Nucleon Structure and the Drell-Yan Process

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The Drell-Yan Process

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

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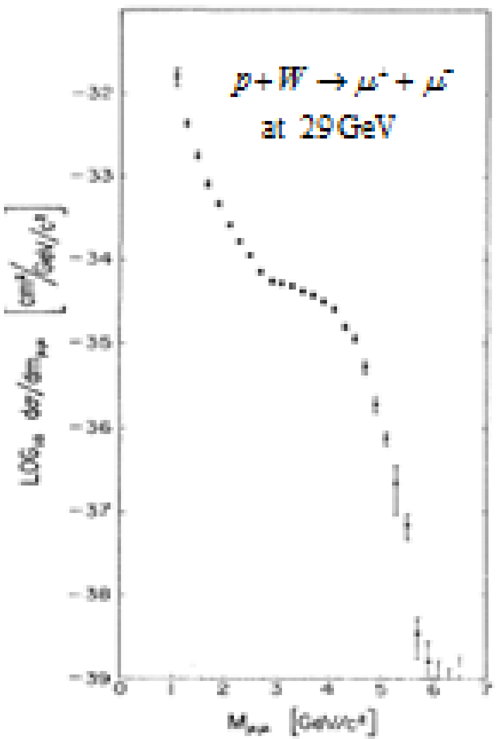
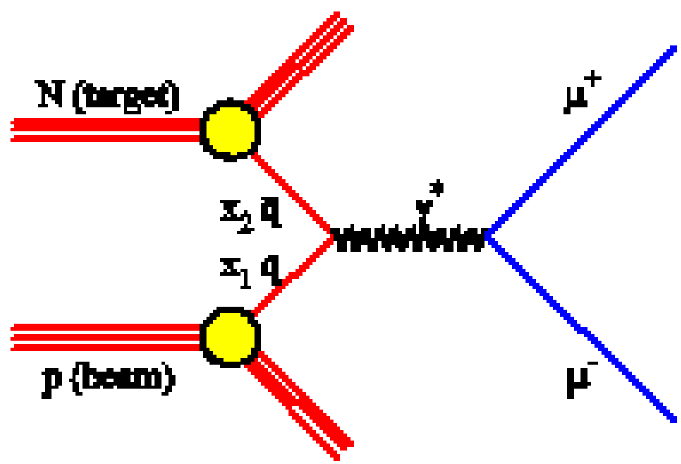
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

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.





$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9 s x_1 x_2} \sum_a e_a^2 \left[q_a(x_1)\bar{q}_a(x_2) + \bar{q}_a(x_1) q_a(x_2) \right]$$

Naive Drell-Yan and Its Successor*

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Ithaca, NY 14853

February 1, 2008

Abstract

We review the development in the field of lepton pair production since proposing parton-antiparton annihilation as the mechanism of massive lepton pair production. The basic physical picture of the Drell-Yan model has survived the test of QCD, and the predictions from the QCD improved version have been confirmed by the numerous experiments performed in the last three decades. The model has provided an active theoretical arena for studying infrared and collinear divergences in QCD. It is now so well understood theoretically that it has become a powerful tool for new phyiscs information such as precision measurements of the W mass and lepton and quark sizes.

- "… our original crude fit did not even remotely resemble the data. Sid and I went ahead to publish our paper because of the model's simplicity…"
- "… the successor of the naïve model, the QCD improved version, has been confirmed by the experiments…"
- "The process has been so well understood theoretically that it has become a powerful tool for precision measurements and new physics."

*Talk given at the Drell Fest, July 31, 1998, SLAC on the occasion of Prof. Sid Drell's retirement.

Success and difficulties of the "naïve" Drell-Yan

(From Yan's 1998 article)

Success:

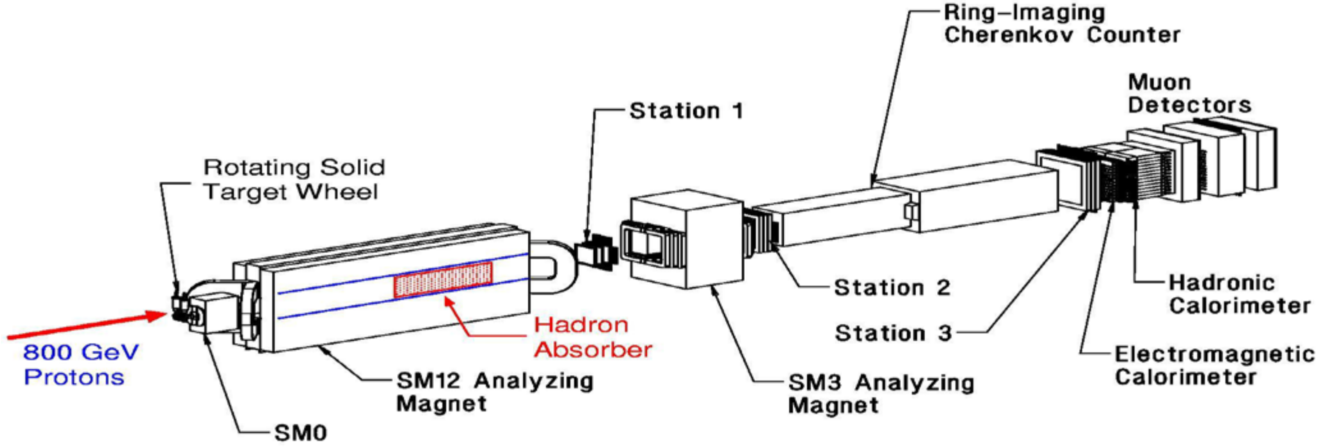
- Scaling of the cross sections (depends on x_1 and x_2 only)
- Nuclear dependence (cross section depends linearly on the mass A)
- Angular distributions ($1+\cos^2\Theta$ distributions)

Difficulties:

- Absolute cross sections (K-factor is needed)
- Transverse momentum distributions (much larger $\langle p_T \rangle$ than expected)

Fermilab Dimuon Spectrometer

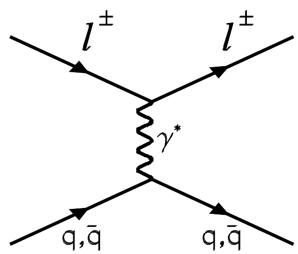
(E605 / 772 / 789 / 866 / 906)

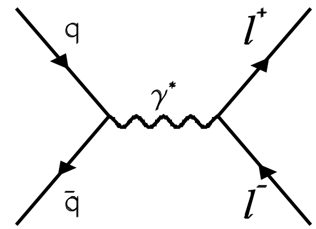


1) Fermilab E772 (proposed in 1986 and completed in 1988)
   "Nuclear Dependence of Drell-Yan and Quarkonium Production"
2) Fermilab E789 (proposed in 1989 and completed in 1991)
   "Search for Two-Body Decays of Heavy Quark Mesons"
3) Fermilab E866 (proposed in 1993 and completed in 1996)
   "Determination of $\bar{d}/\bar{u}$ Ratio of the Proton via Drell-Yan"
4) Fermilab E906 (proposed in 1999, will run in 2011-2013)
   "Drell-Yan with the FNAL Main Injector"

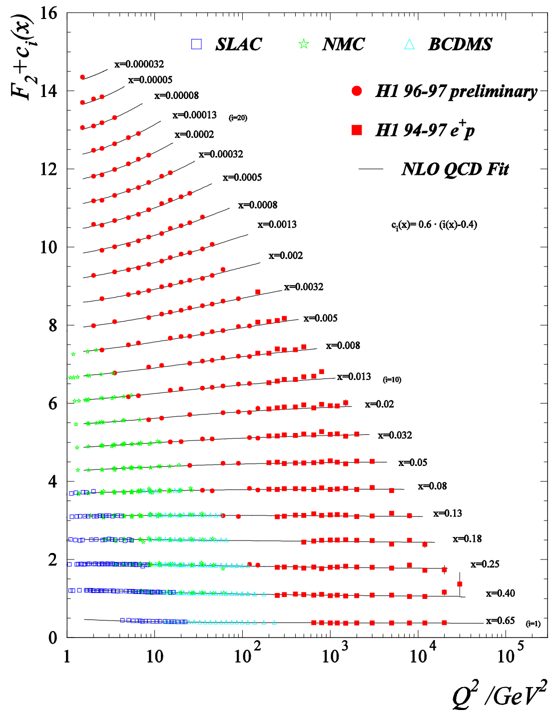
Complimentality between DIS and Drell-Yan

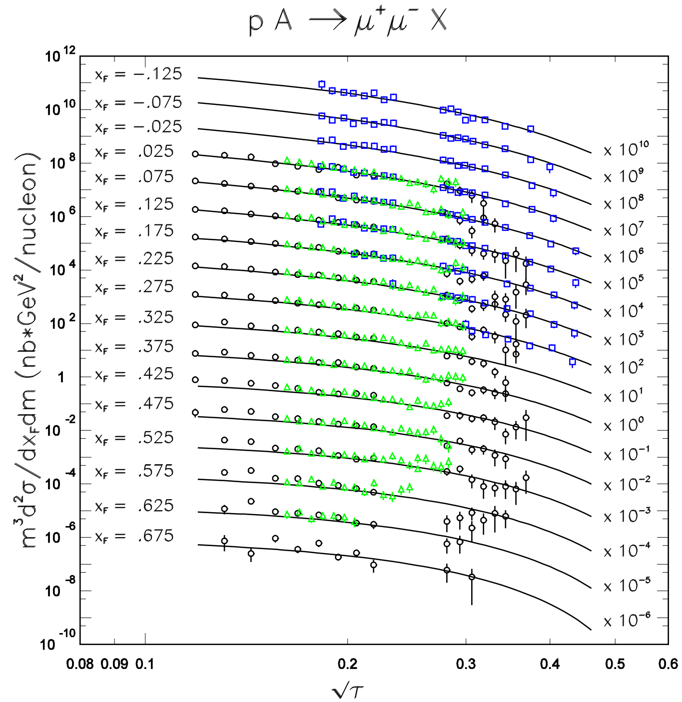
DIS





Drell-Yan





McGaughey, Moss, JCP,

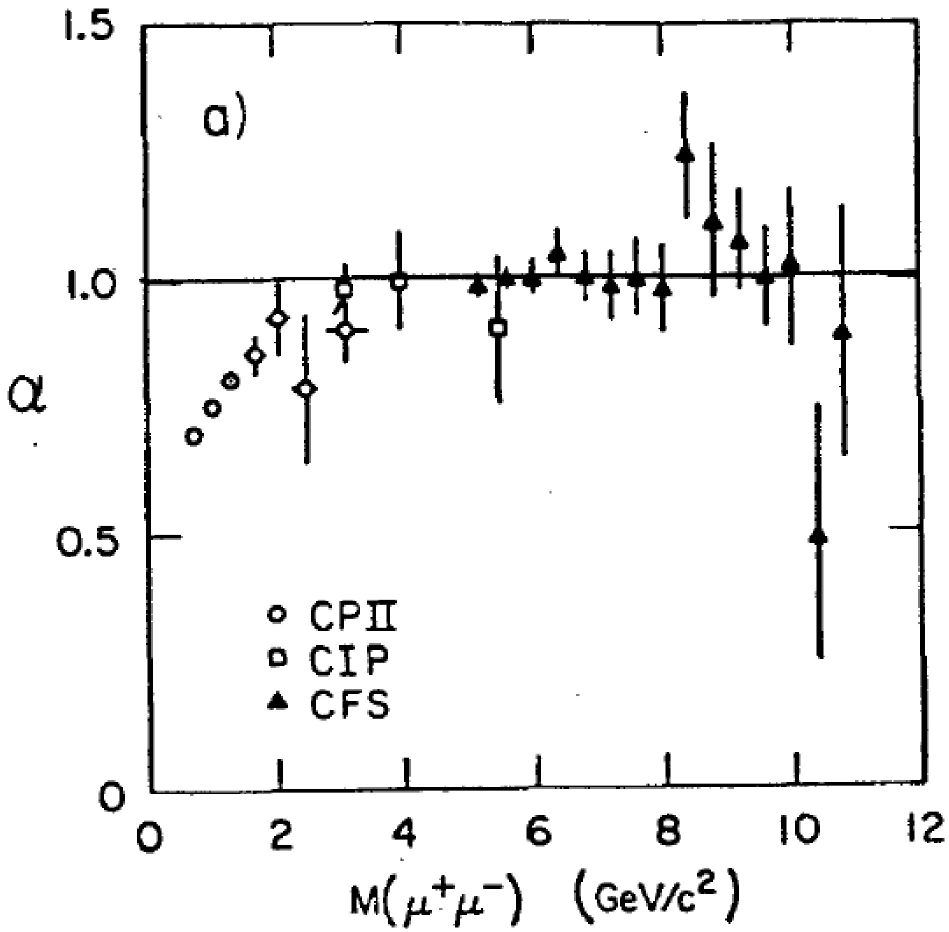
Ann.Rev.Nucl. Part. Sci. 49 (1999) 217

Both DIS and Drell-Yan process are tools to probe the quark and antiquark structure in hadrons (factorization, universality)

