Lepton Pair and Weak Boson Production: Focused Introduction

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University of Maryland
CTEQ Summer School
1 July 06

Outline

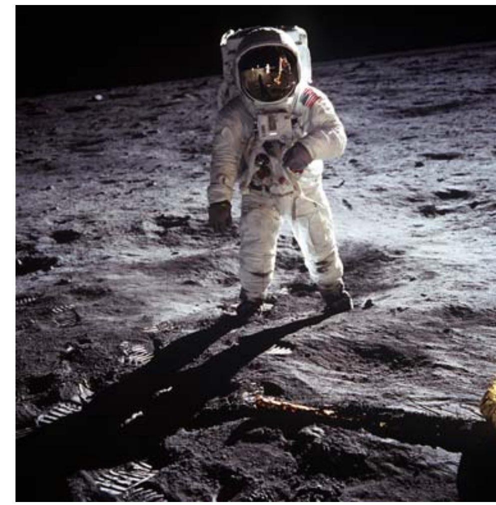
- Di-leptons and the development of the parton model
- Di-leptons as a tool for learning about QCD
- Di-leptons, Precision Electroweak, and QCD
- Di-leptons, Searches for New Physics, and QCD

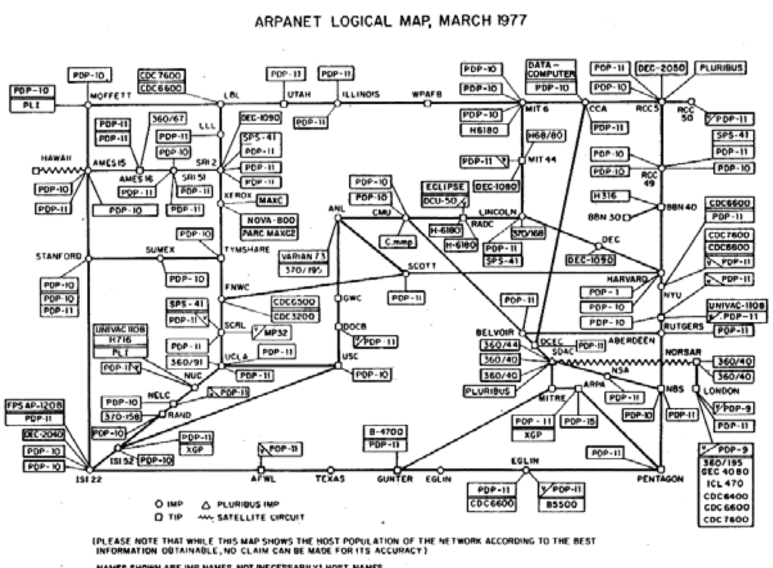
(all material stolen and was damaged in the process, sources on last slide)

Historical Importance

1969

- Nixon becomes president
- Beatles break up
- Wal-Mart is incorporated
- creation of ARPANET
- First men on the moon





Historical Importance

VERY HIGH-ENERGY COLLISIONS OF HADRONS

Richard P. Feynman
California Institute of Technology, Pasadena, California
(Received 20 October 1969)

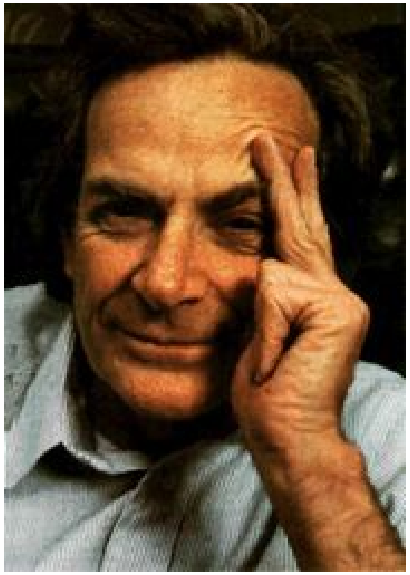
Proposals are made predicting the character of longitudinal-momentum distributions in hadron collisions of extreme energies.

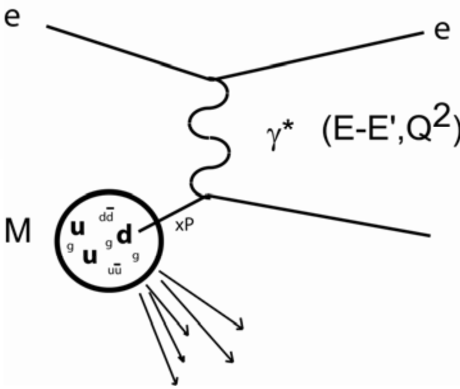
Of the total cross section for very high-energy hadron collisions, perhaps $\frac{1}{3}$ is elastic and 10% of this is easily interpreted as diffraction dissociation. The rest is inelastic. Collisions involving only a few outgoing particles have been carefully studied, but except for the aforementioned elastic and diffractive phenomena they all fall off (probably as a power of the energy at high energy). The constant part of the total inelastic cross section cannot come from them. And we know that at such energies, the majority of collisions lead to a relatively large number of secondaries (perhaps the multiplicity increases logarithmically with energy). These collisions have not been studied extensively because, with the large number of particles, so many quantities or combinations of quantities can be evaluated that one does not know how to organize the material for analysis and presentation.

an extraction of those features which relativity and quantum mechanics and some empirical facts[1] imply almost independently of a model. I have difficulty in writing this note because it is not in the nature of a deductive paper, but is the result of an induction. I am more sure of the conclusions than of any single argument which suggested them to me for they have an internal consistency which surprises me and exceeds the consistency of my deductive arguments which hinted at their existence.

Only the barest indications of the logical bases of these suggestions will be indicated here. Perhaps in a future publication I can be more detailed.[2]

Supposing that transverse momenta are limited in a way independent of the large z-component momentum of each of the two oncoming particles in the center-of-mass system (so $s = 2W^2$), an





Historical Importance

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

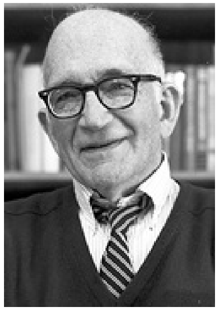
On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s \to \infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s \to 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.

Feynman's parton model[1] for deep-inelastic weak or electromagnetic processes is an expression of the impulse approximation as applied to elementary-particle interactions. In order to apply the impulse approximation we demand the following. We analyze the bound system—be it a nucleon or nucleus—in terms of its constitutents, called "partons." Nucleons are the "partons" of the nucleus and the "partons" of a nucleon itself are still to be deciphered. If we specify the kinematics so that the partons can be treated as instantaneously free during the sudden pulse carrying the large energy transfer from the projectile (or lepton) then we can neglect their binding effects during the interaction and we can treat the kinematics of the collision as between exists a finite k_{max}—then as viewed in an infinite-momentum frame these parton states are long-lived by virtue of the characteristic time dilatation. The derivation of this intuitively appealing picture from a canonical quantum field, modified by imposing a maximum constraint on $k_\perp$, has been discussed as well as its applicability to the particular class of amplitudes with "good currents."[3] In particular, the ratio $Q^2/2M\nu$, where $Q^2 > 0$ is the negative of the square of the invariant momentum transfer and $q \cdot P = M\nu$, measures the fraction $x \equiv Q^2/2M\nu$ of the longitudinal momentum on the parton from which the electron scatters and is a finite fraction $0 < x < 1$ in the Bjorken limit.

It is easy to show that the ratio x must be finite

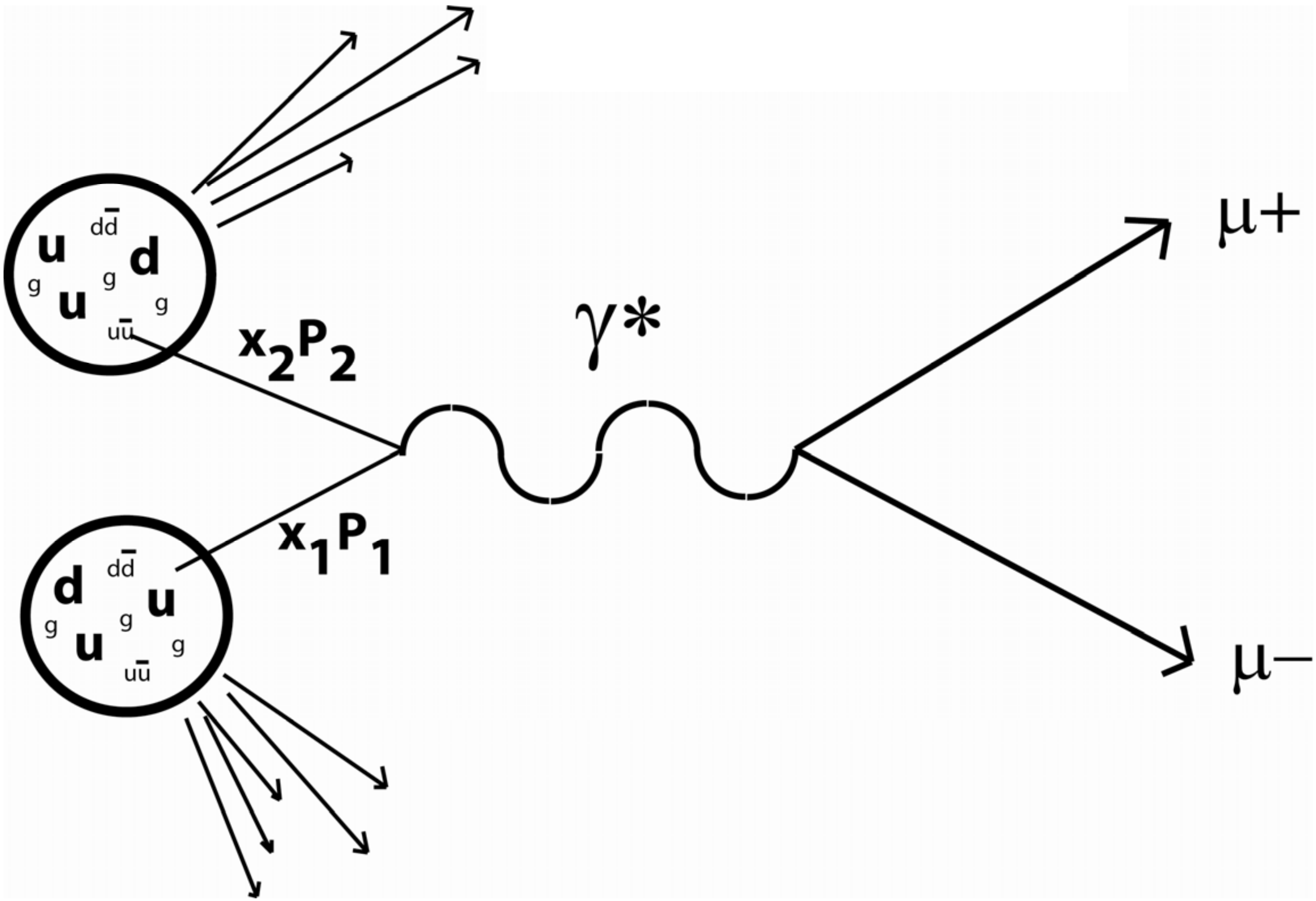
Sidney Drell and Tung-Mow Yan showed results on parton ideas developed for DIS could be applied to calculate "Drell-Yan" production of di-leptons

PRL 25, 316 (1970)



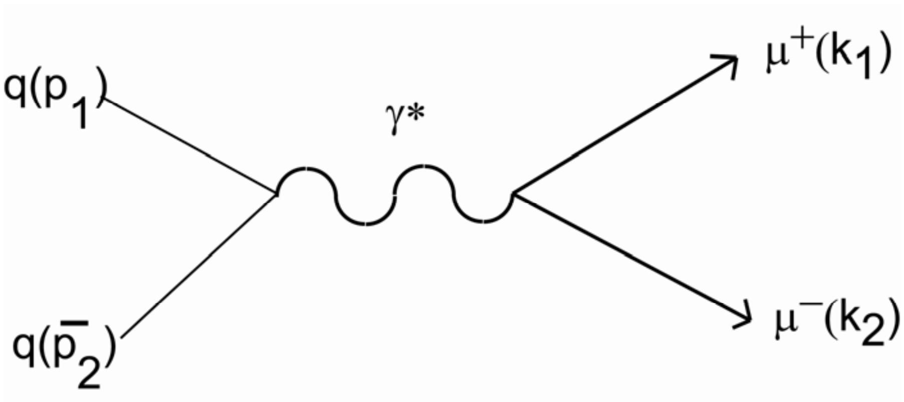
$$pp \to \mu^+ \mu^- + X$$

Drell-Yan Diagrams



Drell-Yan Calculation

Some important kinematic variables



$$\hat{s} = (p_1 + p_2)^2 = (k_1 + k_2)^2 \qquad \hat{t} = (p_1 - k_1)^2 = (p_2 - k_2)^2$$

$$\hat{u} = (p_1 - k_2)^2 = (p_2 - k_1)^2$$

Mass of the virtual photon squared

Center-of-mass energy squared of parton collision

Mass of the di-muon pair squared

Q^2 of the interactions

(CTEQ SS: J. Owens)

Drell-Yan Calculation

Cross section for $e^+e^- \to \mu^+\mu^-$

$$\sigma = \frac{4\pi\alpha^2}{3s}$$

cross section for $q\overline{q} \to \mu^+\mu^-$ need to adjust for charge and color-averaging

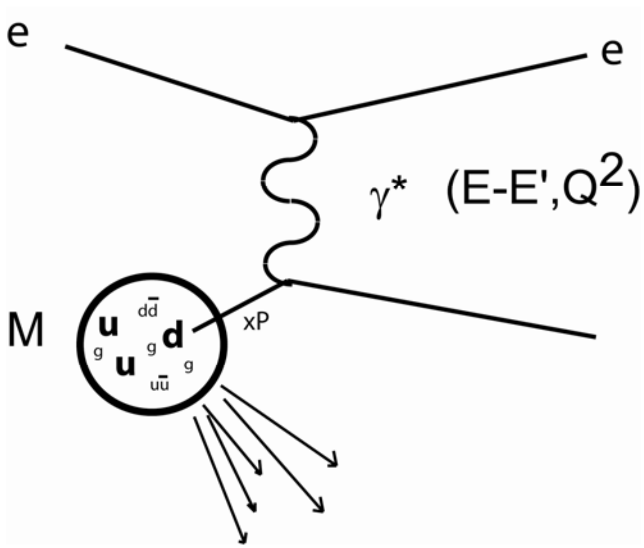
$$\sigma_0 = \frac{4\pi\alpha^2}{9\hat{s}} e_q^2$$

And convolute with the probabilities for quarks at different momenta (from DIS)

$$\sigma(AB \to \mu^+\mu^- + X) = \sum_q \int dx_a dx_b \sigma_0 [q(x_a)\overline{q}(x_b) + a \leftrightarrow b]$$

$$= \sum_q \int dx_a dx_b \frac{4\pi\alpha^2 e_q^2}{9Q^2} [q(x_a)\overline{q}(x_b) + a \leftrightarrow b]$$

DIS



The Parton Model: the q's should be the same ones we got studying DIS

$$\frac{d\sigma(eq \to eq)}{dxdy} = \frac{2\pi\alpha^2}{Q^4}[1+(1-y)^2]\sum_q e_q^2 x q(x)$$

$$x = \frac{Q^2}{2M(E-E')}$$

$$y = -\frac{\hat{t}}{\hat{s}} = \sin^2(\frac{\hat{\theta}}{2}) \simeq \frac{2P \cdot q}{s}$$

 (Collider Physics: Barger&Phillips)

Christenson, Hicks, Lederman, Limon, Pope, Zavattini

Total cross section kind of hard to measure experimentally…

First experiment to see muon pairs produced in hadron-hadron collisions

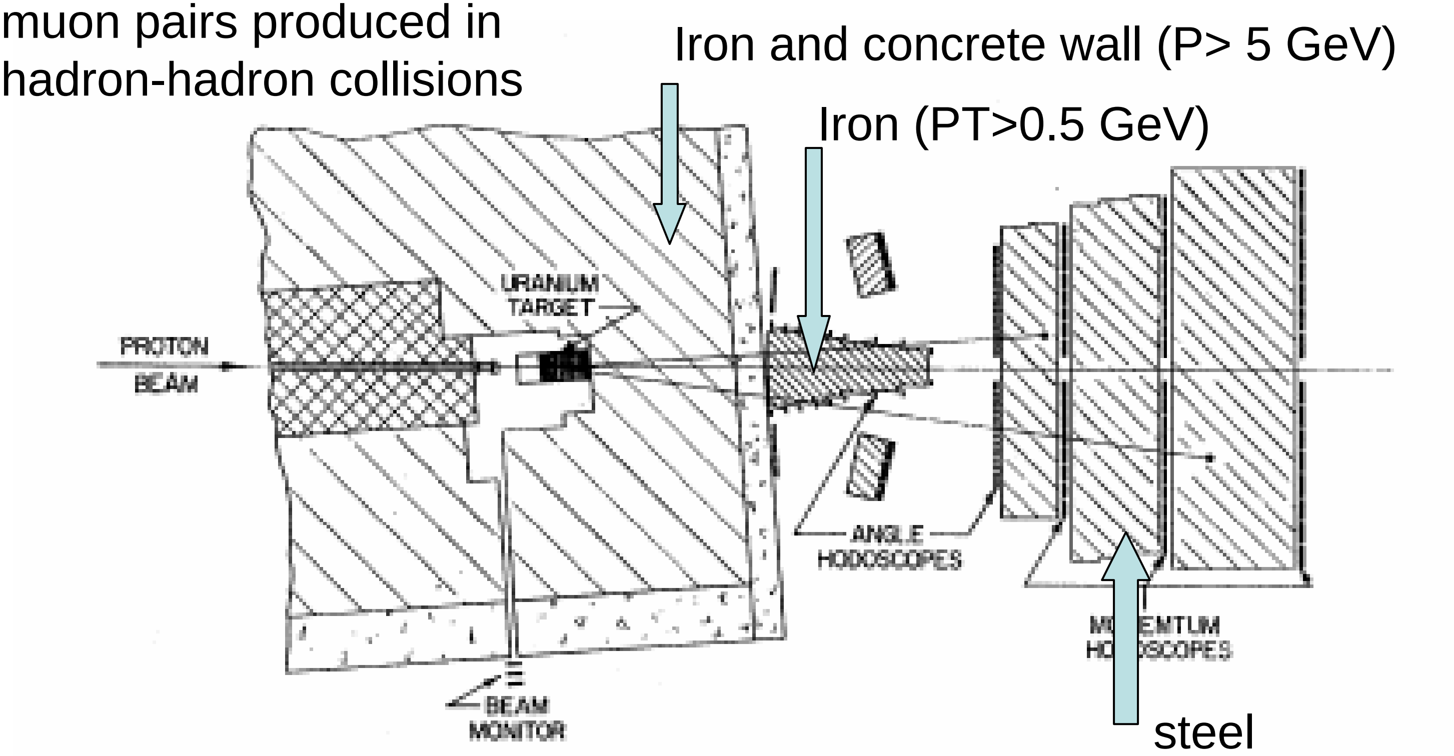


FIG. 1. Plan view of the apparatus.

Brookhaven AGS, protons (29 GeV) on Uranium

PRL 25, 1523 (1970)

Christenson et al., cont.

VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

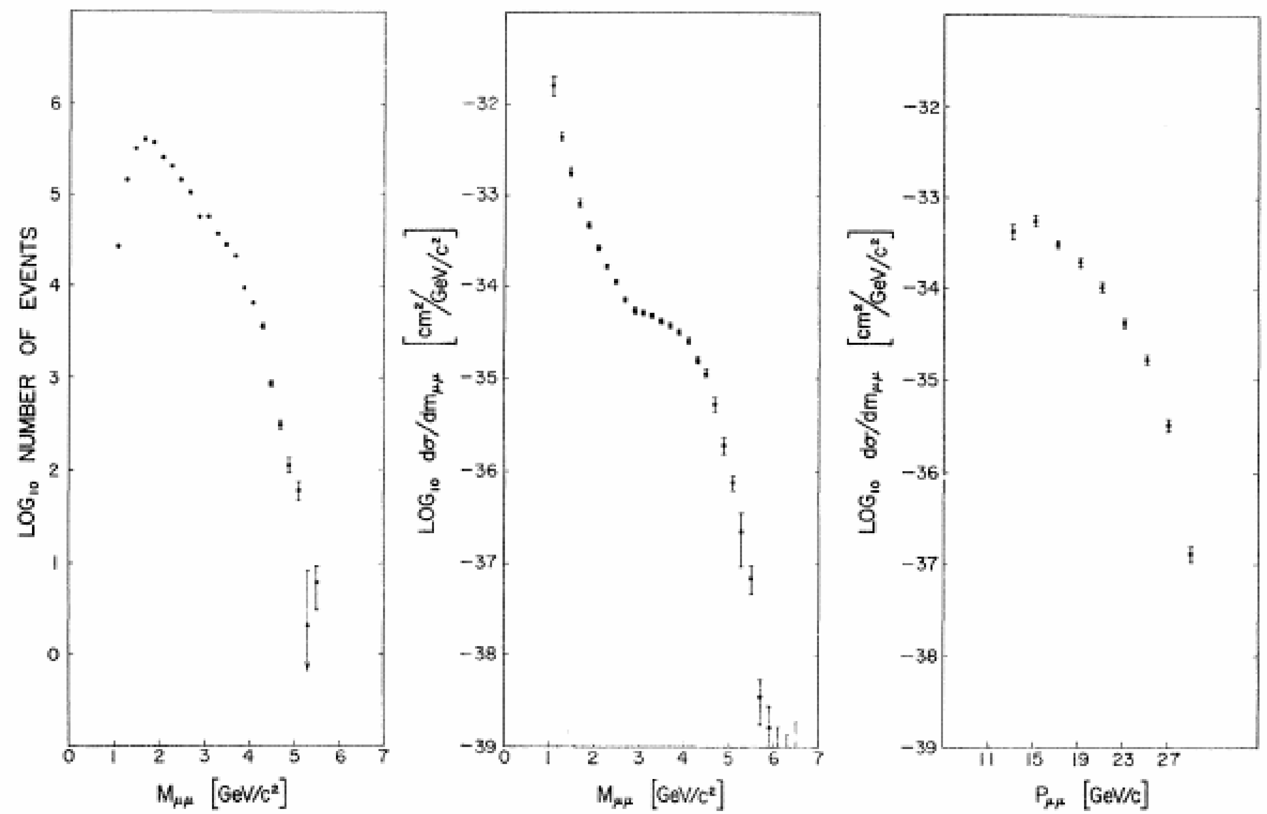


FIG. 2. (a) Observed events as a function of the effective mass of the muon pair. (b) Cross section as a function of the effective mass of the muon pair (these data include the wide-angle counters). (c) Cross section as a function of the laboratory momentum of the muon pair.

