Hadron Structure with Dimuon Production

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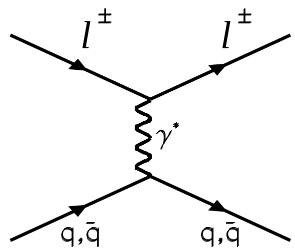
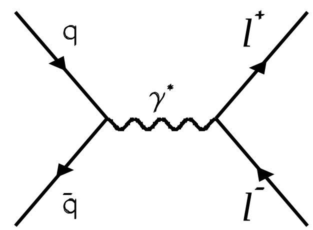
Outline

- Some highlights from Fermilab dimuon experiments
- Recent results from Fermilab E866
- Future prospects at Fermilab and J-PARC

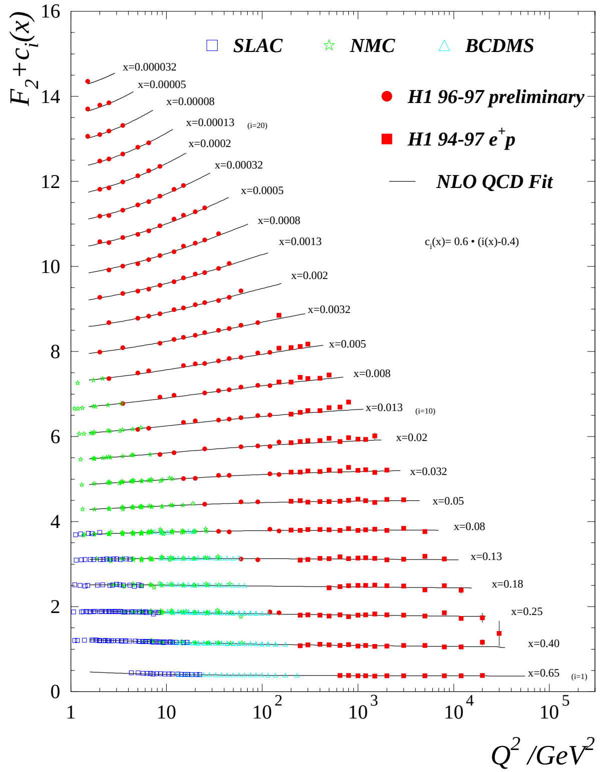
Deep-Inelastic Scattering versus Drell-Yan

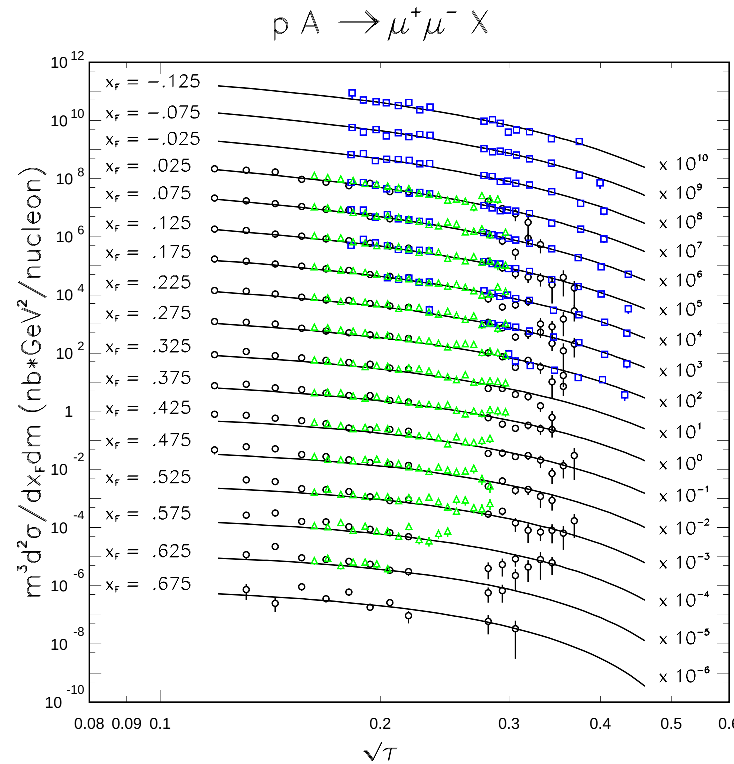
DIS





Drell-Yan





Drell-Yan cross sections are well described by NLO calculations

A Brief History

1) Fermilab E772
- "Nuclear Dependence of Drell-Yan and Quarkonium Production"
- Proposed in 1986 and completed in 1988

2) Fermilab E789
- "Search for Two-Body Decays of Heavy Quark Mesons"
- Proposed in 1989 and completed in 1991

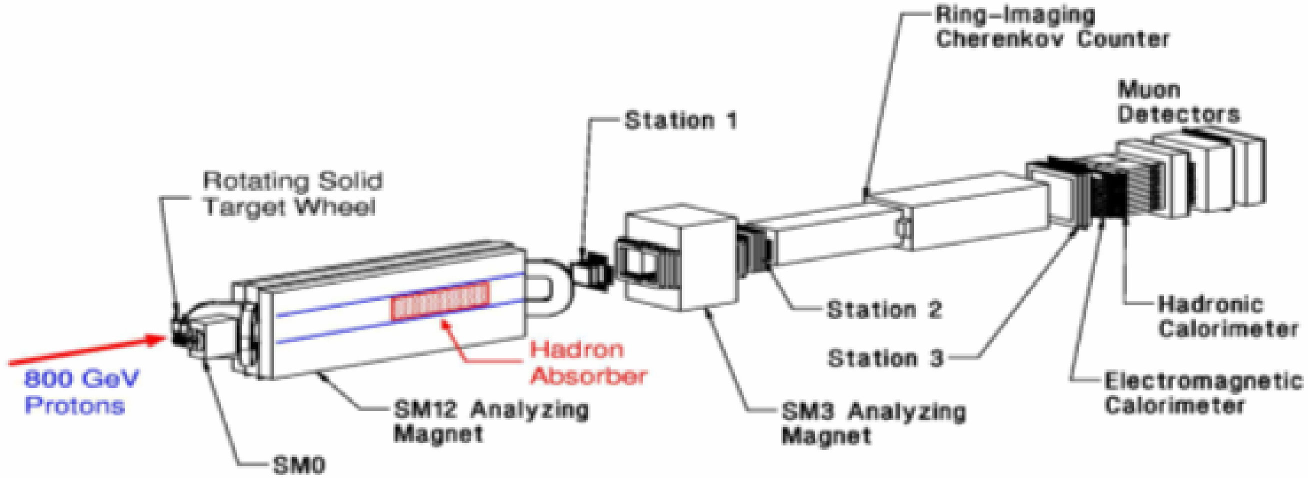
3) Fermilab E866
- "Determination of $\bar{d}/\bar{u}$ Ratio of the Proton via Drell-Yan"
- Proposed in 1993 and completed in 1996

4) Fermilab E906
- "Drell-Yan Measurements of Nucleon and Nuclear Structure with the FNAL Main Injector"
- Proposed in 2001

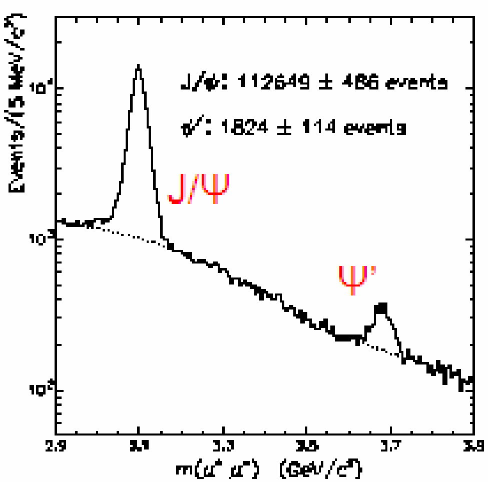
5) J-PARC P-04 (P-24)
- "Measurement of High-Mass Dimuon Production at the 50-GeV Proton Synchrotron" ("Polarized Proton at J-PARC")
- Proposed in 2007/2008

Meson East Spectrometer

(E605/772/789/866)

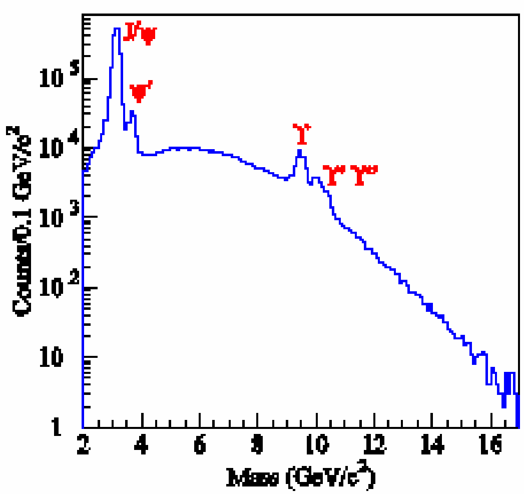


Open-aperture



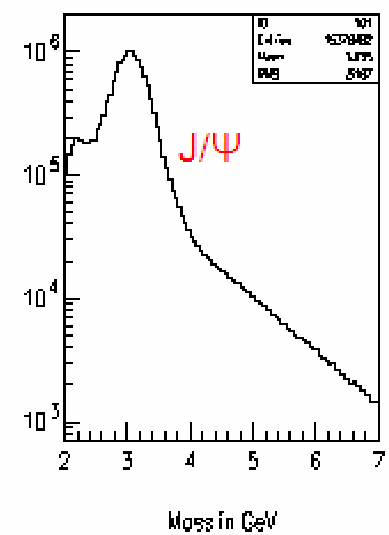
σ(J/ψ) ~ 15 MeV

Closed-aperture



σ(J/ψ) ~ 150 MeV

Beam-dump (Cu)



σ(J/ψ) ~ 300 MeV

Physics with High-Mass Dimuons

1) Drell-Yan process:

- Antiquarks in nuclei and nucleons
- Quark energy loss in nuclear medium
- Drell-Yan angular distributions

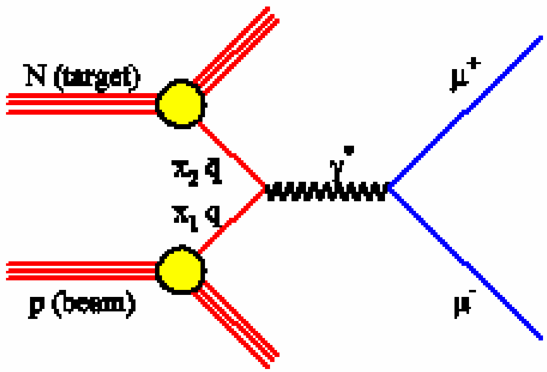
2) Quarkonium production:

- Pronounced nuclear dependence
- Production mechnism and polarizations
- Gluon distributions in the nucleons

3) Heavy quark production:

- Open charm production
- B-meson production

EMC Effect and the Drell-Yan Process

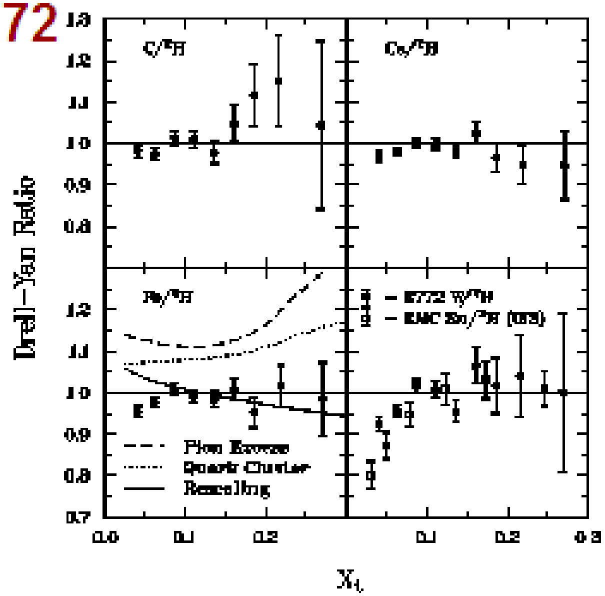


$$pA \rightarrow \mu^+ \mu^- X$$

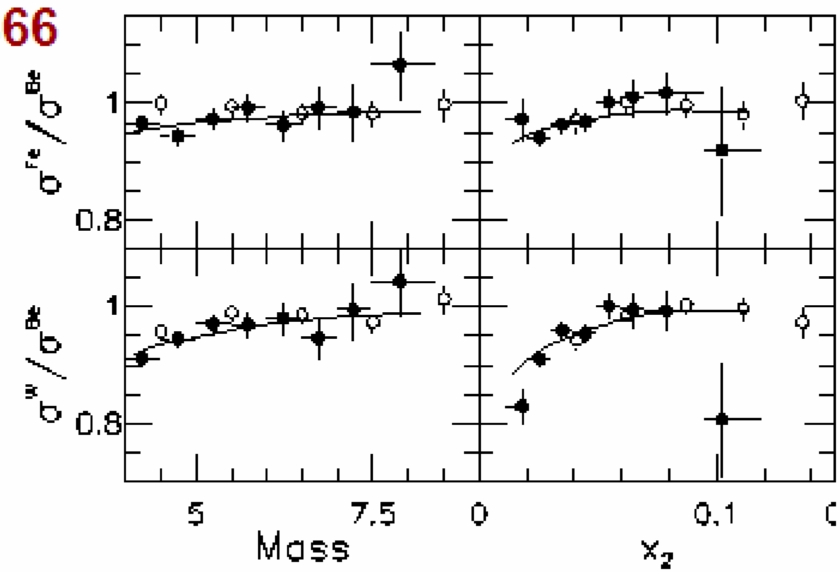
$$\frac{\sigma^{pA}}{\sigma^{pd}} \approx \frac{\bar{u}_A(x)}{\bar{u}_N(x)}$$

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

E772



E866



No evidence for pion excess in nucei

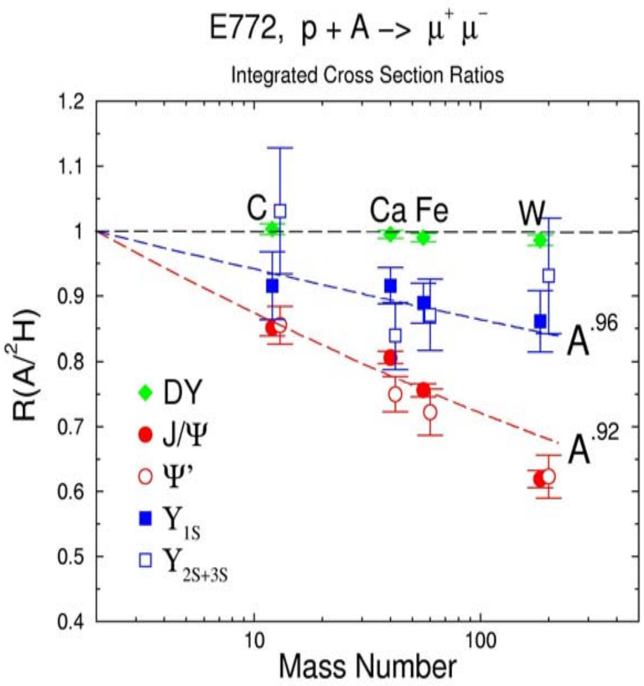
Nuclear effects of quarkonium productions

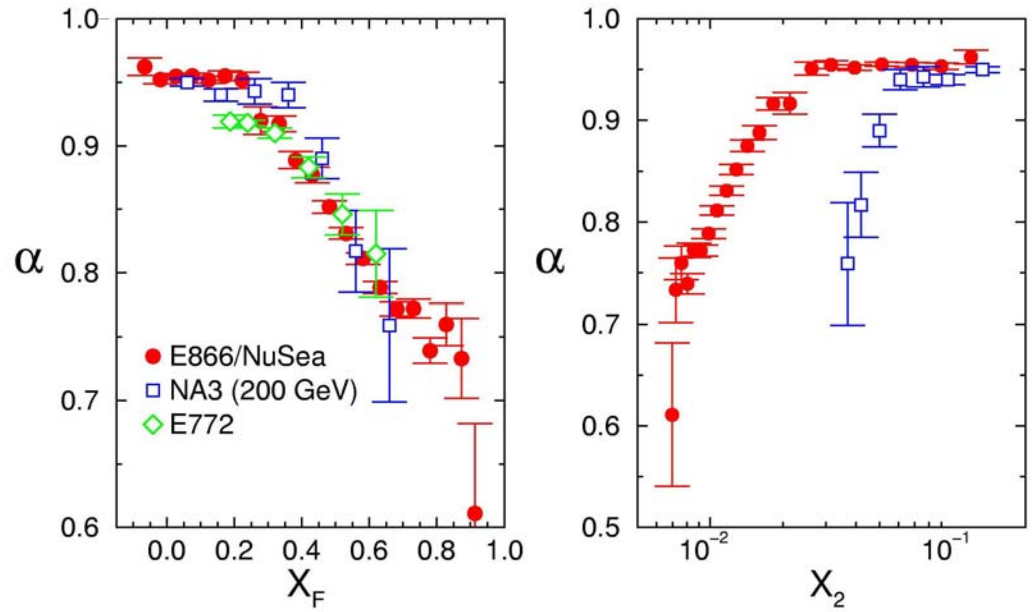
p + A at 800 GeV/c

E772 data

$\sigma(p+A) = A^{\alpha}\sigma(p+N)$

Strong x_F - dependence



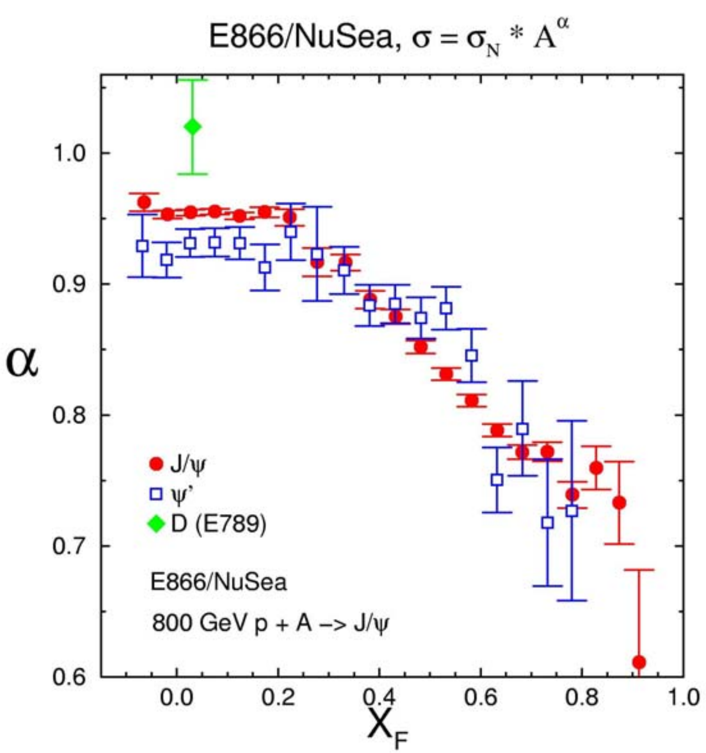


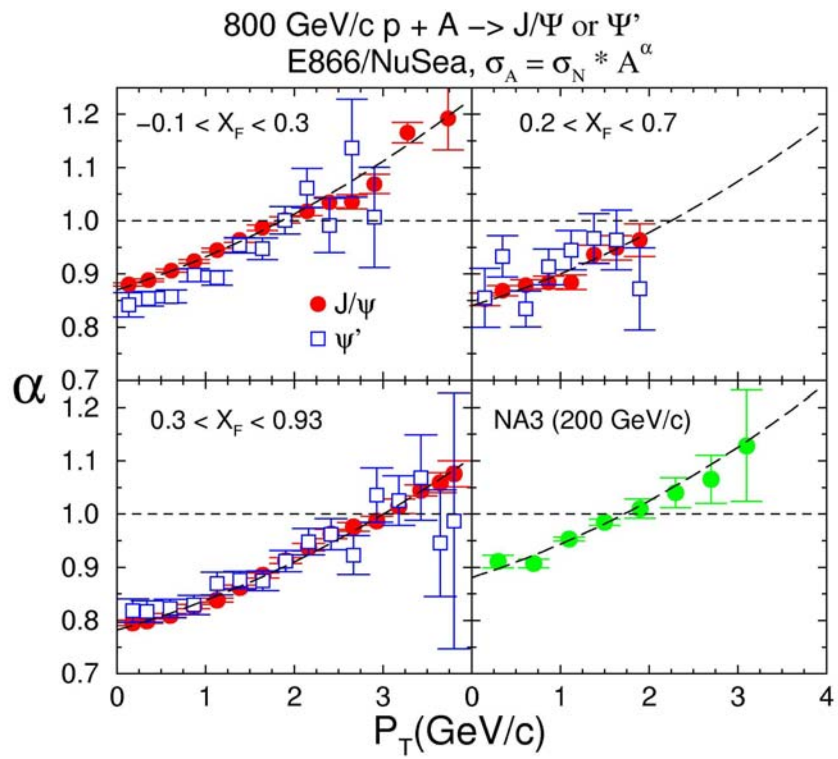
Nuclear effects scale with x_F, not x_2

What about A-dependence of Ψ' or open-charm production?

