# Probing Transverse Momentum Distributions with the Drell-Yan process

Paul E. Reimer
Physics Division
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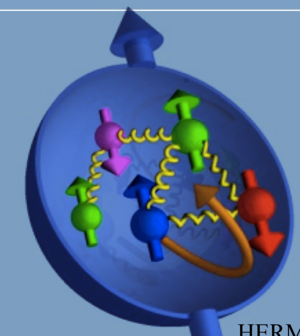
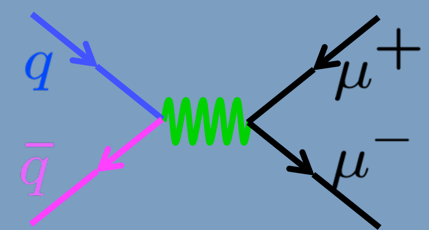

HERMES
U. Elschenbroich

1. The Drell-Yan Process: History and Future
2. Unpolarized Transverse Momentum Measurements

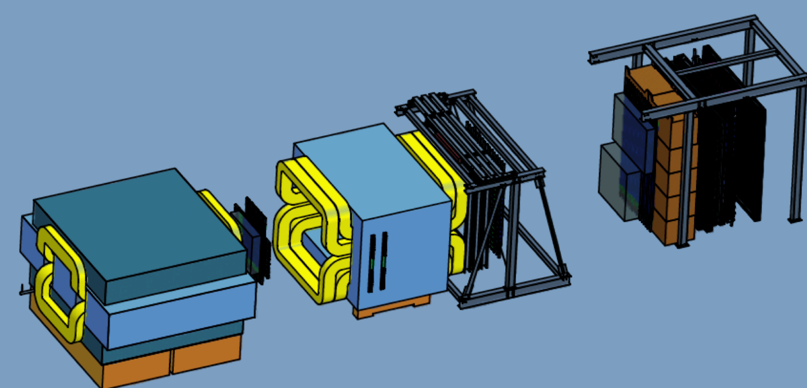



$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi$$

3. Polarized Measurements

$$f_{1T}^{\perp q}\Big|_{DIS} = -f_{1T}^{\perp q}\Big|_{D-Y}$$

4. What can the future hold?



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

# The journey begins

# Early Muon Pair Data—soon to be called Drell-Yan

VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

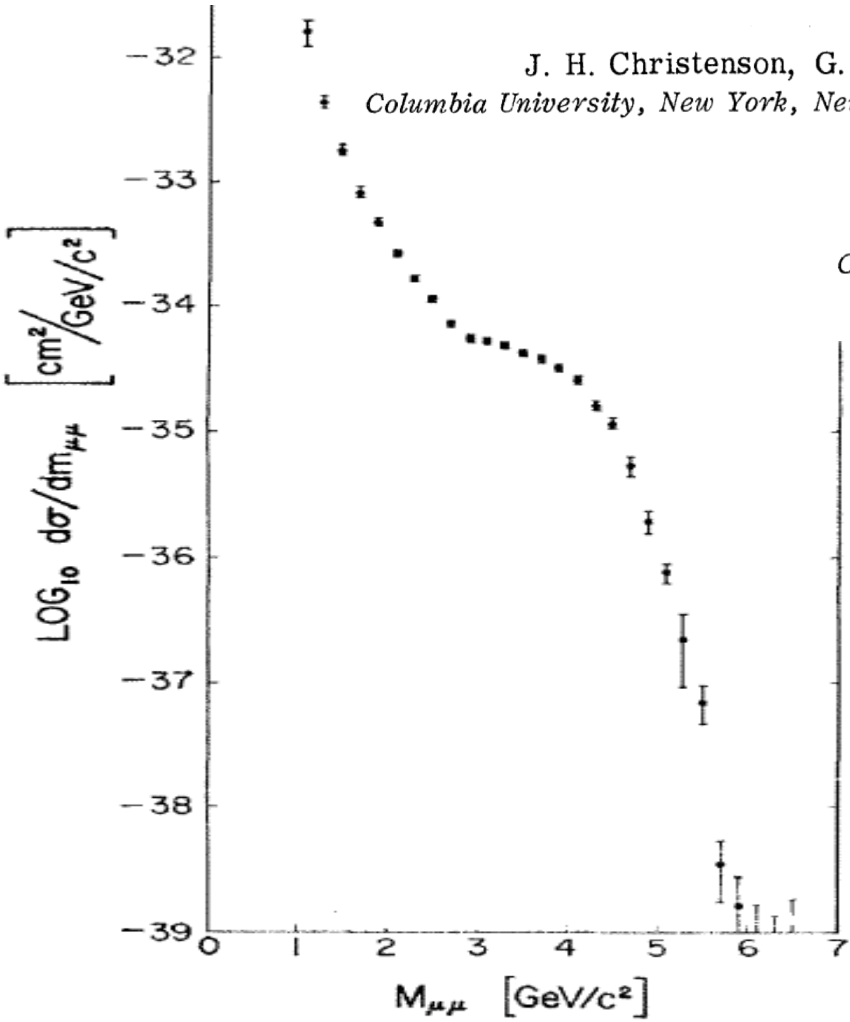
## Observation of Massive Muon Pairs in Hadron Collisions*

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, Switzerland*

(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.

# Early Muon Pair Data—soon to be called Drell-Yan

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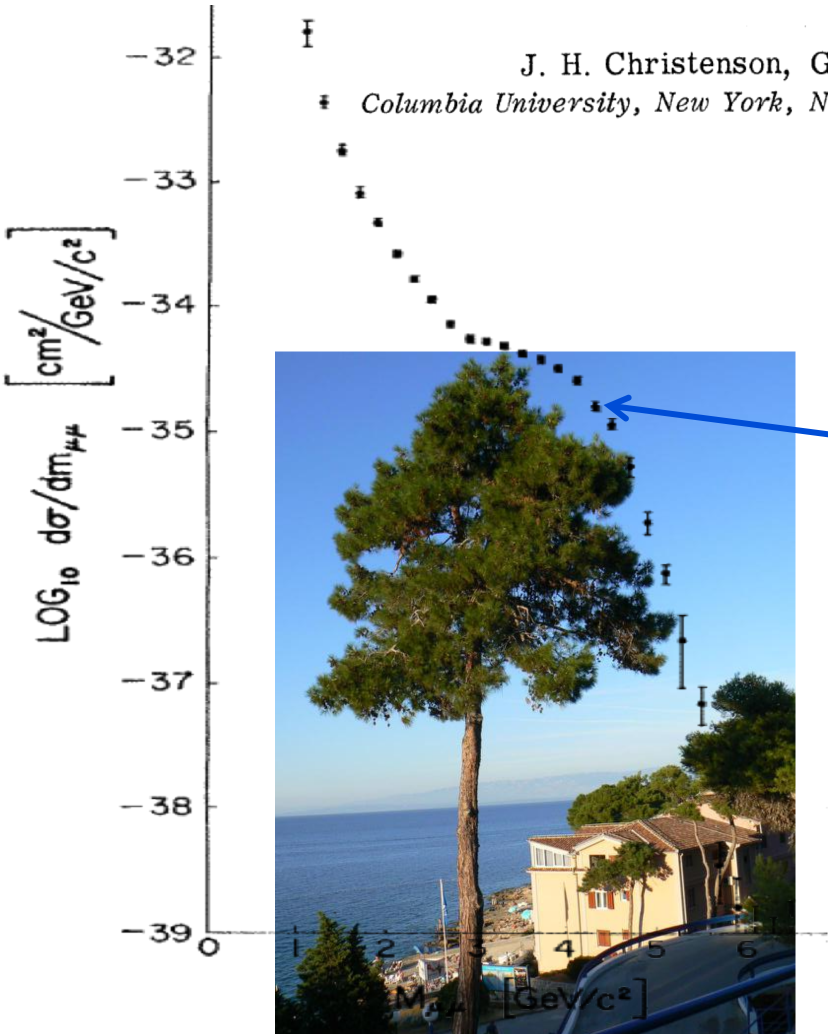
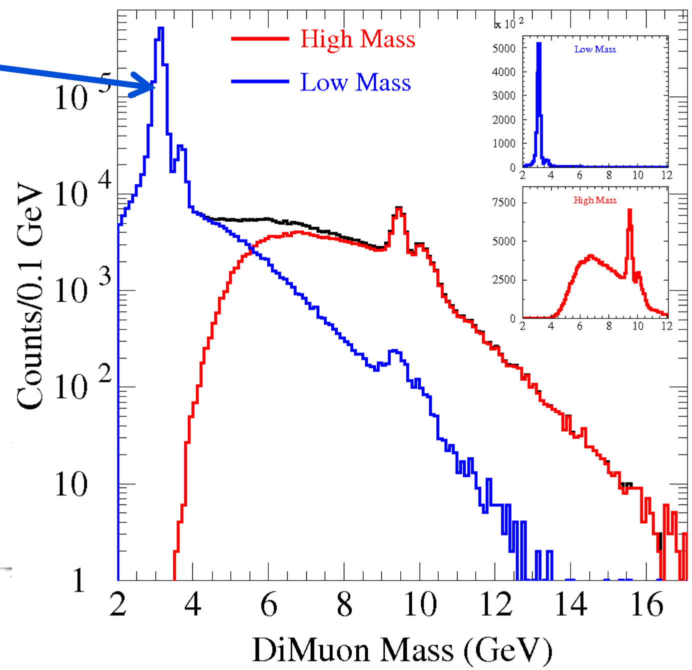



Don't miss the tree when looking at the beautiful scenery

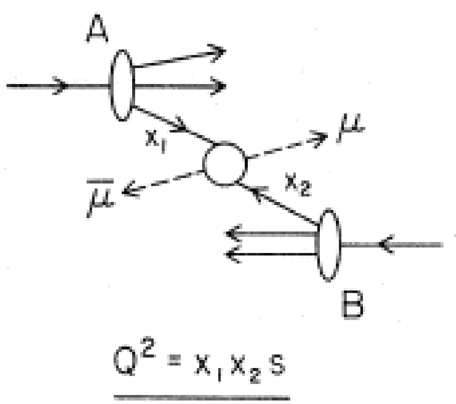
# Drell and Yan's explanation

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 $\nu W_2$ near threshold.




(b)

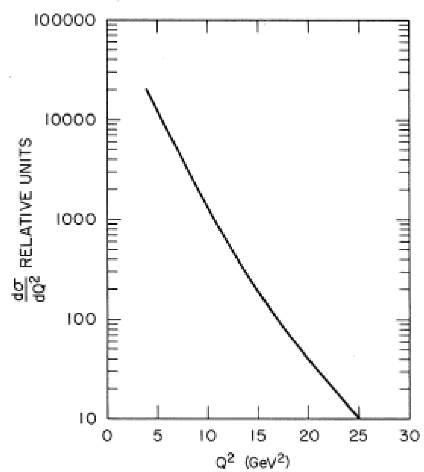
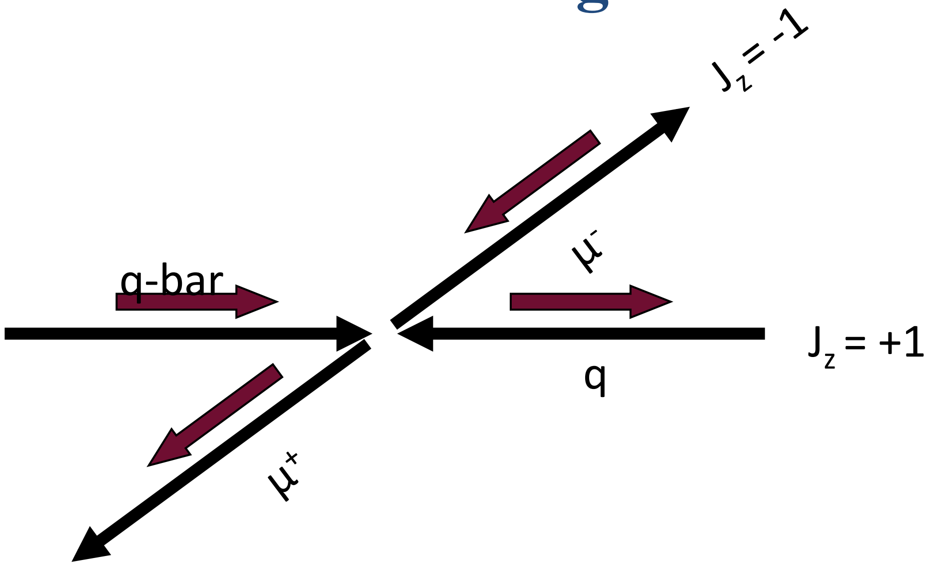



FIG. 2. $d\sigma/dQ^2$ computed from Eq. (10) assuming identical parton and antiparton momentum distributions and with relative normalization.

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

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

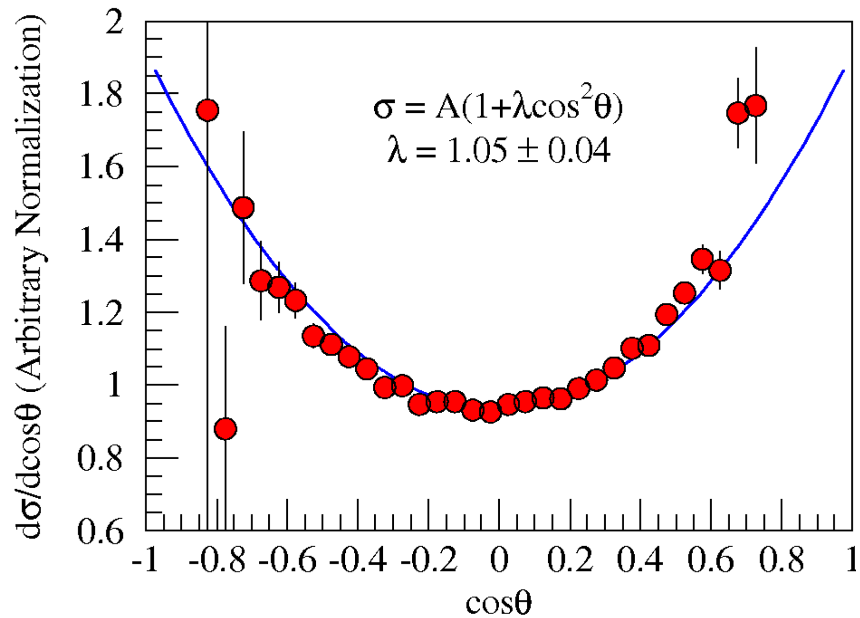



$$\mathcal{M} \propto d^{j}_{\lambda',\lambda(\theta)} = \langle j\lambda'|e^{-i\theta J_y}|j\lambda\rangle$$

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

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

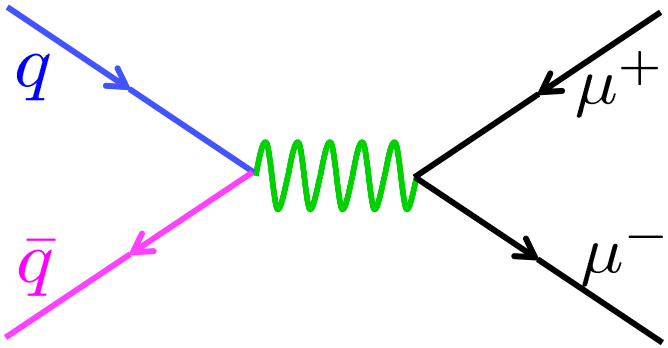
$$\frac{d\sigma}{d\Omega} \propto \mathcal{M}^2 \propto (1+\cos^2\theta)$$