Drell-Yan Calculation

$\hat{s}$ is not fixed, so differential cross section is more interesting…

First, write $\hat{s}$ (mass of muon pair) in terms of s

$$s = (p_A + p_B)^2 = p_A^2 + p_B^2 + 2 p_A \cdot p_B$$

$$= 2 p_A \cdot p_B = 2 \frac{p_1}{x_1} \cdot \frac{p_2}{x_2} = \frac{\hat{s}}{x_1 x_2}$$

Define $\tau = x_a x_b = \dfrac{\hat{s}}{s} = \dfrac{Q^2}{s} = \dfrac{M(\mu^+ \mu^-)}{s}$

Drell-Yan Calculation

$$\frac{d\sigma}{dQ^2} = \sum_q \int dx_a dx_b \delta(Q^2 - \hat{s}) \frac{4\pi\alpha^2 e_q^2}{9Q} [q(x_a)\overline{q}(x_b) + a \leftrightarrow b]$$

$$\int dx_a dx_b \delta(Q^2 - x_a x_b s) = \int \frac{dx_a}{x_a s} \delta(x_b - Q^2 / x_a s)$$

$$\frac{d\sigma}{dQ^2} = \sum_q \int \frac{dx_a}{x_a} \frac{4\pi\alpha^2}{9Q^2 s} e_q^2 [q(x_a)\overline{q}(\tau / x_a) + a \leftrightarrow b]$$

$$= \sum \int \frac{dx_a}{x_a} \frac{4\pi\alpha^2}{9Q^4} \tau e_q^2 [q(x_a)\overline{q}(\tau / x_a) + a \leftrightarrow b]$$

$$Q^4 \frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{9} \sum_q \int \frac{dx_a}{x_a} \tau e_q^2 [q(x_a)\overline{q}(\tau / x_a) + a \leftrightarrow b]$$

Universal Curve

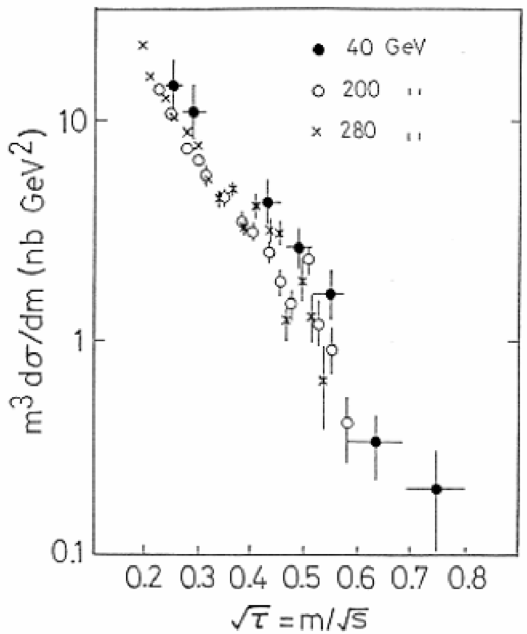


Fig. 5.13. Approximate scaling of $m^3 d\sigma/dm$ for Drell-Y duction in $\pi^- p$ scattering with lab momentum from 40 to 280 GeV [Phys. Lett. **96**B, 417 (1980)].

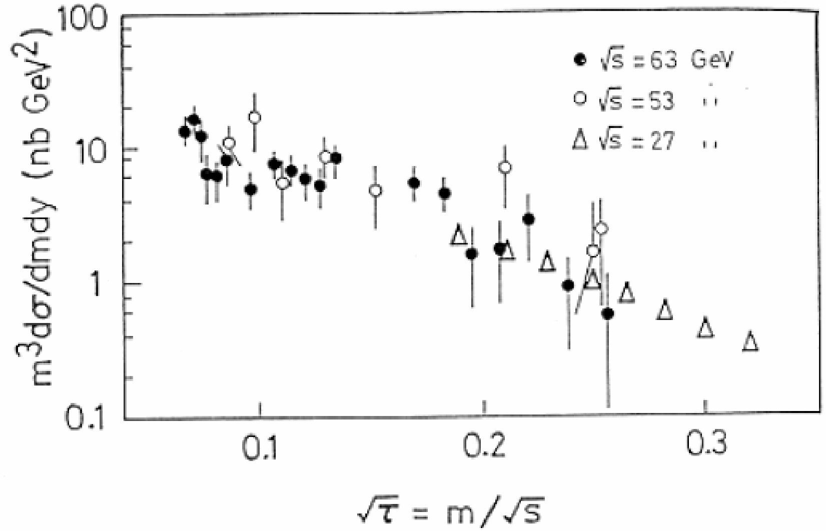
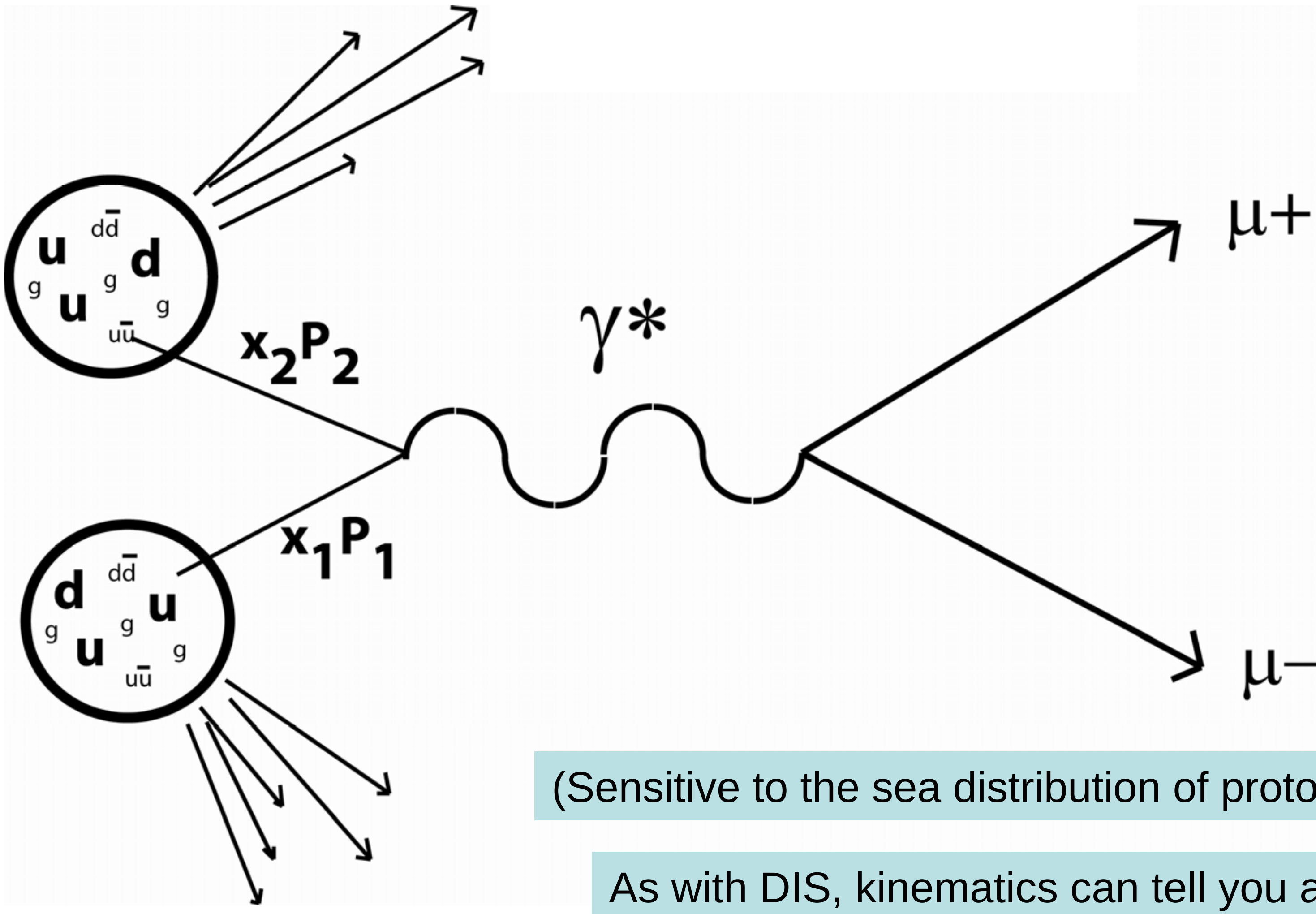


Fig. 5.14. Approximate scaling of $m^3 d\sigma/dm\,dy(y=0)$ for Drell-Yan pair production in pp scattering [Phys. Lett. **91**B, 475 (1980)].

Parton Model seems to work!

We can actually understand the collision of 2 hadrons!

Drell-Yan Diagrams



(Sensitive to the sea distribution of proton)

As with DIS, kinematics can tell you about x (harder parton usually valence)

Kinematics

What is the rapidity of the boson?

$$y = \frac{1}{2}\ln(\frac{E+P_L}{E-P_L})$$

Start with partons with mometum:

$$p_a = (x_a E_B, 0, 0, x_a E_B)$$
$$p_b = (x_b E_B, 0, 0, -x_b E_B)$$

Make a γ* of mass M with mometum

$$p_{\gamma*} = (x_a E_b + x_b E_B, 0, 0, x_a E_b + x_b E_B)$$

Rapidity is then:

$$Y = \frac{1}{2}\ln(\frac{x_a}{x_b})$$

But, remember to make a particle with mass M, need:

$$x_a x_b = M^2 / s$$

Put the last 2 together:

$$Y = \ln(\frac{\sqrt{s}\cdot x_a}{M}) = \ln(\frac{\sqrt{s}\cdot x_a}{Q}) = \ln(\frac{x_a}{\sqrt{\tau}}) = -\ln(\frac{x_b}{\sqrt{\tau}})$$

PDF and fixed target D-Y

$$Q^4 \frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{9} \sum_q \int \frac{dx_a}{x_a} \tau e_q^2 [q(x_a)\bar{q}(\tau / x_a) + a \leftrightarrow b]$$

$$\frac{d\sigma}{dQ^2 dy} = \frac{4\pi\alpha^2}{9Q^4} \sum_q \int \frac{dx_a}{x_a} \tau e_q^2 [q(x_a)\bar{q}(\tau / x_a) + a \leftrightarrow b] \delta(y - \ln(x_a / \sqrt{\tau}))$$

$$\frac{d\sigma}{d\tau dy} = s \frac{4\pi\alpha^2}{9Q^4} \sum_q \int dx_a \tau e_q^2 [q(x_a)\bar{q}(\tau / x_a) + a \leftrightarrow b] \delta(x_a - \sqrt{\tau}\, \mathrm{e}^y)$$

$$= \frac{4\pi\alpha^2}{9s\tau^2} \sum_q e_q^2 \tau [q(\sqrt{\tau} e^y)\bar{q}(\sqrt{\tau} e^{-y}) + a \leftrightarrow b]$$

$$\frac{d\sigma}{dQ^2 dy} = \frac{4\pi\alpha^2}{9s} \sum_q \frac{e_q^2}{\tau} [q(\sqrt{\tau} e^y)\bar{q}(\sqrt{\tau} e^{-y}) + a \leftrightarrow b]$$

Drell-Yan Experiments: Past

2. The Data

Index to the data

p *Nucleus* $\rightarrow \mu^+ \mu^- X$

FNAL-288
FNAL-325
FNAL-444
FNAL-439
CERN-NA-003
FNAL-605
FNAL-772

$p\ p \rightarrow \mu^+ \mu^- X$

CERN-R-209

$p\ p \rightarrow e^+ e^- X$

CERN-R-108
CERN-R-808

$\overline{p}$ *Nucleus* $\rightarrow \mu^+ \mu^- X$

FNAL-537

$\overline{p}$ *Nucleus* $\rightarrow e^+ e^- X$

CERN-UA-002

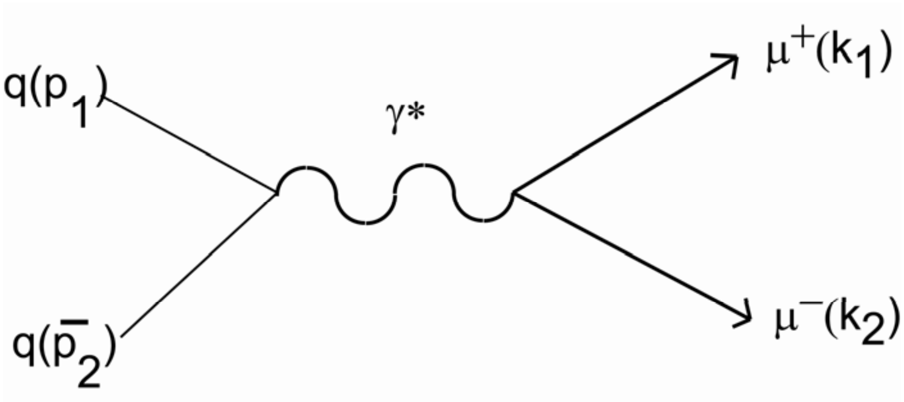
$\pi^\pm$ *Nucleus* $\rightarrow \mu^+ \mu^- X$

FNAL-326
FNAL-444
FNAL-537
CERN-WA-11
CERN-NA-010
CERN-WA-039
FNAL-615

Ellis & Whalley, A Compilation of Drell-Yan Cross sections, Journal of Physics G, 19 (1993) D1

QCD?

I thought this was a school on QCD?!?!?!?!?



EWK calculation

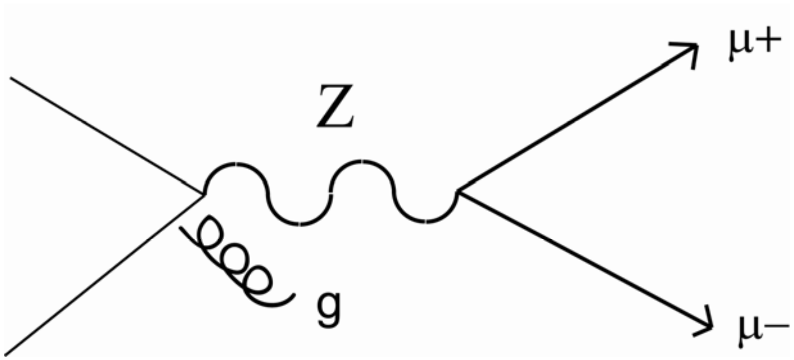
$$\sigma(AB \to \mu^+\mu^- + X) = \sum_q \int dx_a dx_b \sigma_0 [q(x_a)\overline{q}(x_b) + a \leftrightarrow b]$$

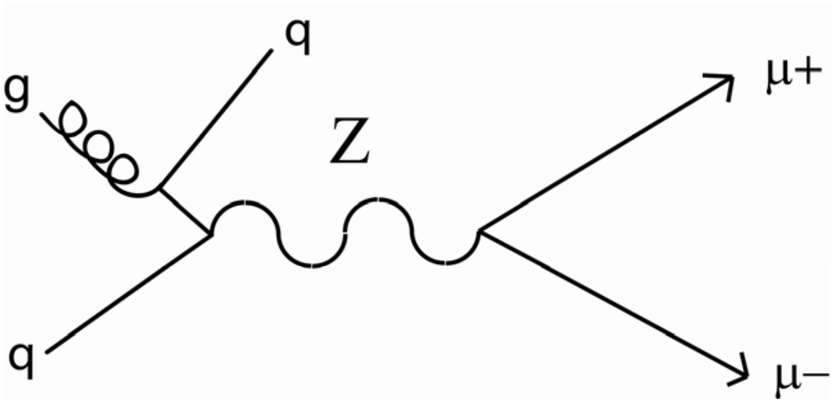
Proton is made of partons

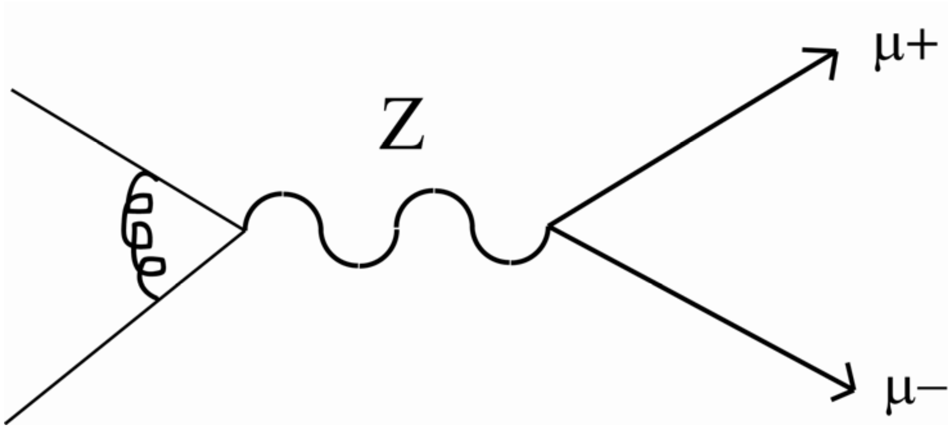
$$\frac{d\sigma(AB \to \mu^+\mu^- + X)}{dy\,d\tau} = \frac{4\pi\alpha^2}{9s} \sum_q \frac{e_q^2}{x_q x_{\overline{q}}} [q(x_q)\overline{q}(x_{\overline{q}}) + (A \leftrightarrow B)]$$

γ*+g

For QCD, we'll need some vertex that depends on alpha_s







Just like with the DIS, collinear divergences exist which can be absorbed into the PDF's

The Drell-Yan process is one of the few for which the factorization theorem has been proved (Collins, Soper, Sterman, 1985)

γ*+g

$$\frac{d\sigma(AB\to\mu^+\mu^-+X)}{dy\,d\tau}=\frac{4\pi\alpha^2}{9s}\sum_q\frac{e_q^2}{x_q x_{\bar q}}[q(x_q)\bar q(x_{\bar q})+(A\leftrightarrow B)]$$

becomes

$$\tau = x_a x_b$$

$$\hat s = \tau s$$

$$\frac{d\sigma(AB\to\mu^+\mu^-+X)}{dy\,d\tau}=\frac{4\pi\alpha^2}{9s}K\sum_q\frac{e_q^2}{x_q x_{\bar q}}[q(x_q,q^2)\bar q(x_{\bar q},q^2)+(A\leftrightarrow B)]$$

DGLAP

$$K = 1+\frac{\alpha_s(q^2)}{2\pi}\frac{4}{3}(1+\frac{4}{3}\pi^2)+\dots$$

$$\cong 1.6 \quad \alpha_2 = 0.2 \ (\mathrm{Q} \simeq 5\ \mathrm{GeV})$$

$$\cong 1.3 \quad \alpha_2 = 0.1 \ (\mathrm{Q} \simeq 100\ \mathrm{GeV})$$

K-factor

(some dependence on x)

(Collider Physics: Barger&Phillips)

K factors

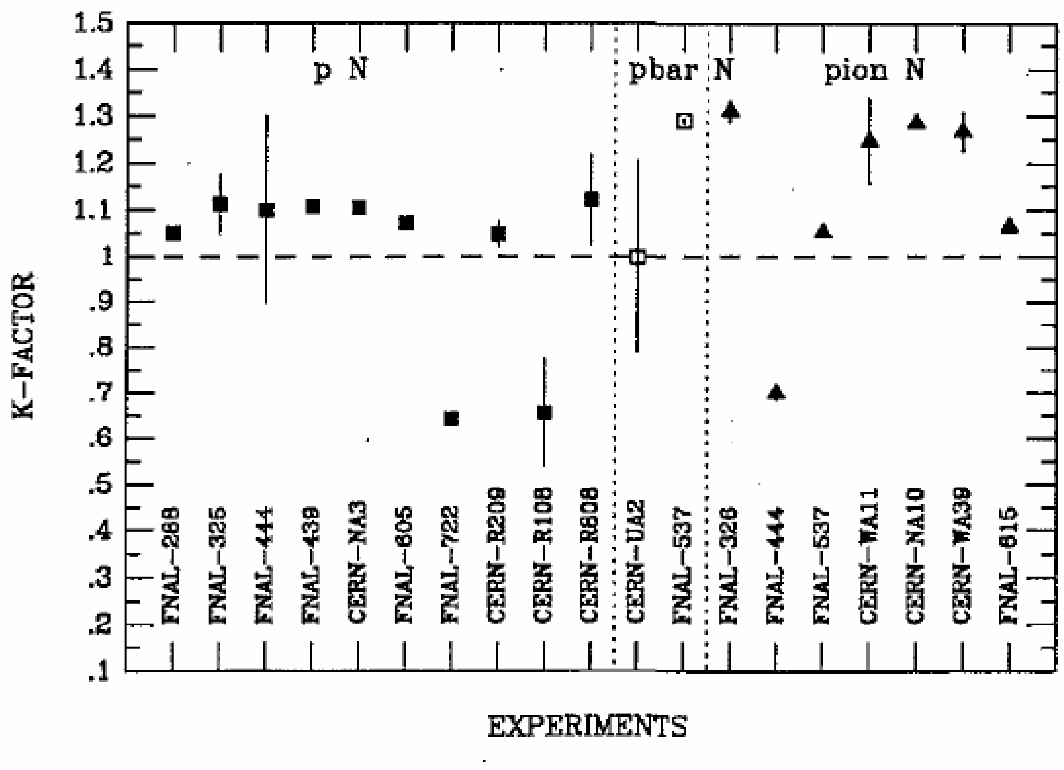


Figure 26. The overall 'K-factors' from each experiment.

K factor relative to a NLO calculation

Ellis & Whalley, A Compilation of Drell-Yan Cross sections, Journal of Physics G, 19 (1993) D1

Fixed Target Drell-Yan today

- intrinsic parton P_T
- anti u – anti d asymmetry
- higher twist contributions
- nuclear dependencies to aid experiments at RHIC and like NuTeV

NA10

$$\pi p \rightarrow \mu^+ \mu^- + X$$

CERN, 1981-1985

Collins-Soper

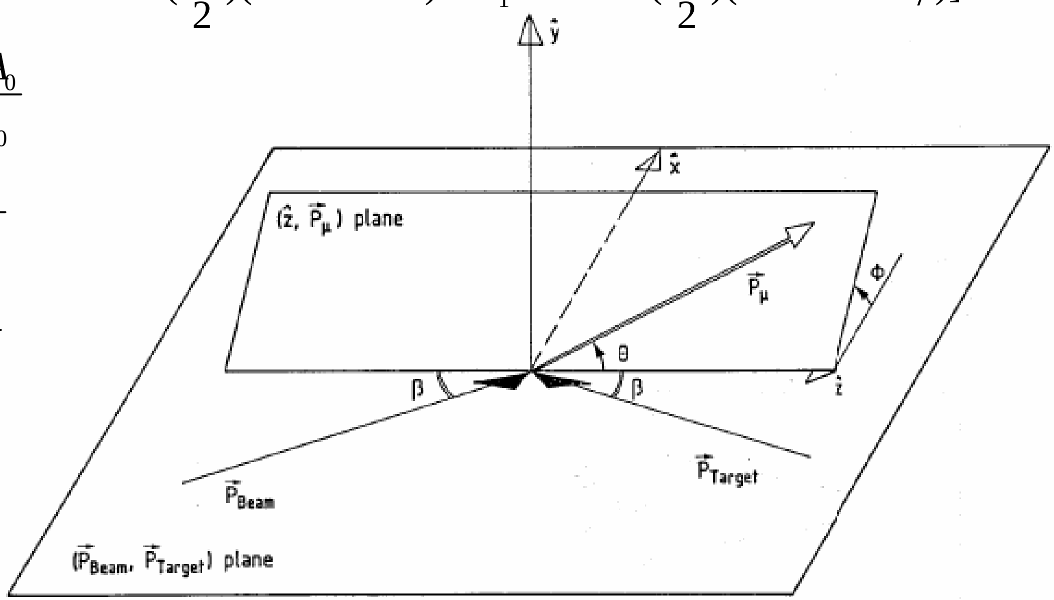
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = [\frac{3}{4\pi(\lambda+3)}][1+\lambda\cos^2\theta + \mu\sin 2\theta\cos\varphi + \frac{\nu}{2}\sin^2\theta\cos 2\varphi$$

$$= (\frac{3}{16\pi})[1+\cos^2\theta + (\frac{A_0}{2})(1-3\cos^2\theta) + A_1\sin 2\theta + (\frac{A_2}{2})(\sin^2\theta\cos 2\phi)]$$

