Four Decades of Drell-Yan Scattering: An Experimental Overview

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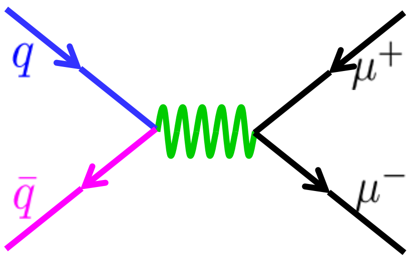
26 April 2010



- *The Drell-Yan Process*

- *Longitudinal Parton Distributions*
- *Transverse Parton Distributions*

} *Review of what has been measured*

HERMES
U. Elschenbroich

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Early Muon Pair Data

VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

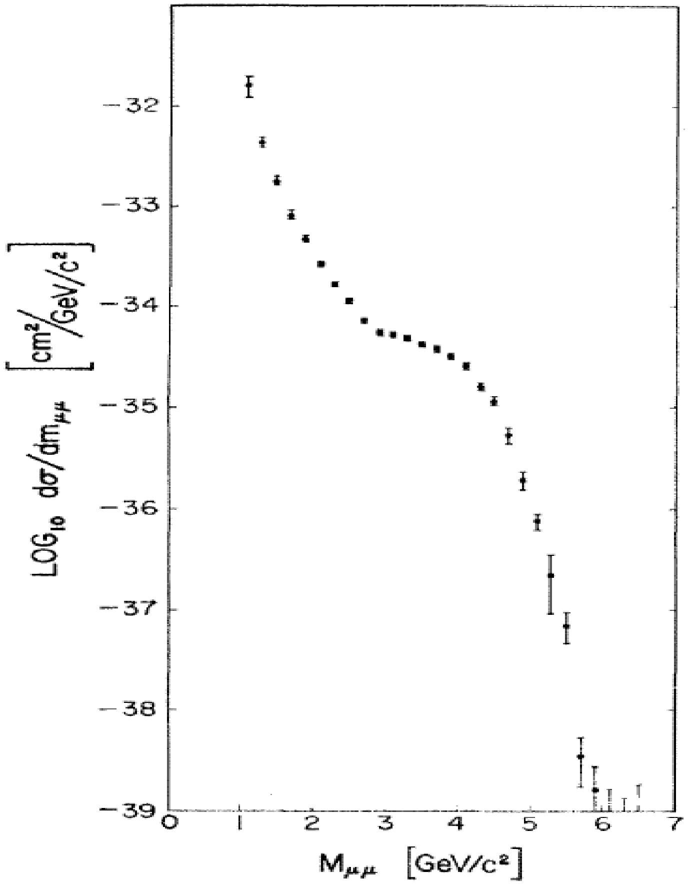
Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

E. Zavattini
CERN Laboratory, Geneva, Switzerla

(Received 8 September 1970)



Muon Pairs in the mass range $1 < m_{\mu\mu} < 6.7$ GeV/c^2 have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, **the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32} / m_{\mu\mu}^5$ cm^2 (GeV/c)$^{-2}$ and exhibits no resonant structure.** The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.

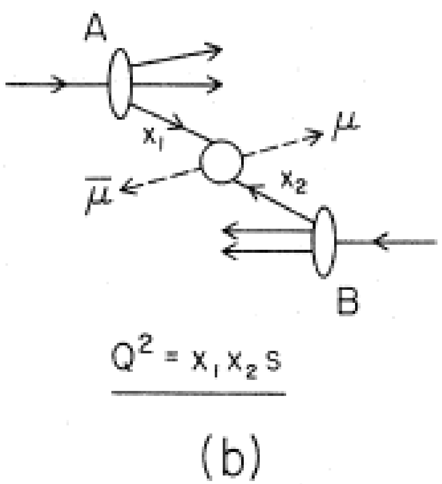
Drell and Yan’s explanation

VOLUME 25, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1970

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.



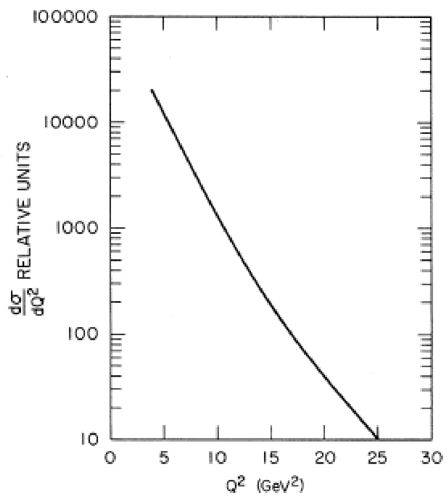
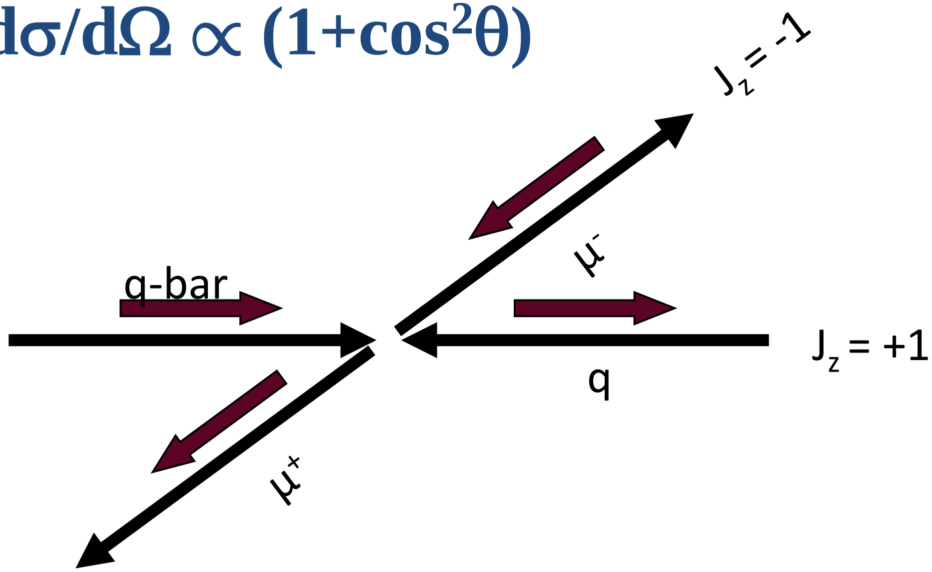


FIG. 2. $d\sigma/dQ^2$ computed from Eq. (10) assuming identical parton and antiparton momentum distributions and with relative normalization.

Also predicted $\lambda(1+\cos^2\theta)$ angular distributions.

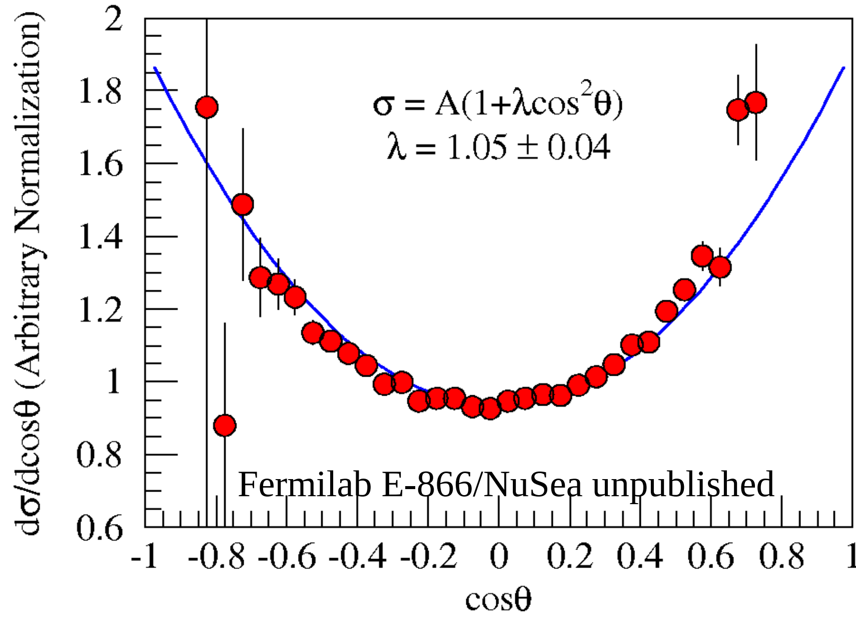
LO Drell-Yan Angular Distributions: $d\sigma/d\Omega \propto (1+\cos^2\theta)$



$$\mathcal{M} \propto d^j_{\lambda'\lambda(\theta)} = \langle j\lambda' | e^{-i\theta J_y} | j\lambda \rangle$$

$$d^1_{11} = d^1_{-1-1} = \frac{1}{2}(1+\cos\theta)$$
$$d^1_{-11} = d^1_{1-1} = \frac{1}{2}(1-\cos\theta)$$

