Other Physics Opportunities in Future Drell-Yan Experiments

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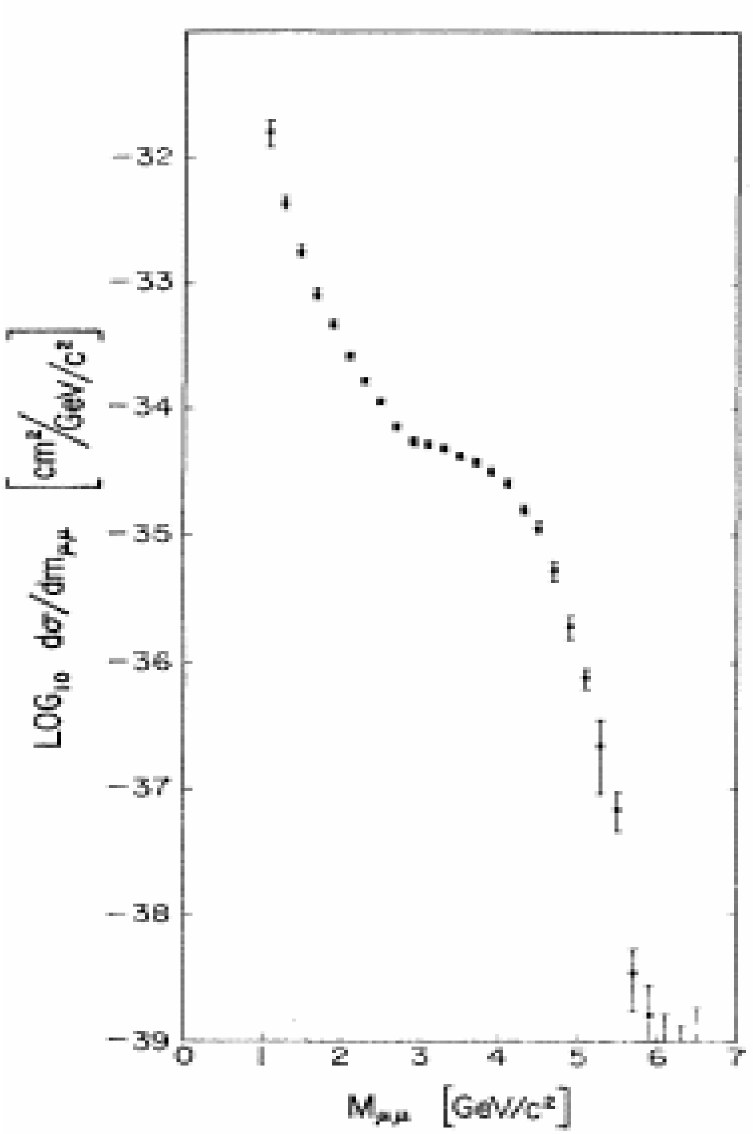
Workshop on “Opportunities for Drell-Yan Physics at RHIC”
BNL, May 11-13, 2011

Outline

- “Intrinsic sea-quarks” of the nucleons.
- Flavor dependence of the EMC effect.
- Equalities and inequalities in Drell-Yan azimuthal angular distributions.
- Flavor and *x*-dependence of quark intrinsic transverse momentum distributions.
- Drell-Yan and quarkonium duality.

First Dimuon Experiment at AGS

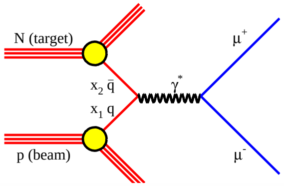


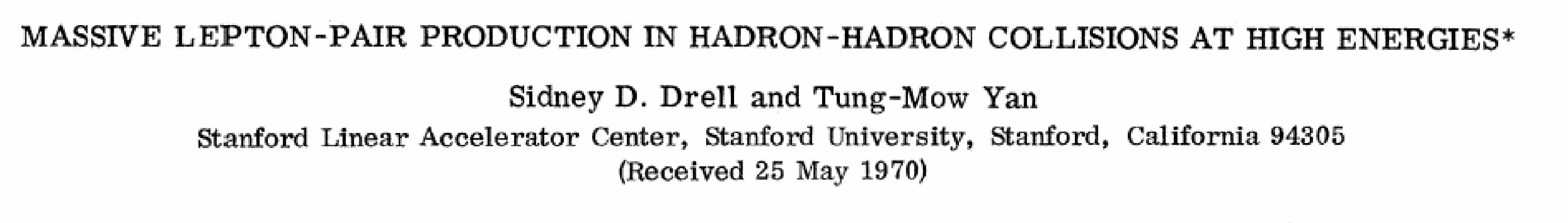
$p + U \rightarrow \mu^{+} + \mu^{-} + X$ 29 GeV proton

Lederman et al. PRL 25 (1970) 1523

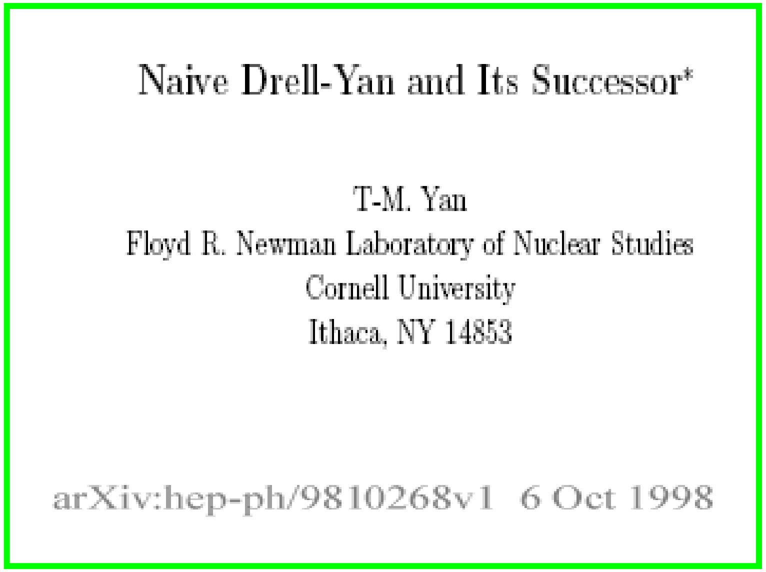
- Experiment originally designed to search for neutral weak boson (Z^0)
- Missed the J/Ψ signal !
- “Discovered” the Drell-Yan process

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)


Naive Drell-Yan and Its Successor*

T-M. Yan
Floyd R. Newman Laboratory of Nuclear Studies
Cornell University
Ithaca, NY 14853

arXiv:hep-ph/9810268v1 6 Oct 1998

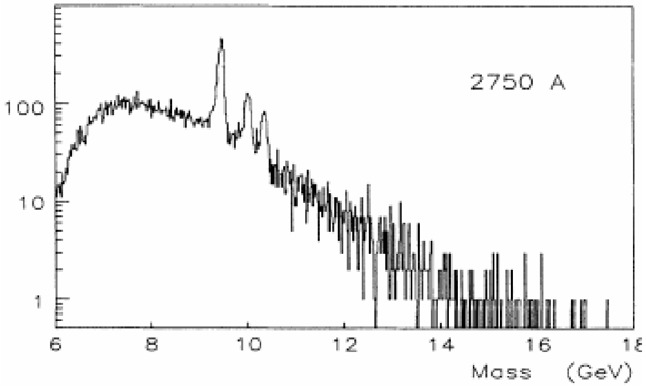
- "… our original crude fit did not even remotely resemble the data. Sid and I went ahead to publish our paper because of the model's simplicity…"
- "The process has been so well understood theoretically that it has become a powerful tool for precision measurements and new physics."