Scaling violation has not been observed in Drell-Yan yet

Nuclear dependence of the Drell-Yan process

- As an electromagnetic process, the Drell-Yan cross section is expected to depend linearly on the nuclear mass number A



$$\sigma = \sigma_0 A^{\alpha}$$

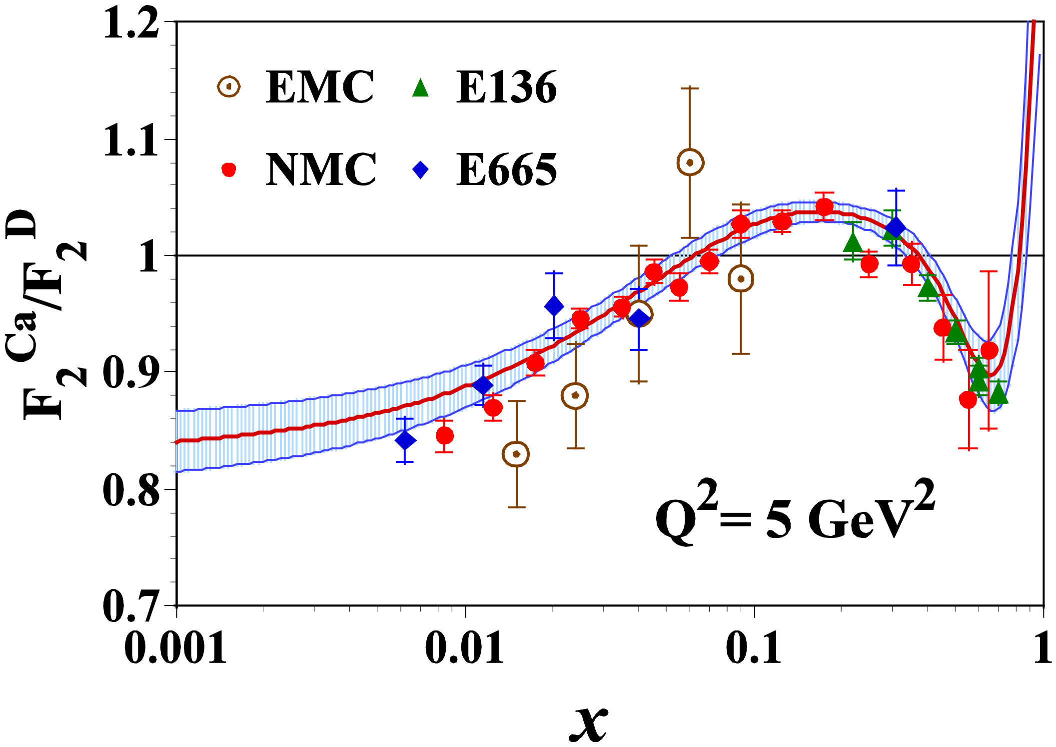
σ_0: cross section on a nucleon

(From review article of Kenyon in 1982)

α is consistent with 1

Modification of Parton Distributions in Nuclei

EMC effect observed in DIS



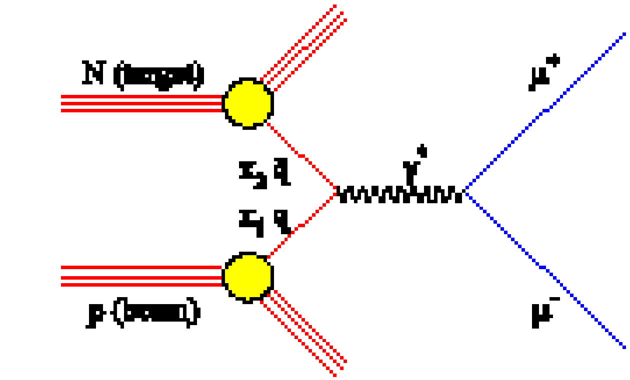
(Ann. Rev. Nucl. Part. Phys., Geesaman, Sato and Thomas)

Talk by Kumano

F_2 contains contributions from quarks and antiquarks

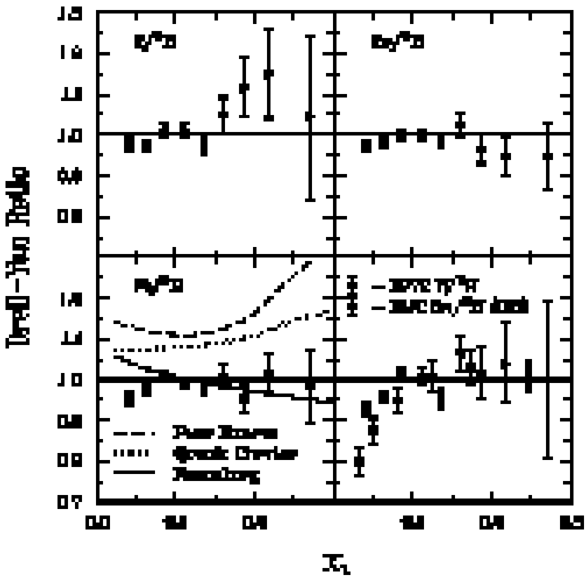
How are the antiquark distributions modified in nuclei?

Drell-Yan on nuclear targets

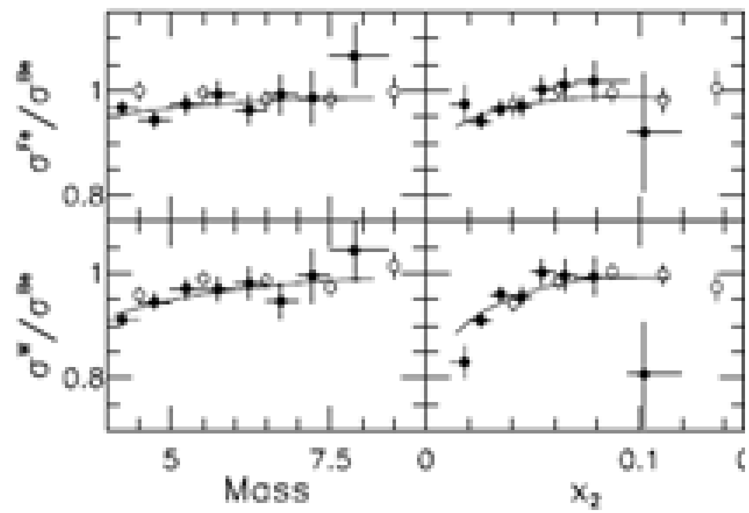


$$\frac{\sigma^{pA}}{\sigma^{pd}} \approx \frac{\bar{u}_A(x)}{\bar{u}_N(x)}$$

The x-dependence of $\bar{u}_A(x)/\bar{u}_N(x)$ can be directly measured



PRL 64 (1990) 2479

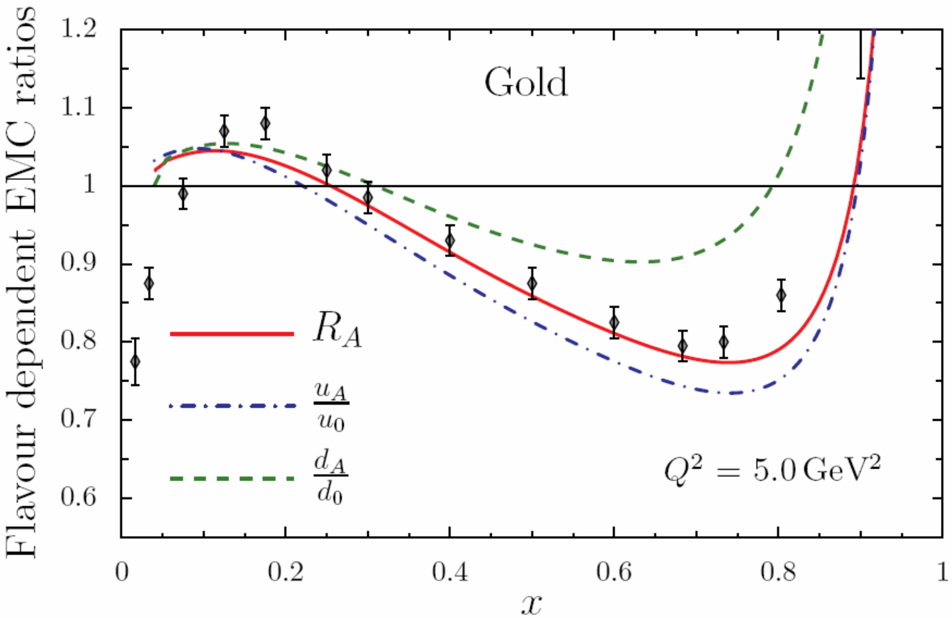


PRL 83 (1999) 2304

No evidence for enhancement of antiquark in niclei !?

E906 will extend the measurement to larger x

Flavor dependence of the EMC effects ?



Isovector mean-field generated in Z≠N nuclei can modify nucleon's *u* and *d* PDFs in nuclei

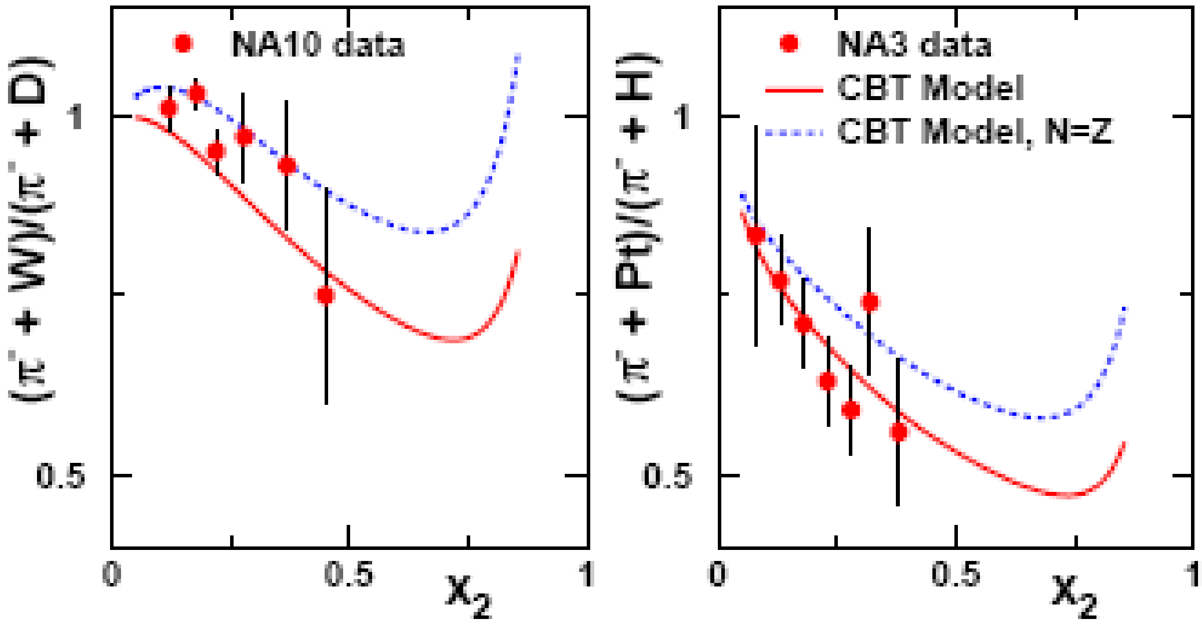
Cloet, Bentz, and Thomas, arXiv:0901.3559

How can one check this prediction?