Fermilab E-866/NuSea unpublished

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

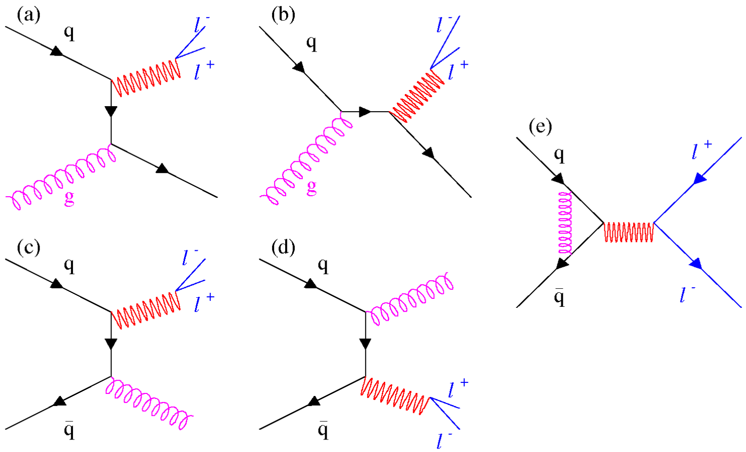
# Drell-Yan Cross Section




- Measured cross section is a convolution of beam and target parton distributions

$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{x_b x_t s} \sum_{q\in\{u,d,s,\dots\}} e_q^2 \left[\bar{q}_t(x_t) q_b(x_b) + \bar{q}_b(x_b) q_t(x_t)\right]$$

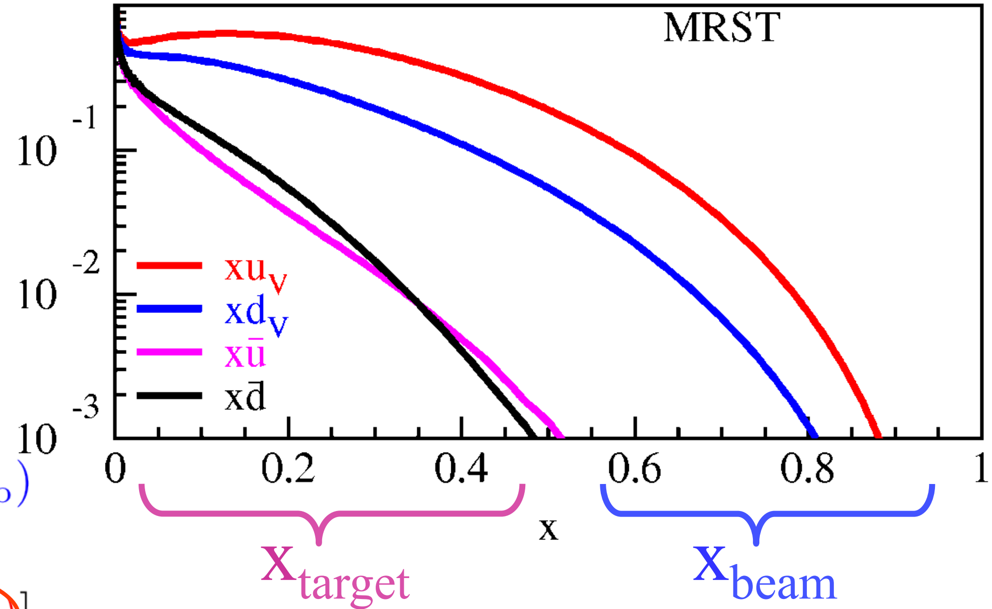
- u-quark dominance
  - $(2/3)^2$ vs. $(1/3)^2$




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

# Drell-Yan Cross Section

- Measured cross section is a convolution of beam and target parton distributions




- **Proton Beam**
  - Target antiquarks and beam

$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{x_b x_t s} \sum_{q\in\{u,d,s,\dots\}} e_q^2 \left[\bar{q}_t(x_t) q_b(x_b) + \bar{q}_b(x_b) q_t(x_t)\right]$$

Acceptance limited

- **$\pi^-$ beam**
  - Valence beam anti-u quark and u target quark

$$\left.\frac{d^2\sigma}{dx_\pi dx_N}\right|_{\pi-N} = \frac{4\pi\alpha^2}{x_\pi x_N s}\left[\frac{4}{9}\bar{u}_\pi(x_\pi) u_N(x_N) + \frac{1}{9} d_\pi(x_\pi)\bar{d}_N(x_N) + \frac{4}{9} u_\pi(x_\pi)\bar{u}_N(x_N) + \frac{1}{9}\bar{d}_\pi(x_\pi) d_N(x_N)\right]$$

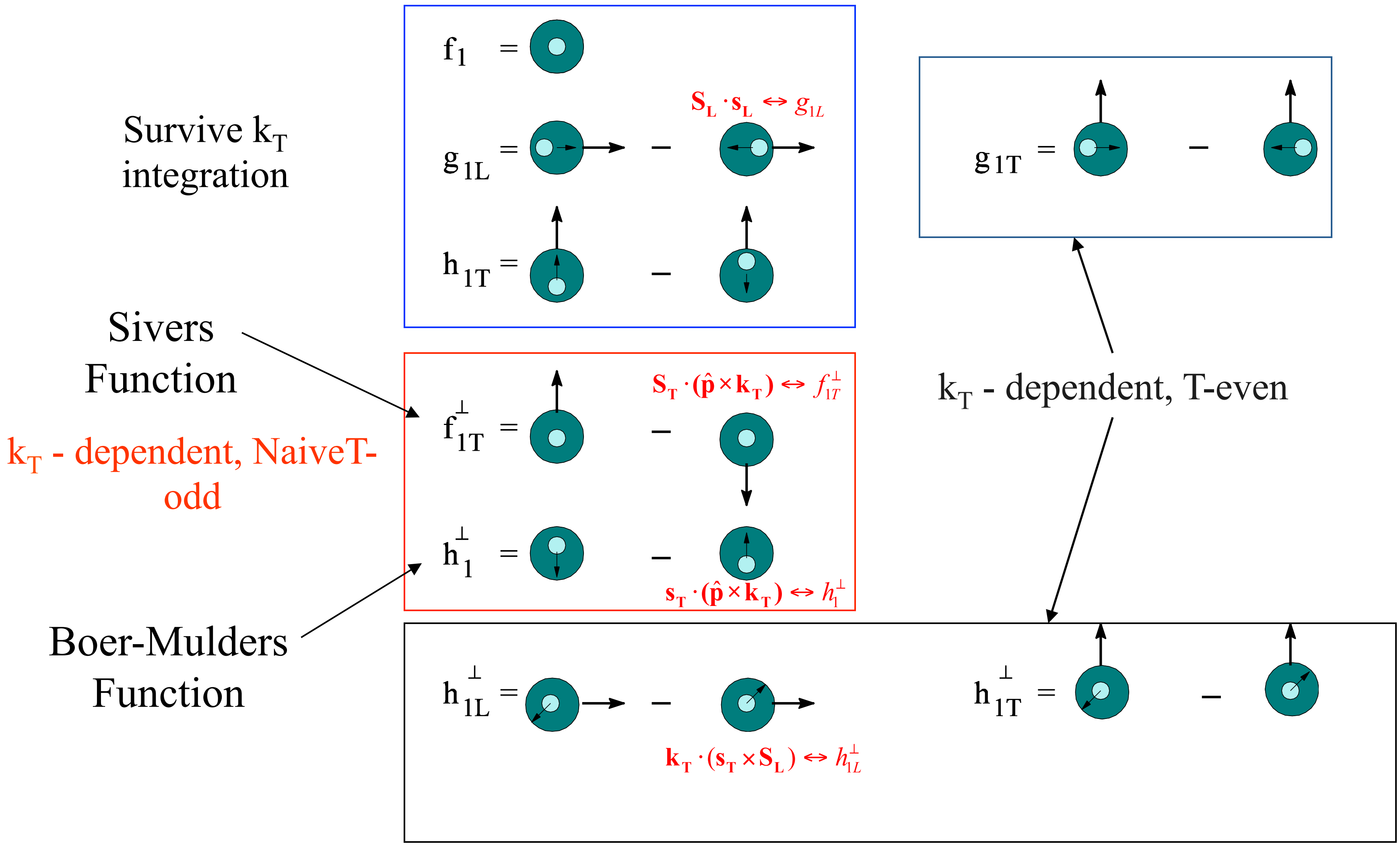
Valence × Valence

Valence-sea ×¼

Sea-Sea

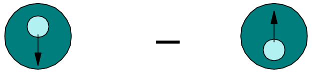
| Beam | Target | Experiment |
|---|---|---|
| Hadron | Beam valence quarks target antiquarks | Fermilab E-906, RHIC (forward acpt.) J-PARC |
| Anti-Hadron | Beam val. antiquarks Target valence quarks | GSI-FAIR Fermilab Collider |
| Meson | Beam val. antiquarks Target valence quarks | COMPASS |

# Transverse Momentum Distributions: Introduction



# Transverse Momentum Distributions: Polarized Drell-Yan

1. What is the Lam-Tung relation? How does it relate to transverse structure?
   - Boer-Mulders Function

$h_1^\perp =$  $-$

$\mathbf{s}_T \cdot (\hat{\mathbf{p}} \times \mathbf{k}_T) \leftrightarrow h_1^\perp$

$k_T$ - dependent,
Naïve T-odd

2. What do the available data teach us?
   - πN (CERN NA10, Fermilab E-615)
   - pp and pd (Fermilab E866)

3. Is it consistent?

# Generalized Angular Distributions & Lam Tung relation

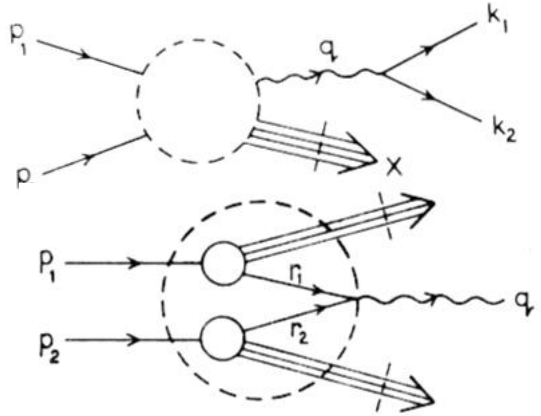
Chi-Sing Lam and Wu-Ki Tung—basic formula for lepton pair production angular distributions PRD **18** 2447 (1978)

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

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

$$W_T = 2W_{\Delta\Delta}$$

# 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)

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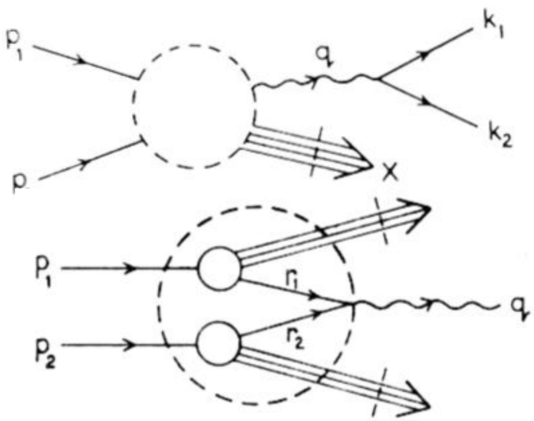



Lam-Tung relation

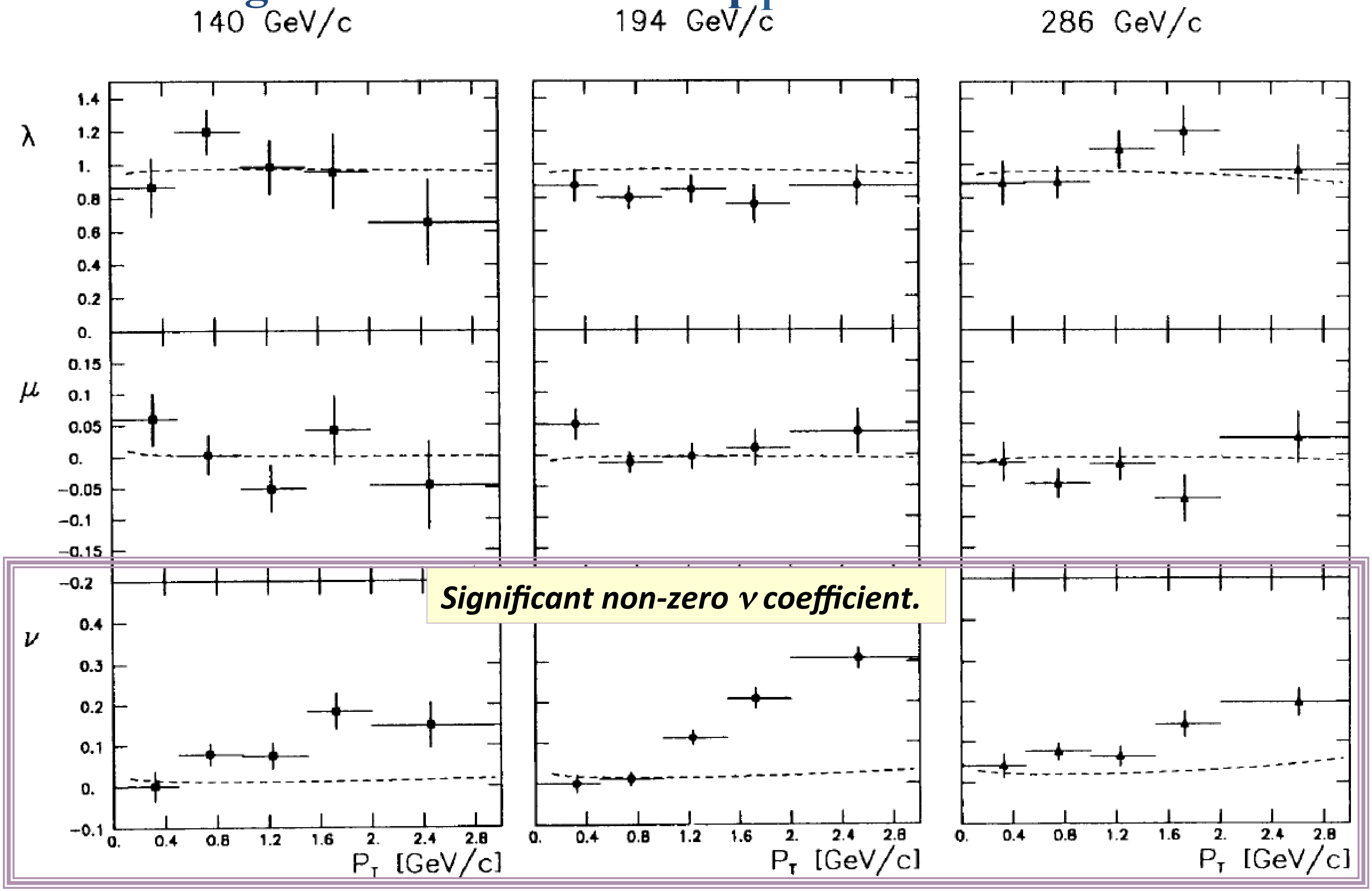
- Derived in analogy to Colin-Gross relation of DIS

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

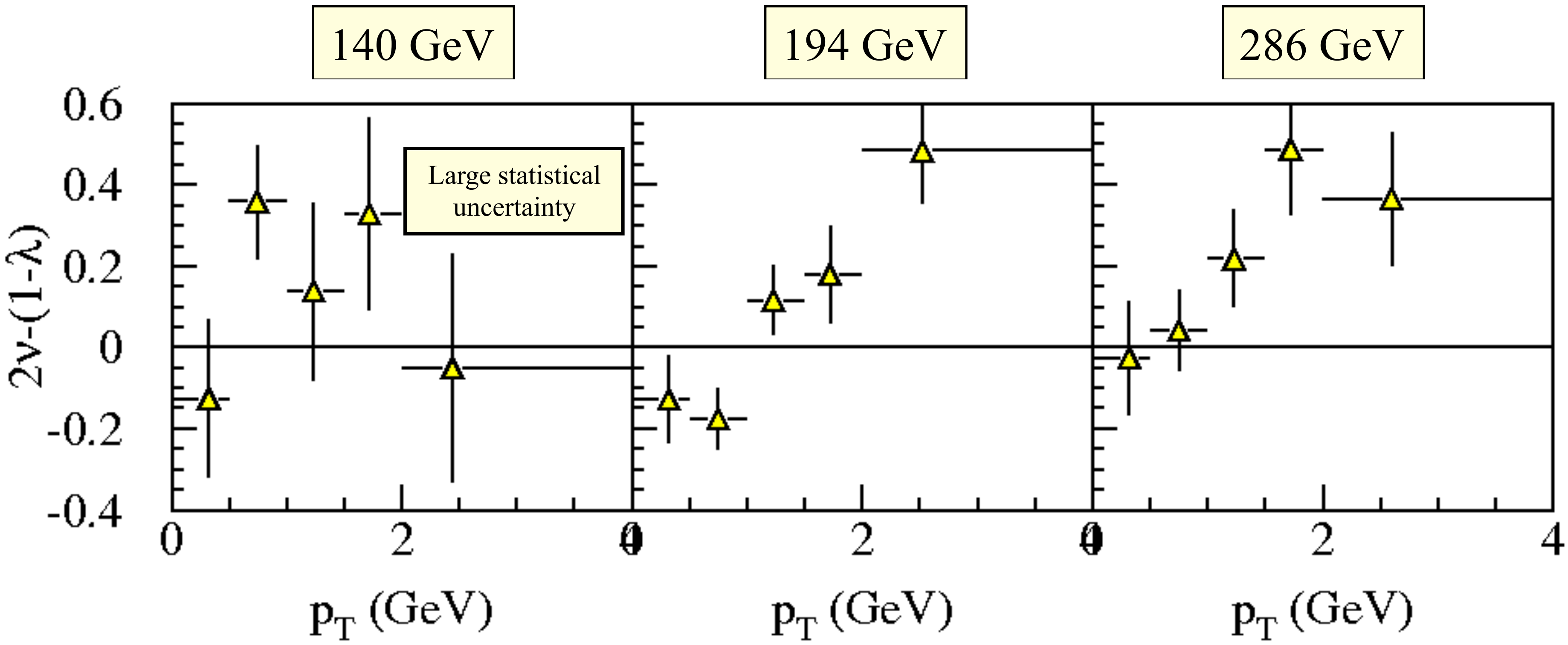
# Why is Lam-Tung relation important? What does it have to do with Transverse Momentum?