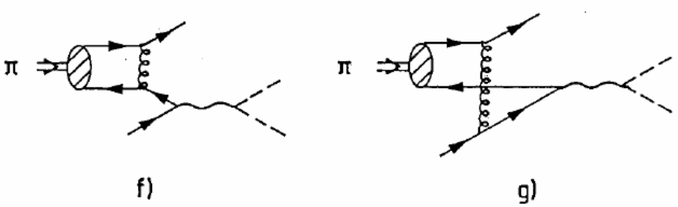
$$\lambda = \frac{2-3A_0}{2+A_0}$$

$$\mu = \frac{2A_1}{2+A_0}$$

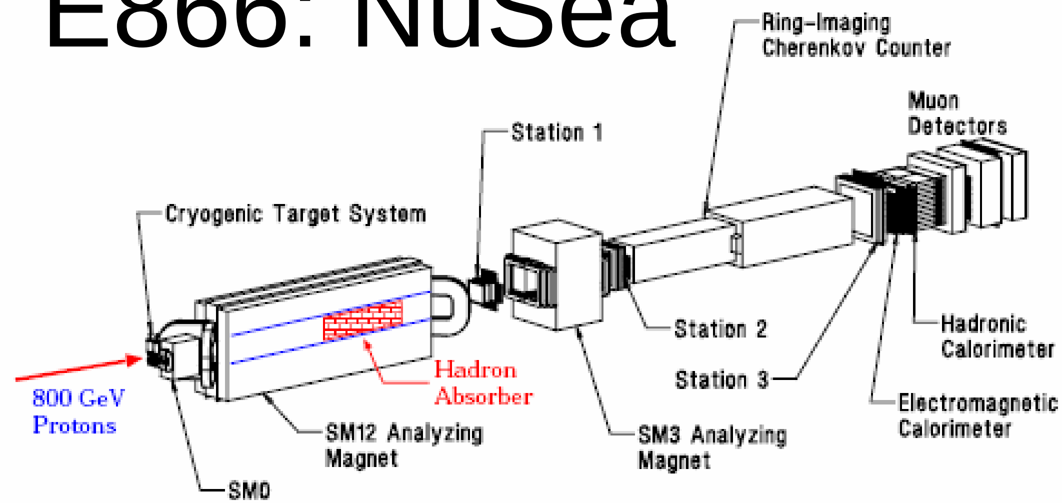
$$\nu = \frac{2A_2}{2+A_0}$$



- no phi dependence in parton model; comes in with QCD (PT of γ*)
- Parton intrinsic transverse momenta
- ratio of gluon brem to compton diagram
- higher twist diagrams



E866: NuSea



FNAL
1996-1997
Deuterium and
hydrogen targets

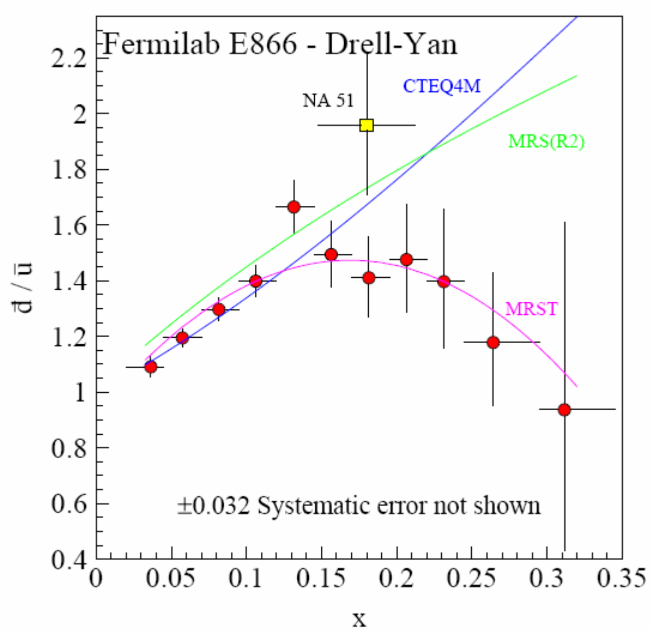
- studies unexpected effect first seen in NMC DIS experiment (1991)

$$S_G \equiv \int_0^1 (F_2^p - F_2^n)\frac{dx}{x} = \frac{1}{3} + \frac{2}{3}\int_0^1 (\bar{u}(x) - \bar{d}(x))dx$$

- Large asymmetry between ubar and dbar at low x (x<0.25)
- unexpected if source of the sea is gluon splitting

$$\sigma_{pp} \propto \frac{4}{9}u(x_1)\bar{u}(x_2) + \frac{1}{9}d(x_1)\bar{d}(x_2)$$

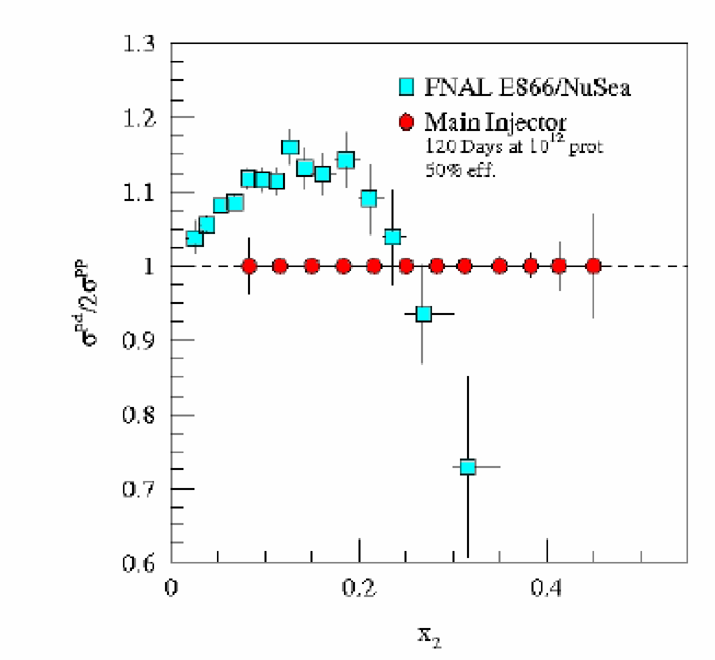
$$\sigma_{pn} \propto \frac{4}{9}u(x_1)\bar{d}(x_2) + \frac{1}{9}d(x_1)\bar{u}(x_2)$$



Drell Yan Experiments: Future?

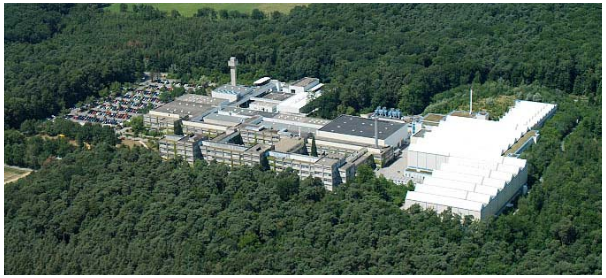
E906: continuation of e866

- sea quark studies
- approved, 2009



PAX at GSI (near Frankfurt)

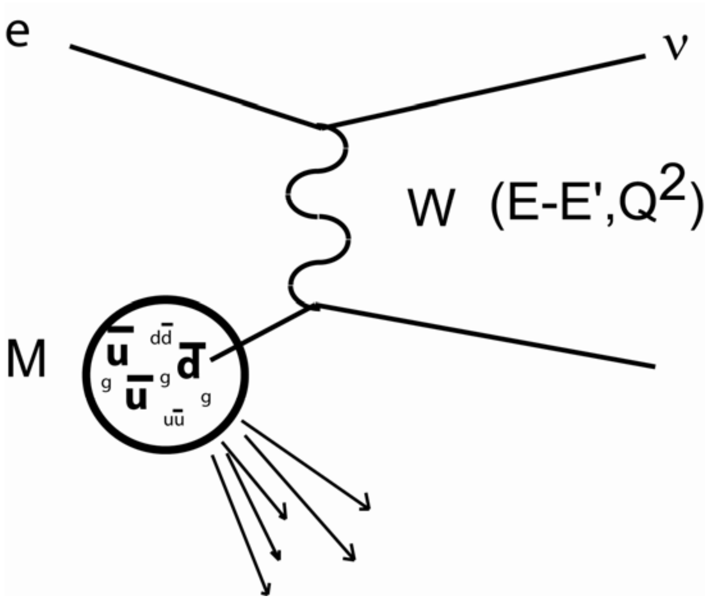
- antiprotons on polarized hydrogen target
- spin tomography of proton, higher twist effects (Collins, Soper, Ralston, Ji, Raffe)



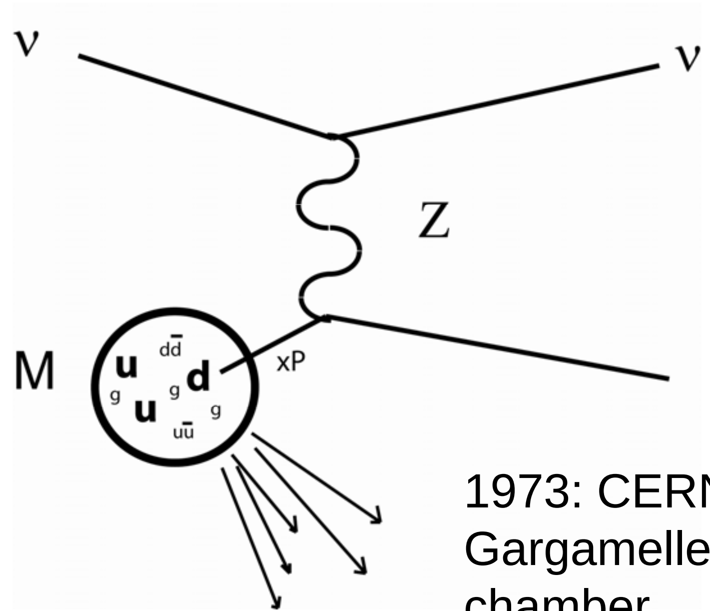
Other Bosons

Low energy evidence from beta decay, DIS, etc with mass about 100 GeV

$$_{83}Bi^{210} \rightarrow {}_{84}Po^{210}\ e^{-}\ \nu \quad (n \rightarrow p e \nu)$$



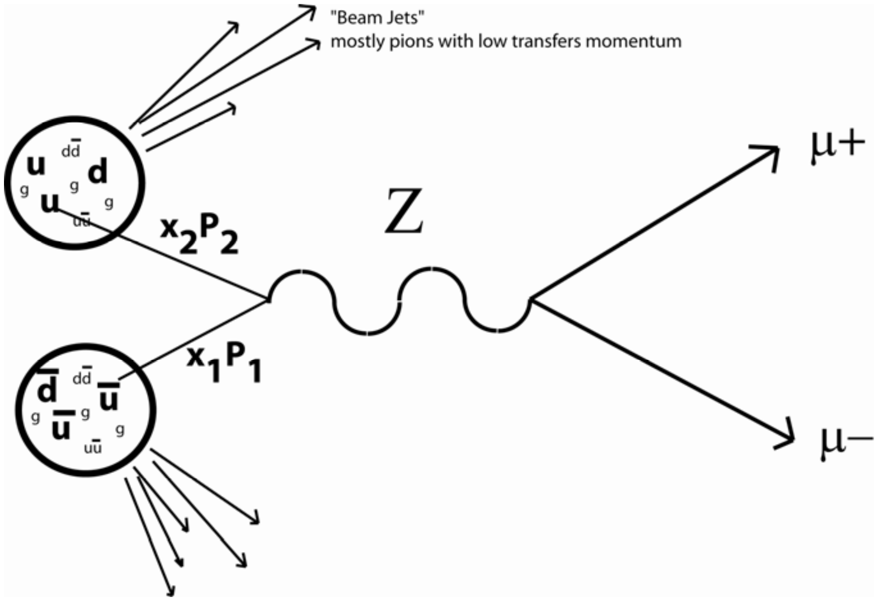
Charged Current

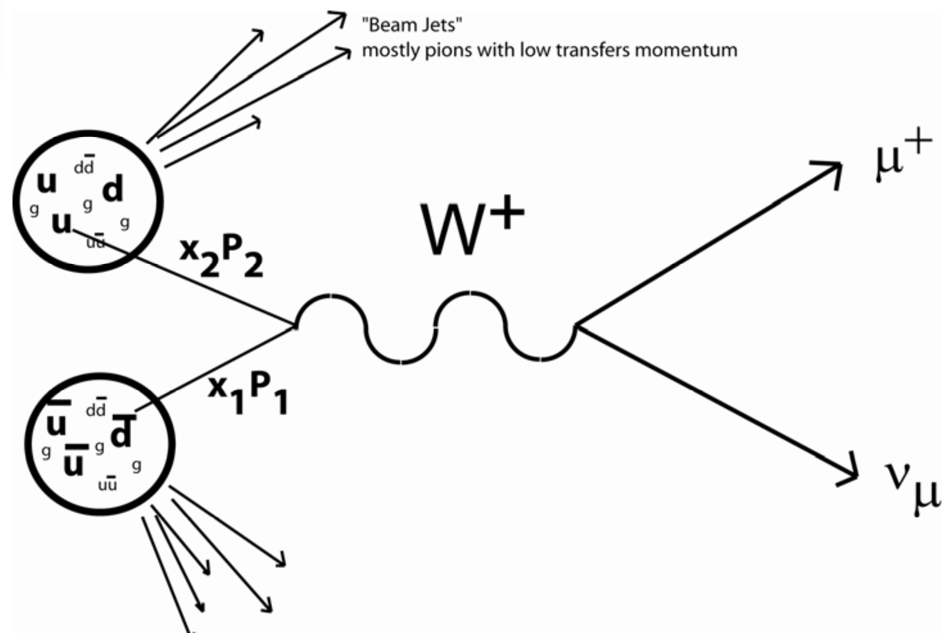


1973: CERN: Gargamelle bubble chamber

Neutral Current

W and Z production

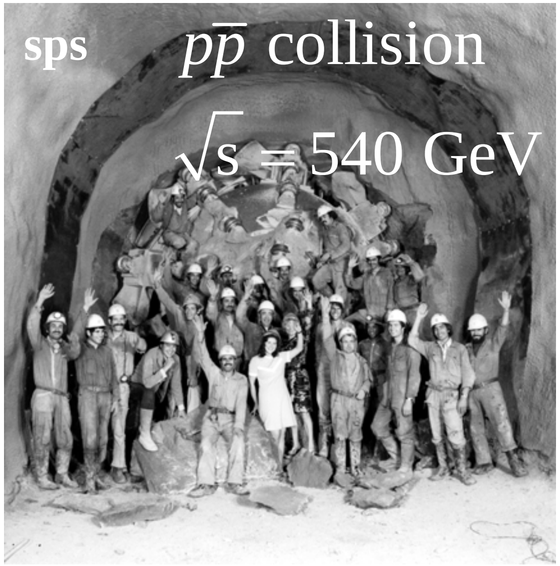


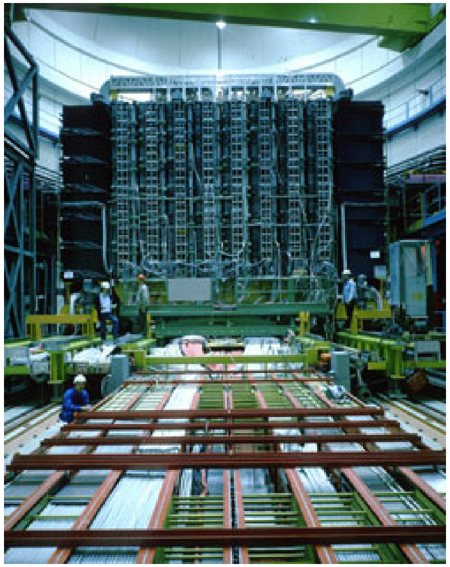


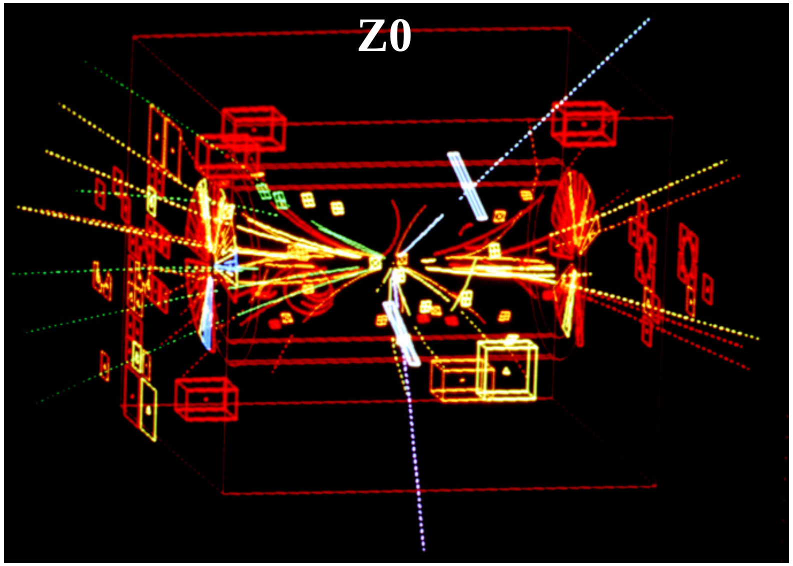
Mass of Z: 91 GeV

Mass of W: 80 GeV

UA1/UA2







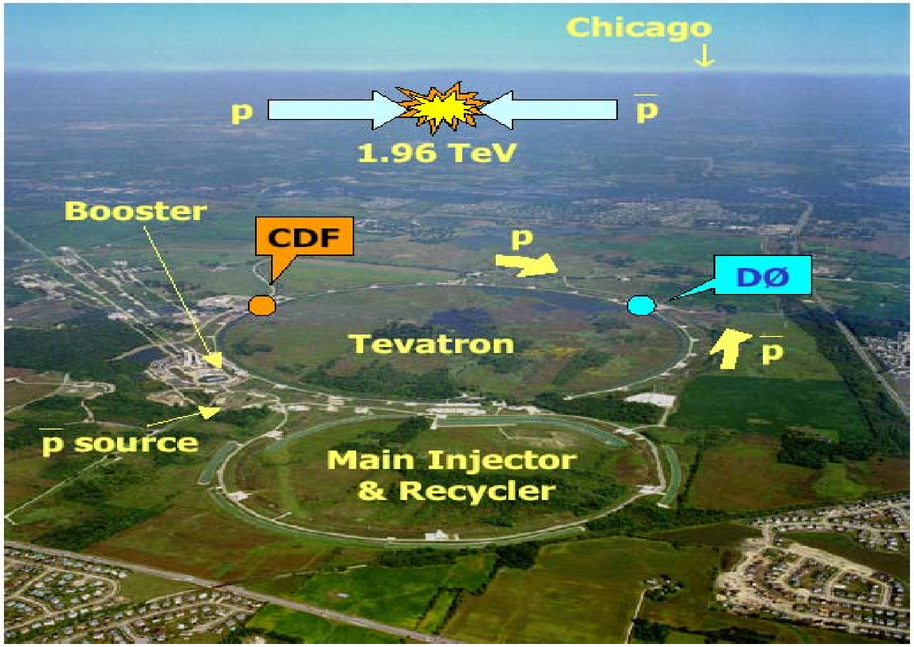
1983

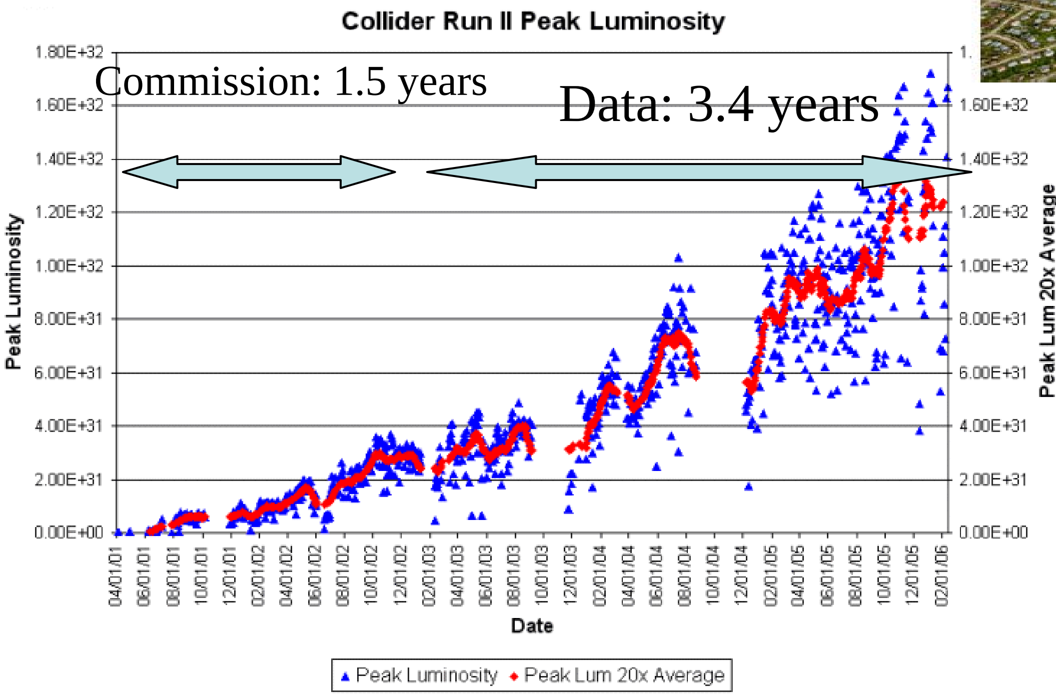
FNAL Tevatron

1983: Tevatron reaches 500 GeV

1985: Tevatron reaches 800 GeV

1987: First collisions in CDF

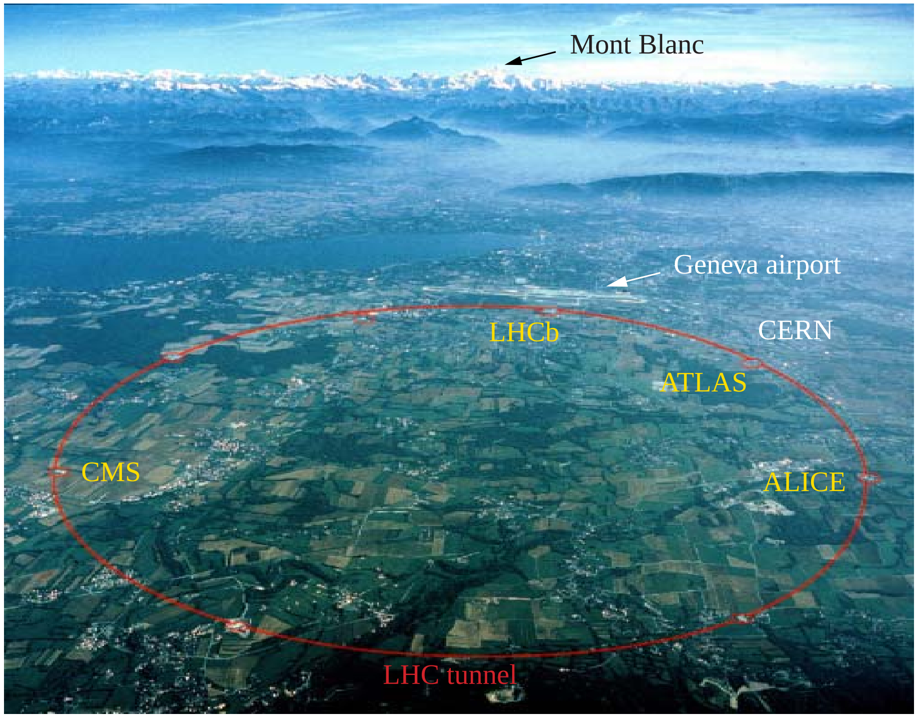


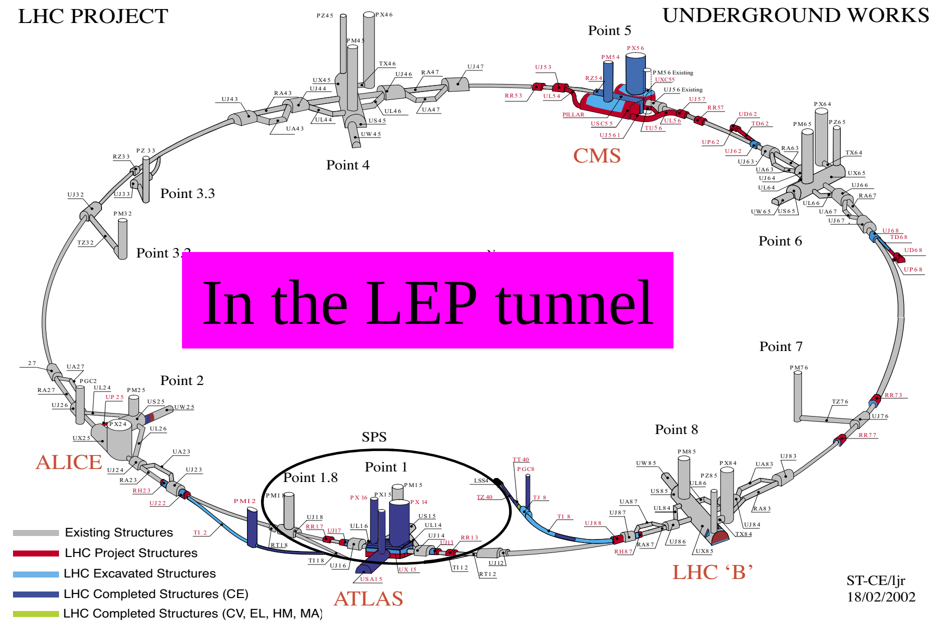


ppbar

Sqrt(s) about 2 TeV

LHC





In the LEP tunnel

- proposed in 1993, turn-on "fall" 2007
- **pp $\sqrt{s}$ =14 TeV L=10^{34} cm^{-2} s^{-1}=10 mb^{-1}MHz**
- **crossing rate 40 MHz (25 ns)**
- **circumference of 27 km (16.8 miles)**
- **Cost of about $3B?** **(depending on accounting method, conversion rate, etc**

