Overview of Drell-Yan experiments

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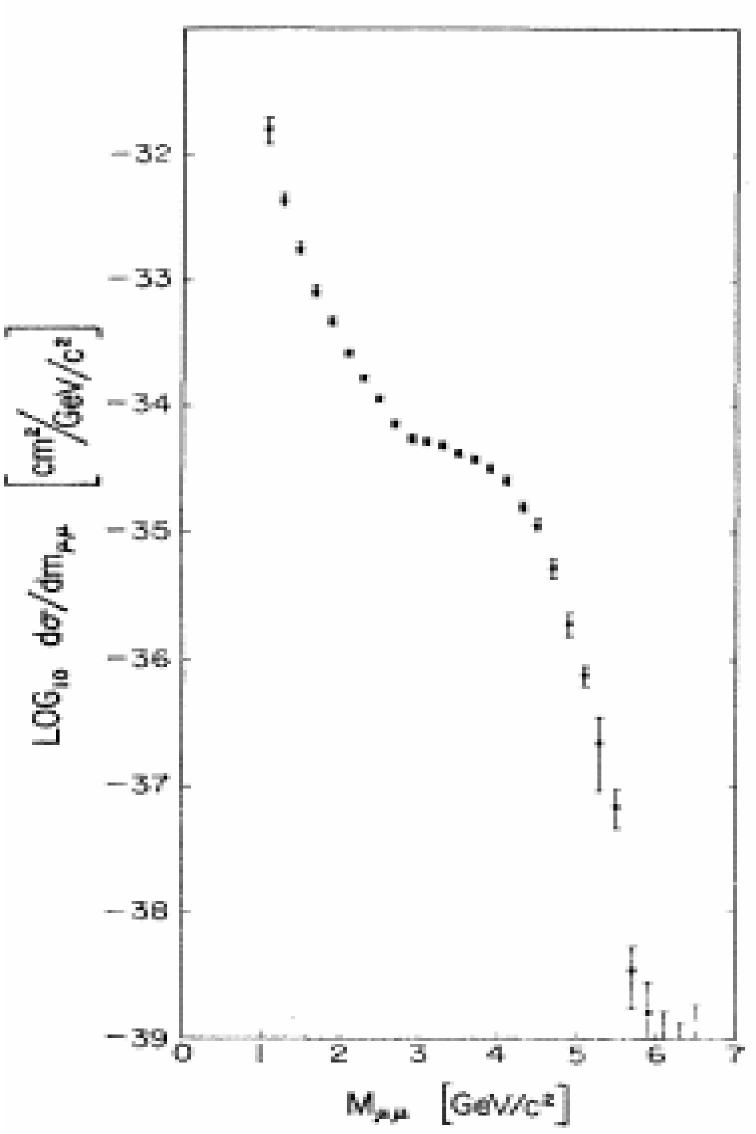
Polarized Drell-Yan Workshop
Santa Fe, Oct. 31 – Nov. 1, 2010

Outline

- What have we learned from Drell-Yen experiments?
- What are the remaining puzzles from existing data?
- What are the crucial future experiments?

First Dimuon Experiment

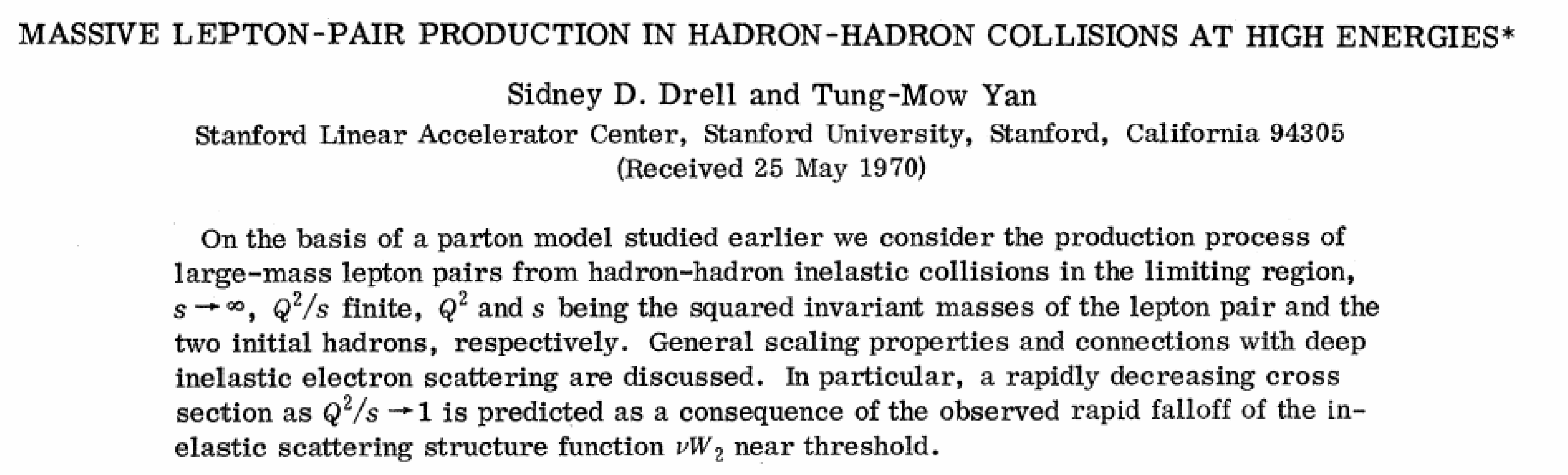


$p + U \rightarrow \mu^+ + \mu^- + X$ 29 GeV proton

Lederman et al. PRL 25 (1970) 1523

- Experiment originally designed to search for neutral weak boson (Z^0)
- Missed the J/Ψ signal !

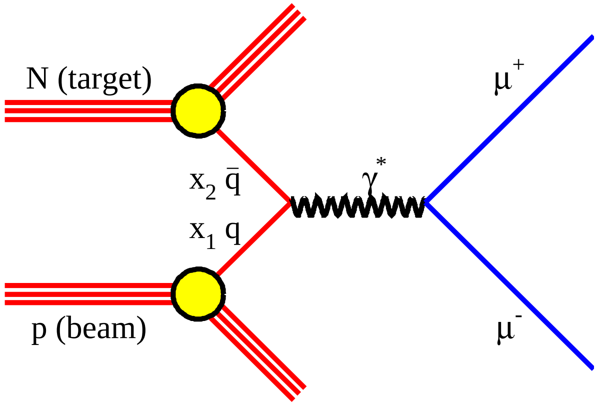
The Drell-Yan Process



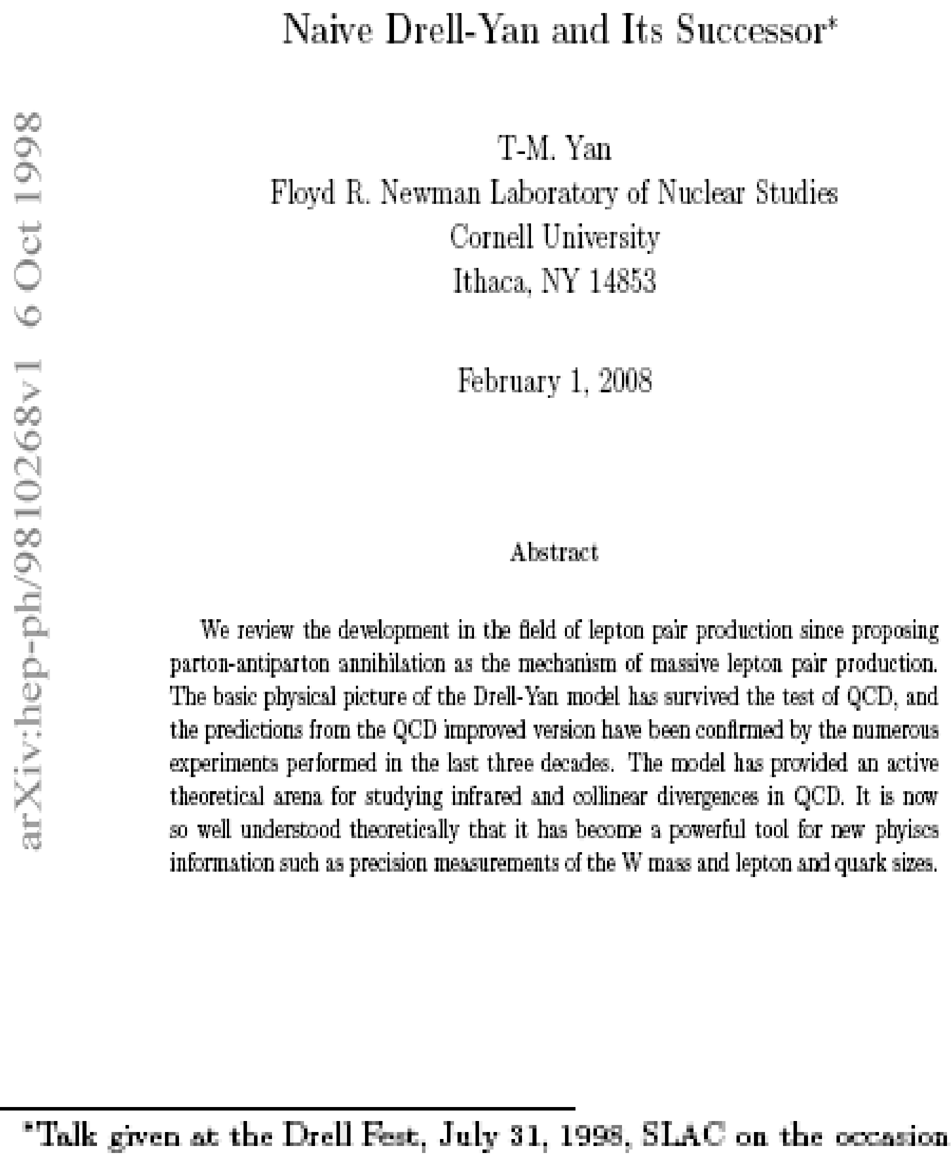
MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

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.



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



Naive Drell-Yan and Its Successor*

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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.

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

- "… 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."