- SIDIS (JLab proposal) and PVDIS (P.Souder)
- Pion-induced Drell-Yan

Pion-induced Drell-Yan and the flavor-dependent EMC effect

$$\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$

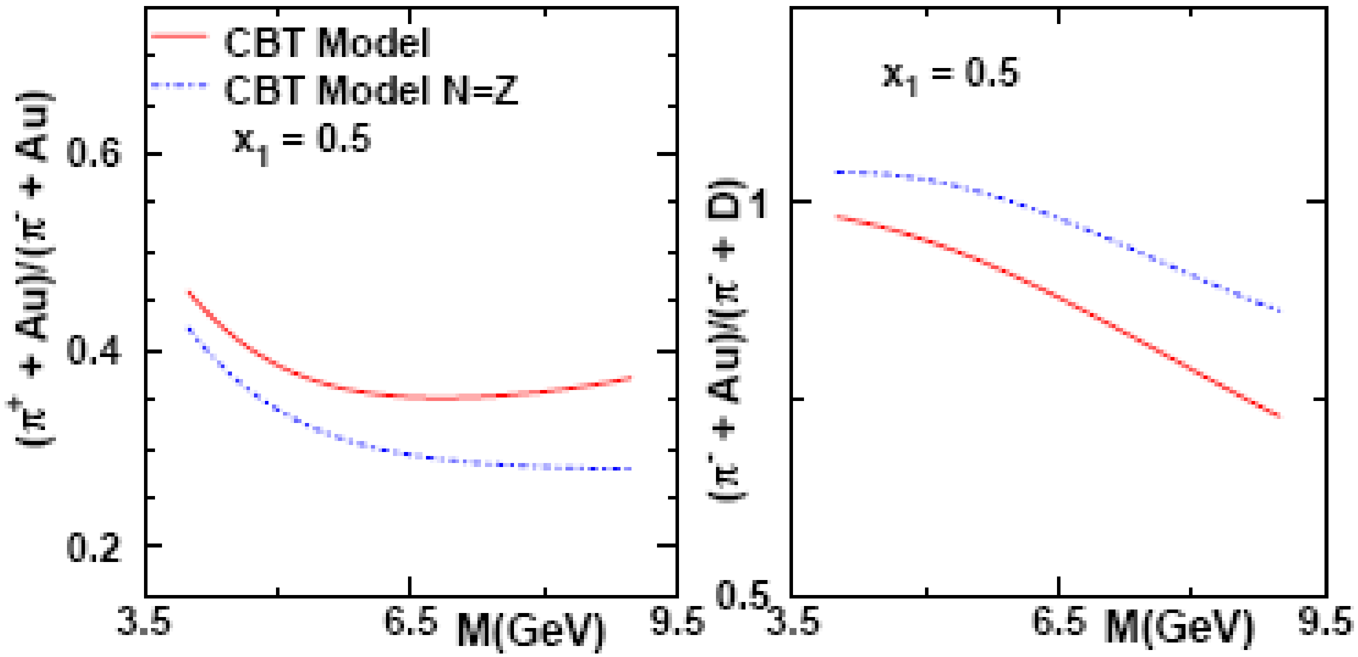


Red (blue) curves correspond to flavor-dependent (independent) EMC

(D. Dutta, JCP, Cloet, Gaskell, arXiv: 1007.3916)

Pion-induced Drell-Yan and the flavor-dependent EMC effect

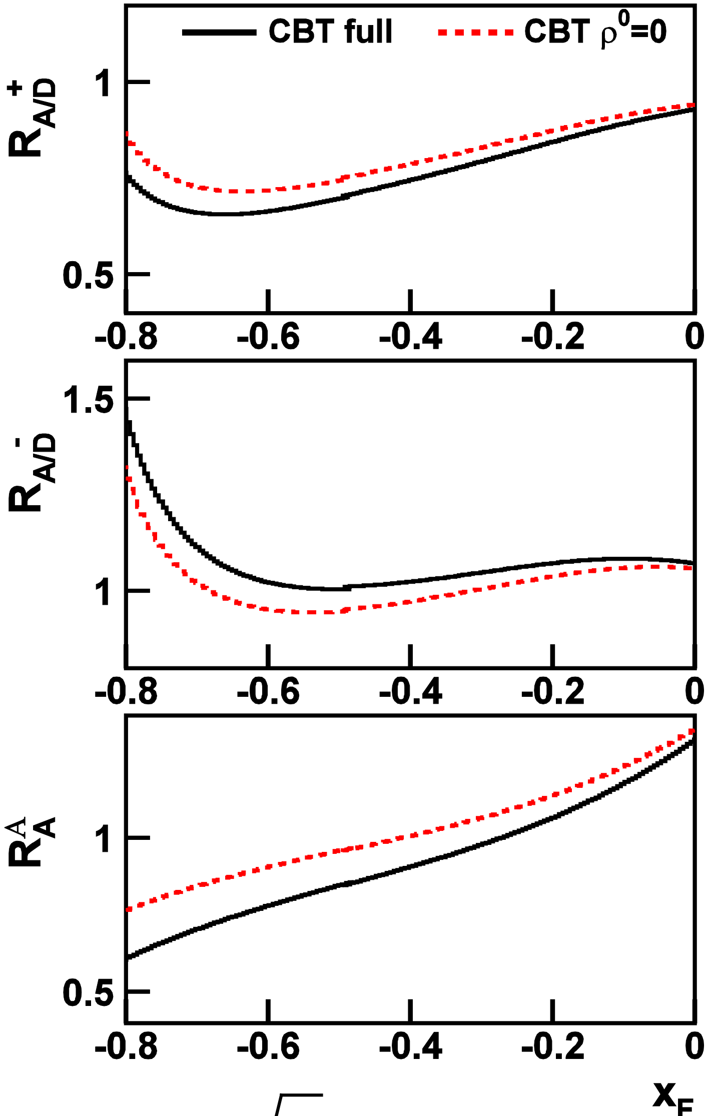
$$\frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4u_A(x)}; \qquad \frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$



160 GeV pion beam

Drell-Yan data from COMPASS with pion beams could provide important new information

W-production at LHC and the flavor-dependent EMC effect



$$\sqrt{s} = 7\text{TeV}$$

$$R^+_{A/D} \equiv \frac{d\sigma(p+A \to W^+ + x)}{d\sigma(p+D \to W^+ + x)} \approx \frac{u_A(x_2)}{u_D(x_2)}$$

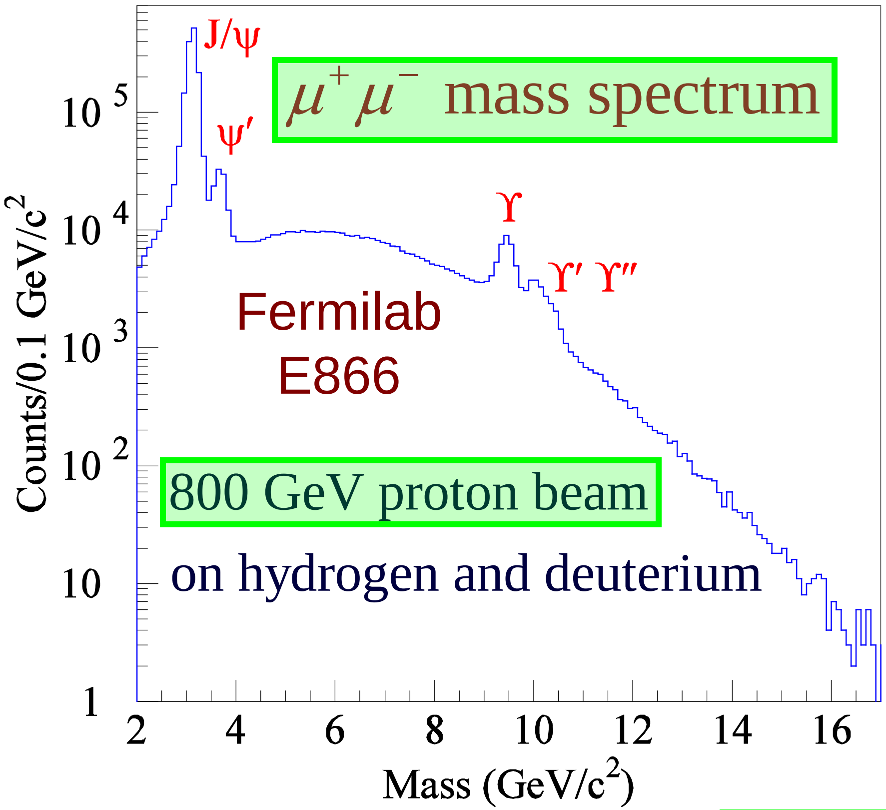
$$R^-_{A/D} \equiv \frac{d\sigma(p+A \to W^- + x)}{d\sigma(p+D \to W^- + x)} \approx \frac{d_A(x_2)}{d_D(x_2)}$$

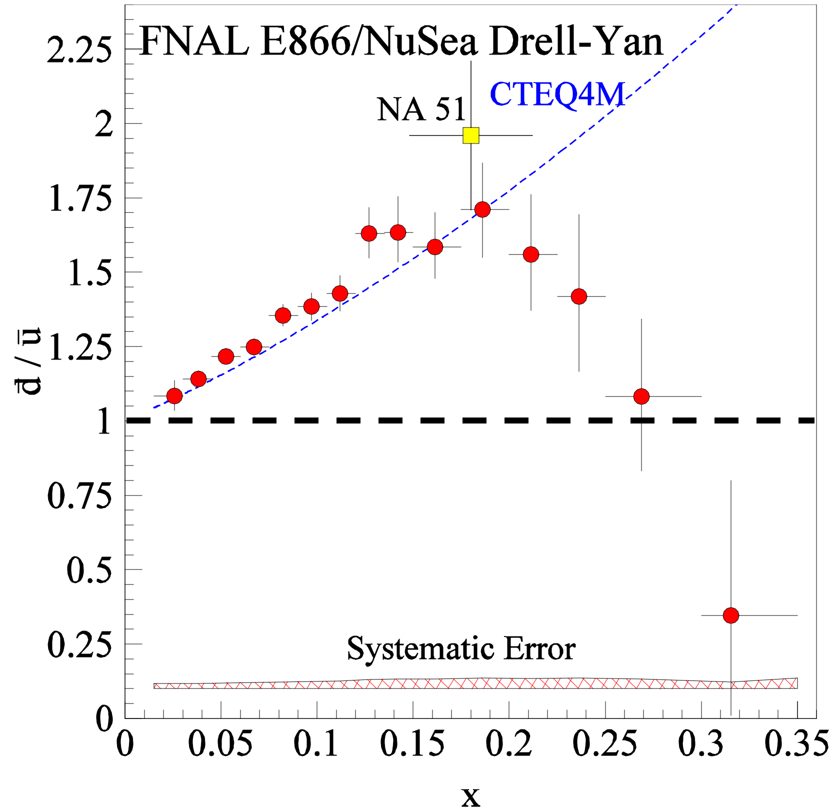
$$R^\pm_A \equiv \frac{d\sigma(p+A \to W^+ + x)}{d\sigma(p+A \to W^- + x)} \approx \frac{\bar{d}_p(x_1)}{\bar{u}_p(x_1)} \frac{u_A(x_2)}{d_A(x_2)}$$

(Chang, Cloet, Dutta, JCP)

$\bar{d}/\bar{u}$ flavor asymmetry from Drell-Yan

$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_a e_a^2\left[q_a(x_1)\bar{q}_a(x_2)+\bar{q}_a(x_1)q_a(x_2)\right]$$



