Lepton Pair and Weak Boson Production

George Sterman
Stony Brook
2005 CTEQ Summer School
Puelbla, Mexico

- Introduction: From quark model to QCD
- The rest of the standard model
- Observation
- The inclusive Drell-Yan cross section; factorization
- One-loop corrections and the transverse momentum distribution
- Applications as prologue

- **Introduction: From quark model to QCD**

- Spectroscopy and the quark model
  - The discovery of quarks: qqq and $\bar{q}q$ with $q = u, d, s$ generate observed spectrum of baryons and mesons
  - Decay of $\bar{s}s$ states to K, $\bar{K}$ states (OZI rule) indicates continuity of quark lines
  - Non-relativistic wave functions $\rightarrow$ ratios of magnetic moments μ_n/μ_p etc.

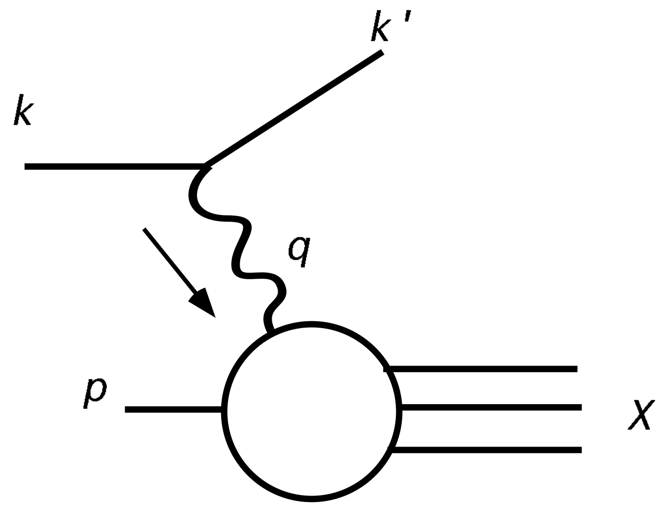
- Dynamical evidence: form factors & structure functions
  - Form factors: ep $\longrightarrow$ ep elastic

$$\frac{d\sigma}{d\Omega_e} = \left[\frac{\alpha_{\rm EM}^2 \cos^2(\theta/2)}{4E^2 \sin^4(\theta/2)}\right] \frac{E'}{E} \left(\frac{|G_E(Q)|^2 \; + \; \tau |G_M(Q)|^2}{1+\tau} + \; 2\tau |G_M(Q)|^2 \tan^2 \theta/2 \right)$$

  - schematically:

$$\frac{d\sigma_{\rm ep\to ep}(Q)}{dQ^2} \sim \frac{d\sigma_{\rm ee\to ee}(Q)}{dQ^2} \times G(Q) \quad \text{with} \quad G(Q) \sim \frac{1}{\left(1+\frac{Q^2}{\mu_0^2}\right)^2}$$

– Structure functions: ep inclusive



$$\frac{d\sigma}{dE'\,d\Omega} = \left[\frac{\alpha_{\mathrm{EM}}^2}{2SE\,\sin^4(\theta/2)}\right]\left(2\sin^2(\theta/2)F_1(x,Q^2)+\frac{m\cos^2(\theta/2)}{E-E'}F_2(x,Q^2)\right)$$

$$\text{with} \quad x = \frac{Q^2}{2p_N\cdot q}$$

– Scaling: $F_2(x, Q^2) \sim F_2(x) \Rightarrow$ Point-like, quasi-free scattering

– $F_2 \sim 2xF_1$: Spin-1/2

– Parton model structure functions

$$F_{2,N}(x) = \sum_q e_q^2 \, x f_{a/N}(x)$$

– Notation: $f_{u/N} = u_N$ etc.

- At the same time, a quark model paradox $\Rightarrow$ color
  - First of all, nobody had $seen$ a quark (confinement), but also
  - A problem with the quark model: quarks have spin-$1/2$ and share
  - "isospin": $u, d \leftrightarrow I = \pm 1/2$
  - $p = uud$(spin 1/2) and $n = ddu$(spin 1/2) are symmetric in spin & isospin. And lowest-lying spatial wave function should be symmetric
- But spin-$1/2$ particles are all fermions – right?

- Fast-forward resolution:
  - Greenberg 1964: quarks *para*fermions of order 3, *or* ...
  - Han, Nambu 1965: quarks come in 3 triplets of different colors
  - Quarks in baryons are antisymmetric in color quantum number
  - A new symmetry SU(3)
  - But excited color states not seen (confinement again?)
  - So what *is* this color quantum number? The answer found from
  - Yang,Mills 1954: Generalization of electric charge to $N(=3)$ conserved charges: for color $3^2 - 1 = 8$, generalized photon!
  - By 1971 ‘t Hooft,Veltman: Nonabelian Gauge theories consistent & all the rage for the weak interactions (Higgs!)

- The birth of QCD: SU(3)
  - A nonabelian gauge theory built on color ($q = q_1 q_2 q_3$):

$$\mathcal{L}_{QCD} = \sum_q \bar{q}\,(i\not{\partial} - g_s \not{A} + m_q\,)\,q - \frac{1}{4} F_{\mu\nu}^2[A]$$

    (Pati-Salam 1972, 3; Fritzsch,Gell-Mann,Leutwyler, 1973)

  - Think of: $\mathcal{L}_{EM} = K_{\mathrm{e}} + J_{EM} \cdot A + (E^2 - B^2)$
  - The Yang-Mills gauge theory of quarks (q) and gluons (A)
    Gluons: like "charged photons". The field is a source for itself.
  - Just the right currents to couple to EM and Weak AND . . .

- Just the right kind of forces: QCD charge is "antishielded" and *grows* with distance

$b_0 = 11 - 2n_{\rm quarks}/3$ we get:

$$\alpha_s(\mu') = \frac{g_s^2}{4\pi} = \frac{\alpha_s(\mu)}{1 + b_0 \frac{\alpha_s(\mu)}{4\pi} \ln\left(\frac{\mu'}{\mu}\right)^2} = \frac{4\pi}{b_0 \ln(Q^2/\Lambda^2_{\rm QCD})}$$

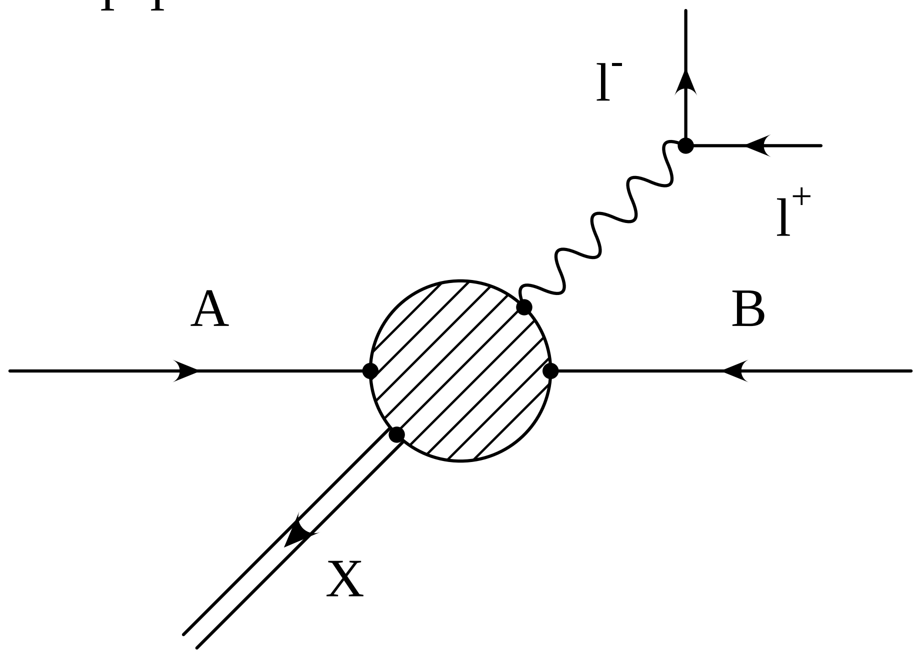
Quantum field theory: every state with the same quantum numbers as uud in the proton . . . is present at least some of the time

So antiquarks are in the nucleon: $uudd\bar{d}$, etc.