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

Drell-Yan process provides unique information on parton distributions

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

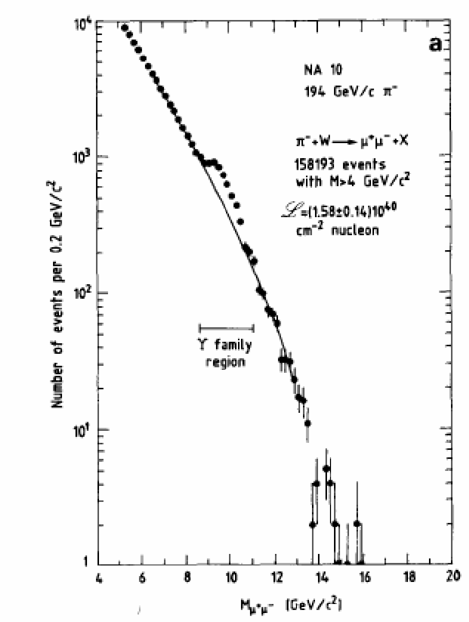
800 GeV/c



Probe antiquark distribution in nucleon

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

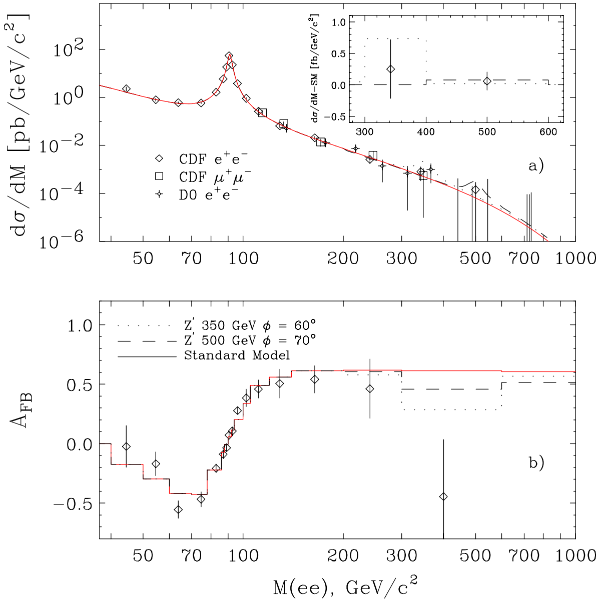
194 GeV/c



Probe antiquark distribution in pion

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

1.8 TeV

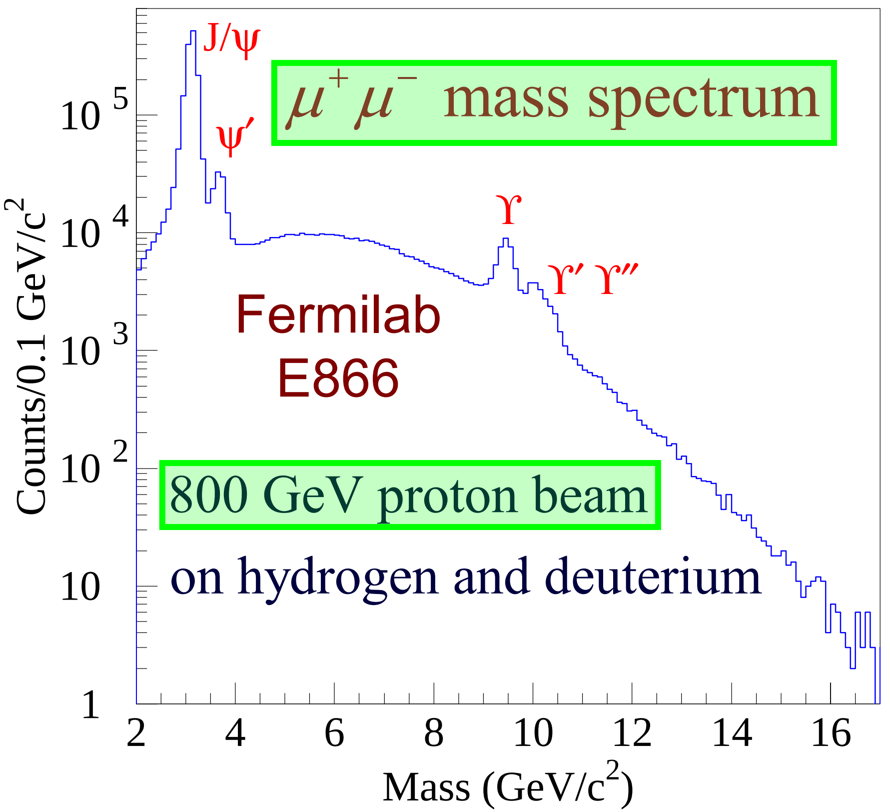


Probe antiquark distributions in antiproton

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

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

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

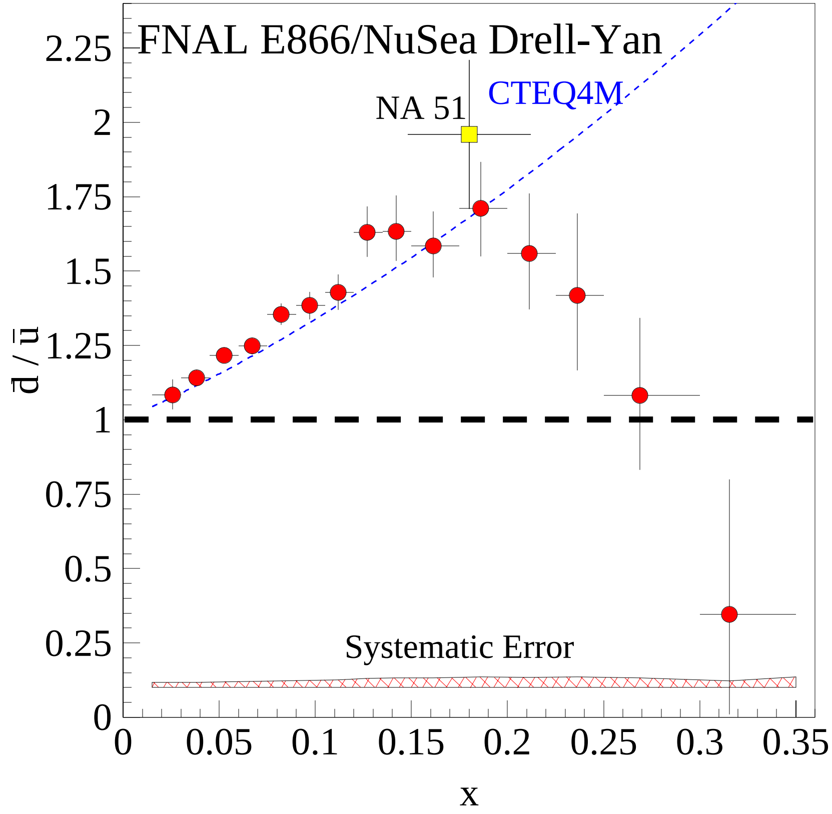


$\mu^+\mu^-$ mass spectrum

Fermilab
E866

800 GeV proton beam

on hydrogen and deuterium



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

Sea-quark flavor asymmetry and the "intrinsic" quark sea

In the 1980's, Brodsky et al. (BHPS) suggested the existence of "intrinsic" charm

$$|p\rangle = P_{3q}\,|uud\rangle + P_{5q}\,|uudQ\bar{Q}\rangle + \cdots\cdots$$

The $|uudc\bar{c}\rangle$ intrinsic-charm can contribute to charm-production at large x_F

No conclusive experimental evidence for intrinsic-charm so far

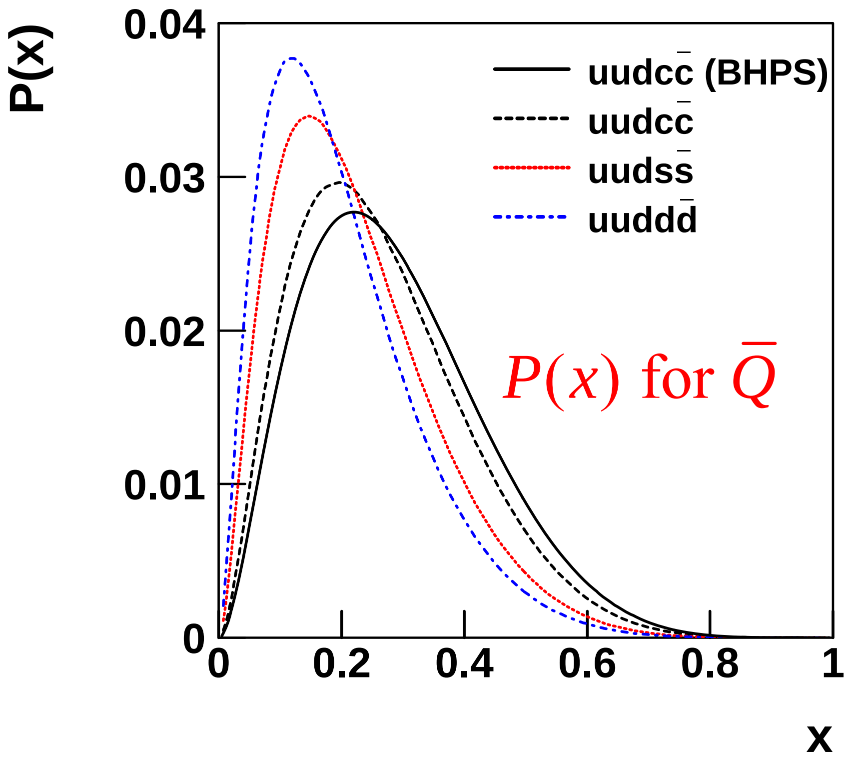
Are there experimental evidences for the intrinsic $|uudu\bar{u}\rangle, |uudd\bar{d}\rangle, |uuds\bar{s}\rangle$ 5-quark states ?

$$(P_{5q}^{uudQ\bar{Q}} \sim 1/m_Q^2)$$

Sea-quark flavor asymmetry and the “intrinsic” quark sea

Brodsky et al. (BHPS) give the following probability for quark *i* (mass m_i) to carry momentum x_i

$$P(x_1,\cdots,x_5)=N_5\delta(1-\sum_{i=1}^{5}x_i)[m_p^2-\sum_{i=1}^{5}\frac{m_i^2}{x_i}]^{-2}$$

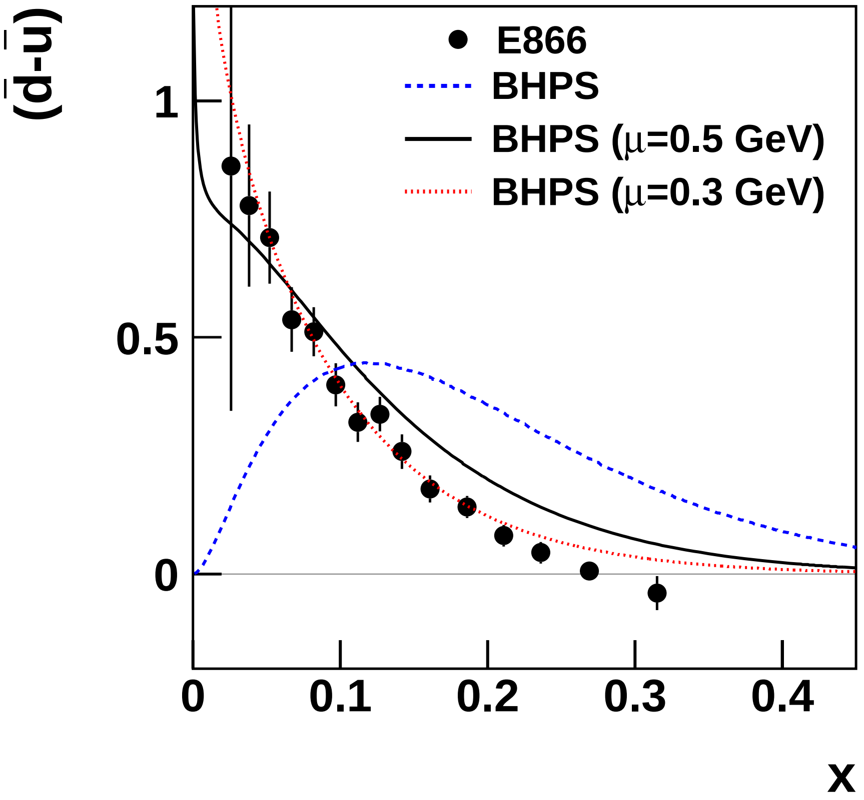


In the limit of large mass for quark Q (charm):

$$P(x_5)=\frac{1}{2}\tilde{N}_5x_5^2[(1-x_5)(1+10x_5+x_5^2)-2x_5(1+x_5)ln(1/x_5)$$

One can calculate $P(x)$ for antiquark $\bar{Q}$ $(\bar{c},\bar{s},\bar{d})$ numerically

Comparison between the $\bar{d}(x)-\bar{u}(x)$ data and the intrinsic 5-*q* model



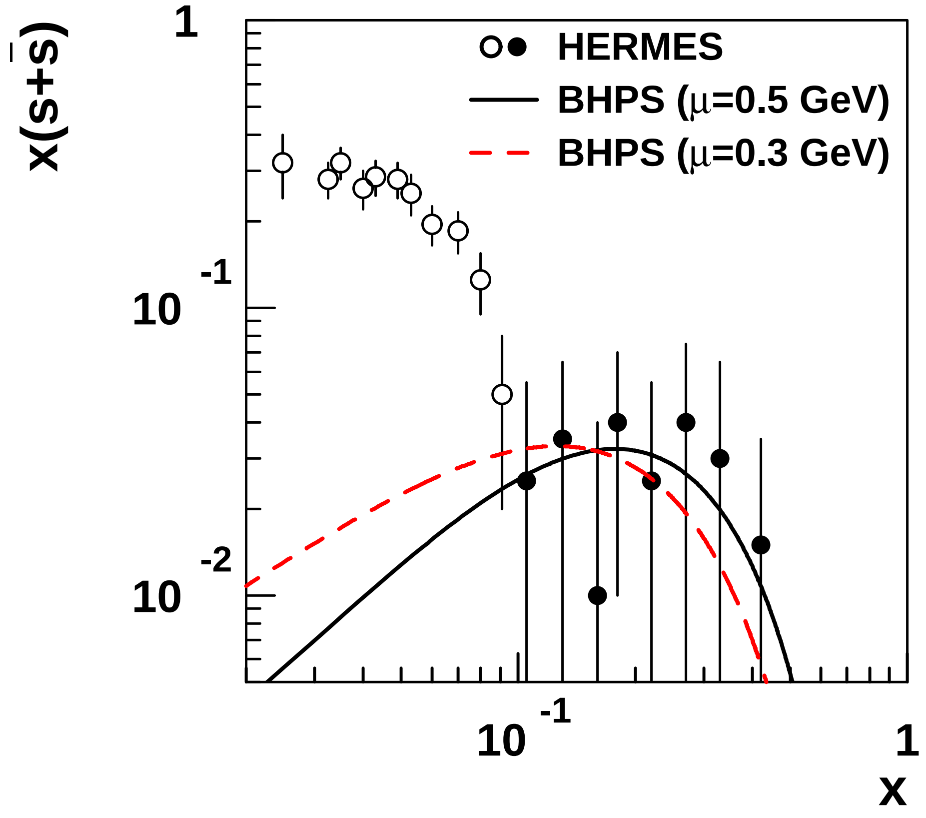
E866 data measured at $\langle Q^2\rangle = 54\ \mathrm{GeV}^2$