Spps, LHC & Tevatron

	spps	Tevatron	LHC
Sqrt(s) (TeV)	0.63	1.96	14
Design lum ($cm^{-2}s^{-1}$)	$6x10^{30}$	$3x10e^{32}$	$10e^{34}$
Int lum (fb-1)	0.014 (UA2)	4?	300?
# experiments (that do W/Z physics)	2	2	2

W/Z vs γ*

Back to the naïve parton model

$$qq \to \gamma^* \to \mu^+ \mu^-$$

$$M = e_q e^2 \frac{\overline{u}(k_1)\gamma_5 v(k_2)\overline{v}(p_2)\gamma^5 u(p_1)}{\hat{s}}$$

$$q\overline{q}' \to W \to \mu\nu$$

$$M = \frac{G_F}{\sqrt{2}} M_W^2 V_{qq'} \frac{v(\overline{q}')\gamma^\alpha(1-\gamma_5)u(q)\overline{u}(\nu)\gamma_\alpha(1-\gamma_5)v(\mu)}{s - M_W^2 + iM_W\Gamma_W}$$

$$q\overline{q}' \to Z \to \mu\mu$$

$$M = \frac{ig^2}{4\cos^2\theta_W} \frac{[\overline{v}_2\gamma^\mu(g_V^u - g_A^j\gamma^5)u_1][\overline{u}_3\gamma_\mu(g_V^e - g_A^e\gamma^5)v_4]}{s - (M_Z - i\Gamma_Z/2)^2}$$

W/Z vs γ*

After some tedious calculation…

$$\frac{d\sigma(AB \to \gamma^* \to \mu^+\mu^- + X)}{dy\,d\tau} = \frac{4\pi\alpha^2}{9s} K \sum_q \frac{e_q^2}{x_q x_{\bar{q}}} [q(x_q, q^2)\bar{q}(x_{\bar{q}}, q^2) + (A \leftrightarrow B)]$$

W.Z have (ignoring their width) fixed mass, so

$$\frac{d\sigma(AB \to W^\pm \to \mu^\pm \nu + X)}{dy} = 2B(W \to \mu\nu) \frac{2\pi G_F}{3\sqrt{2}} K \sum_{q,\bar{q}'} \left|V_{qq'}\right|^2 x_q x_{q'} [q(x_q, M_W^2)\bar{q}'(x_{\bar{q}}, M_w^2)]$$

$$\frac{d\sigma(AB \to Z \to \mu^+\mu^- + X)}{dy} = B(Z \to \mu^+\mu^-) \frac{8\pi G_F}{3\sqrt{2}} K \sum_q [(g_v^q)^2 + (g_A^q)^2] x_q x_{\bar{q}} [q(x_q, M_Z^2)\bar{q}(x_{\bar{q}}, M_Z^2)]$$

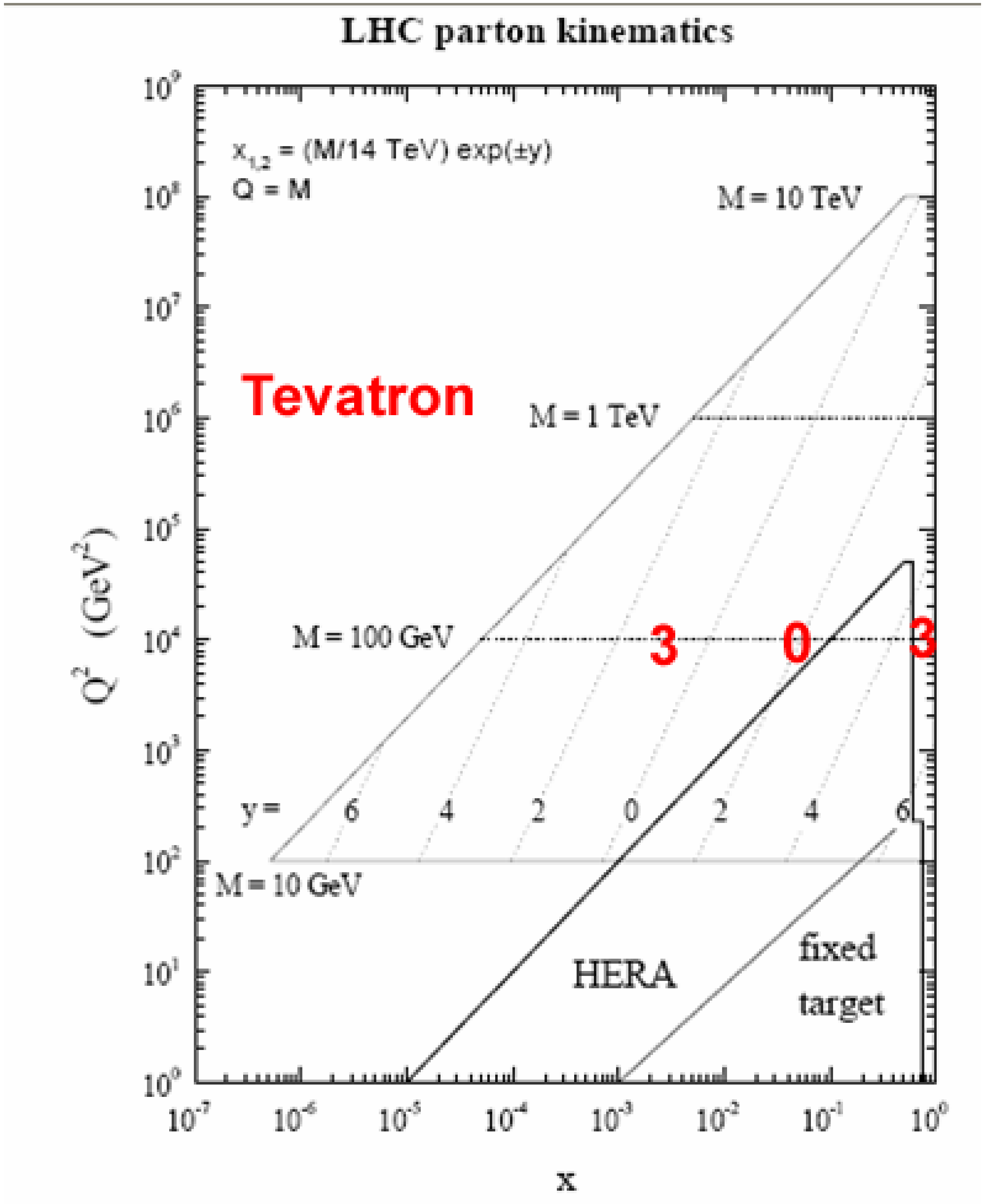
Kinematics

$$Y = \ln(\frac{\sqrt{s} \cdot x_a}{M_W})$$

$$Y_{\max} = \ln(\frac{1800 \cdot 1}{80}) \simeq 3 : \text{Tevatron}$$

$$Y_{\max} = \ln(\frac{14000 \cdot 1}{80}) \simeq 5 : \text{LHC}$$

Kinematics



Hep-ph/9907231
Hep-ph/0509002

Flavors

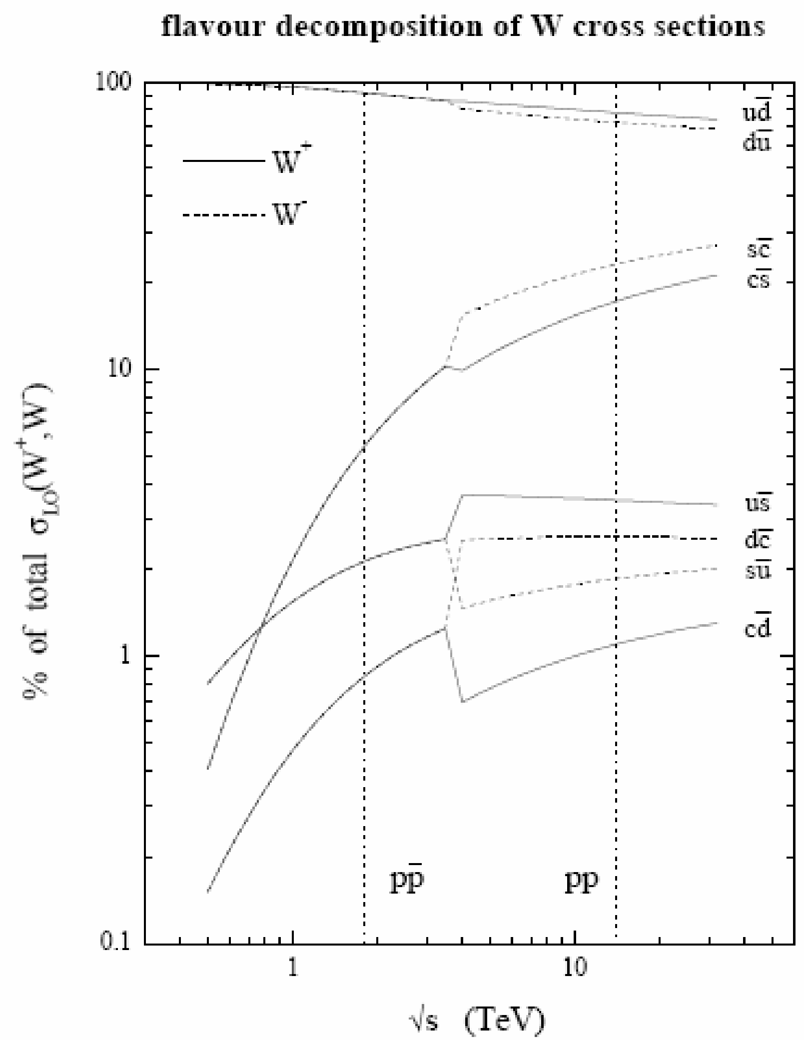


Figure 5: Parton decomposition of the W^+ (solid line) and W^- (dashed line) total cross sections in $p\bar{p}$ and pp collisions. Individual contributions are shown as a percentage of the total cross section in each case. In $p\bar{p}$ collisions the decomposition is the same for W^+ and W^-.

Hep-ph/9907231

Ratio of cross sections x B(leptons)

At Tevatron:

W

$$y = 0 \Rightarrow x = \sqrt{\tau} = 80/1960 = 0.041$$

$$\frac{d\sigma_W}{dy}(y=0) \approx 2BK\frac{2\pi G_F}{3\sqrt{2}}(x_u u(u))(x_d u(d)) = 2(.106)(1.2)\frac{2\pi(1.2x10^{-5}GeV^{-2})}{3\sqrt{2}}(.42)(.58)$$

$$= 1.1x10^{-6}GeV^{-2} = .43nb$$

Z

$$y = 0 \Rightarrow x = \sqrt{\tau} = 90/1960 = 0.046$$

$$\frac{d\sigma_Z}{dy}(y=0) \approx BK\frac{\pi G_F}{3\sqrt{2}}[(.57x_u u(u))(x_u u(u)) + (.74x_d d(d))(x_d u(d))]$$

$$= (.034)(1.2)\frac{\pi(1.2x10^{-5}GeV^{-2})}{3\sqrt{2}}[.57(.58)^2 + .74(.42)^2]$$

$$= 1.2x10^{-7}GeV^{-2} = .047nb$$

Ratio **10**

Spps, LHC & Tevatron

Particle / year*	SppS	Tevatron	LHC
Z's	65	$1x10^4$	$9x10^8$
W's	$2.5x10^5$	$4x10^7$	$2x10^{10}$

(spps, ppbar, 0.0004 nb-1s-1= 0.04 fb-1/yr, 0.63 TeV)

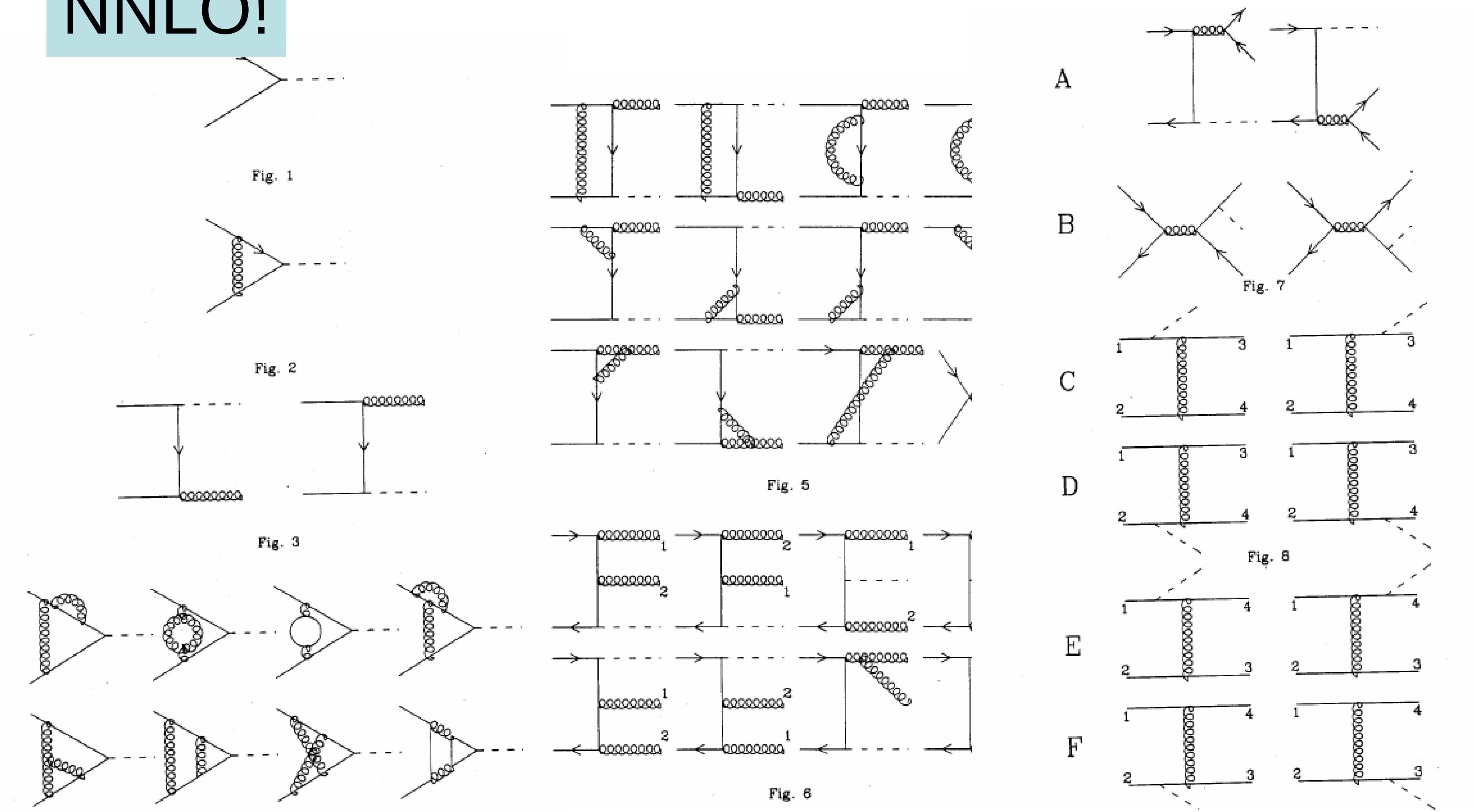
(Tevatron: ppbar, 0.2 $nb^{-1}s^{-1}$=2 fb^{-1}/yr, 1.96 TeV)

(LHC: pp, 10 $nb^{-1}s^{-1}$=100 fb^{-1}/yr, 14 TeV)

*** 1 "snowmass" year = 10^7 s**

Cross Section

NNLO!



Hamberg, Van Neerven, Matsura, Nucl. Phys. B359, 343 (1991)

Cross Section

W⁺ + W⁻ production (nb)								
	$Sp\bar{p}S$		Tevatron		LHC		SSC	
	$\overline{\text{MS}}$	DIS	$\overline{\text{MS}}$	DIS	$\overline{\text{MS}}$	DIS	$\overline{\text{MS}}$	DIS
Born								
$q\bar{q}$	4.91	4.87	15.9	15.6	119.	118.	262.	259.
$\mathcal{O}(\alpha_s)$								
$q\bar{q}$, $S+V$	0.61	1.78	1.15	5.64	7.5	42.6	14.7	93.1
$q\bar{q}$, H	0.93	−0.21	3.40	−0.96	26.2	−7.8	58.2	−17.8
$q\bar{q}$, total	1.54	1.57	4.55	4.67	33.6	34.7	72.9	75.3
qg	−0.18	−0.10	−1.56	−0.98	−20.8	−15.4	−47.9	−37.5
$\sigma^{(1)}$	1.36	1.47	3.00	3.70	12.8	19.4	24.9	37.7
σ_1	6.26	6.34	18.9	19.3	132.	138.	287.	297.
$\mathcal{O}(\alpha_s^2)$								
$q\bar{q}$, $S+V$	−0.05	0.58	−0.11	1.86	−0.8	14.0	−1.8	30.7
$q\bar{q}$, H	0.47	−0.12	1.31	−0.59	9.5	−4.8	20.3	−10.9
$q\bar{q}$, total	0.43	0.47	1.22	1.32	9.0	9.9	19.5	21.5
qg	−0.13	−0.09	−1.04	−0.79	−14.3	−10.2	−32.4	−22.3
gg	0.0022	0.0006	0.043	0.020	1.5	1.1	4.4	3.6
$qq + \bar{q}\bar{q}$	0.0020	0.0016	0.016	0.029	0.4	0.7	1.0	1.8
$\sigma^{(2)}$	0.31	0.38	0.24	0.58	−3.5	1.5	−7.5	4.6
σ_2	6.57	6.72	19.2	19.9	129.	139.	279.	302.

Hamberg, Van Neerven, Matsura, Nucl. Phys. B359, 343 (1991)

Update in, for example, MRST hep-ph/0308087

Kinematics

Experimenters need more than just total cross section, need effect on kinematic distributions

Z kinematics

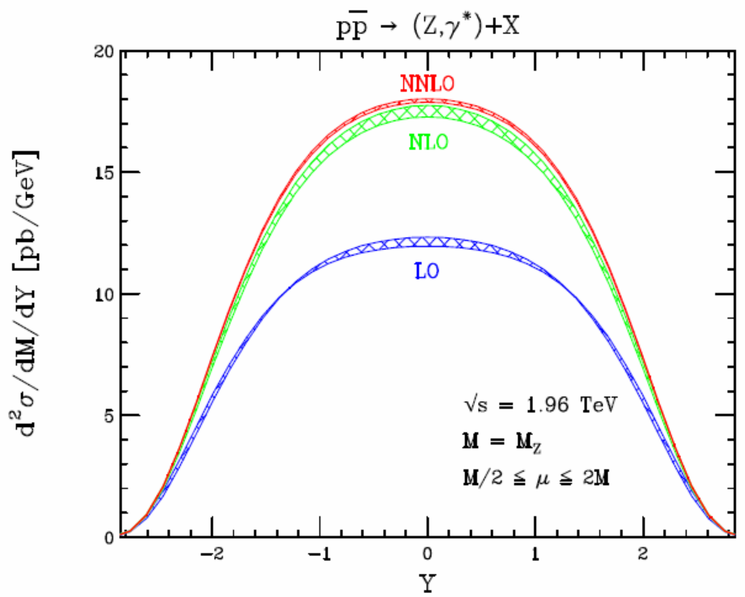


Figure 5: The CMS rapidity distribution of an on-shell Z boson at Run II of the Tevatron. The LO, NLO, and NNLO results have been included. The bands indicate the variation of the renormalization and factorization scales in the range $M_Z/2 \leq \mu \leq 2M_Z$.

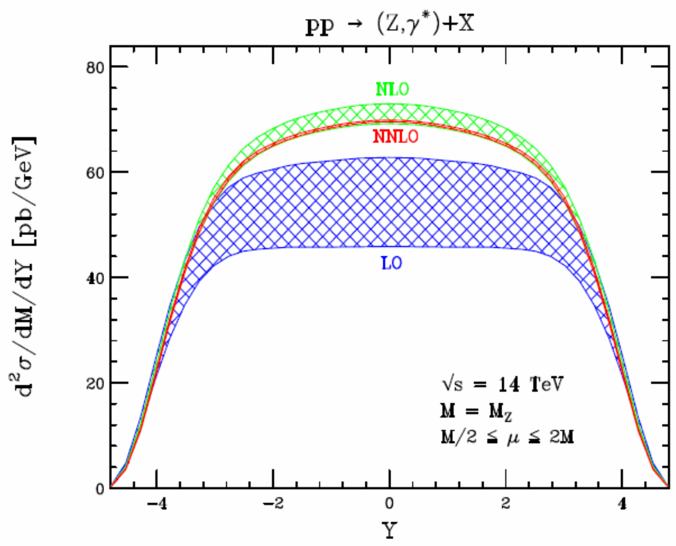
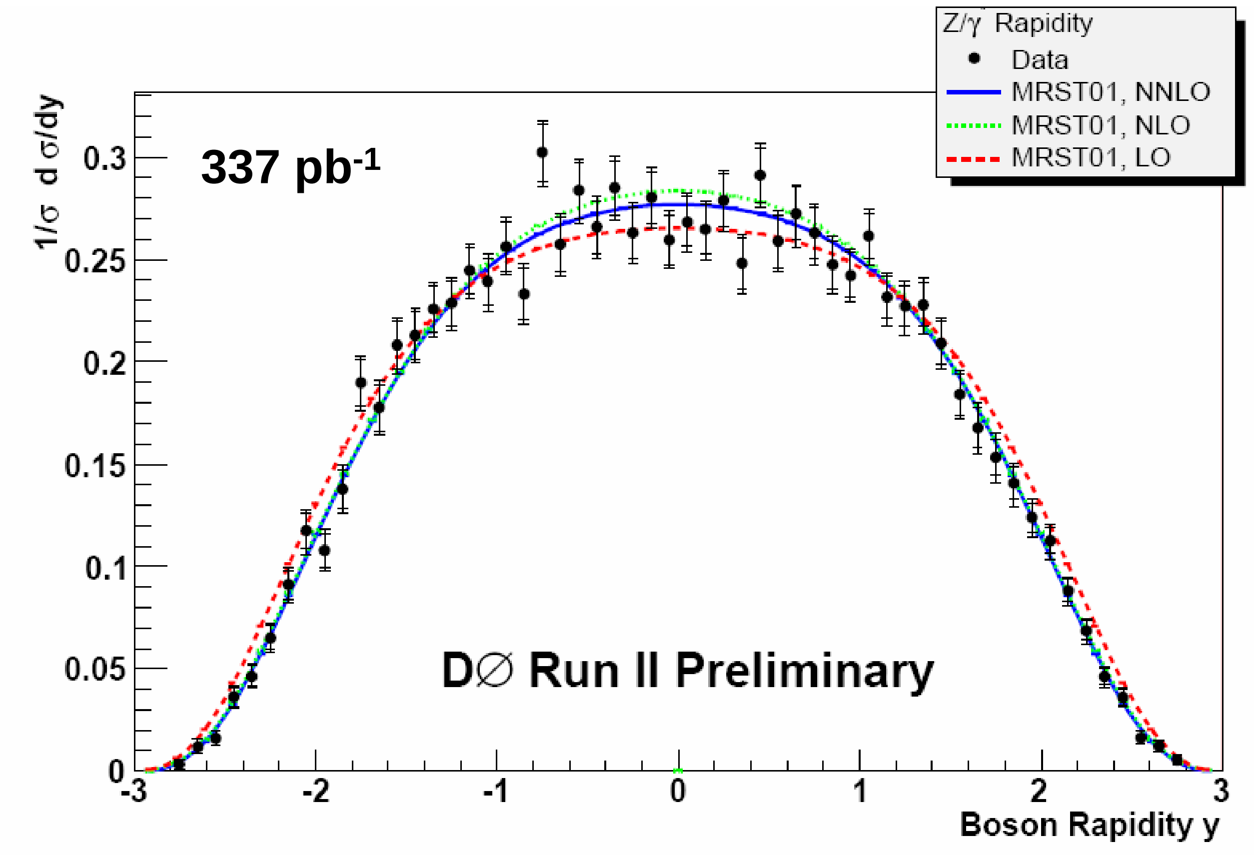


Figure 3: The CMS rapidity distribution of an on-shell Z boson at the LHC. The LO, NLO, and NNLO results have been included. The bands indicate the variation of the renormalization and factorization scales in the range $M_Z/2 \leq \mu \leq 2M_Z$.