Success and difficulties of the “naïve” Drell-Yan

Success:

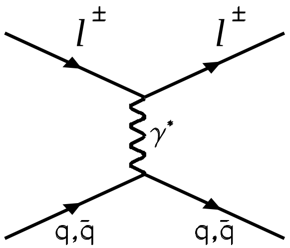
- Scaling of the cross sections (depends on x1 and x2 only)
- Nuclear dependence (cross section depends linearly on the mass A)
- Angular distributions ($1+\cos^2\Theta$ distributions)

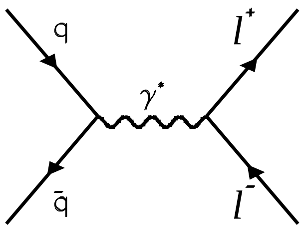
Difficulties:

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

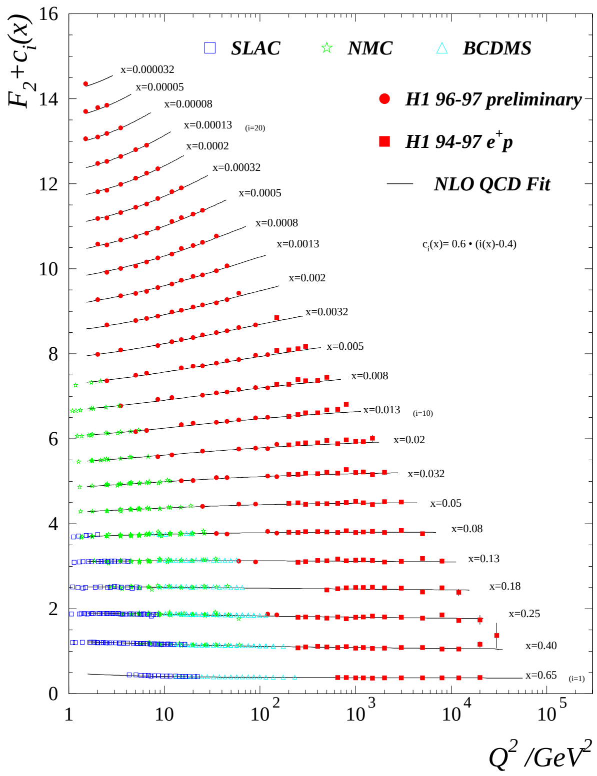
Complimentality between DIS and Drell-Yan

DIS

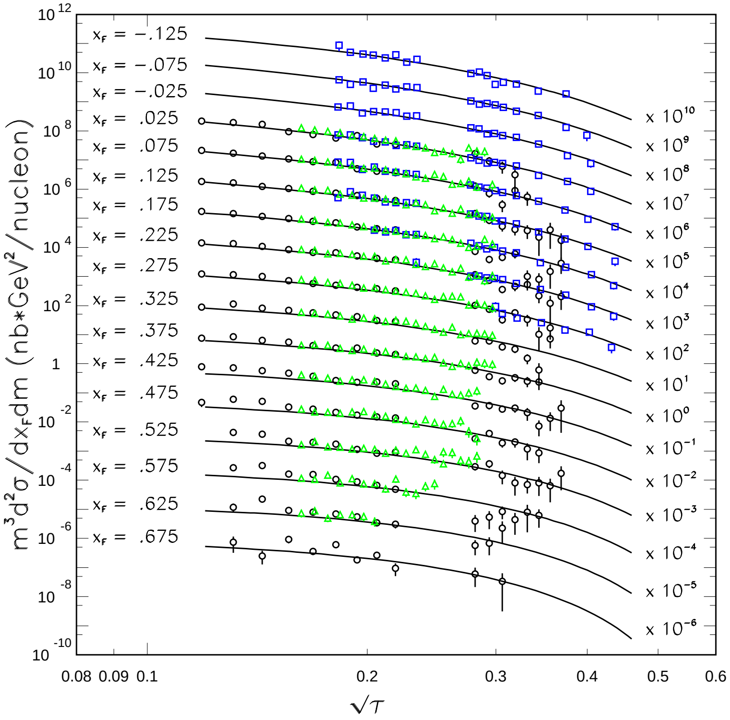




Drell-Yan



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



McGaughey, Moss, JCP,

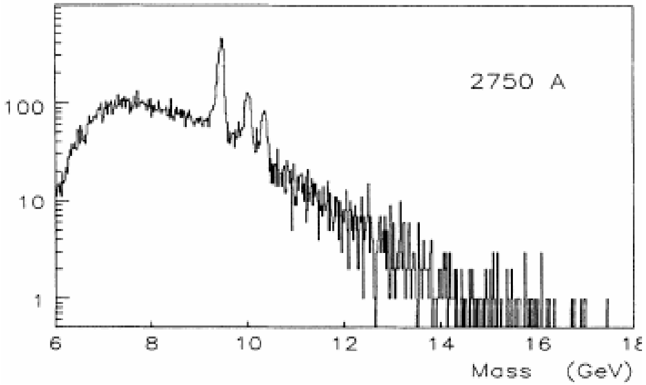
Ann.Rev.Nucl. Part. Sci. 49 (1999) 217

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

Lepton-pair production provides unique information on parton distributions

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

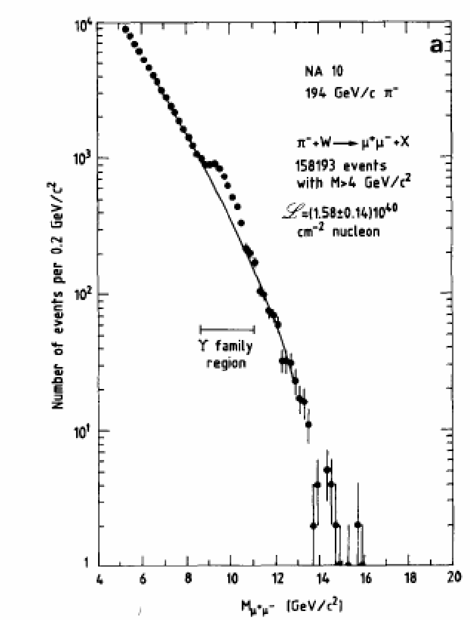
800 GeV/c



Probe antiquark distribution in nucleon

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

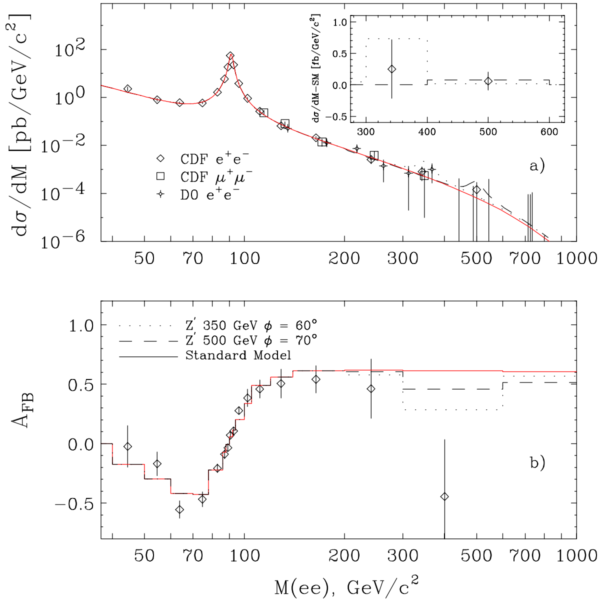
194 GeV/c



Probe antiquark distribution in pion

$\bar{p} + p \rightarrow l^+ l^- X$

1.8 TeV

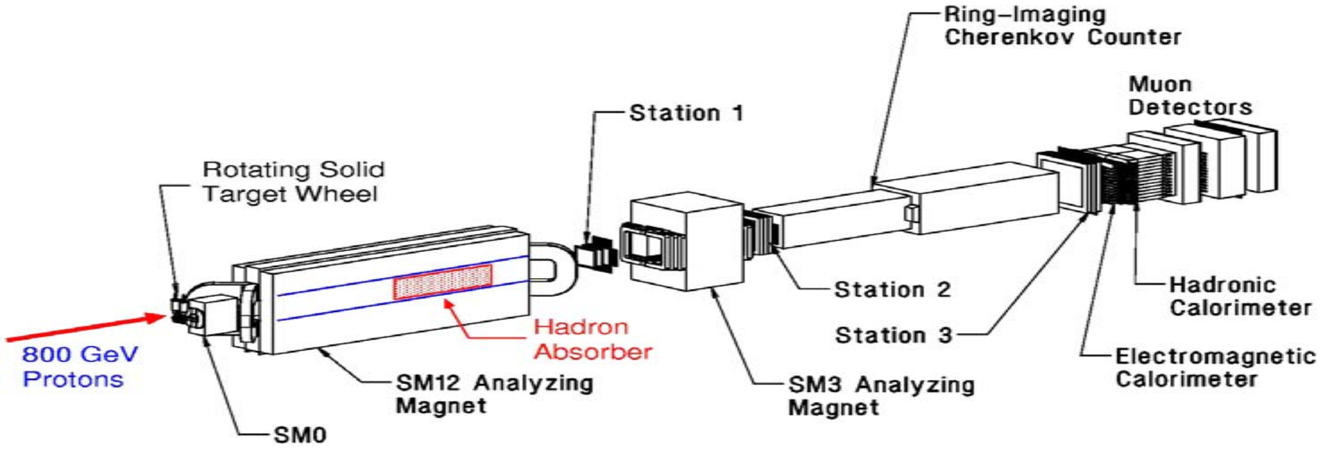


Probe antiquark distributions in antiproton

Unique features of D-Y: antiquarks, unstable hadrons…

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"

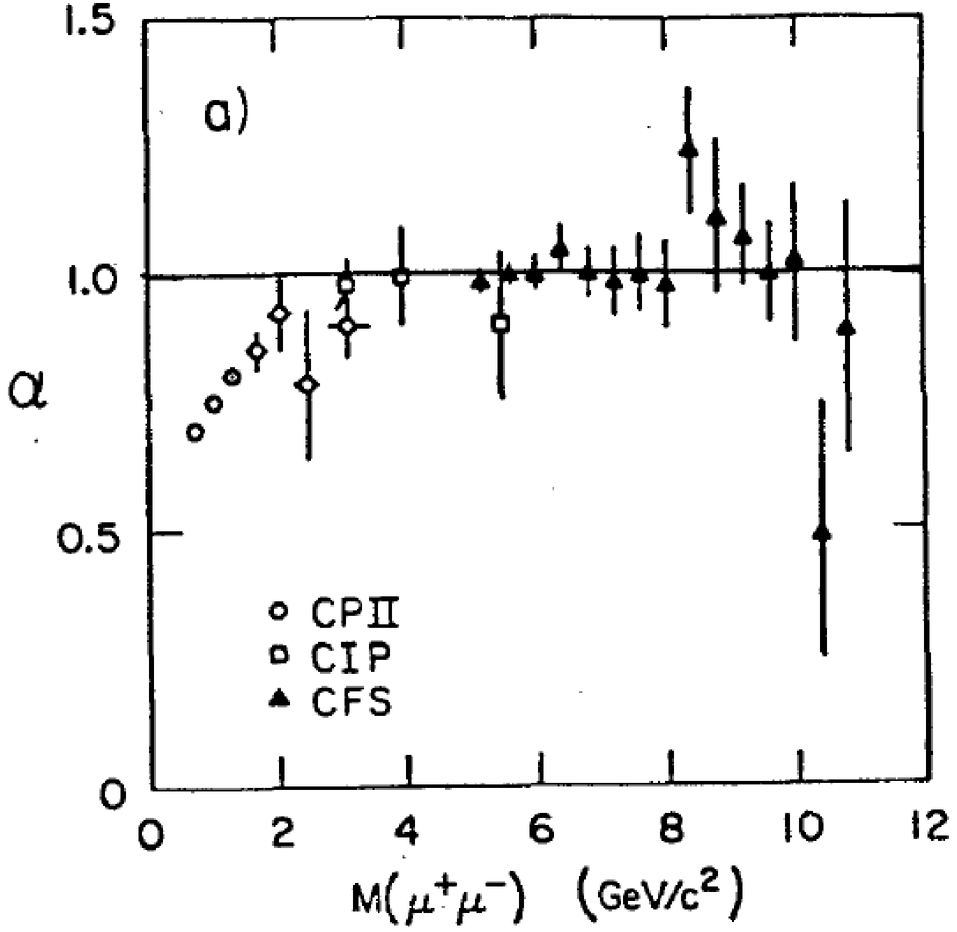
4) Fermilab E906 (proposed in 1999, will run in 2010-2013)

   "Drell-Yan with the FNAL Main Injector"

Great efforts and contributions by C. Brown, J. Moss, P. McGaughey, M. Leitch, G. Garvey, D. Kaplan and collaborators