Comparison between the J/Ψ and Ψ' nuclear effects

p + A → J/Ψ or Ψ' at $s^{1/2}$ = 38.8 GeV





α(x_F) is largely the same for J/Ψ and Ψ'

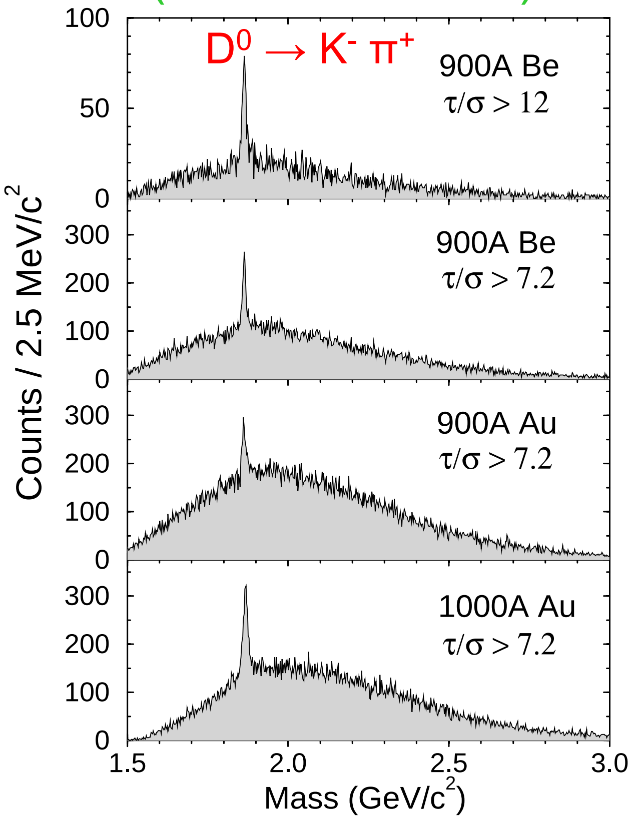
'Universal' behavior for α(p_T) (similar for J/Ψ, Ψ')

Nuclear effects of open-charm production

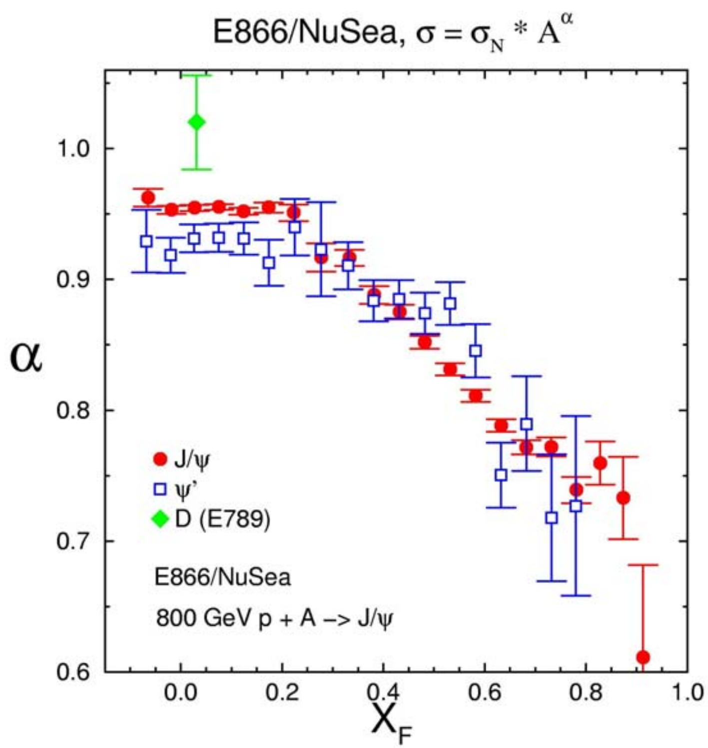
$p + A \rightarrow D + x$ at $s^{1/2} = 38.8$ GeV

E789 open-aperture, silicon vertex + dihadron detection

h^+h^- mass spectrum
(after vertex cut)



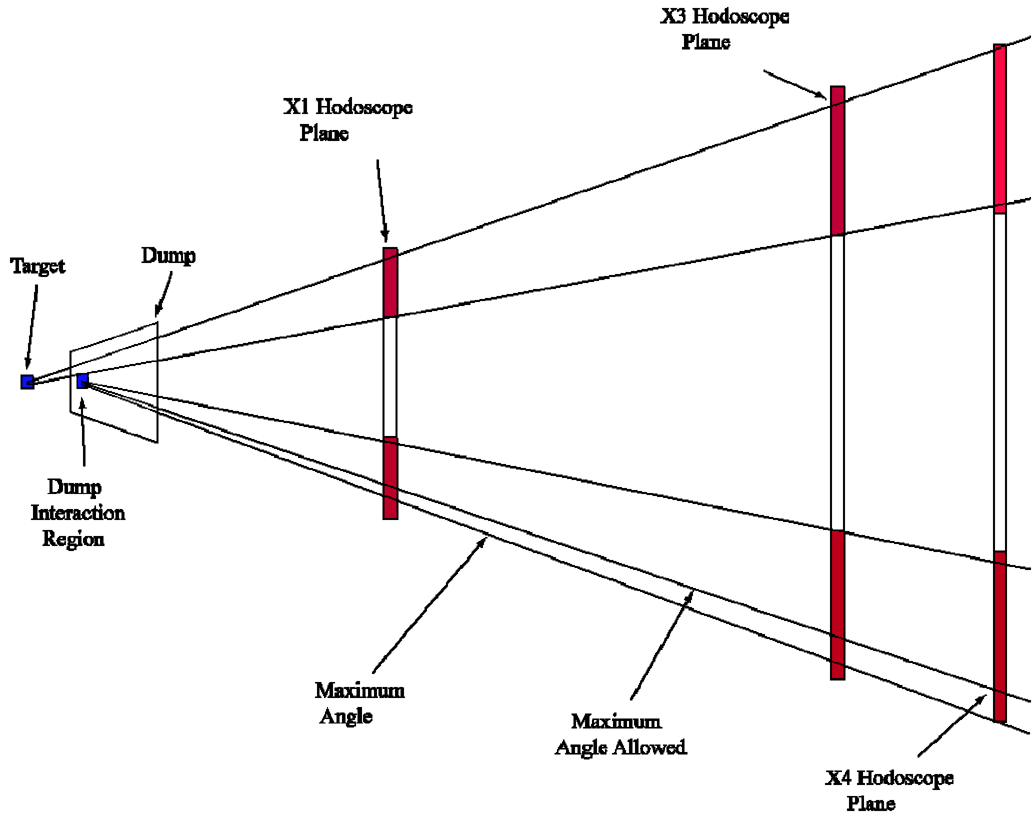
No nuclear effect for D production (at xF ~ 0)



Need to extend the measurements to large x_F region

Single muon measurement in E866 p+A

Thesis of Stephen Klinksiek



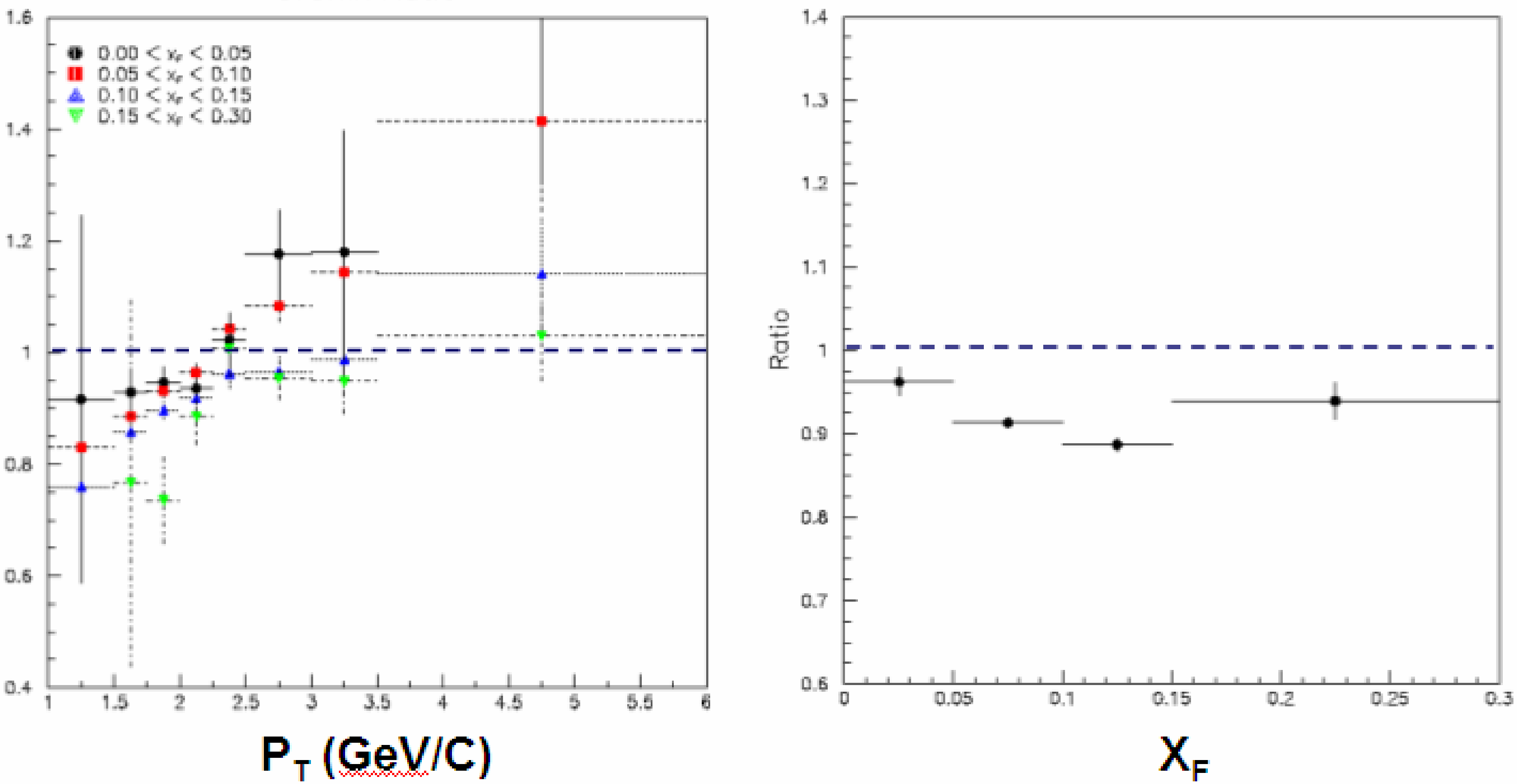
Targets (Z = -24.0")
0 = Empty
1 = 0.502 " Copper
2 = 2.036 " Beryllium
3 = 1.004 " Copper

High-p_T Single Muon Trigger

High-p_T single muon events are dominated by D-meson decays

Preliminary E866 results on the single-muon (open-charm) nuclear-dependence

Cu / Be Ratios



P_T and X_F dependences have similar trend as J/Ψ

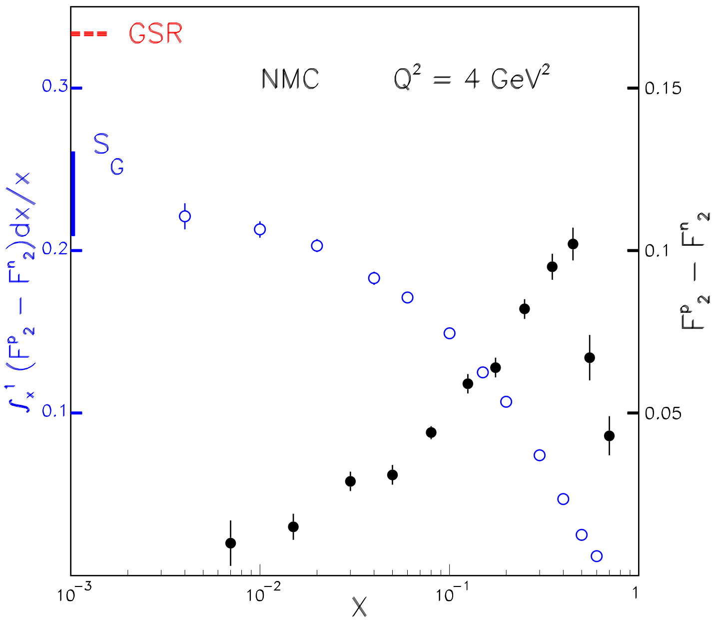
Is $\bar{u} = \bar{d}$ in the proton?