- 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)
- **Factorization breaking QCD Vacuum**
- **$k_T$ dependent transverse momentum distribution (Boer Mulders $h_1^\perp$)**
- Alternatives:
  - → Nuclear effects
  - → Higher-Twist effects from quark-antiquark binding in pion
  - → Neither seen in data

# NA10 angular distributions vs. $p_T$



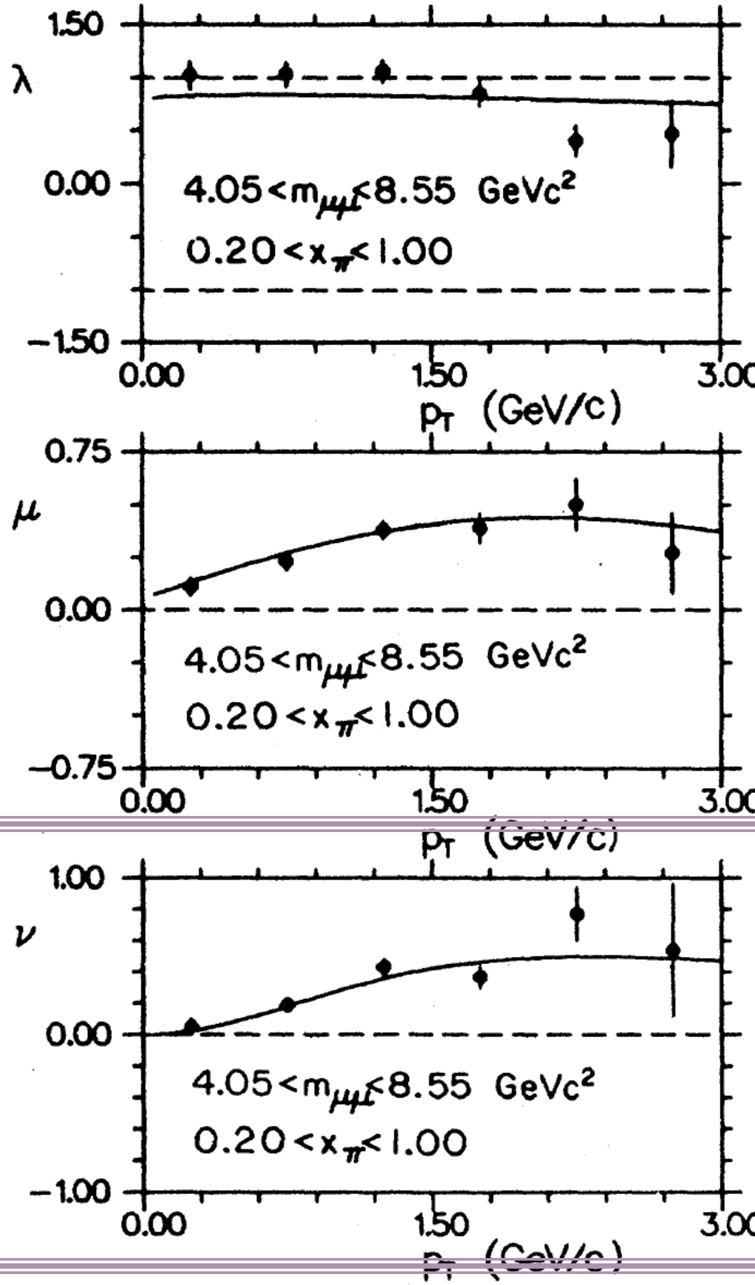
# NA10 Lam-Tung Relation vs. $p_T$




- 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

# Pionic Data Fermilab E615

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




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

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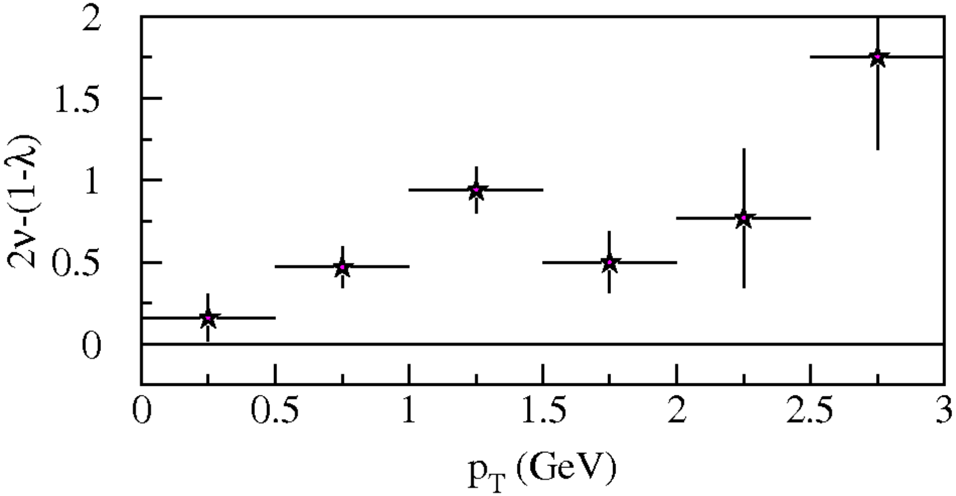
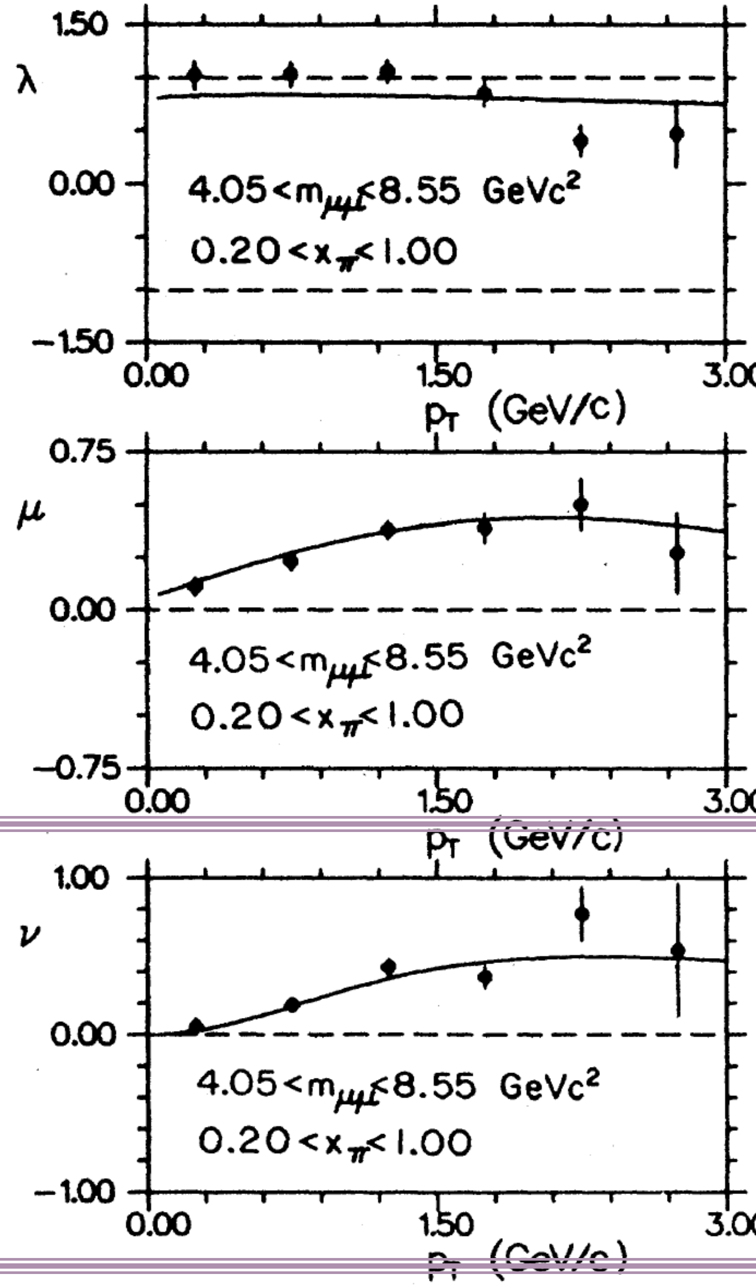



- Clear violation of Lam-Tung Relation vs. $p_T$.
- *Violation larger than NA10*



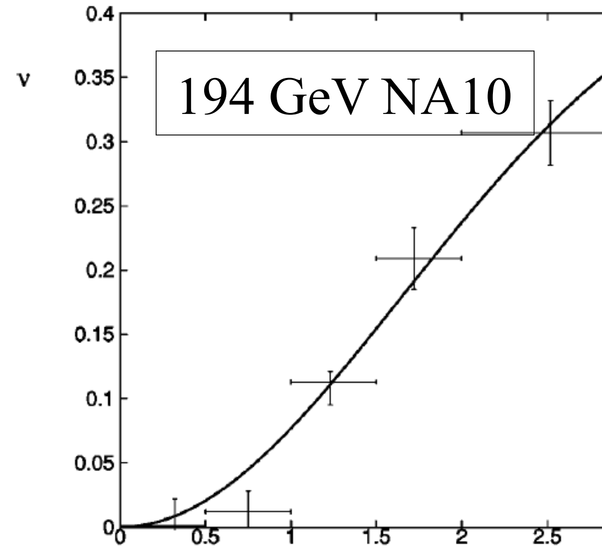

Conway *et al.* PRD **39** 92 (1989)

# Boer-Mulders Structure Function

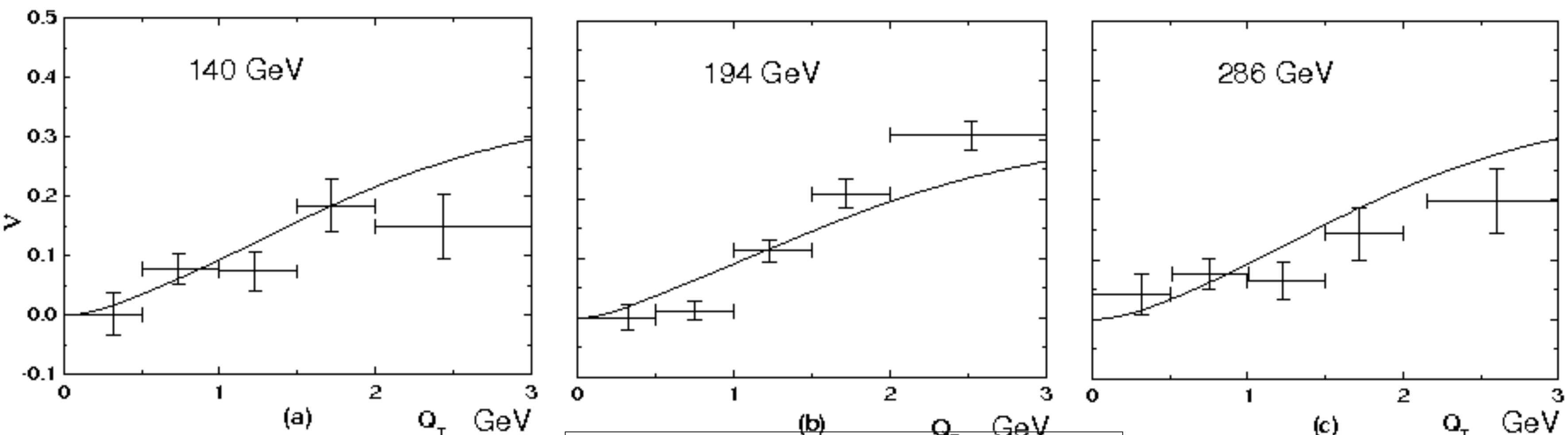
- Relates transverse spin and transverse momentum ($k_T$) in an unpolarized nucleon.
- Presence in both quark and antiquark in annihilation could form correlation contributing to cos(2ϕ) distribution

$$\nu \propto h_{1q}^{\perp}(x_1) h_{1\bar{q}}^{\perp}(x_2)$$

- Reasonable fits to pionic data




Boer **PRD 60** 014012 (1999)




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

# Lam-Tung Relation—Alternative View: QCD effects

- 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).