What it means: $q\bar{q}$ annihilation processes in NN collisions as d, u from one nucleon collides with $\bar{d}, \bar{u}$ from another

Annihilation into what? Back to quarks, and gluons, yes, but also

$l^+ l^-$



Electroweak annihilation (γ, W, Z, H to leptons)

Which brings us to . . .

• The rest of the standard model: SU(3) $\times$ SU(2)$_L$ $\times$ U(1)

- Quark and lepton fields: L and R
  - $\psi = \psi^{(L)} + \psi^{(R)}R = \frac{1}{2}(1-\gamma_5)\psi + \frac{1}{2}(1+\gamma_5)\psi$; $\psi = q, \ell$
  - Helicity: spin along $\vec{p}$ (R=right handed) or opposite (L=left handed) in solutions to Dirac equation
  - $\psi^{(L)}$: only L particle solutions; but R antiparticle solutions
  - $\psi^{(R)}$: only R particle solutions, L antiparticle

$$q_i^{(L)} = \left(\, u_i, d'_i = V_{ij} dj \, \right) \qquad u_i^{(R)},\ d_i^{(R)}$$

$$(u, d') \qquad (c, s') \qquad (t, b')$$

$$\ell_i^{(L)} = \left(\, e_i, \nu_i \, \right) \qquad e_i^{(R)},\ \nu_i^{(R)}$$

$$(\nu_e, e) \qquad (\nu_\mu, \mu) \qquad (\nu_\tau, \tau)$$

  - V_{ij} is the CKM matrix (viz. lectures of Neubert, Sharma)

- Weak vector bosons: electroweak gauge groups
  - SU(2): three vector bosons B_i, coupling g
  - U(1); one vector boson C, coupling g'

  - The physical bosons:

$$W^\pm = B_1 \pm iB_2$$

$$Z = -C\sin\theta_W + B_3\cos\theta_W$$

$$\gamma \equiv A = C\cos\theta_W + B_3\sin\theta_W$$

$$\sin\theta_W = g'/\sqrt{g^2 + g'^2} \qquad M_W = M_Z/\cos\theta_W$$

$$e = gg'/\sqrt{g^2 + g'^2} \qquad M_W \sim g/\sqrt{G_F}$$

– The interactions of quarks and leptons with the photon, W and Z

$$
\begin{aligned}
\mathcal{L}_{\mathrm{EW}}^{(fermion)} &= \sum_{\text{all } \psi} \bar{\psi}\left(i\partial\!\!\!/ - e\lambda_\psi A\!\!\!/ - (g m_\psi 2 M_W) h\right)\psi \\
&\quad -(g/\sqrt{2}) \sum_{q_i, e_i} \bar{\psi}^{(L)}\left(\sigma^+ W\!\!\!\!/^{\,+} + \sigma^- W\!\!\!\!/^{\,-}\right)\psi^{(L)} \\
&\quad -(g/2\cos\theta_W) \sum_{\text{all } \psi} \bar{\psi}\left(v_f - a_f\gamma_5\right) Z\!\!\!/\ \psi
\end{aligned}
$$

– Interactions with the Higgs $h \propto$ mass

– Interactions with W are through ψ_L's only

– Neutrino Z exchange is sensitive to $\sin^2\theta_W$, even at low energy. Observation made it clear by early 1970's that $M_W \sim g/\sqrt{G_F}$ is large (need for colliders)

- Symmetry violations in the standard model
  - W's interact through $\psi^{(L)}$ only $\psi = q, \ell$
  - Left-handed quarks, leptons; right-handed antiquarks, leptons
  - Parity (P) exchanges L/R; Charge conjugation (C) exchanges particles, antiparticles
  - CP combination OK $L \to R \to L$ if all else equal, but it's not (quite). Complex phases in CKM $V \to$ CP violation.

- **Observation**

- Electroweak annihilation: hadronic window
  to the electroweak sector and beyond

  The idea of vector exchange to explain the weak interactions, a "W", was around in the early 1960's. But nobody knew the mass yet.

  Could they be produced in NN experiments at 10's of GeV?

  SLAC DIS results & parton intepretation encouraged a close look for dilepton pairs from decays of new vector bosons.

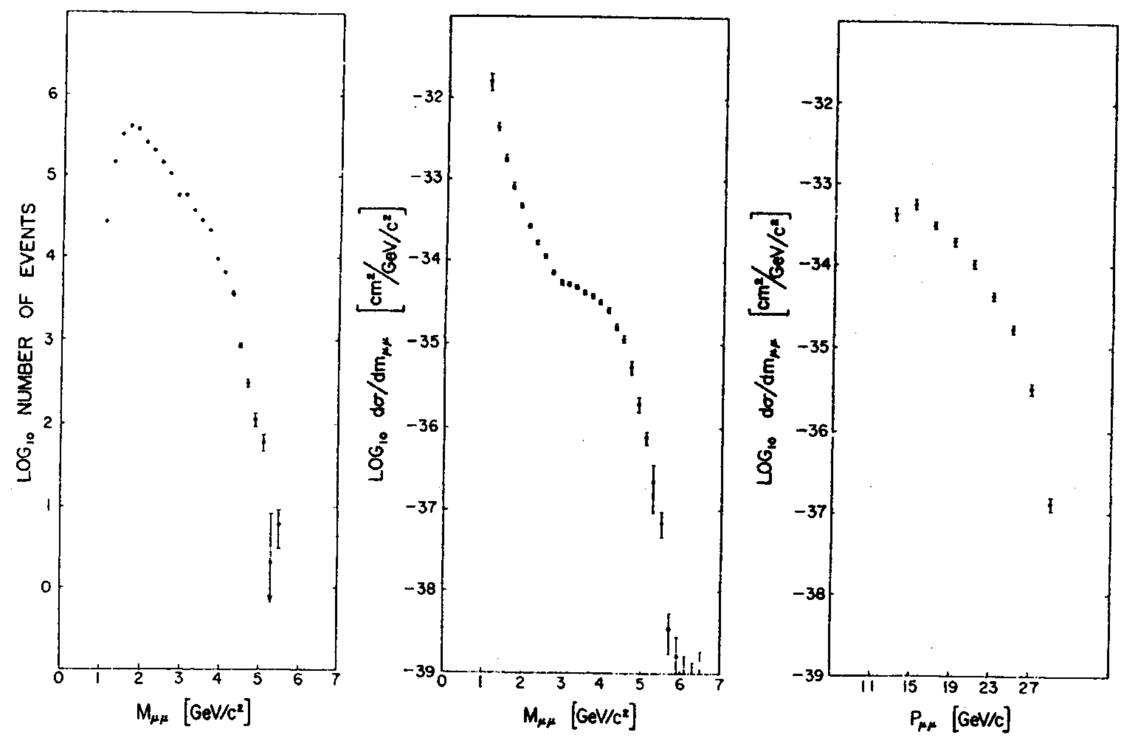


FIG. 2. (a) Observed events as a function of the effective mass of the muon pair. (b) Cross section as a function of the effective mass of the muon pair (these data include the wide-angle counters). (c) Cross section as a function of the laboratory momentum of the muon pair.

– First observation: Brookhaven AGS; $E_{\mathrm{beam}} \leq 30$ GeV

J.H. Christenson, G.S. Hicks, L.M. Lederman, P.J. Limon and B.G. Pope

PRL 25, 1523 (1970)

Power-law falloff in M_{pair}. No new weak boson, but J/ψ in data.