Need to evolve the 5-q model prediction from the initial scale *μ* to Q^2=54 GeV^2

(W. Chang and JCP arXiv:1102.5631, to appear in PRL)

$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = \int_0^1 (\bar{d}(x)-\bar{u}(x))\,dx = 0.118$$

Comparison between the $s(x)+\bar{s}(x)$ data with the intrinsic 5-q model



$s(x)+\bar{s}(x)$ from HERMES kaon SIDIS data at $\langle Q^2\rangle = 2.5\ \mathrm{GeV}^2$

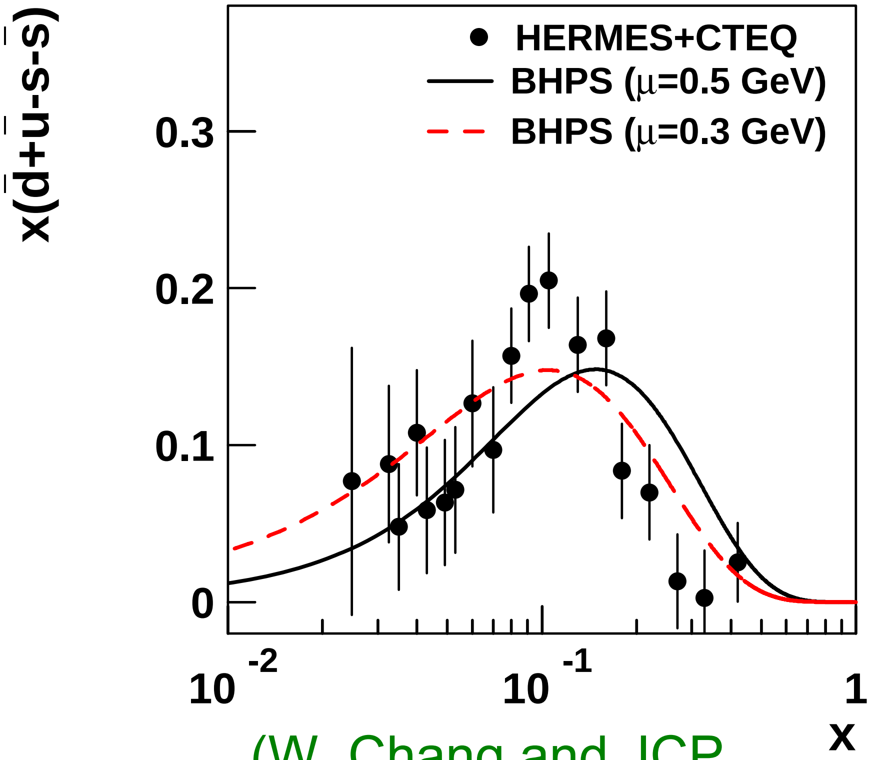
Two distinct shapes in the x distribution: extrinsic ($g \to s\bar{s}$) and intrinsic $uuds\bar{s}$ state

Assume $x > 0.1$ data are from the intrinsic $uuds\bar{s}$ 5-quark state

(W. Chang and JCP arXiv:1102.5631, to appear in PRL)

$$\boxed{P_5^{uuds\bar{s}} = 0.032}$$

Comparison between the $\bar{u}(x)+\bar{d}(x)-s(x)-\bar{s}(x)$ data with the intrinsic 5-*q* model



(W. Chang and JCP arXiv:1102.5631)

$\bar{d}(x)+\bar{u}(x)$ from CTEQ6.6

$s(x)+\bar{s}(x)$ from HERMES

$$\int_0^1 (\bar{u}(x)+\bar{d}(x)-s(x)-\bar{s}(x))\,dx$$

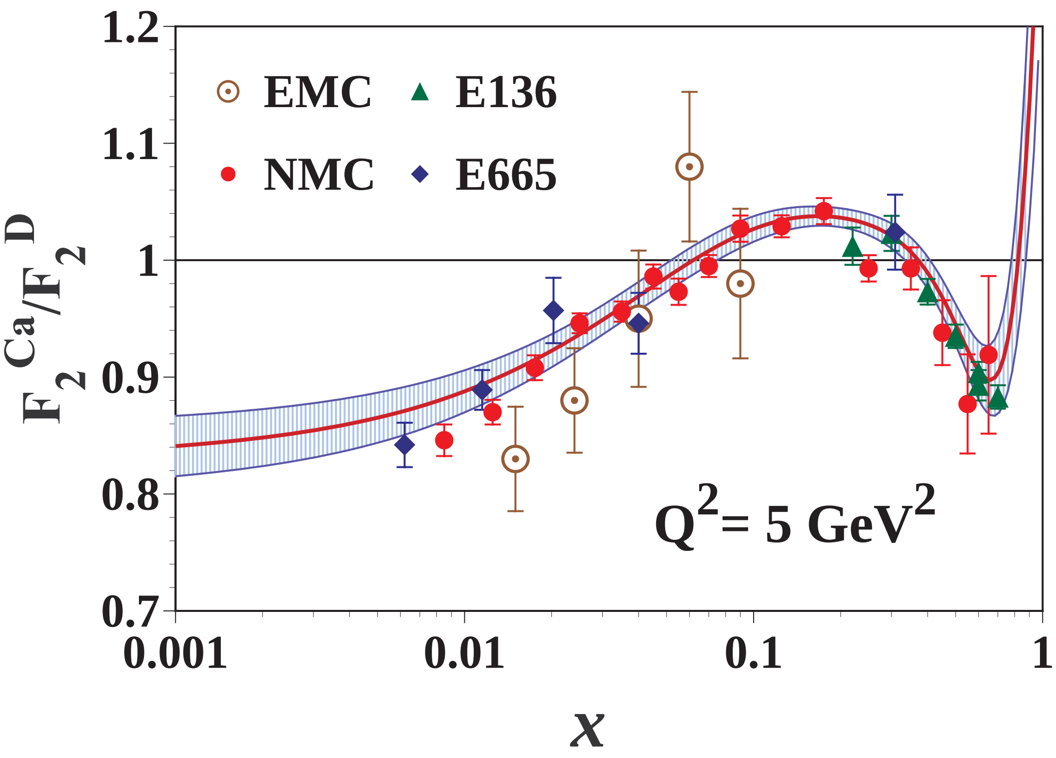
$$= P_5^{uudd\bar{d}} + P_5^{uudu\bar{u}} - 2P_5^{uuds\bar{s}}$$

$$P_5^{uudd\bar{d}} = 0.248,\ P_5^{uudu\bar{u}} = 0.130,\ P_5^{uuds\bar{s}} = 0.032$$

Kaon-induced Drell-Yan could probe strange quark sea

Modification of Parton Distributions in Nuclei

EMC effect observed in DIS

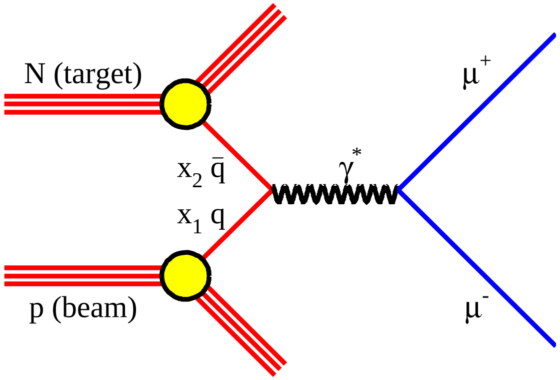


(Ann. Rev. Nucl. Part. Phys., Geesaman, Sato and Thomas)

F_2 contains contributions from quarks and antiquarks

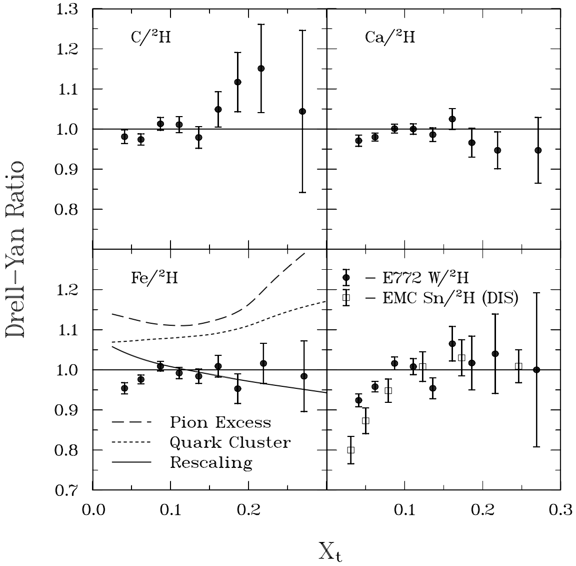
How are the antiquark distributions modified in nuclei?

Drell-Yan on nuclear targets

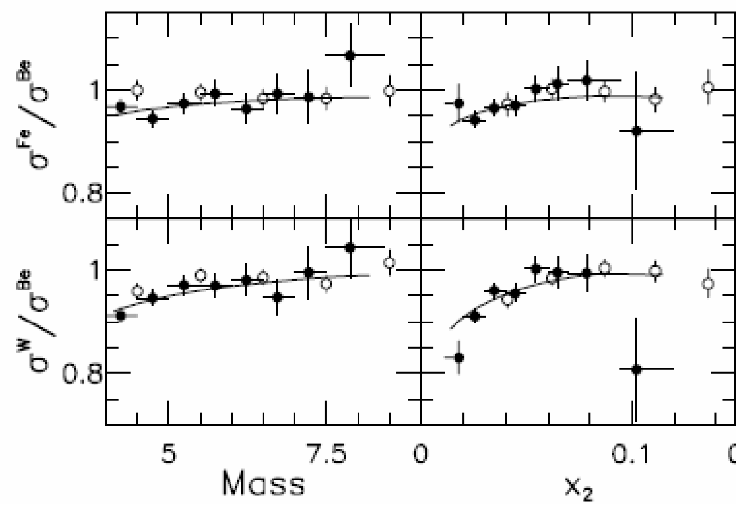


$$\frac{\sigma^{pA}}{\sigma^{pd}} \approx \frac{\bar{u}_A(x)}{\bar{u}_N(x)}$$

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



PRL 64 (1990) 2479

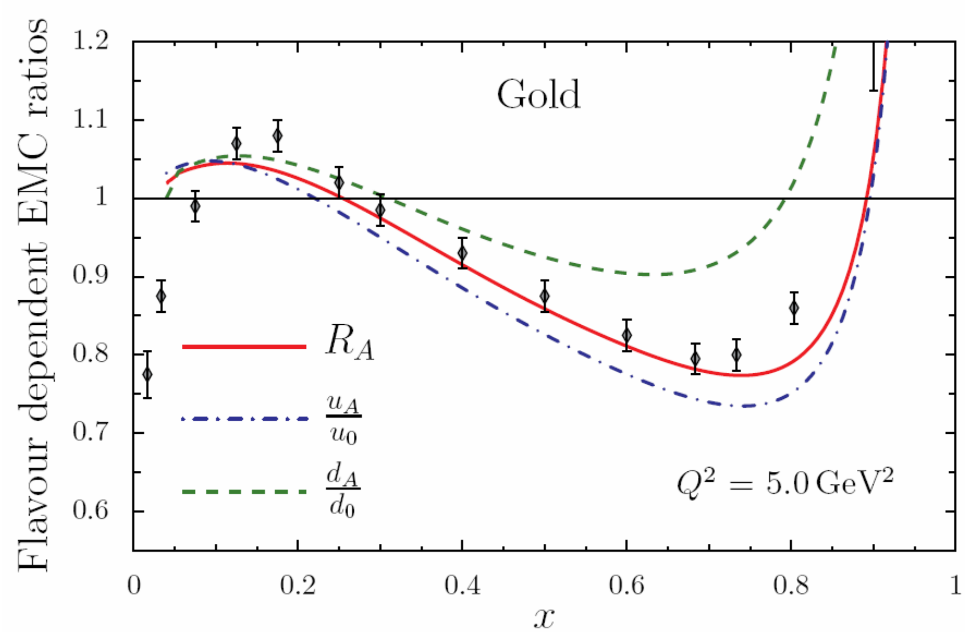


PRL 83 (1999) 2304

No evidence for enhancement of antiquark in nuclei !?