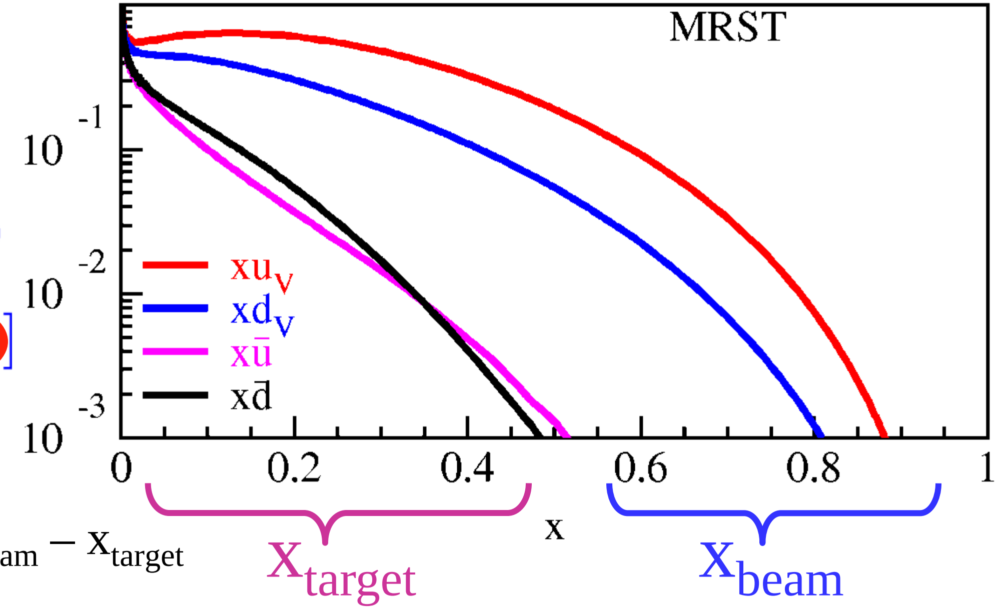
$$\frac{d\sigma}{d\Omega} \propto \mathcal{M}^2 \propto (1+\cos^2\theta)$$



Helped to validate the Drell-Yan picture of quark-antiquark annihilation for lepton pair production

Drell-Yan cross section

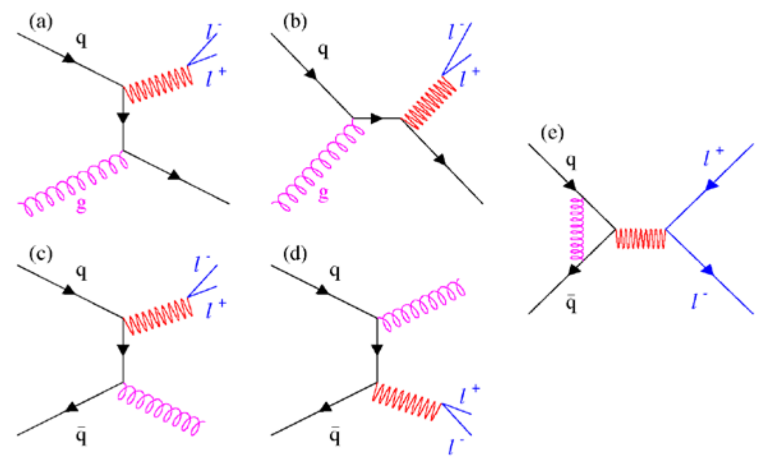
$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_1x_2s}\sum e^2\left[\bar{q}_t(x_t)\,q_b(x_b) + \bar{q}_b(x_b)\,q_t(x_t)\right]$$



Detector acceptance chooses x_{target} and x_{beam}.

- **Fixed target, dipole focus** ⇒ high $x_F = x_{beam} - x_{target}$
- Valence Beam quarks at high-x.
- Sea-target quarks at low/intermediate-x.

  - Next-to-leading order diagrams complicate the picture and must be considered
  - These diagrams are responsible for **50% of the measured cross section**
  - Intrinsic transverse momentum of quarks (although a small effect, $\lambda > 0.8$)



Longitudinal Parton Distributions

- Unpolarized Drell-Yan
  - πA–CERN NA10, Fermilab E-615 (pion structure)
  - pp, pd—dbar/ubar—CERN NA51, Fermilab E-866
  - pA—Fermilab E-772

- Polarized Drell-Yan
  - Could provide independent measurement of Δq-bar—but not yet done?

$$\langle s_z^N \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g,$$

$$A_{LL}^{\mathrm{DY}} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}}$$

$$= \frac{\sum_i e_i^2 \left[\Delta f_i(x_1)\Delta \bar{f}_i(x_2) + \Delta \bar{f}_i(x_1)\Delta f_i(x_2)\right]}{\sum_i e_i^2 \left[f_i(x_1)\bar{f}_i(x_2) + \bar{f}_i(x_1) f_i(x_2)\right]}.$$

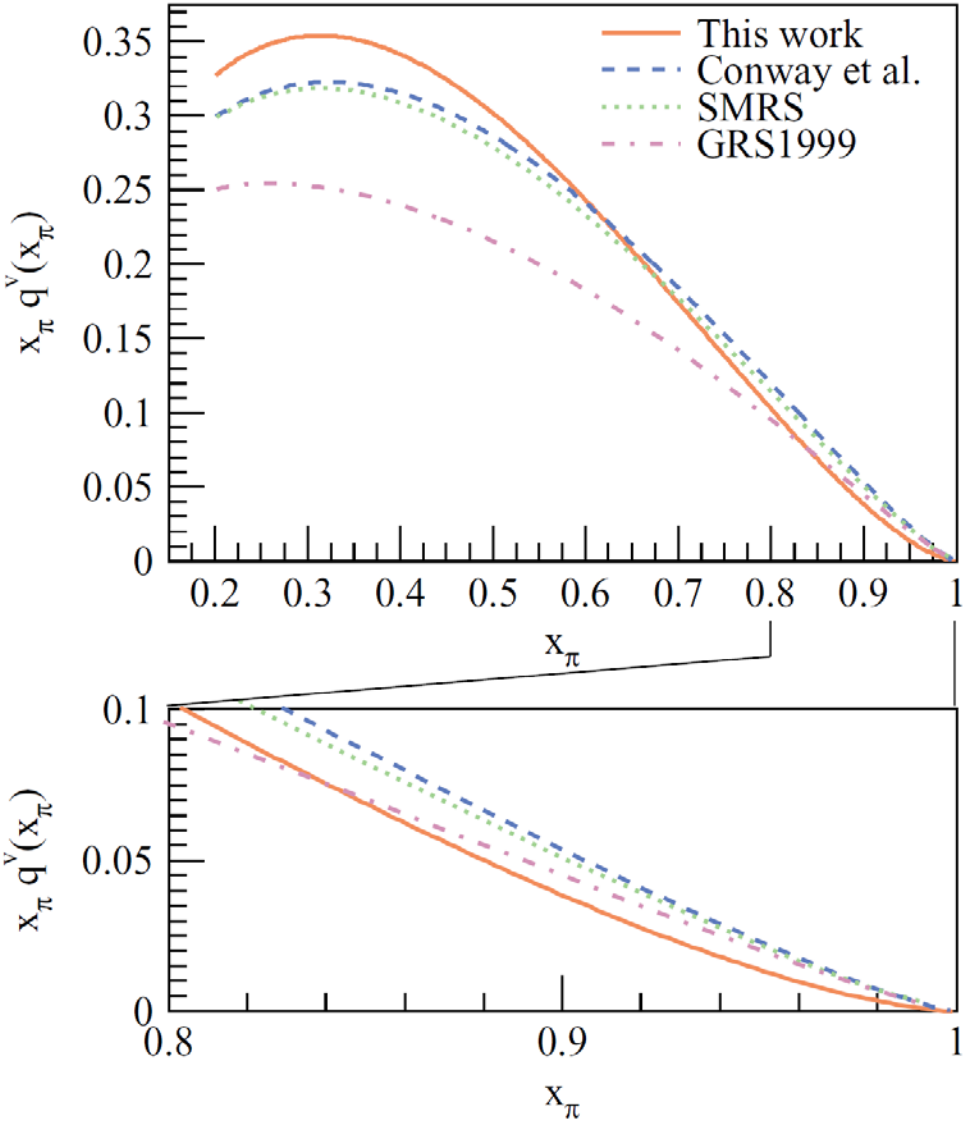
In fixed target, large-x_F spectrometer, measures Δubar

$$A_{LL}^{\mathrm{DY}}(x_1, x_2) = \frac{1}{3}\frac{g_A}{g_V}\frac{\Delta \bar{f}(x_2)}{\bar{f}(x_2)}.$$

In exact SU(6)
Close and Sivers, PRL **39** 1116 (1977)