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



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

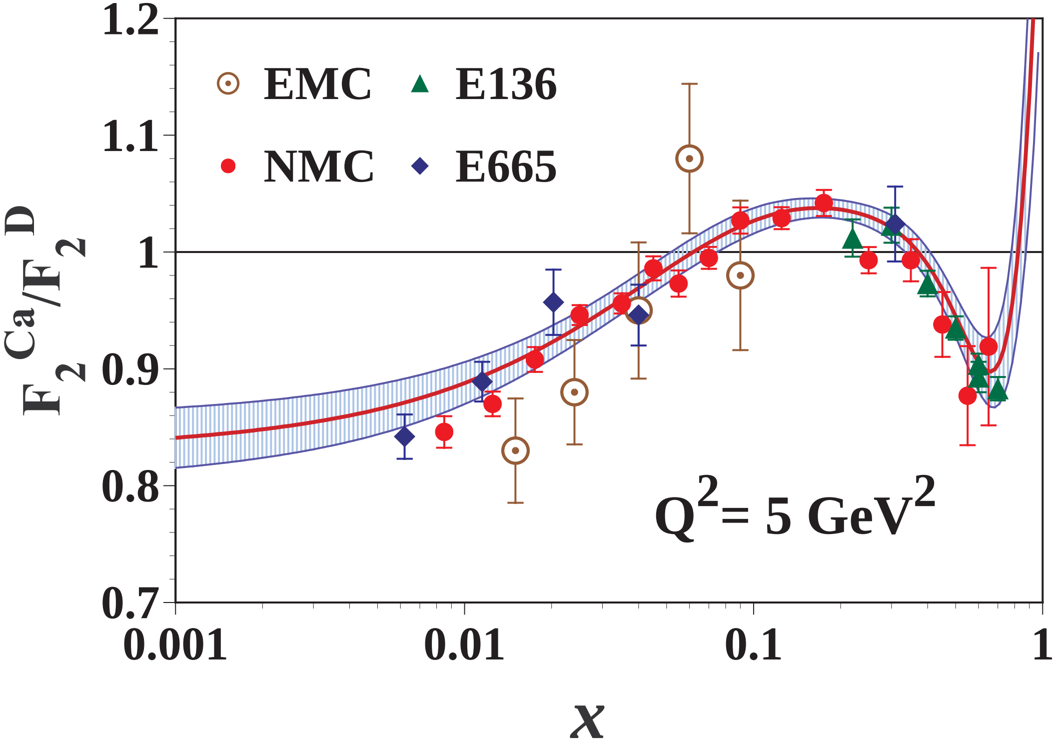
σ_0: cross section on a nucleon

(From review article of Kenyon in 1982)

α is consistent with 1

Modification of Parton Distributions in Nuclei

EMC effect observed in DIS



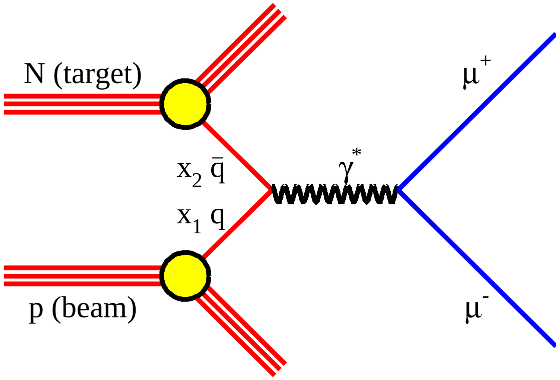
(Ann. Rev. Nucl. Part. Phys., Geesaman, Sato and Thomas)

Extensive study by Kumano et al. and Strikman et al.

F_2 contains contributions from quarks and antiquarks

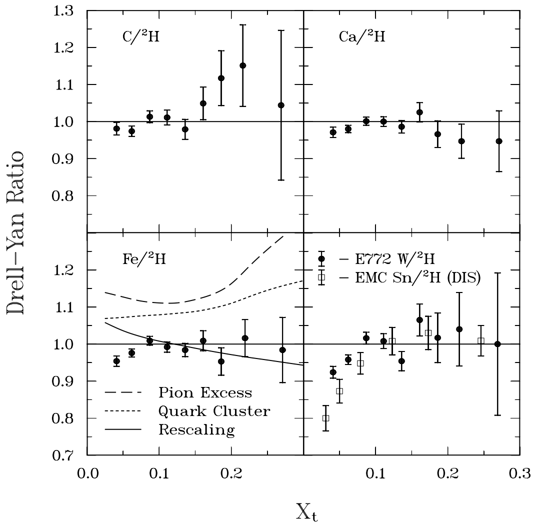
How are the antiquark distributions modified in nuclei?

Drell-Yan on nuclear targets

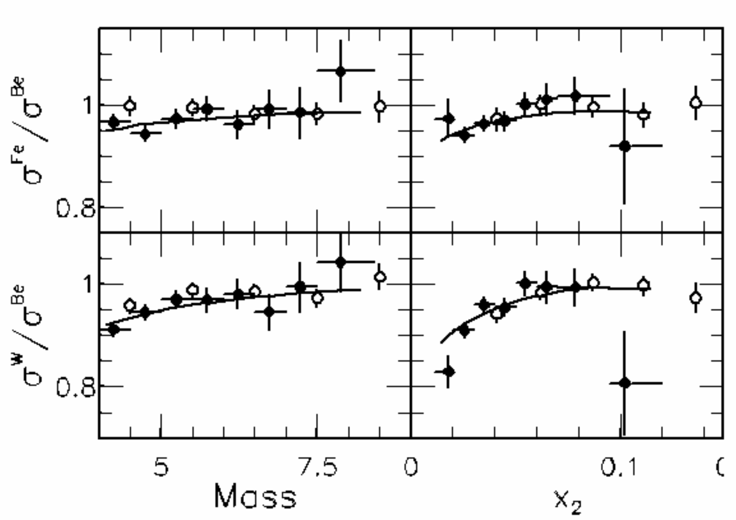


$$\frac{\sigma^{pA}}{\sigma^{pd}} \approx \frac{\bar{u}_A(x)}{\bar{u}_N(x)}$$

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



PRL 64 (1990) 2479

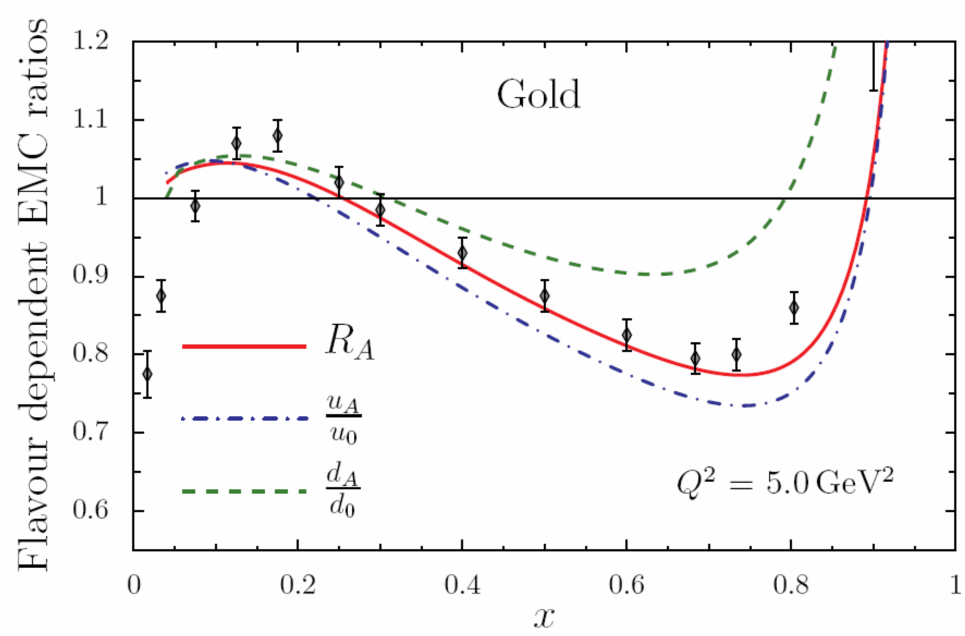


PRL 83 (1999) 2304

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

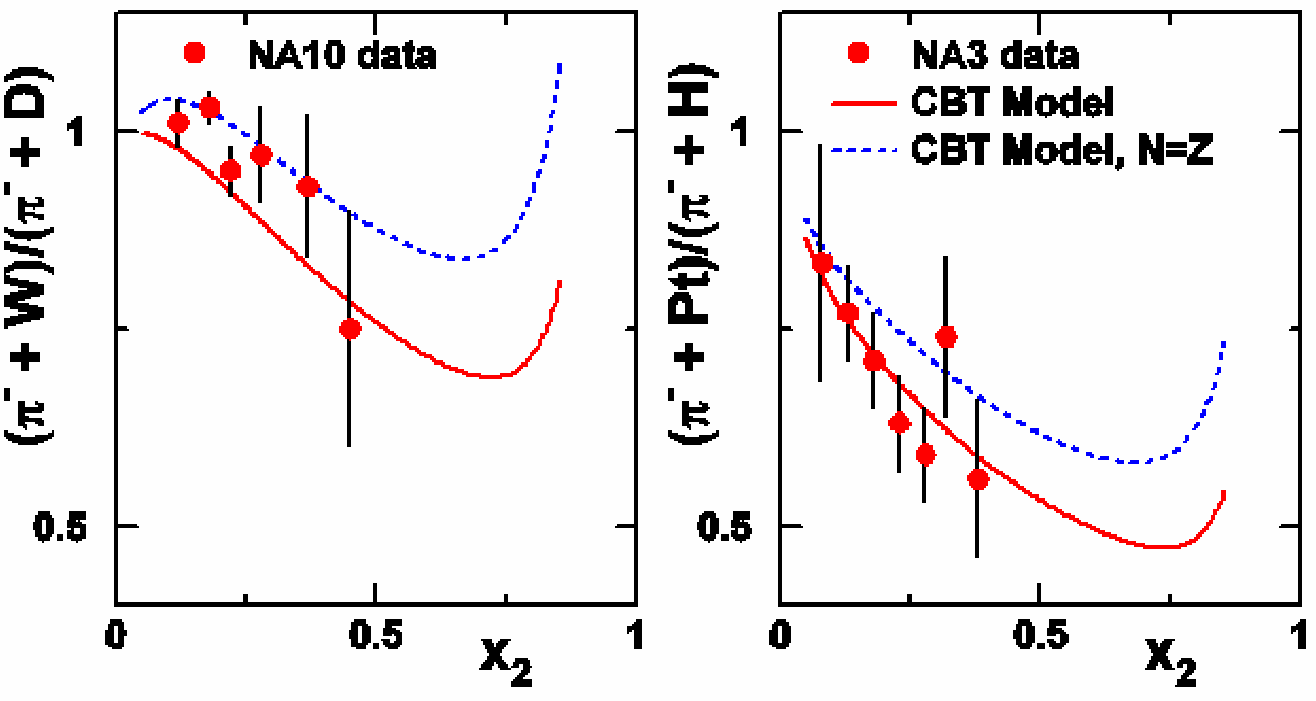
Cloet, Bentz, and Thomas, arXiv:0901.3559