Some EMC models are disfavored by D-Y data

Flavor dependence of the EMC effects ?



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

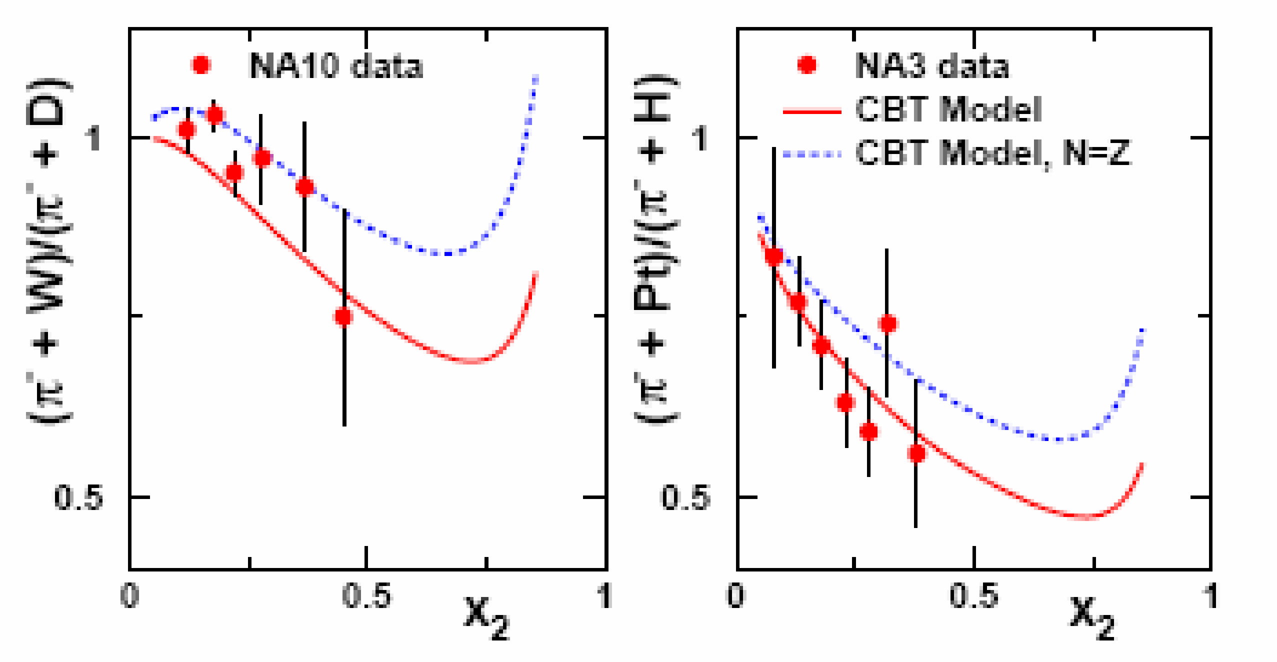
Cloet, Bentz, and Thomas, arXiv:0901.3559

Can provide new constraints on EMC models

How can one check this flavor dependence?

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

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

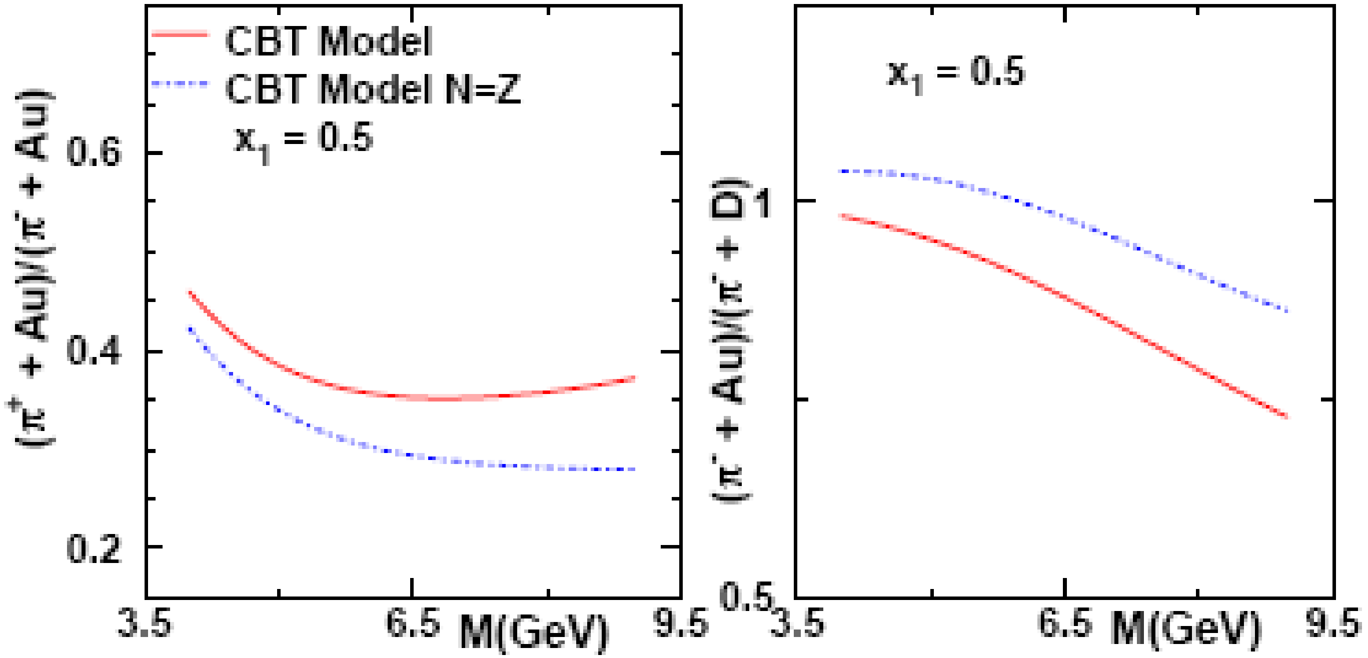


Red (blue) curves correspond to flavor-dependent (independent) EMC

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

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

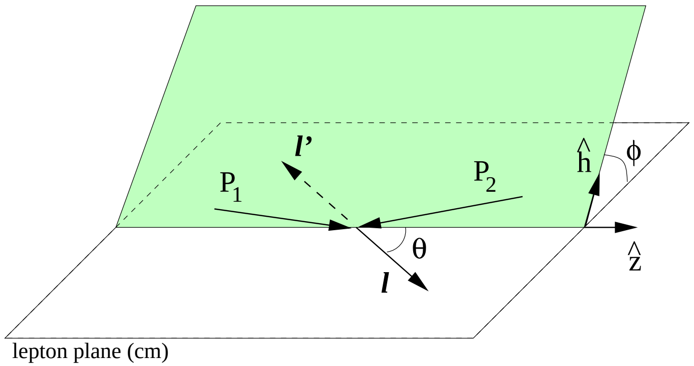
$$\frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4u_A(x)}; \qquad \frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$



160 GeV pion beam

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

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:

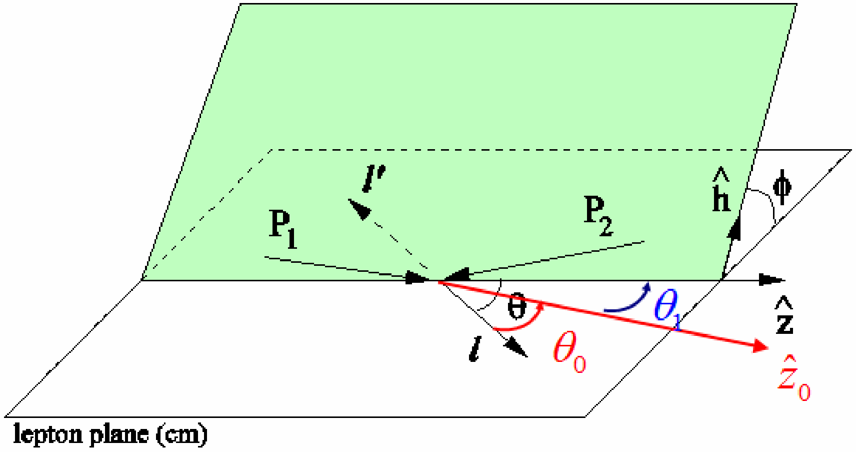
$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right) = \left[\frac{3}{4\pi}\right]\left[1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

$\lambda = 1, \mu = \nu = 0$ for "naive" Drell-Yan (collinear). For non-zero P_T, 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 $q-\bar{q}$ axis

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

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

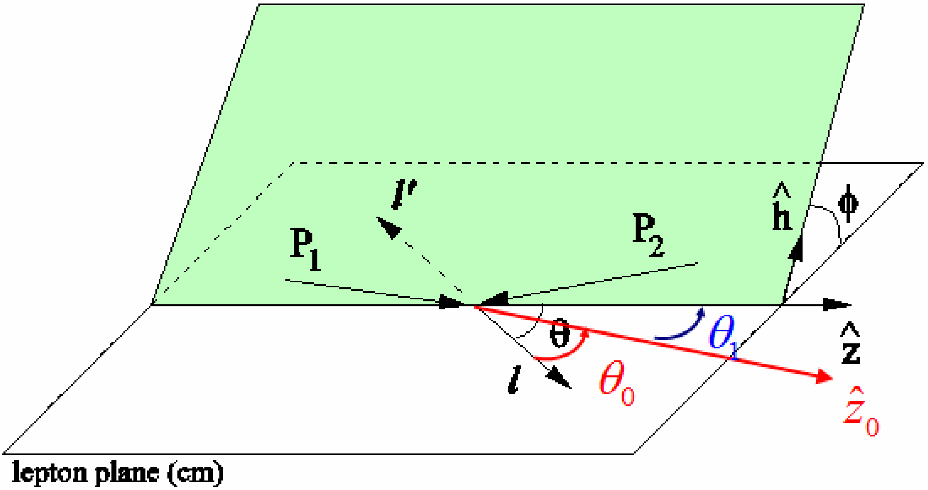
($\lambda_0 = 1$ for spin-1/2 quark;
$\lambda_0 = -1$ for spin-0 quark)