Pionic Parton Distributions

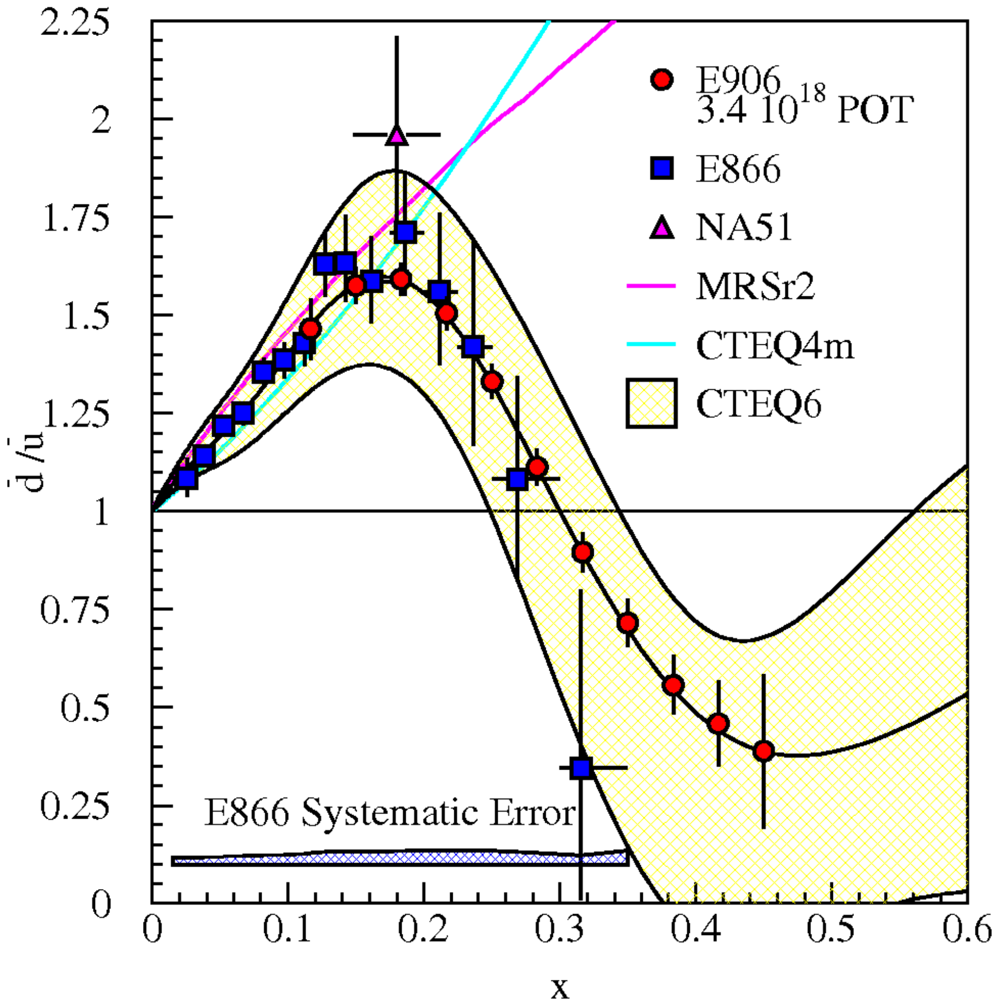
- Pion as q-qbar meson vs pion as the Goldstone Boson.
- Models predict very different behavior as x→1
  - Dyson-Schwinger models ∝ $(1-x)^2$
  - NJL models, Drell-Yan-West Relation ∝ $(1-x)^1$
- Assume that $\bar{u}_\pi(x) \equiv d_\pi(x)$
- NLO fit to Fermilab E-615 data (including higher twist possibility) give $(1-x)^{1.5}$
  - Caveat δx_π is likely to be large as x→1
  - Better pion data would be very useful
    COMPASS?



Proton Parton distributions

$$\bar{d}(x)/\bar{u}(x)$$

- NMC μ-DIS indicated dbar ≠ubar
- Confirmed by Drell-Yan data from CERN NA-51
- x-dependence determined by Fermilab E-866/NuSea data
  - Non perturbative models partially explain data.
  - Unexpected drop in ratio for x > 0.25
  - Fermilab E-906/SeaQuest will have more data soon



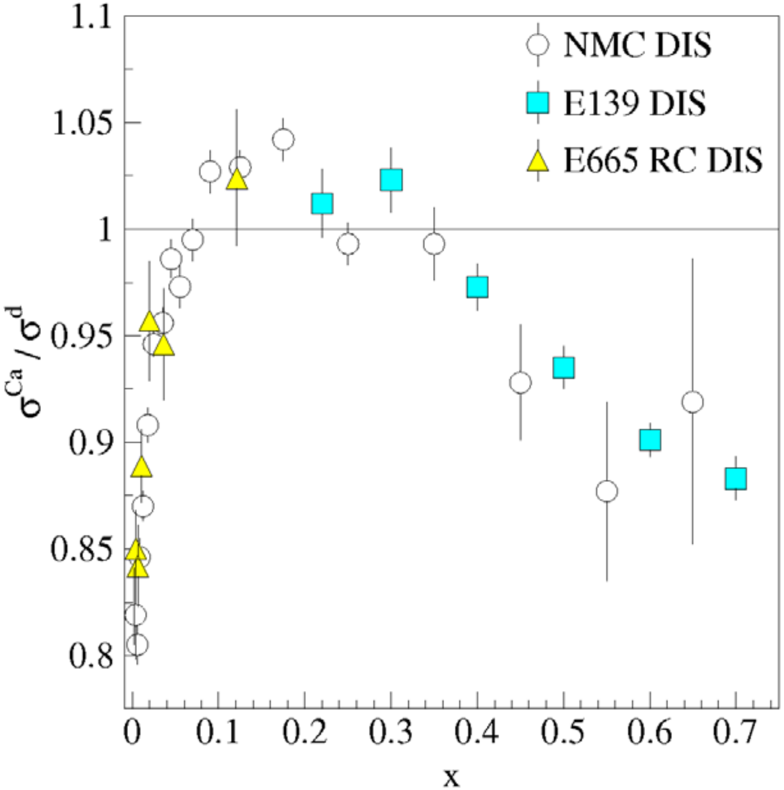
$$\left.\frac{\sigma^{pd}}{2\sigma pp}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left(1+\frac{\bar{d}}{\bar{u}}\right)$$

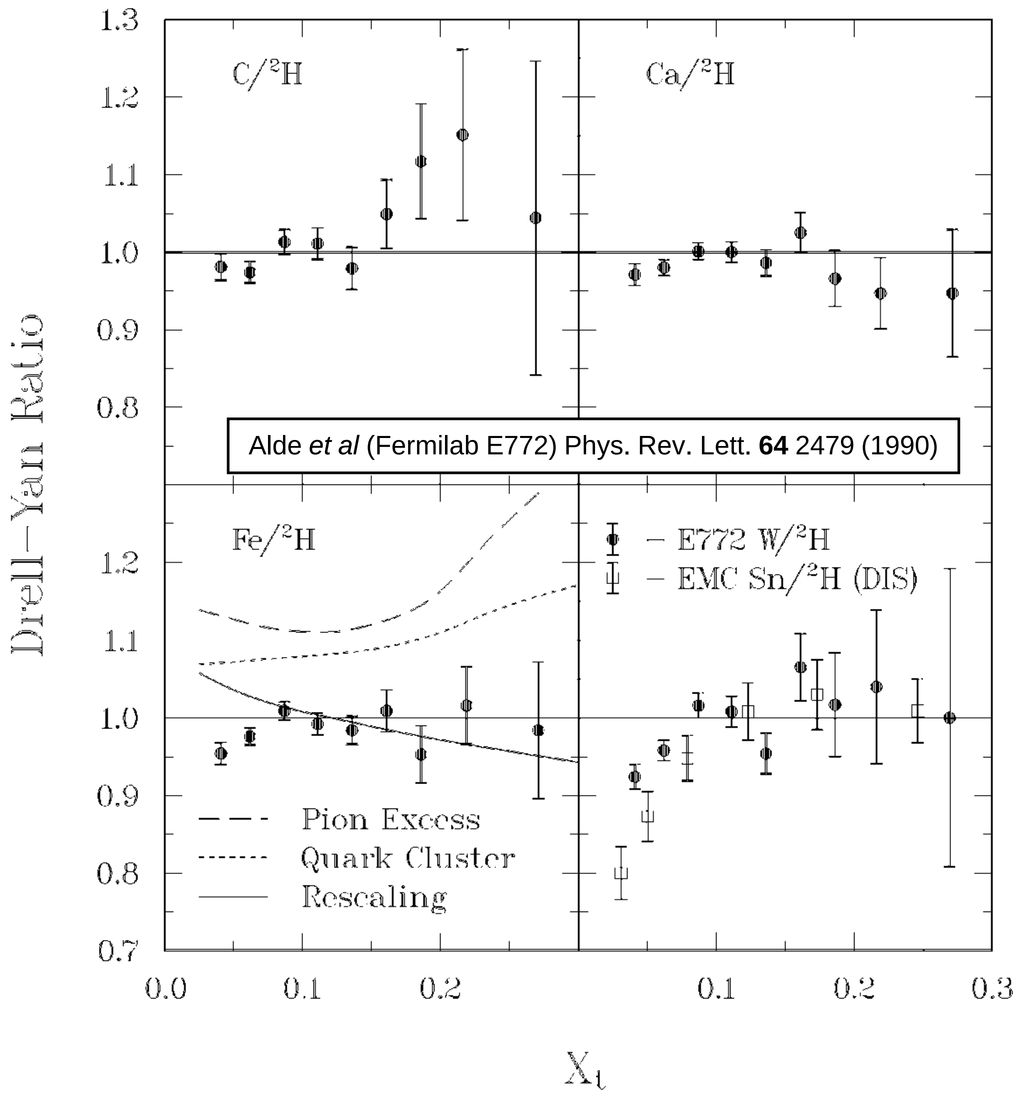
Absolute Cross Sections

- Measure absolute sea quark magnitude
- Large-x beam parton distributions

Nuclear Parton Distributions; Nuclear Binding; and the EMC Effect

- EMC: Parton distributions of bound and free nucleons are different.
- Antishadowing not seen in Drell-Yan—Valence only effect?





Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

Longitudinal Structure
What data would I like to see? (My personal view)

- Proton deuterium Drell-Yan ratios –dbar/ubar
  - Fermilab E-906/SeaQuest
- Deuterium/A ratios—EMC and nuclear binding
  - Fermilab E-906/SeaQuest
- Unpolarized π-p Drell-Yan—nature of Goldstone Boson
  - CERN Compass
- Double Polarized p-p or π-p Drell-Yan—$\Delta q(x)$ nice complement for SIDIS and $W^{\pm}$
  - CERN Compass, J-PARC, RHIC

Transverse Parton Distributions

- Unpolarized Drell-Yan
  - πA–CERN NA10, Fermilab E-615
  - pp, pd—Fermilab E-866

- Polarized Drell-Yan (future)
  - CERN COMPAS
  - GSI PAX
  - NCIA
  - Fermilab, RHIC, J-Parc

Generalized Angular Distributions & Lam Tung relation

Chi-Sing Lam and Wu-Ki Tung—basic formula for lepton pair production angular distributions PRD **18** 2447 (1978)

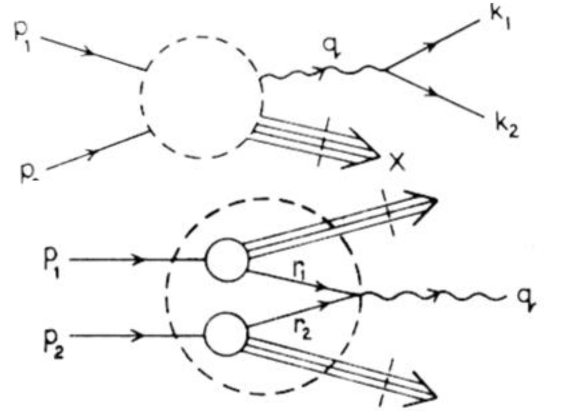
$$\frac{d\sigma}{d^4q\,d\Omega} = \ldots \left(\frac{\alpha}{\ldots}\right)^2 \left[W_T(1+\cos^2\theta) + W_L(1-\cos^2\theta) + W_\Delta \sin 2\theta \cos\phi + W_{\Delta\Delta}\sin^2\theta\cos 2\phi\right]$$

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi$$

Structure function formalism

- Derived in analogy to DIS
- Independent of Drell-Yan and parton "models"

- Showed same relations follow as a general consequence of the quark-parton model

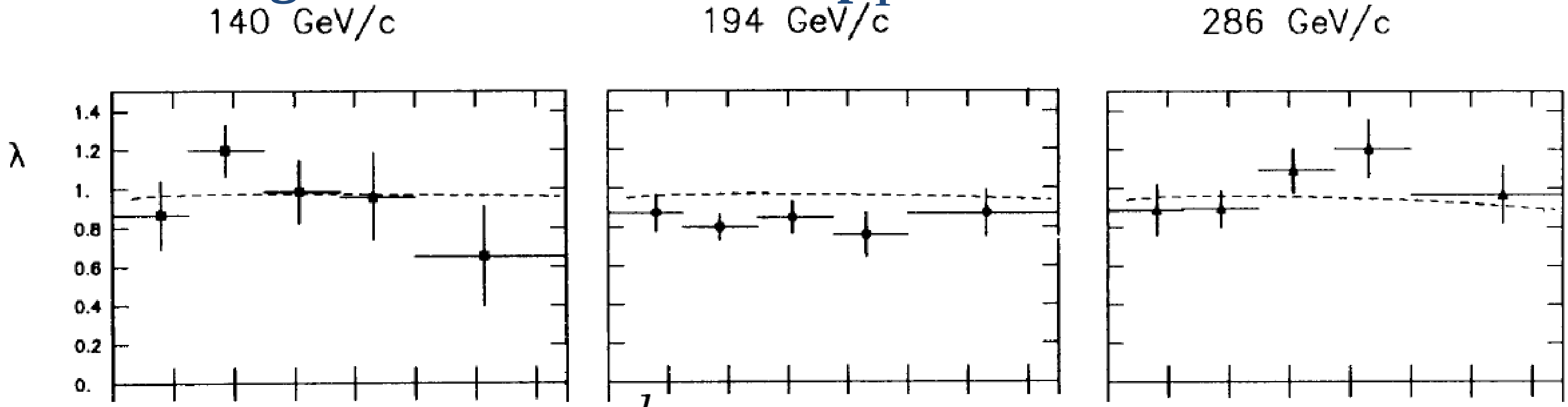


Lam-Tung relation

- Derived in analogy to Colin-Gross relation of DIS
- Unaffected by $O(\alpha_s)$ (NLO) corrections
- NNLO $[O(\alpha_s^2)]$ corrections also small Mirkes and Ohnemus, PRD **51** 4891 (1995)

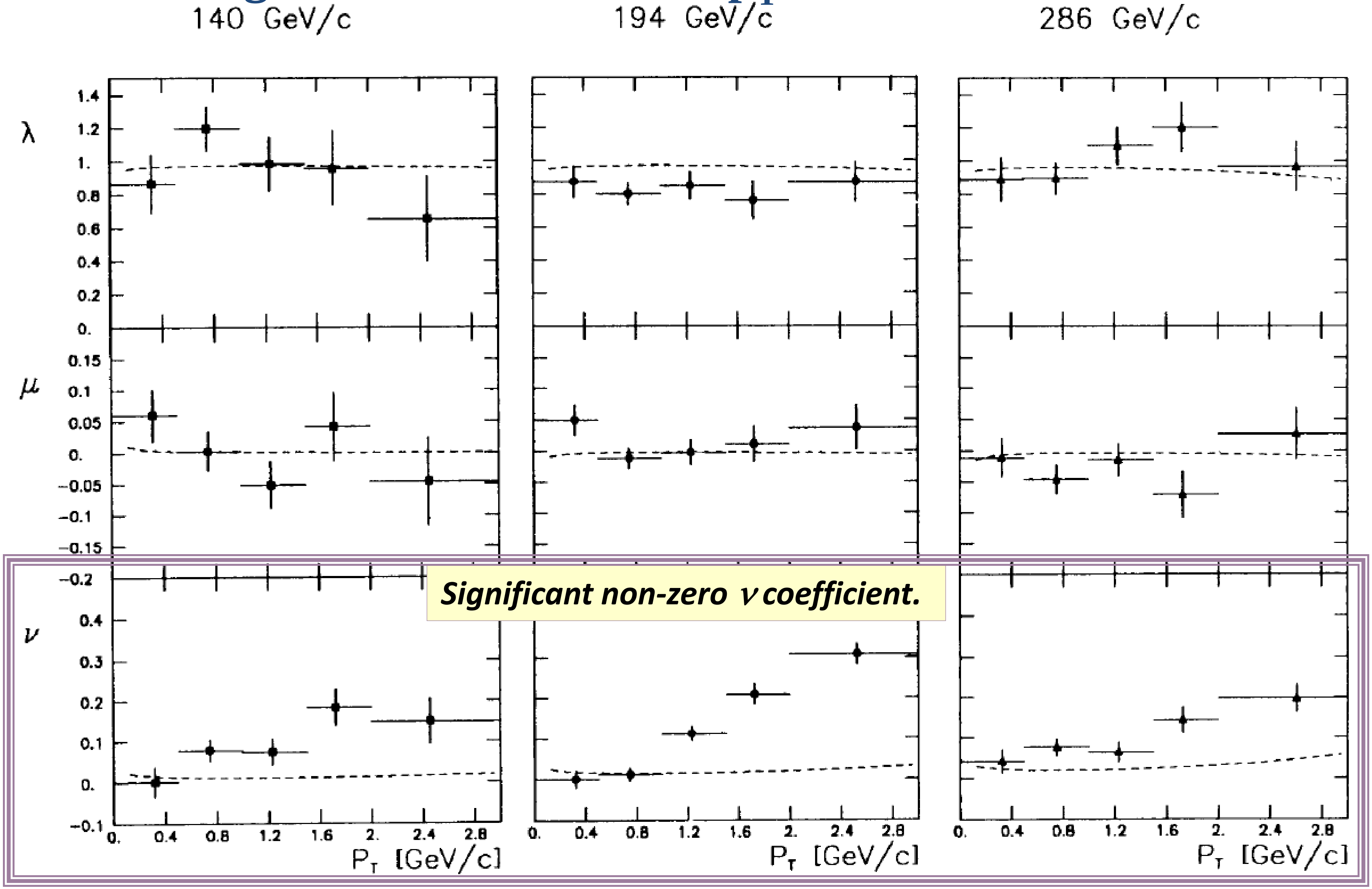
$$1 - \lambda = 2\nu$$

NA10 angular distributions vs. p_T



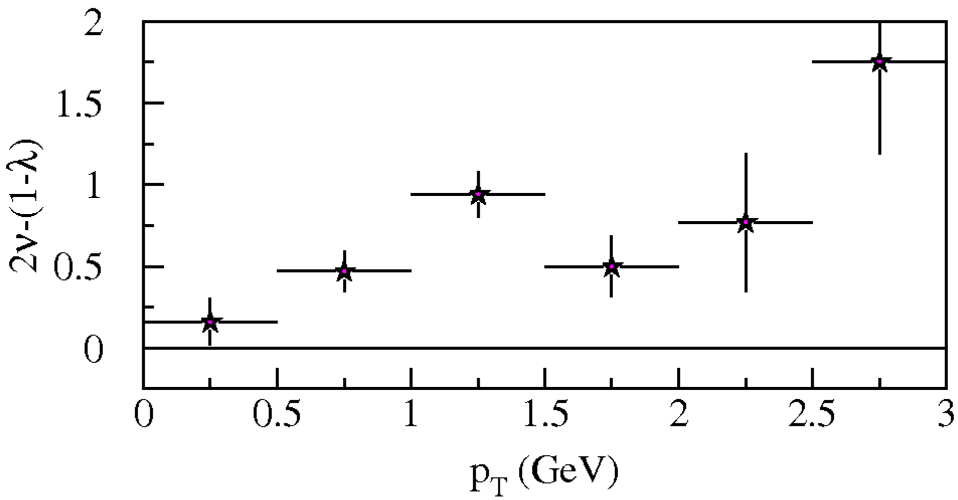
$$\frac{d\sigma}{d\Omega} \propto 1 + \cos^2\theta$$