Hep-ph/0312266: Anastasiou, Dixon, Melnikov, Petriello

Compared with Data



In forward region, data favors NLO,NNLO calc

Kinematics

$p_\perp^{e,\min}$	LO	NLO	NNLO
Inc	11.70,13.74,15.65	16.31,16.82,17.30	16.31, 16.40, 16.50
20	5.85,6.96,8.01	7.94,8.21,8.46	8.10,8.07,8.10
30	4.305, 5.12,5.89	6.18,6.36,6.54	6.18,6.17,6.22
40	0.628,0.746,0.859	2.07,2.10,2.11	2.62,2.54,2.50
50	0,0,0	0.509,0.497,0.480	0.697,0.651,0.639

TABLE I: The lepton invariant mass distribution $d\sigma/dM^2$, $M = m_W$, for on-shell W production in the reaction $pp \to W^- X \to e^-\bar{\nu}W$, in pb/GeV^2, for various choices of $p_\perp^{e,\min}$, GeV and $\mu = m_W/2, m_W, 2m_W$.

Now fully differential NNLO calculation is available.

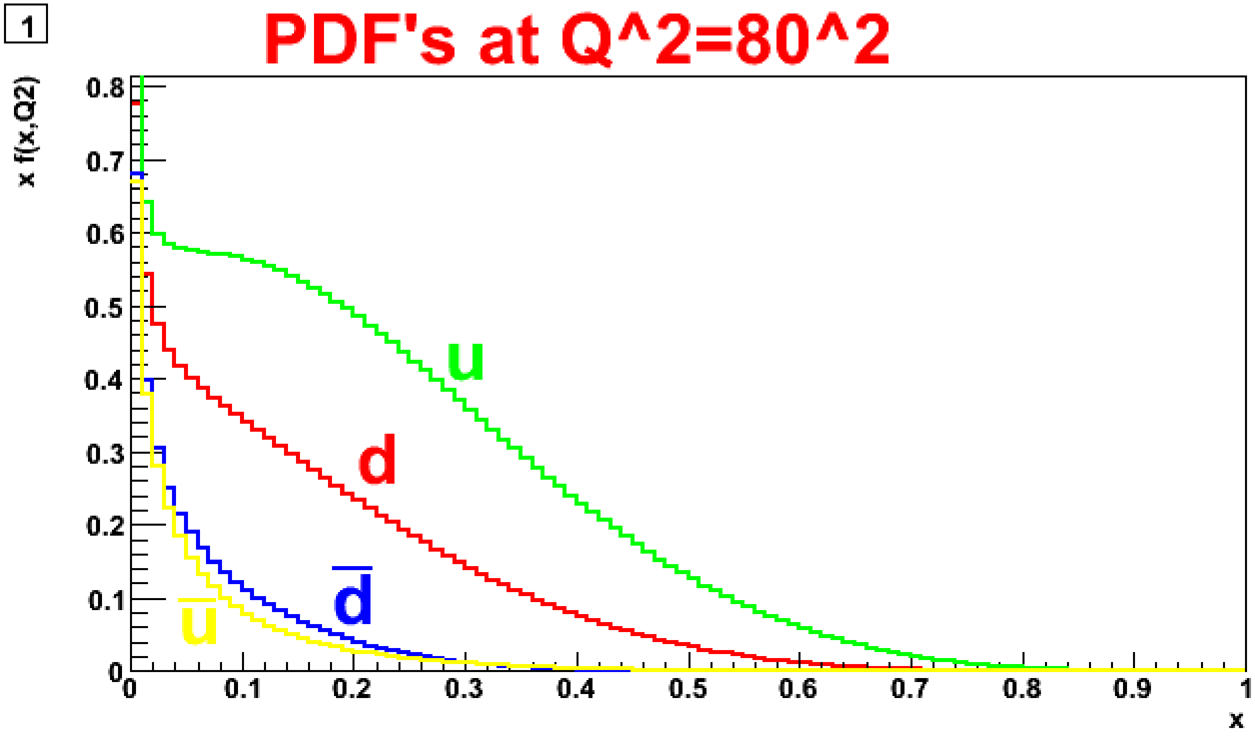
$p_\perp^{e,\min}$ (GeV)	A(NLO)	A(NNLO)
20	0.487,0.488,0.489	0.497,0.492,0.491
30	0.379,0.378,0.378	0.379,0.376,0.377
40	0.127,0.125,0.122	0.161,0.155,0.152
50	0.0312,0.0295,0.0277	0.0427,0.0397,0.0387

TABLE II: Acceptances at NLO and NNLO for various choices of $p_\perp^{e,\min}$ and $\mu = m_W/2, m_W, 2m_W$.

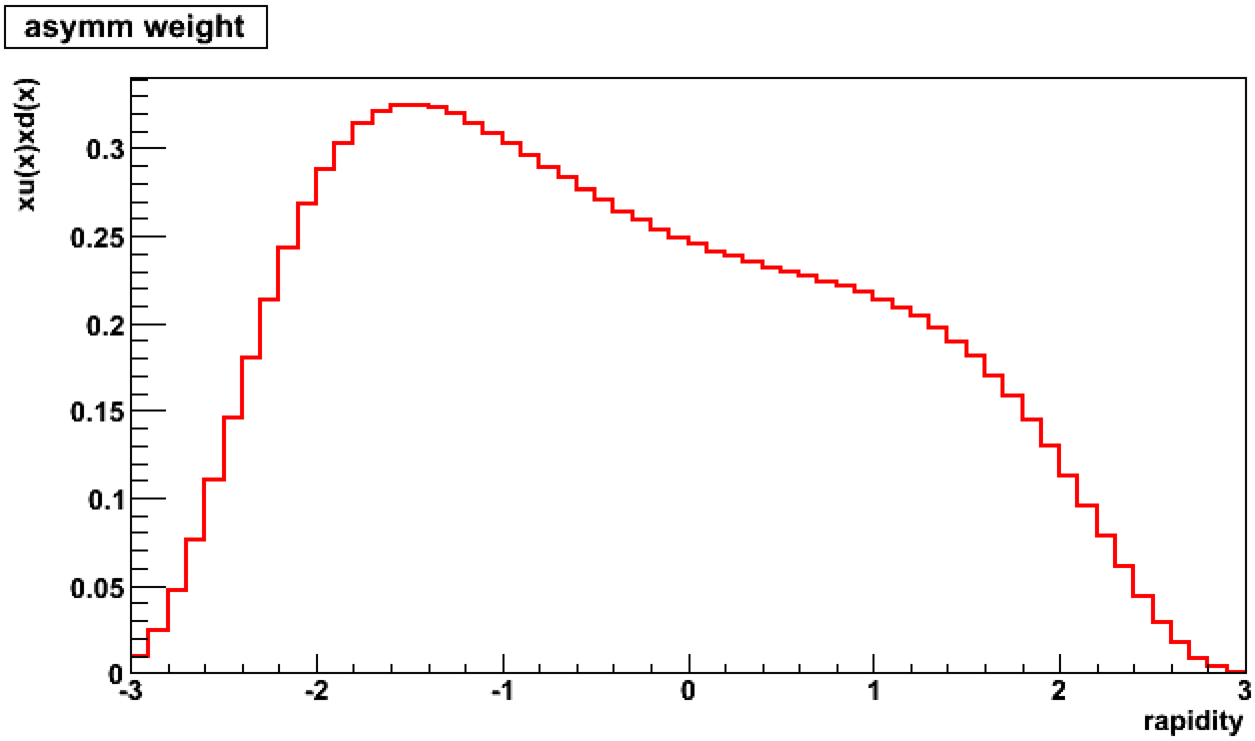
Hep-ph/0603182:
Melnikov & Petrielo

W- rapidity at the Tev

$$\frac{d\sigma_W}{dy}(y) \approx 2BK\frac{2\pi G_F}{3\sqrt{2}}(x_u u(\sqrt{\tau}e^{y}))(x_d d(\sqrt{\tau}e^{-y}))$$

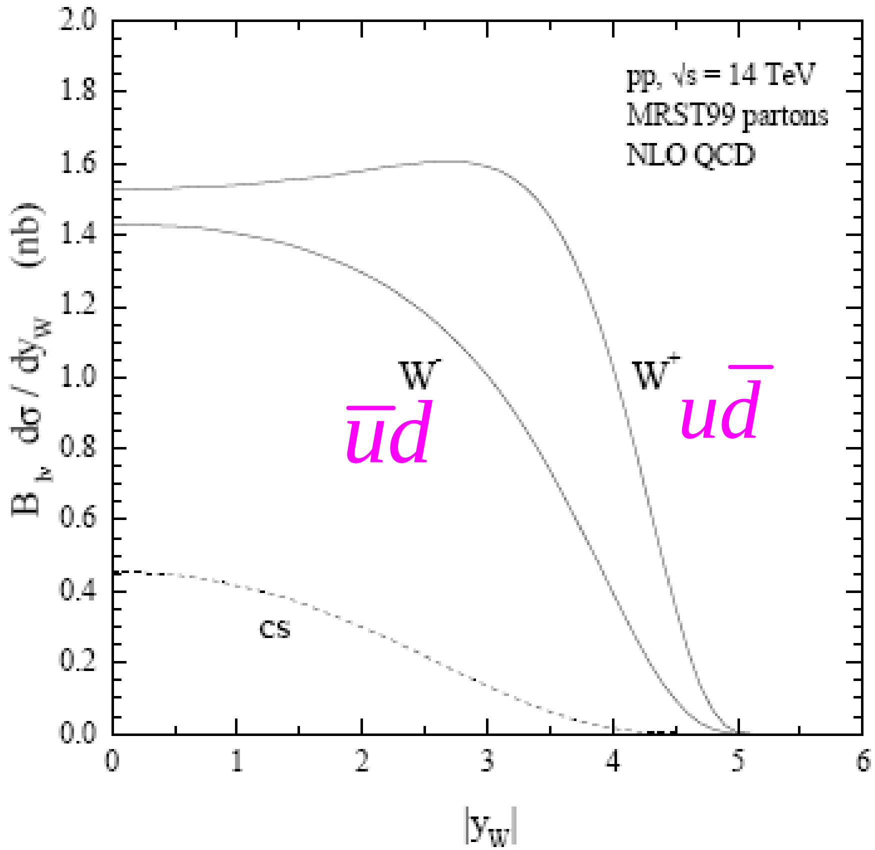


W rapidity at the Tevatron



Useful for understanding the difference between u quarks and d quarks

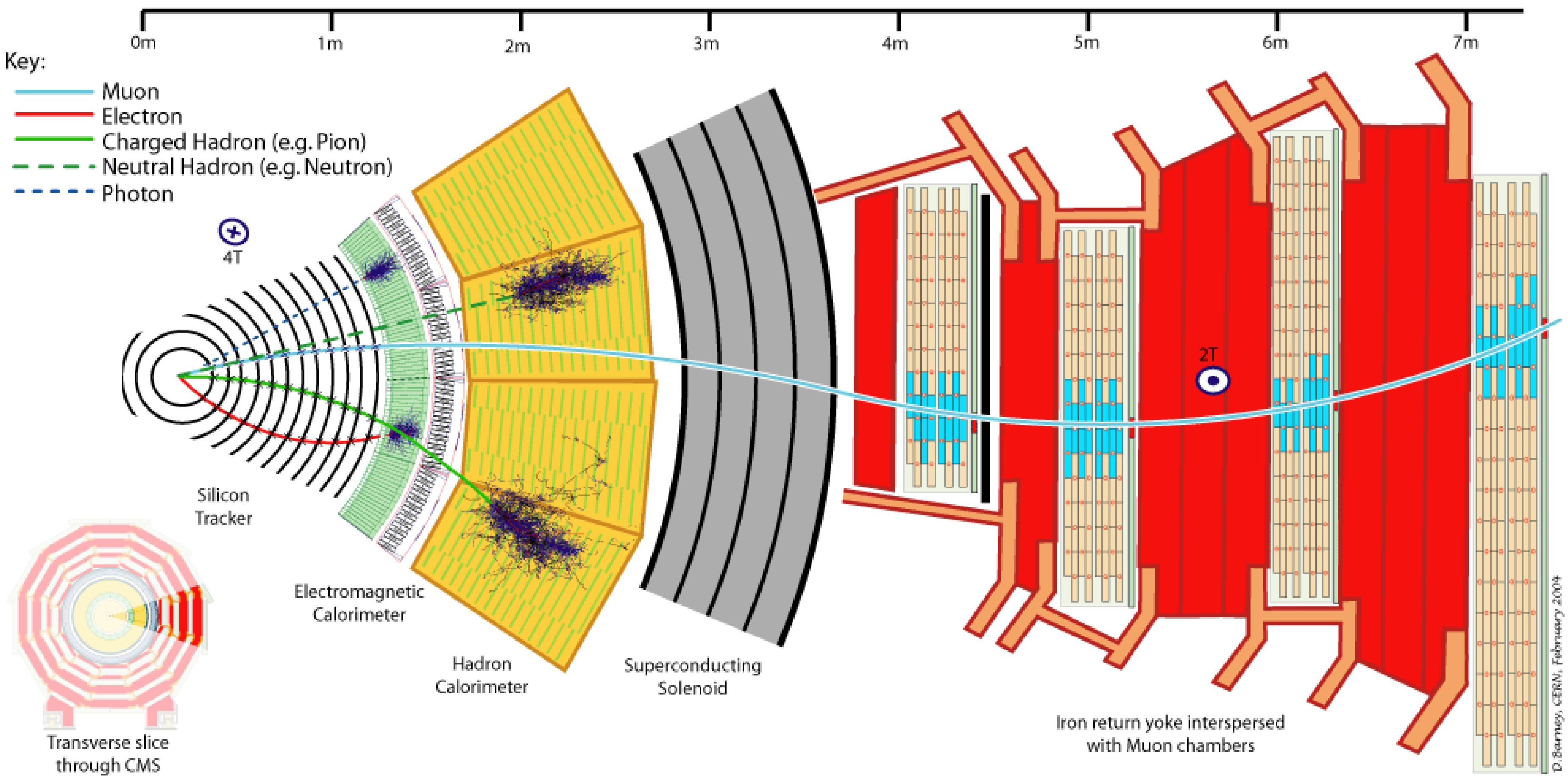
W+ vs W- at LHC



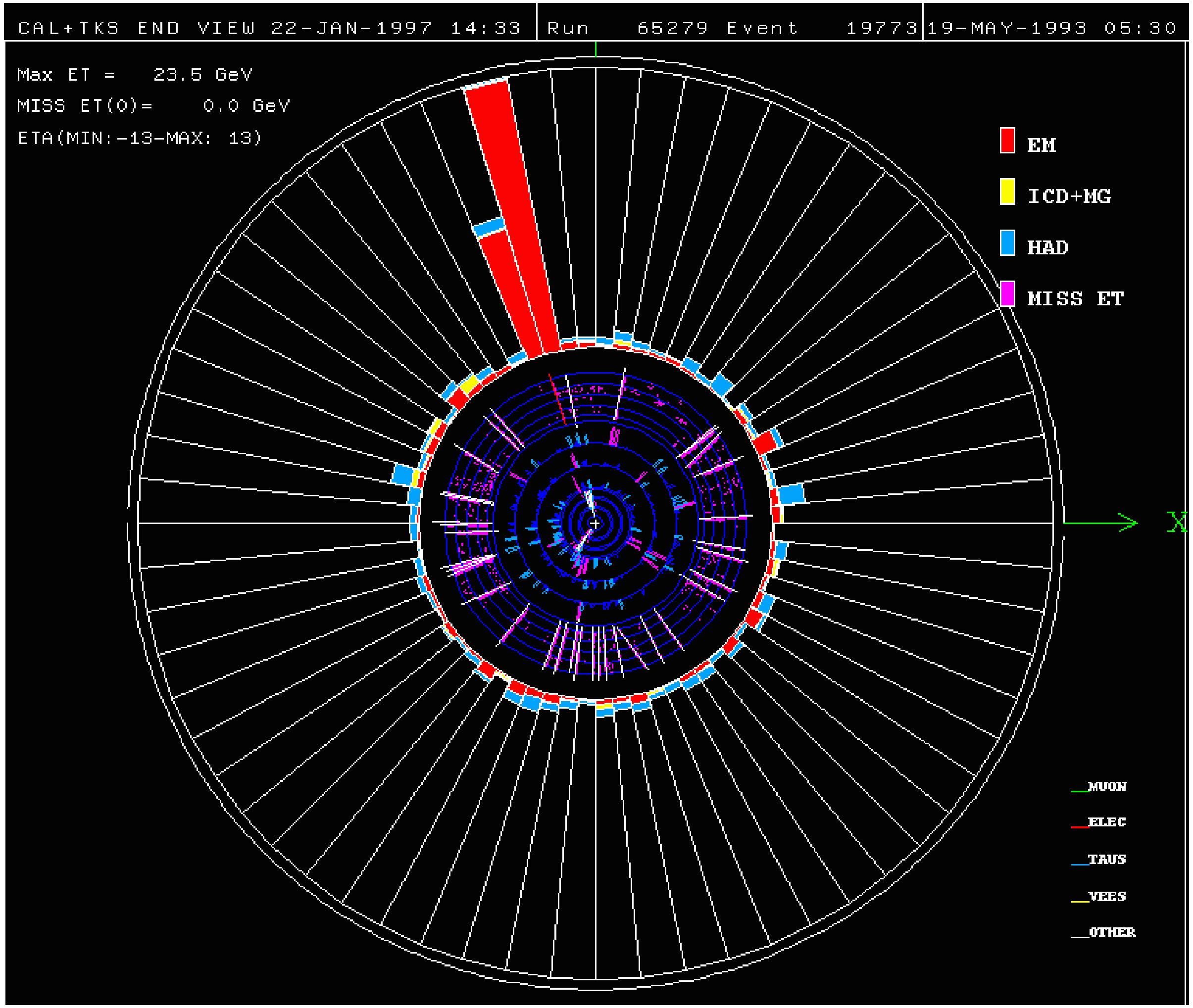
Should be useful for studying differences in the u/d sea

Hep-ph/9907231

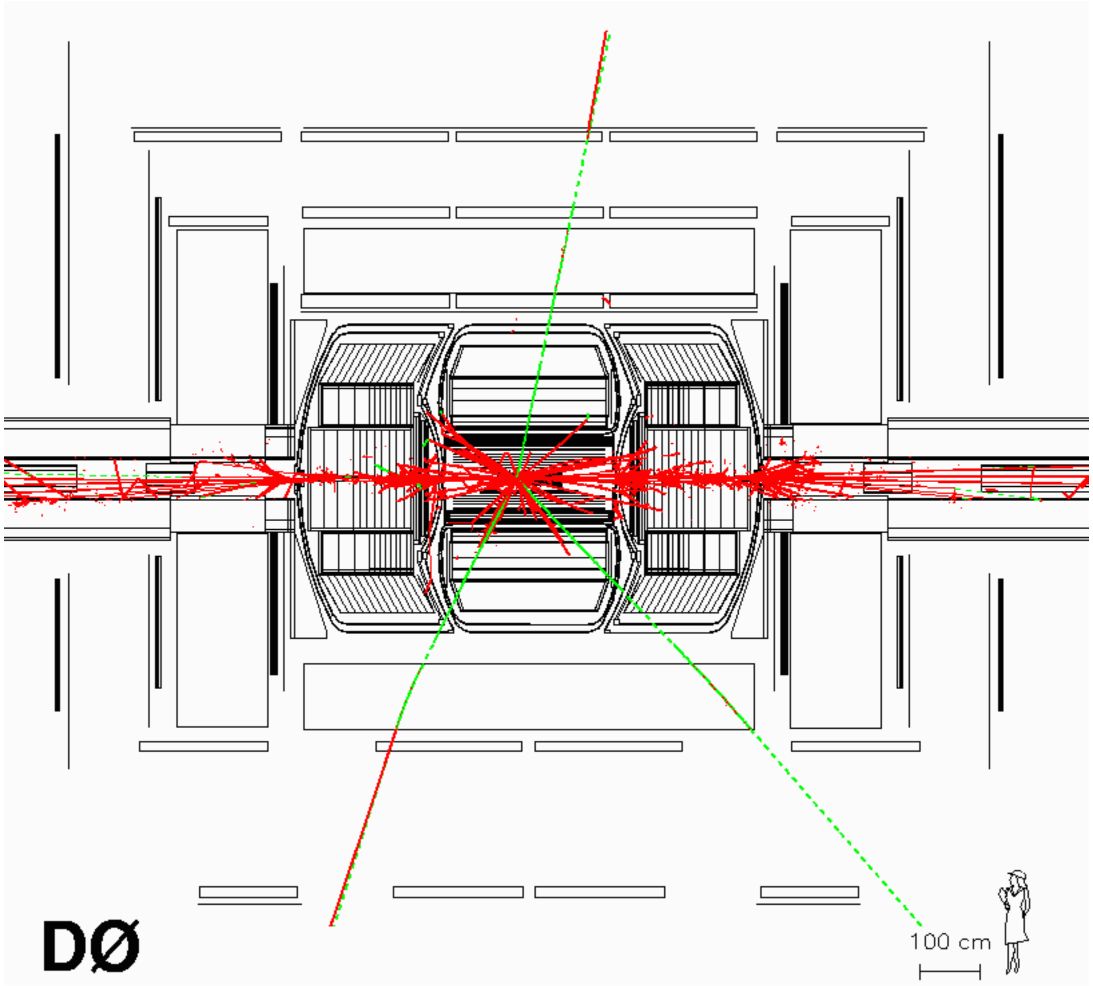
Particle Identification



W identification



Z component of Neutrino momenta



2 TeV of energy near beam

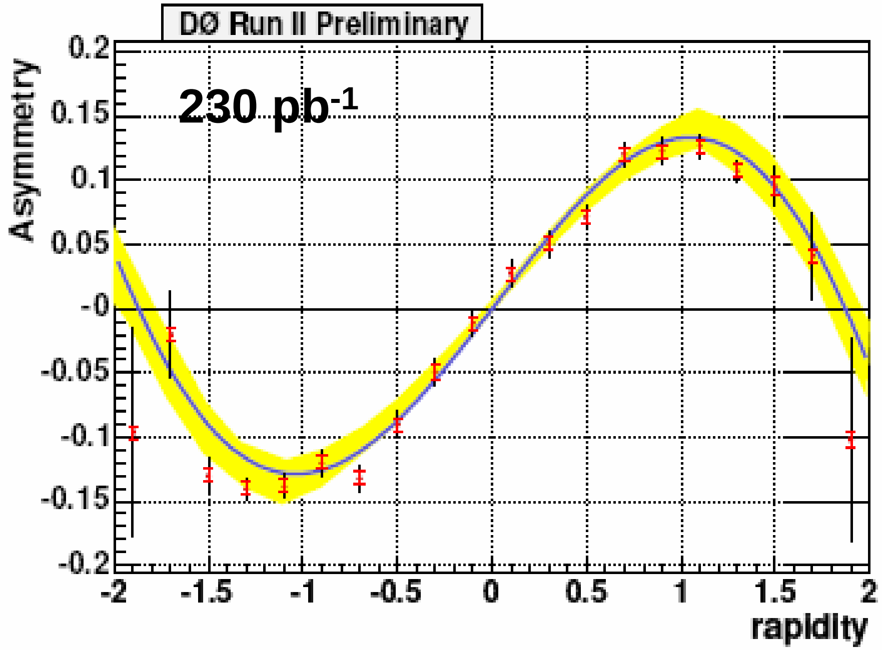
Even if you somehow could put a calorimeter there…