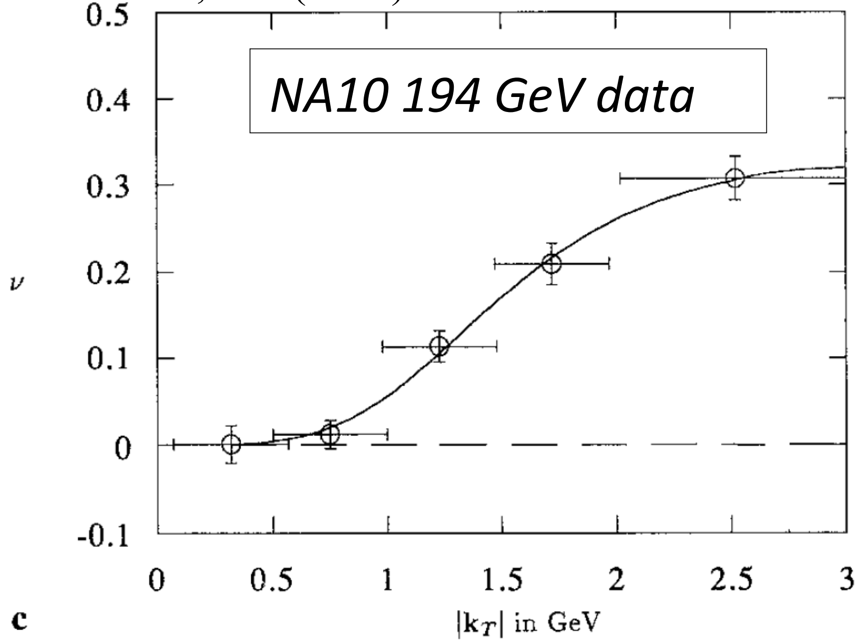
$$\nu \approx 2\mathcal{K} = 2\mathcal{K}_0 \frac{p_T^4}{p_T^4 + m_T^4}$$

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

  - Fit NA10:

$\kappa = 0.17$

$m_T = 1.5$

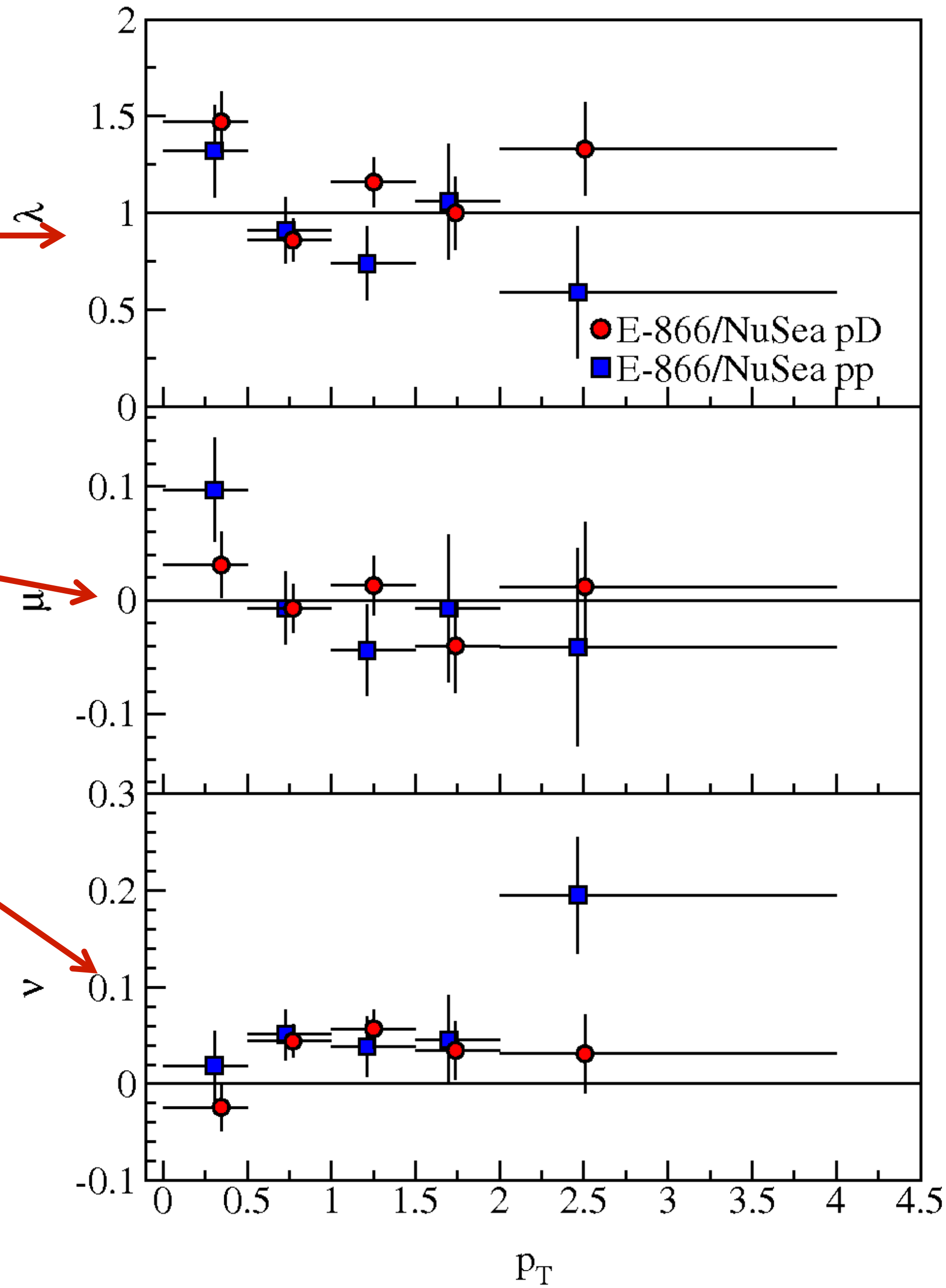



**Should be flavor blind and seen in both sea and valence distributions**

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

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

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



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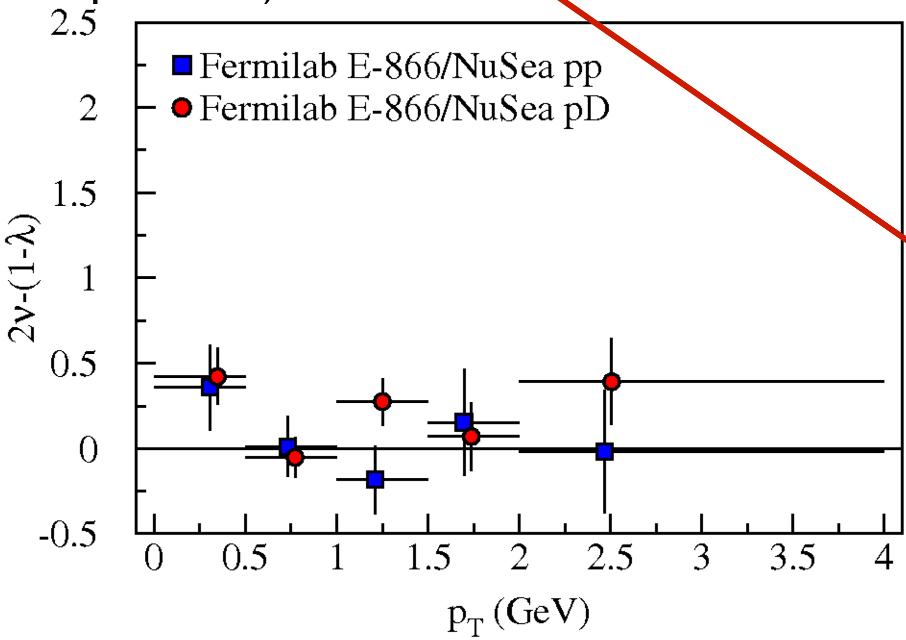
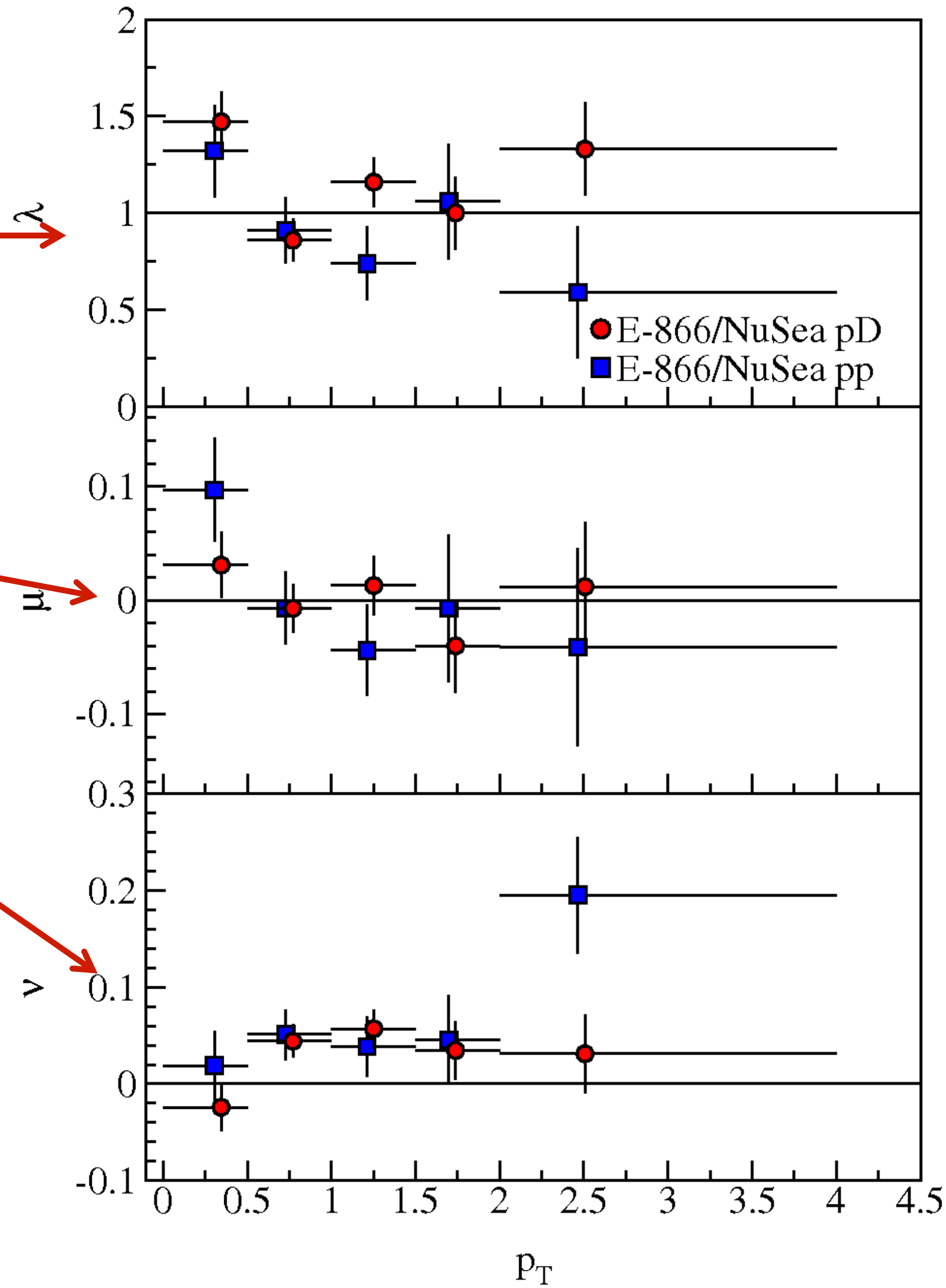


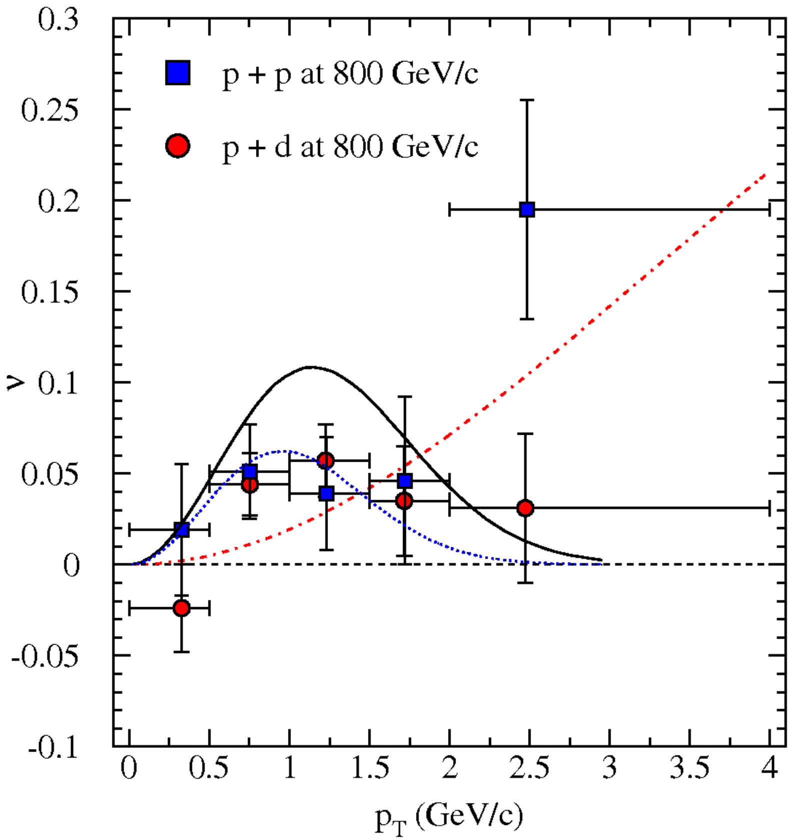
# Extraction of Boer-Mulders function from pD Drell-Yan

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

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

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

Small sea quark $h_1$?




***QCD effects in Drell-Yan***

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

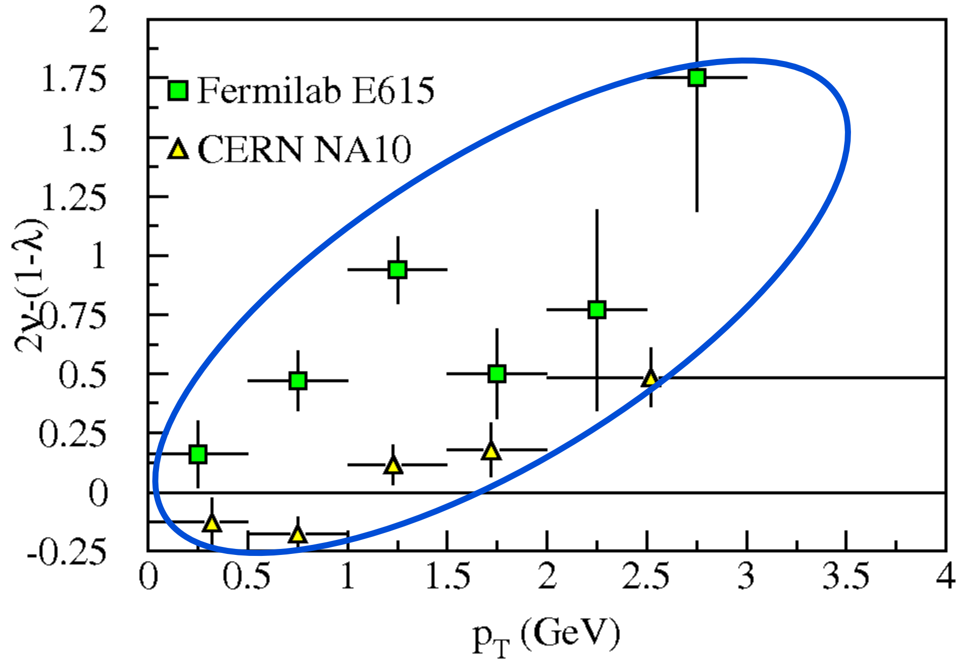
$$\nu = \frac{Q_\perp^2/Q^2}{1+\frac{3}{2}Q_\perp^2/Q^2}$$

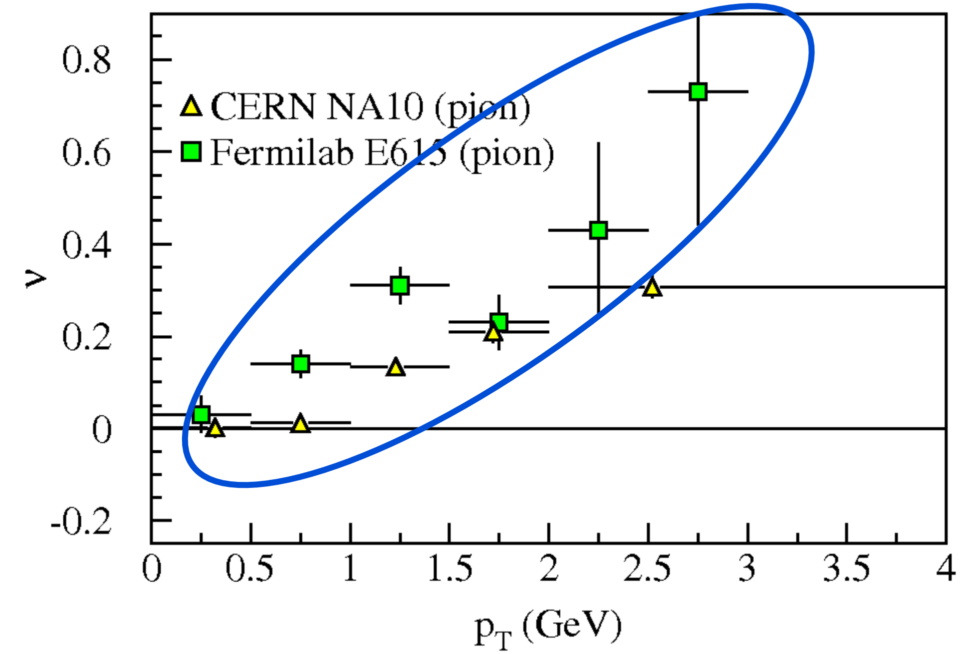
Boer *et al* EPJ **C 40**, 55 (2005) and