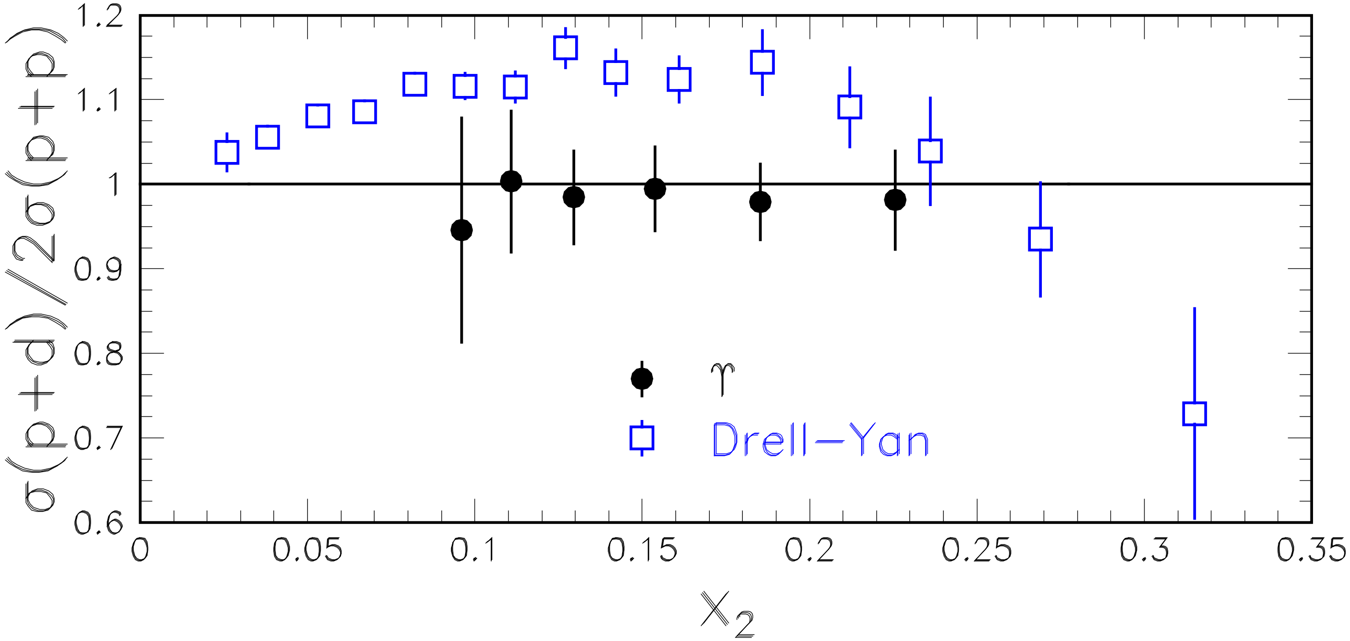


at $x_1 > x_2$: Drell-Yan: $\sigma^{pd}/2\sigma^{pp} \sim \frac{1}{2}(1+\bar{d}(x_2)/\bar{u}(x_2))$

See talks by Wen-Chen Chang and Fu-Guang Cao

Gluon distributions in proton versus neutron?

$$\text{E866 data}: \sigma(p+d \to \Upsilon X)/2\sigma(p+p \to \Upsilon X)$$



Lingyan Zhu et al., PRL, 100 (2008) 062301 (arXiv: 0710.2344)

$$Drell-Yan: \quad \sigma^{pd}/2\sigma^{pp} \sim [1+\bar{d}(x)/\bar{u}(x)]/2$$

$$J/\Psi, \Upsilon: \quad \sigma^{pd}/2\sigma^{pp} \sim [1+g_n(x)/g_p(x)]/2$$

Gluon distributions in proton and neutron are very similar

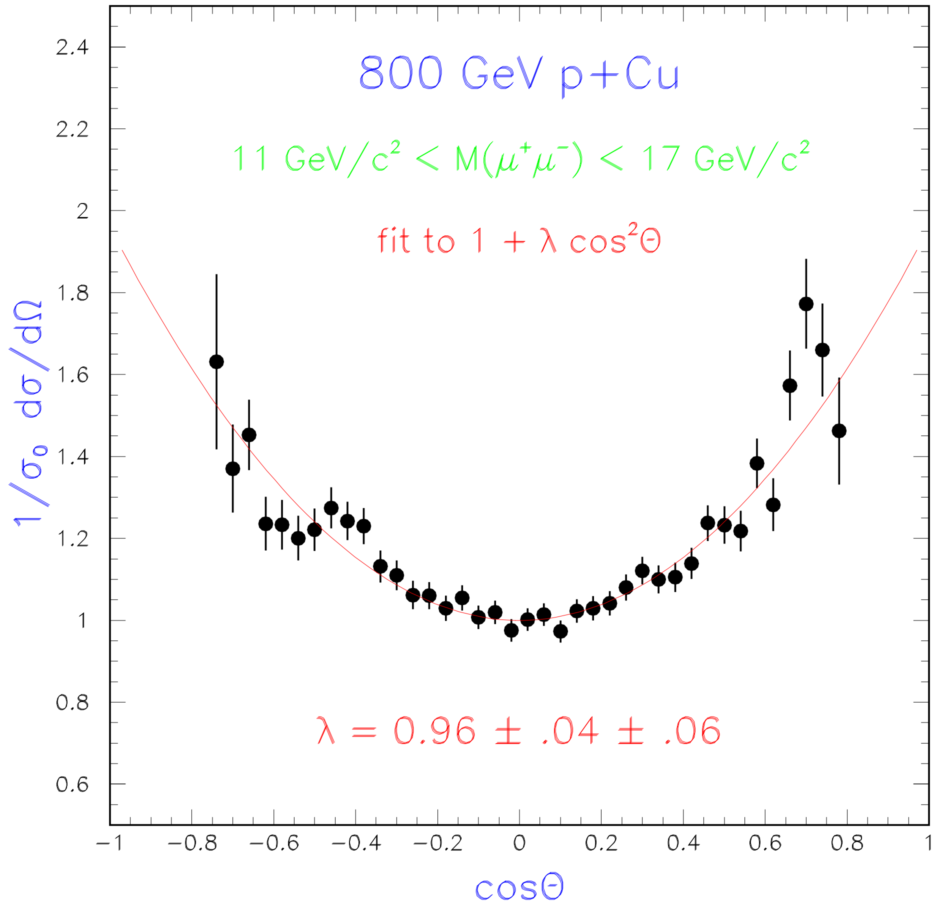
New data on $\sigma(p+d \to J/\Psi)/2\sigma(p+p \to J/\Psi)$ expected for E906

Ratios at lower energies might deviates from 1 due to q q-qbar annihilation

Drell-Yan angular distribution

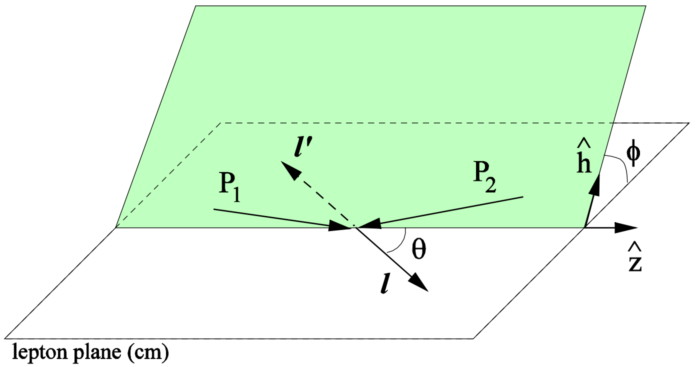
Decay Angular Distribution of "naïve" Drell-Yan:

$$\frac{d\sigma}{d\Omega} = \sigma_0 (1 + \cos^2\theta)$$



Data from Fermilab E772

Drell-Yan decay angular distributions



Θ and Φ are the decay polar and azimuthal angles of the μ^+ in the dilepton rest-frame

Collins-Soper frame

A general expression for Drell-Yan decay angular distributions:

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

λ can differ from 1, but should satisfy $1-\lambda=2\nu$ (Lam-Tung)

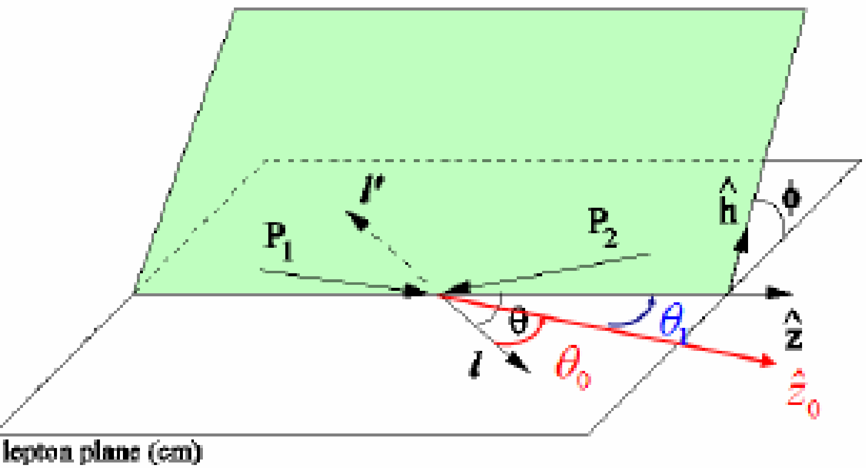
- Reflect the spin-1/2 nature of quarks

  (analog of the Callan-Gross relation in DIS)

- Insensitive to QCD - corrections

A simple geometric derivation of the generalized Lam-Tung relation (a la Oleg Teryaev)

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



In the γ^* rest frame:

$\hat{z}$ signifies the Collins-Soper frame

$\hat{z}_0$ is along the collinear $q-\overline{q}$ axis

Leptons are emitted with uniform azimuthal distribution, and with θ_0 dependence:

$$d\sigma \sim 1+\lambda_0\cos^2\theta_0$$

($\lambda_0 = 1$ for spin-1/2 quark;
$\lambda_0 = -1$ for spin-0 quark)

$$\cos\theta_0 = \cos\theta\cos\theta_1 + \sin\theta\sin\theta_1\cos\phi$$

$$\begin{aligned} d\sigma &\sim 1+\lambda_0(\cos\theta\cos\theta_1+\sin\theta\sin\theta_1\cos\phi)^2 \\ &= [1+(\lambda_0/2)\sin^2\theta_1]+\cos^2\theta[\lambda_0\cos^2\theta_1-(\lambda_0/2)\sin^2\theta_1] \\ &+\sin 2\theta\cos\phi[(\lambda_0/2)\sin 2\theta_1]+\sin^2\theta\cos 2\phi[(\lambda_0/2)\sin^2\theta_1] \end{aligned}$$

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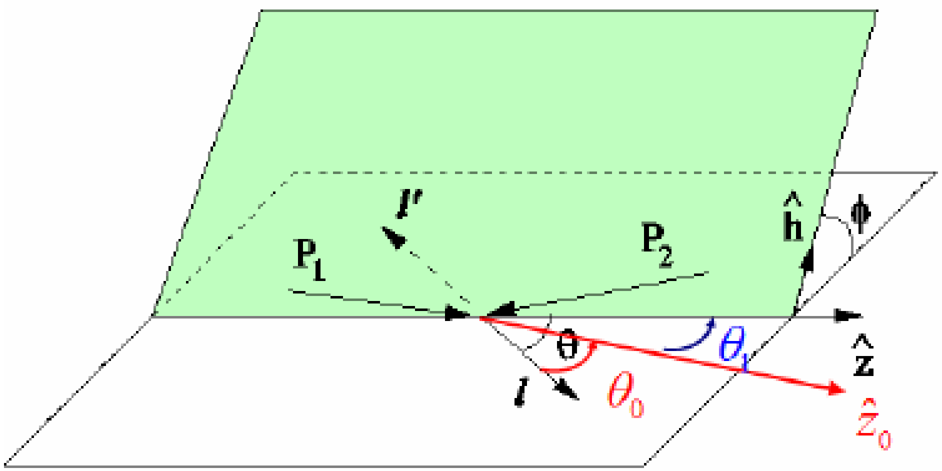
$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$



Therefore, we have

$$\lambda = \lambda_0 \frac{2-3\sin^2\theta_1}{2+\lambda_0\sin^2\theta_1}$$

$$\mu=\lambda_0 \frac{\sin 2\theta_1}{2+\lambda_0\sin^2\theta_1}$$

$$\nu=\lambda_0 \frac{2\sin^2\theta_1}{2+\lambda_0\sin^2\theta_1}$$

and

$$\lambda_0=\frac{\lambda+\frac{3}{2}\nu}{1-\frac{1}{2}\nu}$$ (Generalized Lam-Tung relation)

If $\lambda_0 = 1$, we have $2\nu=1-\lambda$ (Lam-Tung relation)

If $\lambda_0 = -1$ (spin-0 quark), we have $-\nu = 1+\lambda$

$$d\sigma \sim 1+\lambda_0(\cos\theta\cos\theta_1+\sin\theta\sin\theta_1\cos\phi)^2$$
$$=[1+(\lambda_0/2)\sin^2\theta_1]+\cos^2\theta[\lambda_0\cos^2\theta_1-(\lambda_0/2)\sin^2\theta_1]$$
$$+\sin 2\theta\cos\phi[(\lambda_0/2)\sin 2\theta_1]+\sin^2\theta\cos 2\phi[(\lambda_0/2)\sin^2\theta_1]$$