NA10 angular distributions vs. p_T

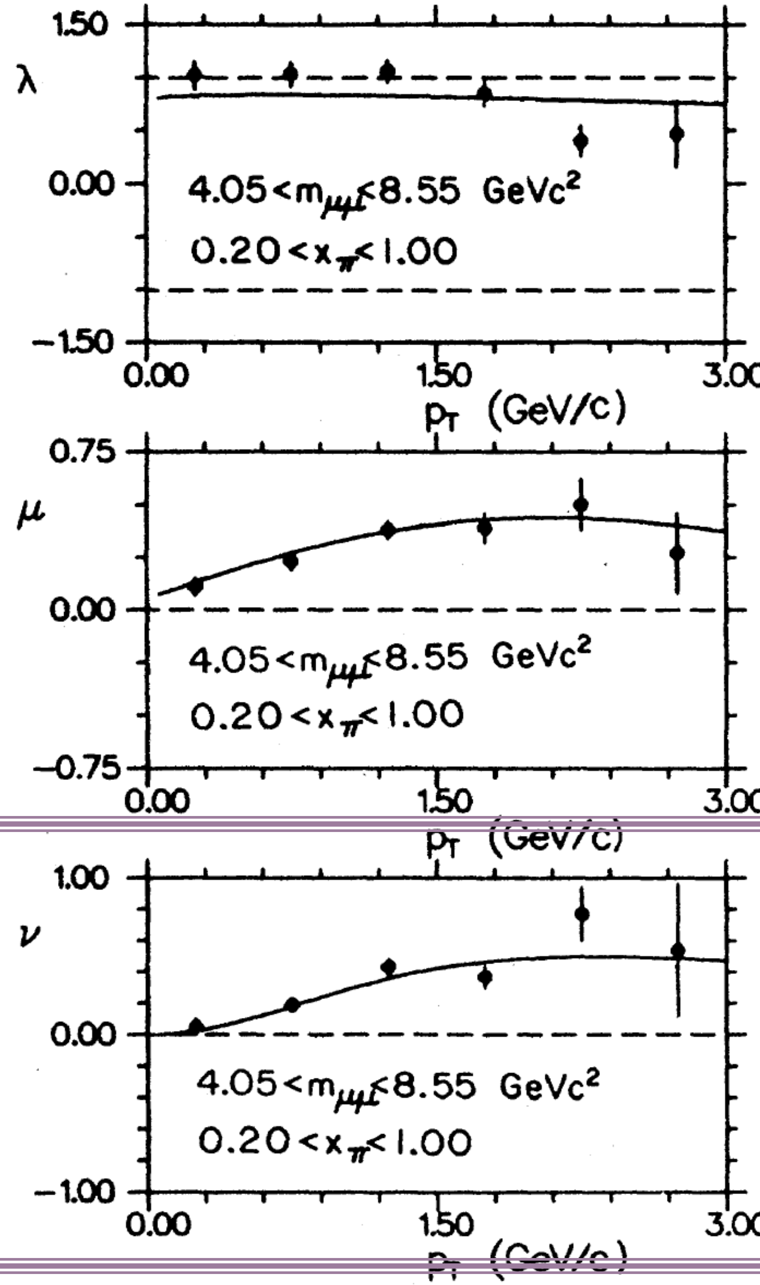


Pionic Data Fermilab E615

- *Significant non-zero ν coefficient*
- Shows other kinematic dependencies

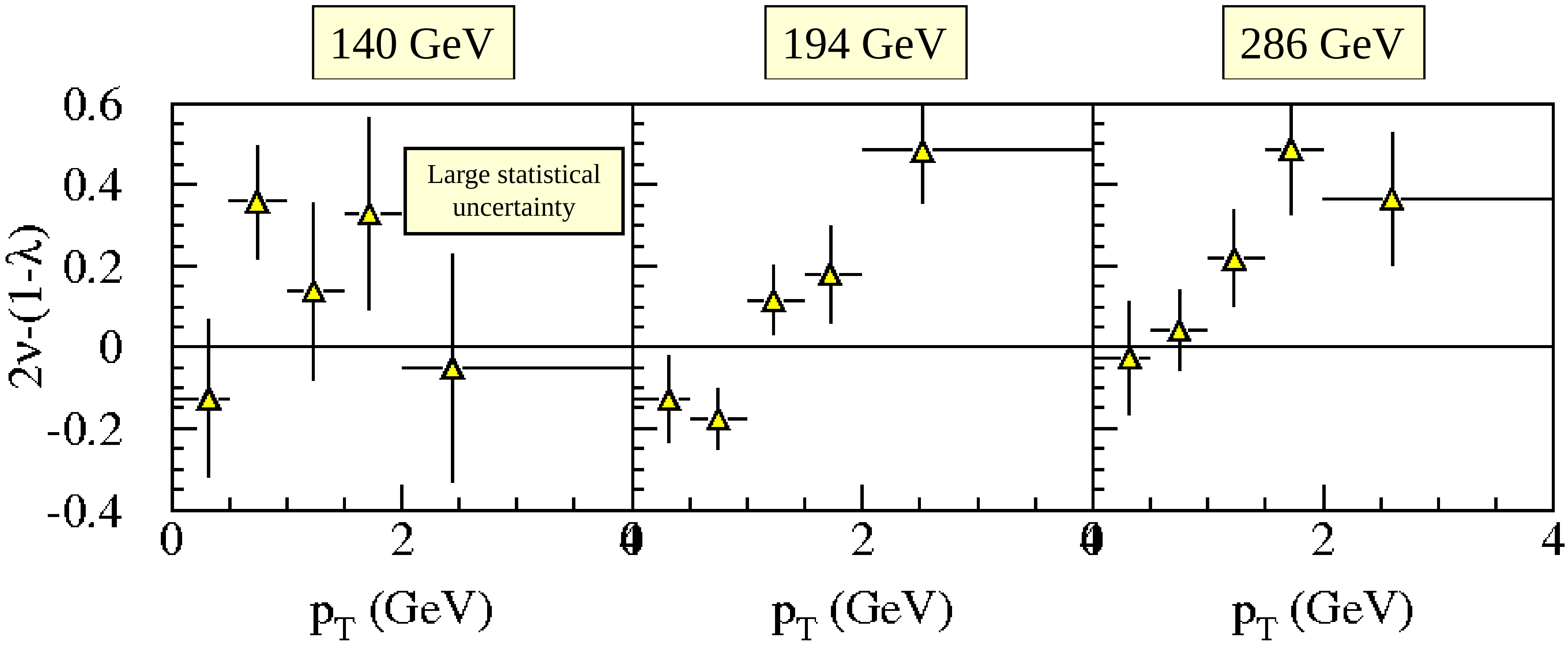


- Clear violation of Lam-Tung Relation vs. p_T.
- *Violation larger than NA10*



Conway *et al.* PRD **39** 92 (1989)

NA10 Lam-Tung Relation vs. p_T



- Violation of Lam-Tung relation as p_T increases in higher momentum data. Statistics poor in 140 GeV data.
- Note: Correlation between λ and ν uncertainties not considered.
- Since most data is at low p_T, *on average* the Lam-Tung relationship holds

Possible explanations?

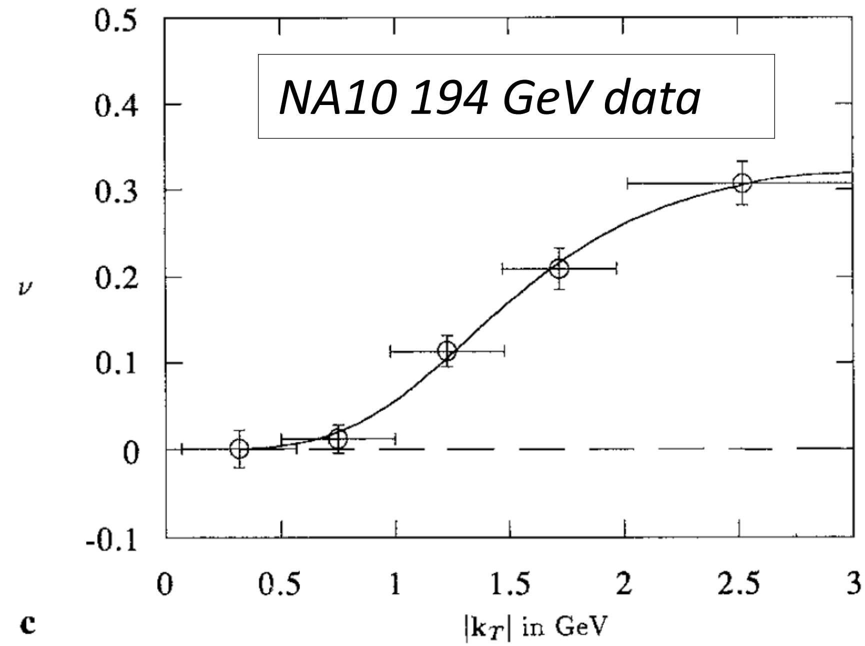
- Lam-Tug Relation is theoretically robust?
  - → Unaffected by $O(\alpha_s)$ (NLO) corrections
  - → NNLO $[O(\alpha_s^2)]$ corrections also small Mirkes and Ohnemus, PRD **51** 4891 (1995)
  - → Soft Gluon Resummation–Berger, Qiu and Rodrigues-Pedraza showed that **the Lam-Tung relation is preserved** under resummation. arXiv:0707.3150, and PRD **76** 074006 (2007)
- Nuclear effects
  - → Not seen (within stat. uncertainty) by NA10.
- Higher-Twist effects from quark-antiquark binding in pion
  - → Expected to increase at large-x, but not seen in data.
- **Factorization breaking QCD Vacuum**
- **k_T dependent transverse momentum distribution (Boer Mulders $h_1^{\perp}$)**