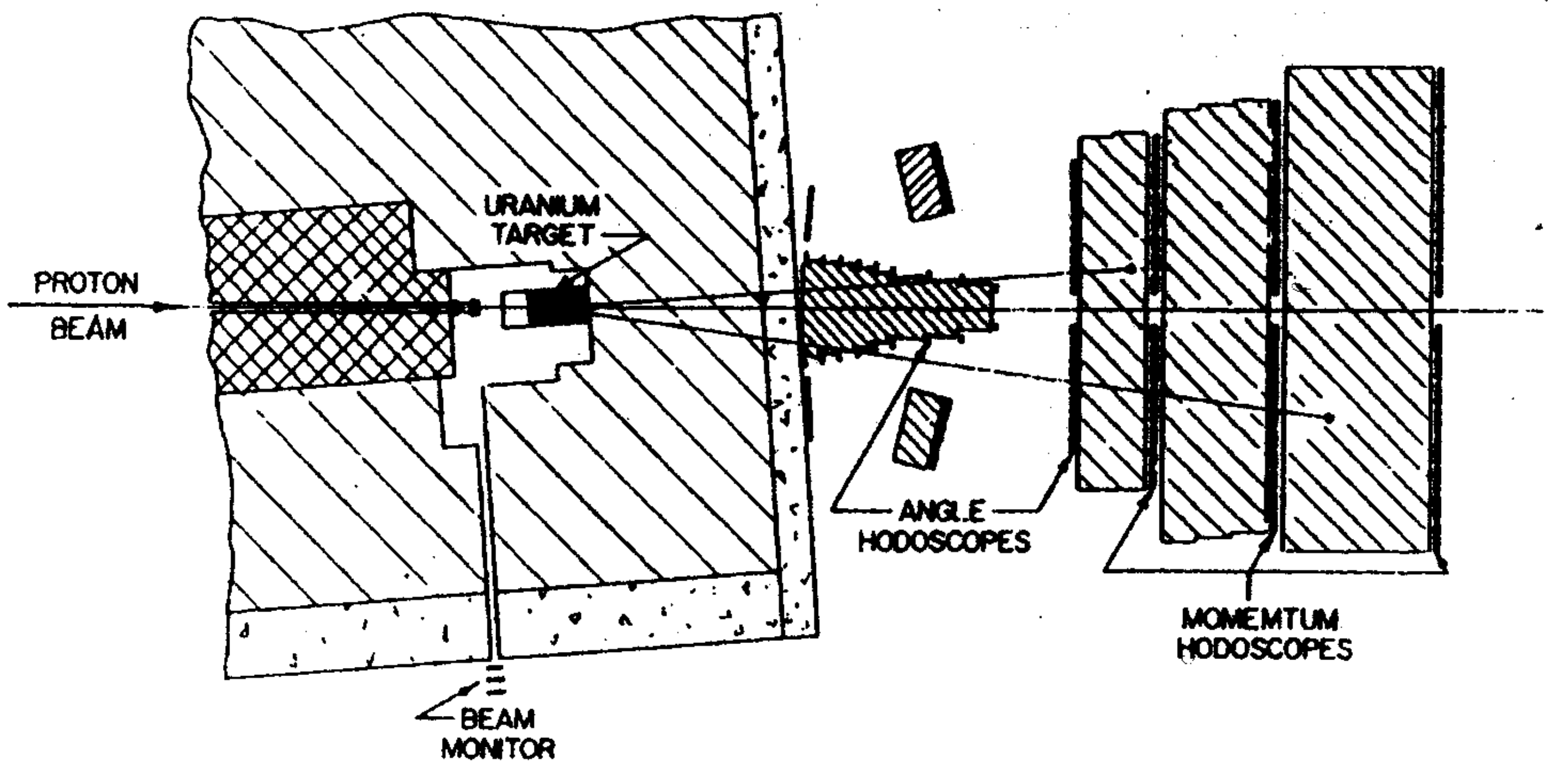


FIG. 1. Plan view of the apparatus.

Experimental set-up at the AGS.

- **The Inclusive Drell-Yan Cross Section**

Parton Model: "Impulse approximation". The template:

$$\frac{d\sigma_{NN\to\mu\bar{\mu}+X}(Q,p_1,p_2)}{dQ^2 d\ldots} \sim d\xi_1 d\xi_2 \sum_{a=\mathrm{q}\bar{\mathrm{q}}} \frac{d\sigma^{\mathrm{EW,\,Born}}_{\mathrm{a}\bar{\mathrm{a}}\to\mu\bar{\mu}}(Q,\xi_1 p_1,\xi_2 p_2)}{dQ^2 d\ldots}$$
$$\times(\text{probability to find parton a}(\xi_1)\text{ in }N)$$
$$\times(\text{probability to find parton }\bar{\mathrm{a}}(\xi_2)\text{ in }N)$$

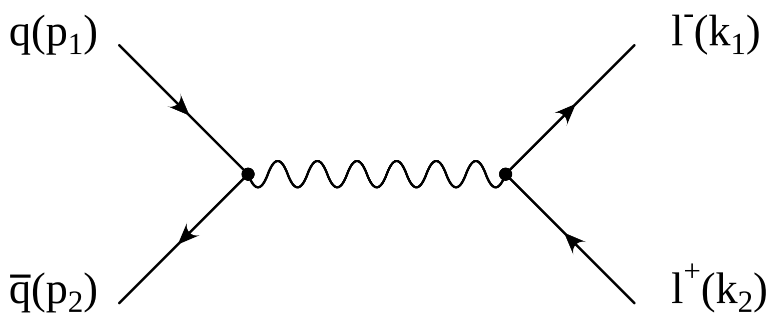
S.D. Drell and T.-M.Yan, PRL 25, 316 (1970)

The probabilities are $f_{c/N}(x)$'s from DIS!

How it works (with colored quarks) . . .

- The Born cross section (with thanks to Jeff Owens)

$\sigma^{\mathrm{EW,Born}}$ is all from this diagram (ξ's set to unity):



With this matrix element

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

- First square and sum/average M. Then evaluate phase space.

1. Average spin **and** color & square the matrix element

$$\overline{\sum}|M|^2 \;=\; \frac{e_q^2 e^4}{\hat{s}^2}\left(\frac{1}{2}\right)^2 3\left(\frac{1}{3}\right)^2 \mathrm{Tr}\left[\not{p}_1\gamma^\nu\not{p}_2\gamma^\mu\right]\mathrm{Tr}\left[\not{k}_2\gamma_\nu\not{k}_1\gamma_\mu\right]$$

$$= \frac{4}{3}\frac{e_q^2 e^4}{\hat{s}^2}\left[p_1^\nu p_2^\mu + p_1^\mu p_2^\nu - g^{\mu\nu} p_1\cdot p_2\right]\left[k_{2\nu}k_{1\mu} + k_{2\mu}k_{1\nu} - g_{\mu\nu}k_1\cdot k_2\right]$$

$$= \frac{4}{3}\frac{e_q^2 e^4}{\hat{s}^2}\left[2p_1\cdot k_2 p_2\cdot k_1 + 2p_1\cdot k_1 p_2\cdot k_2\right]$$

$$= \frac{2}{3}\,\frac{e_q^2 e^4}{\hat{s}^2}\left[\hat{t}^2 + \hat{u}^2\right]$$

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

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

- In the (partonic) center of mass frame, momenta are:

$$
\begin{aligned}
p_1 &= \frac{\sqrt{\hat{s}}}{2}(1,0,0,1) \\
p_2 &= \frac{\sqrt{\hat{s}}}{2}(1,0,0,-1) \\
k_1 &= \frac{\sqrt{\hat{s}}}{2}(1,\sin\theta,0,\cos\theta) \\
k_2 &= \frac{\sqrt{\hat{s}}}{2}(1,-\sin\theta,0,-\cos\theta)
\end{aligned}
$$

$\hat{t}^2 + \hat{u}^2$ gives a simple form:

$$\overline{\sum}|M|^2 = \frac{e_q^2 e^4}{3}(1+\cos^2\theta)$$

Differential $1+\cos^2\theta$ in c.m. $\leftrightarrow$ spin-1/2 $\rightarrow$ spin-1/2

2. Invariant phase space

$$\begin{aligned}\int PS^{(2)} &= \int \frac{d^3k_1}{(2\pi)^3 2E_1}\frac{d^3k_2}{(2\pi)^3 2E_2}(2\pi)^4\delta^4(p_1+p_2-k_1-k_2)\\ &= \int \frac{d^3k}{16\pi^2 E_1 E_2}\delta(\sqrt{\hat{s}}-E_1-E_2).\end{aligned}$$