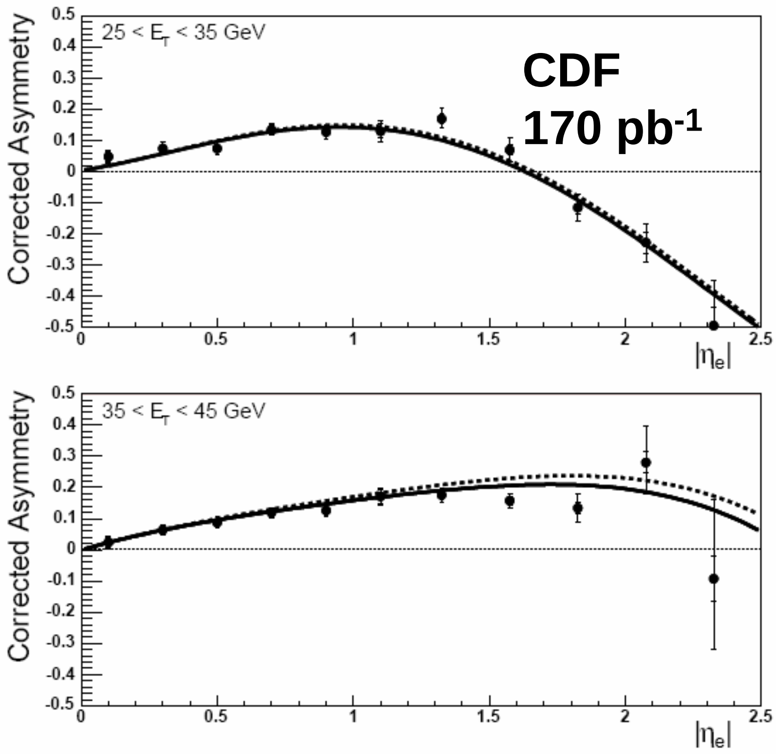
100%*sqrt(E)=45 GeV resolution

Now: PDF

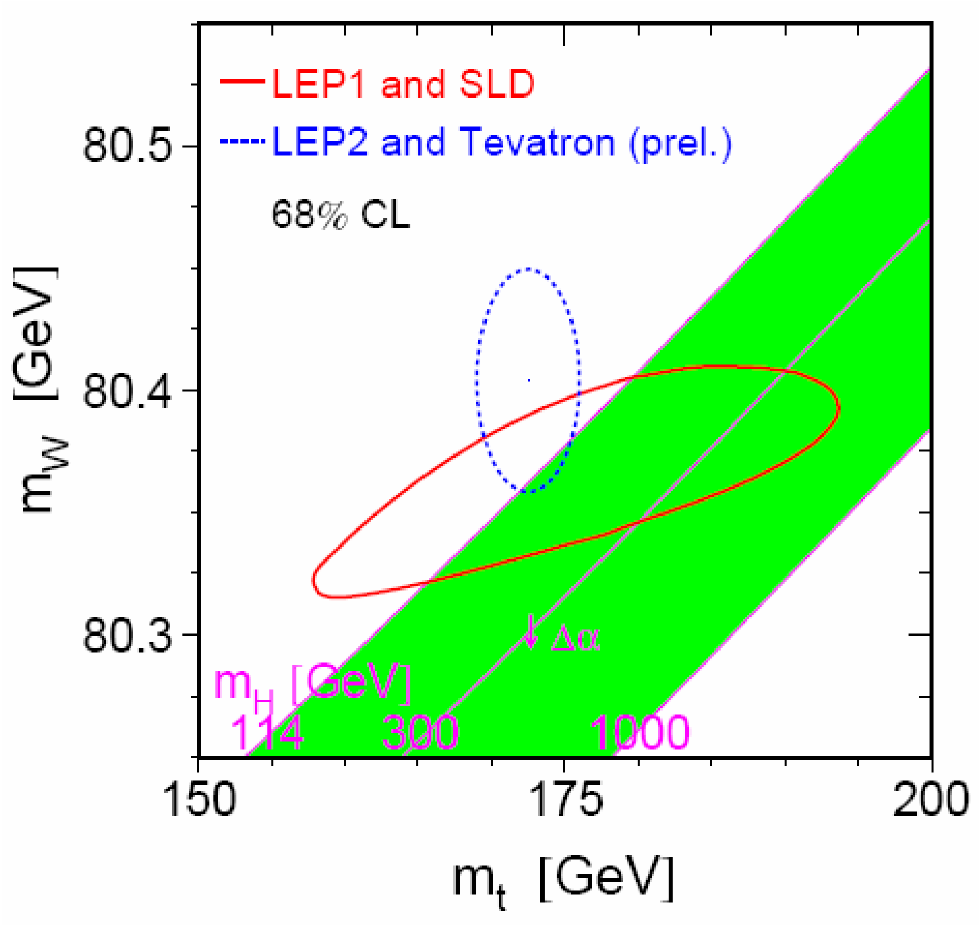
- can not measure the W rapidity since can not measure neutrino Pz
- use angular distribution of lepton

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}(1+\cos^2\theta^*)$$





Di-Leptons and Precision EWK



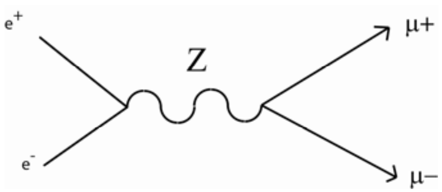
QCD as the problem…

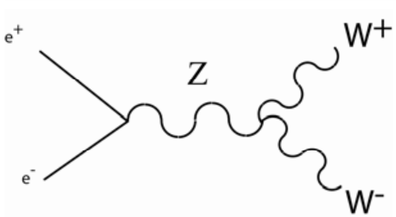
e+e- vs pp

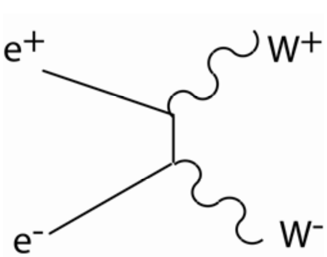
Normally, “precision” physics is done at electron/positron colliders…

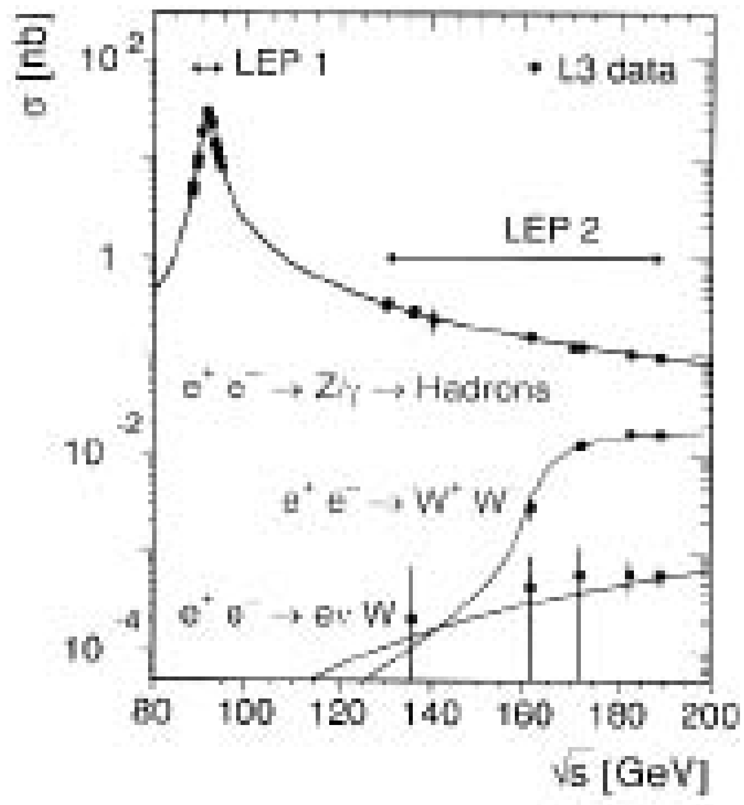
However, precision measurements need large statistics

Z’s easy to make in e+e-, W’s not so easy.







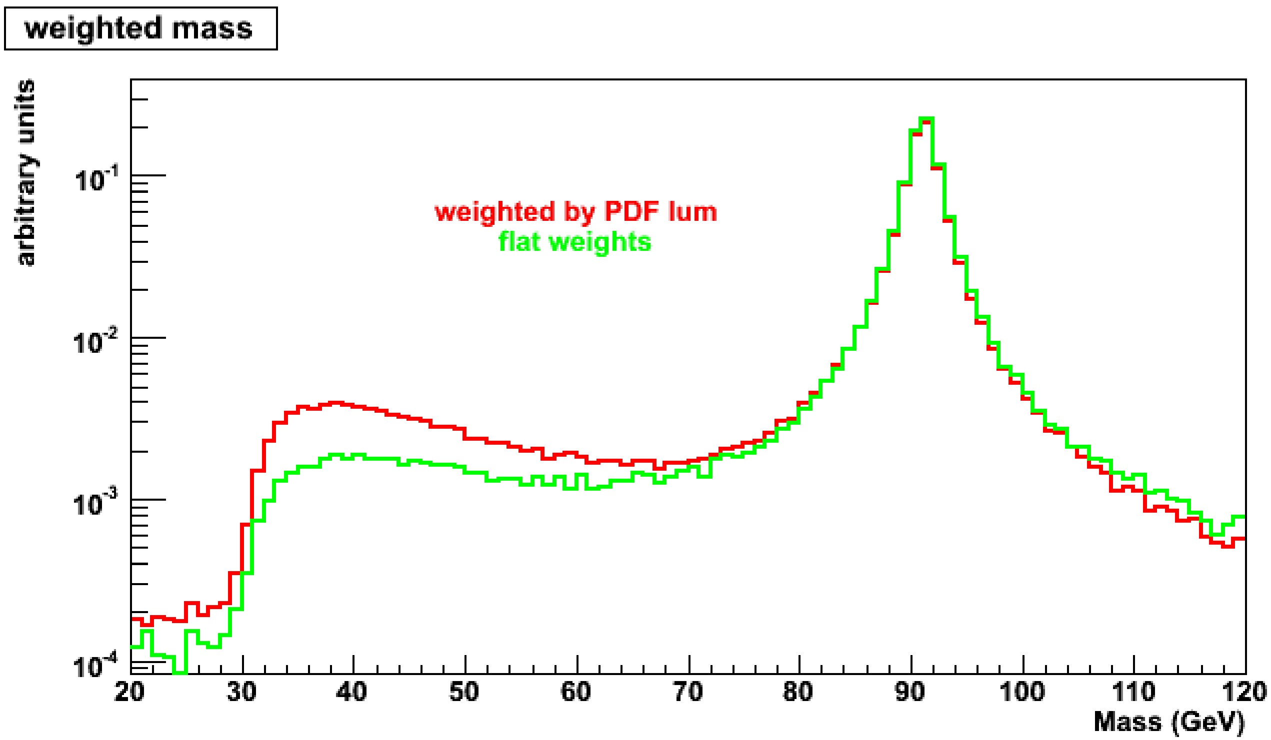


Can precision physics be done with W’s at hadron colliders?

Z mass and QCD

In the naïve parton model, "QCD" comes in through the PDF's

If only we could reconstruct that @$%$%@#$ z-component of the neutrino momenta

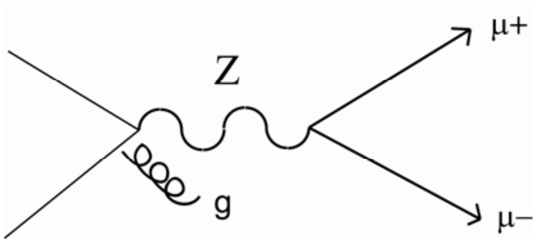


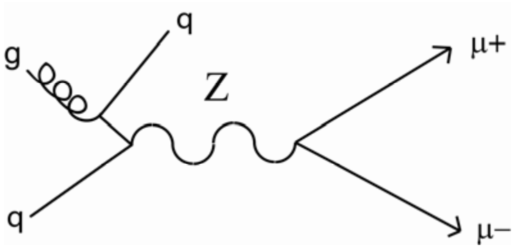
But we can not, so we are stuck trying to use transverse variables…

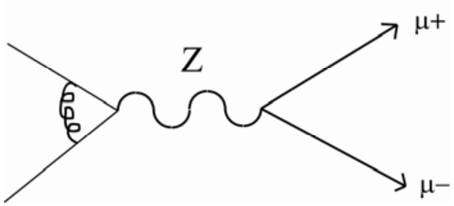
W P_T: Problem

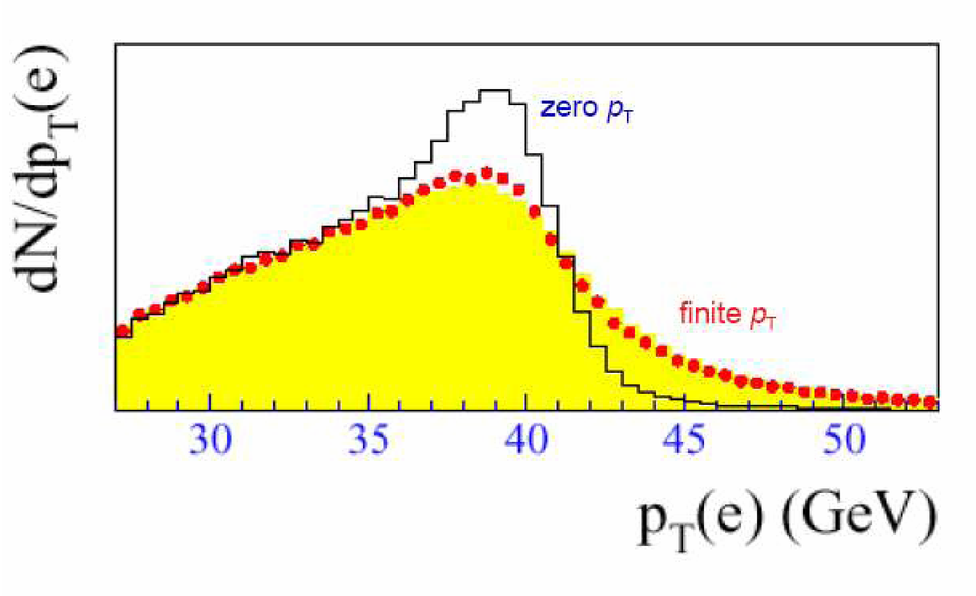
What about the electron P_T? Isn't that equal to M/2 when decays perp to beam axis?

QCD… it's not just a K factor…

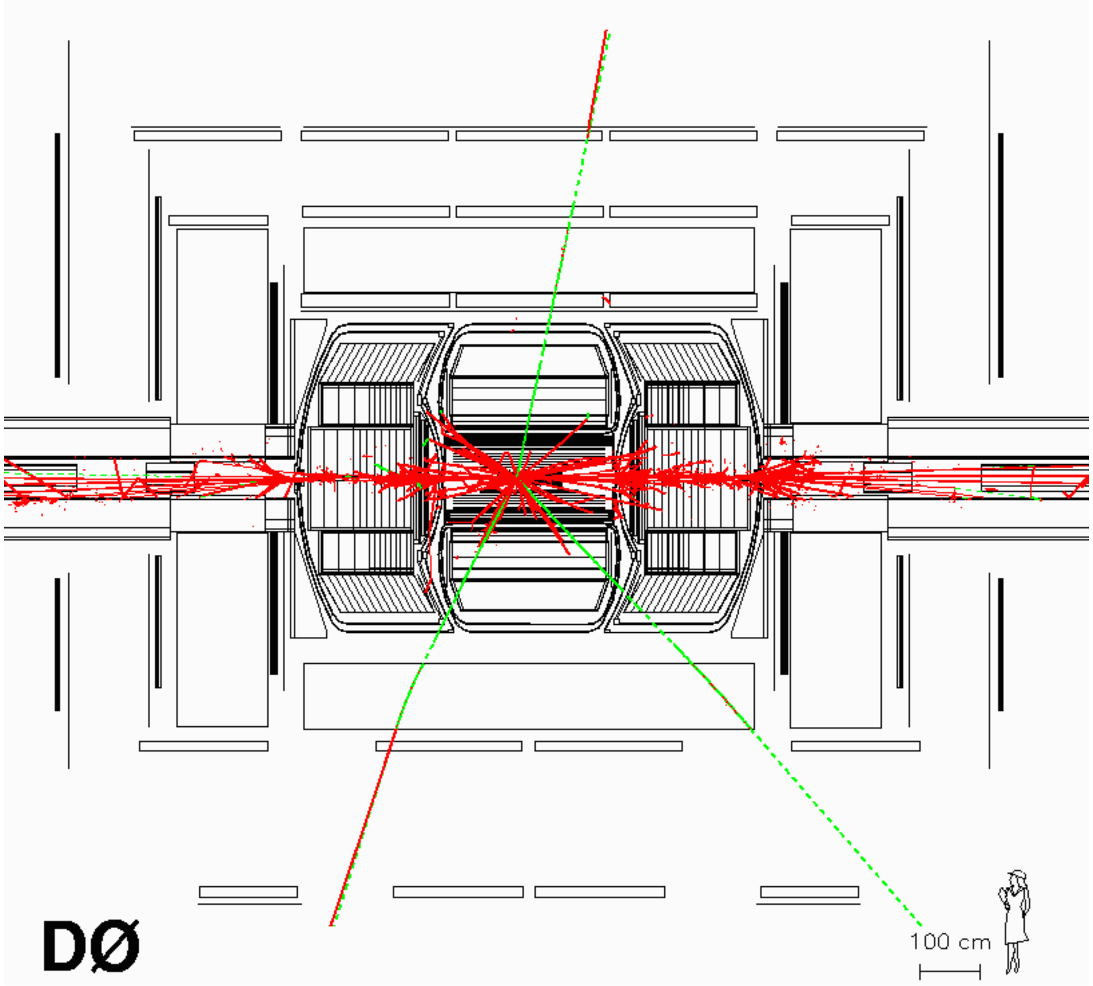








Missing Transverse Energy



$$\vec{\not{E}}_T = - \sum_{\textit{all}\ \text{calorimeter cells}} \vec{E}_{Ti}$$

$$\not{E}_\mathrm{T} \equiv \mathrm{MET}$$

(T means x sin(polar_angle))

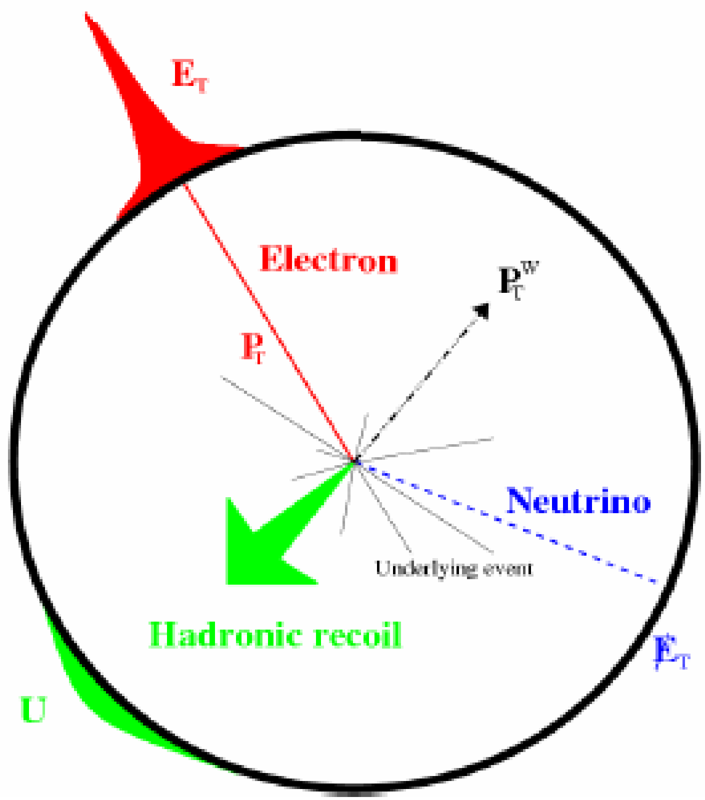
Transverse Mass

$$M_T = \sqrt{(E^e + E^\nu)^2 - (P_x^e + P_x^\nu)^2 - (P_y^e + P_y^\nu)^2}$$

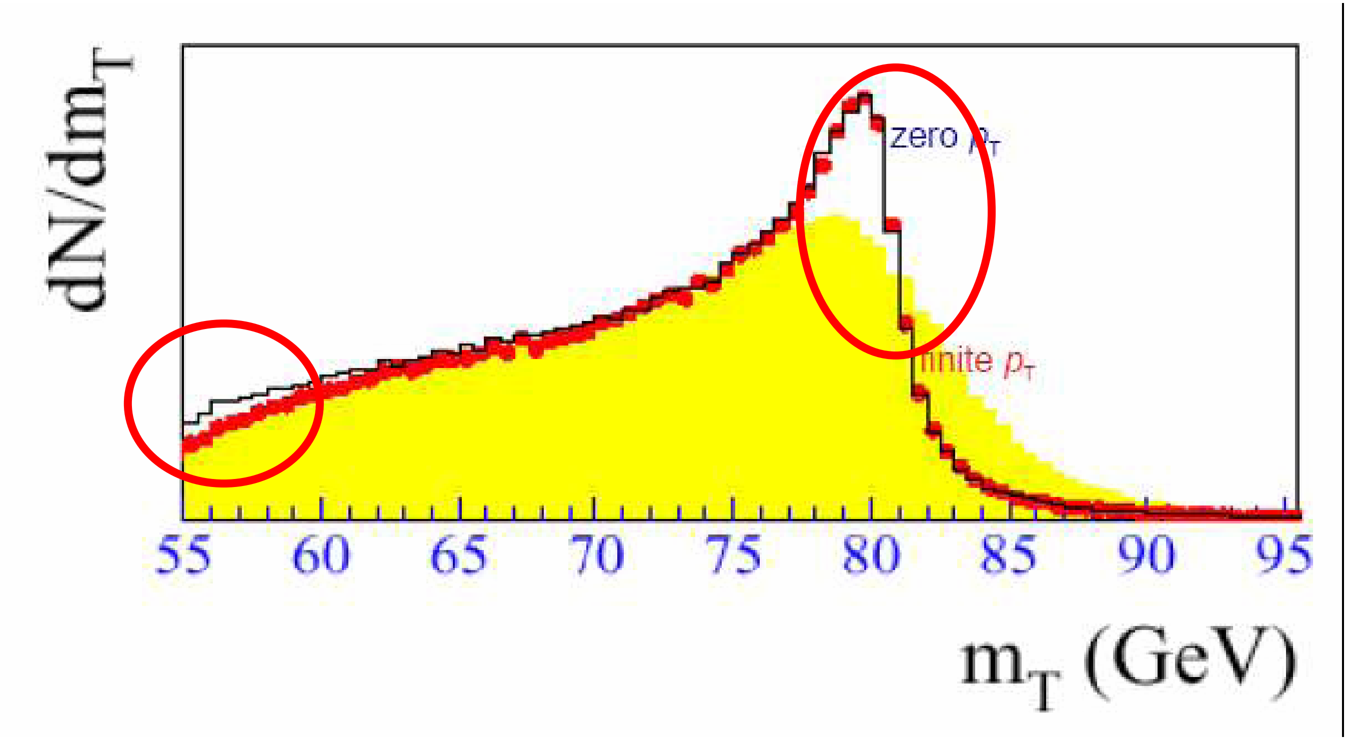
$$= \sqrt{2E_T^e E_T^\nu (1 - \cos\Delta\varphi)}$$

$$\simeq 2E_T^e + u_{||}$$

$$\vec{u}_{measured} = \vec{p}_T^{\,recoil} + \vec{p}_T^{\,UE}$$

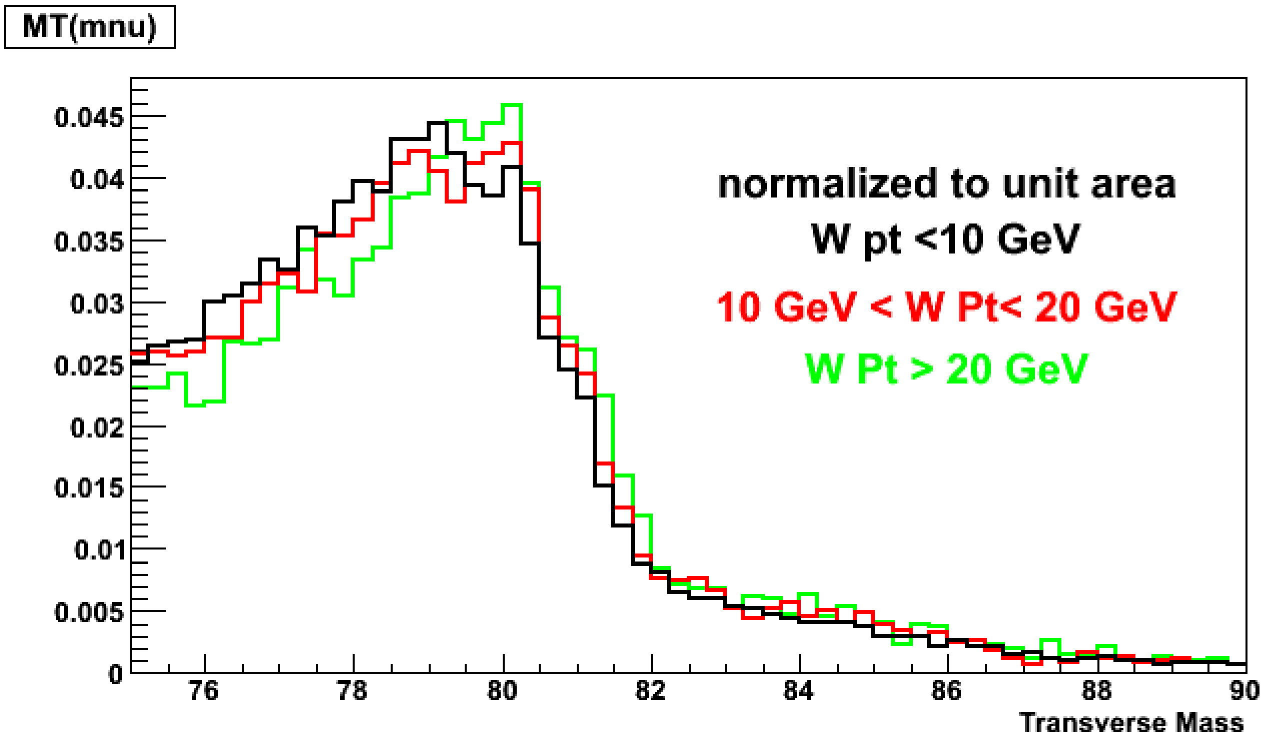


W Mass: QCD "problems": WPT



Better, but…

W P_T



MT(mnu)
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
76
78
80
82
84
86
88
90
Transverse Mass
normalized to unit area
W pt <10 GeV
10 GeV < W Pt< 20 GeV
W Pt > 20 GeV