QCD Vacuum Effect

- Factorization breaking Brandenburg, Nachtmann and Mirkes, ZPC **60**, 679 (1993).
  - QCD Vacuum ***may*** correlate the spins and momenta of incoming partons
  - Effect could be instanton-induced Boer, Brandenburg, Nachtmann, Utermann, EPJC 40 55 (2005), Brandenburg, Ringwald, Utermann NPB 754, 107 (2006).

$$\nu \approx 2\mathcal{K} = 2\mathcal{K}_0 \frac{p_T^4}{p_T^4 + m_T^4}$$

$$\lambda \approx 1 \qquad \mu \approx 0$$



  - Fit NA10:

    $\kappa = 0.17$

    $m_T = 1.5$

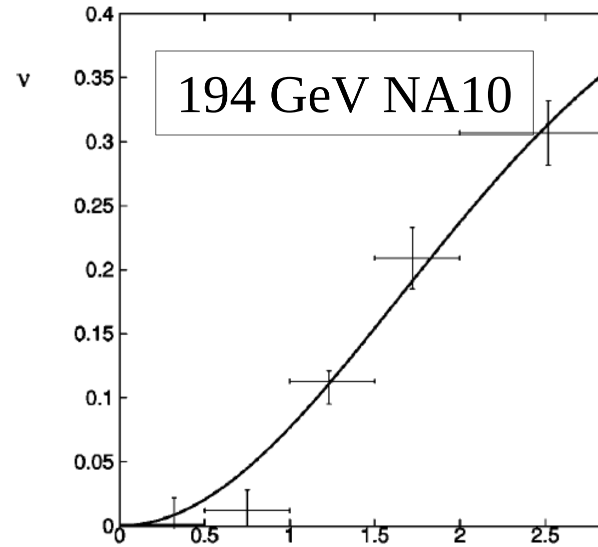
Should be flavor blind and seen in both sea and valence distributions

Boer-Mulders Structure Function

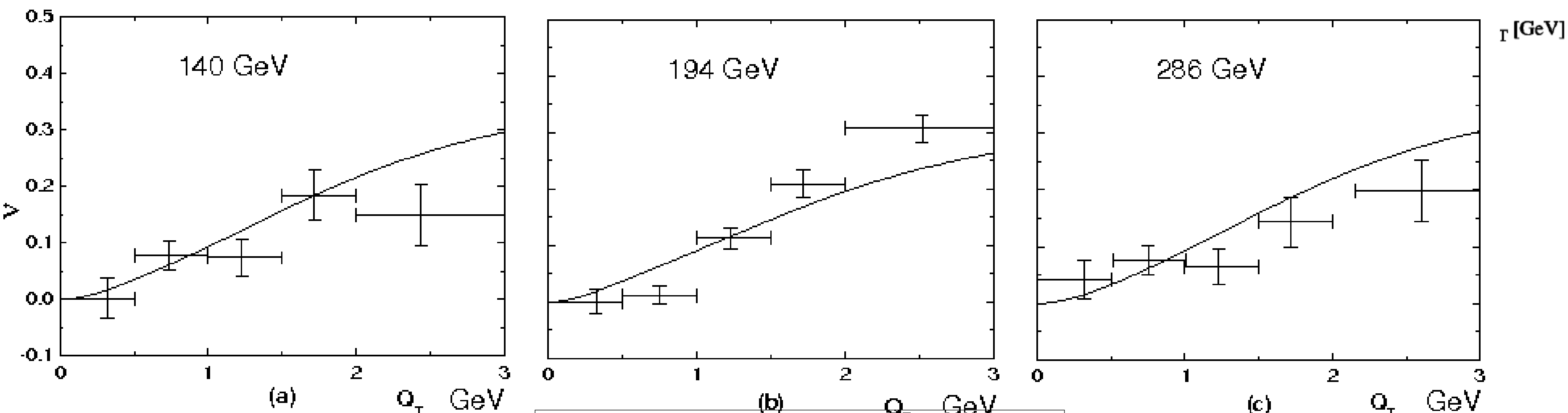
- Relates transverse spin and transverse momentum (k_T) in an unpolarized nucleon.
- Presence in both quark and antiquark in annihilation could form correlation contributing to cos(2ϕ) distribution

$$\nu \propto h^{\perp}_{1q_b}(x_b) h^{\perp}_{1,\bar{q}t}(x_t)$$

- Reasonable fits to pionic data



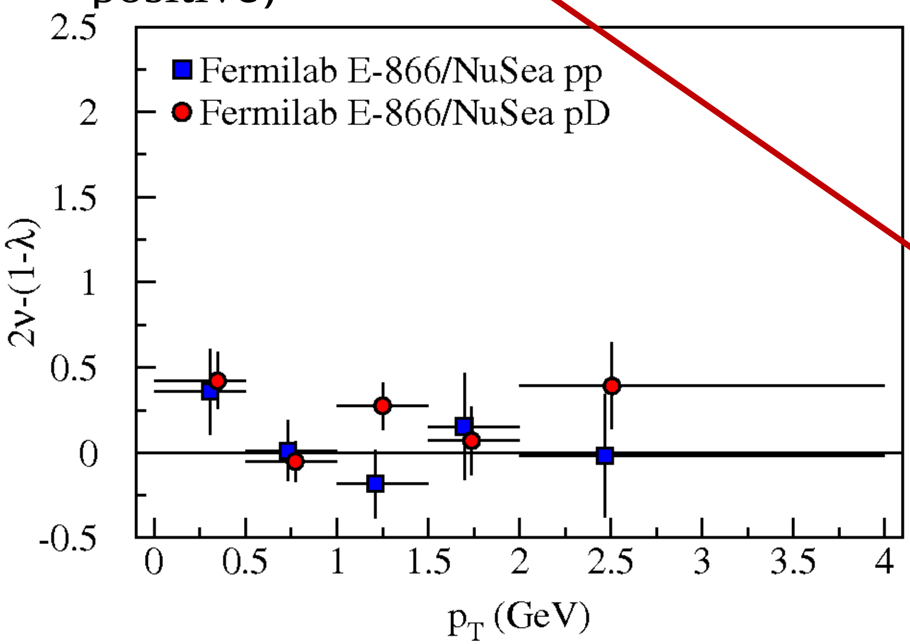
Boer **PRD 60** 014012 (1999)

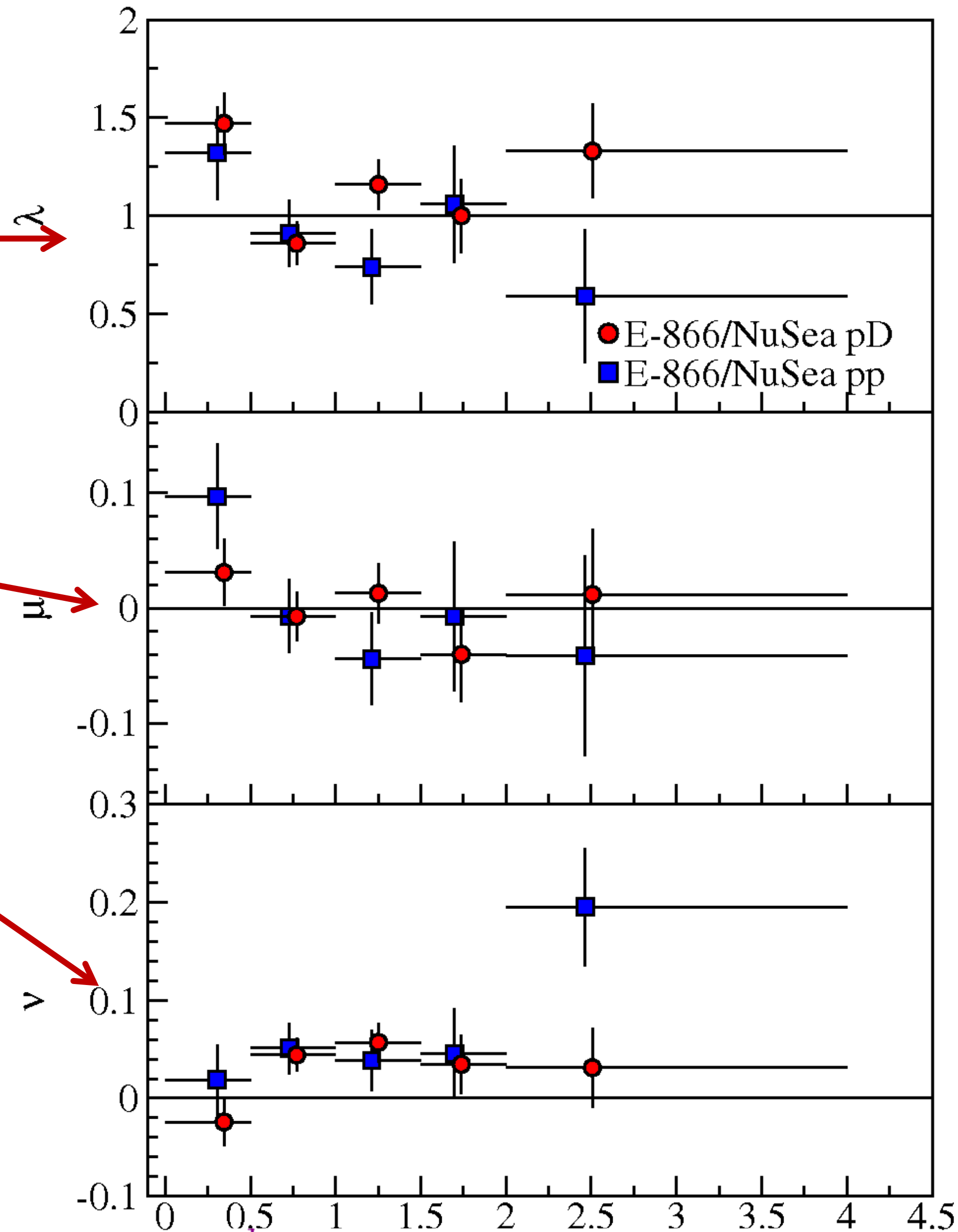


Lu, Ma, PL**B 615**, 200 (2005)

Protonic Drell-Yan
E-866/NuSea: Angular distrib.