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

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

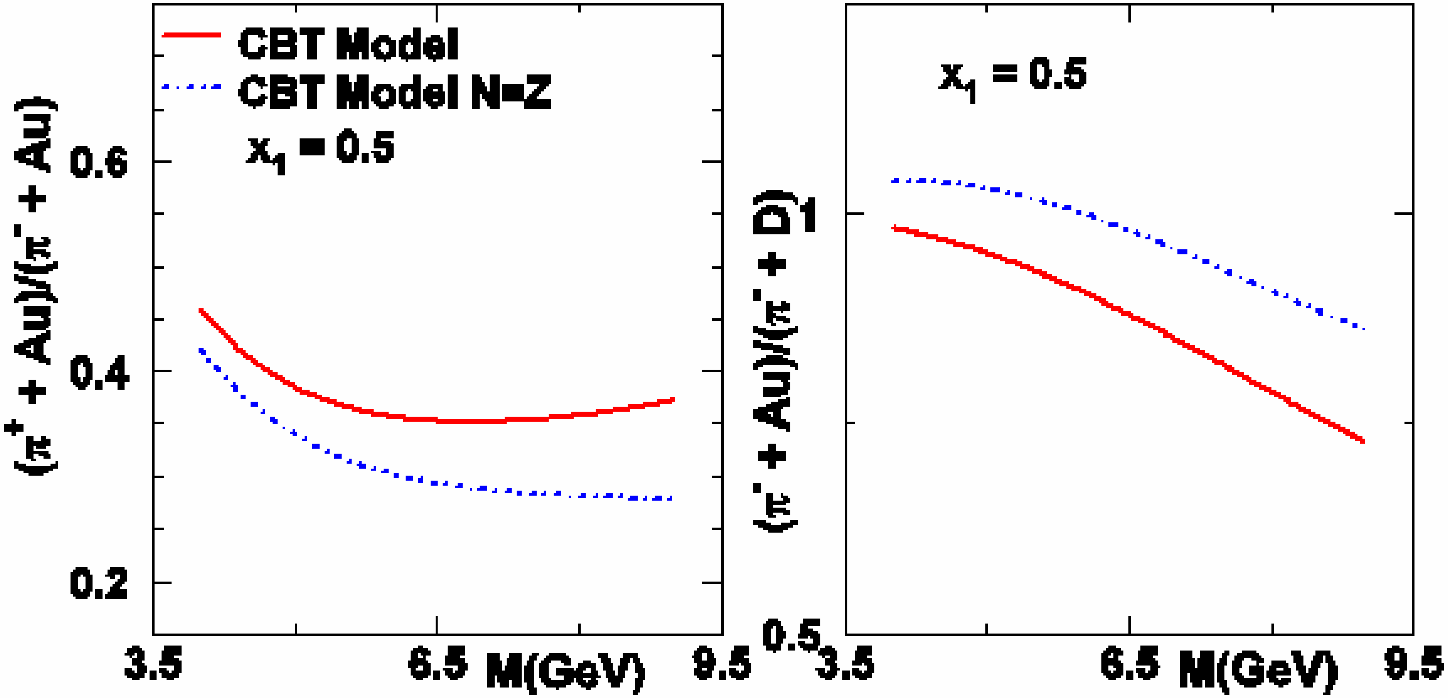


Red (blue) curves correspond to flavor-dependent (independent) EMC

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

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

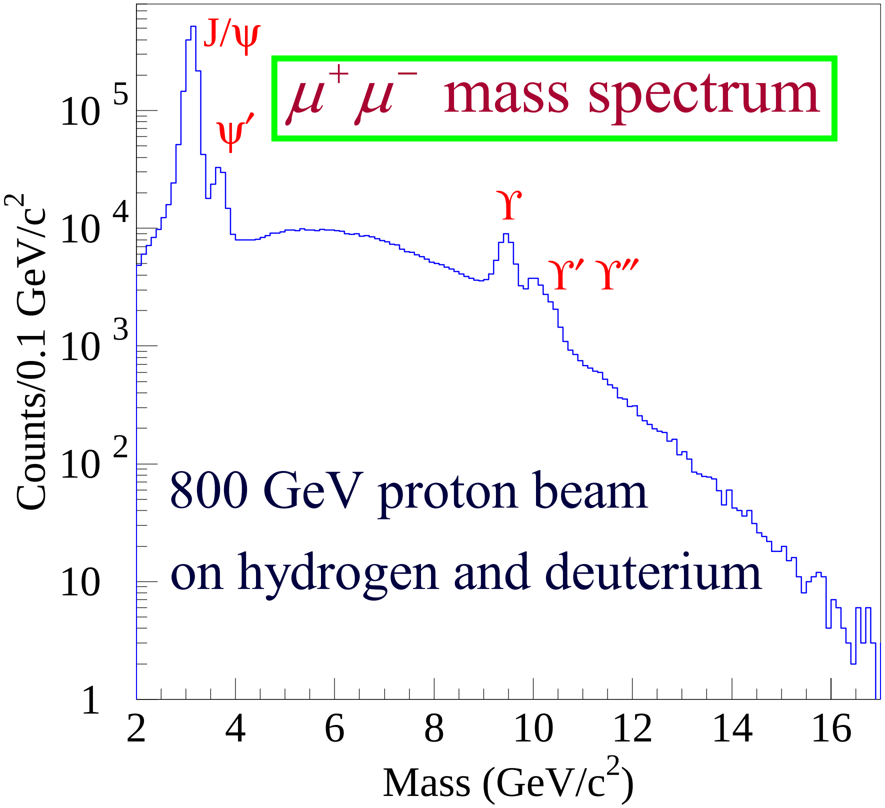
$$\frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4u_A(x)}; \qquad \frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$

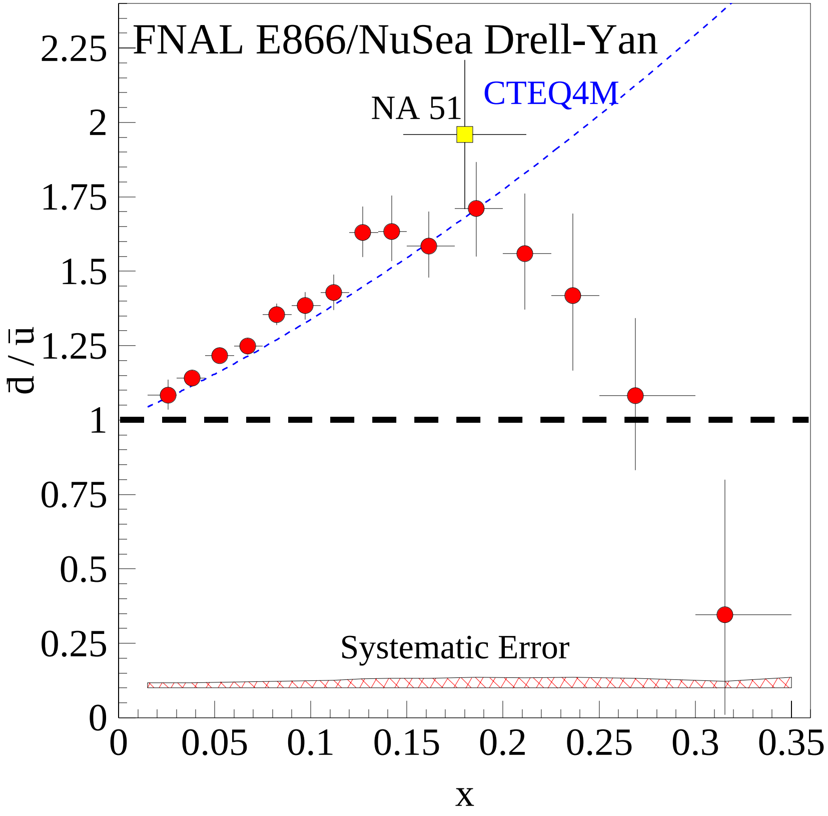


New data from COMPASS or Fermilab with pion beams could provide important new information

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

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

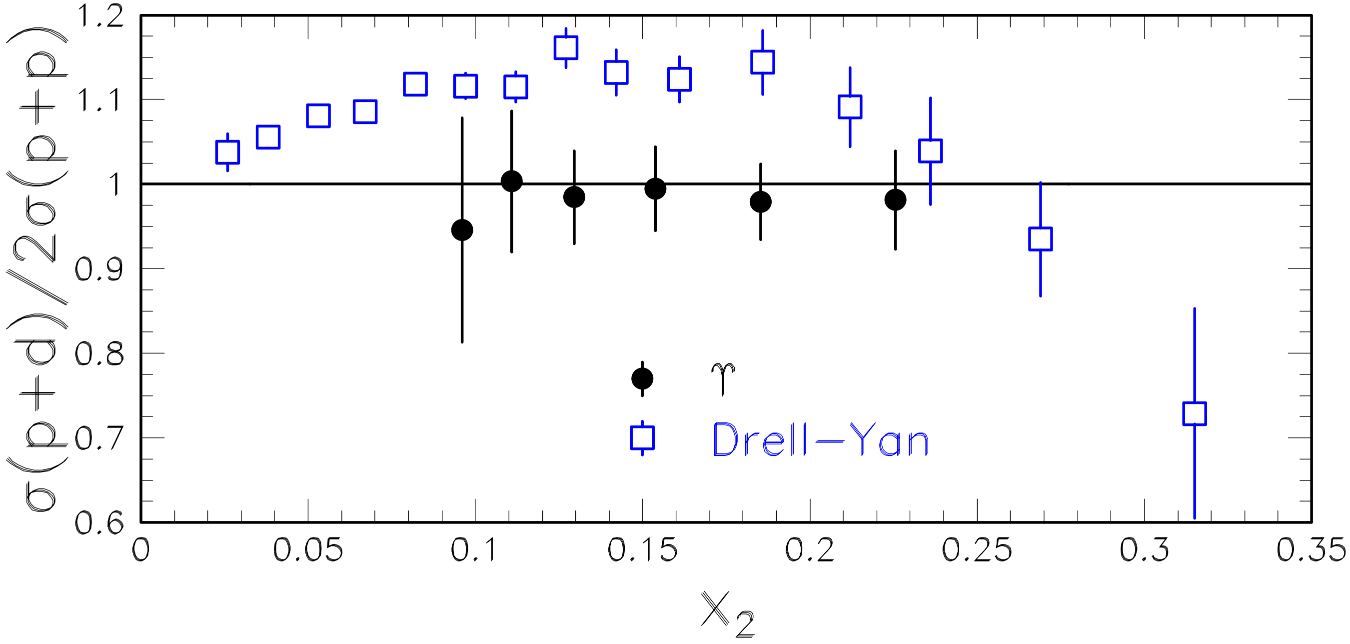




at $x_1 > x_2$: Drell-Yan: $\sigma^{pd}/2\sigma^{pp} \approx \frac{1}{2}\left(1+\bar{d}(x_2)/\bar{u}(x_2)\right)$

Gluon distributions in proton versus neutron?