In c.m. frame with $m=0$, $k=|\vec{k}_1|=E_1=|\vec{k}_2|=E_2$, so that

$$\delta(\sqrt{\hat{s}}-E_1-E_2)=\delta(\sqrt{\hat{s}}-2k)$$

and

$$\int PS^{(2)} = \int \frac{dk\,d\Omega}{16\pi^2}\delta(\sqrt{\hat{s}}-2k) = \int \frac{d\Omega}{32\pi^2} = \int \frac{d\cos\theta}{16\pi}$$

- Total cross section:

$$\begin{aligned}\sigma^{\mathrm{EW,\,Born}}_{\mathrm{a\bar{a}}\to\mu\bar{\mu}}(x_1p_1,x_2p_2) &= \frac{1}{2\hat{s}}\int\frac{d\Omega}{32\pi^2}\frac{e_q^2e^4}{3}(1+\cos^2\theta)\\ &= \frac{4\pi\alpha^2}{9M^2}\sum_q e_q^2 \equiv \sigma_0(M)\end{aligned}$$

With M the pair mass

Now we're ready for the parton model differential cross section for NN scattering:

Pair mass (M) and rapidity

$$y \equiv (1/2)\ln(Q^+/Q^-) = (1/2)\ln[(Q^0+Q^3)/(Q^0-Q^3)]$$

overdetermined $\rightarrow$ delta functions in the Born cross section

$$\frac{d\sigma^{(PM)}_{NN\to\mu\bar{\mu}+X}(Q,p_1,p_2)}{dM^2dy} = \int_{\xi_1,\xi_2} \sum_{a=q\bar{q}} \sigma^{\mathrm{EW,\,Born}}_{a\bar{a}\to\mu\bar{\mu}}(\xi_1 p_1, \xi_2 p_2)$$
$$\times\delta\left(M^2 - \xi_1\xi_2 S\right)\, \delta\left(y - \frac{1}{2}\ln\left(\frac{\xi_1}{\xi_2}\right)\right)$$
$$\times f_{a/N}(\xi_1)\, f_{\bar{a}/N}(\xi_2)$$

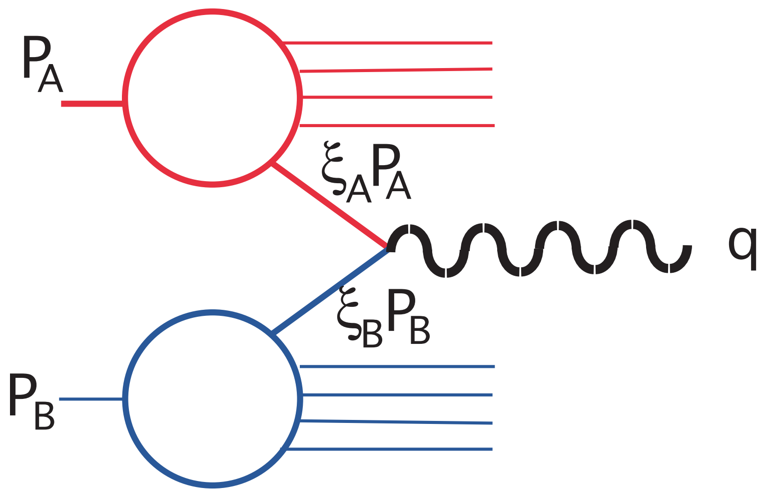
and integrating over rapidity,

$$\frac{d\sigma}{dM^2} = \left(\frac{4\pi\alpha^2_{\mathrm{EM}}}{9M^4}\right)\int_0^1 d\xi_1\, d\xi_2\, \delta\left(\xi_1\xi_2 - \tau\right) \sum_a \lambda_a^2\, f_{a/N}(\xi_1)\, f_{\bar{a}/N}(\xi_s)$$

Drell and Yan, 1970 (aside from 1/3 for color)

Analog of DIS: scaling in $\tau = Q^2/S$

- The parton model picture



- All QCD radiation in the f's (but why?)

- **Factorization**: beyond the parton model

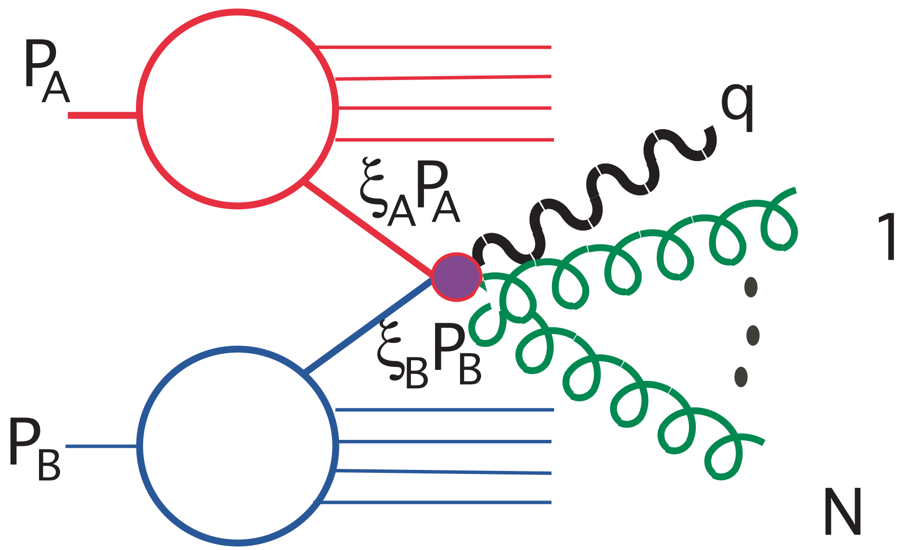
$$\frac{d\sigma_{NN\to\mu^+\mu^-+X}(Q,p_1,p_2)}{dQ^2} = \int_{\xi_1,\xi_2} \sum_{a=\mathrm{q}\bar{\mathrm{q}}} \frac{d\hat{\sigma}_{a\bar{a}\to\mu^+\mu^-(Q)+X}(Q,\mu,\xi_1 p_1,\xi_2 p_2)}{dQ^2}$$
$$\times f_{a/N}(\xi_1,\mu)\, f_{\bar{a}/N}(\xi_2,\mu)$$

μ is the factorization scale: separates IR from UV
in quantum corrections

μ appears in $\hat{\sigma}$, as $\alpha_s(\mu)$ and as $\ln(\mu/Q)$
so choosing $\mu \sim Q$ can improve perturbative predictions

Evolution: $\mu df(x,\mu)/d\mu = \int_x^1 P(x/\xi)\, f(\xi,\mu)$
makes energy extrapolations possible.

- The factorized picture



sum N = 0 (PM) to infinity

- High-p_T radiation "has a place to go."

- **One loop corrections**

  The transverse momentum distribution at order α_s

  Extend factorization to this process

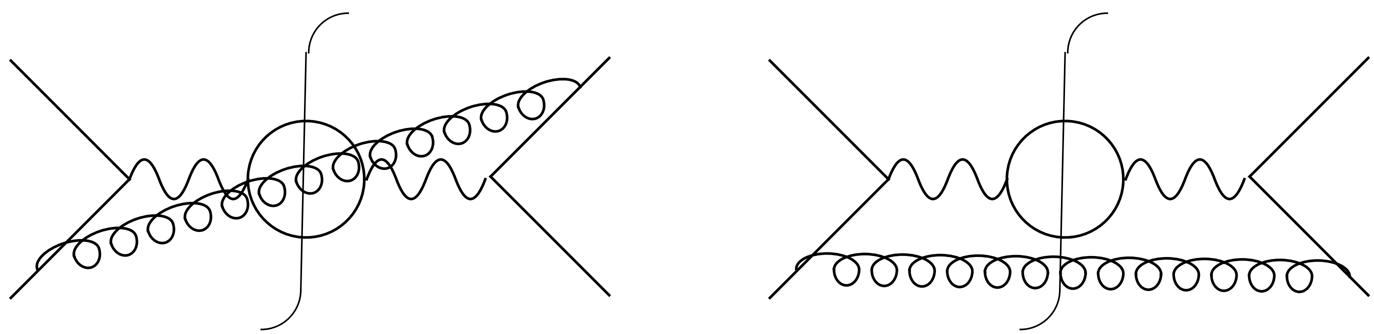
$$q(p_1) + \bar{q}(p_2) \to \gamma^*(Q) + g(k)\,,$$