Test of the Gottfried Sum Rule

$$S_G = \int_0^1 [(F_2^p(x) - F_2^n(x))/x]\,dx$$

$$= \frac{1}{3} + \frac{2}{3}\int_0^1 (\bar{u}_p(x) - \bar{d}_p(x))\,dx$$

$$= \frac{1}{3} \qquad (if\ \bar{u}_p = \bar{d}_p)$$

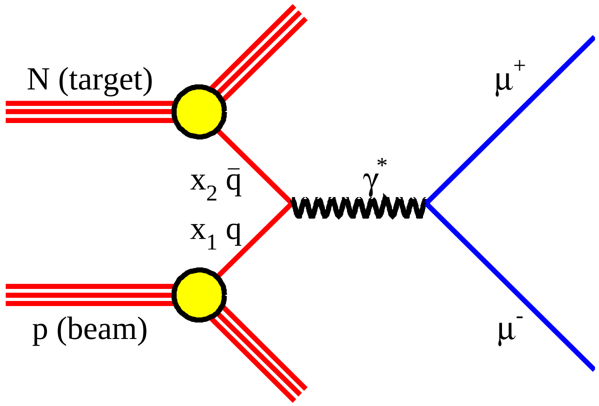


New Muon Collaboration (NMC) obtains

S_G = 0.235 ± 0.026

(Significantly lower than 1/3 !)

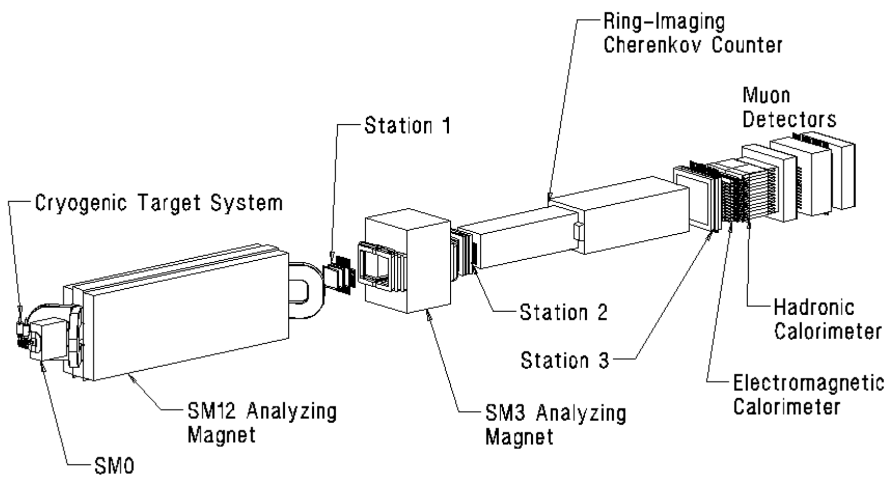
$\bar{d}/\bar{u}$ asymmetry and the Drell-Yan process



$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x)}{\bar{u}(x)}\right]$$

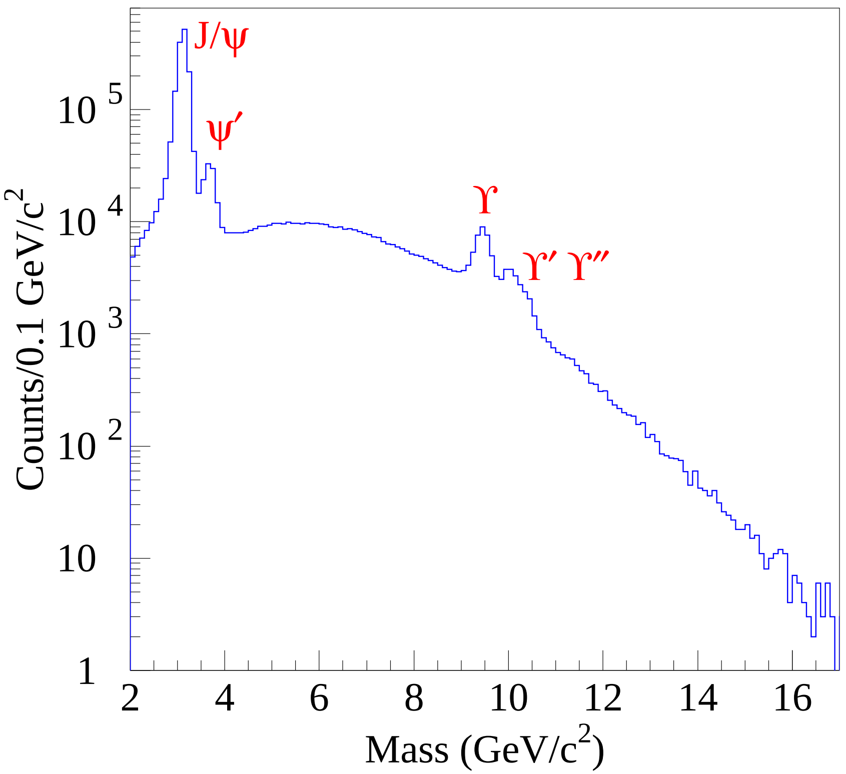
The x-dependence of $\bar{d}(x)/\bar{u}(x)$ can be directly measured

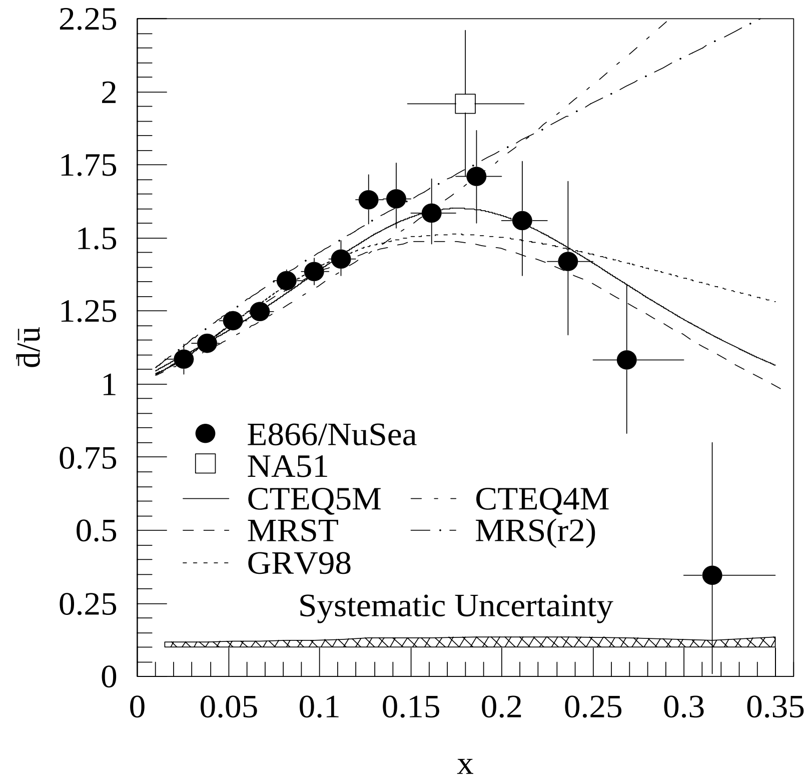
FNAL E866 (NUSEA)



Fermilab E866 Measurements

$$800\ GeV\ \ \sigma(p+d \rightarrow \mu^+ \mu^- X)/2\sigma(p+p \rightarrow \mu^+ \mu^- X)$$

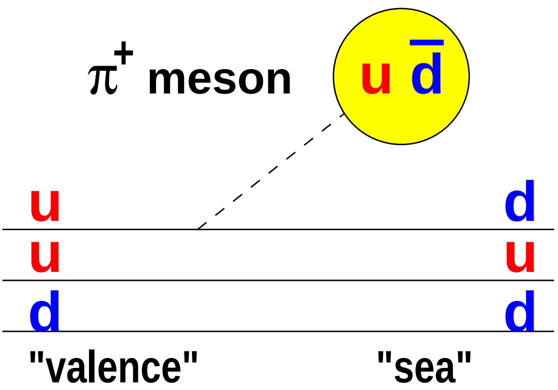




$$Drell-Yan:\ \ \sigma^{pd}/2\sigma^{pp} \simeq \frac{1}{2}[1+\bar{d}(x)/\bar{u}(x)]$$

Models for $\bar{d}/\bar{u}$ asymmetry

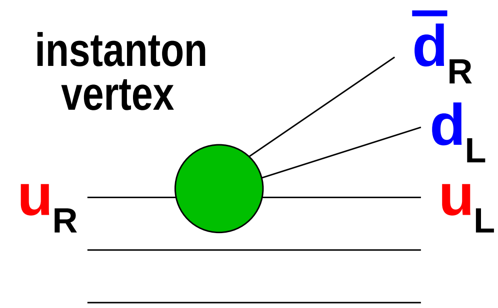
Meson Cloud Models



Chiral-Quark Soliton Model

- nucleon = chiral soliton
- expand in 1/*Nc*
- Quark degrees of freedom in a pion mean-field

Instantons



(For reviews, see Kumano (hep-ph/9702367), Garvey and Peng (nucl-ex/0109010))