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



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

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

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

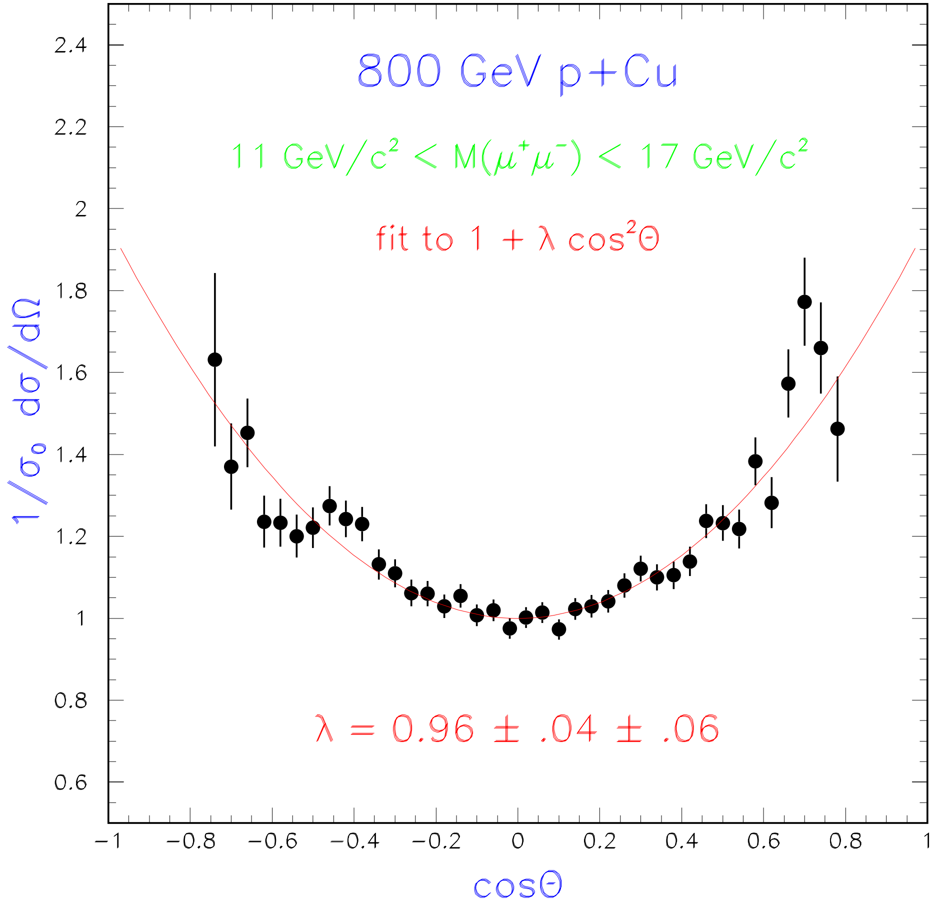
Gluon distributions in proton and neutron are very similar

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

Drell-Yan angular distribution

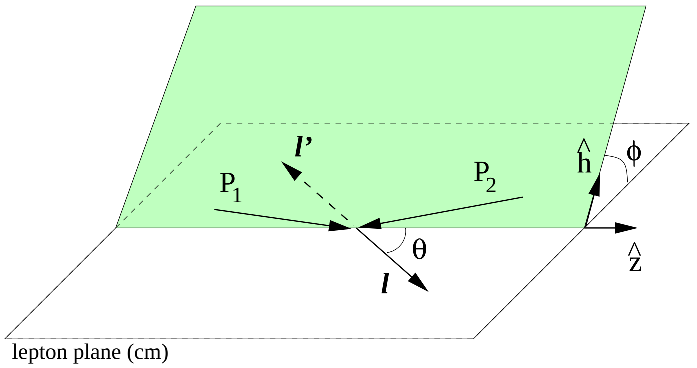
Decay Angular Distribution of “naïve” Drell-Yan:

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



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:

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

Lam-Tung relation: $1-\lambda=2\nu$

- Reflect the spin-1/2 nature of quarks

  (analog of the Callan-Gross relation in DIS)

- Insensitive to QCD - corrections

Decay angular distributions in pion-induced Drell-Yan

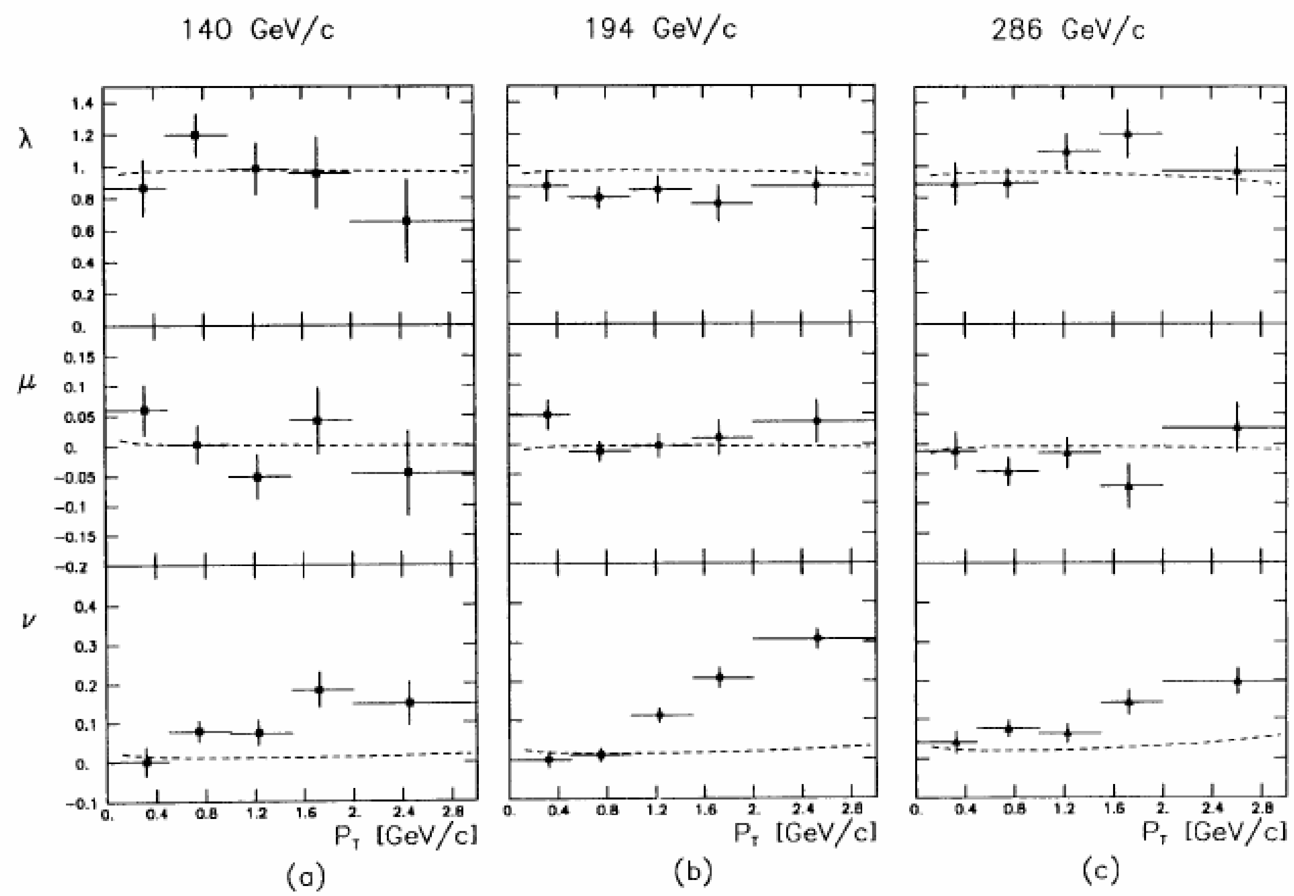


Fig. 3a–c. Parameters λ, μ, and ν as a function of P_T in the CS frame. **a** 140 GeV/c; **b** 194 GeV/c; **c** 286 GeV/c. The error bars correspond to the statistical uncertainties only. The horizontal bars give the size of each interval. The dashed curves are the predictions of perturbative QCD [3]

NA10 $\pi^- + W$

Z. Phys.

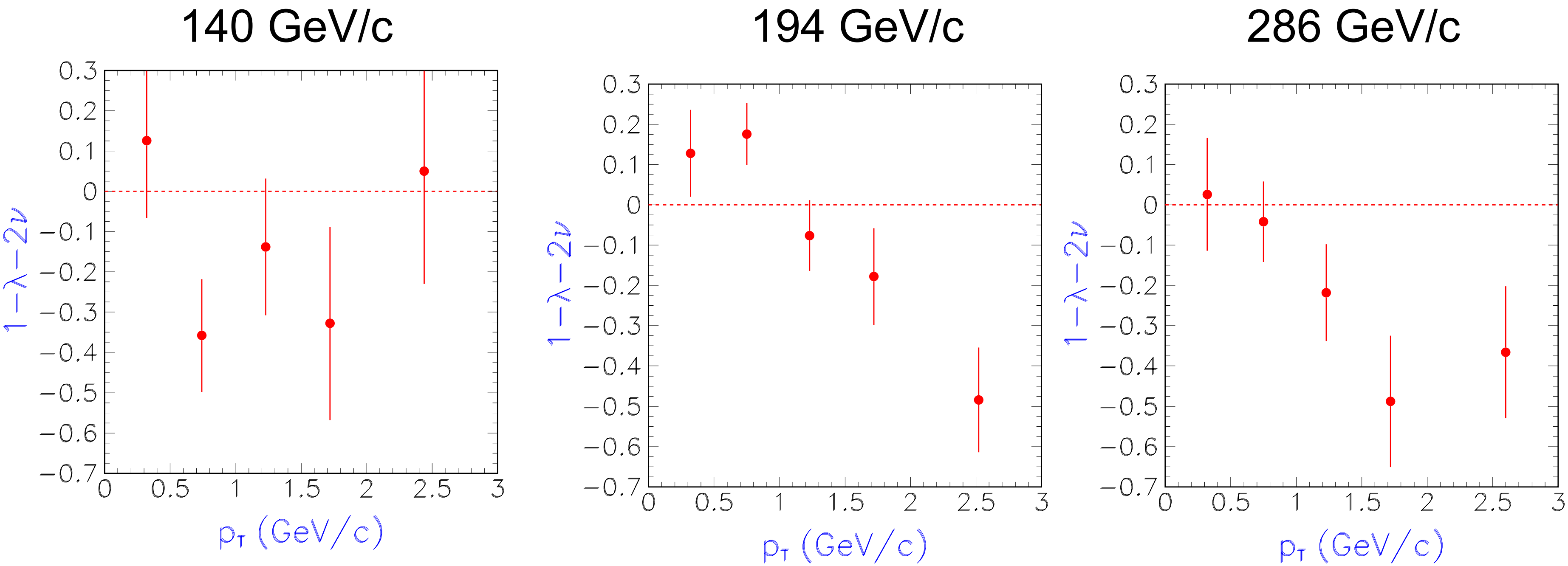
37 (1988) 545

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?