Decay angular distributions in pion-induced Drell-Yan

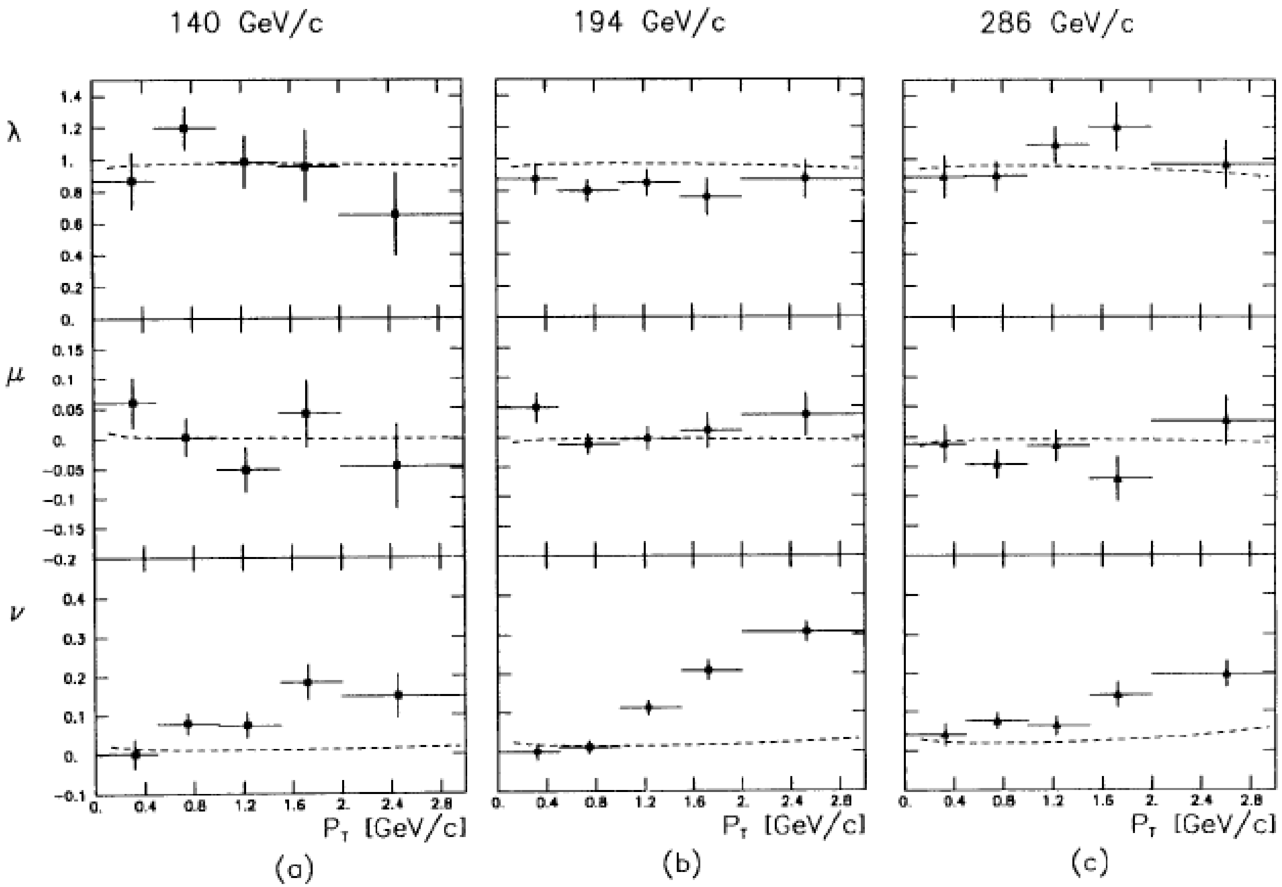


Fig. 3a–c. Parameters λ, μ, and ν as a function of P_T in the CS frame. **a** 140 GeV/c; **b** 194 GeV/c; **c** 286 GeV/c. The error bars correspond to the statistical uncertainties only. The horizontal bars give the size of each interval. The dashed curves are the predictions of perturbative QCD [3]

NA10 $\pi^- + W$

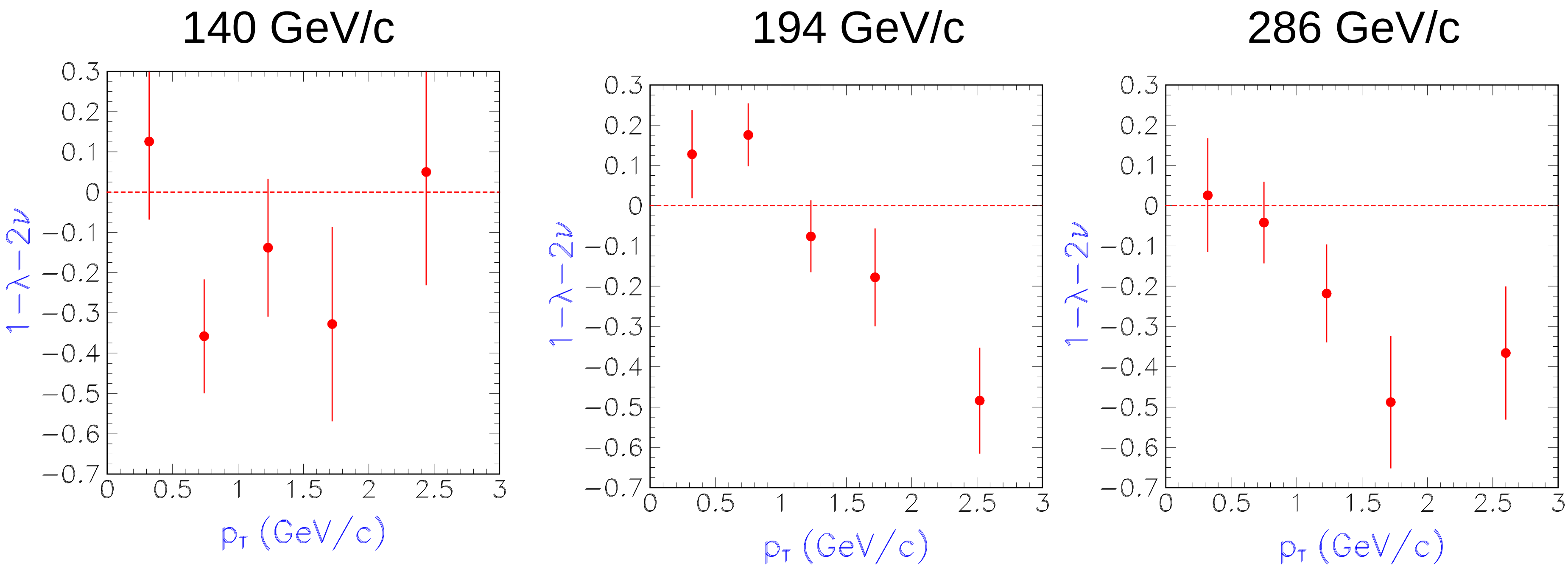
Z. Phys. 37 (1988) 545

Dashed curves are from pQCD calculations

$\nu \neq 0$ and ν increases with p_T

Decay angular distributions in pion-induced Drell-Yan

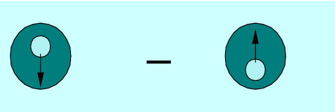
Is the Lam-Tung relation violated?



Data from NA10 (Z. Phys. 37 (1988) 545)

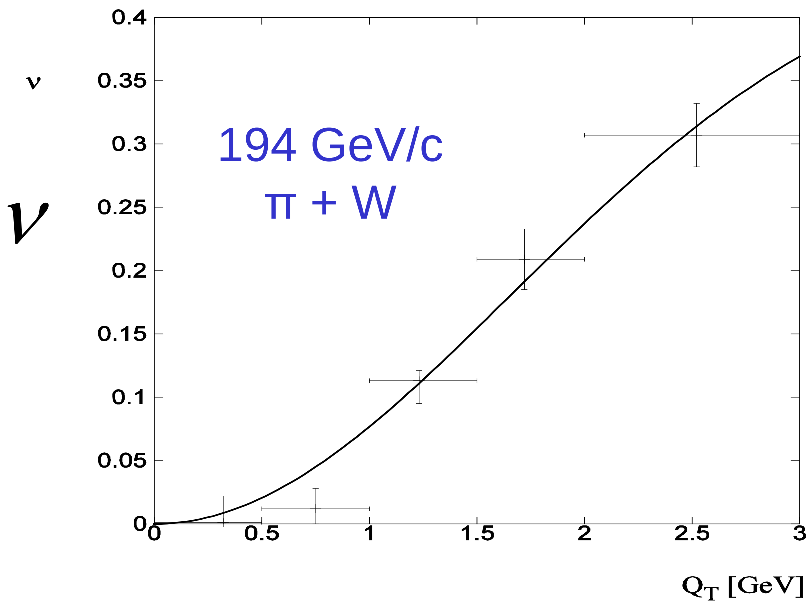
Violation of the Lam-Tung relation suggests new mechanisms with non-perturbative origin

Boer-Mulders function $h_1^{\perp}$



- $h_1^{\perp}$ represents a correlation between quark's k_T and transverse spin in an unpolarized hadron
- $h_1^{\perp}$ is a time-reversal odd, chiral-odd TMD parton distribution
- $h_1^{\perp}$ can lead to an azimuthal cos(2ϕ) dependence in Drell-Yan

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

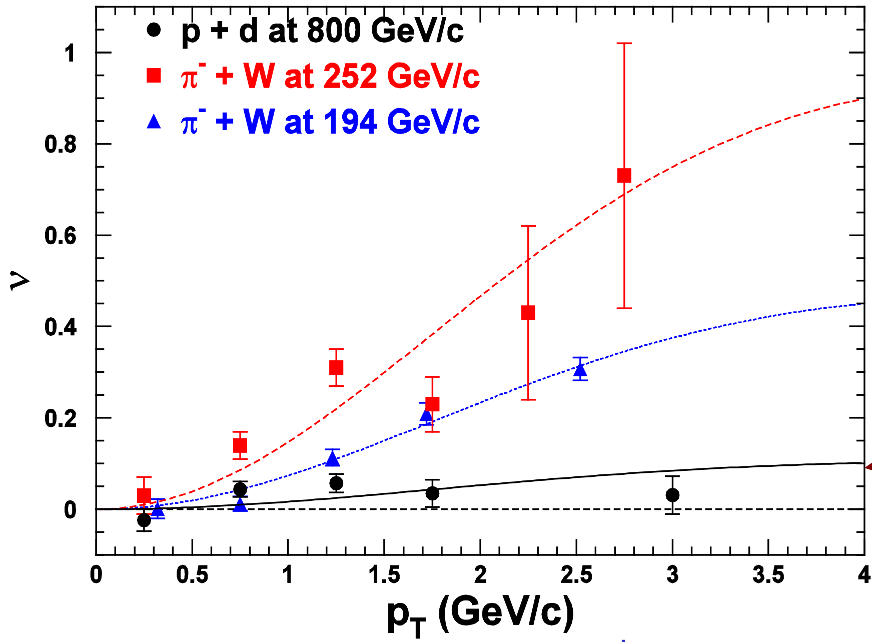


Boer, PRD 60 (1999) 014012

- Observation of large cos(2Φ) dependence in Drell-Yan with pion beam
- $\nu \propto h_1^{\perp}(x_q)h_1^{\perp}(x_{\bar{q}})$
- How about Drell-Yan with proton beam?