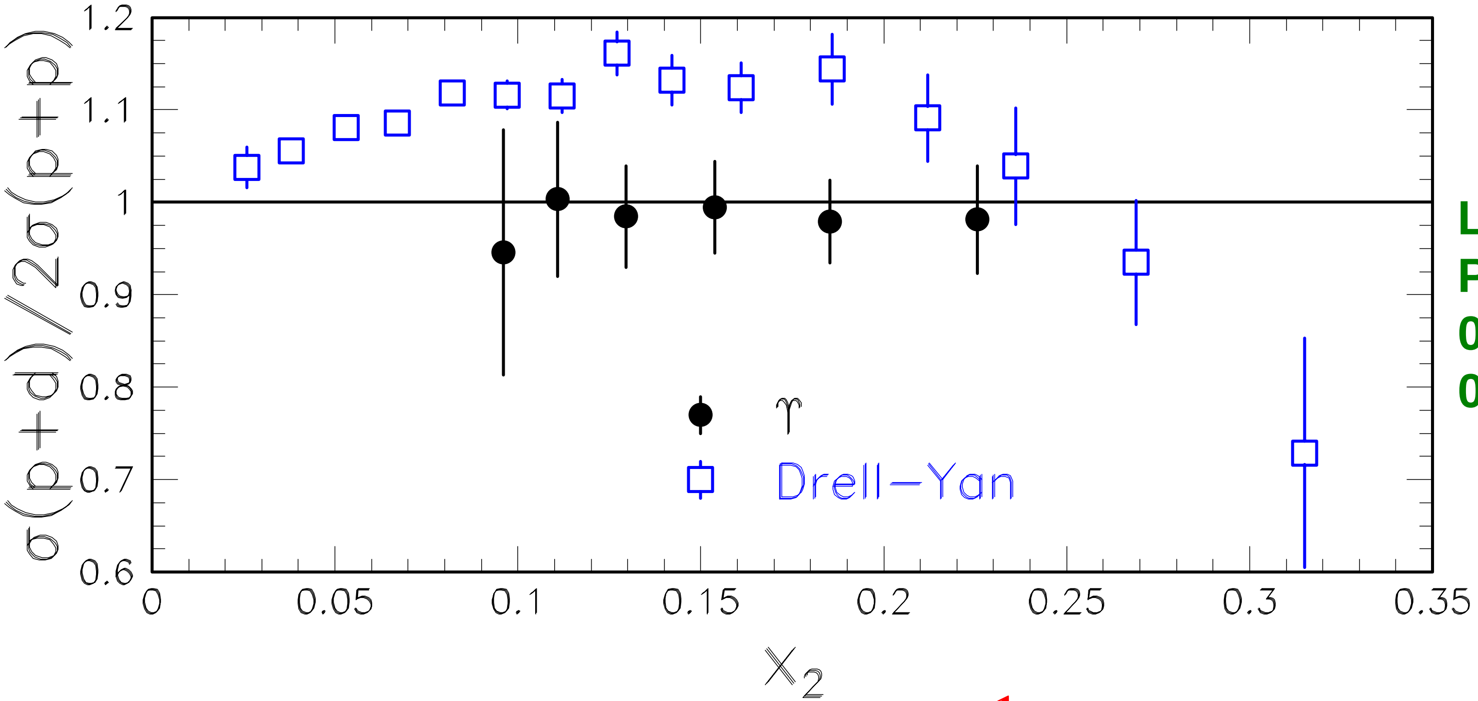
Theses models also have implications on

- asymmetry between $s(x)$ and $\bar{s}(x)$
- flavor structure of the polarized sea

Meson cloud has significant contributions to sea-quark distributions (Thomas (1983))

Do proton and neutron have identical gluon distributions?

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

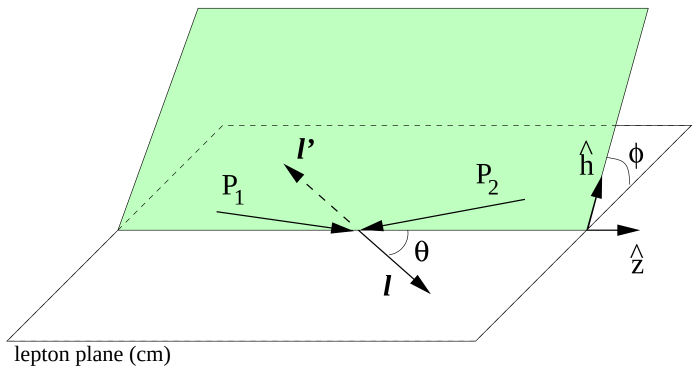


Lingyan Zhu et al., PRL, 100 (2008) 062301 (arXiv: 0710.2344)

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

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

Drell-Yan decay angular distributions



$$h_1 + h_2 \to \gamma^* + x \to l^+ + l^- + x \quad (q + \bar{q} \to \gamma^*)$$

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

Collins-Soper frame

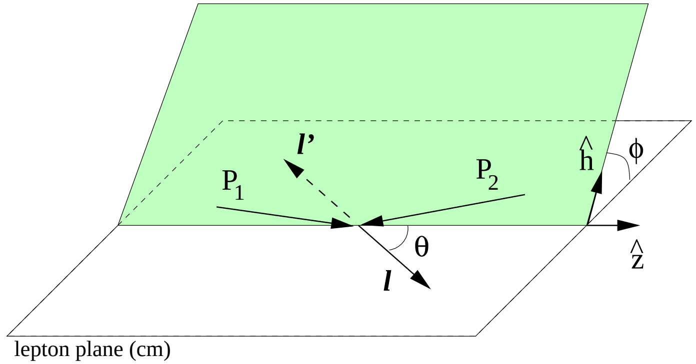
A general expression for Drell-Yan decay angular distributions:

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

"Naive" Drell-Yan (transversely polarized γ^*, no transverse momentum) $\to \lambda = 1,\ \mu = 0,\ \nu = 0$

In general : $\lambda \neq 1,\ \mu \neq 0,\ \nu \neq 0$

Drell-Yan decay angular distributions



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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

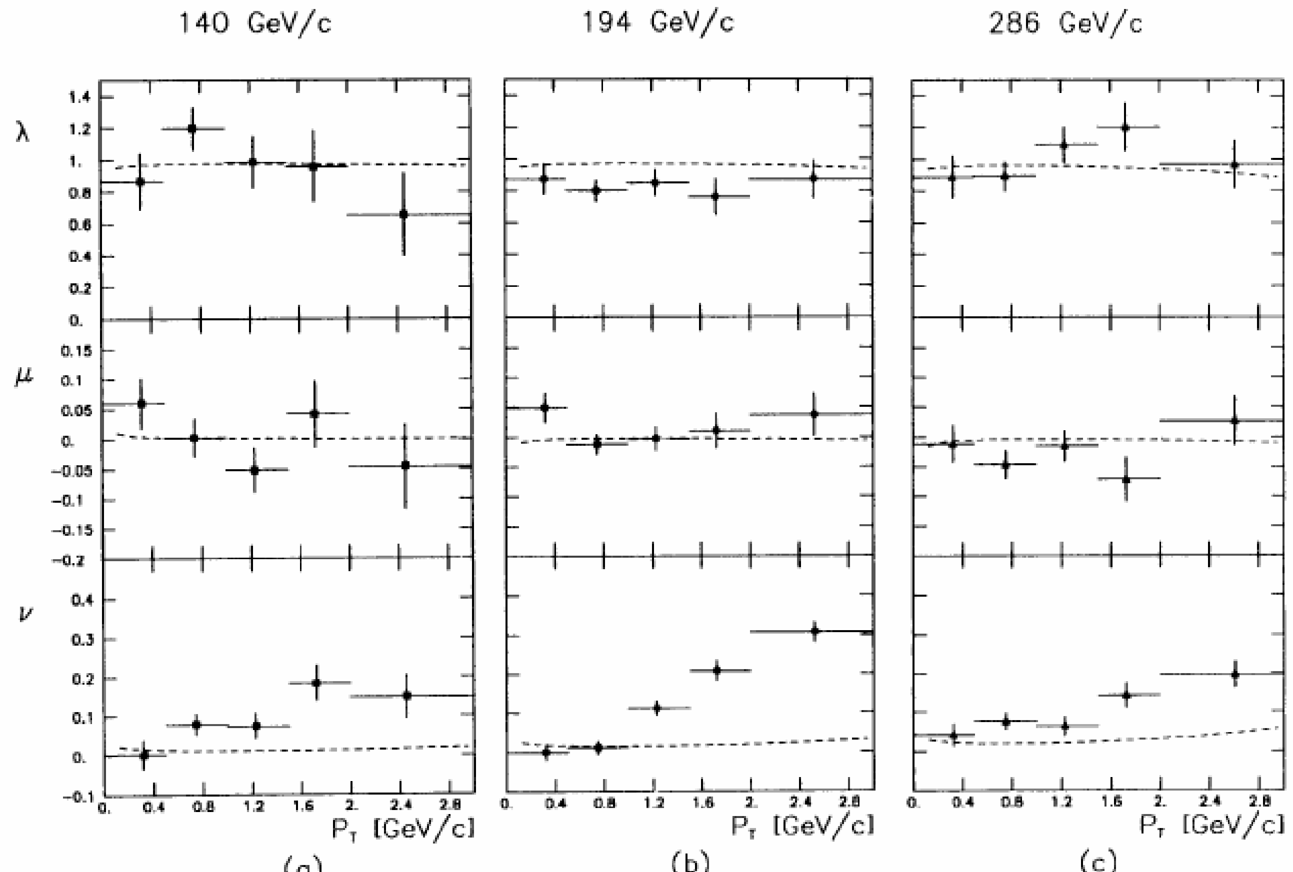


Fig. 3a–c. Parameters λ, μ, and ν as a function of P_T in the CS frame. a 140 GeV/c; b 194 GeV/c; c 286 GeV/c. The error bars correspond to the statistical uncertainties only. The horizontal bars give the size of each interval. The dashed curves are the predictions of perturbative QCD [3]

NA10 $\pi^- + W$

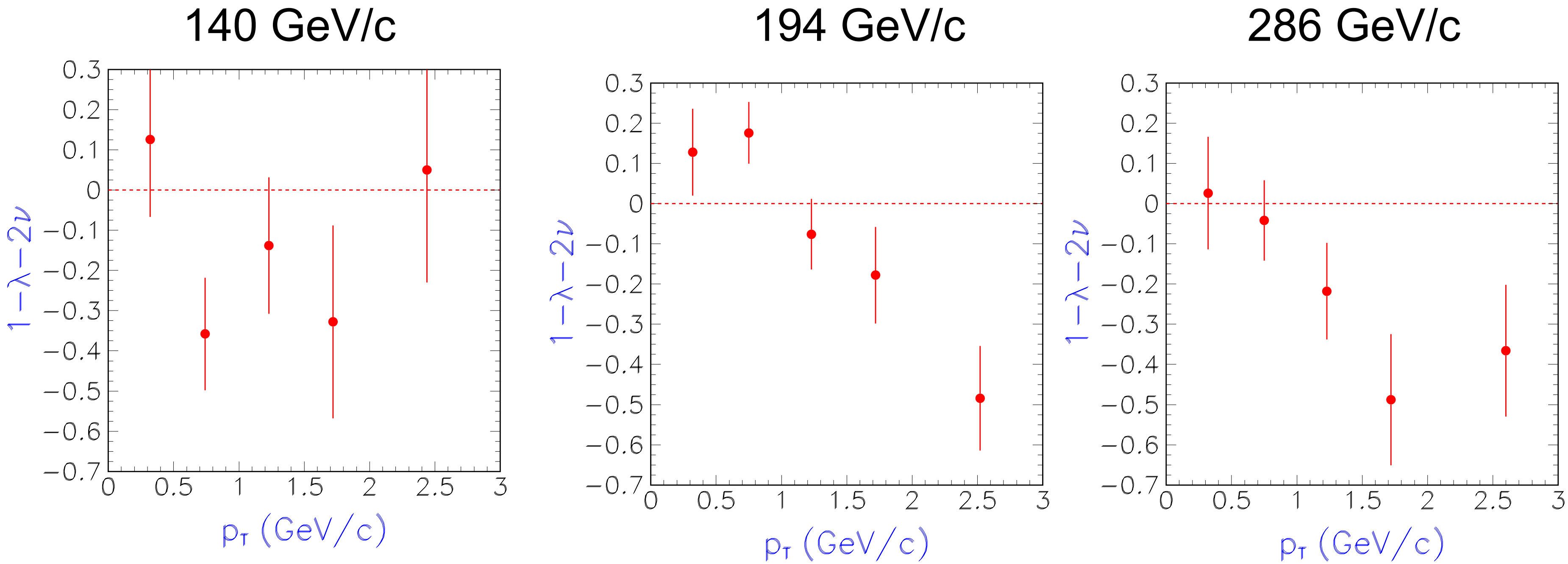
Z. Phys. 37 (1988) 545

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)

