studying QCD with W's and Z's:

- Distinctive event signatures
- Low backgrounds
- Large Q^2 ($Q^2 \sim \text{Mass}^2 \sim 6500\ \text{GeV}^2$)
- Well understood Electroweak Vertex

QCD Corrections: $O(a_s)$

$O(\alpha_s)$



Modifications due to QCD corrections:

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

Connections between W,Z Production, QCD and New Physics

Inclusive Cross Sections

Measure:

$$s\,(p\bar{p} \to W + X) \times BR(W \to lu)$$

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

Form ratio:

$$R \equiv \frac{s\,(p\bar{p} \to W + X) \times BR(W \to lu)}{s\,(p\bar{p} \to Z + X) \times BR(Z \to ll)}$$

$$= \frac{s\,(W)}{s\,(Z)} \times \frac{\Gamma(Z)}{\Gamma(Z \to ll)} \times \frac{\Gamma(W \to lu)}{\Gamma(W)}$$

(Γ(W) = 0.2270 ± 0.0011 GeV)

SM EW

Perturbative QCD

(σ(W)/σ(Z) = 3.29 ± 0.03)

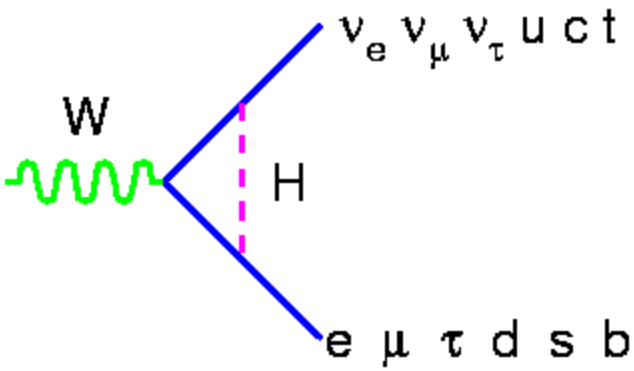
LEP measurement

(BR(Z → ee) = 0.03367 ± 0.00006)

W Width

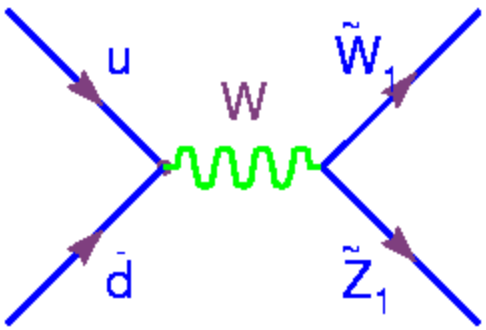
Indirect vs Direct W Width Measurements

Vertex Corrections: same for quarks and leptons, so cancel in BR(W $\rightarrow$ lν)



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.

Inclusive Cross Sections

		$s(W)\times BR(W\to l\nu)\,(nb)$	$s(Z)\times BR(Z\to ll)\,(nb)$
DØ, e, 1b	Preliminary	$2.31 \pm 0.01 \pm 0.05 \pm 0.10$	$0.221 \pm 0.003 \pm 0.004 \pm 0.010$
DØ, e, 1a		$2.28 \pm 0.02 \pm 0.08 \pm 0.10$	$0.211 \pm 0.008 \pm 0.008 \pm 0.009$
DØ, μ, 1b	Preliminary	$2.31 \pm 0.08 \pm 0.10$	$0.170 \pm 0.023 \pm 0.023 \pm 0.007$
DØ, μ, 1a		$2.02 \pm 0.06 \pm 0.22 \pm 0.09$	$0.172 \pm 0.022 \pm 0.021 \pm 0.008$
CDF, e, 1b	Preliminary		$0.246 \pm 0.005 \pm 0.009$
CDF, e, 1a		$2.49 \pm 0.02 \pm 0.08 \pm 0.09$	$0.231 \pm 0.008 \pm 0.009$
CDF, μ, 1b	Updated		$0.237 \pm 0.011 \pm 0.009$
CDF, μ, 1a			$0.217 \pm 0.017 \pm 0.008$
CDF, μ, Run 1	Updated		0.233 ± 0.013

NEW

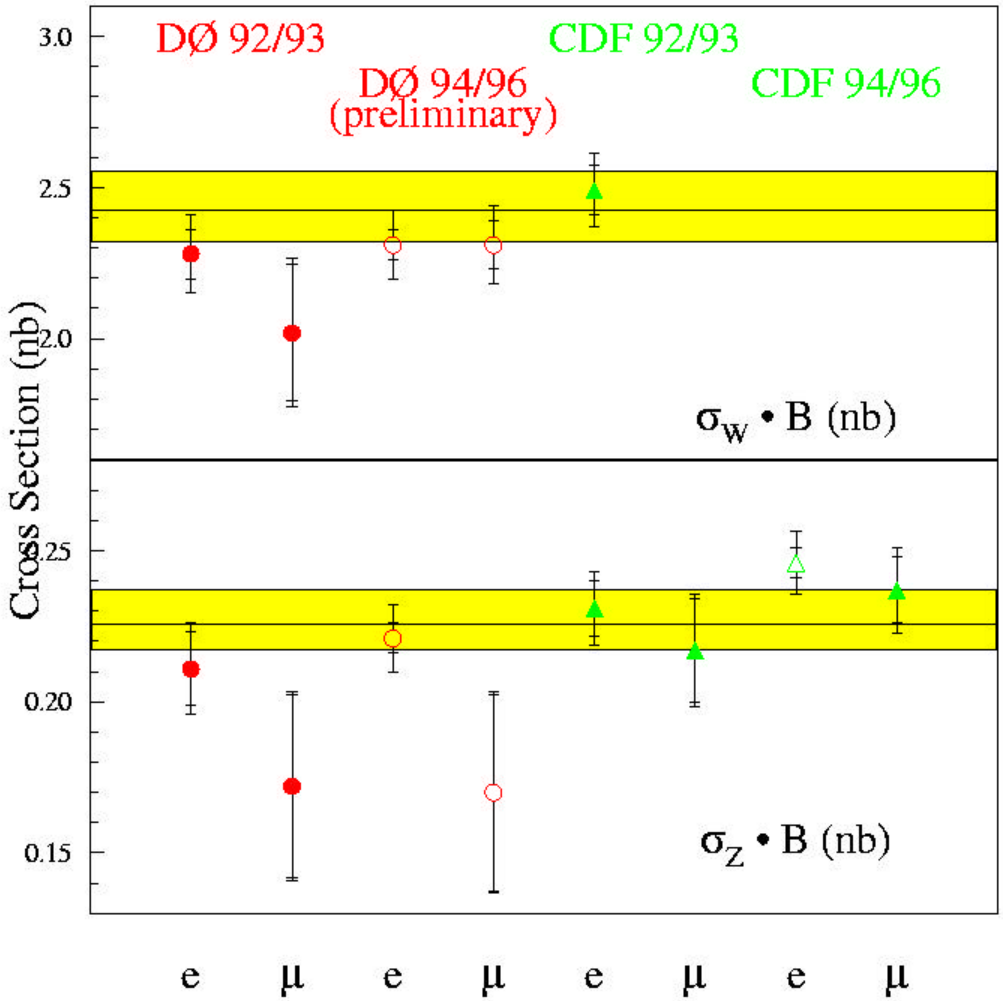
Updated

- **Measurement errors:** Stat ⊕ Sys ~ 2%, Luminosity error ~ 4%
- **Theory error:** ~ 3%, NNLO, $O(\alpha_s^2)$ (Hamberg, van Neerven, Matsuura)

  Dominated by PDF's at NLO…(need NNLO)
- **NB: Luminosity determination:** L(D0) = 1.062 x L(CDF)

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

Inclusive Cross Sections



NNLO theory

NNLO theory

$$R \equiv \frac{s\left(p\bar{p} \to W + X\right) \times BR(W \to eu)}{s\left(p\bar{p} \to Z + X\right) \times BR(Z \to ee)}$$

New

D0 preliminary

R = 10.43 ± 0.15 (stat) ± 0.20 (sys) ± 0.10 (theory)