  Treat this $2 \to 2$ process at lowest order (α_s) "LO"
  in factorized cross section, so that $\mathbf{k} = -\mathbf{Q}$

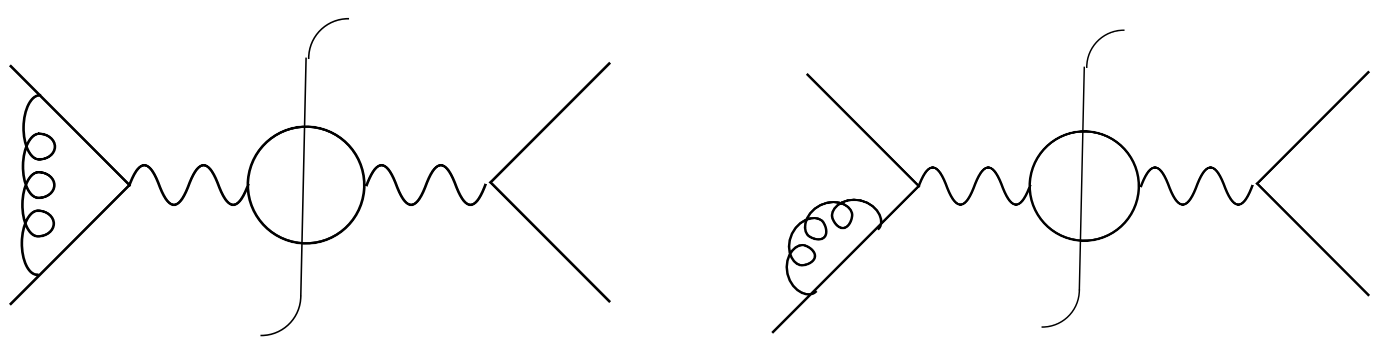
  The result is well-defined for $\mathbf{Q}_T \neq 0$

- The diagrams at order α_s

  Gluon emission contributes at $Q_T \neq 0$



  Virtual corrections contribute only at $Q_T = 0$



$$\frac{d^2\sigma^{(1)}_{q\bar{q}\to\gamma^* g}(z,Q^2,\mathbf{Q}_T)}{dQ^2\,d^2\mathbf{Q}_T} = \sigma_0\frac{\alpha_s C_F}{\pi^2}\left(1-\frac{4\mathbf{Q}_T^2}{(1-z)^2\hat{s}}\right)^{-1/2} \times \left[\frac{1}{Q_T^2}\frac{1+z^2}{1-z}-\frac{2z}{(1-z)Q^2}\right]$$

Fine as long as $\mathbf{Q}_T \neq 0$, $z = Q^2/S \neq 1$.

Q_T integral $\to \ln(1-z)$, z integral $\to \ln Q_T/Q$.

Both off these limits can be dealt with by reorganization, "resummation" of higher order corrections

- Fundamental application: the total cross section

  Integrate over $\mathbf{Q}_T$ at fixed $z = Q^2/S$. $Q_T \to 0$ is singular

  Add diagrams with virtual gluons: *their* Q_T integrals are singular

  Remove (factor) low $\mathbf{k}_T = -\mathbf{Q}_T < \mu$ gluons (as DIS)

  The remainder is now finite at fixed Q_T, $z \neq 1$. Combine with LO $\hat{\sigma}$.

  But the left-over NLO $\hat{\sigma}$ is not a normal function of z!

  Because $d\sigma/dQ^2$ begins at ${\alpha_s}^0$,
  this is next-to-leading order (NLO) here

- $\hat{\sigma}_{\bar{q}q}$ for Drell-Yan at NLO

$$\frac{d^2\hat{\sigma}^{(1)}_{q\bar{q}\to\gamma^* g}(z,Q^2,\mu^2)}{dQ^2} = \sigma_0(Q^2)\,\left(\frac{\alpha_s(\mu)}{\pi}\right)\,\Bigg\{2(1+z^2)\,\left[\frac{\ln(1+z^2)}{1-z}\right]_+ - \frac{\left[(1+z^2)\ln\, z\,\right]}{(1-z)} + \left(\frac{\pi^2}{3}-4\right)\,\delta(1-z)\Bigg\} + \sigma_0(Q^2)\,C_F\,\frac{\alpha_s}{\pi}\,\left[\frac{1+z^2}{1-z}\right]_+\,\ln\left(\frac{Q^2}{\mu^2}\right)$$

  - Plus distributions: "generalized functions" (c.f. delta function)

  - μ-dependence: evolution for hadron-hadron scattering

- What they are, how they work

$$\int_0^1 dx\, \frac{f(x)}{(1-x)_+} \quad \equiv \int_0^1 dx\, \frac{f(x)-f(1)}{(1-x)}$$

$$\int_0^1 dx\ f(x)\left(\frac{\ln(1-x)}{1-x}\right)_+ \quad \equiv \int_0^1 dx\ \left(f(x) - f(1) \right)\ \frac{\ln(1-x)}{(1-x)}$$

and so on . . . where $f(x)$ will be parton distributions

- $f(x)$ term: real gluon, with momentum fraction $1-x$
- $f(1)$ term: virtual, with elastic kinematics

- *A Special Distribution*

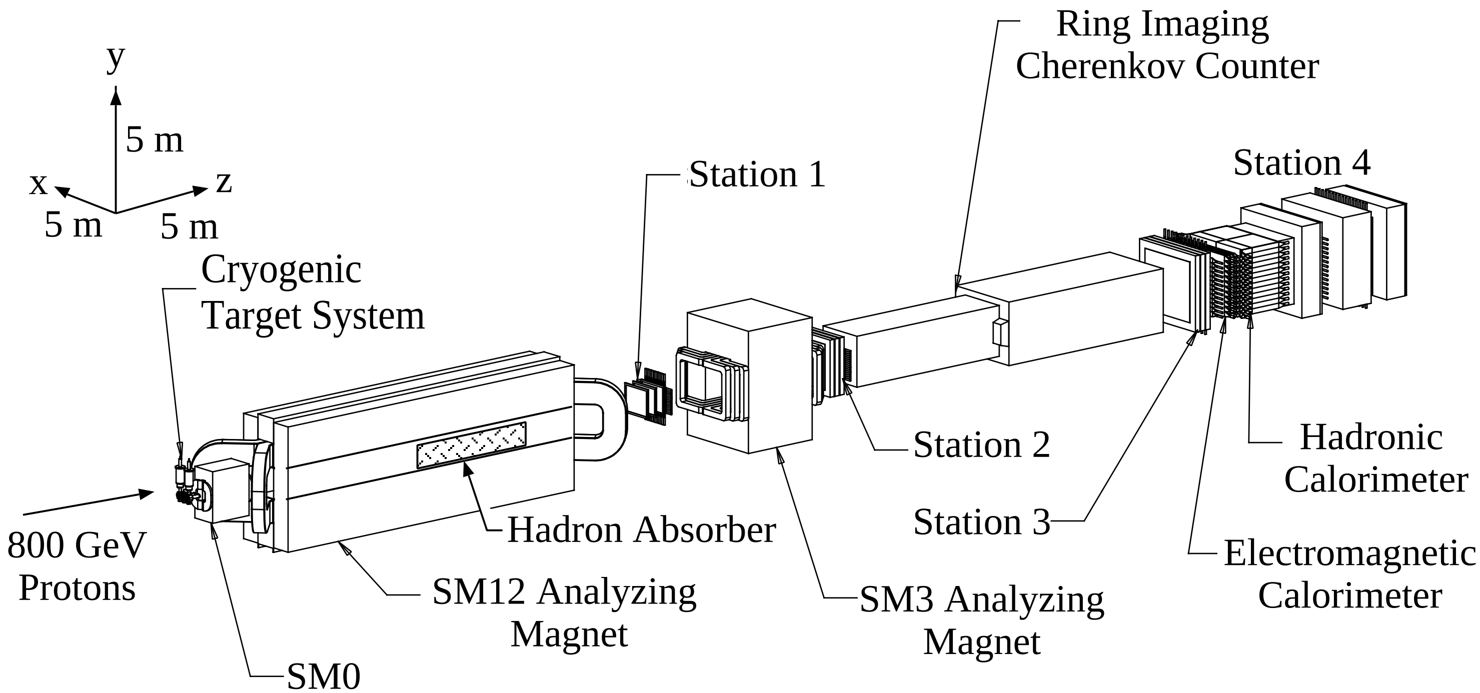
- *DGLAP "evolution kernel" = "splitting function"*