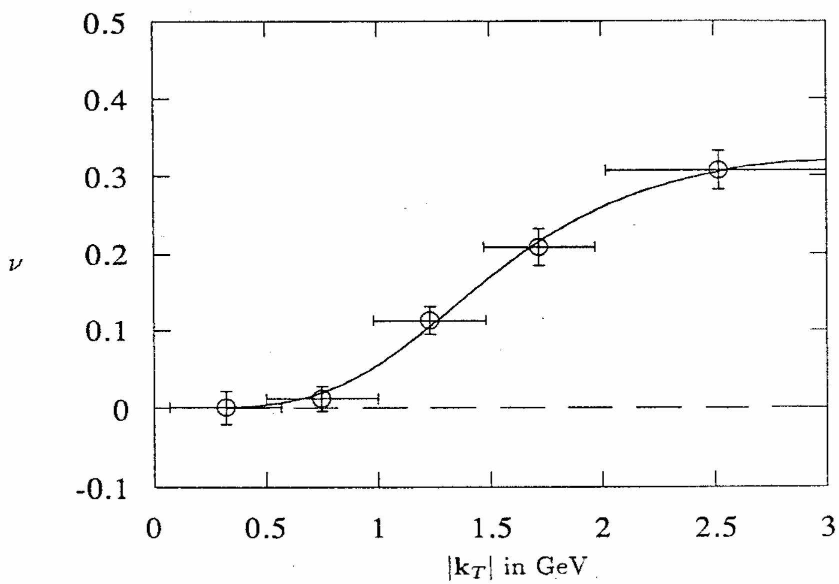
Violation of the Lam-Tung relation suggests

non-perturbative origin

QCD vacuum effects

Brandenburg, Nachtmann & Mirkes, Z. Phy. C60,697(1993)

•Nontrivial QCD vacuum may lead to correlation between the transverse spins of the quark (in nucleon) and the antiquark (in pion).



$q\bar{q}$ spin density matrix contains terms:

$H_{ij}(\vec{\sigma}\cdot\vec{e}_i)(\vec{\sigma}\cdot\vec{e}_j)$ and

$$\nu \simeq \frac{2(H_{22}-H_{11})}{1+H_{33}}$$

$$\nu \approx 2\kappa = 2\kappa_0 \frac{p_T^4}{p_T^4+m_T^4}$$

$$\lambda \approx 1; \mu \approx 0$$

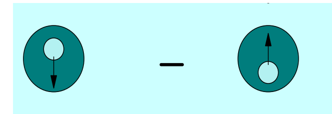
κ_0=0.17, m_T=1.5

•The helicity flip in the instanton-induced contribution may lead to nontrivial vacuum and violation of the Lam-Tung relation.

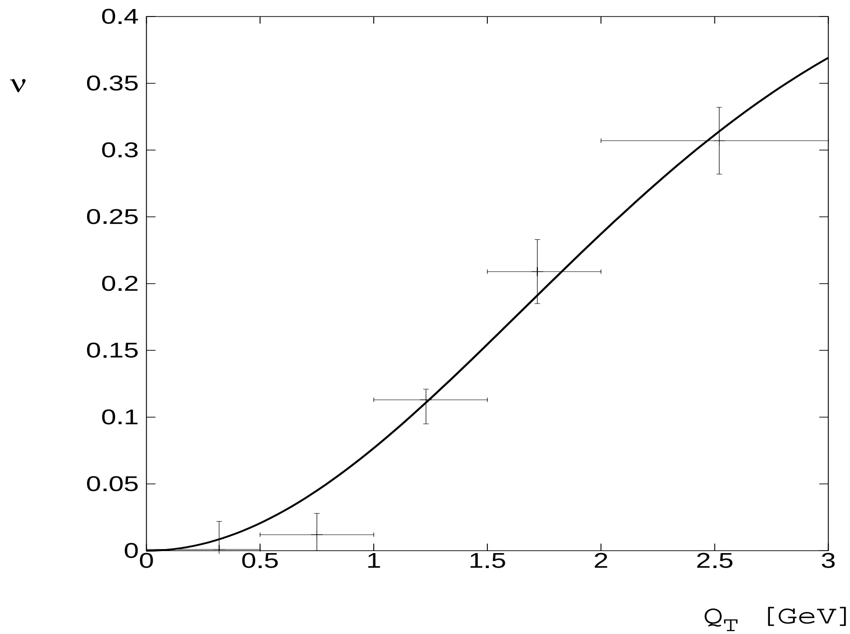
Boer,Brandenburg,Nachtmann&Utermann, EPC40,55(2005).

•This vacuum effect should be flavor blind.

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, k_T – dependent parton distribution
- $h_1^\perp$ can lead to an azimuthal dependence with $\nu \propto \left(\frac{h_1^\perp}{f_1}\right)\left(\frac{\bar{h}_1^\perp}{\bar{f}_1}\right)$



$$h_1^\perp(x, k_T^2) = \frac{\alpha_T}{\pi} c_H \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x)$$

$$\nu = 16\kappa_1 \frac{Q_T^2 M_C^2}{(Q_T^2 + 4M_C^2)^2}$$

κ_1=0.47, M_C=2.3 GeV

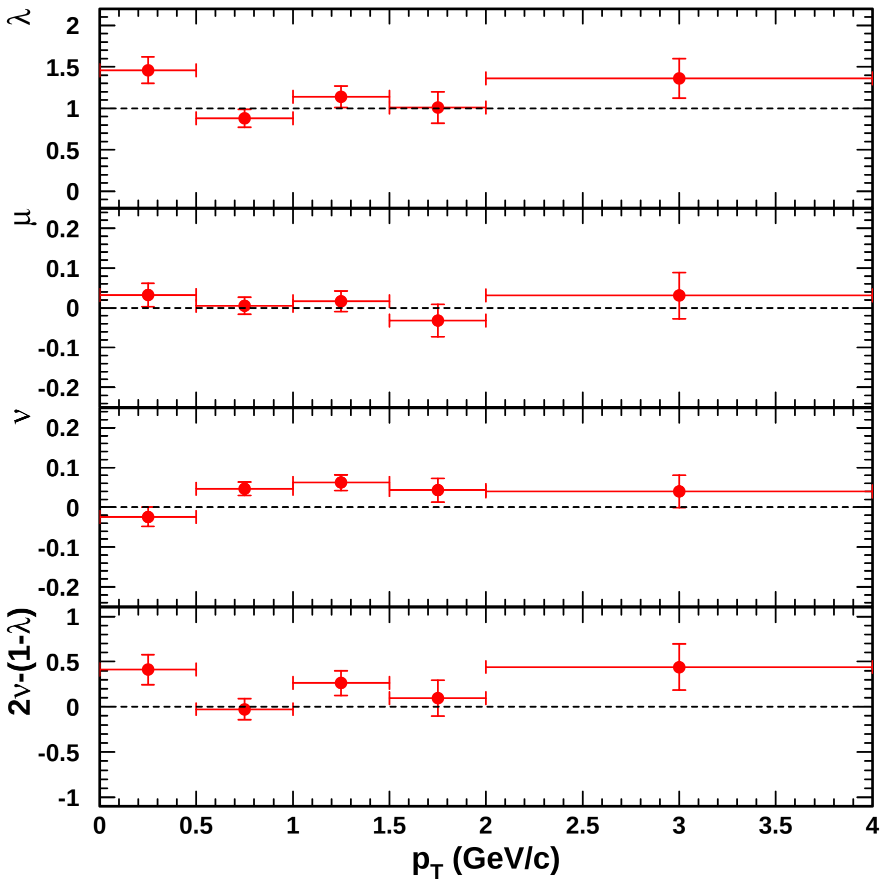
Boer, PRD 60 (1999) 014012

Motivation for measuring decay angular distributions in p+p and p+d Drell-Yan

- No proton-induced Drell-Yan azimuthal decay angular distribution data
- Provide constraints on models explaining the pion-induced Drell-Yan data. ($h_1^{\perp}$ is expected to be small for sea quarks. The vacuum effects should be similar for p+N and π+N)
- Test of the Lam-Tung relation in proton-induced Drell-Yan
- Compare the decay angular distribution of p+p versus p+d

Decay angular distributions for p+d Drell-Yan at 800 GeV/c

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



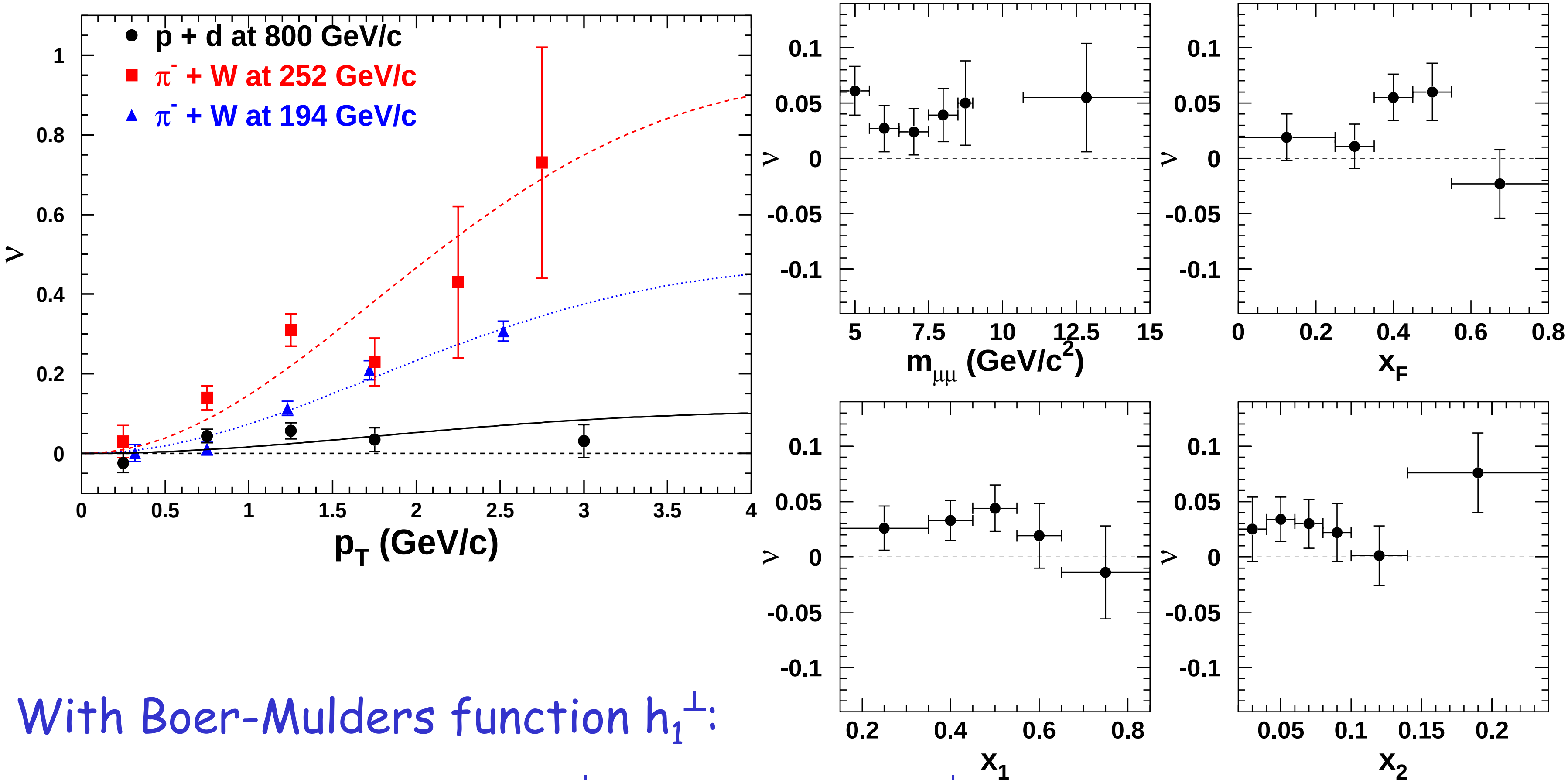
p+d at 800 GeV/c

$<\lambda>$	1.07±0.07
$<\mu>$	0.04±0.013
$<\nu>$	0.03±0.01
$<2\nu-1+\lambda>$	-0.13±0.07

No significant azimuthal asymmetry in p+d Drell-Yan!