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

# Lam-Tung Relation

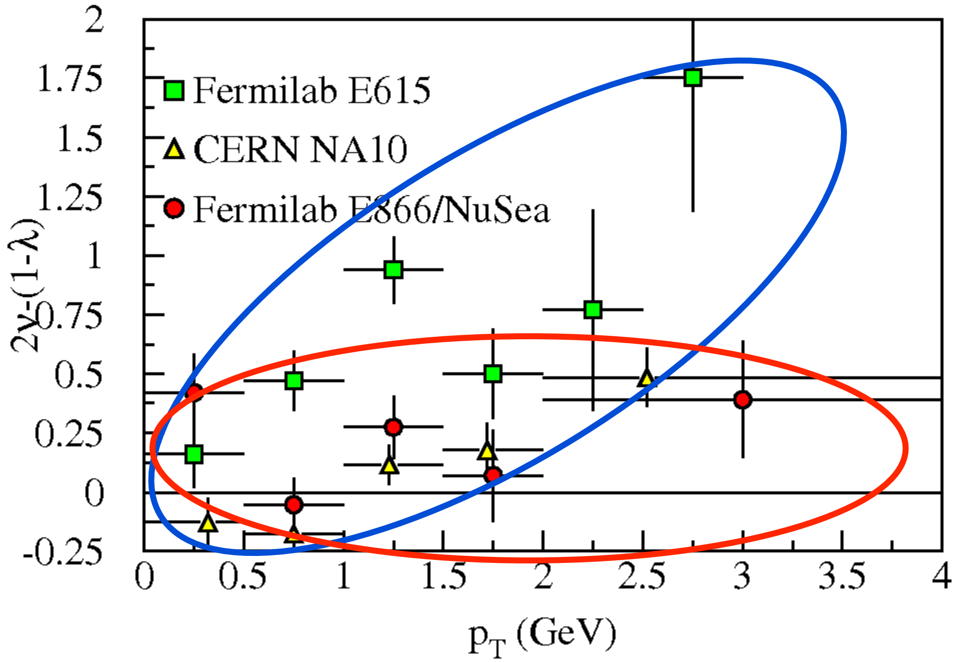
- $\pi^-$ Drell-Yan
  - Violates L-T relation
  - Large $\nu$ ($\cos 2\phi$) dependence
  - Strong with $p_T$

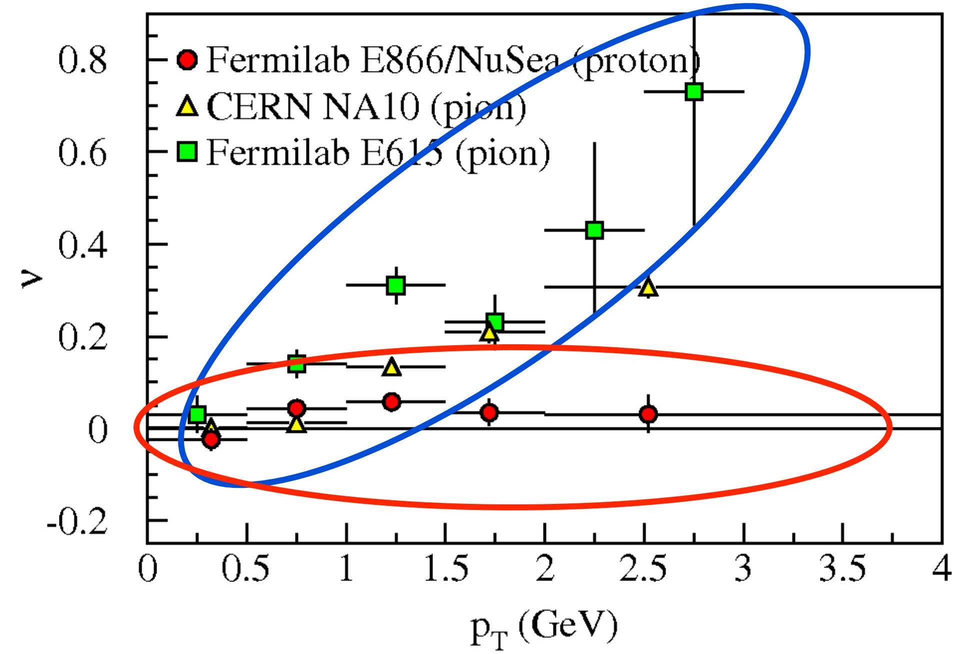


# Lam-Tung Relation

- $\pi^-$ Drell-Yan
  - Violates L-T relation
  - Large $\nu$ ($\cos 2\phi$) dependence
  - Strong with $p_T$
- Proton Drell-Yan
  - **Consistent** with L-T relation
  - **No** $\nu$ ($\cos 2\phi$) dependence
  - **No** $p_T$ dependence

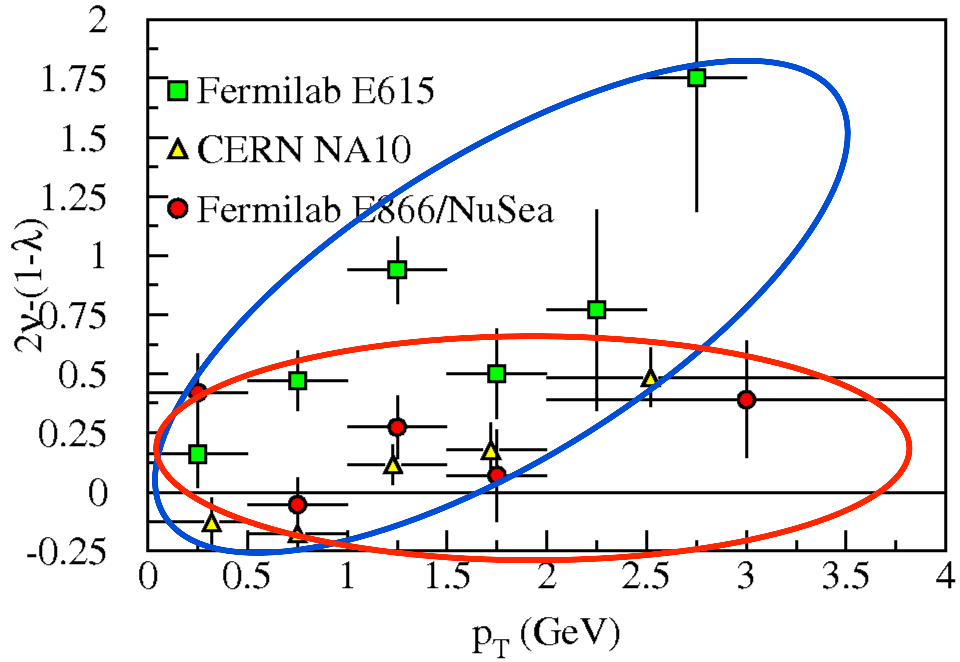


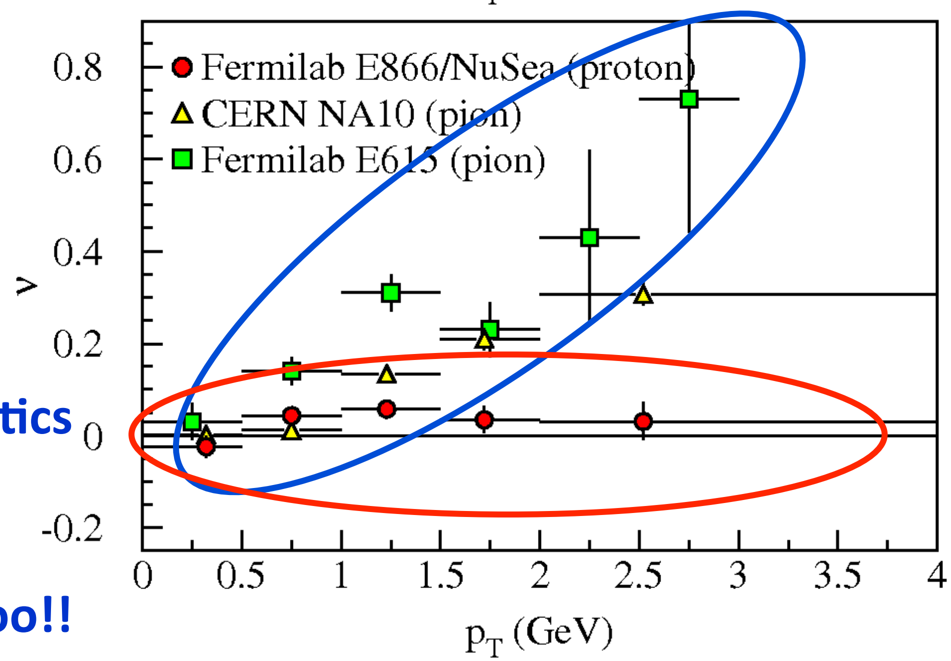



# Lam-Tung Relation

- $\pi^-$ Drell-Yan
  - Violates L-T relation
  - Large ν (cos2ϕ) dependence
  - Strong with $p_T$
- Proton Drell-Yan
  - **Consistent** with L-T relation
  - **No** ν (cos2ϕ) dependence
  - **No** $p_T$ dependence
- With Boer-Mulders function $h_1^{\perp}$:
  - ν π-W → $\mu^+\mu^-X$
    *valence $h_1^{\perp}(\pi)$ * valence $h_1^{\perp}(p)$*
  - ν pd → $\mu^+\mu^-X$
    *valence $h_1^{\perp}(p)$ * sea $h_1^{\perp}(p)$*
- **Consistent story but need better statistics**
  - **π-p → $\mu^+\mu^-X$—CERN Compass**
  - **pd → $\mu^+\mu^-X$—Fermilab E906/SeaQuest**

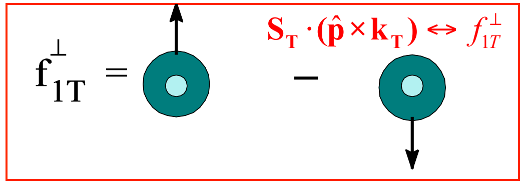
– **Remember QCD effects are important too!!**



# Transverse Momentum Distributions: The Sivers function

1. What is the Sivers function?




$k_T$ - dependent,
Naïve T-odd

2. What do the available Drell-Yan data teach us?
   - Nothing. . . . Yet
3. Is it consistent?
   - The big question

$$f_1^{\perp}(x, k_T)\big|_{\text{DIS}} \overset{?}{=} -f_1^{\perp}(x, k_T)\big|_{\text{D-Y}}$$

$$h_1^{\perp}(x, k_T)\big|_{\text{DIS}} \overset{?}{=} -h_1^{\perp}(x, k_T)\big|_{\text{D-Y}}$$

# Single Spin Leading Order Drell-Yan Cross Section

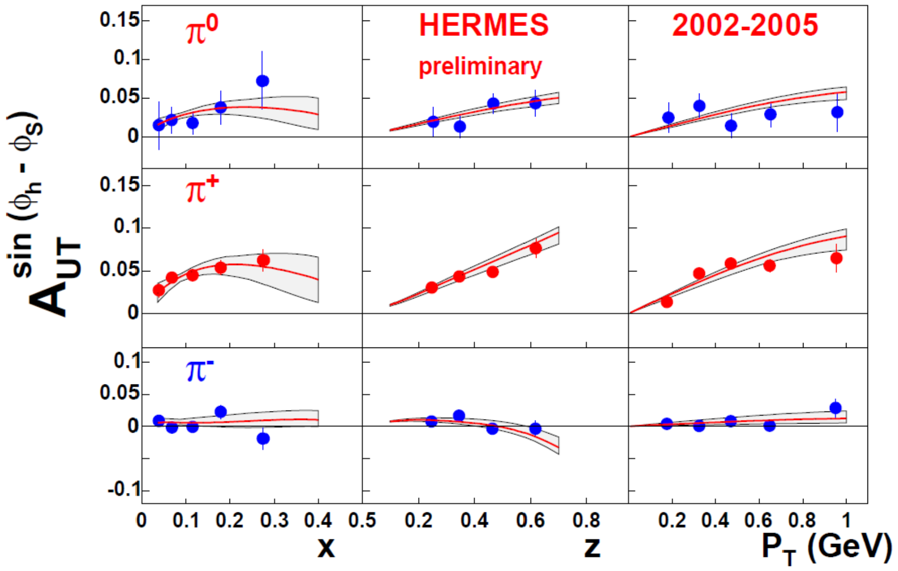
$$\frac{d\sigma^{\rm LO}}{d^4q\,d\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_{\rm U}^{\rm LO}\Big[1 + D^{\rm LO}_{\sin^2\theta} A_{\rm U}^{\cos 2\phi}\cos 2\phi$$
$$+ S_{\rm L} D^{\rm LO}_{\sin^2\theta} A_{\rm L}^{\sin 2\phi}\sin 2\phi$$
$$+ \left|\vec{S}_{\rm T}\right| A_{\rm T}^{\sin\phi_{\rm S}}\sin\phi_{\rm S}$$
$$+ \left|\vec{S}_{\rm T}\right| D^{\rm LO}_{\sin^2\theta} A_{\rm T}^{\sin(2\phi+\phi_{\rm s})}\sin(2\phi+\phi_{\rm S})$$
$$+ \left|\vec{S}_{\rm T}\right| D^{\rm LO}_{\sin^2\theta} A_{\rm T}^{\sin(2\phi-\phi_{\rm S})}\sin(2\phi-\phi_{\rm S})\Big]$$

| | |
|---|---|
| Formula: | from Aram Kotzinian |
| Slide: | content from Oleg Denisov's talk |

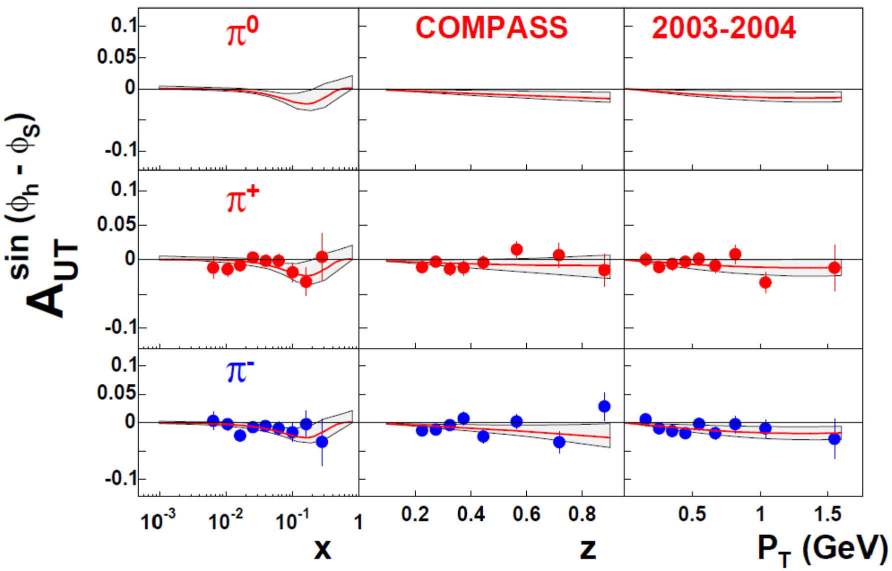
| | |
|---|---|
| $A_{\rm U}^{\cos 2\phi}$ | Boer-Mulders of beam hadron |
| $A_{\rm T}^{\sin\phi_{\rm S}}$ | Sivers for target nucleon |
| $A_{\rm T}^{\sin(2\phi+\phi_{\rm S})}$ | Boer-Mulders of beam hadron and $h_1^{\perp}$ and pretzelosity of target nucleon |
| $A_{\rm T}^{\sin(2\phi-\phi_{\rm S})}$ | Boer-Mulders of beam hadron and $h_1$ and transversity of target nucleon |