- λ consistent with 1
- μ consistent with 0
- ν consistent with 0 (or slightly positive)

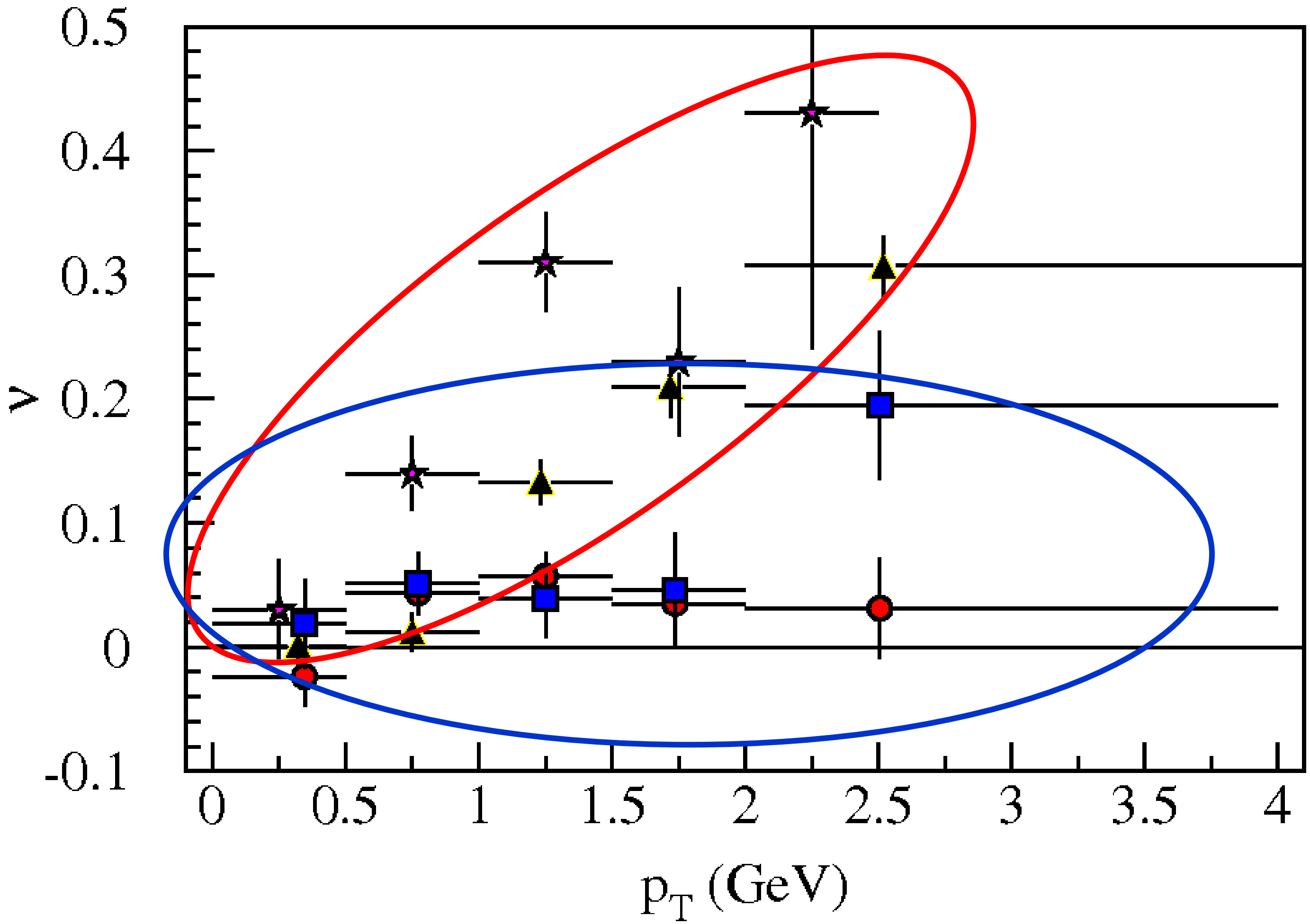




$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + (\nu/2)\sin^2\theta\cos 2\phi$$

What do the data mean?

- ν coefficient is grows as a function of p_T faster for π^- induced Drell-Yan
- **π^- quark structure has a valence anti-u quark** —sensitive to valence u quark distributions of target



- Proton induced Drell-Yan is sensitive only to sea antiquark structure of the target

- Possible valence vs. sea quark effect?
  - $h^1{}_\perp$ expected to be small for sea

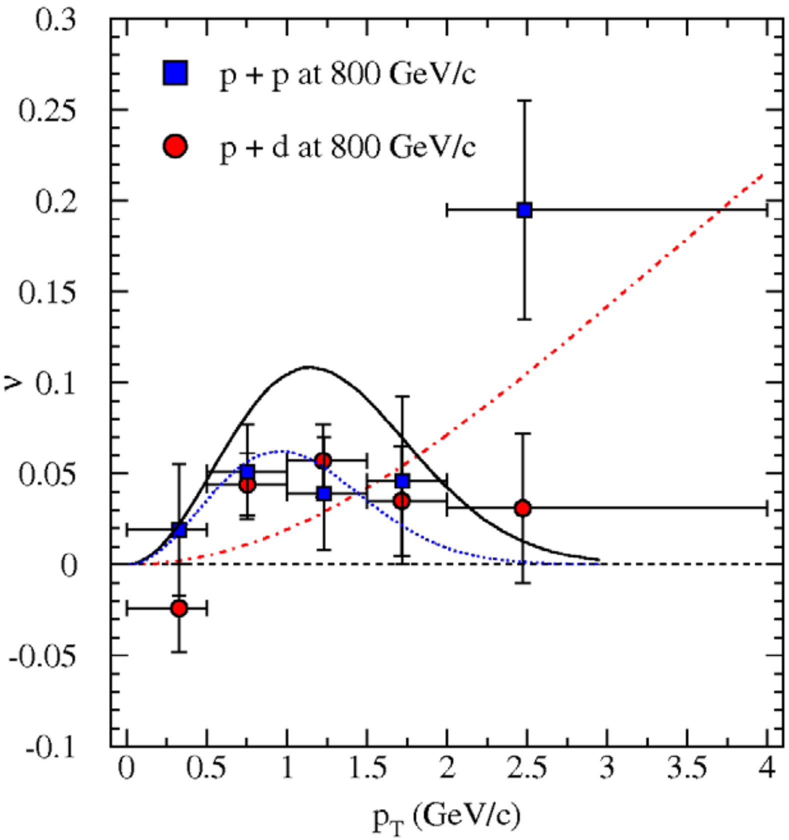
Extraction of Boer-Mulders function from pD Drell-Yan

- Zhang, Lu, Ma, Schmidt, Phys.Rev.**D77**:054011,2008.
- Fit pD data in p_T, x_1 and x_2
- Extract $h_\perp^{1,q}$. (flavor separation)
- Prediction for pp Drell-Yan

$$h_1^{\perp,q}(x, p_\perp^2) = H_q (1-x) x^c e^{-p_\perp^2/p_{\text{B}-M}^2} f_1^q(x)$$

H_u	H_d	$H_{\bar{u}}$	$H_{\bar{d}}$	c	$p_{\text{B-M}}$
3.99	3.83	0.91	-0.96	0.16	0.45

Small sea quark $h_1^\perp$



QCD effects in Drell-Yan

ν(pp) = ν(pD) because of same kinematic coverage

$$\nu = \frac{Q_\perp^2/Q^2}{1 + \frac{3}{2} Q_\perp^2/Q^2}$$

Boer *et al* EPJ **C 40**, 55 (2005) and

Berger *et al* PR **D 76**, 074006 (2007).