Azimuthal cos2Φ Distribution in p+d Drell-Yan

L.Y. Zhu, J.C. Peng, P. Reimer et al., PRL 99 (2007) 082301



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

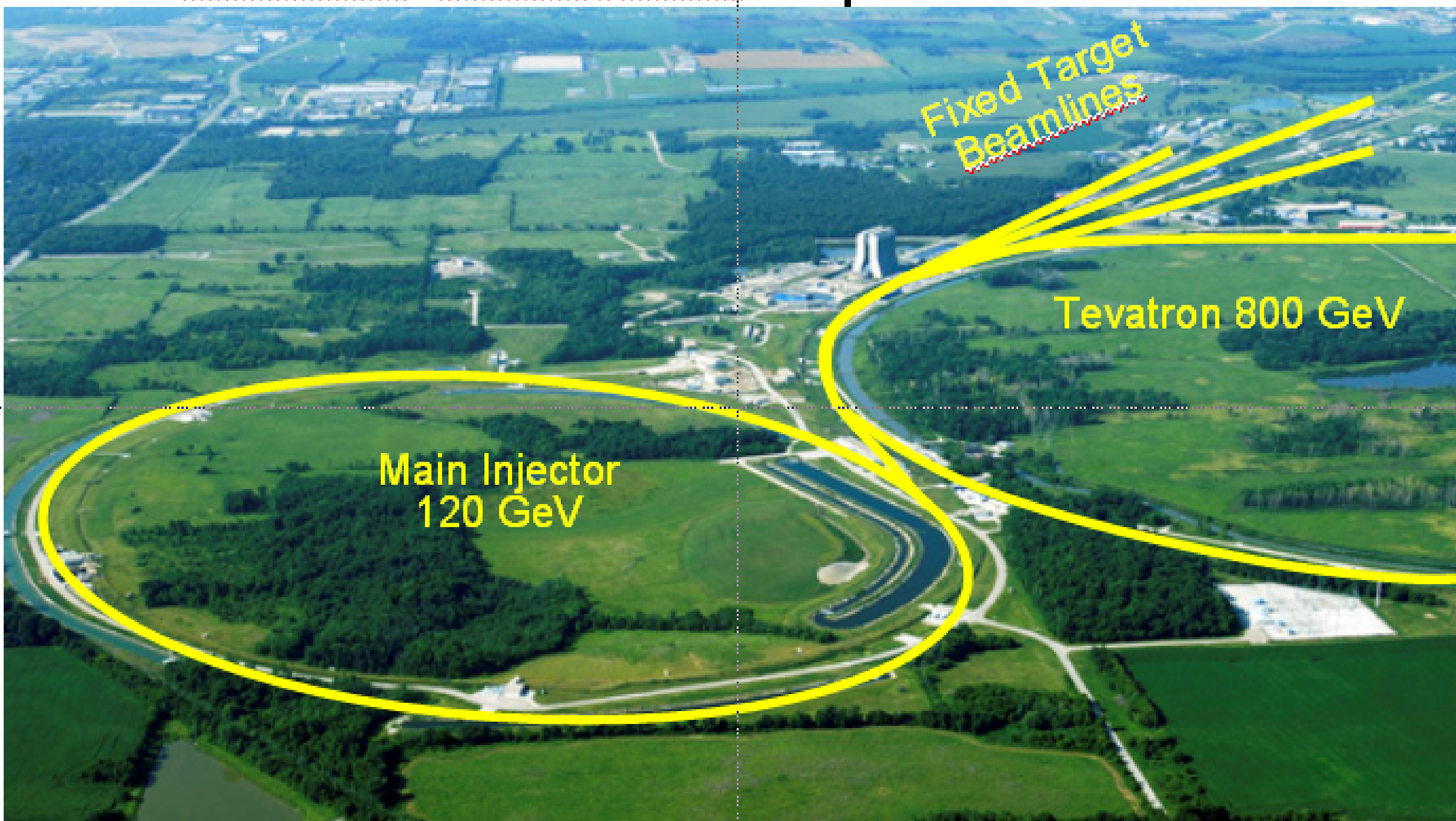
$\nu(\pi^- W \rightarrow \mu^+\mu^- X) \sim$ valence $h_1^{\perp}(\pi)$ * valence $h_1^{\perp}(p)$

$\nu(pd \rightarrow \mu^+\mu^- X) \sim$ valence $h_1^{\perp}(p)$ * sea $h_1^{\perp}(p)$

What does this mean?

- These results suggest that the Boer-Mulders functions $h_1^{\perp}$ for sea quarks are significantly smaller than for valence quarks.
- These results also suggest that the non-trivial vacuum correlation between the sea-quark transverse spin (in one hadron) and the valence-quark transverse spin (in another hadron) is small.
- A combined analysis of p+p and p+d, together with the π+W Drell-Yan cos(2Φ) data can lead to extraction of valence and sea Boer-Mulders functions.

Prospects for future proton-induced dimuon Drell-Yan experiments

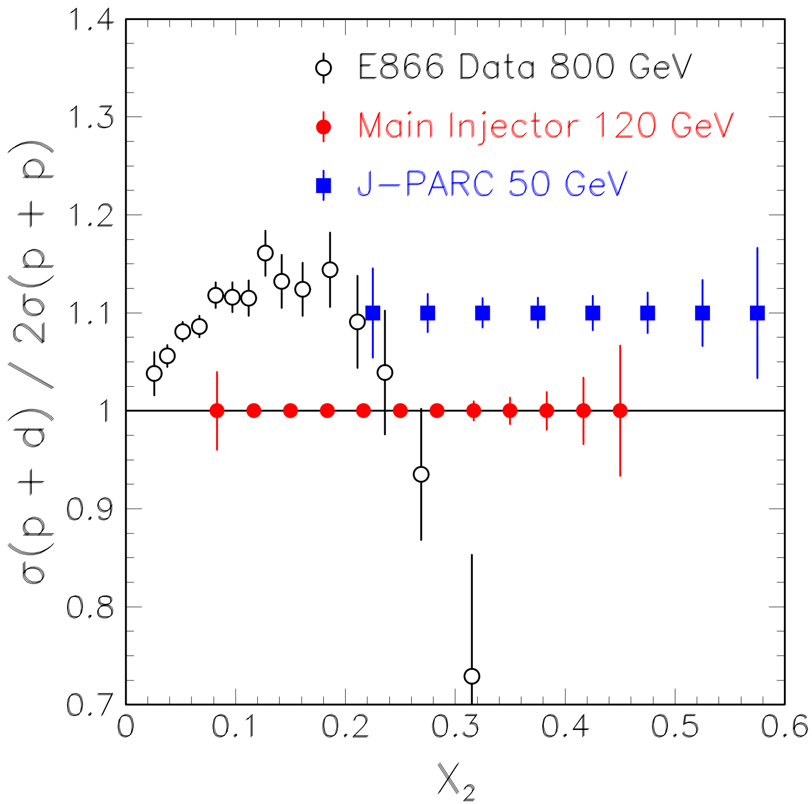


Fermilab E906 dimuon experiment (Geesaman, Reimer et al., expected to run ~2010-2011)

$\bar{d}/\bar{u}$ and $\bar{u}$ at large x using lower energy beams

$$\frac{d\sigma_{DY}}{dx_1 dx_2} \sim \frac{1}{s} \text{ at fixed } x_1,\ x_2$$

DY cross section is ~ 7 times larger at 120 GeV than at 800 GeV



10^{12} protons per spill (3 s)

50-cm long LH_2 / LD_2 targets

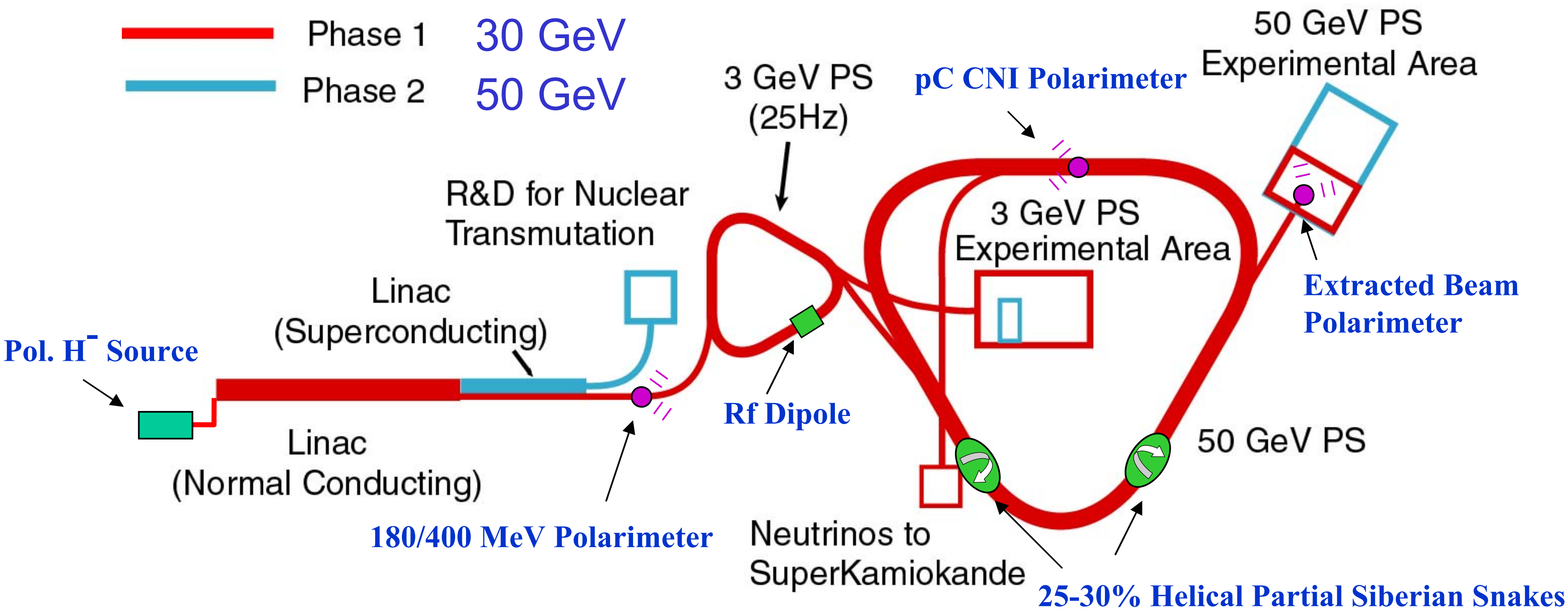
60-day runs for each targets

assuming 50% efficiency

$p + p$ D-Y at 50 GeV also directly measure $\bar{u}$ at large x

Polarized proton beam at J-PARC ?