# SIDIS Sivers measurements

**HERMES**

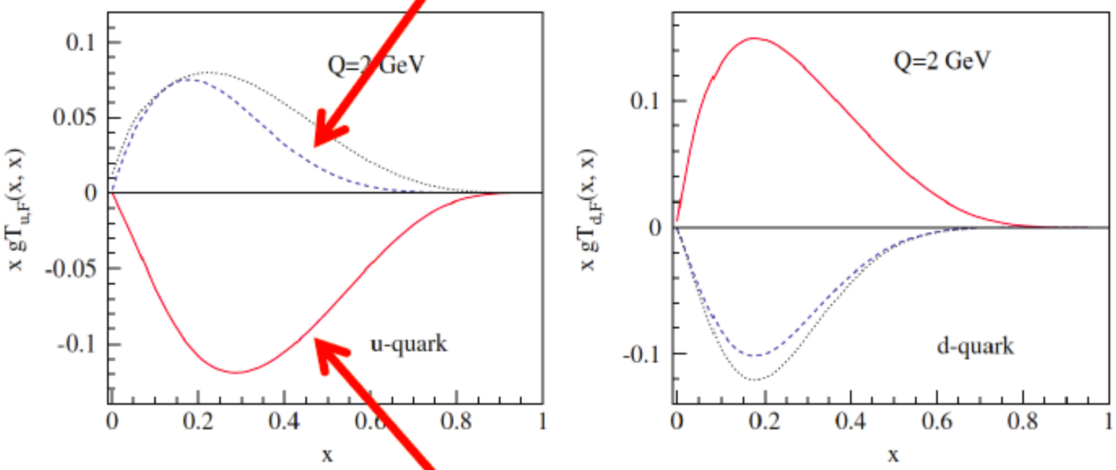



**COMPASS**




- Global fit to sin $(\phi_h - \phi_S)$ asymmetry in SIDIS (HERMES, COMPASS)
- Comparable measurements needed for single spin asymmetries in Drell-Yan process
  - Caution: Nothing excludes a node
  - Must cover same kinematics with Drell-Yan and SIDIS

from $-\int \frac{d^2\vec{k}_\perp}{2\pi}\frac{\vec{k}_\perp^2}{M^2}\left(f_{1T}^\perp(x,k_\perp)\right)_{\rm DIS}$




- basic observation:

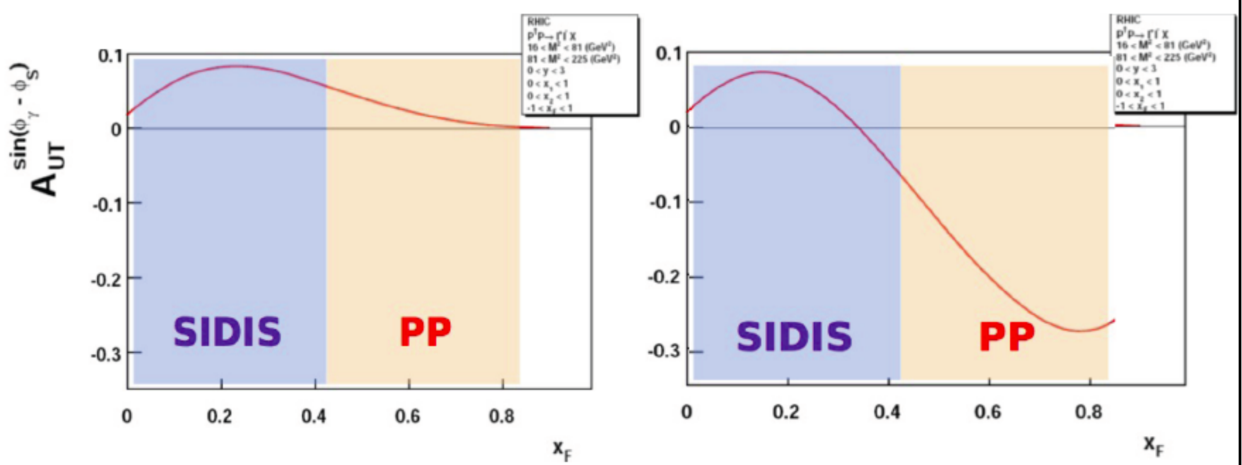
  SIDIS $\pi^+$ : *final-stat*

  $pp \to \pi^+ X$ : *initial-sta*

From V. Vogelsang's talk

Has ramifications for DY spin asymmetry:

Kang,Prokudin




w/o node      with node

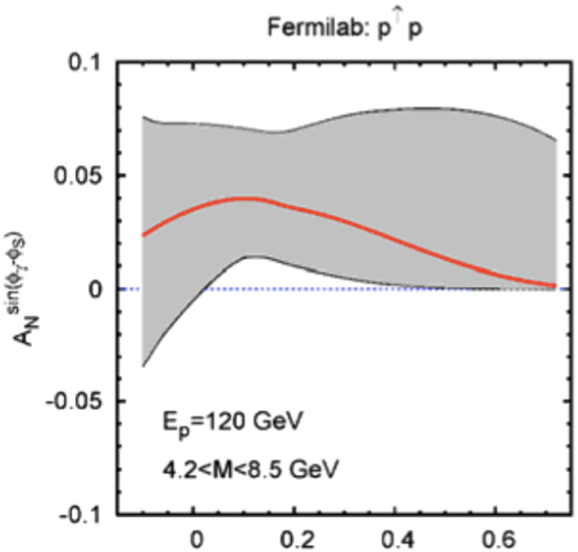
Strengthens case for study of DY "sign change" !

# Future Polarized Drell-Yan Measurements

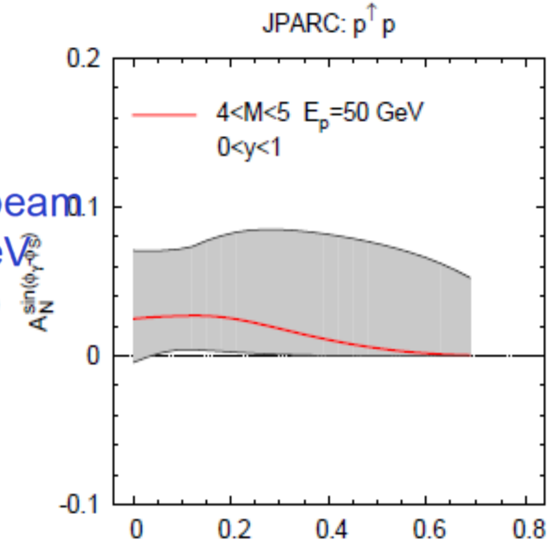
| experiment | particles | energy | $x_1$ or $x_2$ | luminosity | timeline |
|---|---|---|---|---|---|
| COMPASS (CERN) | $\pi^\pm + p^\uparrow$ | 160 GeV $\sqrt{s}$ = 17.4 GeV | $x_2 = 0.2 - 0.3$ $x_2 \sim 0.05$ (low mass) | $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ | >2012 |
| PAX (GSI) | $p^\uparrow + p_{par}$ | collider $\sqrt{s}$ = 14 GeV | $x_1 = 0.1 - 0.9$ | $2 \times 10^{30}$ cm$^{-2}$ s$^{-1}$ | >2017 |
| PANDA (GSI) | $p_{par} + p^\uparrow$ | 15 GeV $\sqrt{s}$ = 5.5 GeV | $x_2 = 0.2 - 0.4$ | $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ | >2016 |
| J-PARC | $p^\uparrow + p$ | 50 GeV $\sqrt{s}$ = 10 GeV | $x_1 = 0.5 - 0.9$ | $1 \times 10^{35}$ cm$^{-2}$ s$^{-1}$ | >2015 ?? |
| NICA (JINR) | $p^\uparrow + p$ | collider $\sqrt{s}$ = 20 GeV | $x_1 = 0.1 - 0.8$ | $1 \times 10^{30}$ cm$^{-2}$ s$^{-1}$ | >2014 |
| PHENIX (RHIC) | $p^\uparrow + p$ | collider $\sqrt{s}$ = 500 GeV | $x_1 = 0.05 - 0.1$ | $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ | >2018 |
| RHIC internal target phase-1 | $p^\uparrow + p$ | 250 GeV $\sqrt{s}$ = 22 GeV | $x_1 = 0.25 - 0.4$ | $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ | >2018 |
| RHIC internal target phase-1 | $p^\uparrow + p$ | 250 GeV $\sqrt{s}$ = 22 GeV | $x_1 = 0.25 - 0.4$ | $6 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ | >2018 |
| $A_n$DY RHIC (IP-2) | $p^\uparrow + p$ | 500 GeV $\sqrt{s}$ = 32 GeV | $x_1$ = ?? | ?? cm$^{-2}$ s$^{-1}$ | >2015 |
| **SeaQuest (unpol.) (FNAL)** | $p + p$ | 120 GeV $\sqrt{s}$ = 15 GeV | $x_1 = 0.3 - 0.9$ | $3.4 \times 10^{35}$ cm$^{-2}$ s$^{-1}$ | 2011 |
| **pol. SeaQuest (FNAL)** | $p^\uparrow + p$ | **120 GeV $\sqrt{s}$ = 15 GeV** | $x_1 = 0.3 - 0.9$ | $1 \times 10^{36}$ cm$^{-2}$ s$^{-1}$ | **>2014** |

From W. Lorenzon's talk

# $A_N^{\sin(\varphi\gamma-\varphi s)}$ prediction Anselmino *et al*

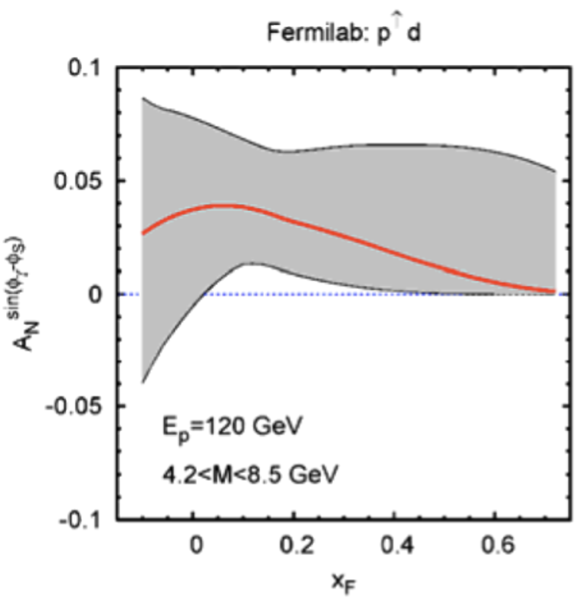



FNAL
120 GeV
polarized beam
√s ~ 15 GeV
(hydrogen)

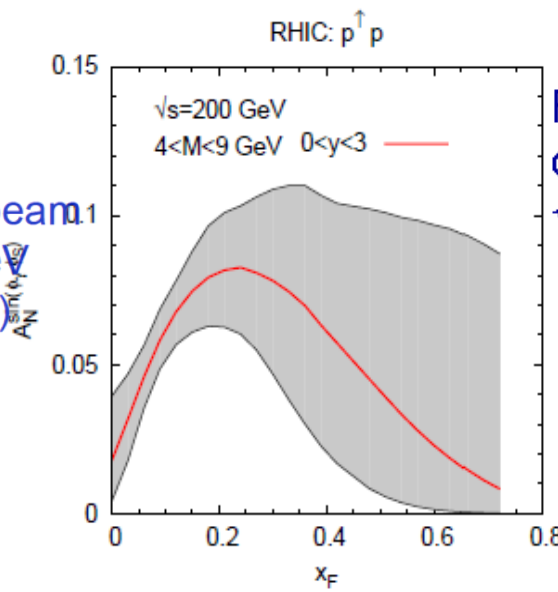



J-PARC
50-GeV
polarized beam
√s ~ 10 GeV

- $A_N \approx 0.04$
- Uncertainty dominated by lack of SIDIS data




FNAL
120 GeV
polarized beam
√s ~ 15 GeV
(deuterium)




RHIC
collider
√s = 200 GeV

Anselmino et al. priv. comm. 2010

Anselmino et al. PRD79, 054010 (2009)

# Drell-Yan Measurements of the Sivers Distribution

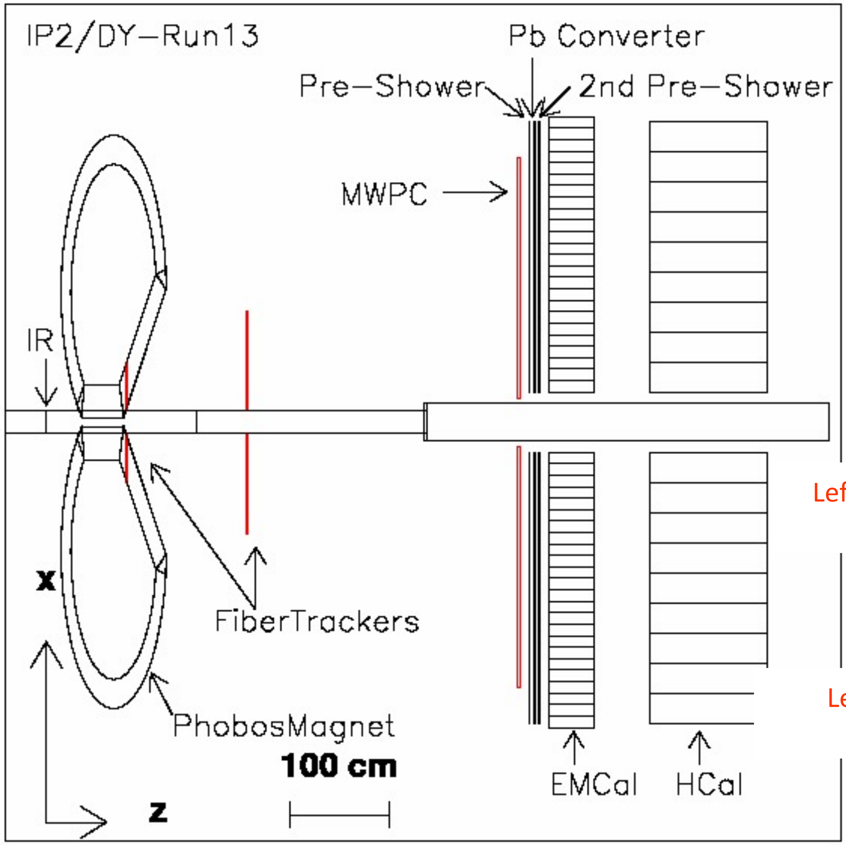
- Brookhaven/RHIC ANDY $p\vec{p}$
  - Possibility for both beams to be polarized?
  - See talk by Les Bland
- CERN Compass $\pi^- \vec{p}$
  - Polarized valence u-quark distributions at small-x
  - See talks by Oleg Denisov and by Oleg Teryaevolfgang Lorenzon
- Fermilab $\vec{p}p$
  - Polarized Valence Distributions at large-x
  - See talk by Wolfgang Lorenzon

**Remember 9beginning of the journey) different beams and targets probe different distribs.**

| Beam | Target | Experiment |
|---|---|---|
| Hadron | Beam valence quarks target antiquarks | Fermilab E-906, RHIC (forward acpt.) J-PARC |
| Anti-Hadron | Beam val. antiquarks Target val. quarks | GSI-FAIR Fermilab Collider |
| Meson | Beam val. antiquarks Target val. quarks | COMPASS |

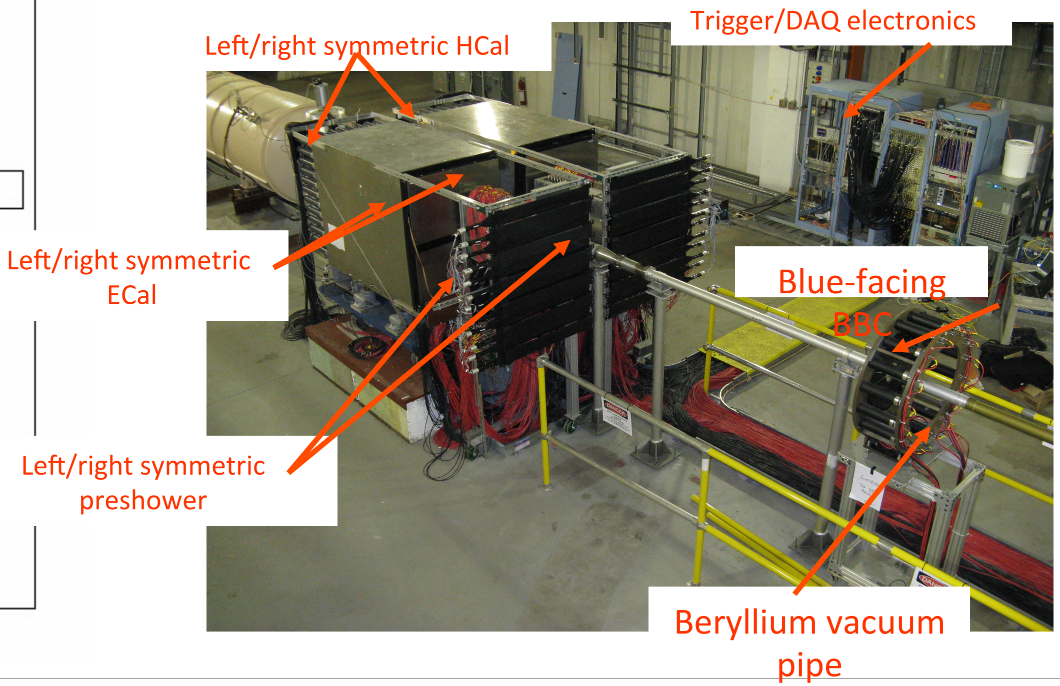
# $A_N$DY@RHIC

- See talk by Les Bland
- Calorimetry required for experiment is at BNL. It is on loan from JLab until July 2014.