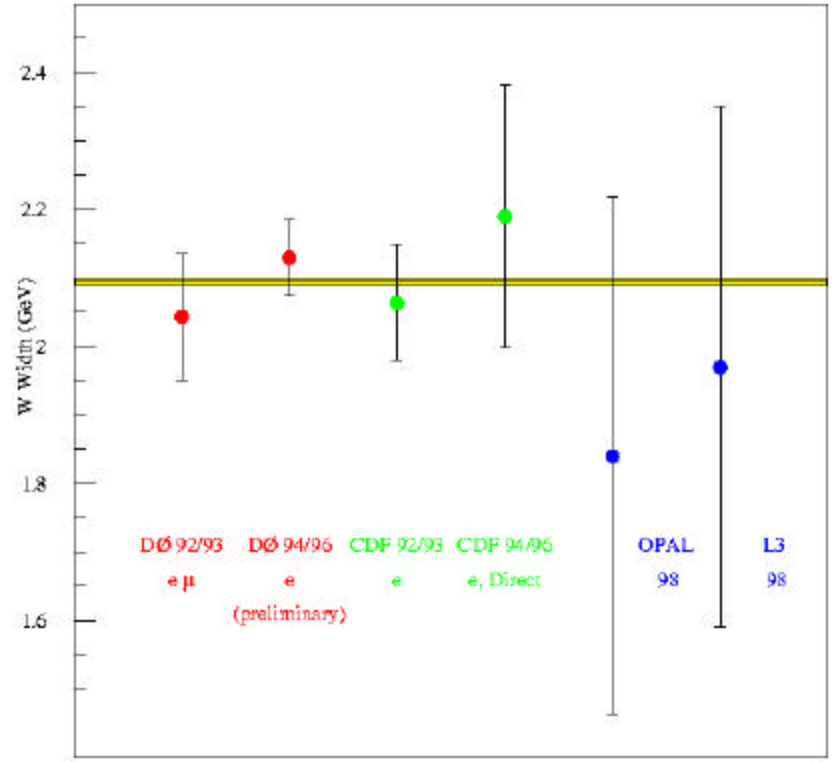
B(W → eν) = 0.1066 ± 0.0015 ± 0.0021 ± 0.0016

Source of uncertainty	Size
backgrounds to the W sample from di-jets	0.158
statistics of the Z sample	0.149
ratio of W and Z acceptance	0.095
ratio of the lepton identification efficiencies for W's and Z's	0.063
backgrounds to the Z sample from di-jets	0.054
backgrounds to the W sample from Z's	0.029
background to W->eν from W->τν	0.022
NLO corrections to Z->eeγ	0.104
sum of systematic uncertainties	0.205
sum	0.274

2.6% total error

Luminosity error cancels in the ratio

W Width



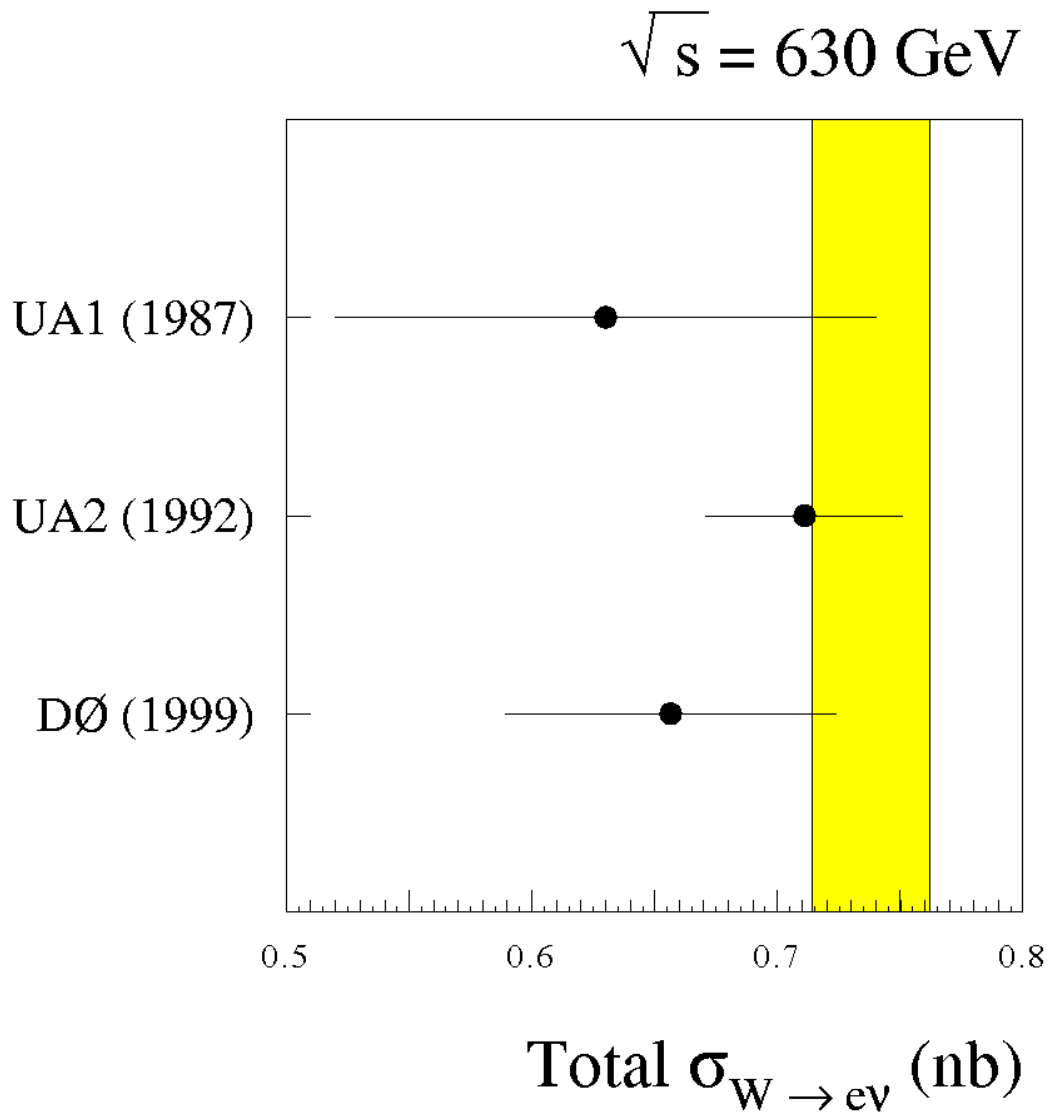
SM: 2.094 ± 0.006 GeV

J.L. Rosner, et al,
PRD 49, 1363 (1994).

NEW

DØ (e + μ), 1b	2.130 ± 0.030 ± 0.047 GeV	Preliminary
DØ (e + μ), 1a	2.044 ± 0.097 GeV	PRL 75, 1456 (1995)
CDF (e), 1a	2.064 ± 0.060 ± 0.059 GeV	PRD 52, 2624 (1995)
CDF (e, direct), 1b	2.19 ± 0.17 ± 0.09 GeV	Preliminary
OPAL (1998)	1.84 ± 0.32 ± 0.20 GeV	CERN-EP/98-197
L3 (1998)	1.97 ± 0.38 GeV	CERN-EP/99-17