$$P_{qq}(x) = C_F \, \frac{\alpha_s}{\pi} \, \left[\frac{1+x^2}{1-x}\right]_+$$

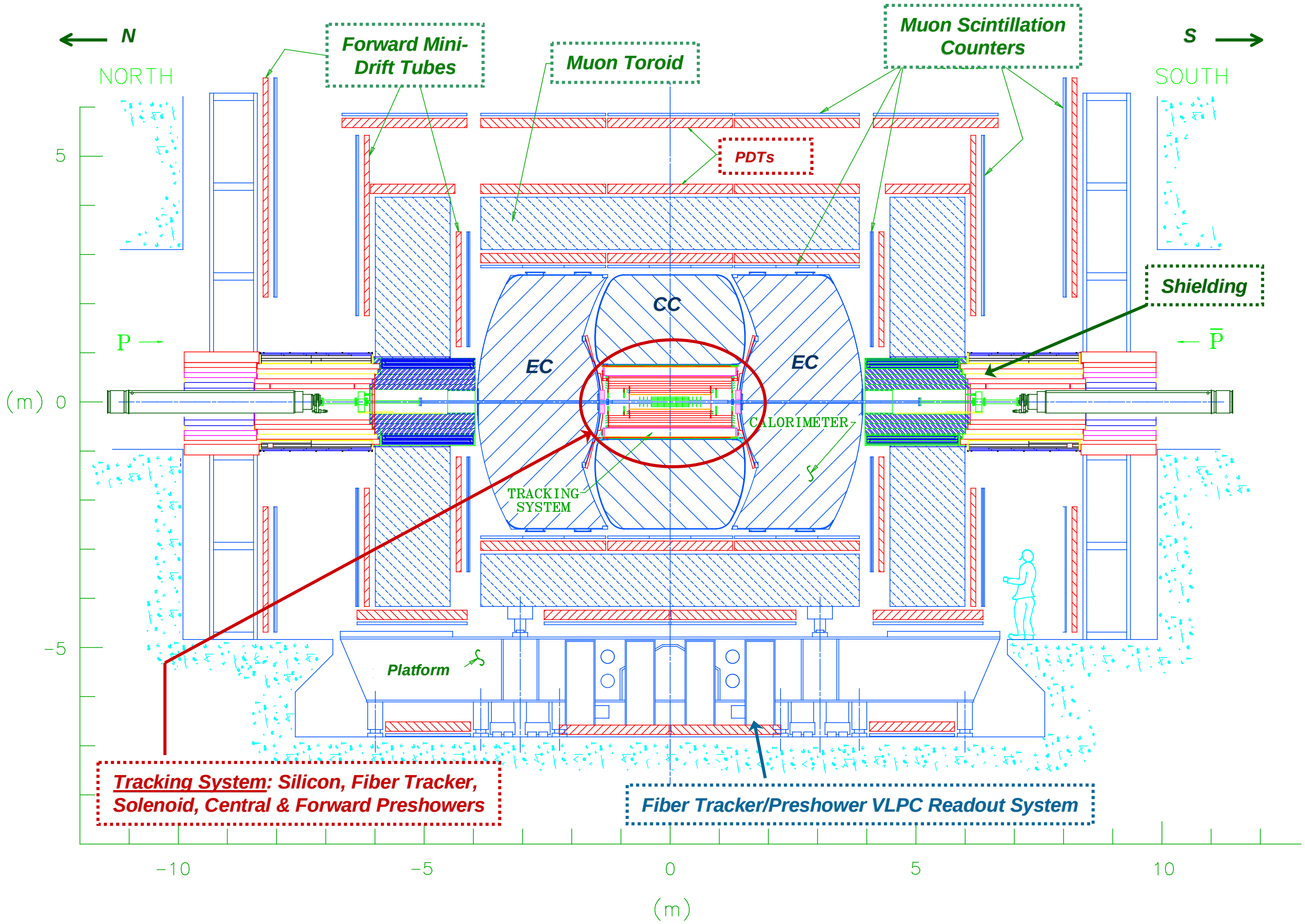
- Nonsinglet, leading order

Applications as Prologue

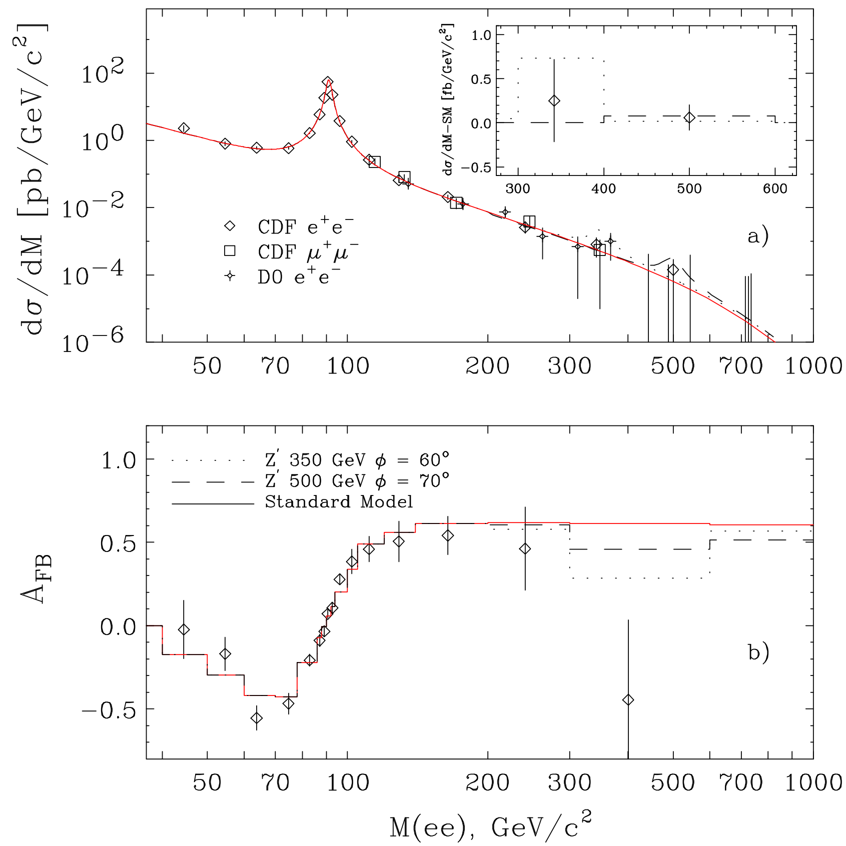
- Contemporary detectors: E866 `FNAL E866 (NUSEA)`



- And Dzero


N
S
NORTH
SOUTH
Forward Mini-Drift Tubes
Muon Toroid
Muon Scintillation Counters
PDTs
CC
EC
EC
Shielding
P
$\overline{P}$
CALORIMETER
TRACKING SYSTEM
Platform
Tracking System: Silicon, Fiber Tracker, Solenoid, Central & Forward Preshowers
Fiber Tracker/Preshower VLPC Readout System
(m)
(m)
5
0
−5
−10
−5
0
5
10

- M-dependence for dileptons at high energy (γ and Z) & forward-backward asymmetry in σ_{Born} compared to NLO
  A test for “new” physics in the hard scattering



- The W mass

How to get M_W from $W \to e\nu$ when you can't see the ν?