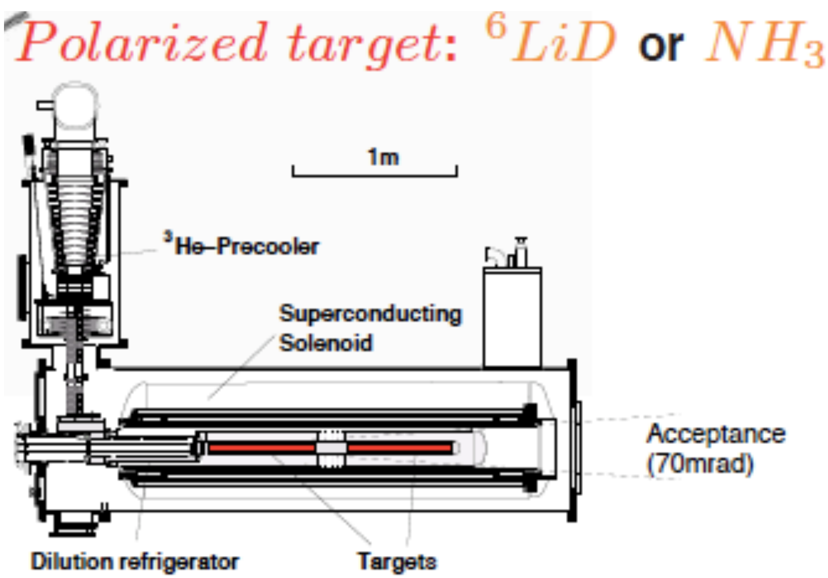

http://www.star.bnl.gov/~akio/ip2/topview_run13.jpeg

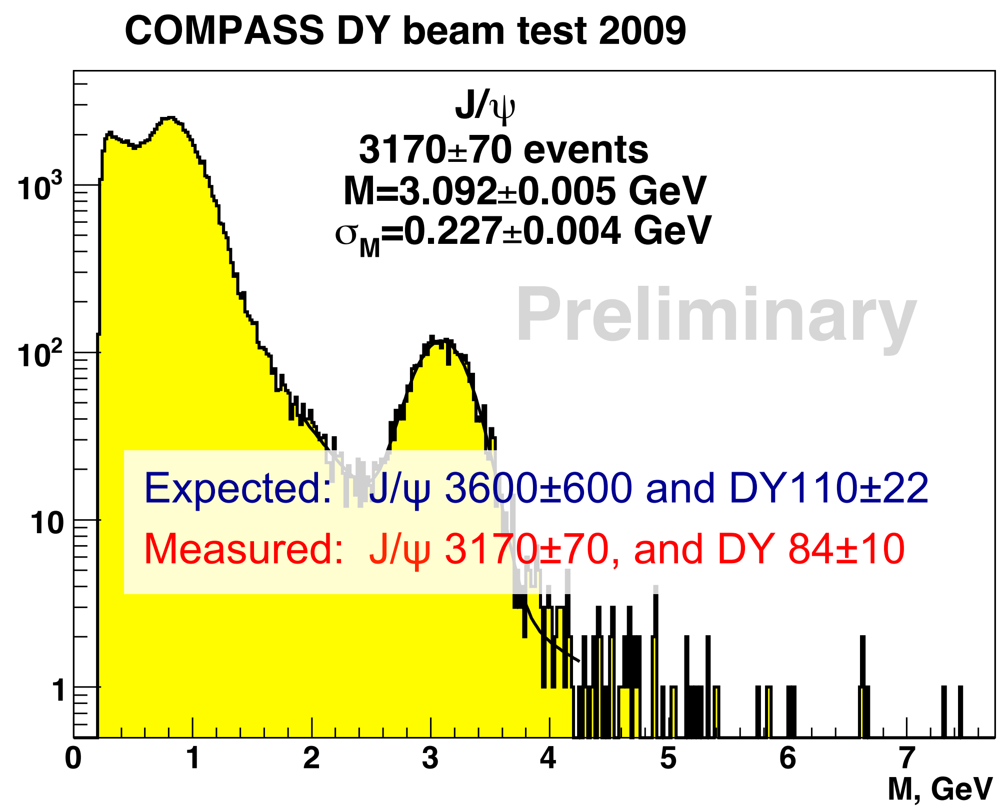
- Layout for second stage (no magnet) is complete, with specification of azimuthally complete HCal, ECal and segmented preshower detector.
- Existing split dipole does require modification to match acceptance of final calorimetry plan.
- Staging of apparatus awaits funding review.
- At present, first attempt at transverse spin DY measurement will be in RHIC run 13



# COMPASS@CERN

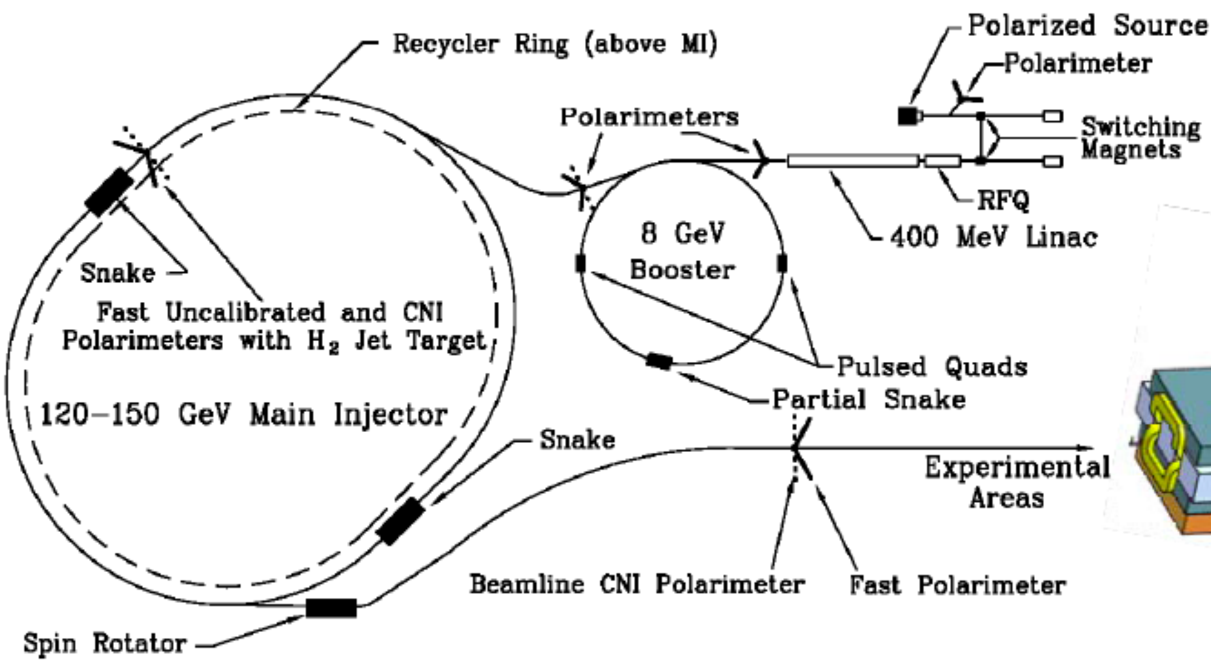
- See talk by Oleg Denisov
- Very well understood apparatus
  - $A_N$ angular measurements already completed for SIDIS
  - MC and test data match
- Polarized target
- Data in 2014

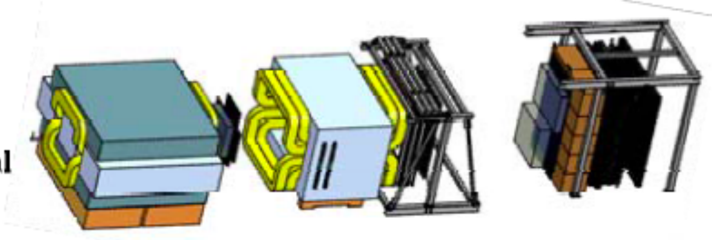


# Fermilab Polarized Main Injector

- See talks by W. Lorenzon, A. Krisch, D. Sivers
- Polarized beam
  - Major advantage—the beam is a blow torch—Luminosity
  - Major disadvantage—the beam polarization is presently virtual—only a proposal
  - **Relatively inexpensive!!**
- By 2014, spectrometer will be well understood, including angular acceptance



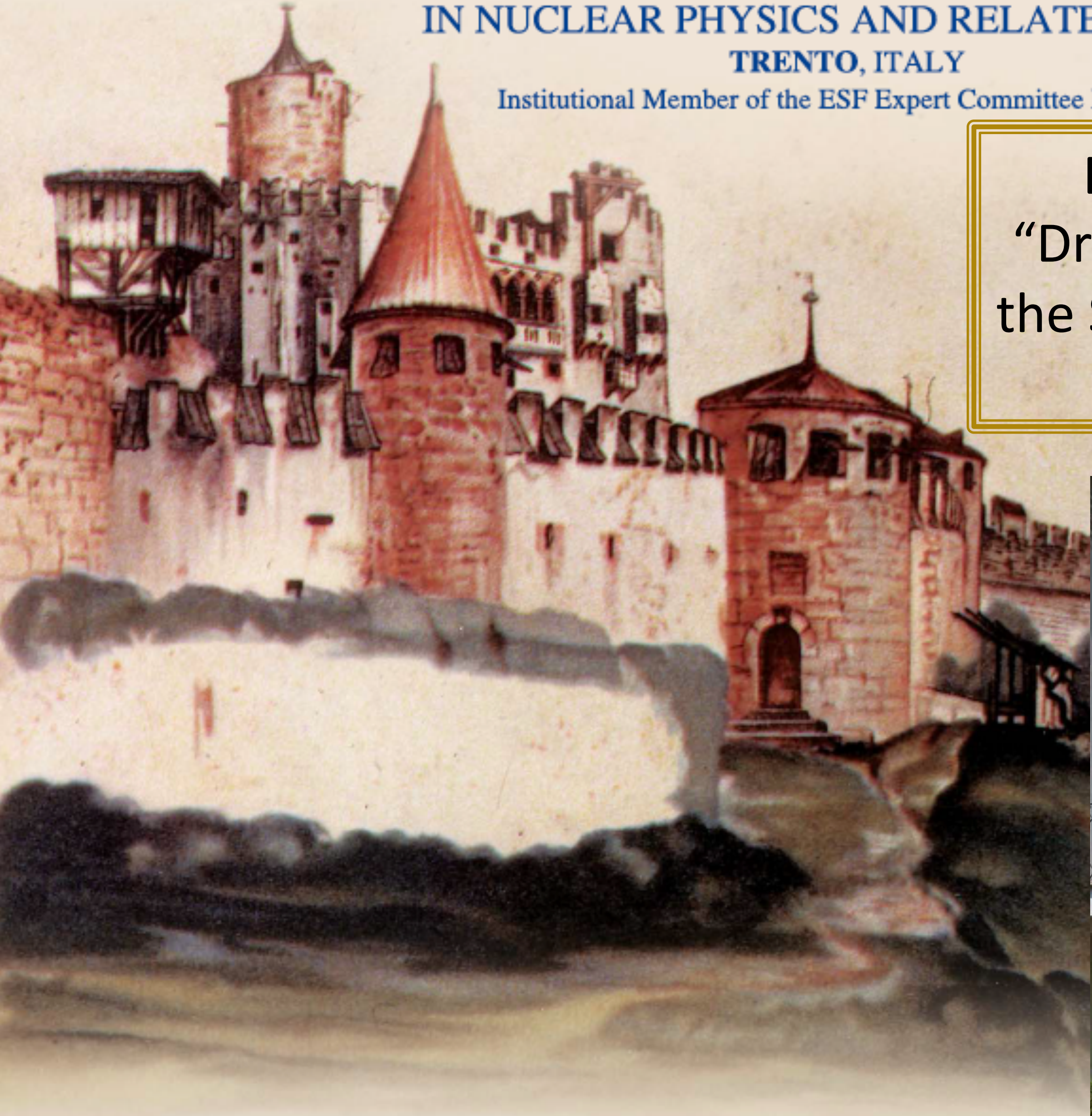
# ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

**TRENTO**, ITALY

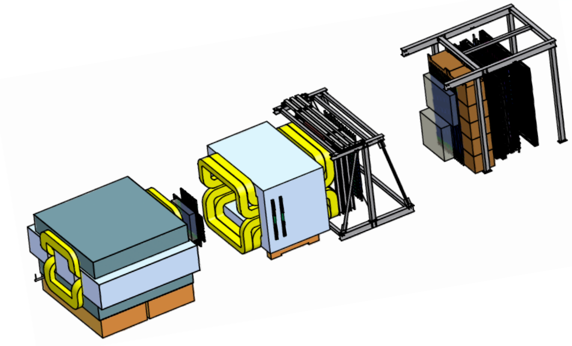
Institutional Member of the ESF Expert Committee NuPECC

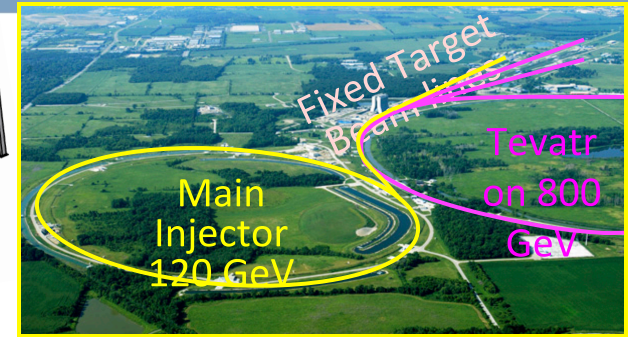
ECT* workshop on
"Drell-Yan Scattering and the Structure of Hadrons"
21-25 May 2012



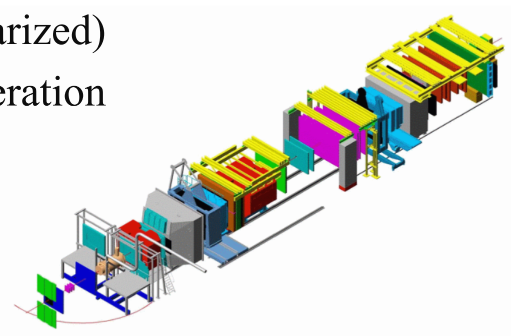
Castello di Trento ("Trint"), watercolour, 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495)