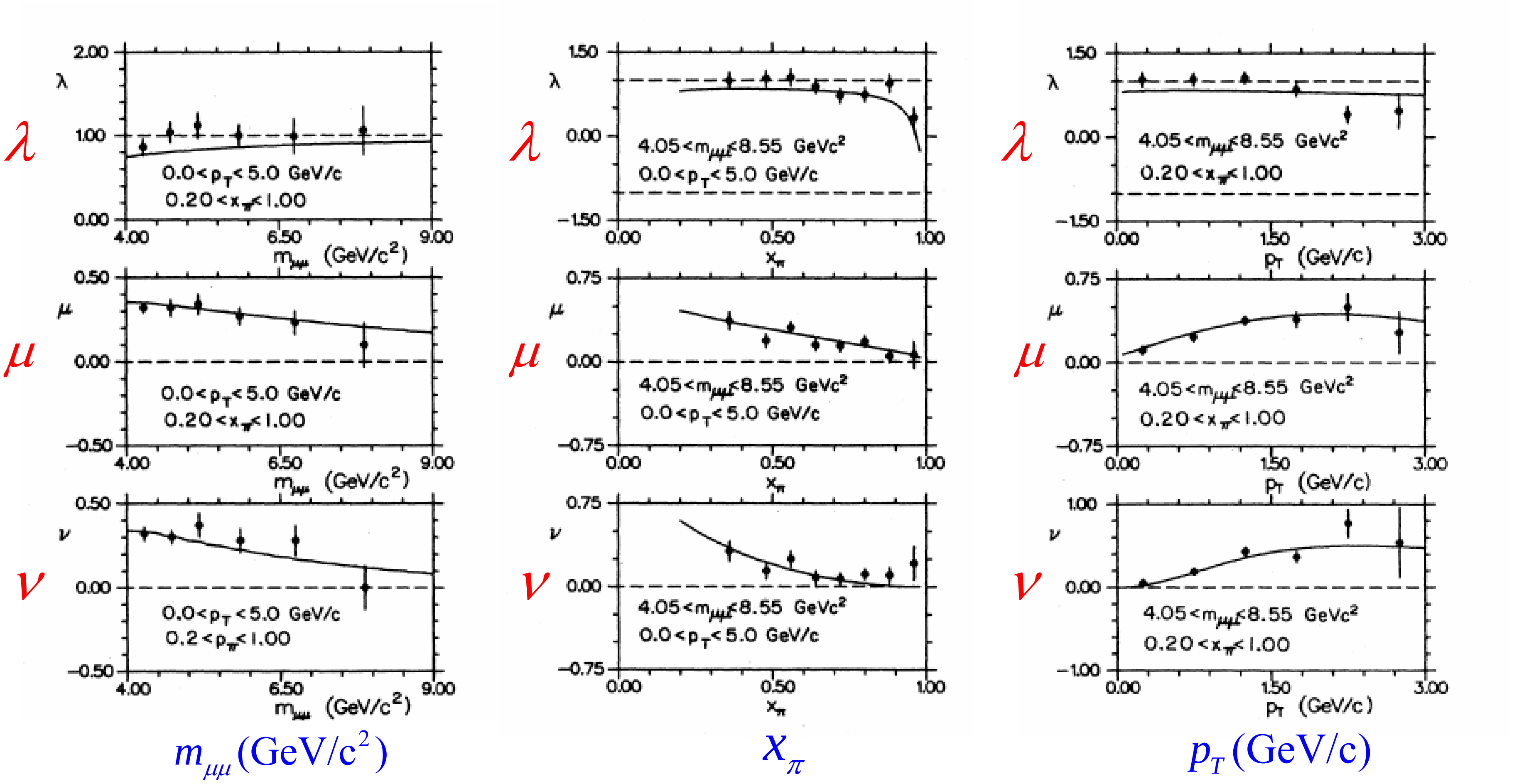


Data from NA10 (Z. Phys. 37 (1988) 545)

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

Decay angular distributions in pion-induced Drell-Yan

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

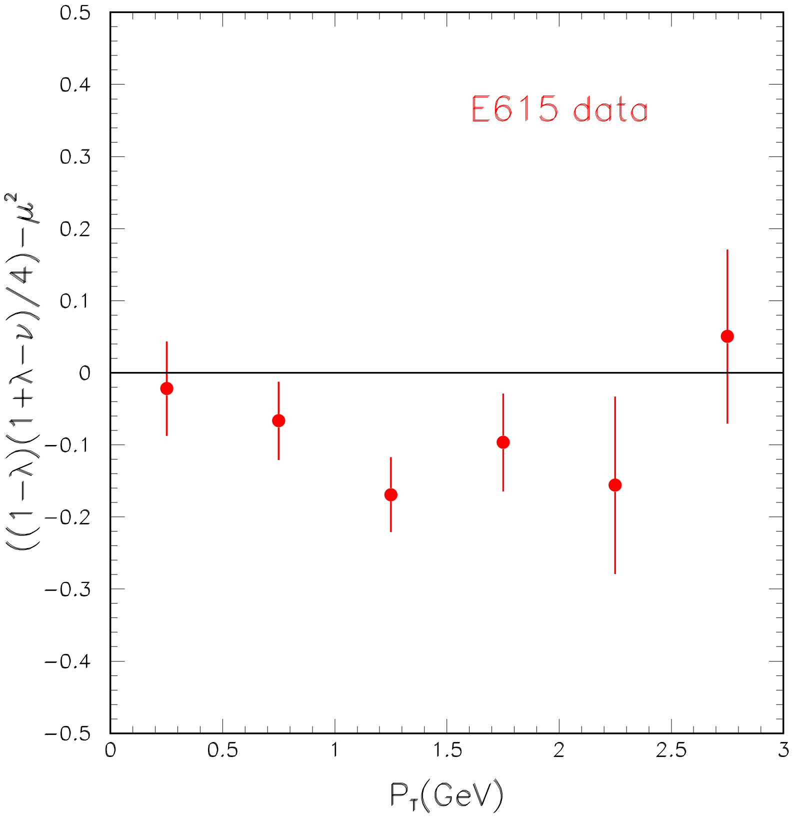


$\lambda \neq 1,\ \mu \neq 0,\ \nu \neq 0$ and they vary with $m_{\mu\mu}$, p_T, and x_π

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

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

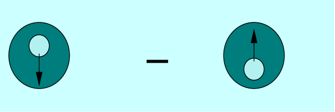
$$(1-\lambda)(1+\lambda-\nu)/4-\mu^2 \ge 0?$$



The inequality appears to be violated!

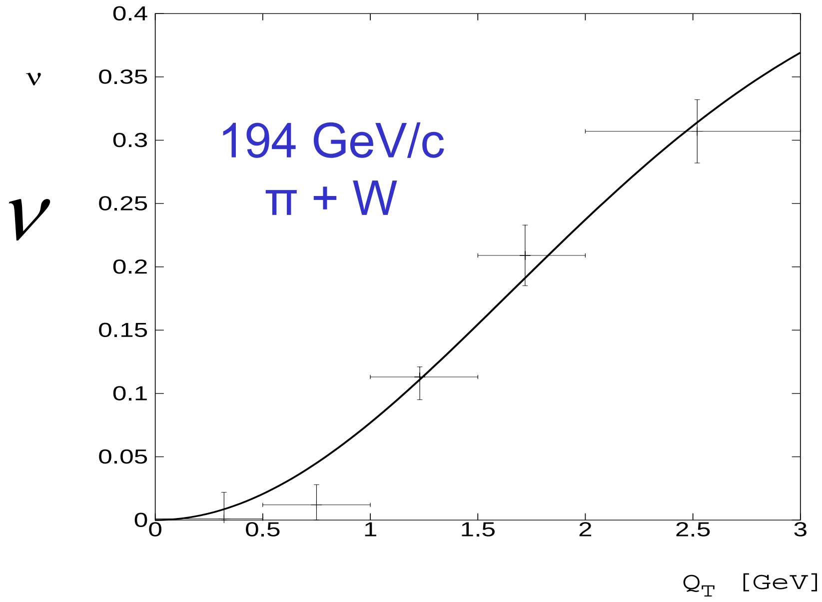
Our knowledge of D-Y azimuthal angular dependence is still incomplete

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 $\cos(2\phi)$ dependence in Drell-Yan

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

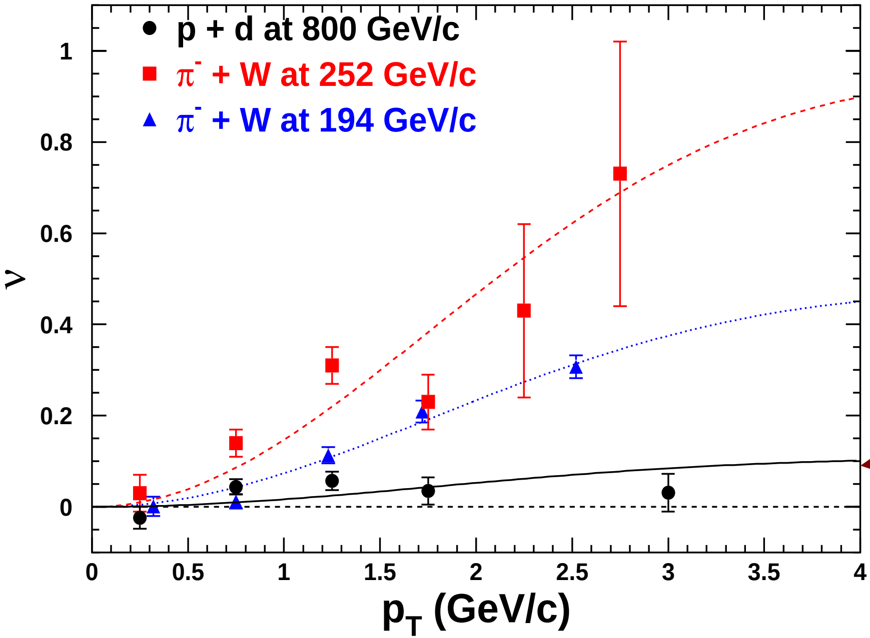


Boer, PRD 60 (1999) 014012

- 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 $h_1^\perp$:

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

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

Sea-quark BM functions are much smaller than valence quarks

Extraction of Boer-Mulders functions from p+d Drell-Yan

(B. Zhang, Z. Lu, B-Q. Ma and I. Schmidt, arXiv:0803.1692)

Parametrization of the BM functions:

$$h_1^{\perp,q}(x,p_\perp^2)=H_q x^c(1-x)f_1^q(x)\exp(-p_\perp^2/p_{BM}^2)$$

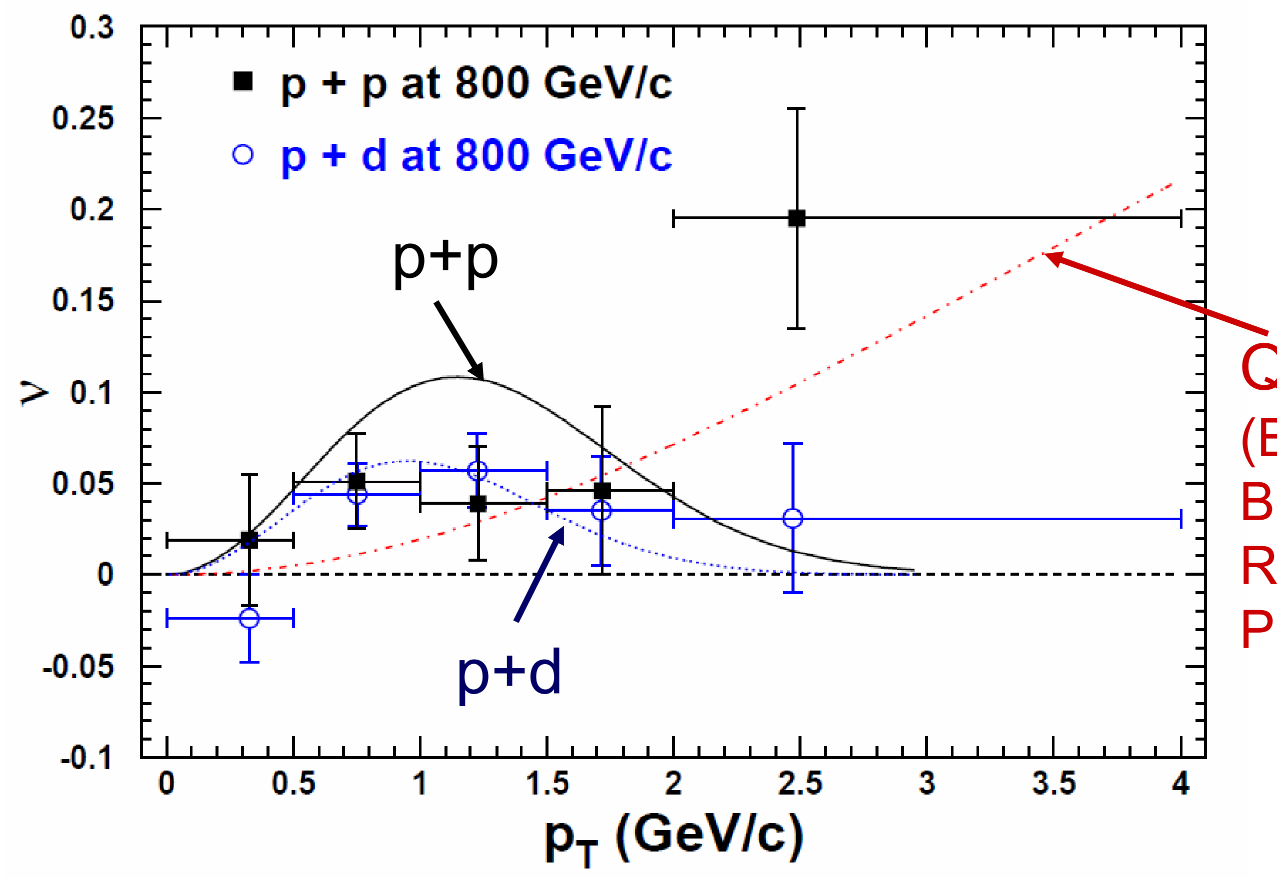
H_u	H_d	$H_{\bar{u}}$	$H_{\bar{d}}$	p_{BM}^2	c	χ^2/dof
3.99	3.83	0.91	-0.96	0.16	0.45	0.79