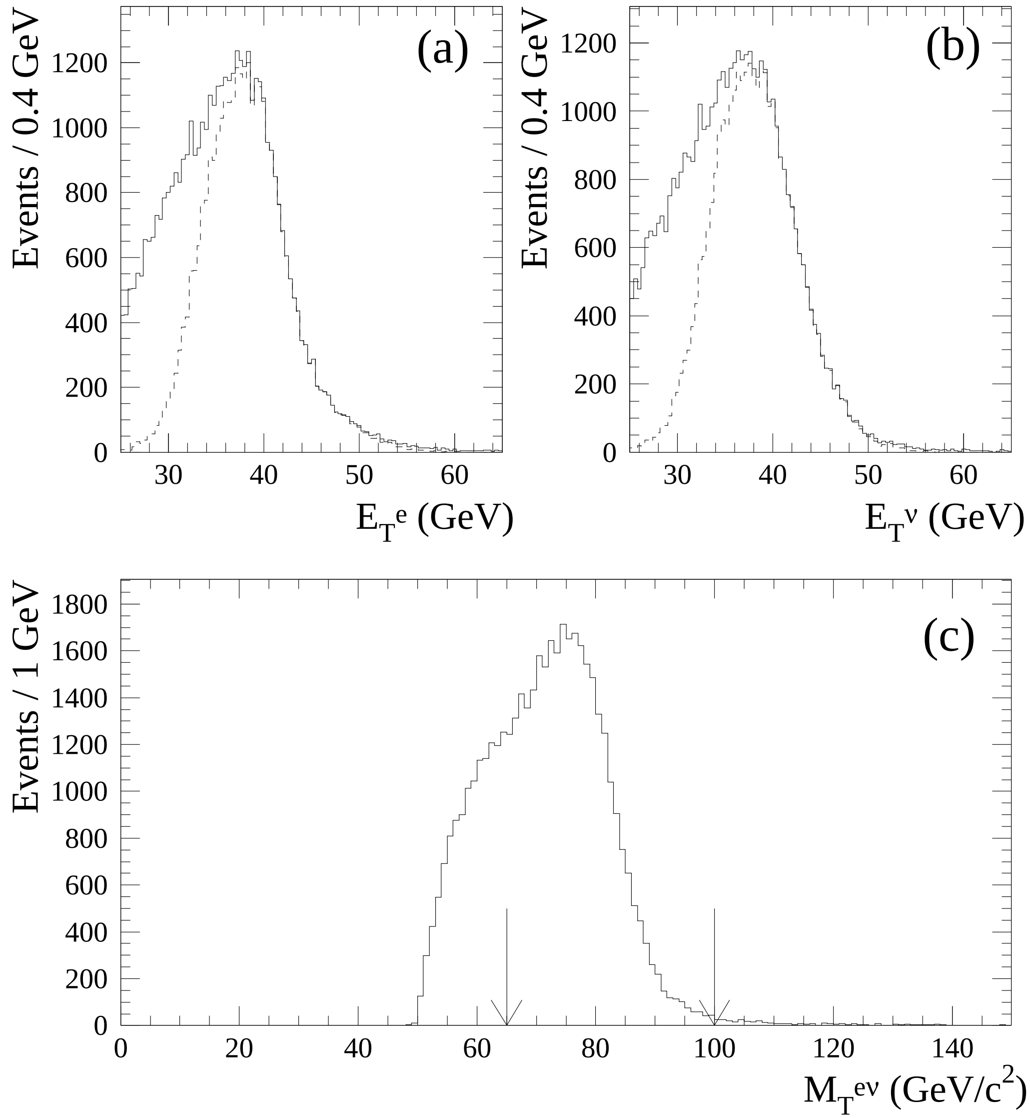
Can measure $p_{T,\nu}$ indirectly; "missing p_T"

The transverse mass:

$$M_T^{e\nu} = \left(|\mathbf{p}_{eT}|^2 + |\mathbf{p}_{\nu T}|^2\right) - \left(\mathbf{p}_{eT} + \mathbf{p}_{\nu T}\right)^2$$

M_T is Boost-invariant *and* $M_{T,\min}^{(e\nu)} = M_W$

Extra bonus: leading term in $\mathbf{p}_{W,T}/M_W = [\mathbf{p}_{eT} - \mathbf{p}_{\nu T}]/M_W$ cancels!



From CDF Collaboration, Phys. Rev. D64 052001 (2001). hep-ex/0007044

For measurements for W boson mass .

- W asymmetries at the Tevatron: d/u

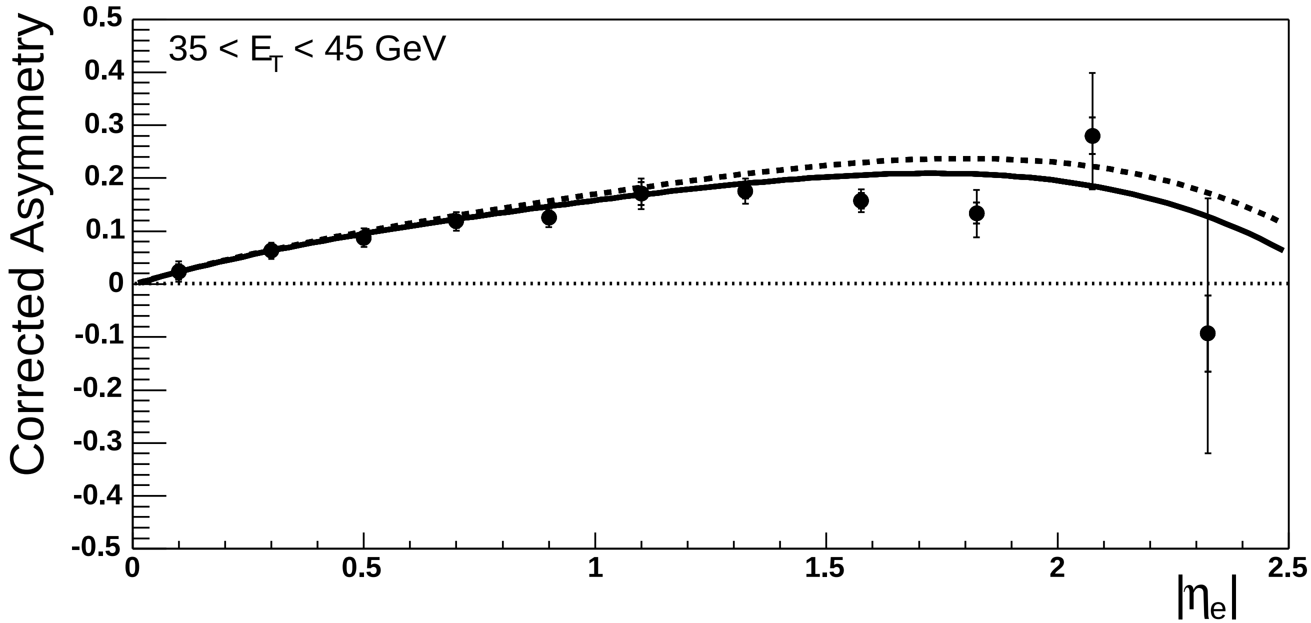
  W^+ requires $u\bar{d}$, W^- needs $\bar{u}d$

  At LO, since $u_p = \bar{u}_{\bar{p}}$, etc.

$$\frac{d\sigma_{W^+}}{dy} = \frac{2\pi G_F}{\sqrt{2}} u_p(x_a = \sqrt{\tau}e^y)\; d_p(x_b = \sqrt{\tau}e^{-y})$$

  Asymmetry tests d/u as a function of

$$A(y) \equiv \frac{\sigma_{W^+}(y) - \sigma_{W^-}(y)}{\sigma_{W^+}(y) + \sigma_{W^-}(y)} = \frac{u_p(x_a)\, d_p(x_b) - d_p(x_a)\, u_p(x_b)}{u_p(x_a)\, d_p(x_b) + d_p(x_a)\, u_p(x_b)}$$



(CDF Collaboration, Phys. Rev. D71, 051104 (2005) hep-ex/0501023)