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

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

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

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



Therefore, we have

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

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

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

and

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

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

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

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

Decay angular distributions in pion-induced Drell-Yan

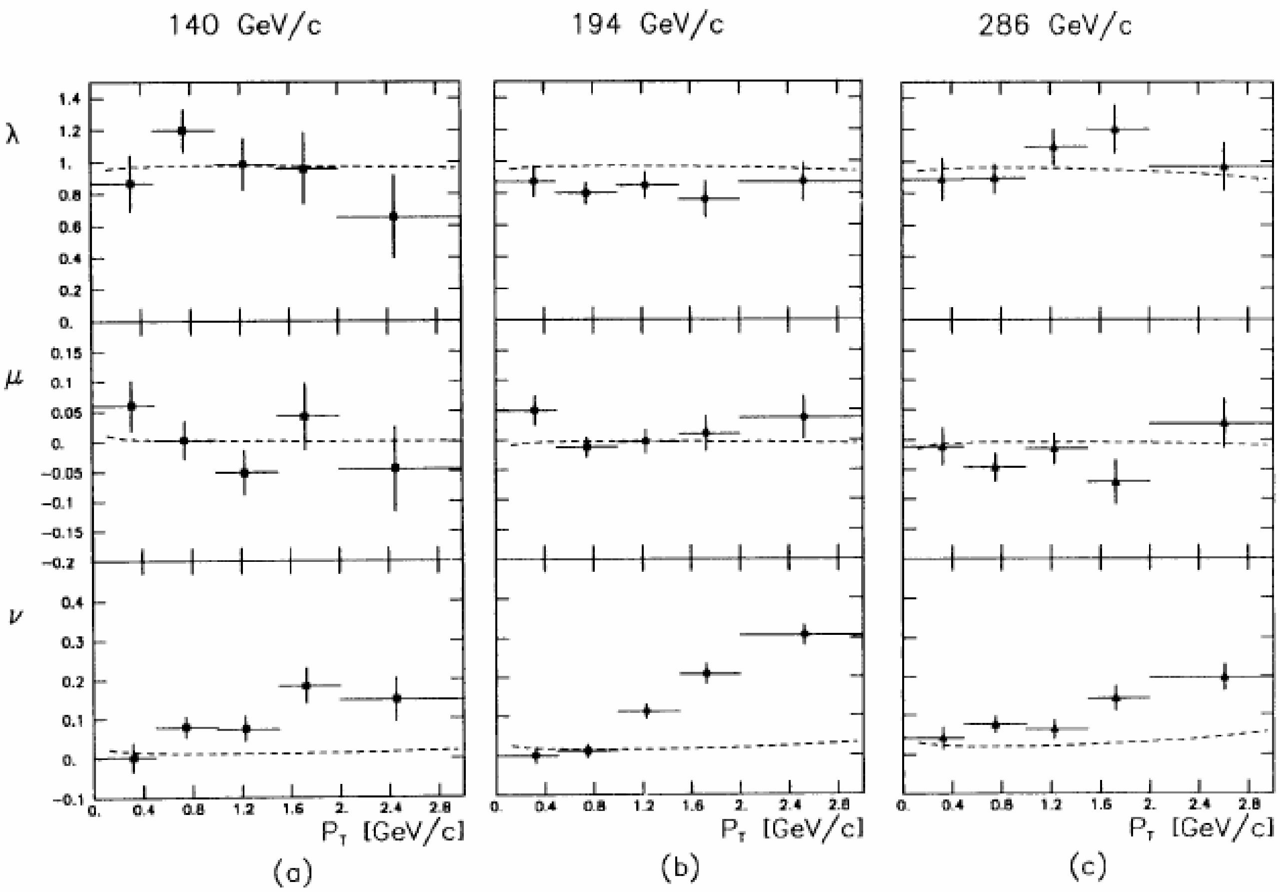


Fig. 3a–c. Parameters λ, μ, and ν as a function of P_T in the CS frame. **a** 140 GeV/c; **b** 194 GeV/c; **c** 286 GeV/c. The error bars correspond to the statistical uncertainties only. The horizontal bars give the size of each interval. The dashed curves are the predictions of perturbative QCD [3]

NA10 $\pi^- + \mathbf{W}$

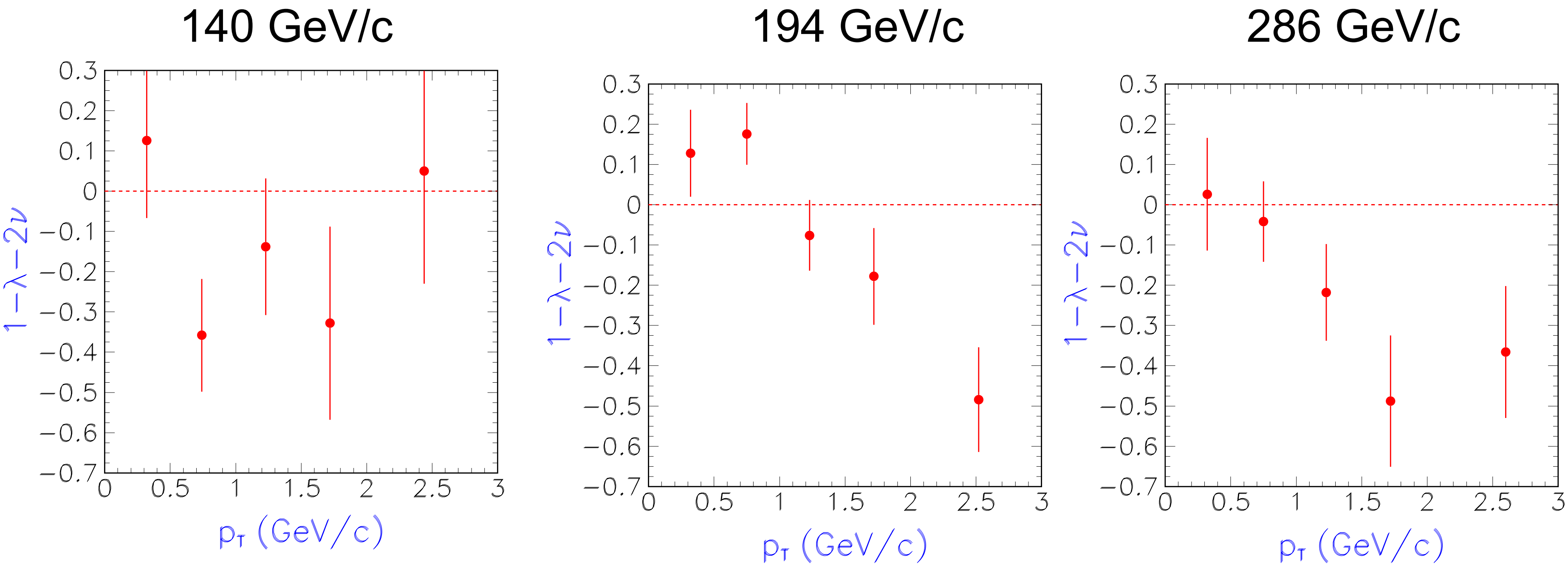
Z. Phys.

37 (1988) 545

Dashed curves are from pQCD calculations

$\nu \neq 0$ and ν increases with p_T

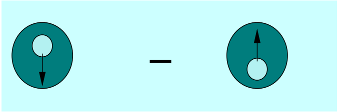
Decay angular distributions in pion-induced Drell-Yan
Is the Lam-Tung relation violated?



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

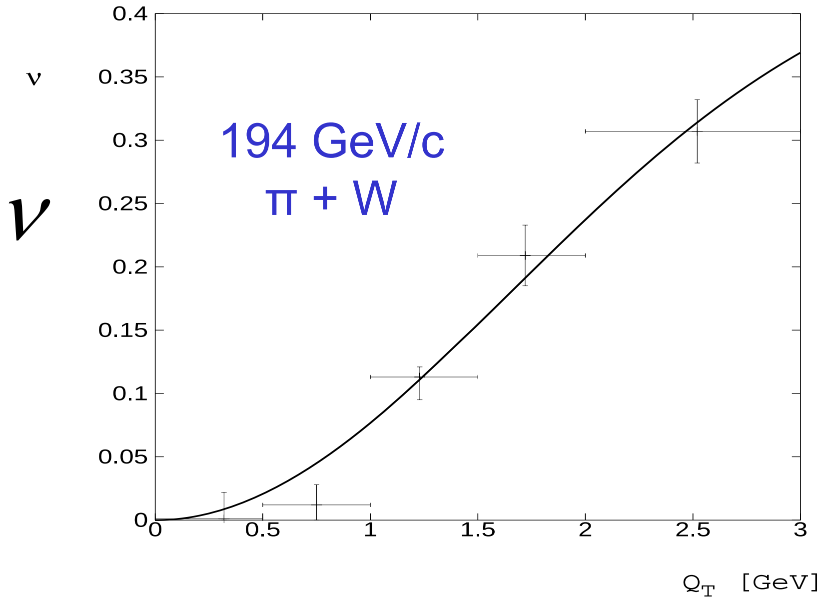
Violation of the Lam-Tung relation suggests new mechanisms with non-perturbative origin

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

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

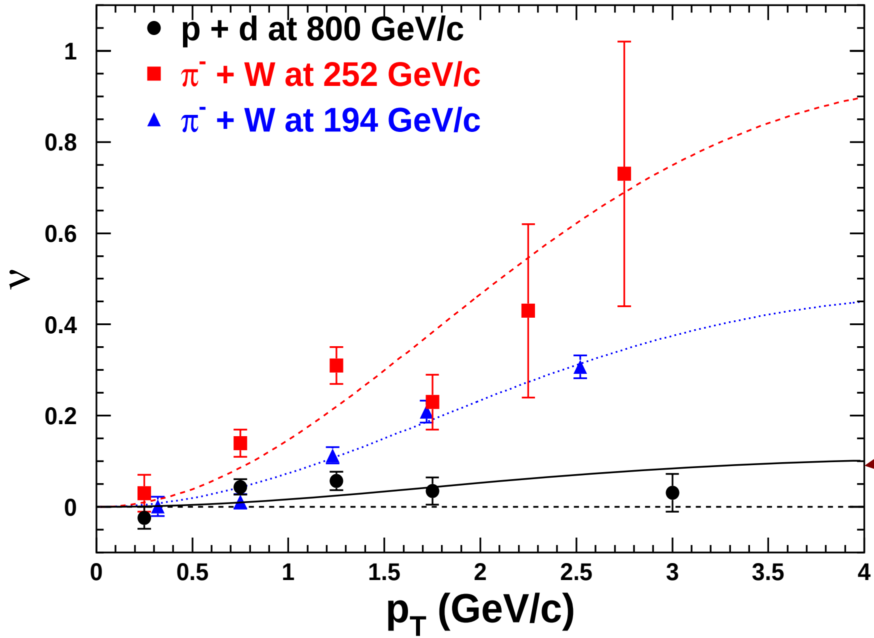


Boer, PRD 60 (1999) 014012

- 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 $h_1^\perp$:

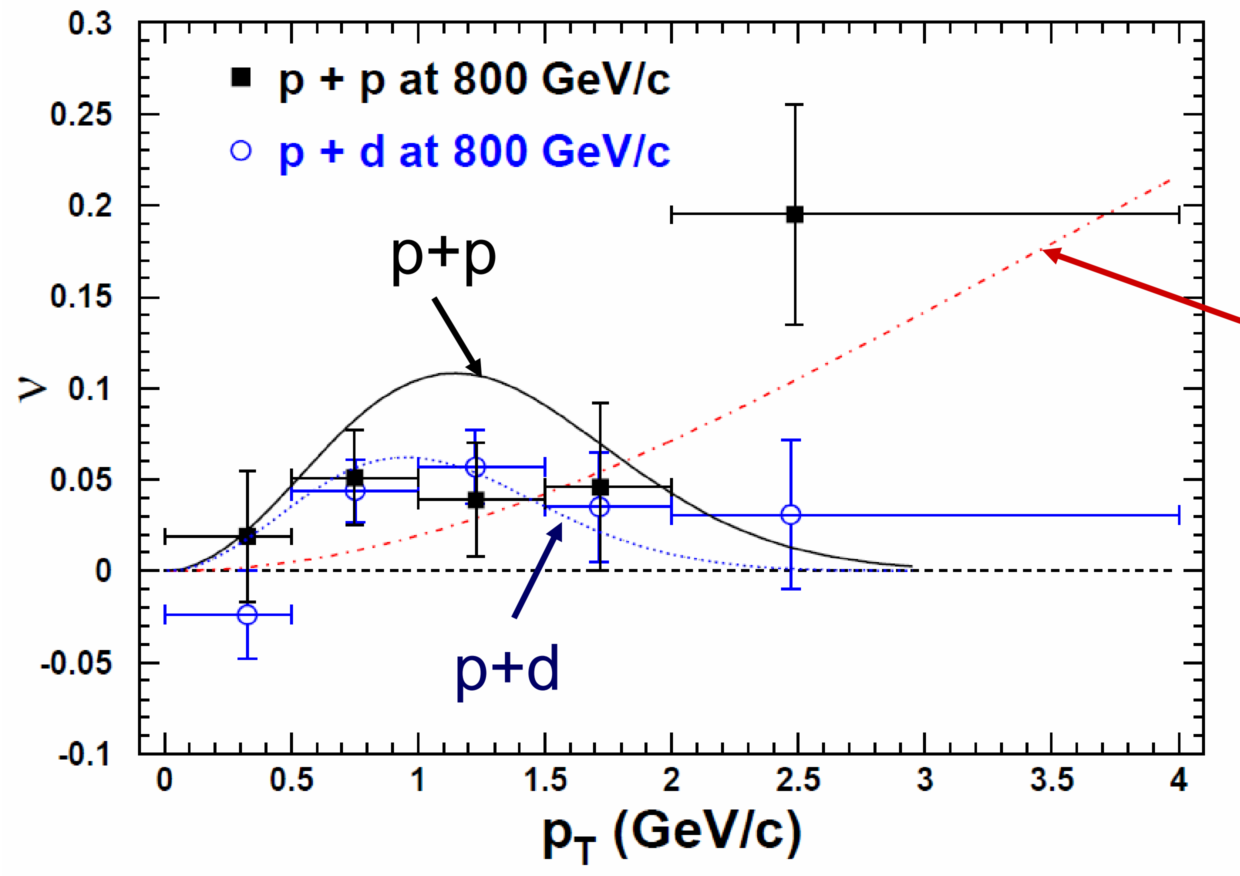
$\nu(\pi^- W \to \mu^+\mu^- X) \sim$ [valence $h_1^\perp(\pi)$] * [valence $h_1^\perp(p)$]

$\nu(pd \to \mu^+\mu^- X) \sim$ [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



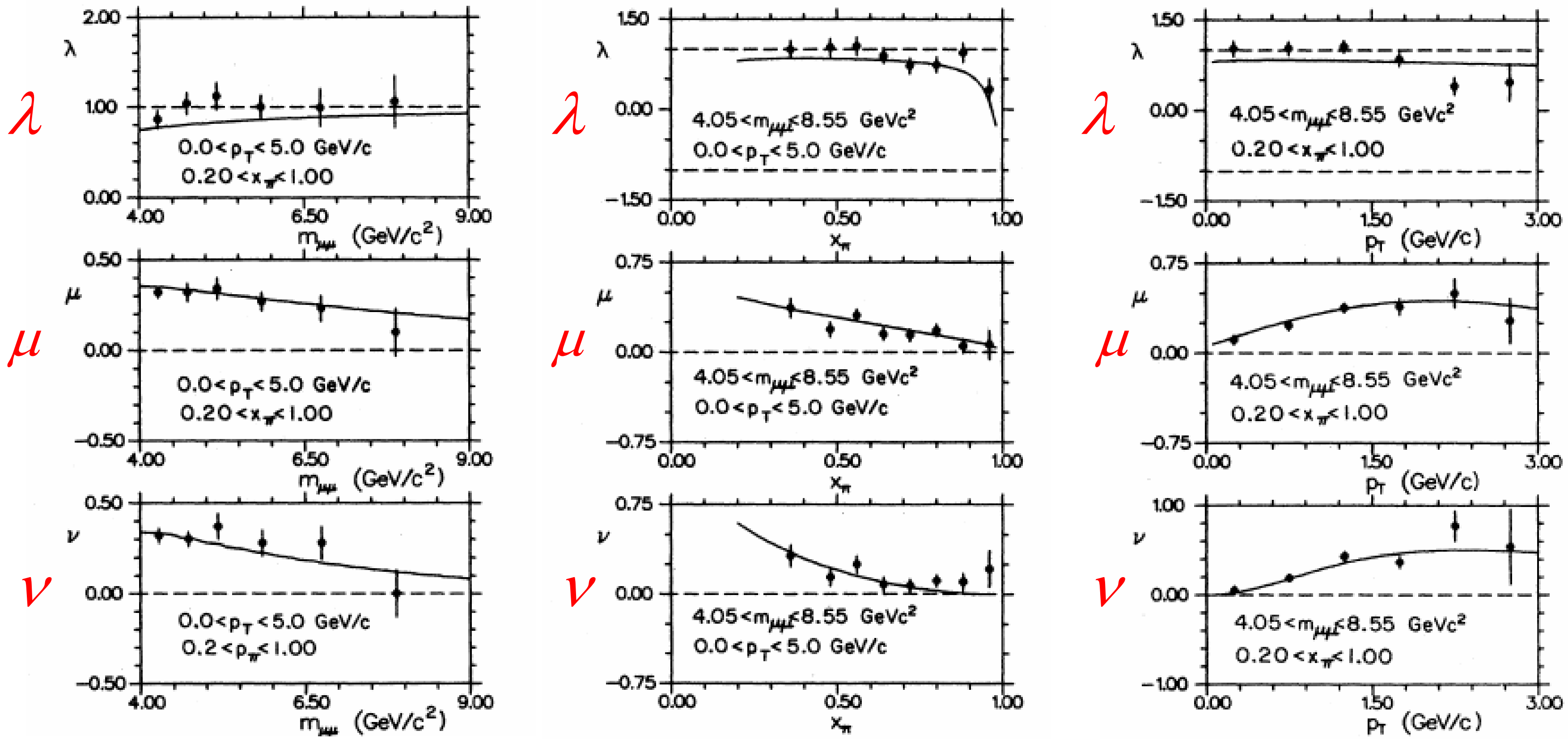
QCD
(Boer, Vogelsang; Berger, Qiu, Rodriguez-Pedraza)

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

More data are anticipated from future DY exps.

Decay angular distributions in pion-induced Drell-Yan

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



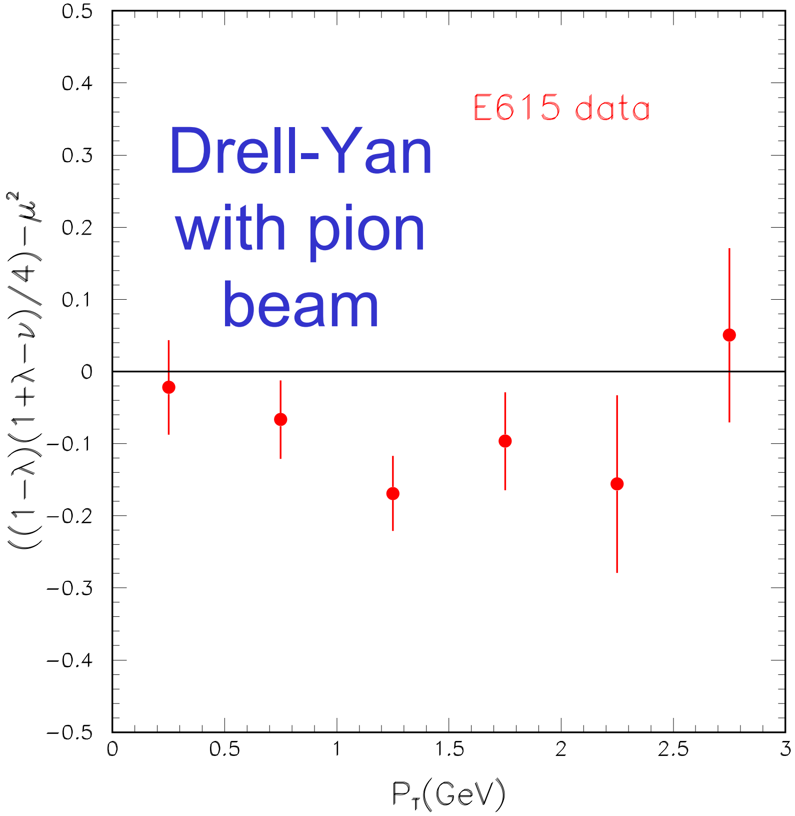
$m_{\mu\mu}(\text{GeV/c}^2)$ x_π $p_T\,(\text{GeV/c})$

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

$\mu^2 \le (1-\lambda)(1+\lambda-\nu)/4$ 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 Drell-Yan data 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)

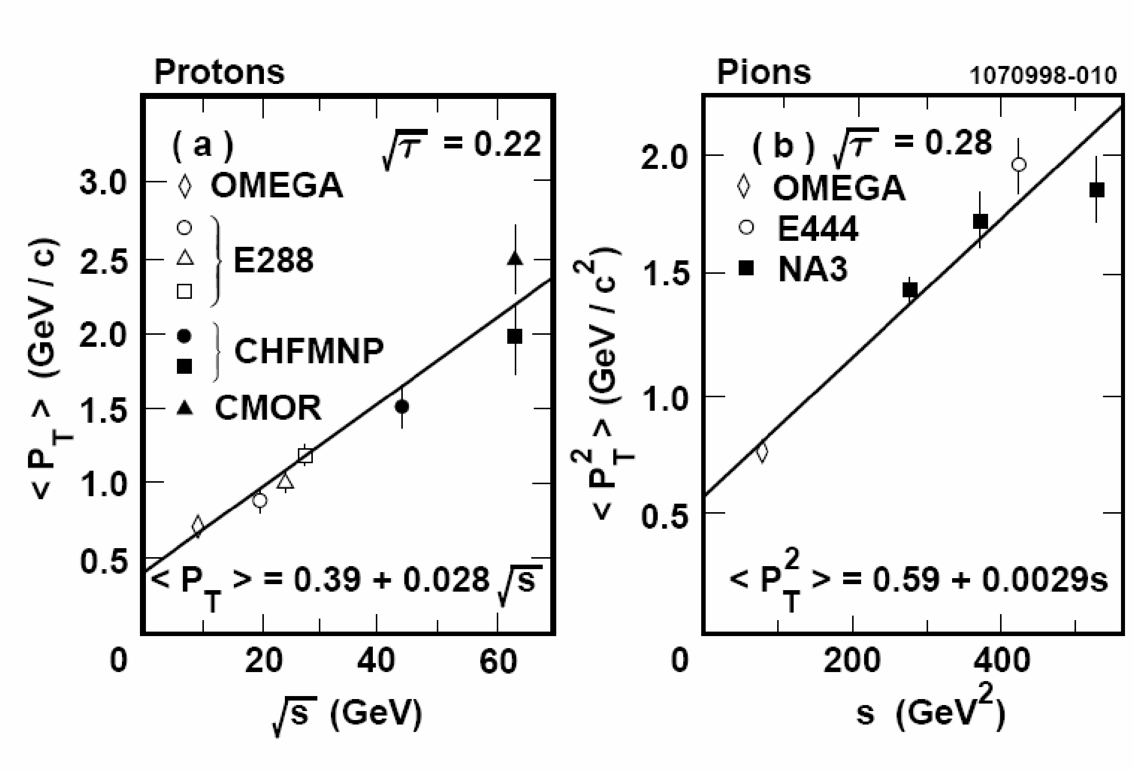
Remains to be tested experimentally!