Azimuthal cos2Φ Distribution in p+p and p+d Drell-Yan

E866 Collab., Lingyan Zhu et al.,
PRL 99 (2007) 082301; PRL 102 (2009) 182001



Small ν is observed for p+d and p+p D-Y

With Boer-Mulders function $h_1^\perp$:

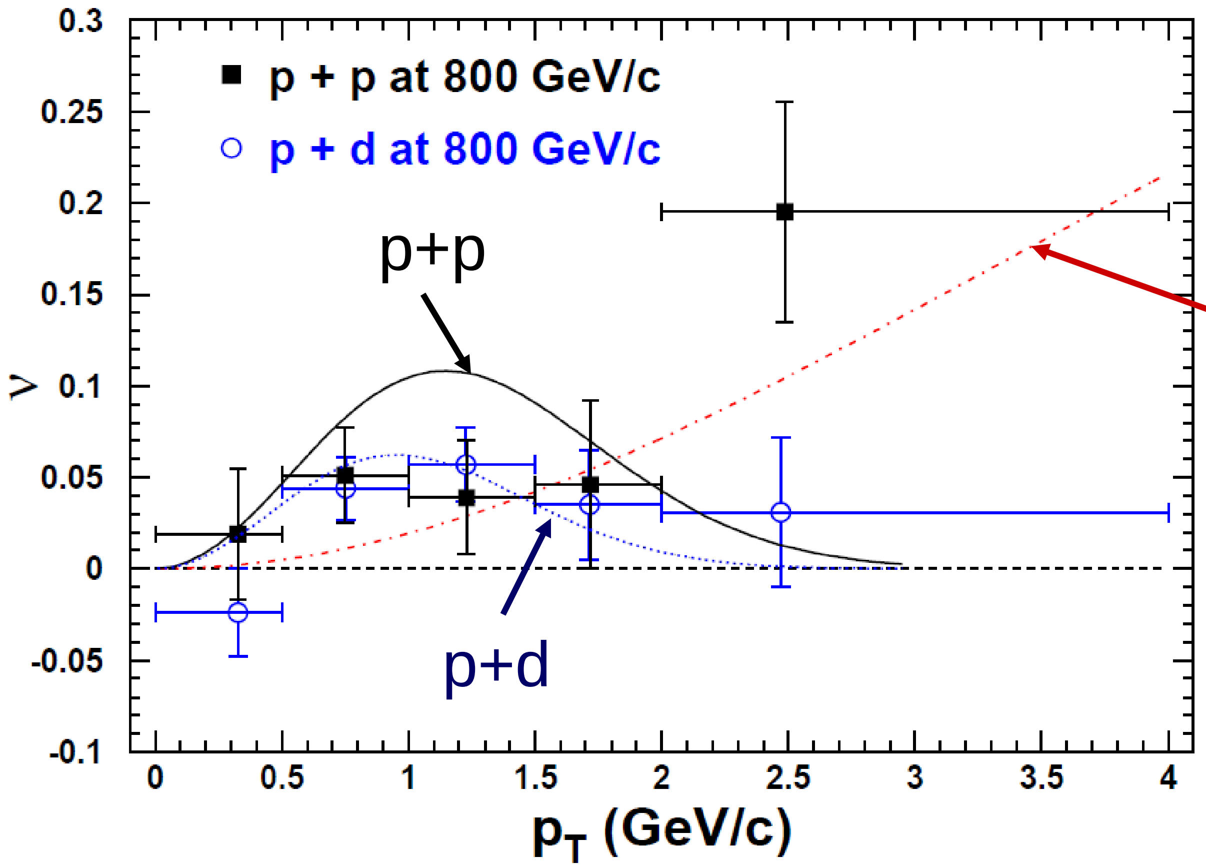
$\nu(\pi^- W \to \mu^+\mu^- X) \sim$ [valence $h_1^\perp(\pi)$] * [valence $h_1^\perp(p)$]

$\nu(pd \to \mu^+\mu^- X) \sim$ [valence $h_1^\perp(p)$] * [sea $h_1^\perp(p)$]

Sea-quark BM functions are much smaller than valence quarks

Results on cos2Φ Distribution in p+p Drell-Yan

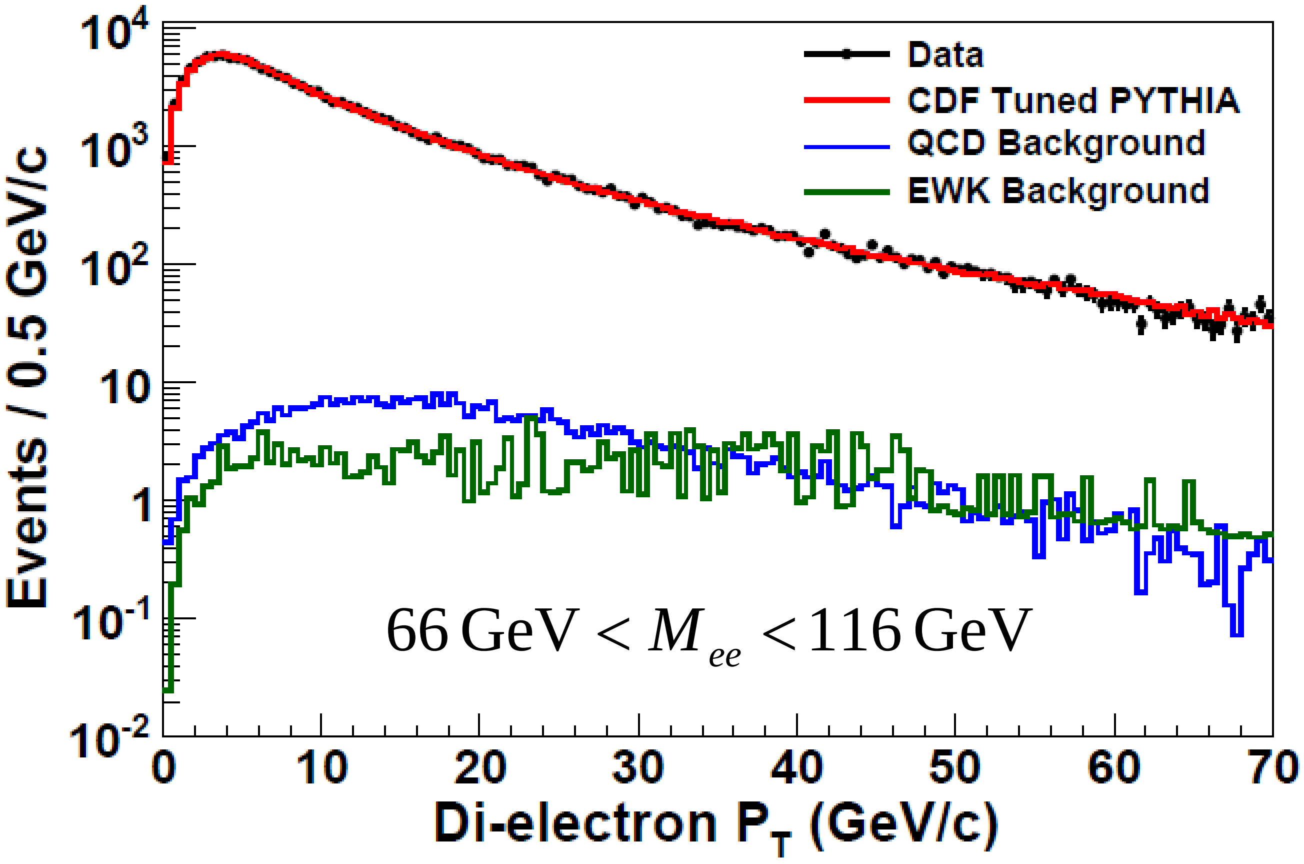
L. Zhu, J.C. Peng, et al., PRL 102 (2009) 182001



More data are anticipated from Fermilab E906 and COMPASS

Recent result from CDF on Lam-Tung relation

$$p + \bar{p} \rightarrow e^{+} + e^{-} + X \quad \text{at } \sqrt{s} = 1.96\,\text{TeV}$$



arXiv:1103.5699

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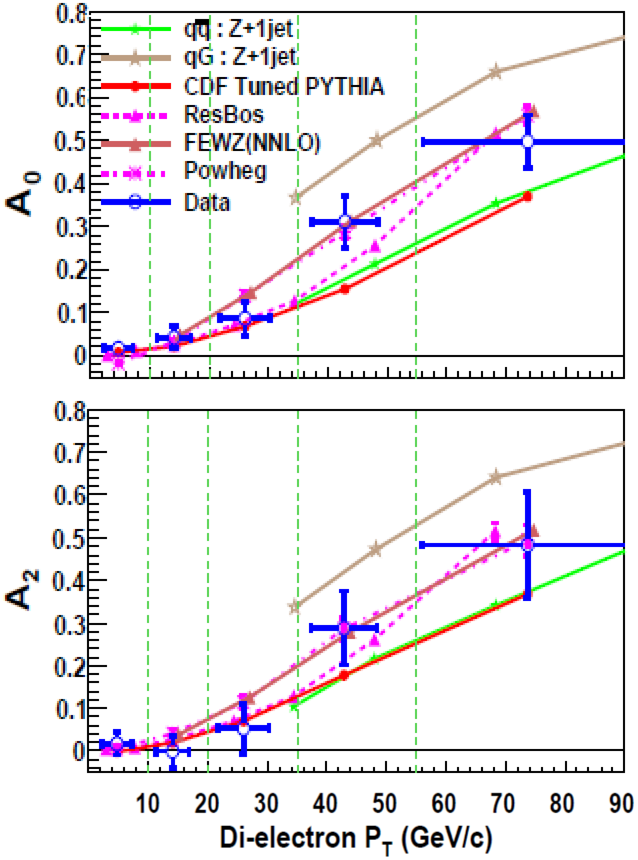


$$\frac{d\sigma}{d\cos\theta} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_4\cos\theta$$

$$\frac{d\sigma}{d\phi} \propto 1 + \beta_3\cos\phi + \beta_2\cos 2\phi + \beta_7\sin\phi + \beta_5\sin 2\phi$$

$$\beta_3 = 3\pi A_3/16,\ \beta_2 = A_2/4,\ \beta_7 = 3\pi A_7/16$$

$$\text{Lam - Tung relation} \Rightarrow A_0 = A_2$$

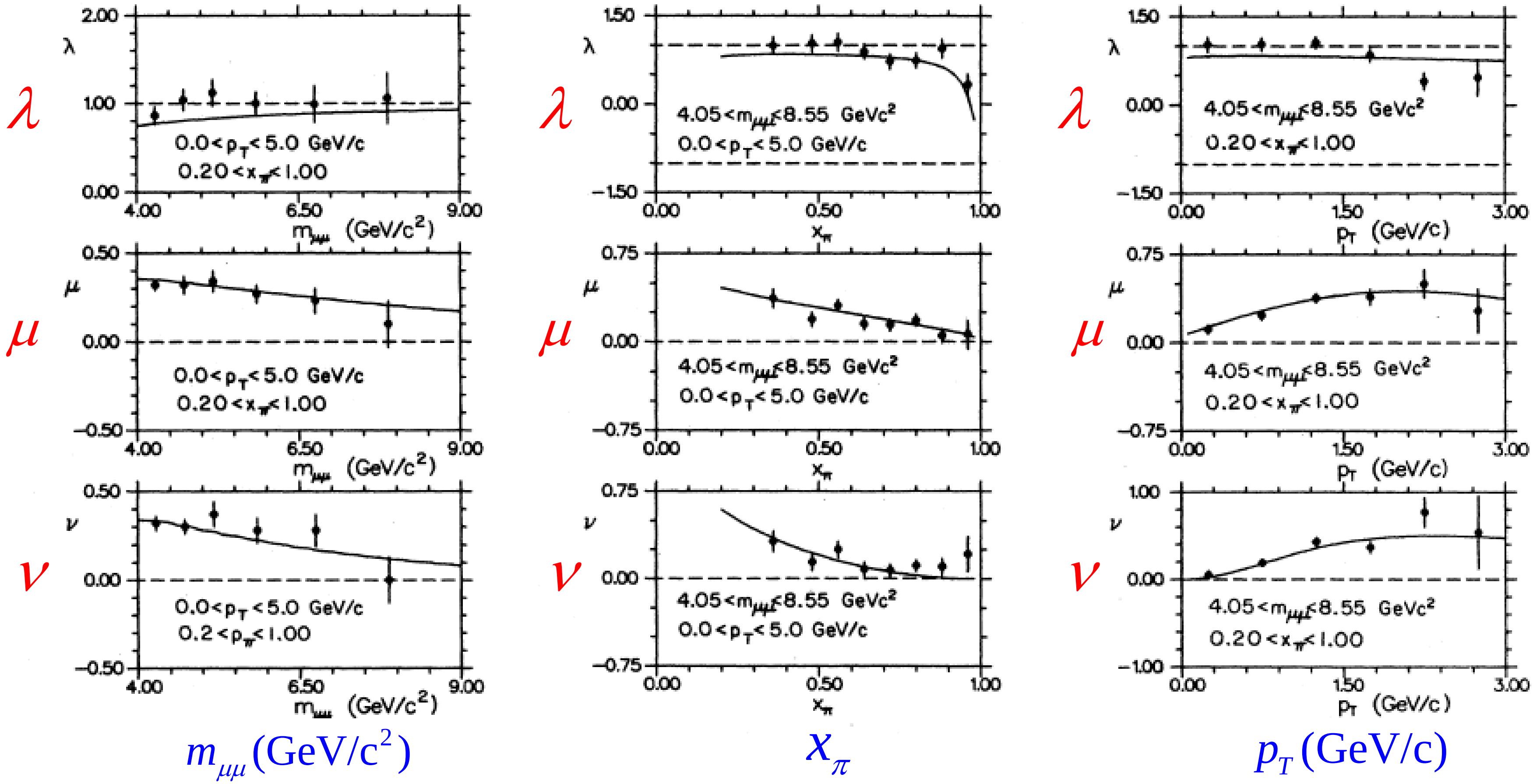
P_T bin	A_0 $(\times 10^{-1})$	A_2 $(\times 10^{-1})$
0–10	$0.17 \pm 0.14 \pm 0.07$	$0.16 \pm 0.26 \pm 0.06$
10–20	$0.42 \pm 0.25 \pm 0.07$	$-0.01 \pm 0.35 \pm 0.16$
20–35	$0.86 \pm 0.39 \pm 0.08$	$0.52 \pm 0.51 \pm 0.29$
35–55	$3.11 \pm 0.59 \pm 0.10$	$2.88 \pm 0.84 \pm 0.19$
> 55	$4.97 \pm 0.61 \pm 0.10$	$4.83 \pm 1.24 \pm 0.02$