- H_u and H_d have the same sign and similar magnitude (in agreement with model calculations (bag-model, quark-diquark, relativistic CQM, Lattice) and the picture given by M. Burkardt)
- $H_{\bar{u}}$ and $H_{\bar{d}}$ are smaller by factor of 4 and have opposite sign

Predictions were made for p+p cos(2Φ) distributions

Results on cos2Φ Distribution in p+p Drell-Yan

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



QCD
(Boer, Vogelsang;
Berger, Qiu,
Rodriguez-Pedraza)

Combined analysis of SIDIS and D-Y by Melis et al.

More data are anticipated from Fermilab E906

Transverseity 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:

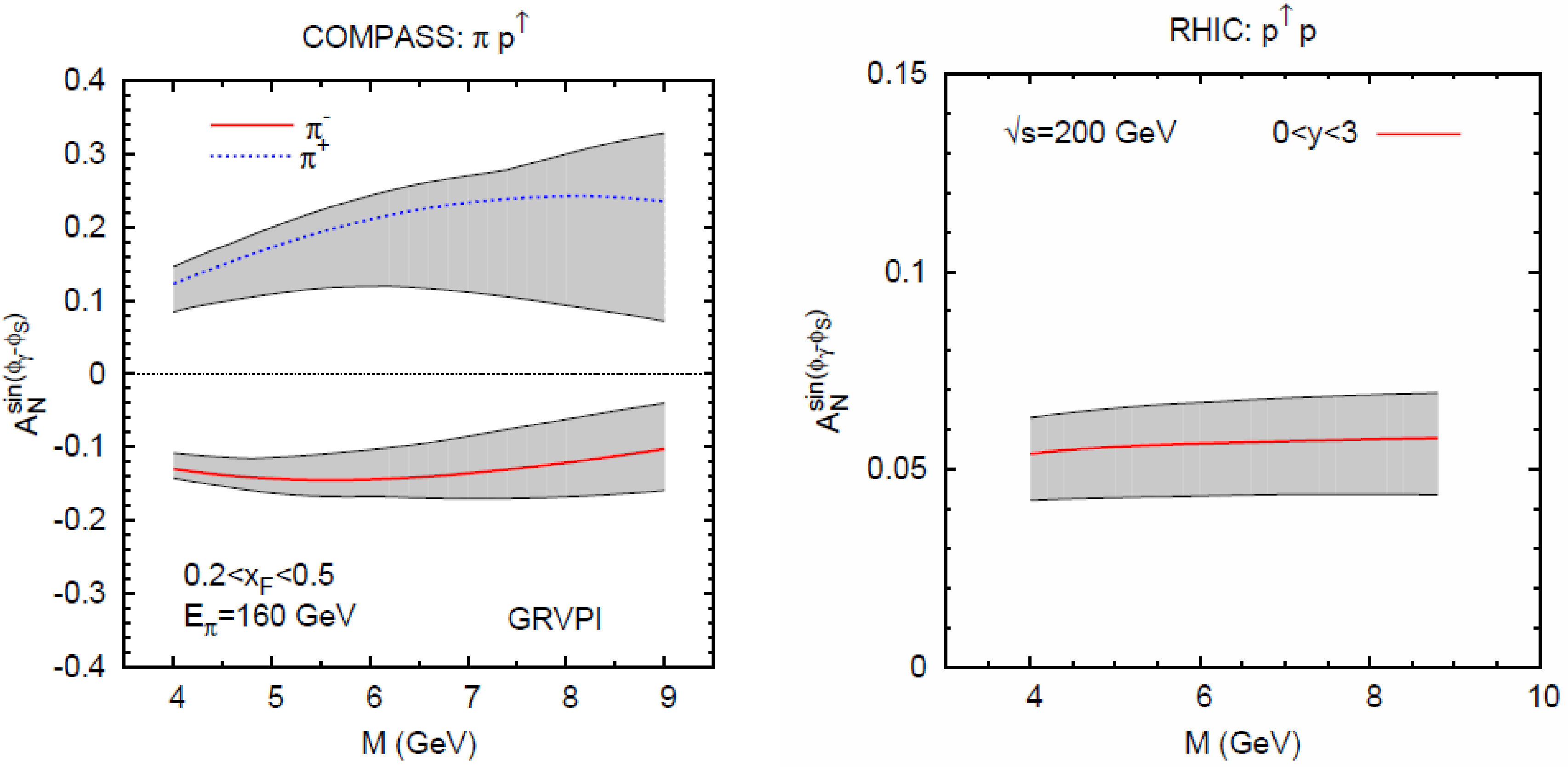
- Double transverse spin asymmetry in polarized Drell-Yan:

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

- 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!

Sivers Effect in Drell-Yan



Anselmino et al., arXiv: 0901.3078

- Use Sivers distributions deduced from SIDIS
- Assume sign change from SIDIS to D-Y

Future prospect for Drell-Yan experiments

- Fermilab p+p, p+d, p+A
  - Unpolarized beam and target
- RHIC
  - Doubly and singly polarized p+p collision
- COMPASS
  - π-p and π-d with polarized targets
- FAIR
  - Polarized antiproton-proton collision
- J-PARC
  - Possibly polarized proton beam and target
- JINR
  - NICA with polarized target
- IHEP
  - SPASCHARM with polarized target p-p and π-p

Outstanding questions to be addressed by future Drell-Yan experiments

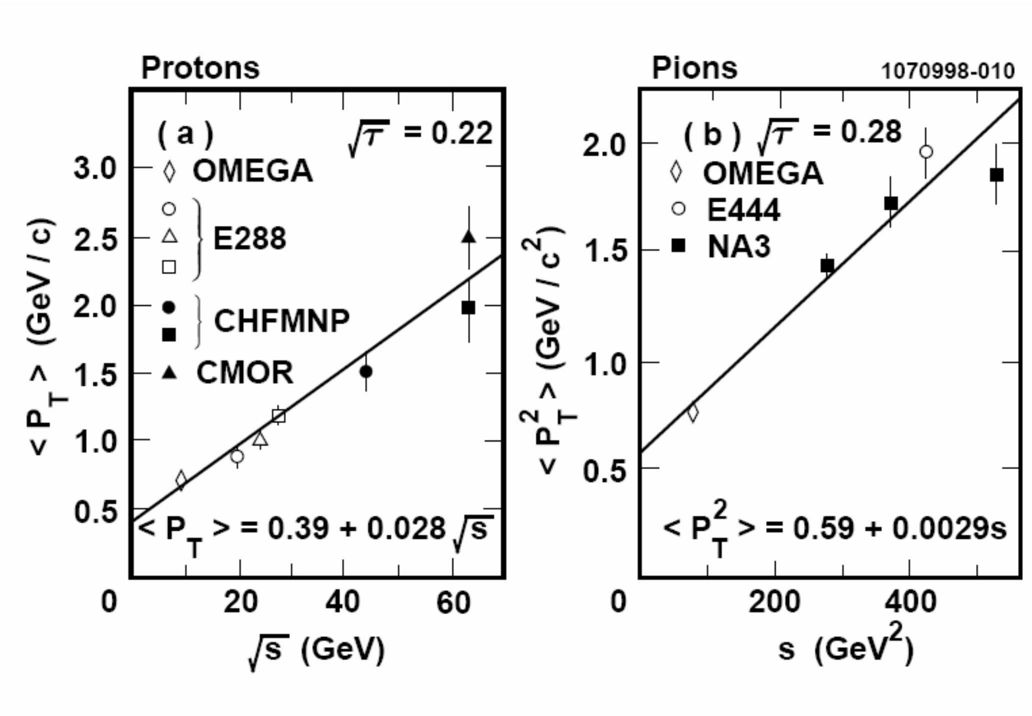
- Does Sivers function change sign between DIS and Drell-Yan?
- Does Boer-Mulders function change sign between DIS and Drell-Yan?
- Are all Boer-Mulders functions alike (proton versus pion Boer-Mulders functions)
- Flavor dependence of TMD functions
- Independent measurement of transversity with Drell-Yan

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

- Does the quark $\mathrm{k_T}$ 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, see many papers by Jianwei Qiu on P_T distribution of Drell-Yan)

- 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

The data suggest:

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

We know

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

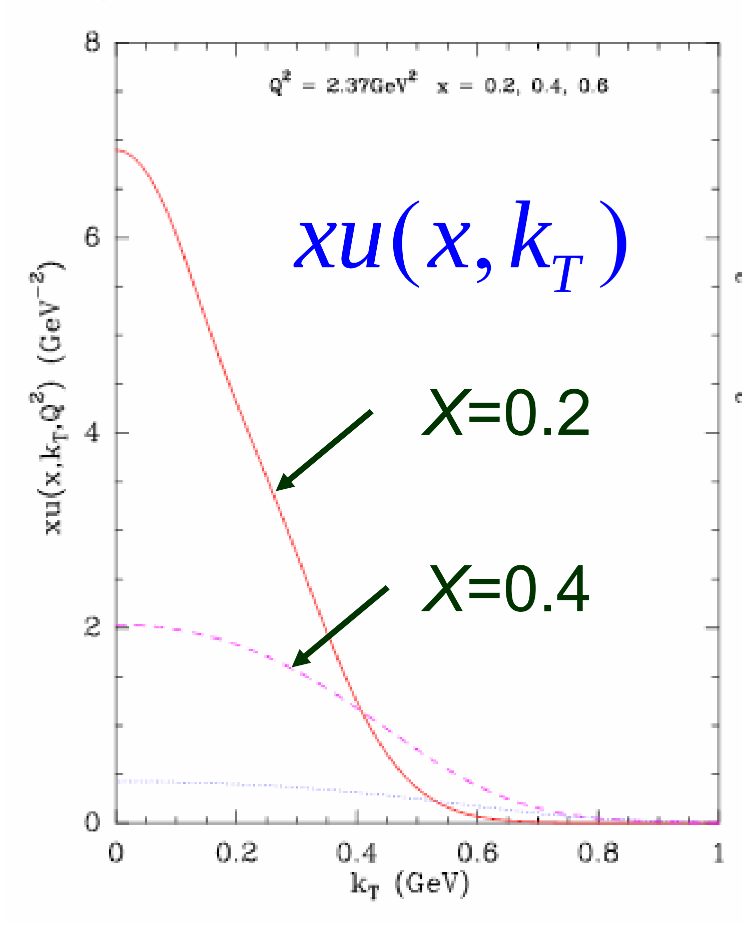
$$\langle r \rangle^{1/2} = 0.58 \pm 0.02\,\text{fm for kaon}$$