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 $\mathrm{P_T}$ of proton, pion, and kaon induced Drell-Yan

Drell-Yan with proton beam:

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

Drell-Yan with pion beam:

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

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

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

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

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

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

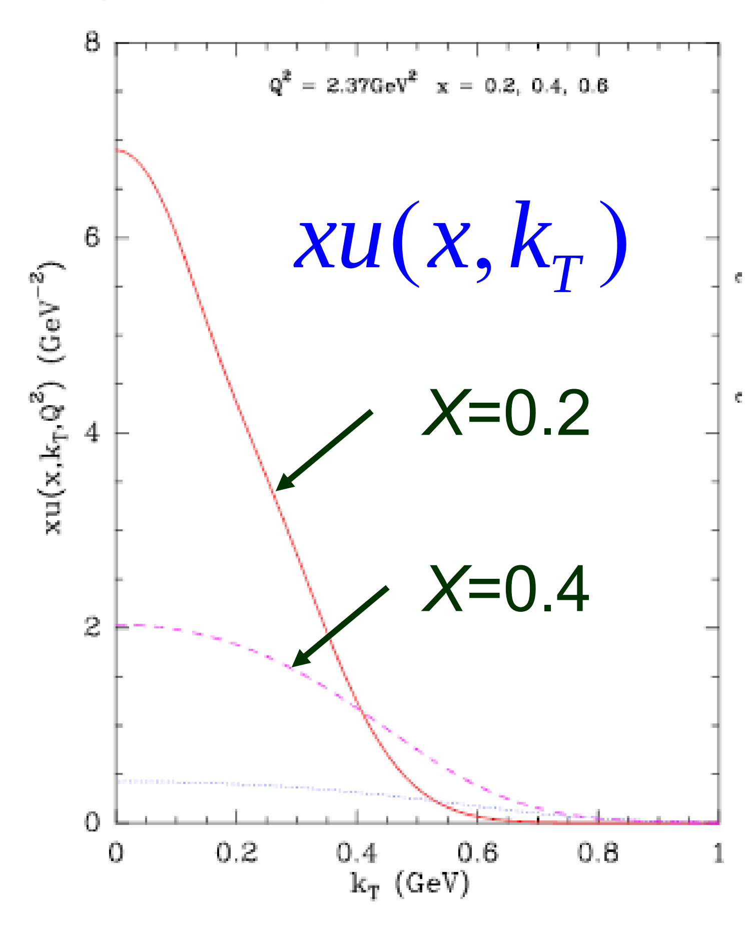
$$\langle r \rangle^{1/2} = 0.58 \pm 0.02 \mathrm{fm} \text{ for kaon}$$

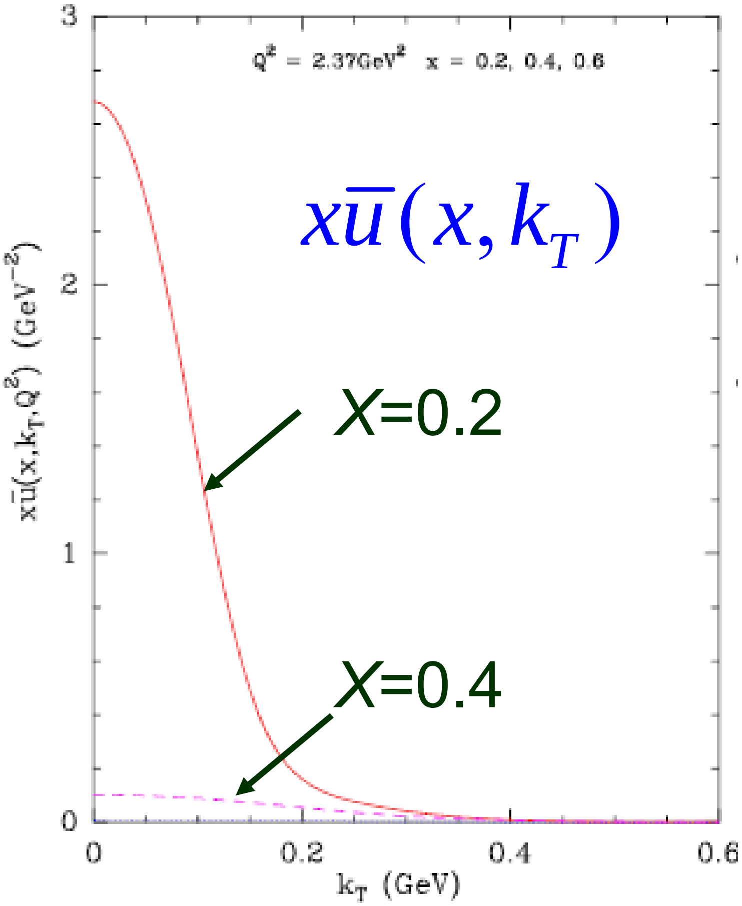
$$\langle r \rangle^{1/2} = 0.67 \pm 0.02 \mathrm{fm} \text{ for pion}$$

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

Flavor and *x*-dependent k_T-distributions?

(Bourrely, Buccella, Soffer, arXiv:1008.5322)

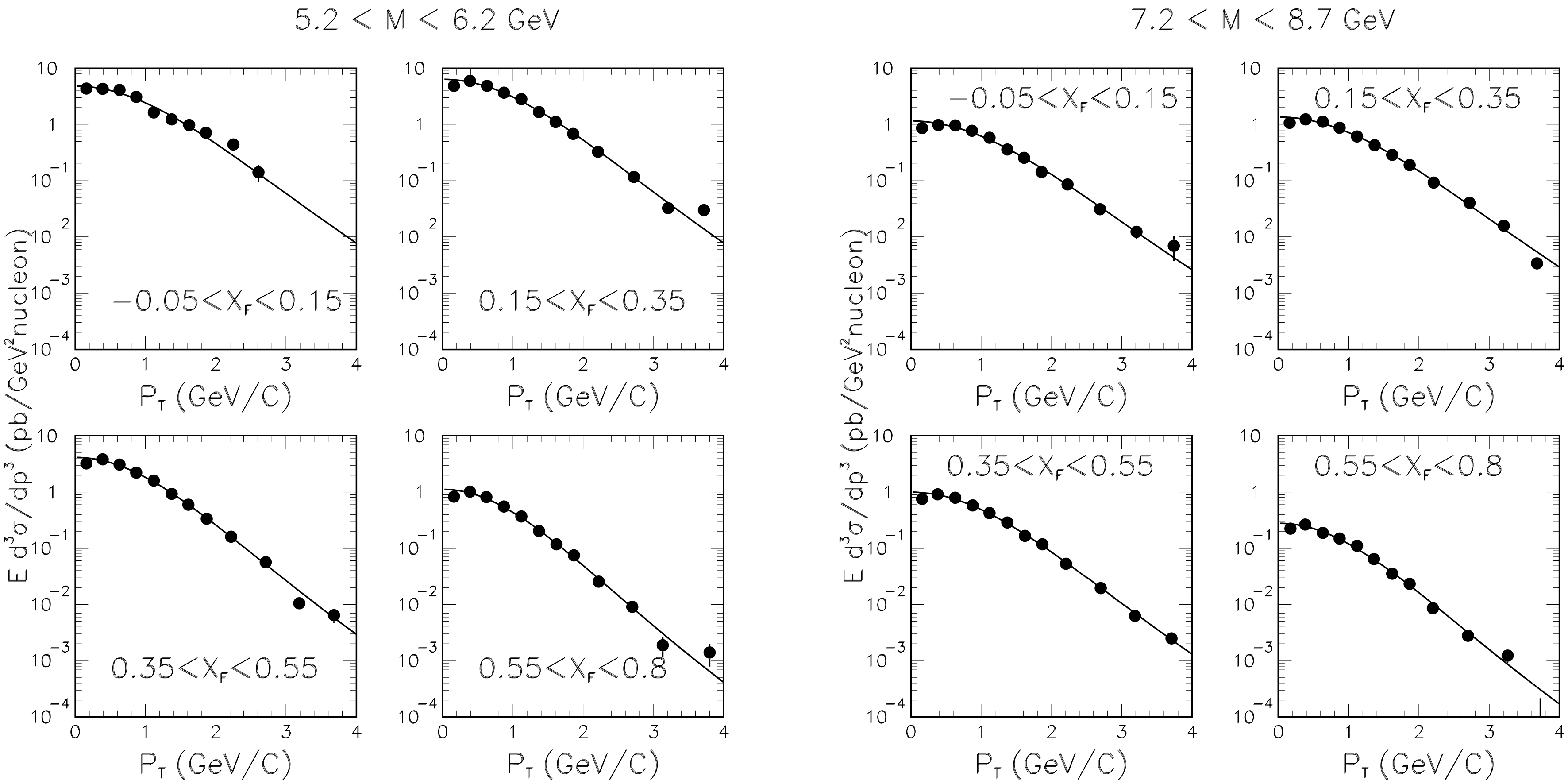




- $\langle k_T \rangle$ increases when x increases
- $\langle k_T \rangle$ for sea quarks is smaller than for valence quarks