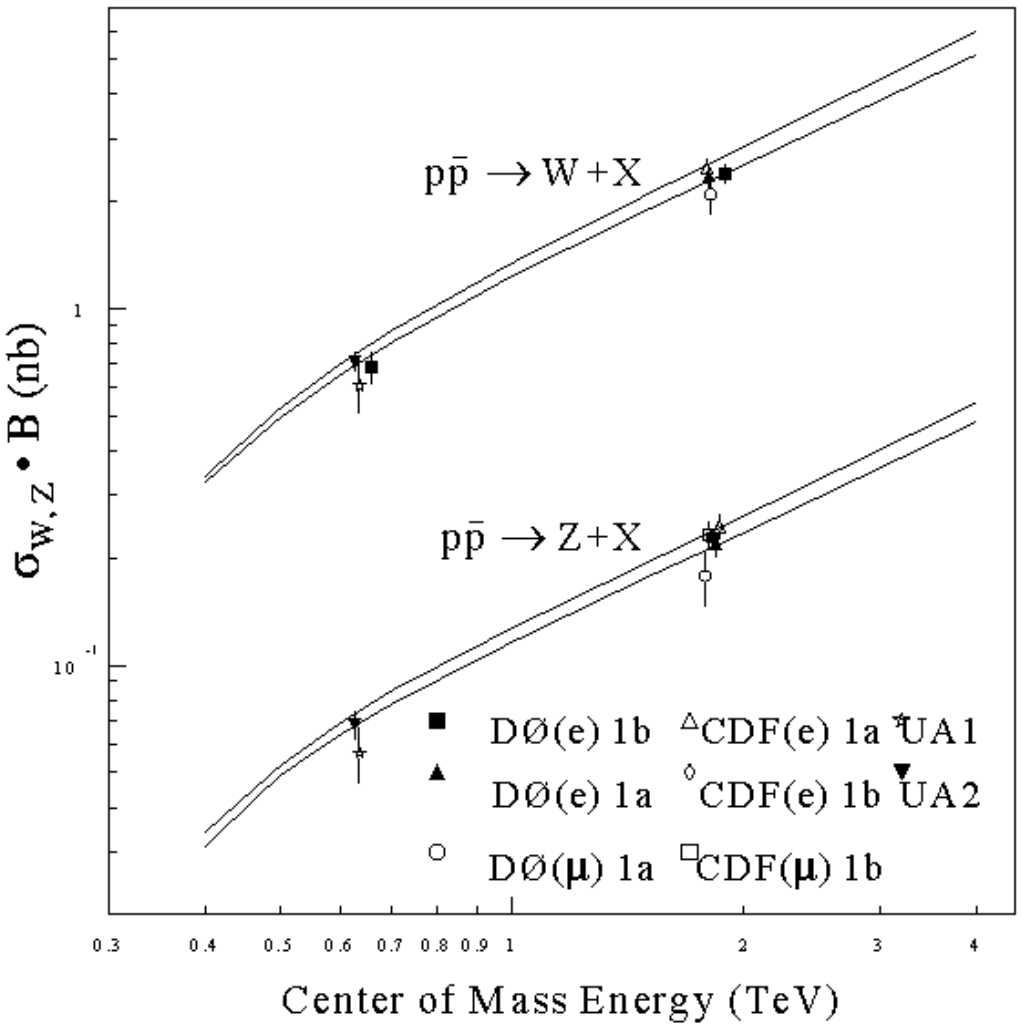
Inclusive Cross Sections



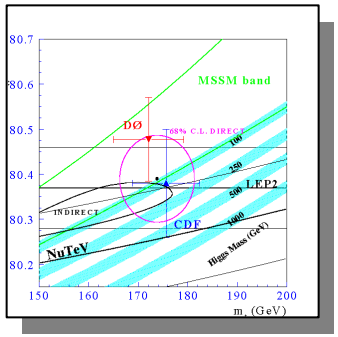
D0 preliminary

$$s\,(p\bar{p} \to WX) = 658 \pm 67\ pb$$

Inclusive Cross Sections



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

Introduction to W, Z P_T Theory

- **Large PT 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: $\ln(Q^2/P_T^2)$

  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-Kaufann (91); **LY**: Ladinsky-Yuan (94)

  qt-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)

Recent W,Z P_T measurements

- **W P_T**
  - D0 Run 1b electrons (82 pb^{-1}) NEW
    (Compared to **AK** $O(\alpha_s^2)$ b-space)
  - CDF Run 1a+1b electrons (110 pb^{-1}) Recent
    (Compared to **ERV** $O(\alpha_s)$ b&qt space)

- **Z P_T**
  - D0 Run 1b electrons (82 pb^{-1})
    (Compared to **AK** $O(\alpha_s^2)$ & **LY** $O(\alpha_s)$ b-space)
  - CDF Run 1a+1b electrons (110 pb^{-1})
    (Compared to $O(\alpha_s)$ **LY** b-space & **ERV** $O(\alpha_s)$ qt-space)