Transverse Structure
What data would I like to see? (My personal view)

- Siver's function relation to DIS tested

$$f_{1T}^{\perp}(x, k_T)\Big|_{\mathrm{DIS}} = - \, f_{1T}^{\perp}(x, k_T)\Big|_{\mathrm{DY}}$$

  – CERN COMPASS, GSI PAX, J-PARC, RHIC

- Unpolarized Angular Distributions—Boer-Mulders Structure Function, QCD
  – Fermilab E-906/SeaQuest, J-PARC, RHIC (pp, pA)
  – CERN COMPASS (πp)

- Double polarized Drell-Yan—$h_1(x)$

$$A_{TT}^{\mathrm{DY}} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}}$$

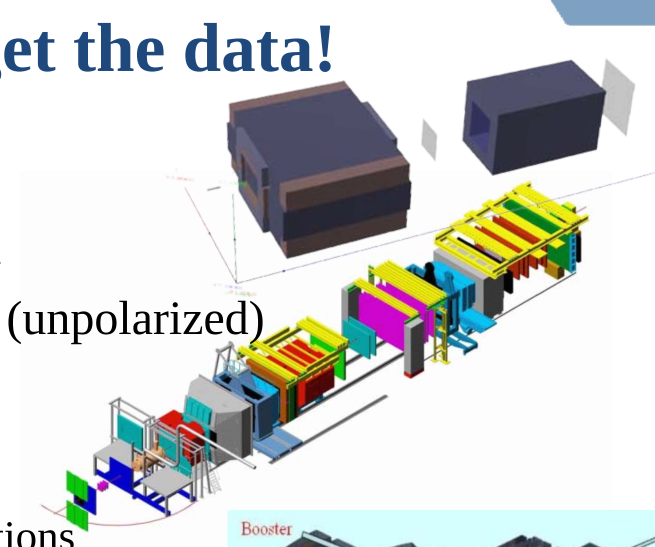
$$= \alpha_{TT} \frac{\sum_i e_i^2 \left[h_{1i}(x_1)\bar{h}_{1i}(x_2) + \bar{h}_{1i}(x_1)h_{1i}(x_2)\right]}{\sum_i e_i^2 \left[f_i(x_1)\bar{f}_i(x_2) + \bar{f}_i(x_1)f_i(x_2)\right]}$$

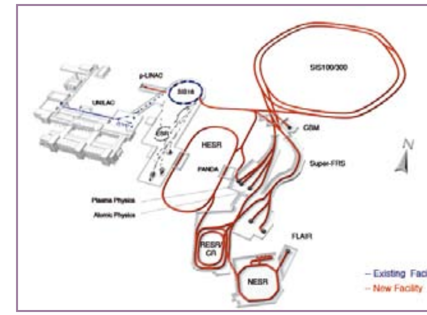
$$\approx \alpha_{TT} \frac{h_{1u}(x_1)h_{1u}(x_2)}{u(x_1) + u(x_2)}$$

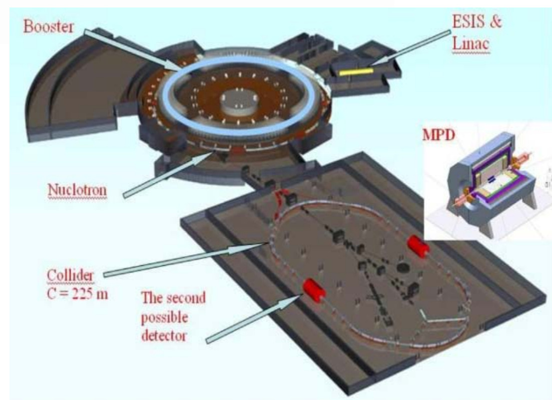
  – GSI-FAIR PAX antiproton-proton

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

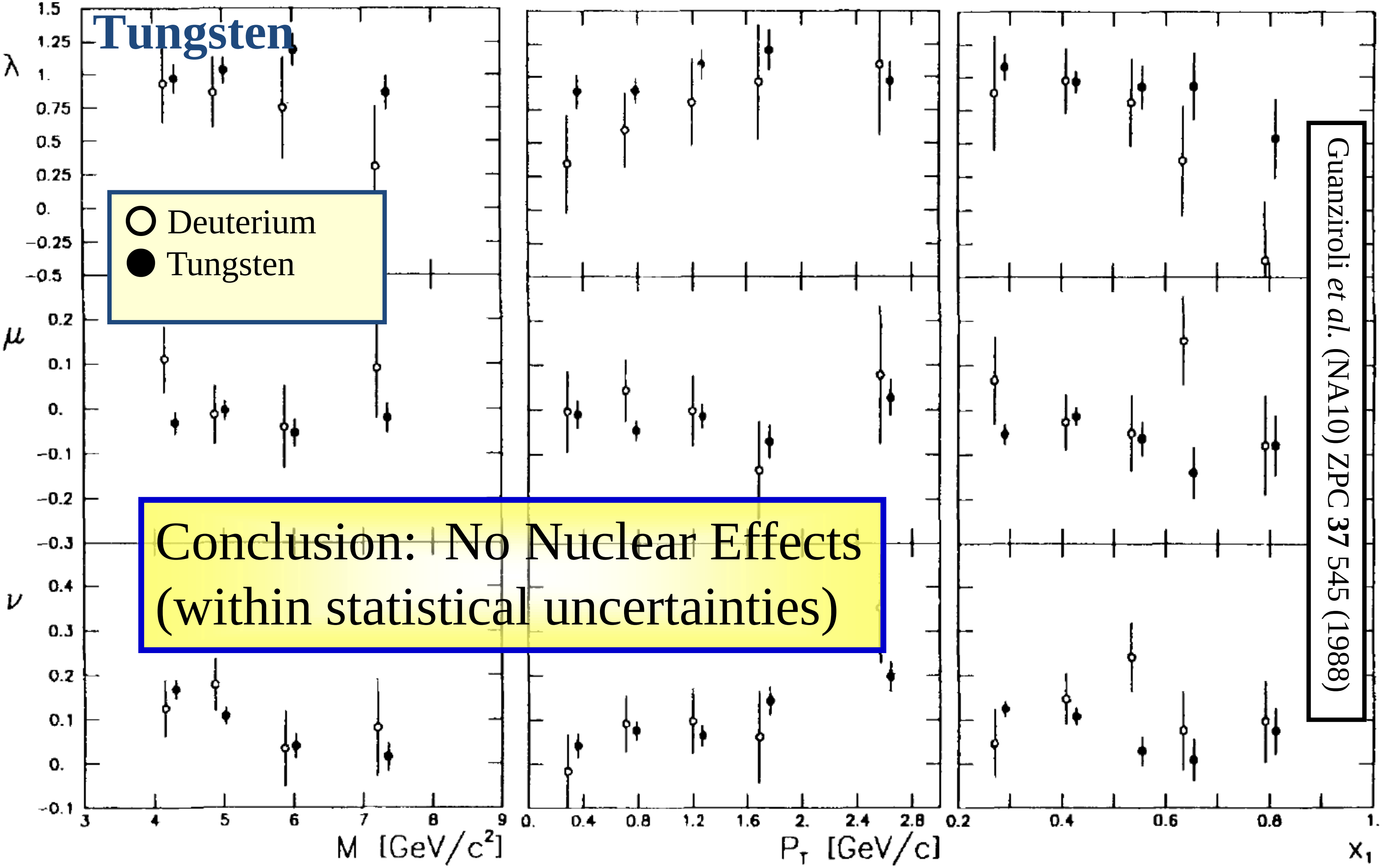






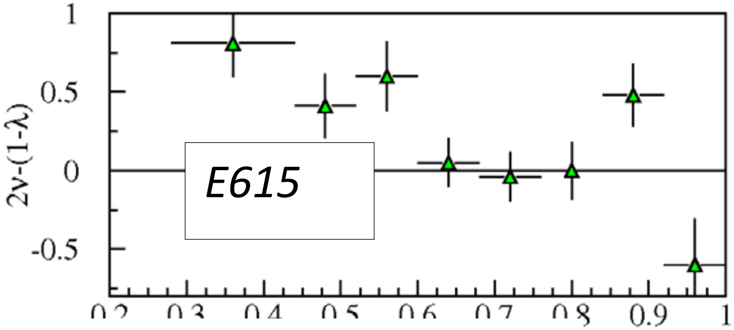
This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

Nuclear Effect? Compare NA10 Deuterium and Tungsten

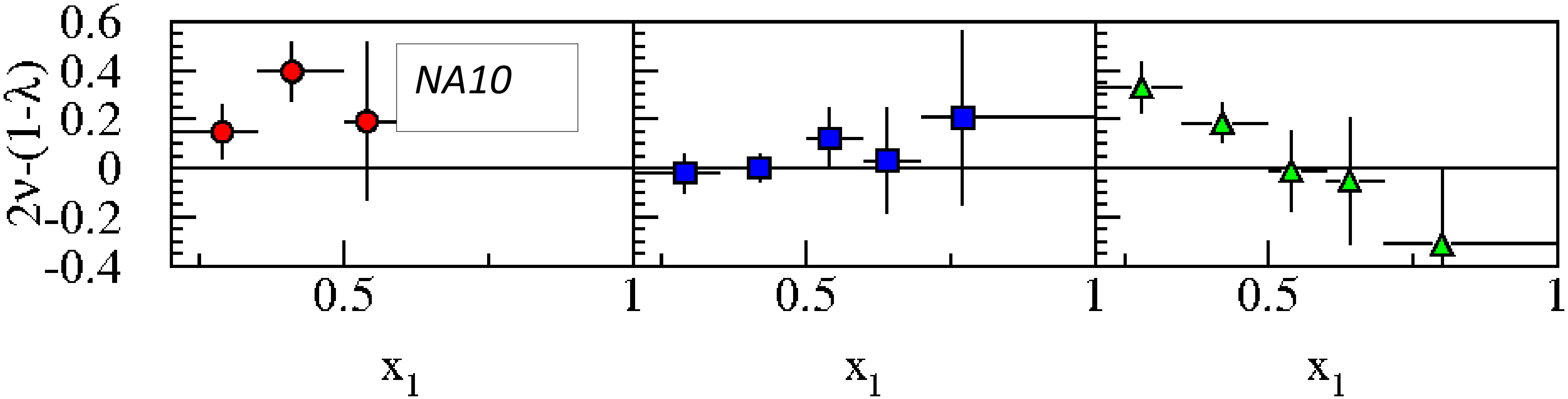


Conclusion: No Nuclear Effects (within statistical uncertainties)

Higher twist/QCD effects in pion



- Expected only as $x_1 \to 1$



- QCD effects in pion—model only applicable for $x_1 > 0.6$ Brandenburg, Brodsky, Khoze and Muller Phys.Rev.Lett.73:939-942,1994
- Effect not large enough