Test of possible *x*-dependent k_T-distributions

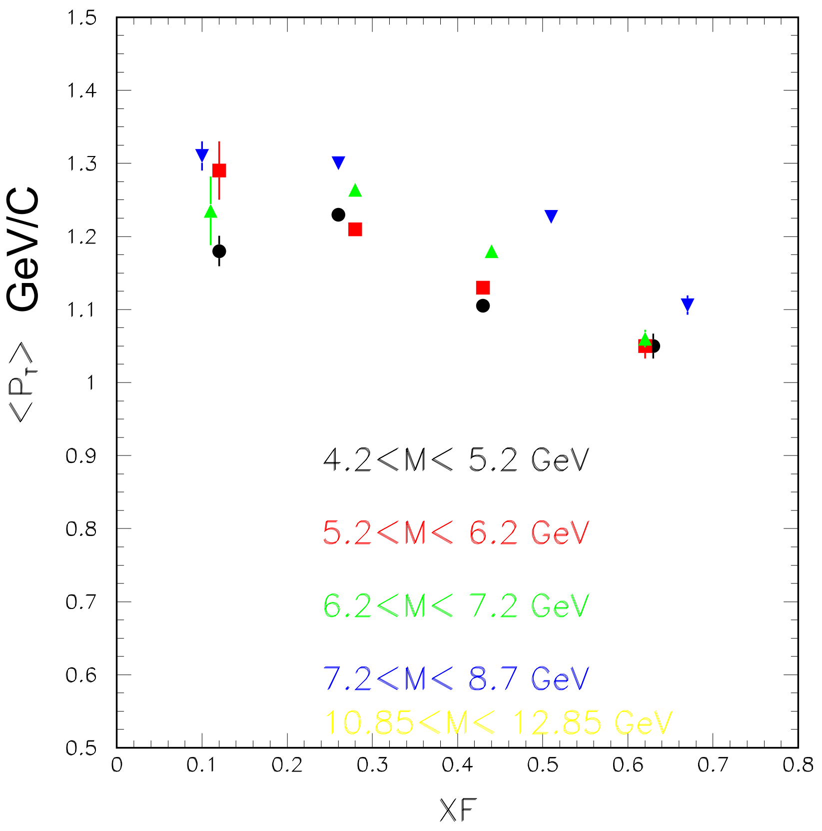
E866 p+d D-Y data (800 GeV beam)

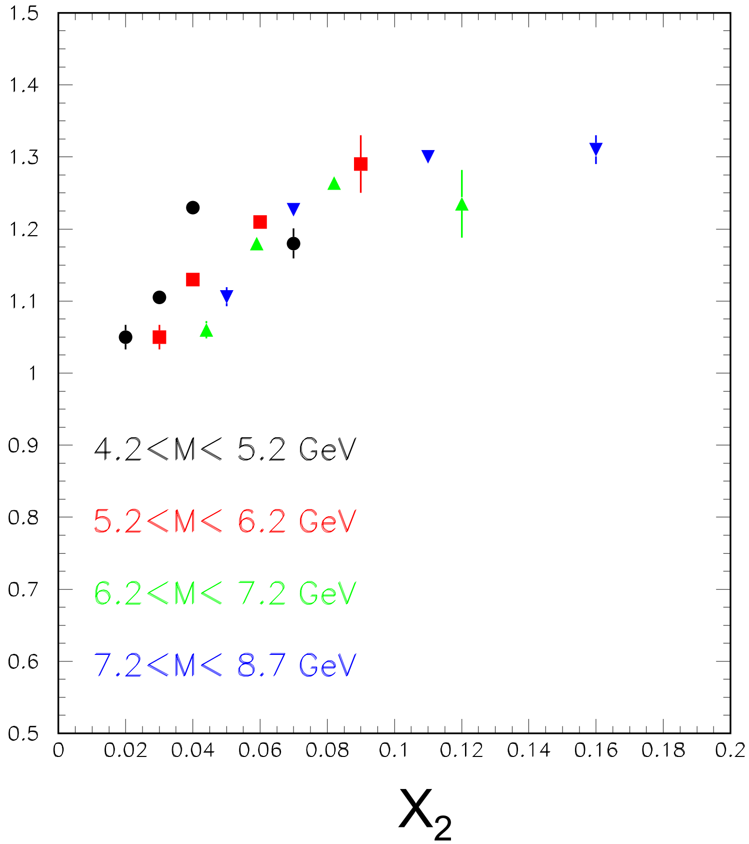


Data from thesis of J. Webb

Possible *x*-dependent k_T-distributions

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



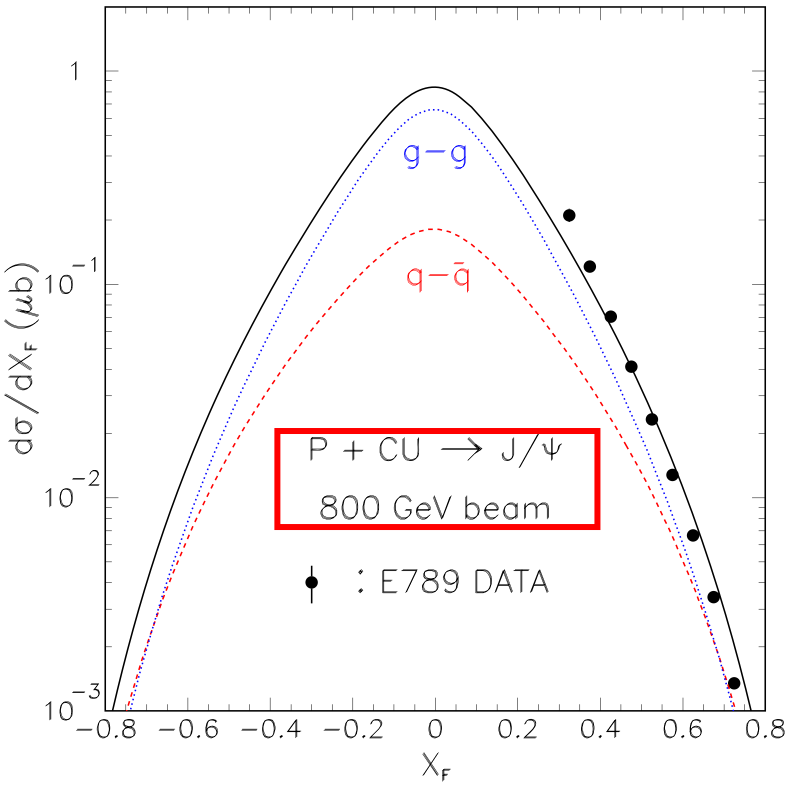


$\langle p_T \rangle$ scale with x_2 ?

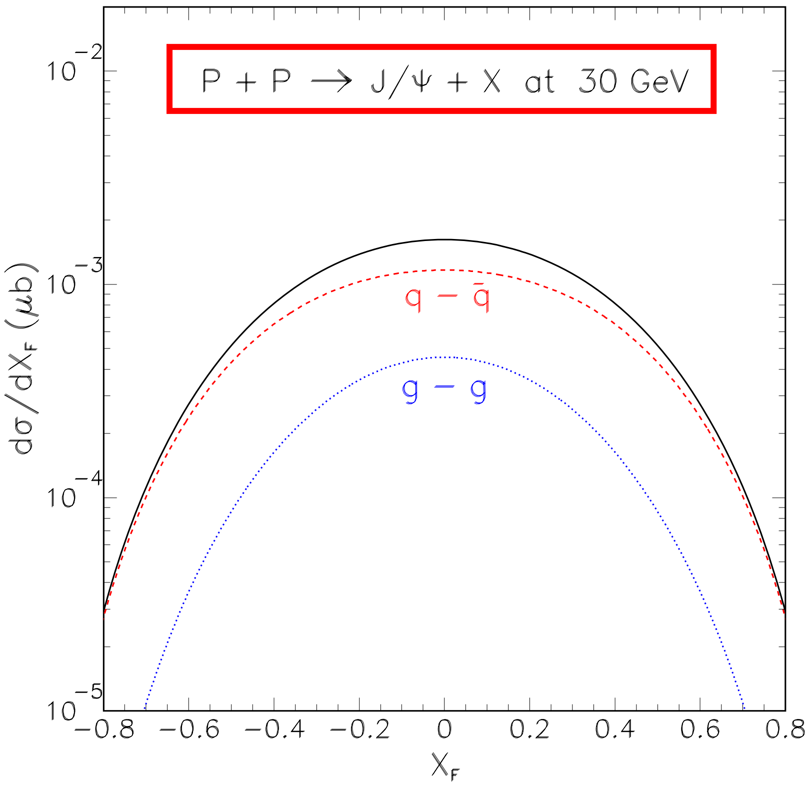
Analysis is ongoing. Future data at lower beam energies are essential

J/Ψ production as an alternative to Drell-Yan?

At 800 GeV, J/Ψ production is dominated by gluon-gluon fusion



At 30 GeV J/Ψ production is dominated by quark-antiquark annihilation

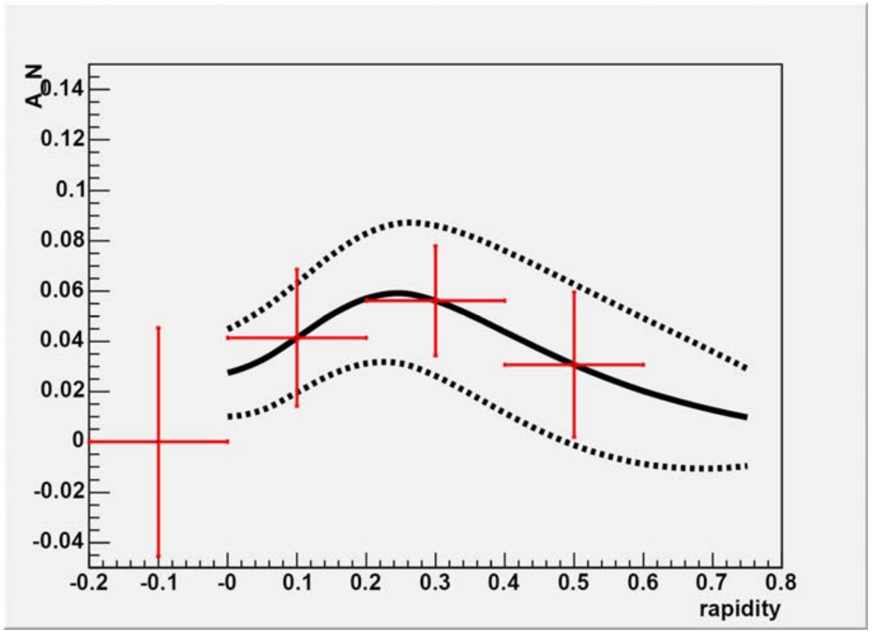


J/Ψ production at 30 GeV is sensitive to quark and antiquark distributions

Single-spin asymmetry in polarized p-p at J-PARC

Single-spin asymmetry (A_N) can probe Sivers function

- Sivers function in Drell-Yan is expected to have a sign opposite to that in DIS



$$A_N^{DY} = \frac{\sum_q e_q^2 f_{1T}^{\perp}(x_q) f_{\bar{q}}(x_{\bar{q}})}{\sum_q e_q^2 f_q(x_q) f_{\bar{q}}(x_{\bar{q}})}$$

← From Y. Goto

- J/Ψ production could also probe the Sivers function

- Much higher statistics could be obtained in J/Ψ production

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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Paul E. Reimer

26 April 2010 24

Slide from Paul Reimer

Summary

- Intrinsic sea quark contents of the nucleons.
  - Probe strange-quark content with kaon-induced DY
- Flavor dependence of the EMC effect.
  - Pion-induced DY on nuclei
- Equalities and inequalities in Drell-Yan azimuthal angular distributions.
  - Unpolarized, singly, and doubly polarized DY
- Flavor and *x*-dependence of quark intrinsic transverse momentum distributions.
  - DY data at low energies
- Drell-Yan and quarkonium production duality.
  - J/Psi as an alternative tool for DY physics at low energies