arXiv:1103.5699

$\langle A_0 - A_2 \rangle = 0.02 \pm 0.02$

Decay angular distributions in pion-induced Drell-Yan

E615 Data 252 GeV $\pi^- + W$ Phys. Rev. D 39 (1989) 92

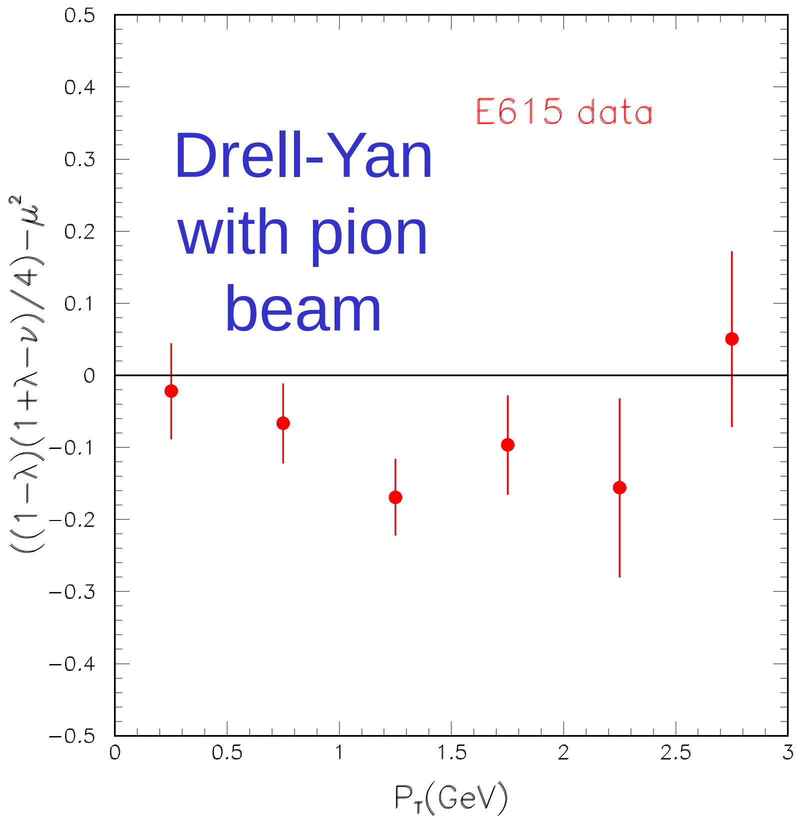


$$\lambda \neq 1,\ \mu \neq 0,\ \nu \neq 0 \ \text{ and they vary with } m_{\mu\mu},\ p_T, \text{ and } x_\pi$$

$\mu^2 \leq (1-\lambda)(1+\lambda-\nu)/4$ predicted by O. Teryaev based on positivity

Is the $\mu^2 \le (1-\lambda)(1+\lambda-\nu)/4$ inequality valid?

$$(1-\lambda)(1+\lambda-\nu)/4-\mu^2 \ge 0\,?$$



The inequality appears to be violated!

(Teryaev and JCP)

Our knowledge of D-Y azimuthal angular dependence is still incomplete (New data from COMPASS are essential)

Transversity and Transverse Momentum Dependent PDFs are also probed in Drell-Yan

a) Boer-Mulders functions:

- Unpolarized Drell-Yan: $d\sigma_{DY} \propto h_1^{\perp}(x_q) h_1^{\perp}(x_{\bar{q}}) \cos(2\phi)$

b) Sivers functions:

- Single transverse spin asymmetry in polarized Drell-Yan:

$$A_N^{DY} \propto f_{1T}^{\perp}(x_q) f_{\bar{q}}(x_{\bar{q}})$$

c) Transversity distributions:

- Double transverse spin asymmetry in polarized Drell-Yan:

$$A_{TT}^{DY} \propto h_1(x_q) h_1(x_{\bar{q}})$$

- Drell-Yan does not require knowledge of the fragmentation functions
- T-odd TMDs are predicted to change sign from DIS to DY (Boer-Mulders and Sivers functions)

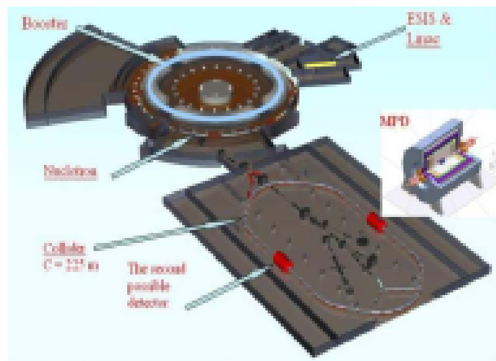
Remains to be tested experimentally!

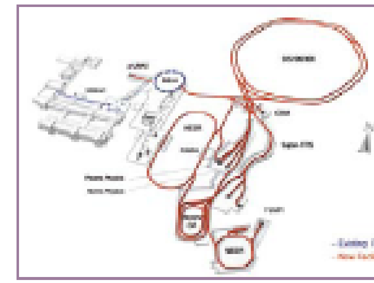
Outstanding questions to be addressed by future Drell-Yan experiments

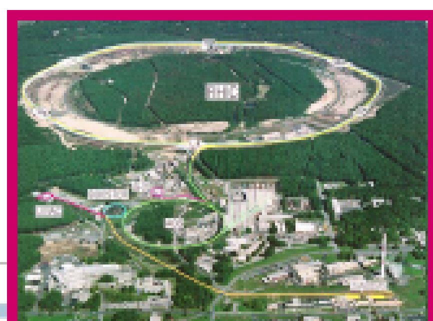
- Does Sivers function change sign between DIS and Drell-Yan?
- Does Boer-Mulders function change sign between DIS and Drell-Yan?
- Are all Boer-Mulders functions alike (proton versus pion Boer-Mulders functions)
- Flavor dependence of TMD functions
- Independent measurement of transversity with Drell-Yan

Conclusion: We'll get the data! Future experiments

- Fermilab E-906/Drell-Yan
  - Better statistical precision (unpolarized)
- COMPASS
  - Pion beam—valence distributions
- GSI FAIR—PAX experiment
  - Antiproton beam will sample valence distributions of targets
- JINR Dubna-NICA
- J-PARC
- RHIC







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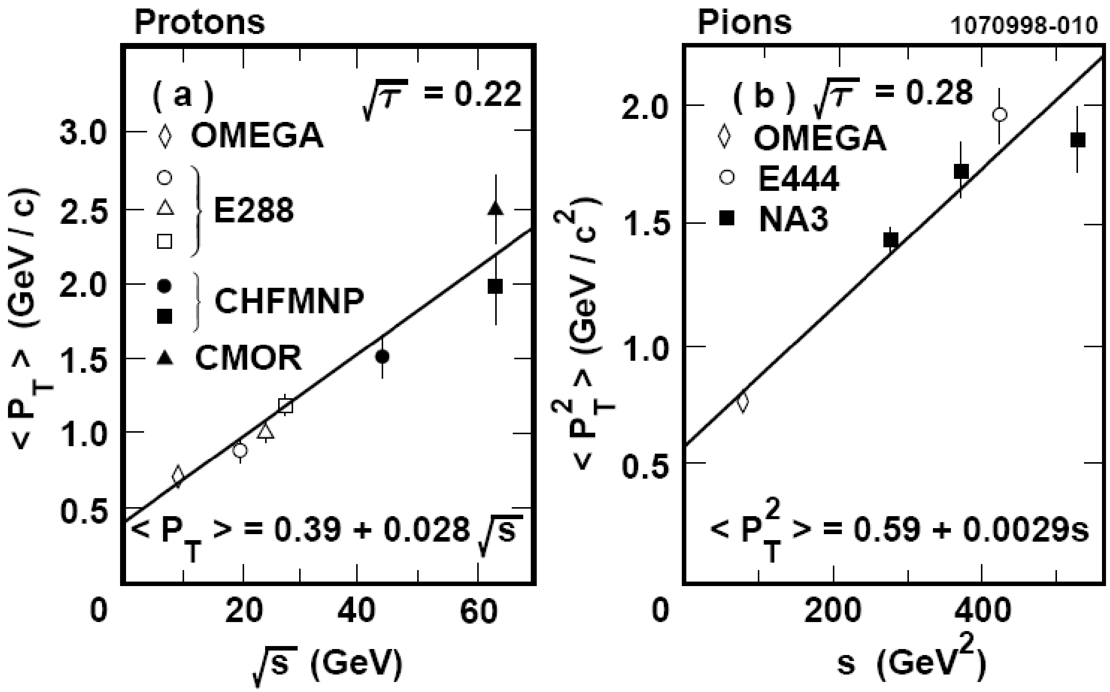
Slide from Paul Reimer

What do we know about the quark and gluon transverse momentum distributions?

- Does the quark k_T distribution depend on *x*?
- Do valence quarks and sea quarks have different k_T distributions?
- Do *u* and *d* quarks have the same k_T distribution?
- Do nucleons and mesons have different quark k_T distribution?
- Do gluons have k_T distribution different from quarks?

- Important for extracting the TMD parton distributions
- Interesting physics in its own right

What do Drell-Yan data tell us about the quark transverse momentum distribution?



- $<P_T^2>$ increases linearly with s (expected from QCD)
- Proton-induced D-Y has smaller mean P_T than pion (expected from the uncertainty principle, reflecting the larger size of the proton)

Comparison of the mean P_T of proton, pion, and kaon induced Drell-Yan

Drell-Yan with proton beam:

$$\langle P_T \rangle = (0.43 \pm 0.03) + \sqrt{s}(0.026 \pm 0.001) \text{ GeV/c}$$

Drell-Yan with pion beam:

$$\langle P_T \rangle = (0.59 \pm 0.05) + \sqrt{s}(0.028 \pm 0.003) \text{ GeV/c}$$

NA3 data also show that $\langle P_T \rangle$ for D-Y with kaon beam is larger than Drell-Yan with pion beam:

$$\langle P_T^2 \rangle = 1.51 \pm 0.08 \,(\text{GeV/c})^2 \text{ for kaon beam}$$

$$\langle P_T^2 \rangle = 1.44 \pm 0.02 \,(\text{GeV/c})^2 \text{ for pion beam}$$

with 150 GeV/c beams

New Drell-Yan data with meson and antiproton beams are essential

The data suggest:

$$\langle k_T \rangle_{kaon} > \langle k_T \rangle_{pion} > \langle k_T \rangle_{proton}$$

We know

$$\langle r \rangle^{1/2}{}_{kaon} < \langle r \rangle^{1/2}{}_{pion} < \langle r \rangle^{1/2}{}_{proton}$$

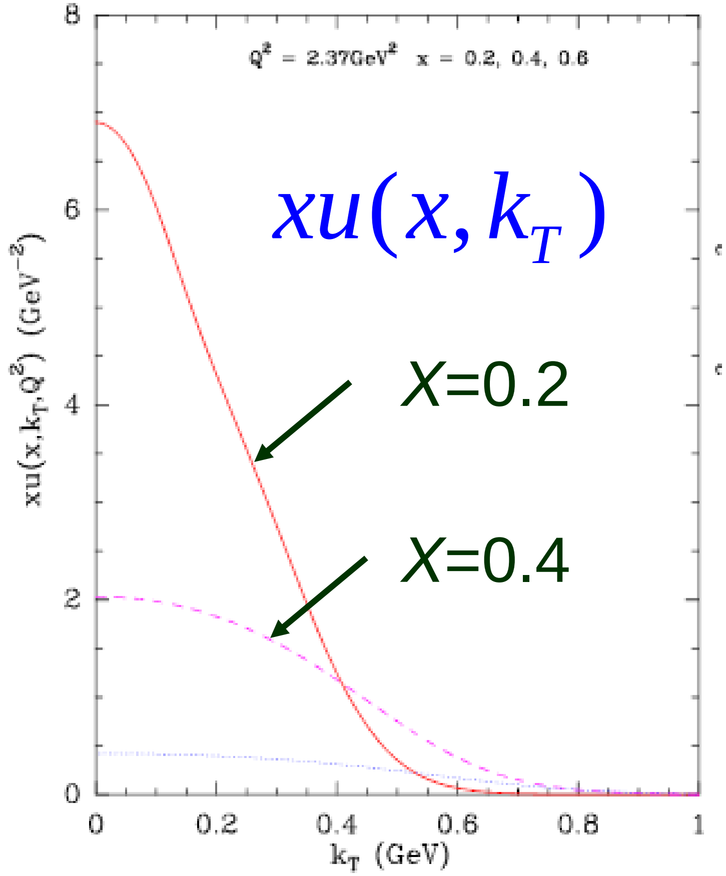
$$\langle r \rangle^{1/2} = 0.58 \pm 0.02 \text{fm for kaon}$$