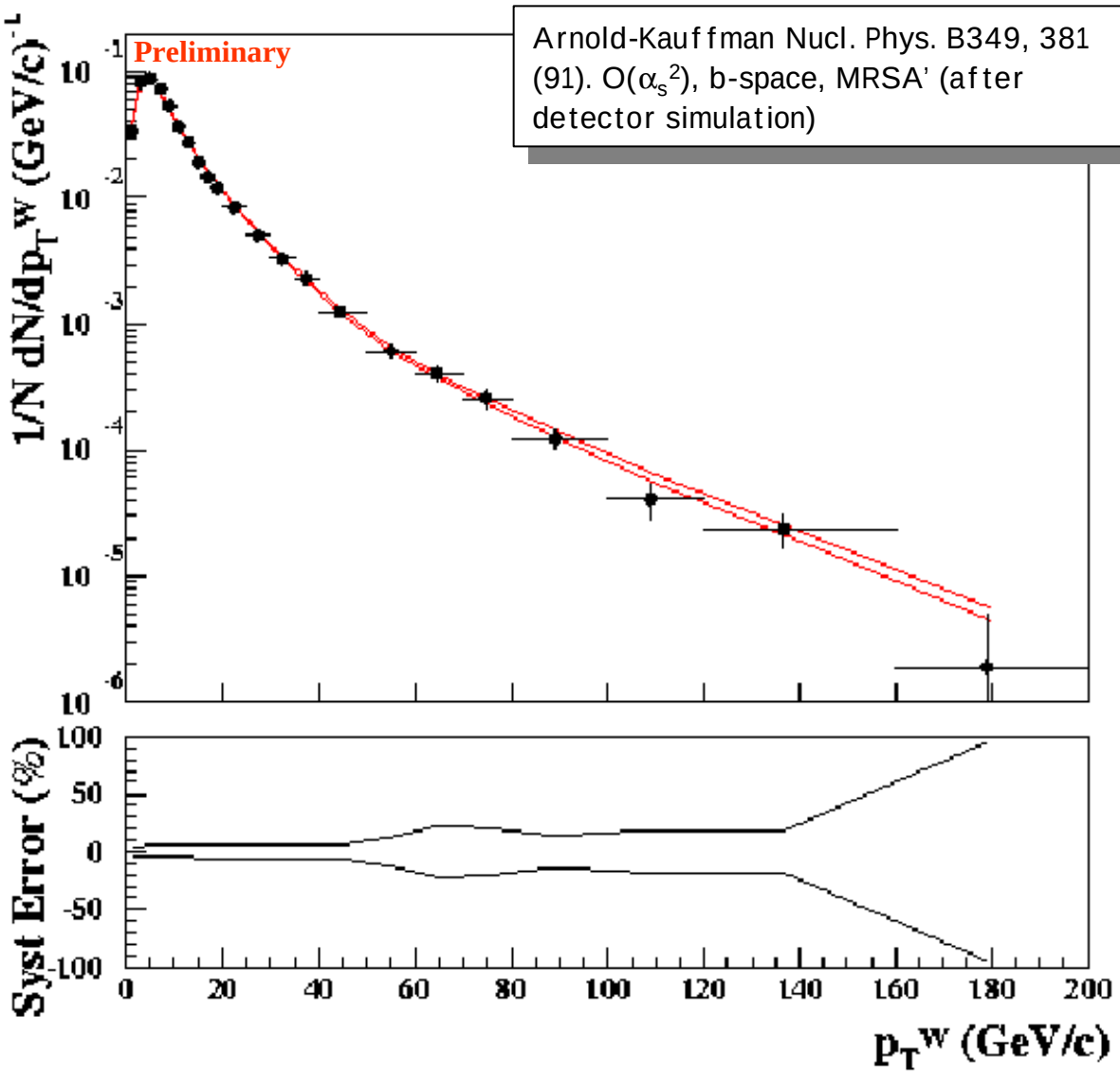
- **W's vs Z's**

  W: x10 more statistics

  Z: Better P_T resolution, lower backgrounds

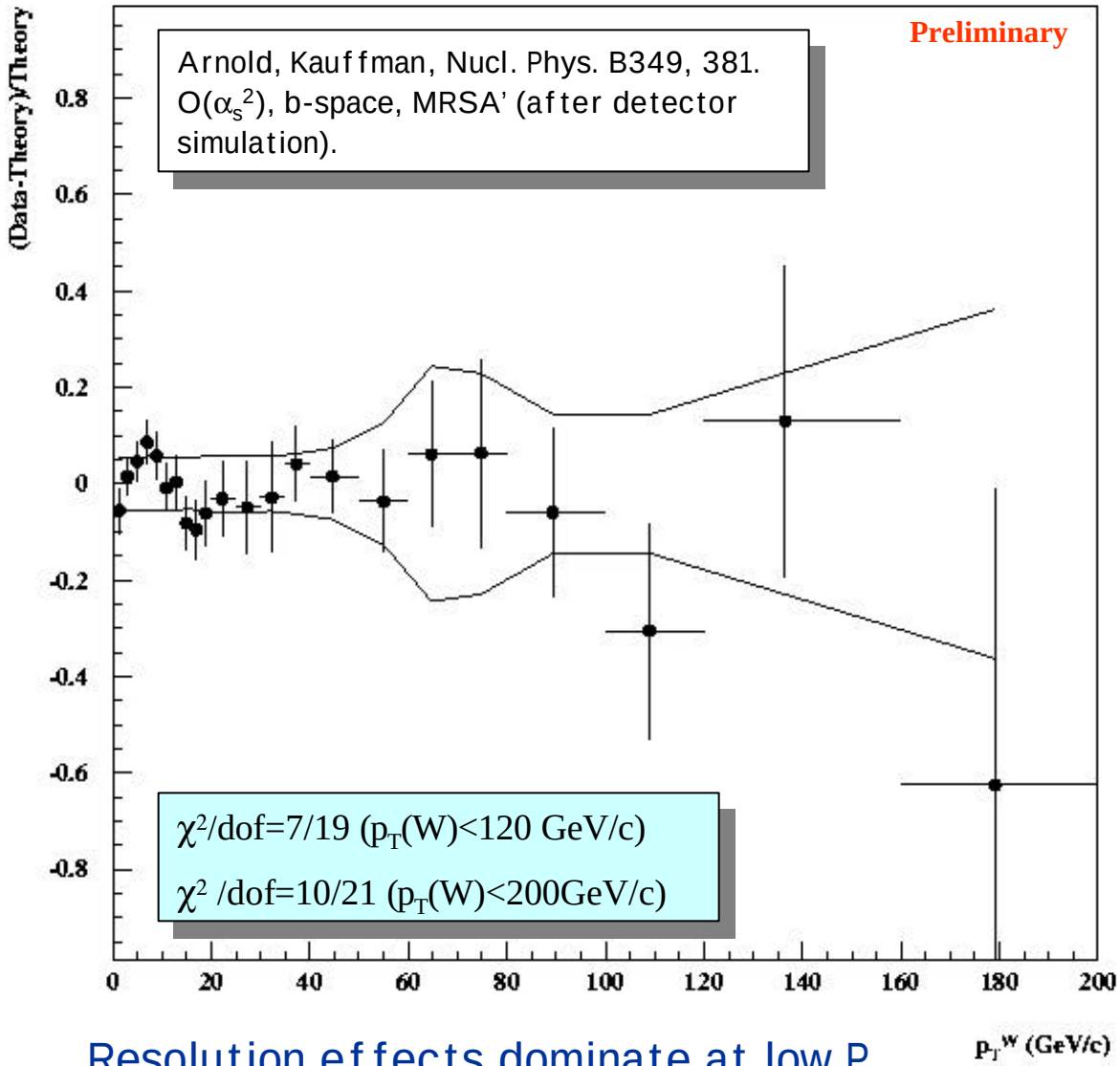
D0 W P_T measurements

New



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

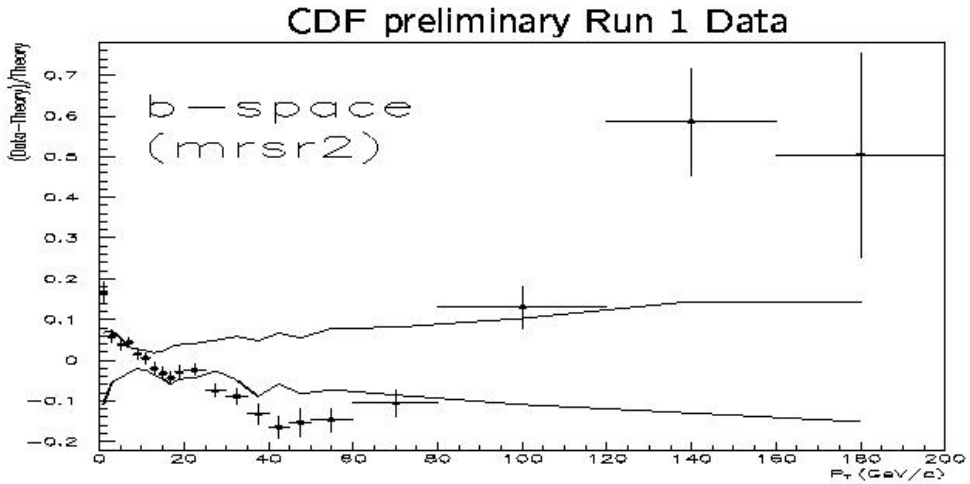
D0 W P_T measurements



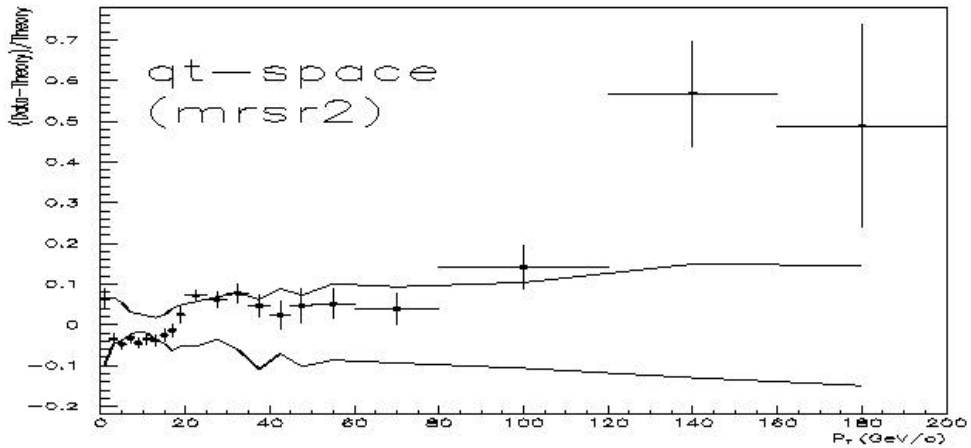
Resolution effects dominate at low P_T

High P_T dominated by statistics & backgrounds

CDF W P_T measurements



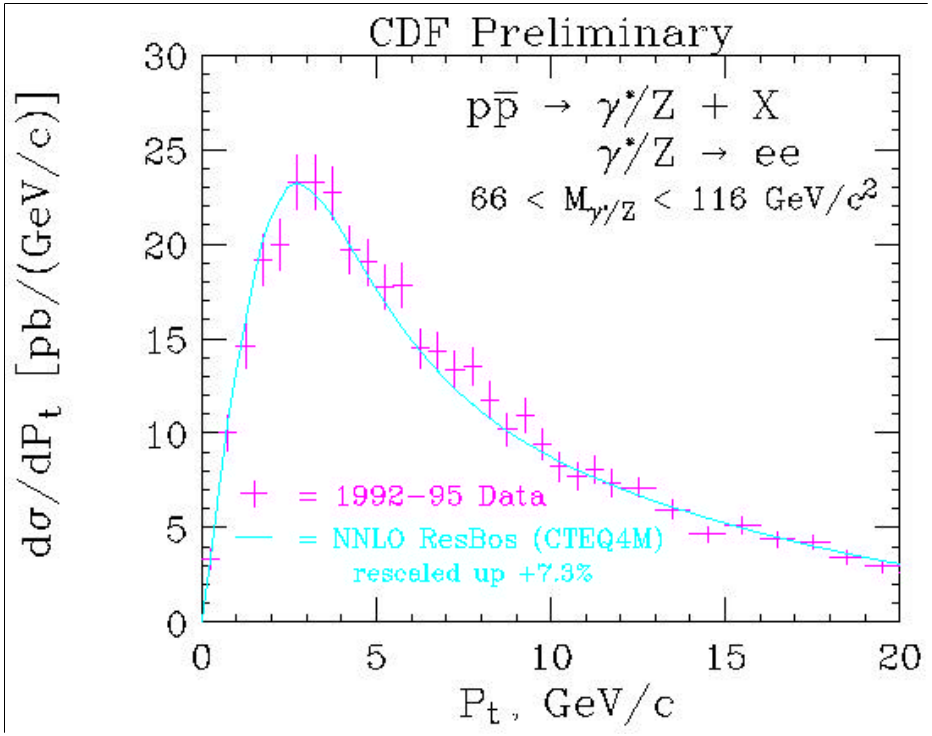
$\chi^2/d.o.f. = 1.85$ ($P_T^W < 120$ GeV/c), 2.49 (< 200 GeV/c)