- Foward fixed target DY and $\bar{d}/\bar{u}$

At LO,

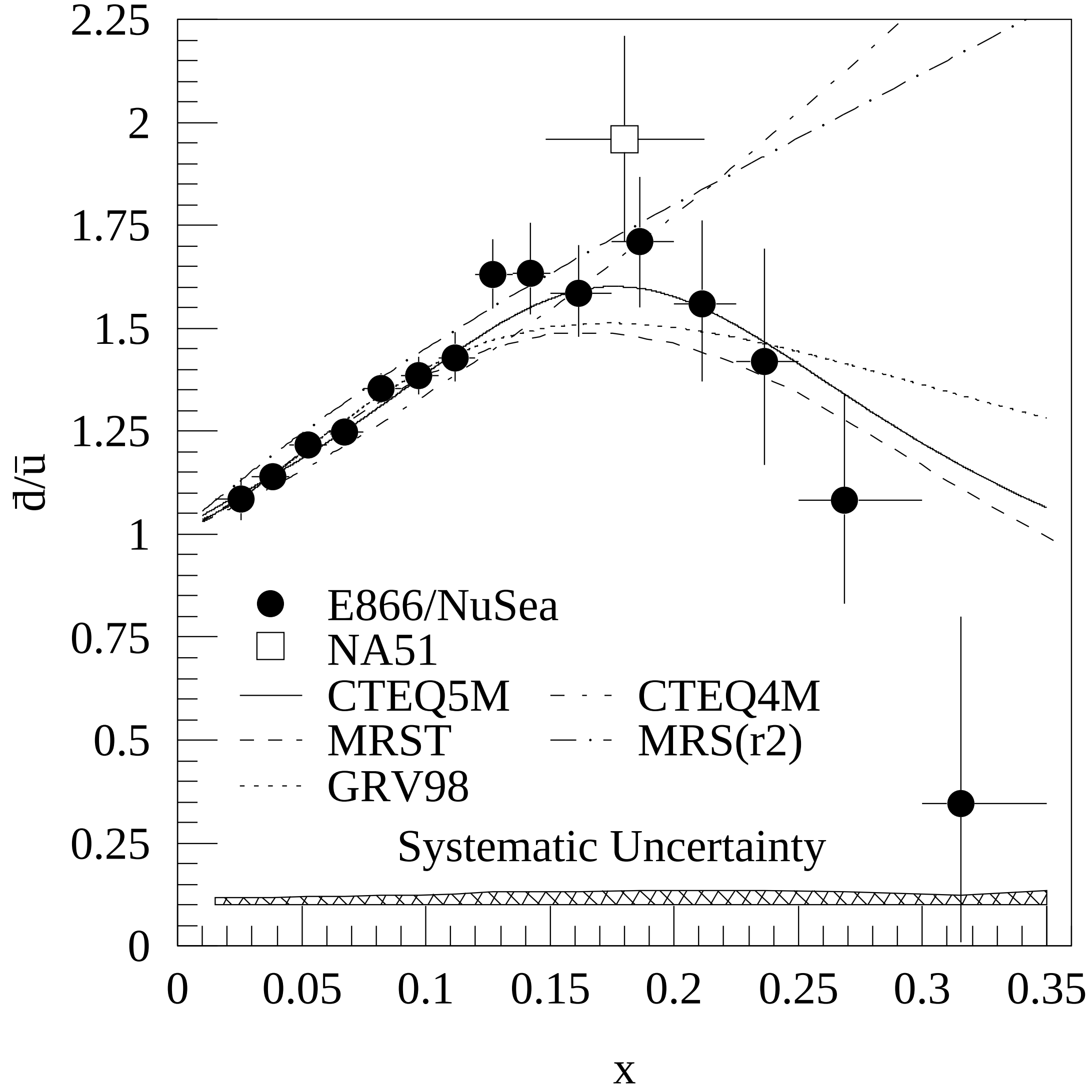
$$\frac{d\sigma_{pN}}{dM^2 dy} = \left(\frac{4\pi\alpha_{\rm EM}^2}{9M^4}\right) \sum_a \lambda_a^2 \, f_{a/p}(\sqrt{\tau}\mathrm{e}^{y}, M) \, f_{\bar{a}/N}(\sqrt{\tau}\mathrm{e}^{-y}, M)$$

Large y; a valence, $\bar{a}$ sea: sensitivity to sea distribution

E866: compare pp and pd

$$\frac{\sigma_{pD}}{2\sigma_{pp}} \sim \frac{1}{2}\left(1 + \frac{\bar{d}_p(\sqrt{\tau}\mathrm{e}^{-y})}{\bar{u}_p(\sqrt{\tau}\mathrm{e}^{-y})}\right)$$

Previously unavailable information on the sea ratio

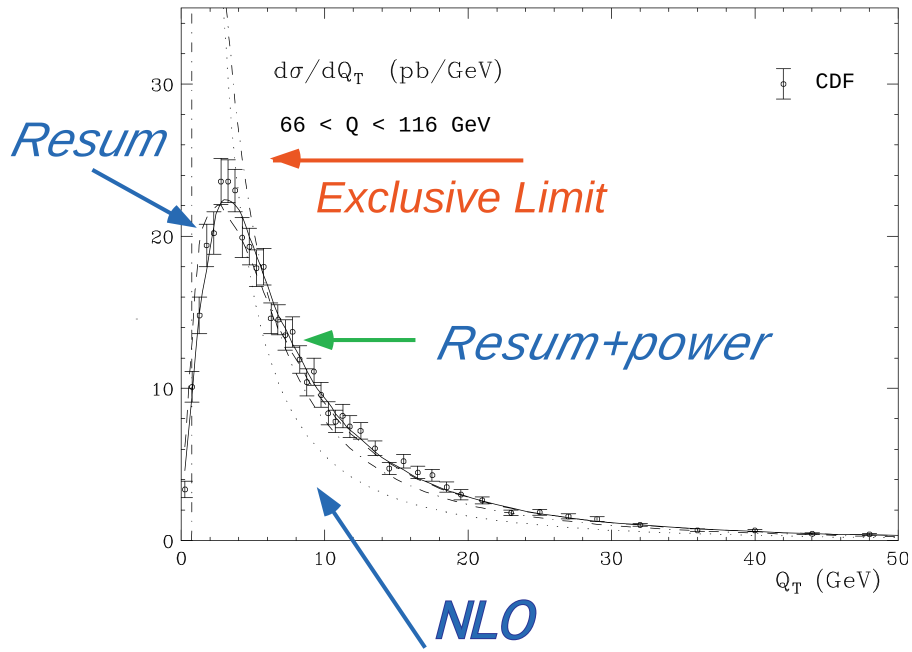


E866/NuSea Collaboration, Phys. Rev. D64, 052002 (2001) hep-ex/0103030

- Low Q_T Drell-Yan & Higgs at leading log (LL) $({\alpha_s}^n \ln^{2n-1} Q_T)$

$$\frac{d\sigma_i(Q)}{dQ_T} \sim \frac{d}{dQ_T} \exp\left[-\frac{\alpha_s}{\pi} C_i \ln^2\left(\frac{Q}{Q_T}\right)\right]$$

$$(DY : C_F = 4/3 \quad H : C_A = 3)$$



(from A. Kulesza, G.S., W. Vogelsang (2002))

Maximum then decrease near "exclusive" limit
(parton model kinematics) replaces divergence at $Q_T = 0$

Soft but perturbative radiation broadens distribution

Typically NP correction necessary for
full quantitative description

Recover fixed order predictions $\sigma^{(1)}$ away from exclusive limit

Generally requires (Fourier) transform (impact parameter)
to go beyond leading log

- Prologue: Electroweak annihilation at the CTEQ School

  Electroweak annihilation will appear again in the next week

  – In global fits to parton distributions (D. Stump)
  – In more depth for Drell Yan, Higgs and QCD (D. De Florian)
  – NLO, the real thing (M.E. Tejeda-Yeomans)
  – Analogs in scenarios/searches for new physics (G. Kribs, T. Han)
  – Parallels to direct photon (J. Owens), jets (A. Korytov), heavy quarks (F. Olness)
  – Strong/electoweak (and beyond) interplay in B-physics (M. Neubert and V. Sharma)

- And more. Enjoy the school!