W P_T

Not all the dependence goes away…

TABLE I. Uncorrelated uncertainties (MeV) in the CDF [8] and DØ [9] W boson mass measurements from the 1994-95 (Run 1b) data. W boson decay channels used (e, μ) are listed separately.

Source	CDF μ	CDF e	DØ e
W statistics	100	65	60
Lepton scale	85	75	56
Lepton resolution	20	25	19
$p_T(W)$	20	15	15
Recoil model	35	37	35
Selection bias	18	-	12
Backgrounds	25	5	9

TABLE II. Systematic uncertainties (MeV) from correlated sources in the W boson mass measurements [8,9].

Source	CDF	DØ
PDF & parton luminosity	15	$7 \oplus 4$
Radiative Corrections	11	12
Γ_W	10	10

At LHC, the neutrino measurement can deteriorate enough to force use of the lepton PT spectra.

Well, how hard is it to calculate the W's transverse momentum?

W P_T

More in George Sterman's talk

$$\left\langle \sum \left| M^{q\bar{q}'\to Wg} \right|^2 \right\rangle = \pi\alpha_s \sqrt{2} G_F M_W^2 \left| V_{qq'} \right|^2 \frac{8}{9} \frac{t^2 + u^2 + 2M_W^2 s}{tu}$$

$$\left\langle \sum \left| M^{gq\to Wq'} \right|^2 \right\rangle = \pi\alpha_s \sqrt{2} G_F M_W^2 \left| V_{qq'} \right|^2 \frac{1}{3} \frac{s^2 + u^2 + 2tM_W^2}{-su}$$

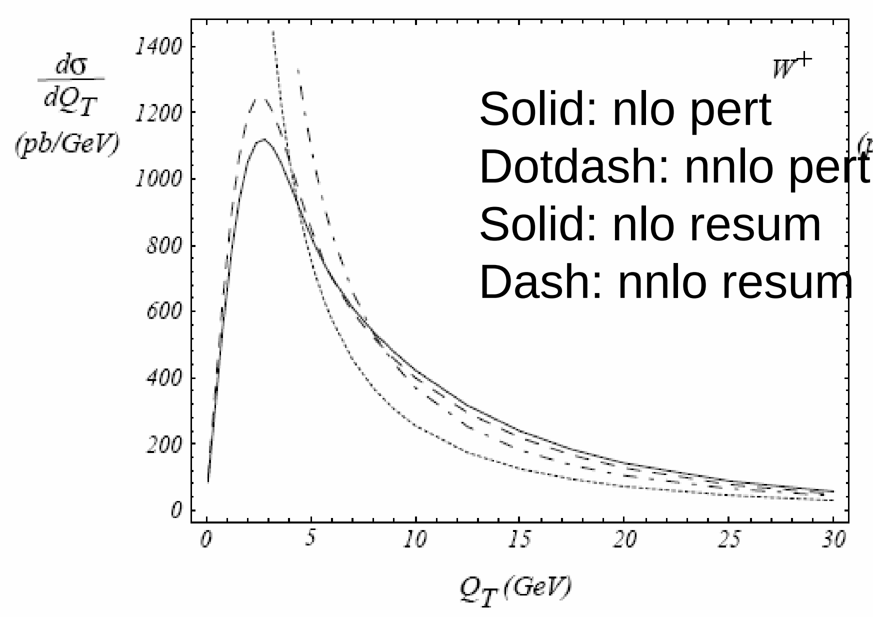
However, for small PT (PT<<M), higher order terms important: need to handle multiple soft gluon emission

$$\frac{1}{\sigma}\frac{d\sigma}{dp_T^2} \simeq \frac{1}{p_T^2}[A_1\alpha_s \ln(\frac{M^2}{p_T^2}) + A_2\alpha_s^2 \ln^3(\frac{M^2}{p_T^2}) + \ldots + A_n\alpha_s^n \ln^{2n-1}(\frac{M^2}{p_T^2}) + \ldots]$$

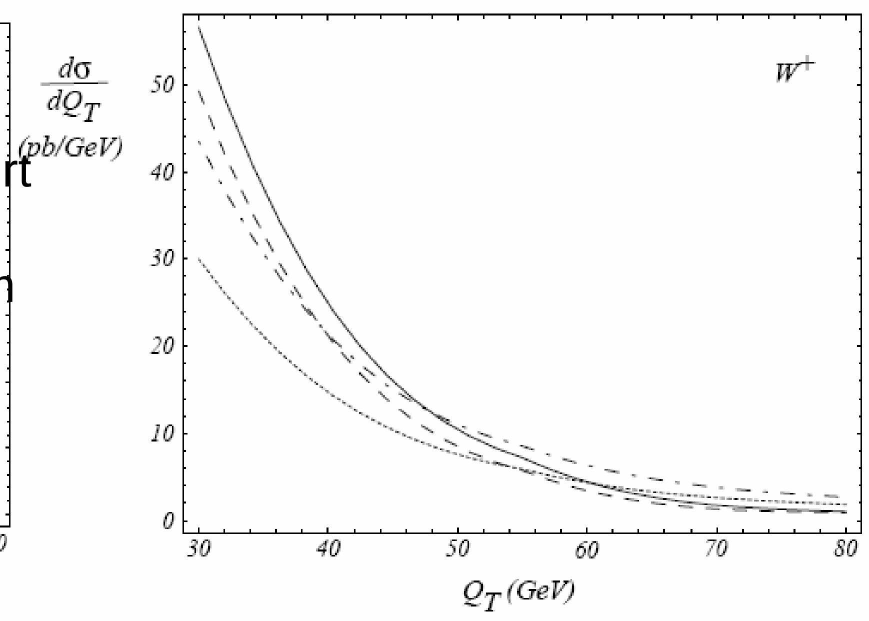
"Resummation" technique (Collins, Soper, Sterman) can give do this, but depends on non-pertubative parameters which must be determined from data

W P_T

Balazs & Yuan, hep-ph/9704258
Nadolsky, hep-ph/0412146

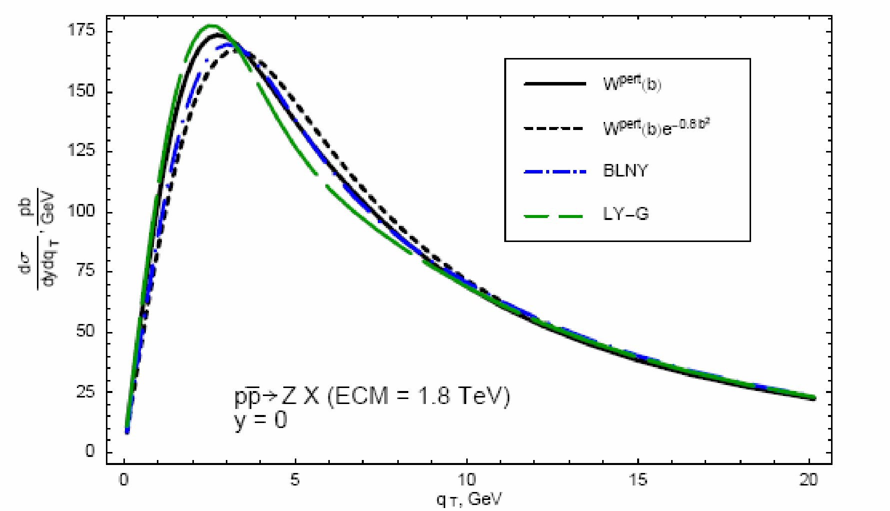


Solid: nlo pert
Dotdash: nnlo pert
Solid: nlo resum
Dash: nnlo resum



Can figure this all out using the Z?

- factor 10 smaller statistics
- acceptance effects



W/Z Pt: acceptance problems?

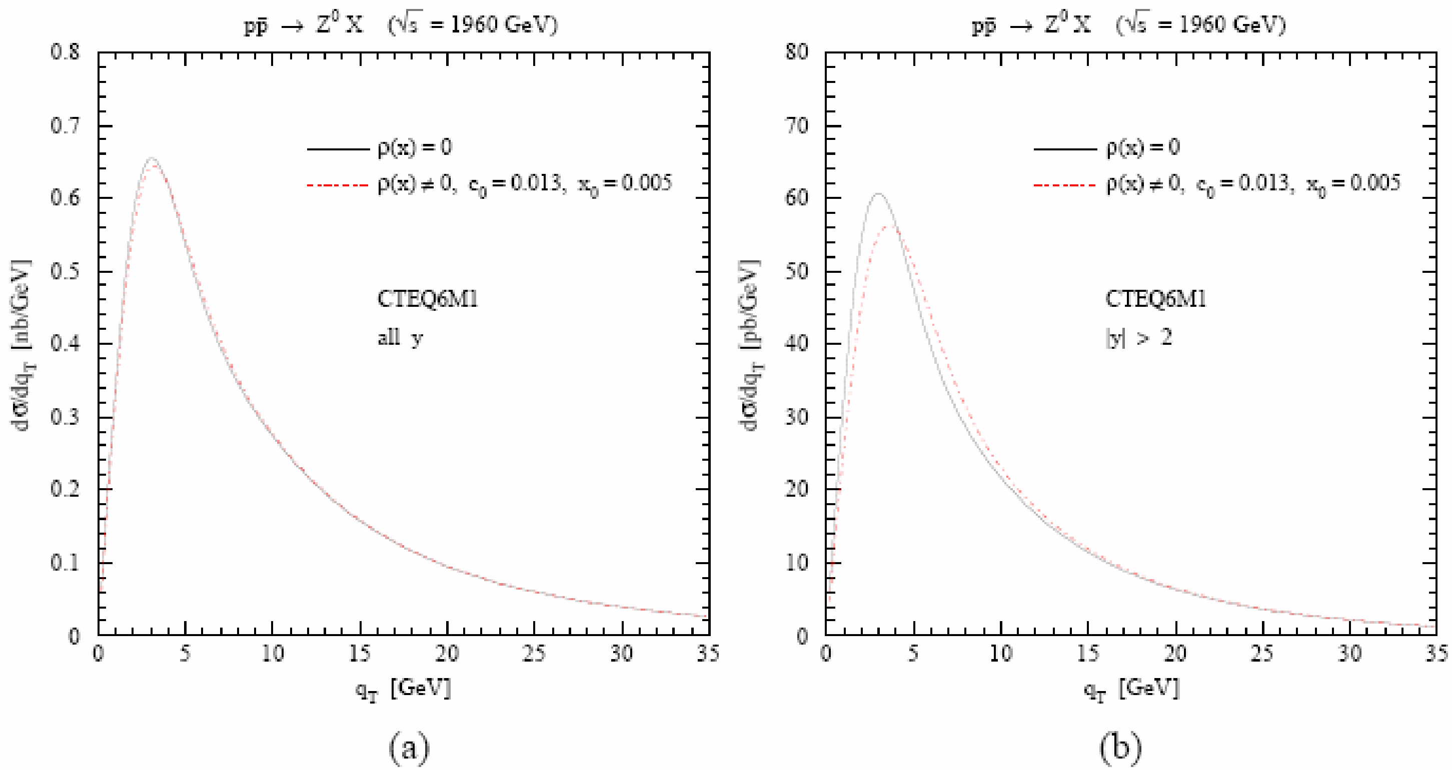
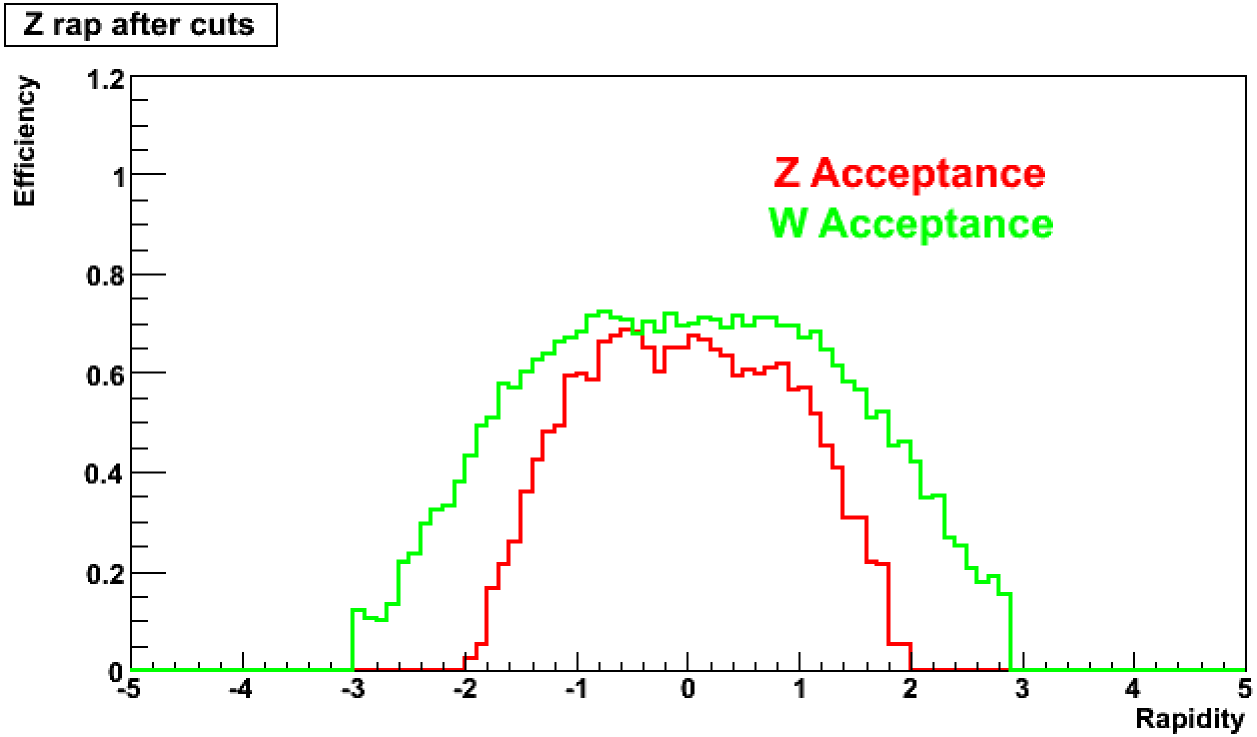


Fig. 1: q_T distributions of Z^0 bosons in the Tevatron Run-2; (a) integrated over the full range of Z boson rapidities; (b) integrated over the forward regions $|y| > 2$. The solid curve is a standard CSS cross section, calculated using the 3-parameter Gaussian parametrization [5] of the nonperturbative Sudakov factor. The dashed curve includes additional terms responsible for the q_T broadening in the small-x region (cf. Eq. (5)).

Hep-ph/0401128: Berge, Nadolsky, Olness, Yuan

Acceptance versus Rapidity



LHC

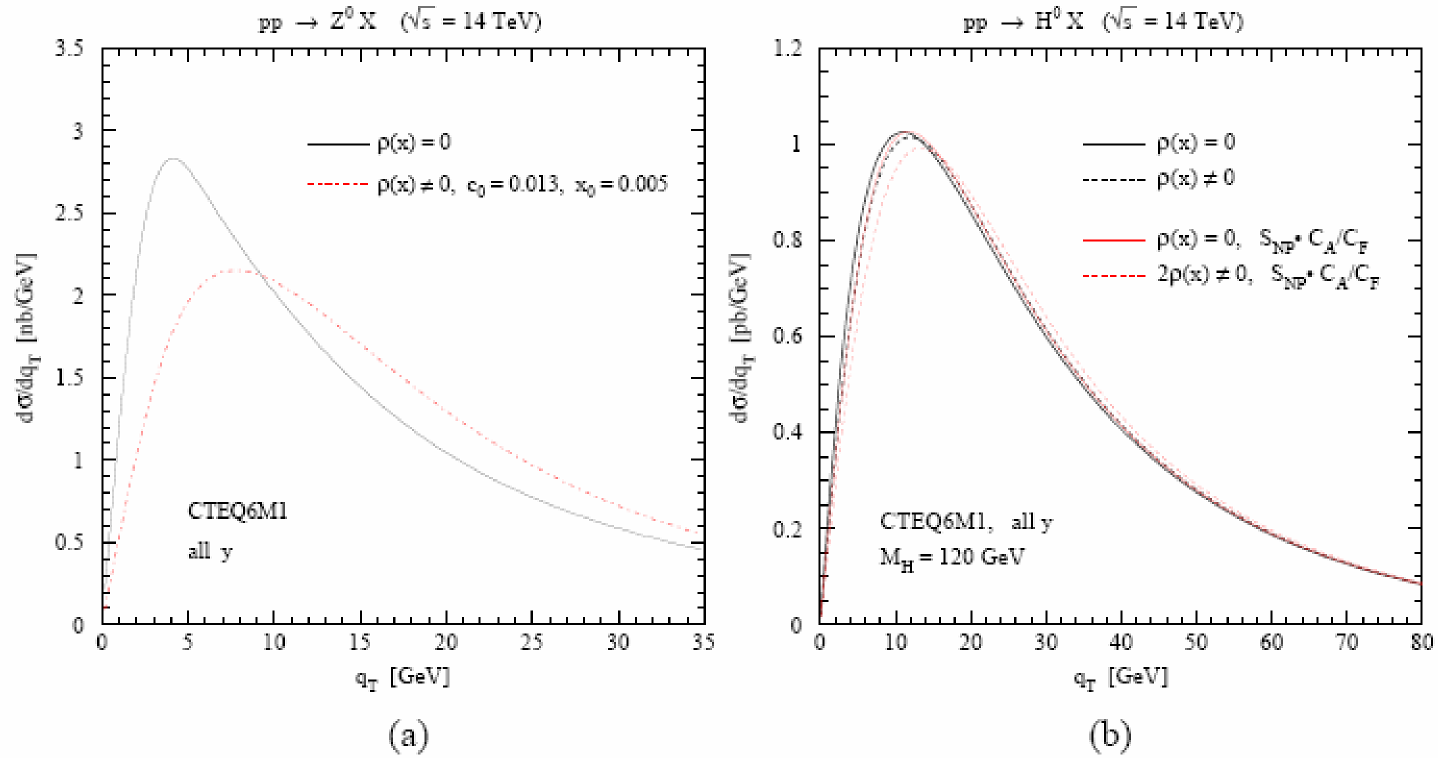
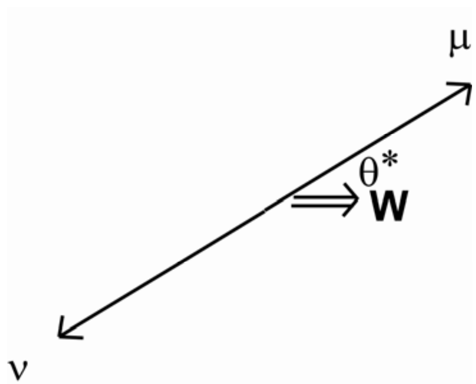


Fig. 2: q_T distributions of (a) Z^0 bosons and (b) Standard Model Higgs bosons at the Large Hadron Collider, integrated over the full range of boson rapidities.

PDF's, Rapidity& Trouble

In W rest frame, neglect W P_T (MT=2 E_T of electron)



$$P_T^e = \frac{P^e}{\sin\theta} = \frac{M}{2\sin\theta}$$

Transverse mass spectra is just going to be this weighted by the angular cross section

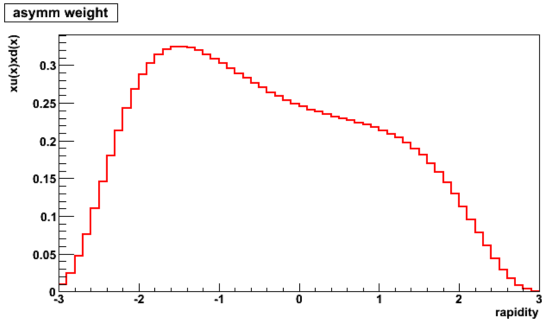
In practice, the mass comes from the ones at 90^o in the W rest frame.