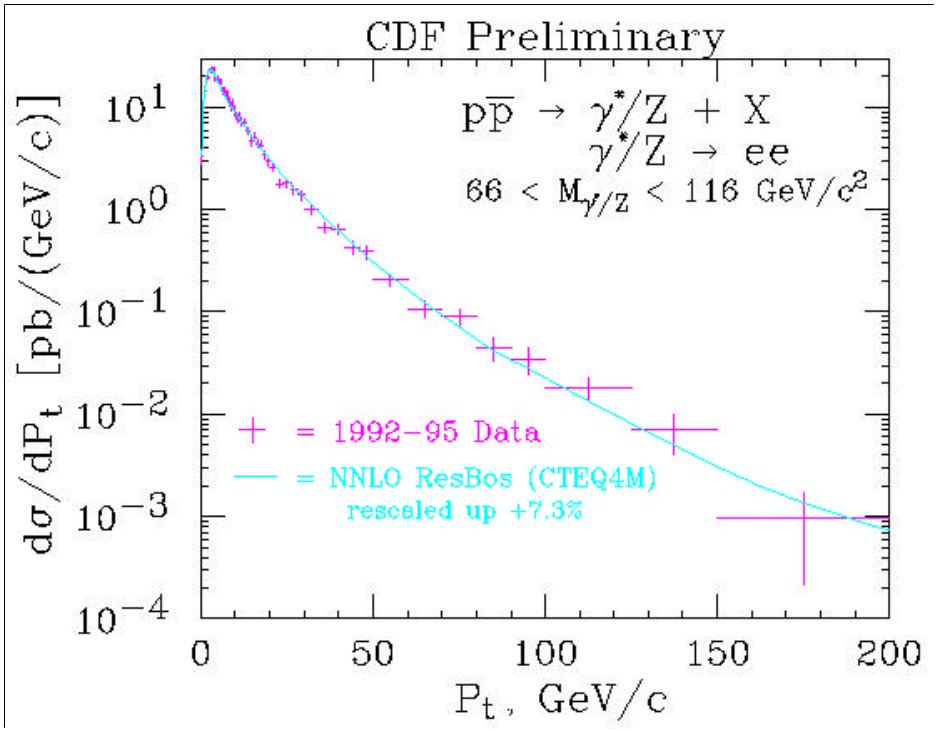


$\chi^2/d.o.f. = 1.05$ ($P_T^W < 120$ GeV/c), 1.71 (< 200 GeV/c)

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

CDF Z P_T measurements

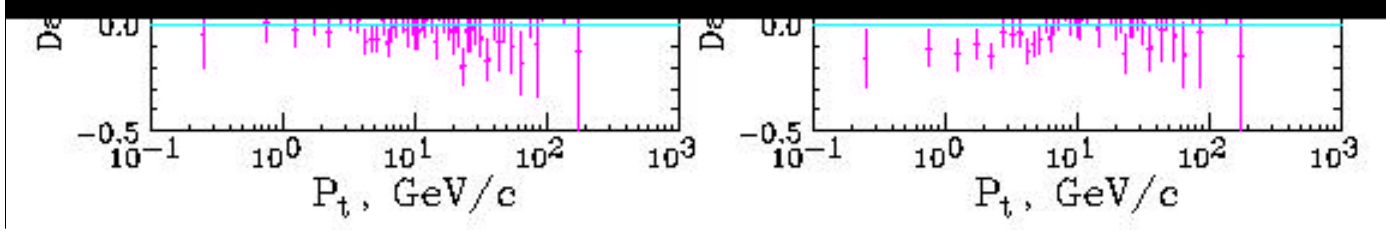




ResBos: Balasz, Yuan, *PRD 56, 5558 (1997)*, $O(\alpha_s^2)$, b-space.