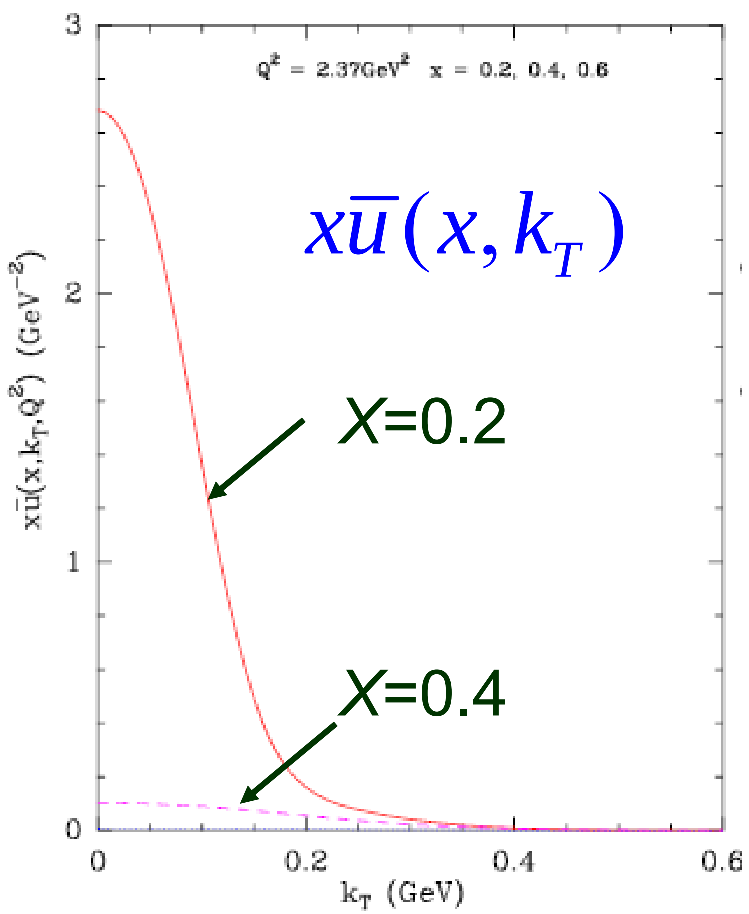
$$\langle r \rangle^{1/2} = 0.67 \pm 0.02\,\text{fm for pion}$$

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

Flavor and *x*-dependent k_T-distribtions?

(Bourrely, Buccella, Soffer, arXiv:1008.5322)

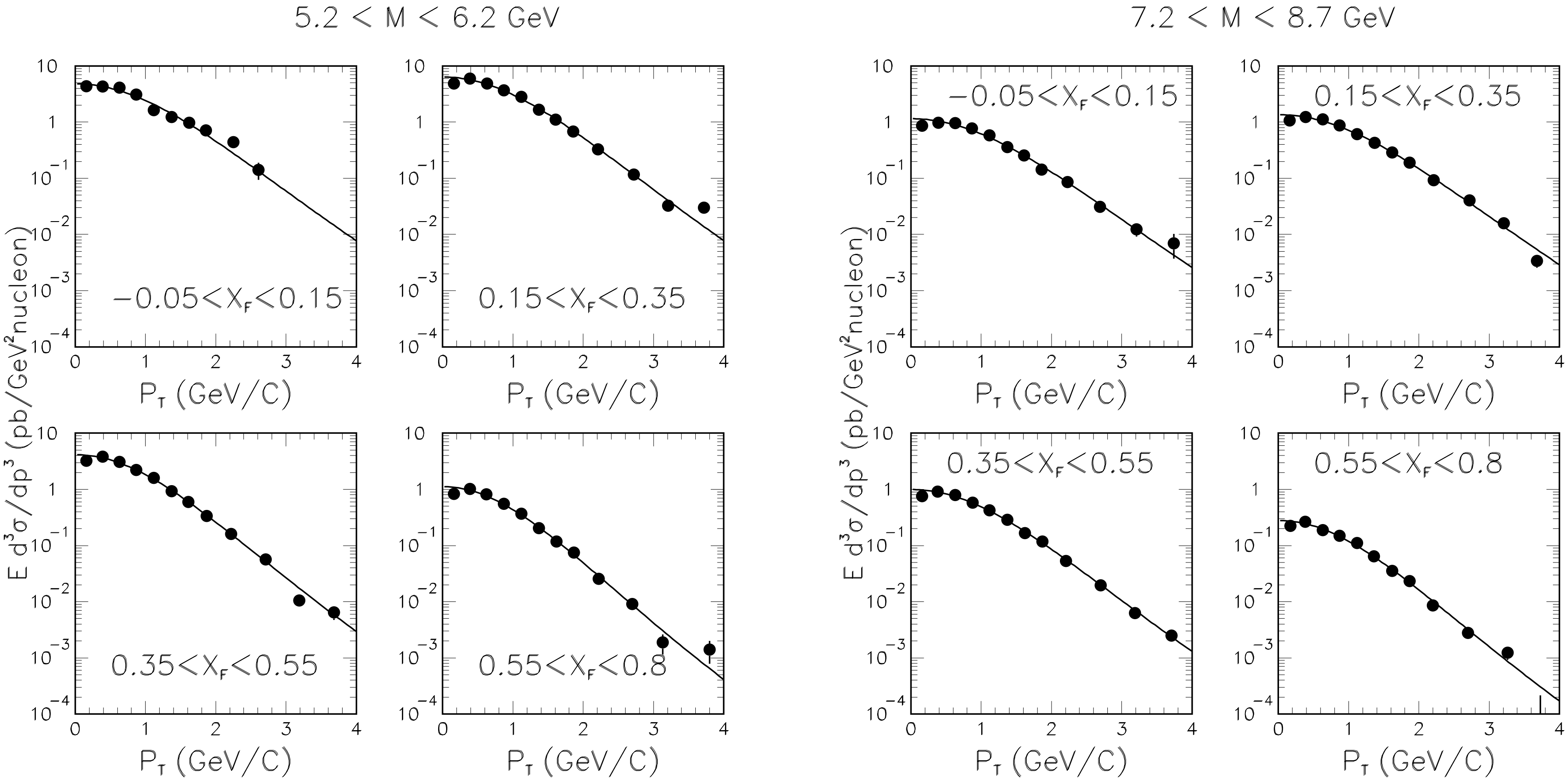




- $\langle k_T \rangle$ increases when x increases
- $\langle k_T \rangle$ for sea quarks is smaller than for valence quarks

Test of possible *x*-dependent k_T-distribtions

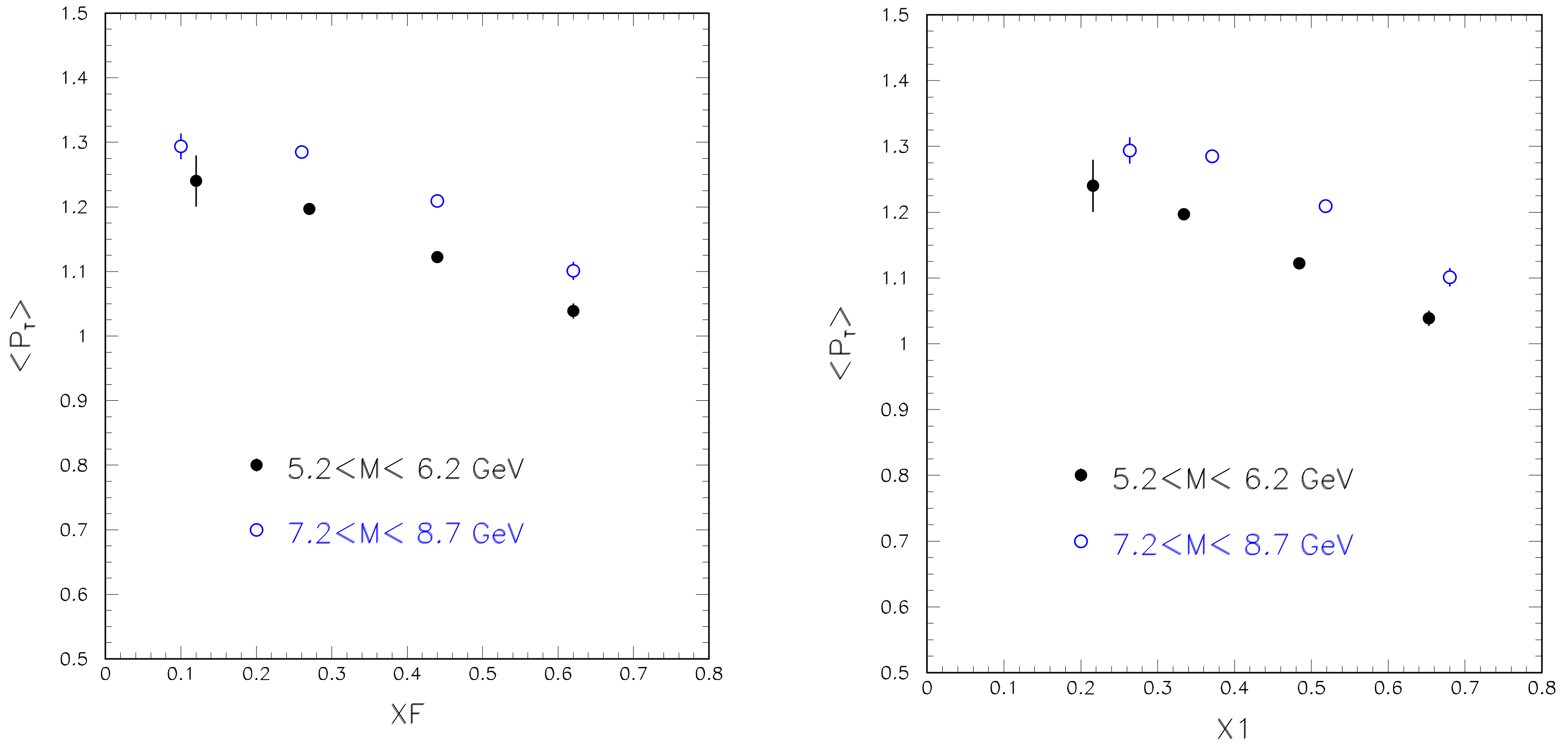
E866 p+d D-Y data (800 GeV beam)



Data from thesis of J. Webb

Test of possible *x*-dependent k_T-distribtions

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



$\langle p_T \rangle$ depends on x_1 (or x_F)?

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 various hadron facilities can address many important unresolved issues in the spin and flavor structures of nucleons and nuclei.