PDF's

In the lab frame…

Angular distribution has two components

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}(1+\cos^2\theta^*)$$



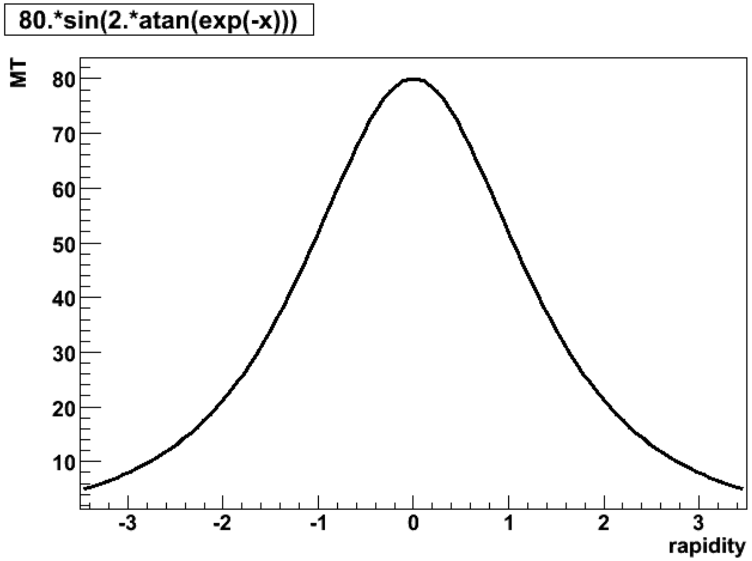
$$y_e = \frac{1}{2}\ln\left(\frac{x_1}{x_2}\right) + \frac{1}{2}\ln\left(\frac{1+\cos\theta^*}{1-\cos\theta^*}\right)$$

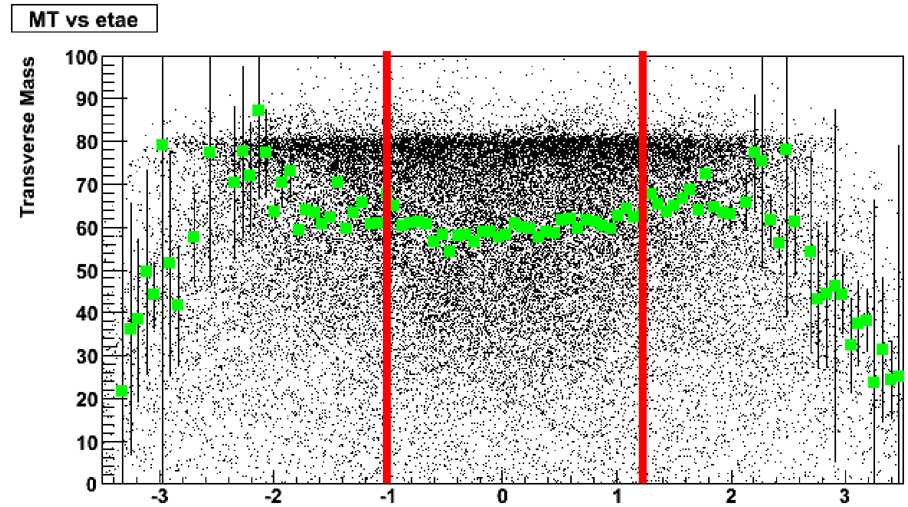
-3 to 3

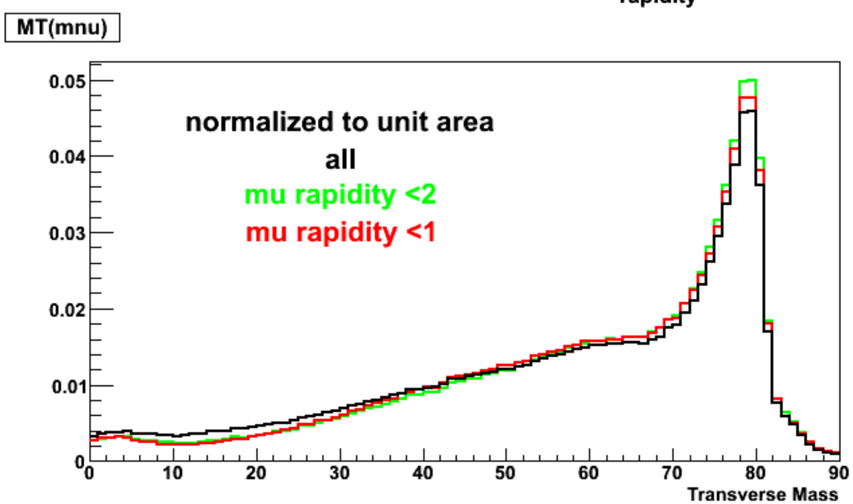
What fraction of the high Pt guys move out of your acceptance, what fraction of the low Pt guys move in, depend on x1/x2

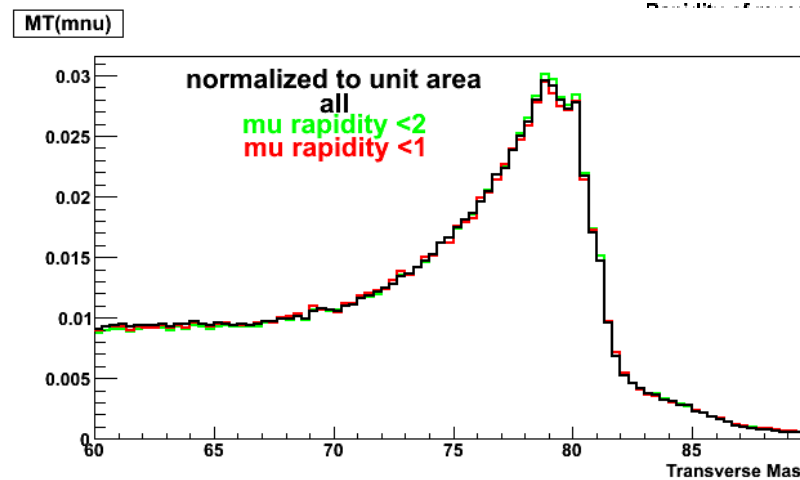
What fraction of the guys at about 40 are low Pt guys on a high Pt W?

Pdf's and W mass









Less of a problem than the boson P_T

Future: Luminosity Measurements

Luminosity is measured at the Tevatron using min bias interactions and the total cross section. However, at the LHC, the rate for W events is large enough to make this a competitive “standard candle”.

• M. Dittmar, F. Pauss and D. Z¨urcher, Phys. Rev. D **56** (1997) 7284 [arXiv:hepex/9705004].

• Proceedings of HERA-LHC workshop 2005, M. Dittmar et al., hepph/0511119; S. Catani et al.,Workshop on Physics at TeV Colliders, Les Houches, France,7-18 Jun 1999, hep-ph/0005114

• S. Catani et al., Standard model physics (and more) at the LHC, CERN-TH-2000-131 and hep-ph/0005025.

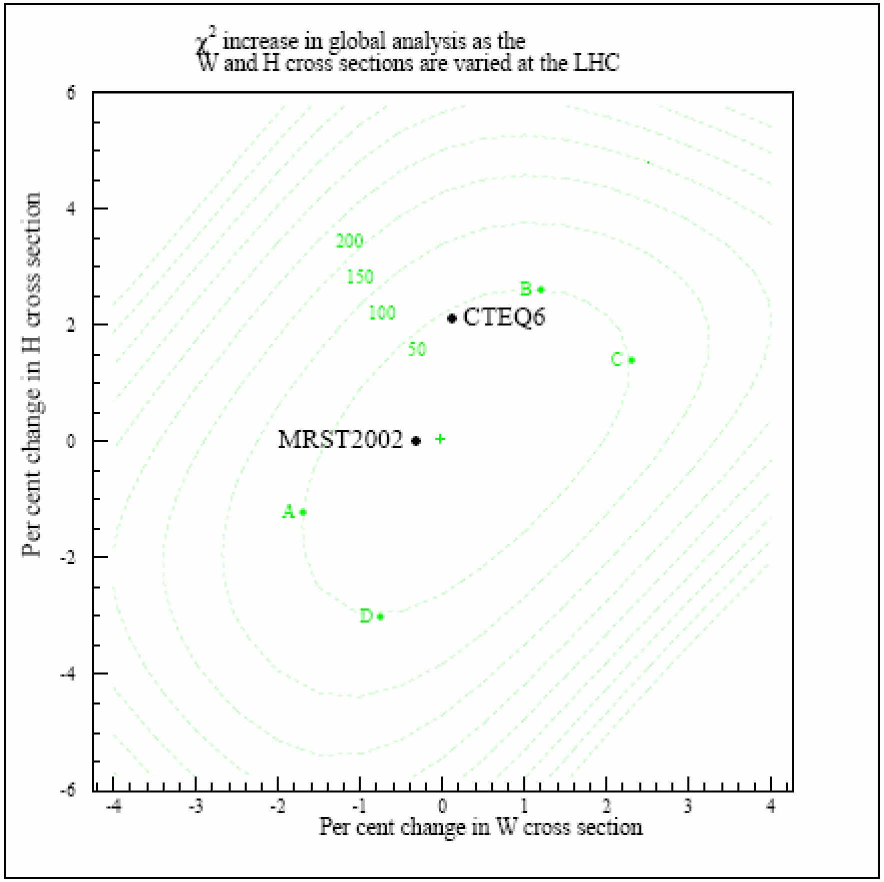
• Giele and Keller, hep-ph/0104033

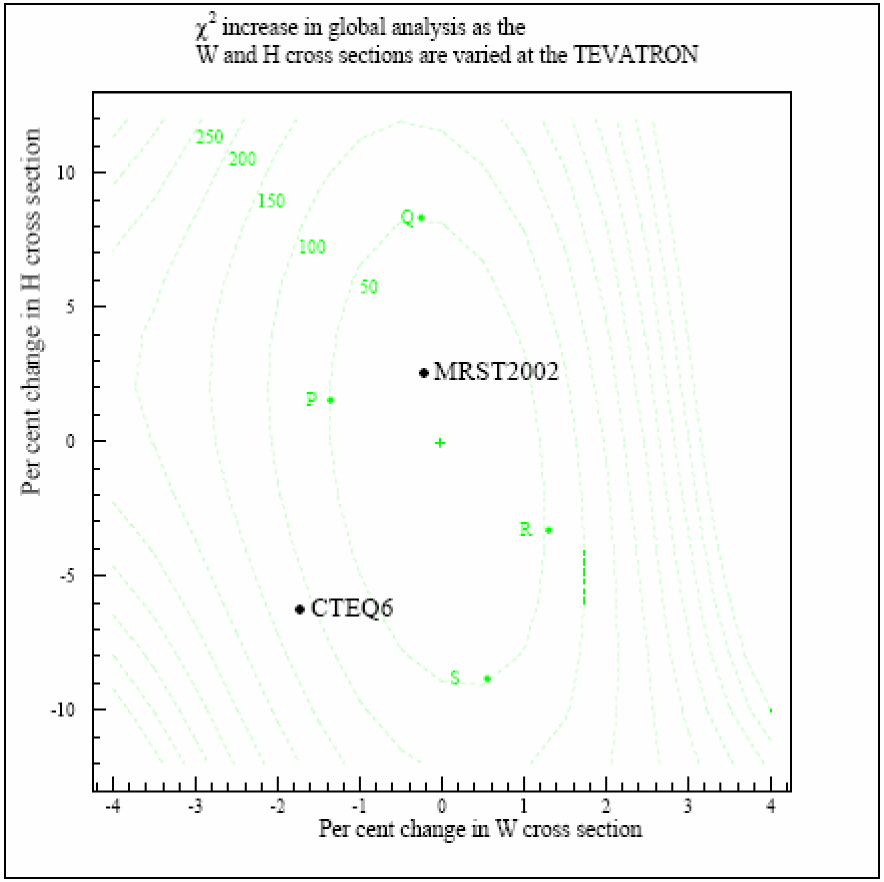
Lum Measurements

Just need to

- understand the K-factor (NNLO good enough?)
- understand the acceptance (NNLO good enough?)
- understand the PDF’s
- understand the EWK corrections
- understand interplay between EWK and QCD corrections

1.5%





MRST, Eur. Phys. J C38 (2003) 45

Backgrounds

oh ya, and some experimental stuff about lepton id efficiencies, backgrounds

Machine	W (nb)	Jet>40 (nb)	ratio
TeV	2.45	1900	0.0013
LHC	20	67000	0.0003

QCD backgrounds 4 x bigger at LHC than Tevatron?

(why isn’t the Tevatron doing this? It’s harder than it looks!)

Future: Searches

- new heavy vector bosons
- contact interactions
- extradimensions
- SUSY (lepton, MET, + jets)

New vector bosons can be fun and easy, but the others are going to require carefully understanding of the QCD systematics

Contact Interactions, Extra Dimensions, Quantum gravity…

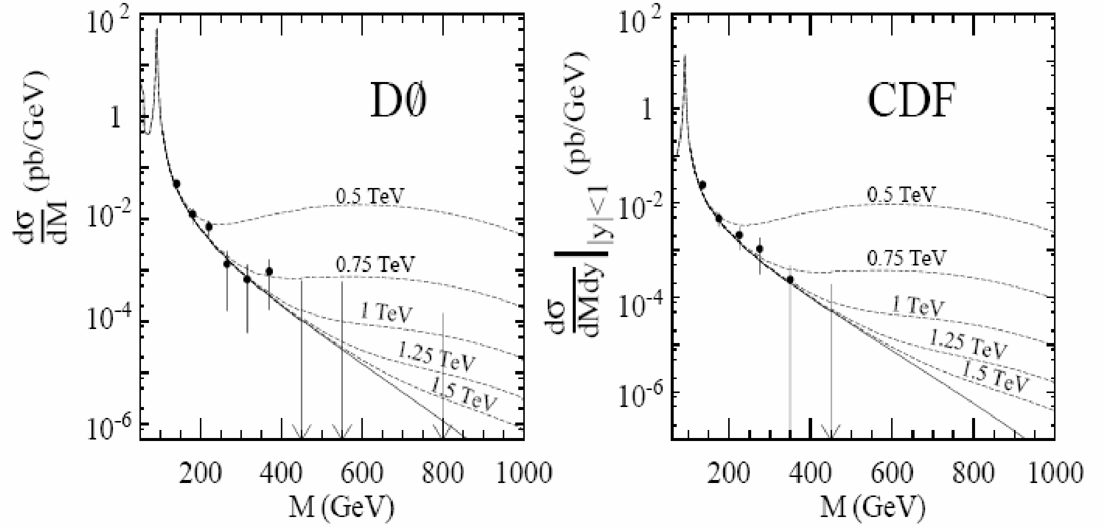
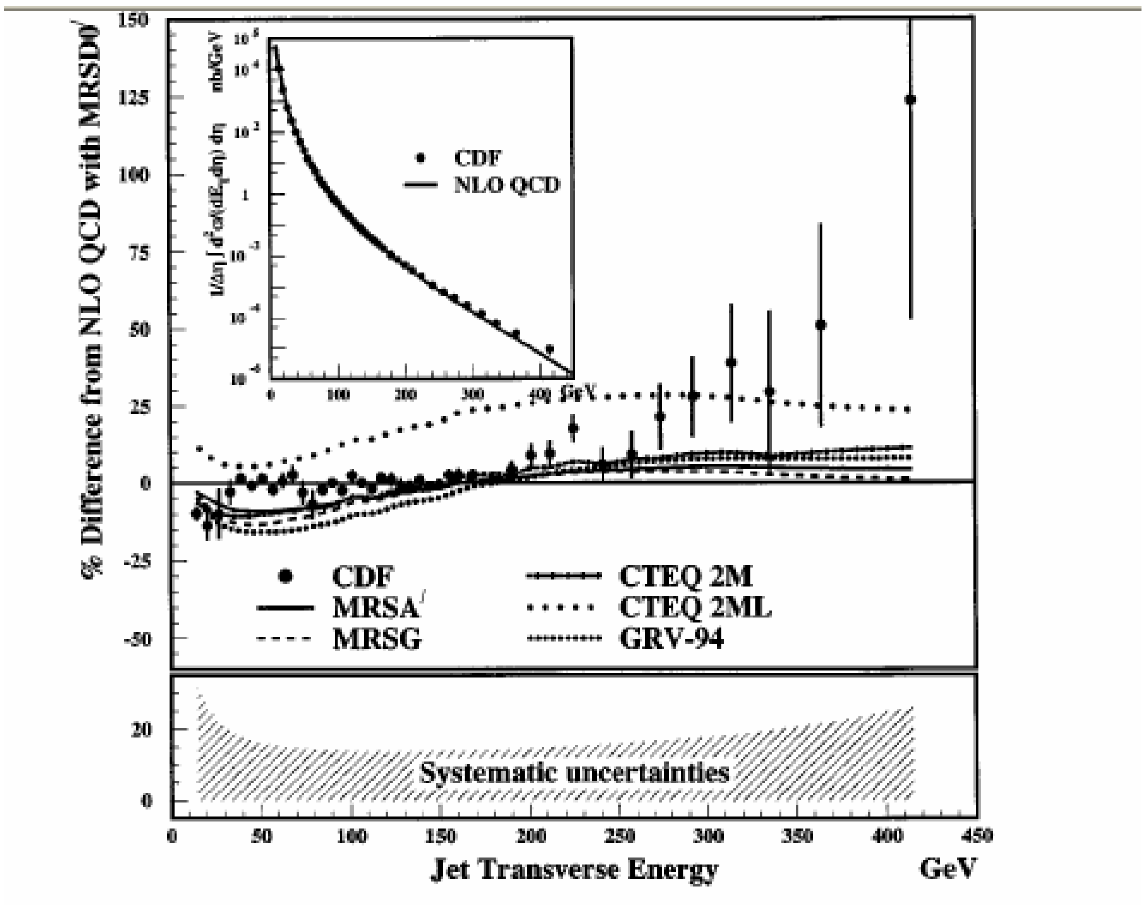


Figure 2. *Illustrating the effects of TeV scale quantum gravity on the invariant mass distributions of dileptons seen at the Tevatron by the DØ and CDF Collaborations respectively. Solid lines show the SM prediction; dashed lines show the predictions of the ADD model for marked values of M_S.*

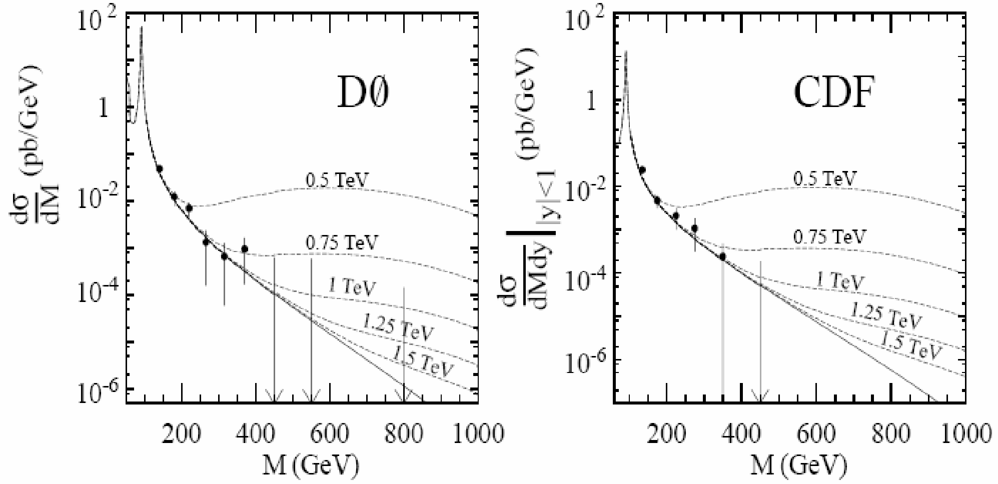
hep-ph/9904234

Flash Back



Phys. Rev. Lett. 77, 438 (1996)

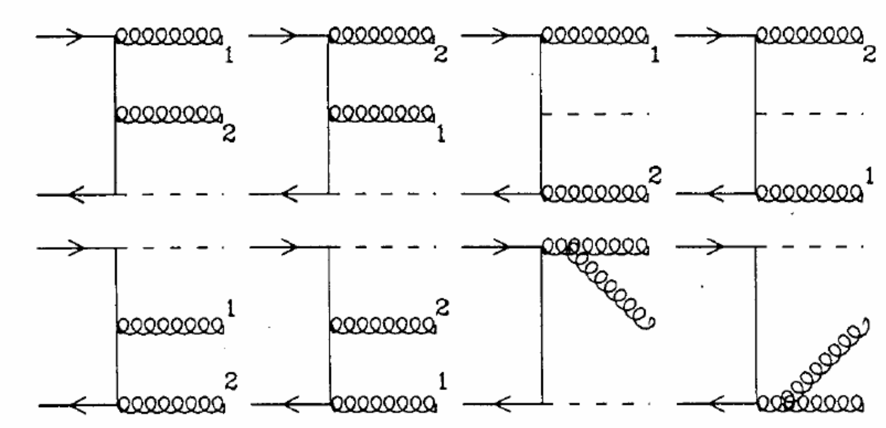
Contact, etc



Is it?

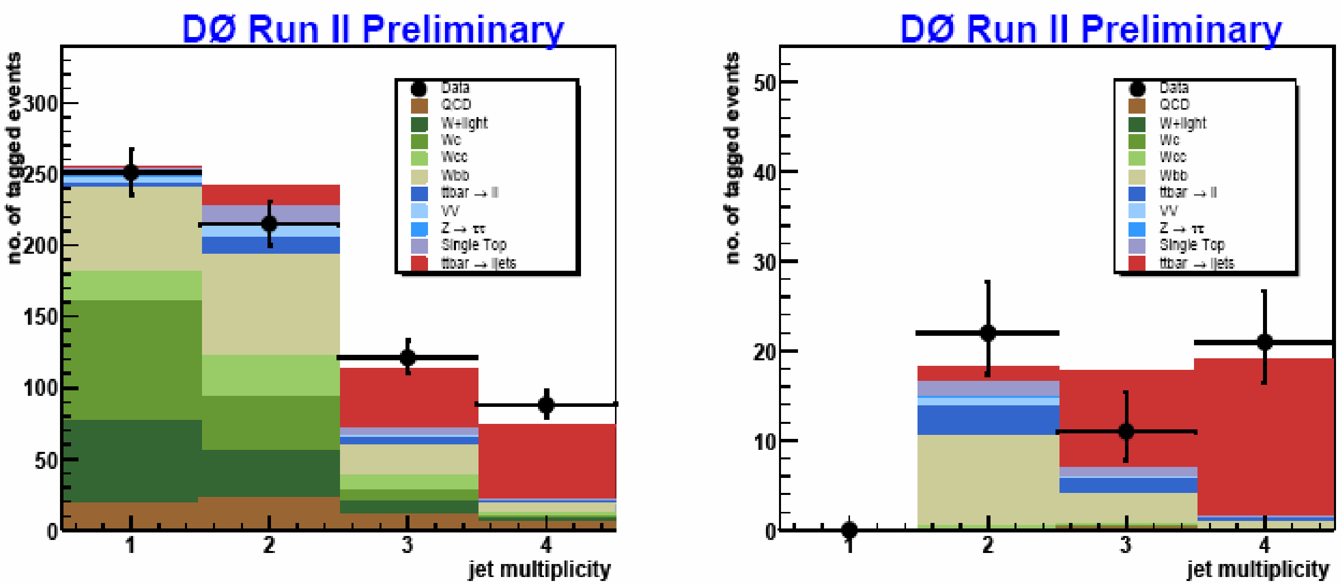
- new physics?
- lack of understanding of the PDF's
- lack of understanding of the Q^2 dependence of the K factor?
- lack of understanding of the shape of the dijet background?

W plus Jets



Exclusive jets?

is the main background for many new particle searches



Always lots to keep QCD-theory types busy here!

FIG. 1: Summary plot of predicted and observed tagged events in ℓ+jets channel: single tags (left) and double tags (right).

References

all material stolen and was damaged in the process

• Collider Physics, Barger & Phillips

• Quarks & Leptons: An Introductory Course in Modern Particle Physics, Halzen & Martin

• QCD and Collider Physics, Ellis, Stirling and Webber

• Perturbative QCD and the Parton Structure o the Nuclear, Wu-Ki Tung

• past CTEQ summer school lectures (http://www.phys.psu.edu/~cteq/#Summer)

• Ellis & Whalley, A Compilation of Drell-Yan Cross sections, Journal of Physics G, 19 (1993) D1

• hep-ph/9907231 (Martin, Roberts, Stirling, Thorne)

• hep-ex/0509002 (Tricoli, Cooper-Sarkar, Gwenlen)

• hep-ph/0412146 (Nadolsky)

• Electroweak Interactions: Peter Renton

• hep-ph/0308087, MRST