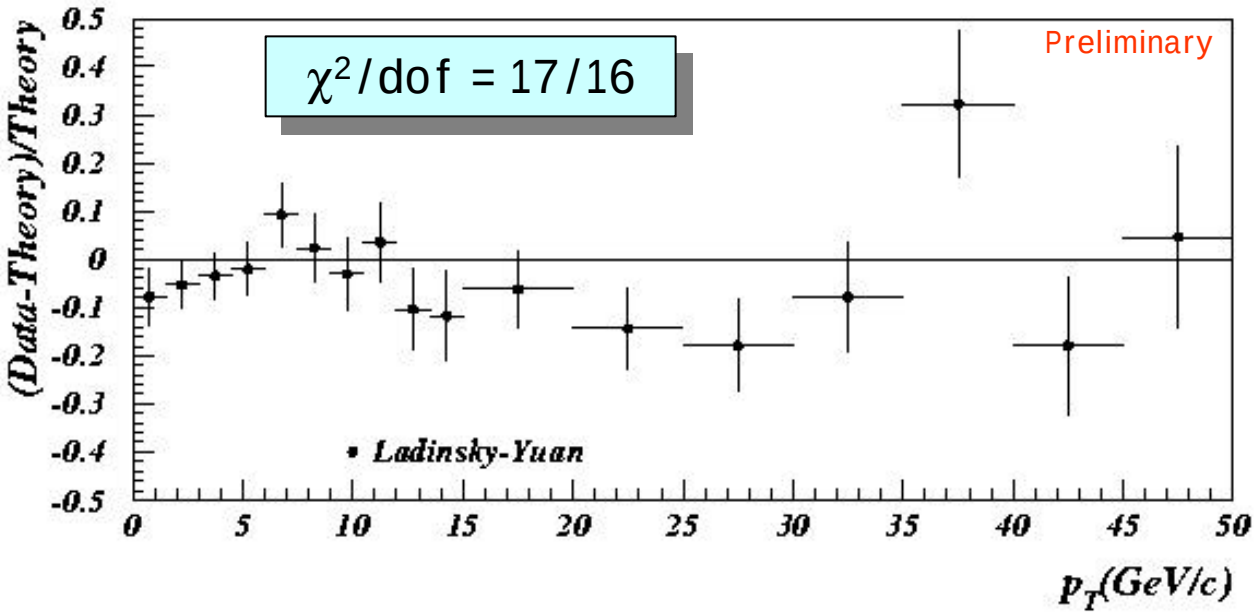
CDF Z P_T measurements

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

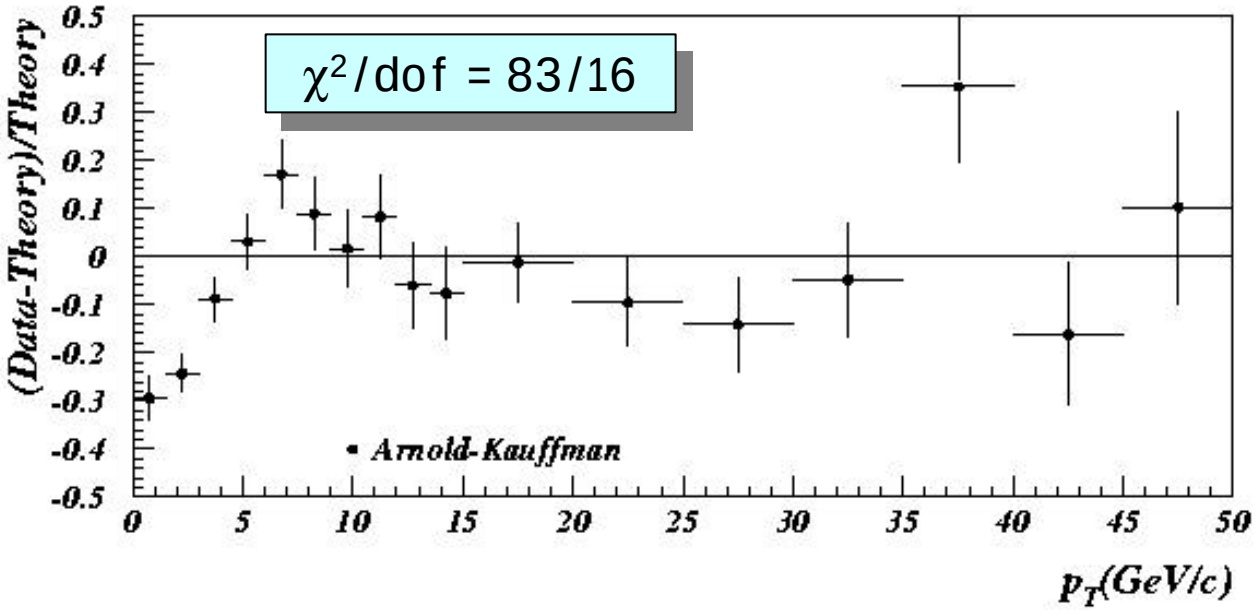


D0 Z P_T measurements

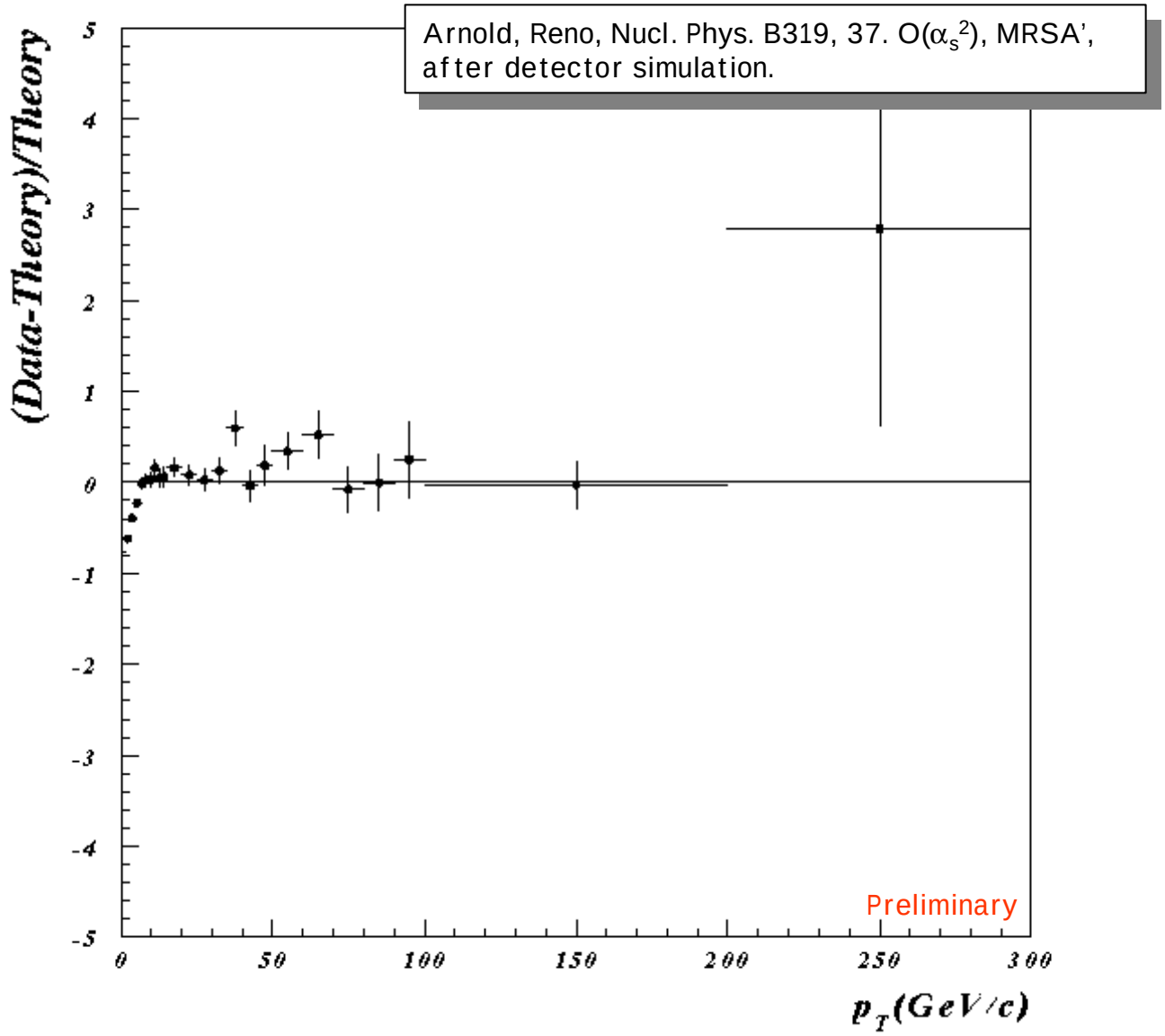
Ladinsky, Yuan, PRD 50, 4239 (94), $O(\alpha_s^2)$, b-space.



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

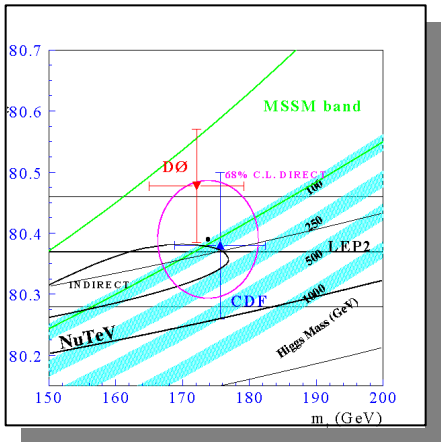


D0 Z P_T measurements



Connections between W,Z Production, QCD and New Physics

W boson mass + top quark mass: Constrain Higgs mass



Current CDF/DØ $\delta M_W \sim$ 5-9 MeV from P_T^W model

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

W production Monte Carlos tuned to Z data

NLO QCD

Non-perturbative QCD

Resummation techniques

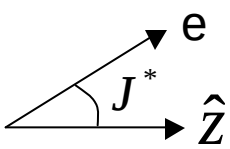
W, Z P_T distributions "confirm" formalism(s)

Z P_T distributions constrain non-pert. parameters

W Decay Distribution

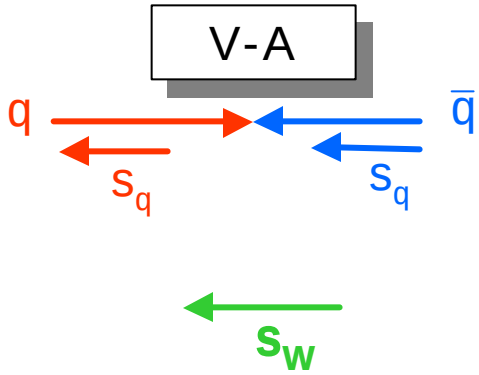
Angular distribution of electron in W rest frame:

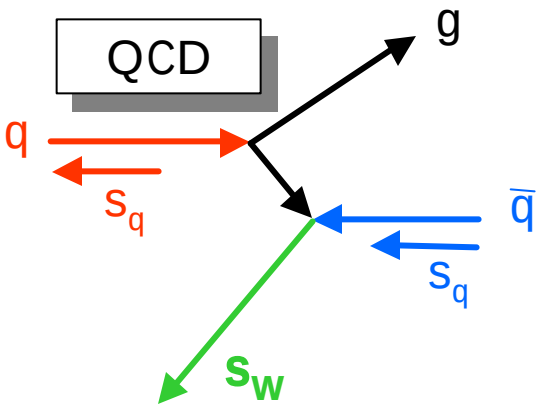
Pure V-A: $$\frac{ds}{d\cos J^*} \propto (1+P(W)\cos J^*)^2$$