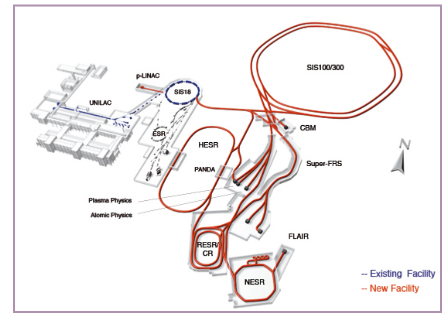
# Future Drell-Yan Experiments



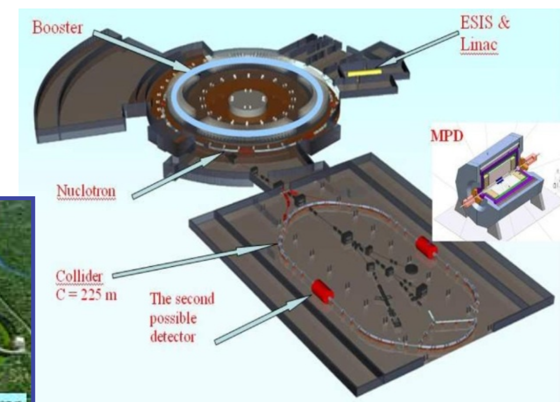



- Fermilab E-906/Drell-Yan
  - Better statistical precision (unpolarized)
  - Polarized extension under consideration
- COMPASS
  - Pion beam—valence distributions

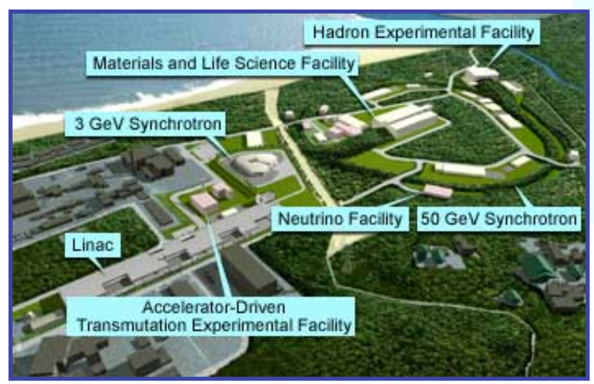




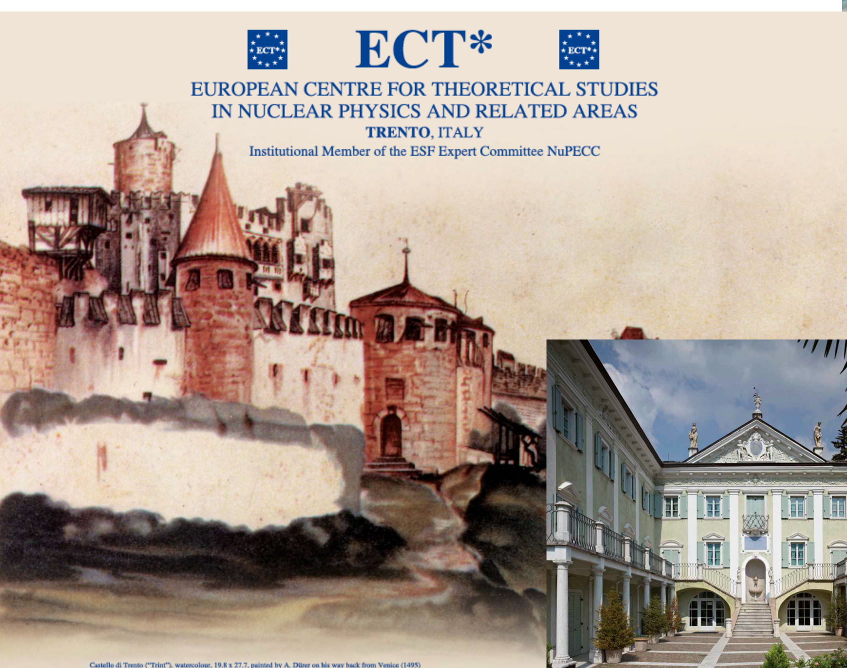

- GSI FAIR—PAX experiment
  - Antiproton beam will sample valence distributions of targets




- JINR Dubna-NICA
- J-PARC
- RHIC

# It is a long trip, but in the end, it's worth it!




# Additional Material

# Boer-Mulders Structure Function

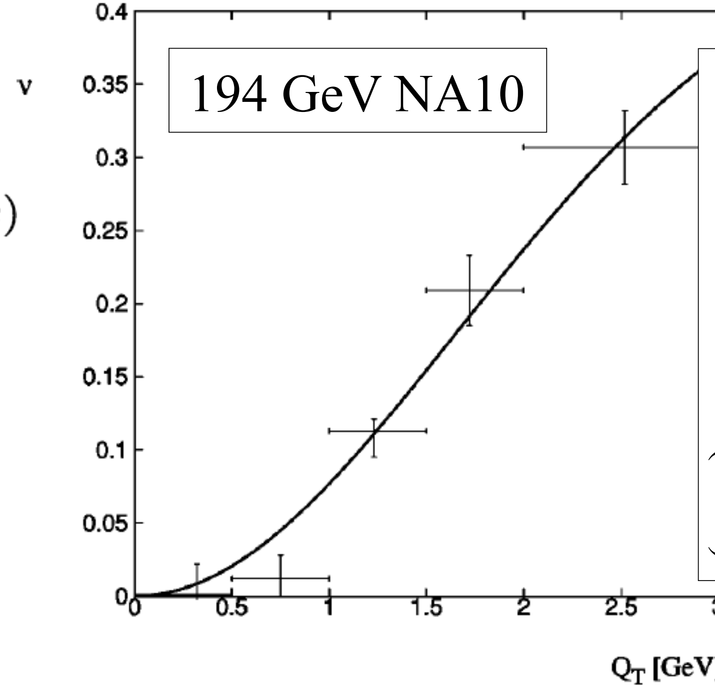
- Relates parton's transverse spin and transverse momentum ($k_T$) in an unpolarized nucleon.
- Presence in both quark and antiquark in annihilation could form correlation contributing to cos(2ϕ) distribution

$$\nu \propto h_{1q}^{\perp}(x_1) h_{1\bar{q}}^{\perp}(x_2)$$

$$h_1^{\perp}(x, k_T^2) = C_H \frac{\alpha_T}{\pi} \frac{1}{k_T^2 + {M_C}^2} e^{-\alpha_T k_T^2} f_1(x)$$

$$\nu = 16 C_1 C_2 \frac{p_T^2 {M_C}^2}{(p_T^2 + 4{M_C}^2)^2}$$

$$M_C = 1.2 \pm 0.5 \text{ GeV}$$
$$16 C_1 C_2 = 7 \pm 2$$




Boer PRD 60 014012 (1999)

FIG. 4. Data from [3] at 194 GeV and fit [using Eq. (49)] to $\nu = 2\kappa$ as a function of the transverse momentum $Q_T$ of the lepton pair. The fitted parameters are $M_C = 2.3 \pm 0.5$ GeV and $16\kappa_1 = 7 \pm 2$.

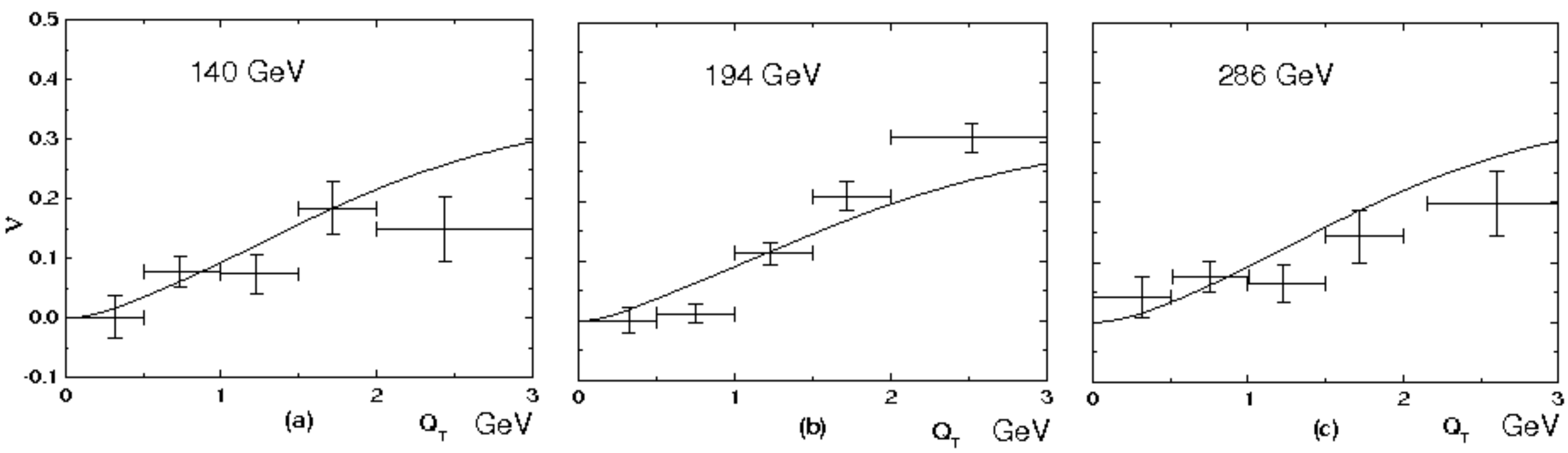
# Boer-Mulders Structure Function

- Lu and Ma—quark-spectator-antiquark model

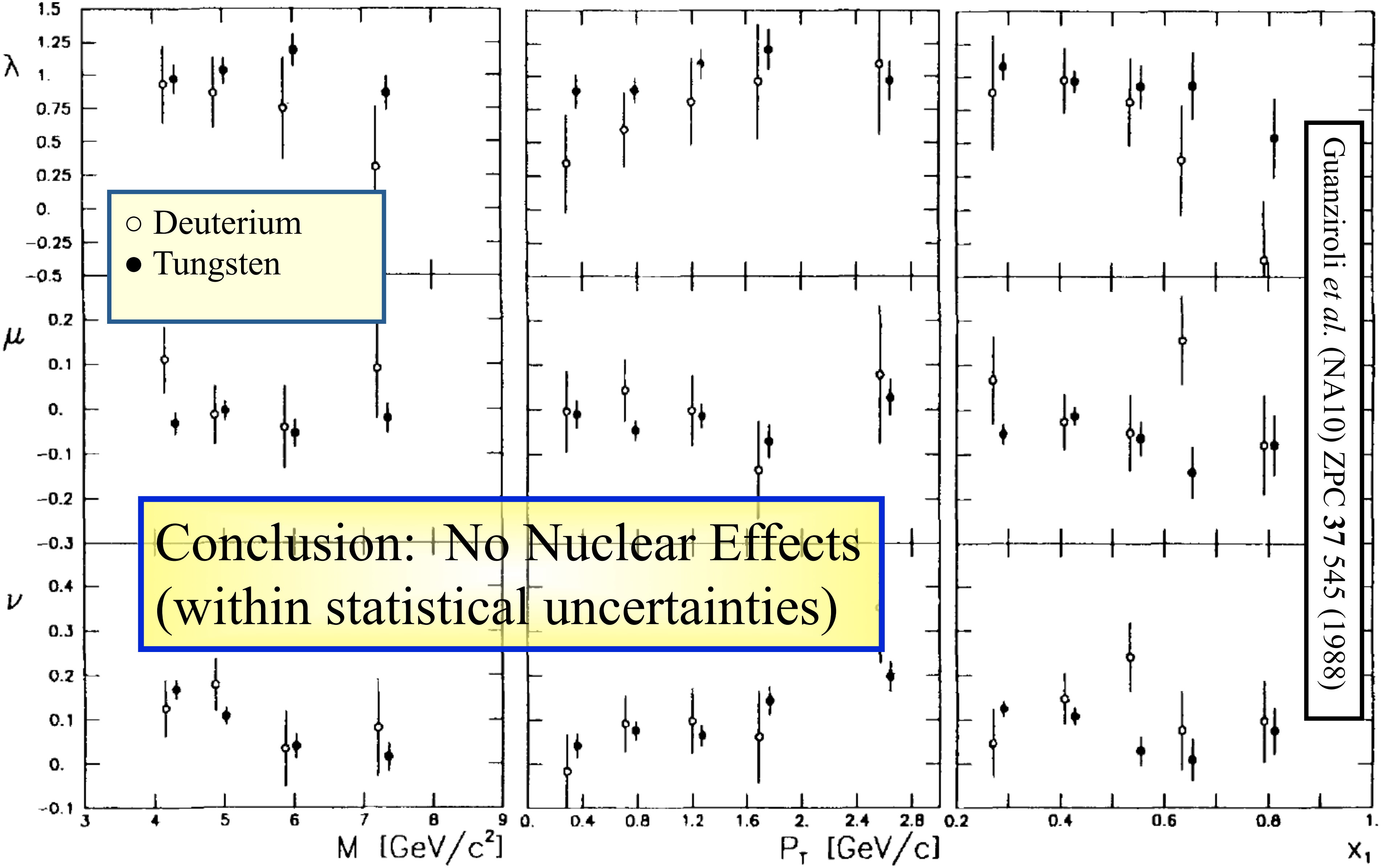
$$h_{1\pi}^{\perp} = \frac{A_\pi(x)}{k_\perp^2\,[k_\perp^2 + B + \pi(x)]} \ln\left[\frac{k_\perp^2 + B_\pi(x)}{B_\pi(x)}\right]$$

- Fit all three NA10 energies

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

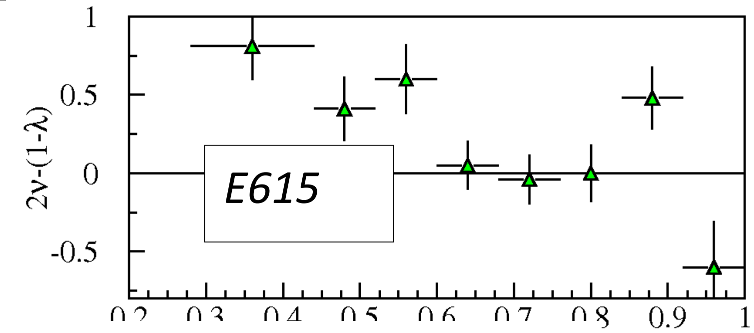


# Nuclear Effect? Compare NA10 Deuterium and Tungsten

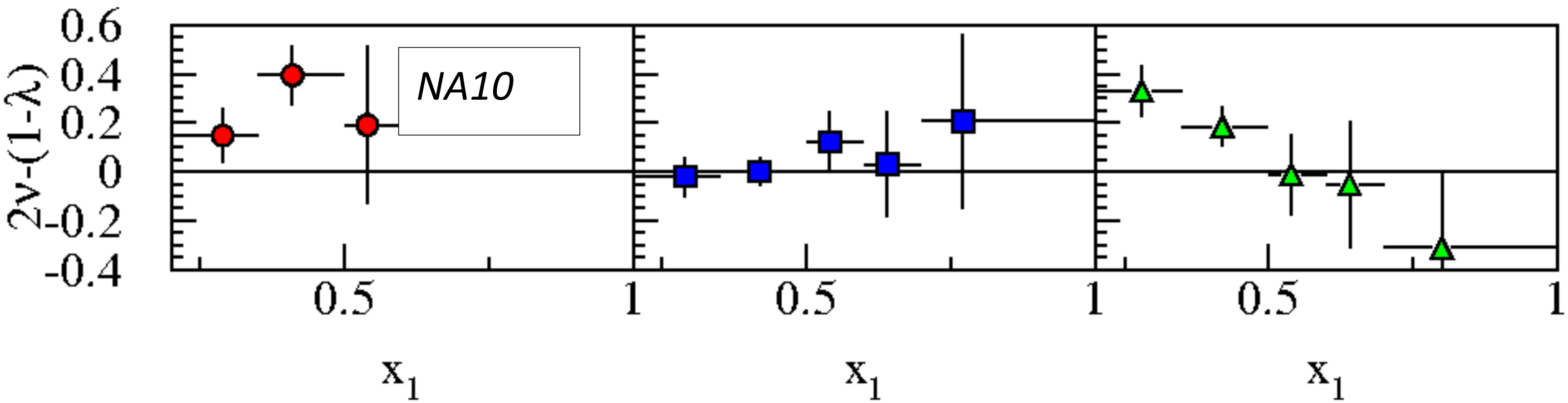



Conclusion: No Nuclear Effects (within statistical uncertainties)

# 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