- **Polarized proton beam at J-PARC with**
  - **Polarized H⁻ source**
  - **RF dipole at 3 GeV RCS**
  - **Two 30% partial snakes at 50 GeV Main Ring**



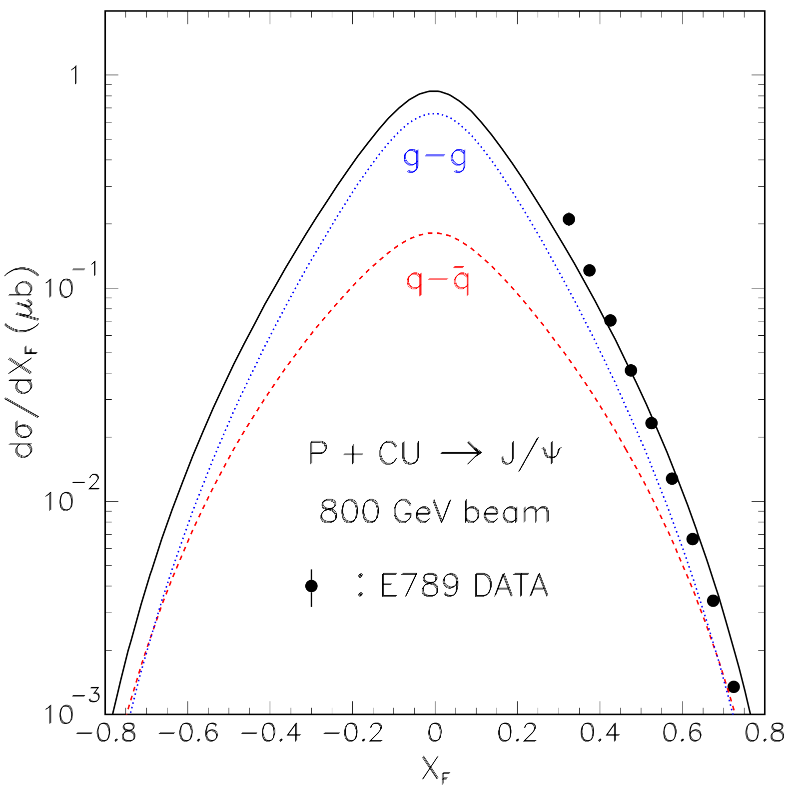
J-PARC dimuon proposals

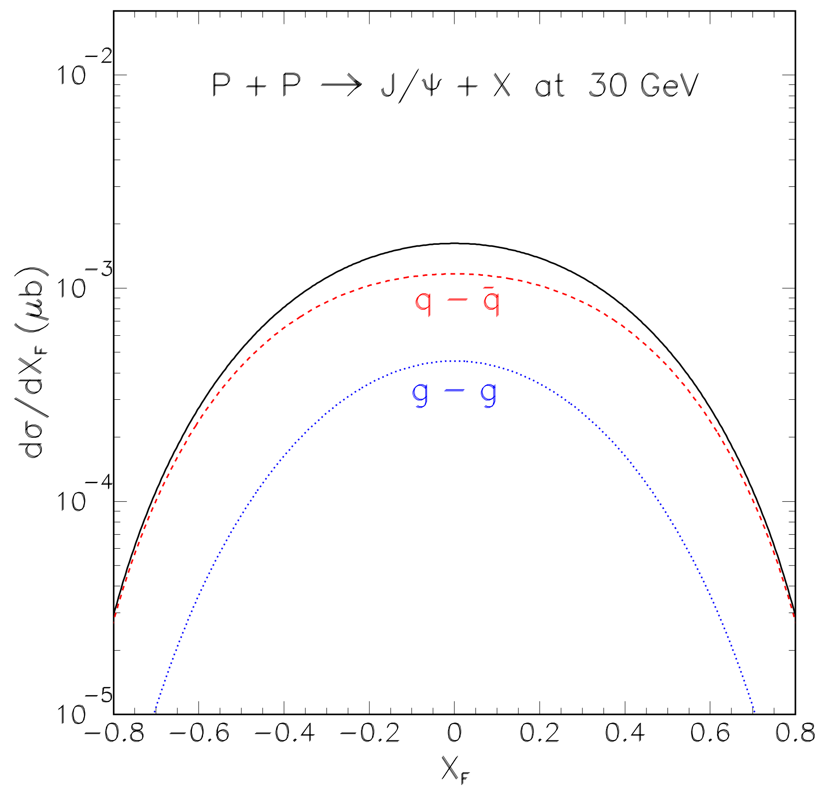
- P04: measurement of high-mass dimuon production at the 50-GeV proton synchrotron
  - spokespersons: Jen-Chieh Peng (UIUC) and Shinya Sawadas (KEK)
  - collaboration: Abilene Christian Univ., ANL, Duke Univ., KEK, UIUC, LANL, Pusan National Univ., RIKEN, Seoul National Univ., TokyoTech, Tokyo Univ. of Science, Yamagata Univ.
  - including polarized physics program.
- P24: polarized proton acceleration at J-PARC
  - contact persons: Yuji Goto (RIKEN) and Hikaru Sato (KEK)
  - collaboration: ANL, BNL, UIUC, KEK, Kyoto Univ., LANL, RCNP, RIKEN, RBRC, Rikkyo Univ., TokyoTech, Tokyo Univ. of Science, Yamagata Univ.
  - polarized Drell-Yan included as a physics case

J/Ψ Production at 30 GeV

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

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



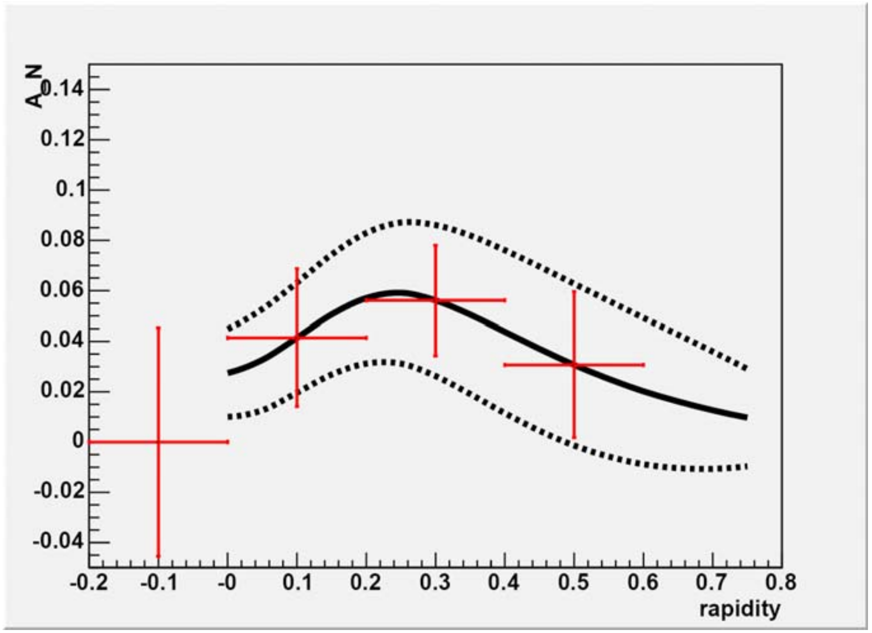


J/Ψ production at 30 GeV is sensitive to quark and antiquark distributions

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



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

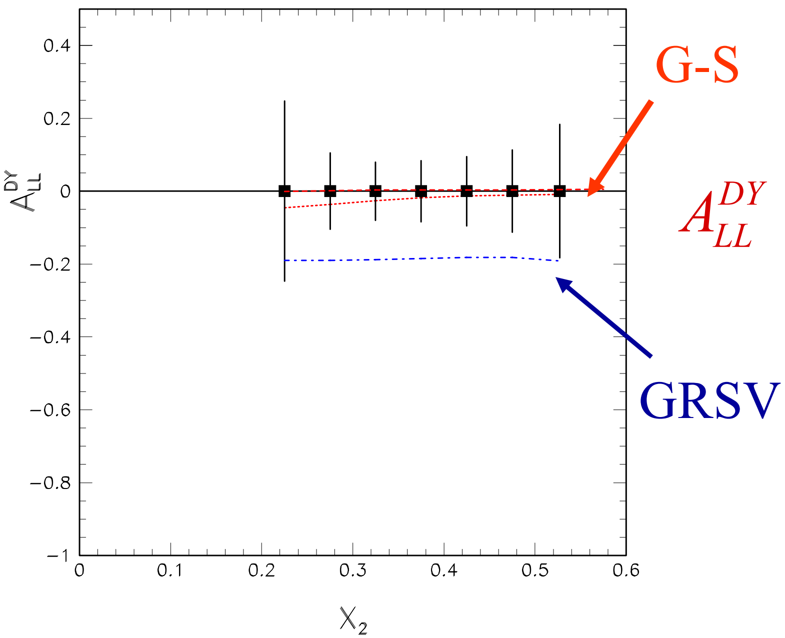
- J/Ψ production could also probe the Sivers function

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

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

Double-spin asymmetry (A_{LL}) with longitudinally polarized beam/target in Drell-Yan (and J/Ψ) probe Sea-Quark polarization

D-Y A_{LL} at 50 GeV



$$A_{LL}^{DY} = \frac{\sum_a e_a^2[\Delta q_a(x_1)\Delta\bar{q}_a(x_2) + \Delta\bar{q}_a(x_1)\Delta q_a(x_2)]}{\sum_a e_a^2[q_a(x_1)\bar{q}_a(x_2) + \bar{q}_a(x_1)q_a(x_2)]}$$

- J/Ψ production could also probe the Sea-Quark polarization
- Much higher statistics could be obtained in J/Ψ production

Conclusion

- Dimuon production experiments have provided unique information and new perspectives on nucleon and nuclear structure and QCD.
- Future dimuon production experiments at lower beam energies (120 GeV Main-Injector and 30/50 GeV J-PARC) could provide interesting new information at large x and spin-dependent parton distributions in the nucleons