Collins-Soper frame

NLO QCD corrections to production modify this distribution:





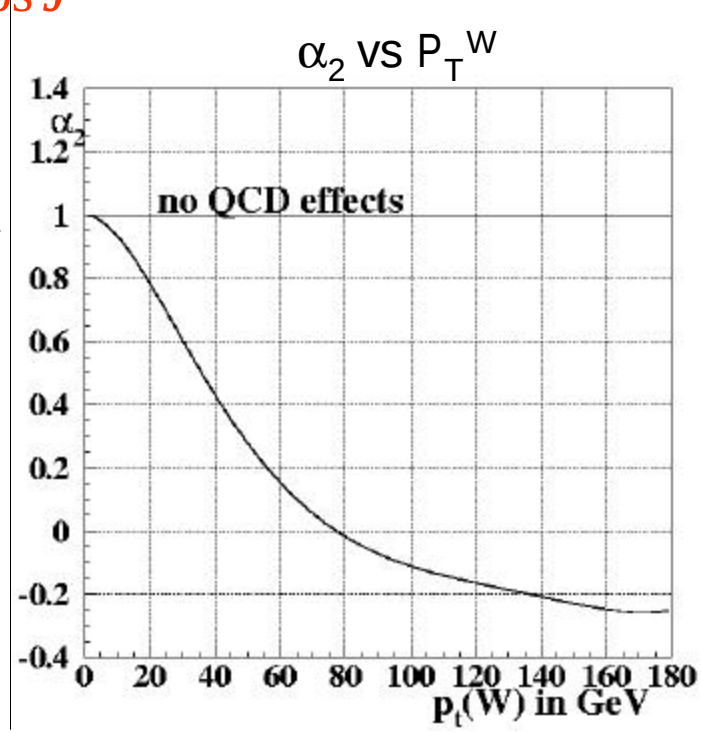
V-A + QCD: $$\frac{ds}{d\cos J^*} \propto 1+P(W)a_1\cos J^* + a_2\cos^2 J^*$$

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

W Decay Distribution - a_2

$$\frac{ds}{d\cos J^*} \propto 1 + P(W) a_1 \cos J^* + a_2 \cos^2 J^*$$

V-A: $\alpha_2 = 1$

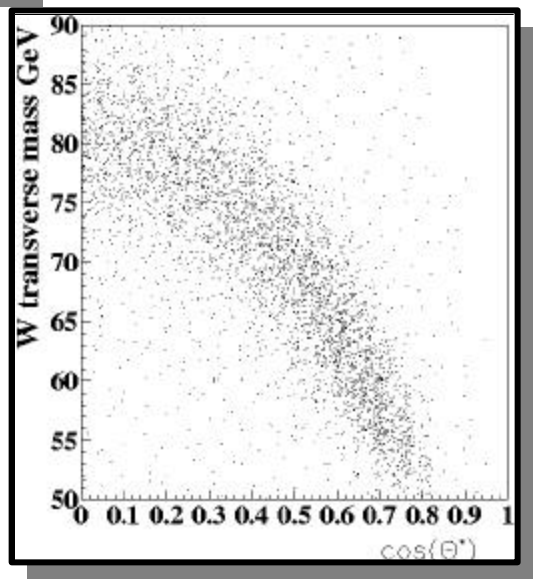


V-A: $\alpha_1 = \pm 1$
D0 only sensitive to α_2

Connections between W,Z Production, QCD and New Physics

Including this effect in W mass Monte Carlo: $\Delta M_W \sim 40$ MeV (D0)

D0 method to measure α_2



- Use correlation between $\cos\theta^*$ and M_T^W to infer $\cos\theta^*$ on a statistical basis