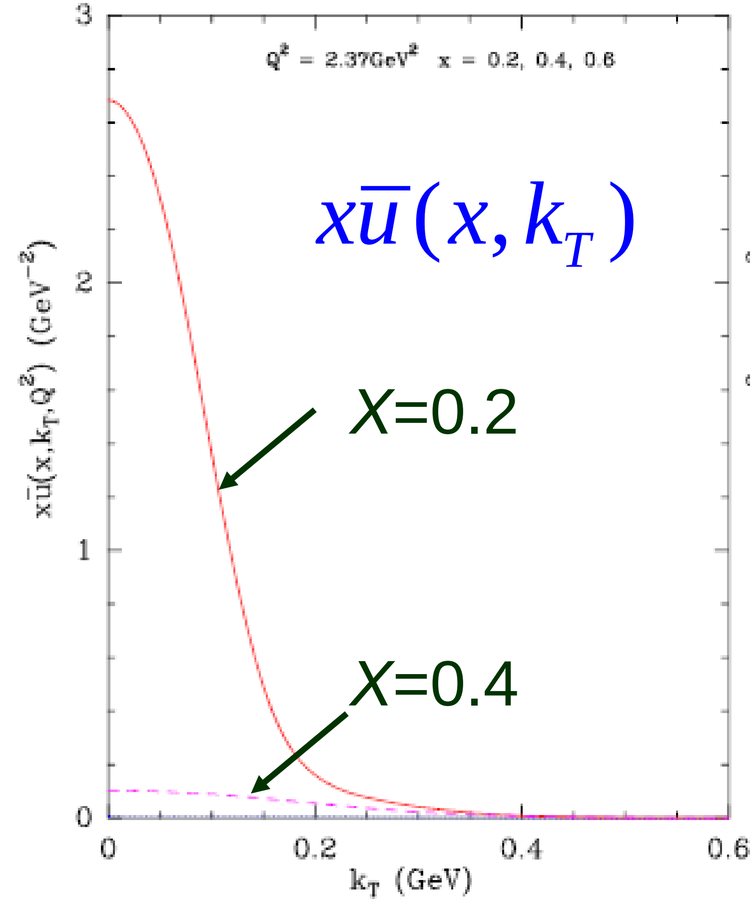
$$\langle r \rangle^{1/2} = 0.67 \pm 0.02 \text{fm for pion}$$

$$\langle r \rangle^{1/2} = 0.81 \text{fm for proton}$$

Flavor and x-dependent k_T-distributions?

(Bourrely, Buccella, Soffer, arXiv:1008.5322)

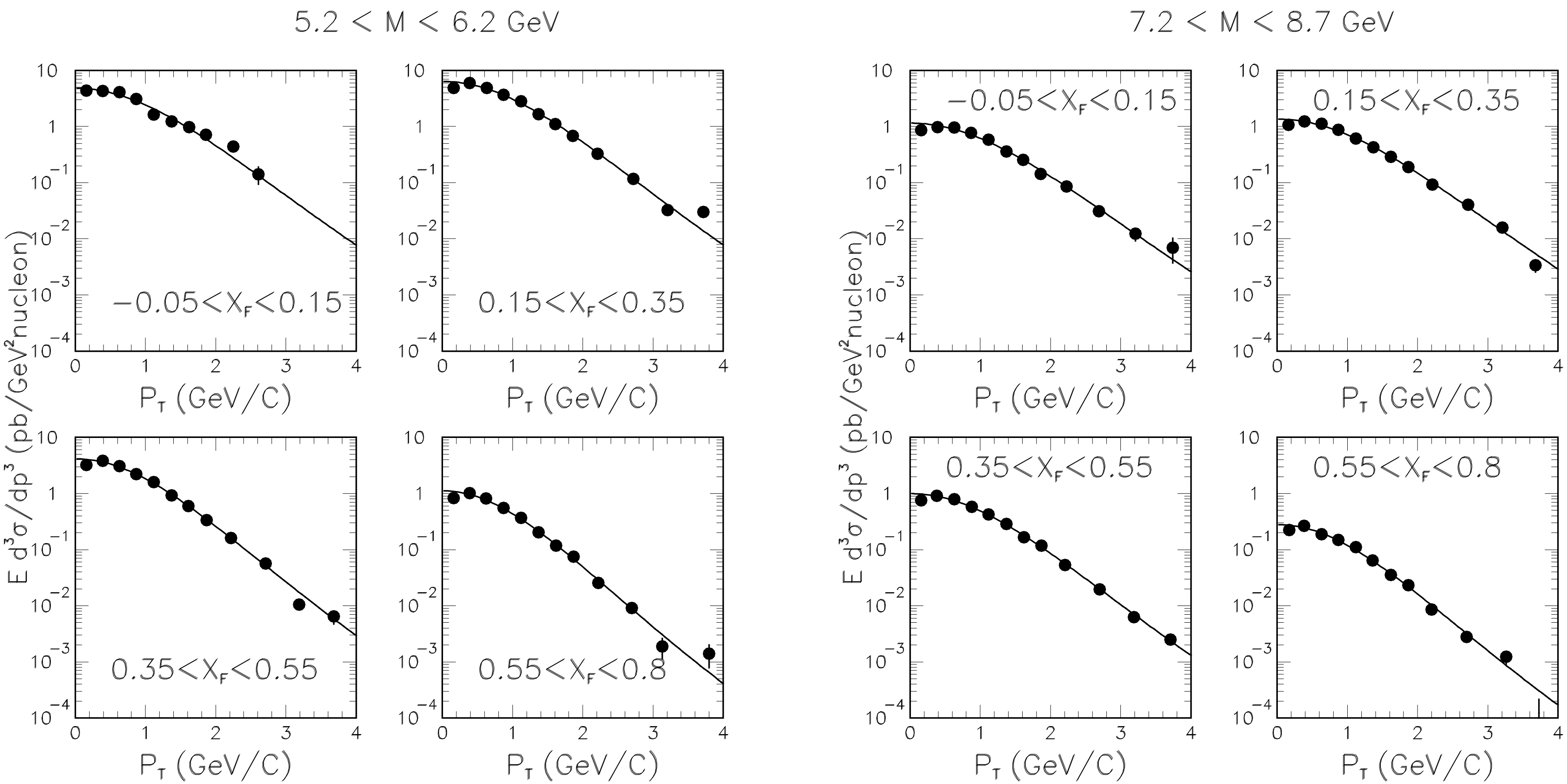




- $\langle k_T \rangle$ increases when x increases
- $\langle k_T \rangle$ for sea quarks is smaller than for valence quarks

Test of possible *x*-dependent k_T-distributions

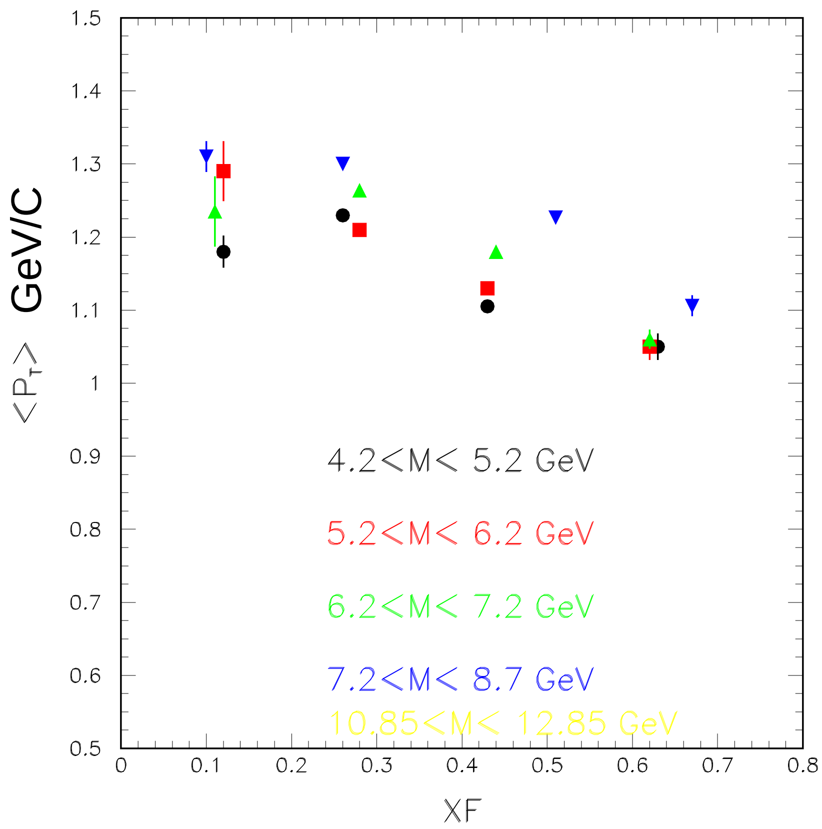
E866 p+d D-Y data (800 GeV beam)

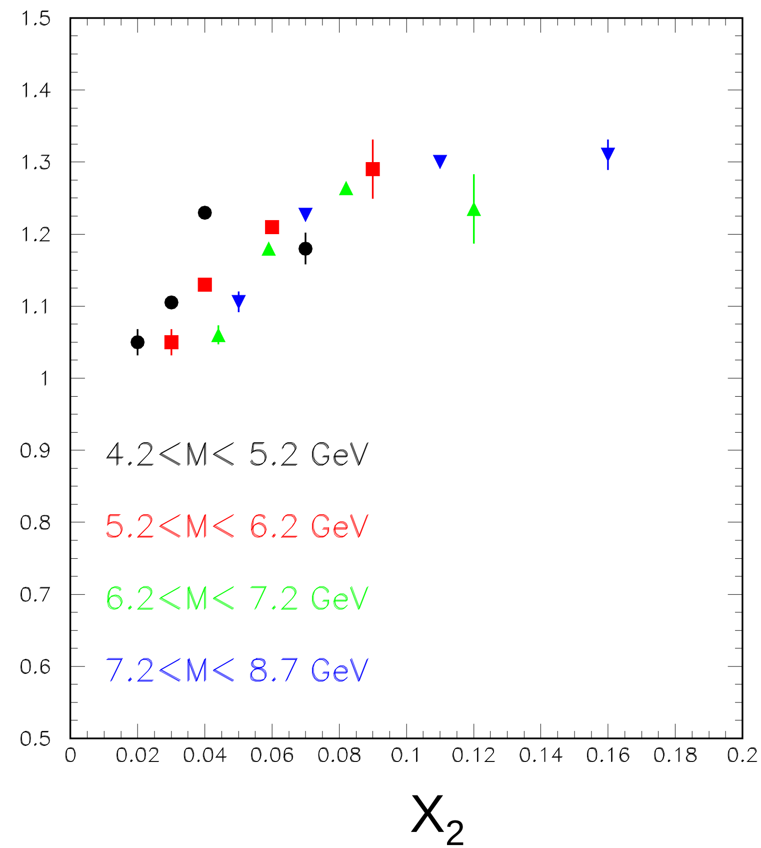


Data from thesis of J. Webb

Possible *x*-dependent k_T-distributions

E866 p+d D-Y data (800 GeV beam)





$<p_T>$ scale with x_2 ?

Analysis is ongoing. Will also check the flavor dependence of k_T-distribution (p+p vs. p+d)

Summary

- The Drell-Yan process is a powerful experimental tool complimentary to the DIS for exploring quark structures in nucleons and nuclei.

- Unique information on flavor structures of sea-quark has been obtained with Drell-Yan experiments. First results on TMD have also been extracted.

- On-going and future Drell-Yan experiments at COMPASS can address many important unresolved issues in the spin and flavor structures of nucleons and nuclei.