- Define probability function

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

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

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

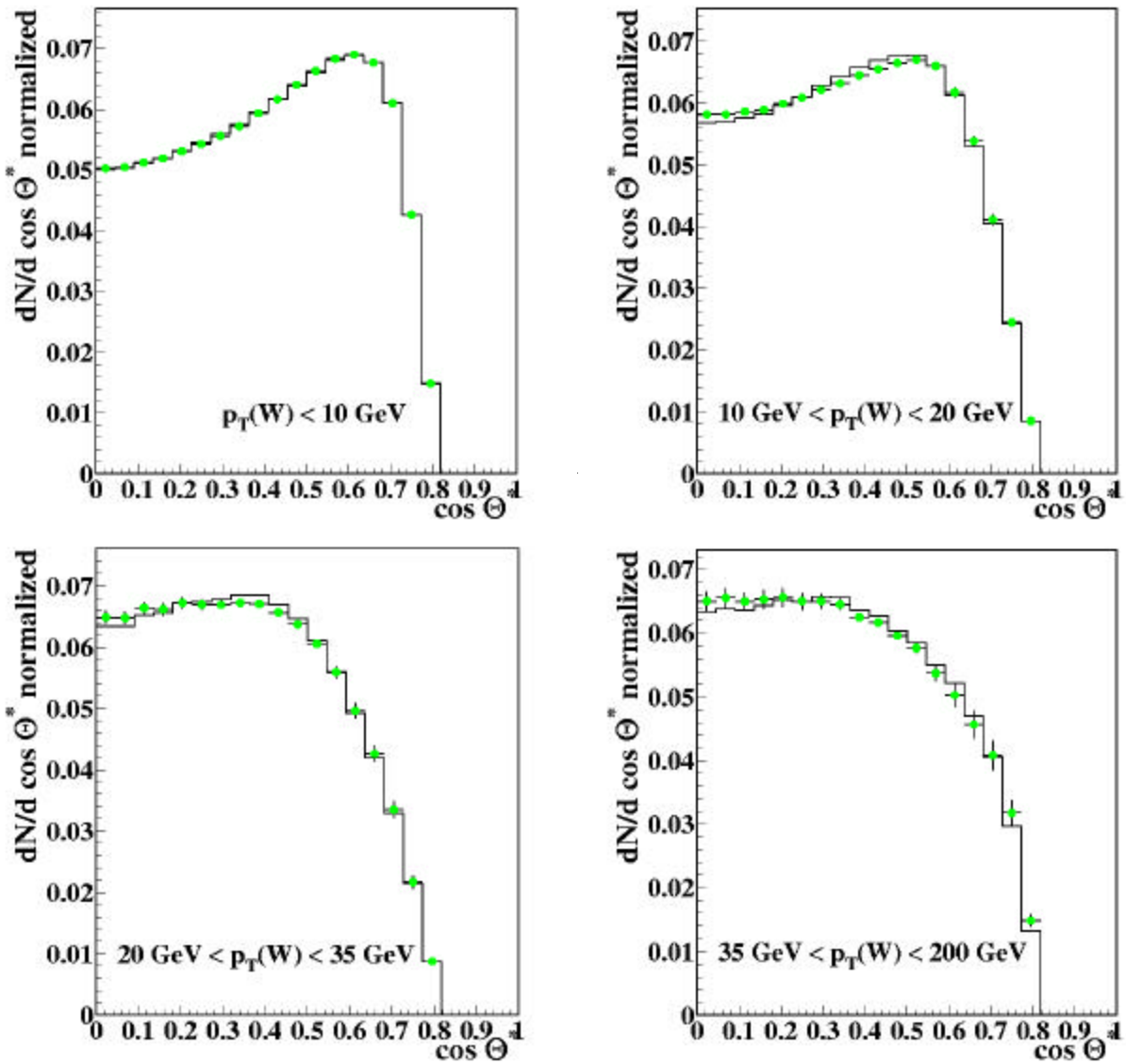
Bayesian

- Compare to n_i templates from MC

- Use log-likelihood to determine best value of $\alpha_2(P_T(W))$

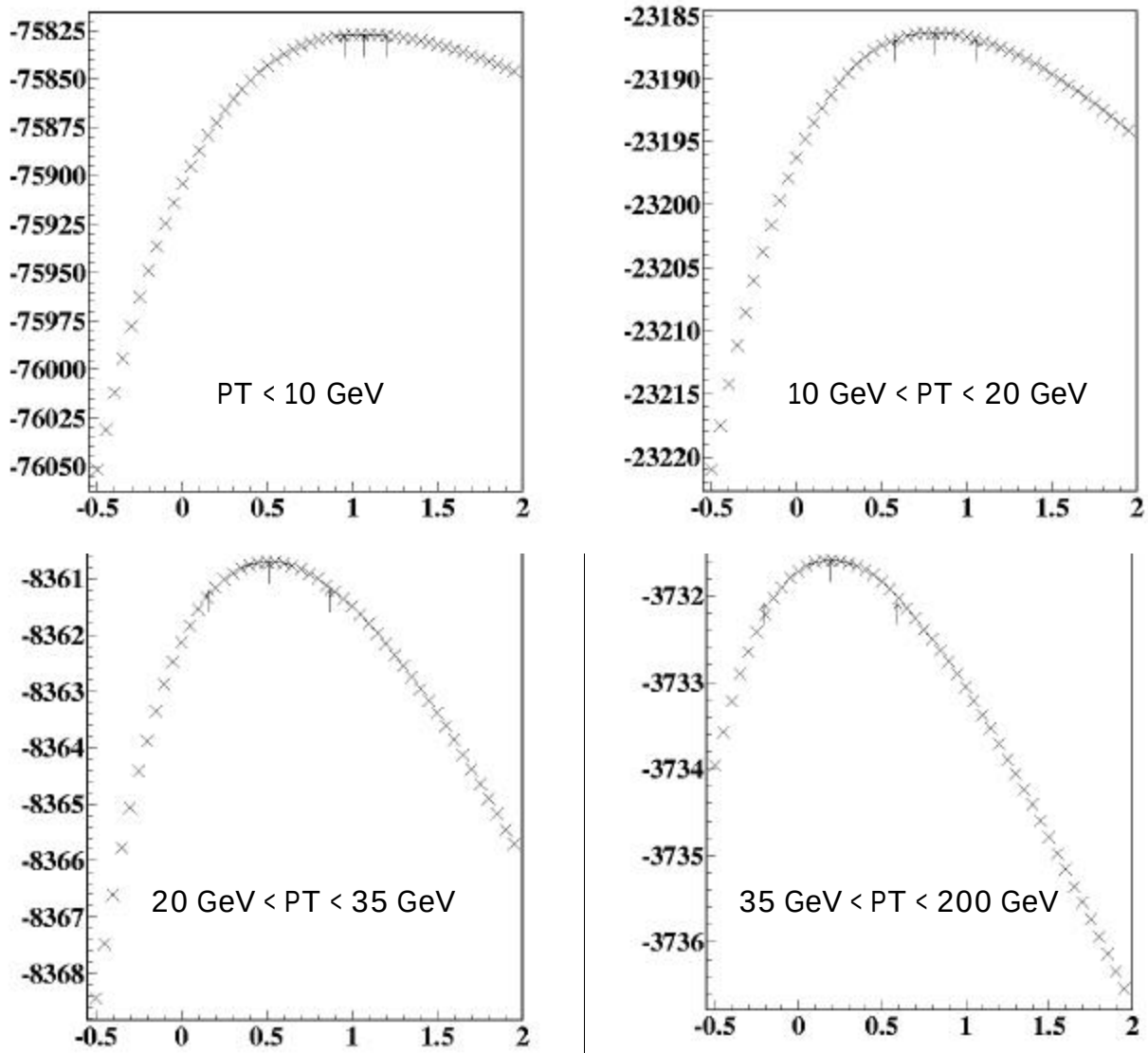
D0 method to measure α_2

Extracted cosθ* distributions



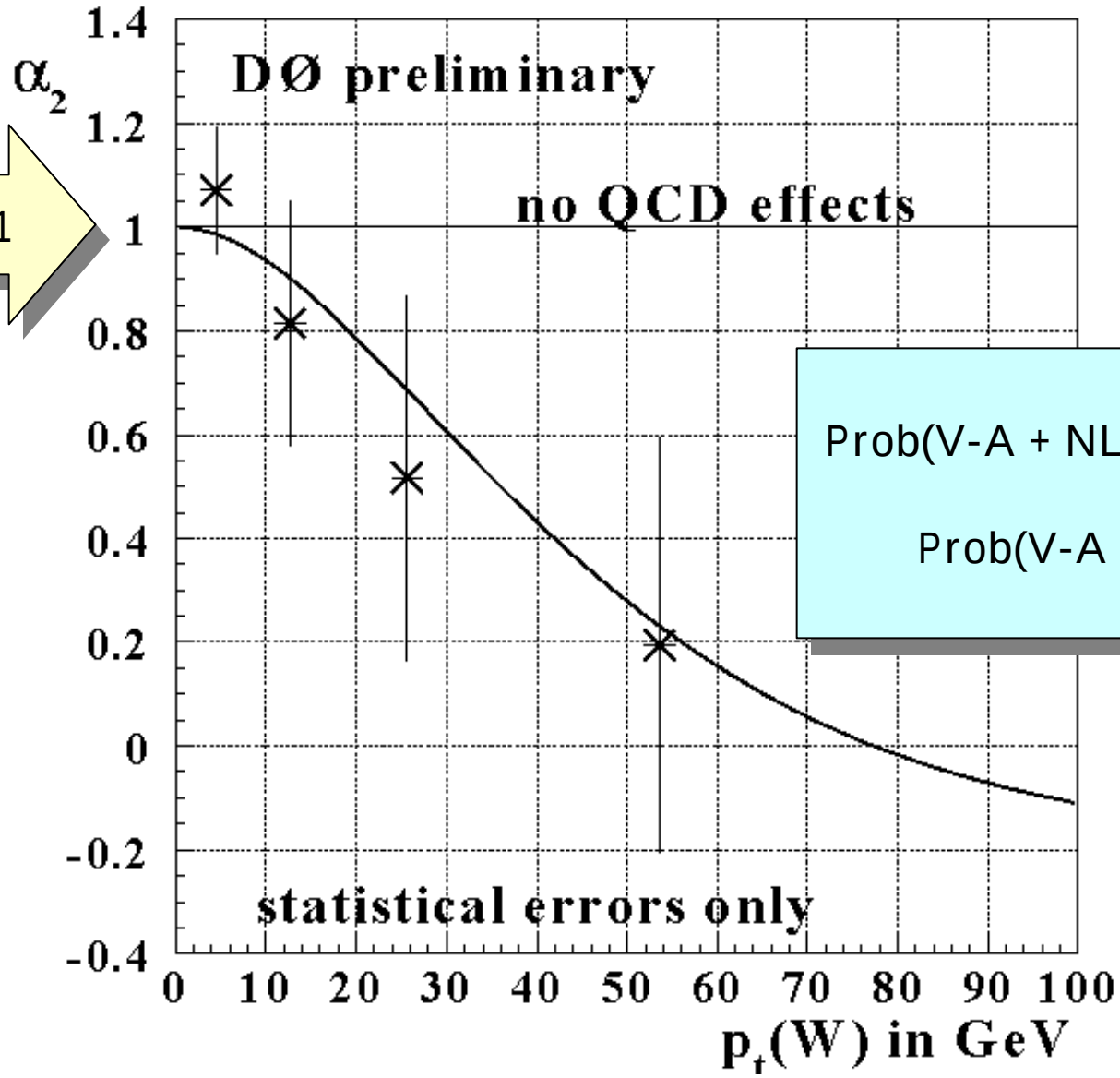
D0 method to measure α_2

Log-likelihoods vs α_2



W Decay Distribution - a_2

V-A: $\alpha_2 = 1$



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

Prob(V-A only) = 7%

Conclusions

- **W, Z inclusive cross sections** in good agreement with SM.
  Stat ⊕ Sys ~ 2%, Luminosity error ~ 4%, Theory error: ~ 3%
  Maybe use to *determine* luminosity in Run II.

- **W width** measurement (direct and indirect) in good agreement with SM.
  Indirect measurement error ~ 3%

- **W, Z P_T distributions** measured.
  CDF & D0 measurements over wide range of P_T with errors ~ 10 - 20%
  Testing NLO QCD + resummation + non-perturbative models

- QCD correction to **W decay distribution** confirmed.
  D0 preliminary measurement of α_2 vs P_T^W